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European effort to improve highly charged heavy ion beam capabilities with ECR ion sources (invited)

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Abstract. The European Electron Cyclotron Resonance Ion Source (ECRIS) community has more than 20 years of experience working together in various EU-funded projects. In the recent project, called ERIBS (European Research Infrastructure – Beam Services), the community will focus on improving ion beam services for the EURO-LABS (European-Laboratories for Accelerator Based Sciences) research infrastructures. The EURO-LABS is a four-year project funded by the Horizon Europe program of the European Commission for years 2022 - 2026. In the ERIBS collaboration the best expertise, know-how and practices of the ECRIS community will be exploited and transferred between the partners to take full advantage of the European ion source infrastructure. The aim is to extend the beam variety available for the European user community by developing beam production methods and techniques. This development includes further improvement of technologies related to high temperature ovens, axial sputtering and MIVOC method for all the participating laboratories. We will also aim to improve both short- and long-term plasma and beam stability, as well as methods for online monitoring of these conditions. This can be 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. An example of the recent developments is the new collaboration proposed by the CNRS-IPHC team to synthesize enriched MIVOC compounds for the other ERIBS partners. For example, the team successfully prepared an enriched chromocene compounds, which were needed to produce intensive ^{54}Cr and ^{50}Cr beams for the JYFL and GANIL nuclear physics programs, respectively.

1. Introduction

The ERIBS (European Research Infrastructure – Beam Services) collaboration brings together the European research teams developing electron cyclotron resonance ion sources (ECRIS) and their beams. The ERIBS collaboration includes ion source teams from the following research institutes: ATOMKI (Debrecen, Hungary), CNRS-IPHC (Strasbourg, France), CNRS-LPSC (Grenoble, France), GANIL (Caen, France), GSI (Darmstadt, Germany), INFN-LNL (Legnaro, Italy), INFN-LNS (Catania, Italy), JYFL (Jyväskylä, Finland) and UMCG-PARTREC (Groningen, Netherlands). The objective of the collaboration program is to improve the ion beam services to enhance the capabilities of participating research infrastructures (RI). Based on the discussions with the user community, the two most important development topics are the variety of available ion beams and the short- and long-term beam stability. Therefore, the ERIBS collaboration aims at providing high-level ion beam services for the EURO-LABS research infrastructures by focusing on improvements in the two aforementioned key categories. This article presents the plans to meet the objectives of the project.

2. Ion beam variety

New intense metal ion beams, including their rare stable isotopes, have been requested by the EURO-LABS user community. These elements typically have a high melting point requiring extreme temperatures (e.g. Ti and Nb) and/or their successful beam production requires special know-how (e.g. ^{50}Ti, ^{50}Cr). In order to enhance the ion beam services for the EURO-LABS users further development of high-temperature ovens, sputtering technique and new MIVOC beams is needed. In addition, the developed know-how to efficiently produce new metal ion beams will be shared between the participating teams.

2.1. Development and dissemination of high temperature oven technology

The lack of a high-temperature, high-capacity evaporation oven limits the ion beam variety available at some EURO-LABS infrastructures. The objective of this task is to develop an oven capable of operating around 2000°C that is compatible with the present European ECR ion sources. The work has been started by constructing first an inductively heated large diameter (26 mm) oven prototype to find technical solutions and boundary conditions to oven structure and its resonant circuit. The prototype was capable of evaporating tens of milligrams of chromium and titanium per hour and it has been tested successfully up to 2500°C at the IPHC oven test bench. The oven diameter should not exceed 20 mm due to the geometric constraints of the present European ECR ion sources and therefore as a next step a smaller 20 mm inductively heated oven will be realised and tested at the test bench during 2024. This oven will be small enough to be used with the GANIL and JYFL ECR ion sources while still offering an adequate capacity for the material of interest. The collaboration is also looking into the possibilities of developing and adopting a resistively-heated high temperature oven design. At the end of the development and testing period the technology transfer and the hands-on-training will be carried out to make the commissioning and maintenance of the oven in other EURO-LABS laboratories possible. The development work of oven is planned to be realized in collaboration between the IPHC, LPSC, GANIL and JYFL teams.

