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# AIDAinnova

Advancement and Innovation for Detectors at Accelerators

Horizon 2020 Research Infrastructures project AIDAINNOVA

# DELIVERABLE REPORT

# INTEGRATE THE DATA ACQUISITION AND CONTROL SYSTEM AT RBI-AF

## DELIVERABLE: D4.1

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**Abstract:**

This document is related to implementation of Task 4.2 ‘Micro-beam upgrade at RBI Accelerator Facility’. The aim is to upgrade the two existing ion micro-beam stations by providing a precise motorized positioning system with the beam current control and Device Under Test (DUT) position monitor, as well as to demonstrate the sample cooling option for the ‘old’ micro-beam station. These upgrades require the necessity for remote control of the various parameters, such as the sample illumination and positioning in front of the ion beam, the ion beam focusing and current control, leading to the development of an integrated control system, using the home made SPECTOR DAQ and Experimental Physics and Industrial Control System (EPICS) which enables not only the fine setting of various options at the end-station but in addition, also the parallel control of accelerator parameters and logging.

For more information on AIDAinnova, its partners and contributors please see http://aidainnova.web.cern.ch/

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## Delivery Slip

| | **Name** | **Partner** | **Date** |
|---|---|---|---|
| **Authored by** | I. Božičević Mihalić<br>D. D. Cosic<br>S. Fazinic<br>M. Jakšić<br>G. Provatas<br>Z. Siketić<br>M. Vićentijević | RBI | 16/07/2024 |
| **Edited by** | Sabrina El yacoubi | | 22/07/2024 |
| **Reviewed by** | F. Ravotti [WP coordinator]<br>Giovanni Calderini [Deputy Scientific coordinator] | CERN<br>CNRS<br>[Short name] | 29/07/2024 |
| **Approved by** | Giovanni Calderini [Deputy Scientific coordinator]<br>Steering Committee | | 31/07/2024 |

# TABLE OF CONTENTS

## Executive summary

*The main goal of Task 4.2 is the upgrade of the RBI accelerator facility for detector characterization, including studying of detector charge collection properties and radiation hardness studies of detector materials at micro-scales. To achieve this goal it has been planned to upgrade two ion micro-beam end-stations with installation and testing of the precise motorized positioning system with the beam current control and Device Under Test (DUT) position monitor. This has been achieved through the upgrade and development of an integrated data acquisition and control system, using the home-made SPECTOR DAQ and widely used Experimental Physics and Industrial Control System (EPICS) platforms.*

# 1. INTRODUCTION

Ruđer Bošković Institute runs the Tandem accelerator facility (RBI-AF) through the Division of Experimental Physics and its Laboratory for Ion Beam Interactions. The facility is used for experiments in nuclear physics and applications [1] in materials' analysis and materials' modification studies. RBI-AF consists of two electrostatic accelerators with four ion sources and nine end stations (*Fig. 1*). Various ions can be accelerated using one of the four available ion sources (S1 to S4).

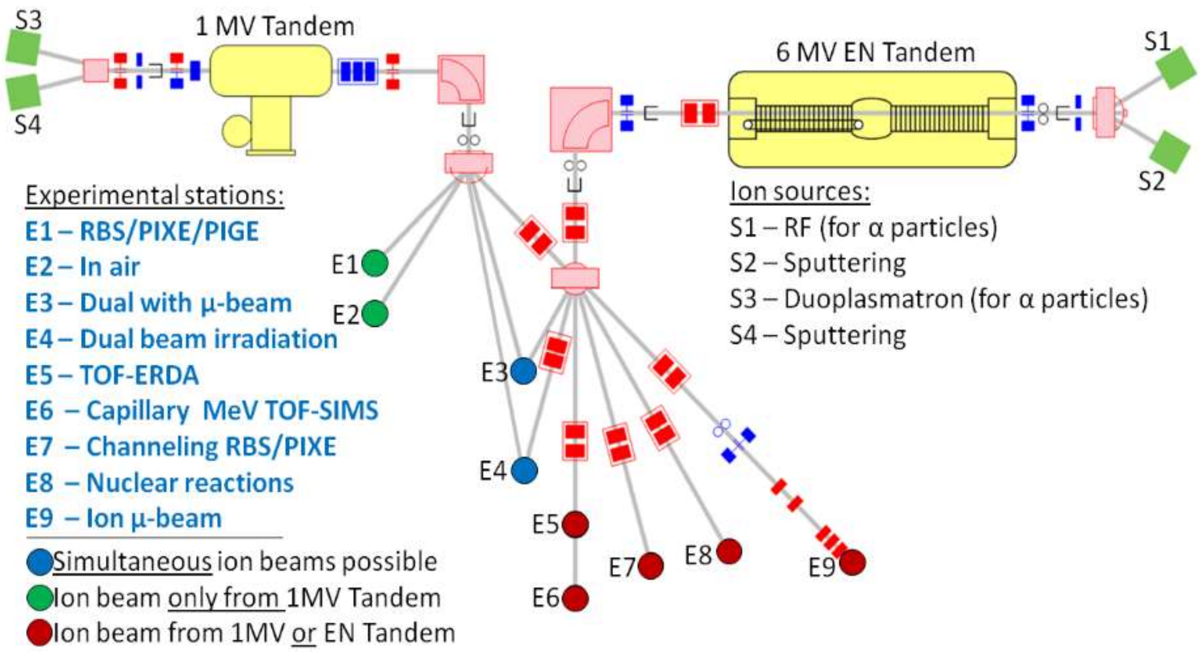



*Fig. 1. RBI Tandem Accelerator Facility (RBI-AF) with its two electrostatic accelerators and 9 end stations.*

Almost all end-stations, except E1 and E2, are reachable from both accelerators. There are two positions where ion beams from both accelerators can be directed into the same intercepting point. The first one is reserved for the DiFU (Dual ion beam for Fusion) scattering chamber (E4), used primarily for dual beam irradiation and which is described elsewhere [2]. The second dual beam scattering chamber (E3) is primarily designed to enable performance of different irradiation techniques and a variety of ion beam characterization techniques, using focused ion beams. Therefore, this end station, named DuMi (Dual Microprobe), is equipped with focusing and scanning systems for both of the ion beams. The other end station with focused ion beams is the 'old ion μ-beam' (E9).

