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EURO-LABS

EUROpean Laboratories for Accelerator Based Sciences

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DELIVERABLE REPORT

REPORT ON SERVICE IMPROVEMENTS

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Abstract:

The main goal of EURO-LABS is not only provide access to the facilities, but to improve the offered service. This is a very important issue because large laboratories invest a lot for their own activities, but the offer to the external users is often overlooked. The Task 2.5 deals with service improvements. Service improvement has multiple facets. The lesson of the pandemics caused by COVID-19 is that laboratories should bestow remote access, i.e. the capability to run the experiments from the home institution. Streamlined and remote access are the topics of Task 2.5.1. Connected to this service are streamlined access via a single, web-based, access point, and a project on travelling detectors (Task 2.5.5 - INTRANS). Other aspects of service improvement are directly toward key opportunities in the accelerators, i.e. targets (Task 2.5.2), sources (Task 2.5.4, ERIBS) and biomedical applications (Task 2.5.3, FLASH@EURO-LABS). All milestones in the Task 2.5 have been reached. The last one, MS16 - Organisation of hands-on workshops & training schools – has been completed within the task 2.2.5 (INTRANS) and deliverable upload. No other milestones in this task are due by the end of the project.

For more information on EURO-LABS, its partners and contributors please see https://web.infn.it/EURO-LABS/

The EUROpean Laboratories for Accelerator Based Sciences (EURO-LABS) project has received funding from the Horizon Europe programme dedicated to Research Infrastructure (RI) services advancing frontier knowledge under Grant Agreement no. 101057511. EURO-LABS began in September 2022 and will run for 4 years.

Delivery Slip

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1. INTRODUCTION

The task on service improvements within WP2 included five different activities whose evolution and accomplishments have been described in previous reports. Here we will briefly summarize the latest accomplishments.

2. STREAMLINED PROCEDURES AND REMOTE ACCESS (2.5.1)

The main goals of the remote-access subtask (within the WP2 Service Improvements framework) are to: i) minimise required access to experimental areas and minimise travel time for on-call experts, ii) maximise external participation, and iii) standardise generally-endorsed approaches and procedures, leading to reduced load on expert resources (local and external), early problem recognition and timely intervention, and improved training opportunities of early-career researchers and inter-institutional knowledge transfer.

In the Streamlined Access part of the subtask, the offer of facilities providing beam for nuclear physics research within the WP2 package is presented in a more uniform and detailed way through the website (still under construction) https://www.slcj.uw.edu.pl/en/tna-euro-labs/. Each facility has its own subpage with a menu that provides easy access to specific information, such as: site details, list of available infrastructures and beams, beam time schedule, application submission deadlines and details, meeting dates of Program Advisory Committies, total number of access units in use and still available, access procedures, details about the TNA support and the application process, and a list of publications.

The Remote Access part of the subtask aims to provide improved remote access to EURO-LABS institutions (i.e., any kind of accessibility to experimental operation from outside of experimental areas, for locals experts and external participants). The main goals are to minimise required access to experimental areas and travel time for on-call experts, thus maximising external participation, and standardise generally-endorsed approaches and procedures. This subtask is divided into three main categories: i) the development of a user-friendly database to disseminate information on remote-access tools currently in use at EURO-LABS facilities, ii) the implementation of new/improved remote-access tools at EURO-LABS facilities, and iii) provide training opportunities to the community. The completion of part i) was reported in EURO-LABS project milestone M12 in February 2024. The database is fully operational (available here: https://eurolabs-remote.gsi.de/) and the collection of further information to expand the content is underway. A set of tools to provide remote control of the experimental irradiation setup are being implemented at the PARTREC facility, with the aim of minimising the amount of personnel needed on-site for guest research groups and/or paying customers of the PARTREC cyclotron. To avoid potential security issues, users will not get direct access to the irradiation control system. Rather, they will receive access (via VPN) to an interface PC connected to the (less privileged) internal network. A Python server running in the irradiation control PC parses the user’s input, and translates them into operations for the irradiation control system written in Labview, via the ActiveX interface. The server code will be open sourced in the near future. With the aim of advertising the "Remote Handling" database, a half-day workshop has been organised as a satellite meeting to the "VIIth Topical Workshop on Modern Aspects in Nuclear Physics" conference on Feb. 4th, held in Bormio (Italy).

A web-accessed database containing information and (where applicable) documentation regarding a wide variety of remote-access tools has been developed by the partner institutions (GSI, IFIN-HH, INFN, UMCG and TU Dresden). The content of the database is based upon the results of

a comprehensive survey targeting EURO-LABS research infrastructures that was carried out in early 2023, where a number of key topics of interest to the EURO-LABS community were identified. The results of the survey can be found here:
https://data.192.135.24.99.myip.cloud.infn.it/s/p3WXj00P2cfD1GB under Milestone M12. The database is accessible via https://eurolabs-remote.gsi.de/.

3. TARGETS (2.5.2)

The goal of the service improvement (Task 2.5) in EURO-LABS is to advance the opportunities for users at the state-of-art services of the Research Infrastructures (RIs) involved in the project, making them more attractive and competitive. Among the services offered within this task, subtask 2.5.2 (targets) is dedicated to the development of targets for high intensity beams. This subtask is carried out in collaboration among different institutions, for the benefit of the entire community with the common aim to enhance the variety and availability of possible reactions (projectile-target combinations) for nuclear physics experiments in the participating RIs.

The “targets” subtask aims at gathering the community of nuclear target makers, having specific expertise in the field of target manufacturing and characterization, both for nuclear and applied physics purposes. Different research areas and applications require high quality targets, ranging from fundamental physics (nuclear reaction studies, nuclear data measurements, etc.) and specific targets for charge-strippers and neutron converters, up to the development of isotope-enriched targets for high quality standard medical radioisotope production. Target preparation is often a crucial step on the path towards the success of nuclear physics experiments, or specific final nuclear “products”. The recent availability of high-intensity beams at different accelerator facilities in Europe and all over the world pushes the requests for demanding targets, which are resistant to high intensity ion beams while maintaining their characteristics in terms of thickness, uniformity, isotopic enrichment, thermal properties etc.

Specific activities of the “targets” subtask deal with the study of existing and novel materials, the improvement of current and development of novel fabrication techniques, the characterization procedures and the sharing of knowledge among the various facilities.

As an example, the new CACTUS (Chamber for Alpha-particle Characterisation of target Thickness and Uniformity by Scanning) setup (Fig. 1) has been installed at INFN-LNS. It has been used to characterize targets in terms of thickness and uniformity, by measuring the energy loss and spread of alpha particles from radioactive source passing through thin target layers. Such method has allowed to characterize and identify the best multi-layer graphene foils to be used as substrate for targets needed for experiments with high intensity beams.

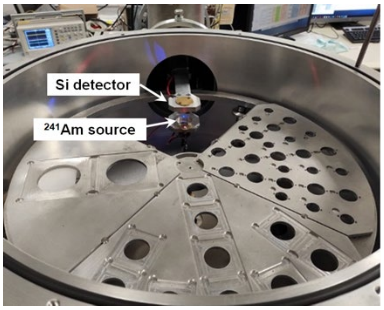


Fig. 1: Internal view of the CACTUS chamber at INFN-LNS. The movable plates with holes of different sizes to mount various target frames are visible

At GANIL, isotopic lanthanide targets are under development using physical vapor deposition (PVD) methods. Large area targets of ^{174}Yb of 22 cm², with thicknesses ranging from 50 µg/cm² to 4 mg/cm², have been produced on thin carbon backings of 35 µg/cm² (*Fig. 2*). The renovation of the target laboratory is now nearing completion, and three new evaporators have already been delivered to meet the high demand for targets requested by S^3.

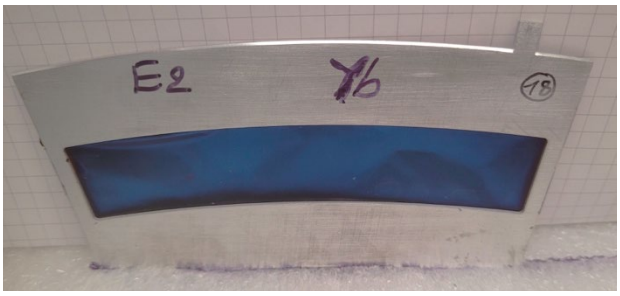


Fig. 2: Thin Ytterbium target made at GANIL

In December 2022, a document reporting on the state of the art in the field of "targets for Nuclear Physics" and collecting the requests and needs from the institutions participating in the first phase of the WP2-5-2 work package of the EURO-LABS project was published (Milestone MS13).

Moreover, this subtask has established a database containing information on the preparation and the characteristics of both available and newly developed targets at the participating institutions. The first version is already completed and has been shared with the members of the collaboration. A web application is currently under development to provide online access to the database, and is expected to be available by the end of 2025, including features allowing activity managers to update data directly. On May 15th, 2025, a joint presentation on this database was given during the EURO-LABS WP2.5.2 collaboration meeting under the title: "Target database within the EURO-LABS project".

On May 15, 2025, an online meeting of the EURO-LABS WP2.5.2 collaboration took place (timetable at https://agenda.infn.it/event/46874/timetable/#20250515.detailed). During the meeting, more than 40 participants joined remotely, and a representative from each institution gave a presentation reporting on the main "targets" activities related to the work package. The meeting featured a very fruitful discussion and exchange of information, and it concluded with the intention to organize an in-person meeting in 2026.

In conclusion, all this work on target development and technological advances is the result of dynamic collaboration, networking and information exchange between the research institutions involved in the EURO-LABS project.

4. FLASH@EURO-LABS (2.5.3)

The goal of the task 2.5.3 was to achieve standardized dosimetry for ultra-high dose rate (UHDR) experiments in different European particle accelerators. Focus was on monitor detectors able to monitor the high-intensity beam during delivery. The task has a large translational potential in clinical environment, with the installation at the proton therapy centers in Delft and Aarhus.

Air-filled Farmer-type ionization chambers are widely used as standard detectors for absolute dosimetry in clinical settings [IAEA TRS-398, 2006]. However, under UHDR conditions these chambers exhibit significant signal loss due to charge recombination, leading to large uncertainties in dose measurements.

During this reporting period, the work was extended to contribute to the improvement of the code of practice for FLASH dosimetry with heavy-ion beams, using compact ionization chambers. A numerical model was applied to investigate dose rate formalisms for FLASH dosimetry in synchrotron beams, which are characterized by strong local dose rate inhomogeneities arising from beam current fluctuations ("ripple"), a typical feature of all clinical synchrotron accelerators operated in slow extraction mode. In addition, collaboration was initiated with the Physikalisch-Technische Bundesanstalt (Germany) and the Universidade de Santiago de Compostela (Spain), both actively engaged in developing and calibrating novel dosimetry techniques.

4.1. Improving the formalism of dose rate definitions for synchrotron-based FLASH dosimetry

In February 2025, an experiment was carried out at the Heidelberger Ionenstrahl-Therapiezentrum (HIT, experimental "Q-room") to evaluate dosimetry uncertainties in synchrotron beam delivery and ionization chamber signal loss due to recombination. Four ionization chambers with different designs and volumes were tested: cylindrical chambers TM31023 (0.015 cm^3), TM31015 (0.02 cm^3), TM30013 (0.6 cm^3), and the parallel-plate chamber TM34045 (0.02 cm^3).

Unlike the first FLASH dosimetry experiment in 2024, this study used a scattering shoot-through technique instead of beam scanning. Figure 3(a) compares saturation curves for scanning versus shoot-through beams. Results indicate that scanning introduces significant uncertainties, especially in the plateau region where recombination losses are normally assumed negligible. These uncertainties arise from the interplay between rapid scanning magnet motion and the millisecond spill structure, which itself exhibits unique microsecond-scale intensity fluctuations [Fig. 3(c)]. The resulting variations in local dose delivery are shown in Fig. 3(d), leading to inconsistent chamber responses.

By contrast, the shoot-through technique [Fig. 3(b)] mitigated these uncertainties in local dose readings. However, it could not eliminate uncertainties related to fluctuations in spill length and instantaneous dose rate. These effects become particularly relevant in the recombination-dominated region (the bending part of the saturation curves), where accurate application of the recombination correction factor is required. Chambers with larger electrode gaps, such as the TM30013 Farmer and TM31015 PinPoint are especially sensitive to this issue.

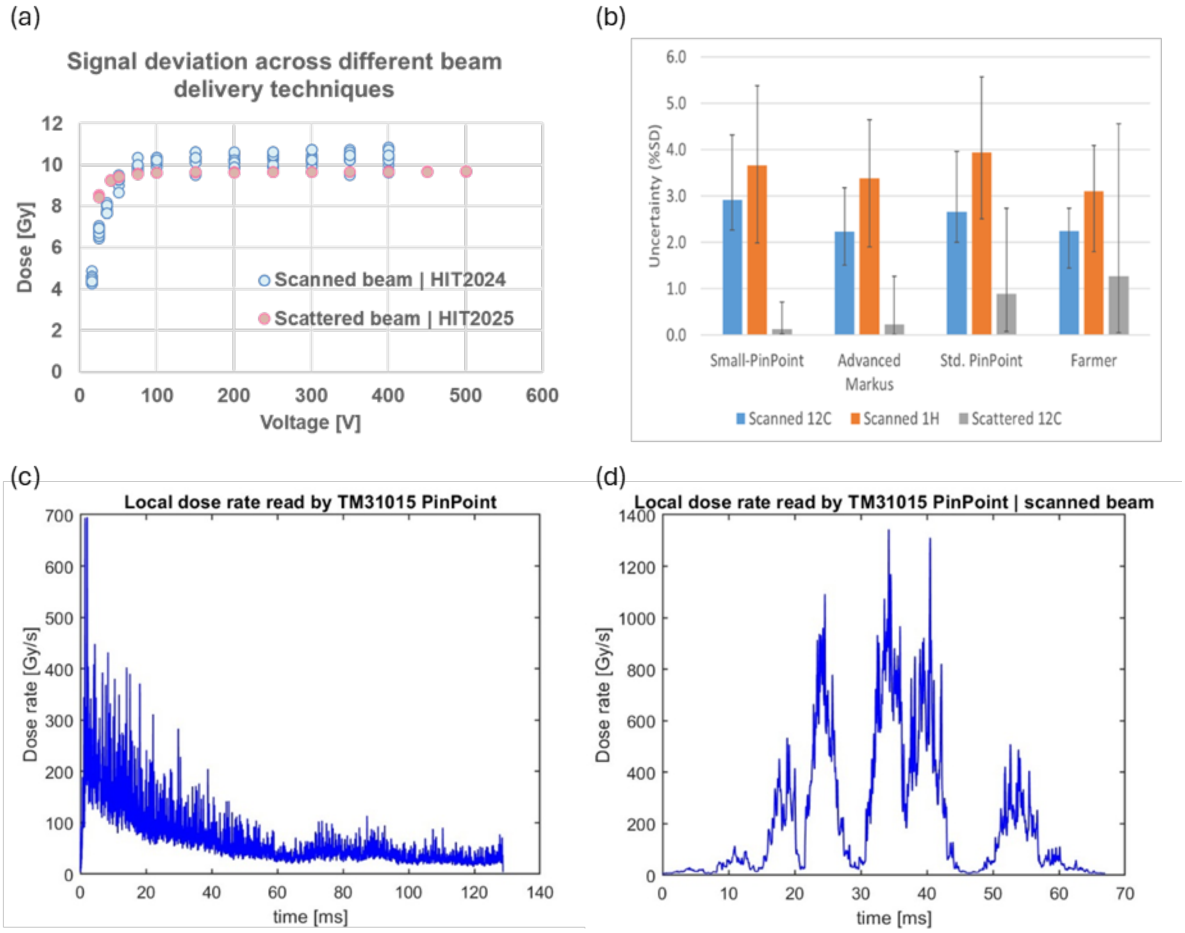


Figure 3. *Comparison of ionization chamber responses and beam intensity profiles under different synchrotron beam delivery modes at HIT, using ^{12}C ions (274.98 MeV/u) and protons (146.56 MeV). (a) Saturation curves measured with TM31023 PinPoint for scanning vs. shoot-through delivery, showing stronger uncertainties with scanning. (b) Uncertainty from full saturation curve measurements for all tested chambers, indicating that shoot-through delivery reduces variability in local dose readings compared to scanning. For the scattered beam, the upper uncertainty bars reflect only internal spill-to-spill beam intensity fluctuations, which become visible when the chamber operates in the recombination regime. (c) Measured intensity fluctuations within a ~100 millisecond synchrotron spill. (d) Resulting variations in local dose deposition patterns during scanning magnet motion.*

Since recombination loss depends directly on dose rate, an appropriate definition of dose rate is critical for recombination correction factor determination on a spill-by-spill basis. The commonly used global average dose rate, $DR_{av} = \frac{total\ dose}{spill\ length}$, is an oversimplification. Therefore, two alternative formalisms were evaluated using our self-developed simulation model:

- Dose-averaged dose rate (DADR): $DADR = \frac{\int_0^T DR^2(t)\,dt}{\int_0^T DR(t)\,dt}$
- Time-averaged dose rate (TADR): $TADR = \frac{\int_0^T DR(t)\,dt}{T}$

Figure 4 demonstrates that simulation results using DADR formalism show much better agreement with measured data than TADR. This marks an important first step toward improving both analytical and practical determination of dose correction in FLASH dosimetry.

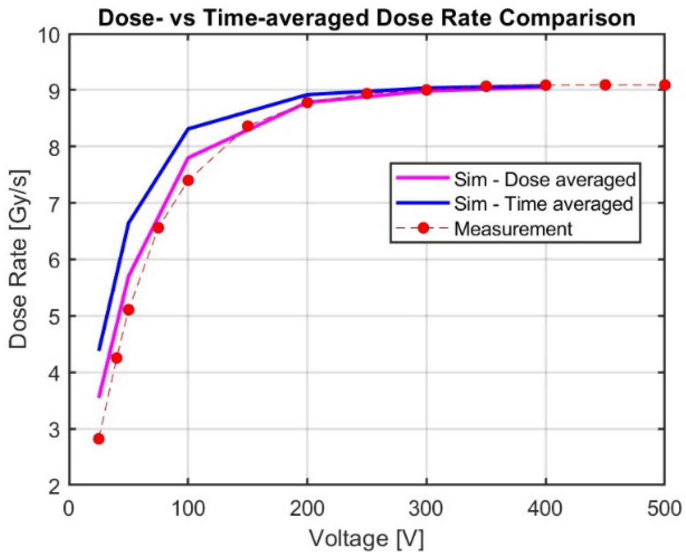


Figure 4. *Comparison of simulation and measurement data using different dose rate formalisms. Simulation results applying the dose-averaged dose rate (DADR) reproduce measurement data more accurately than the time-averaged dose rate (TADR) formalism.*

4.2. Expansion and integration into the FLASH dosimetry community

The work is now directed toward improving the forthcoming AAPM TG-359 code of practice for FLASH dosimetry using compact ionization chambers. Our simulation model is being further developed to:

- propose new correction techniques for recombination
- provide uncertainty estimation methods for secondary standards

To be clinically acceptable, model predictions must reach an accuracy of <2%. For this, benchmarking against a highly stable and reproducible beam facility is essential in order to overcome the unavoidable synchrotron fluctuations. Therefore, research stays at Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, has been arranged for 11th August – 5th September 2025.

PTB's high-precision electron linac is ideally suited for such benchmarking, as it provides stable beams with pulse doses ranging from 2 mGy to 10 Gy per ~2 µs pulse, corresponding to instantaneous and well defined dose rates of $9\times10^2 – 5 \times 10^6$ Gy/s. These values are equivalent to, or exceed, those achievable at GSI and HIT, making PTB an excellent reference facility for recombination effect investigation.

This collaboration builds upon the ongoing efforts of the Particle Therapy Physics group at GSI to integrate FLASH dosimetry expertise. In 2025, joint work with PTB has already begun on exploring beam monitoring strategies for GSI's microsecond FLASH beam experiments. The research stay will strengthen this partnership, enabling cross-validation of results and creating broader inter-institutional synergies.

The planned activities at PTB include:

- Benchmarking numerical model predictions: Comparative experiments with selected ionization chambers across a range of UHDR pulse parameters or Ultra-High-Dose-Per-Pulse (UHDPP).
- Gas parameter investigations: Measurement of ion and electron mobilities, attachment rates, and recombination coefficients in pure gases (N_2, O_2), which are key input parameters for the simulation. These studies will be performed using the GSI-developed vessel for UHDR dosimetry in arbitrary gases with variable pressures (see Fig. 3). This setup enables systematic investigations of drift and recombination processes in air and other detector gases under UHDR conditions, where electric field perturbations inside the chamber are highly relevant and may alter the effective gas parameters.
- He/CO_2 chamber studies: Testing the dose linearity limits of the GSI beam-monitoring chamber gas mixture [L. Baack et al. 2022] under varying UHDRP, with the aim of informing future high-dose-rate monitoring and exploring alternative gas mixtures for dosimetry chambers.
- Cross-validation with external models: Comparison of our simulation results with numerical algorithms dedicated to calculating charge collection efficiency and time-resolved signals in the pulsed-beam regime [J.P. Martín et al. 2022, 2025], developed by José Paz Martín, currently a guest scientist at PTB.
- Knowledge integration: Sharing results and methodologies within the FLASH-dose project [https://flash-dose.eu/], in which PTB's Dosimetry for Radiotherapy Department actively participates

Results from the PTB experiments will be reported in the next reporting period. In the meantime, one paper on the experimental results is being prepared for submission, and another focusing on our recombination model is in preparation.

