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STATUS REPORT ON 60 GHz ECRIS ACTIVITY

Thomas Andre*, Julien Angot, Maud Baylac, Andrea Cernuschi, Pierre-Olivier Dumont,
Etienne Labussière, Myriam Migliore, Christophe Peaucelle,
Patrick Sole, Thomas Thuillier, Olivier Zimmerman
Laboratoire de Physique Subatomique et de Cosmologie, Univ. Grenoble Alpes, CNRS,
Grenoble INP Institute of Engineering Univ. Grenoble Alpes, LPSC-IN2P3, Grenoble, France
François Debray
Laboratoire National des Champs Magnétiques Intenses,
CNRS ALPES, Grenoble, France

Abstract

After a record pulsed ion beam current density measured up to ~1 A cm^{-2} obtained with the 60 GHz SEISM (Sixty gigahErtz Ion Source using Megawatt magnets) ion source in 2014 at LNCMI, the experiment resumed in 2019, following a source repair and a beam line upgrade. New measurements shown a limitation in the beam pulsed current measured at ~0.3 A cm^{-2}. A careful investigation pointed out that the performance reduction is due to the upgrade of the beam line base vacuum from ~10^{-6} mbar to ~10^{-7} mbar. The characteristic time for the ion beam to reach the steady state's space charge compensation is calculated and is found to exceed the 500 µs pulse beam duration in the latter case. This analysis is confirmed using IBSIMU which can reproduce the beam intensities measured in the two pressure configurations, assuming a space charge compensation of 65 % in 2014 and 35 % in 2024. Finally, the development status of the superconducting cusp magnet planned to upgrade the source is presented.

INTRODUCTION

The development of new generation 45 GHz ECR ion sources is ongoing to increase the achievable beam intensities at IMP (Lanzhou, China) [1] and at LBNL (Berkeley, California) [2]. These new developments bring many stimulating technical challenges, among which are the high ion source microwave power and the high intensity ion beam transports. These challenges are being addressed with the LPSC 60 GHz program.

In the 2010s, LPSC developed a 60 GHz ECR ion source named SEISM (Sixty gigahertz Electron cyclotron resonance Ion Source using Megawatt magnets), using a gyrotron delivering high-intensity high-frequency (HF) pulses (up to 1 ms, 300 kW, 2 Hz) [3]. This development was historically intended to be applied to the CERN Beta-Beam factory project, as a radioactive ion source [4]. The source magnetic field is simplified to an axial cusp using a set of un-expensive polyhelix copper coils, resisting to radiations. The SEISM source is installed at the LNCMI high magnetic field facility in Grenoble on a dedicated test bench. The cusp generates a closed ECR magnetic surface at 2.14 T. The source produced its first ion beams in 2014 (extracted from a 1 mm diameter plasma electrode) with a record pulsed current density up to J ≈1 A cm^{-2} [5]. After a long shutdown, the experiment resumed in the allocated room at LNCMI in 2021 and the results obtained so far are presented in this paper.

STATUS OF THE SEISM EXPERIMENT

Experiment Upgrade

After the failure of a set of the ion source copper coils in 2014, new ones were designed and built, using advanced three dimensions printing techniques [6]. Numerical simulations performed with the Tracewin code [7] to reproduce the 2014 results campaign was used to design a new low energy beam line (LEBT), assuming a 80 % ion beam space charge compensation. It is composed of a quadrupole triplet and an available 90° bending magnet (with a 650 mm curvature radius and a 90 mm vertical gap). Figure 1 shows a top view of the experimental beam line. The LEBT is equipped with three faraday cups named: (1) FC-Source, to measure the ion beam intensity 397 mm away from the source extraction, (2) FC-Dipole, located between the quadrupole triplet and the bending magnet and (3) FC-Analysis to measure the beam selected after the dipole. A pepper pot emittancemeter

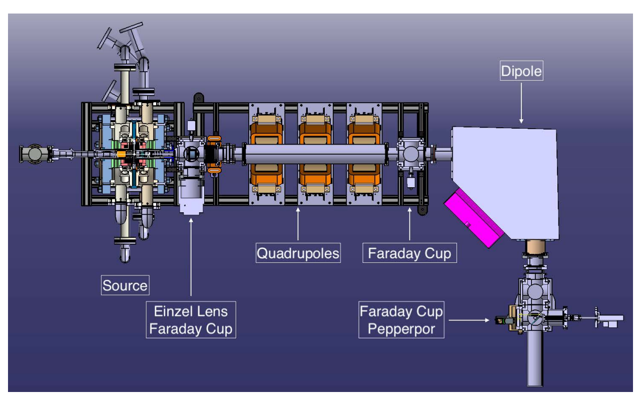

Figure 1: 2D top view of the experimental bench of the SEISM source. From left to right: Source, extraction box (Faraday cup source (FC-source)/Einzel lens), quadrupole triplet, Faraday cup dipole entrance (FC-dipole), dipole, end of line diagnostics (pepperpot/ Faraday cup (FC-analyze)).

is also installed close to FC-Analysis to measure the beam emittance. The IBSIMU simulations indicated a theoretical transmission of 90 % through the LEBT for a 1 mm plasma

* thomas.andre@lpsc.in2p3.fr

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electrode diameter with 1 A cm^{-2} current density [8] . The experimental ion source and the LEBT base vacuum was improved from 10^{-7} mbar to 10^{-6} mbar.