## 2. DETECTOR CHARACTERIZATION AT RBI-AF

The RBI-AF is regularly used by many international research groups for detector characterisation, mainly by exploiting the IBIC (Ion Beam Induced Charge) technique [3] and irradiations with MeV ions for radiation hardness studies [4].

In vacuum and in-air IBIC imaging of detector charge collection properties using protons of up to 10 MeV with 1 µm resolution and heavier ions on demand, and/or time resolved IBIC (TRIBIC) can be performed at the RBI-AF.

Figure 2 shows the sketch of the IBIC experimental setup with focused ion beams. Ion beams focused to micrometer dimensions are scanned over a sample, i.e. the Detector Under Test (DUT). The detector is powered and its signal is recorded as a function of the ion beam position on the detector. In such a way IBIC charge collection efficiency maps are created. If the detector electrodes are positioned perpendicular to the ion beam then we have frontal IBIC configuration. It is also possible to scan the beam between the electrodes and in that case we talk about lateral IBIC experiment.

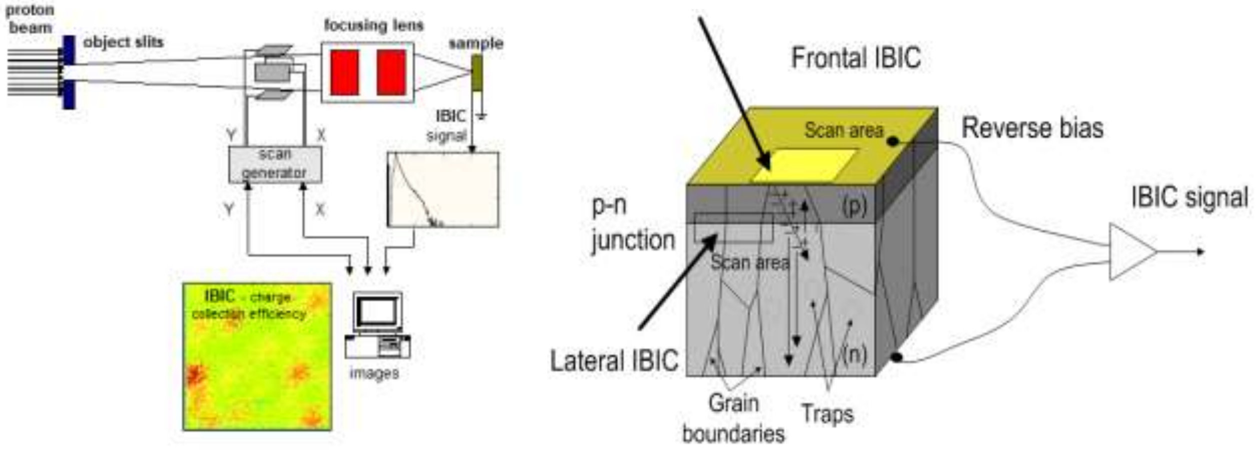



*Fig. 2. Left: Experimental setup for IBIC experiments. Right: Explanation of frontal vs lateral IBIC experiments.*

Such measurements can be performed at two ion micro-beam end-stations: dual µ-beam station DuMi (E3) and old µ-beam station E9 (Figure 3). The left side of Figure 3 shows old µ-beam station [5], equipped with quadrupole triplet magnetic lens that focuses the ion beam to µm range. Samples can be in vacuum or in-air. Figure 3 (right) shows "New" DuMi µ-beam station that enables simultaneous irradiations from both accelerators at microscales. One beam line is equipped with the locally designed and produced quadrupole triplet magnetic lens. The other beam-line is equipped with electrostatic focussing and controlled ion beam scanning over a sample.

Radiation hardness studies typically, involve real-time controlled damaging of small detector areas using protons or heavier ions. This process often includes simultaneous or subsequent ion beam analysis. For these studies potential users have access to two ion microprobe end-stations and additional end stations depending on the actual objectives of the proposed work.

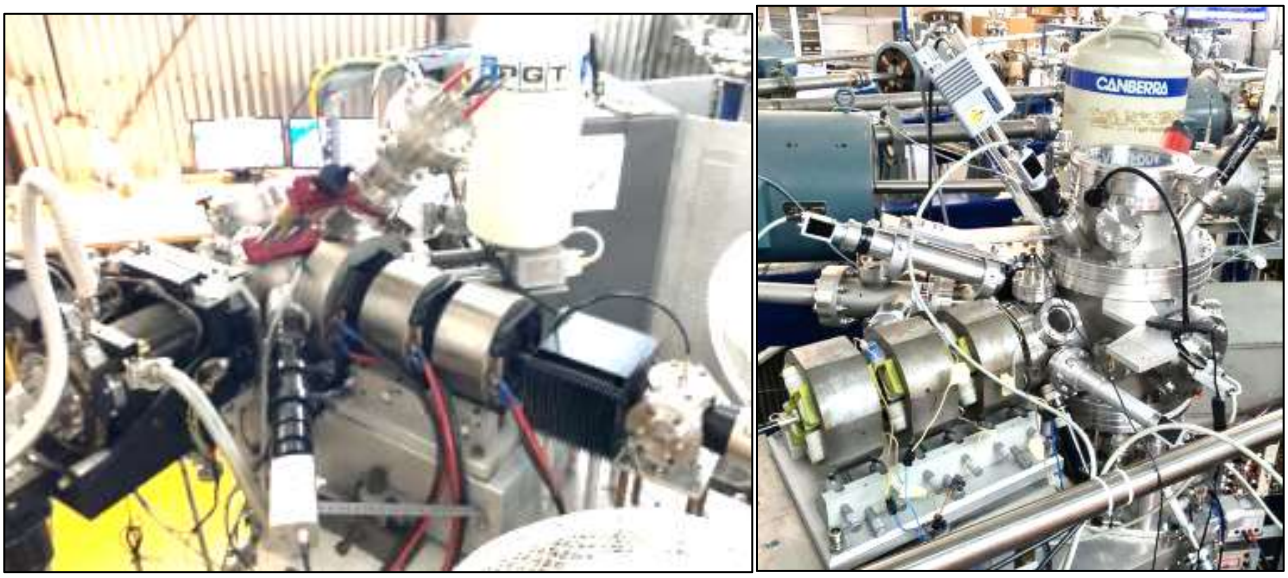


*Fig. 3. Left: 'Old' ion μ-beam station. Right: 'New' dual-μ-beam station (DuMi).*

