ECR ION SOURCE DEVELOPMENTS AT INFN-LNS

L. Celona#, G. Castro, M. Castro, F. Chines, S. Gammino, O. Leonardi, S. Marletta, D. Mascali, L Neri, D. Nicolosi, F. Noto, G. Torrisi, S. Vinciguerra, INFN-LNS, Catania, Italy
G. Ciavola, INFN-LNS, Catania, Italy and CNAO, Pavia, Italy
A. Galatà, INFN-LNL, Legnaro, Italy

Abstract

At INFN-LNS, ECRIS development during the '90s permitted to optimize the K-800 Cyclotron performances: SERSE and CAESAR have well supported Nuclear Physics research, since then. For the new needs of the facility, further improvements are required and they are here described. Activities recently started, aimed to the production of multicharged ion beams and to the production of intense light ion beams with different schemes of plasma generation.

Technological developments led the AISHa source design, in order to adapt a high performance ECR ion source to hospital facilities needing multiply charged ion production with high reliability and brightness, easy operations and maintenance. The realization of a proton source, called PS-ESS, and of its LEBT line for the Linac of the European Spallation Source in Sweden is one of the major activities at INFN-LNS. Other developments are ongoing on high charge state and high intensity beam production: a major update is going to be finalized on SERSE cryogenic system and on CAESAR injection side; at Vancouver, the VIS source is used for producing multi-mA beams of H_2^+ for a high-current cyclotron; a new flexible plasma trap is under test for fundamental research about innovative plasma heating methods.

INTRODUCTION

During the '90s different ion sources have been built at INFN-LNS, two for the production of highly charged heavy ions to be accelerated by the K-800 Superconducting Cyclotron [1,2] and one for the high intensity proton beam injector for the TRASCO/ADS projects [3]. The SERSE source have been working for about 15 years, but during the last three years a shortage in the availability of LHe from the main liquefier has blocked its operation for many months per year. The performances of the second source, CAESAR, have been acceptable for the Cyclotron needs, but the fact that it was the only source has made impossible to proceed to further optimization, after that the injection part has been totally redesigned.

In the recent past, the requests have been more and more relevant either in terms of beam current and in terms of highly charged ion beams from metallic samples, so the decision to update the existing hardware to fulfil the new needs and to improve the two sources has been taken and the first steps have been done; the update operations of the SERSE and CAESAR sources will be completed in 2015. The major changes to the SERSE design will concern the cryostat, that will be operated in stand-alone mode. After this major improvement, a new commissioning phase is to be started, in order to increase the beam current out of the K800 Superconducting Cyclotron. This phase will involve the LEBT revision with the increase of on-line beam diagnostics.

The changes to the CAESAR source are of four types: i) increase of maximum frequency to 18 GHz, ii) update of the control system to decrease the EMI and the related electronics failures, iii) implementation of a compact oven and iv) increase of the injected microwave power.

All these improvements will be even more remarkable if the proposal of the refurbishment of the 20-years-old cyclotron will be funded: in that case the demand of high brightness heavy ion beams will further increase of a factor 10 to 100, in order to support the future studies on double beta decay.

In the meantime, new projects have been started: the AISHA source for hadrontherapy facilities is designed for high brightness multiply charged ion beams with high reliability, easy operations and maintenance.

AISHa has been designed to meet the above cited requirements by means of high field He-free superconducting magnets, while the radial confinement will be provided by a Halbach-type permanent magnet hexapole structure. The source will take profit of all the know-how acquired in the years by the INFN-LNS ion source team. After the prototype, now under construction at INFN-LNS in the frame of a partnership with three Italian SME, a second copy will be built for CNAO and discussion for a third one started.

Another project is going to start as an advanced design study, in the frame of an European collaboration aimed to the construction of a high intensity heavy ion beams accelerator in Huelva, Spain [4]. For this project the design study will be focused on an updated version of AISHA, named ASIA.

On the side of high current proton beams source, following the successful experience of TRIPS and VIS sources, the high intensity proton source named PS-ESS is under construction for the European Spallation Source; it is designed to meet the request of an accelerator chain deemed to produce 2 GeV - 62.5 mA beams, 4% duty cycle. Another activity in this field is the one under way at Best Cyclotron Company, Vancouver, where the VIS source is in use to produce multi-mA beams of H_2^+ for the injection in a high-current cyclotron. Though it is a proof-of-principle experiment, a new customized microwave injection system and plasma chamber for enhanced H_2^+ production has been studied and constructed. The new setup after some off-line tests at INFN-LNS has been moved to Vancouver and in the next month will be tested.