2.2. Development of axial sputtering for European ECR ion sources

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 [1]. 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 [2] and therefore the development and adoption of axial sputtering was included in the ERIBS project. The

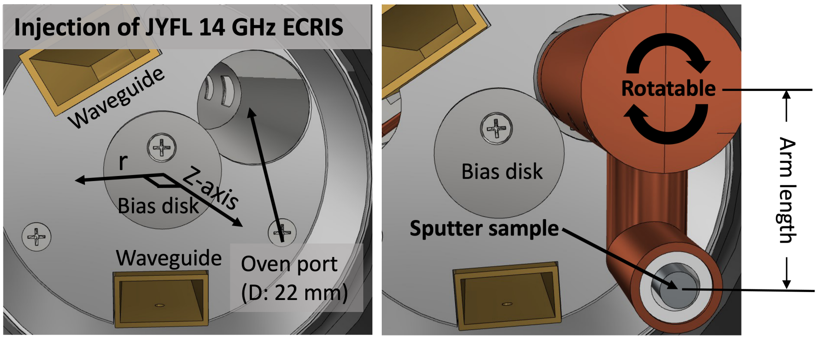

Figure 1. The oven port located in the injection side of the JYFL 14 GHz ECRIS will be used for the off-axis sputter tests. A rotatable insertion rod can be moved along the plasma chamber axis to find the optimum location for the sputter sample.

development work for on- and off-axis sputter systems will mainly be realized in collaboration between the INFN-LNL and JYFL ion source teams. The schematic drawing of an off-axis sputtering test system to find the optimum sputter sample location and geometry is shown in Fig. 1. The sputter sample has been attached to a cooled copper rod, which can be moved in parallel with the plasma chamber axis. Different arm lengths and rotation angles of the sputter sample holder allows placing the sputter sample with three degrees of freedom. The LNL ion source team has developed a simulation tool, which models the sputter process in the complex parameter space of the ECR ion source. The simulations will guide the design process and will help to find the optimum geometry for the sputter sample.

2.3. New MIVOC beams

The MIVOC [3] method is an efficient way to produce ion beams from several metallic elements that require relatively high evaporation temperatures. At JYFL, it has been the main production method, for example, for highly charged, high intensity Ti, Cr, Fe and Ni ion beams. Its global production efficiency is very high when compared to evaporation ovens as is demonstrated in Fig. 2. Due to this feature, the MIVOC method is a very attractive alternative in the case of rare and expensive stable isotopes.

At the beginning of the ERIBS project, a list of the most wanted new ion beams, which can potentially be developed and produced using the MIVOC method, was collected. In this MIVOC related development work the expertise of the CNRS-IPHC team plays an important role. In addition to this beam development aspect, the MIVOC collaboration concept has been established to make the enriched MIVOC ion beams available to partner institutes. This collaboration is based on the know-how of CNRS-IPHC team to synthesize several MIVOC compounds, like chromocene ($Cr(C_5H_5)_2$), ferrocene ($Fe(C_5H_5)_2$) and nickelocene ($Ni(C_5H_5)_2$), making them available also in the enriched form, e.g. $^{50}Cr(C_5H_5)_2$, which will substantially increase the beam intensity for the users. The MIVOC know-how will be transferred to new EURO-LABS research infrastructures during the project to further enhance their metal ion beams in terms of their intensity and variety.

3. Ion beam stability

Most of the beam instabilities and variations are connected to the plasma conditions and therefore, in order to improve the ECRIS stability performance, it is crucial to have an online monitoring system also for plasma parameters and plasma instabilities together with the ion beam intensity. This allows an ion source operator to react proactively to minimize the plasma parameter variations and instabilities. The objective of ERIBS is to develop a low cost online monitoring system for the kinetic plasma instabilities and for a short- and long-term beam stability. In addition, in order to have fully operational beam monitoring and stabilizing system an algorithm has to be developed to maintain and restore stable plasma conditions and the required beam intensity and stability.

