# DESIGN OF THE AISHA ION SOURCE FOR HADRON THERAPY FACILITIES

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## *Abstract*

Different facilities for hadrontherapy have been built or designed in the recent past and Italy is present in the field either with synchrotron-based and with cyclotron-based facilities. For both types of accelerators the availability of high brightness multiply charged ion beams is essential and R&D efforts in this subject are increasing. At CNAO, proton and carbon ion beams will be accelerated up to 400 AMeV by a synchrotron and the beam injection is guaranteed by two identical ECR sources of the SUPERNANOGAN family modified according to the specifications we set. Optimisation of beam emittance and intensity is of primary importance to obtain the necessary current in the RFQ-LINAC and future facilities may require much better performances in terms of beam brightness than the ones provided by such commercial ECRIS. A hadron therapy center is going to be built in Catania and the R&D related to the injector has already started within the frame of a collaboration between the Sicilian Authority and INFN. The design of a relatively compact ECR ion source operating at 18 GHz, named AISHa, has been completed recently and the construction will start at the end of 2012.

## INTRODUCTION

The AISHa ion source has been designed by keeping in mind the typical requirements of hospital-based facilities, where the minimization of the mean time between failures (MTBF) is a key point together with the maintenance operations which should be fast and easy. Therefore, a so-called 3rd generation ECR ion source is not suitable, being quite complex for unskilled operators.

The new AISHa source is designed to be an intermediate step between the 2nd generation ECRIS (unable to provide the requested current and/or brightness) and the 3rd generation ECRIS (too complex and expensive).

It is intended to be a multipurpose device, operating at 18 GHz instead of 14 GHz in order to achieve higher plasma densities. It should provide enough versatility for future needs of the hadron therapy, including the ability to run at larger microwave power to produce different species and higher charge states than it is now for $C^{4+}$. At the same time, the electrical power to be installed for its operation will be kept below 50 kW, for possible installation on high voltage platforms. This demand implies also the simplification of all ancillary systems including an oven for metallic ion beams, which is interesting for new beam for hadrontherapy and for other applications.

The AISHa source is funded within the framework of the program of Sicilian Government named PO FESR 2007-2013 and a pool of Sicilian SME is associated with INFN for this project. The source is potentially interesting for the hadrontheraphy center to be built in Catania (call in progress) and for the CNAO (Pavia), which is the only operational Italian center for deep hadrontherapy at this date. In fact, it aims to offer treatments with active scanning both with proton and carbon ion beams, accelerated up to 400 MeV/amu by a synchrotron. Actually, at CNAO two ECR sources of the SUPERNANOGAN type (built by the Pantechnik company according to specifications set by INFN) are used. The factory tests confirmed the fulfilment of the specifications in terms of beam current and emittance. A further increase of accelerator reliability involves the improvement of the beam brightness, which can be achieved with the design and construction of this new ECR ion source.

## MECHANICAL DESIGN AND BEAMLINE

The plasma chamber design is particularly important because its dimensions determine the plasma dynamics and the microwave coupling, while on the other way its larger dimensions may increase dramatically the construction costs. Since highly charged ions are not required to be produced (highest charge state requested do not exceed $6^+$), the source can be designed with a short plasma chamber.

This will also reduce the number of high energy electrons, with a general improvement of source stability and reliability. Mechanics is essential for reliable operations; the perfect water-cooling permits to avoid hot spots which deteriorate the vacuum, making the beam less stable and the emittance larger and variable with the time.

The plasma chamber will be stainless steel made and it should operate at a maximum power rate of 2 kW by using double wall water-cooling . The insulation will be adapted to 40 kV operation by means of a 4 mm thick PEEK tube surrounding the hexapole, keeping magnets and yoke at ground potential. Polishing of any surface is requested in order to avoid sparks. This value of insulation will permit to adapt the AISHa source to other facilities (e.g. the high voltage platform for INFN-LNL). A new type of dc break has been designed to permit reliable operation even at 40 kV. The layout of the source is shown in Fig. 1.

