I.FAST

Innovation Fostering in Accelerator Science and Technology

Horizon 2020 Research Infrastructures GA n° 101004730

DELIVERABLE REPORT

Strategy for the development of the AMICI TI

DELIVERABLE: D13.1

Document identifier:	IFAST-D13.1
Due date of deliverable:	End of Month 31 (October 2023)
Report release date:	30/10/2023
Work package:	WP13
Lead beneficiary:	CEA
Document status:	Final

ABSTRACT

An extensive inventory of the available accelerator and magnet Technical Platforms (TPs) within different Technological Facilities (TFs) is presented. The characteristics and functionalities of these TPs are documented and are accessible through the AMICI (Accelerator and Magnet Infrastructure for Cooperation and Innovation) website. Additionally, a comprehensive analysis of the global landscape of future accelerator and magnet based RIs is reported. This analysis identified Key Technological Areas essential for constructing future RIs.

This document is intended to serve as a roadmap for enhancing the efficiency and effectiveness of research in accelerator and superconducting magnet technologies across various disciplines.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730. IFAST began in May 2021 and will run for 4 years.

Delivery Slip

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Approved by	Steering Committee		30/10/2023

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Executive summary

Within the AMICI project, an extensive inventory of the available Technical Platforms (TPs) within different TFs was undertaken. The characteristics and functionalities of these TPs were documented and are accessible through the AMICI website. Additionally, the project conducted a comprehensive analysis of the global landscape of future accelerator and magnet-based RIs. This analysis identified Key Technological Areas essential for constructing future RIs.

The overarching objective of Task 13.1 within the project is to outline a strategic roadmap for the development and enhancement of the AMICI TI. The focus is on key Technology Platforms (TPs) in critical technological areas that align with potential engagement in new projects, both within Europe and beyond. This strategic roadmap also emphasizes optimizing the synergy between different Technological Facilities (TFs) and increasing involvement with industrial partners. Furthermore, a vital aspect is to raise awareness about the AMICI TPs and encourage their utilization by external users, particularly in the industrial sector.

To achieve these goals, gaining a comprehensive understanding of the needs in various fields of applications is paramount. This is addressed in section 2, which delves into the scientific landscape across different domains, considering RIs or facilities under construction, upgrade, or planning. Notable examples include Particle Physics, Nuclear Physics, Energy, Material, and Biological Science, Accelerators for Medicine, Accelerators for Radioisotope Production, and various other applications.

Section 3 is devoted to an overview of key TPs in key technology areas that should be sustained over the long term, adapted, upgraded or possibly created in order to meet the needs identified in the previous section. It highlights the crucial role of AMICI laboratories, in collaboration with European institutes, in the field of accelerator research and development. It emphasizes the need for facility upgrades to align with emerging trends in the industry. European expertise in superconducting magnets is showcased.

Collaboration and knowledge sharing are acknowledged as essential, despite the challenges faced in fostering partnerships. The authors identifies future trends, such as increasing duty cycles, advanced cooling solutions, and the utilization of high-temperature materials.

This document serves as a roadmap for enhancing the efficiency and effectiveness of research in accelerator and superconducting magnet technologies across various disciplines.

1 Introduction

The H2020 INFRAINNOV-02 AMICI (Accelerator and Magnet Infrastructure for Cooperation and Innovation) project has led to the establishment of the AMICI distributed Technology Infrastructure (TI) that gathers the main laboratories in Europe operating large scale Technological Facilities (TFs) dedicated to the development, fabrication, assembly and testing of superconducting magnets and accelerator components. These facilities have long been essential for the building, in association with industry for mass production, of major accelerator-based Research Infrastructures (RIs) in many scientific fields. They include a wide variety of Technical Platforms (TPs), ranging from small characterization or measurement labs to big test stations for cryogenic components or large clean assembly room, covering different technology areas, which are or can be made available to industrial companies for other types of applications. The AMICi TFs are shown in Fig.1 from [1].

Figure 1. The AMICI European Technology Infrastructure in the H2020 INFRAINNOV-02 AMICI project.

During the AMICI project, the available TPs in the different TFs with their characteristics and functionalities have been inventoried, and they are presented in the AMICI website [2] and in the booklet [1]. The global landscape of future accelerator and magnet based RIs has been analysed and Key Technological Areas crucial for the construction of future RIs have been identified.

Keeping the AMICI TI at the highest technical standard in the global competition is crucial for both the building of future RIs and for the European industry to develop other applications, with the long-term goal of maintaining European leadership in science and technology. The overall objective of Task 13.1 is therefore to propose a strategy for the development/update of AMICI TI, focusing on areas where European TFs are or could be leaders and fostering its use by industry. This includes:

- Defining the roadmap for the strategic evolution and development of the AMICI TI, in terms of key Technology Platforms (TPs) in key technological areas, which are required in view of the possible opportunities of engagement in new projects, in Europe, and outside Europe.
- Optimizing the complementarity between the different Technological Facilities (TFs) and maximize the involvement of their industrial partners by defining which interventions are needed to adapt the European TI in order to satisfy the requests from Industry.
- Raising awareness about the AMICI TPs and promote their use by external users in particular industry.

To achieve these goals, it is first necessary to have an updated global view of the needs in the different fields of applications. This is done in section 2, which presents the landscape of the different scientific domains, regarding the RIs or facilities that are under construction, upgrade or planned, as far as possible based on roadmaps or reports prepared by the relevant communities. This is the case for instance for particle physics, for which the recently released European Strategy for Particle Physics - Accelerator R&D Roadmap [3] has been extensively used and for nuclear physics, for which the report is based on documents from NuPECC (the Nuclear Physics European Collaboration Committee). Similarly, the sections devoted to accelerator-based photon and neutron sources drew on recently published reports by the respective strategic coordinating bodies, LEAPS (League of European Accelerator-based Photon Sources) and LENS (League of European Neutron Sources). The focus is put on European facilities and facilities outside Europe with which the AMICI TFs are used to or could have the opportunity to collaborate but, when possible, a broader view is presented. Key technological areas common to the different fields are highlighted.

Section 3 is devoted to the implications on the necessary developments/upgrades of the different categories of TPs. In order to facilitate the comparison between different TPs, a standard list of categories have been adopted and is given in section 3.1. For each category, taking into account the needs for the different domains, but also the requests from industry expressed during the IFAST workshops or through the IFAST IAB, necessary improvement, developments or upgrades are identified.

2 Needs for the different fields of applications

2.1 Particle Physics

The European Strategy for Particle Physics Update (ESPPU) [3] has recently proposed a vision for both the near-term and the long-term future of the field. A timeline (which does not include other facilities under discussion in the rest of the world, as for instance the CEPC in China) has been established and is shown below.

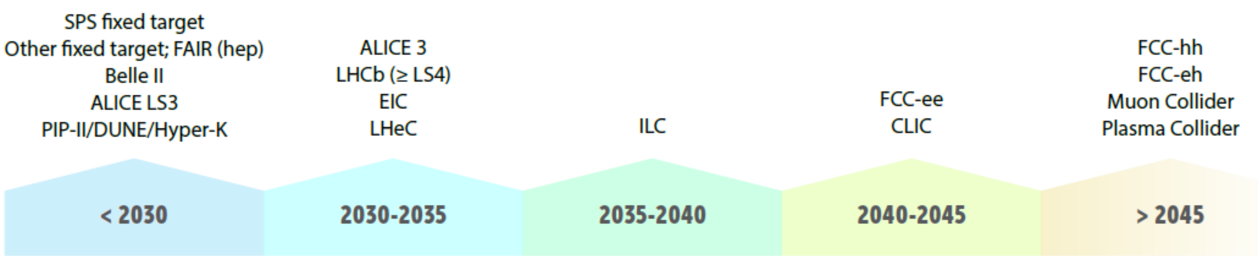

Figure 2. Future accelerator facilities time line from https://arxiv.org/ftp/arxiv/papers/2201/2201.07895.pdf

As of today, all large-scale particle accelerator facilities are based on radio frequency (RF) acceleration and use of superconducting (SC) magnets. The related technologies are still evolving, and the envisaged advanced RF and SC magnets performances are based on several novel developments. Despite recent developments in the field of plasma acceleration, the next generation of particle accelerators will likely be still based on RF technology, but will require operational parameters in excess of state of the art. New Nb3Sn and high critical temperature (HTS) superconductors are also being developed to push the limit of the magnet field in accelerator magnets. An advanced R&D program can be assumed, and details are documented e.g. in the recently published Accelerator R&D Roadmap (https://arxiv.org/ftp/arxiv/papers/2201/2201.07895.pdf) discussed as part of the European Strategy for Particle Physics.

2.1.1 High-field magnets

High field magnets (HFMs) are among the key technologies that will enable the search for new physics at the energy frontier. Since the Tevatron in 1983, through HERA in 1991, RHIC in 2000 and finally the LHC in 2008, all hadron colliders have been built with superconducting (SC) magnets. The magnets used a superconducting alloy of niobium and titanium, like the LHC dipoles, with a nominal field strength of 8.33 T when cooled by superfluid helium at 1.9 K.

At the same time, approved projects and studies for future circular machines include the development of superconducting magnets that produce higher fields than those achieved in the LHC. This is the case for the High Luminosity LHC (HL-LHC) upgrade, which is currently under construction at CERN, and for the design study of the Future Circular Collider (FCC). Similar studies and programmes are underway outside Europe, such as China's Super Proton Collider (SppC). Significant advances in the field of SC accelerator magnets have been made through earlier studies such as Fermilab's Very Large Hadron Collider and the US-DOE muon accelerator program. Similarly, initial thoughts on dipoles using high critical temperature (HTS) superconductors for ultra-high fields (20 T) were encouraged by the High-Energy Large Hadron Collider study at CERN. Finally, new accelerator concepts, such as the muon colliders currently being studied by CERN and its collaborators, will pose significant challenges to their magnetic systems.

The current state of the art in HFM for accelerators is based on Nb3Sn material, with magnets producing fields in the range of 11 T to 14 T. Great interest has also been generated in recent years by the progress made in the field of HTS, not only in the manufacture of accelerator magnet demonstrators for particle physics, but also in the successful testing of magnets in other application areas such as fusion and power generation. This shows that the performance of HTS magnets will exceed that of Nb3Sn magnets, and that the two technologies can be complementary in producing fields of the order of 20 T or more.

HFM R&D programs will need to build on the results achieved over the last 20 years in previous European and international programs such as EU FP6 Coordinated Accelerator Research in Europe (CARE), EU FP7 European Coordination for Accelerator Research & Development (EuCARD), EU FP7 Enhanced European Coordination for Accelerator Research & Development (EuCARD2), EU FP7 Accelerator Research and Innovation for European Science and Society (ARIES), and current work such as HL-LHC, EU H2020 Innovation Fostering in Accelerator Science and Technology (I-FAST), CERN-HFM and US Magnet Development Program (US-MDP).

HFM R&D programs have two main objectives. The first is to demonstrate Nb3Sn magnet technology for large-scale deployment. This will involve pushing it to its practical limits in terms of ultimate performance (towards the 16 T target required by the FCC-hh), and scaling up to production through robust design, industrial manufacturing processes and cost reduction, taking the HL-LHC magnets as a reference, (i.e. 12 T). The second objective is to demonstrate the suitability of high-temperature superconductors (HTS) for accelerator magnet applications, providing a proof of principle of HTS magnet technology beyond the Nb3Sn range, with a target of over 20 T. The above targets are indicative, as the decision on a cost-effective and practical field of operation will be one of the main outcomes of the development work.

The conductor activities are being developed along two axes. R&D on Nb3Sn is pushing the existing limits to critical currents of 1500 A/mm2 at 16 T and 4.2 K, by establishing robust wire and cable configurations at reduced cost. These will then be the subject of an industrialisation process. For HTS superconducting conductors, the intention is to identify and qualify suitable tapes and cables, and to continue with industrial production to prove the feasibility of large unit lengths (target 1 km) of superconducting tapes with characteristics suitable for accelerator magnet applications.

For Nb3Sn magnets, two objectives have been defined: the development of a 12 T demonstrator of proven robustness suitable for industrialization, in parallel with the development of an accelerator dipole demonstrator reaching the ultimate field for this material, towards the 16 T target.

R&D plans for HTS magnets focus on manufacturing and testing of representative models to demonstrate performance and operation beyond the range of Nb3Sn. For HTS magnets, a dual objective is proposed: the development of a hybrid LTS/HTS accelerator magnet demonstrator and a full HTS accelerator magnet demonstrator, with a target of 20 T. Special attention will be devoted to the possibility of operating in an intermediate temperature range (10K to 20 K).

The programs described here depend critically on the availability of R&D, fabrication, and test infrastructure, as well as improved and new instrumentation for measurements and diagnostics.

Distributed infrastructure is needed at the various laboratories involved in HFM development, in particular workshop facilities for short magnet and demonstrator construction (magnet labs), as well as cryogenic test facilities for small components, samples, and short magnets and demonstrators (cryogenic test stations). Consolidating and upgrading these distributed infrastructures, some of which are already available or under construction, is one of the priority activities of the initial phase of the program.

This is particularly true for the Nb3Sn long magnet infrastructure, which is demanding in terms of space, investment, and operational requirements. It is proposed that the acquisition and construction of these facilities and infrastructure be phased throughout the proposed steps of the program, also involving industry that could host some of them, as appropriate.

Significant infrastructure and facilities identified for superconductor and magnet activities are listed below, classified as either manufacturing infrastructure or test infrastructure:

Manufacturing Infrastructure:

- Rutherford-cabling machines for the development and laboratory-scale production of Nb3Sn cables with large in-field current capability and a large number of strands (typically 40 to 60).
- Novel cabling machines for the development and production of long lengths of new types of HTS cables. This will require the prior development and demonstration of HTS cable concepts appropriate for use in accelerator magnets, which will be the outcome of the preliminary R&D phase on HTS conductor.
- Dedicated electrical insulation and braiding machines, providing the electrical insulation of cables.
- Dedicated winding machines for the production of LTS and HTS coils, operated in grey rooms and suitable for a high degree of automation.
- Short (3m for R&D) and long (up to 15m for long magnets) reaction furnaces for the heat treatment of Nb3Sn coils in controlled atmosphere.
- Short (3m for R&D) and long (up to 15m for long magnets) chambers for vacuum pressure impregnation of LTS and HTS coils.
- Short and long presses and tooling for different assembly steps (e.g. curing, collaring or keying, welding).

Test infrastructure:

- Test stations for the electro-mechanical qualification of HTS and LTS wires and tapes, in external magnetic fields up to 18 T for Nb3Sn and in excess of 20 T (ideally up to 25 T) for HTS. Liquid helium conditions are needed (1.9K and 4.5K) but allowing also higher temperatures (10K to 20K range).
- A test station for HTS and LTS cables, requiring conditions of field and temperature comparable to those for single wires and tapes, but also high currents and large aperture.
- A test station consisting of a high-field magnet with a large bore, providing a background field and enabling the measurement of HTS coils in a significant magnetic field. The need of measuring HTS coils in a background magnetic field is a new input for test infrastructure, a specific requirement for the qualification of HTS sub-scale and R&D magnets.
- Vertical test stations for the test of LTS and HTS R&D and demonstrator magnets at cryogenic temperature (1.9K and 4.5K for Nb3Sn, and variable temperatures from liquid helium to liquid nitrogen for HTS).
- Multi-purpose, horizontal or vertical test facilities for long cryomagnet assemblies (including test for lengths of coils/cold masses of up to 15 m).

- Equipment for standard electrical and mechanical tests and measurements.
- Equipment for high voltage tests, tests in Paschen conditions, and partial discharge tests at small and full scales.
- Magnetic measurement benches adapted to the R&D magnets and demonstrators.

Energy efficiency efforts should also be considered as one of the objectives in the development of the next generation of magnets. The use of HTS conductors operating at higher temperatures could be a significant step in the right direction.

The proposed program will also address the impact of HFM magnet development on the industrial ecosystem and on the training and education of future generations of applied researchers. One of the objectives is to propose actions to support European industry, responding to the current evolution of business models, and to promote the deployment of developments and innovations from research to industry.

The program also wishes to emphasize collaborations, and connections with ongoing activities around the world. The realization of the HFM program will build on a broad and resilient skill base, a strong community, and provide an opportunity to educate the next generation on technology-intensive topics.

2.1.2 Advanced technologies for superconducting and normal-conducting radio-frequency (RF) accelerating structures

The R&D covers superconducting RF (SRF), normal conducting RF (NC RF) and ancillary systems such as RF sources, couplers, tuners and the systems that control them. Each new system requires a developing phase, during which new ideas are tried-out, a prototyping phase that leads to the first completely defined components, which are to be extensively tested, a pre-series phase, needed for qualification of vendors and sources for fabrication including assembly, and finally a production phase which is well developed and qualified for series production and testing. All phases need test infrastructures, from a project point of view some of them in-house, some in industry, and some as shared infrastructure. The larger the project i.e. the number of components during series production is, the more important becomes the search for professional and qualified infrastructure. Each new project needs to investigate if the use of already existing test infrastructure is possible and advantageous from an economical point of view, or if such existing infrastructure offers benefits like improved quality assurance based on well trained and specialized teams, or simpler, if the additional set-up of new infrastructure is exhaustive and not recommended as part of the project. The above-mentioned report [4] gives some highlights for actually discussed facilities, be it the International Collider ILC, the CLIC collider, energy-recovery linacs and muon colliders. In the following, some actually envisaged advanced technologies are listed. Comments are made with respect to the required test infrastructure.

Research and development in this field emphasize both, the study of improved or new material and the development of accelerating structures / cavities. In addition, RF power couplers are to be further developed, and the same may hold for other auxiliaries like frequency tuners or integrated diagnostics to support technical interlock systems. At the end, complete system tests are required.

In SRF the development is focused in two areas, bulk niobium and thin-film (including high-Tc) superconductors. In bulk SRF new treatments are allowing niobium cavities to exceed previous record Q factors and avoiding degradation with increasing gradients. This includes nitrogen infusion and doping, and two-step baking processes. There is also an emphasis on limiting field emission.
For thin films the community is investigating creating coated cavities that perform as good as or better than bulk niobium (but with reduced cost and better thermal stability), as well as developing cavities coated with materials that can operate at higher temperatures or sustain higher fields. One method of achieving this is to use multi-layer coatings. Innovative cooling schemes for coated cavities are also being developed. Coupled to the cavity development is improvement in the cost and complexity of power couplers for SRF cavities.

- The required respective test infrastructure starts with the investigation of samples, often adopted to coating infrastructure. The coating often happens at existing apparatus in specialized laboratories, but the test at cold temperature - typically 2 K – requires small test cryostats. There is the tendency to share such infrastructure but the increased interest in the R&D field may bring the community to some limit.
- Advancing cavities built from bulk Niobium requires vacuum furnaces. While samples can be treated in normal laboratory environment, the treatment of cavities requires larger infrastructure. Dedicated furnaces are a must.
- The coating of cavities is a more challenging effort. New set-ups will be needed in due time, an example being facilities for Atomic Layer Deposition which is very promising but also demanding. The sharing of new infrastructure is expected but it should be clear that such new techniques will also require some parallel effort in order to allow for cross-checking and reproducibility check. If successful, the technology needs to be transferred to industry.
- Thin-film and coating effort require a reasonably large number of (at least) single cell cavities to be tested. Basically, all SRF specialized laboratories operate small test cryostats. But with an increased number and throughput more elaborated test facilities may be required. Within AMICI we see the increasing request for cavity testing performed as service for other laboratories. Since the quasi-industrial testing requires the direct connection to a permanently operated helium refrigerator or even plant, the number if actually existing test sites is very few. In a cost-effective manner, the existing test cryostats may need to be extended.
- If the above-sketched R&D successfully passes the proof-of-principle phase then the prototyping needs to start. Multi-cell cavities will be tested, and this can usually happen in existing test cryostats. AMICI partners can share infrastructure, and the possible throughput will count. Since all envisaged projects (see the European Strategy Report) will use SRF technology, there may be a short come. This is of course strongly dependent on the future of the European (and worldwide) particle accelerator scene. The timeline depends on the overall development of the community (funding possibilities, projects to support science diplomacy etc.)
- Each new application of SRF technology will also require R&D wrt. auxiliaries. A clear example are RF power couplers whose design will always depend on particle beam parameters like beam current and time structure, but also on availability of materials and existence of qualified vendors. Usually RF power couplers are developed together with industry but power tested at the laboratories. Even in series production the coupler vendor often has no possibilities for RF conditioning. The necessary infrastructure exists only at the laboratories. Large projects like the European XFEL have shown that shared infrastructure is beneficial. But this usually holds more for the project construction phase and less for the development and prototyping.

Normal conducting cavities are also undergoing significant development both in the industrialization and cost reduction of S, C and X-band (3, 6 and 12 GHz respectively) linacs, as well as novel developments to increase performance. There has also been a major leap forward in the understanding of RF breakdown and conditioning over the last decade, driven by improved test infrastructure and major R&D efforts, but much is still unknown and improvements are likely. To further increase RF performance novel developments in the use of cryogenically cooled copper, higher frequency structures and different copper alloys are under investigation. Finally, for a muon collider significant R&D is required into the decreased RF performance in high magnetic fields.

- The development of warm normal conducting cavities is strongly related to RF conditioning and the study of breakdown. Therefore, the respective test infrastructures include RF power sources. A direct connection with RF power couplers is self-evident.
- The recent interest in cold normal conducting cavities, i.e. cryogenically cooled copper, requires dedicated development programs. The cooling will be easier than for SRF cavities since there is no need to go for Helium systems. But development and testing of cooling schemes well integrated in the copper cavity’s mechanical design brings new challenges. This will have an impact on test infrastructures, which are still to be specified.

Besides the further advancing of RF accelerator systems with their related auxiliaries, there are connected systems, which need attention. Also, all currently discussed and possibly realized large scale facilities will have to address the issue of sustainability which often means decreased energy consumption.

- It is expected that the energy consumption of particle accelerators will be a major driver in the next decade and the RF power is a significant fraction of that. Novel high-efficiency klystrons have been designed in the past few years, but this effort needs to move to a prototyping phase.
- In addition, fast ferroelectric tuners can reduce the required RF power for SRF accelerators, or NC RF accelerators with large beam transients. For all SRF accelerators the path towards continuous wave operation is a hot topic: optimized designs can clearly improve the energy efficiency. New frequency tuners will require extensive testing which is usually done in single cavity test stands.
- Artificial intelligence (AI) has started to show capability for classifying and potentially predicting RF faults making operating and conditioning linacs far simpler, and possibly allowing RF performance to be optimized. Low-level RF (LLRF) systems will also require R&D into standardizing and simplifying hardware to decrease development costs and to aid collaborative efforts. Extensive LLRF studies require the operation of complete accelerator sections; at least one module – for SRF consisting of a certain number of cavities – is required in order to optimize accelerating gradient and phase control. The respective test infrastructure is a must.

The R&D program on RF accelerating structures is based on a network of strongly connected partners. Several of them already share test infrastructures (mostly within AMICI). The new R&D goals will require the sustainable operation of such facilities, but also increase of capacity needs to be discussed. In some areas, parallel efforts can help to emphasize or shorten the development phase.

2.1.3 Bright muon beams and muon colliders

The recent European Accelerator R&D Roadmap [3] includes the possibility of a 10 or more TeV Muon Collider. Recently, EU has funded a design study for a Muon Collider complex at 10 TeV center of mass, MuCol, to deliver a conceptual design report in 2027. Muons are much heavier than electrons and with a much-reduced synchrotron radiation, allowing acceleration and collision of the beam in rings, even at multi-TeV energies. A muon collider will have to deal with the difficulty inherent to the muon production, requiring a **high intensity and power accelerator and target systems** as well as with the very short lifetime of muons, of the order of 2.2 μs in the particle reference frame, requiring **all processes of muon generation and acceleration to be significantly faster** than what is normally done with hadrons or electrons. Moreover, another challenge of a muon collider is to reduce the **emission of neutrinos** coming from the natural decay of muons. To address the two issues above the starting point is the conceptual layout of the chain of accelerators elaborated by the Muon Accelerator Program (MAP) that has coordinated US efforts on muon collider R&D [4]. The layout proposed by MAP is shown in figure 3.

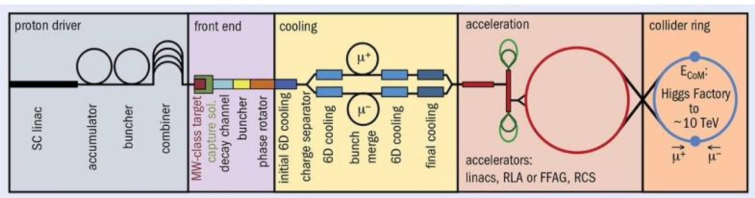

Figure 3. Layout of the Muon Collider complex as elaborated by the MAP

The muon production relies on a state-of-the-art proton complex producing an extremely short (1-3 ns long), high intensity (2 MW and at least 5 GeV) proton pulse that hits a production target and produces pions. The decay channel guides the pions and collects the muons produced by their decay into a buncher and phase rotator system to form a muon beam. The following section made of approximately kilometre-long linacs, based on process called *ionisation cooling,* reduces the six-dimensional emittance of the resultant muons by five orders of magnitude. Muon ionisation cooling must be extremely compact and requires very tight focusing and high-gradient RF cavities to reach the lowest emittance. The integration of RF and magnet structures presents challenge: this includes the need to maintain a thermal barrier between cryogenic magnets and room temperature RF cavities. A sequence of a linac and two recirculating linacs receive the cooled muon beams and accelerate them to 60 GeV. One or more rapid-cycling synchrotrons (RCS) rings then accelerate the beams to the final collision energy. Fixed-field alternating-gradient accelerators (FFAs) are an interesting alternative to RCS that avoids pulsing the magnets of a synchrotron. Finally, the two single bunch beams of opposite charge are injected at full energy into the collider ring to produce collisions at two interaction points.

