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Design and performance of the compact DTL1 Faraday cup for the high-power ESS NCL

E.M. Donegani [a,*], J. Cereijo-Garcia [a], S. Haghtalab [a], E. Laface [a], A. Olsson [a], L. Page [a], M. Ruelas [b], L. Zanini [a]

[a] *European Spallation Source ERIC, Partikelgatan 2, Lund, 224 84, Sweden*
[b] *RadiaBeam Technologies, 1717 Stewart St, Santa Monica, CA 90404, United States*

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ABSTRACT

The commissioning up to the first Drift Tube Linac section (DTL1) in the proton accelerator of the European Spallation Source (ESS) was successfully completed in July 2022. This paper deals with the design and performance of the compact beam dump for the DTL1 commissioning: the DTL1 Faraday Cup (FC).

MCNPX/ANSYS simulations were performed to optimize and validate the design of the beam dump. Special focus is on the results of thermo-mechanical simulations that ensured a safe absorption and dissipation of the volumetric power-deposition due to 21 MeV protons and in the order of MW/cm^3. As a result of the simulations, the operational limits and five proton-beam modes were defined to enable beam-dynamics studies with a proton current up to 65 mA, proton pulses up to 50 μs long, and repetition rate of either 1 or 14 Hz. The results of the first acceptance scan are presented. The low residual dose-rate in the vicinity of the beam dump (below 2 μSv/h, after 8 h of cooling time) allowed the relocation of the dump and its shielding the day after the commissioning was over, thus quickly continuing the installation of the other DTL sections.

1. Introduction

The European Spallation Source (ESS) in Lund (Sweden) is one of the largest science and technology infrastructure projects being built today. The ESS facility will rely on the most powerful linear proton-accelerator ever built, a rotating spallation target, 22 state-of-the-art neutron instruments, a suite of laboratories, and a supercomputing data management and software development centre [1]. The ESS accelerator high-level requirements are to provide a 2.86 ms long proton pulse at 2 GeV, with a repetition rate of 14 Hz. This corresponds to 5 MW of average beam power, with a 4% duty cycle on the spallation target [2]. A comprehensive suite of beam instrumentation and diagnostics [3] is supporting the commissioning of the normal-conducting linac (NCL) section of the ESS linac. The main NCL sections (and the corresponding proton energies) are: the ion source, the Low Energy Beam Transport line (LEBT, 75 keV), the Radio Frequency Quadrupole (RFQ, 3.6 MeV), the Medium Energy Beam Transport line (MEBT, 3.6 MeV) and the Drift Tube Linac section (DTL, up to 90 MeV). In July 2022, the commissioning up to the first DTL section (DTL1) was successfully completed [4]. This paper deals with the design and performance of the Faraday Cup (FC) that acted as beam dump at the end of the DTL1 section.

During the linac commissioning up to the DTL1 section, the main goals of the DTL1 FC were to fully stop the pulsed proton-beam and to measure the beam current ranging from 6 mA to 62.5 mA. The main requirements are: an accuracy in the proton-current measurement better than 10% and a time resolution better than 1 μs. Moreover, the proton-current measurement should be sampled at a rate of at least 10 MHz, with a bandwidth of at least 300 kHz. During the RF tuning of the DTL1, the DTL1 FC detected pulses up to 50 μs long, at repetition rates up to 14 Hz. Considering a maximum proton energy of 21 MeV and a maximum proton current of 62.5 mA, the peak power was 1.31 MW, with an average beam power up to 100 W. The complete list of the beam parameters are listed in Table 1. In this paper, the challenges in the design and manufacturing of the DTL1 FC will be summarized (in Section 2). In particular, the main challenge was to keep under control the thermally induced stresses especially for graphite components that are directly exposed to the proton beam. In fact, the tensile strength of graphite is 19 MPa and the compressive strength is 39 MPa. A safety factor of 1.5 was chosen, resulting in an allowable tensile stress of 13 MPa and an allowable compressive stress of 26 MPa. At the same time, the activation of the beam dump should be minimized, in order to allow access to the accelerator tunnel for maintenance in the NCL area, as well as for installation in the SCL area downstream. The results of activation and residual dose-rates calculations are reported in 2.2. Finally, the DTL1 FC control system and the first results of the DTL1 commissioning are summarized in Sections 3 and 4, respectively.

