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A HIGH INTENSITY PROTON SOURCE FOR THE EUROPEAN SPALLATION SOURCE FACILITY

Luigi Celona, Luciano Allegra, Lucio Andò, Antonio Caruso, Giuseppe Castro, Francesco Chines, Giuseppe Gallo, Santo Gammino, Alberto Longhitano, Salvatore Marletta, David Mascali, Lorenzo Neri, S. Passarello, INFN/LNS, Catania, Italy
Giuseppe Torrisi, INFN/LNS, Catania; Università Mediterranea di Reggio Calabria, Reggio Calabria, Italy

Abstract

Along the last 25 years, INFN-LNS has gained a relevant role in R&D of plasma-based ion sources. The laboratory is currently involved in the construction of the Proton Source and Low Energy Beam Transport (LEBT) line for the European Spallation Source. ESS – based on a 2.0 GeV, 62.5 mA proton accelerator for neutron production – will be a fundamental instrument for research and applications. The proton source is required to produce at least 74 mA proton beam at 2.25 π.mm.mrad emittance (99% normalized), 2.86 ms pulse duration, 14 Hz repetition rate. We will illustrate the design of the source, the ongoing study of the radio frequency to plasma coupling, the result of a parametric study of the extraction system, the final layout of the LEBT – based on beam transport studies and the chopper strategy – and the first steps of the devices installation at the INFN-LNS test-bench site.

INJECTOR FOR THE ESS ACCELERATOR

The source named Proton Source for ESS (PS-ESS) (see Figure 1) was designed with a flexible magnetic system and a compact tetrode extraction system with the goal to minimize the emittance and the time needed for the maintenance operations. The ESS injector design has taken advantage of recent theoretical updates together with the new plasma diagnostics tools developed at INFN-LNS. The proton beam requirements is of 74 mA. The ability to reduce the current up to 6 mA with a precision of 2 mA, without changing the proton source conditions is reached with a six blade iris housed in the LEBT. The beam stability during the normal operations (in terms of current and emittance) shall be within ±3.5% from pulse to pulse variation and ±2% of the beam current averaged over a period of 50 us. This requirement is considered fundamental by the beam physics group, for the high energy RF cavities. The pulse duration is 2.86 ms with 14 Hz repetition rate. The requirements for the proton source and the LEBT are summarized in the Table 1. A detailed study of the beam transport in regime of space charge compensation was done and experimentally verified [1]. A chopper was designed to speed up the beam pulse rise and fall time. The final aim is to achieve a reliability better than 95% for the whole accelerator, thus meaning that the source reliability is expected to be greater than 99%.

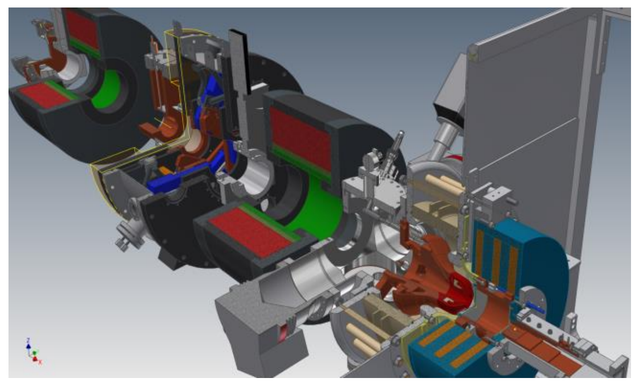

Figure 1: 3D rendering of the PS-ESS with the LEBT.

Table 1: PS-ESS Requirements

Parameters	Value
Proton current range	60-74 mA
Proton fraction	>80%
Current stability (50us averaged)	±2%
Pulse to pulse variation	±3.5%
Beam energy	70-80 ±0.1 keV
Repetition rate	1-14 Hz
Pulse length	5-2880 ±1 us
Current reduced using iris	2-74 ±1 mA
Restart after vacuum break	<32h
Restart after cold start	<16h
Emittance (99% normalized)	<2.25 π.mm.mrad
Twiss parameter α	1.02 ±20%
Twiss parameter β	.11 ±10%
Beam pulse rise and fall time	<20 us
LEBT pressure	<6e-5 mbar

PLASMA AND BEAM MODELLING

The INFN-LNS group fixed a challenging milestone for the simulation of the entire process underlying ion-beam generation. The plasma studies were performed by developing different plasma diagnostics and own code plasma modelling and to simulate the dynamics of space charge compensation (SCC), both in stationary and transient regimes. The new PIC code includes also

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particles self-friction and thermalization. Full-wave simulations including plasma response to electromagnetic field propagation in the plasma chamber have already given valuable results [2].