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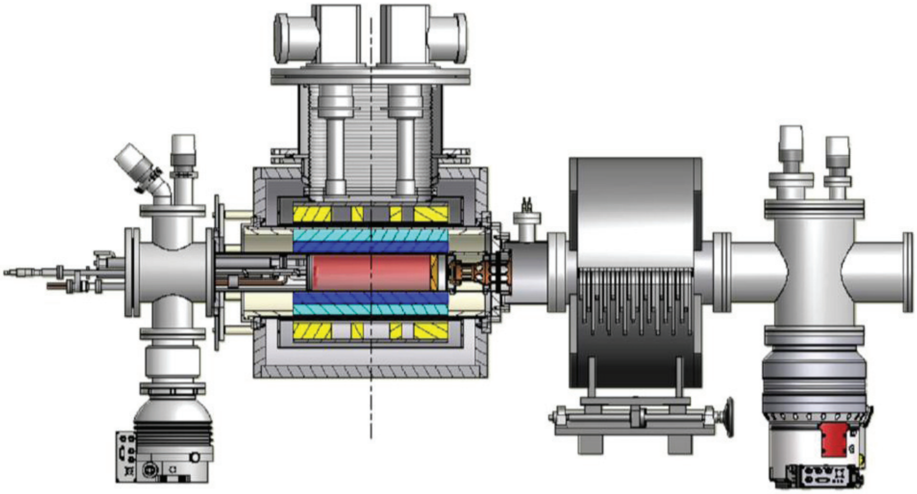

Figure 1: The layout of the AISHa source.

## MAGNETIC SYSTEM DESIGN

The AISHa source will be based on a hybrid magnetic system able to confine the plasma radially by means of a permanent magnet hexapole, providing a maximum field of 1.3 T in the plasma chamber; the axial confinement will be given by a set of superconducting solenoids, enclosed in a compact cryostat. The cryostat will include two cryocoolers that permit to the equipment to run in LHe-free configuration. Studies have been carried out for two different configurations, with 3 or 4 solenoids to generate the mirror field, but the solution with 4 solenoids seems to be preferable for its versatility, even if it increases slightly the construction cost. The use of two middle coils instead of one may allow to finely tune the mirror ratio that is deemed to improve the ECR heating process according to recent achievements [1].

The hexapole demagnetization due to the superconducting solenoidal field has been carefully take into account in the OPERA calculations: Fig.3 shows the resultant of $H_x$ and $H_y$ over the hexapole surface due to the SC coils. The red parts indicate where the absolute value of the demagnetization vector is greater than the coercitivity; such calculations permitted to appropriately choose the permanent magnet materials and to define the final hexapole structure. The magnetic field values obey to the so-called ECRIS standard model for the operational frequency of 18 GHz. The peak field at the injection side is around 2.6 T and at the extraction side it should be about 1.7 T, with a minimum value so low as 0.4 T, about 60% of the ECR resonance field. This design should maximize the plasma density with a moderate microwave power and with a set of magnets that do not present any criticality. The cryostat has quite compact dimensions (its total length is 620 mm and its diameter 550 mm); the ECR region may be sufficiently long to facilitate the production of multiply charged ions; by changing the current in the two middle coils the ECR region may extend it up to 100 mm. The position of the ECR region is a crucial parameter as it strongly influences the electron heating: the tunable magnetic profile allows to improve the heating efficiency, suppressing the production of quasi-collisionless high energy electrons.

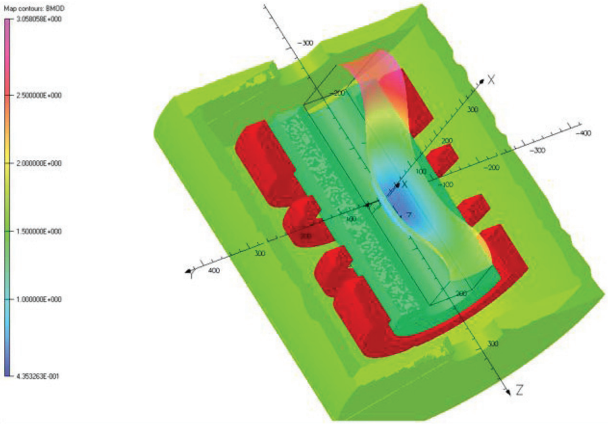

Figure 2: A 3D view of the entire magnetic system.

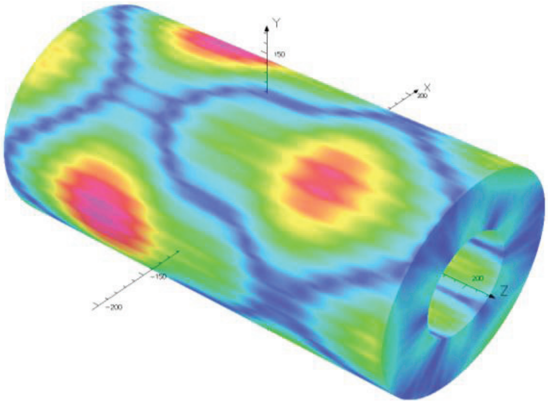

Figure 3: The resultant of Hx and Hy over the hexapole surface.

