I.FAST

Innovation Fostering in Accelerator Science and Technology

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MILESTONE REPORT

IIF Projects interim progress

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ABSTRACT

This milestone reports the IIF projects interim progress and results. The progress, innovations, and technical achievements have been constantly monitored, and a comprehensive overview has been presented during the 3rd Annual Meeting. The financial aspects are periodically supervised and discussed with the CERN IIF financial officer.

I.FAST Consortium, 2024

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

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Delivery Slip

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Executive summary

This milestone summarises each IIF interim progress, detailing theoretical and experimental activities, numerical simulations, prototype manufacturing, tests, and validation. The main achievements, data, and results are reported. Chapter 3 lists the scientific publications, dissemination, and communications performed during P2. Chapter 4 briefly describes the next steps foreseen in P3 until the end of the IIF. The last Chapter is dedicated to the list of references used in this report.

1 Introduction

The scope of the WP4 activities includes the implementation of an internal fund to support innovative technology developments in the project's second phase (3rd and 4th year), namely the Internal Innovation Fund, IIF. The Fund structure intersects the nine thematic areas of I.FAST with the European Community's (EC) priority agenda. That allows tackling similar priorities while connecting the accelerator community and societal thematics. Also, it stimulates the accelerator technology innovation potential by encouraging the I.FAST beneficiaries to identify innovative solutions with viable industrial or commercial potential. The novel projects supported by the IIF should significantly advance the I.FAST state-of-the-art thematic areas while contributing to more sustainable particle accelerator facilities. This context implies reducing accelerators' power demand, footprint, and best performances compared to the same environmental impact or new green accelerator-based technologies.

The IIF budget attributed to CERN within the WP4 is one MEuro (EC contribution, total cost). There will be three different payment instalments for the selected projects. The fund finances innovative projects at early development and prototype stages, with technical maturity up to a Technology Readiness Level (TRL) equal to 4 (validated in the laboratory). The project selection gave priority to those able to raise additional external funding. The Governing Board (GB) endorsed eight projects in November 2022. The selected projects will be executed by ten I.FAST beneficiaries with four new partners. The IIF projects started their activities in February 2023. Each selected project beneficiary received 50% pre-financing of the requested budget in March 2023. A second instalment of up to 80% of the total single project budget is transferred upon submission of a technical report due in M36 (April 2024). The report must prove clear and tangible progress of the ongoing activities. The final 20% of the budget will be transferred in M47 (March 2025) upon proving that final achievements meet the initial objectives.

2 Description of projects progress

2.1 High-Temperature High-Gradient Superconductors (HIGHEST)

The focus of this work package is to develop large width (hopefully up to 50 mm) HTS coated conductors (or "tapes") by KCT for the sake of testing their behaviour in high-gradient RF field at SLAC. The quality of these tapes will be assessed also by standard analysis superconducting techniques and RF test at low field by CSIC-ICMAB.

As preliminary and background work, standard 12-mm tapes will be soldered on cavities for low-gradient test and discs for high-gradient test, to assess and develop the technology.

WP1 (CERN):

- **M1 - Samples and substrates procurement (due 12/2023)**

  The milestone has been achieved and several disc samples have been fabricated and shipped for coating and test. Moreover, cavity segments have been fabricated but some alignment difficulties have still to be solved. A new high-precision support to facilitate alignment has been designed and is being fabricated, will be tested in May 2024.

- **D1 - RF low power characterization of segmented cavities (small tapes) (due 6/2024)**

  This cavity (axion detection) is on track with some potential small delays due to the alignment issued mentioned above, identified with a warm RF test (copper only), and confirmed by simulations, and hopefully solved by 5/2024 with the new support. As soon as these issues are clarified, it will be coated with HTS tape and tested at cryogenic conditions.

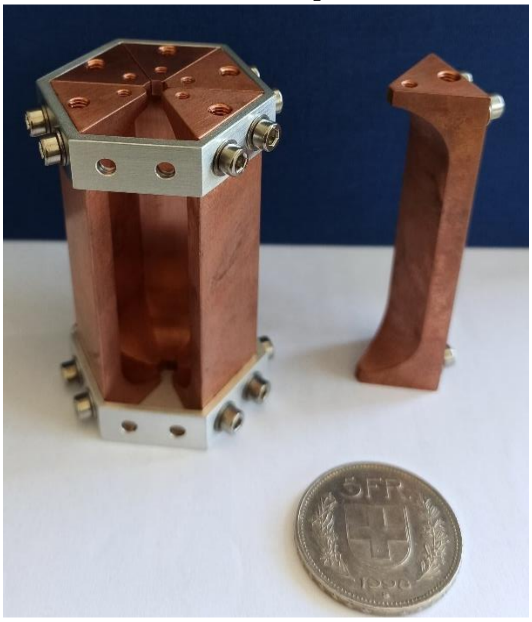

Fig. 1 segmented cavity for axion detection.

WP2 (KCT):

- **M1 - Design and fabrication of sample holder system (due 3/2024)**

  Achieved well in advance and ready for coating of large width tapes.

- **D1 - HTS coating of large samples (due 3/2025)**

  On track for successful completion by the scheduled end date, and already well under way. The first coating run of a first 40 mm wide tape is already coated (final goal is 50 mm, but 40 mm is enough for our final goal of disc testing, see later). Some development has to be performed over the next year to obtain in a reliable way the coating of the buffer layers prior to the HTS coating.

Fig. 2 roll-to-roll coating support adapted to wide tapes.

WP3 CSIC-ICMAB:

- **D1 - Coating on discs and segmented cavities for benchmarking (small tapes) (due 3/2024)**

  Achieved for discs, already high-power tested at SLAC (presented at EUCAS 2023). Waiting for readiness of segmented cavity.

- **D2 - Measurement of superconducting properties of large size tapes (due 3/2025)**

On track and well under way, first 40 mm wide tape already characterized (critical current and RF at low field). This work will serve during the optimization process of the large-width tape coating at KCT.

2.2 Permanent Magnet for High Efficiency Klystrons (PM4HEK)

Work performed:

- The design of the final system is almost finished with enough information to launch the procurement of permanent magnet materials. An approved drawing of the magnet and the tooling already exist.
- The design of the magnetic channel has been done mostly by Elytt with CERN in charge of the verifications by CST simulations.
- We had a preliminary meeting with Canon tubes to discuss the adaptations that the klystron could have to match the magnet. The initiative was very well received, and we are waiting for technical feedback.

2.3 A Field Emission Cathode for a Travelling-Wave RF gun for High Brightness Beams in Industrial and Small Research Facility Settings (FE Cathode)

PSI

- **Design and manufacturing of FE cathodes (towards D1):**

  A set of test cathodes have been fabricated to test the cathode concept on a mock-up of the TW gun's inner geometry. The final cathodes are now in production by VDL (Figure 6).

- **Realisation of high-power test facility (towards D2):**

  The test facility where the TW gun with FE cathode will be tested is now operational. The system is currently testing the SW gun (from IFAST WP 7.4) (Figures 3 and 7).

- **Update of the LLRF (M2 Completed):**

  The LLRF has been updated to fit the requirements of the test with the ability to operate with a phase flip and new RF signals from the waveguide network. Furthermore, new interlock and safety systems have been implemented to have the beamline in full compliance with safety regulations stipulated by the Swiss Federal Office of Public Health (Figure 3).

- **Design, procurement, and installation of diagnostics beamline (towards M1 and D3):**

  A layout of the diagnostics system has been designed; the procurement of components is now under way (Figure 5). Several components already available.

VDL

- **Delivery of Travelling-Wave gun Pieces (towards D2)**:
  Components that once assembled make up the travelling-wave gun were machined and delivered to PSI (Figure 4).

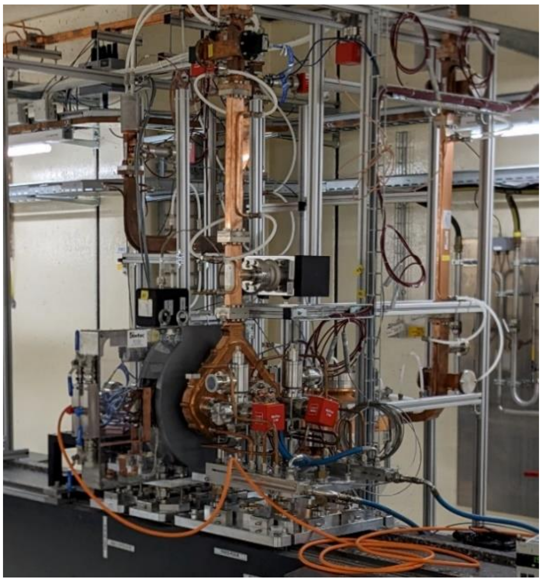

Fig. 3 High-power test stand realised and operational.

Fig. 4 Fabrication of TW gun components.

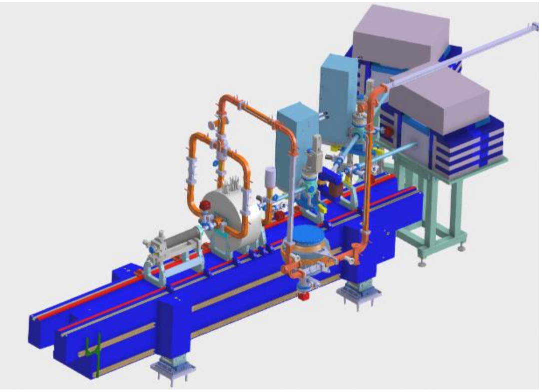

Fig. 5 Instrumentation beamline design.