In PS-ESS design we merged the best solutions already tested in previous sources with a flexible magnetic system able to produce both standard and new magnetic profiles that will allow us to increase the current, increase the proton fraction, reduce the emittance and control the beam formation process. The magnetic system consists of a set of three solenoids with iron yoke in between, featuring high flexibility. To avoid a Penning discharge inside the extraction column, and to avoid emittance growth due to the stray magnetic field, an adequate shield of ARMCO is employed. The field is depleted from 100 mT to 10 mT in 1.6 cm regardless the selected magnetic configurations (see Figure 2).

Recently, the possibility to overcome the cutoff density by converting the incoming electromagnetic wave into a plasma wave has been investigated. At INFN-LNS, signs about the occurred conversion mechanism has been observed with the VIS source equipped with a movable permanent magnets and operating at variable frequency. 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 electrons oscillations (longitudinal electrostatic wave) propagating across the magnetic field and called Electron Bernstein Waves (EBWs). Electron waves travel in plasmas of whatever densities and are absorbed at cyclotron harmonics.

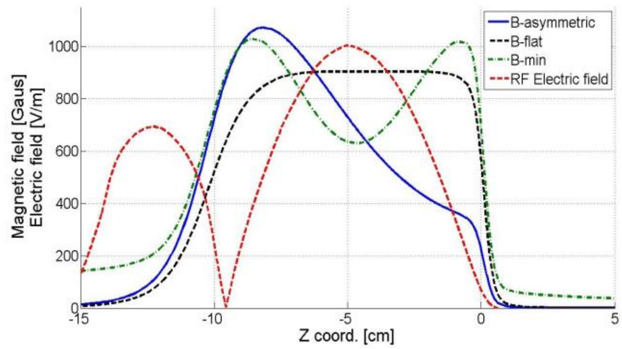

Figure 2: Magnetic system flexibility coupled with a RF stationary mode.

EBWs cannot be externally excited, but they originate from an X mode conversion in a gyro-rotating electrons oscillation at the Upper Hybrid Resonance (UHR). The first experiments (carried out on a simplified prototype) have put in evidence the formation of a overdense plasma with a density up to 10 times the cut-off density when operating in second harmonic mode. To be converted into BWs, the X mode requires a rapidly dropping magnetic field which makes possible either UHR and second harmonic absorption. This configuration is named B-asymmetric in the Figure 2, and sometime called "Magnetic Beach". We expect this second type of RF-plasma coupling will significantly enhance the output currents, but it can be employed in a second phase, once carefully studied the implications on the ion dynamics (possible ion heating as ancillary mechanism) and then on beam emittance. Finally, a second way to optimize the proton generation of a MDIS will be obtained by