ISBN 978-3-95450-158-8

ECRIS FOR HIGHLY CHARGED IONS

After the experience with SERSE operation at 28 GHz, for many years there were no constructions at INFN-LNS concerning ECRIS for highly charged ion beams, though the team was involved in construction of ECRIS elsewhere, e.g. at CNAO, Pavia or within the EU Framework Programmes (MS-ECRIS source). As the SERSE and CAESAR sources were serving the Cyclotron without troubles, the activity was concentrated onto modelling, diagnostics, study of microwave coupling to plasma, etc. Now that a new season of ECRIS construction has started, the accumulated know-how has been used as a basis for innovative design of the next sources. But it does not mean that the already developed ECRIS, SERSE and CAESAR, will be left out; in fact the revamping of the two sources will play a major role in the upgrade strategy of the INFN-LNS accelerators facility.

SERSE Cryostat Refurbishment

The SERSE source was designed in 1994-1996 and installed at LNS in 1998, with the best technology available at that time for such a complex B-minimum trap; the magnets' design was considered safe only in presence of a LHe bath, with conventional current leads. The cryostat designed in collaboration with CEA- SBT, Grenoble has been indeed very reliable and only few problems have been met for about 15 years. The only limitation was coming from the main liquefier plant, which is serving the K-800 Superconducting Cyclotron as a primary duty, with decreasing additional power in the last few years until the major failure occurred in 2013. The decision to restore the SERSE reliability was taken in 2013 and the order for two cryocoolers Cryomech PT415 was placed recently, while the procedure for the reconstruction of the turret is going to start. The conventional current leads will be replaced by High Temperature Current Leads and the liquefiers will be assembled in such a way to minimize the maintenance time (less than one time per year, safely). As the coil mass is larger than 800 kg, the thermal budget was carefully studied and the choice of the two cryocoolers was taken for the sake of additional margins in case of malfunctioning and of X-ray absorption in the cold mass.

The same safety level in case of quench is guaranteed by the new design, while the cooldown time may be slightly increased after a quench. These drawbacks are not relevant, while the gain in terms of manpower savings and of beam availability will be remarkable.

During the preparation of the proposal, a series of tests was carried out and it was observed that the cryostat performance did not change since 1997, while the current leads present some degradation because of the thermal cycles. So their maintenance would be anyway necessary, which makes reasonable this investment.

The choice of pulse tube cryocooler was carried out in the sense of a larger reliability of the system: this type of cryocooler has very low vibrations and the parts subject to degradation are the compressor and a 5-fold valve which follows a scheduled maintenance (one per 2 years). The operation scheme chosen for SERSE will not permit to exploit the full cryocoolers' power, but only 1.35 W per each, which anyway is much more than the expected thermal budget (1.68 W at 4.5 K). It means that even if the pulse tubes may lose 10% of power at the end of their cycle, there is still 0.7-0.8 W for recovering the X-ray losses into the cold mass.

The Cyclotron schedule will define the time schedule for the SERSE turret refurbishment and the cryocooler installation, but it may be possible to complete the work by the end of summer 2015.

Finally, an important advantage for operation will be the removal of the 500 liters dewar close to the source, which may make easier any intervention on the source hardware, including microwaves supplies.

CAESAR upgrade

The CAESAR upgrading had an impact on different parts of the setup; the goal was not only to increase the energy content of the plasma by increasing the magnetic field at the injection side but also the injected microwave frequency and power used, shifting the maximum operating frequency to 18 GHz. The update of the control system allows to decrease the impact of the electromagnetic interferences and the related electronics failures. A compact oven has been also designed and realized to increase the beam variety.

Therefore the injection side has been totally redesigned as shown in fig. 1, removing the "magic cube" with a new setup which permits to house: two WR62 inputs, an oven, two gas inputs and the biased disk. The increase of the magnetic field at injection has been achieved by inserting an iron plug which boosted the maximum value from 1.5 to more than 1.8 T at the chamber entrance (fig. 1 and 2).

The source commissioning in these new operating conditions is in progress and during the preliminary tests in July the operational range was extended up to 18 GHz; the tuning of frequency is important to achieve the best performances especially for highly charged ions. Another remarkable improvement is the lower beam ripple, even below ± 0.5% for highly charged ion species.

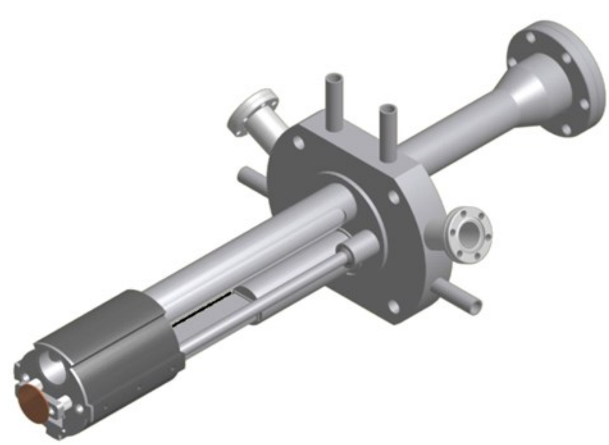

Figure 1: CAESAR new injection system assembly.

