

DESIGN ISSUES OF THE PROTON SOURCE FOR THE ESS FACILITY

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Abstract

The European Spallation Source facility will be one of the fundamental instruments for science and engineering of the future. A 2.5 GeV proton accelerator is to be built for the neutron production. INFN-LNS is involved in the Design Update for the proton source and Low Energy Beam Transport (LEBT) line. The proton source is required to produce a low emittance 90 mA beam, 2.86 ms pulsed with a repetition rate of 14 Hz. Microwave Discharge Ion Sources (MDIS) enable us to produce such high intensity proton beams characterized by very low emittance ($< 0.2 \pi \cdot \text{mm} \cdot \text{mrad}$). The source design is based on a flexible magnetic system which can be adapted to electrostatic Bernstein waves heating mechanism; this will permit a strong increase in the electron density with an expected boost of the output current. The main features of the source design, including the microwave injection system and beam extraction, will be described hereinafter.

INTRODUCTION

The European Spallation Source (ESS) [1] will be at Lund and it is expected to provide 5MW of protons when completed. The Design Update of the Linac has been started in 2011 and it is to be completed with the Technical Design Report by the end of 2012. INFN is responsible of the WP6-Front End and the Laboratori Nazionali del Sud (LNS) are responsible of the WP6 management, of the Proton Source and LEBT design.

The Proton Source for European Spallation Source (PS-ESS) will be based on the know-how acquired during the design phase, the construction phase and the commissioning of the sources named TRIPS and VIS at INFN-LNS [2,3] operating at 2.45 GHz, and of the SILHI source at CEA-Saclay [4], but some remarkable improvements are to be developed because of the high current needed at a lower extraction voltage and because of the request to operate in pulsed mode. A new and flexible magnetic system was designed using three solenoids. Microwave injection system will be deeply revised according to the recent experience gained with the VIS source. Performance of the extraction system was simulated to produce the starting condition for the end to end beam simulation needed for the accelerator design. This different aspects of the new proton source will be presented hereinafter.

SOURCE REQUIREMENTS

ESS initially requires a proton beam of 50 mA (90 mA in the final configuration), at 75 keV with a maximum emittance of $0.2 \pi \cdot \text{mm} \cdot \text{mrad}$, a 14 Hz of repetition rate

with 2.86 ms pulse length, and 99.9% reliability. In terms of emittance, the VIS source, developed by LNS group, is able to largely fulfil the requirements for ESS in continuous mode and the tests carried out on SILHI [5] confirmed also the capability to fulfil them also in pulsed mode. In fact, it was observed that for a pulse duration of 3 ms, for 10 and 20 Hz repetition rate, the beam emittance is around $0.15 \pi \cdot \text{mm} \cdot \text{mrad}$. [5].

The current required for the ESS facility in the baseline configuration can be satisfied by means of conventional Microwave Discharge Ion Source (MDIS) like VIS, based on the plasma direct absorption of the pumping electromagnetic waves through the Electron Cyclotron Resonance mechanism. Recent studies performed at INFN-LNS [6] have shown a critical influence of the magnetic field profile on the plasma properties, especially the density. In particular, two innovative plasma heating methods will be attempted. The first is based on non-conventional ways of RF coupling to the plasma which will be depicted in the following, the latter consist of an optimization given by short plasma confinement. 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 take under control the beam formation.

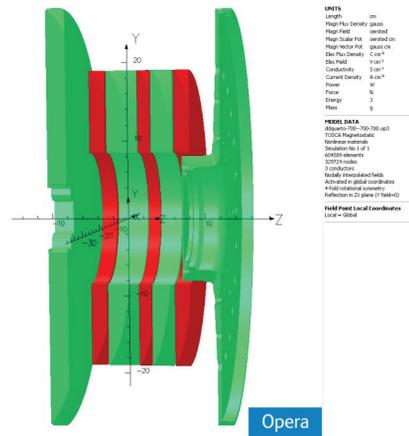


Figure 1: PS-ESS flexible magnetic system.

