ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP044

STATUS OF THE FARADAY CUPS FOR THE ESS LINAC

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Abstract

The proton linac for the European Spallation Source (ESS) is under construction on the outskirts of Lund (Sweden). Four Faraday Cups (FC) are meant to stop the proton beam and measure the beam current in the normal conducting linac section. The first Faraday cup is located in the LEBT and has been operational throughout the commissioning of the source and the LEBT. In June 2019, a second Faraday cup was installed in the MEBT and will undergo verifications without beam in fall 2019. The two most challenging FCs are currently in construction phase and will be installed in two DTL intertanks early in 2020. This contribution summarizes the latest milestones and challenges for the development and operation of all the ESS Faraday cups.

INTRODUCTION

The proton linac for the European Spallation Source (ESS) is currently under construction in Lund (Sweden). Once operational, ESS will be the most powerful and brightest spallation neutron source in the world, relying on an accelerator of protons up to an energy of 2 GeV. The ESS linac is mainly superconducting and has a normal conducting linac section as its injector. At the moment, the installation is progressing for the four normal conducting sections:

1. the Low Energy Beam Transfer (LEBT) line;
2. the Radio Frequency Quadrupole (RFQ);
3. the Medium Energy Beta Transfer (MEBT) line;
4. the Drift Tube Linac (DTL).

During the start-up and commissioning phases of the normal conducting linac, the beam current is measured either with non-interceptive [1] or interceptive devices.

Four Faraday cups (FC) are included in the latter category; they serve as beam destination and measure the beam current. Only the LEBT FC can withstand the nominal ESS beam pulses of 62.5 mA current, 6 ms width and 14 Hz repetition rate, as long as the maximum power density is within 14 kW/cm^2, which corresponds to a 3.7 mm RMS size for 75 keV protons. The other three FCs are specifically designed to withstand only the so-called ESS tuning modes:

- *slow* tuning: 50 µs long pulses at 1 Hz repetition rate;
- *fast* tuning: 5 µs long pulses at 14 Hz repetition rate.

In Table 1, the current status is summarized for each device. This contribution highlights the latest milestones and challenges either in the development or operation of the four FC systems.

Table 1: Status of the Four Faraday Cups for the ESS Linac and Energy of the Proton Beam They Are Exposed To

	FC Status	**Proton energy (MeV)**
LEBT	Operational	0.075
MEBT	Just installed	3.63
DTL2	Under production	21 or 39
DTL4	Under production	39 or 74

LEBT FC

The Faraday cup (FC) in the Low Energy Beam Transport (LEBT) line was designed at ESS [2] and produced in 2014 by Pantechnik [3]. The actual cup is entirely made of copper and water cooled. The cup is inserted or extracted from the beam line by means of a pneumatic actuator.

In 2017, the LEBT FC took part in the ion source and LEBT commissioning in Catania (Italy). From September 2018 to July 2019, it contributed to various types of characterizations of the source and LEBT at ESS in Lund [4]. The current readings from the LEBT FC and the two Beam Current Monitors (BCMs) upstream were compared in several source configurations.

A representative plot is presented in Fig. 1 (left), resulting from the scan of the two LEBT solenoids (namely, Sol1 and Sol2). In particular, the solenoid current was increased from 250 to 350 A, and from 160 to 380 A, for the first and second solenoid, respectively. It is worth noting that the maximum solenoid current is 500 A and the typical operational range is between 250 A and 300 A.

The FC was located about 600 mm downstream of the collimator exit at the end of the LEBT, with an aperture of just 14 mm in diameter. During the solenoid scan, a

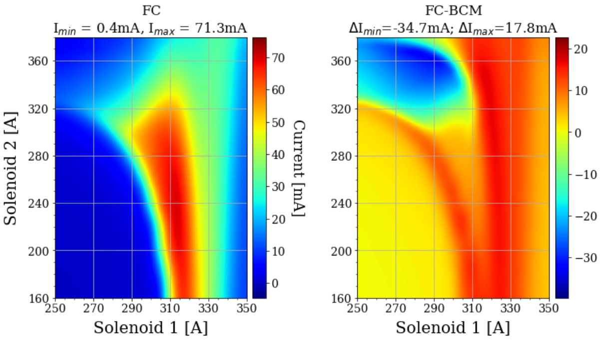

Figure 1: Beam current measurements resulting from solenoid scans: (left) in the LEBT FC and (right) difference between LEBT FC and BCM currents.

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maximum beam current of 71.3 mA was measured by the LEBT FC.