ISBN 978-3-95450-158-8

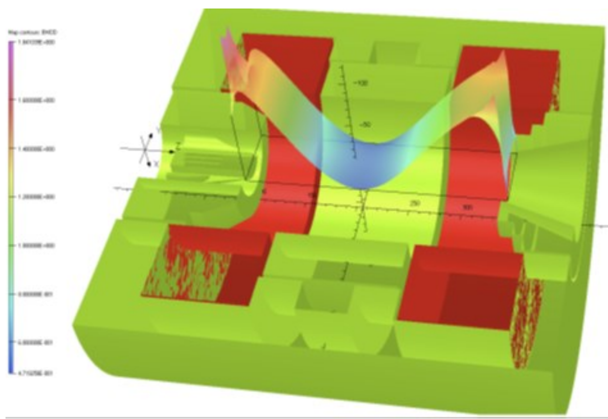

Figure 2: OPERA simulation of the CAESAR axial magnetic field enhancement due to the iron plug insertion.

The AISHa ion source

In order to answer to specific requests of the hadron therapy facilities, the AISHA source was designed in 2012 with the aim to provide highly charged ion beams with low ripple, high stability and high reproducibility; key features were also the low maintenance time and the minimization of electrical consumption. In 2013 the proposal of AISHA construction was approved by the Regional Government of Sicily and the funding was allocated to a private-public partnership including INFN.

The AISHa ion source is a hybrid ion source whose magnetic system is based on a permanent magnet hexapole able to reach up to 1.3 T radial field on plasma chamber walls (ϕ=92mm) and four superconducting coils for the axial plasma confinement. The main characteristics of the source are summarized in table 1.

Table 1: Main AISHa source parameters

AISHa source parameters	
Radial field (max)	1.3 T
Axial field (INJ/MID/EXTR)	2.6 T / 0.4 T / 1.7 T
Operating frequencies	18 GHz (TFH)
Operating power (max)	1.5 kW + 1.5 kW
Extraction voltage (max)	40 kV
Chamber diameter	ϕ=92mm
LHe	Free

The axial magnetic field confinement has been designed on the basis of the previous experiences, in particular to minimize the hot electron component and to optimize the ECR heating process by controlling the field gradient at injection and extraction and the resonance length. For the AISHa source it has been decided to adopt a solution employing four coils which permits to have a good control on the above cited parameters and that will also permit to shift the position of the minimum B field within the ± 15 mm range. Figure 3 shows the magnetic field on source axis, while a 3D view of the magnetic system is shown in fig. 4.

The hexapole has been deeply studied and designed with the OPERA 3D code. The Halbach type hexapole structure is characterized by magnetic elements with nine different directions of magnetization and it is able to reach a radial field close to 1.3 T at 46 mm radius along the whole plasma chamber length, as shown in fig. 5.

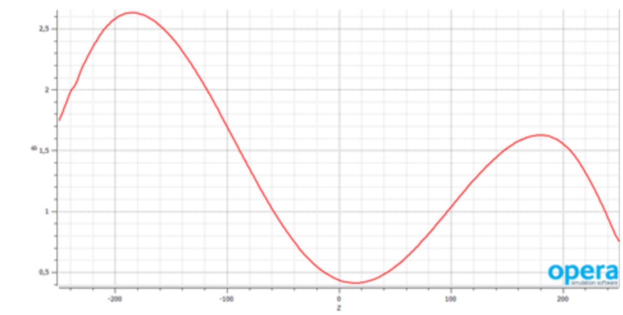

Figure 3: The AISHa magnetic field along plasma chamber axis.

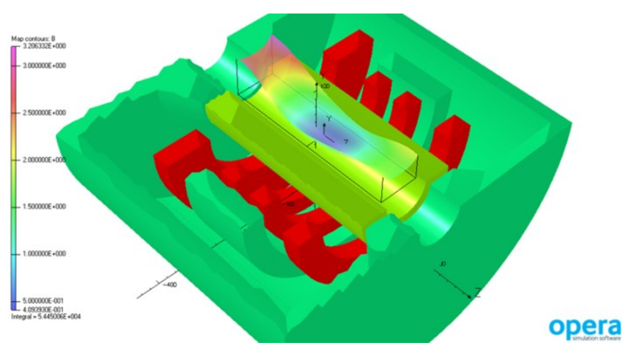

Figure 4: A 3D view of the entire magnetic system.

