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FIRST RESULTS OF BEAM COMMISSIONING ON THE ESS SITE FOR THE ION SOURCE AND LOW ENERGY BEAM TRANSPORT

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Abstract

The European Spallation Source (ESS), currently under construction in Lund, Sweden, will be a spallation neutron source driven by a proton linac of an unprecedented 5 MW beam power. Such a high power requires its ion source (IS) to produce proton beam pulses at 14 Hz with a high peak current more than 62.5 mA and a long plateau up to 3 ms. The IS and the following low energy beam transport (LEBT) section were manufactured and tested with beam to meet ESS requirements at INFN-LNS and delivered to ESS towards the end of 2017. Beam commissioning of these two sections on the ESS site has started in September 2018 and will continue until the end of June 2019. This paper provides an overview on this first beam commissioning period at ESS and also presents results of IS characterization and testing on LEBT functionalities.

INTRODUCTION

The proton linac of the European Spallation Source (ESS) has an unprecedented design beam power of 5 MW [1]. When the 5 MW beam is delivered to the target, the facility provides the brightest neutron source in the world. Such a high power requires production, efficient acceleration, and almost no-loss transport of a high current beam, thus making design and beam commissioning (BC) of this machine challenging. Table 1 summarizes high-level beam parameters of the ESS linac at the ion source (IS) and target.

The IS and following low energy beam transport (LEBT) were in-kind contributions from INFN-LNS and tested with beam at their site (*off-site BC*) [2–5]. BC of these two sections on the ESS site, which is the first stage of several BC stages [6–9], has started in September 2018 and continue until the end of June 2019. This paper provides an overview on statuses of the IS and LEBT systems during this BC and also reports results from characterization and tuning of the IS conducted at ESS. Results on characterization and tuning of the LEBT are covered in [10]. The paper also covers testing of the chopper system in the LEBT in the final part.

IS AND LEBT SYSTEMS AND STATUS

This section provides an overview on the IS and LEBT systems and their statuses during this BC. The IS of ESS is a microwave discharge type, with the nominal extraction voltage of 75 kV. This type of source is known to produce a high current and high quality beam, and the off-site BC demonstrated production of a high quality proton beam with more than 70 mA out of the LEBT [3,4]. The confining field of the plasma chamber is produced by three coils (Fig. 1), and this provides great flexibility in turning. The three coils are referred to as Coil 1, 2, and 3, counting from the extraction side, in the following. During the BC, the IS initially suffered from grounding issues, which even caused damages to some electronics inside the 75 kV platform. This required consolidations against high-frequency discharges, in contrast to the situation of the off-site BC. Since completion of the consolidations in January 2019, the IS has established stable operation and provided as much as 174 hours of beam time in April 2019.

A schematics of the LEBT is shown in Fig. 1. The main components of the LEBT are two solenoids, which focus the diverging beam out of the IS and match it to the following radio frequency quadrupole (RFQ). Each solenoid also

Table 1: High-level Beam Parameters at IS and Target

Parameter	Units	IS	Target
Average power	kW	~0.5	5000
Kinetic energy	MeV	0.075	2000
Peak current (proton)	mA	~70	62.5
Peak current (total)	mA	~85	62.5
Pulse length	ms	~6	2.86
Pulse repetition rate	Hz	14	14
Duty cycle	%	~8	4

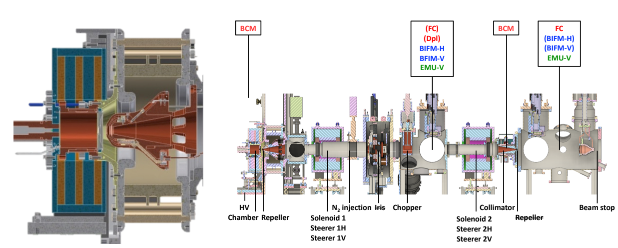

Figure 1: Left: Schematics of IS chamber and extraction system. Right: Schematic of LEBT.

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houses dipole correctors (*steerers*) of each transverse plane. In-between the two solenoids, there is a tank (*Permanent Tank*) which houses diagnostics devices and the chopper. The chopper removes unnecessary head and tail parts of the pulse out of the IS, which is typically ~6 ms, and transmit a pulse of the nominal ~3 ms or a much shorter one, down to 5 µs, for tuning purposes. In-between Solenoid 1 and Permanent Tank, there is an iris, which allows to adjust the beam current with its six movable blades, forming a hexagonal shape aperture. The iris is not available during this BC due to a motion control issue of its blades. It has to be tested and verified in the beginning of the next BC stage, prior to sending the beam to the RFQ. The minimum aperture radius in the LEBT is ~40 mm up to the collimator at the end. The aperture of the collimator reduces to 7 mm at the interface to the RFQ. During this BC stage, an additional tank (*Commissioning Tank*) is placed right after the collimator, and this allows to house additional diagnostics devices and provide information of beam near the RFQ interface.

