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OPTICAL DIAGNOSTIC STUDIES TO ANALYSE ELECTRON CYCLOTRON RESONANCE PLASMA PRODUCED IN THE GTS-LHC ION SOURCE

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Abstract

The GTS-LHC electron cyclotron resonance (ECR) ion source is an integral part of the chain of accelerators at CERN. It produces the heavy ion beams which are accelerated using a series of accelerators from LINAC up to the LHC. The ion beams are extracted from an ECR plasma generated at the GTS-LHC ion source, however, there has not yet been a non-invasive diagnostic device to study the plasma. This research focuses on the implementation of an optical diagnostics and studies the optical emission spectra (OES) as a monitor of the performance of the ion source. Furthermore, we explore the correlation between spectral properties and changing source parameters, offering insights into the behaviour of the ion source, which in turn helps in fine-tuning of the source. Specifically, the study concentrates on long-term OES analysis spanning several weeks, focusing on the production of magnesium and lead ions using the GTS-LHC ion source.

INTRODUCTION

The production of ion beams at CERN is crucial for a wide range of research activities, particularly in the field of heavy-ion physics, where specific ion species are required for diverse experimental needs. The GTS-LHC 14.5 GHz Electron Cyclotron Resonance (ECR) ion source [1], located at the start of the Linac3 accelerator, is essential to this process. It has been predominantly used for producing lead ions, which are vital for many of CERN's high-energy physics experiments.

A new working group was formed recently "Future Ions in the CERN Accelerator Complex" to define future ion operations based on requests from LHC and other fixed target experiments at North Area (NA) of CERN. One light ion selected is magnesium. Mg Highly Charged Ions (HCIs) can be produced by the GTS-LHC ion source, the magnesium atoms are introduced into the source by a micro-oven, which evaporates the metal samples by controlling the oven power based on the required vapour pressure. Helium is injected as a buffer gas to enhance magnesium ion production.

The study of new ions at CERN is limited because there is only one ECR ion source, which is used for both current experiments and developing new ion beams. Due to the complex accelerator setup and long experimental periods (up to six months), only two types of ions can typically be studied each year. These long periods require the ion source to remain stable for extended times, which is an additional challenge for metal ion beams made with oven-based evaporation. Maintaining stability over time is often harder than achieving high beam intensity.

To address these challenges, recent research has focused on optimising the ion source's performance using Optical Emission Spectroscopy (OES). OES is a non-invasive diagnostic tool that allows for the analysis of plasma by examining the emitted light, providing insights into parameters like electron density, electron temperature (T_e), ion temperature (T_i), and the densities of both neutral atoms and ions [2, 3]. These parameters are crucial for fine-tuning the ion source to ensure efficient and stable ion beam production.

The installation of a new OES setup has further enhanced the diagnostic capabilities of the ECR ion source, enabling continuous monitoring of the plasma. This study is focused on finding a correlation between the optical emissions with ion source parameters and thereby helping to optimise the production of HCIs.

EXPERIMENTAL SETUP AND PROCEDURE

The experiment is performed on the 14.5 GHz GTS-LHC ECR ion source at CERN. The HCIs are generated based on stepwise ionisation of neutral atoms. The neutral atoms are primarily introduced to the source by means of evaporation using a micro oven [4]. The resultant ions are extracted via a suitable extraction system [5] and is directed through a dipole magnet, which is employed to isolate and select the specific charge state of interest, a Faraday cup for direct measurement of beam current by blocking the ion beam, and a beam current transformer (BCT), which enables non-invasive beam current measurements. Subsequently, the ions are accelerated through a series of accelerators.

The experimental setup includes an optical spectrometer system designed to observe the optical emissions from the plasma through the port on the first dipole magnet as shown in Fig. 1. A concave mirror is placed at this point which collects and focuses the light onto the entrance of an optical fiber. The other end of the optical fiber is connected to the optical spectrometer (Ocean Optics USB4000 Spectrometer). A vacuum valve is positioned between the concave mirror and the dipole magnet, providing the flexibility to change or adjust the optical components without needing to vent the entire low-energy beamline thereby maintaining the vacuum. This valve also serves as an external shutter for measuring the background spectrum.