# 3. TASK 4.2 MICRO-BEAM UPGRADE AT THE RBI-AF

## 3.1. OBJECTIVES OF T4.2

The E9 ion μ-beam station (Figure 3, left) has been in use for about three decades, while the DuMi E3 end-station has been under development during the last several years. At both ion micro-beam stations testing of samples (DUTs) can be performed in vacuum or in air. At the beginning of the project, sample positioning at both micro-beam stations was manual and lacked sub-micron reproducibility. Additionally, experiments could only be performed at room temperature, with the option to heat samples, but cooling was not possible.

The objectives of this task are to provide a precise motorized positioning system, cooling system, beam current control and DUT position monitor. Sample cooling is considered only for the old micro-beam station. One of the main goals is to improve the existing data acquisition and control system and to adapt it to new hardware (motorized sample stages) in order to optimize the facility operation. Within the task, one milestone (Table 1) and one deliverable (Table 2) have been planned. The milestone has been achieved as planned and the report is available [MS12]. The improved RBI-AF facility will be able to provide the advanced services to the High Energy Physics (HEP) community and beyond (medical physics, hadron therapy, fusion devices, etc.).

*Table 1. Milestone MS12: Upgrade the RBI-AF infrastructure for detector characterization, SEE, micro hardness testing (task 4.2).*

| Milestone number | Milestone name | Related WP | Due date | Means of verification |
|---|---|---|---|---|
| MS12 | Upgrade the RBI-AF infrastructure for detector characterization, SEE, micro hardness testing | 4.2 | M23 | Accelerator runs and comparisons with test samples |

*Table 2. Deliverable D4.1: Integrate the data acquisition and control system with the motorized sample stages (task 4.2).*

| Deliverable number | Deliverable name | Related WP | Due date |
|---|---|---|---|
| D4.1 | Integrate the data acquisition and control system at RBI-AF | 4.2 | M40 |

It has been planned that integrated data acquisition (DAQ) and control system for use with DuMi motorized sample stages, especially important for flexible and reproducible work at the DuMi station will be available at month 40 of the project.

## 3.2. INTEGRATION OF THE DATA ACQUISITION AND CONTROL SYSTEM

The DuMi end-station (Figure 3 on the right and Figure 4) has been developed in order to provide simultaneous as well as fast switch between two focused beams from the two accelerators. Figure 4 on the left shows the position of the DuMi end-station in respect to two beam lines connecting it to 1 MV Tandetron and 6 MV Tandem accelerators. The focusing of the ion beams from the Tandem is performed with electrostatic lens (2), and from Tandetron by magnetic quadrupole triplet (4), while the focused ion beam can be scanned using scanner coils (3). The end-station is also equipped with possibilities of using two working distances, namely at the short focus (70 mm) and the main, long focus (363 mm). The short and long focus positions are marked at the central part of Figure 4. In both positions, samples are precisely controlled with appropriate piezo-stages. Piezo-stage at long focus is seen on the right figure (E). The vacuum chamber is equipped with various detectors (right) for Ion Beam Analysis (IBA) applications, including gamma ray (A), X-ray (B) and particle detectors (C, D, F).

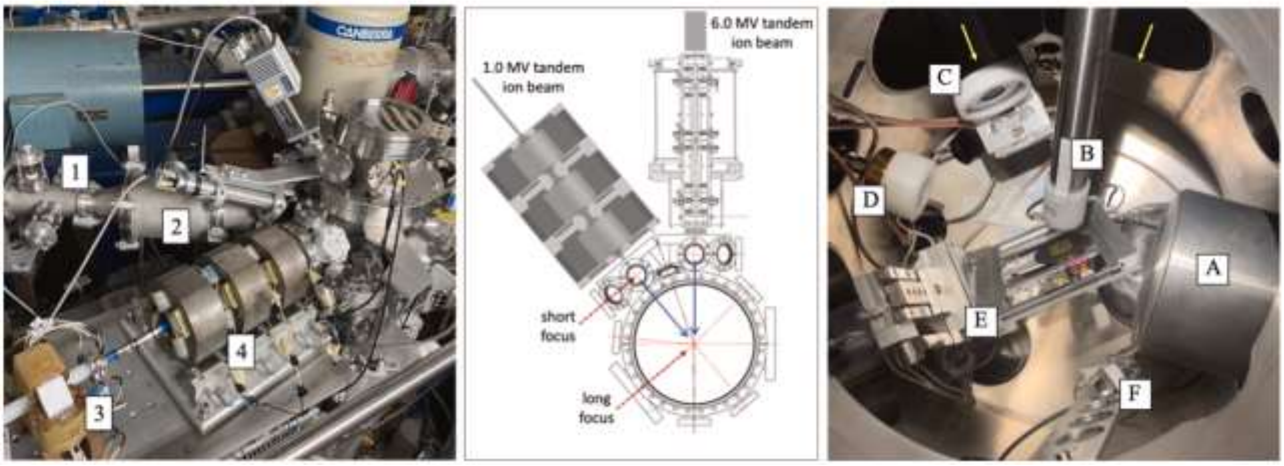



*Figure 4. View of the DuMi end-station (left) with electrostatic lens (2) for beams from the 6.0 MV tandem (center), scanner coils (3) and magnetic quadrupole triplet (4) for ions from the 1.0 MV tandem (center). The chamber is equipped with various detectors (right) for IBA applications and offers possibilities for short or long focus working distances*

*(center), enhancing the beam resolution possibilities. In both distances, samples are precisely controlled with appropriate piezo-stages. Piezo-stage at long focus is seen on the right figure (E).*

As the construction of the system progresses, the necessity for remote control of the various parameters, such as the beam focusing elements, the current control and the sample illumination and positioning, lead to the development of an integrated data acquisition and control system, using SPECTOR DAQ and EPICS which enables not only the fine setting of various options at the end-station but in addition, enables the parallel control of accelerator parameters and logging.