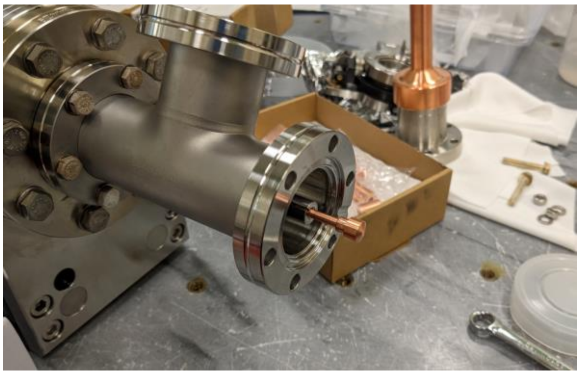

Fig. 6 Cathode mounting system and first test cathodes.

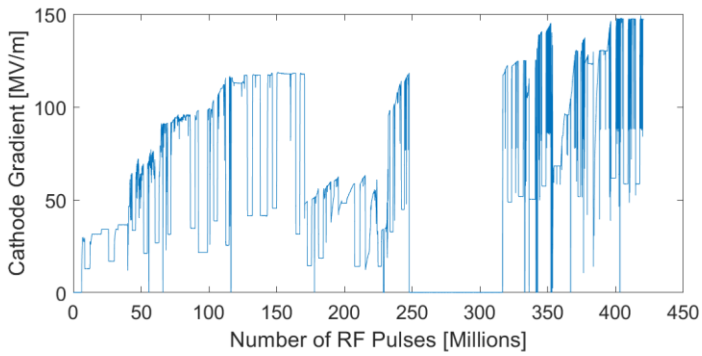

Fig. 7 Conditioning of the SW Gun.

2.4 KAIO ACCELERATOR

Compact high-flux laser-plasma accelerators (LPA) are expected to enable entirely new modalities in medical diagnostics, radiation therapy and industry-scale imaging [1]. While LPA science is well-established in many laboratories, its market deployment is limited by the fact that it is almost entirely based on Titanium:sapphire (Ti:Sa) laser technology that operates at low repetition rate, thereby offering very limited flux for applications. The kHz LPA operated at LOA is based on a Ti:Sa laser followed by temporal pulse compression in a nonlinear optical waveguide to boost the laser peak power up to the TW level for LPA [2], but this compression technology has already hit its performance limits. The KAIO ACCELERATOR project (see figure 8) aims at exploiting a new compression technique, based on nonlinear pulse propagation inside a multi-pass cell (MPC) [3], to efficiently boost the peak power of industry-grade Ytterbium (Yb)-based lasers for LPA compatibility. MPCs are energy efficient and enable high compression factors over compact footprints, which combined the high average power (kW-class) and high wall-plug efficiency (10-30%) of Yb-based lasers, hold the promise of sustainable and cost-effective commercial LPA value chains for medical and industrial applications.

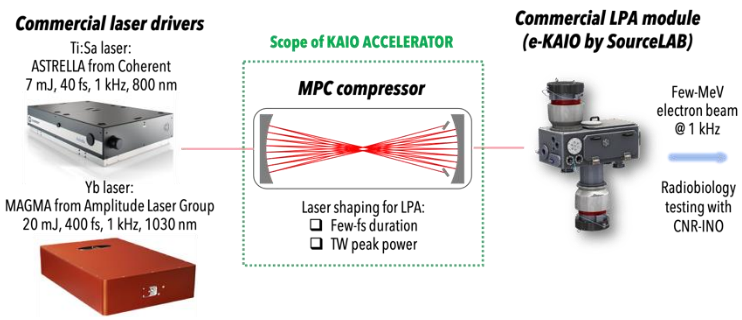

Fig. 8 Organization of KAIO ACCELERATOR project.

WP1: successfully completed by the end of 2023.

- **Objective:** Design and test MPC compressor for commercial ultrafast Ti:Sa-based laser and demonstrate compression performance comparable to nonlinear waveguide technology

- **Milestone:** Compression of 7 mJ 40 fs 1 kHz pulses from ASTRELLA USP (Coherent)
- **Team:** LOA, SourceLAB
- **Timeline:** T0 + 12 months

Figure 9 shows the MPC compression results obtained for the ASTRELLA USP Ti:Sa laser from Coherent. The 7 mJ 40 fs pulses were successfully compressed down to 4 fs with 60 % efficiency (> 4 mJ measured directly at the output of the MPC) after 28 passes through a 3 m long MPC filled with Helium gas at a pressure of approximately 1.8 bar. The compressed pulses exhibit high spatio-temporal beam quality. To the best of our knowledge, this is the shortest pulse duration (~ 1.5 optical cycle) ever measured out of an MPC compressor, the performance of which is comparable to that achieved using nonlinear waveguide technology [2], which should lead to a high-impact publication.

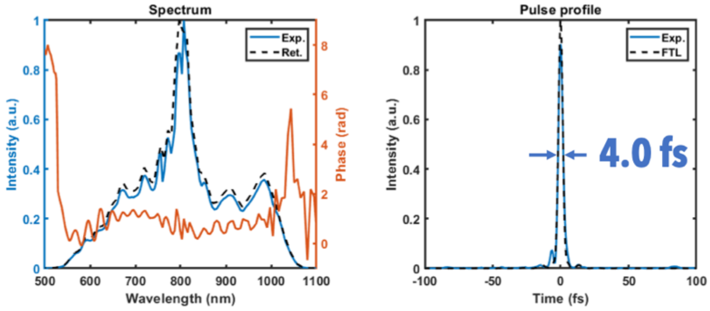

Fig. 9 MPC compression results for ASTRELLA USP laser: nonlinear spectral broadening and spectral phase (left), reconstructed temporal profile of the compressed pulse (right).

WP2:

- **Objective:** Design and test MPC compressor for commercial ultrafast Yb-based laser and demonstrate continuous LPA operation at high repetition rate (kHz).
- **Milestone 1:** Compression of 20 mJ 400 fs 1 kHz pulses from MAGMA (Amplitude Laser Group)
- **Milestone 2:** Continuous MPC-compressed Yb-driven LPA operation at 1 kHz driven.
- **Team:** LOA, SourceLAB
- **Timeline:** T0 + 18 months

Procurement of materials for the first milestone of WP2 is now complete. Experiments on first MPC compression stage of the MAGMA laser system have begun. Final compression performance is expected to be achieved before the end of Q2 2024. The compression performance will determine the design of the second MPC stage that will allow to reach the few-optical-cycle regime for LPA compatibility.

Procurement of materials for transporting the compression Yb laser beam towards the LPA module is underway. Building of the transport beamline from the MPC compressor to the radio-shielded area will start at the beginning of Q3 2024 and first LPA experiments with the compressed MAGMA laser are expected to start in Q1 2025. **WP2 is expected to be completed no sooner than the end of Q4 2024.**

WP3:

- **Objective:** Radiobiological study on single-strand DNA breaking using Yb-driven LPA beam
- **Milestone:** Benchmark Yb-driven LPA performance against conventional electron source [4]
- **Team:** LOA, CNR-INO
- **Timeline:** T0 + 24 months

CNR-INO is planning dosimetry protocols in preparation for the radiobiological studies [4] using the Yb-driven LPA at LOA. These will heavily depend on 1) the expected electron beam specifications and 2) available on-site support for biological endpoint evaluation. Discussions are underway between LOA and CNR-INO teams to this effect. **Radiobiological testing for WP3 is expected to start after completion of WP2, no sooner than Q2 2025.**

WP4:

- **Objective:** Market study of Yb-driven LPA technology
- **Deliverable:** Report
- **Team:** DF Photonics Consulting
- **Timeline:** T0 + 24 months

Almost all deliverables for the market study have been completed by DF Photonics Consulting. **WP4 is expected to be fully completed by Q4 2024.**

2.5 Development of Highly Efficient MW Class Cross Field Vacuum Tube Amplifier for Particle Accelerators Driven by a Solid-State Power Amplifier at 750 MHz

The project started effectively in April 2023, as all the people involved were not in place at Uppsala University. Since then, the design Work package, i.e. WP1 was finalized and the first development and manufacturing work package, i.e. WP2 Slow-wave structure development was also finalized with satisfactory first results, in good agreement with the simulations. Clear and measurable details of the contribution and work performed by Uppsala University is presented below. The other partners involved with this project, i.e. Scandinova AB and Exir Broadcasting AB will contribute later with equipment loan or acquisition.

The project is well progressing towards its objectives. Significant results, and achievements are presented. Our proposal focuses on innovations to improve the gain, efficiency, phase coherence, and longevity (as mentioned in Table 1).

Table 1

	Efficiency	Gain	Power	Frequency	Phase coherence	Longevity	Compactness	TRL
CFA proposed	85%	30dB	1 MW	750 MHz	yes	>50k hours	0.5*0.5 m2 <10kg	3

Theoretical design points:

There are two major variants of cross-field amplifiers: 1. Injected beam 2. Reentrant electron beam. The reentrancy of an electron beam increases the efficiency of cross-field amplifiers like magnetrons.

Parameters	Injected beam	Reentrant beam
Forward wave	Bratron	Dematron
Backward wave	Bitermitron	**Amplitron**

- **Efficiency:** As per the literature, Amplitron has demonstrated the highest efficiency among the cross-field amplifiers, which have the lowest insertion loss. Re-entrant distributed emission CFA has the same efficiency as magnetron (85%). Compared to magnetrons, CFA has efficiency enhancement opportunities as it can implement the non-uniform vane pitch and AK gap to match the electron velocity to the RF wave. Electrons lose energy near the output section and desync with the RF wave. So, the vane pitch tapering makes the phase velocity of the RF wave equal to the electron drift velocity. we can go/try above 85 %. Due to low quality factor, the chance of RF breakdown near to SWS is lower than the Magnetron oscillator.

