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MILESTONE REPORT

CONCEPTUAL PLAN FOR ONLINE MONITORING OF LONG-TERM OPERATION BEAM STABILITY

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Abstract:

ERIBS collaboration aims at providing high-level ion beam services for the EURO-LABS research infrastructures by focusing on improvements in the ion beam variety and operation stability. This milestone report describes the conceptual plan for online monitoring of long-term operation beam stability. The monitoring method is needed to maintain and/or restore the ion beam intensity. The report proposes several options for the realisation of this goal.

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

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Executive summary

The beam stability can be evaluated in two separate domains: as short- and long-term beam stability. Both instabilities adversely affect the ion beam quality and their exploitation. In this report a conceptual plan to improve the online monitoring of long-term operation beam stability is presented.

The approach starts with a feasibility study that includes the evaluation of several online beam monitoring methods. The study is proposed to cover simulations, literature surveys and/or testing of a prototype. As a next step the most promising approach will be selected for the final development work. The final beam monitoring system is expected to be available by Month 36.

In addition to the online beam monitoring method, a feasibility study for long-term plasma monitoring by using optical emission spectroscopy will be performed. The method may provide a direct information on the plasma conditions, not accessible by any other method. The method will be developed further, if justified by the feasibility study, to be used as an additional tool to improve the beam stability. In order to have fully operational monitoring system for the long-term beam stability, in addition for long-term monitoring, an algorithm to maintain and restore the requested beam intensity needs to be developed.

1. INTRODUCTION

ERIBS (European Research Infrastructure – Beam Services, see: https://wiki.jyu.fi/x/hI4iBg) brings together the research teams (https://wiki.jyu.fi/x/LJAiBg) developing ion sources and beams. A survey conducted in the EURO-LABS laboratories showed that, the most important development related to the production of ion beams are to increase the variety of available ion beams and to improve the operation stability and durability of highly charged ion beams. 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 milestone report presents a conceptual plan to improve the online monitoring for long-term beam stability. The report is divided to four separate sections: the first section presents the background affecting the beam instability and divides stabilities into short- and long-term. The second section introduces several potential online monitoring methods and is the core of the report. The third part introduces optical emission spectroscopy which possibly can be used as an additional monitoring tool to mitigate beam variations. The last section describes the plans how to use the online monitoring and feedback system to maintain and restore the optimum operation conditions and requested beam intensity.

2. ION BEAM INSTABILITIES

The beam stability can be evaluated in two separate domains, later referred to as 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 instabilities. Figure 1 shows, as an example, the effect of the kinetic instability on the O^{7+} and O^{3+} ion beams. The intensity variation due to the kinetic instability can be tens of percent depending on the charge state. The recovery 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 typically varies from ~0.1 kHz to several tens of kHz, depending on the ion source tuning. In terms of this project, it is justified to define that the timescale for the short-term instabilities/beam variations are less than one second in length. 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 users. The kinetic instabilities will also cause sputtering of plasma chamber structures. The sputtered elements originating from the plasma chamber are ionized inside the plasma, extracted as a beam and therefore leading to 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. Such long-term aspect of the kinetic instabilities is not included in the plan for the online monitoring of long-term instabilities and beam intensity variations.

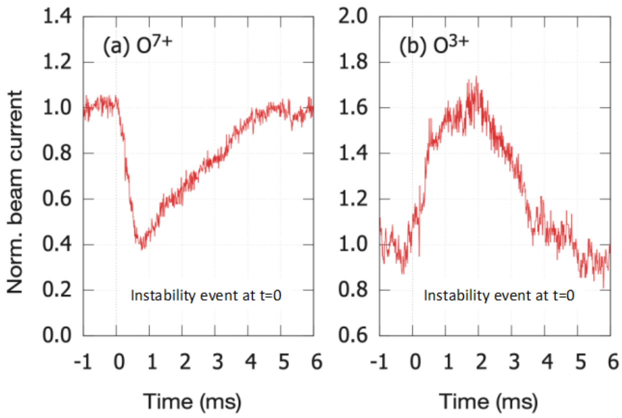

Fig. 1 The effect of instability event on a high charge state (O^{7+}) and a low charge state (O^{3+}) oxygen ion beam current. The signals were recorded using the Faraday cup of the JYFL 14 GHz ECRIS setup. The start of the instability is taken to be at t=0.