A DAQ system based on the SPECTOR software system has been in constant development since its first version has been installed at the first RBI microprobe back in the nineties [6-8]. Gradually, along with several changes in hardware, more specifically the move to FPGA technology, many other options have been implemented into SPECTOR. The most important, in the contest of this work, is the beam scanning control, the possibility to scan the sample, either in specific area (x,y) or by angular control (θ,φ) for channeling. Additionally, with the recent procurement and installation of motorized sample piezo-stages, the need to incorporate sample positioning in a reproducible manner at the sub-micron scale in SPECTOR become a necessity.

The target positioning at both short and long focus positions at the DuMi end-station is carried out within nm precision using SmarAct motorized piezo stages. In the long focus position the working range is extended to 100 x 100 x 50 mm. The samples can be positioned at 90° and 60° with respect to the beam. For the sample positioning at the short focus position, another SmarAct motorized piezo stage with 10x10x10 mm working range has been procured, installed and tested. The movement and positioning control is done within SPECTOR, using the developed integrated StepMotion code. The latter provides three possibilities in target positioning, namely fixed, step and constant move. Additionally, the user can store different position coordinates. Figure 5 shows the user interface to control the sample position with StepMotion code.

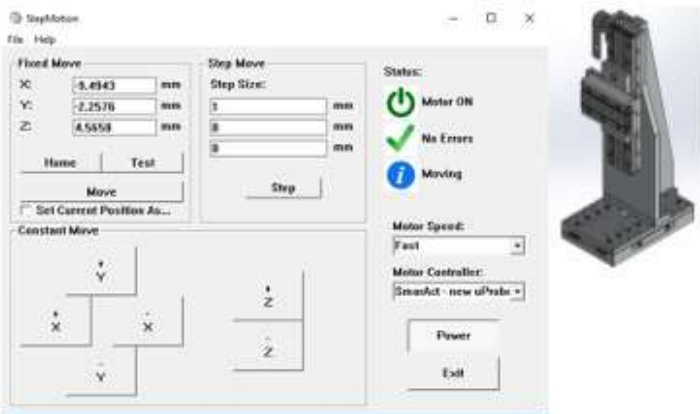



*Figure 5: The two piezo-stages at the DuMi end-station are controlled with the developed StepMotion software incorporated in SPECTOR.*

The precision and reproducibility of this setup has been tested over the last year in numerous experiments involving detectors characterization or IBA studies. A set of tests of the integrated software have been performed, including: tests of different scanning options, tests of collecting multiple spectra, tests of creating multiple 2D spectral arrays, testing off-line analysis of collected experimental data. Some tests have been presented in the Milestone report MS12 [Link].

Additional two examples are shown at Figure 6. The first example on top of the figure shows the setup used in the study of the $^{3}He$ + $^{nat}B$ nuclear reaction cross sections in a range of scattering angles and $^{3}He$ ion beam energies suitable for the so called Nuclear Reaction Analysis (NRA) technique, using a novel high solid angle measurement setup based on a large area segmented particle detector. The precise positioning of a sample was initially tested using various well studied nuclear resonances, such as the one of $^{28}Si(p,p)$ elastic scattering at proton energy of about 1.7 MeV .

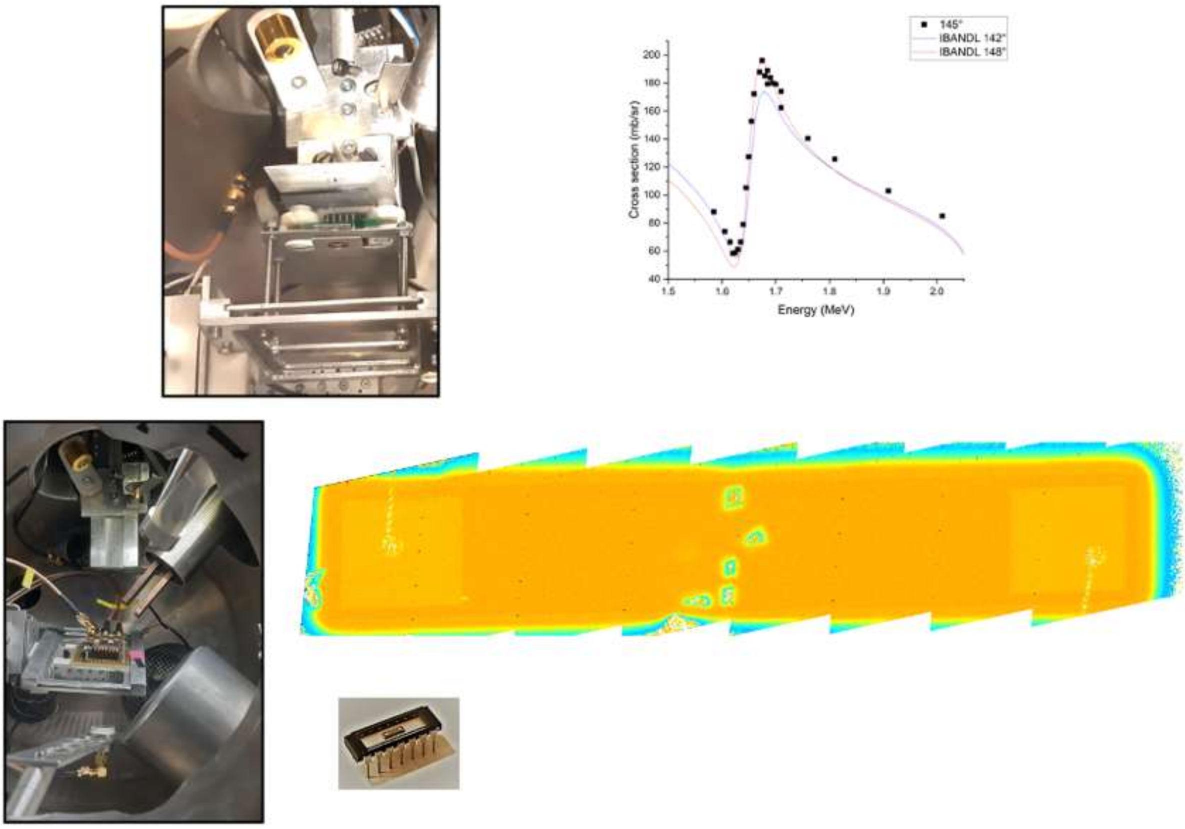



*Figure 6: Top, a high solid-angle setup used for cross section measurements of 3He+natB reactions. Bottom, IBIC study of a 1D position sensitive detector after controlled irradiations.*