- **Magnetic flux:** However, designing the magnetic flux is more challenging for backward wave interaction-based cross-field tubes. The permanent magnet-based system is essential to increase the system's energy efficiency. (Most crossed-field tubes necessitate a uniform magnetic field within a range of 5 to 1.5 percent and symmetrically positioned around the magnet's axis within roughly 3 percent across the entirety of the electron cloud's volume. However, the field uniformity standards for a BWO are stricter, requiring symmetry around the axis within 1 percent.) So, the uniformity of magnetic flux over the axial length of CFA is limiting factor in case of permanent magnet-based system. For guiding a magnetic flux, a cold cathode with an inner magnet is also an option to investigate.

Hence, we prefer a Re-entrant beam-based CFA. We have two design options: Forward wave and backward wave CFA named Dematron and Amplitron, respectively. The last design point is about the longevity of CFA.

- **Longevity**: Like other vacuum electron devices, the Longevity of CFA depends on cathodes significantly in addition to anode vanes in the case of megawatt-class operation. A kW class driver is required to achieve the megawatt-class power in low gain CFA, and kW of RF power eases the implementation of **cold cathodes** with secondary emission. Platinum-based secondary emission cathodes have a lifetime of 100,000 hours and are independent of an on/off cycle, which is a limiting factor for the magnetron. Despite the platinum cost, its more straightforward construction lowers the cost of the cathode. Chemically inert platinum is free from poising and makes the CFA handling, repair and development more manageable in the vacuum range 10-6 to 10-7 Pa, i.e. Ultra-high vacuum (UHV).

Similarly, press-fitted Molybdenum or tungsten vane tips increase the life of Anode vanes, and press-fitted arrangement eases the replacement of anode vanes, if any. Hence, it reduces the cost of the CFA tube. With these arrangements, the tube can achieve a lifetime of more than 50,000 hours and reduces the cost of tubes.

- **Emission:** The DC electric field is required to maintain the drift velocity of electron near to phase velocity of wave regardless of emission mechanism. This DC electric field enables the field emitter. FE emitters offer several advantages, such as no need for heating, high average current density, uniformity and copious emission, which make FE especially suitable for use in these microwave devices. Development of field emitters are compatible with microfabrication technique and less labour intensive than thermionic cathodes. So, integrating field emitters with CFA will reduce the cost of microwave tubes. Field emitters are more robust, free from poisoning and have a higher lifetime. Integration of field emitters in cross-field vacuum tubes could be beneficial in terms of improved power density efficiency and lifetime.

RF wave propagation: There are two major variants of CFA based on bandwidth: narrowband and wideband CFA. For accelerator applications, narrowband CFA is the preferable choice. We will develop a slow wave structure to slow down the RF wave to interact with drifting electrons. Maximization of interaction, extraction of electron energy with minimum insertion loss is goal. Our project goal is to achieve a gain **of 30 dB,** which can be achieved by multi-stage SWS and separated by sever/lossy structure to achieve stability. A cathode-driven cross-field amplifier (CFA) is also an attractive option.

To address the abovementioned design issues, we proposed innovation at the component level. In Table 2, the study/method is mentioned to evaluate our component design.

Table 2

Parameter	**Component level Innovation**	**Study**
Frequency **VSWR**	Slow wave structure Coupler	Modelling Eigenmode Simulation Scattering parameter study
Efficiency	Re-entrant Distributed Emission Misaligned A-K gap & nonuniform SWS period Employment of a permanent magnet-based system	PIC efforts on reentrant CFA Solution identified. Magnetostatic simulation
Longevity	Cold emission cathodes	Simulation ongoing field emitters

Design of Slow-wave structure: Eigenmode Simulation has been performed to determine the frequency and phase, i.e., dispersion characteristics for a slow-wave structure. Geometric parameters have been varied to achieve the desired frequency of 750 MHz. Also, the phase velocity of the RF wave is ensured to be less than 0.5*c and is near the drift velocity of the electron.

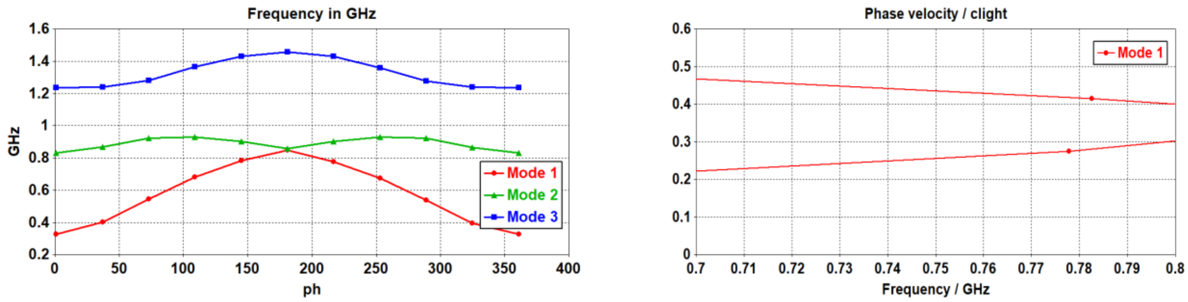

Fig. 10 (a) Dispersion diagram of SWS and (b) Phase velocity of RF wave.

From the figure 10, multiple modes are travelling in SWS but only mode 1 (red colour) is in operating regime near to 750 MHz. SWS support the 750 MHz at the phase of pi/3 and 2pi/3. The phase velocity of the RF wave is slowed down by 0.43*c and 0.26*c. Similarly, we analysed the RF propagation characteristics of the model given in Figure 11(a) using s-parameter simulation. The scattering parameter analysis is performed using the adaptive meshing technique to improve the accuracy. Figure 11(b) shows that reflections are below -20 dB and transmission is -0.05 dB.

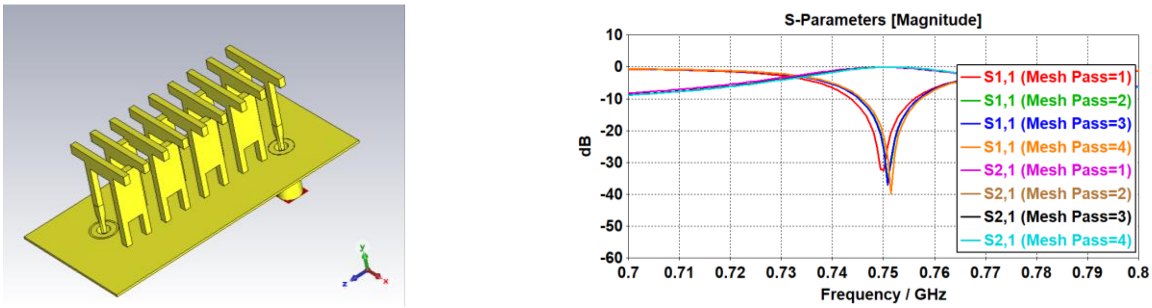

Fig. 11 (a) CST model of slow wave structure (b) Scattering parameter of SWS.

<u>Current status</u>: The drawing of the proposed slow wave structure has been sent for manufacturing and will be tested once it is manufactured. The first manufactured devices were assembled and tested on March 31, 2024, see Fig. 12.

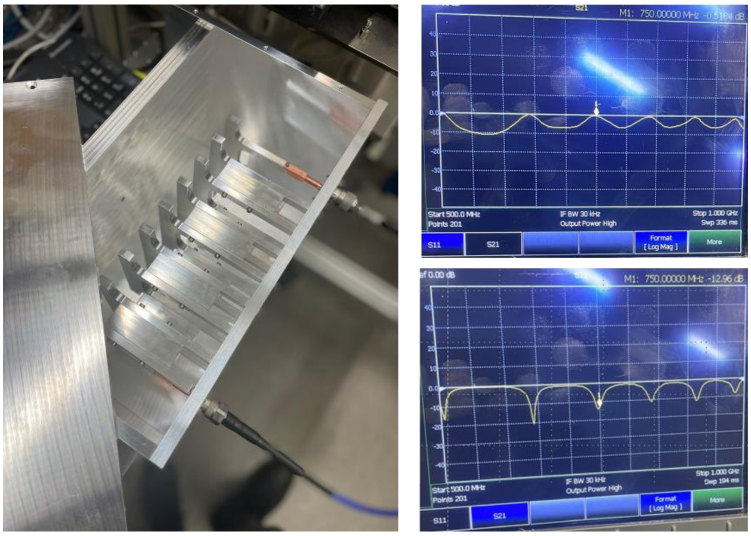

Fig. 12 Fabrication and assembly of the first Slow Wave Structure, and first measurements demonstrating satisfactory response, i.e. return loss, RL = 13 dB and insertion loss, IL = 0.5 dB at 750 MHz, in very good agreement with the simulations.

Current calculation and Field Emitter:

Desired Performance metrics at 750 MHz		
Desired RF power	1 MW	We need a megawatt-class compact and efficient amplifier.
Desired Efficiency	0.85	
Rough Electromagnetic calculations		
Beam Voltage	30kV	To design a 750 MHz cross-field amplifier, We have determined these preliminary parameters using analytical calculations. At 30kV, we need 0.27 Tesla to operate, so the cathode length is crucial to make uniform magnetic flux.
AK gap	6 mm	
Cathode length	45 mm	
Cathode radius	18 mm	
Emitter area	51 cm2	
Beam Voltage	30kV	
Required current		
DC input power	1/0.85=1.176MW	Field Emitter can supply enough current
Required current	1.176MW/30kV=39.21 A	
Required current density	0.76 A/cm2	

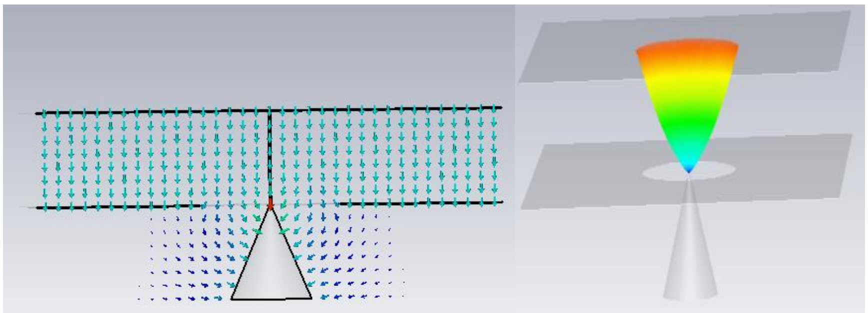

Fig. 13 Electrostatic simulations for the e-emitter. (a) Electric field distribution of field emitter (b) Electron trajectories

Cathodes in cross-field vacuum electron devices are vulnerable to ion bombardment and current suppression due to space charge effects. The Gated Field emitter tips are a suitable design, which is simulated using CST particle studio. According to the literature, a single emitter tip in a field emitter array generates current in the range of 10-100 mA.

