ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRC1I1

THE BEAM DESTINATIONS FOR THE COMMISSIONING OF THE ESS HIGH POWER NORMAL CONDUCTING LINAC

Elena Maria Donegani*,[1], Saverio Ardovino[1], Vincent Bertrand[2], Ibon Bustinduy[3], Viatcheslav Grishin[1], Tara Hodgetts[4], Emanuele Laface[1], Carlos Neto[1], Anders Olsson[1], Laurence Page[1], Marcos Ruelas[4], Thomas Shea[1]
[1]European Spallation Source (ESS) Lund, Sweden
[2]Pantechnik, Bayeux, France
[3]ESS Bilbao, Zamudio, Spain
[4]RadiaBeam Technologies, Santa Monica, CA, USA

Abstract

At the European Spallation Source (ESS) in Lund (Sweden), the commissioning of the high-power normal conducting linac started in 2018. This paper deals with the beam destinations for the commissioning phases with initially the proton source and LEBT, then the MEBT and lately four DTL sections. The beam destinations were designed to withstand the ESS commissioning beam modes (with proton current up to 62.5 mA, pulse length up to 50 µs and repetition rates up to 14 Hz). The EPICS-based control system allows measurements of the proton current and pulse length in real-time; it controls the motion and the power suppliers, and it also monitors the water cooling systems. Special focus will be on the results of thermo-mechanical simulations in MCNP/ANSYS to ensure safe absorption and dissipation of the volumetric power-deposition. The devices' materials were chosen not only to cope with the high-power proton-beam, but also to be vacuum-compatible, to minimize the activation of the beam destinations themselves and the residual dose nearby. The results of neutronics simulations will be summarized with special focus on the shielding strategy, the operational limits and relocation procedures.

INTRODUCTION

The European Spallation Source (ESS) is going to be a 5 MW pulsed neutron source, relying on a 2 GeV proton linac to produce neutrons via the spallation process [1]. Once fully installed and commissioned, the linac will deliver 2.86 ms long proton pulses with 14 Hz repetition rate. The proton linac comprises firstly the NCL (Normal Conducting Linac) and secondly the SCL (Super Conducting Linac).

First of all, the NCL commissioning started in fall 2018, with protons initially dumped on the Faraday cup (FC) in the Low Energy Beam Transport line (LEBT) [2]. Following the RFQ conditioning and the installation of the Medium Energy Beam Transport (MEBT) [3], the commissioning continued up to the MEBT Faraday cup [4] between fall 2021 and spring 2022. In June 2022, the protons were accelerated for the first time through the first Drift Tube Linac section (DTL1) and dumped in the shielded Faraday cup downstream the DTL1 section [5]. After the installation of three additional DTL sections [6], the protons were accelerated and transported down to the DTL4 section and dumped in the DTL4 Faraday cup in April 2023. Each Faraday cup was designed for specific proton energies and the foreseen beam power density. Table 1 lists the beam destinations that were operational during ESS NCL commissioning phases, as well as the average beam power and the calculated peak temperature.

* elena.donegani@ess.eu

Table 1: List of beam destinations used for the subsequent phases of the ESS NCL commissioning, at increasing proton energy (E) and average proton beam power (P). The corresponding maximum core temperature (T) was computed via thermo-mechanical simulations.

Destination	E (MeV)	P (W)	T (°C)
LEBT FC	0.075	0.005	800
MEBT FC	3.6	16	960
DTL1 FC	21	170	620
DTL4 FC	[21, 74]	323	1010

GOALS

During the ESS NCL commissioning, four Faraday cups were used as beam destinations, in place of expensive and bulky beam dumps. The goals of the Faraday cups were to fully stop the proton beam, to safely absorb and dissipate the beam power, and to provide real-time measurements of the proton current as well as the pulse length. In addition, the DTL FCs had to be installed in a dedicated shielding for the following three reasons: (I) tunnel accessibility during commissioning, (II) installation work in the SCL in parallel to the commissioning, and (III) dismantling within few weeks after the end of the DTL1 and DTL4 commissioning. All the beam destinations were operated under ultra high vacuum, water-cooled and movable in/out of the beam line by means of a pneumatic actuator.

