# THE MISHA ION SOURCE FOR HADRON THERAPY FACILITIES

G. Ciavola, S. Gammino, L. Celona, L. Andò, F. Maimone, D. Mascali
INFN-LNS, Via. S. Sofia 62, 95123 Catania, Italy

*Abstract*

During the last years it was demonstrated that slight variations of microwave frequency used in ECRIS strongly influence their performances either for extracted current and for beam brightness and stability. Theoretical investigations put in evidence that such frequency tuning is linked to the electromagnetic field structure inside the resonant cavity. PIC simulations have shown that the frequency tuning influences the plasma properties and the beam brightness. Such analysis allowed to define the optimum setup as for plasma chamber dimensions and microwave injection. The dimensions of the MISHA source (Multicharged Ion Source for HAdrontherapy) are chosen as a compromise between the ideal size for microwave-plasma coupling, the need to get long ion confinement time and the request of compactness. The magnetic trap is based on the use of steep gradient to improve plasma confinement and heating, but the cryogenics issues are simplified; the extractor is designed to minimize the aberrations. The main items of the source design will be given in the following.

## INTRODUCTION

The Centro Nazionale di Adroterapia Oncologica (National Center for Oncological Hadrontherapy, CNAO) of Pavia is the Italian center for deep hadrontherapy. It aims to offer treatments with active scanning both with proton and carbon ion beams, accelerated up to 400 MeV/amu by a synchrotron. At CNAO two ECR sources of the SUPERNANOGAN type (built by the Pantechnik company according to specifications set by INFN) have been installed in 2007/08. The sources are identical and they can provide both beams after a simple switching of gases. Optimisation of beam emittance and intensity has been pursued to maximize the current out of the RFQ. The factory tests confirmed the fulfilment of the specifications in terms of beam current and emittance and the commissioning tests, still under way, featured a transmission in the RFQ around 60%, close to the design values and better than for similar setups in other facilities [1]. A further increase of accelerator reliability involves the improvement of the beam brightness, which can be achieved with the design and construction of a new ECR ion source, able to provide more than 600 eμA of $C^{4+}$ within the same emittance (better than 0.75π mm. mrad). This source should be easy-to-use as the existing sources.

For hospital based accelerators it is essential that the mean time between failures (MTBF) be very high and the maintenance be fast and easy. Therefore, a so-called 3$^{rd}$ generation ECR ion source is not suitable, being quite complex for unskilled operator.

The new MISHA source should be an intermediate step between the 2$^{nd}$ generation ECRIS (unable to provide the requested brightness) and the 3$^{rd}$ 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 have a higher cutoff density. 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 should be kept below 50 kW, for possible installation on high voltage platforms [2]. This demand implies also the simplification of all ancillary systems including an oven for metallic ion beams, which is not essential for the case of hadron therapy, but it is for other applications. The design here presented will be considered for funding by CNAO Foundation in the second half of this year, so that the construction of the source may be completed in the first months of 2011.

## EXPERIMENTAL EXPERIENCES

The experience gained during the acceptance tests of the SUPERNANOGAN sources at CNAO [3] will be relevant to the design of this new source, particularly the emittance measurements and the stability tests. Minor sparks and no break down of the source were observed, accounting a total availability figure for the two installed sources of 98.2 and 99.7% over 36 h for $C^{4+}$ at 200μA, above the contractual limit (98%). The lack of stability observed for the 1$^{st}$ source because of the poor thermal shielding of the UDV gas valves has been corrected by using the electrically controlled thermal mode of the valves, and by placing them in a thermally insulated box. Finally the current was well above the requirements, i.e. 250 eμA for $C^{4+}$ (25% more than requested) and 1100 eμA for $H_3^+$ (50% more than requested) and we decided to decrease the plasma electrode hole diameter to 6 mm, to get a better emittance. From these data we draw the conclusion that additional steps towards higher brightness may be viable with a different source design, still keeping the reliability and stability excellent.