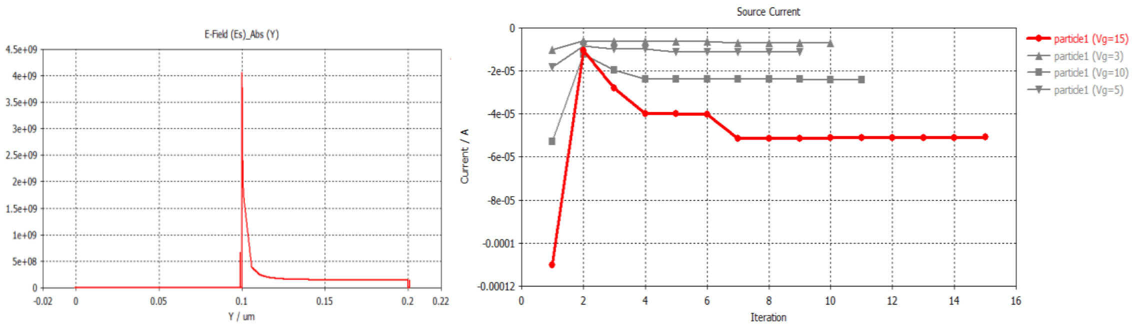

Fig. 14 (a) Electric field value (b) emission current variation for different gate voltage.

Beam wave interaction study: We are invetigating beam wave interaction mechanism in circular and planer structures, which is in progress. To achieve this, we chose a different approach. In **reverse design approach** we designed an 810 MHz Magnetron operating in pi mode and converted it into non-pi mode 750 MHz CFA. In figure 15 the model of 750 MHz CFA is hown with and without electron beam. But so far, we have not received any significant results. However, magnetron is demonatrating the 1.5 megawatt of power at 811 MHz as shown in figure 16 (a) and (b).

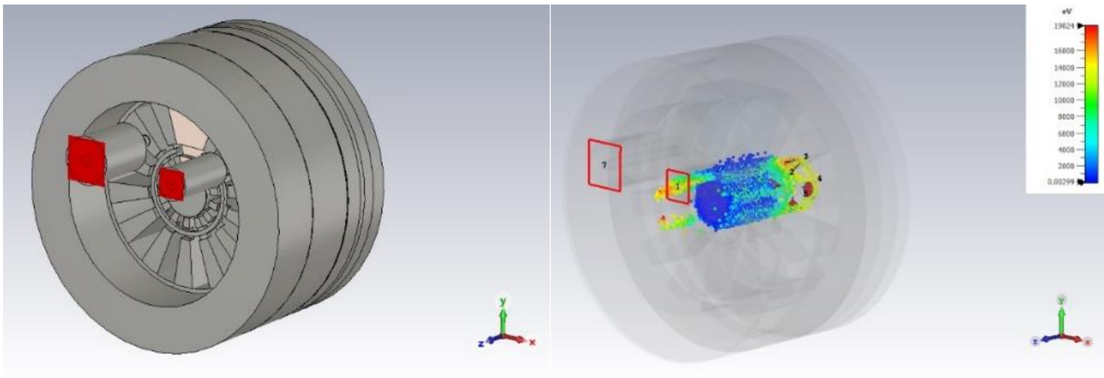

Fig. 15 (a) CST model of 750 MHz CFA (b) Particle preview in model.

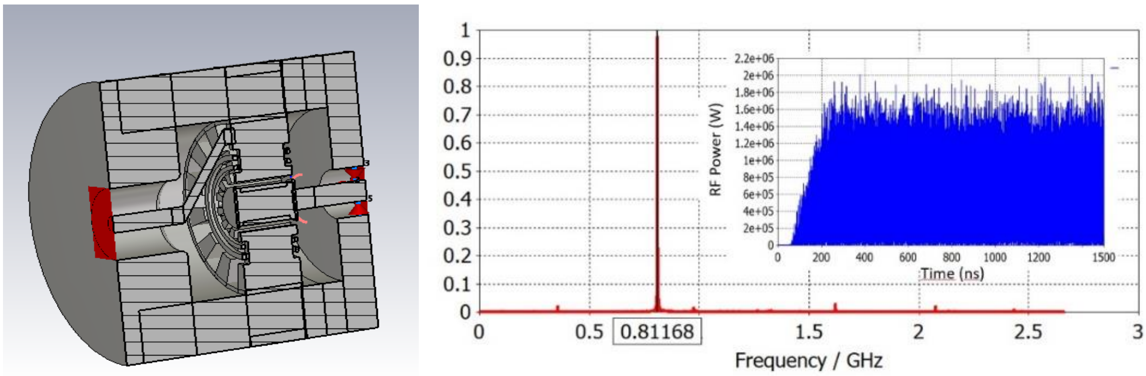

Fig. 16 (a) CST model of 811 MHz Magnetron(b) RF output power and frequency.

2.6 MILLISECOND FLASH LAMP TREATMENT FOR SRF ACCELERATING CAVITIES

The main goal of the project is the development of the technology for the fabrication of 6 GHz cavity made of copper and high T_C coatings. The Nb_3Sn coating is deposited by magnetron sputtering at elevated temperature. Due to thermal instability of copper at high temperatures the maximum allowed temperature for thin film deposited is about 650 ^oC that limits the performance of coating film. Therefore, the post grown thermal annealing is required. Within the project we have tested the ms-range flash lamp annealing (FLA) for improvement of the coating crystallinity without affecting basic properties of copper substrate. Due to very short annealing time, below 25 ms the peak temperature in coating layer can significantly exceed the 650 ^oC without activation of Cu diffusion that is the main drawback of high temperature annealing.

The project is in accordance with the planned schedule. 2 milestones planned at this time MS1 and MS2. MS1 was reached a couple of months early, while the MS2 is nearing completion due to delays in commissioning the vacuum chamber. The delay is beyond the control of the project contractors. However, the delivery of the chamber with a two-week delay should not affect the realisation of subsequent milestones. However, the delay will not affect in future period 3 milestones. We report for completeness, in addition to the milestones, the status of the various tasks (Tn) of the project.

- **T1 - Design of the annealing chamber for high-temperature treatment of Cu-cavity by FLA is approved. (June 2023). Realised at time.**

  Chamber is designed at time and the chamber fabrication was ordered from Rovak GmbH. The dimension of the chamber allows to anneal not only 6 GHz cavities but also 1.3 GHz. Moreover, the design of the chamber allows to use it for different proposes going beyond tasks designed in the project e.g. annealing of different shaped elements for medical applications.

  - The design of the chamber was made by HZDR team with support of other project partners e.g. dimensions, required annealing parameters.

- **MS1 (T2) - The crystalline quality of Nb-film on Cu substrate is improved by FLA treatment. (September (2023). Realised at time.**

  Nb and Nb3Sn films were deposited on planar Cu-substrates and annealed by FLA. We have tested an influence of annealing atmosphere e.g. Nitrogen and Argon, on the properties of coatings. It was found that the annealing in argon is preferential. Rutherford Backscattering spectrometry reveals much small changes in the surface composition after annealing in Ar than in nitrogen. It can be due to better control of the gas environment in the chamber using heavier gas like Ar than nitrogen. Next experiments will be performed in vacuum to further reduce potential contamination of the sample with oxides that may degrade the layer performance. The structural investigation shows significant increase of the average diameter of Nb nanocrystals in the coating after FLA. We expect that the further improvement of superconducting properties like critical magnetic field and critical temperature will be achieved after vacuum annealing.

  - Samples were deposited by INFN, FLA and structural and magnetic investigation were made by HZDR.

- **T3 - Nb_3Sn coated planar Cu-substrate are presented (December 2023). Realised at time.**

  Nb3Sn layers were deposited on Cu substrates at different temperature and with or without Nb-buffer layers. Good quality coatings required high temperature deposition that may activate Cu diffusion and degradation of coating properties. Therefore, we have tested the influence of the deposition temperature and post-grown annealing on the layer performance. To reduce the diffusion of Cu into the Nb_3Sn the Nb-buffer layer was added. The thickness of the buffer layer was up to 30 μm. Next, we have tested the post-deposition FLA. It was found that the annealing for 20 ms significantly improves the crystal quality of the coating on planar samples. Moreover, the X-ray diffraction reveals the strain reduction in the layer after FLA that is favourable for high Tc material. After deposition at 650 ^{o}C and FLA the Tc of 1 mm thick Nb_3Sn is about 17.5 K that is close to the theoretical limit for bulk Nb3Sn that is 18.3K.

  - Samples were deposited by INFN, FLA and structural and magnetic investigation were made by HZDR.

- **T4 - Fabrication of Cu-cavity with Nb-coating (January 2024 → 4 months delay according to the schedule → minor impact on future milestones).**

  Three 6 GHz copper cavity produced by Piccoli Srl by seamless spinning for this project. One cavity polished at INFN by standard protocol (vibro-tumbling + EP + SUBU) and ready for the Nb coating. The Nb coating will be done in the first two weeks of May. As the flash annealing chamber is ready in mid-May, this delay will not impact future milestones (MS4 in August 2024).

  - Cavity spun by Piccoli Srl, Polishing made by INFN.