The beam-intercepting components were designed to withstand the so-called commissioning beam modes: Probe-beam (6 mA, 5 µs, 1 Hz), Fast-tuning (62.5 mA, 5 µs, 14 Hz), and Slow-tuning (62.5 mA, 50 µs, 1 Hz). In addition, the LEBT FC can withstand also the so-called Production-mode (62.5 mA, 2860 µs, 14 Hz).

68th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams HB2023, Geneva, Switzerland JACoW Publishing
ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRC1I1

The control-system relied on EPICS [7] for: I) monitoring the status of the water cooling systems, II) controlling the high-voltage and the motion in/out of the beam line, III) the data acquisition (DAQ) and IV) the timing synchronization [8]. The µTCA is the adopted technology for high speed processing and communication interfaces. For the ESS Main Control Room, Operator Interfaces were developed in Phoebus. For instance, the measured proton pulses, the history of the maximum proton current during the last 20 minutes and the status of the water cooling system were constantly monitored. In particular, the DAQ allowed the beam current ranging from 0.1 mA to 65 mA with an accuracy better than 1% and a time resolution better than 1 µs. Figure 1 shows two representative examples of measured proton pulses by the LEBT FC and by the DTL4 FC.

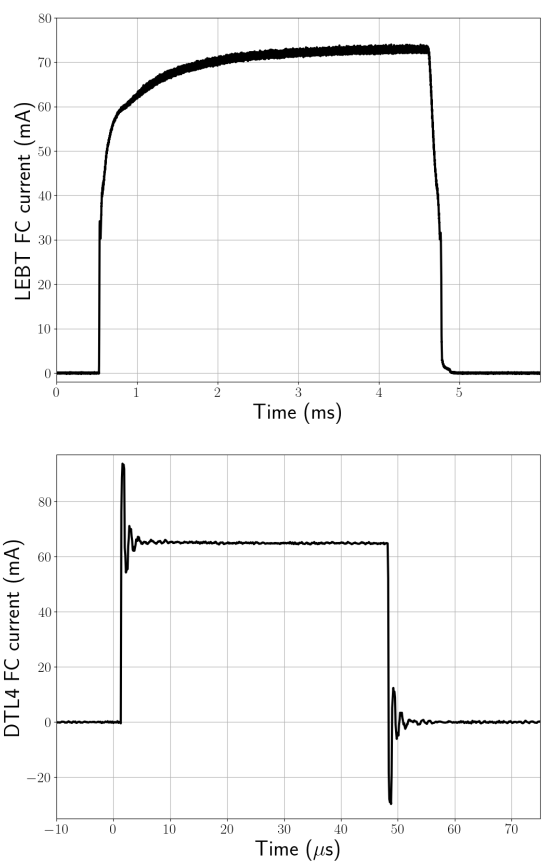

Figure 1: Example of proton pulses measured by: (top) the LEBT FC and (bottom) the DTL4 FC.

WORKFLOW AND CHALLENGES

The workflow for each Faraday cup from the conceptual design to the operation in the ESS proton linac is summarized as follows:

1. *DESIGN*: including thermo-mechanical simulations of the beam-intercepting devices, calculations of activation and residual dose-rates, shielding design, CAD modelling and integration in the overall linac model.

2. *PRODUCTION*: including the call of tenders, final design review, manufacturing, assembly and factory acceptance tests.

3. *INSTALLATION*: including acceptance tests, installation in the linac, cables and water pipes connections, electronics and rack installation, DAQ calibration (ADC/mA), survey and alignment, verification of the control system and verification without beam.

4. *DOCUMENTATION* of technical reports, test results, licensing and review reports.

5. *OPERATION*: including the definition of the operational limits, verification with beam, verification of the operator interfaces, control-room shifts and data analysis of commissioning results.

During the design phase, the main challenges were posed by the limited space for allocating the beam-intercepting devices to be exposed to demanding beam power-densities. In fact, the available space was very limited both outside and inside the beam line. In particular, the beam-intercepting components had to be designed with high-strength, heat-resistant and radiation-resistant materials. Moreover, the devices were designed with the intent of minimizing the radiation-induced activation. The computing time for the Monte Carlo simulations in MCNPX [9] were significantly reduced by running on the DMSC cluster [10].

During the manufacturing and testing phase, the main challenges were posed by the tight schedule and the limited availability of materials caused by the COVID-19 pandemic.