* Corresponding author.
E-mail address: elena.donegani@ess.eu (E.M. Donegani).

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Table 1
Beam parameters during the ESS DTL1 commissioning.

Parameter	Value
Proton energy	[21 ± 0.8] MeV
Proton current	[6, 62.5] mA
Pulse length	≤50 μs
Pulse rate	1 or 14 Hz
$FWHM_x$	9.81 mm
$FWHM_y$	2.56 mm
Peak power	1.31 MW
Average power	100 W

2. Design of the DTL1 Faraday cup

The ESS DTL1 Faraday cup was designed at ESS in Lund (Sweden), via thermo-mechanical simulations in MCNPX/ANSYS (par. 2.1). MCNPX/CINDER'90 simulations provided the activation levels and residual dose-rate after the exposure of the DTL1 FC to 21 MeV protons (par. 2.2). The manufacturing and assembly of the DTL1 FC was performed by the RadiaBeam company in Santa Monica (USA) [5]. The DTL1 FC is made up of two major components, namely the actual cup and its actuator system for insertion in the ESS linac beampipe.

The actual cup (Fig. 1) is composed of:

- An entrance foil and a collector, for stopping protons of non-nominal and nominal energies, respectively. The foil is 2.5 mm thick, while the collector is 7 mm tick; both components are made of graphite. The collector was isolated by alumina standoffs and a Shapal^{TM}-M disk that also provides a thermal path. The Shapal^{TM}-M material was selected because of its high heat conductivity and low specific electrical resistance [6].
- A bias ring between the foil and the collector that can be operated down to −1000 V, for preventing the contamination of the primary proton signal from secondary electrons. The repeller ring is isolated by alumina ceramic standoffs.
- A water-cooled copper body. A seamless stainless-steel tube was brazed into the copper body, so that there are no vacuum-to-water joints to fail under high pressure. Four threaded holes in the copper body avoid virtual leaks.

The modular design allows the replacement of the most critical components i.e. the foil and the collector. The DTL1 FC has an effective aperture diameter of 31 mm and a total length of just 26.56 mm, making it one of the most compact designs ever realized to the authors' knowledge. In fact, after the temporary installation within the DTL1 shielding, the device will be relocated in a DTL intertank where the available space is just 30 mm (along the z-axis, i.e. in the beam direction), thus requiring an extremely high precision in the motion and in the flatness of the front and rear surfaces. All the in-vacuum components have to operate in UHV conditions once permanently installed in the DTL intertank. All materials to be used in vacuum needed to be approved by ESS Vacuum team. In particular, plastics, non-water soluble machining lubricants, glues and greases are strictly prohibited. Only the highest-purity grade of copper (Oxygen-free, high thermal conductivity copper) is allowed for use as heat sink. The actuator system must hold the device in its position (either inserted or extracted) at any time, even if there is a failure in the air supply. The cup is actuated by a custom bellows-sealed pneumatic actuator. A rod-lock mechanism requires compressed air (max 8.6 bar) to allow the actuator motion. A loss of air pressure or electrical signals will result in the pneumatic cylinder being locked in its position. Three seconds are required to allow the rod-lock mechanism to be fully open. Two terminal blocks are included for all control and read-back signals with interfaces: one to the air-control valve for the pneumatic cylinder and for the rod-lock, and a second one to the machine protection system for the position and motion control. The limit switches are mechanically actuated by the movement of the bellows and thrust screws allow for independently-settable actuation points. Two limit switches are installed for the extracted position, whereas three limit switches (of which one redundant) are used for controlling the inserted position. Solenoid valves include flow-limiters on the exhaust ports to limit the actuation speed. The valves are configured for 5.5 bar pressure and can be adjusted if required.