The experiments were performed by simultaneously collecting optical spectra and monitoring the total beam current using the BCT. An OES measured during magnesium pro-

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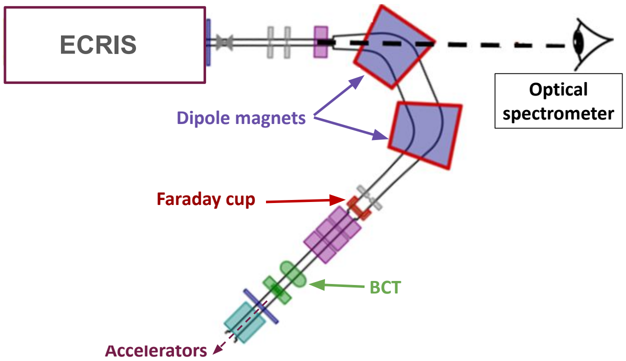

Figure 1: Schematics of the experimental setup show the ECR ion source, followed by dipole magnets, the newly installed optical spectrometer, along with a faraday cup and beam current transformers positioned downstream from the dipole magnet.

duction is shown in Fig. 2 where emission peaks of neutral Mg (i.e. Mg I), singly ionised Mg (Mg II), neutral helium (He I) and singly ionised He (He II) have been detected. The subsequent analysis is focused on isolating the emission peak of interest, quantifying its integrated intensity and correlating it with the beam current, as recorded by the BCT.

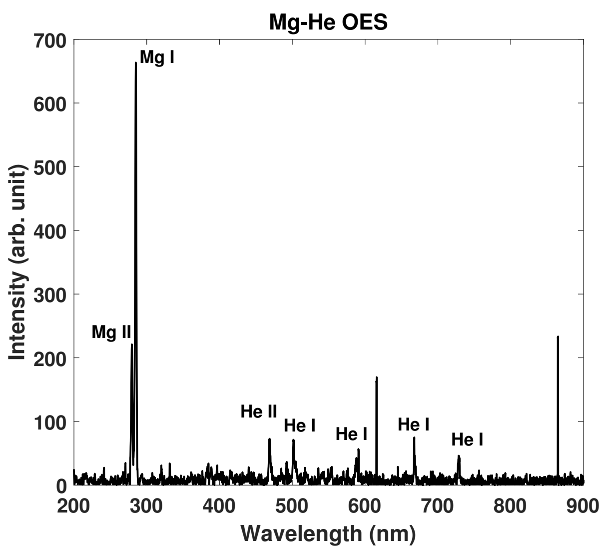

Figure 2: Recorded optical emission spectra of magnesium, where helium is used as a buffer gas. The spectrum shows emissions lines corresponding to neutral and singly ionised magnesium and helium.

A series of optical emission spectra of magnesium was recorded and one such representative of the recorded spectrum is shown in Fig. 2. It should be noted that in all cases, the source was operated in afterglow mode with an RF pulse duration of 50 ms and a repetition rate of 10 Hz. The optical spectrometer collected sufficient light with an integration time of 1 second, and the spectra for magnesium were averaged over 50 acquisitions.

A dedicated experimental campaign to study the influence of various source parameters on the spectrum was conducted for magnesium, with the results detailed in the following sections. The term *'intensity'* is used to refer the integrated signal from one particular transmission line in the OES spectrum (i.e. for Mg I at ~285 nm and He I at ~668 nm). Throughout the measurements, Mg^{7+} was selected using the dipole magnet spectrometer and is accelerated downstream from the dipole magnet. Furthermore, the reader should note that the optical notation "I" indicates optical emission from a neutral atom, while "II" denotes emission from 1^+ ion and so on.