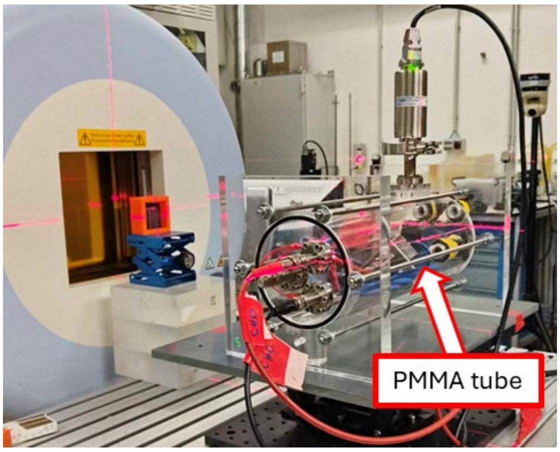


Figure 5. *A custom-designed PMMA tube used for special gas-filling process. The tube was designed to accommodate the ionization chamber and its cables while allowing signal measurements via an electrometer or oscilloscope positioned outside. A digital pressure sensor was attached to the top of the PMMA tube for continuous pressure monitoring. To minimize contamination by ambient air, the gas filling process was repeated three times. First, the ambient air was evacuated using a portable vacuum pump, followed by flushing the chamber with the desired gas.*

5. ERIBS (2.5.4)

The ERIBS (European Research Infrastructure – Beam Services) collaboration aims at providing high-level ion beam services for the EURO-LABS research infrastructures. The best expertise, know-how and practices of the Electron Cyclotron Resonance Ion Source (ECRIS) community have been used and transferred between the partners to take full advantage of the European ion source infrastructure. The project brought together the following research teams developing ion sources and their beams: ATOMKI (Hungary), CNRS-IPHC (France), INFN-LNL (Italy), INFN-LNS (Italy), GANIL (France), GSI-FAIR (Germany), JYFL (Finland), UMCG-PARTREC (Netherlands) and CNRS-LPSC (France, associate partner). During the project the beam variety available for the European user community was extended by improving beam production methods and techniques. This development included further improvement of high temperature ovens, axial sputtering and MIVOC method. In addition, a short- and long-term ion beam stability, as well as methods for online monitoring of these conditions were developed. This was realized, for example, by optical emission spectroscopy, identifying kinetic plasma instabilities by means of hard x-ray detection and using online beam current monitoring systems. After this development period the improved technologies and methods are made available for all participating infrastructures.

The project has been divided into two separate tasks to achieve the above-mentioned objectives. Task1 focuses on extending the ion beam selection and intensities to make new projectile-target combination available and/or low-cross section reaction studies possible. In this task we have focused on the development of evaporation ovens, the MIVOC method and sputtering technology to increase the beam intensities of already existing ion beams and to make new ion beam elements available. The laboratories have different kind of ECR ion sources - in terms of size and operation hardware - making this task challenging. Practically each device needs, at least at some level, a customized and optimized solution to adopt the developed technology. Task2 focuses on developing online beam monitoring to maintain the requested beam intensity. The diagnostics includes the plasma stability monitoring as well. The latter allows to avoid unstable plasma condition which typically causes both short- and long-term challenges in ion beam production and operation.

Both tasks had several subtasks, and each subtask has a responsible team to implement the development work. Both tasks had their own leaders assigned as well. The task leaders followed the progress of the tasks and reported to the steering committee three-four times per year. The steering committee monitored the overall progress and made suggestions or recommendations when they deemed it necessary. As both tasks have several approaches it is expected that relevant service improvements for the EURO-LABS user community would be achieved.

A website which facilitates project management, monitoring, and especially provides instructions and other relevant information on producing ion beams from different elements was established (https://jyufi-fys.atlassian.net/wiki/x/FgBB). The website includes also other project relevant information and documentation – for example concerning the annual meetings of the ERIBS project. The main page includes a link to the beam database which contains information about the stable ion beams, which have been produced in the partner laboratories using ECR ion sources. It gives all relevant information about the production technique and operation parameters. These pages are updated as the project progresses, new ion beams have been produced, or their production method has been improved.

Next, we will review the results achieved and the progress made during the project. First, we will review the achievements related to the production of ion beams and then the improvements related to the monitoring and maintenance of the ion beam stability. We also explain how the developments improve the operation and efficiency of the infrastructure.

5.1. MIVOC

The MIVOC method (Metal Ions from VOlatile compounds) is an efficient way to produce ion beams from several metallic elements that require relatively high evaporation temperatures. MIVOC method is based on the use of so-called MIVOC compounds, which are organometallic compounds with sufficient vapor pressure at room temperature to provide the metallic elements of interest into the ion source plasma for intense beam production - like ferrocene ($Fe(C_5H_5)_2$) for Fe ion beams. At JYFL, the MIVOC method has been the main production method for highly charged, high intensity Mg, Ti, Cr, Fe and Ni ion beams. The method is very versatile in use and can be adopted with all kinds of ion sources without significant structural modifications. Studies have shown that its global production efficiency is very high when compared to evaporation ovens. Due to this feature, the MIVOC method is a very attractive alternative in the case of rare and expensive stable isotopes.

The presently available MIVOC compounds are all commercially available but only based on isotopes present with their natural abundances. The intensity of the ion beam could substantially be increased when the synthesis of the compound is realised from highly enriched material. For example, in the case of ^{64}Ni, that has only a 0.93 % natural abundance, the intensity would increase by a factor of about 100 when the MIVOC compound is synthesized using 95% enriched ^{64}Ni as a starting material. This idea of using enriched MIVOC beams was proposed at JYFL but this endeavor was discouraged by a lack of sufficient chemistry-related know-how. As a continuation, the IPHC Strasbourg team successfully developed the demanding synthesis of isotopic titanium MIVOC compound to produce intense ^{50}Ti beams at JYFL.

This idea has been refined further within the EURO-LABS service improvements program. In this MIVOC related collaboration concept the know-how of the CNRS-IPHC team plays a crucial role. The team has an experienced chemist who is not only capable of synthesizing several MIVOC compounds but who has also optimized the procedures to efficiently synthesize the compounds from small amounts of costly materials. These organometallic synthesis skills associated to inorganic quite delicate chemistry know-how has made the enriched MIVOC ion beams available to the partner institutes.

Table 1 shows the MIVOC compounds which can be synthesized by the CNRS-IPHC team for the use of the EURO-LABS partner institutes. The table also shows the stable isotopes, their natural abundances and the intensity gain if the isotopic enrichment level of 95 % is used instead of using natural starting material. Here the intensity gain has been calculated by dividing the enrichment level of 95 % by the natural abundance of the isotope of the interest. The team also aims to synthesize new MIVOC compounds in accordance with the requests from the EURO-LABS community. This will make new enriched MIVOC beams available which would significantly increase the beam intensity of those isotopes. Table 2 shows the enriched beams which have been accelerated for the nuclear physics experiments at the EURO-LABS partner laboratories during the EURO-LABS program. The table also shows the beam intensity extracted from the ECR ion source to meet the intensity requirement set by the experiment. The objective has been to minimize the usage of the expensive material, i.e. the reported values are not the highest intensity available from the ion source. The ERIBS collaboration services are available for all EURO-LABS partners. In the case of the enriched MIVOC beams the expertise is available as a collaboration which is based on a separate mutual agreement.

Contact for further information and MIVOC collaboration: Benoit Gall from CNRS-IPHC: benoit.gall@iphc.cnrs.fr. More information regarding the enriched MIVOC beams and hazard statements can be found also from the ERIBS website: https://jyufi-fys.atlassian.net/wiki/x/CgVB

Element	Compound	Isotope	Nat. abundance	Intensity gain
Mg	$Mg(C_5H_5)_2$	24	79 %	1.2
		25	10 %	9.5
		26	11 %	8.6
Ti	$(CH_3)_5C_5Ti(CH_3)_3$	46	8.3 %	11.5
		47	7.4 %	12.8
		48	73.7 %	1.3
		49	5.4 %	17.5
		50	5.2 %	18.3
V	$V(C_5H_5)_2$	50	0.25 %	380
		51	99.75 %	1
Cr	$Cr(C_5H_5)_2$	50	4.3 %	22.1
		52	83.8 %	1.13
		53	9.5 %	10
		54	2.4 %	40
Fe	$Fe(C_5H_5)_2$	54	5.8 %	16.4
		56	91.8 %	1.04
		57	2.1 %	44.8
		58	0.28 %	340
Ni	$Ni(C_5H_5)_2$	58	68.1 %	1.4
		60	26.2 %	3.6
		61	1.14 %	83
		62	3.63 %	26
		64	0.93 %	102

Table 1: MIVOC compounds which can be synthesized for the EURO-LABS partners. Stable isotopes, their natural abundance and intensity gain are shown also. Intensity gain shows the intensity increase factor if the compound is synthesized using 95 % enrichment level for the isotope of interest.

Ion	I [µA]	Nat. abundance	Enrichment level	Intensity gain	Duration	Laboratory
$^{54}Cr^{11+}$	2.5	2.37 %	93.8 %	39.6	15-19.3.2023	JYFL
$^{64}Ni^{13+}$	4.7	0.93 %	94.9 %	102	2-9.4.2024	JYFL
$^{50}Cr^{10+}$	15.5	4.3 %	94.6 %	22.1	3-11.4.2023	GANIL

Table 2: Enriched MIVOC beams, which have been accelerated for the experimental program of the EURO-LABS partners. The intensity gain achieved as a result of the MIVOC service, duration of the experiment and venue of the experiment have also been shown in the table.

5.2. MIVOC technology transfer

At INFN-Legnaro National Laboratories the ECR ion source LEGIS (LEGnaro ecrIS), produced by the Pantechnik company, has been delivering positive ion beams to the PIAVE-ALPI complex since 2009. It is a 2nd generation ECRIS whose magnetic structure is produced by permanent magnets and employing an optimum operating frequency of 14.428 GHz. It can produce beams from gaseous elements as well as from solid ones, thanks to the availability of a resistive oven (maximum operating temperature around 1400 °C) and a movable sputtering system. Even if the available beams presently satisfy the requests from the users, there is a growing interest in the implementation of new techniques that could, on one hand, increase the ion species available for the accelerator, on the other hand make the production of already available beams easier and/or more reliable. On this basis, LNL expressed interest in the implementation of the MIVOC technique and took benefit of the expertise already present in European laboratories like JYFL and IPHC, to adopt the method within the ERIBS collaboration.

Starting from the second half of 2023, very fruitful discussions on the necessary know-how to implement the new technique have been undertaken between LNL, JYFL and IPHC. In particular, the IPHC team made available the necessary components to handle the MIVOC compound:

- containers with vacuum-tight valves,
- a Peltier cell,
- a controller for the Peltier cell.

In July 2024 colleagues from IPHC visited LNL for one week, during which LNL ion source operators have been trained on the handling of the different MIVOC compounds and on the use of the Peltier cell. Then, a first evaporation test using ferrocene was done on a test bench. The lay-out of the set-up is shown in Fig. 6.

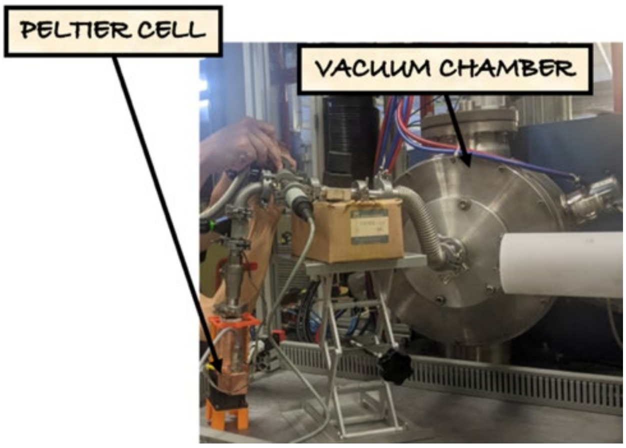


Fig. 6 Layout of the set-up used for the evaporation test of ferrocene at INFN-LNL.

With reference to Fig. 6, the components employed for the test were as follows:

- the Peltier cell and its controller,
- the MIVOC compound and its container connected to a vacuum-tight manual valve,
- a manual dosing valve,
- a Pirani gauge,
- another manual dosing valve,
- a Penning gauge already installed in the vacuum chamber.

The test consisted in cooling down ferrocene to the minimum temperature allowed by the Peltier cell, open all the valves and then increase the temperature of the cell taking note of the pressure measured by the Penning gauge. The result is shown in Fig. 7, which clearly demonstrates a successful evaporation of ferrocene.

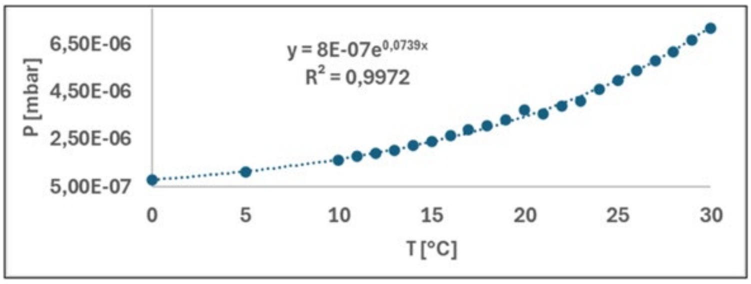


Fig. 7 Evaporation of ferrocene on the test bench as a function of the temperature of the Peltier cell.

Fig. 8 shows the main components of the ECR source LEGIS and its vertical section. Normally the gas is injected at ground above a small turbo pump, and after a slightly complex path the gas arrives into the plasma chamber (see the light blue line in the picture on the right). During the meetings held in 2023, this path was judged not optimal for the injection of the MIVOC compound, due to the possibility of condensation and consequent loss of material before reaching the plasma chamber. For this reason, it was agreed to install the MIVOC system and related hardware at high voltage, using a KF flange connected to an internal tube of internal diameter of 12 mm pointing directly to the plasma chamber. The position of the connection is shown in Fig. 9.

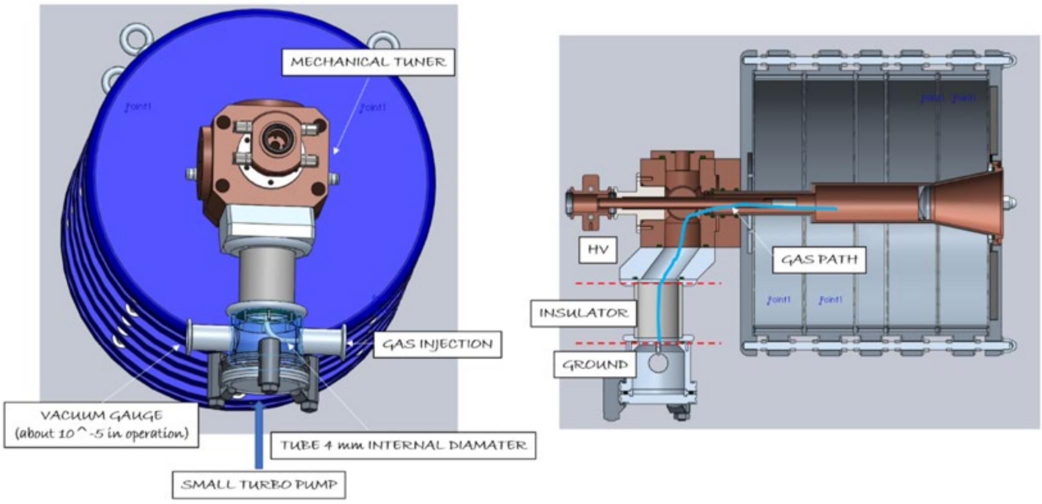


Fig. 8 Main components of the ECR source LEGIS (left) and its vertical section (right). The gas path towards the plasma chamber is indicated by the light blue line in the picture on the right.

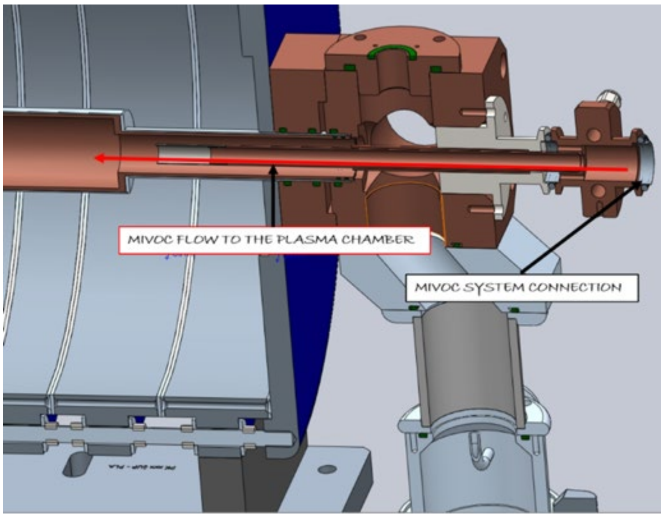


Fig. 9 More suitable position for the connection of the MIVOC system to the LEGIS source.

The connection at high voltage required the construction of an insulated rack, designed and built at LNL. Fig. 10 shows a 3D picture of the rack and its connection to the ion source. The available space between the high voltage and ground was very limited, which posed significant design challenges.

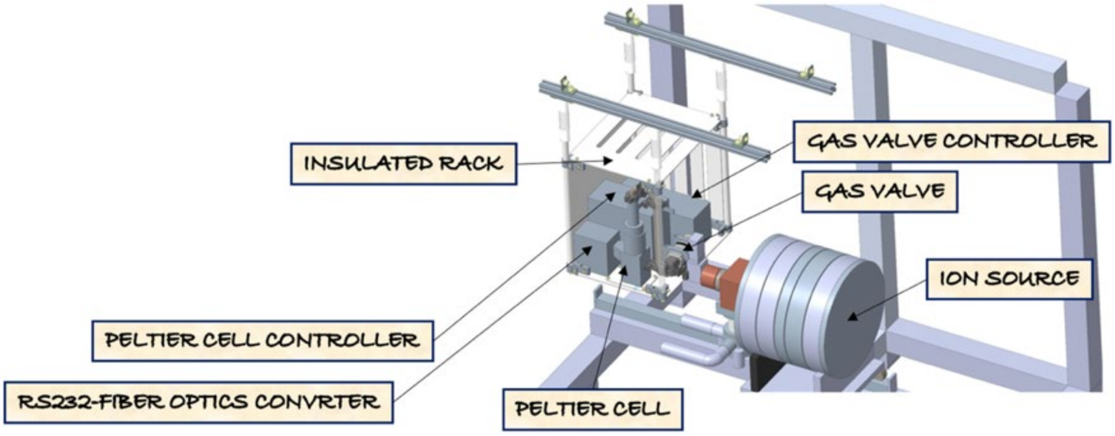


Fig. 10 Insulated rack for the MIVOC system and its connection to the LEGIS source.

The rack was completed at the beginning of 2025 and installed in the ion source box in early summer. Unfortunately, it has been verified that the installation of the rack caused oscillations of the source high voltage. After a careful analysis, problems of insulation towards ground due to the vicinity of the source box were excluded. Then, the problems could be ascribed to a capacitance effect due to the presence of the rack, but the limited time available prevented us from investigating deeper the problem. More, the control through serial communication of the Peltier cell could not be completed due to problems of hardware compatibility. To try to carry out a test, it has been decided not to use the Peltier cell and connect the MIVOC system to the usual gas injection port of the LEGIS source (see Fig. 8). Luckily, after an initial outgassing of the MIVOC container, Fe peaks were clearly visible in the spectra, as shown in Fig. 11. Despite the initial difficulties, more than 2 μA of Fe^{10+} was easily extracted, with a limited amount of microwave power and total extracted current. Considering the limited time available for the experiment, the results are satisfactory and the know-how for the implementation of the MIVOC technique at LNL can be considered successfully transferred.