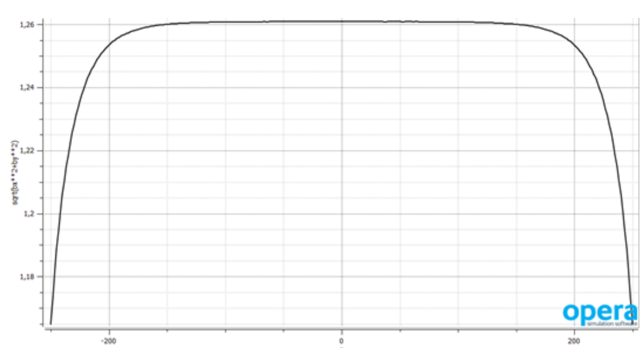

Figure 5: Radial component along z at the inner wall of the AISHa plasma chamber (radius=46 mm).

During the design the efforts have been focused to analyze and minimize the permanent magnet demagnetization. In fact, due to the presence of high values of H_x and H_y generated by the SC coils a local demagnetization of part of the hexapole assembly may happen.

Since only the radial field component may be cause of demagnetization in an already fabricated sector with a given radial direction of magnetization, the z component

ISBN 978-3-95450-158-8

can be neglected, while the x and y components play the key role in the hexapole performance.

A solution to the problem of demagnetization consists in the selection of the sectors where the phenomenon takes place by calculating for each sector the resultant, along the direction of magnetization, of the H_x and H_y vectors. Demagnetization takes place in the sectors where such resultant has an opposite direction with respect to the magnetization itself and a value higher than the coercitivity of the used material. To avoid that the radial confinement magnetic field be decreased, the sector must be replaced with one having higher coercitivity.

In fig. 6 only the region where the resultant magnetic field H is above than 1.1×10^3 kA/m is shown (a 15% safety factor has been taken into account with respect to the minimum coercitivity value).

Since, in such zones, the resultant of H_x and H_y along the direction of magnetization of the sector considered is greater than the coercitivity, another material with higher H_{cJ} must be adopted to avoid demagnetization. Therefore to optimize the structure it is necessary to divide the hexapole in two shells as shown in fig. 7.

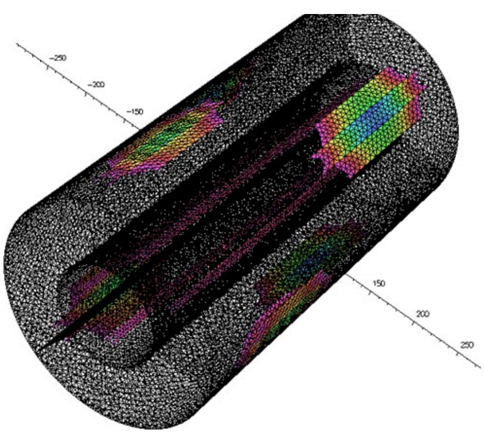

Figure 6: AISHa's hexapole sectors where the field is higher than the coercitivity value are shown.

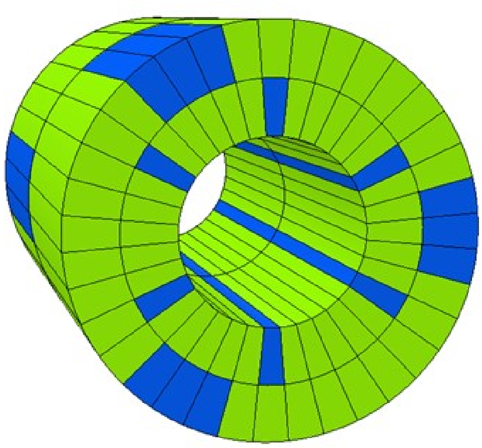

Figure 7: Double shell hexapole geometry (blue sectors have higher coercitivity).

Moreover, on the outer side the maximum radial field values are located in different sectors depending if we are considering the forward half of the structure or the rear half. Therefore, to have the maximum flexibility in the choice of the material, trying to keep material with high value of B_r, the outer shell has been divided in two parts.

The magnetic system has been ordered and it is actually under construction, the delivery is expected for mid-2015.

ION SOURCES FOR HIGH CURRENT OF MONOCHARGED LIGHT BEAMS

Different ion sources have been constructed at INFN-LNS for this purpose. The TRIPS source for the TRASCO/ADS accelerator study paved the way at the end of the 90s. TRIPS met all the requirements [3] and then was moved to INFN-LNL in November 2005 to be coupled to the RFQ. Since then a parallel work on the realization of test-bench called "plasma reactor" and of the optimized source named VIS started. The Versatile Ion Source (VIS) is an off-resonance Microwave Discharge Ion Source (MDIS) which produces a slightly overdense plasma at 2.45 GHz. It is able to produce more than 50 mA of proton beams and He^+ beams at 65 kV, while for H_2^+ a current slightly below 20 mA was obtained. The entire source has been designed in order to present many advantages in terms of compactness, high reliability, capability to operate in cw mode or in pulsed mode, reproducibility and low maintenance. The know-how obtained with the VIS source has been useful for the design of the proton source for the European Spallation Source which is nowadays one of the major engagement for the INFN-LNS.