The main challenges for the **RF system** are:

- <u>The RF system of the muon ionisation cooling is unique</u> compared to other machines and requires dedicated developments and tests. Indeed, to get a very compact lattice, a strong magnetic field of the solenoids (above 40 T), guiding the beam, surrounds the absorbers and RF systems, which see a fringe field of few tesla coming from the solenoids. The ambient magnetic field may focus the electrons emitted at one location on the cavity surface, which cause local damage at the cavity surface. The fringe field from the solenoids strongly increases the tendency to RF breakdown, which limits the cavity electric field. Two approaches have been tested to mitigate this effect: using beryllium instead of copper, which is less prone to damage, or filling the cavity with high-pressure gas, limiting the energy gain of the electrons. To validate the theoretical models and study the behaviour of the cavity prototype under high magnetic field (up to several teslas), **we need an experimental facility able to apply a magnetic field of several teslas to a cavity and with a power supply in the frequency range 600-800 MHz.**
- The normal-conducting cavities of the muon cooling system need to be filled with short high-power RF pulses to avoid excessive power losses in the walls. This requires cost effective and efficient high-power klystrons. That implies developing the concept of these klystrons to minimise the cost and establish realistic performance targets. This need is not specific to muon colliders and **can benefit from the generic developments of high-efficiency klystrons**.
- The RF system in the RCS is an important factor for the design of the ring and for the cost and power consumption of the facility. Currently, superconducting cavities are the baseline to accelerate the beam. Beam loading due to high peak muon current may be the source of instabilities and may require some dampers. However, the high-energy complex RF system does not need specific developments and **will rely on the advances made in the SRF programme**.

The **magnets** requires for a muon collider span a very broad range of technologies, from ultra-high field superconducting solenoids to very fast resistive pulsed dipoles and quadrupoles. The main challenges for the **magnets** are:

- The target solenoid required a large aperture and high field. A HTS target solenoid could produce the desired field requiring less shielding and operating at temperature higher than liquid helium, i.e. improved energy efficiency. Such a solenoid can **strongly benefit from advances in HTS technology and synergy with fusion magnet programme**. Indeed, the target solenoid is in the range of field and geometry relevant for full-body MRI for neuroscience, or solenoid magnets for thermonuclear fusion.
- The final cooling solenoids aim at a maximum bore field. The considered magnet designs are either based on cables, or on the novel partial-insulation technique, so to extend the present reach of HTS solenoids from 32 T (user facility), to the 60 T target required to maximise the ultimate beam luminosity. Like the target solenoid, the cooling area will benefit from the HTS technology development.
- The very high field ramp (several kT/s) of the pulsed magnets of the accelerator complex requires an integrated effort with energy storage and power management, striving for a true system optimum. The project will also benefit from HTS pulsed magnet developments to reduce magnet losses. A larger field

swing will enable at the same time to reduce the accelerator dimension and stored energy, and increase the useful lifetime of the muons.

- Finally, the collider magnets will profit from synergy with the recently initiated EU High Field Magnet R&D Program (HFM), and the on-going US Magnet Development Program (US-MDP). HFM and US-MDP are considering stress management concepts for Nb3Sn magnets, as well as HTS dipole magnets for accelerators. Of particular importance for the collider magnets will be energy deposition and radiation dose. The magnets for the collider itself should have a geometry and material alternatives that could minimize the heat load (e.g. open mid-plane) and maximise lifetime (e.g. rad-hard insulation). The programme will benefit from generic developments on magnet radiation protection.

The **ionization cooling cells are unique** to the muon collider. They pose specific challenges not only for the components but also for the integration. The cells have to be to maximise focusing and acceptance. They have to tightly integrate superconducting solenoids with normal-conducting RF, absorbers, beam instrumentation and auxiliary systems, such as vacuum and cryogenics. **That requires a dedicated test facility for the ionization cooling cell.** In this aim, the next steps are to make a full design of a representative cooling cell, to investigate the state of the art for the components, to select the most promising technologies for each component, and then to cooperate to build a full 3D technical model of a cell. Phenomena such as increased breakdown in RF cavities, radiation load to superconducting solenoids, extreme energy deposition in absorber materials and vacuum windows are to be taken into account to mitigate the risk that they may limit the performance of such a system.

The **target systems** present significant challenges and are generally an order of magnitude above the technologies applied in current operational facilities. These includes the production target itself as well as all the front-end systems which are employed to generate, focus and shape the pion/muon beam before injection in the cooling section.

There is a clear synergy between the RF, magnet and target system technology programmes and a muon collider will benefit from the recent development in these fields. We will cite here the **required test infrastructures** specific for a muon collider **for the period 5-10 years** (2023-2033):

- A test station consisting of a high-field magnet with a large bore, providing a background field and enabling using normal conducting cavities in the frequency range 600-800 MHz. The need of measuring RF breakdowns is an important input to get the maximum electric field.
- A new test facility to host a complete ionization cooling cell, including RF cavities, vacuum, absorbers, and high-field solenoids. That is of the utmost importance to validate the 3D model of the cell and check the performances are reached.
- A beam test facility where to test the behaviour of a production target within the solenoidal field magnet and subsequent capture system, including the integration of a beam dump, especially in case liquid or fluidised target materials. Such a facility is required in order to validate production, gain expertise with running such a system in operational conditions, and guarantee reliability of the final machine.

On the period 10-15 years (2033-2038), a new test facility to host a mock-up cell of the collider to test the wobbling is required. Indeed, to mitigate the neutrino hazard for a 10 TeV collider, that is necessary to increase the average emission angle of the neutrinos. Mechanically moving the elements is a proposed solution to generate an angle. The aim of this test facility is to verify that all the elements can be moved by a reproducible way to wobble the beam trajectory.

2.1.4 Energy-recovery linacs

The Energy-Recovery Linacs (or ERLs) share many characteristics with ordinary linacs, as their beam phase space is largely determined by electron source properties. However, in common with classic storage rings, ERLs possess a high average-current-carrying capability enabled by the energy recovery process, and thus promise similar efficiencies. The efficient recycling of the kinetic energy of a used beam to re-excite cavities and accelerate a newly injected beam, reducing thus the power consumption and dumping at injection energy, was suggested first in 1965 by Maury Tigner [5], and experimented for the first time, twenty years later for normal conducting facilities accelerating beams at rather low power [6-7]. The concept became really viable thanks to the major advances in SRF technology within the last decades, quantified by reaching high cavity quality factors ($Q_0 > 10^{10}$) enabling continuous wave (CW) and high average current operation. Since, ERLs start to assert their potential as game changers in the field of accelerators and their fundamental principles have been successfully demonstrated across the globe in SRF facilities (JLAB who holds the record on circulated current in an ERL (8.5 mA) at JLAB-FEL [8] and the beam energy reached by an ERL (1 GeV) at CEBAF [9]; Daresbury (ALICE) [10]; TU Darmstadt (S-Dalinac) [11] and KEK (c-ERL) [12]. ERLs are used in light sources, high-energy electron cooling devices, electron-ion colliders, and other applications in photon science, nuclear and high-energy physics.

Their unique combination of linac-like beam quality, extremely flexible time structure and unprecedented operating efficiency open the door to previously unattainable performance regimes. In addition, the consideration of multi-pass recirculation allowing high beam energy is paving the way to a green generation of high energy, high brightness, high average current electron beams in relatively compact footprint machines.

The 2020 Update of the European Strategy for Particle Physics clearly stated that ERLs are among the innovative accelerator technologies that deserve a vigorous R&D effort in the upcoming years. Especially the high-intensity, multi-turn ERL machines. The main challenges for these ERLs are the CW operation, the high beam average current handling, the low beam energy spread and the low beam emittance delivery. The realisation and success of tested machines will provide valuable input and crucial validation for the future energy and intensity frontier machines making ERL a real design option for future colliders.

To achieve this goal, many technical challenges have to be addressed first and technical infrastructure are needed to perform R&D program, prototype qualification and series tests. In the following, we list a number of required key technical developments for ERLs and the related technological infrastructures needed for it.

Key technologies development and required Infrastructure:

- **High-current electron source**:
  Future ERL injectors require electron sources at high average current, combined with a complex temporal beam structure. The electron gun can be powered by RF (RF gun) or biased at a high voltage (DC gun), normal conductive (NCRF gun) or superconducting (SRF gun). A common requirement for all these guns is the very low vacuum level (typically 10^{-12} mbar), which requires a good knowledge of thin NEG coatings, surface characterization, and R&D on dynamic vacuum, mitigating effects of residual gas ions, electron cloud…
  Furthermore, all of these sources are typically based on photocathode guns. Photocathodes based on (multi)alkali antimonides or GaAs are used for high average current generation when irradiated by a laser in an extreme high vacuum (EHV) medium ($<10^{10}$ mbar). The quality of the photocathodes is relevant to the performance of the photoinjector in terms of emittance and current, and a long photocathode lifetime is essential. Ongoing research topics in the field of photocathodes are the understanding of the electronic properties of the materials, the photoemission process and their intrinsic emittance. New growth procedures of high quantum efficiency, smooth, mono-crystalline or multilayers photocathodes, and the screening of new materials. All indicated R&D requires specific infrastructure for thin layers development and characterization.
- **SRF Technology**:

Future CW ERLs are supposed to handle a very high beam current (typically in the range of 100-150 mA). They have to balance the requirement for high cryogenic efficiency and beam stability in a reasonably compact and cost-efficient machine design. Thus, ERL SRF system developments must focus on the following items to improve the energy sustainability:

- SRF cavities: Near-term 2K developments, and the 4K perspective:
  For the development of 2K SRF cavities, in addition to high Q_0 requirement and all the effort carried by the community in this sense (N_2 doping and infusion), a particular interest has to be paid on a cavity design that minimizes the excitation and trapping of High-Order Modes (HOMs), facilitates their extraction, and enables their efficient damping outside of the helium bath. Good candidates are low frequency cavities (< 1 GHz), with larger apertures, and having fewer cells to provide the same voltage. Once designed and fabricated, cavity surface preparation and cryogenic test in the appropriate technical infrastructures are necessary to validate the RF design of the bare cavity, then the dressed cavity qualification.

  For ERLs, a significant part of the power consumption is related to the wall-plug power required to cool the dissipated RF power in CW operation. As example, for the Large Hadron-electron collider (LHeC), this value is about 15MW for 1.8K operation [13]. A particularly interesting prospect is to design and possibly build an energy efficient, ultra-high-luminosity ERL-based electron-positron collider, which would enable the exploration of the Higgs vacuum potential with a precise measurement of the tri-linear Higgs coupling. For this machine, production cross-section is maximal near 500 GeV collision energy with a value of about 0.1 fb [14]. For percent-level measurements, a luminosity of 1036 cm^{-2} s^{-1} is required. Such a linear collider will have 10-20 times more cavities than the LHeC, and thus requires a few hundred MW of power to dissipate the dynamic loads. This can be reduced by about a factor of three with 4.4K technology, for similar gradient and Q_0 characteristics. Achieving this value must be based on novel cavity technology that exploits 4.4 K cryogenics for which pure niobium is not suited as its Q_0 drops to the 10^8 range. Nowadays, several options of thin film compound materials with specific physical properties (Nb_3Sn, NbN, NbTiN, MgB_2…) deposed on substrate are extensively explored. While Q_0 values > 10^{10} at 4.4K are predicted, the accelerating field is considerably limited because of imperfection in the deposits inducing early flux penetration. Several approaches (multi-layers) and several deposition processes (Vapour Diffusion, Sputtering techniques, Atomic Layer Deposition) are studied to mitigate limitations.

  While these requirements, as historically, arise with particle physics, they are relevant and beneficial to general technical developments and applications. The 4.4 K technology is suited to reduce cryoplant cost and heat load for HOM extraction. This reduces both the capital and operating cost of SRF technology. Examples of industrial interest include semiconductor lithography, medical isotope production and gamma sources for nuclear industry. During previous studies of such applications with comparable scale, the capital cost of cryogenics comprised about 25 % of the full facility cost. The operating cost of electricity and maintenance again typically comprises 25 % of the full operating cost. Reducing these therefore has a significant impact on the economics of commercial deployment. Finally, at 4.4 K, SRF technology becomes accessible to smaller research labs or universities by avoiding the very special and expensive requirements posed by superfluid technology. This is expected to feed back to SRF industry, on which particle physics depends to a considerable extent.

- Higher Order Mode Damping:
  HOM power produced in ERL cavities operating at high current can be very high. The deposition of this heat load in cold mass surface is highly inefficient. Hence, the power must be extracted and deposited into room-temperature loads. HOM couplers are of two main types: coaxial (usually for low

power) and waveguide (more for high power). The design of HOM couplers must be multidisciplinary, balancing both RF and mechanical (thermal) requirements, as well as balancing dynamic and static heat loads.

HOM dampers have to be carefully chosen and optimized regarding beam parameters and cavity design. Solutions include space-efficient waveguide-coupled absorbers with high power capability or more readily implemented beam line absorbers between cavities could be chosen. The ultimate efficiency of solutions must be measured in SRF labs and later in beam test facilities.

- Fast Reactive Tuners:
  The RF power fed into a cavity during steady state ERL operation is ideally very small. However, to cope with beam transients and microphonics, strong over-coupling is necessary. This over-coupling leads to a lowered Q_{ext} and thus to significant higher power requirements. Most of the power is reflected and dumped. The side effect of the microphonics is that RF stability and hence beam stability is also affected. A Fast Reactive Tuner (FRT), fast enough to cope with microphonics and beam current transients, would allow operation with larger Q_{ext} and thus much reduced RF power. Recent development of FRTs based on piezoelectric material, not mechanically deforming the cavity avoiding the excitation mechanical resonances, show very promising results. Their suitability and longevity with the full SRF systems is still to be demonstrated by performing long-term tests in the appropriate technical platforms and later with beam in a real machine.

2.2 Nuclear Physics

In Nuclear Physics, which encompasses both the study of the nucleon (more specifically called hadronic physics) and the study of the nucleus, increasing emphasis has been given, in the last decades, to investigations of nuclei far from the valley of stability, both on the proton-rich and the neutron-rich sides. This applies to both the European and to the world-wide scenario.

This is achieved, in general, through the interaction of radioactive beams with fixed targets. Radioactive beams can be produced either in-flight or by the ISOL (Isotope Separation OnLine) methods. In most cases and depending on the characteristics of the facility and the local interests, such machines are also devoted to complementary purposes, such as their use with stable primary beams and a variety of applications.

We shall briefly review, below, the machines which are either being built or planned in Europe (par. 2.2.1), and in the rest of the world (par. 2.2.2). Technical challenges connected to future developments of accelerators for nuclear physics are summarised in paragraph 2.2.3, split between those which are specific for such field and those which are in common to other applications. Finally, in par. 2.2.4, those European technology platforms which might serve the purposes of technological advances in these fields will be briefly mentioned, together with those which the filed would require to progress in a faster and better coordinated way.

2.2.1 Nuclear physics facilities under construction, upgrade or planned in Europe

In Europe the precursor facility in the field of radioactive beams is Isolde at CERN, which has been recently upgraded in both energy and intensity with the HIE-Isolde project. The HIE-ISOLDE project aims at several important upgrades of the present ISOLDE radioactive beam facility at CERN. The focus lies in increasing the energy of the radionuclide beams from 3 MeV/u up to 10 MeV/u through a superconducting post-accelerator. The upgrade substantially enhanced the research opportunities in most aspects of nuclear structure and nuclear astrophysics, making ISOLDE the first facility in the world capable of accelerating medium to heavy radioactive isotopes in this energy range. The HIE-ISOLDE project also includes production targets to accommodate the increase of proton intensity delivered by the new LINAC4 proton driver. This improvement, combined with the solid-state lasers of the RILIS laser ion source and the radiofrequency quadrupole cooler and buncher ISCOOL, will lead to an increase of the radioactive beam intensities of up to an order of magnitude. Soon, a last upgrade on HIE-Isolde is expected to be the replacement of the present REX (normal conducting) injector with two low-beta superconducting cryomodules.

Another facility based on the ISOL technique is SPIRAL 2 in GANIL (France). It is based on a high power, CW, superconducting linac, delivering 5 mA of deuteron beams at 40MeV (200KW) directed on a C converter -Uranium target and producing more than 10^{13} fissions/s. The experiments carried out in the S3 room (following a high-resolution separator) will allow several radioactive ions to interact, albeit at low energy, with fixed targets. Complementarily to the production of radioactive beams is the generation of intense neutron beams, the LINAC can be also used to generate extremely intense neutron fluxes, with features which are unique in the world, to be used in the NFS room for both nuclear physics experiments and applied research (energy, electronics, etc.). Now, the initially planned acceleration of radioactive beams is deferred in time.

At SCK-CEN (Belgium), the radioactive ion beam facility for Nuclear Physics is an added option to the main project, MYRRHA, an accelerator driven system (ADS) which is being built there (see Section 2.3.2): a radioactive ion beam (RIB) facility of the ISOL type will use a fraction (up to a maximum of 0.5 mA) of the 100 MeV proton-beam intensity delivered by the accelerator, to this purpose. Thus far, only the first portion of the SC primary linac (a project called MINERVA) has been approved and is in full exploitation.

Another relevant ISOL-based facility in Europe is SPES at INFN-Legnaro (Padova, I), where the driver is a proton cyclotron (70 MeV, 700 uA) and the re-accelerator is the SC Linac ALPI, used at present for stable ion acceleration. All planned technological developments are being fully exploited at SPES, with the whole facility being built and the first non-accelerated beams expected for late 2023 and the first accelerated ones in 2024. The facility has a robust ancillary programme of nuclei for medicine, to be produced in a dedicated bunker (collaborations with the local hospital are being discussed).

At GSI-FAIR, the ambitious European facility for in-flight production FAIR is in full construction and first beams are anticipated in 2027. Based on an extension of the GSI stable beam facility, it will deliver – thanks to the SIS100 synchrotron - beams ranging from protons to uranium (energy from 29 GeV for protons to 2.7 GeV/u for uranium) onto a high-power target followed by a sophisticated high resolution mass separator (S-FRS, Super Fragment Separator). The newly produced particles can be captured in storage rings. Acceleration of anti-protons is foreseen too. Further upgrades or extensions are not expected to be approved, before the presently built facility shall have been built and commissioned.

At CNRS-Orsay (F), the ALTO research platform brings together two accelerators, a 15 MV Tandem-type electrostatic accelerator for accelerating stable beams from protons to aggregates, and a linear electron accelerator to produce radioactive beams by photofission. These machines are associated with a wide variety of experimental devices on 10 beam lines. The diversity of the produced beams makes it possible to carry out nuclear physics, astrophysics and multidisciplinary studies. ALTO provides beams such as ^{3}He and ^{14}C and is also the only facility in the world delivering low-energy neutron-rich beams from the photofission of uranium.

In hadronic physics, in addition to the programme foreseen at FAIR with anti-protons, MESA (Mainz Energy recovery Superconducting Accelerator) in Mainz (Germany) has recently received initial funding. It is based on a SC Energy Recovery Linac and will accelerate electrons at 155 MeV with high e-beam luminosity above background for precision experiments.

2.2.2 Global landscape

In Russia, JINR intends to enter the field of radioactive-beam facilities with the new accelerator DERICA (Dubna Electron-Radioactive Isotope Collider fAcility). It is meant to be a RIB factory with the unique feature of RI-electron interactions in a collider. DERICA intends indeed to combine a 100 A MeV heavy ion linac, followed by an in-flight target and a separator (DFS, Dubna Fragment Separator) and by a reacceleration linac (5÷30 A MeV radioactive beams), with a 500 MeV electron beam (from a dedicated linac) into a common e-RIB collider. The facility is planned to be realised in stages and is pending funding, going beyond the R&D phase.

The above-mentioned radioactive-beam facilities nicely complement those which are being developed in other areas of the world, such as FRIB (USA), recently commissioned, RIBF and J-PARC (Riken, Japan) and the being built ARIEL (Canada), HIAF (China), RAON (S. Korea).

The recently approved Electron-Ion Collider (USA) EIC is the next-priority in hadronic physics in the United States. It will feature high energy, high luminosity collisions at a centre-of-mass energy 20÷100 GeV, and a $10^{33÷34}$ /cm^{2}s luminosity.

2.2.3 Technical challenges

The variety of future potential machines for Nuclear Physics is wide, and such is the portfolio of technologies connected to it. It is not straightforward to recap, in brief, all the technical advancements that the field would require. Therefore, only some of them are highlighted hereafter, without claiming to be exhaustive. Some are specific of the field; others may be common with accelerators having different scopes.

A few technical challenges are specific to radioactive beam facilities, as for examples:

- Within the broad area of high-power target applications, for instance, improvements of those targets which are specific for ISOL-type production of secondary beams can come from unconventional materials, optimised shaping of the targets themselves and their associated ion sources. Additive manufacturing is being looked at as a promising pathway, among others.
- The French network on beam instrumentation (RIF, Réseau Instrumentation Faisceau, IN2P3), started in 2018 with the aim of bringing together experts in the fields of beam instrumentation, could be extended to the design and tests of novel beam diagnostics devices for very low intensity beams, which are peculiar of exotic re-accelerated beams and deserving constant attention and improvements.

Technical advancements on high-power targets regard the field of accelerators for nuclear physics as well as several others: for instance, spallation neutron sources (e.g. ESS), accelerators for neutron science and material tests (e.g. Spiral2 at GANIL), neutrino facilities (such as PIP-II to be built at Fermilab in the US), and also energy applications, such as irradiation facilities for fusion energy reactor materials (e.g. IFMIF- DONES) and accelerator driven systems for sub-critical fission reactors, such as MYRRHA.

- Driver accelerators for several exotic beams facilities have technological components, the specifications of which are similar to those needed by other applications.
- High current ion sources, benefitting transversally several fields of application, are being strongly developed in many laboratories. Higher and higher beam currents, while keeping space charge and beam emittance under reasonable values and featuring high availability values, are the primary aims.
- Developments on low-beta superconducting resonators, taking place e.g. at GANIL, INFN-LNL, HIE-Isolde at CERN, will help to develop accelerators of even better performance and compactness. Novel cavity conditioning techniques, with the contribution of machine learning (ML) algorithms, will help sparing on RF power and speeding up machine preparation. Novel cavity designs and helium cooling jackets may help sparing both on the helium cooling medium. Still in the SC resonator field, ERL-based machines (MESA in our case) may benefit from enhanced methods to control microphonics and higher order modes of the resonators.
- More in general, high-level applications for efficient beam tuning automation is making important progress, both in Europe and elsewhere, in accelerators for many different purposes. Models based on

Reinforcement Learning and Bayesian Optimisation, well know artificial intelligence (AI) tools, can significantly reduce accelerator preparation time and improve operational reliability. This also helps sustainability, as the ratio of the scientific outcome over the spent energy will improve, if the preparation time is reduced and the anticipation of issues is more effective.

- An improvement on machine reliability aspects, transverse to all technical instruments, will be brought by the experience which is being made at MYRRHA. This is motivated by the exceptionally high availability that its energy application requires. These achievements will impact not only ISOL@MYRRHA, but all accelerators in general, both in nuclear physics and other applications.
- Precision, reliability, user-friendliness, environmental and radioprotection acceptance of nuclear physics machines will be highly impacted by improvements in the fields of radiation-resistant electronics, robotics (handling of the highly radioactive target regions is an issue common to them all), general energy optimisation, digital mock-up of accelerators, improved automatism in survey and alignment. These fields are also transverse to accelerators for various applications.

2.2.4 Existing and needed technological facilities for Nuclear Physics accelerators

Technological developments on most of the aspects described in section 2.2.3 are quite project-specific and carried out in the laboratories mentioned in section 2.2.1 and others. Synergies among, for instance, target laboratories or material laboratories in these centres could be fruitfully investigated in a broader context. Existing of future collaborations among the laboratories shall have to be encouraged.

New shared platforms, which the nuclear physics accelerators (and other fields) would benefit from, are e.g., those for:

- Development and tests of high current ion sources
- Development and tests of high-power targets from the largest possible variety of beam species, currents, and energies
- Non- specific Low Level RF developments for accelerating cavities
- A larger number of test stations for testing high-power RF amplifiers (of higher energy efficiency) and RF couplers
- European network of laboratories, bringing together experts, technologies, instrumentation for beam diagnostics of the most varied features

On the other hand, there are several Technology Platforms which have already been declared available in the framework of the AMICI project. They refer mostly to the developments, treatments (e.g. thermal and chemical) and tests of superconducting resonators and their ancillaries, such as power amplifiers, couplers, cryomodules (CEA, INFN, DESY, CIEMAT and FREIA). The reader may see the details in https://amici.ijclab.in2p3.fr/home for reference.

2.3 Energy

Accelerator and superconducting magnet technologies are playing an important role in the domain of nuclear energy: in magnetic confinement fusion, many Technology Platforms owned by some of the AMICI partners have been or are currently used to test large-scale magnets for fusion projects, such as ITER, JT60 or W7X. Clearly, the development of high-temperature superconducting materials will open new opportunities for more compact fusion devices. In the domain of accelerator technologies, IFMIF, the International Fusion Materials Irradiation Facility, needed to test materials in irradiation conditions comparable to those of a fusion reactor requires very high power ion accelerators. Similarly, Accelerator-Driven sub-critical Systems (ADS), which could be used to transmute long-lived nuclear waste, involve a high power proton beam producing the neutrons necessary to sustain the chain reaction.

2.3.1 New Magnet Developments for Future Fusion Power Plant

The potential of high-temperature superconducting materials for fusion makes it possible to envisage fusion power plants that are more compact than ITER and therefore more economically attractive for industrial development.

ITER is an essential stepping stone on the road to fusion power, as it will be the first device to approach fusion power on a power plant scale, thanks to the integration of all the required technologies. With most of the ITER subsystems built, all ITER members are now preparing for the operational phase and gathering the science that will enable power plant-scale plasma combustion to be mastered from 2030 onwards.