During the DTL1 commissioning, the DTL1 FC was vertically installed in the dedicated shielding after the DTL1 and always locked in the inserted position in order to act as beam dump. The actuator stroke is 10 cm in length, with adjustable mechanical hardstops. The distance between the entrance flange and the beam axis is 41 cm. ISO bakeable knife-edge flanges (ConFlat type, 22 cm×13.8 cm) were used for UHV application, with a metal seal made of Oxygen-Free High thermal Conductivity (OFHC) copper. The vacuum feed-through hosts the signal cable, the HV cable for powering the bias ring, and the water pipes. The connector for the signal cable and for the HV cable are SMA and SHV-5, respectively. The water pipes for cooling the cup have an outer diameter of just 4 mm, with the inner diameter being of 2 mm where the cooling water circulates with a pressure of 6 bar. The cooling lines are made of stainless-steel (AISI-316). The electrical isolation of the water cooling lines was difficult but achieved by mounting the flange tube feed-through on a ceramic break isolator. In this way, it was possible to fully isolate the FC system using a dielectric tubing on the air-side in conjunction with low-conductivity water. The vacuum vessel and Faraday cup holder are made from high-quality, low-carbon stainless steel of the AISI-304L and AISI-316L varieties. The bellow is made from AM350 stainless steel for long-life. At the end of the assembly (Fig. 2), the DTL1 FC weights 25 kg and four main categories of tests were performed. A "hot" leak check and Residual Gas Analyzer (RGA) scan were performed to demonstrate vacuum compliance. Motion-repeatability tests were performed under vacuum, with the actuator cycled several hundred times and the repeatability demonstrated. The RGA scan excluded more than 1% hydrocarbon partial pressures for masses greater than 44 amu. A high-pot tester demonstrated the dielectric strength of the HV and signal readouts are sufficient. A hydrostatic leak-check was performed to show seamless sealing of the cooling joints. A 13 bar hydrostatic pressure was held for 20 min with no loss of pressure or visible leaks.

2.1. MCNPX/ANSYS for thermo-mechanical calculations

The scope of the DTL1 FC was to act as a beam dump throughout the duration of the DTL1 commissioning, ensuring a safe absorption and dissipation of the proton beam power. On one hand, the materials of a beam dump should have high specific heat capacity, high melting point, high strength and low thermal expansion. On the other hand, low Z materials are preferable because of the lower efficiency in producing secondary particles in intranuclear cascades. During the DTL1 commissioning in 2022, the maximum proton energy was in the [21 ± 0.8] MeV range and the proton current was up to 62.5 mA, making the corresponding thermal load the most severe one during the commissioning of the five ESS DTL sections. Considering the challenging beam power and the residual activity to be minimized, graphite was the only possible choice for the DTL1 FC components directly exposed to the proton beam i.e. the entrance foil and the collector. Therefore, a market survey was conducted, selecting in the end the extruded graphite C-00-FL-000160 type (with a density of 1.72 g/cm^3). All the graphite properties provided by the supplier are in Table 2, from [7]. Ahead of the device procurement, the graphite density was conservatively assumed to be 1.80 g/cm^3 in the simulations while aiming to procure graphite components with a density less than 1.80 g/cm^3. Given the average power to be dissipated (100 W), water cooling was necessary. The DTL1 FC relies on a single U-shaped water loop at the very back of the device, to avoid the direct exposure of the water to protons. Considering that the heat transfer had to be maximized, Shapal^{TM}-M and copper were chosen for the collector insulation and the FC body, respectively.

