THE PROTON INJECTOR FOR THE EUROPEAN SPALLATION SOURCE

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Abstract

The update of the design of the PS-ESS source and of its LEBT has been carried out in 2013 and the construction is now ongoing. The Ion Source will be able to provide a proton beam current larger than 74 mA to the 3.6 MeV RFQ. Several innovative solutions have been implemented in the redesign phase in order to cope with high-reliability/high-performance requirements of the ESS project. A flexible magnetic system will allow to investigate alternative configurations for future beam current upgrade of the machine, based on the formation of a denser plasma. New set-ups have been also explored for beam extraction, transport and chopping. Calculations have shown that space charge compensation up to 95 % is needed to preserve the low emittance in the low energy beam transfer line (LEBT). In order to obtain the optimal proton beam pulse rise and fall time we propose a LEBT chopping configuration that permits hundred nanosecond rise and fall times despite the LEBT compensation needs few microseconds. Some hints about numerical modelling efforts at LNS will be also given.

INTRODUCTION

The European Spallation Source will be one of the most advanced technological tools for scientific and industrial development in Europe in the next decades. A linear accelerator is going to be built for the production of 2 GeV protons to be used for neutron production via nuclear spallation. Neutrons will be finally used for fundamental science and applied research.

INFN-LNS is responsible of the design and construction of the accelerator front-end, including the high intensity proton source (PS-ESS, Proton Source for ESS) and the Low Energy Beam Transport line.

Recently, the decision of the ESS board to upgrade the source and LEBT requirements, made more challenging the machine design both in terms of proton current (+25% increase from 50 to 62.5 mA on target) and beam ripple minimization (±3.5%). In order to cope with the new requirements, several solutions have been adopted thus making the source a flexible machine fulfilling the project expectations.

More in detail, the maximum extracted beam current from the ion source shall exceed 90 mA, with a proton fraction above 80 %, this way producing a nominal beam pulse of 74 mA. Besides the nominal current, the injector (ion source + LEBT) is requested to deliver different levels of peak proton beam current, between 10 and 100% of the maximum one, under stable conditions. Stringent conditions are also given in terms of fast tuning of the machine, and easy/fast startup operations (16 hours, 32 hours after vacuum breaks), requiring specific efforts to be paid to vacuum issues and mechanical assembly. The pulsed beam length shall exceed 3 ms but less than 6 ms, with particular attention to the beam ripple: the level of ± 3.5 % averaged over the flat top of the pulse (200 µs time average) is quite critical for weeks of operation, thus requiring an extensive period of test in nominal conditions in the last part of 2015. The extraction voltage is fixed at 75 kV within 0.01 kV of setting accuracy and 100 eV steps allowed for fine proton energy tuning up to ± 5 keV from the nominal value, in order to optimize energy matching with RFQ.

Concerning the emittance, the source is designed for fulfilling a transverse output emittance requirement of (less than) 0.20 π.mm.mrad RMS normalized; assuming a 25 % emittance growth in the LEBT, the maximum value before the RFQ entrance must be less than 0.25 π.mm.mrad.

Variable beam current are requested to be delivered by the IS-LEBT to the RFQ, without major modifications of the source parameters, in order to keep the emittance plot unchanged. The requirements go from 6.5 mA to 70 mA with a step size of 6.3 mA, meaning that a specific item into the LEBT (an iris) must be inserted for selecting different portions of the beam. At the LEBT output, the length of the nominal beam pulse will lie in range 2.9 ms – 3 ms, guaranteed by an on-purpose developed chopping system. During this time, Twiss parameter should be adapted for RFQ matching.

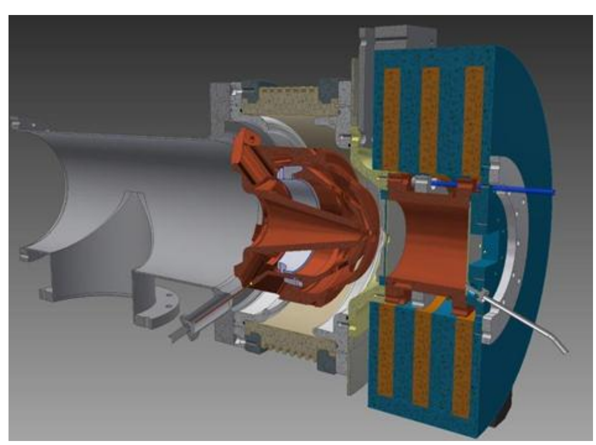

Figure 1: The PS-ESS source.

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SOURCE DESIGN

The source design already described in previous papers [3] has been upgraded according to the new requirements. Figure 1 shows the general layout of the source, including the plasma chamber, the magnetic and extraction systems.