EXPERIMENTAL RESULTS AND DISCUSSION

Optical Emission Studies on Magnesium

This study of intensities of Mg I with the simultaneous measurement of BCT current resulted in identifying a linear correlation with the intensity of neutral magnesium optical emission spectra with BCT current (which measures Mg^{7+} beam current).

The temporal behaviour of the optical intensity of Mg I and He I is shown in Fig. 3, along with the beam current of Mg^{7+} measured on the BCT. The correlation of the optical emission from Mg I with the current measured in the BCT are shown in Fig. 4. This data was taken over a span of

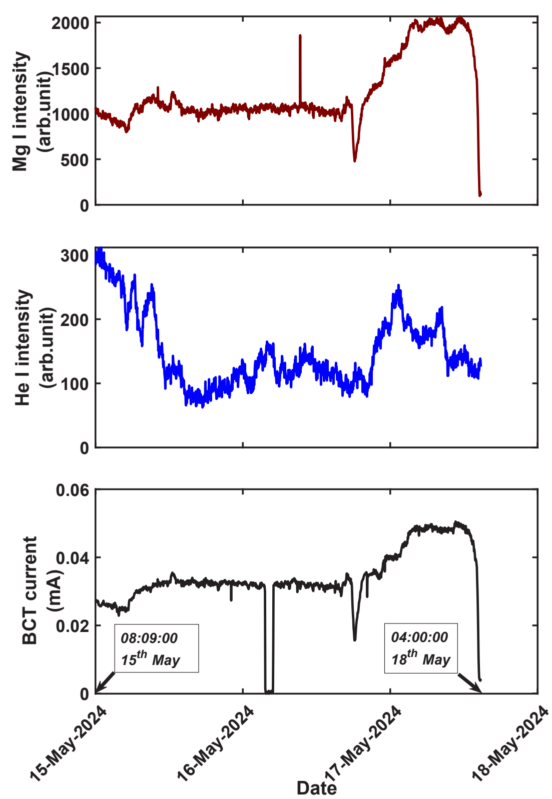

Figure 3: Figure showing the temporal evolution of the optical spectral intensities of neutral magnesium (top plot), neutral helium (middle plot) and the total beam current measured in the BCT (bottom plot) for Mg^{7+} ions.

115 hours 50 minutes from May 15th, 2024 (08:09:00 CEST) to May 18th, 2024 (04:00:00 CEST). During this period, the only source tuning parameter that was increased was the oven power (by 2 W), while all other source tuning parameters

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remained nearly constant, (with variations of less than ±1 %). Additionally, the optical spectrometer settings also remained the same throughout the measurement.

Another observation is the linear increase in the optical emission from Mg II with the increase in intensity of neutral magnesium optical emission (Fig. 5). These two relationships suggest that the increase in Mg^0 intensity increases the intensity of Mg^{1+}, with a high fraction of ions possibly being further ionised to Mg^{7+} in the ECR plasma. However, it is important to emphasise that this observation is based on a specific measurement and therefore cannot be generalised to all conditions especially because of the the complex ionisation mechanism in ECR ion source. A similar observation was reported by Kronholm et al. [6], where an increase in the optical emission intensity of Ar^{13+} correlated with an increase in Ar^{13+} ion beam current (as a function of microwave power), while no such correlation was observed for Ar^{9+}.

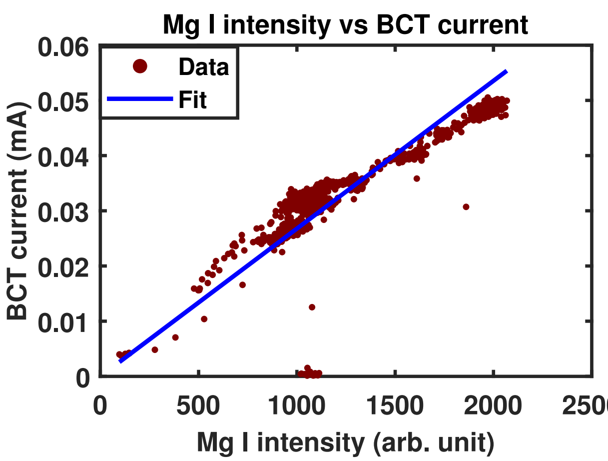

Figure 4: Figure showing the linear correlation between the measured beam current using BCT and the intensity of optical emission spectrum from the neutral magnesium.

