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An improved AISHa ion source for new clinical protocols, nuclear-physics and material experiments

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Summary. — Hadrontherapy is a well-known clinical practice to treat an increasing number of oncological pathologies, in particular inoperable or radioresistant cancers, when it is essential to minimize the dose absorbed by healthy tissue, as in pediatrics or brain tumors. Due to its unique peculiarities, the ECR ion sources able to produce multiply charged ion beams with low ripple, high stability and reproducibility, are the most suitable choice for medical applications, but also to nuclear physics and material experiments. In the framework of the INSpIRIT project, in collaboration with the Centro Nazionale di Adroterapia Oncologica (CNAO), an improved Advanced Ion Source for Hadrontherapy (AISHa) was assembled in Pavia in order to increase the CNAO potential in the field of experimental and industrial research, particle physics, and with the long-term goal of introducing new ionic species into clinical practice such as helium, oxygen and later also iron and lithium useful for bio-spatial research. The key peculiarity and the experimental results of the AISHa ion source will be presented together with an overview of the INSpIRIT project.

1. – Introduction

Hadrontherapy, today applicated in more centers for the treatment of patients affected by oncological pathologies, uses beams of fast charged particles. They have the advantage of an inverted dose profile, *i.e.*, the Bragg peak is at the end of their range, but also the additional advantage of a reduced lateral scattering and an increased Relative Biological Effectiveness (RBE) at the end of their range, making them well suited for the treatment of radioresistant tumors [1] or in pediatrics and brain tumours, where it is essential to minimize the dose absorbed by healthy tissue [2].

The species used today in hadron therapy centres are protons, carbon, and recently also helium ions [3]. Due to their unique peculiarities, the Electron Cyclotron Resonance (ECR) ion sources [4] are the most suitable choice to produce multiple charged ion beams with low ripple, high stability and reproducibility, together with the typical requirements of hospital facilities: compactness, minimization of the mean time between failures, and fast maintenance operations.

In this work, we report the description of a key peculiarity of the AISHa ion source developed at INFN-LNS in Catania and the experimental results achieved during the last commissioning carried out in 2019. Furthermore, a brief description of the INSpIRIT project is given, that allowed the construction and installation of an upgraded AISHa source to increase the CNAO potential in the field of hadrontherapy, particle physics, experimental and industrial research.

2. – The Advanced Ion Source for Hadrontherapy

The AISHa ion source was designed in order to adapt the high performance of an ECR ion source to hospital facilities. This implies the simplification of all ancillary systems including the possibility of hosting an oven for the production of metallic ion beams.

The core of the AISHa source is its hybrid magnetic system consisting of a 36-segment permanent Halbach-type hexapole magnet and a set of independently superconducting coils. These coils are enclosed in a compact cryostat equipped with two double-stage cryocoolers that allow reaching the operating conditions in around 40 h in helium-free operation [5]. The plasma chamber is placed at high voltage and insulated to the ground by a glass/carbon fiber tube surrounding the hexapole to keep the superconducting magnets and the yoke at ground potential, allowing reliable operation up to 40 kV [6]. The microwave injection system was designed to operate in both single and double frequency modes through two high-power klystron amplifiers able to deliver up to 1.5 kW around 18 and 21 GHz respectively. The microwave amplifiers are located on ground potential and they are insulated from the plasma chamber by two *ad hoc* electromagnetic passive devices acting as a DC-break, designed and developed entirely at the LNS [7]. The three electrodes movable extraction system was designed to pull out a particle beam preventing the electrons transported by the ion beam from being accelerated again backward.

The Low Energy Beam Transport (LEBT) consists of a focusing solenoid placed downstream of the extraction, a 90° bending dipole for ion selection and two diagnostic boxes, each consisting of a Faraday Cup (FC), two beam wire scanners and four slits, forming an Allison scanner, to measure the transverse emittance and allow a complete characterization of the beam. Figure 1 shows the AISHa source at INFN-LNS in Catania.