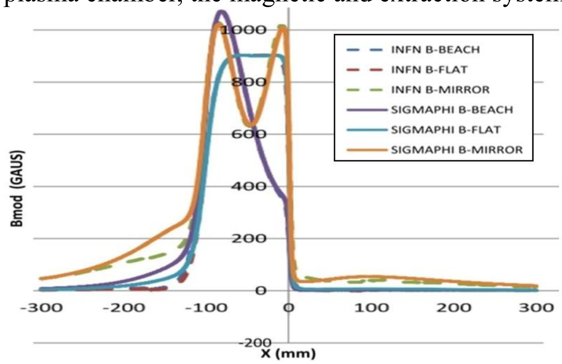

Figure 2: The PS-ESS magnetic field (in Gs) profiles along the chamber axis. The plasma chamber is placed between the positions -100 and 0 mm.

Figure 2 shows the measured profiles (solid lines) of the on-axis B-field performed by of the Sigma-Phi company during the Factory tests of the magnetic system, as compared with our requirements (dashed lines). The field has been made as flexible as possible in order to explore different schemes of plasma heating: i) flat-B field profile for conventional off-resonance heating at 2.45 GHz or larger frequency, reaching a plasma density around $n \approx 10^{17}$ m^{-3} and electron temperature T=15-20 eV [1]; ii) magnetic "beach" configuration for exploring innovative heating schemes based on the generation of Electron Bernstein Waves [2], which may boost consistently the plasma density well above the cutoff, and iii) simple-mirror like configuration for exploring proton fraction and beam emittance response to plasma confinement times and plasma density structure. The magnets delivery is expected for October 2014.

About the RF field, the microwave injection system has been on-purpose investigated in order to optimize the power deposition in the plasma core, i.e. obtaining the maximum of the electromagnetic field in the central region of the chamber. The new and more stringent low beam ripple requirements have imposed to revise the microwave injection strategy, which will be based on a solid-state amplifier minimizing RF fluctuations. This new solution will additionally allow the tuning of the frequency over a 500 MHz band from 2.45 to 2.95 GHz (not possible with conventional magnetrons), thus providing an additional "knob" for plasma heating optimization. The orders concerning the solid-state microwave generator and the ancillary equipment have been placed and their delivery is expected for November 2014.

Another subsystem that has been interested by a deep campaign of study and design optimisation is the source extraction. The design has included – other than the use of several toolkits for beam dynamics and electrostatic issues studies – a detailed thermal characterization, performed by COMSOL, in order to address efficient cooling of the extraction column. Different solutions of the extraction electrodes shapes were designed and will be tested already in the early stage of the machine characterization. Another innovative solutions consists in the use of an aluminum nitride insulation in order to ensure good thermal conductivity in addition to the necessary electric insulation of the repelling electrode, that is used to preserve the space charge compensation of the LEBT (Figure 3).

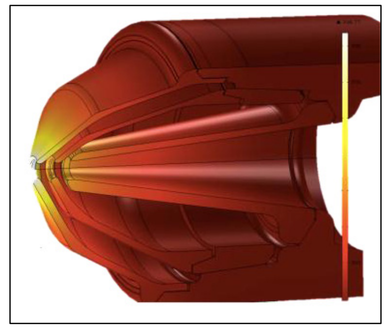

Figure 3: The PS-ESS extraction system: thermomechanical study.

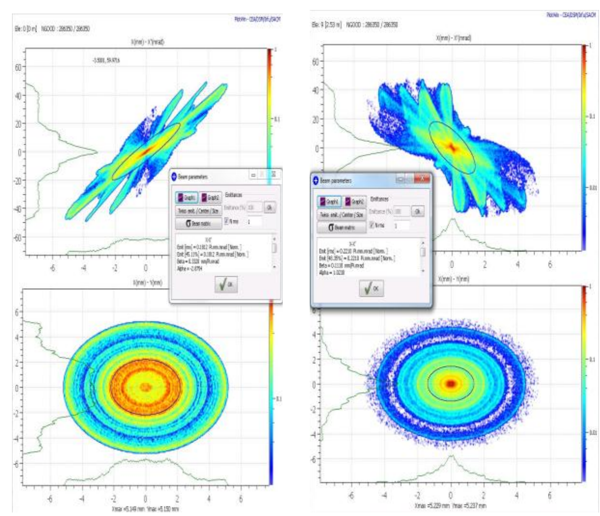

Figure 4: proton beam shape in phase space (x-x', upper Figures) and in the real space (down) at the beginning (left-hand column) and at the end (right-hand column) of the LEBT.