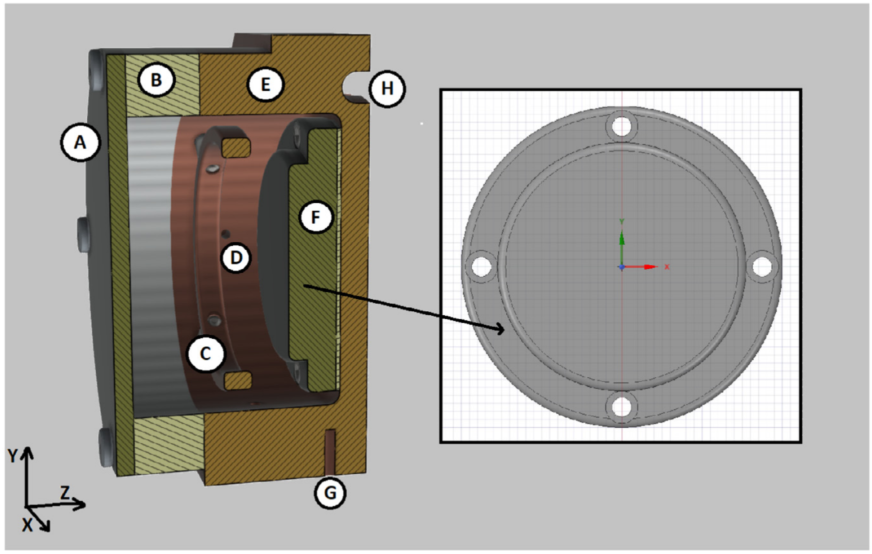

Fig. 1. A cross-section view of the actual cup in the DTL1 FC showing: (A) the 2.5 mm thick entrance foil, (B) the 1 cm thick copper spacer, (C) the bias ring, (D) one of the four threaded holes which are symmetrically located as if cardinal points, (E) the copper body, (F) the 7 mm thick collector whose front view is visible in the insert, (G) the location of one of the two bolts for mounting the cup on the actuator arm, and (H) the location of the cooling pipes. The total thickness of the cup (including the copper spacer) is 2.656 cm; the foil diameter and collector diameter are 6.0 cm and 3.1 cm, respectively. The proton beam flies from left to right, firstly passing through the foil, then in the middle of the bias ring and finally is stopped within the collector.

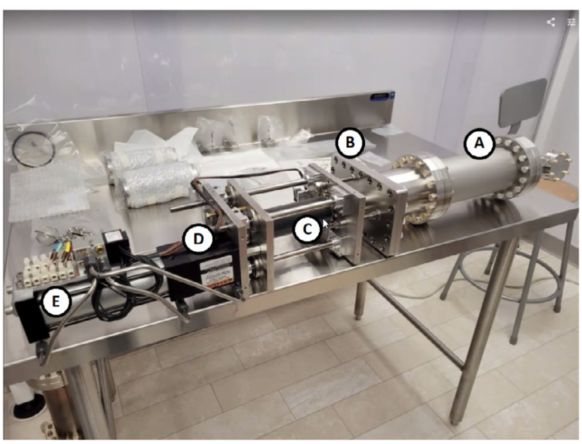

Fig. 2. The DTL1 FC after assembly at RadiaBeam. (A) Vacuum chamber enclosing the actual cup, (B) entrance flange, (C) bellow and flange tube feed-through, (D) rod-locking system and (E) piston. The overall height is 120 cm; the length and width are 25 cm and 15 cm, respectively, to fit in the holder within the shielding and (in the future) within the DTL intertank.

Table 2
Extruded graphite (C-00-FL-000160) properties for the foil and collector, as received from [7].

Property	Value
Average grain size	0.8 mm
Density	1.72 g/cm^3
Electrical Resistivity	7.8 - 9.5 μΩ m
Flexural Strength	19 MPa
Compressive Strength	39 - 40 MPa
Coeff. Thermal Expansion (293-473 K)	3.0 - 3.5 10^{-6}/K
Thermal Conductivity (293 K) parallel to grain direction	160 - 190 W/K/m
Thermal Conductivity (293 K) perpendicular to grain direction	130 - 140 W/K/m
Specific Heat Capacity (293 K)	830 J/kg/K
Ash content	≤800 ppm