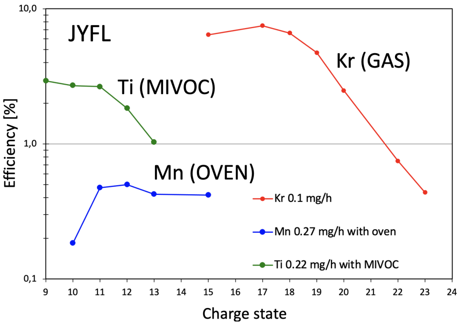

Figure 2. The production efficiency comparison for Kr, Ti (MIVOC) and Mn (oven) as a function of the charge state.

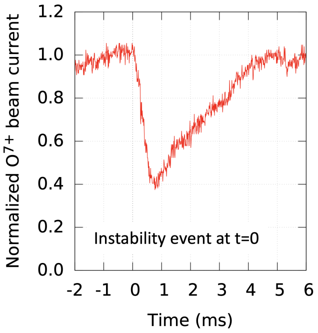

Figure 3. The effect of instability event on the O^{7+} ion beam current. The start of the instability is at t=0.

The 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 [4, 5, 6]. Figure 3 shows, as an example, the effect of the kinetic plasma instability on the O^{7+} ion beam. As the figure demonstrates, the instabilities decrease the average beam intensity and this effect increases with the charge state. The intensity variation due to the kinetic instability can be tens of percent depending on the charge state. The time to restore the original beam intensity after the onset of the instability increases with the charge state and can be tens of milliseconds. The repetition rate of the kinetic instabilities can be up to several kHz [4], depending on the ion source tuning, which will strongly limit the intensity of highly charged ion beams. For the purposes of this project, it is defined that the timescale for the short-term instabilities/beam variations is less than one second in duration.

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 by certain applications. The kinetic plasma instabilities will also cause sputtering of plasma chamber structures [7]. The sputtered elements originating from the plasma chamber are ionized inside the plasma, extracted as a part of the total beam and therefore leading to possible beam contamination at the end of the beam line, i.e. at the production target. The sputtering can also cause negative long-term effects on beam intensity due to the wear and tear of critical parts and components.

The long-term beam instability includes intensity variations caused by drifts in plasma conditions and/or by unstable power supplies. The plasma conditions typically drift at the beginning of the production run and as a result of the contamination of the plasma chamber surfaces. The unwanted and inevitable contamination takes place especially during the production of metal ion beams and its severity also increases with the amount of accumulated material. The contamination may have a strong impact on the ion source performance and its effect depends strongly on the element accumulated on the surfaces. Therefore, the variation (or decay) of the beam intensity is directly linked to the element of interest, duration of the run, and the intensity of the requested beam. The long-term intensity variations occur also, for example,

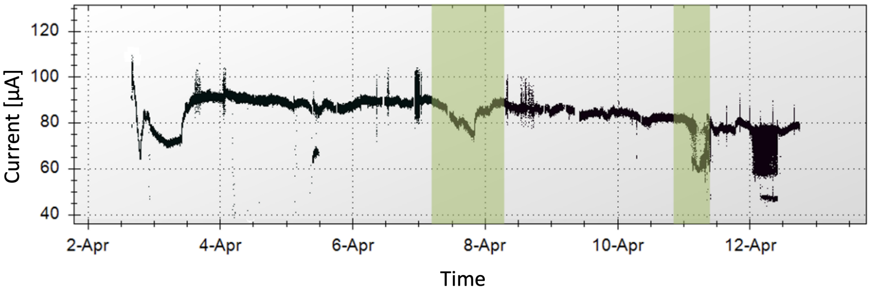

Figure 4. The intensity of the $^{48}\mathrm{Ca}^{10+}$ ion beam during the run of 10 days [13]. The beam intensity has been measured using the GSI current transformer.

when the gas flow into the ion source is not regulated with sufficient precision. The time constant for the long-term beam intensity variations can vary from seconds to days. Some processes, like surface contamination, causing the beam variation (or a decay in the performance) cannot be avoided, which makes the stabilization of the long-term beam intensity very challenging.