The long-term beam stability 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 surfaces of the plasma chamber. The unwanted and inevitable contamination takes place 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 severity 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, when the pressure of gas feeding line is not regulated with sufficient precision. The time constant for the long-term beam intensity variations can vary from seconds to days. Some processes causing the beam variation (or a decay in the performance) cannot be avoided, which makes the stabilization of the beam intensity very challenging.

The operation of the **ECR I**on **S**ource (ECRIS) with chemically reactive materials like calcium and magnesium is characterized by occasional plasma instabilities caused by material outbursts from the deposited parts inside the plasma chamber or from the resistively heated oven as a result of parasitic heating**.** This issue leads to higher material consumption, decreased beam intensity in the extracted charge state, and the occurrence of long-term instabilities. Figure 2 shows a typical long-term intensity behaviour of 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 section shown in green. In addition, a slow decay in the beam intensity can be observed.

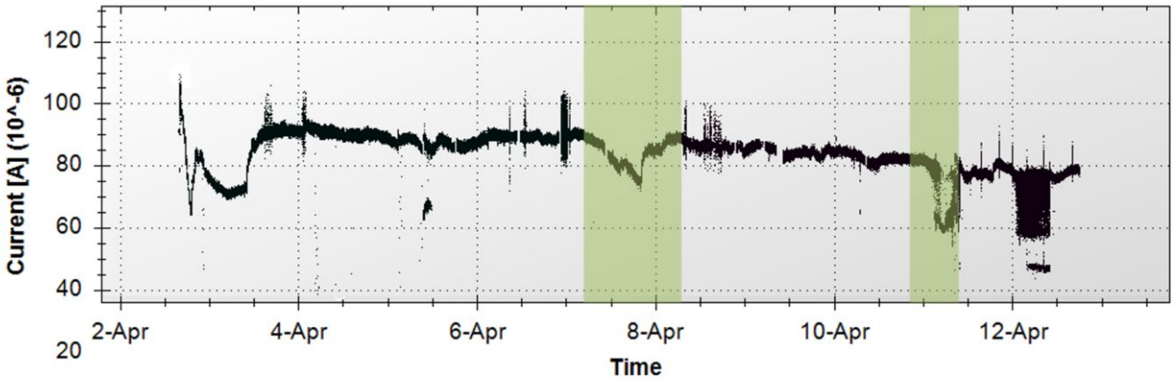

Fig. 2 The intensity of the $^{48}Ca^{10+}$ *ion beam during run of 10 days. The beam intensity has been measured using the GSI current transformer.*

In this subtask a method for the online monitoring of long-term beam stability is developed. The conceptual plan (i.e. core of MS15) is presented in section 2. Our approach starts with a feasibility study that includes the evaluation of several online beam monitoring methods. The study is proposed to cover simulations, literature surveys and/or testing of a simple prototype. The feasibility study will be completed by month M24. As a next step the most promising approach will be selected for the final development work and the final beam monitoring method is expected to be available by month M36.

The project encompasses a multiple-diagnostics approach, in which several techniques will be studied for the monitoring in parallel. This will improve the probability of successfully delivering a working method at the end of the project. In addition to the online beam monitoring method, a feasibility study for long-term plasma monitoring by using optical emission spectroscopy will be performed (section 3). The method may provide direct information on the plasma conditions, which is not accessible by any other methods. This method will be developed further, if justified by the feasibility study, to be used as an additional tool to improve the beam stability. The timeline for this subtask is parallel with the work for the online beam monitoring. In order to have fully operational monitoring system for the long-term beam stability we have to develop, in addition to long-term monitoring, an algorithm to maintain and restore the required beam intensity. Section 4 presents a plan to achieve this. It is worth noting that section 3 and 4 are suggested as additional sections in regard to the milestone report, however they are necessary to complete a fully operational monitoring and feedback system. The know-how will be transferred at the end of the project so that the developed method will be made available to all partners in form of reports and/or journal articles, and potential presentations.