During the commissioning phases, the main challenges were the definition of the operational limits while no measurements of the beam size, beam emittance nor the beam energy were possible. Therefore, thermo-mechanical calculations allowed to predict and avoid conditions that could have induced permanent damages to the devices, caused linac downtime or contamination of linac cavities.

In the following sections, highlights are given for each beam destination. The recent developments and results are summarized in order to provide an update to the previously published information and results in [11–13].

LEBT FC

The Faraday cup (FC) in the Low Energy Beam Transport (LEBT) line was designed at ESS [14] and manufactured by Pantechnik in 2014 [15]. A second unit was manufactured in 2019 in order to support the testing of the second ESS proton source and in case a replacement is needed, too. Both LEBT Faraday cups are visible in Fig. 2 when they were installed in a vacuum tank for testing their pneumatic actuators, the motion and HV control system.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRC1I1

The actual cup is entirely made of copper, with two separate cooling loops: one for the front repeller and one for the conical copper body. In 2017, the LEBT FC supported the very first tests on the ion source at the INFN Catania division in Italy. Since September 2018, the LEBT FC contributed to all the four NCL commissioning phases. The current measurements by the LEBT FC were useful for: proton-source characterization [16] as well as to pave the way for installation, test and verification procedures of beam diagnostics devices [17]. The LEBT FC was also useful in order to study the impact of the proton source repeller on the space charge compensation [18].

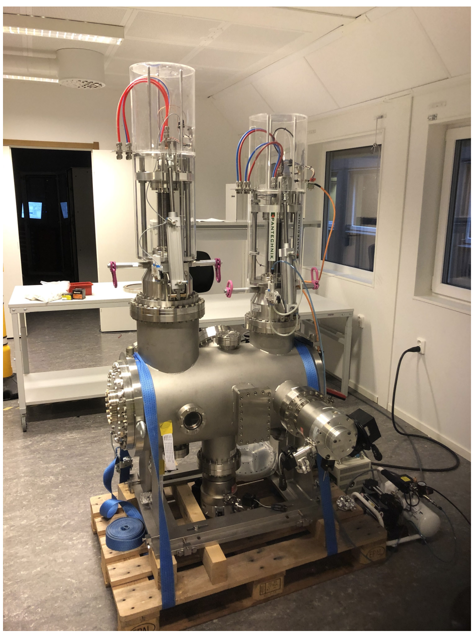

Figure 2: The two LEBT FC in the tank for testing prior to installation in the ESS linac.

MEBT FC

The Faraday cup (FC) in the Medium Energy Beam Transport (MEBT) line was designed by ESS-Bilbao [19] and manufactured by Pantechnik [15]. A spare unit was produced by Pantechnik in 2021, too. The MEBT FC has been operational since November 2021. The main challenge of keeping the thermal load and stresses below the mechanical limits was solved by shaping the collector surface in a saw-tooth path (see Fig. 3). During the design phase and for defining the operational limits, dedicated beam power density calculations and thermo-mechanical calculations were performed in MCNPX [9] and ANSYS [20], respectively.

During the operation of the MEBT FC as well as all the other FCs, the temperature of the water cooling was constantly monitored; the temperature of the cooling water and the water flow had dedicated interlocks. In Fig. 4, it is possible to observe that the cooling water temperature remained below 20.3°C while sending the nominal proton current (62.5 mA) to the MEBT FC in the Slow-tuning mode. It is also possible to observe that the readings from the water

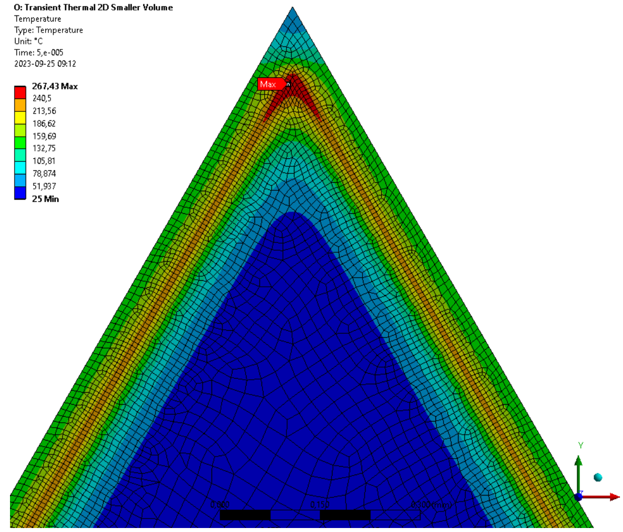

Figure 3: Calculated temperature distribution in the MEBT FC graphite collector, zoomed in the central part of the saw-tooth surface, after 3.6 MeV protons. The peak value is just 130 µm deep into the graphite.

temperature sensors follows the current measurements after several seconds.

