BEAM COMMISSIONING OF THE HIGH INTENSITY PROTON SOURCE DEVELOPED AT INFN-LNS FOR THE EUROPEAN SPALLATION SOURCE

L. Neri†, L. Celona, S. Gammino, A. Miraglia, O. Leonardi, G.Castro, G. Torrisi, D. Mascali, M. Mazzaglia, L. Allegra, A. Amato, G. Calabrese, A. Caruso, F. Chines, G. Gallo, A. Longhitano, G. Manno, S. Marletta, A. Maugeri, S. Passarello, G. Pastore, A. Seminara, A. Spartà, S. Vinciguerra,
Instituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud, Catania, Italy

Abstract

At the Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud (INFN-LNS) the beam commissioning of the high intensity Proton Source for the European Spallation Source (PS-ESS) started in November 2016. Beam stability at high current intensity is one of the most important parameter for the first steps of the ongoing commissioning. Promising results were obtained since the first source start with a 6 mm diameter extraction hole. The increase of the extraction hole to 8 mm allowed improving PS-ESS performances and obtaining the values required by the ESS accelerator. In this work, extracted beam current characteristics together with Doppler shift and emittance measurements are presented, as well as the description of the next phases before the installation at ESS in Lund.

STATUS OF COMMISSIONING

The design of the PS-ESS source [1-2] started in 2012 taking into account the experience gained at INFN-LNS with the sources TRIPS [3] and VIS [4]. The source construction started in November 2015 and the first plasma was produced in June 2016 while the beam commissioning started in November 2016. During the overall project [5] the interaction with ESS accelerator division and CEA for the beam diagnostics and the control system was intense. The whole design was driven by the future installation at ESS. A major performance upgrade was accepted in 2014 with 25% of increase of the proton current in the linear accelerator (from 50 mA to 62.5 mA), leading to a required ion source proton current of 74 mA. The commissioning was divided in two main stages. The first consisted of the characterization of the source performance with a Faraday Cup (FC), one Emittance Measurement Unit (EMU) and a Doppler shift measurement unit. To increase the reliability of the source measurements, these instruments were inserted as close as possible to the source plasma, 626 mm after the plasma hole. Several thousands of ion source configurations were tested by changing the magnetic profile, microwave power, the hydrogen (H_2) gas flow, and by using two different designs of the extraction electrodes. The last step will characterize the fully assembled Low Energy Beam Transport Line (LEBT) [6-7] with an additional diagnostic box to measure the beam parameters at the LEBT-RFQ interface. This stage will be useful for understanding the effects of different amount and type of gas addition in the LEBT for the space charge compensation of the beam. The magnetic beam transport optimization, the optimum parameter of the chopper and the effects of the Iris will be tested.

SOURCE COMMISSIONING RESULTS

The characterization of the source was optimized using a custom code able to test several configurations, one every 10 seconds, practically unmanned. The post analysis of the collected data is ongoing. Table 1 shows a comparison between the required values, and collected data from the commissioning.

Table 1: ESS requirements at source-LEBT interface and already collected data during the commissioning

Requirement	Value	Measurement
Total beam current	>90 mA	95.6 mA
Nominal proton beam current	74 mA	74.8 mA
Proton beam current range	67-74 mA	60-80 mA
Proton fraction	>75%	78.3%
Pulse length	6 ms	6 ms
Pulse flat top	3 ms	3 ms
Flat top stability	±2 %	±1.5 %
Pulse to pulse stability	±3.5 %	±3 %
Repetition rate	14 Hz	14 Hz
Beam energy	75±5 keV	75 keV
Energy adjustment	±0.01 keV	±0.01 keV
Transverse emittance (99%)	1.8 pi.mm.mrad	1.06 pi.mm.mrad @ 82 mA
Beam divergence (99%)	<80 mrad	50 mrad @ 82 mA
Start-up after source maintenance	32 hours	32 hours

Beam Current Verification

The total current produced out of the source was measured with two devices. A large bandwidth (from 3 Hz to 1 MHz) AC Current Transformer (ACCT) inserted on the high voltage cable measured the current delivered to the