The other example refers to the need of producing IBIC images of detectors having active areas larger than the beam scan sizes, typically limited below 1.5x1.5 $mm^2$. The figure 6 (bottom), is related to the IBIC study of a 1D position sensitive detector after controlled ion beam micro-irradiations. In this case the IBIC microscopy of the whole detector active area was mandatory. Therefore without the possibility for precise reproducible positioning of large samples, such studies would not be possible.

That is the reason why a new option was added in SPECTOR, i.e. to enable the scan of the sample in XY plane in front of the fixed ion beam, extending the 2D mapping capabilities up to few $cm^2$. Figure 7 shows the test of the scanning capabilities using 2 MeV proton beam on the standard Cu mesh. The measured two dimensional off-axis Scanning transmission ion microscopy (STIM) map of the Cu mesh demonstrates the capability of new option of scanning the sample in front of the beam to obtain high quality images.

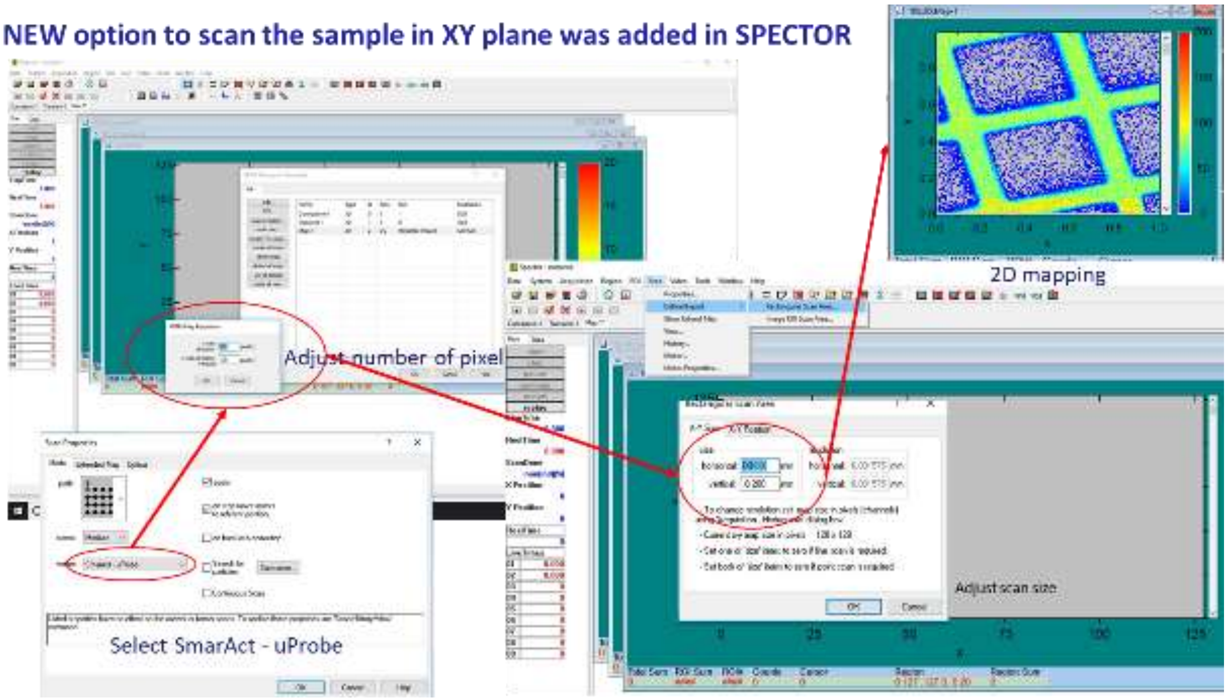



*Figure 7: The new option added to SPECTOR to enable scanning of samples in XY plane with example of 2D off-axis STIM image of a Cu mesh.*

Samples can also be scanned in tilt and azimuth in front of the ion beam to perform ion beam channeling experiments [9]. Angular control (θ,φ) for channeling is incorporated in SPECTOR and adopted to new piezo stages. Figure 8 shows a test of performing ion beam channeling 2D map on single crystal Si wafer to orient the crystal to specific orientation for selective ion beam irradiations on selected crystal orientations. The left figure shows the obtained 2D (azimuth, tilt) map based on the transient ion backscattering detector signals (the spectrum in the central figure). The figure on the right shows the cumulative ion backscattering spectrum obtained for the whole 2D image on the left.