NEW MAGNETIC SYSTEM

PS-ESS will be similar to the VIS proton source except for the magnetic system that will consists of a set of three solenoids (instead of two). The new magnetic system shown in Fig. 1 was designed to obtain very high flexibility, by using three different coils that can be differently energised and that can be also changed in polarity. Key point of obtained flexibility is the use of

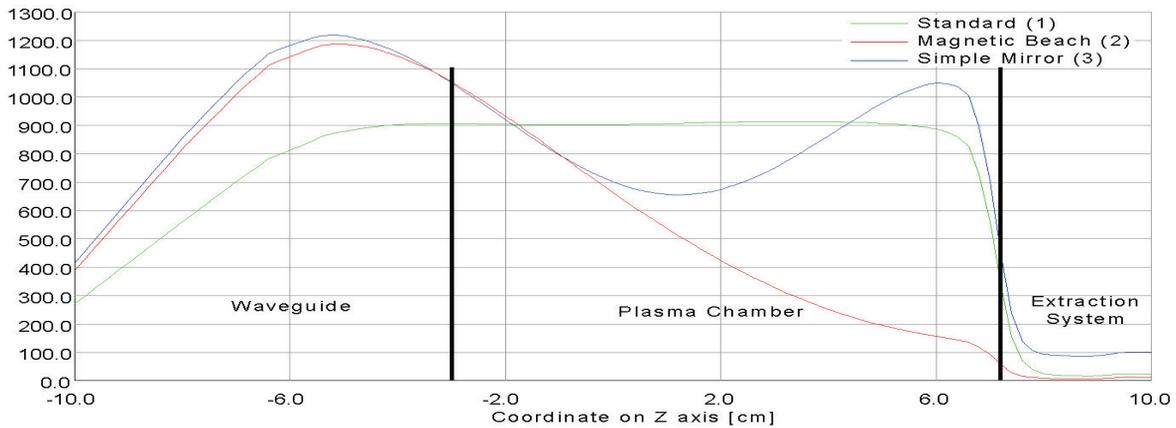


Figure 2: Magnetic profiles generated by three shielded coils.

ARMCO Pure Iron disc between the solenoids to spatially confine the magnetic field produced by each one.

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 will be employed. The field is depleted from 1000 to 100 Gs in 1.6 cm regardless the selected magnetic configurations, as shown in Fig. 2.

The typical shape of the magnetic field for MDIS machines is therefore the one labeled by (1) in Fig. 2, 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 ($n \approx 10^{17} \text{ m}^{-3}$), temperatures sufficient for hydrogen ionization ($T = 15\text{-}20 \text{ eV}$) and H_2 molecule lifetimes long enough for complete ionization and proton generation. Such plasma parameters require RF power around 1-1.5 kW and background pressures down to 10^{-5} mbar.

Recently, the possibility to overcome the cutoff density by converting the incoming electromagnetic wave into a plasma wave has been investigated [7]. This study goes in parallel with similar investigations in fusion science, where large plasma densities are needed to fulfill Lawson criterion [8]. 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 [6]. 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 (BW's). Plasma waves travel in plasmas of whatever densities and are absorbed at cyclotron harmonics. Since they are sustained by the electron motion, BW's cannot be externally excited, but originate from an X mode interacting with gyro-rotating electrons at the Upper Hybrid Resonance (UHR) [9]. The first experiments have put in evidence the formation of a 10-20 times overdense plasma when operating in second harmonic mode. To be converted into a BW's, the X mode requires a rapidly dropping magnetic field which makes possible either UHR and second harmonic absorption. This configuration

is labeled as (2) in Fig. 2, and sometime called "Magnetic Beach". 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, once carefully studied 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 attempted by designing a simple-mirror-like trap, like the one labeled by (3) in Fig. 2. Studies about balance equations of the different plasma species (H_2 , H_2^+ , 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 prolongation of H_2^+ molecule lifetime, obtained when using the simple-mirror configuration, should increase the ionization efficiency thus boosting the proton fraction already at moderate RF power, thus improving also the reliability of the source.

MICROWAVE COUPLING

In order to improve the performances of such ion source a detailed electromagnetic study of the plasma chamber as a cavity has been carried out with Ansoft HFSS™ eigenmode solver.