Concerning the beam extraction dynamics, Figure 4 shows the simulation outputs based on the last extraction system design. The left column of Figure 4 illustrates the distribution of the beam in phase space (x-x') and real space coming out from a 2D axis-symmetric simulation by AXCEL and turned in a 3D distribution by our own code, at 70 mm after the plasma electrode. A specific procedure for converting the 2D distribution coming out from AXCEL has been implemented in MATLAB in order to retrieve a 3D distribution of the beam that is suitable for TRACEWIN. The total beam current used in the simulation was 92.5 mA: the proton fraction considered was 80%, 20% was H_2^+.The right hand

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column of Figure 4 depicts the output beam shape (again, in phase-space and in real space) after the flight into the LEBT, i.e. just before the injection into the RFQ: the calculated final emittance is around 0.22 π mm.mrad, that is in agreement with the required values.

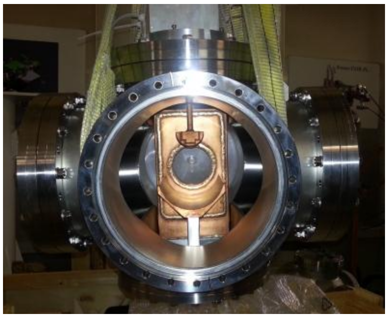

Figure 5: the new "curved electrodes" chopper during the assembly stage at CEA-Saclay for preliminary tests.

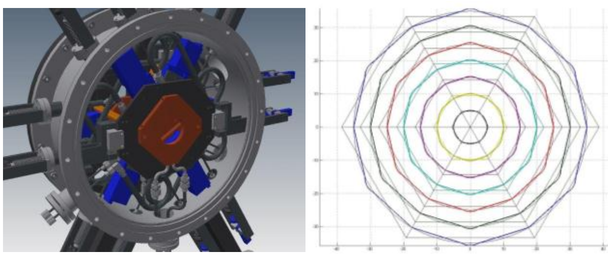

Figure 6: LEBT Iris: left- mechanical design of the driver and iris box; right-study about cutters shape for ensuring quasi-circular apertures.

ADVANCEMENTS IN LEBT DESIGN

Several improvements have been added recently to the LEBT [3]. Although the final set-up can be subject to minor changes of dimensions, the overall layout is already clear. Some distances (flange-to-flange) have been already defined such as the extraction system length (270 mm), the solenoids length (400 mm), the iris box (300 mm), the diagnostics box (400 mm) and the chopper length (200 mm). Concerning the latter item, the new solution adopted for the shape of chopper electrodes (curved electrods) has been already implemented. Figure 5 shows the chopper already tested at CEA-Saclay on the BETSI testbench. The measurements campaign allowed to estimate rise and fall times: we measured few hundred nanosecond rise time, and less than hundred nanosecond fall time.

Fig. 6 shows another element of the LEBT, i.e. the iris, which design phase is almost complete. The mechanical driver has been defined (see Figure 6-left) while specific attention has been paid to the cutters design. To preserve quasi-circular profiles for whatever aperture, the six "petals" were designed to obtain a dodecagonal aperture shape (as shown in Figure 6-right). TraceWin simulations shows that using the iris the solenoids can be tuned to preserve the twiss parameters of nominal beam even for the lower requested current values. As expected, the emittance will be reduced proportionally to the current reduction.

PLASMA AND BEAM MODELLING

The INFN-LNS group fixed a challenging milestone for the simulation of the entire process underlying ion-beam generation: from plasma dynamics, to ion extraction and transport, a cascade of numerical codes is going to be implemented. The transport, in particular, is a critical issue of ESS accelerator, due to space charge effects and needed compensation. We are trying to simulate the dynamics of space charge compensation, both in stationary and transient regimes. The SCC simulations have already given a valuable support in the chopper tests (estimation of rise and fall times) and they could continue supporting the PS-ESS developments, especially during the experimental tests expected during 2015 in Catania in order to find the best operative conditions.

Another task is the analysis of sheath and plasma meniscus formation: we are developing a new PIC code including particles self-friction and thermalization. Full-wave simulations including plasma response to electromagnetic field propagation in the plasma chamber have already given valuable results [4].

SCHEDULES AND DEADLINE

After the new requirements, the construction schedule was revised trying to minimize the delays in the deadline. The mechanics will be completed by February 2015, while the testbench site preparation will take some months to date, until November 2014. The high voltage power supply (100kV-150mA) will be tested at factory in mid-September and its installation will be carried out immediately after the availability of the site, at INFN-LNS. At the same time, the power supply will be delivered, so that the main developments of the control system may start in due time. The source assembly is to be completed for March 2015 while the commissioning will last about 6 months. After this phase, there will be a long run test in nominal conditions and the design optimization phase, which will take to the final release of the two copies of the PS-ESS source. The deadline is set to summer 2017 with the installation of the first source on the RFQ testbench, while one year later the second copy of PS-ESS will be delivered.

ACKNOWLEDGEMENTS

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