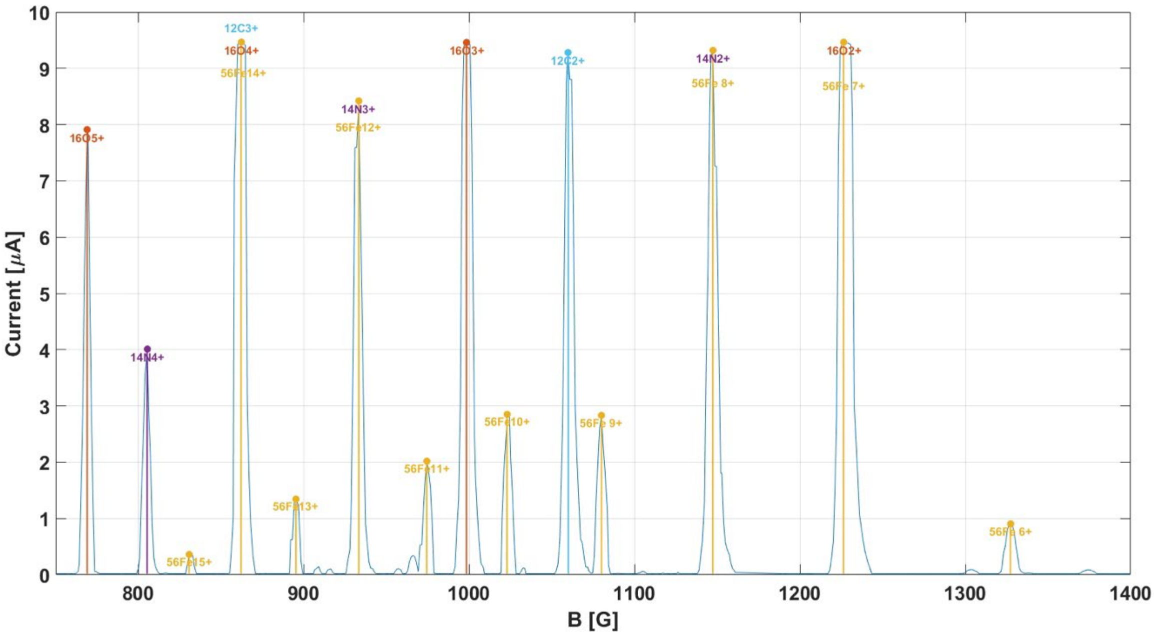


Fig. 11 Fe charge state distribution extracted from the LEGIS source.

5.3. High temperature foil oven

The JYFL ion source team developed a very promising prototype of evaporation oven in 2007 capable of reaching about 1900˚C in the test bench. In this oven a very thin resistive metal foil was used instead of the traditional filament wire. This approach made it possible to avoid the need for insulating materials in the hottest parts of the oven. As a result, a higher evaporation temperature in the crucible, where the material of interest is evaporated, can be reached. However, this prototype was unreliable in use, no solution was found and therefore this prototype was abandoned for almost 20 years. Due to the potential of this evaporation oven, different options were sought to solve the problem through the ERIBS collaboration.

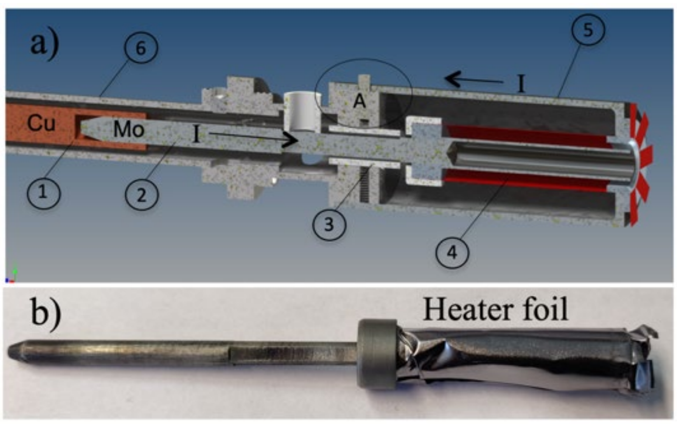


Fig. 12 The structure of the original JYFL foil oven. The heater foil assembly is shown and highlighted in the upper sub-figure using red colour. The actual heater foil and Mo support structure is shown in the lower sub-figure. The parts of the foil oven are: 1) copper rod, 2) Mo support structure, 3) Al_2O_3 insulator, 4) Ta foil (25 µm in thickness), 5) outer Mo oven structure for return current, 6) stainless steel tube for return current, A) locking/connection system (bajonet).

The original foil oven structure is shown in Fig. 12a) and the heater foil connected to Mo support structure is shown in Fig. 12b). As is demonstrated by the figure the 25 µm thin heater foil quite often suffered from geometrical deformations which severely affected the reliability of the operation. The deformation taking place during the assembly of the foil caused, for example, short circuit between the foil and the outer oven structure. The JYFL ion source team members visited GANIL in May 2024 for the know-how transfer regarding the high temperature ovens. During the visit the differences between the JYFL foil oven and the GANIL high temperature oven design were discussed. The original design of the JYFL foil oven was revisited and solution for the issues in the JYFL design were found. The new modified structure allows the assembly of the heater foil to its support structure before inserting it into the oven. The modification can be seen by comparing Fig. 12 and Fig. 13. The modified structure is in the front-end of the oven shown by the red circle. As a result, the assembly of the heater foil to the oven structure is clearly improved, which also greatly improves the operation reliability.

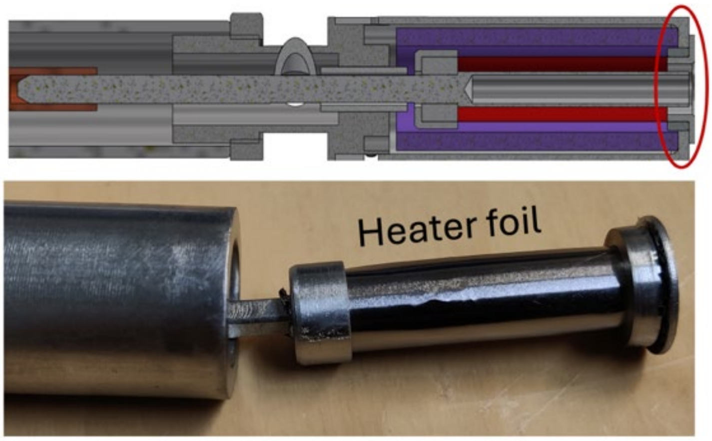


Fig. 13 The modified JYFL foil oven. The realised modification is on the front end of the oven shown by the red circle. The new geometry allows the foil assembly before inserting it into the oven, which greatly improves the operation of the oven.

The first test period of the upgraded foil oven was realised in December 2024 at the test bench when the oven was tested up to 1800˚C without any problems. The temperature was reached at the heating power of 450 W. The result is a significant step forward compared to traditional evaporation ovens, which is the main technology in use in the EURO-LABS community. For example, the maximum safe operation temperature of the JYFL miniature oven is about 1200˚C. It is a classical oven type which is widely used in the ECRIS community. Consequently, the achieved temperature with the upgraded foil oven will allow the production of new ion beams for the EURO-LABS user community. The test period also revealed a new development point to further improve the oven in terms of reliability and performance. This modification will be realised later in 2025, after which the technology will be made available to all EURO-LABS partners.

After a successful test bench period, the foil oven tests were continued with the JYFL 14 GHz ECRIS. For these tests, chromium was chosen as the material to be evaporated for the following reasons: 1) although the required temperature for the beam production is not particularly high, it still substantially exceeds the safe operation temperature of the JYFL miniature oven and 2) this is an interesting ion beam element for GSI-FAIR. Performing measurements in the presented manner allows for direct comparison of the MIVOC method and the foil oven. The GSI-FAIR ion source team has a plan to adopt MIVOC method, and this comparison will support their consideration.

The foil oven was tested using the JYFL 14 GHz ECRIS. A small chromium metal piece (≈ 300 mg, 99.7 %) was placed in the Ta crucible of the foil oven. The plasma was produced using nitrogen as a mixing gas. Typical operation parameters of the JYFL 14 GHz ECRIS were used. The oven power was gradually increased until the first signs of Cr ion beams were seen in the spectrum. At the beginning of the test a substantial outgassing was observed, which strongly affected the performance of the source, purity of the charge state spectrum and intensity of highly charged ion beams. After the outgassing period the source tuning was optimized to produce the Cr^{12+} ion beam. The oven temperature was increased gradually until the saturation of Cr^{12+} ion beam intensity was observed. At this point the intensity of 36.3 μA was reached at the oven power of 166 W corresponding to temperature of 1520˚C. The charge state distribution and ion beam intensities extracted from the JYFL 14 GHz ECRIS using the extraction voltage of 10 kV is shown in Fig. 14.

The GSI ion source team is considering implementing the MIVOC method in their laboratory. Chromium, and especially ^{54}Cr isotope, is one of the most important ion beams regarding the superheavy program of GSI-FAIR. The service concept implemented during the ERIBS project for enriched ion beams would make the MIVOC method very tempting. It is essential to conduct an experimental comparison to find the best method to meet the beam production requirements.

For a reliable performance comparison, we ran the MIVOC test immediately after the oven tests. The beam was produced using the enriched compound ($^{54}Cr(C_5H_5)_2$) prepared by IPHC Strasbourg due to material availability issues. The testing time was limited to half day to limit the consumption of the enriched material. The plasma was produced using oxygen as a mixing gas and typical tuning parameters of the JYFL 14 GHz ECRIS to maximize the intensity of Cr^{12+} ion beam. The opening of the gas dosing valve for adjusting the feed rate of the MIVOC material into the plasma chamber was gradually increased until the saturation of the Cr^{12+} was observed. The charge state distribution and ion beam intensities extracted from the JYFL 14 GHz ECRIS at 10 kV using the MIVOC method are shown in Fig. 15.

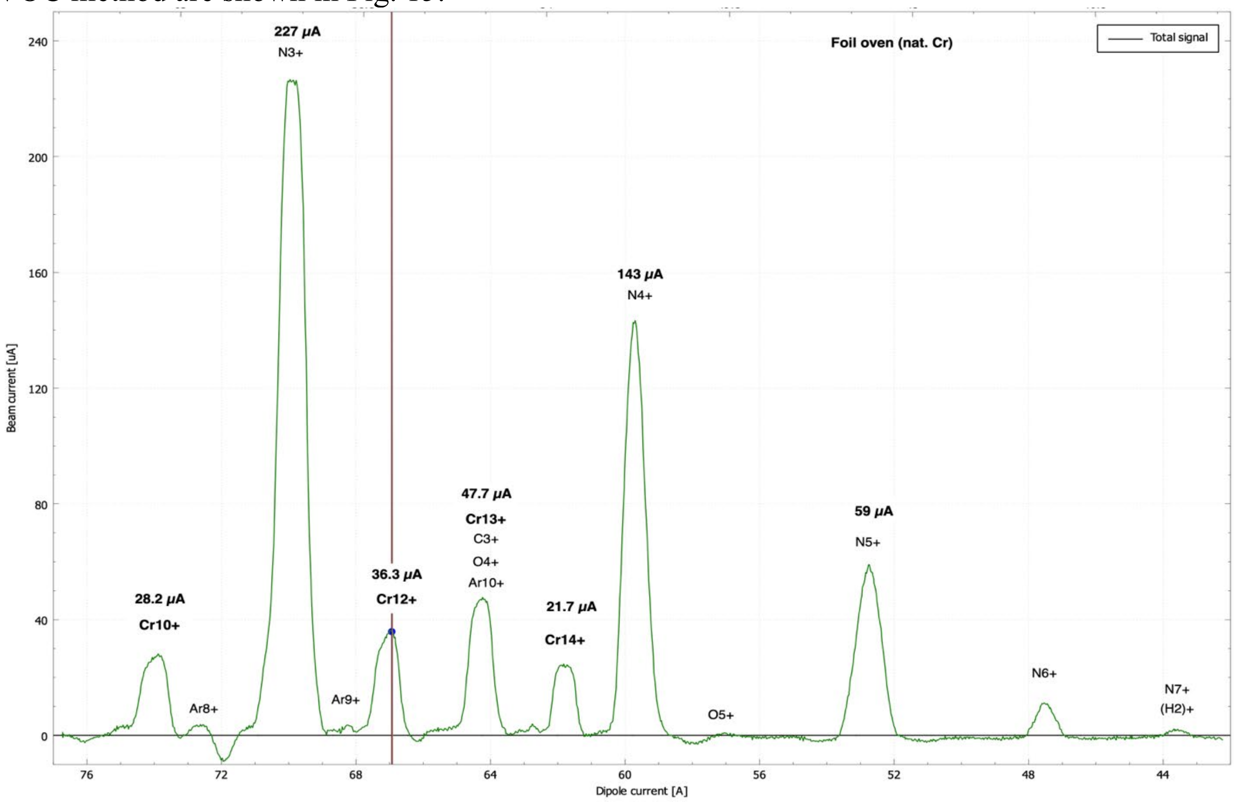


Fig. 14 Chromium charge state distribution extracted from the JYFL 14 GHz ECRIS. The material was evaporated with the foil oven at around 1520˚C.

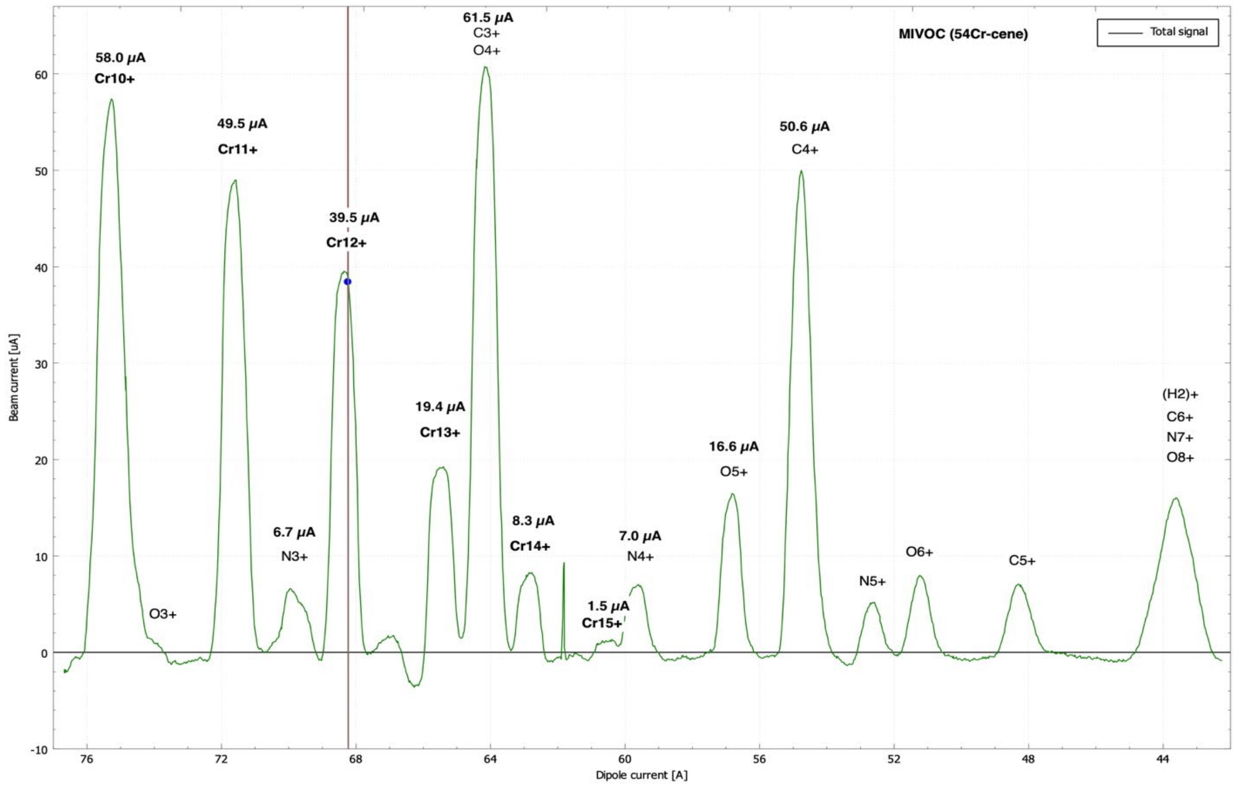


Fig. 15 Chromium charge state distribution extracted from the JYFL 14 GHz ECRIS. The material was produced using enriched chromocene with the MIVOC method (^{54}Cr, enriched 95 %).

In both cases the ion source parameters were optimized to maximize the intensity of Cr^{12+} ion beam. As figures 14 and 15 shows the intensities for the Cr^{12+} ion beam are practically identical when the enrichment level of the material is taking into account (84 % for oven vs 95 % for MIVOC). It is worth noting a significant difference in the charge state distribution as demonstrated in Fig. 11. It can be concluded that the MIVOC method is more effective for low charge states while the upgraded foil oven is more effective for high charge states. The difference may be due to different tuning parameters but may also be related to the production method.

Contact for further information and/or advice for adapting the high temperature foil oven: Hannu Koivisto (hannu.a.koivisto@jyu.fi) and Ville Toivanen (ville.a.toivanen@jyu.fi).

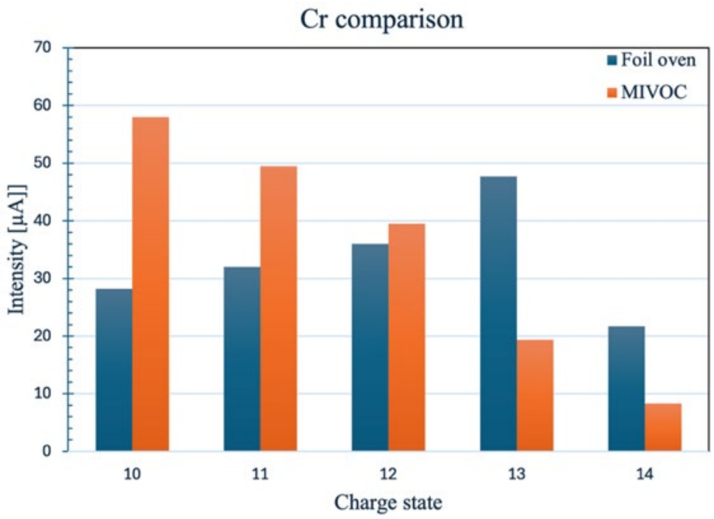


Fig. 16 Comparison of chromium ion beam intensities produced by using upgraded foil oven and the MIVOC method. In both cases the ion source parameters were optimized for Cr^{12+} ion beam. Note: In the case of the foil oven intensity data the charge state 13+ is overlapped by the residual ions of argon, carbon and oxygen. The actual Cr^{13+} intensity is assumed to be some microamperes lower.

5.4. High temperature inductive oven

The unique Calcium-48 isotopic beam, combined with increasingly heavy targets, has enabled the synthesis of the heaviest elements known to date. To access elements heavier than oganesson (Z=118), intense metal beams beyond calcium-48 are now required, i.e., isotopic titanium-50, vanadium-51, and chromium-54. Achieving these beams at the desired intensities of several particle microamperes on target (1pµA = 6 x 10^{12} particles/s) requires the development of high-temperature ovens capable of sublimating these elements directly into highly charged plasma of ECR ion source.

In addition to the development of organometallic compounds (MIVOC) that had enabled access to these beams but had also shown some limitations in terms of ECR plasma saturation, the IPHC Strasbourg launched a high-temperature oven development based on the principle of induction. These developments are entirely complementary and parallel to the development of resistive ovens. They should allow access to higher evaporation temperatures, higher intensity beams and higher charge states distributions for these ions.

This development project finds its roots in a collaboration between the Strasbourg and Jyväskylä universities. A first induction oven was tested at JYFL in 2011. This furnace was entirely built by the JYFL ion source team. The IPHC had brought a tungsten inter-crucible to prevent the high-temperature attack of the molybdenum furnace by titanium. It was possible at the time to create a first titanium beam from metallic titanium or titanium dioxide by heating it to a temperature between 1650 and 1750 °C. These tests also revealed the need for thermal insulation of these furnaces to protect the magnets from ECR sources.

The success of developing a titanium-50 isotope beam based on MIVOC compounds synthesized by IPHC had paused the oven development. These compounds have also been used successfully at GANIL in France, RIKEN in Japan, and FLNR Dubna in Russia, enabling the delivery of stable beams at intensities close to the pµA level with very reasonable isotope consumption.

The transition at Dubna to intensities on target exceeding 1 pµA was a great success for this method, but it ultimately revealed plasma saturation and a loss of performance if the increase is continued. The MIVOC method needed to be reinvented in order to reach the 10 pµA beam intensity level. It was at this point that the IPHC relaunched the development of a micro induction oven. This development was conducted in parallel in Strasbourg and Dubna, with regular tests at the FLNR until the outbreak of the Russia-Ukraine conflict. During this time, a first oven was set up and chromium could be evaporated at around 1250°C and titanium at around 1650°C, demonstrating the feasibility of the method. This oven could be ramped above 2000°C which was the initial aim. Unfortunately, geopolitical conditions have frozen this collaboration.

The development continued in Strasbourg as part of the IN2P3 FMI (FMI: Intense Metallic Beams in French) master project which aims at a high-temperature oven that can be inserted into a 25mm diameter tube for use with the GANIL ECR sources. At the start of the EURO-LABS project, this oven development was also associated with the goal of allowing European collaborators who wish to benefit from this technology to have access to it.

A first update of the test bench at IPHC was carried out in 2022 to resume these developments in their entirety. We initially worked to make the oven more integrable and scalable to meet the needs of the collaborative EURO-LABS laboratories. A laboratory dedicated to this development project was set up at the IPHC in 2024.