DTL1 FC

The Faraday cup (FC) for the commissioning up to the first Drift Tube Linac (DTL1) was designed at ESS and manufactured by RadiaBeam Technologies in 2020 [21].

The DTL1 FC acted as beam dump during the DTL1 commissioning, with typical beam power densities in the order of MW/cm^3. The DTL1 FC was temporarily installed in its dedicated shielding located at the exit of the DTL1 section. The actual cup stopped up to 21 MeV protons and has a remarkably small thickness of 27 mm, driven by the spatial constraints in its future and permanent location within the DTL2 intertank. Further details regarding the design and the performance of the DTL1 FC can be found in [22].

Here, it is worth noticing that the device has an entrance foil made of graphite that entirely stops the low energy protons fallen out of the RF bucket. The graphite collector is isolated from the rest of the cup body to measure the current of protons at the nominal 21 MeV energy. It was therefore possible to perform phase scans [23] at different amplitudes of the DTL1 accelerating field in the range [2.7, 3.1] MV/m (see Fig. 5). In addition, the DTL1 FC foil reduces the energy of protons at the nominal energy and scatters the beam, so that the thermal load on the collector is reduced.

At the end of the DTL1 commissioning, the low residual dose-rate in the vicinity of the DTL1 FC (below 2 µSv/h, after 8 hours of decay time), allowed the relocation of the dump and its shielding the day after the commissioning was over, thus quickly leaving the floor for the installation of the DTL2-3-4 sections.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRC1I1

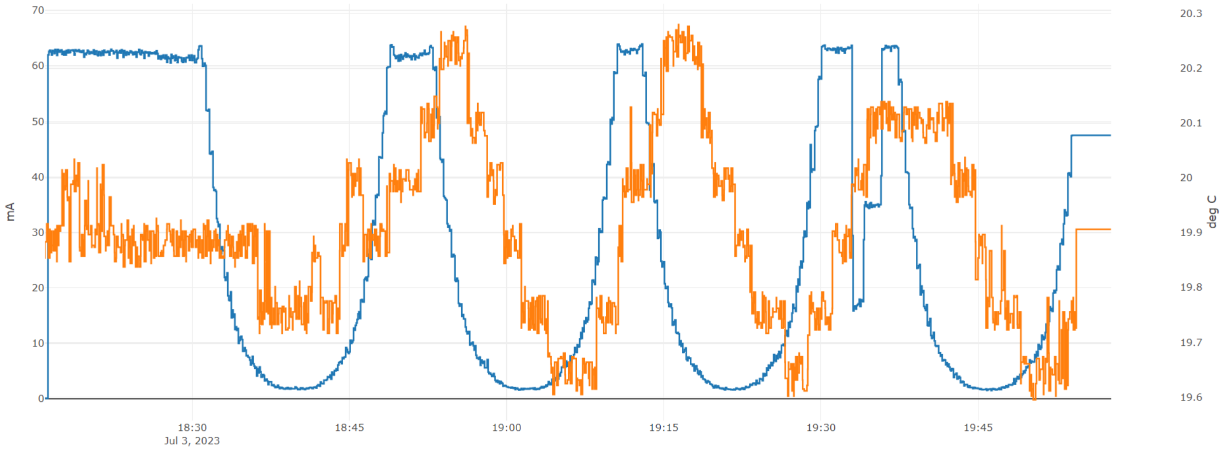

Figure 4: Measurements as a function of the time: (blue) proton current in the MEBT FC and (orange) temperature of the MEBT FC cooling water. Values were extracted from the EPICS [7] Archiver Appliance.