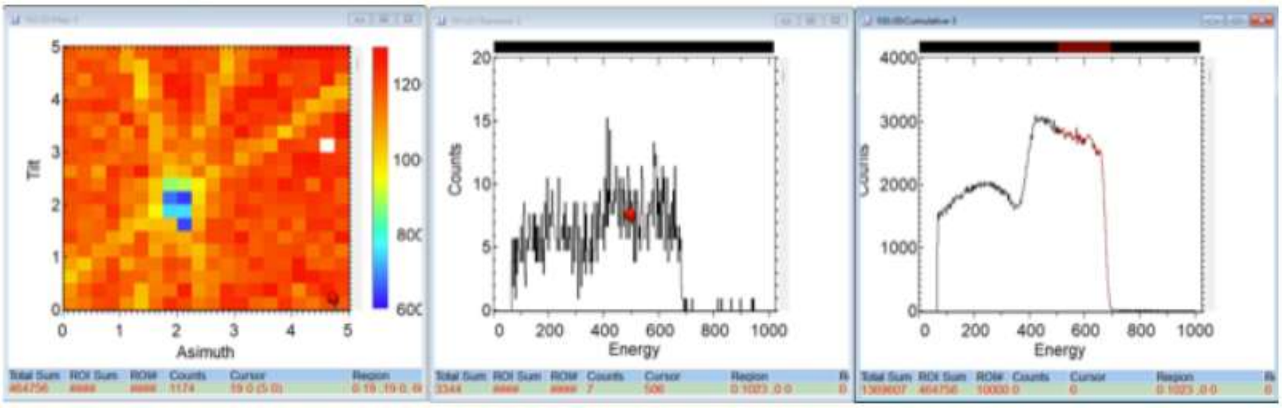



*Figure 8: The new opportunity at the DuMi end-station allows channelling experiments in single crystals for ion beam irradiation in selected crystal orientations.*

The DAQ system can also control various ion beam options like ion beam pulsing, which is important for switching on and off two microbeams in a dependent or independent ways. The beam pulsing parameter is also important for timing measurements. Therefore, SPECTOR software has been adapted to control an ion beam chopper, which is important for indirect ion beam fluence measurements at the DuMi end-station.

The latest developments, important for the DuMi system are focused on a more integrated environment achieved by integrating the DAQ system with the Experimental Physics and Industrial Control System (EPICS) [10] that has been applied recently to control the accelerators operation instead of the old software based on the LabVIEW platform. This allows the microprobe acquisition system to automatically control various aspects of the accelerator system, such as the beam line values and Faraday cups to precisely monitor the beam current in order to achieve accurate and reproducible irradiation doses. Furthermore, the integration of the DAQ system with EPICS allows for important accelerator and experiment setup parameters to be automatically logged and saved as metadata with the acquired spectra.

Aiming for remote controlling of the ion beam focusing lenses, as well as the monitoring and controlling the ion beam current, the power supplies, pico-ammeter as well as the Faraday cups pneumatic valves are all integrated in EPICS. As such, the Faraday cups can be closed/opened within a specific time frame or after a specific beam charge is accumulated, increasing the precision in irradiation experiments.

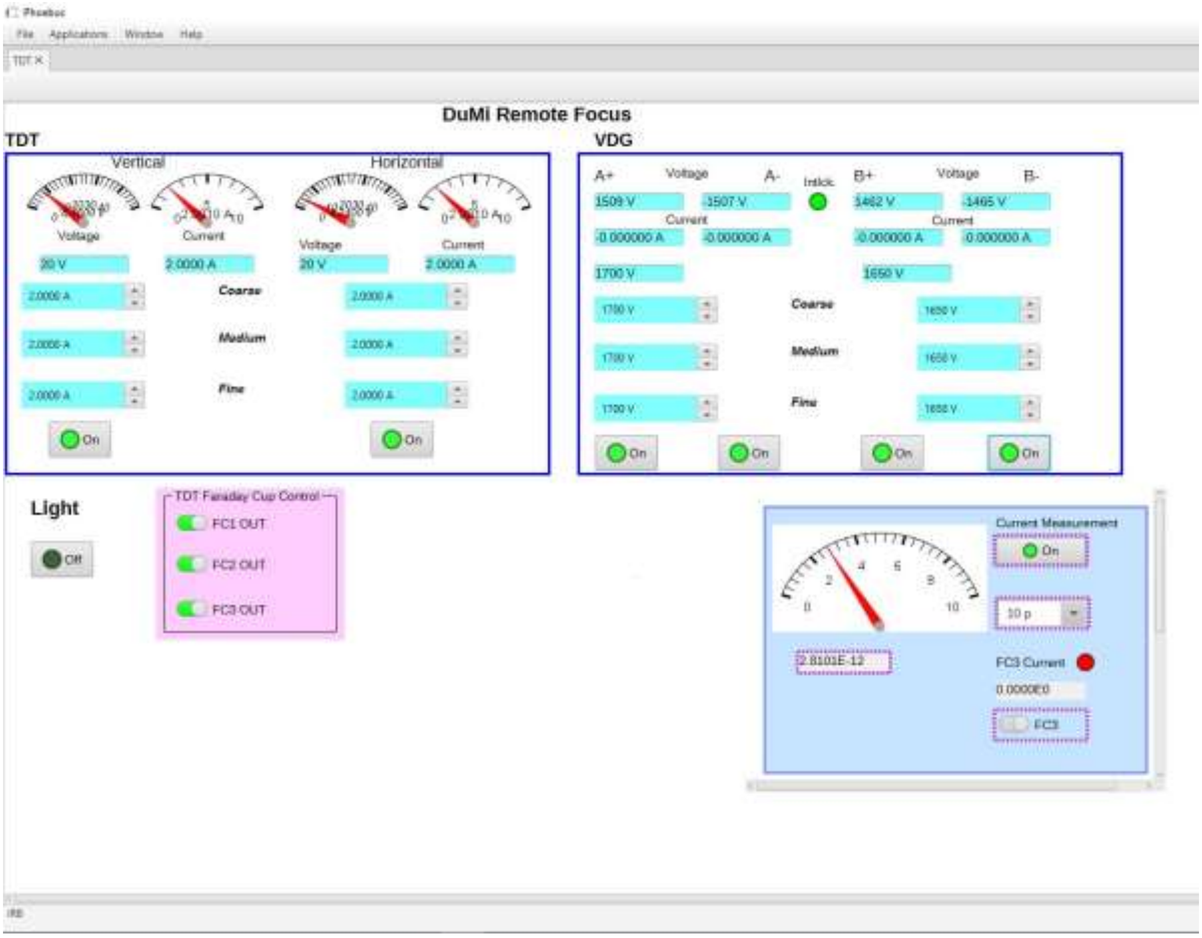



*Figure 9: The ion beam focusing in the DuMi setup is remotely controlled through EPICS. Faraday cups as well as ion beam current reading is also obtained in the same way.*

Figure 9 shows the remote ion beam focussing control unit for the DuMi setup through the EPICS platform. Faraday cups as well as ion beam current reading is also obtained in the same way.