In addition to the afore-mentioned beam instabilities, plasma conditions are varied by occasional material outbursts from the deposited parts inside the plasma chamber or by a resistively heated oven as a result of parasitic heating. This unwanted behavior leads to higher material consumption, decreased beam intensity of the extracted highly charged ions, and the occurrence of long-term instabilities. Figure 4 shows a typical long-term intensity behaviour of $^{48}\mathrm{Ca}^{10+}$ ion beam measured using the GSI current transformer during the CAPRICE ECRIS operation. The figure demonstrates two long-term instabilities and their effect on the beam intensity in the sections shown in green. In addition, a slow decay taking place over the whole recorded period in the beam intensity can be observed.

3.1. Online plasma stability monitoring

The stability and intensity of the ion beams extracted from the ECR ion source are strongly compromised by plasma instabilities. They restrict the parameter space available for optimisation of the source performance. They are often overlooked by the ion source operator attempting to maximise the average beam current with limited diagnostics. The instability event is triggered when the build-up rate of the electron energy distribution (EED) energy content exceeds the damping rate. During the instability event the kinetic energy of (mainly) perpendicular velocity component of 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. As a result of the energy transfer, a part of the hot electron population is lost from the confinement which is observed as a thick target bremsstrahlung burst originating from the plasma chamber walls (see Ref. [8]). The objective of this project is to develop reliable, low-cost diagnostics tools to detect the onset of instabilities and to guide the ion source operator to maintain and restore stable operation conditions of highly charged plasma. Four approaches were chosen to achieve this goal: to measure the signal of A) microwave emission using an RF diode connected to the waveguide, B) microwave emission using an internal RF antenna positioned in the injection side of the plasma chamber, C) burst of bremsstrahlung using for example a scintillator setup and D) visible light emission using optical emission spectroscopy (OES). In each case minimum requirement is to provide binary information about the plasma stability (stable vs unstable). After the development work, each partner can choose the plasma stability monitoring method that best suits their use. More information about diagnostics techniques of the kinetic plasma instabilities can be found from Ref. [6, 9, 10]. The development

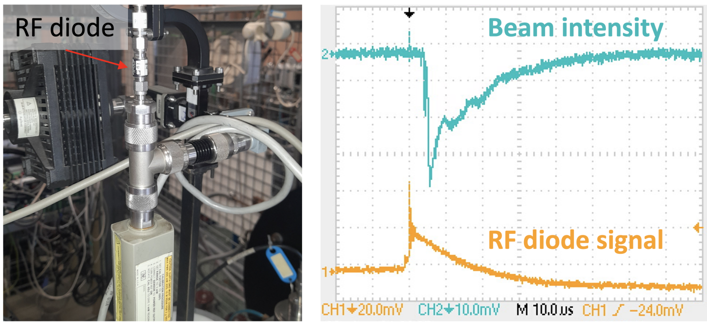

Figure 5. Online monitoring of microwave emission taking place during the instability event. The plasma emitted microwave pulse can be measured with the RF diode connected to the waveguide.

of low-cost online plasma monitoring system will be realised in collaboration between ATOMKI, INFN-LNS, JYFL and GSI ion source teams.

A) Microwave signal measurement using RF diode: 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. Figure 5 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 q/m separation. The measured signal, especially if it occurs peridiocally, indicates that the plasma is in unstable operating condition. This method requires an RF power diode with adequate signal attenuation and data acquisition making it a simple, reliable and low-cost option.