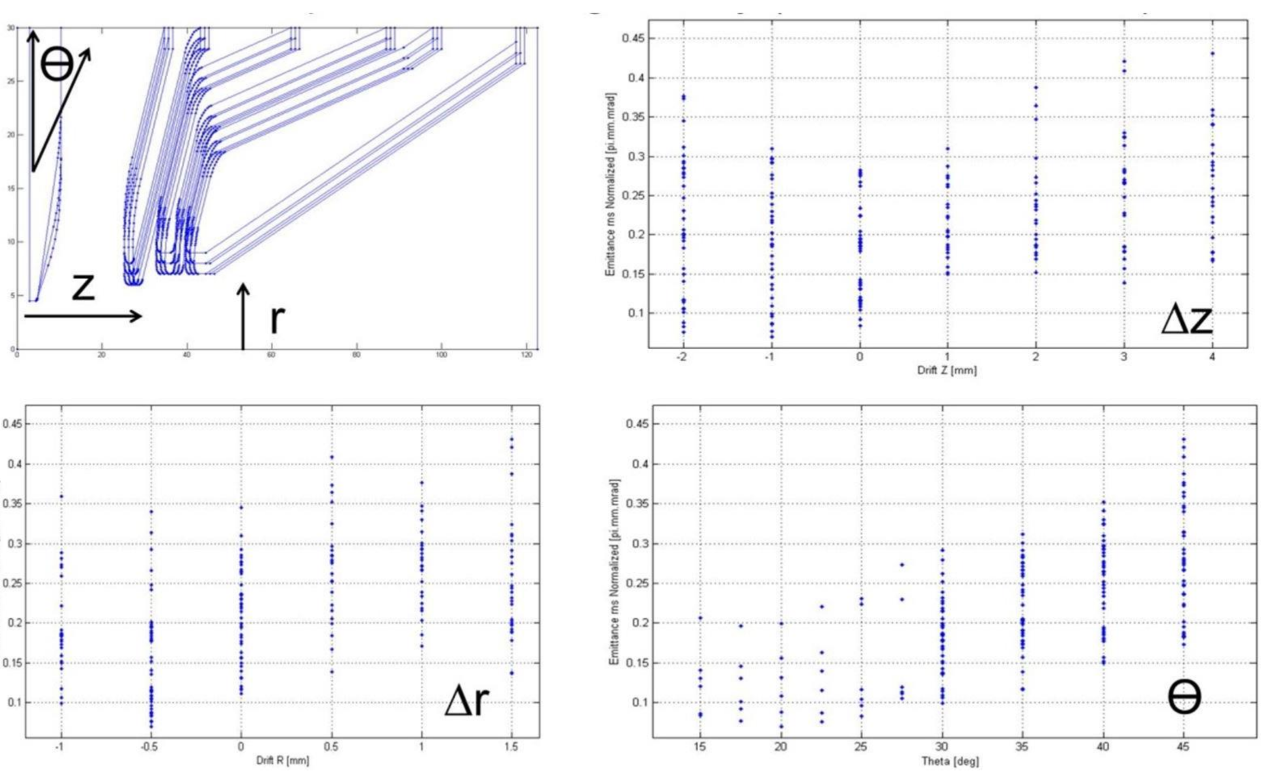

Figure 3: Result of the parametric study of the extraction system to minimize the produced beam emittance.

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designing a simple-mirror-like trap, like the one named B-min in the next figure. Studies about balance equations of the different plasma species (H2, H2+, H+) reveal that their reciprocal abundance is regulated by the relative lifetimes. In a quasi-flat magnetic field, under normal operative pressure conditions, ions lifetime is only governed by collisional diffusion across the magnetic field, which is a rather fast process.

The H2+ molecule lifetime might be increased when using the simple-mirror configuration, thus increasing the ionization efficiency boosting the proton fraction already at moderate RF power.

The study, though not fully checked, has been useful to define the extraction system, consisting of four electrodes: a plasma electrode placed on the HV platform at a voltage of 75 kV and a set of three electrodes, the first and the last attached to the grounded flange, and between them a repelling electrode placed at few thousands volt. In Figure 3 the parametric study of the geometry of the extraction system is shown. For the simulation of the extracted beam we used the Axcel code, that is a commonly used 2D code. Although the physics issues involved in the extraction system are more complex than the oversimplified calculations performed, the results are a good starting point for the design optimization. In the simulation both proton and H_2^+ beams are taken into account. A parametric study (more than 400 simulations) of the geometry to reach the optimum configuration was performed. The starting point was the geometry used for the VIS source and few parameters were used to reduce the emittance values: the distance between the plasma electrode and the first ground electrode (Δz being the variation with respect to VIS configuration), the aperture hole (Δr, variation with respect VIS configuration) and the angle of the plasma electrode (Θ). The configuration that is able to satisfy the ESS requirements (0.2 π.mm.mrad emittance rms normalized) was found in a wide range of values (see Figure 3), showing that the extraction is not so critical as the transport.

DEFOCUSING CHOPPER

One of the most important part of the LEBT that required a lot of studies regarding beam dynamics and space charge compensation during transients was the chopper. This element was designed to adapt the pulse produced from the source to the requirements of the ESS accelerator. The heating problem due to a focused chopped beam in the LEBT collimator was also taken into account as the minimization of the beam pulse rise and fall time in presence of an high SCC degree. The shape of the electrodes was chosen to provide two electric field components, one for the deflection of the beam and the latter for the defocusing of the beam [1]. The chopper voltage is 0 to 10 kV, 14 Hz repetition rate, electronic rise and fall time are 15 nanosecond; the system was designed to be as reliable as possible because it is part of the beam stop chain of the machine protection system.

Using the knowledge gained during the chopper prototype test a completely new chopper has been designed fulfilling the faster beam chopping strategy, the needed compactness (157 mm length along the beam direction), the increased shielding (to protect the power electronics), the presence of the feedback antenna and the water-cooling needs.

TESTBENCH AND NEXT STEPS

One of the critical issues of the site commissioning at LNS in terms of reliability is the grounding, due to the fact that the site is not directly connected to ground. An engineered design of grounding has allowed the installation of a permanent copper mesh of 60X60 cm with stripes 6 cm width, for the grounding of the source and LEBT. Appropriate switches will protect electronics from possible surges. Highly sensitive equipment such as computers will be placed in electromagnetic compatibility (EMC) shielded cabinets. The proton source itself is a X-ray source (up to 75 keV), so it is shielded by a lead wall.

Figure 4: Site preparation at INFN-LNS.

All the work done and those ongoing are in agreement with the schedule of INFN in-kind contribution to the ESS project (see Table 2). The site preparation at INFN-LNS is complete (see Figure 4) and we are waiting for the components' delivery before to start the assembly of the source.

Table 2: Commissioning Schedule

Schedule	Date
First source procurement completed	June 2015
Start of plasma studies	Oct. 2015
Start of extracted beam studies	May 2016
Start of long run test	July 2016
LEBT installation completed	Nov. 2016
Delivery of the first source and LEBT to Lund	Sep. 2017
Delivery of the second source to Lund	Oct. 2018

REFERENCES

[1] L. Neri et al., Rev. Sci. Instrum. **85**, 02A723 (2014).
[2] G. Torrisi et al., Journal of Electromagnetic Waves and Applications, **28**(9), 1085 (2014).