The bottom-left section of Fig. 1 should be addressed as the *standard* operation region. In such triangular region, extending approximately over 290-320 A of Sol1 and 220-290 A of Sol2, good transmission can be achieved and the difference in the current reading between LEBT BCM and FC are minimal. In Fig. 1 (left), the area with Sol1 current above 320 A is named an under *over-focused* condition where the beam waist occurs upstream the collimator exit. In such condition, a significant fraction of the proton beam hits the collimator and generates electrons, thus spoiling the current measurement by the surrounding LEBT BCM. In this regard, the difference between the currents measured by the LEBT FC and BCM is shown in Fig. 1 (right).

In one limit, differences up to 17.8 mA were observed in the FC with respect to the BCM. It is worth noticing that, at the time of the measurements, a repeller at the collimator exit was unavailable, meaning that the LEBT BCM is more sensitive against the secondary electrons. The measurement of the LEBT BCM will be repeated in the next commissioning phase once the repeller is fixed, and thus providing a better comparison. In another limit, the LEBT FC measures less current (down to −34.7 mA) with respect to the LEBT BCM, when the beam is larger than the FC aperture. This case happens when the Sol2 current values are way higher than Sol1 values (see the blue region in Fig. 1 (right)).

Many lessons were learned during the verifications of the LEBT FC system with and without beam. The corresponding documentation will serve as reference for the acceptance tests of the other three Faraday cups. Here we especially mention that the LEBT FC readout electronics was updated from the legacy VME/IOxOS system in Catania to a µTCA/Struck system in Lund. This is a step on the roadmap to a common platform for readout of current-monitoring systems and will enable common protection features for FC and BCM. Concerning the control of the LEBT FC in the ESS local control room, a dedicated operator interface in Control System Studio (CSS) was deployed. It will represent the starting point for the integration of interlocks and alarms needed when dealing with the exposure of FCs up to 74 MeV protons and higher beam power densities.

MEBT FC

The Faraday Cup in the Medium Energy Beam Transport (MEBT) line was designed by ESS-Bilbao and fabricated by Pantechnik starting from the middle of 2017. The initial integration and tests were performed at the ESS-Bilbao injector with 45 keV protons (see Fig. 2). In June 2019, the beamline device was installed in the ESS tunnel.

The MEBT FC operation will be restricted to the ESS tuning modes. In order to withstand the irradiation load, the MEBT FC includes an indented graphite collector and the stainless steel body is water cooled. The collector is insulated from the cup body by an alumina layer. A repeller ring can be operated down to −1 kV to reduce the escape of secondary electrons produced by the primary beam in the collector. The modular design is meant to ease the replacement of repeller, collector and insulators. More details about the design of the MEBT FC are given in this same conference proceedings [5].

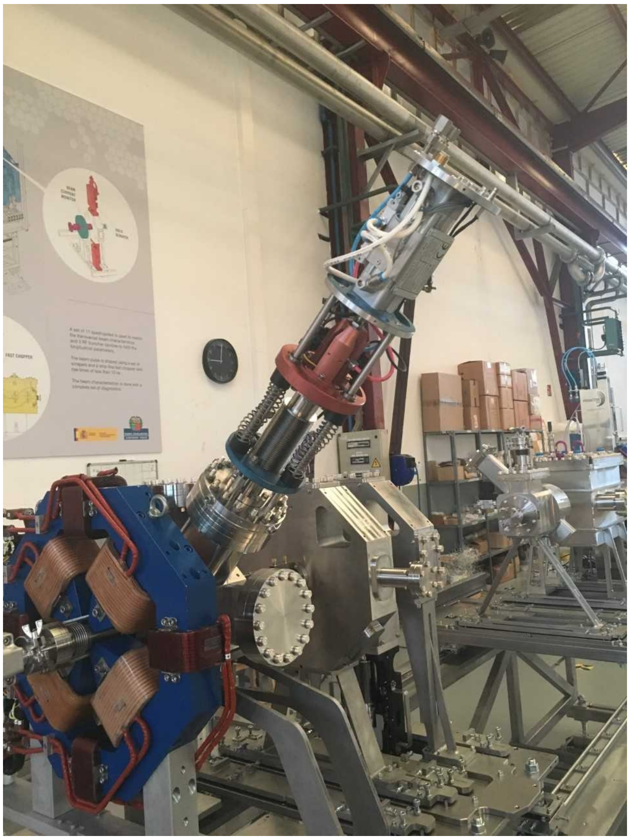

Figure 2: The MEBT FC, tiltly mounted on the eight raft and closed to the eight quadrupole of the MEBT section.

The key requirements for the MEBT FC signal acquisition are a 2 MHz bandwidth and a 0.1% noise. The acquisition chain electronics designed and produced by ESS-Bilbao relies on active electronics to convert and amplify the collected current from the MEBT FC in a Front-End (FE) located on the MEBT support structure. This FE is currently being verified at ESS before its deployment in the accelerator tunnel.