An emittance meter was developed at the IPHC based on the drift of the oscillation frequency of a quartz induced by the mass flow deposited on its front surface (Fig. 17). Such a microbalance was already used at GANIL. It enables the measurement of the evaporated titanium flow with respect to the emission angle. In parallel, the parts for a major upgrade of the test bench necessary to integrate the emittance meter and a turbo pump were purchased. This development makes it possible to perform the oven tests at high temperature under secondary vacuum.

The test bench was then used to optimize the power supply electronic circuits and their integration. The optimal number of pairs of oscillating power circuits was determined, as well as the operating frequency. The oven was able to operate continuously at high temperatures for several days, thus validating its ability to operate 24/7. In parallel, mechanical design continued in anticipation of a test planned at the ECR ion source in Grenoble. The various elements are being tested at the IPHC. Everything related to control and command is also being prepared. The oven part of the assembly is shown in Fig. 18. We are currently equipping the oven with several sensors, including cooling flow sensors, to characterize its performance in real time. We have arrived at a version that is compatible with the geometric limitations of the specifications. The oven is now close to its final projected version but will need several validations tests.

Contact for further information: Benoit Gall from CNRS-IPHC: benoit.gall@iphc.cnrs.fr

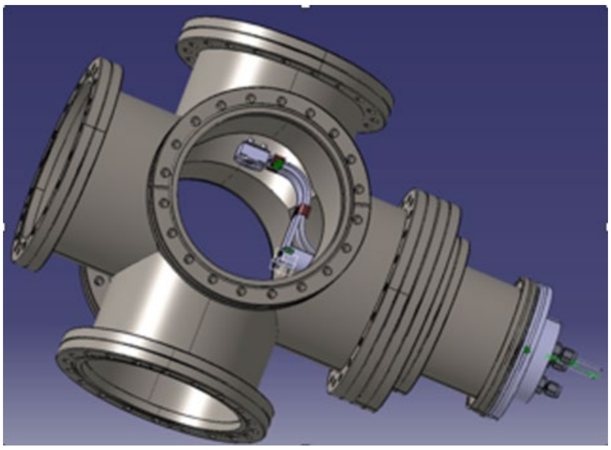


Fig. 17 Emittance meter to measure the flow of evaporated material.

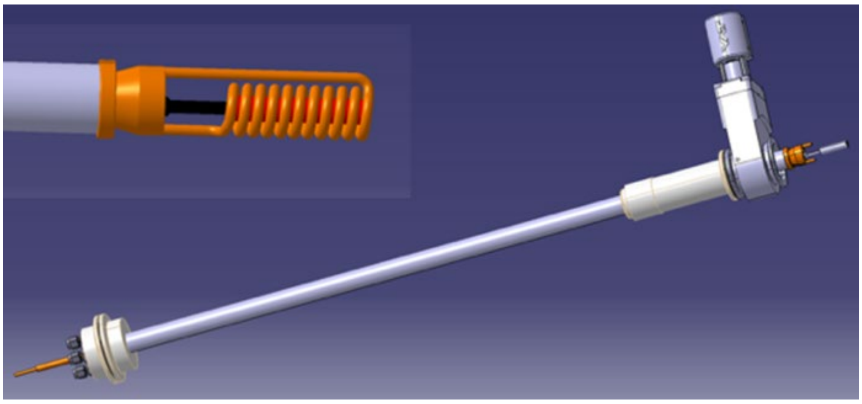


Fig. 18 The induction oven showing its heater coil, crucible inside the coil and the insertion system allowing oven operation and material changes without venting the ion source.

5.5. *Axial sputtering*

The first metal ion beams using sputter technique have successfully been produced using radial port through an open hexapole structure and since then this approach has been adopted in several laboratories. The majority of the European ECR ion sources are equipped with the closed Halbach magnet structure making this radial approach impossible. The axial sputtering has successfully been developed for example by the RIKEN ion source team and therefore the development and adoption of axial sputtering was included in the ERIBS project. The off-axis location was decided to be used to avoid a hole in the magnetic iron plug. The iron plug is needed to improve the magnetic confinement of plasma and therefore the performance of the room temperature ECR ion source. The hole would have a negative impact on the plasma confinement, and this effect is most significant if the magnetic hole is on the magnetic axis of the ion source. The objective of the development work was to find the optimal location and shape for the sputtered sample.

The technical design work, which was guided by the plasma-sputter simulations, was completed during the fall, 2023. The sputter simulations were realized by the INFN-LNL team. The mechanical work for the sputter device was completed, and the first sputter experiments were realized in March 2024 at JYFL using the JYFL 14 GHz ECRIS. Very promising intensity of 4.5 µA was obtained for the $^{90}Zr^{18+}$ (51.45 % abundance) ion beam using normal operational values of the JYFL 14 GHz ECRIS. The intensity value was achieved using the sputtering voltage (current) of 2.25 kV (3.5 mA). The sputter sample was inserted 50 mm into the plasma chamber. The sample was not cooled because the sputter yield increases with the temperature of the sample. As a next step, the sample was moved 10 mm closer to the plasma. The intensity exceeded immediately 8 µA but disappeared in couple of seconds. At this point the sputter voltage was only 1.3 kV while the other parameters were same as in the previous run. Because no solution to this failure was found the ion source was vented, and the sputter system was dismantled. The connection between the Zr sample and copper holder had melted, which caused a short circuit between the sputter sample and outer structure of the sputter device (see Fig. 19). Figure also reveals that visible amount of Zr exists on the surface of copper shield. Therefore, we assumed that part of the produced beam may be produced due to the vaporization of the zirconium sample.

The sputter system was re-designed to allow the sample cooling. The new experimental campaign using the upgraded sputter device was realised in June 2025. During the period of several days no confirmed Zr beams were measured. This suggests that the previously measured zirconium intensities were mainly produced by evaporation due to lack of sample cooling. We decided to back off from further measurements because further steps (higher sputter voltage, steps closer to the plasma, etc.) could cause significant and expensive water accident. The solution could be possible but would also require significant amount of time and technical/human resources which were not available at the time of this reporting period.

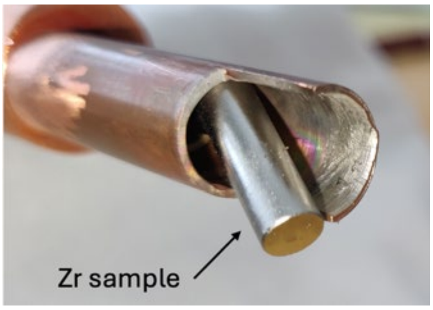


Fig. 19 Connection between the Zr sputter sample and the supporting rod melted, which caused a short circuit.

5.6. New metal ion beams and beam database

Delivering a wide range of different heavy ion beams for the users of the EURO-LABS collaboration laboratories is the main service responsibility of the ion source teams collaborating under ERIBS. An important part of this work was to develop and make available new beams (elements, ion species) to fulfill the requests of the users. An equally important aspect of this work is to keep track and document the information that is required to produce these ion beams and disseminate this information and associated techniques and good practices among the collaborating teams to promote the availability and high performance of these beams as widely as possible. For this purpose, the ERIBS community maintains a dedicated ion beam database.

During the ERIBS project several new metal ion beams have been tested and made available for users in the participating laboratories. The beam development has taken advantage of the beam production method development work and dissemination of beam production related know-how between the different ion source teams of the laboratories that has been carried out during ERIBS. The new beams are presented in Table 3. The beams from the elements which have not been available earlier are shown using bold letters while others are isotopically new beams – mainly thanks to the MIVOC service concept presented in section 2.1.

Table 3: New metal ion beams produced during ERIBS collaboration.

Element	**Mass [amu]**	**Optimized charge state**	**Beam current [µA]**	**Production method**	**Laboratory**	**Comments**
Cr	52	10+	40-50	Resistive oven	GSI	Delivered for the first time at GSI with an ECR ion source.
Cr	54	10+	40-50	Resistive oven	GSI	Effect of support gas studied. Effect of hot liner to mitigate material deposition investigated.

Cr	52	12+	36.2	Foil oven	JYFL	Comparison of production method (oven vs. MIVOC) studied.
Cr	54	12+	39.7	MIVOC	JYFL	Produced using isotopically enriched chromocene compound.
Ge	76	15+	20.2	Resistive oven	JYFL	Produced using isotopically enriched ^{76}Ge sample.
Mn	55	9+	70-80	Resistive oven	GSI	Effect of hot liner to mitigate material deposition investigated.
Pb	206	31+	1	Resistive oven	GANIL	First delivery of this isotope.
Pd	106	18+	2.6	Resistive oven	JYFL	Delivered for the first time in Europe.
Sn	120	21+	4.0	Resistive oven	JYFL	Delivered for the first time at JYFL.
Th	232	30+	2-2.5	Resistive oven	GANIL	Produced using ThF_4.
Tm	169	27+	8.1	Resistive oven	JYFL	First delivered beam of this element in the world.

Contact for further information: Hannu Koivisto (hannu.a.koivisto@jyu.fi) and Ville Toivanen (ville.a.toivanen@jyu.fi).

The ion beam database is hosted online by University of Jyväskylä. It can be accessed here: https://jyufi-fys.atlassian.net/wiki/spaces/ensar2/pages/4554967/Stable+beams
The beam database was originally initiated during the ENSAR2/MIDAS-NA collaboration project funded by EU. Following this, the database has been maintained and updated by the partner laboratories, and this work has been continued and expanded during the EURO-LABS/ERIBS project.

The information in the database includes the produced ion beam species, beam performance in terms of ion beam current, descriptions of production techniques and additional notes about possible safety considerations or other relevant aspects of beam production. The collaborating ion source teams from the different European laboratories have jointly provided information for 42 elements, ranging from hydrogen to uranium. All the available elements are shown in Fig. 20.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt									
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Fig. 20 All elements marked with blue font color have ion beam production and performance information available.

5.7. *Online monitoring of plasma instabilities*

Ion beams extracted from an ECRIS can be divided into two distinct domains based on their stability: short- and long-term beam stability. Short-term beam instabilities are mainly caused by electric sparks, taking place for example in the extraction region of the ion source, and by kinetic plasma instabilities. This report focuses on the detection and monitoring of the short-term beam instabilities caused by kinetic plasma instabilities. At unstable plasma conditions fast drop of the beam intensity of highly charged ions are observed and the recovery time to restore the original beam intensity after the onset of the instability can be in the range of milliseconds depending on the charge state and on the magnetic field configuration. The repetition rate of the kinetic instabilities typically varies from ~0.1 kHz to several tens of kHz, depending on the ion source tuning. The plasma instabilities are detrimental because they tend to decrease the time integrated beam intensity of highly charged ion beams. They will cause strong and fast intensity variations which are unacceptable for certain experiments. The kinetic instabilities will also cause outgassing and sputtering of plasma chamber structures. The outgassed and sputtered elements originating from the plasma chamber are ionized inside the plasma, extracted as a beam and therefore leading to possible beam contamination at the end of the beam line (i.e. at the target for the experiment). The outgassing caused by the instabilities can have a dramatic impact on the charge state distribution due to the recombination of highly charged ions. The sputtering can also cause negative long-term effects on beam intensity behaviour due to the wear and tear of critical parts and components. Such long-term aspect of the kinetic instabilities is not included in this report. Fig. 21 shows a typical example of the effect of the kinetic plasma instability on the O^{7+} ion beam.

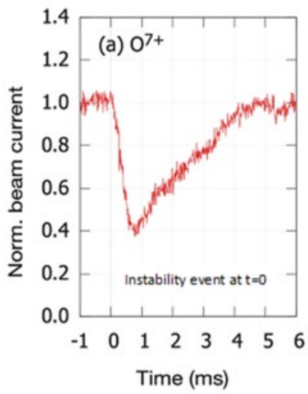


Fig. 21 The effect of instability event on ion beam intensity of highly charged (O^{7+}) oxygen. The experiment was realized using the JYFL 14 GHz ECRIS setup. The start of the instability is taken to be t=0.

Due to the negative effects of the kinetic plasma instabilities, intensity of the ion beams extracted from the minimum-B ECR ion source are strongly compromised. They restrict the parameter space available for optimization of the source performance. They are often overlooked by the ion source operator attempting to maximize the average beam current with limited diagnostics. The instability event is triggered when the build-up rate of the EED (Electron Energy Distribution) energy content exceeds the damping rate. During the instability event the kinetic energy of (mainly) perpendicular velocity component of energetic electron with respect to the magnetic field B is transferred to a low amplitude plasma wave. In this process (ns scale) the wave is amplified which can be observed as a short microwave pulse. In addition, because of the energy transfer, the part of the hot electron population is lost which is observed as a thick target bremsstrahlung burst originating from the plasma chamber walls. Therefore, kinetic plasma instabilities are always associated by RF and X-ray bursts. This fact opens the possibility to monitor the plasma stability in a non-destructive way by measuring the temporal behaviour of the plasma emitted RF power and of the high energy X-rays produced by electrons escaping from the plasma confinement and colliding with the plasma chamber structures. Due to the high repetition rate of the instability events, any diagnostic tools used for instability monitoring should be characterized by high temporal resolution, at least in the range of ~100 μs.

In this approach the plasma emitted microwave pulse coupled into the waveguide and propagating towards the microwave generator is measured with an RF diode connected to the waveguide with a directional coupler. Fig. 22 shows the monitoring setup. In addition, the figure shows the measured instability-induced microwave burst and the subsequent beam instability observed by the Faraday cup (FC) located downstream from the m/q separation. The measured signal, especially if it occurs periodically, indicates that the plasma is in unstable operating condition. This method requires only an RF power diode with the adequate signal attenuation making it a simple, reliable and low-cost option. One should note that since the plasma emitted RF power coupled into the waveguide can be very high in case of strong instability events, the RF diode should be protected by high-power attenuators and more preferably by inserting a limiter before the RF diode.

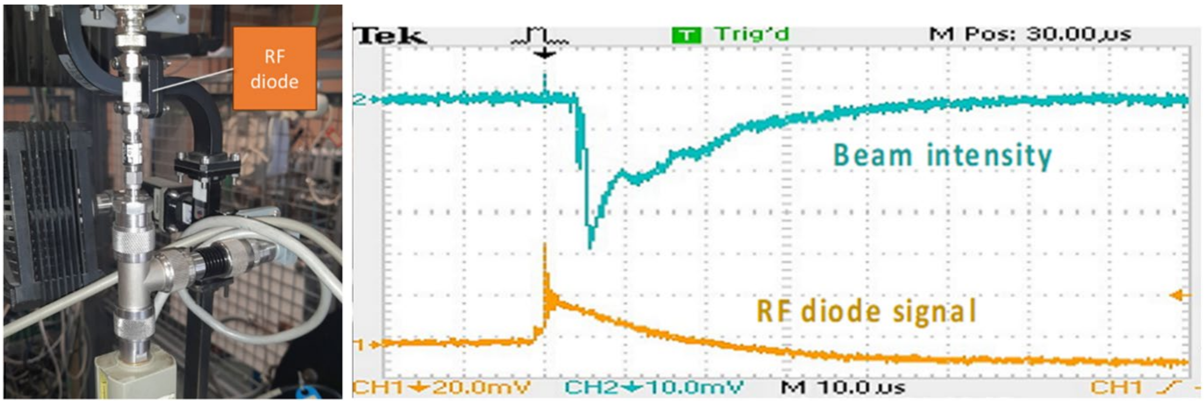


Fig. 22 Online monitoring of microwave emission taking place during the instability event. The plasma emitted microwave pulse can be measured with the RF diode connected to the waveguide.

In this approach the Bremsstrahlung burst generated by the sudden flux of escaping electrons is measured using scintillators. The use of X-ray diagnostics is a well-established technique to study kinetic instabilities of highly charged ECRIS plasma. In this project, the development work to realize an online, low-cost instability monitoring system was realized using two approaches: (1) combining a (Tl)CsI scintillator coupled with a Silicon Photomultiplier (SiPM) unit, (2) low-cost X-ray detector based on scintillating plastic fibers coupled to commercial SiPM. The latter approach has never been used in connection with the ECR ion sources but due to its simplicity, it is important to investigate its suitability for this purpose.

The detector was operated in photon counting mode, every single event generates analogue output of the electronics proportional with the incoming X-ray energies. The measurement setup was located inside the high-voltage cage close to ATOMKI ECRIS. The diagnostic generates a short (of the order of 10 μs), high amplitude peak during the event of instability. The required binary information (stable vs unstable operation condition) is obtained when the trigger level for the signal is set slightly above the normal background level. A typical temporal behaviour of the measured analogue output from the scintillator is presented in Figure 23 (purple line).

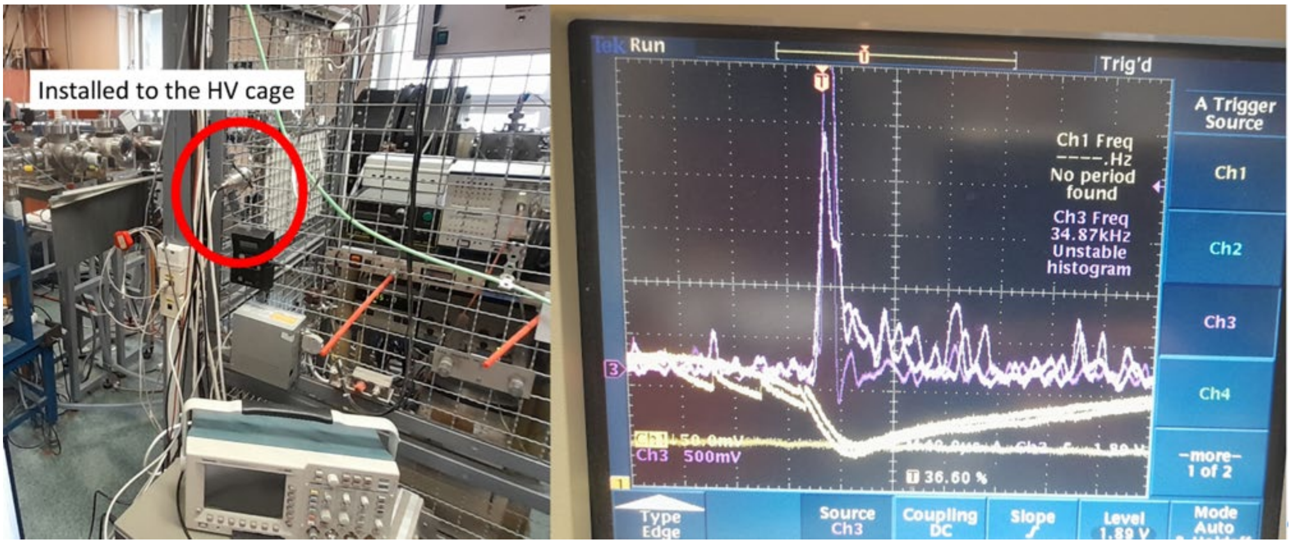


Fig. 23 Left: Thallium doped CsI scintillator installed to the high voltage cabinet of the ATOMKI ECR ion source. Right: Scope photo taken of the signals coming from the analogue output of the detector electronics (purple).

A scintillating fiber produces light when it is exposed to radiation. The light propagates along the flexible fiber to photo sensitive silicon photomultiplier (SIPM) which detects the light and produces the measurable current pulse. The installation of the scintillating fibers and their location are illustrated in Fig 24. The pictures show the two fibers installed with 4-5 windings around the plasma chamber, at the injection side, and around the middle pancakes in the gap between the two iron covers of the axial solenoids. In this way, the two detectors were sensitive to predominantly axial or radial X-ray emissions. In the insert, zoomed image on the left, the position of the SiPM detecting the scintillating light is shown. This setup allows to place all the electronics outside the HV zone, being intrinsically safe and easy-to-install since scintillating fibers are made of fully insulating materials.