The first results of the source were achieved in the first months of 2017 [5]. The gas pressure and magnetic field configuration was optimized to maximize the microwave-to-plasma coupling and plasma stability. During this first commissioning, a few criticalities were observed and quickly fixed in a subsequent redesign phase of the subsystems [8]. The best results achieved during the last commissioning at 18 GHz are summarized in table I. During this experimental phase, more than 5000 eμA of $^4He^{2+}$ were produced, and 1400 eμA of O^{6+} together with 200 eμA of O^{7+}. More details about the Charge State Distribution (CSD), emittance and working conditions can be found in refs. [8, 9].

Fig. 1. – The Advanced Ion Source for Hadrontherapy at INFN-LNS in Catania.

3. – The INSpIRIT project

The ECR ion sources are the most common devices used in hospital environments as well as for research purposes. To date, the Centro Nazionale di Adroterapia Oncologica (CNAO) has been using two identical commercial ECR sources to provide beams of protons and carbon ions with sufficient intensities and stability to treat its patients [10].

A recent expansion project, named INSpIRIT —INnovative accelerator facility with Sources Ions for Research and radiation hardness studies with IndusTrial and clinical applications— approved by the Ministry of Health and financed by the Lombardy Region with European funds, foresees together with the revamping of synchro critical components, also the addition of a third source with the long-term goal of introducing new ionic species into clinical practice such as helium, lithium and oxygen, and later also iron, useful for bio-spatial research. Helium and lithium ions will be studied for their better lateral dose distribution with respect to protons. Oxygen is also considered, due to its energy deposition characteristics [11].

Table I reports the intensities of ions extracted by the AISHa source together with the requirement of the INSPiRIT project. The table shows that AISHa source is able to fulfill the requirements of the project.

Table I. – *Intensity of the ion beams extracted from the AISHa source with respect to the requirements of the INSpIRIT project.*

Ion	AISHa [μA]	INSpIRIT [μA]
H^+	8000	–
Ar^{11+}	155	–
C^{4+}	520	110
He^{2+}	5400	344
O^{6+}	1400	64

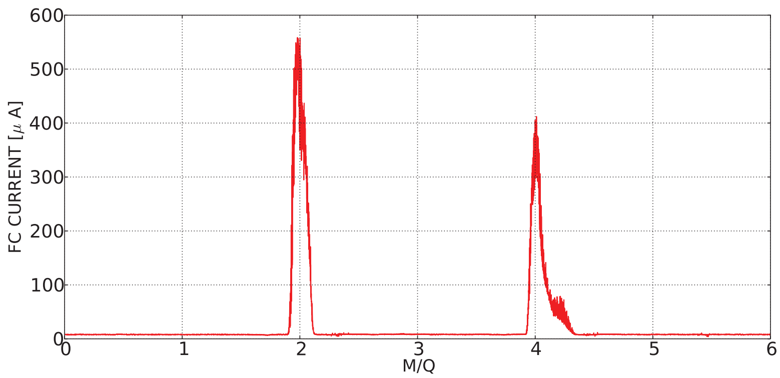

Fig. 2. – First helium beam produced by the AISHa-CNAO source.

So, in the framework of the INSpIRIT projects, an improved copy of the AISHa source was assembled in close collaboration with INFN-Sezione Pavia. The AISHa-CNAO source differs only slightly from its predecessor. It has an improved hexapole containment chamber, a new titanium bias disk with improvements to the injection cooling system, a new electrode handling system in extraction, and the predisposition to host a resistive oven for the evaporation of metallic elements with an improved cooling system.

The ion source and ancillary equipment were preassembled in INFN-PV in July 2022. The deployment into the synchrotron room was carried out starting on 3 September 2022, the displacements were done in several time slots allocated for synchrotron ordinary maintenance. Figure 2 reports the first ion beam extracted on 19 November 2022, when a He^{2+} intensity of 500 μA was produced. A constant and attentive debugging of the control and safety systems is currently in progress to provide the highest security operation during short-term commissioning.

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