The success of this strategy depends on the full exploitation of the assets of the EU community and in the first place of its valuable experience in the operation of one of the main European tokamaks. EU is also strongly involved in experiments on other machines (JET, ASDEX Upgrade, MAST-U, WEST and TCV in Europe, DIII-D in the United States, EAST and HL-2M in China, KSTAR in Korea, and later JT-60SA in Japan).

Since the beginning of its fusion power roadmap, EU has been following a stepladder approach, building on existing and well-qualified technologies (magnets, plasma-oriented components, etc.) to connect the DEMO demonstrator to the grid in the 2050s. This approach leads to a tokamak with a major radius 1.5 times larger than that of ITER, and therefore carries technical and financial risks due to its large size, investment cost and complexity. In fact, what finally determined the size of ITER was the magnetic field that can be obtained with superconducting magnets in such a large volume (1000 m3). The EU roadmap for DEMO envisages using a similar technology for the next step.

However, the breakthroughs made in recent years in the field of high-temperature superconducting (HTS) magnets make the prospect of doubling the magnetic field increasingly realistic. This could lead to a significant reduction in the size, capital cost and complexity of an installation, but this approach carries technological risks, in terms of the complete qualification of the coils and the mechanics of the machine due to the increased forces. Successfully maturing and eliminating the risks associated with HTS technologies could therefore be a game changer in the development of fusion energy and lead to a major update of the EU roadmap. Incidentally, these developments are synergistic with those of the next generation of high field magnets for high energy physics. They would also lead to spin-offs, as has already been the case with the current fusion magnet technology used to build the ISEULT magnet for medical imaging at 11.8 Tesla.

The reduced capital costs potentially enabled by HTS magnets could make national FPP development programs affordable. This strategy is central to the U.S. and U.K. fusion roadmaps, with the SPARC (2025)/ARC public-private partnership and the STEP project. China also recently revised its roadmap to include a compact, high-field, tritium (T)-capable machine (BEST) before building the ITER-sized Chinese Fusion Test Reactor (CFETR).

Making this vision a reality requires a wide range of advances: improving the HTS database and manufacturing techniques, designing coils capable of withstanding extreme electromagnetic forces, developing technologies for superconducting junctions, and systems to protect against quenching (loss of superconductivity). A tokamak requires both steady state magnets for the toroidal field coils generating the largest component of the magnetic field, and pulsed magnets for the central solenoid and poloidal field system. Different technological solutions need to be developed for these two types of coils, which need to be tested individually in dedicated technological facilities, and together in a relevant geometry to evaluate the effect of pulsed fields on the steady state magnets.

2.3.2 High power accelerators

2.3.2.1 LIPAC

The main goal of the Linear IFMIF Prototype Accelerator (LIPAc) [15] built in Rokkasho (Japan) is to show the technological feasibility of operating a deuteron accelerator with the targeted beam performance in terms of high beam power and beam intensity in continuous mode. LIPAc is a compact 36-meter long accelerator. It requires state-of-the-art technologies to fulfill their requisites: the world's longest RFQ, the world's highest light hadron current through SRF cavities, 1.1 MW of continuous beam power, and world's highest current in continuous wave in a LINAC.

The LIPAc accelerator consists of an injector with an Electron Cyclotron Resonance (ECR) ion source (H+ 50 keV/ D+ 100 keV), a Low Energy Beam Transport section (LEBT), the Radio Frequency Quadrupole (RFQ) Linac, the Medium Energy Beam Transport section (MEBT) [16], the Superconducting Radiofrequency (SRF) Linac [17], the High Energy Beam Transport section (HEBT) [18-19] merged with the Diagnostic Plate (D-Plate) and the Beam Dump (BD).

2.3.2.2 IFMIF-DONES

The main goal of IFMIF-DONES [16], which should be built in Spain in the coming years, is to produce a CW 125 mA deuteron beam at 40 MeV impinging in a liquid lithium target with a rectangular footprint varying from 10x5 cm to 20x5 cm, to fulfill the main mission of the facility which is to provide fluences of 20-30 dpaNRT in <2.5 years to 0.3 l samples or 50 dpaNRT in <3 years to a smaller volume of 0.1 l, using neutron fluxes of around 10^{14} n/m^2-s compatible with the characteristics of the ones generated at the DEMO plant.

The IFMIF-DONES accelerator includes all the technologies implemented in LIPAc, but pushing even higher the average power, from the 1.1 MW of LIPAc up to 5 MW.

IFMIF-DONES is composed on three main group of systems: the Accelerator Systems delivering the 125 mA CW 40 MeV deuteron beam, the Lithium Systems providing a stable curtain of 25 mm with a speed of 15 m/s and temperature of 300ºC, and the Tests Systems providing the containers and the materials samples to be analyzed.

2.3.2.3 Accelerator Driven sub-critical Systems (ADS)

The flagship Accelerator Driven System (ADS) project worldwide is MYRRHA, a research infrastructure led by SCK·CEN in Belgium. MYRRHA (**M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications) is the world's first large scale ADS. It consists of a subcritical nuclear reactor driven by a high-power linear accelerator. The current development phase of MYRRHA is MINERVA.

MYRRHA linac has twin redundant 17 MeV injectors. The remaining part of the accelerator up to 600 MeV is based on super-conducting radio-frequency modules, a common choice in view of optimized performance with high beam currents.

At the end of the linac, the 4 mA proton beam is injected into the reactor, generating a flux of fast neutrons through spallation. Simultaneously, protons are also fed to the multi-purpose Proton Target Facility and to the Full Power Beam Dump (400 kW), which can be used for Fusion Material Research.

Largely based on ESS choices, the MYRRHA design incorporates significant differences (ESS: pulsed proton beam; MYRRHA CW beam). The MYRRHA choice is for a significantly shorter normal conducting injector than ESS, transferring to super-conducting cavities as early as reasonably achievable given the relativistic aspects.

2.4 Material and Biological Science

Material science is more and more relying on large scale accelerator-based research infrastructures producing powerful X-ray or neutron beams. Accelerator-based photon sources, synchrotron radiation and Free Electron Laser (FEL) facilities, and neutron sources are complementary probes for understanding the structure and behaviour of materials at the atomic and molecular level and therefore play an essential role in the design and characterisation of advanced materials, chemistry and biotechnologies. European light sources have come together to form the LEAPS consortium while neutron sources (including reactor-based ones) are gathered in LENS. Both of them have recently issued a scientific roadmap for their respective domains.

2.4.1 Accelerator-based photon sources

The further advancement of synchrotron based light sources in Europe was started with the upgrades of MAX-IV and ESRF. The recent development of the here used so-called MultiBend Achromat (MBA) lattices, allowing dramatic increase of photon beam brilliance and coherence, is pushing the advances in several accelerator systems. For example, in the use of permanent or hybrid magnets for (with respect to energy consumption) green facilities; the related vacuum technology; new Insertion Devices extending the photon energy range and tunability; advanced instrumentation for beam control and diagnostics; Radio Frequency acceleration systems with new functionalities. There are more projects in the planning phase. An excellent overview is available via https://www.wayforlight.eu/en/synchrotrons.

Free Electron-Lasers are described also https://www.wayforlight.eu/en/fels. FELs' key challenges are better control of spectral and temporal properties to match the requirements for extreme time resolution (down to the attosecond region), high repetition rates, better time synchronization with external lasers, increased peak intensity and improved longitudinal coherence. The corresponding fields of research focus are the integration of the FEL sources with the experiments under these conditions; novel concepts for the control of FEL light properties; cavity based FELs; refined electron beam control. A longer-term goal is the development of compact sources based on plasma wakefield acceleration to make some of the capabilities of the current RIs available for industrial applications, hospitals and smaller laboratory environment.

The LEAPS Initiative acts as a strategic consortium initiated by the Directors of the Synchrotron Radiation and Free Electron Laser (FEL) user facilities in Europe. Its primary goal is to actively and constructively ensure and promote the quality and impact of fundamental, applied and industrial research carried out at each facility to the greater benefit of European science and society. LEAPS has recently published the European Strategy for Accelerator-based Photon-Science, ESAPS 2022, in which a timeline of existing, approved upgrades and plans for storage rings and FEL facilities in Europe is presented and shown in Fig. 4.

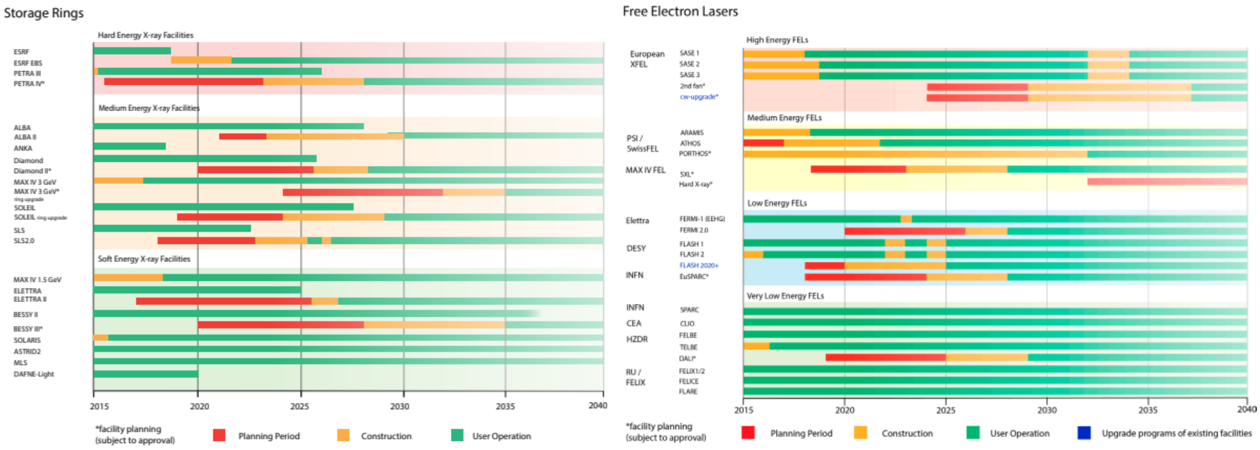

Figure 4. From ESAPS 2022: Timeline of existing storage rings and FEL facilities, approved upgrades and plans for upgrades not yet approved (marked with an asterisk), latest update Feb 2022.*

In principle all large scale accelerators being built for the creation of light can profit from I.FAST AMICI ETIAM Test Infrastructures. The best example is the European XFEL which was built based on the in-kind model, and which led to the creation of essential infrastructure made available now within AMICI. Free-Electron Lasers are based on long linacs with many serialized components which need extensive testing. Synchrotron based machines are using extremely precisely defined i.e. constructed and aligned girder sections which need an utmost accuracy; the number of RF systems is relatively small.

Long linac based facilities can benefit from shared infrastructures. The long-distance transport of complete accelerator sections was successfully done; most recently for the European Spallation Source ESS in Lund with its accelerator modules being assembled at CEA Saclay, Paris. Ring accelerator projects have the tendency to assembly and align the mentioned girders as close as possible to the facility construction site. This is related to the envisaged very high alignment precision. Nevertheless, a well-defined quality assurance program is still necessary and can lead to pre-testing of certain components. This could profit from shared test infrastructures. Where- and whenever beam test facilities are offered within AMICI, they can of course be offered to many research facilities.

2.4.2 Accelerator-based neutron sources

The landscape of neutron sources for material science in Europe is currently undergoing major structural changes. The European Spallation Source, currently under construction in Lund, Sweden will, when it has reached its design performance, be the world's most powerful neutron spallation source. Although first neutron beams would become available by 2026 with the accelerator operating at 2 MW with 15 instruments, the funding for reaching full design performance with 5 MW and in total 22 instruments has not yet to been allocated. At the same time several reactor-based neutron sources for material science have been shut down in 2017-2019 such as Orphée in France, BER II in Germany, JEEP-II in Norway and RPI in Portugal. Currently, neutrons in Europe are provided by a few large facilities – the reactors at ILL in France and at MLZ in Germany and the spallation sources ISIS in the UK and SINQ in Switzerland. The ILL source is approaching its end of life and will be shut down in the beginning of the 2030's.

All in all, the result is that the total capacity from neutron-based material science in Europe will be reduced if not new investments soon be made. This situation is summarized in the report Neutron Science in Europe published in June 2022 by the BrightnESS H2020 project (https://brightness.esss.se/) and the LENS, from which the graph here below showing the evolution of the European neutron capacity in terms of instrument-days per year, assuming full implementation of all identified opportunities, has been taken. In addition to the need for funding to ESS to reach full design performance, there is a need to upgrade the existing neutron sources and to develop and build several smaller High Current Accelerator-driven Neutron Sources (HiCANS). The latter would take the role earlier played by national reactor-based sources. A HiCANS consist of a high current low energy (order 10 MeV) accelerator producing neutrons by nuclear reactions. This new type of neutron source technique was reviewed at the 1st International Meeting on Opportunities and Challenges for HiCANS 20-22 June 2022 (https://www.imoh.eu/).

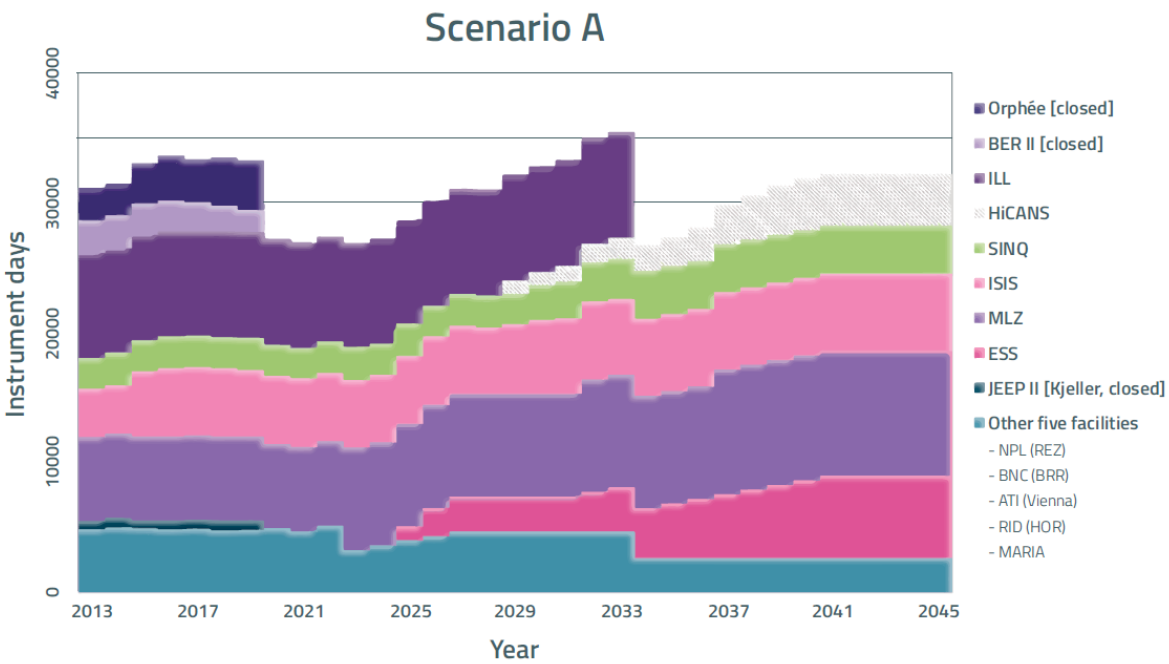

Figure 5. From Neutron Science in Europe: A projection of available capacity in Europe based on full implementation of all identified opportunities.

ESS was built in a green field with most of its high-tech components being delivered in-kind from accelerator technology laboratories in its member countries, most of which are part of the AMICI ETIAM Technology Infrastructure. Further upgrades of ESS, like making possible the compression of ESS' 2.84 ms long neutron pulses to about 0.1 ms to satisfy special needs for material science and building a world-uniquely intense neutrino-beam for particle physics - two projects between which there is significant technological synergy - would requires high-tech in-kind contributions from the AMICI ETIAM Technology Infrastructure. An important upgrade of ISIS (ISIS II) is being planned to which many contributions from AMICI ETIAM Technology Facilities can be foreseen. And the development of HiCANS will require development and production work within the activity fields of the AMICI ETIAM Technology Infrastructure.

2.5 ACCELERATORS FOR MEDICINE

2.5.1 Synchrotrons and others for therapy

Every year, close to 20 million patients will be diagnosed with cancer globally in Europe. For more than five decades the treatment of cancer with accelerated beams has been an integral part of oncology treatment in Western Europe. The central aim is to deposit high doses of energy deep within the cancerous tumour, disrupting its DNA, whilst simultaneously trying to cause as little damage as possible to the surrounding healthy tissue.

By far the most commonplace machines are X-ray devices, based around few-MeV electron linacs. With commercial options well established, development of the accelerator system itself is largely incremental, with the majority of R&D effort devoted to improved patient planning and throughput via enhanced imaging and machine learning techniques. Existing commercial vendors are well positioned to support technical developments in-house, although knowledge exchange and collaborative programmes with the Research Institutes will continue to be beneficial.

Whilst widespread adoption of radiotherapy in mainland Europe is commonplace, there exists a significant desire to extend its adoption in low and middle income (LMIC) countries. This will require a more modular and robust architecture, accessible/remote diagnostics and local staff training to enable in-field servicing and maintenance. The proposed STELLAR project, including partners such CERN, UKRI and ICEC is one such example. The need to fundamentally re-assess the make-up of the accelerator system and the development of prototypes will fundamentally require support across the TIs including test stations and support laboratories.

A significant development in recent years is the increasing adoption of proton therapy, where the more precise energy deposition profile within the body can be used to treat more complex cases such as head, neck, spinal and paediatrics. However, accelerating the heavier protons to higher energies necessitates a larger, more complex and more costly accelerator. The current roll-out of proton therapy is generally restricted to a limited number of national specialist medical centres rather than widely within regional-level hospitals. Commercial systems are available from a number of vendors, typically using superconducting cyclotron-based solutions.

Current R&D efforts are underway by a number of commercial vendors to develop proton linacs suitable for oncology as a potential option to reduce the scale and/or overall cost of facilities. The development of these complex, higher energy machines is naturally synergistic with the technical support and platforms offered by the European Research Infrastructures. Developments in FLASH beam delivery, artificial intelligence and machine learning, and remote diagnostics for example are readily translatable across disciplines. However, the pathway to enabling new accelerator concepts to translate to viable patient treatment is complex, requiring close integration with medical clinicians, radiobiologists and the services needed to deliver medical device validation and certification.

The radiobiological benefits in the transition from X-ray photons to protons may be further amplified with the use of heavy ions such as carbon. Synchrotron facilities such as HIT, Heidelberg have demonstrated the capability, although a further step change in development is needed to constrain the growth in size, cost and complexity. Projects such as SEEIIST will investigate technologies including lightweight superconducting gantries to inform future investment in heavy-ion facilities. Other gantry options under development include the SIGRUM and GaToroid concepts, as well as a number superconducting gantry options being developed independently by commercial vendors in the Far East.

Very high energy electrons (VHEE) have also been identified as a further potential development area. Here, high gradient linacs are used to generate a few-hundred MeV electron beam. There are a number of proposed facilities under consideration (e.g. CERN-Lausanne, PHASER) and initial biological studies have been conducted at the UKRI CLARA facility. Further work is required to understand the detailed radiological response of tissues, although the intrinsic linac technology is well-understood.

2.5.2 Accelerators for radioisotope production.

Compact, reliable and low-cost accelerators can guarantee an important source of medical isotopes in future. Useful reactions combine maximum yield of the desired species with lowest co-production of impurities. Higher beam energies and currents are key to the variety of medical isotopes that can be produced. However small footprint and low cost are frequent choice drivers, particularly if the facility is meant to be built at a hospital. Being close to a hospital makes short-life radioisotopes attractive, even when the modest accelerator specifications do not allow large quantities to be produced. Moreover, higher energies open reaction channels that may cause impurity production, while higher intensities complicate target design, shielding and maintenance. Consequently, minimum performance to achieve the desired radionuclide (RN) production is always the preferred choice.

Cyclotrons, linacs, Fixed Field Alternating Gradient (FFAG) and electrostatic machines can be used for direct beam-target reactions. Electron machines stimulate photo reactions, while neutron-induced reactions are obtained with compact neutron sources, high energy beams inducing spallation or ADS facilities inducing fission.

Cyclotrons are the most wide-spread kind of accelerators, as they are compact and relatively low-cost. Most commercial ones accelerate negative ions and employ stripping extraction towards one or more target stations. Positon Emission Tomography (PET) cyclotrons are <15 MeV energy and low (25-100 uA) current (for ^{18}F, ^{11}C, ^{13}N and ^{15}O) with short lifetime and built close to treatment centres. Those for SPECT and for longer lifetime PET RN feature a 15-30 MeV energy range and high currents (300 uA).

Many PET cyclotrons employ SC magnets, making them lighter and smaller. High B-field (up to 4-5 T) cold iron machines offer reasonable compactness, without need of superconductivity. Some replace heavy accelerator shielding with a beam line, separating the target system from the accelerators. Several are offered with integrated radiochemistry solutions.

Positon Emission Tomography-Single Photon Emission Computed Tomography (PET-SPECT) cyclotrons allow a larger RN production (e.g. 67Ga, 124I, 123I, 111In, 201Tl), the higher energy making them heavier and more expensive. The longer lifetime of SPECT RN allows these machines to be farther from the clinical centres. Some of these (ideally up to 25 MeV) are specialised in the 99mTc production, via bombardment of a 100Mo solid target. A range of cyclotrons with medium energy (15-30 MeV) and relative high current (>300μA) are commercially available for a more versatile radionuclide production

High Energy cyclotrons (~70 MeV, ~ 1 mA) allow producing 82Sr, 68Ge, 67Cu, 211At, 47Sc, 52Fe, 55Co and 76Br. Energy is variable (e.g. 30-70 MeV) and some accelerate also alphas or deuterons.

Ion linacs can serve several target stations at the same time, at several beam energies. The accelerator itself is a radiation shield, and the only remaining shielding is for the target system, thus allowing easier accelerator access and maintenance. RFQ or RFQ-DTL linacs are the standard solutions, up to 7-10 MeV. They achieve a few hundred uA average beam current: while Ipk can achieve 10 mA, a duty cycle beyond a few % is unpractical and expensive. They are far lighter than small cyclotrons and some can be hosted on ad-hoc trucks.

25-50 MeV, kW-range electron linacs (either RT or SC) may let the beam to impact on a high-Z converter into Bremsstrahlung, delivering RNs via photo-nuclear or photo-fission reactions. They are reliable, simple, small size and weight, cheaper than hadron linacs. The number of reaction channels is smaller, yielding purer RN and less radioactive waste. However, the production yield is generally much smaller, demanding a high-power machine. ERLs, "if" economically favourable, would mitigate this drawback, with more than 90% of the beam power recycled (better energy efficiency in the RN production).

Promising routes for higher-energy electrons accelerators are PET RN (11C, 13N, 15O, 18F) production via γ-n reaction on their cheap abundant nucleus target (12C, 14N, 16O, 19F). With 14 MeV photons from an electron beam, the "electron-accelerator-way" to 99mTc (100Mo(γ,n)99Mo) is achievable, although with a lower specific activity than with ion induced reactions.

Some robust models of electrostatic accelerators were conceived and are very promising, integrating the DC voltage generator within the accelerator structure and its electrical insulation: with 10 MeV p (and 5 MeV d) beams, they achieve some mA of CW current, on a limited footprint (a few square meters). Similarly to low energy PET cyclotrons, these electrostatic machines may produce fairly large quantities of short lifetime RNs, and may be located close to a hospital.

Fixed-Field Alternating Gradient (FFAG) accelerators, with their strong focusing, achieve ~ 30 MeV energies with high beam currents (in CW operation thanks to lower than 0.5% isochronism in non-scaled field gradients). The magnet radius can be smaller than 2 m, allowing them to be of a size suitable for a hospital environment.

Plasma based acceleration or high-power lasers are being investigated nowadays. High power lasers allow producing medical isotopes via (γ, n) and (γ, p) reactions. TSNA (Target-Sheath-Normal-Acceleration) of protons, via petawatt lasers interacting with a solid target, can achieve 10 MeV energies for PET production (their economic competitiveness versus traditional techniques, and the achievable energy precision have to be controlled). Table-top TW laser proposals, easy to shield and compact, suggest a future option for on-site isotope production.

2.5.3 Role of public institutions and private companies.

The field of accelerators for medicine is, in general, well covered by private companies, which often offer the full equipment including. Given the lengthy development times, also in relationship to the expensive authorisation procedures involved, public institutions are not real competitors of private vendors for the realisation of the complete product. However, especially on the accelerator side, specific developments on many of the above-mentioned fields are indeed carried out at public institutions (in Europe often in the framework of ad-hoc EU projects), where non-profit and often high-risk R&D improvements can be carried out and then made openly available.

Public laboratories are often searched by private vendors as they may offer radiation-shielded areas for beam-target tests. These deals are outside the very scope of the technology infrastructure network and are often based on bilateral agreements.

The network of EU technology infrastructures can be made available, in general, to public researchers or, under specific agreements, to private companies on all types of the above-mentioned developments.

2.6 Other applications

Magnetic fields are a valuable experimental tool for investigating new materials and phenomena, and have contributed to more than 15 Nobel Prizes in the last century. Magnetic fields have various engineering applications, such as purification, fluid control, levitation, magneto-metallurgy, motors and generators, power transmission cables. Magnetic field-based research and manipulation techniques are widely used in physics, chemistry, and biology, and can be performed using commercially available magnets and equipment such as MRI scanners, NMR spectrometers, and separation devices. High magnetic fields that are homogeneous in space and stable over time are necessary for many studies in these fields.