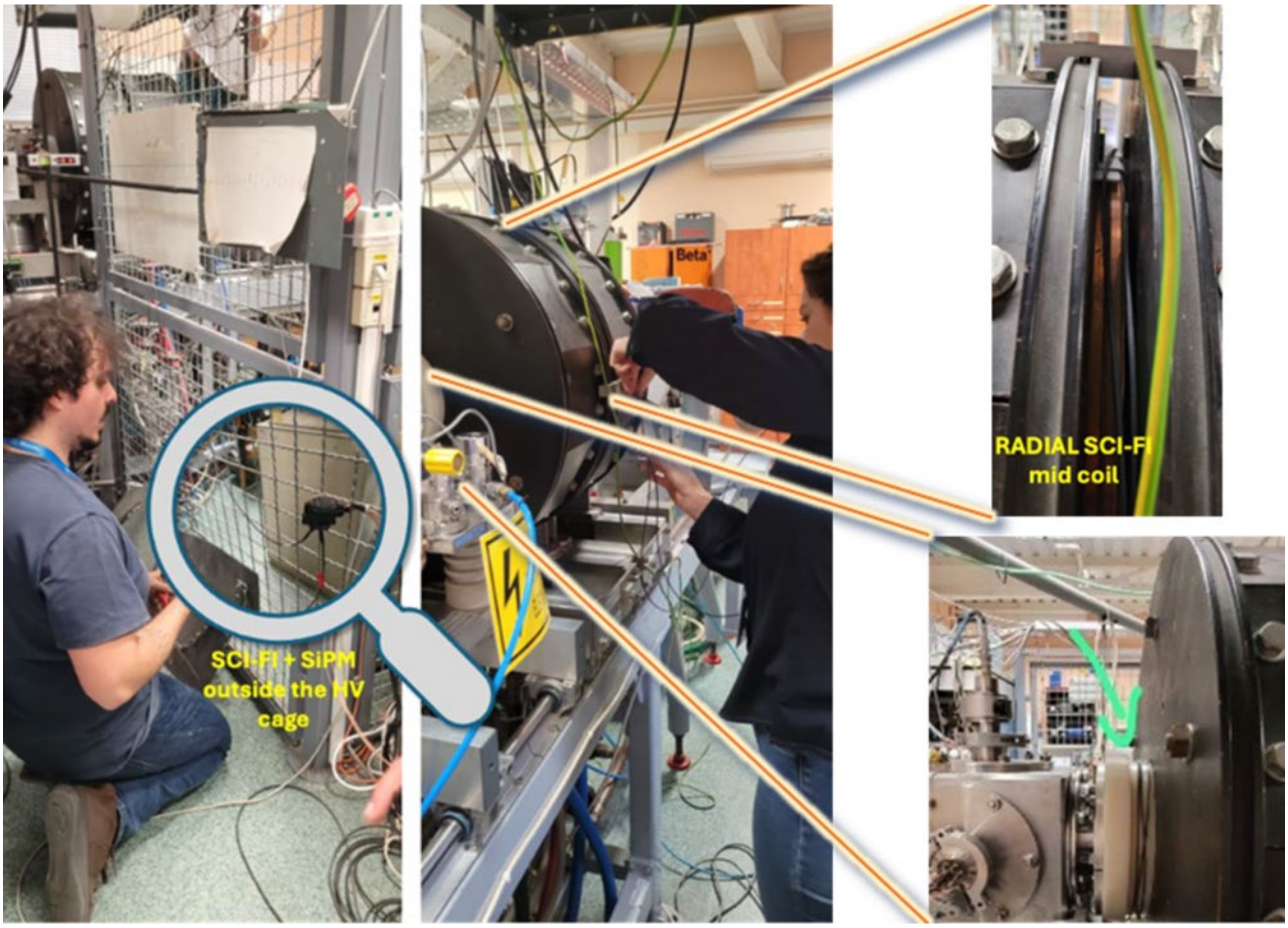


Fig. 24. Setting up the SciFi detector setup at the ATOMKI ECR ion source laboratory.

Experimental activities were done to investigate the short-term plasma instabilities by measuring the temporal behaviour of the extracted analysed ion beam, the reflected microwave power (P) and the high energy X-ray intensities emitted by the plasma and plasma chamber complex. Argon plasma was generated, and all the setting parameters were tuned to optimize Ar^{11+} current. The fast response of CsI(Tl) X-ray scintillator detector was used to trigger the measured beam and the plasma emitted RF power. It should be noted here that the RF detector measures the reflected power of the microwave directed into the chamber and the superposition of the microwave power pulse emitted by the plasma during the instability event. The emission event caused by the plasma instability is seen as a transient peak on top of the microwave power reflected from the chamber. The X-ray detector was placed close to the ATOMKI ECR ion source (but outside of its vacuum chamber) while the analogue output of the detector was monitored by a scope. The fluctuation of the ion beam and the reflected power were measured simultaneously. Three essential ECR settings parameters were systematically changed (starting from the optimized conditions) like gas pressure, microwave power and B_{min}/B_{ecr}, while the beam intensity and the presence of instability event were noted. In such a way parameter maps were recorded, and the stable operation phase-space were identified. Typical intensity map series of Ar^{11+} measured by the Faraday cup can be seen in Fig. 25 at four different pressures.

6E-7 mbar

B_{min}/B_{ECR}	100	300	400	500	600	700	800 W
0,6825		13%	13%	8%	10%	3%	
0,704		20%	22%	13%	10%	5%	
0,729		30%	28%	18%	9%	3%	
0,755		25%	55%	6%	3%	0%	
0,778		20%	15%	0%	0%	0%	
0,803		3%	0%	0%	0%	0%	
0,827		0%	0%	0%	0%	0%	
0,853		0%	0%	0%	0%	0%	
0,879		0%	0%	0%	0%	0%	
0,905		0%	0%	0%	0%	0%	
0,931		0%	0%	0%	0%	0%	

7E-7 mbar

B_{min}/B_{ECR}	100	300	400	500	600	700	800 W
0,6825	0%	9%	15%	20%	43%	43%	43%
0,704	1%	16%	26%	60%	64%	63%	58%
0,729	1%	38%	73%	82%	80%	80%	66%
0,755	3%	56%	80%	100%	20%	25%	0%
0,778	5%	79%	75%	35%	0%	0%	0%
0,803	8%	15%	6%	0%	0%	0%	0%
0,827	10%	1%	0%	0%	0%	0%	0%
0,853	6%	0%	0%	0%	0%	0%	0%
0,879	4%	0%	0%	0%	0%	0%	0%
0,905	0%	0%	0%	0%	0%	0%	0%
0,931	0%	0%	0%	0%	0%	0%	0%

1E-6 mbar

B_{min}/B_{ECR}	100	300	400	500	600	700	800 W
0,6825	0%	6%	10%	13%	17%	25%	30%
0,704	0%	7%	14%	25%	30%	33%	31%
0,729	1%	14%	25%	32%	36%	41%	33%
0,755	1%	17%	28%	33%	24%	23%	25%
0,778	2%	16%	23%	25%	18%	15%	0%
0,803	3%	10%	8%	5%	2%	1%	0%
0,827	4%	4%	2%	0%	0%	0%	0%
0,853	6%	2%	0%	0%	0%	0%	0%
0,879	1%	0%	0%	0%	0%	0%	0%
0,905	1%	0%	0%	0%	0%	0%	0%
0,931	0%	0%	0%	0%	0%	0%	0%

1.3E-6 mbar

B_{min}/B_{ECR}	100	300	400	500	600	700	800 W
0,6825	0%	0%	1%	3%	3%	4%	6%
0,704	0%	0%	2%	4%	5%	7%	8%
0,729	0%	0%	3%	6%	8%	12%	16%
0,755	0%	0%	5%	10%	13%	18%	22%
0,778	0%	0%	11%	18%	20%	25%	30%
0,803	0%	0%	14%	25%	31%	13%	6%
0,827	0%	0%	14%	10%	6%	3%	0%
0,853	0%	0%	15%	5%	3%	3%	0%
0,879	0%	0%	10%	0%	3%	1%	0%
0,905	0%	0%	5%	0%	0%	1%	0%
0,931	0%	0%	1%	0%	0%	0%	0%

Fig. 24. Relative Ar^{11+} beam intensity in the Pressure-Power-B_{min}/B_{ecr} parameter space.

The blue line presented in Fig. 20 divides the (Power-B_{min}/B_{ecr}) phase space to two regions. Settings corresponding to the upper regions provides stable plasma operation modes. At high B_{min}/B_{ECR} and high-power settings cause unstable plasma conditions and parallelly the beam intensity starts to drop. The beam intensities have been normalized in such a way that 100 % corresponds to the highest intensity of the parameter sweeps.

By recording these (B_{min}/B_{ECR} -P) scans at different pressures a multidimensional map can be generated. This map guides the operator to restore the stable operation conditions and to maximize the beam intensity. It also helps to minimize the beam contamination and wearing of the plasma chamber components and structures.

The feasibility of scintillating fibers to detect plasma instabilities were studied. The X-ray counts were measured as a function of microwave power and B_{min}/B_{ECR}-ratio. The quantum efficiency (QE) of Sci-Fi is quite modest being above 0.1% from around 50 keV up to nearly 800 keV. Fig. 21 shows the detected count rates for both parameters and for both the axial and the radial sensors. The experimental campaign was realized using the ATOMKI 14 GHz ECR ion source.

Observing the trends of Fig. 21, it is clear the Sci-Fi could capture the expected non-linear increase of X-ray dose emitted by the ECR plasma when increasing B_{min}/B_{ECR}. Notably, according to the past experimental findings, in the ATOMKI ECR the plasma becomes turbulent, owing to the kinetic cyclotron instabilities, at $B_{min}/B_{ECR} \geq 0.78$. As the Fig. 26 shows, the instability transient cannot be identified from the measured data. One can also note the difference in X-ray intensity measured at axial and radial directions, however it is not possible to conclude the anisotropy, since further consideration are required to estimate the geometrical and detection efficiency of the experimental setup placed at radial and axial directions.

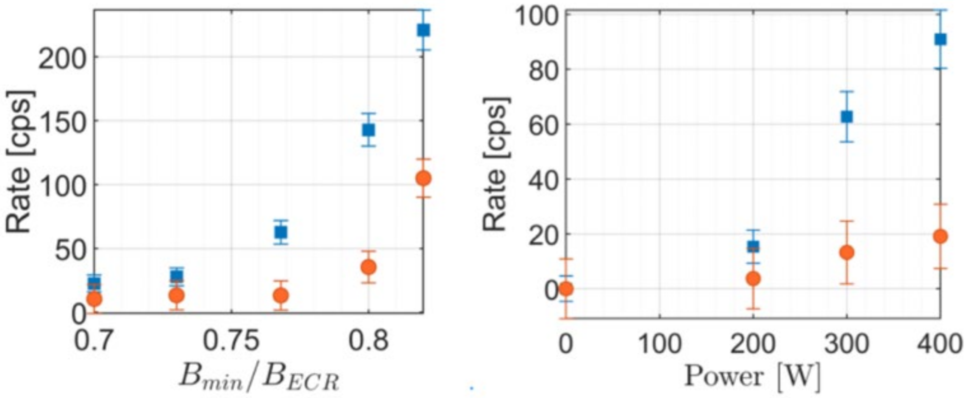


Fig. 261 Detected count rates as a function of B_{min}/B_{ECR} and microwave power. The blue and orange symbols denote the axial and the radial sensors, respectively

The Sci-Fi system demonstrated its intrinsic flexibility, enabling an easy and (very) fast installation around the ECR ion source and full compatibility with the HV. Optimal operation conditions were found for signal-to-noise ratio. The detector proved to be sensitive to the ECRIS physics: time integrated measurements provided reliable and meaningful responses and produced expected trends. However, in this preliminary test the setup could not measure adequate x-ray flux to define the instability threshold, i.e. the transition from stable to unstable plasma condition. The temporal baseline was not set optimally. By using other electronics, it is possible to get sub-msec temporal resolution. This approach has potential to be used as a low-cost solution for short-term plasma monitoring and therefore development work will be continued to discover its full potential.

According to the obtained results there are two already well tested, reliable and relatively cheap solution to be used to monitor the short-term plasma instabilities. Those are microwave emission monitoring by RF diode and hard X-ray monitoring by CsI(Tl) scintillator + SiPM detector system. The minimum requirements of the diagnostics are listed below:

Microwave emission monitoring:

- secondary waveguide attached to the injection plate of the plasma chamber, or a directional coupler attached to the main waveguide line to transfer the reflected RF to the diode,
- RF diode, which provides voltage signal proportional to the measured RF power,
- the RF diode must be protected by attenuators and more preferably by inserting a limiter before the RF diode and
- the temporal evaluation of the signal provided by the RF diode should be followed by an ordinary oscilloscope.

Hard X-ray monitoring:

- temporal resolution of the detector should be at least in the range of 100 us,
- thallium doped CsI scintillator coupled to a SiPM operated in photon counting mode,
- electronics providing analogue output proportional with the energy of the incoming photons and
- the temporal evaluation of the signal provided by the electronics should be followed by an ordinary oscilloscope.

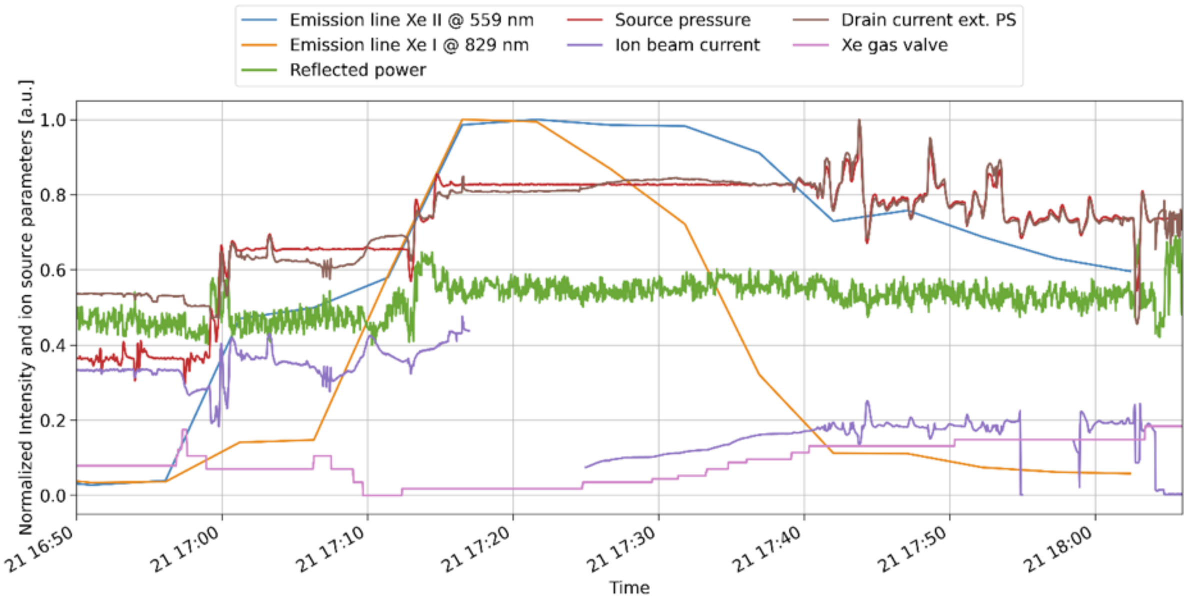
The scopes should be triggered. The trigger level may depend on the position of the detector and diode, on the given ion source and even on the ion source tuning parameters varying as a function of the ion type to be produced. Implementing the system seems easy to use but preliminary characterizations of the monitoring system (similar to Fig. 20.) are required to find the trigger parameters to reliably use the recommended systems for short-term plasma instability monitoring.

Contact for further information and/or advice for adapting the plasma instability diagnostics: Richard Racz (rracz@atomki.hu).

5.8. *Optical emission spectroscopy for plasma monitoring*

The goal of this subtask was to evaluate the feasibility and benefits of using the optical emission spectroscopy as a diagnostic tool to improve ion beam stability and operational efficiency in Electron Cyclotron Resonance Ion Sources (ECRIS). A diagnostic tool based on an optical emission spectrometer (OES) was installed at the ECRIS at the High Charge State Injector (HLI) and ECR injector setup (EIS) test bench of GSI to monitor plasma condition in real time. It has been shown that the measurement of the plasma spectral content in the visible wavelength range, which is obtained by the OES looking through the ECRIS extraction aperture, allows to analyse some features affecting the internal plasma and thereby improve the beam stability. For example, during ^{48}Ca ion beam operation the intensity of the Ca I emission line at 732 nm correlates with the amount of material in the plasma and the infrared part of the optical spectrum around 827 nm provides an estimate of the oven temperature. Monitoring the time variations of these spectral lines allowed to improve $^{48}Ca^{10+}$ ion beam stability and optimize material consumption. The work performed in ERIBS demonstrated that the OES can also be used for early instability detection during the production of gaseous beams, aiming to establish it as a reliable tool for ion source optimization and stability monitoring with any kind of extracted ion beam.

Experiments were conducted with argon, xenon, and krypton ion beams, measuring their visible spectral content with the OES diagnostic tool. These measurements were correlated with key ECRIS parameters such as the gas flow, the reflected microwave power, the source pressure, the ion beam current measured after the dipole magnet, and the drain current of the extraction power supply. Since no spontaneous plasma instabilities were observed, controlled parameter variations were introduced to simulate instability conditions. The response of the plasma to these changes was analysed, demonstrating that variations in specific emission lines (e.g., Xe 559 nm and 829 nm) provide valuable diagnostic signals. Fig. 22 shows the time variations of the xenon spectral lines at 559 and 829 nm together with the ECRIS settings during the operation with oxygen as support gas. Two ion source settings were selected to maximize the intensities of two different charge states: Xe^{18+} and Xe^{23+} beams. The setting change can be noted at 17:25 in Fig. 27 (upper). One can see that the intensity of the measured emission lines increases with the gas pressure thus affecting the microwave power to the plasma coupling, as well. The long-term stability of the Xe beam operation is shown in Fig. 27 (lower). At 14:45 and 15:45 the ECRIS has been optimized and the effect on the intensity of the measured emission lines is evident. The analysis of the data obtained for noble gases confirmed that the ion source operation remains stable as long as the ECRIS settings remain unchanged. However, when plasma conditions begin to drift, gradual variations in the intensity of specific emission lines can be observed. These changes often precede fluctuations in the extracted ion beam current, making OES a valuable diagnostic tool for detecting and tracking long-term drifts in plasma conditions that can impact ion beam intensity. These results confirmed that OES can serve as a tool for detecting and tracking drifting plasma conditions, that cause variations in beam intensity in gaseous ion beams, as previously shown for metallic beams.



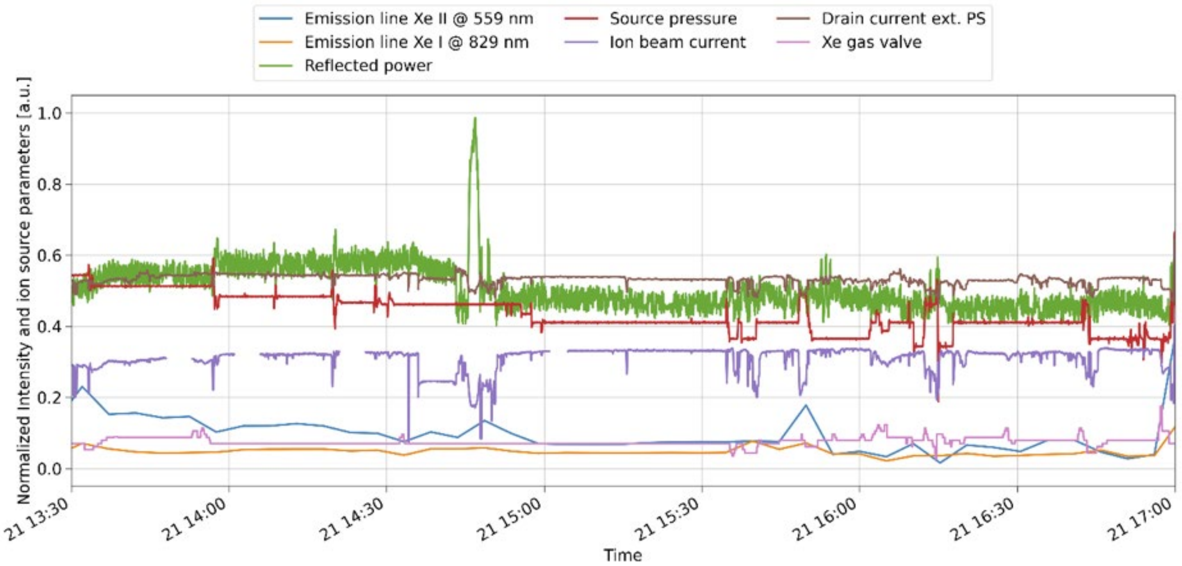


Fig. 27 Normalized ECRIS parameters and xenon emission lines intensity measured for 1.25 hours (upper) and for 3.5 hours (lower), respectively.

Additionally, the feasibility study concerning the use of the OES for gaseous elements has been extended to a dedicated study for mixed carbon-helium beams, motivated by their potential application in carbon ion therapy and helium radiography. Since $^{12}C^{4+}$ and $^{3}He^{+}$ cannot be distinguished in mass spectra, OES measurements at 465 nm (carbon) and 728 nm (helium) successfully provided an estimate of the C-to-He ratio, proving the benefits of OES for monitoring mixed plasma compositions.

To extend the OES diagnostic capabilities, a near-infrared spectrometer (950–1650 nm) was tested for monitoring of the oven temperature. A feasibility study at the EIS test bench showed that the calculation of the temperature using Wien´s Displacement law (λpeak·T=2.898 mm·K°) provides a reliable result only at the maximum oven power where the calculated temperature of T=1559° C matches the theoretical one (see Fig. 28). The results indicate that to accurately measure oven temperature, an OES system must cover at least the intermediate infrared range (3000–8000 nm).

Summary of achievements:

- Demonstrated OES feasibility for gaseous ion beams confirming its ability to detect plasma instabilities and potential to improve ECRIS performance
- Validated OES for mixed plasma composition analysis**,** specifically for C-He beams, enabling real-time monitoring of element ratios.
- Investigated OES for oven temperature monitoring**,** highlighting the need for extended infrared range for accurate temperature measurements.

Through these activities, OES has proven to be a valuable tool for detecting changes in plasma parameters, helping to prevent beam instabilities and optimize ECRIS operation.