PS-ESS

The European Spallation Source facility will be one of the fundamental instruments for science and engineering of the future. A 2 GeV proton accelerator is to be built for the neutron production. INFN-LNS is responsible of the design of the proton source and Low Energy Beam Transport (LEBT) line. It is required to produce at RFQ entrance a low emittance 75 keV - 74 mA proton beam pulse, 2.86 ms long, with a repetition rate of 14 Hz. Microwave Discharge Ion Sources (MDIS) enable us to produce such high intensity proton beams with an rms normalized emittance around 0.2 π.mm.mrad. The source design is based on a flexible magnetic system which can be even adapted to electrostatic Bernstein waves heating mechanism; that will permit to explore a new heating method, already tested at INFN-LNS, with an expected increase in the electron density and in the output current with respect to the classical flat magnetic field profiles.

The typical shape of the magnetic field for MDIS machines is the one labeled by (Standard) in Fig. 8, i.e. a quasi-flat profile everywhere above the resonance value of 875 Gauss. This ensures electron densities around the cutoff at 2.45 GHz or slightly larger ($n_e\approx10^{17}$ m^{-3}), temperatures sufficient for hydrogen ionization (T_e=15-20 eV) and H_2 molecule lifetimes long enough for complete

ISBN 978-3-95450-158-8

ionization and proton generation. Such plasma parameters require RF power values close to 1 kW and background pressures down to 10^{-5} mbar. The PS-ESS source and its extraction system are shown in fig. 9.

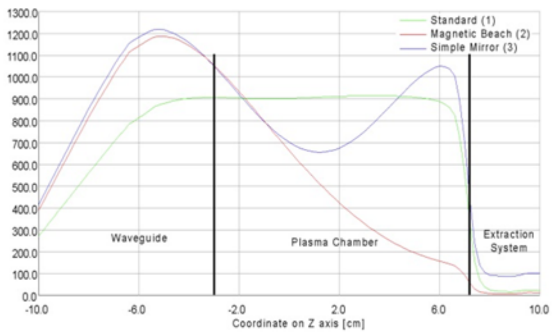

Figure 8: PS-ESS magnetic field profiles.

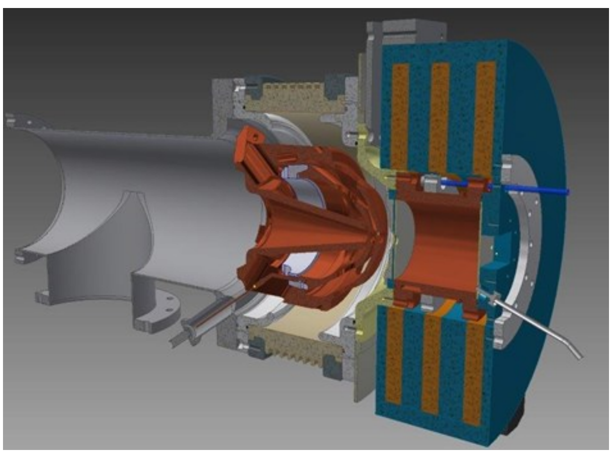

Figure 9: The PS-ESS body source layout.

Recently, the possibility to overcome the cutoff density by converting the incoming electromagnetic wave into a plasma wave has been investigated [5]. This study goes in parallel with similar investigations in fusion science, where large plasma densities are needed to fulfil Lawson criterion [6]. At INFN-LNS the evidence about the occurred conversion mechanism has been observed with the VIS source equipped with a movable permanent magnets and operating at variable frequency [7]. The process is based on the conversion of an oblique (with respect to the applied magnetic field) electromagnetic wave (called extraordinary mode, or X mode) into an electron oscillation (longitudinal wave) propagating across the magnetic lines and called Bernstein Waves (BWs). Plasma waves travel in plasmas of whatever densities and are absorbed at cyclotron harmonics. Since they are sustained by the electron motion, BWs cannot be externally excited, but it originates from an X mode interacting with gyro-rotating electrons at the Upper Hybrid Resonance (UHR) [8]. The first experiments have put in evidence the formation of a two times overdense plasma when operating in second harmonic mode [5]. To be converted into a BWs, the X mode requires a rapidly dropping magnetic field which makes possible either UHR and second harmonic absorption. This configuration is labeled as (Magnetic Beach) in Fig. 8. We expect this second way of RF-plasma energy coupling will significantly enhance the output currents, but it can be employed in a second phase, after a careful study of its implications on ion dynamics (possible ion heating as ancillary mechanism) and then on beam emittance.