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The permanent magnet hexapole is made of NdFeB and it has a total length of 331 mm, slightly longer than the plasma chamber, which length is 300 mm, roughly corresponding to the distance between the two maxima of the mirror field. The superconducting solenoids are NbTi made and they are surrounded by an iron yoke, 30 mm thick, with 50 mm thick end plates on both sides. The current density in the four coils is 145, 121,120 and 121 A/mm$^2$ respectively, with the second and third coil current running in opposite direction with respect to the injection and extraction coil. The maximum axial gradients is about 13 T/m, enough to run the plasma in "strong gradient regime" [1,2] even for moderate microwave power (500 W to 1 kW).

## MICROWAVE SETUP

The microwave injection system is the key element of the AISHa source design, according to our recent studies [1-2]. The source will use the frequency tuning effect with two electromagnetic waves of different frequencies injected in the chamber through separate input. The chamber dimensions have been chosen as a compromise between compactness and frequency gap between the modes in vacuum in the range 17.3-18.1 GHz. The position of the input waveguides was determined on the basis of the field pattern for the different modes. An estimation was performed on the maximum intensity of the modal electric fields excited in a vacuum filled cylindrical cavity, representing the plasma chamber. Simple considerations indicated that a position close to the value of 0.6r is the best choice.

The two frequency heating has been largely used to generate moderate currents of the highest charge states, but it has never been used to optimize the beam brightness. It may be helpful whether both the frequencies would be separately tuneable. In this way the electron energy distribution function may be optimized for the ionization of a definite charge state. Two 'traveling wave tube' (TWT) amplifiers will be used and their microwaves frequencies may be determined numerically, to use a maximum power much lower than it is for fixed frequency generator (at INFN-LNS a factor two or three difference was measured in similar experiments). Even from the point of view of the loss cone, the so-called 'plug-in' mechanism is enhanced in such a way and a larger number of electrons is confined, which improves the stability and reliability of the source. A "multi-frequency heating" has been also studied but the improvement does not balance larger cost and complexity. The microwave injector is shown in Figs. 4 and 5.

## EXTRACTION SYSTEM

The extractor is an important element in the coupling between the ECR source and the following accelerator as it determines the shape and the width of the beam in the real space and in the phase space.

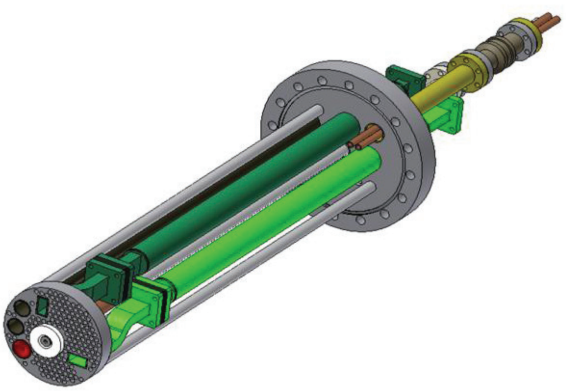

Figure 4: The injection system.

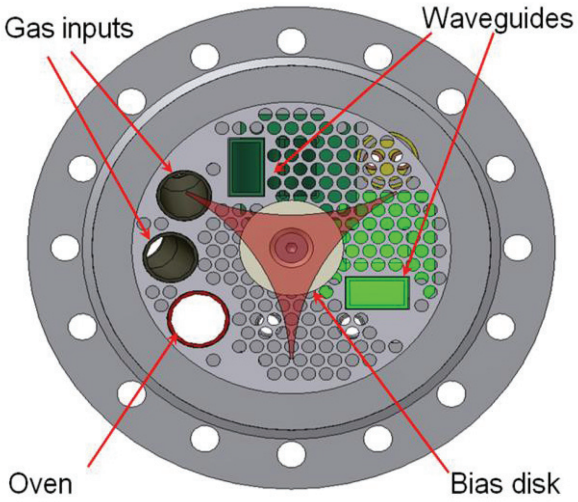

Figure 5: The injection flange.

The SUPERNANOGAN CNAO extractor was optimized by taking into account the constraints of the existing design, that permitted a limited increase of beam brightness. A further step is possible and it is under way with the design of the AISHa extraction system. At this moment the study is not yet complete, it will be defined as soon as the effective fringing field of the magnetic trap will be available for the KOBRA3D simulations.

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