As a result of the successful realisation of the planned work not only the beam stability can be improved, but the complete monitoring system will also help in finding the origin of the unwanted beam variation. This would improve the problem-solving process, minimize the ion beam downtime and, as a result, would enhance the efficiency of the entire accelerator infrastructure.

3. ONLINE LONG-TERM BEAM STABILITY MONITORING

In this section we present a list of the methods that have been selected for the feasibility study for a long-term beam stability monitoring. The planned study will be completed by month M24 and, as a result, one or two of the most promising methods will be selected for the further development. The monitoring method will be available for the EURO-LABS infrastructures by month M36.

3.1. A HIGH TRANSPARENCY GRID, FOIL OR WIRE SYSTEM THAT THE BEAM OF INTEREST PASSES THROUGH WITH NEGLIGIBLE LOSSES

In this approach the detection foil consists of a strip of tungsten that is approximately 2 mm wide and 0.2 mm thin and 10 mm long. The foil is vertically positioned behind the opening of the collimator just downstream the collimator and before the Faraday cup (FC) and 3 mm away from the beam centre with the thin side facing the beam. A foil is chosen to conduct the deposited beam energy away from the centre and to the side where the foil is cooled. Furthermore, as the foil has a thickness, it is not so susceptible for wearing out by sputtering effects of the beam. This method could be used for both short- and long-term beam monitoring.

3.2. SMALL FC MEASURING THE BEAM INTENSITY IN FRONT OF THE COLLIMATOR

A small Faraday cup mainly a copper insert in the downstream side of the collimator, that is parasitically measuring the beam ions at the edge of the emittance (Figure 3). 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. The small Faraday cup moves in and out with the collimator. This setup does not generate extra secondary electrons and therefor 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. This method could be used for both short- and long-term beam monitoring.

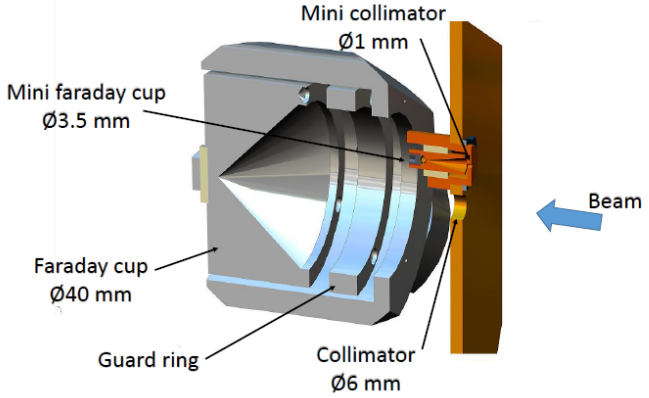

Fig. 3 Miniature Faraday cup for online beam monitoring.

3.3. 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 (for example Bergoz Company: https://www.bergoz.com/). The GSI team will perform an experimental campaign to define if the transformer is able to meet the monitoring requirements of other EURO-LABS partners. The commercially available alternatives will be considered as well and their feasibility will be evaluated.

3.4. 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 4. 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 also to monitor short-term beam instabilities.