High-Temperature Superconductors (HTS) have the potential to fulfill the growing demand for high magnetic fields. Since their discovery in the 1910s, superconducting technologies have been utilized in a wide range of applications, owing to their ability to generate high magnetic fields with negligible losses in small conductor cross-sections. Superconductivity has enabled both the discovery of the Higgs boson in the LHC and the widespread use of MRI in the past few decades. Today, superconducting technologies are driving private sector initiatives to develop compact magnetic fusion power plants.

The rapid development of HTS has the potential to revolutionize superconductivity in society. Unlike Low-Temperature Superconductors (LTS), HTS can generate much higher magnetic fields (> 20-30 T) at low temperatures (4 K-20 K). For low-field applications (< 2 T), HTS can operate at much higher temperatures close to the boiling point of liquid nitrogen (> 77 K). The ability to generate higher magnetic fields can be a game-changer and advances in HTS technologies will benefit in many areas:

For fusion energy, doubling the field, currently limited to 12 T with LTS, would produce the same fusion power as ITER in a magnetized volume 16 times smaller.

Motors and generators that typically operate at an average field level of about 1 T could be made more efficient and cost-effective by using superconductors instead of copper or rare earth neodymium. Using HTS coils in rotating machines could reduce their weight by a factor of 2, increase their efficiency, and lower the manufacturing and operating costs of wind turbines by 10-20%.

Power transmission cables are low-field applications. HTS cables can be placed underground, providing a significant space advantage in large cities, and offer greater robustness with relatively low cooling efforts at 77 K compared to traditional cables.

High-field materials science would benefit from 20 T to 40 T superconducting magnets, enabling more high-field experiments on a smaller scale, leading to the discovery of new materials

Europe needs high magnetic field research infrastructures to compete globally in research. It has three existing facilities in France (LNCM I), Germany (HLD), and the Netherlands (HFML). These facilities have integrated into a multi-site European Magnetic Field Laboratory (EMFL) to provide researchers access to high magnetic fields. The UK and Poland have joined EMFL, and other countries are considering it. EMFL was awarded Landmark Status in 2016 for its progress towards a coherent infrastructure. It offers access to static resistive magnets (up to 38 T) and pulsed magnets (up to 200 T) of varying strengths. Recent advancements may allow for high temperature superconductor magnets at EMFL. Two hybrid magnets, combining superconductive and resistive magnets, generating 43+ T, are in their commissioning phase and will soon be integrated in the EMFL user program.

Several breakthroughs have confirmed the great potential of the HTS technology:

- the announcement in August 2019 by the Bruker company of the first results obtained at 28.18 T with a high resolution proton LTS/HTS NMR magnet for 1.2 GHz;
- the successful tests at 32.5 T of the NOUGAT small-scale HTS insert at EMFL-Grenoble in a 19 T resistive background field in April 2019;
- the commissioning of a 32 T LTS/HTS user magnet at the National High Magnetic Field Laboratory (Tallahassee, USA).
- Several ongoing or future projects for high-field science applications, such as the small 45.5 T NHMFL magnet or the EU EMFL strategies to build fully superconducting magnets of 40 T.

All-superconducting magnets offer significant advantages for users and facilities, particularly for experimental techniques that require continuous high magnetic fields for extended periods. For example, NMR measurements typically require long durations, and high field superconducting NMR magnets could lead to new physical measurements and discoveries. Currently, high field measurements are limited to less than an hour, which is problematic for weak signals or long spin-lattice relaxation times. Resistive magnets incur high costs for long duration experiments due to their power supply requirements, and facilities can usually only operate one at a time, limiming magnet time available to users. Superconducting magnets, on the other hand, do not have these limitations, and their absence of a hydraulic cooling system makes them less noisy and enables high sensitivity experiments that are currently not feasible.

We would also like to share a few examples of other initiatives related to HTS technology and applications, which are being implemented at both the European and international levels for various societal purposes. This highlights the importance of HTS technology as a significant area of focus for further progress in other applications:

- The WIND (20 M€ funded by the U.S. Department of Energy) and EcoSwing (13 M€ funded by EU) projects both aim to build superconducting rotors of a few megawatts for wind turbines.
- NASA's N3X project aims, as Airbus' ASCEND project, to use HTS motors and power distribution systems in prototype aircraft.
- As part of the Resilient Electrical Grid project in the United States, Nexans has installed three 200 m 12 kV AC / 3 kA superconductor cables in Chicago's central business district.

All these developments requires facilities housed in the technologies infrastructures to develop, manufacture and test the new conductors, magnets and coils needed for the future applications.

More specifically, the facility requirements largely overlap with those of HFM for high-energy physics purposes (see § 2.1.1) and can be shared in the same technological infrastructure

Nevertheless, in situ validation will be necessary and requires specific and dedicated test facilities for each targeted application, either for a research infrastructure or in an industrial context.

2.7 Summary

It is clear from the above that many large-scale facilities based on accelerators and/or superconducting magnet will or are planned to be built in the future. Most of them will be world-class research infrastructures in a wide range of scientific fields. The AMICI-ETIAM Technology Facilities will continue to be essential for the design and construction of these facilities. The analysis of the landscape in the different fields reveals common needs in many key technological areas. Synergies already exists between labs joining effort in the building of a research infrastructure and between scientific fields with many TPs built to construct or test elements for a given project used, sometimes after some adaptation, for another project in a different scientific field. Examples include the various platforms in different labs dedicated to the construction, testing and integration of superconducting RF cavities into cryomodules built initially for the Eu-XFEL project, now used for ESS and in the future for PIP-II or MYRRHA. Specific TPs for very high power accelerators, in particular ion sources and targets, will be needed for radioactive beam in nuclear physics, neutrino facilities, accelerator-driven systems and fusion material test facilities. In the domain of superconducting magnets, the recent developments in HTS technologies are likely to boost studies for the next generation of particle physics accelerator, compact fusion devices but also MRI or gantries for hadrontherapy and clearly additional and upgraded TPs for R&D, test and prototyping will be needed, which could also benefit other possible applications of HTS, such as superconducting motors for wind turbines or airplanes.

3 Implications on the necessary developments / upgrades of the different categories of TPs

This section is devoted to an overview of key TPs (https://amici.ijclab.in2p3.fr/technology_infrastructure/category) in key technology areas that should be sustained over the long term, adapted, upgraded or possibly created in order to meet the needs identified in the previous section.

3.1 Categories of TPs

In order to make the different TPs from the different partners more visible to external users, it was decided to adopt a classification of TPs according to pre-defined categories and sub-categories:

Categories	***Sub-categories***
A. Facilities for beam tests of accelerator components	
B. Test stations for magnets	*B.1 - Test stations for superconducting magnets*
	B.2 - Test stations for normal conducting magnets
	B.3 - Magnetic measurement facilities
	B.4 - Platforms for Manufacturing, treatments and test of Magnet components for accelerator
C. Test stations for RF equipment	*C.1 - Test stations for superconducting cavities*
	C.2 - Test stations for normal conducting cavities
D. Test stations for High Power RF components	*D.1 - RF wave guides*
	D.2 - RF power sources
	D.3 - Power transistors
	D.4 - High power amplifiers
	D.5 - Solid State Power Amplifiers with their combiners and control system
E. Platform for characterization, treatments and test of materials	*E.1 - Thermal treatment platforms*
	E.2 - Chemical treatment platforms
	E.3 - Facilities for surface analyses
	E.4 - Electromagnetic, mechanical, thermal and associated material characterization Platforms
	E.5 -Test stations for mechanical manufacturing and tests (at cryogenic temperatures)
F. Platforms for clean assembly, alignment and tests of accelerator components	*F.1 - Complete accelerator modules*
	F.2 - RF power couplers

3.2 Necessary developments for the different categories

A. Facilities for beam tests of accelerator components

The beam test facilities at AMICI laboratories (IFJ PAN, INFN-LNL, INFN-LNF, KIT and STFC) are used to perform experimental validation and research vital to advancing the accelerator technology. The **IFJ PAN** is offering access to the proton beams produced by two cyclotrons: the AIC-144 cyclotron and the Proteus C-235 cyclotron. **INFN-LNL** is offering heavy ions produced by the accelerator complex TANDEM–ALPI–PIAVE as well as two Van Der Graaf type accelerators (CN and AN2000). **INFN-LNF** is offering the Frascati accelerator complex DAFNE with BTF (the Beam-Test Facility) and the SPARC_LAB. **KIT** is offering access to the storage ring KARA as accelerator test facility and to electron beams and coherent synchrotron radiation at the linear accelerator FLUTE. **UKRI-STFC** is offering an electron beam produced by a compact linear accelerator for research, CLARA. In order to continue their R&D mission further development and upgrades of these facilities are required.

The mission of AMICI beam test facilities is to provide the experimental testbeds for accelerator related development of accelerator technology and its experimental validation, and support the industry as well as train future scientists and engineers. Currently, the main use of these facilities is the irradiation of electronic components, detectors, beam diagnostics and the study of the behavior of materials under intense particle beams. The new trends in accelerator related research will enlarge class of accelerator components that require to be tested. There were identified following R&D tasks to be studied:

- The influence of low-energy particles on the properties of polymers and adhesives;
- The influence of radiation on the properties of accelerator elements that were created with use of 3D printing;
- The influence of radiation on mechanical properties of nanostructured amorphous-ceramic and metal composites;
- The influence of radiation on the resistance of cable dielectric materials/insulation materials;
- The effect of radiation on the properties of resins used in materials.

❖ **IFJ PAN:**

- *Description:* The **AIC-144** cyclotron delivers a proton beam with energy 60 MeV and intensity 0.5 – 60 Gy/s for two irradiation stations. Available field diameters for the unscattered beam range from 1 cm to 3 cm and a proton flux from 1 x10^7 to 1x10^{11} p/cm^2*s. The field diameter for the scattered beam can be increased up to 12 cm. The range of available beam currents is 2nA – 80nA (short-term current 100nA). Two beamlines with research irradiation infrastructure: the small field irradiation station with high precision sample positioning system and high-intensity beamlines offer enables irradiation over a wide fluence range (from 5x10^5 to 2x10^{12} p/cm^2).The **Proteus C-235** is an isochronous cyclotron with a compact conventional magnet. This facility produces a proton beam with energy from 70 MeV to 230 MeV and intensity from 0.5 nA to 500 nA, an experimental room with a horizontal beam and with a magnetic optical system enabling beam size adjustment, two gantry rooms that enable sample irradiation with energy range from 70 MeV to 230 MeV using scanning beam (with σ=2.7 mm or σ=4 mm spot size) and at a selected angle within the range of 0 to 360^0 and facility for irradiation with the use of horizontal beam with energy ranging from 0 MeV to 70 MeV; this facility gives a possibility of irradiation using Spread Out Bragg Peak, SOBP. Dose rate: from 0.01 to 1Gy/s. An energy degrader and selector, allowing the beam energy to be downgraded continuously to 70 MeV, is an integral part of this installation.

  Both cyclotron facilities are equipped with beam guiding control systems to adjust and control beam parameters. The irradiation lines are equipped with beam-forming and diagnostic systems, including sets of dedicated ionisation chambers (beam monitors) sets of active radiation detectors, including ionisation chambers solid-state detectors, reference sets of ionisation chambers and electrometers, dedicated measurement phantoms, both aqueous and solid-state used for beam quality control for both proton radiotherapy and research work. Equipment based on 2D scintillation detectors and ionisation chamber arrays is also used to control the spatial distributions of the beam. Passive dosimetric methods based on thermoluminescence detectors and 2D thermoluminescence detectors, OSL crystals, alanine dosimeters, and photochromic films are also available to control spatial distributions of dose and beam parameters. Equipment for the precise positioning of radiation detectors and the positioning of irradiated samples is available at irradiation stations.

	Cyclotron	
Parameters	**The Proteus C-235**	**The AIC-144 cyclotron**
Beam energy	70 - 230MeV	60MeV
Beam current	0,5 - 500nA	80nA (100nA)
Beam macrostructure	n/a	50Hz
Macro pulse length	n/a	0,5 ms

- *Activities:* Both cyclotron facilities (AIC-144 and Proteus C-235) are used for research in the field of applications in dosimetry and for developing new methods in proton radiotherapy (proton FLASH and GRID therapy). The tests of the radiation hardness of electronics and construction of material components for the space sector and for designing and constructing the new research facilities are carried out. In addition, the proton beam from the C-235 cyclotron is used for proton radiotherapy in two rooms equipped with an isocentric gantry and dedicated proton eye radiotherapy facility. The proton beam is also used in the experiment hall for research in nuclear physics and industrial applications including tests of new detectors and the development of dosimetry methods in the proton field.

- *Needs:* To fulfill requirements related to new trends the development of AIC-144 test irradiation facility for electronic components is required. It is necessary to upgrade and develop the beam guide lines including modification or change of the torsion magnets which will enable to increase in the transmission of the beam delivered to the irradiation stations and achieve proton fluxes up to $5x10^{10}$ p/s. On the high-intensity irradiation line, it is necessary to upgrade the beam scattering and forming system to provide a larger diameter and homogeneous radiation field. It is also needed the system to automate the data acquisition and installation of an automatic XY scanner for sample moving and positioning.

❖ **INFN-LNL:**

- *Description:* The accelerator complex **TANDEM – ALPI – PIAVE** is offering heavy ions for applied and nuclear physics, produced with energy from 20 MeV/u to 5 MeV/u, and intensity from 2 nA to 200 nA, depending on the ion species. The linac serves several experimental lines: typically 1 is dedicated to material irradiation and 2 for biological sample irradiation. The Linac is equipped with an empty inline diagnostics box (200 mm * 200 mm) that can be used for accommodating external user devices for irradiation tests. The INFN-LNL is offering also light ions produced by two Van Der Graaf type accelerators (**CN** and **AN2000**) used for applied and nuclear physics.

- *Activities:* The superconductive linac is used (besides nuclear physics experiments) for material testing via heavy ion irradiation (such as Xe ions at 1 GeV for aerospace material tests). The Van Der Graaf accelerator CN can be used for neutron irradiation experiments, and it is equipped with a high dose bunker. There are three main lines that can be equipped with neutron converters to generate neutron fluxes and they are used also for material testing. One of the lines is equipped with a thermal neutron moderator that generates a neutron flux of 5×10^5 n/(s·cm^2). Inside this heavy water-graphite moderator, the prototypes neutron converter integrities and their material composition behaviors under proton irradiation are tested. To irradiate the neutron spectra of the sample, there is an area of 0.5 m x 0.5 m outside the moderator exit, which can be used. A sample 3 cm x 3 cm housing for disk prototype neutron converter can be used inside the moderator to directly irradiate with protons. In this case, power densities of 3 kW/cm^2 can be reached (used for testing the neutron converted high temperature resistance) onto a 1 mm diameter beam spot. Central (un-shielded) line can generate several neutron spectra via the usage of proton and deuteron onto Be/Li targets (e.g. neutron spectra of 1.2 MeV peak energy and 10^9 n/s from Be neutron converter). The housing of the equipment can be of the order of 3 m x 3 m. A further line with heavy irradiation bunker for high doses is at disposal with a housing of 1 m x 1 m.

- *Needs:* It is required to develop existing infrastructure by adding eight new target stations available for users. Also, designing and building TRIPS – the low energy high intensity proton source for the production high intensity CW protons beam is needed to fulfill requirements related to new trends in accelerator related R&D.

❖ **INFN-LNF:**

- *Description:* The **Beam-Test Facility (BTF)** is an infrastructure of the Frascati accelerator complex DAFNE. It is mainly dedicated to the development and testing of particle detectors, providing primary, fixed energy beams and secondary electron or positron beams with continuously tuneable energy from 30 MeV to 780 MeV. The beam current (multiplicity) can be varied from 10^{10} particles/pulse, down to a single particle per pulse in a Poisson stochastic regime. The standard beam pulse length is 10 ns and the BTF injections regime is available via pulsed magnet, steering away DAFNE transfer line some of the LINAC 20(40) ms spaced beam bunches. The beam could be pulsed electron and positron bunches: up to 49 pulses/second in relation to DAFNE injection cycle type and operation mode, down to 1.

  SPARC_LAB offers two separate installations, which are the SPARC high-brightness electron photoinjector and the FLAME high-power laser.

  The **SPARC photo-injector** produces electron beams with energies in the range of 5 - 140 MeV, 10 pC – 1 nC charge and with duration tunable in the range 20 fs-5 ps (rms). The beam is provided completely characterized in the 6D phase-space and can be delivered to three different beamlines that have been dedicated so far to Free-Electron Laser (FEL). Recently, at the end of the LINAC, a plasma accelerator module has been installed providing accelerating fields up to 1 GV/m.

  The **FLAME high-power laser** is based on a Ti:Sa laser that has been produced by Amplitude Technologies and can deliver ultra-short pulses (~20 fs, 60-80 nm bandwidth) with energies up to 6 J in the IR range (800 nm). The resulting power peak is ~250 TW.

- *Activities:* Beam Test Facility (BTF) Area has two experimental lines BTF1 and BTF2. BTF1 is used as secondary beam production and low multiplicity regime. The area is released for a maximum current of $3x10^{10}$ particles per second. BTF2 is the new line that steers bunches from BTF1 to a new experimental area. The area will be released for a maximum current of $1x10^6$ particles per second.
  SPARC_LAB offers users the possibility to perform innovative experiments involving electron beams and laser pulses. SPARC_LAB is configured as a test facility, in the framework of the EuPRAXIA project, thus the schedule of the activities can be planned and re-arranged just a few months in advance without big constraints.
  The SPARC photo-injector is used for tests for advanced diagnostics and laser-electron interaction (Thomson scattering).

  The FLAME high-power laser is used for solid-target experiments (production of electrons, protons and heavier ions), laser-driven plasma-based acceleration and as a betatron radiation source.

- *Needs:* BTF2 is one of the parts of the Beam Test Facility and the new line that steers bunches from BTF1 to a new experimental area. The area and the beamline installations started in February 2021 and positively ended in June 2021. Nowadays under beam commissioning. The area will be released for a maximum current of $1x10^6$ particles per second. There will be a limitation of area occupancy that will lead to a maximum number of elements.

The electron beams provided by SPARC have been employed in experiments concerning the generation of radiation in different ranges (visible, EUV, THz, and Xrays), for the development of advanced diagnostics (based on THz, OTR and Electro-Optical Sampling) and, in recent years, for the development of innovative acceleration techniques based on plasma. The laser pulses provided by FLAME have been employed in experiments concerning plasma-based acceleration (up to a few hundred of MeV adopting gas jets in the self-injection regime) and protons/ions generation and acceleration by means of solid-target interactions.

❖ **KIT:**

KARA

- *Description:* **KARA**, the Karlsruhe Research Accelerator, the electron storage ring has two missions: as a test facility for accelerator research, technology, and detector development and as the KIT Light Source, operated by KIT IBPT. The Institute for Beam Physics and Technology (IBPT) at KIT has a highly recognized expertise in fast ultra-short bunch diagnostics, remote operation of accelerators as well as a proven experience in developing, testing and bringing to market of accelerator components like superconducting insertion devices such as wigglers and undulators and related magnetic characterization techniques.

- *Activities:* KARA is an electron storage ring, a platform for development and testing of new beam and acceleration technologies, pooling research of new accelerator concepts and development of new detectors. Accelerator studies at KARA profit from its flexible lattice, large energy range (0.5 - 2.5 GeV), adjustable bunch lengths (50 ps down to a few ps in a dedicated short, single-bunch or multi-bunch operation mode), and the fully synchronized, fast, transversal and longitudinal beam diagnostics. KIT IBPT also hosts the cryogenic test bench experiment (BESTEX) operated by CERN and KIT at KARA down to 80 K, to explore photon stimulated desorption, photon reflectivity, photon heat loads, and photoelectron generation originated on vacuum beam screen prototypes under irradiation of the FCC-hh-like synchrotron radiation spectrum. In 2017, KIT and Bilfinger Noell GmbH (BNG) installed the first superconducting undulator with series-production readiness, SCU20 at KARA. Subsequently, in the last years, several wigglers and undulators are shipped to light sources around the world for which KIT IBPT performs cold tests and quality assurance on-site of BNG customers. During the EU projects EuroCirCol, ARIES and EURO-LABS first FCC beam screen prototypes have been tested at KARA.

FLUTE

- *Description:* **FLUTE**, the far-infrared, linear accelerator (linac) and test experiment (Ferninfrarot Linac und Test-Experiment), a compact linac-based test facility for accelerator R&D and future source of intense THz radiation for photon science, operated by KIT IBPT.

- *Activities:* FLUTE serves as an accelerator test facility for a variety of accelerator physics studies, generating pico- down to femto-second long electron bunches of 5 up to 41 MeV (planned up to 90 MeV), also providing coherent radiation in ultra-short, very intense, light pulses spanning the terahertz and far-infrared spectral range and beyond. FLUTE consists of a 5 MeV photo-injector, a S-band linac and a D-shaped chicane to compress electron bunches covering a large bunch charge range, from 1 pC up to 1 nC, and bunch lengths from 500 fs down to a few fs.
  Within the framework of Transnational Access of the EU project ARIES, PSI together with KIT IBPT have successfully installed an experimental chamber in the 5 MeV diagnostic area of FLUTE. Together, PSI, the University of Bern, both in Switzerland, and KIT IBPT have conducted experiments on split-ring resonators to establish a diagnostic method for determining the longitudinal size of electron bunches, to be

continued in the EU project EURO-LABS. The experimental chamber as well as the corresponding space is available for future user experiments including applications in health or quantum technologies or beyond.

❖ **UKRI-STFC:**

- *Description:* CLARA generates up to 50 MeV, 250 pC electron bunches at 10 Hz. Phase 2 is currently under construction and will elevate the beam to 250 MeV, 250 pC at 100 Hz. Experiments during Phase 1 (up to 50 MeV) have included studies of Plasma afterglow diagnostics, THz driven acceleration and the testing of hybrid pixel detectors.
- *Needs:* The development of the Full Energy Beam Exploitation (FEBE) area will provide a dedicated user experimental area where the 250 MeV electron beam can be combined with a high-power laser beam (up to 100 TW).

Conclusions

The beam test facilities at AMICI laboratories (IFJ PAN, INFN-LNL, INFN-INF, KIT and STFC) are a solid base for the testing of accelerator components, among which beam diagnostics and electronic components, and studies related to materials under irradiation, which can be important for other domains such as space and medical applications. Some new trends in associated R&D have been identified, which call for at least the long-term preservation of these facilities and their upgrading.

B. Test stations for magnets

Over the past, the European laboratories have demonstrated their large experience in large superconducting magnets testing or sub components qualification. They are presently playing a major role in the field of research and development for particle accelerators and magnetic fusion. During the last few decades, they have developed a unique expertise on superconducting accelerators and magnets. The recent development of high-temperature superconductors highlight the challenges for the coming years concerning the test stations for magnets at low and high temperature. AMICI participating European research institutes operate - or are in the process of updating - large number of magnet stations. Several technology platforms will be supplied in the years to come. One of the key factor in the success is the relationship with industry.

B.1 Test stations for superconducting magnets

❖ **CEA Saclay:**

STAARQ (Station Test Aimant Accelerateur Quadrupole)

This new cryogenic test station, which is now in its final commissioning phase, aims to test superconducting magnets in vertical position, in normal liquid helium at 4.5 K or in superfluid helium at 1.9 K while performing magnetic measurements in order to assess the magnetic field generated by magnet.

- *Description*: This test station can host 5 m long magnets, with a maximum diameter of 640 mm, and power them up to 13 kA thanks to HTS current leads. Two Magnet Safety System (MSS) in parallel, one analogic, manage magnet protection and one numeric newly implemented for this station.
- *Activities*: CEA collaborated with Mark&Wedell to design superconducting current leads using liquid nitrogen to cool the junction and liquid helium for the cold terminals. The currents leads have been successfully tested in STAARQ.

- *Plans*: The quadrupole magnet called "short model" MQYYM will be tested soon in STAARQ at 1.9 K. The following tests will be carried on the two prototype magnets (MQYY), and the MQ magnets designed for the LHC consolidation project.

JT-60SA large-scale test facility

This facility was built in the past to performe the tests of the toroidal field coils of the Japanese Tokamak JT-60SA. More recently, the facility has been upgrade by the integration of the "Claudet Bath" and a Helium pump to allow the production of 1.8 K helium. This former facility is one of the largest in the word. It is currently under upgrade with the aim of becoming a versatile station. The main goal is to prepare the future challenges concerning the new detector like dipole magnet for dark matter - Madmax- as well as the magnetic fusion needs. Indeed, in the framework of fusion, and thanks to the recent and rapid development of High-Temperature Superconductors (HTS), it will be necessary to demonstrate the feasibility of HTS magnets in the near future.

- *Description:* This facility is a 12 m long x 7 m large cryostat, associated to 500 watts refrigerator, with a currently power supply of 25.7 kA, hundreds of signals for instrumentation, PLCs, Magnet Control System, Magnet Safety System and Fast Data Acquisition. The new station has the ambition to house a real large-scale HTS demonstrator.

- *Plans*: Station available to demonstrate the large-scale feasibility of HTS magnets

❖ **CERN:**

SM18 SC Magnets Test Facility

This test facility offers testing superconducting magnets and devices refrigerated at low temperatures and high currents. Test subjects can be cooled with LHe and/or Gaseous He to temperatures ranging from 1.9 K up to 80 K, and can be powered up to currents as high as 30 kA.

