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STATUS OF THE AISHa ION SOURCE AT INFN-LNS*

L. Celona†, G. Calabrese, G. Castro, F. Chines, O. Leonardi, G. Manno, D. Mascali,
A. Massara, S. Passerello, D. Siliato, G. Torrisi and S. Gammino
INFN – Laboratori Nazionali del Sud, Catania, Italy
G. Costanzo, C. Maugeri, F. Russo, CNAO, Pavia, Italy

Abstract

The AISHa ion source is an Electron Cyclotron Resonance Ion Source designed to generate high brightness multiply charged ion beams with high reliability, easy operations and maintenance for hadrontherapy applications. The R&D performed by the INFN-LNS team during the 2019/2020 has allowed the improvement of the AISHa performances up to 20% for some of the extracted beams: both injection and extraction flanges has been improved and a movable electrode has been installed. The low energy beam transport has been equipped of an Emittance Measurement Unit (EMU), working through the beam wire scanners principle, for the measurement of the vertical and horizontal emittance of the beams of interest for hadrontherapy applications. Beam emittance has been characterized as a function of q/m and of the beam intensity to highlight space charge effects. If necessary, the beam wire scanners can be used for the characterization of the beam shape. The perspectives for further developments and plasma diagnostics will be also highlighted.

INTRODUCTION

The Advanced Ion Source for Hadrontherapy (AISHa) is an Electron Cyclotron Resonance Ion Source (ECRIS) representing an intermediate step between a 2nd generation ECRIS, unable to provide the requested current and/or brightness, and the 3rd generation ECRIS, too complex and expensive [1].

It has been intended as a multipurpose device and was designed with the typical requirements of hospital facilities in mind, where the minimization of the mean time between failures and the fast maintenance operations are key issues together with the low ripple, high stability, and high reproducibility of the ion beams produced.

For these peculiarities and for the ability to produce highly charged ion beams, it is also a suitable solution to feed accelerators as cyclotrons.

Figure 1 shows a view of the ion source in the experimental area, while the main design features are listed in Table I. The features included in the design exploit all the knowledge acquired from INFN-LNS in the last decades in the ion source design and realization [2].

The AISHa hybrid magnetic system consists of a 36 segment permanent Halbach-type hexapole magnet and a set of 4 independently energized superconducting coils. The coils are enclosed in a compact cryostat equipped with two double-stage cryocoolers that allow us to reach the operating conditions in around 40 h in LHe free operation [3].

The microwave injection system has been designed for maximizing the beam quality through a high-power klystron amplifier operating in the 17.3–18.4 GHz band that allows us to fine tune the frequency by a Digital Fast Tuner System (DFTS). It is scheduled to upgrade the microwave injection system to a higher frequency in order to operate in both single and double frequency modes to exploit at the same time, the Frequency Tuning Effect (FTE) and the Two Frequency Heating (TFH) [4].

A 21 GHz-1.5 kW klystron power amplifier is expected to be delivered by the end of the year and it will be coupled with low losses to the source through the use of an “ad hoc” electromagnetic bandgap device acting as a DC-break.

The plasma chamber, designed to operate around 18 GHz and to hold a maximum power rate of 2 kW is placed at a high voltage (up to 40 kV) and insulated to the ground by a waveguide DC break [5], designed to permit reliable operation up to 50 kV.

The beamline consists of a focusing solenoid placed downstream of the source, a 90° bending dipole for ion selection, and two diagnostic boxes. Each diagnostic box consists of a Faraday Cup (FC), two beam wire scanners, and four slits.

The system of wire scanners and slits has been designed and assembled to allow to beam emittance measurement. The commissioning of the customized Emittance Measurement Unit has started during the late spring with the characterization of the emittance of Argon, Oxygen Carbon, Helium and Proton beams.

Figure 1: Side view of the Advanced Ion Source for Hadrontherapy at INFN-LNS in Catania.

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† Celona@lns.infn.it

Table 1: The Main Design Features of the Source AISHa

Parameter	**Value**
Radial field on plasma chamber wall	1.3 T
Axial field	2.6/0.4/1.7 T
Frequency	17.3/18.4 GHz
Power	1.5 kW
Cryostat length	620 mm
Diameter	650
Extraction voltage	Up to 40 kV
Plasma chamber	92 mm
Extraction aperture	7.2 mm
Resonance zone length	<10 cm

The body source has been totally redesigned paying more attention to the water cooling circuit enabling reliable long time operations. Improvement of the stability of the gas fluxes through the use of mass flow controllers able to provide stable fluxes as low as 0.011 sccm played a key role in the optimization of the source tuning that is in turn beneficial for the emittance minimization.