Experimental Results

The primary objectives of the new experimental campaign were to reproduce the former current density results (obtained in 2014) and validate the higher ion beam transport through the new LEBT. In 2022, early beam transport measurement yields appeared below expectation. An Einzel lens was added as close as possible from the ion source extraction, before the quadrupole triplet to enhance the extracted beam focusing. Measurement made in February 2023 with Oxygen support gas at 18 kV source voltage shows a mean extracted current around 1.4 mA in FC-Source, which corresponds to a current density of 180 mA cm^{-2}. Without any focusing, the beam transport in the LEBT is poor, with a transmission about 23 % (ratio of the current measured in FC-dipole and FC-source, see Fig.1). The tuning of the quadrupole triplet and the Einzel lens allowed the transport of 1 mA beam intensity up to FC-Dipole, improving the transmission to 73 % [8].The experiments stopped after the short-circuit of the two injection coils. The experiments resumed in 2024 after the fixing of the damaged coils. The extracted beam current measured with FC-source was studied as a function of the source high voltage. The results are presented on Fig. 2. Figure 2**a** shows the time evolution

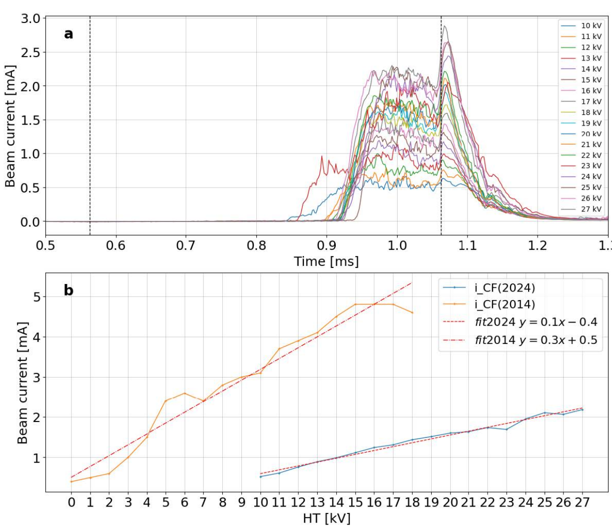

Figure 2: (a) Temporal evolution of the total beam intensity measured in FC-Source for various source high voltage, with a RF power of 80 kW. (b) Evolution of the average ion pulse current as a function of the source high voltage for the 2014 data (orange) and the 2024 data (blue).

of the beam intensity for different extraction voltage. One can see that the ion beam intensity increases with the potential of the source, showing no sign of saturation up to the maximum experimental voltage. The black vertical lines indicate the start and stop time of RF injection in the source. One can also note the presence of an afterglow peak right at the end of the RF pulse. Figure 2**b** shows the mean current intensity (temporal average of the plateau signal) versus the source high voltage for the 2014 (orange curve) and 2024 experiment (blue curve). One can observe that, for both dataset, the current extracted is linearly proportional to the voltage applied. However, the curve slopes and intercepts are different. For 2014 data, the beam intensity increase by ~300 µA/kV applied whereas, for the data of 2024, the slope is about 100 µA/kV. In short, the current density transported in 2024 is ~3 times smaller than the one of 2014 (2.2 mA against 7 mA). After carefully checking that the injected RF power in 2024 was equivalent to the 2014's one, the only remaining parameter different from 2014 was LEBT base pressure.

BASE PRESSURE AND SPACE CHARGE COMPENSATION

Having identified the LEBT base pressure level as the possible factor limiting the beam transport, we investigated the characteristic beam space charge compensation time of our experiment, defined as in Ref. [9]:

$$\tau_{SCC} = \frac{1}{\sigma_i \cdot n_g \cdot v_b}, \tag{1}$$

where σ_i is the ionization cross section of the beam with the residual gas, n_g is the gas density and v_b the velocity of the impinging beam. τ_{SCC} corresponds to the time after which the SCC ratio reached $1/e$ =~37 %.

The ionization cross-section is estimated with an available experimental measurement done for N^+ impact on N_2 [10] at 20 kV, which leads to σ_i ~4 × 10^{-16} cm^2. Indeed, the nitrogen mass being close to the nitrogen one, this cross-section is deemed sufficiently close to our experimental configuration to use it as an estimator.