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† neri@lns.infn.it

high voltage platform. An 80 mm diameter FC measured the beam current at a location as close as possible to the ion source. We observed that the divergence of the extracted current increases linearly with the current density. With extracted current larger than 80 mA the beam size became larger than the FC diameter and only the ACCT could measure the beam current value and ripple. The ACCT voltage droop was taken into account and recovered with a custom code. Figure 1 shows the current in a beam pulse for an ion source configuration providing high beam current. The performances of the source need to be verified between 2.9 and 5.9 ms of the beam pulse. The other part of the beam pulse will be removed by the LEBT electrostatic chopper and not delivered to the RFQ. The mean current measured is about 100 mA, 5% of this amount is due to back streaming electrons, so that the remaining net beam current is 95.6 mA. By changing the magnetic configuration of the source and the microwave power we are able to choose a stable current within the 60 to 80 mA range.

Beam Stability Verification

The beam stability is one of the crucial parameters of the whole accelerator. It is defined by measuring the range of current fluctuation inside the single pulse and between pulses. The pulse shape acquisition was done with 1 Ms/s card, while the current fluctuations at which the accelerator is sensitive is 50 µs period. The acquired current value, measured for the FC and the ACCT was averaged with 50 µs period and the maximum excursion inside the pulse and between pulses were taken into account for the verification of the requirement. For beam currents above 80 mA, the current can only be measured by the ACCT as explained before. Figure 1 shows in blue the acquired signal, after the droop voltage correction, and in red the signal averaged with 50 µs period. The pink lines identify the limit in time of the transmitted beam to the RFQ. The stability measured in the shown configuration is ±1.5 % inside the beam flat top and ±3 % between pulses.

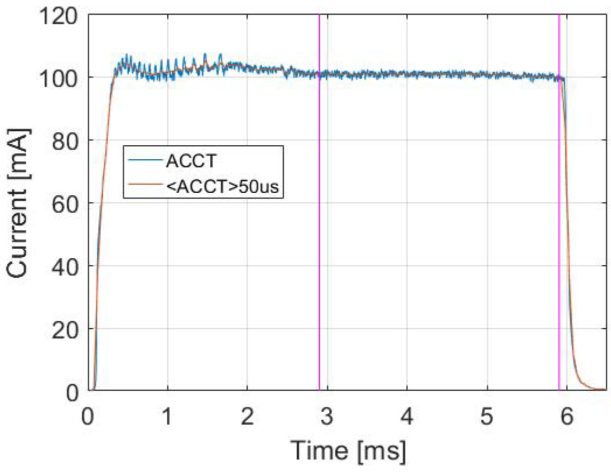
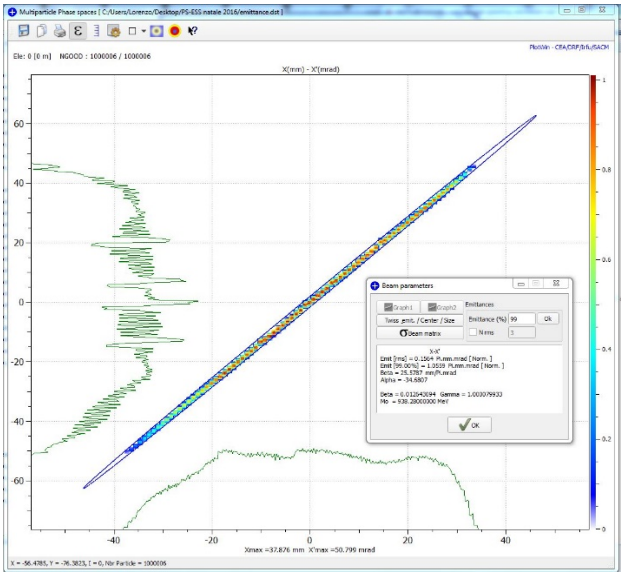


Figure 1: Beam current acquisition using an ACCT on the HV power supply cable.