- *Description*: An area regrouping four vertical cryostats and a feed box is dedicated to the research and development programs. The primary powering is done with a 20 kA power converter while a secondary circuit can be different from cryostat to cryostat from 600 A to 15 kA. The magnet protection can include energy extraction system, for both the 20 and 15 kA circuits. There is one cryostat allowing a variable temperature cooling from 4.5 K to He gas temperature, while the other cryostats allows either 4.5 K, 1.9 K or both. The test stand allows the read out of a high number of instruments via dedicated or mobile channels. The second area regroups 10 horizontal benches with powering capacity of up to 20 kA, and a secondary parallel powering circuit of up to 2 kA.On both areas, magnetic measurements are possible with dedicated systems. The vertical cryostats uses rotating coils in LHe that maybe adapted to the magnet's geometry, while on the horizontal cryostats an "anticryostat" is used and so the magnetic measurements shafts and cryostats are specifically built for each magnet. In addition, MagNet is a platform that includes also a cryogen free cryostat, which allows users to test instrumentation at a range of different temperatures, from 300 and 4.2K.

- *Activities*: The area regrouping horizontal benches has been used to test magnets of the Large Hadron Collider and these days there are partially modified to allow testing the new generation HL-LHC cryo assemblies.

❖ **CIEMAT:**

Test Stations for Superconducting Magnets

- *Description:* The superconducting laboratory for testing magnets and other superconducting devices has de possibility to test magnets up to 2000 A at cryogenic temperatures. It includes power supplies, three helium cryostats, instrumentations, and a dry cryostat cooled by cryocoolers. The dry cryostat allow measuring thermal conductivity or processes like sensor calibration. Two cryostats are available for testing of superconducting magnets at 77 K and 4.2 K. The Lab has a Gifford-McMahon cryocooler for superconducting magnets testing at variable temperature (T >= 10 K).

- *Activities:* Presently, in the framework of the PRISMAC project, one of the most relevant activity in CIEMAT concerns the fabrication, in collaboration with industry, of the so called MCBXFA & MCBXFB magnets for the HI_LUMI project. Non-superconducting components for accelerators like resistive magnets or RF cavities, have also been developed by the Lab. The main objectives of PRISMAC project are:
    a. Developing MCBXF magnets,
    b. Starting a laboratory for High Field Magnet (**HFM**) prototypes, and
    c. To participate in the **HFM** magnet program in order to make Nb_3Sn prototypes and eventually High-Temperature Superconductors (**HTS**) magnets for future accelerators.

- *Plans:* Development of **HFM** prototypes

❖ INFN:

The technological infrastructures at INFN are dedicated to accelerators and superconducting magnets research activities. The geographical distribution of the facilities are linked each other depending on the field of applications. The infrastructure based on large cryogenic facilities is located in four different sections and laboratories (Genova, Laboratori di Legnaro, Milano-LASA and Napoli-Salerno). Main technological facilities are:

MaRiSA@Genova
Test of critical current of high current superconducting **cable** up to 8 T in a bore up to 440 mm and current up to 100 kA with a transformer method.

- *Technical Means*:
    - Magnetic Field of 8T in 330 mm bore with sample temperature 1K<T<300 K;
    - Magnetic Field of 6T in 440 mm with temperature 1K<T<300 K;
    - Sample shaped as a ring with low resistance joint;
    - Maximum current 100 kA.

- *Activities:* Among the most significant results, critical current measurements of conductors for HERA superconducting dipoles, conductors involved in Babar superconducting solenoid (SLAC°, conductors involved in CMS superconducting solenoid (CERN), conductor involved in Mu2e superconducting solenoid. The platform can be operate exclusively by INFN manpower.

SOLEMI@LASA
Facility with a large bore (535 mm) devoted to test superconducting cables and small magnets in a background magnetic field up to 13.5T.

- Vertical test station for superconducting accelerator magnets in Milano - INFN LASA
    - *Description:* The laboratory operates a Vertical Magnet Test Station to test superconducting magnets in a vertical cryostat of 690 mm diameter and 6500 mm height maximum weight 10 ton, and a power supply up to 10 kA with magnet protection ancillaries (breaker, resistors and power circuit for 10 kA magnets). Max operating pressure 4.5 bar with a thermal shield cooled by LN or evaporated GHe.

    - *Plans:* The Vertical Test Station will be integrated by a 515 mm diameter and 3300 mm vertical cryostat for medium-size magnets/samples. In addition to work at variable temperature for High-Temperature Superconducting magnets tests is foreseen.

THOR@INFN-Salerno
Horizontal test station for superconducting accelerator magnet cooled with supercritical helium

- *Description:* INFN Salerno group, linked to INFN Napoli division, operates the Magnet Test Facility THOR, which is an infrastructure dedicated to horizontal test of accelerator superconducting magnets, specifically built to perform final test of complete cryomodules. The infrastructure includes a refrigerator (Linde LR280) system in the isobaric mode (200 W@[4.5 – 6] K, 15 g/s, plus 500 W@ [50-80] K for shields), it has the J-T stage for LHe production (up to 120 l/h) with its internal gas purifier. The laboratory is also equipped with a power converter capable of delivering current up to 20 kA at 25V. The facility will include two test lines.

- *Activities:* The magnetic test stand installation for performing the site acceptance test (SAT) of the quadrupole modules before installing them into the SIS100 synchrotron. This special program is carried on behalf of GSI/FAIR (Darmstadt), according to signed MoUs GSI/INFN in 2019 and GSI/University in 2020, within the Laboratory for Power Superconductivity set at the University of Salerno campus. The laboratory has already started its work (two modules already completed) on the first line, while the second line is under commissioning.

- *Plans:* Presently we have four modules in the lab, one of them is under cold test. The plan for 2024 is to complete the second test line and improve the control electronics. In addition, within the IRIS project we will set a new laboratory for high power energy transmission line where an additional cryoplant and power converters up to 40 kA will be installed.

❖ KIT:

CASPER I

- *Description:* CASPER I is used as a test facility for superconducting undulator technology. CASPER I is an operating vertical cryostat where coils with maximum dimensions of 35 cm length and 30 cm diameter can be immersed in liquid helium for testing (quench tests and local field measurements). With CASPER I we can test new winding schemes, new superconducting materials and wires and new field correction techniques.

- *Activities*: The most relevant tests performed are short mockups in collaboration with industry, superconducting joints and short mockups with switchable period length, short transverse gradient undulator (TGU) for laser wake-field accelerators, and high-temperature superconducting (HTS) tapes for novel undulator concepts, switchable-period-length undulator for ultra-low-emittance light sources and so on. The magnetic field along the beam axis is measured by Hall probes fixed to a sledge moved by a linear stage with the following precision $\Delta B/B=0.015\%$ and $\Delta z/z<10^{-5}$.

CASPER II

- *Description*: CASPER II is a horizontal, cryogen-free test stand that will be used to perform quality certification (max. length 1500 mm, max. diameter 500 mm) of new superconducting systems and insertion devices. It will also serve to test small prototype coils in a cryogen-free environment. The magnetic field along the beam axis will be measured by Hall probes fixed to a sledge moved by a linear stage. The precisions are $\Delta B<1$ mT and $\Delta z<1$ µm. Field integral measurements will be performed using the stretched wire technique. Local and integral field measurements are made in the same thermal cycle.

❖ Uppsala University:

FREIA-GERSEMI:
GERSEMI is a versatile vertical cryostat system for testing superconducting devices such as accelerating cavities and magnets, either in a saturated or a pressurized liquid helium bath.

- *Description:* This unique vertical cryostat is used to test superconducting magnets up to 2.8 m height in helium at a temperature between 4.2 K and 1.9 K. The diameter of the cryostat (1 m below the lambda plate) and its available length (2.4 m) allows for the training of very large magnets. GERSEMI can be used to power up to two magnets or two apertures at the same time since it is associated with a multitude of equipment such as two power converter units of 2 kADC – 10 VDC each and, two IGBT based energy extraction units with different dump resistors (which can be combined in series or in parallel). Up to 36 voltage, taps can be monitored at the same time on the magnet, and on the insert. Voltage taps are used on the redundant quench protection system as well as the acquisition system. A 10-channel digital mutimeter and a 48- channel digital acquisition system can be used to monitor signals from a few miliseconds up to a few days depending on the measurements needed on the magnet.

- *Activities:* Even if Uppsala University is still in the learning phase of using GERSEMI to test low temperature superconducting magnets, this facility is opened for external user projects, for example through the EUROLABS consortium (EU Horizon Europe Research and Innovation program). This grant covers the costs of access to the facility (personal, cryogens,…) and supports the users performing their experiments (travel costs). FREIA is currently designing and fabricating, in collaboration with CERN, a rotating-coil magnetic-field measuring-bench (see section B.3).

- *Plans:* It is planned that the measuring-bench and the anti-cryostat shall be commissioned for operation during 2024.

B.2 Test stations for normal conducting magnets

❖ **CERN:**

The Laboratory is in charge to measure mainly Normal Conducting and Permanent Magnets. The lab is equipped with power converters up to 900 A and several test benches implement advanced measurement techniques (stretched wire, vibrating wire, rotating coils, fluxmeters, field mapper…). The Lab also develop new instruments and there are specific tools for the calibration of the sensors.

❖ **KIT:**

LASMagLab

- *Description:* The installation of a high-end magnetic measuring bench for normal-conducting and permanent magnet-based accelerator magnets at LAS enables a detailed characterization of the FLUTE and LWFA beam transport magnets. The setup integrates different magnetic measurement techniques as 3D hall probe scans, stretched-wire and rotating-coil field integral measurements.

- *Activities:* The hardware experiment control for the hall probe scan and the stretched-wire technique have been implemented in the first step and applied to characterizing the magnets for FLUTE as well as the in-house built magnets for the LWFA beam transport.

A new circular scan technique for longitudinally resolved magnetic multipole mapping was developed which provides an excellent real data basis for efficient particle tracking studies.

B.3 Magnetic measurement facilities

❖ **CERN:**

The Magnetic Measurements section at CERN is in charge of the magnetic tests of magnetic devices for accelerators. For that, CERN uses the latest-available techniques and instruments. High quality and reliable measurements are performed for many of CERN's ongoing-projects. This is why the laboratory is constantly improving its methods and its workflow to serve its clients more efficiently.

❖ **CIEMAT:**

The infrastructure of magnetic measurement facilities, that is a part of superconducting magnets Lab, is composed of magnetic measurements instrumentation, the high precision mechanical 3D system with a Hall sensor for measurement of large magnetic devices and a rotating coil system for the measurement of dipole, quadrupole and sextupole field quality.

❖ **UKRI:**

Magnet Test Lab

The test capabilities at UKRI include:

1. Hall probe mapping with a 5 m long bench, 3-axis motion with a resolution of 1µm. A variety of probes for different applications can be tested. Fiducialization of magnet centers.
2. Wire measurements:
    - Stretched wire (field integrals)
    - Pulsed wire (fast undulator measurements)
    - Rotating coil (accurate harmonics), and
3. Hall probe calibration:
    - Reference dipole magnet
    - NMR reference probe

Commercial partnerships and contracts include normal & superconducting magnet manufacturers, electronics, and battery development.

❖ **Uppsala University:**

Magnetic Measurements

- *Activities:* FREIA is currently designing and fabricating, in collaboration with CERN, a magnetic-field measuring-bench based on a rotating coil, to be inserted in a vertical so called anti-cryostat for precision measurement of superconducting accelerator magnets of aperture equal or greater than 50 mm. This anticryostat will make magnet's measurements possible while the magnet is being operated at cryogenic temperatures in GERSEMI."
- *Plans:* It is planned that the measuring-bench and the anti-cryostat shall be commissioned for operation during 2024.

B.4 Platforms for manufacturing, treatments and test of magnet components for accelerator

Most of the existing tooling available in European laboratories was developed for NbTi magnets more than 20 years ago, in the framework of the LHC. Since the 1980s, a new generation of superconducting materials has appeared, making it possible to operate at much higher and more easily attainable temperatures. Nb_3Sn conductor is subjected to high temperature heat treatments at 650°C during the manufacturing process. During this process, the superconducting phase of Nb3Sn, which is a stress-sensitive material, exhibits significant dimensional changes that could lead to degradation in the performance of the cable and the magnet. We must provide designers with platforms that reproduce the conditions of the manufacturing process in terms of mechanical stress, temperature and gas flow, and that correctly characterize the materials obtained in situ, both mechanically and thermally.
HTS conductors cannot only maintain superconducting properties up to about 100 Kelvin, but can also operate in a magnetic field of more than 20 Tesla, which is of great interest for future accelerator magnets. Due to the very high critical temperature of the material, a very large operational margin is available, which makes it easier to avoid resistive transitions and increases the reliability of the magnet. Also, it is necessary to replace

or update old equipment with a set of new ones adapted to Nb_3Sn and HTS magnets, in order to maintain European leadership in the field.
These new equipment should be modular and flexible. Their designs need to be in order to effectively cover a wider range of coil shapes (dipole coils, block coils splayed, quadrupole coils and solenoids (double layers or pancakes). Due to the complex use of HTS and Nb_3Sn materials, special attention must be paid to quality control at every stage of the manufacturing process. New equipment will be required to precisely control all these steps.

❖ **CEA:**

- *Description*: At CEA IRFU, several technology platforms will be supplied in the years to come:
    - **Modular and versatile winding machine** suitable for several types of winding configuration: dipole coils, flared end block coils, quadrupole coils and solenoids (layers or double pancakes) until 5 meters long.
    - This winding machine should be equipped with a Cobot arm for more accuracy and repeatability.
    - **A furnace to perform magnet heat treatment until 700°C (especially for NB3Sn**) in line with winding machine.
    - **An impregnation facility (vacuum impregnation)** for insulation of coils.
    - **An Equipped platform for control and test**. This station, equipped with various measuring devices, will allow controls: dimensional (3D measuring/scanning arm), electrical (resistance, inductance, capacitance, discharge, insulation short cut …), characterization (viscosity and glass transition of the impregnation resins used), data acquisition.

Conclusions

A wide variety of European test stations for magnets and accelerator components are running often through national, European and international collaborations. To meet the challenges of increasing development of High-Temperature Superconductors (HTS), most of the European test stations are being improved or upgraded in near future to allow testing the new generation of magnets and their associated components. Significant advances include the development of high power energy transmission, power converter up to ~ 30 – 40 kA as well as the test stations available to demonstrate the large-scale feasibility of new HTS magnets.

C. Test stations for RF equipment

The AMICI core team operates a larger number of RF test stations for both superconducting and normal conducting cavities. They are usually supplemented by additional smaller infrastructures needed to study samples or to investigate different steps in the cavity production or treatment sequence. Some of the infrastructures and test platforms are directly linked to larger projects, others are operated in the frame of R&D programs. Until today, only selected TPs are offered within AMICI to others. An extension is probably not excluded per-se, individual negotiations are recommended.

The recently discussed and documented CERN European Strategy on Accelerator R&D is describing the European needs for the upcoming years. In the following we try to link those thoughts with the descriptions of and plans for the AMICI RF test stations. Where adequate, we will also mention the existence of additional test set-ups.

C.1 Test stations for superconducting cavities

The production of SRF cavities and the related R&D program deals with cavities of very different types. The majority is built using bulk Niobium, others apply Niobium (and other material) coating on bulk material, usually Copper. The testing of bare cavities (with or w/o He vessel) is typically done in vertical cryostats, more integrated (dressed) cavities (with e.g. frequency tuners, RF couplers, or diagnostics studying the cavity in its later accelerator module environment) in horizontal cryostats. Vertical cryostats are used for cavity performance checks and in all attempts to improve the gradient or quality factor i.e. reduction of cryogenic losses. A larger number if vertical cryostats exists. Most of them are able to cope with different geometries, but intrinsic limitations exist, and adaptation to different geometries (size, typically frequency driven) is studied on a case by case basis. Some of the AMICI core team's TPs are used to the benefit of different laboratories and projects.

Almost all vertical and horizontal test cryostats are used for the individual owner's R&D program. Small, often single cell cryostats, supplement the larger ones. Detailed studies investigate cavity surface treatment procedures; dedicated UHV furnaces are in use. Such programs are often done in collaboration with local universities. Here one path towards Energy Recovery Linacs (ERL) and Muon Collider (cavities operated in strong magnetic fields) can start. More technical developments probably require long time testing in e.g. horizontal cryostats. It needs to be understood if AMICI RF TPs can be offered or if dedicated infrastructures need to be set-up for projects. Thin film cavity development is actually done with samples and single cells. Material characterization requires microscopy, X-rays, other analysis techniques, and is usually done using the respective local infrastructures and/or collaboration with academic institutes.

Most vertical test cryostats are supplied with sophisticated diagnostics (temperature mapping, second sound, DC magnetic field). Some dedicated set-ups may be used to study new properties. A regular exchange between test stand owners can be fruitful. A respective recent AMICI workshop was organized [ref].

The preparation for RF testing usually happens at the cavity owner. Nevertheless, access to clean rooms next to the test station can be helpful to take care of small interventions. Also important is the qualified use of local cleanrooms as they are needed to install a cavity in the test stand.

There is strong interest in the exploration of SRF cavity operation at 4K. The development or at least investigation of Nb3Sn, NbN, NbTiN, MgB2 -based cavities, in view of future ERL, is of strategic interest. It requires a sufficiently large number of key experts having access to the respective TPs. For the next few years sample and single cell cavity cryostats may be sufficient.

SRF related test stations

❖ **CEA Saclay**:

- *Description*: At CEA Saclay Supratech Cryo/HF has two cryostats dedicated to vertical cavity tests: CV1 and CV2. The tests can be performed on bare and tanked cavities at temperatures ranging from 4 K down to 1.7 K.
    - CV1 is a small cryostat usually dedicated to R&D single cell cavities; typically TESLA type. It has 0.45 m diameter and 1 m effective depth, respectively. Two inserts are dedicated to this cryostat.
    - CV2 is used for larger cavities, typically XFEL, ESS and SARAF cavity types. It has 0.7 m and 1.7 m effective diameter and depth, respectively. Three inserts are dedicated to this cryostat. A removable magnetic shield is available in addition to the cryostat's permanent shielding. This allows to have around 0.1 µT remnant magnetic field during the tests.

  The existing RF equipment can be used for the both test zones. Currently, the RF frequencies / maximum RF powers, which are available for the cavity vertical tests are 88MHz / 200W, 176MHz / 200W, 704MHz / 500W, and 1300MHz / 500W.
  Fully equipped cavity tests are performed in the CryoHoLab horizontal cryostat which was already used for TESLA-like, HIPPI and IFMIF cavities tests.

- *Activities*: Both vertical cryostats are currently used to fulfill CEA's in-kind contributions and support the in-house SRF R&D program.

- *Plans*: The two cryostats can potentially be shared with / reserved for external users, during the next years. CryoHoLab, will continue to be used for fully equipped cavity tests but will probably be upgraded. An improvement plan for instrumentation is ongoing.

❖ **CERN**:

- *Description*: CERN operates two SRF infrastructures. One is SM18 which accommodates four vertical cryostats and two horizontal bunkers. The other is cryolab where one vertical cryostat and other cryogenic equipment for material studies are available.
  - The four vertical cryostats in SM18 have different configurations and purposes. V3 (diameter 1100 mm, 2500 L, 1.7-4.5 K, 300 W) has been dedicated for R&D and is fully equipped with several diagnostic tools. The main project has been SPL 5-cell elliptical cavities (704 MHz) and HL-LHC crab cavities (400 MHz) but the cryostat is versatile for other cavities. V4 (diameter 1100 mm, 1500 L, 1.8-4.5 K, 300 W) has been used for production crab cavities for HL-LHC; however, it can also be available to other cavities. V5 (diameter 1000 mm, 1.8-4.5 K ,100 W) is a unique cryostat with a vacuum insert dedicated to Nb/Cu HIE-ISOLDE (100 MHZ), FCC-SWELL cavities (1.3 GHz), or other dressed cavities. V6 (diameter 1100 mm, 2500 L, 1.8-4.5 K, 300 W) has been dedicated to Nb/Cu LHC cavities (400 MHz) and has not been equipped with magnetic shields or compensation coils. V6 is upgraded in 2022 with a new cryostat and a magnetic shield. M7 and M9 horizontal bunkers are for LHC and HL-LHC cryomodules testing. CERN does not operate horizontal cryostats for SRF cavities.
  - In the cryolab, a small cryostat (diameter 340 mm, 90 L, 1.5-4.2 K, 25 W) has been dedicated to R&D projects with 1.3 GHz 1-cell elliptical cavities and quadrupole resonators (QPRs) (400, 800, 1200 MHz). The QPR has been used to characterize flat samples from other laboratories. Temperature mapping system for 1-cell cavities was deployed in 2022. One limiting factor of this cryostat is radiation dose. There are also other cryogenic apparatuses for material characterization, such as to measure the residual resistivity ratio of superconducting materials.

- *Activities*: Most of the CERN cryostats are currently occupied by on-going SRF program at CERN and external users must contact and negotiate with the SY-RF-SRF section.

- *Plans*: CERN will construct a new building dedicated to SRF activities where all the processes, starting from electron-beam welding, chemical treatment, clean assembly, and cold tests will be performed in close proximity. This major upgrade will avoid internal transports among dedicated buildings located in different sites of CERN today. Procurement of a horizontal cryostat and small vertical cryostats is under consideration.

❖ **CNRS IJCLab:**

- *Description*: The vertical cryostat (CV800) in operation at IJCLab is dedicated to cavity testing between 4.2K and 1.7K. It can accommodate 2 cavities (diameter 1100 mm, total height 1500mm) equipped with their helium jacket (no dunk test). Helium is supplied through 500L Dewars, recovered and liquefied on site. It benefits from a complete instrumentation for cavity characterization (temperature sensors, magnetic sensors, X-ray sensors).

- *Activities*: IJCLab has been leading development of low-beta SRF cavities in Europe, and delivered production cavities for Spiral2 (14 QWR at 88 MHz), is delivering production Double Spoke resonators for ESS (26 cavities at 352 MHz) and is today strongly involved in R&D and production phases for MYRRHA/MINERVA (Single Spoke at 352 MHz) and PIP2 (Single Spoke 325 MHz) projects.

- *Plans*: A new larger cryostat (CV1250) is being installed and will be available from next year. This cryostat will be dedicated to PIP-II spoke cavity (325 MHz) testing in coming years. It can accommodate 2 cavities (diameter 1250 mm) equipped with their helium jacket (no dunk test).

❖ **DESY**:

- *Description*: DESY is operating two vertical test cryostats which can be used for quite a variety of single and multi-cell SRF cavities. Several accelerator module test stands – at present not being part of the AMICI offered facilities - are specialized for the testing of complete accelerator modules; here 1.3 GHz XFEL or ILC type modules, and 3.9 GHz XFEL can be performance checked or studied during longer runs. The infrastructure will be extended by a dedicated injector test stand to study SRF electron guns.

- *Activities*: The DESY vertical cryostats are available with high throughput. Specially adopted inserts allow for the installation of 1.3 GHz multi and single cell cavities, for SRF Gun cavities, for a Quadrupole Resonator, and for the installation of lower frequency multi-cell cavities (ESS 704 MHz, and in future FNAL PIP-II 650 MHz). The test program follows a standard format, and includes a number of incoming and outgoing quality checks. Service is done for a larger number of laboratories and companies.

- *Plans*: DESY is going to continue its service in the sense of AMICI. Adaptation to new, again different cavities is planned but, in case of larger modifications, a sufficiently large number of cavities should be tested. Service agreements follow a well-established scheme, with minor modifications depending on the project. The R&D interest of European XFEL and DESY, together with Hamburg University, allows for continuation of the regular testing. Involvement in new directions specific to the HEP oriented European Strategy strongly depends on the funding situation. At the time of writing, no respective adaptation of TPs is scheduled.

❖ **INFN LASA**:

- *Description*: INFN LASA operates a vertical cryostat for bare and dressed (with He-tank) cavities. The cryostat is 0.7 m in diameter and 4.5 m in depth and allows testing cavity from 500 MHz up. Two inserts are available: one multi-purpose and one specific for large multicell cavities with 2 K filling capability. A permanent magnetic shielding lowers the residual magnetic field below 0.8 μT. A full set of diagnostics are implemented: second sound, fast thermometry, photodiode and scintillator for X-ray detection, fluxgate. The cryogenic system operates in a temperature range from 1.6 to 4.2 K. Different RF sources cover the ranges 500-900 MHz (500W) 1200-1400 MHz (500 W) and 3500-3950 (200 W). An ISO-4 clean room with Ultra-Pure Water and HPR is used for final cavity assembly prior cavity test, when necessary.

- *Activities*: The activities are nowadays focused on internal R&D on diagnostic and testing cavity prepared at the industry, Medium Beta ESS cavities (704 MHz) and upgrade of the infrastructure for PIP-II cavities for very High Q0 measurements. A remanent magnetic field compensation system is under development for this purpose as well as modification to the cryogenic system to achieve faster cooling rate.

- *Plans*: Besides the ESS activity, PIP-II will be our main project, and we will focus on it in the coming years. R&D activities are planned to optimize treatment and ensure reproducibility of performance, with particular attention to achieving high Q/high gradient for cost savings and sustainability, as required by the European Strategy and future colliders. As part of this effort, a new dedicated cryostat for single-cell cavities is being planned.

❖ **Uppsala University:**

- *Description*: Uppsala University operates a vertical cryostat GERSEMI, a horizontal cryostat HNOSS, and a small cryostat CoW. GERSEMI (1100 mm bore diameter, 2650 mm available length) is a multi-purpose vertical cryostat and can accommodate multiple bare SRF cavities. HNOSS (1200 mm bore diameter, 3300 mm available length) can operate multiple dressed SRF cavities even with fundamental power couplers and higher-order mode dampers. These two major cryostats can be operated at 1.8-2.0 K with cooling capacity of around 100 W. CoW (260 mm bore diameter, 635 mm available length) is for testing electronic components inside 4 K liquid helium.
- *Activities*: The availability of GERSEMI and HNOSS is strongly dependent on main projects of the laboratory that occupies the cryogenic helium capacity. With the present cryogenic system, simultaneous operation of HNOSS and GERSEMI would be challenging as well. CoW is an independent apparatus and can be flexible for external users. Up to now, Uppsala University has concentrated on cavities of relatively low frequencies, such as ESS single/double spoke cavities (352 MHz), ESS 5-cell high-ß elliptical cavities (704 MHz), and HL-LHC double quarter-wave crab cavities (400 MHz).
- *Plans*: For external user projects, Uppsala University participates in EUROLABS consortium (EU Horizon Europe Research and Innovation program). This grant covers the cost for user access to the facility and supports the users performing their experiments with the test platforms. A couple of procurements are planned for service improvements with respect to SRF cavity testing, such as broadband solid-state-amplifiers and 3-dimensional fluxgate sensors.