The Back-End contains the power supplies of the system, and the motion control I/O systems consists of Beckhoff modules. The FC control system is integrated in a µTCA crate, where the signal control and acquisition is done by IOxOS boards, and the trigger synchronization is done by the MRF EVR-300U board. For the control integration, the software is developed in the ESS EPICS Environment and CSS is the Engineering GUI for the FC commissioning.

During the tests with 45 keV protons at the ESS-Bilbao injector, a background noise was observed and possibly caused by different grounding for the beam line and the acquisition system. As the performance requirements and the cable length for the MEBT FC meet the one of the LEBT FC, the same FE as the LEBT FC one, based on passive electronics [6] instead, is being used until the verification of the ESS-Bilbao FE is completed.

DTL FCS

The two FCs for the ESS Drift Tube Linac (DTL) are the most challenging ones to be designed. The DTL FC2 and FC4 will be installed in the second and in the fourth DTL intertank, respectevely. The DTL FC2 will stop and measure the current of a 21 or 39 MeV proton beam, while the DTL FC4 will be exposed either to 39 or 74 MeV protons. The FCs will be among the main diagnostics devices used for the beam commissioning, with a reduced beam duty cycle. The maximum average beam power to be absorbed by FC2 and FC4 is 170 W and 324 W, respectively. Space constraints are posed by the intertank dimension, limiting the thickness of FC2 and FC4 to 28 mm and 35 mm, respectively. Both the DTL FCs are currently under design which is particular challenging for DTL FC2. The main idea is to have an entrance foil to scatter the incoming proton beam and to stop the beam in a water cooled collector. Both the entrance foil and the collector are made of graphite, chosen for its high melting point and for minimizing the cup activation. A repeller is placed between the foil and the collector of FC2 to send secondary electrons back to the collector.

In Fig. 3 the total energy deposition is plotted as a function of the position within the actual cup of FC2. The colored areas represent the five materials that the beam is passing through, from left to right. Each material or void thickness is expressed in cm at the top of Fig. 3. It can be noticed that the Bragg peak is located very close to the collector surface in the case of a 21 MeV proton beam. On the contrary, 39 MeV protons will be stopped almost at the interface between the graphite collector and the collector insulator. Therefore, the current efforts are aimed at optimizing the limited space available and increasing the margin after the Bragg peak.

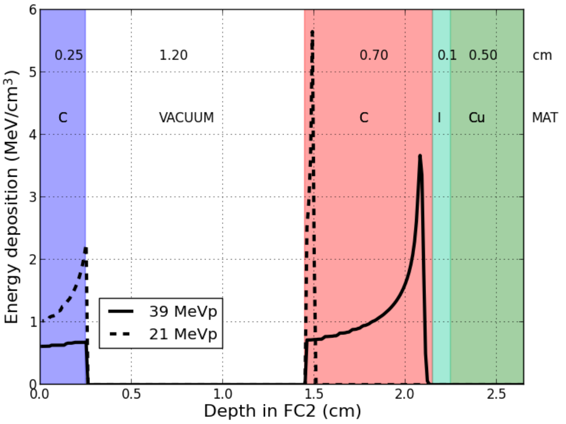

Figure 3: Energy deposition in the DTL FC2 by 21 and 39 MeV protons.

The design of DTL FC4 is completed and the main structural components of the actual cup are: an entrance foil made of TZM and a graphite collector. Both DTL FCs rely on a copper body that is water cooled from the back part. Before being installed in the intertanks, the DTL FCs will be temporarily located in dedicated vacuum pipes, just after each DTL section to be commissioned. Therefore a dedicated shielding had to be designed and validated in Monte Carlo simulations in MCNP6 [7]. The residual dose rate at contact from gammas was calculated as resulting from irradiation at the four possible energies of the proton beam and at subsequent cooling times. As representative example, Fig. 4 shows the residual gamma dose rate in 2D, soon after irradiation of FC4 with 74 MeV protons. The results are expressed in mSv/h/μA. According to the simulations and as soon as the irradiation is over, a maximum dose rate of few tens of mSv/h/μA is found at the FC4 location. The dose rate decreases along the beam pipe and is six orders of magnitude less outside the shielding.