Finally, another way to operate the PS-ESS source will be the simple-mirror trap, like the one labeled by (Simple Mirror) in Fig. 8. Studies about balance equations of the different plasma species (H_2, H_2^+, H^+) revealed that their reciprocal abundance is regulated by the relative lifetimes. In a quasi-flat magnetic field, under normal operational pressure conditions, ions lifetime is only governed by collisional diffusion across the magnetic field, which is a rather fast process. The prolongation of H_2^+ molecule lifetime, obtained when using the simple-mirror configuration, may increase the ionization efficiency thus boosting the proton fraction already at moderate RF power and improving also the reliability of the source. Reliability has been sought for in the design of any source component; e.g. in the case of the extraction system, the four electrodes are all directly or indirectly cooled: the plasma electrode is placed on the HV platform at a voltage of 75 kV and the set of the remaining three electrodes is attached to the grounded flange, with the repeller electrode placed between two grounded electrodes to preserve the space charge compensation of the LEBT.

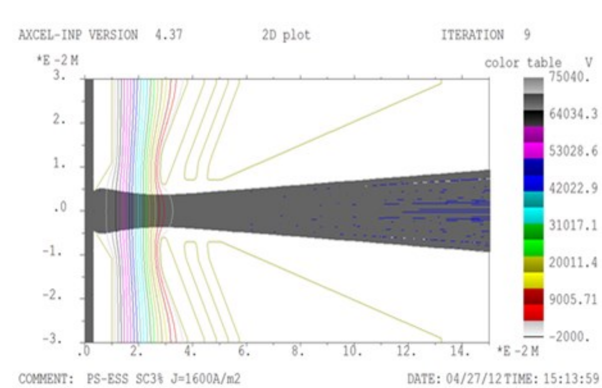

Figure 10: PS-ESS four electrode extraction system.

A multi-parametric optimization of the geometry was done using AXCEL for a 2D axial symmetric simulations (Fig. 10) and converted in a 3D distribution by an on-purpose developed code to be used as input for the TraceWin code to optimize the LEBT lattice. The total beam current used in the simulation is 74 mA : the proton fraction considered is 80%, while 20% is H_2^+.

A two solenoid LEBT will match the beam into the first acceleration stage, the Radio-Frequency Quadrupole (RFQ), and the requested Twiss parameters are obtained. The correct strength of the two solenoids' field was evaluated by using the optimization features of TraceWin code that take also in consideration the space charge of the beam.

ISBN 978-3-95450-158-8

The ESS requirements update of June 2013 defined that the injector must be able to provide current from 10% to 100% of the nominal value with step of 10% and precision of 2% without change of the proton source parameters. This was satisfied by inserting in the LEBT an iris that will cut the beam with high precision. With TraceWin we estimated that the beam must be cut in the range from 5 mm to 30 mm of radius, and we also evaluated for each desired current value the optimum magnetic field strength of the two solenoids to keep the nominal Twiss parameters. As expected, when reducing the current by eliminating peripheral beam the emittance was reduced as well. The LEBT will be equipped with an electrostatic chopper in order to remove the unwanted part of the beam pulse during the beam rise and fall times.

In the low energy beam transport of high intensity beams the self-generated repulsion between charged particles can generate a large and irreversible emittance growth, while the optimum matching with the RFQ require high focusing and low emittance. To reduce this effect the space charge neutralization of the beam can be obtained by ionizing the residual gas. The generated electrons are captured by the beam potential, while the generated ions are repelled by the beam and lost on the surface of the vacuum chamber. In order to preserve the space charge compensation (SCC) from the high electric field located in the extraction system and inside the RFQ, a repelling electrode was inserted both in the extraction system and in the RFQ collimator. Such SCC regime has many similarity to a plasma but the electric field produced by the chopper and the change of the trajectory of the beam inside the LEBT introduces many significant variations in the two transitions: from chopper ON to OFF (beam pulse rise time), and from chopper OFF to ON (beam pulse fall time). We have studied these transitions by performing PIC simulation and by experimental measurements done at CEA, Saclay; the simulations properly represented the measured few hundred nanosecond rise time (Fig. 11) and less than 100 nanosecond fall time.

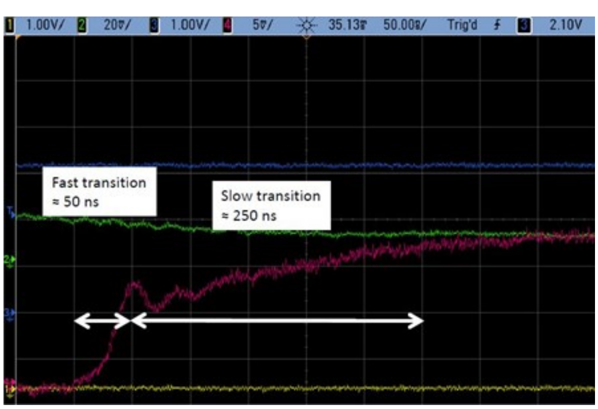

Figure 11: Beam pulse rise time measured.