- **MS2 (T5) - The flash lamp annealing chamber for Cu-cavity is tested. (January 2024 → 4 months delay according to the schedule → minor impact on future milestones).**

  The MS2 is not yet realised due to the delay of delivery. The Rovak GmbH company inform us about the delay due to problems with some components that are not yet delivered. Currently the predicted delivery is the second week of May (before May 14th), in time for MS4.

  - The ordering and commissioning done or will be done at HZDR.

2.7 AM APPLICATIONS OF REFRACTORY METALS FOR ION SOURCES

- **Objectives:** Development of FEBIAD-like ion sources via Additive Manufacturing (AM) technology, exploring the possibility of improving some specific aspects, such as the reliability of the assembly procedures and the ionization performance.

- **Development of Refractory Metals by AM Technology:**

  - Pure Ta development: INFN - Padua Division

    Process parameter optimization is essential for achieving high-density components through Additive Manufacturing (AM) technology, particularly Laser Powder Bed Fusion (LPBF) processes. The EOS M100 machine, located at the Development and Innovation on Additive Manufacturing (DIAM) laboratory of the INFN Padua Division, was utilized for this purpose.

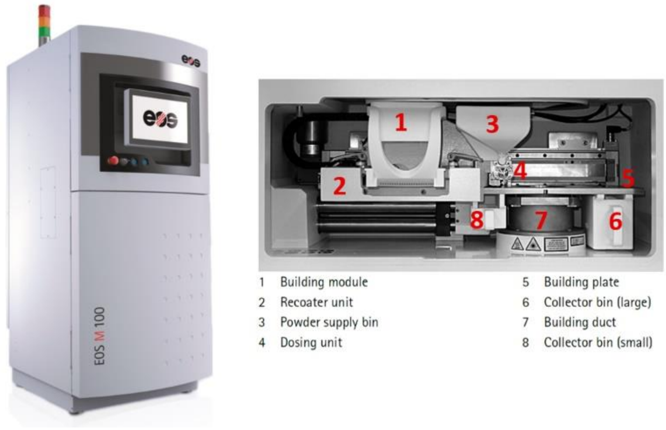

Fig. 17 EOS M100 System use for the LPBF process of pure Ta.

The outcomes of the final two stages of the process parameter optimization procedure are depicted in Tables 1 and 2. The density values attained indicate the successful achievement of the intended objective, which is to obtain the maximum achievable density in the solid components.

Table 1. Process Parameters tuning intermediate step.

Sample	Power [W]	Speed [mm/s]	Hatch distance [mm]	Layer thickness [mm]	Stripe width [mm]	Stripes overlap [mm]	E_v [J mm^{-3}]	Density [%]
1	110	350	0.06	0.03	3	0.05	174.60	98.84
2	110	400	0.06	0.03	3	0.05	152.77	98.00
3	110	450	0.06	0.03	3	0.05	135.80	98.16
4	130	350	0.06	0.03	3	0.05	206.34	97.89
5	130	400	0.06	0.03	3	0.05	180.55	97.74
6	130	450	0.06	0.03	3	0.05	160.49	97.83
7	110	350	0.06	0.03	2	0.05	174.60	99.69
8	110	400	0.06	0.03	2	0.05	152.77	99.26
9	110	450	0.06	0.03	2	0.05	135.80	98.81
10	110	350	0.06	0.03	2	0.05	174.60	99.84
11	110	350	0.06	0.03	3	0.05	174.60	99.49

Table 2. Process Parameters tuning final step.

Sample	Power [W]	Speed [mm/s]	Hatch distance [mm]	Layer thickness [mm]	Stripe width [mm]	Stripes overlap [mm]	E_v [J mm^{-3}]	Density [%]
1	90	350	0.06	0.03	2	0.05	142.8571	94.05
2	100	350	0.06	0.03	2	0.05	158.7302	97.27
3	120	350	0.06	0.03	2	0.05	190.4762	99.56
4	130	350	0.06	0.03	2	0.05	206.3492	98.83
5	110	200	0.06	0.03	2	0.05	305.5556	99.99

6	110	250	0.06	0.03	2	0.05	244.4444	99.93
7	110	275	0.06	0.03	2	0.05	222.2222	99.40
8	110	225	0.06	0.03	2	0.05	271.6049	98.19

- **Production of Refractory Metals samples and components for AM Technology:**
  - Pure Ta samples production for geometrical characterization: INFN - Padua Division

    The determination of optimal process parameters for assessing the geometric integrity of the material amidst varying thicknesses was investigated. By implementing a dual contour approach, it became feasible to fabricate intact thin walls ranging from 0.5 to 0.1 mm. Subsequently, the examination of overhang angles constituted the second phase of geometrical characterization. This optimization endeavour aimed to enhance parameters associated with component production. Through the refinement of down-skin process parameters, walls inclined at 20 degrees were successfully manufactured. Additionally, the surface roughness of these inclined walls was measured to demonstrate the consistent quality of down-skin surfaces, irrespective of the wall's degree of inclination.

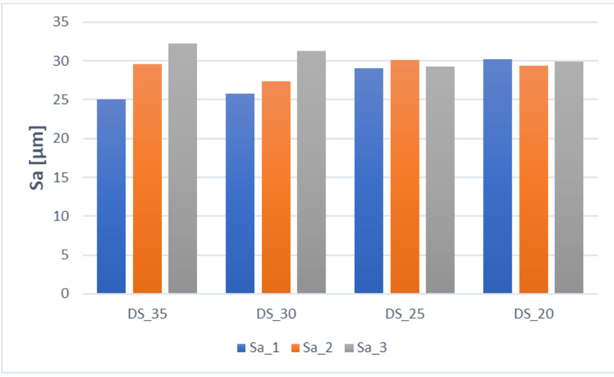

Fig. 18 Successful production of different inclined walls (top) result of the surface roughness measurement of down skin surfaces.

  - Pure Ta samples production for mechanical static test: INFN - Padua Division

    Once the parameters had been finely tuned to yield samples with high density, specimens were manufactured for the mechanical properties' characterization. These samples featured a cylindrical section to facilitate testing under "machined" conditions, implying they underwent lathe processing. They were tested in two distinct orientations:

    - Horizontal: where the specimen's axis aligns parallel to the building platform.
    - Vertical: where the specimen's axis is perpendicular to the building platform.

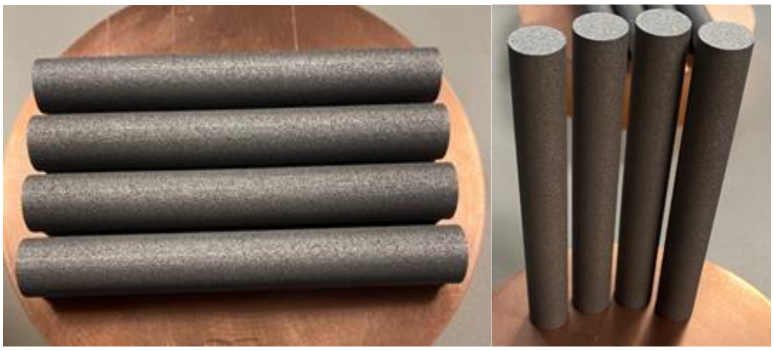

Fig. 19 Specimens for mechanical static test with two different geometries (rectangular and cylindrical) and orientation (horizontal and vertical).

- Pure Ta components production for tests: INFN - Padua Division

  The components of the FEBIAD type ion source, including the cathode, anode, and extraction, were additively manufactured utilizing the EOS M100 available at the DIAM lab. These components were produced using the fine-tuned process parameters. Figure 24 illustrates these components.

- Pure Ta characterization: INFN-LNL

  The samples fabricated by the Padua Section of the INFN underwent testing to measure their mechanical properties, facilitating a comparison between the properties of AM-produced samples and those produced with Ta via conventional techniques. As depicted in Figure 20 and summarized in Table 3, the σ-ε curves illustrate that AM-produced samples exhibit higher strength at the expense of reduced elongation at break when compared to conventionally produced counterparts. It's noteworthy that these properties pertain to mechanically processed samples without any heat treatment, which could potentially refine these properties to achieve the desired results.

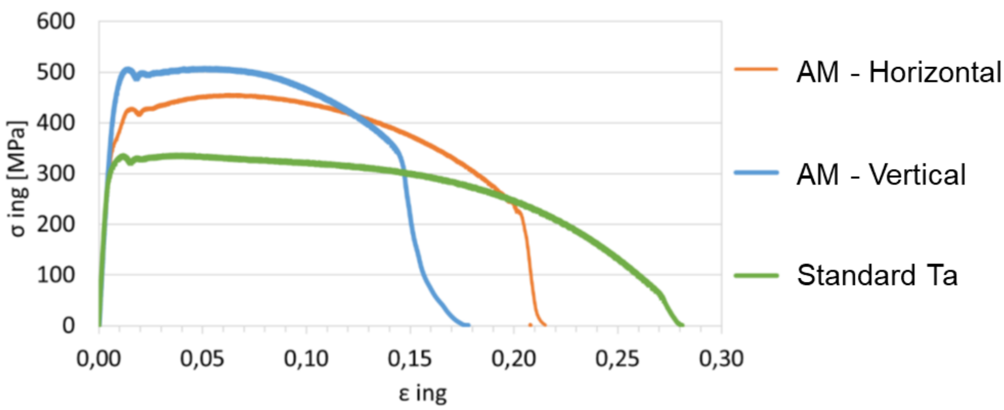

Fig. 20 Comparison of the σ-ε curves obtained from mechanical tests on AM Vertical, AM Horizontal, and STD cylindrical specimens.

Table 3. Comparison of mechanical properties obtained from mechanical tests on AM Vertical, AM Horizontal, and STD cylindrical specimens.