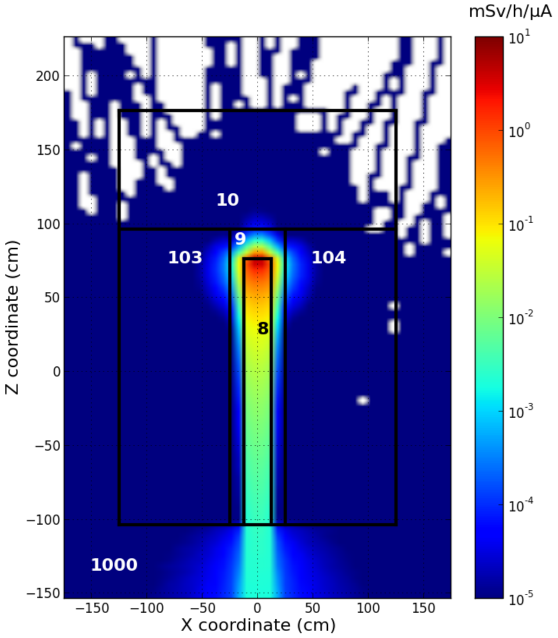

Figure 4: Residual gamma dose rate at contact of DTL FC4 (located in the red hot spot), immediately after exposure to 74 MeV protons. White numbers indicate shielding materials around the FC4: (9) SSL306 (10,103,104) concrete and (1000) air.

CONCLUSIONS AND OUTLOOK

The recent milestones and the current challenges for the four Faraday cups in the ESS linac are reported.

The LEBT FC is at the most advanced stage. A replica of the LEBT FC is being produced at Pantechnik for characterizing the second ion source. The LEBT FC replica has an additional locking feature in case pneumatic air is lost to the actuator system. The new feature will increase the safety of the overall LEBT FC system which will have to be installed

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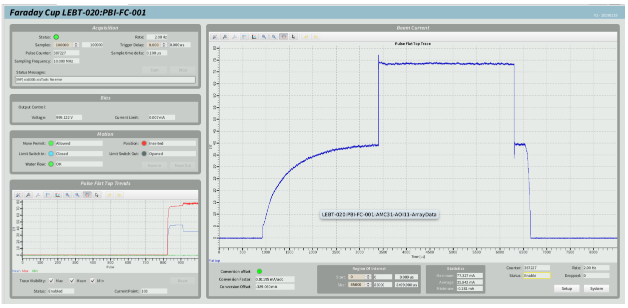
in the same tank position of two Emittance Monitor Units (EMU) and a Doppler system.

The LEBT FC interface for operators in the ESS control room was developed in CSS (see Fig. 5). It allows to control cooling, motion and current measurements of the LEBT FC. This interface will serve as starting point for the operation and control of all the other FCs, as well as for the implementation of interlocks and alarms on relevant process variables.


Faraday Cup LEBT-020:PBI-FC-001

Status: ●
Rate: 2.00 Hz
Samples: 100000 100000
Trigger Delay: 0.000 0.000 us
PulseCounter: 387227
Sample time delta: 0.100 us
Sampling Frequency: 10.000 MHz
Status Messages: [INF] sis8300::sisTask: No error

Voltage: 999.122 V
Current Limit: 0.007 mA

Move Permit: ● Allowed
Position: ● Inserted
Limit Switch In: ● Closed
Limit Switch Out: ● Opened
Water Flow: ● OK

Trace Visibility: ☑ Max ☑ Mean ☑ Min
Status: Enabled
CurrentPoint: 103

LEBT-020:PBI-FC-001:AMC31-AOI11-ArrayData

Conversion offset: ●
Conversion Factor: 0.01195 mA/adc
Conversion Offset: -389.060 mA

Start: 0 0 0.000 us
Size: 85000 85000 8499.900 us

Maximum: 77.327 mA
Average: 35.842 mA
Minimum: -0.281 mA

Counter: 387227
Rate: 2.00 Hz
Status: Enable
Dropped: 0

Figure 5: Operator interface for the LEBT FC.

The experience accumulated during the commissioning of the ESS ion source and LEBT will be useful for all the other FC systems as well. As the performance requirements and the cable lengths for the MEBT FC meet the one of the LEBT FC, it is currently planned to employ the same FE as the LEBT FC one, which is based on a passive electronics solution installed in the rack [6]. Once the verification of the ESS-Bilbao FE is completed, the MEBT FC FE will be upgraded.

The design is completed for the DTL FC4, while space optimization is necessary for the DTL FC2 structural components. The production of DTL FCs will be completed by RadiaBeam [8] in October 2019. According to the current installation plan, starting from June 2020 the DTL FCs will be the key diagnostics devices for the ESS normal conducting linac tuning.

ACKNOWLEDGMENTS

The authors are grateful: to Edvard Bergman, Rick Bebb, Lars Rosberg and James Stovall for their technical support; to Emanuele Laface and Ryoichi Miyamoto for their support in data taking and fruitful discussions; to the staff at the Pantechnik and RadiaBeam, and in particular to Fabrice Duboist and Marcos Ruelas, for their dedication throughout the procurement phases.

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