EXPERIMENTAL RESULTS

The performances of the AISHa ion source has been characterized by the simultaneous measurements of the Charge State Distribution (CSD), of the beam emittance ε and beam brilliance B^q.

The beam emittance has been performed by slicing the beam along the x/y direction and measuring the current for different position of a beam wire scanner, moving parallel to the horizontal/vertical slit. The experimental data have been analysed by means of a home-made code that evaluates the root mean square (rms) normalized emittance.

Normalized emittance is a relativistic invariant, which is expected to be independent of the extraction voltage. Hereinafter we will refer to the rms normalized emittance as the emittance.

The beam brilliance is a measured of the beam current per unit of phase space. Beam brilliance enables us to compare beams characterized by different intensity and emittance. Beam brilliance has been evaluated as the ratio between the ion beam current and the emittance squared:

$$B^q = \frac{I^q}{\varepsilon_x \varepsilon_y}$$

In case of symmetric emittance, $\varepsilon_x \sim \varepsilon_y$, the brilliance can be simply evaluated as:

$$B^q = \frac{I^q}{{\varepsilon_{x,y}}^2}$$

Figures 2, 3 and 4 shows the CSD of the AISHa ion source when producing Argon, Oxygen and Helium respectively. During the test AISHa was able to produce up to 1.3 mA of O^{6+}, 0.35 mA of O^{7+} and more than 5 mA of He^{2+}.

However, it is noteworthy that, for any of the ion beam investigated, maximum brilliance has been always achieved in the highest current conditions.

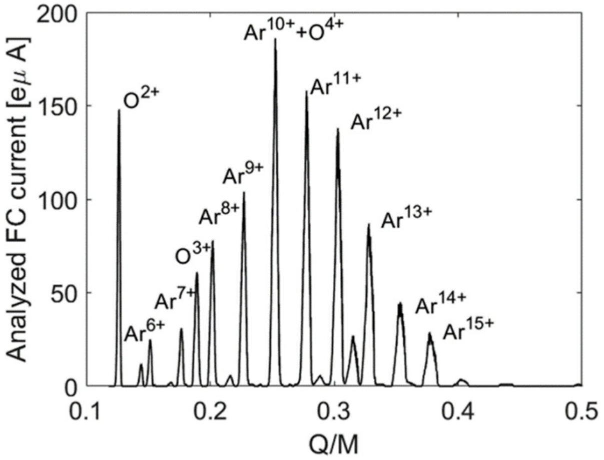

Figure 2: Argon charge state distribution for the ion source tune optimized for the Ar^{11+} charge state.

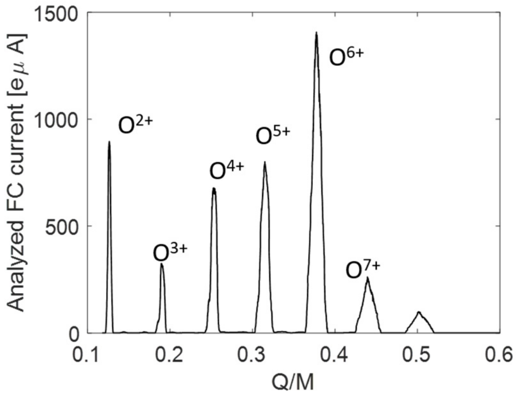

Figure 3: Argon charge state distribution for the ion source tune optimized for the O^{6+} charge state.

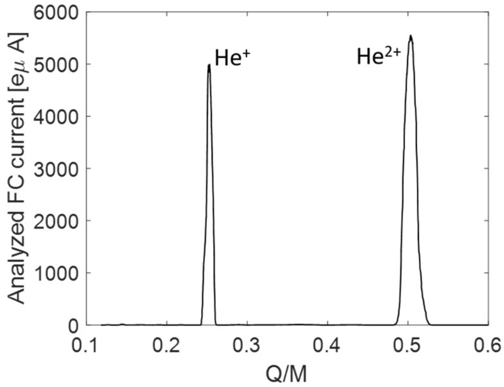

Figure 4: Argon charge state distribution for the ion source tune optimized for the He^{2+} charge state.