Beam Emittance Verification

The beam emittance was measured using an Allison scanner in the same position of the FC. The same limitation was observed also for the EMU and the measurement was only possible for beam sizes smaller than 95 mm diameter. Figure 2 shows a measurement made with 82 mA total beam current. The beam emittance can be calculated with the beam fraction defined by a multiple of the rms value, or by a percentage. The ESS specifies a beam emittance calculated on the 99% of the beam. The estimated Twiss parameters of the beam are shown in the figure 2: Emitt. [99%] = 1.0559 pi.mm.mrad, Beta = 25.6 mm/pi.mrad, Alpha = -34.7. This estimation was made with PlotWin. Cumulative sum of beam emittance on the X' axis (green line on the left) shows four peaks due to a bug in the acquisition interface that is still under debugging but that do not affect consistently the emittance estimation.



Ele: 0 [0 m] NGOOD : 1000006 / 1000006

Emittance (%) 99

☐ N rms 3

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X-X'
Emit [rms] = 0.1564 Pi.mm.mrad [ Norm. ]
Emit [99.00%] = 1.0559 Pi.mm.mrad [ Norm. ]
Beta = 25.5787 mm/Pi.mrad
Alpha = -34.6807

Beta = 0.012643094  Gamma = 1.000079933
Mo  = 938.28000000 MeV
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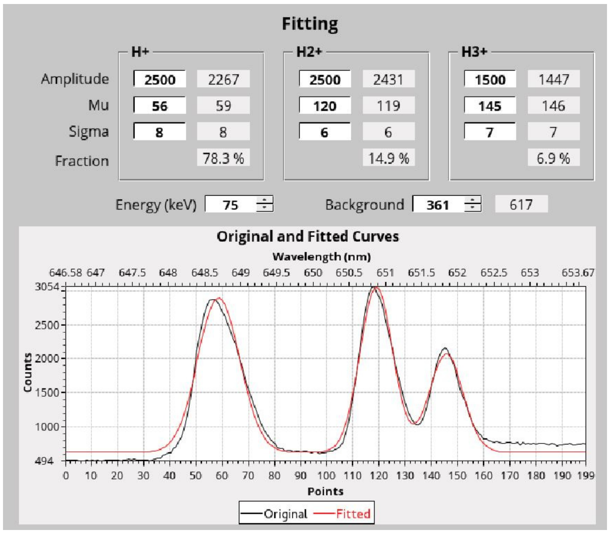
Xmax =37.876 mm X'max =50.799 mrad

X = -56.4785, Y = -76.3823, I = 0, Nbr Particle = 1000006

Figure 2: Measured beam emittance imported on PlotWin for Twiss parameter estimation.

Beam Proton Fraction Verification

Because of the differential pumping obtained by the small extraction hole, the plasma chamber contains 99% of H_2 gas, even if a different gas is introduced in the LEBT for beam space charge compensation. The positive ions species generated in the plasma are therefore protons, H_2^+ and H_3^+. The fraction obtained at the equilibrium is sensitive to the type of microwave to plasma coupling, which is sensitive to the magnetic configuration of the plasma chamber, and the heating microwave power used. The species fraction of the extracted beam was measured using the spectral analysis of the beam-emitted light at an angle of 25°. Due to the different velocity of the different ion species, the Doppler shift of the emitted light enable to distinguish the different species. Figure 3 shows the control system interface for the diagnostic equipment that is able to perform the background subtraction and the three Gaussian fit needed to estimate the amount of the three beam species. The proton fraction measured for a beam of 95.6 mA was 78.3%. We have observed that an increased microwave power injected in the plasma chamber increases this fraction. With this measured proton fraction amount, we can estimate an extracted proton current of 74.6 mA. The ESS request of 74 mA proton beam out of the source takes into account a loss of 5% in the LEBT. Due to the low emittance beam produced we suppose that the LEBT losses will be lower and we will reach the 68 mA of proton beam at the end of the LEBT with smaller extracted total current with respect to the case shown in Figure 1.