DTL4 FC

The Faraday cup (FC) for the commissioning up to the fourth Drift Tube Linac (DTL4) [24] was designed at ESS and manufactured by RadiaBeam technologies in 2021 [21]. Details about the design and performance can be found in [25]. The DTL4 FC was originally intended to dump protons in the [57, 74] MeV range, but actually also stopped protons down to 21 MeV whenever it was unexpectedly impossible to achieve the full acceleration in the DTL. At such low energy, the proton current was limited up to 6 mA, following the results of the thermo-mechanical calculations. Contrary to all the other FCs, the DTL4 FC does not have a biased repeller mainly because of lacking space to include a repeller in addition to the entrance foil, the collector, the heat sink and the water pipes within a cylindrical envelope with just R=60 mm and h=33mm. Moreover, the secondary emission yield is larger at the lower proton energies stopped by the LEBT, MEBT and DTL1 FCs.

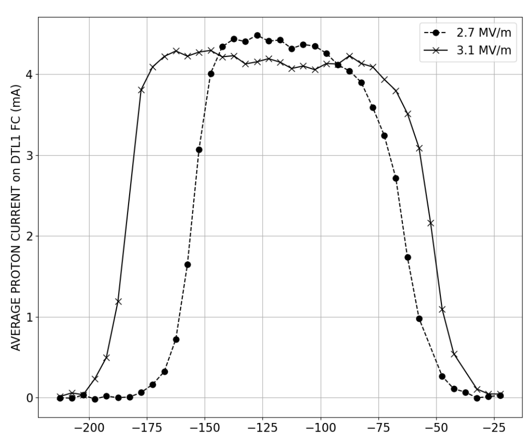

Figure 5: Average proton current measured by the DTL1 FC, as a function of the DTL1 RF phase, after two values of the accelerating DTL1 field.

Similarly to the DTL1 FC case, the DTL4 FC was installed in a dedicated shielding that allowed the tunnel access for maintenance during the DTL4 commissioning, and storage for four weeks at the end of the commissioning. MCNPX/CINDER90 [26] calculations were performed to determine the activation and residual dose rates before dismantling of the dump and its shielding. Figure 6 shows the computed neutron fluences and the residual dose rates in the region of the DTL4 FC shielding. During the routine checks, measurements confirmed the calculated dose value of 150 µSv/h at the shielding aperture close to the DTL4 exit. The central part of the shielding was made of carbon steel for shielding fast neutrons, whereas the outer part is made of concrete blocks arranged in a modular structure. The dismantling was possible after four weeks of decay, while the residual dose rate at 30 cm from the dump was about 1 mSv/h. Once the DTL5 is in place, it is planned to install a Faraday cup within the DTL4 intertank.

CONCLUSIONS AND OUTLOOK

This paper summarized the last five years of operations of the beam destinations during the commissioning of the ESS normal conducting linac. The devices acted as beam dumps and provided measurements in real-time of the proton current as well as the pulse length. Monte Carlo and thermo-mechanical simulations were key tools not only during the design phase, but also during the commissioning phase when it was not possible to actually measure the beam size, the beam emittance nor the beam energy. The simulations allowed to select high-strength, heat-resistant and radiation-resistant materials to withstand the demanding beam power density and the radiation environment. In particular, the DTL FCs had to be shielded in order to simultaneously allow the NCL commissioning and the SCL installation.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRC1I1