## MAGNET DESIGN

The MISHA 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 1.25 T in the plasma chamber; the axial confinement will be given by a set of superconducting solenoids, enclosed in a compact cryostat including a cryocooler that permits 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 preferrable 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 [4].

The solenoids must be built so that the hexapole demagnetization is avoided. The magnetic field values follow the so-called ECRIS standard model for the operational frequency of 18 GHz. The peak field at the injection side should be above 2.3 T and at the extraction side should be about 1.7 T, keeping 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 problem in terms of feasibility. 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 favour the production of highly charged ions; the change of current in the two middle coils 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.

The permanent magnet hexapole (fig. 1) is made of NdFeB and it has a configuration similar to the one of the GTS source [5] and 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 (fig. 2) 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" [4,6] even for moderate microwave power (500 W to 1 kW).

## MICROWAVE SETUP

The microwave injection system is the key element of the MISHA source design, according to our recent studies [4,6,7]. 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. In particular, the distribution of maxima was studied with respect to the radius of the circular cavity base, i.e. the injection flange. In particular all the maxima except the ones connected with low order modes are localized far from zero and between 0.5r and 0.7r. Furthermore, the maxima decrease with the function order. These simple considerations indicated that a position at 57 mm radius, close to the value of 0.6r, may be a good choice.

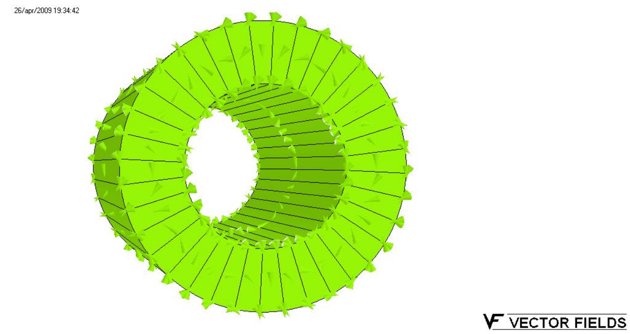


Figure 1: A picture of the hexapole.

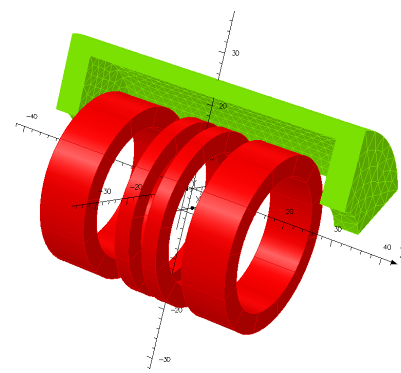

Figure 2: A picture of the solenoids with the iron yoke.

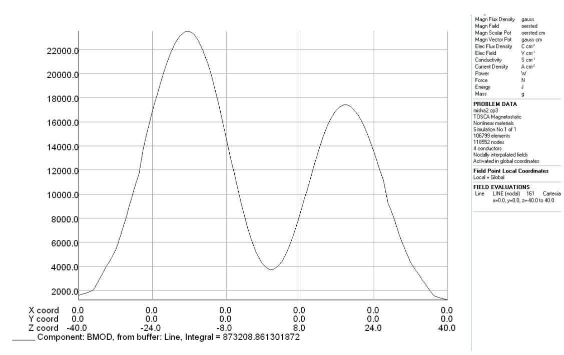


Figure 3: Values of the axial field along the axis.

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 provided that both the frequencies are 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 have to 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). Even from the point of view of the loss cone, the so-called 'plug-in' mechanism is enhanced and a larger number of electrons is confined [6], 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 fig. 4.