THEORETICAL ADVANCES

A better comprehension of electron heating, ionization and diffusion processes, ion confinement and ion beam formation is mandatory in order to further increase ECRIS performances. Investigation of plasma dynamics in ECRIS still remains a challenge. At INFN-LNS we have developed a series of releases of a numerical code able to simulate electron heating inside a resonant cavity (i.e. including cavity electromagnetic modes) [9]. Now we are working on an advanced version which attempts three-dimensional (3D) full-wave simulations (including the effects of the cylindrical metallic walls) coupled to a kinetic code to self-consistently retrieve a solution of Vlasov equation via PIC – Particle-In-Cell strategy.

The Vlasov equation:

$$\frac{\partial f_\alpha}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f_\alpha}{\partial \boldsymbol{r}} + \frac{q_\alpha}{m_\alpha}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \frac{\partial f_\alpha}{\partial \boldsymbol{v}} = 0$$

is solved starting from Klimontovich sampling of the phase-space electron distribution, where the mean fields ***E*** and ***B*** are calculated via FEM solvers including the cold plasma approximation, which allows calculating the three dimensional dielectric tensor assuming the following form:

$$\bar{\bar{\varepsilon}} = \varepsilon_0 \bar{\bar{\varepsilon}}_r = \varepsilon_0 \left(\bar{\bar{I}} - \frac{i\sigma}{\omega\varepsilon_0}\right)$$

$$= \begin{bmatrix} 1 + i\dfrac{\omega_p^2}{\omega}\dfrac{a_x}{\Delta} & i\dfrac{\omega_p^2}{\omega}\dfrac{c_z + d_{xy}}{\Delta} & i\dfrac{\omega_p^2}{\omega}\dfrac{-c_y + d_{xz}}{\Delta} \\ i\dfrac{\omega_p^2}{\omega}\dfrac{-c_z + d_{xy}}{\Delta} & 1 + i\dfrac{\omega_p^2}{\omega}\dfrac{a_y}{\Delta} & i\dfrac{\omega_p^2}{\omega}\dfrac{c_x + d_{yz}}{\Delta} \\ i\dfrac{\omega_p^2}{\omega}\dfrac{c_y + d_{xz}}{\Delta} & i\dfrac{\omega_p^2}{\omega}\dfrac{-c_x + d_{zy}}{\Delta} & 1 + i\dfrac{\omega_p^2}{\omega}\dfrac{a_z}{\Delta} \end{bmatrix}$$

with: $a_m = \left(-i\omega + \omega_{eff}\right)^2 + B_{0m}^2\left(\frac{e}{m_e}\right)^2$,

$c_m = B_{0m}\left(\frac{e}{m_e}\right)\left(-i\omega + \omega_{eff}\right)$,

$d_{mn} = B_{0m}B_{0n}\left(\frac{e}{m_e}\right)^2$.

Where: $m = x, y, z,\ n = x, y, z$ and $\Delta = \left(-i\omega + \omega_{eff}\right)a_x + \left(\frac{e}{m_e}\right)\left[B_{0z}\left(c_z - d_{xy}\right) + B_{0y}\left(c_y + d_{xz}\right)\right]$

ω the angular frequency of the microwave, $\omega_p = \sqrt{\frac{n_e e^2}{n_e \varepsilon_0}}$ the plasma oscillation angular frequency, n_e the electron density, m_e the electron mass, e the electron charge, i the imaginary unit and ω_{eff} the collision frequency; the latter accounts for the collisional friction.

Figure 12 depicts the full-wave solution of the field inside an ECRIS cavity (SERSE is the test case). In order to cope with time-consuming computational procedure, the operational frequency was decreased to 8 GHz (by scaling the magnetostatic field as well). In this way the FEM solver retrieves a solution via a direct solver and the self-consistent loop runs for a couple of days; 8 GHz is the upper level of frequency currently producing significant results. In particular, figure 12-up shows the 1D plot – along the plasma chamber axis – of the current density

ISBN 978-3-95450-158-8

$j = \bar{\sigma}E$, where $\bar{\sigma}$ is the tensorial conductivity. This plot is particularly significant since illustrates the plasma response on the electromagnetic field propagation: the current is in fact enhanced in proximity of the resonance zones, where the conductivity and the electric field tend to increase (or even diverge without collisional friction). This demonstrates the model is able to "catch" the wave absorption mechanism in a correct way. Fig. 12-down shows the electromagnetic field structure in case of plasma filled cavity. Localized areas of high field intensity demonstrate that even in a full-wave view the resonant nature of the cavity is not completely destroyed, thus supporting the theoretical explanation of the frequency tuning effect (and its impact on output current and beam shape) given elsewhere [10,11]. Results about full-wave simulations and the entire self-consistent loop have been largely discussed in [12] and [13].

In order to carry out more advanced studies on these subjects, we have designed a new test-bench machine named "Flexible Plasma Trap" with flexible magnetic system and a injection system permitting both axial and radial injection of microwaves [14].