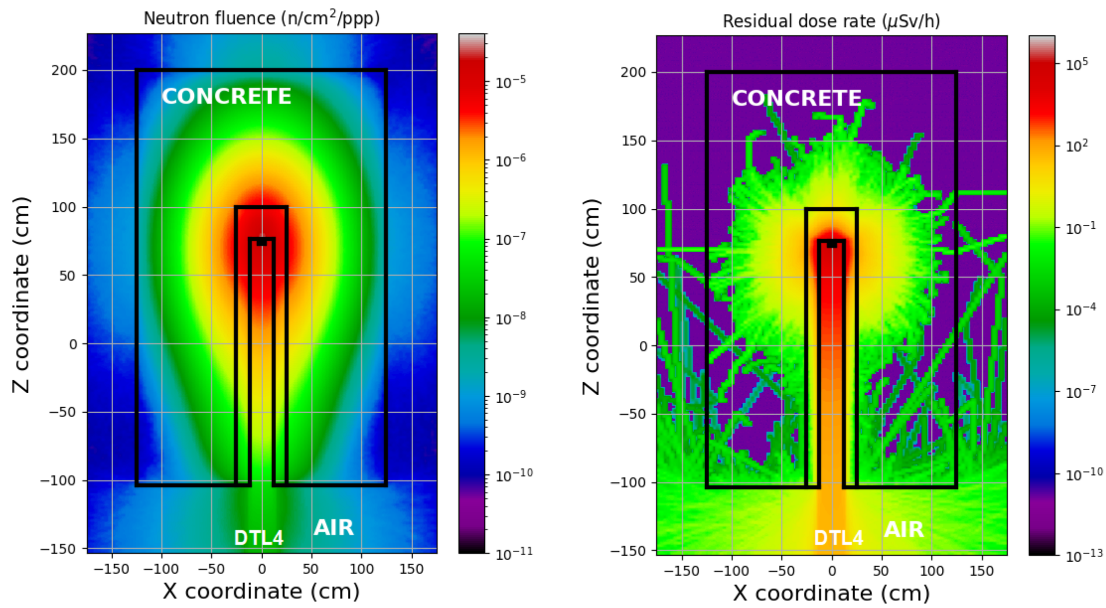

Figure 6: Calculated (left) neutron fluences after 74 MeV protons on the shielded DTL4 FC, and (right) residual dose rates after 50 hours of continuous beam on the DTL4 FC at the average current of 1 μA.

The control-system of all the Faraday cups relied on EPICS for the water cooling system, the high-voltage control, the motion in/out of the beam line, the timing synchronization and the data acquisition. The data analysis will continue and the current measurements will be compared with the beam current monitors upstream. The permanent installation of the DTL FCs in the compact DTL intertanks will require dedicated motion reliability tests and careful alignment.

Four Faraday cups will be permanently installed in the ESS proton linac in the decades to come: one in the LEBT, one in the MEBT, one in the DTL2 intertank and one in the DTL4 intertank. For all the FCs, preventive maintenance will include routine maintenance of the actuator, cooling system, cables and connectors in order to keep the devices up and running for decades and avoid costly linac downtime.

ACKNOWLEDGEMENTS

This work was performed at the European Spallation Source (ESS) in Sweden, in collaboration with many former or present colleagues in various ESS groups including: Beam Physics, Beam Diagnostics, Vacuum, Radiation Protection, Infrastructure, Integrated Control Systems, Mechanical Engineering, Operations, Rigging, Facility Management, Project Management, Alignment and Metrology, Procurement and Logistics, and the ESS Workshop.

The Monte Carlo simulations ran on the DMSC Computing Center in Denmark.

Special thanks go to all the collaborators at the two companies that manufactured the Faraday cups: Pantechnik in France for the LEBT and MEBT FCs; RadiaBeam Technologies in the USA for all the DTL FCs.

REFERENCES

[1] R.Garoby *et al.*, "The European Spallation Source design", *Phys. Scr.*, vol 93, p. 014001 (121 pages), 2018. doi:10.1088/1402-4896/aaecea

[2] N. Milas *et al.*, "Commissioning of the ESS front end", in *Proc. 64th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'21)*, Batavia, IL, USA, Oct. 2021, pp. 225–230. doi:10.18429/JACoW-HB2021-THDC2

[3] I. Bustinduy *et al.*, "Progress on ESS medium energy beam transport ", in *Proc. 27th Int. Linear Accel. Conf. (LINAC'14)*, CERN, Geneva, Switzerland, Aug.-Sep. 2014, pp. 484-486, https://accelconf.web.cern.ch/linac2014/papers/tupp025.pdf

[4] A. Sosa *et al.*, "Status of testing and commissioning of the MEBT of the ESS normal conducting linac ", in *Proc. 31st Int. Linear Accel. Conf (LINAC'22)*, Liverpool, UK, Sep. 2022, pp. 376–379. doi:10.18429/JACoW-IPAC2019-MOPTS084

[5] C. Plostinar *et al.*, "Status of the normal conducting linac at the European Spallation Source", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)* , Bangkok, Thailand, Sep. 2022, pp. 2019–2022. doi:10.18429/JACoW-IPAC2022-WEPOTK001

[6] F. Grespan *et al.*, "ESS Drift tube linac manufacturing, assembly and tuning", in *Proc. 12th Int. Particle Accel Conf. (IPAC'21)* , Campinas, SP, Brazil, Aug. 2021, pp. 1797–1800. doi:10.18429/JACoW-IPAC2021-TUPAB173

[7] Experimental Physics and Industrial Control System (EPICS), https://epics-controls.org

[8] A. Gorzawski *et al.*, "Commissioning of the timing system at ESS", in *Proc. 11th Int. Beam Instrum. Conf (IBIC'22)*,

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRC1I1

Krakow, Poland, Sep. 2022, pp. 281-285. doi:10.18429/JACoW-IBIC2022-TUP23

[9] *MCNPX Users Manual Version 2.7.0*, D. B. Pelowitz, Ed., Los Alamos National Laboratory, NM, USA, Rep. LA-CP-11-00438, 2011.