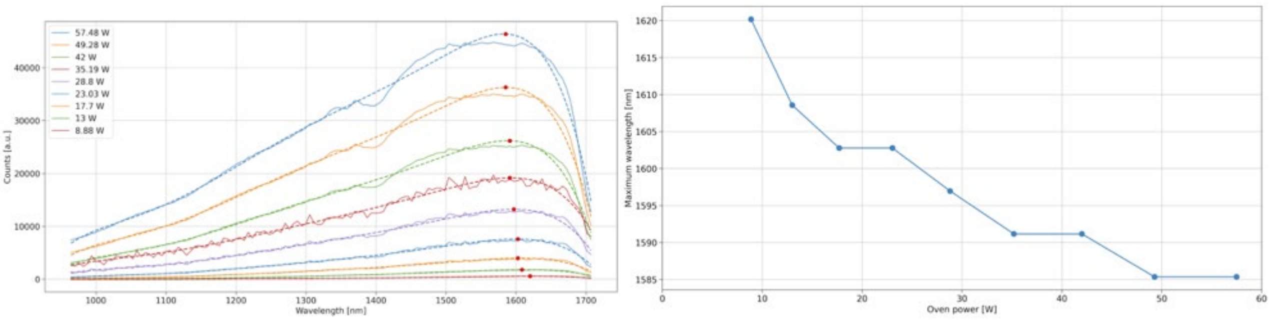


Fig.28 Near infrared emitted spectrum (left) and maximum wavelength at the highest count (right) for oven heating power.

An overview of recommended steps allowing to implement an online monitoring system using OES is given below. It should be noted that the actual implementation may require further customization and adaptation, which are based on the specific requirements, capabilities, and constraints of an individual ECRIS or LEBT.

Measurement setup:

- ***Selection of spectrometer:*** Choose an OES instrument with a sufficient spectral resolution, sensitivity and a spectral range covering key emission lines of the plasma species of interest, including near-infrared wavelengths for temperature estimations (for instance Ocean Optics QEPRO). For applications involving the monitoring of oven temperature, a spectrometer capable of detecting infrared radiation beyond 950 nm is recommended (for instance Ocean Insight Flame NIR+).
- ***Optical access to the plasma*:** An appropriate optical access point must be designed and implemented. A dedicated optical port flanged with a quartz window should be used. For example, each LEBT is equipped with a dipole magnet allowing for ions separation. The port used for mechanical alignment of the dipole chamber could be used for instance as an optical

port. The light collection system should be designed to efficiently capture emitted light and direct it to the spectrometer. For example, this system may include an optical splitter and a collimator. A tele-objective or reflector telescope should be used to focus the image before it is transmitted to the spectrometer, with its specifications depending on the beamline length and available access points.

- ***Data Acquisition and Processing****:* Establish a software interface to connect the OES instrument to a computer for real-time data acquisition. Ensure that the interface allows to continuously acquire the spectral data at a frequency appropriate for monitoring the ECRIS operation. Implement data pre-processing algorithms to select individual emission lines corresponding to the elements of interest and compensate for background level for accurate analysis, as well as calculate additional information such as a total integral or an integral of the infrared part of the optical emission spectrum during oven operation. Identify, either manually or with a dedicated algorithm, the emission lines corresponding to the ion species of interest. This can be done by comparing the acquired spectra with reference spectra or using the NIST database [https://physics.nist.gov/PhysRefData/ASD/lines_form.html]. Define stability metrics based on the acquired data to evaluate the long-term stability of the ECRIS plasma. This may involve trend monitoring or comparison with predefined stability thresholds.

This subtask demonstrated that optical emission spectroscopy can be utilised in many ways to improve the quality and operation of ion beams:

- One of the main advantages of OES is its ability to monitor plasma conditions without perturbations in real time, providing early indications of long-term beam intensity variations by detecting gradual drifts in emission line intensities. Beam intensity fluctuations caused by material over-evaporation or microwave coupling effects can be detected through changes in spectral line intensities. The ECRIS operators can take corrective actions before beam intensity drops, significantly reducing ion beam downtime.
- During gaseous ion beam production, feasibility studies with xenon, krypton, and argon confirmed that OES allows for the detection of drifting plasma conditions, that cause variations in beam intensity, making it a valuable tool for the ion beam stability monitoring.
- For metallic ion beams, particularly those produced from rare and expensive isotopes like ^{48}Ca, controlling material evaporation is essential. By detecting passive microwave heating of the oven, OES helps prevent unintended material over-evaporation, further optimizing material consumption. This is particularly beneficial for long-duration beam times, where material efficiency directly impacts operational costs.
- The ability of OES to provide real-time spectral data could open possibilities for its integration into automated monitoring and alerting system. This system could provide instantaneous feedback on the performance and alert the ECRIS operators if any instability or deviation from predefined thresholds is detected.

Contact for further information and/or advice for adapting the OES diagnostics: Fabio Maimone (F.Maimone@gsi.de) and Aleksandr Andreev (a.andreev@gsi.de).

5.9. Online beam monitoring using beam current transformer

In the framework of subtask, a measurement campaign was conducted to evaluate the feasibility of using the GSI Alternate Current - Current Transformer (ACCT) for detecting short-term ion beam intensity variations. The GSI ACCT has been specifically developed for pulsed ion beams, enabling monitoring of beam intensity without disturbing or interrupting the beam. The goal was to assess whether the ACCT could provide real-time diagnostic capabilities and contribute to a possible feedback loop for stabilizing ion beam intensity. The measurements were carried out with Chromium ion beam with the CAPRICE ECR Ion Source (ECRIS) at the High Charge State Injector (HLI) of GSI. A $\mathbf{^{54}Cr^{10+}}$ ion beam was produced via thermal evaporation using a resistively heated oven, with helium as a support gas. The primary ECRIS parameters related to ion source operation were recorded (see Fig. 24). These include the oven current, the support gas valve setting, the reflected microwave power, the ECRIS pressure, the $^{54}Cr^{10+}$ beam current measured after the dipole magnet, and the drain currents of the extraction and screening electrode power supplies. The ion beam current after the dipole magnet and chopper was measured using either the GSI ACCT or a Faraday cup (see Fig. 30). Both devices are equipped with electronics with a maximum bandwidth of 300 kHz, enabling the detection of transient beam current fluctuations on the order of up to 3.33 μs. However, the data acquisition system at GSI currently samples beam current at **50 Hz**, averaging the signal over the beam pulse length, meaning that rapid fluctuations below **20 ms** cannot be captured from the archived data. Despite this limitation, both, the ACCT and the Faraday cup successfully identified short-term beam intensity fluctuations caused by high-voltage discharges in the extraction system (see Fig. 31 and 32, respectively). The recorded data demonstrated that the ECRIS required approximately **1.5 seconds** to recover from these discharges and restore the desired $\mathbf{^{54}Cr^{10+}}$ beam intensity.

These results confirm that the current GSI ACCT-based diagnostic system can identify and track short-term ion beam intensity variations in real time. While the current system is limited by the 50 Hz sampling rate of the data acquisition, which restricts effective resolution to changes occurring over 20 ms or longer, the ACCT can detect transient changes on the order of microseconds. Upgrading the present data handling system could further improve its ability to detect rapid transient changes of the ion beam intensity.

Additionally, integrating the ACCT into an automated feedback loop would allow for dynamic tuning of the ECRIS parameters in response to short-term beam fluctuations. This could further enhance beam stability and potentially reduce the need for manual operator interventions during the ECRIS operation.

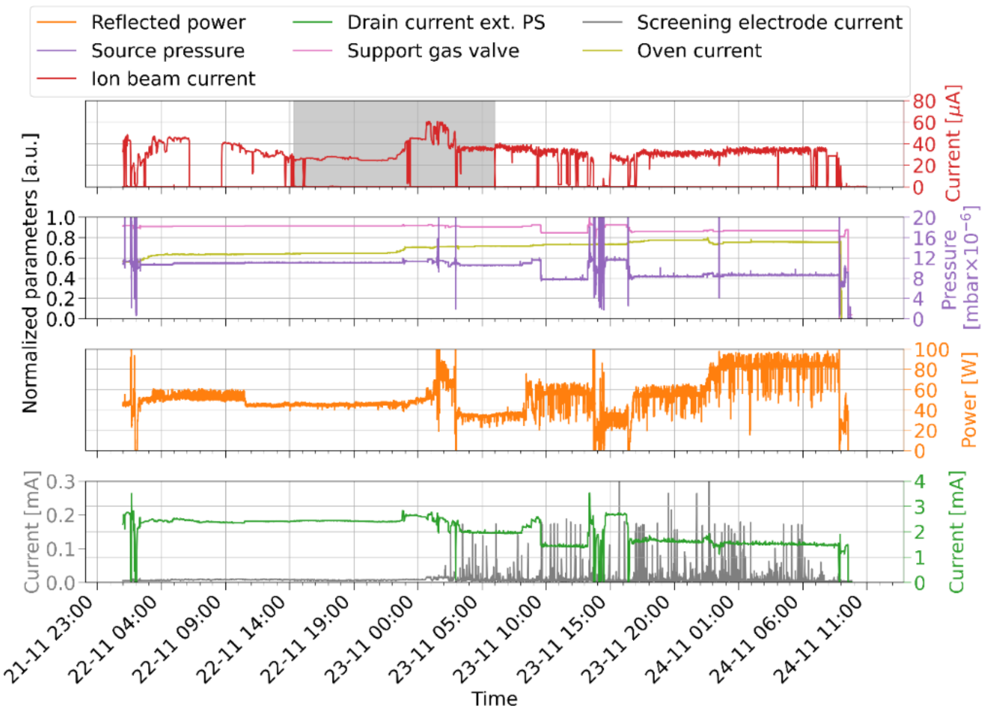


Fig.29 ECRIS parameters measured during ^{54}Cr operation. The grey shaded area marks the interval when Faraday cup was measuring the ion beam current.

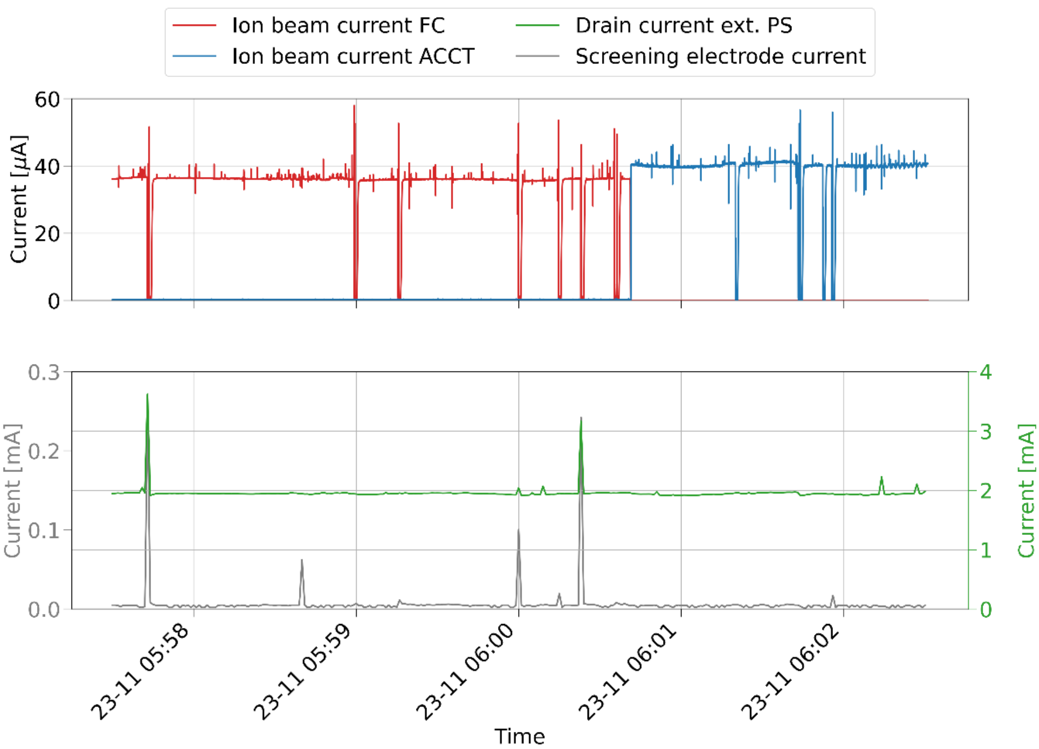


Fig.30 ECRIS current signals measured during ^{54}Cr operation, zoomed interval of 5 minutes. FC denotes beam current measured with the Faraday cup; ACCT denotes beam current measured with the beam current transformer.

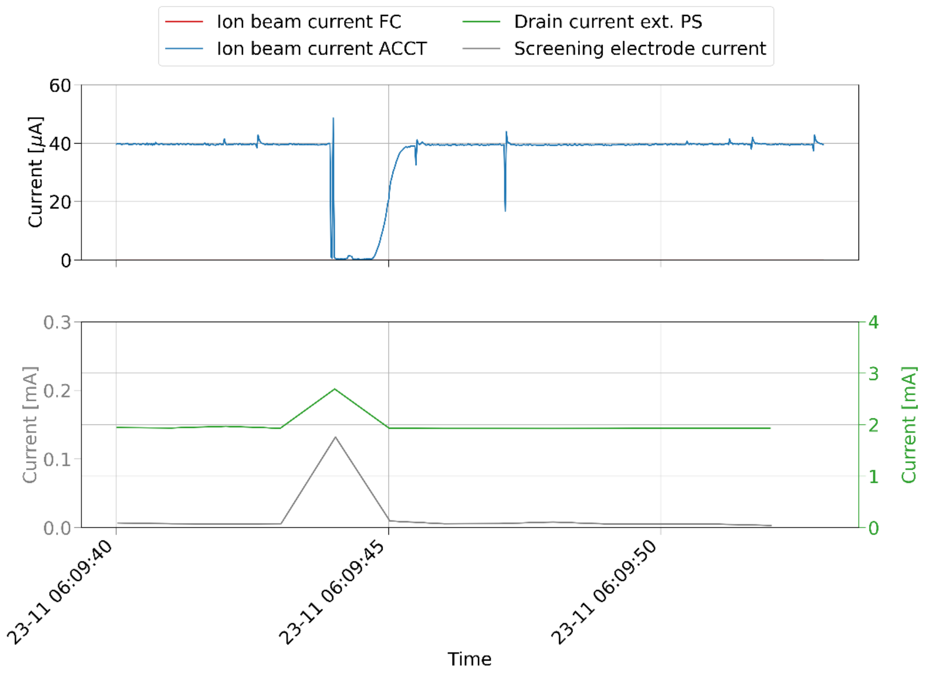


Fig.31 ECRIS current signals measured during ^{54}Cr operation, zoomed interval of 12 s. A beam current drop measured by the beam current transformer (ACCT) is caused by a high-voltage discharge in the extraction system.

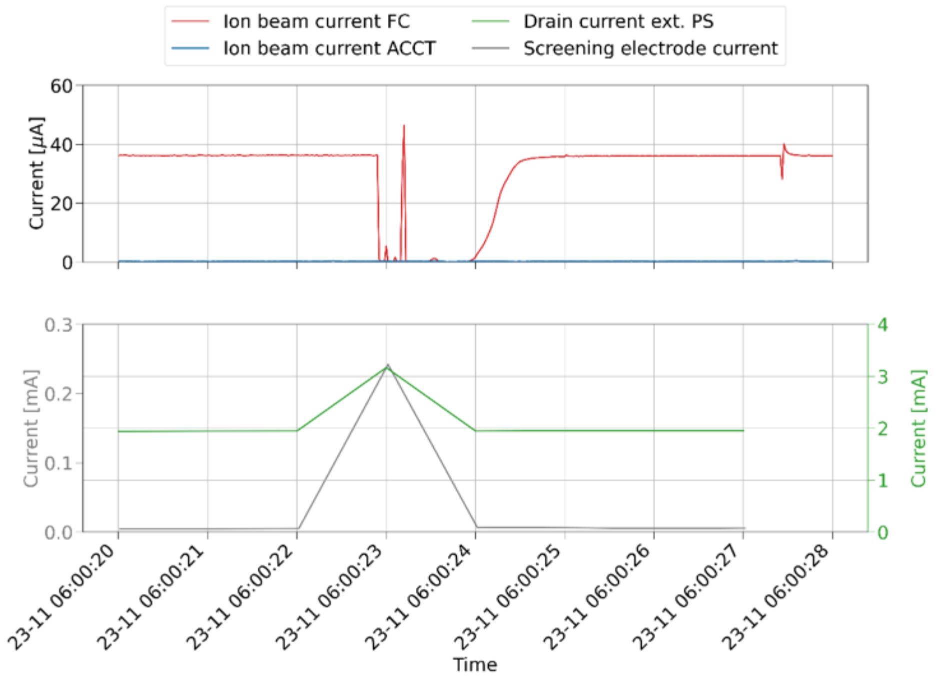


Fig.32 ECRIS current signals measured during ^{54}Cr operation, zoomed interval of 7 s. A beam current drop measured by the Faraday cup (FC) is caused by a high-voltage discharge in the extraction system.

Next, various current transformer options are presented for considerations of partner laboratories. Each may choose the option that best meets the requirements of the partner laboratory.

The GSI ACCT is optimized for measuring **pulsed ion beams**, with specifications including:

- **Current range:** 1 µA to 100 mA
- **Resolution:** 0.2 µA (full bandwidth)
- **Upper cutoff frequency:** 1 MHz (electronics limits effective measurement bandwidth to 300 kHz)
- **Maximum pulse length:** 8 ms

The device is suitable for laboratories operating with pulsed ion beams, such as GSI, where typical ion beam pulses are 5 ms long with a repetition rate of 50 Hz.

However, for **continuous (DC) beams**, the ACCT is not a suitable diagnostic tool due to its principle of operation. GSI has DC current transformers (DCCT, [1]) installed at the synchrotron, which could provide an alternative solution for monitoring DC beams. The DCCT specifications include:

- **Current range:** 300 µA to 1 A
- **Resolution:** 2 µA
- **Bandwidth:** DC to 20 kHz
- **Rise time:** 20 µs

This device can be used to monitor DC beams at laboratories operating in continuous mode, such as ATOMKI, INFN-LNS, INFN-LNL, GANIL, JYFL and UMCG-PARTREC. However, the relatively high lower detection limit of 300 µA restricts its application for low intensity beams, which should be considered when evaluating the feasibility of implementing the GSI DCCT by partner institutions.

The company Bergoz Instrumentation is one of the leaders in the production of current transformers and/ or analog electronics for the measurement of current of DC, CW beams and macropulses. It is worth mentioning here that Bergoz uses the term “CW beam” to refer to continuous beams that have a time structure, such as RF bunching, and the term “DC beam” is used for truly unmodulated, continuous beams. For instance, the CWCT is a current transformer with strict limits on lower and upper cut-off frequencies, tailored to the beam structure. Its lower cut-off assures negligible droop between bunches. Yet, droop is high enough to allow fast differentiation. Its upper cutoff is high enough to allow output signal return to baseline after each bunch, yet low enough to assure an output duty factor close to 50%. Thus, it is tailored to the bunch length, facilitating the measurement of short bunches. The main features are

- **Resolution** of 1 µArms (optional low-current version available with ≤ 8 nArms resolution)
- **Operating frequency:** from 15 MHz to 200 MHz
- **Response time**:1 µs

With this high sensitivity, the CWCT can be considered for use at facilities operating low-intensity continuous beams, including those in the 1–10 µA range. These features make the CWCT suitable for monitoring DC beams at partner laboratories such as ATOMKI, INFN-LNS, INFN-LNL, GANIL, JYFL, and UMCG-PARTREC, where low-intensity beams are commonly used. All the technical information together with the pricelist are available at [https://www.bergoz.com/products/cwct/]. If it is requested to measure the average beam current the New Parametric Current Transformer (NPCT) with large dynamic range, the wide bandwidth and high resolution make it the ideal instrument. The main features are

- **Full Scale Range** ±20 mA, ±200 mA, ±2 A and ±20 A

- **Resolution** down to 0.5 µA rms/√(Hz)
- **Output Bandwidth** from DC to 10 kHz (-3dB)
- **Linearity error** ≤ 0.1 %

The NPCT offers a broad dynamic range and sub-microamp resolution, which makes it suitable for laboratories in the EURO-LABS network operating either DC beams (ATOMKI, INFN-LNS, INFN-LNL, GANIL, JYFL, and UMCG-PARTREC) or pulsed beams, such GSI. All the technical information together with the pricelist are available at [https://www.bergoz.com/products/npct/].