The optimization and validation of the DTL1 FC design were performed with advanced numerical techniques in MCNPX/ANSYS simulations. The volumetric power deposition was computed with MCNPX (Monte Carlo N-Particle eXtended code [8]), in order to provide accurate input to thermo-structural simulations in ANSYS [9]. Given the cylindrical symmetry of the graphite–copper assembly, the volumetric power deposition was scored in just half of the device to halve the computational time. To further reduce the computational time, the MCNPX calculations ran on the cluster of the DMSC computing center in Copenhagen [10]. In particular, the 24 compute nodes of the so-called 'Newlong queue' were used to speed up the energy-deposition calculations. The nodes are DELL PowerEdge FC430 systems with two processors (Intel Xeon E5-2680 V4 2.4 Ghz with 14 cores each), a memory of 132 GB and one system disk (100 GB SAS 6 GBPS). The maximum wall time is seven days. The 10 Gb/s Gigabit Ethernet controller is used for management, whereas the QLogic HPA InfiniBand controller is used for production interconnect. On a standard laptop the energy deposition calculations would have taken weeks, whereas with the 24 DMSC nodes the calculations were generally shorter than 24 h.

Four particle types were transported in MCNPX: neutrons, protons, photons and electrons without energy cut-offs. In general, when protons interact with matter, they lose their energy either with the nuclei or the electrons of target atoms. In the case of MeV protons, the nuclear stopping in a solid target is about a factor 10^{-3} less than the electronics stopping. The proton beam was assumed to be monochromatic (with 21 MeV energy). The source type is Gaussian with the smallest possible beam sizes for the DTL1 FC installation point: σ_x = 9.81 mm and σ_y = 2.56 mm. In fact, a beam pipe of 1 meter connects the DTL1 section to the actual location of the DTL1 FC, thus the beam cannot have smaller beam sizes than σ_x and σ_y according to the results of beam dynamics simulations.

The five loading cases of interest for the DTL1 commissioning are listed in Table 3 which includes all the relevant beam parameters. In particular, the cases A-B-C are the standard conditions, while the cases D-E are two potential incidents at the minimum and maximum proton current, respectively. Such incidents would imply that just one pulse of 100 μs could reach the DTL1 FC due to a failure of the LEBT chopper upstream. The volumetric power density was mapped in MCNPX simulations, within the entrance foil and the collector; no mesh was setup in the other structural components, since the 21 MeV