[10] ESS DMSC, https://europeanspallationsource.se/data-management-software-centre

[11] B. Cheymol *et al.*, "Conceptual design of the ESS DTL Faraday cups", in *Proc. 27th Int. Linear Accel. Conf. (LINAC'14)*, CERN, Geneva, Switzerland, Aug.-Sep. 2014, pp. 313-317, https://accelconf.web.cern.ch/linac2014/papers/mopp037.pdf

[12] T. Shea *et al.*, "Overview and status of diagnostics for the ESS project ", in *Proc. 6th Int. Beam Instrumentation Conf. (IBIC'17)* , Grand Rapids, MI, USA, pp. 8–15. doi:10.18429/JACoW-IBIC2017-MO2AB2

[13] E. M. Donegani *et al.*, "Status of the Faraday cups for the ESS linac", in *Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19)*, Malmö, Sweden, Sep. 2019, pp. 205–208. doi:10.18429/JACoW-IBIC2019-MOPP044

[14] B. Cheymol *et al.*, "LEBT FC functionalities", European Spallation Source, Lund, Sweden, Rep. ESS-0297532, Apr. 2018.

[15] Pantechnik, Z.I. 13 Rue de la Resistance 14400 Bayeux, France, Contact: contact@pantechnik.com

[16] R. Miyamoto *et al.*, "Highlights from the first beam commissioning stage at ESS for its ion source and low energy beam transport", *J. Instrum.*, vol. 15, p. P07027, 2020. doi:10.1088/1748-0221/15/07/P07027

[17] C. Derrez *et al.*, "Initial performance of the beam instrumentation for the ESS ion source and LEBT", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, Jun. 2019, pp. 2650–2653. doi:10.18429/JACoW-IPAC2019-WEPGW076

[18] L. Bellan *et al.*, "Space charge and electron confinement in high-current low-energy transport lines: experience and simulations from IFMIF/EVEDA and ESS commissioning", in *Proc. 31st Int. Linear Accel. Conf (LINAC'22)*, Liverpool, UK, Sep. 2022, pp. 618–622. doi:10.18429/JACoW-LINAC2022-TUPORI29

[19] A. R. Paramo *et al.*, "Design of the ESS MEBT Faraday cup", in *Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19)*, Malmö, Sweden, Sep. 2019, pp. 106–110. doi:10.18429/JACoW-IBIC2019-MOPP014

[20] ANSYS Inc., http://www.ansys.com/.

[21] RadiaBeam Technologies, LLC. 1735 Stewart Street, Suite A, Santa Monica, CA 90404, Contact: info@radiabeam.com

[22] E. M. Donegani *et al.*, "Design and performance of the compact DTL1 Faraday cup for the high-power ESS NCL", in *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1047, p. 167827, 2023. doi:10.1016/j.nima.2022.167827

[23] Y. Levinsen *et al.*, "First RF phase scans at the European Spallation Source", in *Proc. 11th Int. Beam Instrumentation Conf (IBIC'22)*, Krakow, Poland, Sep. 2022, pp. 313–317. doi:10.18429/JACoW-IBIC2022-TUP35

[24] Y. Levinsen *et al.*, "ESS Normal Conducting Linac Commissioning Results", presented at the 68th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams Conf. (HB'23), Geneva, Switzerland, Oct. 2023, paper TUA3I3, this conference.

[25] E. M. Donegani *et al.*, "Design and performance of the shielded DTL4 Faraday cup for the commissioning of the high-power proton linac", in *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1057, p. 168727, 2023. doi.org/10.1016/j.nima.2023.168727

[26] F. X. Gallmeier *et al.*, "The CINDER transmutation code package for use in accelerator applications in combination with MCNPX", in *Proc. ICANS XIX Conf.*, Grindelwald, Switzerland, Mar. 2010,