One of the task objectives is to design and install the sample cooling system to allow low temperature IBIC measurements at the ‘old’ ion micro-probe. This required additional upgrade to enable temperature readings within SPECTOR. An example of such low temperature IBIC measurements on a diamond detector set at the temperature of 114 K is shown at Figure 10. In addition, the temperature value is stored in the corresponding list file so to obtain off-line analysis observables variations with respect to temperature.

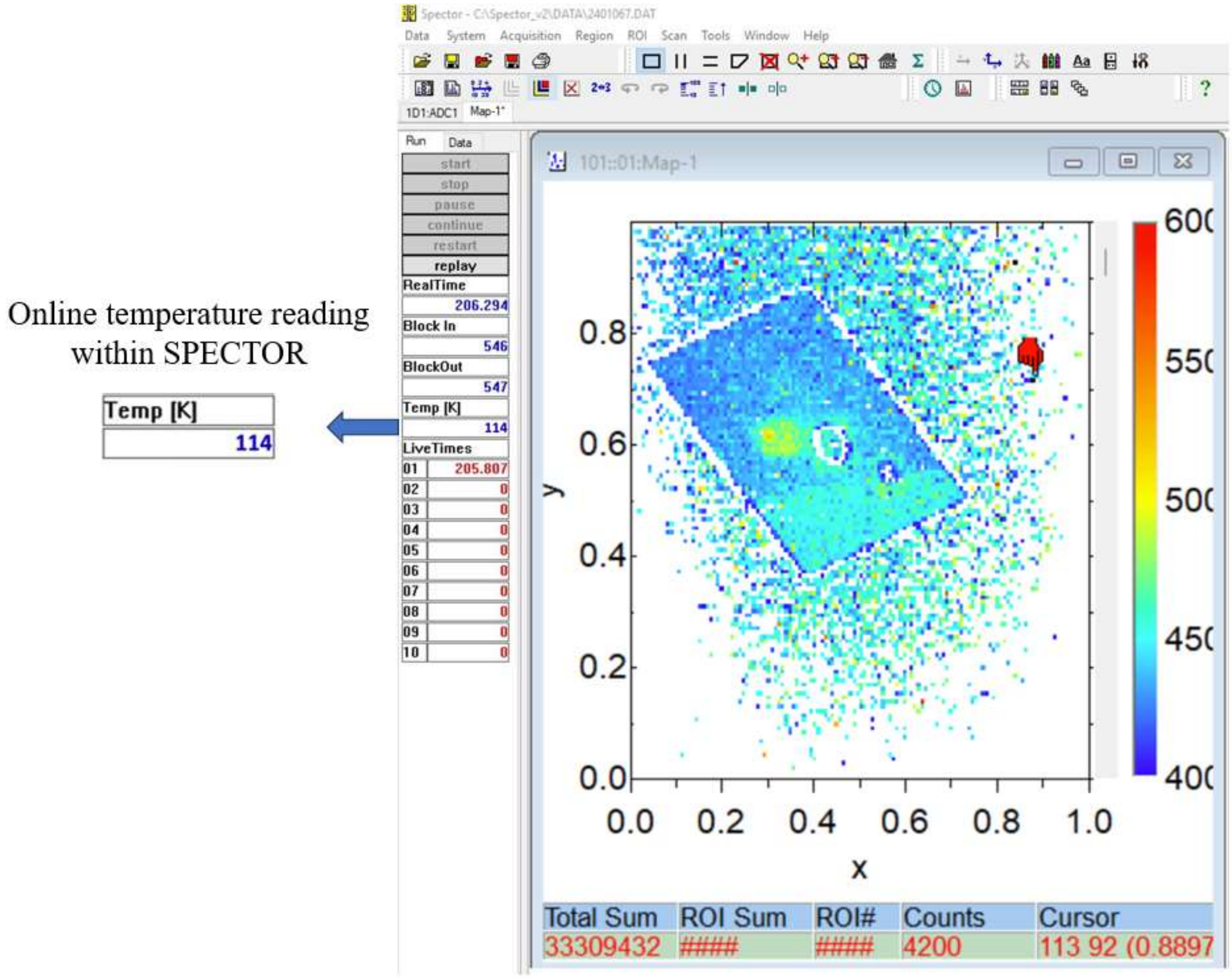
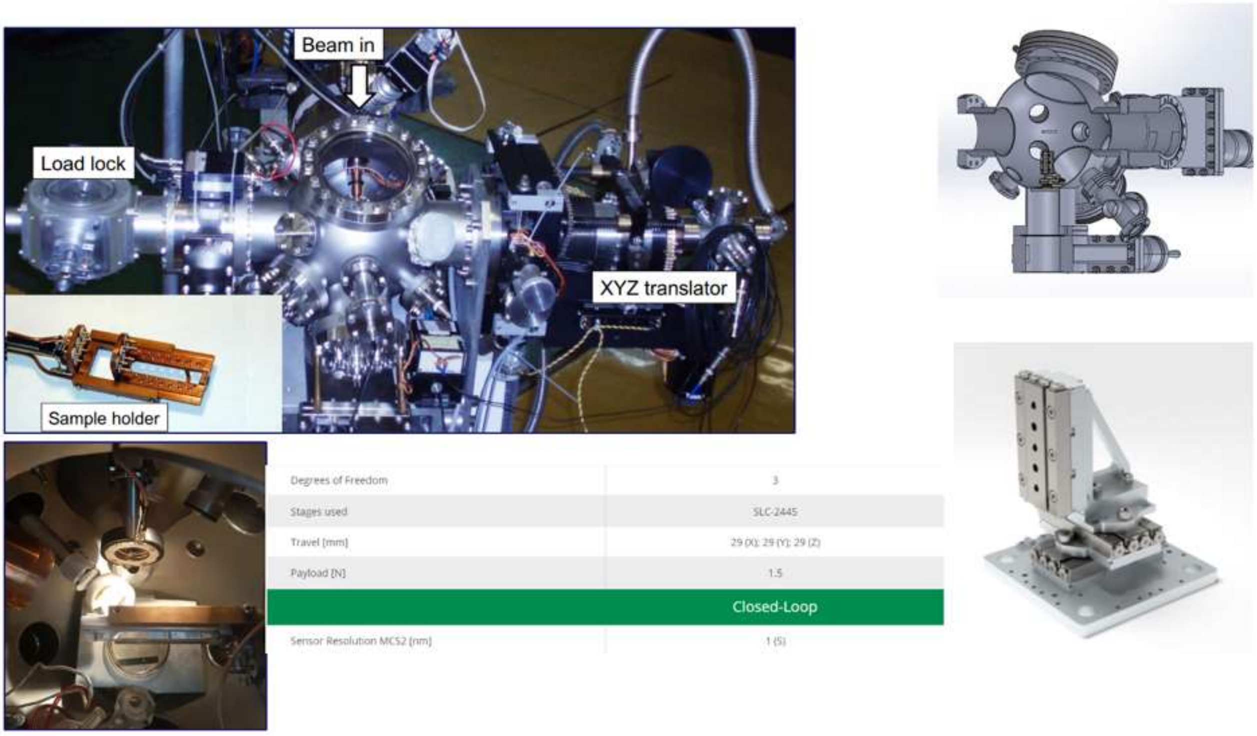