C.2 Test stations for normal conducting cavities

High gradient acceleration through NC, high frequency structures (S-C-X band) provides at present the highest accelerating fields on a scale suitable for a high energy physics facility like an e+/ e- linear collider. Gradients at the level of 100 MV/m have been demonstrated in many CLIC-type X-band accelerating sections. Reaching the highest gradients at an acceptable breakdown rate requires a long-lasting conditioning process, with a typical duration of several months. At present, high gradient experimental R&D is carried out in a limited number of test facilities around the world, with a testing capability of few tens of structures per year. The number of the klystrons installed in these test facilities is also limited. The high gradient X band technology, moreover, has been adopted for the design and realization of low/medium-energy (a few GeV) electron linac facilities based on high gradient NC RF. This will drive the design and integration of full RF modules, the realization over larger scales of components, and ultimately will test the reliability of the technology as a user facility backbone. The EuPRAXIA program at INFN Frascati and the AWAKE e-linac at CERN are examples.

Low frequency NC RF cavities operating in strong magnetic fields are interesting for the developments of a muon collider. To date, a muon collider is the only viable solution for a lepton collider with center-of-mass collision energy at the scale of 10 TeV. The accelerating cavities are key to cooling efficiently with limited loss of muons. They need to operate in the frequency range of 300 to 700MHz and provide a high gradient in a strong magnetic field, up to 30 MV/m in 13 T. The main challenges are to show the feasibility of stable operation at high gradient in a strong magnetic field and to develop practical RF cavities suitable for mass production. To perform this program, a dedicated RF test stand is mandatory. In addition to a MW level peak RF power source, it must have high field (10 T) solenoid.

To further increase RF performance and accelerating gradients novel developments in the use of cryogenically cooled copper, higher frequency structures and different copper alloys are under investigation.

NRF related test stations

Consolidating and expanding the activities carried out at the present existing Technology Infrastructures, as well as promoting the implementation of new ones, are crucial actions. An increased capability of testing and conditioning a large number of components, in particular accelerating structures of various kinds, is required to push further up the breakdown limits, and to qualify different materials and/or design approaches. Experimental optimization of the conditioning process, to increase the effectiveness and reduce the duration, is also a collateral strategic goal that should be pursued, guided by conditioning process modeling to be elaborated and refined iteratively on the base of theoretical considerations benchmarked. At present there are several test stand facilities that operate in the field of NC RF test.

❖ **CERN**:

- *Description*: CERN operates 3 standalone X-band Test Stands called Xbox-1, -2 and -3. The primary objective of the test stands is to support the development of high-gradient, X-band, accelerating structures and high-power, 50-100 MW range, RF components for the CLIC and related projects. The first two Xboxes are powered by a 50 MW/1.5µs/50 Hz klystron each. Both are equipped with a pulse compressor, which can obtain a peak power compression ratio of 3, when compressing the 1.5 μs klystron pulse to a 250 ns output pulse. In addition, the Xbox-2 RF power distribution network contains a variable power splitter able to distribute independently power with variable phase to two structure (or device) devices under test. The third Xbox test stand is powered by two coupled 6 MW/5 µs/400 Hz klystrons. Xbox3 uses a novel way of combining relatively low peak, but high average power from both klystron, and using again a pulse compressors, can steer and feed the combined power to two test stations in pulses with up to 200ns, 40 MW with a repetition rate of up to 200 Hz.

- *Activities*: The high gradient testing of X-band RF structure prototypes covers R&D towards the CLIC super accelerating structure, structures fabricated from two halves, a structure from rectangular disks, deflecting cavities as well as new RF components such as RF pulse compressor, and RF windows. Low power tests address the development of RF components, field flatness measurements, and tuning of accelerating structures.

- *Plans*: The CERN plan is to operate, do maintenance at and upgrade the CERN Xboxes: #1, #2 and #3.

❖ **INFN Frascati**:

- *Description*: INFN Frascati TEX is presently in operation with a 50 MW / 1.5 µs / 50 Hz X Band CPI klystron supplied by a K400 Scandinova modulator.

- *Activity*: The test station is used for studying EuPRAXIA@SPARC_LAB X band accelerating structures, waveguide components (directional couplers, pumping ports, hybrid power splitters, loads), pulse compressors, and CLIC structures. The TEX Facility is also opened to industries and external companies. Low power test of RF components, field flatness measurements and tuning of accelerating structures.

- *Plans and upgrades*: Implementation, in the next two years, of a 25 MW / 1.5 µs /400 Hz X Band Canon klystron with K300 Scandinova modulator and of a high efficiency X Band CPI klystron 50 MW / 1.5 µs / 100 Hz with K400 Scandinova modulator. Implementation of a 25 MW / 1.5 µs / 400 Hz C Band Canon klystron with K300 Scandinova modulator to test high cathode peak field RF guns (150-200 MV/m). Possibility to implement an electron source based on photo-cathodes to characterize the beam generated by C band guns and accelerated by X band structures.

❖ **Uppsala University:**

- *Activity*: Uppsala University operates a cryo-cooler system dedicated to study surface conditioning and DC breakdown fields in cryogenic environment (from room temperature down to 4K). The system typically uses parallel plate electrodes that are subject to a pulsed DC voltage of high repetition rate (few kHz) which creates electric fields of up to 150 MV/m in the gap between the electrodes. This breakdown setup is independent from the main cryogenic system of the laboratory and can be flexible for external users.

- *Plans*: Complement the system with diagnostics to monitor changes in surface residual resistivity ratio in-situ by low-field RF. So far, the tests have been done only on copper surface but qualifying niobium is within our scope.

❖ **Other NRF test facilities**:

- *Description and Activities*: Several European laboratories operate NRF test platforms to carry our R&D, often related to local accelerator based research facilities.
  - **Trieste and IFIC Valencia** are performing tests of S band structures and components.
  - **PSI** operates a C-band test stand for structures and modules.
  - At the **Cockcroft Institute** an S-band test stand is under construction.
  - **CEA** constructs an RF test platform (bunker, magnet installation, control room, wave guides, etc) for the test of structures in magnetic field construction and testing of cavities.
  - **STFC** studies S Band RF guns and its breakdown in moderate magnetic fields. The plan exists to construct a high gradient test stand with a large superconducting magnet.

D. Test stations for High Power RF components

Accelerator laboratories have many parallel developments occurring without collaboration, instead of partnering on different development tracks. It is also essential to seek broader competences beyond labs that specialize only in RF development. For instance, improving the duty cycle necessitates better cooling solutions, including cryogenics. Enhancing overall efficiency requires microwave expertise in both solid-state power amplifiers and power combiners. Developing amplifier protection aspects and interlocks would benefit the entire community and could be approached through collaboration. Sharing knowledge via conferences and meetings, as well as through collaborative frameworks such as the AMICI community, can facilitate dissemination. Collaboration is essential for scientific research and new discoveries, but there are often challenges to achieving successful partnerships. One reason for these issues is the competitive nature of scientific research. Scientists are under pressure to produce original research that will advance their careers and secure funding, which can lead to a reluctance to share their findings with others or collaborate with potential competitors. However, to ensure a transfer of knowledge, it is crucial to invite industry to participate in the process. Logistical challenges can also impede collaboration. Collaborators may have different schedules or workloads, might be linked to different running project, which makes it difficult to find time for meetings or share on unfunded projects. Distance and travel expenses can also be a barrier to faceto-face collaboration, particularly for international partnerships.

A synthesis of future trends that address the expressed needs of various areas of the roadmap. For example, increasing the duty cycle from 5% to 95% would allow for longer use of cavities, necessitating the construction of machines that allow for continuous operation. However, limitations related to power generation using solid-state power amplifiers must be resolved, particularly cooling issues. Collaborative initiatives require significant resources, which could be financed through mechanisms such as in-kind contributions to different developments. Raising awareness of expertise in different partner laboratories can be achieved through various ways: Attending conferences and workshops related to the research area and engage in discussions with scientists and engineers from different laboratories. This will allow for exposure to a diverse range of expertise and promote opportunities for collaboration. Collaboration platforms such as LinkedIn, ResearchGate, or other similar platforms to connect with scientists and engineers from different laboratories. These platforms allow for the sharing of research findings, exchanging ideas, and identifying potential collaborators. Workshops and training programs to share knowledge and expertise between different partner laboratories. This will allow for the transfer of skills and expertise, promoting collaboration and innovation. Publish research findings in high-impact journals to promote the expertise available in partner laboratories. This will allow for exposure to a wider audience and provide opportunities for collaboration. Establish different partnerships between laboratories to facilitate the sharing of knowledge and expertise. This will allow for joint research initiatives and provide opportunities for cross-disciplinary collaboration.

Follows the description of the laboratories (UU, CEA Saclay, KIT, DESY, CIEMAT, CERN, INFN, IFJ PAN and STFC), who have power sources generation activities:

❖ **CEA-Saclay:**

- *Description:* The CEA operates a 704 MHZ RF PLATFORM, equipped with two pulsed klystrons, with peak powers of 1.1 MW (55 kW on average) and 1.5 MW (75 kW on average), with pulse durations ranging from 10 to 3600 µs, a repetition rate ranging from 1 to 50 Hz and a duty cycle of 5%.

- *Current Activities*: The klystrons were 100% used for ESS until the end of 2022. After that, they are available for other projects (tests/coupler and cavity conditioning...). We can currently supply the coupler conditioning area, the ESS/SARAF casemate and the horizontal cryostat casemate on Supratech.

  The 704 MHz RF platform has enabled the realization of: The coupler packages for the ESS elliptical cavities, Tests of cryomodules for ESS elliptical cavities, Test of couplers, cavities and LLRF in the framework of the European projects FP6 CARE/HIPPI (CERN, INFN) and FP7 SLHC-PP (CERN), Packaging of SPL couplers for CERN.

- *Future Plans*: For the moment, there are no plans for future use of the 704 MHz platform.

❖ **CERN:**

- *Description of the Lab*: The RF Group at CERN is responsible for all cavities, couplers, high-power RF amplifiers, LLRF and RF controls at CERN, ranging from 1 MHz to 30 GHz, pulsed & CW, with power output of up to 50 MW per system. The technologies in use are solid state, IOTs, klystrons & tetrodes.

- *Current Activities*: Active development of high-efficiency klystrons together with industry (Thales, CPI, and Canon) for 400 MHz, 800 MHz, and 12 GHz. Combining technologies for solid state amplifiers. uTCA deployment and white Rabbit. Ferroelectric fast reactive tuners (FeFRT) for the suppression of transient detuning.

- *Future Plans*: Future R&D aims at the FCC RF system with a focus on high-efficiency. In the next years more of the ageing existing systems may evolve towards µTCA. We also see a trend of replacing ageing tetrode systems with solid state solutions.

- *For the Community*: The development of high-efficiency klystrons will be beneficial for everyone in the field. The exploration of FeFRTs is of specific interest for low-current machines such as ERLs and there are collobarations in place. The RF group regular advises international projects on RF topics and also collaborates with institutes (e.g. ESS, EIC, PIP-II, LCLS, EUPRAXIA, GSI, DESY, Uppsala, etc), industry (Thales, Canon, CPI, etc.), medical accelerators (MedAustron, CHUV, NIMMS, etc) and various universities.

- *Trends, future necessities*: Optimization of energy efficiency in all the aspects of RF power: klystrons, transistor combination technologies, magnetrons, multi-IOT systems, LLRF strategies. Development of compact RF sources suitable for underground use.

RF power systems (acc)

Machine	Type	P [MW]	f [MHz]	T_{pulse} [µs]	Rep rate [Hz]	$N_{systems}$	N_{units}
Linac3	Tetrode	0.3 - 0.7	101/202	350 - 1000	1 - 10	2 + 2	6 + 6
Linac4	Klystron	1.2 - 2.8	352	1000	1	14	14
Linac4	Solid State	0.035 – 0.065	352	1000	1	3 + 1	4
Linac4	Tetrode	0.1	2	1000	2	1	1
REX	Tetrode	0.1	101/202	1000	1 - 100	5 +1	13
HIE ISOLDE	Solid State	<0.001	100			20	20
RFQD	Tetrode	1.7	202	150	1	1	2
PSB (finemet)	Solid State	0.002	1 - 20	100 ms	0.9	4	144
LEIR (finemet)	Tetrode	0.14	0.7 – 4.7	CW	CW	2	2
AD	Tetrode	0.9	9.54	300	0.012	2	6
AD (finemet)	Solid state	0.002	0.5 – 1.6	CW	CW	5	5
ELENA (finemet)	Solid state	0.002	0.1 - 2	CW	CW	1	1
PS10	Tetrode	0.06	2.8 – 10.1	600 ms	0.9	12	12
PS20	Tetrode	0.02	20	300	150 ms	2	2
PS40	Tetrode	0.4	40/80	300	18 ms	5	15
PS200	Tetrode	0.075	200			6	6
SPS	Tetrode	1	202	10 µs - 5 s	43 kHz/0.1 Hz	4	88
SPS (LIU)	SSA towers	1 - 1.4	202	10 µs - 5 s	43 kHz/0.1 Hz	2	32
SPS	IOT	0.24	808	10 µs - 5 s	43 kHz/0.1 Hz	2	16
LHC	Klystron	0.3	400	CW	CW	16	16
XBOX 1,2	Klystron	50	12000	1.5	50	2	2
XBOX 3	Klystron	6	12000	5	400	1	4
Total						**116**	**417**

❖ CIEMAT:

- *Description of the Lab*: Ciemat is a Spanish research institute specializing in the development of RF systems and components oriented to fusion applications. The high-power RF laboratory, and it is complementary to IFMIF-DONES RF laboratory for fusion applications. Available is a clean room, xray shielding, etc. Available RF power infrastructure: 200 kW CW @175 MHz RF tetrode-based amplifier with its fully digital LLRF.

- *Current Activities*: Development of advanced solutions for the IFMIF-DONES RF power system. Development of 750 MHz RFQs for the initial stages of acceleration. Current prototype: two high efficiency solid state 200 kW CW @ 175 MHz

- *Future Plans*: Ciemat aims to continue developing efficient SSPA solutions and solutions for ICRH plasma heating in low frequencies. They also plan to optimize efficiency in all aspects of RF power, including transistor technologies and high efficiency polarization techniques.

- *For the Community*: Ciemat's work in the field of RF systems and components is important for various applications, including high energy physics and hadron therapy. The research and development in these areas can contribute to advancements in the field and lead to improved RF solutions for the wider community. Presently, a collaboration is ongoing with CERN on a future carbon ions linear accelerator for hadron therapy.

- *Trends, future necessities*: Continue the development of SSPA solutions due to its advantages in modularity, maintenance, absence of high power, etc. For example: development of efficient combination (cavity combiner or other solutions). Development of solutions for ion cyclotron resonance heating (ICRH) plasma heating in low frequencies. Optimization of energy efficiency in all the aspects of RF power: transistor technologies (fabrication and materials technologies, high efficiency polarization techniques, etc.)

❖ **Uppsala University**:

- *Description of the Lab*: The FREIA Laboratory is part of the Department of Physics and Astronomy at Uppsala University, which employs over 30 researchers, engineers, and technicians. The Laboratory's scientific objective is to enable innovative experimental research in various fields, such as particle and nuclear physics, atomic and molecular physics, chemistry, molecular biology, as well as material, energy, and environmental science. The FREIA Laboratory is equipped with a high-capacity Helium liquefier, a large horizontal and vertical cryostat, two 400 kW vacuum-tube radiofrequency sources at 352 MHz pulsed power with a 5% duty cycle, and advanced hardware and software for process control and secure test bunkers. These facilities allow for testing of high-power equipment, including magnets and superconductive accelerating cavities. The FREIA Laboratory is located in a 1000 m2 large, 10 m high hall forming part of the Ångström Laboratory in Uppsala. The primary focus was on testing the prototypes of the spoke cryomodules for the ESS' linac, which comprises of 26 superconducting double spoke cavities.

- *Current Activities*: The collaboration with MYRRHA, the Belgian transmutation project, is started on the development of solid-state power amplifiers at 704 MHz at 10 kW and 20 kW levels in CW. The scientific collaboration is also ongoing with the IFMIF-DONES project, in Spain via EUROFUSION, and is related to the development of cavity combiners and efficient amplifier design. We are also participating in the EU project I.FAST, developing a 1 kW CW SSPA at 750 MHz in GaN technology and a megawatt cross field amplifier based on a magnetron architecture. As part of our work in GaN technology, we are developing two amplifiers for the AWAKE project at CERN. The first amplifier operates at 3 GHz and delivers 500 W, while the second at 12 GHz and delivers 1500 W. The EU Marie Skłodowska-Curie -Curie fellowship programme is funding two additional complementary projects. Recently, we completed the Eurostars project ENEFRF, which involved the development of amplifiers for use in cyclotrons used in positron emission tomography (PET) for cancer diagnosis. The amplifiers operate at 27 MHz for 20 kW and 100 MHz for 10 kW.

- *Future Plans*: The FREIA laboratory in close collaboration with ESS and Swedish industrial partners is developing the first pilot RF power station delivering 400 kW at nominal power. The station is composed of 256 high-power solid-state amplifiers, each delivering 1.6 kW. The modules are combined in two steps, i.e. using a 4:1 combiner at 400 kW level and four 64:1 100 kW combiners.

- *For the Community*: Our objective is to share the knowledge and advancements made in the field with other AMICI partners, project members, and the broader community. We take an active role in the Traineeship Programme established by I.FAST, providing a platform to develop and mentor the next generation of scientists and engineers. This facilitates knowledge transfer between laboratories and industry, and encourages collaboration with key players in the technology domain. Additionally, we intend to publish in prestigious journals and present our findings at high-profile conferences such as IMS, EUMW, and IPAC to reach a wider audience.

- *Trends, future necessities*: To meet the forthcoming demands and advancements in solid-state power amplifiers, a durable and reliable test-stand for multi-kilowatt level amplifier modules and stations must be established. Additionally, it would be worthwhile to investigate the feasibility of implementing hot-swap solutions that permit module replacement while the station is functioning at nominal power. Alongside this, module protection systems should be implemented to prevent excessive reverse power and assess the requirement for RF power circulators. Another area that would require consideration is the implementation of a controlled drain voltage modulation system. This system can help optimize the DC to RF power conversion efficiency, leading to better performance and reduced power consumption.

❖ **INFN-LNL**:

- *Description*: LNL is devoted to nuclear physics, interdisciplinary physics and accelerators science. In the accelerator framework LNL is devoted to:
    - Development of warm cavities for high intensity and high-power beam acceleration, but also for Radioactive Isotopes or Radioactive Ion Beams i.e. IFMIF and SPES Radio-FrequencyQuadrupole (RFQ) cavities and ESS Drift-Tube-Linac (DTL);
    - Development of Super-Conducting (SC) cavities for heavy ions beams i.e. PIAVE-ALPI Quarter-Wave-Resonators (QWR) (81 cavities) and PIAVE Superconducting-RFQs (2 cavities);
    - Collaboration with industry for high-power RF amplifiers development;
    - Development of Low-Level-Radio-Frequency (LLRF).

  A low power RF test stand for SC cavities is currently in operation. Until 2021, LNL had a provisional high-power RF test stand based on a 220 kW 175 MHz CW amplifier. It was a two stage RF amplifier: 16 kW first stage based on solid-state and a 220 kW second stage based on tetrode. In 2021 high-power test-stand was dismantled and in the meantime the construction of a new high power test stand was started.

- *Current activities*: The new 200 kW RF power test-stand is under assembly. Its final goal will be to power SPES RFQ cavity that is foreseen to reaccelerate RIBs in 2026. In the meantime, it will be used for high power test of RF components. Test stand time schedule will be affected by LNL ALPI accelerator schedule until the end of 2023 due to sharing of the water cooling system with the main accelerator. At the end of the year high power test stand will use its own cooling system. Three high power amplifiers are under development to be used/tested on the 200 kW test station:
    - N.1 200 kW 175 MHz full solid state CW amplifier (test already started);
    - N.1 200 kW 80 MHz full solid state CW amplifier (under construction);
    - N.8 125 kW 352 MHz full solid state CW amplifiers (5 over 8 already completed and tested and to be upgraded, three over 8 to be constructed).

- *Future plans*:
    - 02/2023 – 07/2023 high power test of 200 kW 175 MHz solid-state amplifier;
    - 09/2023 – 12/2023 high power test of 200 kW 80 MHz solid-state amplifier;
    - 07/2024 – 12/2024 ANTHEM project high power couplers test (125 kW 352 MHz CW);
    - 01/2025 – 02 /2025 high power test of N. 3 125 kW 352 MHz solid state amplifiers;
    - 01/2026 – 02/2026 high power test of N.5 125 kW 352 MHz solid state amplifiers.

  As just mentioned, high power test stand will be independent from ALPI accelerator services at the end of this year and RF power station will be remotely controlled. Nevertheless, access to high power test area will be not completely free, because it will require no beam acceleration with ALPI accelerator. This means that any test must be included in the LNL accelerator schedule.

- *Future needs*:
    - ***LNL***: LNL aims to continue developing high power accelerators and high efficiency SSPA. On the latter topic, LNL would like to improve efficiency not only demonstrating the feasibility of an innovative architecture, leading to a base power module of 20-25 kW on 50 Ohm load (current LNL base power module can reach 8-9 kW), but also mastering the GaN technology.
    - **Community:** LNL can offer strong expertise on high power RF structures design, construction, control and test. High power test-stand, up to 400 kVA, can be made available to community for testing both RF amplifier and RF structure. For RF structure testing, three RF power source can be made available: 200 kW - 80 MHz, 200 kW - 175 MHz, 125 kW - 352 MHz (the latter until 2026).

❖ **NCBJ**:

- *Description of the Lab*: NCBJ is a Polish research institute specializing in the manufacturing of the electron linear accelerators for scientific purposes and for medical and industrial applications. Thanks to the existing resources - infrastructure and trained personnel, NCBJ participates also in many international accelerator projects.
- *Current Activities*: Development of an electron accelerator and beam transport system for HyperKamiokande far-detector calibration, development of FLASH-radiotherapy machines, construction of several-dozen-MeV machine for neutron-beam based experiments and production of new radioisotopes, construction of POLFEL (THz-UV FEL light source), development of fast energyswitching accelerators for cargo scanning, development of RF power compressors.
- *Future Plans*: Continuation of current activities
- *For the Community*: Experience in beam dynamics and beam optics calculations, infrastructure and skills in warm cavities production, RF conditioning and beam-based experiments. Equipped test infrastructure for RF components, magnets, radiation-induced material damages etc. Advanced machine park available.

Recommendations:

In summary, there are some common issues in accelerator laboratories that hinder collaboration, such as parallel developments occurring without collaboration and a lack of seeking broader competencies beyond RF development. However, collaborative initiatives are essential for scientific research, and several future trends address the expressed needs of various areas of the roadmap. Raising awareness of expertise in different partner laboratories can be achieved through attending conferences, using collaboration platforms, workshops and training programs, publishing research findings, and establishing partnerships. Mechanisms such as in-kind contributions can finance collaborative initiatives. Industrial partners should be involved from the definition of specifications to the realization and acceptance tests to ensure a common development tracks. Collaboration and resource sharing, including testing facilities, research equipment, and expertise, can facilitate alignment and promote collaboration. Collaboration frameworks can help ensure project progress and awareness among stakeholders. Participation in upgrades to existing machines, such as LINACs in the US (PIP2 and Fermilab), ESS, XFEL, GANIL, and Linearo, can accelerate the development. RF/MW power generators developed for accelerator applications can benefit other industrial sectors, including high-power microwave technology for mining, geothermal applications, bitumen heating, and sewage sterilization. For the medical application effort led by CERN and the UK, portable RF power stations are required for art analysis.

E. Platform for characterization, treatments and test of materials

The platforms considered in this category serve for the characterization and treatment of materials and components used for accelerator and superconductive magnets development. They are crucial in the in the R&D phases and post-production process and play a key role in the qualification of materials and the validation of the new treatment processes aiming at enhancing their performances. Thus, the platforms could be used for several purposes:

- Quality-control and material characterization
- Improvement of material performances
- Qualification of new developed materials
- Treatment process optimization and qualification
- Materials treatment before tests and measurements

Such platforms are widely present in the main European institutes hosting accelerator activities, offering a wide range of functionalities and characteristics in accordance to the user requirements. In the following, we propose an overview of the existing platforms in the main European accelerator labs (not exhaustive), their activities and functionalities, their main technical characteristics and their upgrading plans, if any. The platforms being mostly open to external users, industrial or academic, the aim is to provide the important inputs describing the current potentialities and possible evolution of the platforms.