Figures 5 and 6 show respectively an example of vertical and horizontal beam emittance acquired by wire scanner system developed at INFN-LNS. The vertical emittance has a spatial dimension larger than the horizontal emittance due to the symmetry breaking introduced by the analysing magnet along the beam transport line. On the other hand, the dimension in the dx/dz dimension is larger in horizontal emittance.

Several studies has been performed with the aim of decreasing the beam emittance for a given ion beam. In particular beam emittance has been characterized versus charge state current I^q. Best value of emittance has been generally obtained for lower values of extracted current. For example, in the case of O^{6+}, the best value has been achieved when producing 0.230 mA (peak value 1.4 mA). In the case of He^{2+}, when producing 0.7 mA (peak value 5.4 mA).

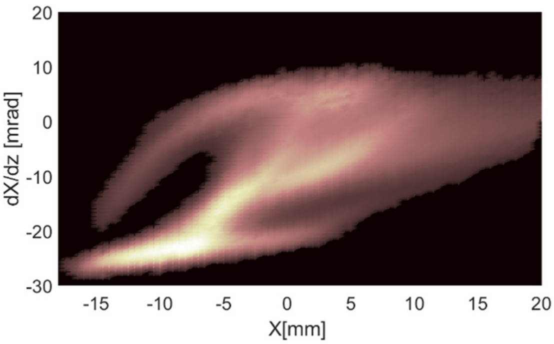

Figure 5: Measure of the vertical emittance of a O^{6+} beam.

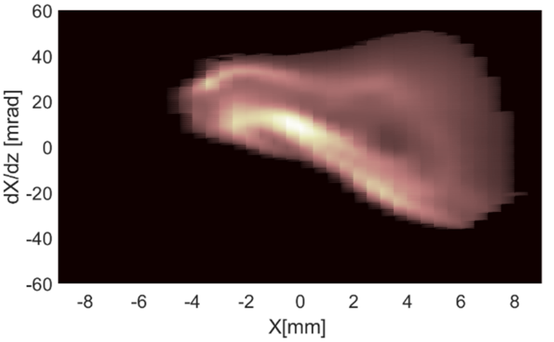

Figure 6: Measure of the horizontal emittance of a O^{6+} beam.

Table 2 summarizes those results in terms of beam current (mA), beam emittance (π·mm·mrad) and beam brilliance (mA/π·mm·mrad²).

Further improvement in terms of peak current and brilliance are awaited as soon as the AISHa shall be upgraded to 21 GHz. Installation of the novel 21 GHz-1.5 kW klystron power amplifier is expected within the end of this year.

CONCLUSION AND PERSPECTIVES

The AISHa ion source is LHe hybrid ECRIS designed in order to work in hospital environment, but is also capable to produce intense highly charged ion beams and for this reason it may be also used in nuclear physics laboratories as a multipurpose source.

The source is going to be moved in a new dedicated laboratory where it is planned to be used for the R&D activities of the LNS ion source group.

A series of experiment and developments have been funded in the next three within the experiment IONS.

Table 2: Best results achieved by the AISHa Ion Source in terms of extracted current (mA), beam emittance (π·mm·mrad) and beam brilliance (mA/π·mm·mrad²)

Charge State	**I^q**	**$\varepsilon_{rms.norm}$**	**Brilliance**
$^{16}O^{6+}$	1.4	0.2198	28.9
$^{16}O^{6+}$	0.23	0.115	17
$^{16}O^{7+}$	0.35	0.247	5.7
$^{12}C^{4+}$	0.65	0.272	8.8
$^{12}C^{4+}$	0.15	0.222	3
$^{12}C^{5+}$	0.17	---	---
$^{40}Ar^{11+}$	0.16	0.201	3.8
$^{40}Ar^{12+}$	0.14	0.201	3.4
$^{4}He^{2+}$	5.4	0.418	30.9
$^{4}He^{2+}$	0.7	0.245	11.6

A second source is under realization for the CNAO hadrontherapy center located in Pavia. Magnetic system have been already realized, the procurement phase is under way and the first assemblies are expected for March-April 2021 at INFN-Pavia. The pre-assembled source is expected to be deployed at CNAO synchrotron room within the fall of the next year.

ACKNOWLEDGEMENTS

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