B) Microwave signal measured using internal RF antenna: The waveguide may limit the frequency spectrum of the plasma emitted microwaves. This limitation is avoided if the signal of microwave emission is measured directly from the plasma chamber using a multi-pins RF antenna. The antenna is integrated into the injection plate facing towards the ion source plasma. The antenna picks a large spectrum of emitted RF signals, which are delivered to a spectrum analyzer or to an RF diode for further analysis or response [6]. In this setup, the probes can operate on high voltage, which allows characterization of plasma radio-emission during the typical operation of an ECR ion source [11]. This approach is slightly more complicated than previously mentioned due to the connection between the source high voltage and the ground. However, this approach does not have the aforementioned waveguide limitation, and as a result it has high potential to reveal additional information about the plasma conditions, making it an attractive alternative. It can be used also for quantitative plasma instability monitoring [6, 10] and correlation with the beam extraction performance [12].

C) Bremsstrahlung signal measured using x-ray diagnostics: In this approach a bremsstrahlung burst generated by the burst of escaping electrons is measured using scintillator coupled to a light sensor/amplifier unit. The use of x-ray diagnostics is a well-established technique to study kinetic instabilities of highly charged ECRIS plasma (see for example [4, 9, 10]). In this project, the development work to realize an online, low-cost instability monitoring system was started by combining a TlCsI scintillator with a PIN diode. The measurement setup was located inside the high-voltage cage of the ATOMKI ECRIS. The diagnostic generates a short (of the order of 10 µs), high amplitude peak during the event of instability. The amplitude of the peak is proportional to the photon energy and flux. 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.

D) Optical emission spectroscopy of ECRIS plasma: The monitoring of the plasma's spectral content in the visible wavelength range is a powerful and non-perturbing method to analyse and optimize the ECRIS performance. As soon as the emission lines of the desired gases or vapours are identified, the variation in their intensity provides useful information for monitoring the long-term stability of the extracted ion beam. During the metallic ion beam production with a resistively heated oven, this diagnostic tool is also able to detect variations in the oven temperature. The feasibility of the OES method for the monitoring and operation of ECR ion source plasma for metal ion beam production has successfully been demonstrated at GSI [14]. The method will be developed further during the ERIBS collaboration and, in addition, its feasibility with gaseous elements will be evaluated.

3.2. Online beam stability monitoring

A feasibility study for several online beam monitoring methods will be performed to define the most suitable method for further development. The ideal monitoring system would have a negligible disturbance on the beam intensity, wide dynamic range in terms of beam intensity (from tens of nanoamperes to milliamperes) and high sampling rate (up to tens of kHz) to monitor also short-term beam instabilities. The feasibility study for the beam monitoring options will be done in collaboration between PARTREC, JYFL and GSI ion source teams.

Small FC integrated into a collimator: A small Faraday cup, which is mainly a copper insert in the downstream side of a collimator, monitors parasitically ions at the edge of the ion beam (Figure 6). The insert is filled with a ceramic isolator and at the centre a copper tube with a cone shape "catcher" to avoid electrons to be emitted towards the front of the FC. This setup does not generate extra secondary electrons and therefore it is not affecting the measurement in the main FC setup. When the main Faraday cup is retracted, the small FC monitors the ion beam intensity and its fluctuations by continuously sampling the edge of the beam. This method could be used for both short- and long-term beam monitoring.

Beam current transformer for online monitoring: A beam current transformer provides a non-perturbative measurement of the beam intensity during the ECRIS operation. The data provided by such an instrument can be integrated into the online monitoring system for the detection of the long-term instability. GSI has designed its own beam current transformer and similar measuring devices are commercially available. The GSI team will perform an experimental campaign to define if the transformer is able to meet the requirements for beam intensity and sampling rate set by the EURO-LABS partners. The commercially available alternatives will be considered as well and their feasibility will be evaluated.