E.1 Thermal treatment platforms

❖ **CNRS:**

High Temperature Vacuum Furnace

- *Current activities*: Hydrogen outgassing of different type of SRF cavities: 1.3 GHz one-cell elliptical resonators (Commissioning and R&D), 352 MHz ESS Double-Spoke resonators (Prototypes and serials), Medium and High beta ESS elliptical cavities, MYRRHA single spoke resonators (prototypes), PIP II single spoke resonators (Prototypes and serial: ongoing project), Advanced Heat Treatment R&D program (TTC collaboration (CEA and DESY), HELOISE project: N-doping, N-Infusion, Medium temperature Annealing)

- *Description of the lab*: The main features of IJCLab High Temperature Vacuum Furnace developed in the framework of ESS for hydrogen outgassing of Double-Spoke niobium cavities are: 1) Thermal chamber volume: 4.5 m3; Maximum cavity diameter and length: 700 mm and 1600 mm, 2) Molybdenum Heaters (3 heating zones, 5 Mo radiation shields); Heating rate: 1-10 °C/min; Maximum temperature: 1400°C, 3) Dry pumping system (Screw pimp, Roots pump and Cryogenic pump); Residual Pressure: 5 10-7 mbar-10-6 mbar at 300K; Nitrogen doping/infusion circuit (AlphaGaz 2 grade N2) with micrometric valve and catalytic and adsorption filter (Gas flow @300K: 10-10 at 500 mbar.l.s-1)

❖ **DESY:**

High Temperature Vacuum Furnace

- *Current activities:* All current activities are related to the European XFEL R&D program which aims for improved Q(E) behavior. The goal is CW gradients above 25 MV/m at Q0 larger than 3 1010 or >30 MV/m in pulsed mode with Q0 above 1 1010. N-infusion as well as mid-T bake is under study. The sample and the single-cell furnaces offer more possibilities including the study of SIS layers.

- *Description of the lab*: DESY is operating several UHV furnaces in order to treat Niobium cavities or samples. The standard furnace - also used during the construction of the European XFEL - can house up to 4 cavities of the 1.3 GHz 9-cell type; the furnace is usually used for 800°C baking. The workhorse for present treatment is a recently modified all Niobium retort UHV furnace which is directly attached to an ISO 4 cleanroom and is hence perfectly suited for treatment studies. It is operated by two cryogenic pumps and as the vacuum systems for heater and niobium retort are separated, it reaches a starting pressure at room temperature of 2 10-8 mbar, and at 300° C about 3 10-7 mbar. A dedicated sample furnace as well as a new UHV furnace suited for 1.3 GHz single cell cavities is operated by the Hamburg University, on DESY premises.

❖ **INFN:**

High Vacuum Furnace LATINO (INFN-LNF)

- *Current activities:* During this two first years of activities the vacuum furnace was used for the R&D activities concerning the development of X-Band Accelerating Structure of the EUPRAXIA@Sparc_Lab project. Furthermore, other requests from the companies and other RI's, concerning vacuum firing treatments and brazing of other vacuum technology components have been fulfilled.

- *Description of the lab*: The High Vacuum Furnace is a facility developed for mainly two different kinds of activities requested for vacuum technologies: Thermal treatments and vacuum brazing. The operating volume of the furnace is a cylinder 400 mm (diameter) and 1300 mm (height) and can operate up to 1200°C. This temperature is enough for vacuum firing treatment and also for the most kind of vacuum brazing. The base pressure out of thermal cycle is of 1.10-6 mbar.

- *Upgrading plans:* Future upgrade is correlated to increasing the vacuum pumping in order to better treat larger mass components, reducing issues related to thermal desorption during operation.

High Vacuum Furnace (INFN-LNL)

- *Current activities:* Originally, the system was used for the production of copper modules for ALPI accelerator at Legnaro National Laboratory (LNL), obtained by brazing with copper-silver and palladium-based alloys. Subsequent productions involved the production of components for the IFMIF/EVEDA, ESS and SPES projects. All these projects have in common the production of mechanical assemblies in which strong mechanical joint between copper-to-copper or copper-to-steel must be formed without compromising the thermal and electrical conductivity of the materials.

- *Description of the lab*: LNL's high vacuum furnace is a system that combines the ability to realize a homogeneous hot zone - at temperatures up to 1300°C - with the need to ensure a high vacuum degree (10-6 mbar) in operation, such that no contamination is generated at the surfaces. This particular environment generally finds applications in material heat treatment or in brazing with precious alloys. For example, vacuum furnace is used when it is necessary to make a joint between dissimilar materials such as metal-ceramic joints.

  The furnace is a batch-type, with a load capacity of up to 1000kg. The use of molybdenum heating elements organized into four independently controlled heating zones can create a hot zone of about 2m3 (a cylinder with diameter 1.3m and height 1.6m) with a homogeneity within +/-4°C. It is possible to increase the height of the furnace to reach useful heights of 2.1m by installing a volume extension.

  The vacuum system is dry-type, with one primary screw pump in the early stages of evacuation and two cryogenic pumps during operation. In addition to pressure control, a residual gas analyzer is also installed for qualitative determination of the composition of the residual atmosphere during the process.

- *Upgrading Plans:* The development of a system for the use of reactive or reducing atmospheres is being planned. In practice, in addition to a high degree of vacuum, atmospheres of high-purity gases such as hydrogen, nitrogen, and argon are expected to be available.

E.2 Chemical treatment platforms

❖ **CEA:**

Vertical electropolishing cabinet

- *Current activities:* The set-up was used for the preparation:
  - 5-Cell 704MHz prototype cavity for SPL (EuCard program)
  - 5-Cell 704MHz high beta ESS prototype cavities
  - R&D for 1,3GHz and 704 MHz electropolishing recipes (FJPPL-TYL collaboration program)
  - 1,3GHz 1-cell cavities for different R&D activities (multilayers, thermal treatments, doping and infusion)
- *Description of the lab:* This station is dedicated to chemical and electrochemical treatment of elliptical cavities (maximum cavity height: 1.8 m and maximum mass: 200 kg). It allows to perform chemical or electrochemical polishing of the internal surface of niobium cavities. Here some technical characteristics:

  - Power supply: 20V, 1200A.
  - Acid flow rate: 40 l/min.
  - 300 l acid tank.
  - Pipes and pumps made of PFA material, Teflon coating of the acid tank.
  - Cavities are handled by a crane with specific tooling for each cavity. The station is also equipped with a table for horizontal insertion of cathodes.
  - Use of rotating cathodes for uniform material removal (CEA-KEK-Marui collaboration)

- *Upgrading plans:* A similar vertical electropolishing cabinet will be built within the next 3 years for the surface preparation of single cell and multicell elliptical cavities made of aluminium or copper (multilayer R&D).

Chemical Treatment cabinet

- *Current activities:* The platform has been used for:
  - The prototypes and series treatment of 1/4 and 1/2 resonators of cavities for Spiral2 (12 cavities for type-A cryomodules, 88MHz), IFMIF Eveda, SARAF accelerators (13 low beta cavities and 14 high beta cavities, 176MHz).
  - The preparation of ESS 704MHz medium beta prototype cavities.
  - The preparation of 1,3GHz cavities for R&D activities (thermal treatments, Atomic layer deposition).
  - The preparation of elleptical and spoke cavities for CARE HIPPI program
  - The chemical treatment for DONES prototype 1/2 wave cavity

- *Description of the lab:* Integrated chemical treatment station for elliptical cavities (h ≤ 150 cm). Buffered chemical polishing (BCP) station for 1/4 and 1/2 wave cavities,
  - PNF bath: H_3PO_4(85%), HNO_3(65%) et HF(40%) in the proportions 2.4–1– 1,
  - Acid tank with a capacity of 200 l,
  - Acid circulation from bottom upwards with a maximum flow rate of 30 l/min,
  - Gravity draining, PVDF piping,
  - Station under ventilated fume hood.

❖ **CNRS:**

- *Current activities:* IJCLab has been leading development of low-beta SRF cavities in Europe, and delivered cavities for Spiral2 (14 QWR at 88 MHz), is delivering production Double Spoke resonators for ESS (26 cavities at 352 MHz) and is today strongly involved in R&D and production phases for MYRRHA/MINERVA (Single Spoke at 352 MHz) and PIP2 (Single Spoke 325 MHz) projects. For all these projects and activities, the chemical treatment of the cavities is made in the local platform.

- *Description of the lab:* A chemical treatment platform dedicated to Niobium cavities is in operation at IJCLab. BCP etching can be performed on large cavities (max inner volume ~ 100L). 2 chillers allow to cool down the acid bath down to 8°C and the cavity (if equipped with helium tank) down to 10°C. Rotational BCP has been recently implemented and validated. A clean room (ISO4) is also in operation for the final assembly of cavities. It hosts a High-Pressure-Rinsing (HPR) unit for the final cleaning of cavities.

❖ **DESY:**

- *Current activities:* DESY has a chemical treatment platform dedicated to Niobium cavities used for its internal operation for 1.3 GHz cavities and SRF Guns.

- *Description of the lab:* BCP etching as well as Electropolishing of single and 9-cell cavities at 1.3 GHz is possible. The platform was used as a mockup for comparable platforms at cavity vendors. Today it is only operated for DESY internal campaigns. High pressure rinsing (two stations) is available. An ISO4 clean room is right next to it, to allow assembly of cavities.

E.3 Facilities for surface analyses

❖ CIEMAT:

Microstructural Characterization Lab

- *Description*: The facility has different rooms with distinct electron microscopy and surface analysis devices for microstructural studies of materials. It is a valuable tool in a variety of fields (materials science, metallurgy, nanotechnology…), crucial for advancing in the understanding of materials and developing new technologies with improved performance and reliability. This facility is composed by the following infrastructures: Scanning electron microscope with tungsten filament (SEM), Scanning electron microscopy (FEGSTEM-EDX, BSE, EBDS), Scanning Auger microprobe, X-ray photoelectron spectroscopy (XPS/ESCA) and Transmission electron microscope (TEM).

- *Activities*:
  - Examination of the crystal structure and materials composition to understand their properties and behaviours.
  - Analysis of the morphology and distribution of particles, defects, and phases in materials to assess their -quality and performance.
  - Observation of the surface topography and roughness of materials to evaluate their surface properties and behaviour.
  - Identification of any defects or abnormalities in materials that may affect their functionality or reliability.
  - Development and testing of new materials with specific microstructural properties tailored to meet specific applications and requirements.

❖ CNRS:

Vacuum and surface platform

- *Current activities*: The Surface & Vacuum platform is involved in all R&D activities and project of the accelerator department. It is today strongly involved in the R&D for superconducting cavities and the study of dynamic vacuum in accelerators and the mitigation of E-cloud (LHC, FCC).

- *Description of the lab:* A surface & vacuum analysis platform dedicated to accelerator components is in operation at IJCLab. It is equipped with several commercial equipment as laser confocal microscope, SIMS, SEM equipped with EDS and EBSD, GDRX and as well in-house developed equipment for the measurement of SEY (Secondary Electron Yield) and surface desorption yield at room temperature. The platform is also equipped with NEG deposition system.

- *Future plans:* The analysis capability of the platform will be greatly improved by the acquisition aof a commercial XPS and a multi-technique system equipped with XPS and SEY operational between 300K and down to 10K.

- *Upgrading plans:* The analysis capability of the platform will be greatly improved by the acquisition of a commercial XPS and a multi-technique system equipped with XPS and SEY operational between 300K and down to 10K.

❖ **DESY:**

Quality Control of Niobium sheets

- *Current activities*: The canning facility is used to check Niobium sheets of different size. All sheets for the 800 European XFEL cavities but also all sheets for LCLS-II and LCLS-II HE were scanned during the last years. Since the facility is unique, many more institutes in the SRF community asked for QC of sheets for a large number of research facilities (e.g. SNS, ESS, MYRRHA, SHINE, ...).

- *Description of the lab:* The scanning facility based on the eddy current in order to determine the so-called RF side of the Niobium sheet. In case of inclusions, additional detailed studies are possible to help identifying the cause.

- *Upgrading plans:* The platform is going to be upgraded according to the today known needs. It is used for many service contracts (research labs and industry).

❖ **INFN:**

Outgassing characterization Facility – LATINO

- *Current activities*: LATINO is High Vacuum Station for specific outgassing investigation on materials for vacuum applications. In these years the system was commissioned and used for the characterization of standard materials, such as Stainless Steel and Aluminium alloys. Presently, the facility is integrated in the R&D activities for the characterization of materials impinging on the vacuum system of the cryogenic tower of future gravitational wave detector, the Einstein Telescope.

- *Description of the lab:* The installation is based on the Throughput Method and it is composed of a main chamber, the measurement one, and two other chambers dedicated to high outgassing materials and low outgassing materials. These two sample chambers are cylinders of 200mm(d)x300mm(h) and 250mm(d)x450mm(h). The facility is also equipped with an RGA to complete the characterization with the spectrum of the gas emitted by the materials.

- *Upgrading plans*: In order to increase the sensitivity of the system, in the future plans the possibility of characterization with the accumulation method and/or the combination of accumulation and throughput one will be integrated.

❖ **STFC:**

Vacuum Interface and Surface Technologies for Accelerators: VISTA Laboratory

- *Current activities*: VISTA laboratory is the main hub for both vacuum science and surface science R&D within the UK accelerator community. Recent work programmes have been centred around activities such as NEG and novel coating developments for DLS-II and PETRA-IV; secondary electron suppression schemes for CERN; superconducting thin film development for iFAST; CsTe photocathode development for UK-XFEL. The facilities and expertise within the VISTA laboratory can be accessed by both academic and industrial researchers, subject to availability.

- *Description of the lab:* The laboratory's suite of instruments cover specialisms such as vacuum system analysis, vacuum metrology and gauge calibration, and XHV processing for large vessels. As well as supporting PVD, CVD and ALD deposition development for complex freeform and long structures, the laboratory is equipped with full surface analysis capabilities including RBS, NRA, MEIS, LEIS, AES, XPS, SIMS, SEM and TEM.

- *Upgrading plans:* Short-term development plans centred around the expansion of thin film coating capability to ever larger, longer and more complex substrates, and further developments in surface micro-structuring capabilities.

E.4 Electromagnetic, mechanical, thermal and associated material characterization platforms

❖ CEA:

Characterisation laboratory at cryogenic temperature (LABCAF)

- *Current activities*: A cryostat with a removable bottom insert, currently used for first critical field HC1 measurements by local magnetometry. A second cryostat used for RRR measurements. The lab performs quality-control measurements on materials and is used on R&D programs.

- *Description of the lab:* The useful dimensions of the first cryostat are: h = 1.33 m and Φ = 30 cm,
  The useful dimensions of the second cryostat are h = 1 m and Φ = 15 cm.
  Nitrogen and helium Dewars ($T \geq 1.9$ K),
  Precision voltmeters and amperemeters, temperature controllers

❖ CNRS:

Electrical resistivity & RRR measurements

- *Current activities*: These measurements are crucial for: 1) Quality Control (QC) of Niobium used for producing SRF cavities, 2) SRF cavities processing qualification and thermal process (H outgassing) optimization, 3) R&D on Advanced Heat treatment (N-Infusion, N-doping, Intermediate Temperature baking), 4) Characterization of material for High Power RF couplers (Stainless steel and cooper films), 5) Development of new materials (e.g. superconducting thin films or produced by additive manufacturing or other methods).

- *Description of the lab:* RRR measurements are performed using the standard DC four probes method with reversing the sensing current to eliminate parasitic thermoelectric voltages. The electrodes are clamped to the flat test sample by means of copper-beryllium springs (contact pressure: ~12 Bars). The test sample (length: 80 mm), which is equipped with a calibrated Cernox thermometer, is immersed in a saturated liquid helium bath at T= 4.2K. The sensing current of 1 A, is delivered by a precise standard DC voltage supply, is on-line measured via the voltage drop across a precision resistor.

The thermal conductivity k(T) measurement device allows the test of four samples simultaneously during each run. The measurements are performed at low temperature (1.5 K- 30K) using the steady-state axial heat flow method with a careful control of heat leaks to the surrounding.

❖ IFJ-PAN:

Superconductor characterization test stand

- *Current activities*: The platform can be used to characterise critical current of superconducting wire strands made of various materials. Additionally, it will be possible to perform resistance and RRR measurements.

- *Description of the lab:* The platform is based on 16 T superconducting magnet with a Variable Temperature Insert (VTI). The temperature inside the VTI is controlled by a calibrated Cernox sensor and can be regulated between 1.8 K and 200 K. The current of up to 1000 A can be delivered to the sample form external power converter using two current leads.

- *Upgrading plans*: The capability of the test station could be further improved by the acquisition of the sample holder which enables applying variable mechanical stress to the sample.

Conclusions:
A wide variety of complementary Technical Platforms (TPs) for accelerator developments are available in the several European labs and institutes. Most of those European TPs were, and still, implicated in the main accelerator projects realization in Europe and worldwide. Others are mostly involved in the R&D effort made by the labs to optimise some pre-treatment recipe, to improve the performances, to develop new materials with new performances… and also in the prototyping and series production phases with single or batch treatment process, Quality Control and qualification of components.

Some upgrading plans are foreseen for some TPs to meet required performances for some future needs. Most of the TPs, if not all are open to external collaboration, especially industrial one.

E.5 Test stations for mechanical manufacturing and tests (at cryogenic temperatures)

This section is devoted to the Technological infrastructures for mechanical/thermal characterization, treatments and test of materials at warm and low temperature.

❖ **CEA:**

The performances of many particle accelerators key components, like the SRF accelerating cavities or the beam lines themselves, or superconducting magnet components are often limits by the behavior of the component materials. To face the next scientific and technical challenges of particle acceleration systems, it is therefore mandatory to go beyond the present state-of-the-art and try to develop new materials, new fabrication methods, new innovative surface treatments (chemical, thermal, mechanical …) and master in an optimal way the preparation and assembling processes. This specially applies to the case of SRF accelerating cavities, the performance of which is limited by phenomena occurring in a very thin surface layer inside the cavities.

The CEA/Irfu-Synergium infrastructure includes, among others, two platforms devoted to the characterization of materials at warm and low temperature:

- **MACHAFILM** : platform for the manufacturing and characterization of thin film of superconducting layers on radiofrequency cavities and,
- **CRYOMECHA**: a platform for the mechanical/thermal characterization, measurement and analysis of materials.

MACHAFILM
The facility is composed of homemade thin film deposition and characterizations capabilities. The platform current research fields are Superconducting cavities used in particle accelerators, Qubits, diffusion barriers for nuclear applications, multipacting mitigation, 3D printing of metallic alloys etc…

- *Description and Activities*: MACHAFILM platform at CEA-Saclay includes two main activities concerning:
  - **The Atomic Layer Deposition laboratory (ALD)**

  ADL laboratory has a research bench dedicated to optimizing conditions for the growth of thin films on samples using the deposition technique called Atomic Layer Deposition. It is a synthesis technique that can deposit very thin films (typically less than 1 microns). ALD can be easily apply to industrial processes, as it has been done in microelectronics (RAM), displays, batteries, PV etc…The deposition facilities includes a research scale reactors can that handle samples size up to 4 cm x 40 cm where we develop/verify thin films growth chemistry. The facility also includes a newly developed scale up reactor that can handle larger objects, typically 70 x 60 cm where we apply the processes developed on the small reactor.

- **The Characterization Laboratory**

The characterization techniques encompasses low temperature facilities such as the newly developed RRR set up that enable the resistivity measurements between 4.2 K and 295 K of a metal purity for Nb, Cu, Al, Ti…, and the critical temperature of superconductors down to 4.2K. The lab has the capability to probe the magnetic field response of superconductors by measuring the superheating critical field (vortex penetration threshold). The sample size max is equal to 5 cm diameter and ~1 cm thick, the temperature range is from 300 K to 4.2 K with a field up to 120 mT.

In addition, we measure the fundamental quantities such as surface electronic properties with a mapping capability from 10 µm to 1 mm lateral size. The sample size is about 10 x10 x 4 mm.

CRYOMECHA

The platform consists of the **Mechanical Test Laboratory** and the Cryogenic Test Station **MECTIX**, and provides equipment as well as technical and scientific support. It is devoted to the characterization, measurement and analysis facilities for materials at warm/low temperatures. The Mechanical test laboratory can perform measurements under traction, compression, flexion, shear and slippage at 300 K, 77 K (liquid nitrogen), and 4.2 K (liquid helium)

- *Description:* The mechanical test laboratory provides:
  - A hydraulic press with a compression capacity of 1600 kN
  - Two Instron electromechanical machines with a traction or compression force of 300 kN and 150 kN. The 150 kN machine can be fitted with two cryostats for tests at cryogenic temperatures.
  - Different load cells plugged on the machines, ranging from 2.5 kN to 300 kN.

  Cryogenic inserts on the 150 kN machine:
  - "Small" insert (300 K, 77 K, 4.2 K) with a usable volume of 50 mm x 200 mm, and 45 kN in traction or flexion
  - "Big" insert (300 K, 77 K, and 4.2 K) with a usable volume: 150 mm x 140 mm. Maximum traction force equat to 80 kN in traction and 150 kN in compression.

- *Current Activities:* Many challenges for future accelerator magnets development need testing different types of samples on our machines. For example, 10-stacks compression tests on Rutherford cable for characterize the mechanical behavior of a coil with representative samples made of 10 layers, the upgraded setup in the framework of Nb_3Sn CERN-CEA collaboration, Tensile test on Nb_3Sn strand to characterize the mechanical behavior of a strand for correlation with multi-scale FEA model. Development in the framework of ANR Cocascope and re-launched with Nb3Sn CERN-CEA collaboration.

  The Lab is equipped with several cryogenic stands designed for the characterization of materials and fluid flows. The Cryogenic Test Station MECTIX, which has been greatly improved and automated in recent years, has a cryocooler cooled variable temperature measurement cell for carrying out thermal conductivity measurements on samples of around 10 cm in length in a temperature range from 4.2 K to 80 K.

- *Plans, Trends and Futur Needs*: The increasing use of superconductors HTS will require their mechanical characterization at a temperature not accessible in our current stations. The mechanical characterization should extend to composite blocks comprising the superconductor and its insulation at a controlled temperature between **4 K** and **150 K**, or even more if possible using the **300 kN** electromechanical traction machine that the laboratory already has. The design of a new cryostat devoted to mechanical test on samples at high stress level is under development. Furthermore, one of the major challenges for the development of future machines/detectors is to manufacture and operate superconducting magnets reaching magnetic inductions higher than 20 T. It was already demonstrated in the past the significant influence of strong magnetic field (> 15 T) on the variation of the critical flux in liquid helium. With the aim of cooling these superconductors properly, one needs to better characterize and quantify disturbances induced by magnetic fields on liquid helium. A development of a modular test station allowing to carry out various cryo-magnetic studies.

❖ CERN:

The Engineering Department (EN) provides CERN with the Engineering Competences, Infrastructure Systems and technical Coordination required for the design, installation, operation, maintenance and dismantling phases of the CERN accelerator complex and its experimental facilities.

The activity of the Engineering Department is, among others, in the field of Mechanical engineering and materials expertise group (MME) for design, prototyping, manufacturing and the assembly of accelerator and detector components.

- *Description of the Lab*: the group includes the largest design office using computer-aided design (CAD) software. From the early concepts of a device to its final solution, the engineering unit works in close collaboration with designers. The unit evaluate and improve the components' behavior in the extreme conditions in cryogenic or extremely high temperatures, high radiation, intense magnetic fields or vacuum conditions. The Mechanical Measurements Laboratory, part of the MME group, is specialized in thermal and mechanical characterization. The materials are tested from 1.8 K up to 2000 °C.

- *Plans, Trends, future necessities:*
  - Incipient collaboration on Low temperature measurements, interlaboratories benchmarking campaign – first discussion with CryoMak – KIT ongoing.
  - Workshop on CTE measurements host by CERN in autumn 2023.
  - By the fact that hydrogen liquid (20.28 K) seems to be one of the energy vectors of the future, this involve the emergence of research with strain sensing at cryogenic temperatures.
  - Digital transformation brings new challenges as the traceability and documentation of activity, interoperability of the measurement electronics, open and quick access to measurement data by external collaborators.

❖ CIEMAT:

The Division of Materials for Engineering at CIEMAT composed of four laboratories:
- Mechanical Properties Laboratory,
- Microstructure Laboratory,
- Corrosion Laboratory,
- Radioactive Laboratory,

with the aim to characterize the material behavior from stress to corrosion and cracking (SCC)

MECHANICAL PROPERTIES LABORATORY
- *Description of the Lab:* Laboratory for Mechanical Properties of Structural Materials is a facility with specialized instruments and devices to perform tests and measurements on various types of materials in order to obtain information about their mechanical parameters such as *strength,stiffness, fatigue,toughness,* among others for various fields of engineering and materials science.

- *Current Activities:* Mechanical characterization of materials through testing, which can be carried out with irradiated materials. Innovative Structural Materials For Fission And Fusion - INNUMAT; European Database For Multiscale Modelling Of Radiation Damage (ENTENTE).

- *Future plans:* in operation for several years. No large change presently planned.

CORROSION LABORATORY

- *Description:* The Corrosion Laboratory is dedicated to the study of the development of corrosion in materials. The corrosion test are done in static and dynamic autoclave for high temperature in water chemistry of PWR, molten salts, liquid metals (Pb-B), supercritical water. SCC test with irradiated samples.
- *Activities:* Component test infrastructure. In operation for several years. No large change presently planned. The main user community concerns the nuclear materials and metallic materials for energy sector.

RADIOACTIVE LABORATORY

- *Description:* The Radioactive Laboratory for material testing is a platform dedicated to R&D and projects. The Lab is composed by the radioactive facility, HALDEL facility and NAYADE facility.
- *Activities – Applications:* Electronics for aerospace industry, study of accelerated aging of materials in nuclear industry, genetics, food preservation and microbiological sterilization and irradiation of gemological materials.
- *Plans, Trends, future necessities*: The development of innovative cryogenic magnet systems of compact devices and high magnetic fields require appropriate materials to widen a possible design space. Beside the structural integrity, applied cooling techniques put constraints on the functional materials (conductivity, insulation etc.).

Goal is to provide cryogenic testing possibilities and methods for development, qualification and quality assurance of such materials up to component level.