Sample	***Standard Ta***	***AM - Vertical***	***AM - Horizontal***
UTS [MPa]	337.60 ± 2.31	512.26 ± 4.37	459.42 ± 1.25
Modulo di Young: E [MPa]	180244 ± 2549	193650 ± 3222	181568 ± 497
A (%)	27.54± 0.64	17.03 ± 1.08	23.81 ± 1.25

- Innovative ion source component development: INFN-LNL

  The development of innovative ion source components foresaw several steps: the design conceptualization, the evaluation of the proposed design through a set of numerical simulations, the production and test of a prototype. A Multiphysics simulation approach was adopted for the analysis of the new designs proposed for the FEBIAD ion source. Such strategy foresaw the development of a thermal-electric-structural model of the ion source in the ANSYS® Finite Element environment. High temperature tests were performed for the validation of the proposed FEM model.

  The following figure reports the different stages of the innovative ion source components development process:

1. Firstly, an AM Ta prototype reproducing the standard cathode geometry was developed, with minor design changes, oriented to guarantee the suitability of the production with the LPBF process. Such prototype was employed to verify the suitability of the LPBF process to produce structural components of the ion source, since the cathode is normally subjected to intense thermal stresses. This cathode was extensively and successfully tested, confirming the possibility of producing ion source critical components by LPBF. A detailed description of the performed experimental activity is reported in the following paragraphs.
2. Exploiting the design flexibility provided by the LPBF technique, a new version of the FEBIAD cathode was proposed. Such design was developed thanks to the FEM model, employed for evaluating the temperature uniformity of the component we fed with intense Dc currents.
3. The proposed cathode was integrated into a fully AM FEBIAD ion source, with a radical revision of the assembly procedure. With the proposed mounting route, higher repeatability of the ion source is expected, as components were provided with self-aligning features.

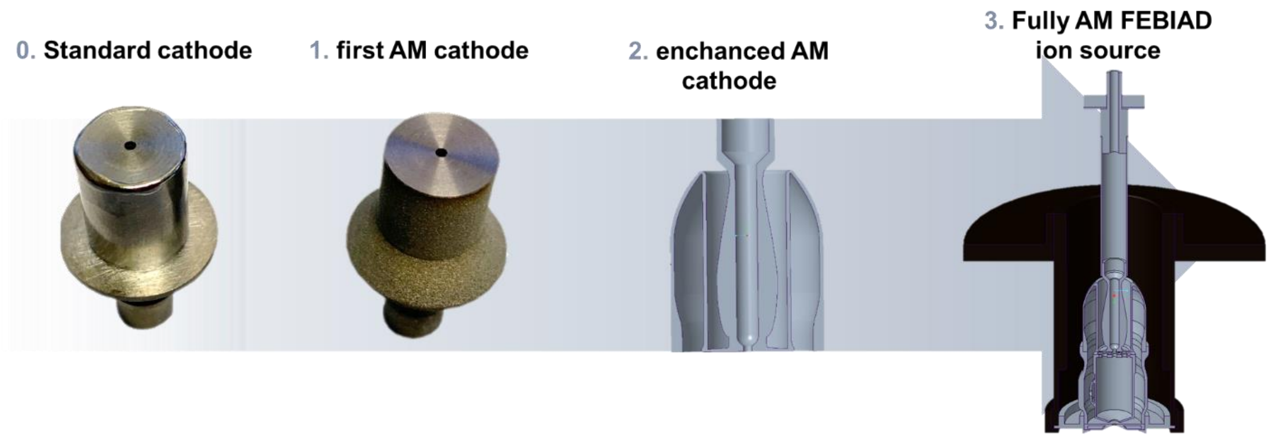

Fig. 21 Development stages for the innovative components for the FEBIAD ion source.

- High temperature test of ion source components: INFN-LNL

  A tantalum cathode produced by Laser Powder Bed Fusion (LPBF) was successfully tested and characterized. Characterization tests foresaw the high temperature testing at different heating current levels and the maintaining at 2200°C for more than 120 hours.

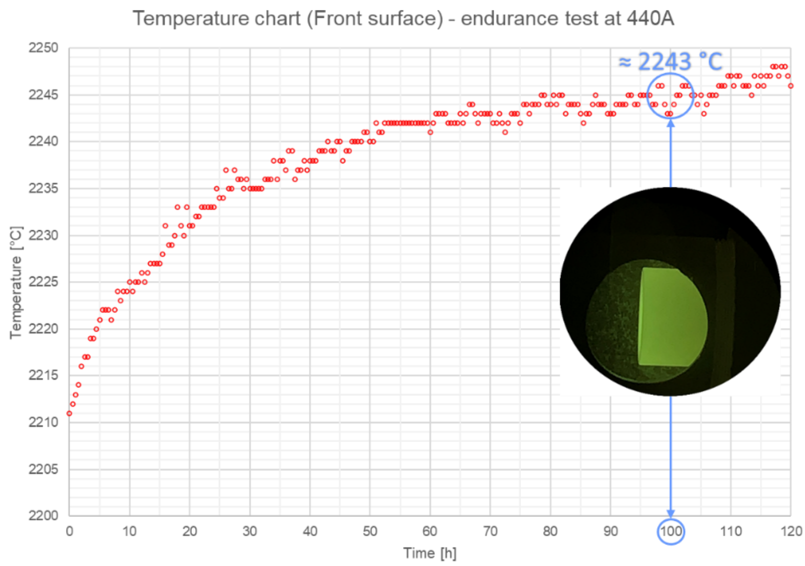

Fig. 22 Example of the LPBF cathode endurance test. It is possible to appraise that the measured temperature stabilizes after a transient initial phase of conditioning.

After the testing campaign the residual deformation of the cathode was observed with a Coordinate Measurement Machine (CMM) highlighting the limited deviation of the cathode geometry from the initial configuration. The tests were supported by a series of FEM simulations reproducing the adopted test benches.

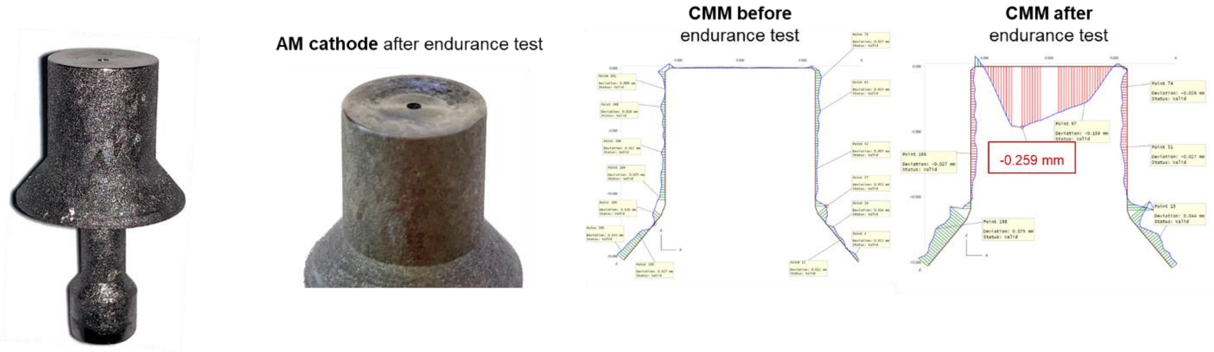

Fig. 23 CMM measurement of the cathode profile before and after endurance test. A limited deformation was observed.

- TEST off-line: CERN (Isolde Facility, Off-line System) – INFN-LNL

  A first version of an ion source including several additively manufactured tantalum and molybdenum components was assembled and tested at the offline test bench of the ISOLDE facility at CERN (CH). Such ion source included LPBF cathode (tantalum), a LPBF anode (tantalum or molybdenum) and a LPBF extraction that were produced with minor geometrical modifications respect to the standard parts produced by subtractive traditional techniques.

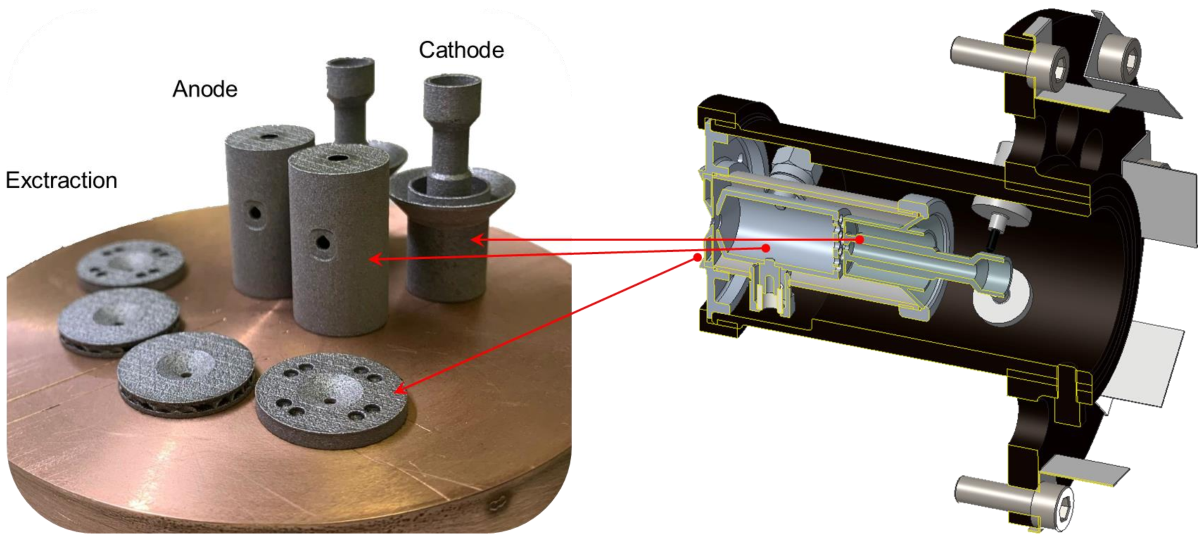

Fig. 24 LPBF components employed for the FEBIAD ion source tested at the ISOLDE offline facility.