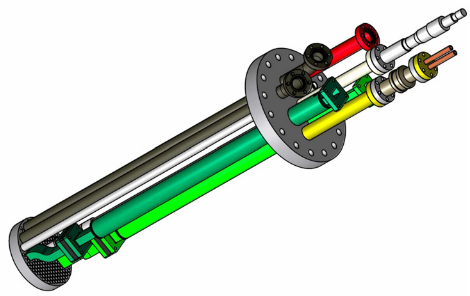

Figure 4: The microwave injection flange.

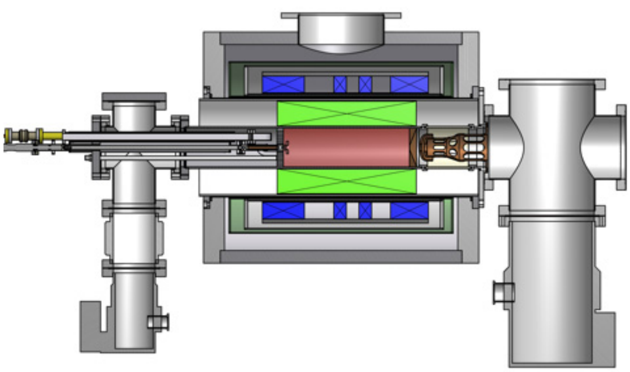

Figure 5: A cut view of the source.

## EXTRACTION SYSTEM

The extraction system of the CNAO ion source has to meet the requirements of the matching with RFQ (0.75π mm mrad acceptance) and to operate continuously without beam interruption. The original extraction system presented a MTBF that was good but still not acceptable for the CNAO facility. The improvements were focused on the electrodes shape and on the decrease of their relative distances, in order to reduce the path where the beam is uncompensated. The reduction of the gap between the plasma electrode and the puller electrode, as well as of the next gap, permitted to meet the specifications [3] and to decrease the extractor' s sparks.

The extractor is an important point in the coupling between the ECR source and the following RFQ as it determines the shape and the width of the beam in the real space and in the phase space. The SUPERNANOGAN extractor was optimized by taking into account the constraints of the existing design, that permitted a limited increase of beam brightness, but a further step is possible and it is under way with the design of the MISHA extraction system. At this moment the study is not yet complete, but the final drawing will be quite similar to the one described in fig. 5. It will be defined as soon as the effective fringing field of the magnetic trap will be available for the KOBRA3D simulations.

## 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. A longer plasma chamber may be preferable to have longer confinement times, but this parameter affects essentially the production of the highest charge states. 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. The value for the insulation is higher than the one requested for the CNAO project, in order to permit the MISHA source to be adapted to other facilities (e.g. the high voltage platform for INFN-LNL [2] or a cyclotron-based facility for hadron therapy [8]). A new type of dc break has been designed to permit reliable operation even at 40 kV. Vacuum system will be based on two turbomolecular pumps 350 and 1000 l/s at injection and extraction respectively), because the pressure should be in the order of $10^{-7}$ mbar. The beamline will be a copy of the one used for the existing SUPERNANOGAN sources at CNAO, in order to permit an easy installation and a good reliability.

## ACKNOWLEDGEMENTS

The support of the CNAO foundation is gratefully acknowledged. The authors wish to thank M. Pullia, S. Rossi and D. Hitz. The help of L. Allegra in the technical drawings preparation is also acknowledged.

## REFERENCES

[1] M. Pullia, private communication
[2] G. Bisoffi et al, Proc. Eur. Part. Acc. Conf., Edinburgh (2006) 1597
[3] G. Ciavola et al, Proc. Eur. Part. Acc. Conf., Genoa (2008) 415
[4] S. Gammino et al, submitted to Plasma Source Sci.&Tech. (2009)
[5] D. Hitz et al., Rev. Sci. Instr. 75, (2004) 1403
[6] S. Gammino, et al., IEEE Trans. on Plasma Science, (2008) vol. 36, 4 part II, 1552
[7] D. Mascali et al., these proceedings
[8] M. Maggiore et al., Proc. Part. Acc. Conf., Albuquerque (2007) 2748