❖ IFJ-PAN:

Test stand for voltage-current characterization of superconductors

- *Description of the Labs:* This lab has been developed in the framework of an agreement signed between IFJ PAN and Oxford Instruments for delivery of equipment for voltage-current characterization of superconductors. The main magnetic requirements are (≤ 120 A), a central magnetic field equal to 16 T with ramp rate to full field of one T.min^{-1}. Magnetic field homogeneity ≤10-3 total variation over a 10 mm diameter sphere, and magnetic field stability in persistent mode ≤10-4 relative/hr. The lab is equipped with a helium that is able to liquefy uo to 35 l/hr with LN2 precooling system and 1000 liters storage Dewar.
- *Current activities*: The test stand is being developed in close collaboration with CERN and it is meant to be compatible with Nb3Sn type sample holders. Residual Resistance Ratio (RRR) measurement of copper sample mockup.
- *Plans, Trends, future necessities:* The full operation of the test stand is foreseen on January 2024. The nano-voltmeter component is in purchasing process.

❖ INFN:

INFN Lasa

- Chemical treatments facility consisting of a clean room ISO4 Class (standard ISO- 16644-1) with a surface available of 9 m^2, and ultra-pure water rinsing filtered at 20 nm, at 100 bar pressure (18 MΩcm)

- RF measurement facility – RF cavities test bench with amplifiers frequency ranges and power: 500-800 MHz (650 W), 3 GHz (100 W), and 9 GHz (200 W)
- Magnet Vertical Test Station can accommodate magnets up to 700 mm diameter x 6500 mm in length maximum weight 10 ton (soon will be integrated by a 515 mm diameter x 3300 mm vertical cryostat for medium-size magnets/samples) with a maximum pressure of 4.5 bar. The thermal shield could be cooled by LN or evaporated GHe. Variable temperature for high temperature superconducting magnets tests is foreseen.

INFN LNF

- Outgassing characterization Facility based on throughput method and remotely controlled. Specific outgassing rate properties of new materials.
- High Vacuum Furnace with ultimate pressure < 10^{-6} mbar, operating pressure from 10^{-1} to 10^{-4} mbar, temperature max equal to 1230 °C, operative temperature equal to 1200 °C, 400 mm chamber diameter and 1300 mm chamber height.

INFN LNL

- High Vacuum Furnace with ultimate pressure < 10^{-7} mbar, operating pressure from 5.10^{-5} to 10^{-6} mbar, temperature max equal to 1300 °C, operative temperature equal to 1200 °C, 1300 mm chamber diameter and 2100 mm chamber height (with extension), maximum mass 1000 kg.
- Chemical treatments facility is ISO 5 Class room available for cavity assembly or small components packaging. The main activities that can be performed are the preparation of surfaces for UHV systems assembly (ultrasonic, degreasing, deoxidation; drying with solvents); the surface preparation of components for subsequent braze welding in a high vacuum furnace; chemical and electrochemical polishing of the surface of copper and niobium components (resonant cavities, cryostats, detectors), and treatments of low-melting alloys; supply of ultrapure deionized water, ultra-cleaning of copper components from radioactive contaminants.

- *Current activities:* High vacuum measurements of ESS Drift tube and IFMIF accelerator (LNF). INFN acquired the know-how on hard coatings deposited via PVD techniques.

- *Plans, Trends, future necessities:*
  - Variable temperature for High Temperature Superconducting magnet test in the Vertical test station is foreseen (Lasa)
  - Technology transfer
    - Through the collaboration with INFN, Eurolls gained access to the expertise and the PVD Lab at INFN-LNL premises
    - This technique is suitable to coat the wire and tube rolls and can provide a wide range of different hard coating.

❖ CNRS-IJCLab:

SUPRATECH Technological Infrastructures

SUPRATECH is dedicated to the development of superconducting RF technology for particle accelerators, surface treatment, testing and assembly of SRF cryomodules. It provides the technical platforms to support R&D or construction projects and activities related to superconducting accelerators.

- *Description*: SUPRATECH technological Infrastructures is composed of several platform devoted to the surface treatment of SRF cavities, vacuum and surface platform, vacuum and surface commercial equipment, and Vacuum and surface equipment for surface treatment and analysis.

- *Current Activities:*
  - Prototype and construction phase for European Spallation Source ESS of 13+1 cryomodules, 30 cavities, 30 power couplers and 28 tuners.
  - MYRRHA prototyping phase ongoing, contribution to MINERVA construction (pre-series cavity tests, series power couplers preparation and conditioning, series tuning qualification at 80 K, discussion on-going for potential series cavity test
  - Prototyping phase and series cavity test for PIP-II contribution

- *Plans, Trends, future necessities:*
  - Multipacting, Alternative Polishing of Niobium, Plasma processing, heat treatments for SRF R&D
  - Cryogenic R&D in sub-kelvin refrigeration, cryogenic instrumentation and acquisition, low temperature thermometry, sub-kelvin material properties.

❖ KIT:

Cryogenic Material Test Facility Karlsruhe (CryoMaK)

- *Description of the lab:* CryoMaK within the Institute of Technical Physics (ITEP) at the Karlsruhe Institute of Technology (KIT) is designed to meet the special requirements of various characterization methods, mainly in the temperature range from 4.2 K to 400 K. One of the major advantage is the combination of test methods in one laboratory with expertise of about 30 years. These include superconducting magnet technology, cryogenic energy applications for superconducting motors, generators, and transformers as well as topics in aerospace and medical technology. Many material developments (metal alloys or fiber composites) are defined, and analyses are performed on manufactured test specimens, for example from melts or additive manufactured material samples, under operationally relevant conditions. Material Qualification are based on standardized test methods, adapted test conditions are created in order to match the extraordinary requirements of material characterization and analysis of the very different R&D work or, if necessary, to develop new ones. Mechanical parameters as well as various physical properties can be determined. Microstructure investigations using X-ray diffraction, electron microscope or spectrometry allow a detailed analysis of the tested materials.

- *Current Activities:* The possible methods of cryogenic testing for **mechanical properties** are divided in dynamic and static test setups. The machines are used for the measurement of specimens and components of metal and non-metal materials on the scale from 25 kN to 650 kN depending on the machine. The facilities in operation are Galdabini 450 J, INSTRON CEAST 9350, and MTS25&MTS50.

- *Plans, Trends, Future necessities:* The development of innovative cryogenic magnet systems of compact devices and high magnetic fields require appropriate materials to widen a possible design space. Beside the structural integrity, applied cooling techniques put constraints on the functional materials (conductivity, insulation etc.). Goal is to provide cryogenic testing possibilities and methods for development, qualification and quality assurance of such materials up to component level.

❖ STFC:

- *Description of the Lab:* STFC is the perfect neutral space where academia, industry partners and the national laboratories can collaborate. Cryogenic Test Lab, Magnet Test Lab and Vacuum Interfaces and Surface Technologies for Accelerators (**VISTA**) Lab are among others devoted to the component tests and analysis.

CRYOGENIC TEST Lab

- *Current activities:*
  - The **R**esidual **R**esistivity **R**atio (RRR).
  - The critical temperature of superconductors ($\mathbf{T_c}$).
  - Magnetic field penetration for planar TF samples which replicates conditions similar to ones in an RF cavity.
  - Measurement of superconducting coatings at 7.8 GHz using closed cycle refrigerator.

MAGNET TEST Lab

- The HALL probe mapping
  - 5 m long bench
  - 3-axis movement
  - 1 □m resolution
  - Variety of probes for different applications
  - Fiducialisation of magnet centres
- Wire measurement
  - Stretched wire (field integrals)
  - Pulsed wire (fast undulator measurements)
  - Rotating coil (accurate harmonics)
- Hall probe calibration
  - Reference dipole magnet
  - NMR reference probe

Conclusions:

One of the major challenges for the development of future machines/detectors is to manufacture and operate superconducting magnets reaching magnetic inductions higher than 20 T at HTS temperatures. The development of these innovative systems requires appropriate materials to widen a possible design space. Beside the structural integrity, applied cooling techniques put constraints on the functional materials (conductivity, insulation etc.).

An effective and transparent technology watch in collaboration with academic and industrial partners would be highly appreciated in the years to come, in order to meet the challenges posed in the fields of cryogenic, thermal and mechanical detection and measurement.

F. Platforms for clean assembly, alignment and tests of accelerator components

The AMICI core team operates a number of platforms for the clean assembly of complete accelerator modules. Such platforms address the requirements related to the clean / particle-free assembly of superconducting accelerating structures, but also the further integration of so-called cavity strings (in some cases of single cavities) into a cryostat. The assembly procedures usually include careful alignment of the individual structures which may require dedicated assembly stations. Essential for the later successful operation of accelerator modules is the preparation and testing of additional components such as RF power couplers, or superconducting magnets, or frequency tuners.

F.1 Complete accelerator module assembly

❖ **CEA:**

- *Description and Activities*: The cryomodule assembly platform at CEA-Saclay includes two clean rooms, two assembly and cryostating areas, and one shipment hall.

  The clean rooms are:
  - The 124 NORD clean room, 190 m² in surface, including 112 m² class ISO 4, equipped with a semi-automated high pressure rinsing. It was the site of European XFEL cavity string assemblies and it is currently used for the cavity trains and power couplers of the ESS cryomodules.
  - The 124 EST clean room, 90 m² in surface, including 52 m² class ISO 5 equipped with a fully automated high-pressure rinsing installation (0.04 µm final filtration). It is currently used for R&D activity needs, for assembling power couplers and cavities, and cavity train assembly activities.

  The assembly and cryostating areas have a total surface of 740 m² and are almost in the immediate vicinity of the clean rooms in order to optimize the transportation operation of cavity trains. They were used for the XFEL cryomodules and are currently used by ESS and SARAF for the same purpose. A 400 m² shipment hall is also available; short term storage is also possible.

  The CEA-Saclay cryomodule test stand allows the RF power testing of the cryomodules at 4K and 2K. The maximum cooling capacity is around 80 W at 1.8 K. The 2 K superfluid helium is obtained by using 2 identical and independent sealed pumping units (oil sealed rotary vane pumps and canned Roots pumps) having an individual He pumping capacity of 2 g/s. In the current cryomodule test configuration, the thermal screen is cooled down to 80 K by liquid nitrogen. The cold mass of the cryomodule is then cooled to 4K by liquid helium flowing from a dedicated 2000 l Dewar. A new cold box is currently being procured as a part of cryomodule test stand implementation for the PIP-II project. This will allow supercritical helium operation for 4.5 K distribution and the cooling of the cryomodule thermal shields at 40K using high pressure GHe. The liquefaction capacity will be upgraded up to more than 200 l/h.

  The bunker dimensions are 18 m long and 5 m width, allowing testing long cryomodule type (XFEL like). It was used to test some of the ESS cryomodules at 2 K. It is used for the 4 K SARAF cryomodules in 2023. Upgrades can be discussed with the future users.

❖ **CNRS IJCLab:**

- *Description*: A dedicated cleanroom to cavity and cavity-string assembly is in operation at IJCLab. It hosts a High-Pressure Rinsing unit (HPR) for final cleaning of SRF cavities and ISO4 area for drying and clean assembly of short cryomodules up to 3.5m. Dedicated equipment for particle counting, slow pump down, leak test and low temperature baking (~ 120°C) are available in the clean room. A large hall next to the cleanroom is today dedicated to cryomodule assemblies once the cavity string assembly is out of cleanroom. This hall is equipped with a crane and alignment capabilities.

- *Activities*: IJClab was involved in series production of 7 Spiral2 medium beta cryomodules and is involved till mid of 2023 in the assembly of 14 ESS Spoke cryomodules.

❖ **CERN:**

- *Description*: CERN operates two horizontal bunkers M7 and M9 for cryomodule operations. Cryomodule assembly can be performed in the same building as the bunkers. In past 20 years, CERN assembled and tested LHC cryomodules and HIE-ISOLDE cryomodules in M9 bunker, and HL-LHC prototype crab cavity cryomodules in M7.

- *Activities*: The M7 bunker is fully occupied by the crab cavity project at this moment. The M9 bunker is reserved for LHC and HIE-ISOLDE cryomodules and a spare LHC module is sometimes tested there.

- *Plans*: CERN focuses on series cryomodules of HL-LHC crab cavities in coming years. After that, a spare HIE-ISOLDE cryomodule will be fabricated and tested. In parallel, prototype FCC cryomodules are under consideration. In order to facilitate such challenges, a new building will be constructed near the bunkers for more modern clean rooms optimized for cryomodule assembly.

❖ **DESY:**

- *Description and Activities*: Since almost 30 years DESY is operating an assembly facility for TESLA type 1.3 GHz accelerator modules. The facility was used for the development of the well-known 8-cavity modules. During the 90ies several members of the TESLA Collaboration helped exploring the required infrastructure. The facility was used during the construction of the European XFEL, and is now in operation for the repair or refurbishing of modules for DESY's FLASH and XFEL facilities. The assembly platform and the related expert team are the core of DESY's R&D towards superconducting accelerators. DESY's assembly platform was the 'role model' for similar platforms at CE Saclay, Fermilab, KEK, SARI, and others.

  The assembly platform consists of a large almost 300 m2 ISO4/ISO6 clean room with cavity preparation infrastructure (BCP & EP chemistry, High Pressure water Rinsing, UHV furnace, and others) attached. The clean room has the necessary air showers to insert material after proper cleaning. The required teams are qualified to prepare single cavities including rf couplers and antennas, and to assemble complete 8-cavity strings with a quadrupole / BPM package attached. A sufficiently long rail system carries the string and allows the roll-out to the next assembly station, outside the clean room.

  In front of the clean room many important assembly steps follow (2-phase line welding, magnetic shielding, sensors, rf measurements, cavity alignment, frequency tuners, and others) before the string is finally attached to the upper half of the so-called accelerator module cold mass. The next step, which is the attachment of the lower half cold mass but also includes cryogenic piping, cabling, and again others, is meanwhile done in the separated Accelerator Module Test Facility AMTF; here also the cantilever system is located which is required to insert the almost finished module in its outer vacuum vessel. RF power couplers are finally attached using local clean rooms.

  The DESY team is well trained and capable of assembling some few standard modules per year. Recently, two high performance modules were built for DESY's FLASH facility.

  The AMTF facility houses several test stands. Single cavities of very different type such as 9-cell, single-cell, SRF guns, lower frequency multi-cells, and others can be tested with a high through-put. In total three test benches for the performance check of (or extended R&D programs with) completed accelerator modules were built and used for the European XFEL series production of 100 modules. Meanwhile one bench is optimized for 3.9 GHz modules, and another one is under preparation for extensive SRF Gun Injector R&D.

- *Plans*: The single cavity test stands are in use for both, internal R&D and small series cavity testing, and cavity testing for external projects. Service contracts related to ESS and LCLS-II exist, PIP-II is coming. The module test benches are currently only used for DESY and European XFEL purposes. To some extent, service for our research facilities would be possible. Clear models exist regarding the administrative definition of service contracts.

❖ **Uppsala University:**

- *Description*: Uppsala University operates a cryomodule test stand currently dedicated to double-spoke cavity cryomodules for ESS. Cryomodules are tested at 2 K with high-power RF power stations at 352 MHz in pulsed operation (peak power 400 kW, duty cycle 4.5%). The cryogenic system provides 4 K liquid helium from a 2000L Dewar to a valve box dedicated to the ESS testing where 2 K superfluid helium is generated by being pumped through a JT-valve by subatomic pressure pumps in the infrastructure. The cooling capacity is around 90 W at 2 K. Thermal screens are cooled down to 80 K with a liquid nitrogen line.

- *Activities*: A bottleneck of the facility is the cryogenic system shared with cryostats described in C1 for superconducting cavities. When one of the cryomodule or cryostats is in operation, others cannot be operated in parallel. Thus, C1 and G1 conflict in their availability.

- *Plans*: The ESS cryomodule testing will finish in the middle of 2023 and the university will contribute to other similar types of projects after adaptation work in the infrastructure. A potential future upgrade is to double the cryogenic capacity if funding allows it. This would enable cavity testing and module testing at the same time and is a critical step forward to playing a leading role in the future accelerator projects in Europe and in the world.

❖ **STFC**:

- *Description*: STFC at Daresbury Laboratory hosts the UK's national program for Superconducting RF technologies. The Superconducting RF Laboratory (SuRFLab) houses a suite of cavity preparation and test facilities, utilized to optimally qualify SRF structures. The capability consists of two large Cavity Support Inserts (CSI) which is able to load up to three SRF cavities of large diameter and length, fundamentally in a horizontal configuration which ideally replicates operational expectations. A single 1.5m diameter cryostat is then utilized to accept the CSI test fixtures (one at a time), which can then be cooled to 2K cryogenic temperatures using an Air Liquide Liquid Helium liquefier, which has a cooling capacity of up to 100 W@2K, at a maximum pressure of ~11 g/s. The cryostat being house in a suitably sized radiation shielding enclosure. A High Pressure Rinse (HPR) system is also available, house in a suite of ISO6/5/4 cleanrooms, which can be utilized to clean and repair SRF cavities which fail their initial tests. SuRFLab is also currently undergoing a significant upgrade program, to provision for complete SRF cryomodule integration capability. The added infrastructure includes a new 14m x 4.5m ISO4 cleanroom to facilitate cavity string integration, along with cold-mass and cryomodule vessel assembly tooling and fixtures to facilitate complete cryomodule integration.

- *Activities*: Current activities for SuRFLab are to qualify 704 MHz, high-beta SRF cavities for the ESS project in Lund, Sweden. The upgrade program being implemented for cryomodule integration is to facilitate the In-Kind UK delivery of three high-beta cryomodules to FNAL for the PIP-II project, each consisting of six, 1.45 m long, high-beta 650 MHz cavities.

- *Plans*: In addition to closing-out the SRF cavity delivery for ESS by the summer 2023, instigating the new infrastructure to be able to deliver the cryomodules for PIP-II over the period 2025-26, new CSI configurations are being prepared to be able to test SRF thin film cavities of various frequencies and geometries, starting in 2023/24. The UK also has longer term aspirations to develop SRF technology solutions for both an X-ray FEL accelerator and a high power, short-pulse spallation neutron source, each of which is anticipated to require SRF technologies. By the time these activities are expected to start in earnest, SuRFLab is expected to be optimally equipped to facilitate all such development requirements.

F.2 RF power couplers

The successful operation of high-performance accelerator modules requires dedicated RF power couplers. Since they are directly connected to superconducting cavities, the preparation of the couplers – at least the so-called cold part – is somewhat sophisticated. The inner surface has to be as particle-free as the superconducting cavities itself. But also surface cleaning procedures are well-thought. Finally, before attachment to the cavities, an RF power conditioning can be useful or is a must, if high peak or average power is to be achieved. Several laboratories operate dedicated platforms.

❖ **CNRS-IJCLab:**

- *Description*: IJCLab has available several clean rooms at different ISO standards for different power coupler preparation steps: The ultrasonic cleaning (ISO6), the clean assembly (ISO4), the in-situ baking up to 200°C in appropriate ovens and the RF conditioning (ISO5) in an all-equipped test stands with the required diagnostics. The RF processing is automatically monitored and all the measured data (power, diagnostics and interlocks) are stored in database during the RF processing. The existent infrastructures and equipment are sized for mass production and could adapt to a high production rate (up to 8-10 couplers per week for Eu-XFEL project).
  The platform includes also RF power sources at 1.3 GHz (klystrons at 2MW and 5 MW pulsed power) and 352 MHz (Solid State Amplifier at 80kW CW).

- *Activities:* Over the years essential contributions were made to several European projects.
  - About 60 so-called TTF3 power couplers were cleaned, assembled and RF processed before installation on the FLASH facility (DESY)
  - Mass production (preparation and RF processing) of 850 power couplers for the European XFEL was carried out
  - 40 RF power couplers for spoke cavities were cleaned, assembled and RF processed for the European Spallation source (ESS)
  - cleaning, assembly and RF conditioning of prototype couplers designed for spoke cavities Minerva (1st phase of ADS MYRRHA) was done

- *Plans*: Cleaning, assembly and RF conditioning of series couplers (about 40) designed for Minerva spoke cavities (1st phase of ADS MYRRHA).

❖ **DESY:**

DESY recently finished the set-up of a new platform for 1.3 GHz RF power couplers of the XFEL or FLASH type. Pairs of couplers are assembled to wave-guide boxes; this work is done by DESY's clean room experts. Based on an older IJCLAB furnace, baking can be applied before RF conditioning. RF power is provided by one 5 MW klystron, capable of > 1 ms pulses at 10 Hz repetition rate. A similar set-up is under preparation of 3.9 GHz couplers.

Conclusions:
The AMICI core team, and also CERN, operate assembly facilities which are dedicated to either in-house projects or to European research facilities, and also to PIP-II at Fermilab, U.S. Large multi-lab projects are more and more often based on in-kind contributions. Thus, the networking of laboratories but also industries will be emphasized. Companies are taking over assembly duties; in the first step, and for smaller projects the technical platforms existing at the laboratories will continue to play a major role. AMICI can offer services to industry, and our research infrastructures will clearly benefit. Knowledge and technology transfer is guaranteed.

4 Conclusion

Research Infrastructures based on accelerators and superconducting magnets are at the heart of scientific and technological advancements in various domains, from fundamental physics research to medical applications and energy generation. Over the years, many European laboratories have set up numerous Technical Platforms (TP) to design, manufacture and test high-tech components for the field. Most of these TPs have been established initially to contribute to the construction of a particular RI, but are now often used for other projects in different scientific fields. Given the considerable investments made and the technological know-how accumulated, it is important to ensure the sustainability of this TP network and its adaptation to the challenges of the field.

In section 2, we have examined the projects in the different scientific domains that would lead to upgrading existing or building new accelerator or magnet-based RIs in the future. It is clear that needs are continuing to grow and that the technologies are becoming increasingly demanding, both for the near future and for the long term, not forgetting possible societal applications beyond RIs. This is particularly the case for particle physics, light sources and high-intensity neutron sources that are increasingly used in many fields. To effectively meet the subsequent growing demand in design, manufacturing and testing of components, it is important to identify the relevant TPs in Europe, check their sustainability and foster collaboration through the AMICI network in order to raise awareness about the common challenges and better share resources. In Task 13.1, the numerous TPs belonging to the AMICI/IFAST-WP13 partners have been grouped into categories and sub-categories so that members of a given category can get to know each other and identify common needs and challenges. Section 3 give the list per category or sub-category of the existing TPs, their capabilities and plans for the future.

Finally, following discussions within the different groups, it is possible to issue a set of recommendations to guide the future exploitation of technological platforms, with the aim of enhancing collaboration, efficiency, and innovation in this critical field:

1. Fostering Collaborative Research Ecosystem

One of the key recommendations is to foster a collaborative research ecosystem that encourages active participation from accelerator laboratories, academic institutions, and industrial partners. Such an ecosystem facilitates the sharing of knowledge, expertise, and resources. Collaboration should not be limited to individual disciplines but should embrace interdisciplinary efforts that leverage common needs and resources across various scientific domains. This collaborative approach reflects the laboratories' vision for a dynamic research community.

2. Infrastructure Development

The development of cutting-edge infrastructures is vital to support a broad spectrum of research and development activities related to accelerators. Laboratories should prioritize the creation of state-of-the-art facilities capable of accommodating the evolving demands of accelerator research. Investments in expanding and modernizing existing infrastructures are essential to ensure researchers have access to the necessary tools and environments for their work.

3. Standardization and Knowledge Sharing

To promote consistency and comparability of results, particularly concerning superconducting magnets and RF equipment, the establishment of standardized testing procedures and protocols is recommended.

Additionally, knowledge sharing within the scientific community should be facilitated through channels such as publications, conferences, mentoring programs, and collaborative initiatives.

4. Energy Efficiency and Sustainability

Efforts to optimize energy efficiency in all aspects of RF power generation, including the exploration and development of semiconductor-based solutions, should be encouraged. Research activities should align with sustainability goals and consider the environmental impact of accelerator technologies.

5. Advanced Materials and Cryogenic Testing

Advanced material characterization techniques and equipment should be invested in to support research and development activities. Special emphasis should be placed on understanding material properties and behaviours under varying temperatures and conditions. Laboratories should also strengthen their cryogenic testing capabilities, ensuring they can effectively work with superconductors and materials that require testing at low temperatures.

6. Assembly and Testing Facilities

The development and maintenance of advanced assembly facilities equipped with modern cleanrooms and state-of-the-art testing equipment are crucial. These facilities should be optimized for the assembly of accelerator components, requiring high precision during assembly processes. Furthermore, facilitating knowledge and technology transfer among laboratories, academic institutions, and industrial partners is essential for enhancing the assembly and testing of accelerator components.

7. Cross-Border Collaboration

Collaboration beyond national and institutional borders should be encouraged and facilitated. Joint efforts in constructing research infrastructures and addressing common technological challenges can lead to efficient resource utilization. Exploring synergies between scientific domains and research infrastructures is another valuable approach, as laboratories can adapt and repurpose existing platforms for different projects across diverse scientific fields.

8. Future Technology Focus

Staying at the forefront of technological advancements, especially in the realm of High-Temperature Superconductors (HTS), is essential. Laboratories should plan for the development of additional and upgraded Technology Platforms (TPs) to accommodate research, testing, and prototyping of next-generation accelerator components. HTS-based solutions hold the potential to revolutionize accelerator technologies.

9. Diversification of Applications

Beyond particle physics, accelerator technologies should be considered for diversification into other fields, such as MRI, wind turbine motors, and gantries for hadron therapy. Exploring opportunities to adapt and apply accelerator technologies in emerging fields creates synergies and expands the impact of these technologies beyond their traditional domains.

In conclusion, the future exploitation of technological platforms for accelerator and superconducting magnet research should be guided by collaboration, innovation, and forward-looking strategies. Addressing common needs, adopting new technologies, and fostering partnerships are fundamental steps in ensuring that accelerator laboratories and research infrastructures continue to play a pivotal role in advancing scientific knowledge and technological innovation across a wide range of disciplines. This report serves as a roadmap for enhancing the efficiency and effectiveness of research in this vital field.

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