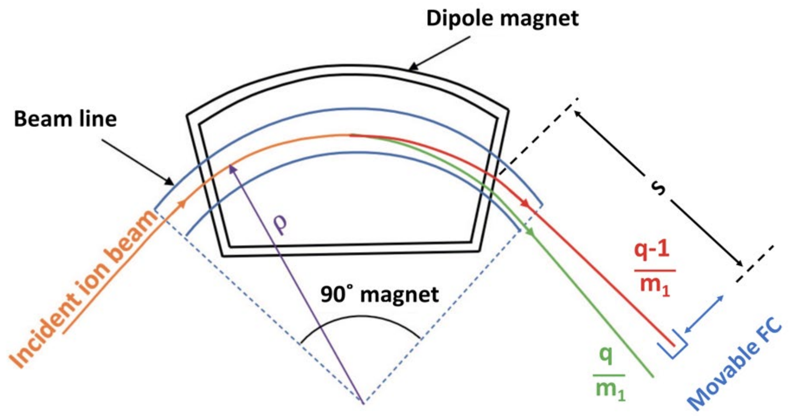

Fig. 4 *Movable FC to continuously measure the current of the adjacent q-1 ion beam while beam of interest (charge state q) is transported in beam line.*

3.5. A WIRE SCANNER

A wire scanner, shown in Fig. 5, 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 stability/drift by sampling the beam with the adjustable sampling rate. However, it is assumed that the applicability of the method for the online beam tuning might be limited.

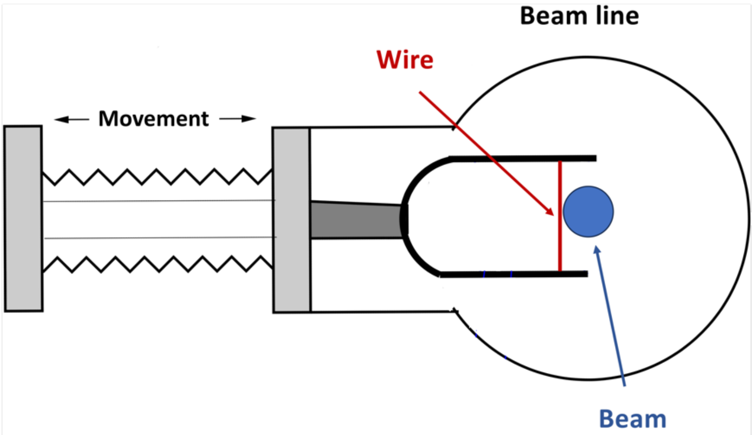

Fig. 5 *Linear wire scanner to obtain horizontal ion beam profile.*

4. OPTICAL EMISSION SPECTROSCOPY (OES) TO MONITOR PLASMA PARAMATERS

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. For metallic ion beam production with a resistively heated oven, this diagnostic tool is also able to detect variations in the oven temperature.

In order to improve the ECRIS stability performance, it is crucial to monitor and prevent the plasma parameters variation. The response of the ECRIS to a parameter change or early signs of upcoming instabilities can be detected with the optical emission spectrometer as time variations of individual optical emission lines or full wavelength range of the spectrometer. This allows an ion source operator to react proactively and compensate for the associated variations of the plasma parameters by tuning the ECRIS parameters. Below, a conceptual plan providing an overview of the steps allowing to implement such an online monitoring system using OES is given. 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 (Low Energy Beam Transport) system.

4.1. MEASUREMENT SETUP

Acquire a suitable optical emission spectroscopy instrument capable of measuring and analysing the emission spectra of the ECRIS plasma. Ensure that it has the necessary spectral resolution, sensitivity, and range to capture the emission lines of interest. Design and implement a light collection system that efficiently collects the emitted light from the plasma. This system should include appropriate optics, such as lenses and fibre optics, to direct the light to the spectrometer.

4.2. 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. Define stability metrics based on the acquired data to evaluate the long-term stability of the ECRIS plasma. This may involve monitoring the trend or comparison with predefined stability thresholds.