5.10. Online beam monitoring using innovative q-1 diagnostic

In this innovative approach the beam of interest, having the charge state q, is transported towards the acceleration without measuring its intensity. Simultaneously, the beam stability and intensity variation of an adjacent charge state q-1 is continuously monitored after the q/m separation as is presented in Fig. 33. Here, it is assumed that in the case of highly charged ions the adjacent charge state (q-1) of the same element has practically an identical beam intensity behaviour when compared to the charge state of interest (q). Therefore, the adjacent beam can be used for the online beam monitoring and beam tuning to keep the intensity within the pre-determined values and to restore the beam stability. Ion beam simulations were realized to define the optimum location (S) for the movable FC and the resolving power at this location, i.e. the feasibility of the method. According to the simulations, the idea is feasible, after which the technical design work of the prototype was started. The design was completed in fall 2024 and the protype was ready for testing in May 2025. This innovative method also enables the monitoring of short-term beam instabilities and fast intensity changes, which is why this method opens new ion source plasma and beam formation related research.

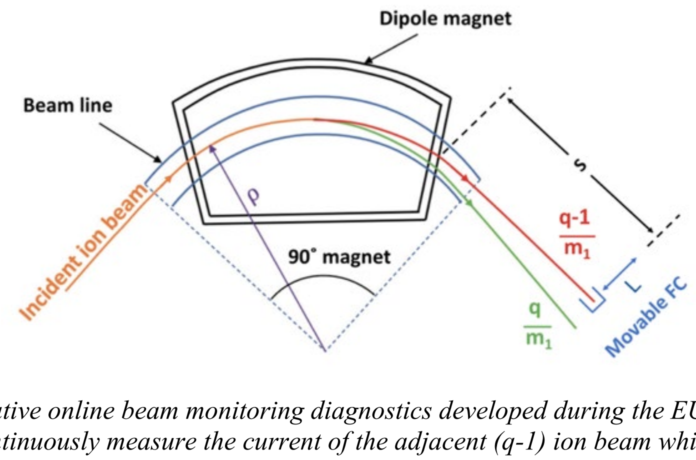


Fig.33 Idea of the innovative online beam monitoring diagnostics developed during the EURO-LABS/ERIBS project. Movable FC is used to continuously measure the current of the adjacent (q-1) ion beam while the beam of interest (q) is transported further in the beam line.

The objective of the feasibility study was to define and estimate following parameters with the aid of the beam transport simulations: 1) resolving power of q-1 diagnostics, 2) distance S (location) between the edge of dipole and movable faraday cup (FC) and 3) movement range L of the movable q-1 faraday cup. As a resolving power objective, it was decided that the q-1 diagnostics must be able to separate $^{54}Fe^{13+}$ and $^{16}O^{4+}$ ion beams at 10 kV extraction voltage. These beams are clearly separated in the conventional q/m spectrum of the JYFL 14 GHz ECRIS. This guarantees that the adjacent charge of highly charged ion beams at least up to xenon can be separated and therefore q-1 diagnostics, i.e. online beam monitoring, will be feasible for majority of the accelerated ion beams.

As is demonstrated by Fig. 34 the afore-mentioned oxygen and iron ion beams can be separated if the q-1 FC is located just before the collimator. Therefore, the q-1 faraday cup is located about 850 mm (S) from the exit edge of the dipole. It was also decided that the q-1 diagnostic must be able to monitor the intensity of O^{6+} ion beam while O^{7+} ion beam is transported further along the beam line. The simulation indicated that this is realised when the movement range (L) for the q-1 FC is at least 150 mm (see Fig 33).

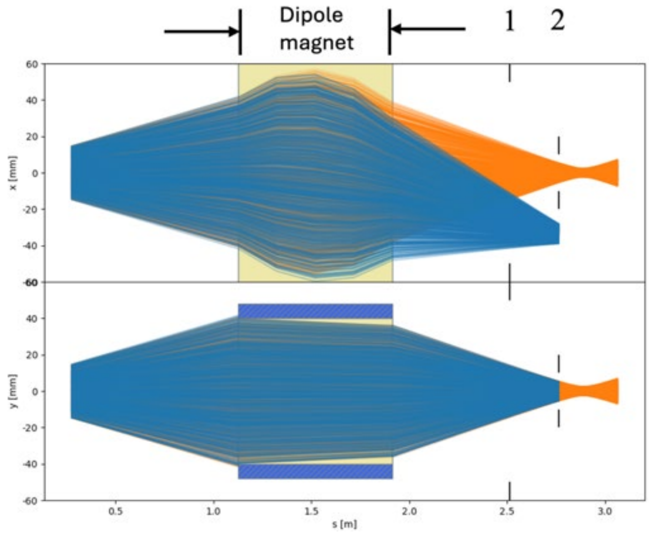


Fig 34 Beam transport simulation for $^{54}Fe^{13+}$ and $^{16}O^{4+}$ ion beams along the beam line axis. Figure shows the location of the dipole magnet, the starting point (1) of the present diagnostic chamber and the location of the collimator (2).

The technical design work was started immediately after the simulation results. As is presented in Fig 35 new vacuum chamber for the dipole magnet (A) and beam diagnostics (B) are needed to allow the access to the q-1 ion beam, the q-1 faraday cup (2) and for its moving mechanism (5). The technical work for the q-1 diagnostics was started in the beginning of 2025 and the construction was completed in May 2025. The new diagnostic setup showing its main components are shown in Fig 36.

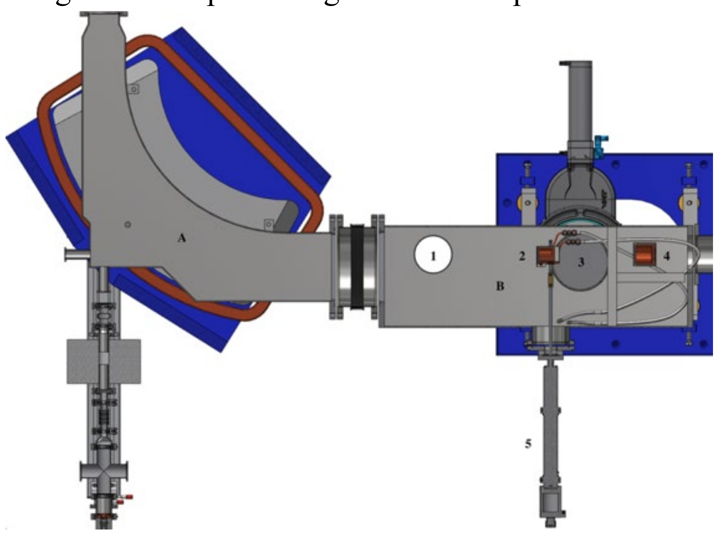


Fig 35 New vacuum chamber (A) for the dipole magnet and diagnostic chamber (B) for q-1 diagnostic setup. Other components are: 1) viewing port, 2) movable q-1 faraday cup, 3) collimator, 4) primary faraday cup for the charge state q and 5) the moving mechanism for the q-1 faraday cup.

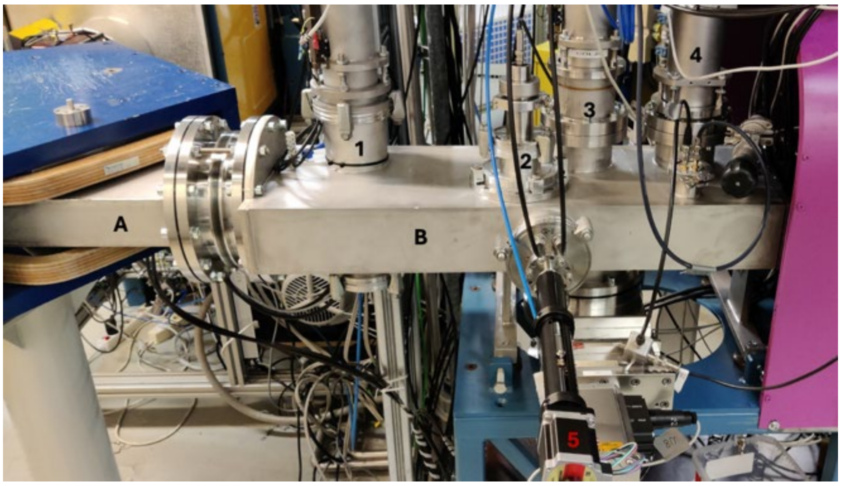


Fig 36 New vacuum chamber (A) for the dipole magnet and diagnostic chamber (B) for q-1 diagnostic setup. Other components are: 1) viewing port, 2) movable q-1 faraday cup, 3) collimator, 4) primary faraday cup for the charge state q and 5) the moving mechanism for the q-1 FC.

The commissioning of the q-1 diagnostics was started in May 2025 using oxygen beam. The charge state spectra were measured with both faraday cups, i.e. by using the primary and q-1 faraday cups. In this measurement the location of the q-1 faraday cup was 65 mm from the beam line axis. As Fig. 37 and 38 demonstrate the resolving power of the q-1 diagnostics is at least as good as in the case of the primary faraday cup. Therefore, the objective regarding the resolving power was clearly met. The q-1 faraday cup is smaller when compared to primary faraday cup which explains the lower ion beam intensity. The commissioning will be continued by studying and defining the correlation between the intensity behaviour of the primary and q-1 faraday cups. It can be concluded that this project has been a great success, enabling the online beam monitoring and opening new research opportunities. This diagnostic technology is now available to all EURO-LABS partners.

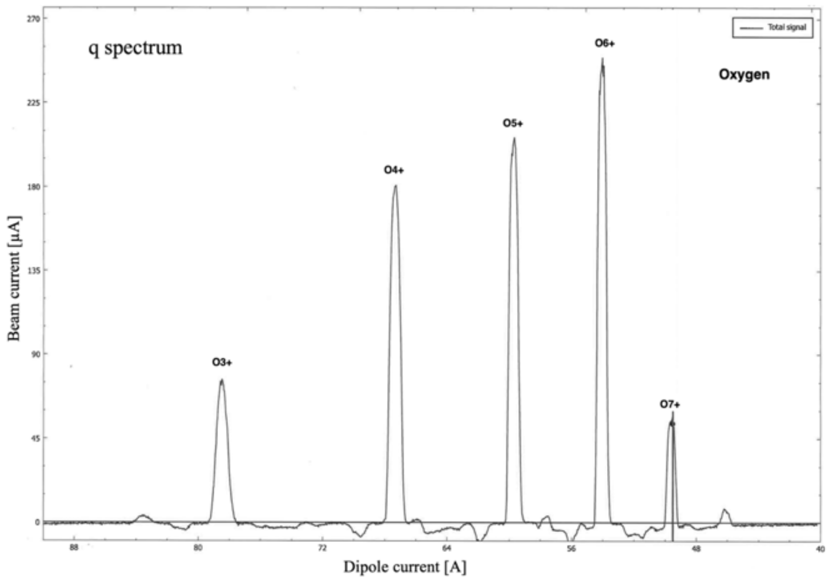


Fig 37 Oxygen spectrum extracted from the JYFL 14 GHz ECRIS at 10 kV extraction voltage. The primary faraday cup was used to measure the ion beam currents.

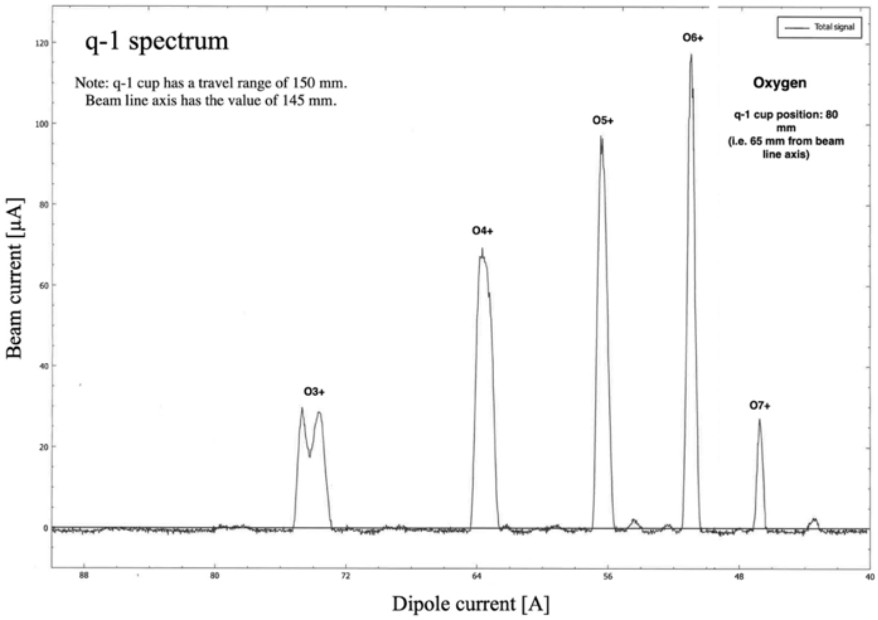


Fig 37 Oxygen spectrum extracted from the JYFL 14 GHz ECRIS at 10 kV extraction voltage. The q-1 faraday cup was used to measure the ion beam currents.

Contact for further information and/or advice to adopt the q-1 diagnostics: Hannu Koivisto (hannu.a.koivisto@jyu.fi).

5.11. Mini-FC for online beam intensity monitoring

At UMCG-PARTREC, in the framework of the EUROLABS-ERIBS program, an online intensity and stability monitor has been developed in combination with a semi-feedback loop to keep the beam intensity and stability within preset values. The online intensity and stability monitor measures the beam intensity in the unused phase-space of the ion beam. Unused as this part of phase-space is cut off by a collimator in the image plane of the analysing dipole directly downstream the AECR ion source. Additionally, a semi-feedback loop was created by presenting plasma variables on the side of the monitor to correlate the beam fluctuation/deviations directly to changing plasma variables. An ion source operator is now able to quickly evaluate the state of the plasma in the ion source and act on changing parameters to steer towards normal operating conditions.

A key issue for all accelerator operators is to develop the beam and keep all the involved systems stable while developing the beam through the accelerator systems. So, one of the main questions an operator deals with is: “Is the beam stable and do we have enough intensity? Even more, in situations where the intensity and/or stability is changing, “can we get the intensity and stability back as it was?”. As basically every measurement of the beam is destructive, a non-intercepting online monitor of the beam would be especially useful to have. Therefor the EUROLABS-ERIBS collaboration started the task of developing an online monitor in combination with a feedback loop as an added operator tool for beam development. At UMCG-PARTREC a method has been developed which makes use of the ions in a beam which are unused as these ions normally hit the collimator as they move on the outer perimeter of the beam. Therefore, in the image plane of the double focusing analysing magnet, a mini-faraday cup has been installed just on the side of the main collimator opening. The signal of the mini-Faraday cup signal is sampled, averaged, and the ripple is defined and presented constantly to the operator. Thanks to previous research on beam transport through the analyzing section, we have identified a location where the beam can be monitored continuously without disrupting ongoing operations. The beam stability monitor is fully integrated into the main control system and actively utilized by operators. It enables immediate detection of ion beam instabilities without the need for intrusive diagnostics, such as deploying the main Faraday cup. This non-destructive approach allows for continuous monitoring of source performance. The system is designed with simplicity in both hardware and signal interpretation. Its intuitive visualization of plasma parameters facilitates rapid identification of the underlying causes of beam drift and instability. In this sub-report, the design and construction are presented of the mini-faraday cup, electrical schematics is described sampling of the signal is discussed and measurements are shown as well as the presentation to the user (GUI).

In the past we have studied our analysing magnet, and it turned out that this magnet had large second order aberrations. To mitigate the effects of these aberrations, transport calculations for several ion-optical configurations were carried out to overcome these ion-optical defects by making use of proven analysis models. The most effective and cheapest solution was to install an Einzel lens between the ion-source extraction and the analyzing magnet. This Einzel lens improved our transport efficiency from 50 to 76% for 23kV helium beams. The use of the Einzel lens not only boosts beam intensity at the center of the beam spot but also alters the beam spot's shape on the collimator. The observed beam spot on the copper collimator closely matches the fifth-order transport simulations of the beam spot performed with COSY Infinity 9.1 (see Fig. 39a). The new beam spot exhibits four distinct tails. Fig. 39a shows the 6 mm diameter aperture of the collimator and the 3 mm diameter opening of the mini-Faraday cup. One of the lower tails is used to parasitically sample a fraction of the analyzed beam. The mini-Faraday cup is positioned as close as mechanically possible to the 6 mm aperture to ensure optimal signal collection without interfering with the main beam path. While scanning with the magnetic field of the analysing dipole and measuring both signals, one sees that the maximum of the mini-faraday cup and the maximum of the main faraday cup do not match (see Fig. 34b). A future step would be to position the mini-FC better to the tail.

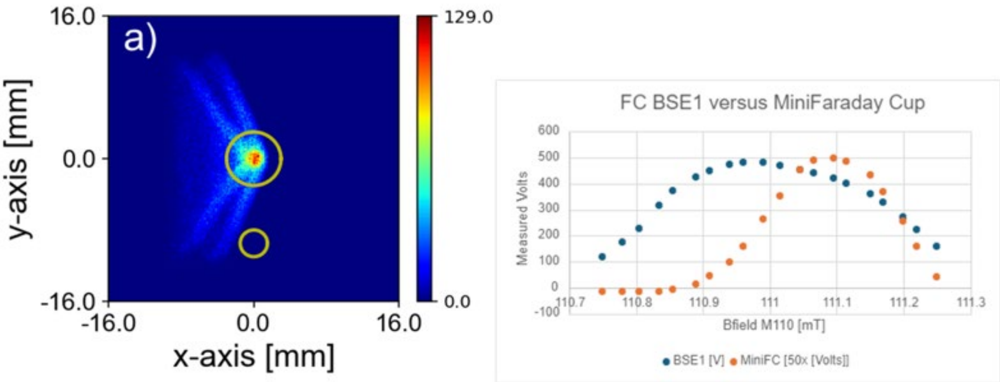


Fig. 39a) Fifth order COSY 9.1 density calculation of the beam spot on the collimator. The large circle is the collimation aperture of 6 mm diameter, and the small circle is the opening of the mini-FC 3 mm in diameter. b) beam intensity as function of the magnetic field dipole analyser.

The signal from the mini-Faraday cup is read in by an ADC from a NI-card with a rate of 1kHz and calculates online the average and standard deviation when the monitor is switched on. In our setup, the beam gets sampled by 1000 samples (x_i) per 1 sec. From these samples, the average is calculated and the standard deviation of the ripple on the signal. As a result, an accurate measurement of the average beam intensity as well as the ripple over one second are obtained. One should realize that this easily can be modified by averaging over 100 seconds or around 0.01 seconds and getting a monitor signal of the intensity and stability measured over 100 sec or 0.01 sec. It is even possible to have several monitors over different time domains. It is up to the designer of the monitor what to monitor. Averaging over smaller time domains requires higher sampling rates and more expensive hardware.

The mini-faraday cup (Fig. 40b) is mounted in the collimator (Fig. 405a), which is in the image plane of the double focusing dipole magnet downstream of the AECR ion source.

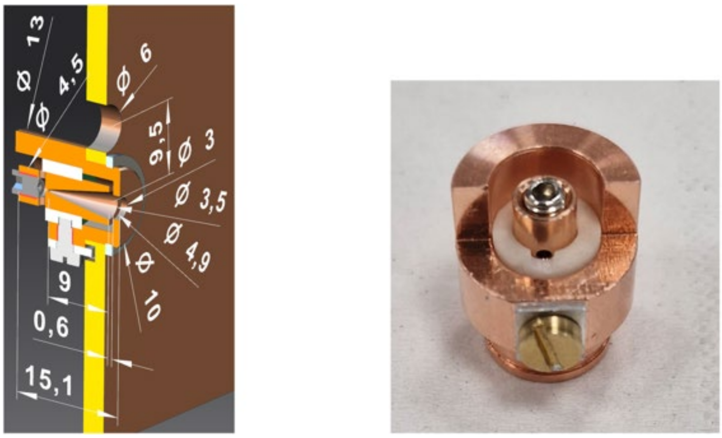


Fig. 40 a) 3D CAD drawing with measurements of the mini-FC, b) photo of the mini-FC from the back side.

The centre of the small faraday cup is located 9.5 mm vertically lower than the centre of the main collimator. The mini-FC consists of a copper cylinder of 11 mm long with a cone inside with a length of 9 mm and is electrically isolated by alox-spacers (white material in Fig. 35b). The entrance aperture of the mini-FC is 3.5 mm in diameter. The opening in the copper collimator is 3 mm in front of the cone. The ring in the front fixes the faraday cup to the collimator plate. The screw on top of the mini-FC fixes the rotation and the screw in the back is used for to tighten the electrical connection.

The mini-FC is isolated from the main collimator it is built on. The main collimator is grounded as it is enclosed by an aluminium oxide holder. The signal of the faraday cup is led outside the vacuum by a feedthrough with a SHV connector in atmosphere. On atmosphere the signal is led to a current to voltage amplifier i.e., the low noise DLPCA-200 current amplifier from FEMTO. We make use of this device to filter out the noise which has been put on the beam (3dB cutoff 50kHz). Subsequently the output signal is led over 5m by an RG59 cable to an input module PCI-6023 budget I/O card of NI and at the same time it is also going to an oscilloscope to present the monitor signal to the ion source user/operator (see Figure 13).