Figure 3 represents the evolution of τ_{SCC} with the LEBT pressure. The green area corresponds to the 2024 operational range while the blue is the 2014's one. The red line represents the 500 µs beam duration. Before the up-

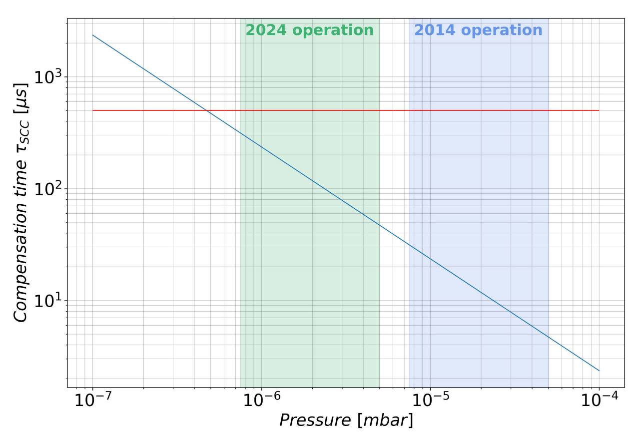

Figure 3: Space Charge compensation time τ_{SCC} as a function of the LEBT pressure. Range of operation of the ion source, blue for 2014, green for 2024.

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grade, due to a rough base vacuum level (7.5×10^{-6} mbar to 5×10^{-5} mbar), τ_{SCC} varies respectively from 31 µs to 5 µs. After the upgrade, the vacuum level span from 7.5×10^{-7} mbar to 5×10^{-6} mbar which gives a τ_{SCC} between respectively 314 µs and 47 µs. One can assume that a SCC steady state is achieved after $T \approx 3 \cdot \tau_{SCC}$. In 2014, we observed that the worst SCC steady state time is T_{2014} ~90 µs, a value much lower than the beam duration of 500 µs. In comparison, T_{2024} can be three times higher than the beam duration itself, leading to a low SCC and resulting in a low beam transport yield.

The future experimental campaign will investigate the current extracted as a function of the pressure in the beam line injecting heavy noble gas, such as argon or krypton.

PACIFICS PROJECT: FUTURE OF THE 60 GHz PROGRAM

Funding was approved by the French Agence Nationale de la Recherche for the PACIFICS project which will allow pursuing the R&D on the 60 GHz ion source. The project includes the design and procurement of a new superconducting cusp, with a magnetic field intensity on the extraction side adjustable from 2.5 to 3.5 T and the radial component $B_r \leq$ 4 T. Equipped with a 200 mm plasma chamber diameter, the plasma will feature a closed 2.14 T ECR surface inside for all the foreseen magnetic configurations. The superconducting coils have been ordered and are currently under construction. The project also funds the upgrade of the gyrotron high voltage power supply to operate in continuous working (CW) operation to deliver up to 20 kW of 60 GHz RF (see Fig. 4).

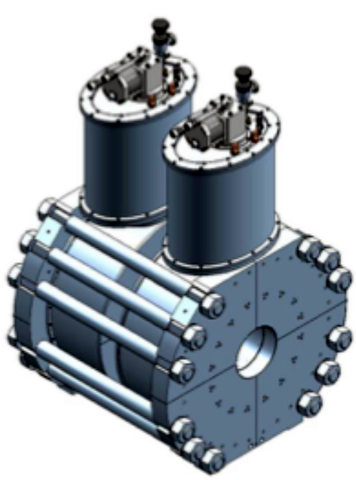

Figure 4: 3D conceptual view of the future superconducting 60 GHz ion source.

One goal of the project is to transform the pulsed current densities measured so far into actual CW high intensity ion beams. Recently, Vybin [11,12] demonstrated the extraction and the transport of ion beams with current density up to 1.15 A cm^{-2} using a point effect extraction system. Such a design will be adapted to the new source to target at least 100 mA beam intensity measured in a faraday cup.

CONCLUSION AND PROSPECTS

The new SEISM LEBT installed since 2019 at LNCMI has demonstrated a significant improvements in the ion beam transmission up to 73%. The reduction of the base pressure in the new LEBT by a decade dramatically increased the time for the pulsed beam to reach a sufficient SCC yield and to be efficiently extracted from the source and transported. This effect resulted in the reduction of the total current extracted from the source with the new LEBT. Such a reduction is well understood by calculating the characteristic time of SCC. The effect is finally reproduced by an (IBSIMU) ion beam simulation with a decrease of the beam SCC from 65% in 2014 down to 35% in 2024. A new system of gas injection will be installed to adjust the LEBT pressure and study the pulsed ion beam current transported as a function fo the pressure and the time. A new budgeted 60 GHz source using superconducting coils, an upgraded CW RF injection and a new extraction system is under design at LPSC. The project's goal is to demonstrate the production of ~100 mA of multi-charged ion beams.

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