Fitting

	H+		H2+		H3+	
Amplitude	2500	2267	2500	2431	1500	1447
Mu	56	59	120	119	145	146
Sigma	8	8	6	6	7	7
Fraction		78.3 %		14.9 %		6.9 %

Energy (keV) 75

Background 361 617

Figure 3: Species fraction estimation using Doppler shift measurement.

NEXT STEPS

The installation of the LEBT is ongoing without interruption of the ion source characterization. The assembly and the cabling of the full LEBT has already started from the last part of the beam line. The last step will be a fast substitution of the diagnostic cross, which was used in the first beam commissioning stage, with the first LEBT solenoid. This parallel work advances the final commissioning stage of approximately 10 weeks.

The first stage of the commissioning will define few candidates, for the nominal ion source configuration, to be used during the following stage. The LEBT commissioning will focus on reducing the beam emittance growth by optimizing the gas type and pressure inside the LEBT. The beam chopping inside the LEBT will also require studying the beam space charge compensation during the transient. The chopper parameter will play an important role in the rise and fall time of the beam pulse formation. The Twiss parameter verification at the LEBT-RFQ interface will be characterized as function of the two solenoid fields for different apertures of the six-blades Iris that is housed after the first solenoid.

The source and LEBT configuration for the installation at ESS will be identical from the version installed at INFN-LNS except for an additional main frame with wheels. This common frame for the source and the LEBT is necessary for the assembly in the ESS tunnel, where the lifting equipment will have limited capability, and for the alignment of the whole structure with respect the theoretical beam axis. Figure 4 shows a render-view of the source and the LEBT as they will be installed in Lund, the diagnostic tank will be used for the beam commissioning before the RFQ assembly and commissioning stages.

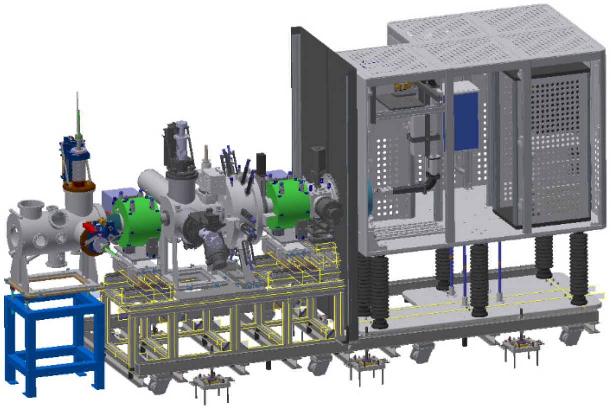


Figure 4: Render-view of the source, LEBT and diagnostic tank, for a total length of 5.8 m, as they will be installed for beam commissioning in Lund.

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REFERENCES

[1] L. Celona et al., “Design issues of the proton source for the ESS facility”, in *Proc. LINAC2012*, Tel-Aviv, Israel, paper THPB076, pp 1008-1010.

[2] L. Celona et al., “A high intensity proton source for the European Spallation Source facility”, in *Proc. IPAC2015*, Richmond, VA, USA, paper WEPWA010.

[3] L. Celona et al., “TRIPS: The high intensity proton source for the TRASCO project”, Rev. Sci. Instrum. 71, 771.

[4] S. Gammino *et al.*, “Tests of the Versatile Ion Source (VIS) for high power proton beam production”, in *Proc.ECRIS’10*, Grenoble, France, paper MOPOT02

[5] R. Garoby et al., “Progress on the ESS Project Construction”, presented at the 8th Int. Particle Accelerator Conf. (IPAC’17), Copenhagen, Denmark, paper MOXBA1, this conference.

[6] L. Neri and al., “The ESS Low Energy Beam Transport line design”, in *Proc. LINAC2012*, Tel-Aviv, Israel, paper THPB028, pp 912-914.

[7] L. Neri and al., “Commissioning of the High Intensity Proton Source Developed at INFN-LNS for the European Spallation Source”, in *Proc. LINAC2016*, East Lansing, USA, paper MOPLR057.