Several tests were conducted and a procedure for the fully characterization of an ion source was defined for the first time. Such experimental route foresaw the high temperature calibration, the measurement of the anode drain current, the evaluation of the ionization efficiency for noble gasses such as Ne, Ar, Kr and Xe and the assessment of the extracted beam emittance. Respect to a standard ion source, the tested prototype exhibited higher anode drain currents under equal working conditions, furthermore similar ionization efficiency and emittance were achieved.

Additionally, once the optimal operative conditions were identified, the tested prototype was continuously run for more than 15 days. Such successful experimental campaign paves the way for the further development of optimised ion source components with free-form geometries.

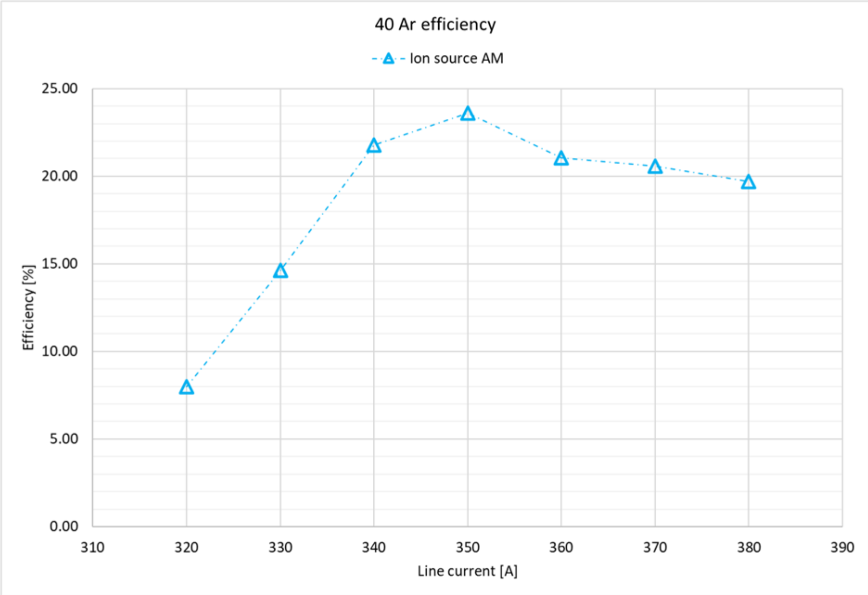

Fig. 25 Ionization efficiency for Ar as a function of the ion source heating current.

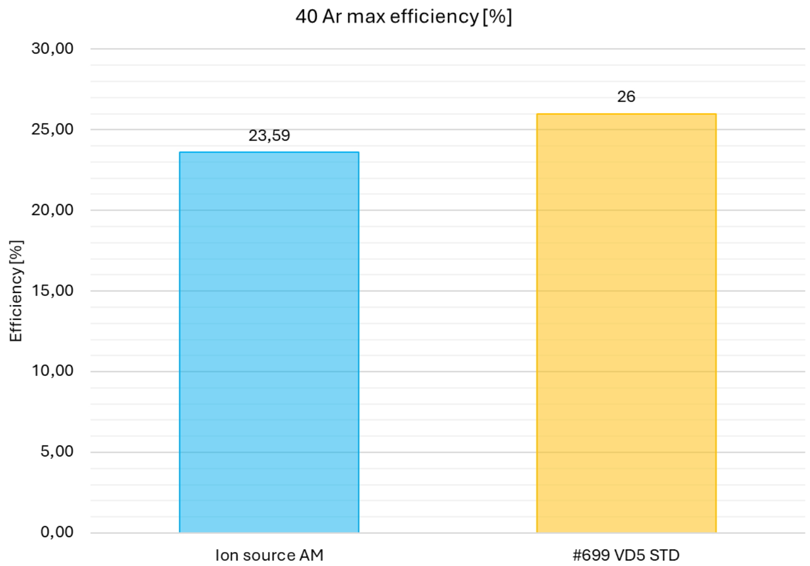

Fig. 26 Comparison between the Ar ionization efficiency of the tested AM ion source and a standard referential ion source tested at the same setup.

PARTNERS

- **TRIUMF:** proposed a novel geometry for the anode grid, namely the surface facing the cathode. Such design was produced at INFN-PD and is ready to be characterized in detail with a dedicated experimental campaign. As illustrated in Figure 27, small features are present in the optimal solution, but were removed for AM production.

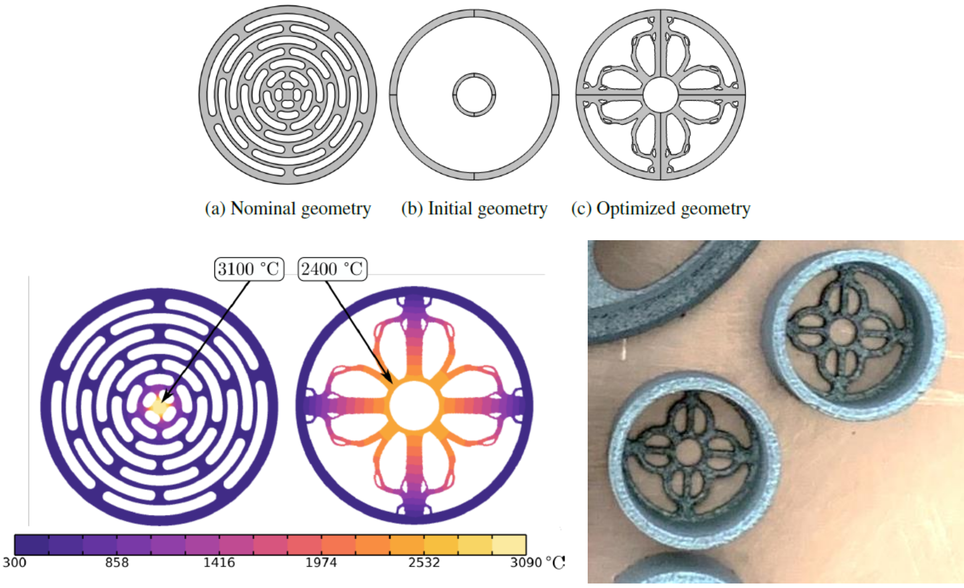

Fig. 27 Geometry comparison for the generative design of the grid (top). Temperature contour plot comparison between nominal and improved grid design (bottom left). LPBF Production of the improved grid design. Small features are present in the optimal solution but were removed for AM production.

Additionally, in the perspective of further innovation on the ion source development, a fist set of simulations with the COMSOL software was performed, evaluating the possibility of producing cathodes and anodes with a non-planar interface. Such kind of geometries are not feasible with traditional machining and welding process but can be easily produced with LPBF. Conical shapes were proposed as first iteration of non-planar interface.

Fig. 28 Example of Results of the simulations with the COMSOL software.

- **EOS Electro Optical Systems Finland Oy – EOS GmbH:** The Turku division of EOS has extended support for the advancement of Ta-based and W-based refractory metals through an ongoing 6-month internship conducted by Silvia Candela, a PhD student at INFN-PD, at the agency's Finnish headquarters. The undertaken work enabled the testing of powder blends featuring various alloy element ratios and the production of samples with two primary aims:
    1. Minimize cracks observed in additively manufactured pure W.
    2. Generate defect-free samples with high density.

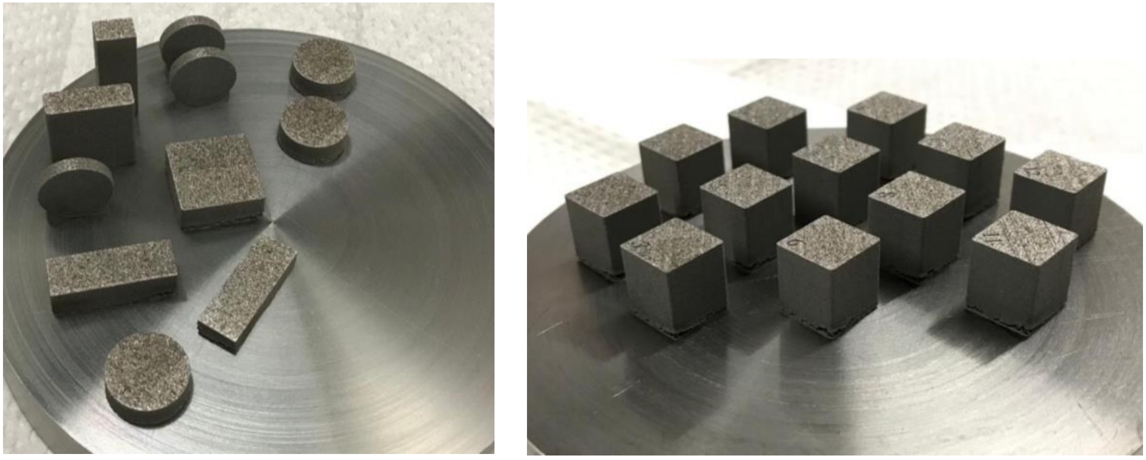

Fig. 28 W-based alloys samples production performed at EOS Turku, Finland.

- **TANIOBIS GmbH:** Offering pure Ta at a heavily discounted rate.

- **SAES group:** Participation in project meetings aimed at initiating market analysis and exploring the potential for product commercialization. The outcomes of this effort will be accessible during the second year of the project.

- **GE Healthcare:** Participation in Work Package meetings focused on the advancement of W alloys, contributing ideas for their development based on gained experience in the field. Additionally, involvement in project meetings such as Kick-Off Meetings (KOM) and annual meetings.