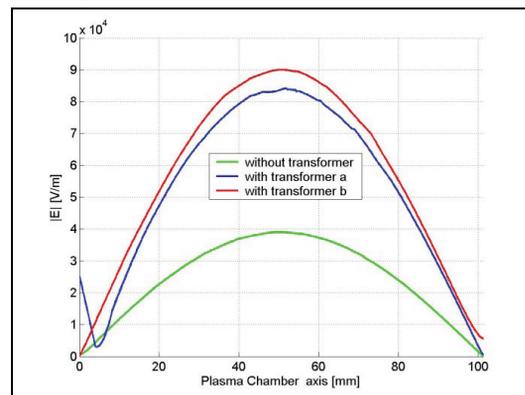


Figure 3: Comparison of electric field amplitude simulated for three different configurations.

As a result of this analysis the plasma chamber dimensions has been determined in order to have a TE₁₁₁ dominant mode at the frequency of around 2.5 GHz and the effect of two different matching transformers on the microwave coupling has been fully studied [10]. Fig. 3 shows the electric field distribution concerning the TE₁₁₁ mode inside a cylindrical resonance cavity with 101.2 mm length and 45.3 mm radius. It can be noticed that it is possible to increase the ion source performances by introducing a matching transformer (Fig. 4) that reduce the reflected power.

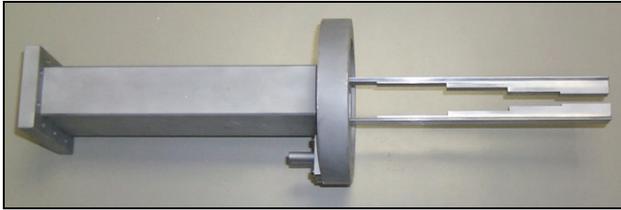


Figure 4: Matching transformer

FOUR ELECTRODE EXTRACTION SYSTEM

The extraction system consists 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 hundred volt to preserve the space charge compensation of the LEBT.

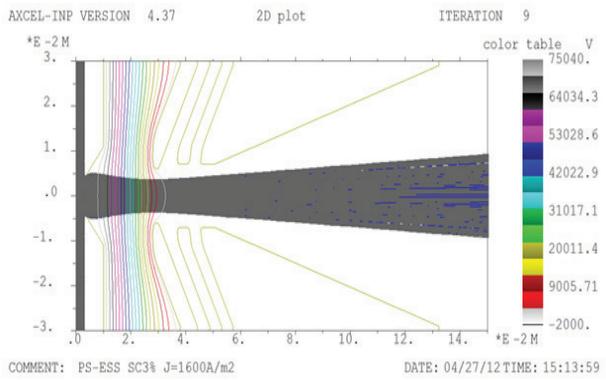


Figure 5: Four electrode extraction system.

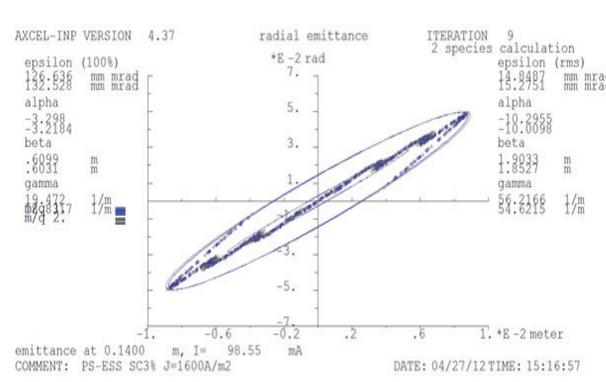


Figure 6: Extracted beam emittance simulated with AXCEL.

The simulations have been made with AXCEL and a typical trajectory plot is shown in Fig. 5, while Fig. 6 shows the rms beam emittance ellipses at $z = 0.14$ m far from the extraction aperture. The total beam current used in the simulation is 100 mA circa: the proton fraction considered is 90%, while 10% is H_2^+ .

CONCLUSION

ESS requirements for proton source are quite restrictive. Considering the experience gained with the already designed and optimized sources at INFN-LNS, the needs of the initial phase of the facility will be fulfilled by using a "conservative" approach, based on a standard MDIS configuration (VIS-like machine). The second phase requirements are more stringent in terms of currents (up to 90 mA or more), but possible solutions for the source upgrading have been considered already in the design phase, by proposing a new flexible magnetic system. More standard solutions for performance optimization (which do not require any ab-initio design modification) will be implemented, as the alumina tubes introduced into the plasma chamber [11]. Therefore we will not only take care about currents, emittance, efficiency and reliability requirements, but also to a continuous MDIS development.

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