*Figure 10: Online temperature reading within SPECTOR.*

Based on the high performance of the developed data acquisition and control system of the DuMi setup, a compatible configuration has been considered for the RBI old microprobe, where samples are traditionally placed on a copper made sample holder manually controlled with an XYZ translator (Figure 11). A new compatible piezo-stage has been designed and procured from SmarAct. The integrated software developed for DuMi end-station based on the SPECTOR and EPICS can be simply applied to the other micro-probe.




| | |
|---|---|
| Degrees of Freedom | 3 |
| Stages used | SLC-2445 |
| Travel [mm] | 29 (X); 29 (Y); 29 (Z) |
| Payload [N] | 1.5 |
| | Closed-Loop |
| Sensor Resolution MCS2 [nm] | 1 (S) |

*Figure 11: In the RBI microprobe end-station, the samples are manually placed with an XYZ translator. A new SmarAct piezo-stage has been designed and procured.*

## 4. FUTURE PLANS

Initial tests with channelling experiments carried out at DuMi end-station have been successful. A novel holder is planned to be constructed, enabling easy installation of the rotation piezo-stage in the setup. In addition, a new cryostat was recently obtained, which is planned to be installed at the DuMi end-station for carrying out measurements at low temperatures in the main vacuum chamber. Installation and tests will be performed by a PhD student.

The RBI-AF will soon be transferred to a new building currently under construction. This process is expected to begin at the end of December 2024 or the beginning of January 2025. The transfer will include the 1 MV Tandetron and all existing experimental beam-lines and end-stations. This process is expected to take six months, after which the first experiments are planned. Additionally, the existing 6 MV EN Tandem will be replaced by a new 5 MV Tandetron accelerator. The delivery of this new accelerator is anticipated in July-August 2025, followed by approximately three months for installation and commissioning. All developments successfully achieved within this AIDAinnova project will be moved and re-commissioned in the new RBI-AF building complex, ensuring continuity and advancement in our research capabilities.

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## 5. REFERENCES

[1] Bogdanović Radović, I. (2020) Ruđer Bošković Accelerator Facility, *Nuclear Physics News*, 30, p 4.

[2] Tadić, T. et al. (2023) Development of the Dual-Beam Ion Irradiation Facility for Fusion Materials (DiFU), *Materials* 16, pp 1144.

[3] Jakšić, M. et al. (2022) Ion Microbeam Studies of Charge Transport in Semiconductor Radiation Detectors With Three-Dimensional Structures: An Example of LGAD, *Front. Phys.*, 10, pp 877577.

[4] Gloginjić, M. et al. (2021) The quantitative 6H-SiC crystal damage depth profiling, *Journal of Nuclear Materials* 555, pp 153143.

[5] M. Jakšić et al. (2007) New capabilities of the Zagreb ion microbeam system, *Nucl. Instr. and Meth. B* 260, pp 114-117.

[6] Bogovac, M. et al. (1994) Data acquisition and scan control system for nuclear microprobe and other multiparameter experiments, *Nucl. Instr. Meth. B 89*, pp 219–222.

[7] Bogovac, M. et al. (2009) Digital pulse processor for ion beam microprobe imaging, *Nucl. Instr. Meth. B 267*, pp 2073–2076.

[8] Cosic, D. et al., (2019) Data acquisition and control system for an evolving nuclear microprobe, *Nucl. Instr. Meth. B 451*, pp 122–126.

[9] Gloginjić, M. et al. (2024) The quantitative damage and impurity depth profiling of the MgO single crystal, *Vacuum 227*, 113420.

[10] EPICS (2024) *The Experimental Physics and Industrial Control System* [online]. Available from: https://epics-controls.org [Accessed 16 July 2024].

[11] Cosic, D. et al. (2022) Charge collection efficiency of scCVD diamond detectors at low temperatures, *Diamond and Related Materials* 127, pp 109184.

# ANNEX: GLOSSARY

| **Acronym** | **Definition** |
|---|---|
| DAQ | Data acquisition system |
| EPICS | Experimental Physics and Industrial Control System |
| IBA | Ion Beam  Analysis |
| IBIC | Ion beam induced current |
| NRA | Nuclear Reaction Analysis |
| PIGE | Particle Induced Gamma-Ray Emission |
| PIXE | Particle Induced X-Ray Emission |
| RF | Radio-frequency (Ion Source) |
| RBS | Rutherford Backscattering Spectroscopy |
| RBI-AF | Ruđer Bošković Institute Accelerator Facility |
| STIM | Scanning Transmission Ion Microscopy |
| TOF-SIMS | Time of Flight Secondary Ion Mass Spectrometry |
| TOF ERDA | Time of flight elastic recoil detection analysis |
| TRIBIC | Time resolved ion beam induced current |