Continuous monitoring of an adjacent (q-1) beam: In this method 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 m/q separation as is presented in Figure 7. 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 also to restore the beam stability. Ion beam simulations will be 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. The method can be used to monitor also short-term beam instabilities.

Wire scanner: A wire scanner is typically used to obtain the beam profile by passing the measurement wire through the beam. With proper measurement parameters, the beam loss at measurement can be considered non-interfering for most applications, allowing on-line measurement. In other words, this could be a feasible method to monitor a long-term beam

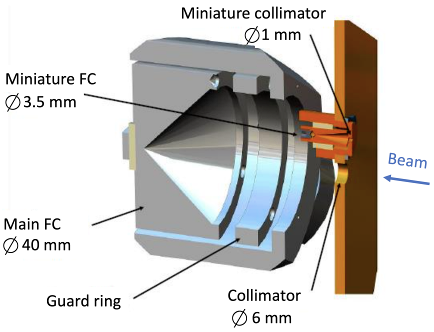

Figure 6. Miniature Faraday cup (FC) for online beam monitoring.

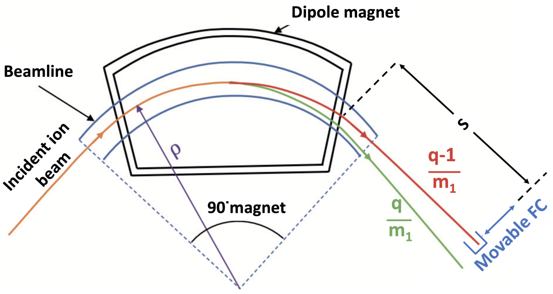

Figure 7. Movable FC to continuously measure the current of the adjacent *(q-1)* ion beam while the beam of interest *(q)* is transported further in the beam line.

stability/drift by sampling the beam with adjustable sampling rate. However, it is assumed that the applicability of the method for online beam tuning might be limited.

3.3. Response to maintain beam stability

A feedback and response system has to be developed in order to have a fully operational monitoring and stabilizing system for the short- and long-term beam stability. The objective for the ERIBS project is to have a system which informs the operator when the beam stability and/or its intensity has not remained within the pre-determined threshold values. In addition to this, the feedback system has to guide the operator to restore the requested beam conditions. In order to make this happen, it is crucial to define the most relevant operation parameters (multidimensional map) and track them to maintain the stable beam condition, or restore them, if the beam intensity or stability has not remained within the pre-determined threshold values.

4. Conclusion and perspectives

This article described a wide EU funded European collaboration project, which main objective is to improve beam production methods to make new and/or more intensive ion beams available and to develop online methods to monitor the short- and long-term plasma and ion beam stability. In order to improve the availability of metal ion beams, the project focuses on the development of induction ovens and the axial sputtering method so that the technique best suited for each laboratory will be available by the end of the project (funding period 1.9.2022-31.8.2026). The new oven design must be capable of reliably operating at around 2000°C and it needs to be flexible in a way that it can be easily modified to be compatible with different ion source geometries. The axial sputtering is needed for elements requiring evaporation temperature beyond the capabilities of the oven. New MIVOC beams will be developed and, in addition, MIVOC technology transfer to new partner laboratories will be realized. As a new important collaboration concept, the expertise of the CNRS-IPHC team makes more intensive enriched ion beams available for the partner institutes.

Several options for the online monitoring of plasma instabilities and ion beam intensity variations have been selected for the feasibility studies. This phase will be completed during 2024 and the most viable methods will be selected for the realization of the final monitoring system. The goal is to demonstrate that the system is able to reliably provide relevant online data and information about the operating conditions and to aid the operator to maintain the required beam properties and, for example, to guide in restoring stable ion source plasma conditions in a situation where the source has become unstable. Each operator may define the limits after which actions to maintain the required beam conditions (for example intensity and standard deviation), required by the beam users, is taken. After the system is completed, it is made available for all participating institutes at the end of the project.

Acknowledgments

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