2.8 Demonstration of additive manufacturing for large and complex shaped vacuum chambers by Plasma Metal Deposition (PMD®)

The following activities were performed in chronological order:

- **Vacuum chamber design and tool path generation [RHP/SBI]:**
  The vacuum chamber was designed as a spherical-shaped vessel, with an internal diameter of 450 mm. Room for up to six flanges were included (two DN250CF and four DN125CF). Three stages were planed: “as printed”, “sub-scale” (upper DN250CF machined) and “full-scale” (all flanges machined), see Figure 29. Ti-6Al-4V was the selected material, despite its limited usage in vacuum technologies due to costs; however, its competitiveness emerges when processed using additive manufacturing techniques. RHP was the leader of this task, responsible for proposing designs and creating 3D-models; SBI supported the task with consulting, proposing of modifications to improve the processability in their equipment (i.e. dimensional adjustments, geometrical considerations, etc.).

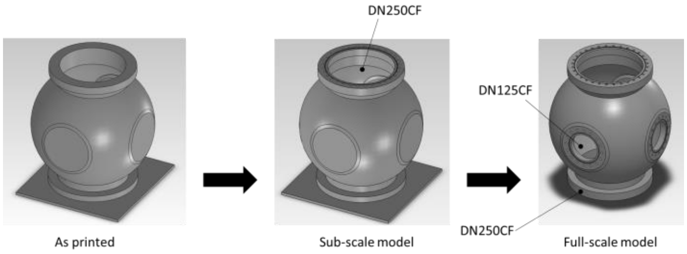

Fig. 29 Implemented vacuum chamber design.

- **Manufacturing of vacuum chamber [RHP/SBI]:** The vacuum chamber was 3D-printed in a M3DP machine (SBI, Austria) by RHP. The process used was the Plasma Metal Deposition (PMD®), which is a directed-energy deposition (DED) additive manufacturing technique using plasma as the energy source. In this case, the precursor material was a Ti-6Al-4V wire. After the 3D-printing progress was concluded, the upper flange (DN250CF) was machined. The progress of the manufacturing activities is shown in Figure 30. RHP was the leader of this task, responsible for manufacturing the chamber and the machining; SBI provided technical assistance with troubleshooting tool-path issues that arose during the 3D-printing stage.

Fig. 30 Progress of vacuum chamber manufacturing.

- **Evaluation of vacuum chamber [RHP]:** The evaluation consisted of vacuum tests employing both mechanical and turbomolecular pumps arranged in series, capable of achieving pressure levels as low as 10^{-6} mbar. With this set-up, an internal pressure of 1.64 x 10^{-6} mbar was achieved after 108 h of pumping (2.5 x 10^{-6} mbar after 24 h). After shutting off the pumps, the pressure was monitored for around 5 hours; a leakage rate of 2.9 x 10^{-6} Pa.m³/s was derived. RHP was the sole responsible for this task.

- **Technology assessment [SBI/RHP]:** Alongside the experimental work, RHP developed upscaled mock-up vacuum chamber concepts, while SBI proposed machine concepts for their manufacturing. The concepts considered geometries, dimensions, and weight of the benchmark vacuum chamber, as well as features such as machine footprint and shielding gas consumption. For this exercise, a virtual vacuum chamber of 3.8 meters in height was benchmarked. Two machine concepts were proposed (**Error! Reference source not found.**1). Both concepts resorted to a combination between robotic arm and tilt & turn (or simply "turn") tables.

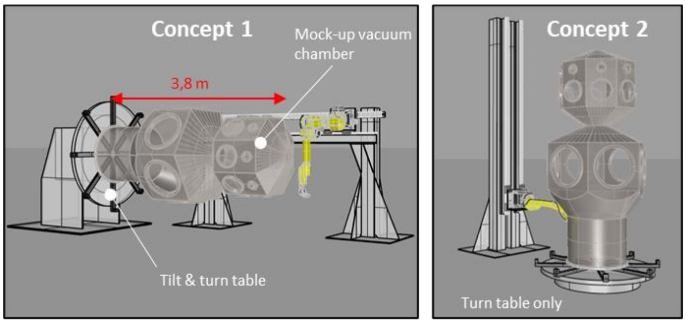

Fig. 31 *Machine concepts proposed for the manufacturing of a mock-up vacuum chamber with 3.8 m in height.*

Concept 1 has a compact design, requiring minimal vertical space, which is advantageous for maintenance and accessibility. However, the tilting action may result in enormous stresses on the table, especially for heavier alloys. In contrast, Concept 2 presents a pragmatic solution, significantly reducing stress on the table, despite its height (around 5 m). Regardless, opting for an enclosed chamber instead of local shielding gas results in a tenfold decrease in Argon consumption.

3 Scientific publications, dissemination, and communication of work

- Poster "REBCO Coatings for High-Gradient RF Applications" at EUCAS 2023 Conference (Bologna, IT)
- Public Talk by S. Calatroni at KIT Karlsruhe (DE) on 16.11.2023
- Publik talk by S. Calatroni at CSIC-ICMAB - University of Barcelona (ES) on 31.01.2024
- T. G. Lucas, et al., Toward a brightness upgrade to the SwissFEL: A high gradient traveling-wave rf photogun. Phys. Rev. Accel. Beams 26, 103401 https://doi.org/10.1103/PhysRevAccelBeams.26.103401
- T.G. Lucas, Workshop on Longitudinal Electron Beam Dynamics for Coherent Sources (LED23), (October 2023) https://indico.elettra.eu/event/29/
- T.G. Lucas, Physics and Applications of High Brightness Beams (July 2023), https://indico.classe.cornell.edu/event/2170/
- T.G. Lucas 67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (August 2023) https://indico.jacow.org/event/51/
- D. Dancila and A. S. Singh, "Development of Highly Efficient Megawatt Class Cross Field Vacuum Tube Amplifier for Particle Accelerators Driven by a Solid State Power Amplifier at 750 MHz", I.FAST 2nd Annual review meeting Trieste, April 21, 2023.
- A. S. Singh and D. Dancila, "Report on WP4 / IFF: Development of Highly Efficient Megawatt Class Cross Field Vacuum Tube Amplifier for Particle Accelerators Driven by a Solid State Power Amplifier at 750 MHz", I.FAST Open Steering Committee, Dec 14, 2023.
- L. Garolfi, "Overview of the IFAST Innovation Fund Projects (programme and status)", I.FAST 3rd Annual review meeting Paris, April 17, 2024.

- C. Pira.et al, Progress in European thin film activities, In Proc. of SRF2023, Grand Rapids, USA, 25-30 June 2023, p. 607, paper WECAA01.
- Conference Talk: C. Pira, Progress in European thin film activities, An oral talk at SRF2023, Grand Rapids, USA, 25-30 June 2023.
- Workshop Talk: S, C. Pira, HTS R&D for RF cavities, An oral talk at Industry Workshop on HTS developments and applications (organized by I.FAST), Trieste, 18 April 2023
- Workshop Talk: S. Prucnal et al. Modification of coated films on different substrates by Flash lamp annealing., An oral talk at Bilateral workshop with industry: Science for application, Dresden, Germany, 22.04.2024.
- KOM: April 2024 – Online mode
- Annual meeting: November 2023 – Hybrid mode (in person and online) @ Formnext – Frankfurt, Germany
- Periodic meetings: Individual Work Package members convened monthly – online mode
- The 3D-printed vacuum chamber manufactured within the present project has been (and is planned to be) exposed on RHP booths in conferences and exhibitions around Europe, namely:
    - Metal Additive Manufacturing Conference (MAMC), Vienna, 2023
    - Formnext, Frankfurt, 2023
    - V2023 – Vacuum & Plasma Conference, Dresden, 2023
    - Vacuum Technologies for Tomorrow (V2T), Grenoble, 2024 (upcoming, May)
    - Plasma and Surface Engineering Conference & Exhibition, Erfurt, 2024 (upcoming, September)
    - results from this project enabled the application of a project within the ESA Φ-lab program to which the technical readiness level of the technique can be driven forwards; nowadays, the TRL can be classified in the 5-6 range.

4 Future plans / Conclusion / relation to other IFAST work

The third phase of the IIF management and projects progress follow-up will affect the second instalment of up to 80% of the total single project budget to be transferred upon submission and review of a technical report due in M36 (April 2024). The report must prove clear and tangible progress of the ongoing activities and describe significant achievements toward the final milestone foreseen in April 2025. All the information collected from each report has been carefully transferred to this document.

A meeting (remote) with the representative of SourceLab, F. Sylla, was held in March 2024. The company is a spin-off from the Laboratoire d’Optique Appliquée (LOA) based in Paris. SourceLab is interested in enhancing its technology and application, especially in the Very High Energy Electron (VHEE) radio-therapy domain. The Task Leader is committed to facilitating the collaboration between SourceLab and the CERN Linear Electron Accelerator for Research (CLEAR) facility to pave beam-time availability and experimental activities on VHEE at CERN.

Fruitful collaboration and synergy are established with the WP3: Industry Engagement. The first project's business case survey was performed in March 2024 with Dr. D. Safi as the Knowledge Transfer and Business opportunities in accelerator R&D representative. The plan is to arrange other business case surveys with the most interested and TRL-advanced projects in P3. Eventually, support for intellectual property (IP) protection strategy and patent process submission may be possible in collaboration with the Knowledge Transfer (KT) service at CERN.

5 References

[1] Albert et al., (2021) 2020 roadmap on plasma accelerators, *New Journal of Physics 23*, 031101

[2] Ouillé et al., (2020) Relativistic-intensity near-single-cycle light waveforms at kHz repetition rate, *Light: Science & Applications 9*, 47

[3] Viotti et al., (2022) Multi-pass cells for post-compression of ultrashort laser pulses, *Optica* 9, 197-216

[4] Andreassi et al., (2016) Radiobiological Effectiveness of Ultrashort Laser-Driven Electron Bunches: Micronucleus Frequency, Telomere Shortening and Cell Viability, *Radiation Research* 186, 245-253 (2016)