4.3. MONITORING AND ALERT SYSTEM

Develop a real-time monitoring system that continuously analyses the acquired spectral data to assess the stability of the ECR ion source. This system should provide instantaneous feedback on the performance and alert operators if any instability or deviation from predefined thresholds is detected. Establish a graphical interface that displays the stability metrics, and relevant time trends with time variations of the selected spectral lines or alarms. This interface should allow an ion source operator to track the long-term stability of the ECRIS. Implement an alarm system that generates alerts or notifications when significant deviations or predefined threshold is exceeded. These alerts should be transmitted to responsible personnel via email, SMS, or other suitable communication channels to ensure prompt attention and corrective action if necessary.

At GSI, OES has already pointed out its suitability for metallic ion beam operation. The diagnostic tool based on OES has recently been implemented and its reliability will be verified during gaseous ion beams operation. The feasibility study aims to find a correlation between the intensity of the measured optical emission lines from noble gases plasmas, e.g., argon, krypton, and xenon, and the ion beam current measurements, the main ECRIS parameters, and the extracted beam currents. The measurement results will show if Optical Emission Spectroscopy can be used as a tool for the long-term instability detection of gaseous ion beams. The measurement setup and the obtained results will be documented. The recorded datasets will be made available so they can either be used to build a feedback loop or be integrated into monitoring algorithms for instability detection.

A monitoring system based on OES has several limitations that need to be considered:

1. Not every ECRIS and LEBT have the necessary setup to monitor the plasma through the extraction aperture using a quartz-flanged optical window inside a bending dipole magnet. This limitation restricts the applicability of the measurement tool to only those systems that have the required infrastructure in place.
2. During metallic ion beam operation with elements, which have higher evaporation temperatures, the brightness of the image obtained from the optical emission spectrometer can interfere with the emission lines. Oven glowing leads to a high background level in the infrared part of the optical emission spectrum and compromises the accuracy and reliability of the measurements, particularly for metallic elements with higher evaporation temperature, e.g. chromium.
3. The cost of the optical emission spectrometer can be relatively high if a wideband capability and a high resolution are required. This may limit its accessibility to certain research facilities having constrained budgets.

5. RESPONSE TO RESTORE THE BEAM INTENSITY AND STABILITY

5.1. MAPPING

The recovery of the beam intensity and ensuring the stability of the ion beam intensity is a complicated process. For its successful implementation, the ion-source operator keeps track of many dependable and in-dependable variables to assess the operating conditions of the ion-source. When the ion source performance deviates away from steady state operations, the operator evaluates these variables, acts and brings back the steady state of the ion-source performance. Therefore, it is crucial to define the most relevant operation parameters (multidimensional map) and track them to maintain the stable operation condition. The tracking is also needed to restore the beam intensity back to the required value if the beam intensity has not remained within the pre-determined threshold values (online monitoring system described in section 2). The reliable online beam monitoring system is required to provide a warning about unwanted ion beam behaviour.

5.2. RESPONSE

The ion-source operator applies the afore-mentioned multidimensional map during the tuning process to maintain or restore the beam intensity. The response software could be used to predict improved performance by using the recorded multi-dimensional map described above. As every ion-source is different, the software parameters and algorithms need to be adjusted to the behaviour of the specific ion-source. During online monitoring of the beam average and stability, the software should constantly check the operational state of the ion-source in the multidimensional map. If the stable steady-state of the ion beam current is deviating from the initial steady state conditions and beyond pre-determined margins, the multidimensional map helps to restore the original beam intensity. The independent variables such as, RF power, magnetic field, bias voltage are the dimensions of the map and the dependant variables such as beam current, gas pressure and bias current define the landscape of the map.

5.3. IMPLEMENTATION

The response implementation starts with recording the beam current values. For the beam current sampling/monitoring it is mandatory to calculate via an RMS-routine the average beam current and its standard deviation. Secondly, a set of variables needs to be measured continuously to define the actual operation point in the multidimensional map. Whenever needed, the routine should use this information to provide the variable parameters to restore the optimum operation point. The implementation could also include spectral line detection, provided by OES, as an additional variable to detect an early-stage plasma instability in the case of metal ion beam production. Additionally, the calibration of sensors is added to the software to improve the reliability of the method.