The LEBT houses five types of diagnostics devices, whose details are provided in [11]. For current measurement, there are two beam current monitors (BCMs) and one Faraday cup (FC). One of the BCMs measures the current in the cable from the high-voltage power supply to the platform, thus providing an indirect measurement of the IS current. Another BCM measures the current out of the collimator. The FC can be placed in either tanks. Beam induced fluorescence monitors (BIFMs) measure centroid position and profile of the beam. A pair for each plane has been installed and used in Permanent Tank, and another pair in Commissioning Tank is currently under deployment. One Allison scanner type emittance measurement unit (EMU) is housed in each tank, allowing to measure emittance at two locations. Doppler detector (Dpl), which measures fractions of ion species as well as their energies, are currently under deployment.

IS CHARACTERIZATION AND TUNING

Characterization and tuning exercise of the IS have been repeated during this BC, despite thorough studies performed during the off-site BC [2,4]. There is a chance that the IS may have to operate at off-nominal settings due a situation of the rest of the linac, and thus it is crucial to raise expertise at ESS and establish a systematic way to retune the IS.

Five main adjustable parameters of the IS are magnetron power, amount of H_2 gas injection, and strengths of the three coils. It was found that there is an easy way to establish a local optimum setting of the IS in the space of these five parameters, mostly with just Coil 2. Figure 2 shows changes in beam pulse shapes during a scan of Coil 2, observed by the IS BCM (left) and FC in Permanent Tank (right). We can see that the IS current increased along with the Coil 2 strength. (If the Coil 2 strength had been increased further, the beam had no longer been extracted at some point due to loss of stability in plasma.) On the contrary, between 67 and 68 A of Coil 2 current, the current reaching to the FC saturates, and the pulse shape starts to show a drooping

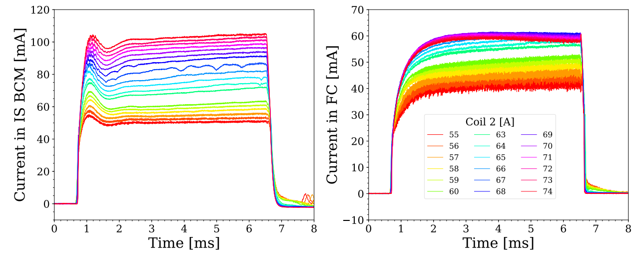

Figure 2: Beam pulse changes during a Coil 2 scan. Magnetron power, Coil 1 current, Coil 3 current, and H_2 injection were kept to 500 W, 120 A, 217 A, and 3.5 sccm.

effect. Clearly, this turnaround point give the local optimum setting in terms of both current and flatness. Increment of the H_2 injection tends to raise the tail of the pulse, and thus allows to compensate the drooping effect. When fine-tuning the flatness, it is easier to select a Coil 2 value such as having slight drooping and then compensate it with the H_2 injection.

The above mentioned simple scheme worked well over a large space of the five IS parameters. This allowed to establish many operation points and study global characteristics of the IS, in a prompt manner. For operation points established this way, Fig. 3 summarizes the relation between the IS current and the part reaching to the FC in Permanent Tank. Note that Solenoid 1 was kept to a fixed strength (−249 mT), and the listed current is the mean over the 2.9 ms plateau towards the end of the pulse. As seen in the figure, the IS current is correlated with the magnetron power, as expected, but also depends a lot on coils settings. The current reaching to the FC in Permanent Tank is mostly determined by the initial divergence and fractions of ion species out the IS. The figure also indicates that these two factors are highly correlated to the resultant IS current alone.

IS SETTINGS AND BEAM QUALITY

The previous section saw that many operation settings are possible for the IS of ESS. Out of many settings, two summarized in Table 2 have been most frequently tested; *Standard Setting* has a 87 mA IS current and *Low (Current) Setting* has 58 mA. Figure 4 shows the beam pulses for these two settings, observed by two BCMs and FC (in Commissioning

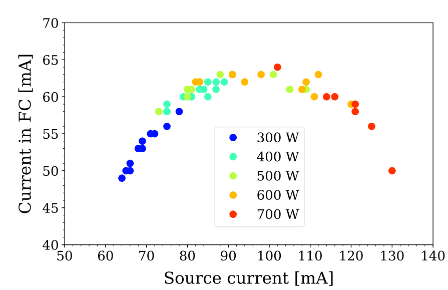

Figure 3: Currents at the IS and in Permanent Tank (from FC) for IS operation points. Solenoid 1, Steerer 1H, and Steerer 1V were kept to −249 mT, −2.72 mT, and −0.35 mT.