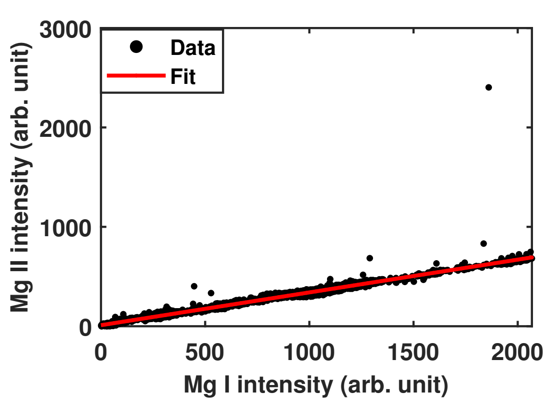

Figure 5: Figure showing the linear correlation between the optical emission from neutral magnesium and singly ionised magnesium.

Consequently, the study was further extended to systematically investigate the effects of source parameters such as microwave heating power, biased disk potential (a negatively biased electrode placed axially at the injection end of the source), and neutral buffer gas pressure (adjusted by adjusting the valve control value ranging from 0 to 10 V). The microwave power and biased disk potential were held constant for two-minute during the experiment. For the gas valve control settings, a four-minute interval was chosen to allow sufficient time for the changes to be fully reflected in the plasma conditions.

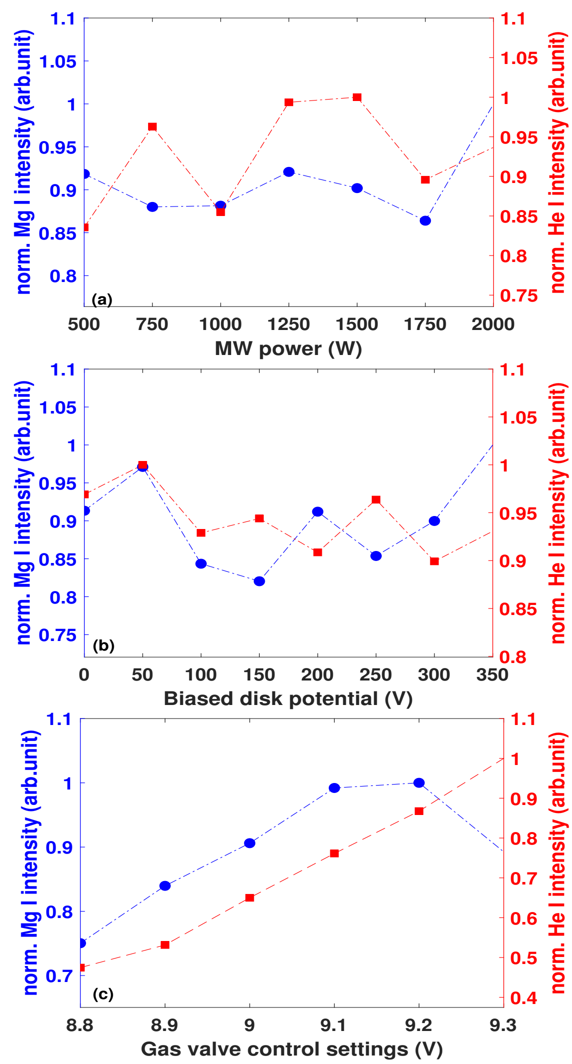

Figure 6: Systematic study of optical emission from neutral magnesium and helium is studied by varying (a) the input microwave power, (b) the biased disk potential, and (c) the gas valve settings, while keeping all other parameters constant throughout the measurements (i.e the nominal settings of the source for this experiment are: microwave power at 1700 W, biased disk potential at 200 V and gas valve control settings at 8.89 V).