CONCLUSION

The overview of the activities concerning ECR ion sources and related equipment, described in this paper, is not exhaustive, as the major development in the field of plasma diagnostics have not yet been completed and they will reported in future workshops.

Additionally we expect that the R&D to be done with the Flexible Plasma Trap will permit to trigger the construction of a new third generation ECRIS to be coupled to the K-800 Superconducting Cyclotron, after its upgrade. The same expertise is also going to find an application in the construction of ad-hoc traps for the Nuclear Physics, which conversely will make easier to find the support for the construction of new devices focused to the ion beam production.

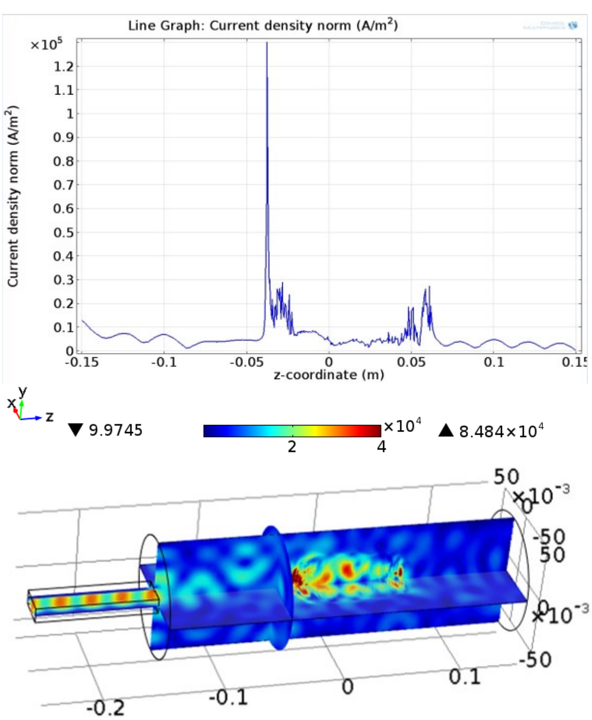

Figure 12: *up* – simulated current density $j = \bar{\sigma}E$ trend along the plasma chamber axis; *down* – simulated electromagnetic field distribution inside a plasma filled cavity at 8 GHz.

ACKNOWLEDGMENT

The authors acknowledge the support given by all the LNS divisions to the above reported activities. The work here reported got benefit of the contributions of M. Cafici (Cryogenics group), G. Gallo, L. Allegra, S. Passarello and E. Zappalà (Mechanical Design group), M. Piscopo and G. Schillaci (Technical Division) and A. Caruso and A. Longhitano (RF group).

The AISHa project is supported by the incentives in favour of Research Development and Innovation Art.5 Regional law 16/12/2008 - Intervention line 4.1.1.1 POR FERS Sicilia 2007-13 devoted to small and medium companies integrated with Research Institutions (Partners: INFN-LNS, HITEC2000 srl, UNICO srl, C3SL). The cooperation of the personnel of the three companies is to be underlined.

Finally we wish to thank the colleagues of CEA-IRFU, Saclay for their support during the tests of the PS-ESS chopper, particularly R. Gobin and O. Tuske.

REFERENCES

[1] S. Gammino et al., Rev. Sci. Instrum. 70, 9 (1999), 3577

[2] S. Gammino, G. Ciavola, Rev. Sci. Instrum. 71, 2 (2000), 631

[3] L. Celona et al., Rev. Sci. Instrum. 75, 5 (2004),1423.

[4] I. Martel et al., "ECOS-LINCE: a high intensity multi-ion superconducting LINAC for nuclear structure and reactions", THPME036, IPAC'14, Germany (2014).

[5] G. Castro et al., Rev. Sci. Instrum. 83, 02B501.

[6] H.P. Laqua, "Plasma Physics and Controlled Fusion" 49 (2007) R1

[7] D. Mascali et al., Nucl. Instr. & Meth. A, 653-1, 11-16 (2011).

[8] F. F. Chen, "Introduction to the Plasma Physics and Controlled Fusion", U.K., London Press, London, 1986.

[9] L. Neri et al., Rev. Sci. Instrum. 83, 02A330 (2012);

[10] D. Mascali et al., Rev. Sci. Instrum. 83, 02A336 (2012).

[11] L. Celona et al., Rev. Sci. Instrum. 79, 023305 (2008).

[12] G. Torrisi et al Journal of Electromagnetic Waves and Applications, 28(9), 1085-1099 (2014)

[13] D. Mascali et al., accepted for publication on European Physical Journal – D.

[14] D. Mascali et al., "ECR Ion Sources Developments at INFN-LNS for the production of high brightness highly charged ion beams", MOPP066, LINAC'14, Switzerland, (2014).

ISBN 978-3-95450-158-8