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Table 2: IS Parameters for Two Settings with IS and LEBT Output Currents and Emittance in Permanent Tank

Parameter	Units	Standard	Low
Magnetron power	W	400	350
Coil 1 current	A	130	60
Coil 2 current	A	68.5	120
Coil 3 current	A	219	200
H_2 injection	sccm	3.70	5.70
IS current	mA	87	58
LEBT current	mA	71	51
Emittance	π mm mrad	0.40	0.31

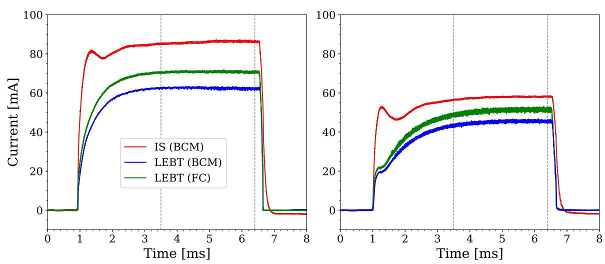

Figure 4: Beam pulses for the Standard Setting and Low Setting. The dotted lines indicate the 2.9 ms plateau.

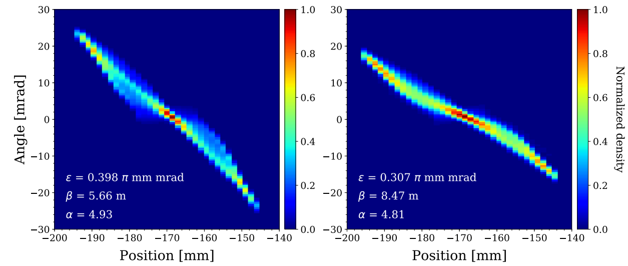

Figure 5: Preliminary EMU measurements in Permanent Tank for the Standard Setting and Low Setting.

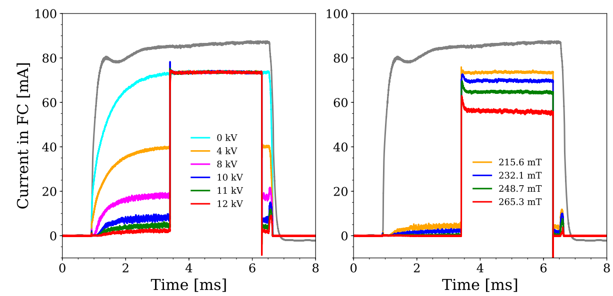

Figure 6: Chopped beam pulses for different chopper voltages (left) and different solenoid 2 strengths (right). The gray trace is the IS pulse as a reference.

Tank). Note that the Low Setting has a slower rise time, and the extracted pulse length has to be extended to achieve the same level of flatness as the Standard setting. This is often the case for a setting with a low magnetron power. The discrepancy between the LEBT BCM and FC has not been well understood, and further investigation is planned [11]. Figure 5 compares preliminary EMU measurements for both settings in Permanent Tank. Measurements based on the BIFM have estimated emittances of 0.42 π mm mard for the Standard Setting and 0.29 π mm mard for the Low Setting [10], and thus we have two methods showing consistent results for both settings. The reason why we tried IS settings with lower current was this smaller emittance. Additional measurements also showed that the Low Setting has a better matching condition as well at the RFQ interface [10].

CHOPPER TEST

The LEBT chopper is an electric deflector with a flat conducting plate and a U-shaped ground [12], and its dump is the collimator. The conducting plate has been selected to be biased with a negative voltage of ~10 kV. This is to repel electrons due to secondary emissions and thus to prevent for the power supply to draw an excess amount of current, which could potentially occur for the positive polarity case. The negative polarity also has a positive impact on beam dynamics in terms of space charge compensation, since it does not remove electrons from the beam unlike the positive polarity case [12]. One minor issue of this chopper is that the geometry of the conductor and ground is not necessarily optimized for the negative polarity. The produced field from this geometry is such that the particles on the side of the deflection direction (conductor side) receive large kicks than those on another side, and this situation is not optimal for efficiency of chopping. Figure 6 (left) shows beam pulses of the Standard Setting for different levels of the chopper voltage, where the current was observed by the FC in Commissioning Tank. Strengths of the two solenoids and four steerers in the LEBT were set to maximize the transmission [10]: for solenoids 257 mT and 216 mT and for steerers −0.34 mT, 0.49 mT, −0.85 mT, and 0 mT, in the order of 1H, 1V, 2H, and 2V. As concerned, in this particular condition, there is leak current of ~5 mA outside of the unchopped part of 2.9 ms. Figure 6 (right) shows the beam pulses for a 11 kV case with different strengths of Solenoid 2. A larger field in Solenoid 2 squeezes the beam size at the collimator, and thus reduces the level of the leakage. In this way, the efficiency of the chopping is also sensitive to the LEBT optics.

CONCLUSION

Beam commissioning has started at the ESS site from the IS and LEBT. After the initial issue in grounding was solved, the IS has been running stably and producing the required level of current. Among the completed and ongoing activities, this paper presented results of IS characterization, properties of the two selected IS settings with an intermediate and low currents, as well as results of chopper testing.

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