It has been observed that increasing the neutral buffer gas pressure (using helium) resulted in a higher optical emission intensity from neutral helium, whereas no significant changes were noted with variations in microwave power or biased disk potential (see Fig. 6). Additionally, as helium neutral gas pressure increased, the intensity of Mg I also increased, reaching a peak at a gas valve setting of 9.2 V and subsequently decreasing. This behaviour indicates the role of the buffer gas in the production of highly charged Mg ions (HCIs).

Preliminary Optical Emission Studies on Lead

The optical spectrum produced by evaporating lead using micro-ovens was recorded at a later stage (refer Fig. 7) with oxygen as the buffer gas. In this case, adequate light was only obtained for lead after integrating for 10 seconds and averaging over 15 acquisitions. However, unlike the case with magnesium, no systematic measurements of the source parameters for lead ions were performed, as the source was no longer available for further experimental studies. In

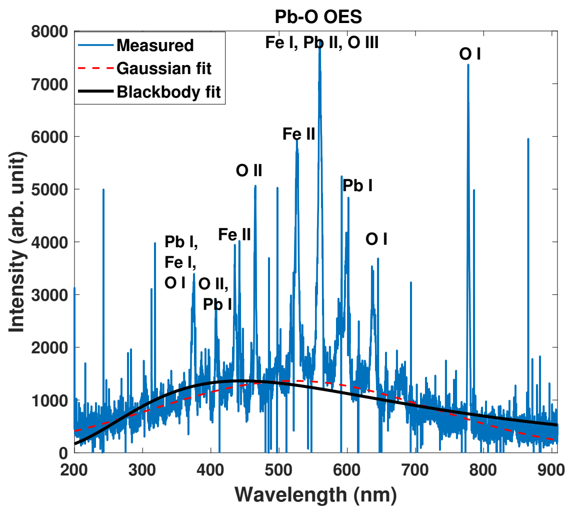

Figure 7: Recorded optical emission spectra during lead operation, where oxygen is used as a buffer gas. The spectrum shows emission lines from lead, oxygen and iron.

analysing the spectrum, it was observed that, in addition to the expected emission lines from lead and oxygen, there are also distinct emission lines from iron present. Moreover, the spectrum exhibits a continuous background signal that spans across the wavelength range, which is not accounted for by the discrete emission lines alone. To investigate this background continuum more thoroughly, two different fitting techniques are employed (i.e. Gaussian and blackbody). The fitting results, shown in Fig. 7, could provide insights into the characteristics of the background and may help to identify its underlying cause. The blackbody fit resulted in a temperature of ~0.44 eV. However, this result does not match with any known energy or temperature in the source indicating the need for further investigation into other possible mechanisms that could be contributing to the broad signal in the spectrum.

CONCLUSION AND FUTURE SCOPE

The study demonstrates the successful implementation of a new optical diagnostic setup for continuous plasma monitoring. Optical spectra were collected for two ion beam operations at CERN (i.e. Mg and Pb). The Mg spectra showed a linear relationship between the optical emission from neutral magnesium and the extracted HCI beam current, indicating that OES could play a role in optimising the ion source. Further analysis with other source parameters also showed a clear correlation between neutral buffer gas pressure and the optical emission spectra. Measurement with lead ion plasma displayed a background continuum requiring further investigation.

The future work will focus on investigating the origin of the background continuum observed in the optical spectrum measured for the lead run, as understanding this will improve understanding of the physics of ECR ion sources. Additionally, the study will explore the correlation between optical spectra and different charge states of the ion beams, which could simplify and optimise the operation of the ion source. Both tasks aim to enhance the efficiency and control of ion sources in future applications.

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