Several plasma variables are monitored to provide a semi feedback loop for the ion source operator, i.e. drain current of the extraction voltage, the bias disk current, the pressure in the plasma chamber, and the reflected rf power. To monitor also the ion-optical stability, we have also read in the magnet field of the analysing magnet as well as the lens voltage. These variables are read into the mainframe with different sampling rates and resolutions. Reflected rf power is read in by the NI card in the PC which gives a high-resolution signal. The drain current and bias disk also have a high-resolution signal. This in contrast with the pressure signal, which has a very low resolution of 0.4 x10-7 mbar on a pressure in the order of 1 x 10-7 mbar and needs to be upgraded preferably to a resolution of 0.04 x 10-7 mbar as small pressure changes have a large effect on the production of high charge state ions.

The Graphical user interface (GUI) is designed from the premise to normalize all values to one moment in time. The moment in time when the ion source specialist hands over the beam to the accelerator operator. At that moment the references for normalization are made (top horizontal row in the GUI) and all deviations of parameters are seen with respect to that reference in percentage (horizontal row of coloured bars in Fig. 41). The actual value of each parameter can always be followed visually in time (second horizontal row from the top). An extra parameter is created out of the intensity and the standard deviation (s.d.), which I call for now "beam quality" as the beam quality is defined as the intensity divided by the s.d. High beam quality means high intensity and low ripple. A stripped version of this LabVIEW GUI is operational in our main control system VISTA and presents the normalized variables to the accelerator operators. Operators find it it useful tool as the source status can be always seen during the beam development process.

Four measurements will be described here, i.e. an explanation of the graphical user interface in operation during a 23kV 16O^{4+} ion beam, proof of principle test of the methodology how to measure intensity and stability during a frequency scan of the plasma scanning measurement of the new TWT system, a 7 hour monitor measurement and a measurement of a cross correlation between the Main FC (BSE1) and the mini-faraday cup.

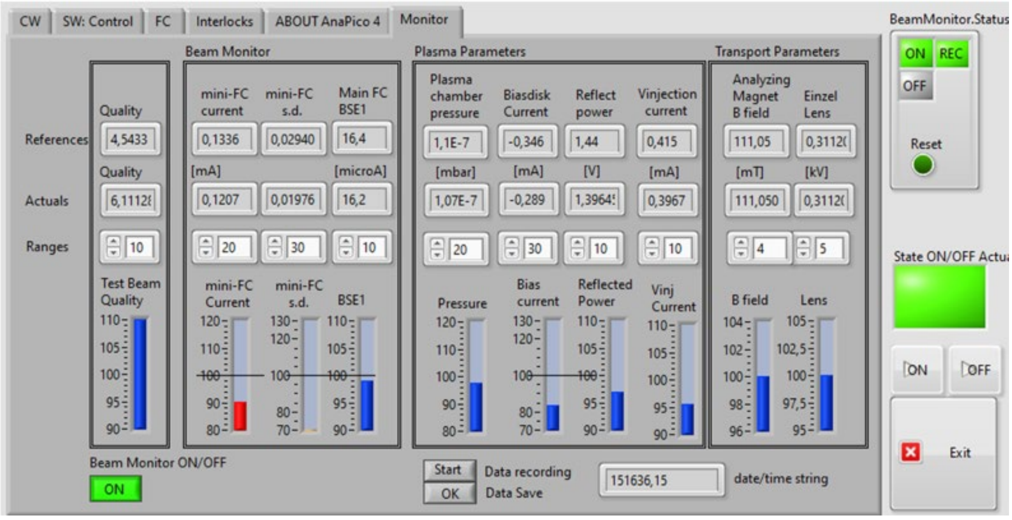


Fig. 41 Snapshot of the GUI of the beam monitor of a 16.2 µA, 23 kV $^{16}O^{4+}$ beam after 2 hours.

In Fig. 41, one sees a snapshot of beam delivery after 2 hours of running 23 kV $^{16}O^{4+}$ beam. One can see that the Main Faraday cup BSE1 dropped 1% while the mini-FC dropped 10%. The stability increases as the standard deviation (s.d) went down from 0.029 to 0.019 more than the 30% range it was set to. The beam quality has improved significantly since the start of the delivery. Furthermore, one sees that the optical parameters were not changed. The magnetic field was still 111.050 mT. What you do see is that the bias disk dropped 18% and the drain current from the extraction voltage supply dropped 4%. As the main current only dropped 1% but the beam quality improved more then 30%.

The method to measure the beam as described under "signal sampling of the mini-FC" was tested for the first time in a characterization experiment after the installation of a new TWT generator. Part of the characterization experiment entailed a measurement of the beam intensity and beam stability (measured by the main FC as the mini-FC was not constructed yet) as a function of the RF plasma heating frequency (Fig. 42) In the measurement, the frequency is increased in steps of a MHz This resulted in an intensity distribution as a function of the plasma heating frequency. It turned out that we were able to find stable regions in frequency in the beam stability domain. (see Fig. 42). This proved that the sampling method was working but had not yet been executed on the mini-FC.

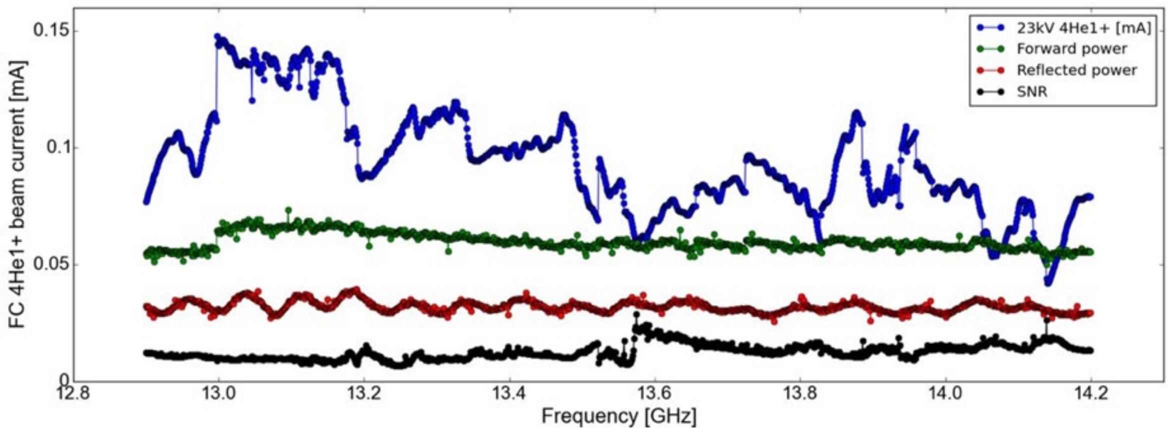


Fig. 42 The intensity of a 23kV $^{4}He^{+}$ beam as function of the frequency, combined with the forward and reflected power and s.d. of the intensity signal.

The mini-FC was used in an experiment to produce a 23kV $^{16}O^{4+}$ beam and accelerated this beam to an energy of 30 MeV/u with the AGOR accelerator and delivered this beam to the experimental setup. This was repeated three times over three days for operator training and optimization purposes. On day 3, the ion source parameters were recorded. In Fig. 43 the normalized values are plotted. After 50 minutes the pressure was lowered by the operators and put on automatic pressure control, keeping the pressure constant in the plasma chamber on 1.4x10-7 mbar. After a bit more than 2 hours the operators tried to see if an ion source pressure change would lead to a better result. This turned out to be negative. At about three hours an increase is seen in the intensity and a decrease in the ripple on the signal. No effect was seen on the plasma parameters. I presume that the analysing magnet was changed and therefore we saw no changes in the plasma parameters.

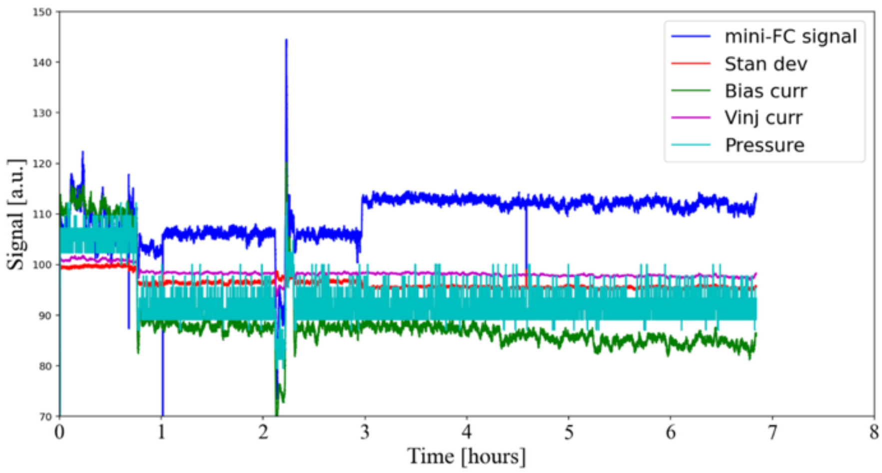


Fig. 43 Recorded normalised parameters using the developed online monitoring system.

Here we compared the mini-FC signal with the main FC signal. Again, a 23kV ^{16}O4+ beam is produced and both signals, mini-FC and main faraday cup, are measured for more than 5 hours. In Fig. 44, one can see a cross correlation between the main FC and the mini-FC after 4.5 hours in which the main faraday was taken out of the beam. No effect was seen on the signal from the mini-faraday cup. Fig. 45 shows the other intensity correlation between the main and mini Faraday cup.

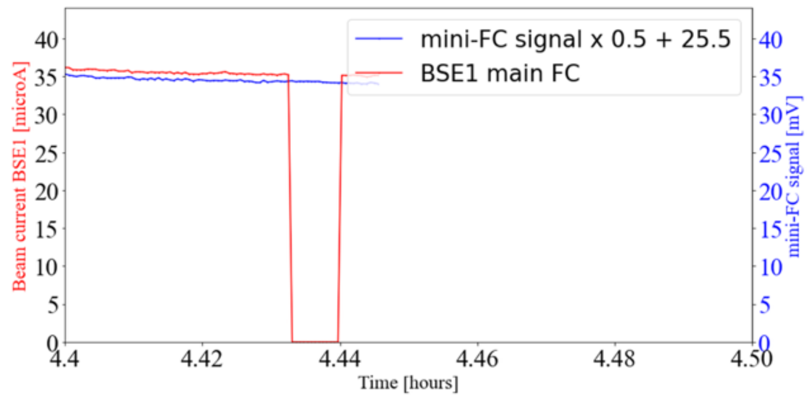


Fig 44 Measurement of a 23kV $^{16}O^{4+}$ beam where in blue the signal is seen of the mini-FC and in red the signal from the main faraday cup. The peak down shows that the main cup is removed to let the beam through. In blue, you see no effect on the monitor.

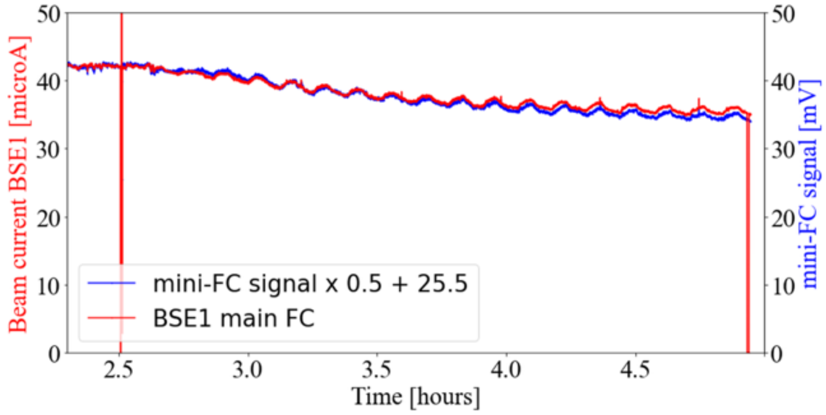


Fig. 45 The correlation between the main Faraday cup and the mini faraday cup during the monitoring of about 5 hours. The measurement demonstrates good correlation and how the intensity of mini-FC closely follows the small ripple in the main signal.

Operational tuning of ion optical transport components—such as the analyzing magnet, extraction lenses, and vertical correction coils—located immediately downstream of the ion source can induce measurable changes in the beam current, as detected by the mini-FC monitor. To identify the source of such variations, it is essential to plot the monitor signal alongside the setpoints of the beam transport elements. When these setpoints are normalized to a common starting time and displayed concurrently with the monitor signal, correlations become evident. This approach allows for the direct attribution of signal changes to specific transport element adjustments. Therefore, for effective drift analysis and beam stability diagnostics, the mini-Faraday cup signal should be plotted in parallel with the analyzing magnet field strength, extraction lens voltages, and vertical correction coil currents.

Before an Electron Cyclotron Resonance (ECR) plasma reaches a stable state—where the heating from the RF power is balanced by the plasma's cooling mechanisms, resulting in a constant temperature of the plasma chamber wall—a stabilization period of several hours is typically required. In contrast, beam extraction for accelerator operation usually occurs within the first hour of startup. Consequently, when the beam is handed over to the accelerator operator, the plasma has not yet reached thermal and dynamic equilibrium.

This lack of equilibrium is evident in the drifting plasma parameters observed during this early phase. The effect is particularly pronounced if a different ion species was used the previous day, as residual conditions can influence the plasma behavior. While the beam demonstrates good overall stability, initial instabilities are consistently observed during startup.

It is also important to note that during the example run (Fig. 38), the operating pressure was deliberately reduced and stabilized at 1.4×10^{-7} mbar. This adjustment moved the system away from parameter regimes associated with plasma mode hopping, resulting in significantly improved operational stability.

Two observations can be highlighted: first, the mini-FC is more sensitive to noise measurements than the main cup. This is still a mystery. According to the measurements there are more ripple on the perimeter of the beam and at the centre. Second, it became clear that the resolution of the pressure signal is low. This means that small pressure changes over time can hardly be seen. This can cause that plasma can act very differently if the pressure changes a little bit.

Contact for further information and/or advice to adopt the mini-FC diagnostics: Rob Kremers (h.r.kremers@rug.nl).

5.12 Conclusions and outlook

The ERIBS project had two main objectives to improve the operation and ion beam services for the EURO-LABS infrastructures: 1) improve the production and availability of metal ion beams and 2) improve the stability of ion beams. Several approaches were taken to ensure that the objectives of the project could be met. As was demonstrated by the sub-reports of this deliverable document, remarkable improvements were made, and the objectives of the project were met.

During the project a MIVOC service concept was established to make enriched MIVOC beams available to all partner laboratories. This concept substantially increases the intensities of several ion beams needed for the nuclear physics experiments. In addition, the know-how for the implementation of the MIVOC technique was successfully transferred from IPHC and JYFL to INFN-LNL. Despite the installation not yet being in the final optimized condition, a Fe^{10+} beam has already been easily produced, with an intensity and a charge-over-mass ratio suitable for the acceleration with the PIAVE-ALPI complex. The implementation of the MIVOC technique is an important step forward for INFN-LNL from the point of view of the possible beams available for the users. It will in fact open a possibility for the development of new beams or an easier way to produce the already available ones, as in the case, for example, for the isotopically enriched beams of Mg.

Significant improvements were made to the evaporation ovens in terms of their performance and usability. The solution for the issues of the previously abandoned JYFL foil oven were found which made it possible to use it for elements requiring high evaporation temperature. This extended the safe oven operation temperature at JYFL from around 1200˚C (JYFL miniature oven) to 1800˚C. In addition to this development the IPHC team has successfully developed and tested the inductively heated high-capacity oven. The final tests are still to be done but it is assumed that this oven will further extend the maximum temperature of the evaporation ovens available for the EURO-LABS laboratories.

Several approaches were taken also to improve the short- and long-term ion beam stability. The work, for example, demonstrated that the adoption of optical emission spectroscopy (OES) as a diagnostic tool for ion beam production could provide significant advantages to facility users. It can provide more stable and reproducible ion beams, which improves the reliability of the facility. It also reduces downtime, allowing for longer operational periods without interruptions. It may also yield more efficient material use, ensuring that rare isotopes are used efficiently. During the project, the most cost-effective ways to detect plasma instabilities were also determined. Detailed instructions are provided for implementing this diagnostic and to generate multidimensional operation parameter map, which guides the cyclotron operator to restore stable plasma conditions and even to avoid unstable operation space. The instability diagnostics will improve both short- and long-term beam stability and therefore have a positive impact on the operation efficiency of the entire infrastructure.

As a result of the ERIBS project, several options are offered for the online beam intensity monitoring. Commercial option was studied for specifications for different ion beam intensities and operation modes of accelerators. The commercial diagnostics was readily available, but it is not feasible for all conditions and partners. Therefore, in addition to this option, two innovative approaches were studied and developed to meet the needs of the EURO-LABS infrastructures. The first of the new innovative methods is the so-called mini-faraday cup. It has proven to be important and effective tool for the online beam monitoring, and it can be used to monitor both short- and long-term beam stability. The diagnostic is fully integrated into the main control system of PARTREC and actively utilized by operators. The beam stability monitor offers promising avenues for further application and enhancement. Two potential uses include dynamic adjustment of cyclotron radial probe scanning based on real-time beam fluctuations, and providing a continuous ion source signal to experiments for correlation or compensation of beam-related effects. Despite its effectiveness, further investigation is needed. For instance, it remains to be determined whether the system performs equally well for high-charge-state ion beams (xenon), which typically exhibit lower emittance. Additionally, the correlation between signals from the mini-FC and the main Faraday cup under varying RF power conditions is an area of ongoing investigation. Enhancing temporal resolution by adding shorter (0.01 s) and longer (100 s) averaging windows would allow for more comprehensive stability analysis across different timescales. A significant improvement in signal-to-noise ratio can be achieved by optimizing the mini-Faraday cup's position relative to the beam density distribution (see Fig. 34). As a conclusion, the monitor represents a valuable diagnostic tool, enhancing operational insight and contributing to more stable beam delivery in accelerator environments.

The q-1 concept is another innovative solution for online ion beam monitoring. In this approach the adjacent charge state is continuously monitored while the charge state q of the same element is transported further towards the accelerator. The idea was first studied with ion optical simulations and after a successful feasibility study the technical work for the prototype was started at JYFL. The first results exceeded the expectations. The specifications of the q-1 setup will be studied further, including, for example, further studies of the correlation of ion beam intensity beahviour between the charge state of interest (q) and the adjacent charge state (q-1). When combined with the plasma stability monitoring, the setup allows simultaneous monitoring of plasma and ion beam stability without disturbing the beam transport to the accelerator. This provides a new tool when, for example, it is necessary to resolve the origin of ion beam instability (plasma versus beam formation and extraction). The q-1 diagnostics has also a remarkable potential in the field of fundamental ion source research.

As a next step, all developments and improvements will be made available to all partner laboratories for the maximum utilization of the service improvements in the EURO-LABS infrastructures.

CONFERENCE PAPERS

H. Koivisto, et. al. European effort to improve highly charged heavy ion beam capabilities with ECR ion sources (invited), In *20th International Conference on Ion Sources, ICIS2023*, IOP Publishing. Journal of Physics: Conference Series, 2743, (2024), Article 012049.

WORLD WIDE WEB DOCUMENTS

Koivisto H., (2022), *Website for European collaboration on ECR ion sources, ERIBS*, Available from: https://jyufi-fys.atlassian.net/wiki/x/FgBB [Accessed 8 July 2025].

6. INTRANS (2.5.5)

The INTRANS (INstrumentation and Training for Nuclear Spectroscopy and Reaction Dynamics) Service Improvement subtask of the EURO-LABS Horizon EU program, promotes the coordination between the research infrastructures and research groups involved in nuclear spectroscopy and reaction studies, to optimize the use of valuable resources and enhance synergies among researchers on a broad European scale for frontline research in these fields. The milestone MS16 reports on the hands-on training schools organized by INTRANS. The full document is available on the euro-LABS website as milestone report (https://zenodo.org/records/15039933). An additional workshop has also been planned at Legnaro National Labs in Italy during Feb 2^{ND} -5^{TH} . More details are at https://agenda.infn.it/event/46675/.

ANNEX: GLOSSARY

Acronym	Definition
ATOMKI	Institute for Nuclear Research, Hungarian Academy of Sciences
CsI	Cesium Iodine (scintillation detector)
CsI(Tl)	thallium doped cesium iodine
CNRS-IPHC	Centre National de la Recherche Scientifique - Institut Pluridisciplinaire Hubert Curien
CNRS-LPSC	Centre National de la Recherche Scientifique – Laboratoire de Physique Subatomique et de Cosmologie
ERIBS	European Research Infrastructure – Beam Services
ECR	Electron Cyclotron Resonance
ECRIS	Electron Cyclotron Resonance Ion Source
FMI	Intense Metallic Beams (in French)
GANIL	Grand Accélérateur National d'Ions Lourds
GUI	Graphical User Interface
INFN-LNL	Instituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro
INFN-LNS	Instituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud
JYFL	Jyväskylän Yliopiston Fysiikan Laitos (University of Jyväskylä Department of Physics)
MIVOC	Metal Ions from VOlatile Compounds
OES	Optical Emission Spectroscopy
Sci-Fi	Scintillating Fibers
SiPM	Silicon PhotoMultiplier
UMCG- PARTREC	University Medical Centrum Groningen - Particle Therapy Research Center