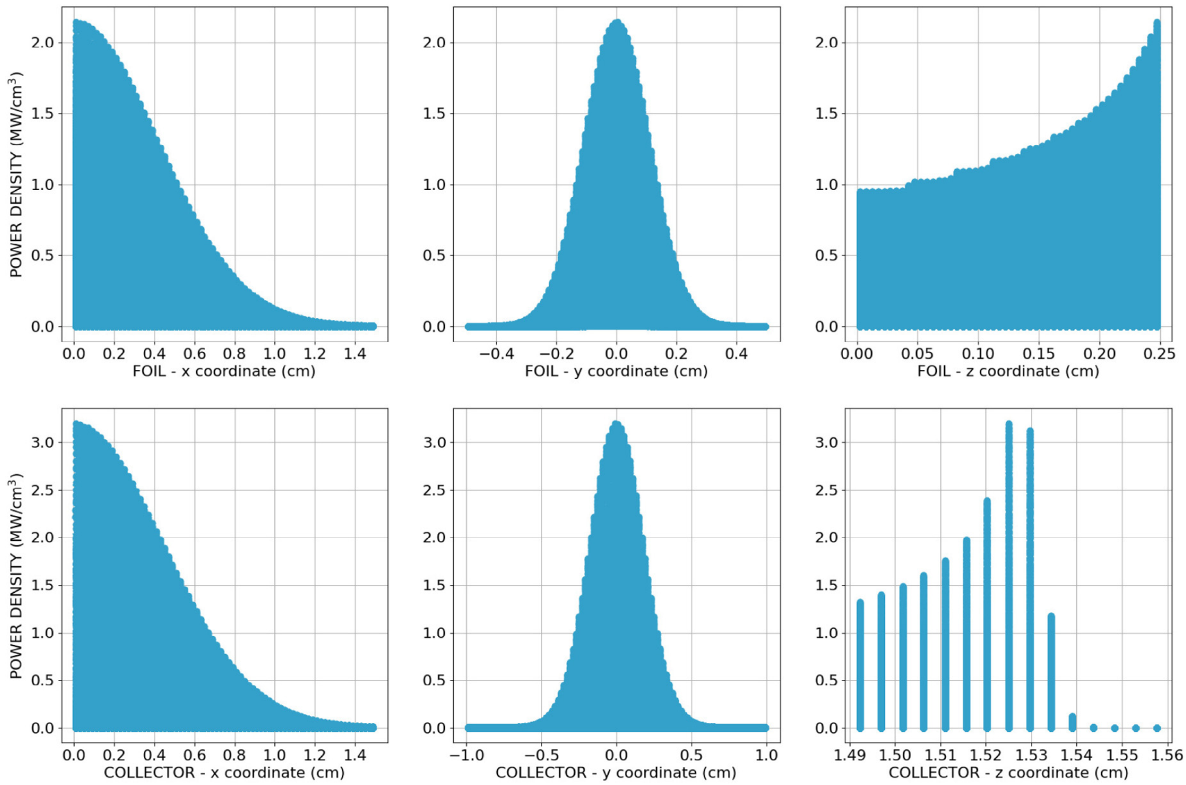

Fig. 3. Volumetric power density, projected within the DTL1 FC foil and collector (after 21 MeV protons, 65 mA current, σ_x = 9.81 mm and σ_y = 2.56 mm). The coordinate system is the same as in Fig. 1, with the *z*-axis being the beam direction, with the *x*-axis and the *y*-axis having positive numbers in the first quadrant while facing the ESS target.

Table 3
Beam parameters on the DTL1 FC, as input to MCNPX/ANSYS simulations: three standard cases (A-B-C) and two potential incidents (D-E).

	Current I (mA)	Pulse length Δt (μs)	Repetition Rate (Hz)	Beam size σ_x (mm)	Beam size σ_y (mm)
A	65	5	14	9.81	2.56
B	65	50	1	9.81	2.56
C	65	20	1	9.81	2.56
D	6	100	–	9.81	2.56
E	65	100	–	9.81	2.56

protons are fully stopped in the collector, with a total range of 3 mm in graphite. A margin of 4 mm is left between the Bragg peak and the end of the collector. The minimum voxel size is 50 μm, whereas the maximum voxel size is 200 μm. The error on the calculated energy deposited in the voxels is less than 3 %. The projections of the volumetric power density in *x*, *y* and *z* are shown in Fig. 3, within the foil and the collector. It can be noticed that the power density is greater in the collector with respect to the foil. The maximum power density in the collector is 3.20 MW/cm^3, while it is 2.15 MW/cm^3 in the foil, assuming a proton current of 65 mA. The energy deposited by the proton beam induces a local temperature rise after few microseconds, and in turn rapid thermal expansions and thermally-induced stress on the DTL1 FC components. For the temporary installation of the DTL1 FC within the shielding (where there are no space constraints as tight as in the DTL2 intertank), a spacer made of copper (10 mm thick) was included, to further reduce the volumetric power density onto the collector.

The results of MCNPX simulations were post-processed in ANSYS:

- Transient thermal simulations post-processed the MCNPX results for the beam power densities, in order to determine the corresponding temperature evolution over time.
- Quasi-static structural simulations loaded the ANSYS transient temperature results, in order to calculate the corresponding volume changes and the (von Mises equivalent, tensile and compressive) stresses.
- Steady state simulations to determine the thermal equilibrium, after which the peak temperature remains constant over time.

For copper and stainless steel components the default properties in ANSYS are used (see Table 4), without temperature-dependency due to the fact that there is no relevant temperature increase in copper nor in stainless steel components. The following considerations should be given regarding the graphite properties implemented in ANSYS:

- The specific heat does not vary between different graphite types, therefore the same values as in [11] for the ESS MEBT FC were implemented. Increasing values of the specific heat with increasing temperature values were taken into account in the ANSYS calculations, ranging from 824.29 J/kg/°C at 18.5 °C up to 1927.8 J/kg/°C at 1000 °C.
- The density variation with temperature is negligible, therefore no temperature variation is considered.
- The strength increase with temperature is negligible for the DTL1 FC temperature, therefore no change in the flexural and compressive strength with temperature is included.
- A maximum tensile stress of 13 MPa, as well as a maximum compressive stress of 26 MPa, are the evaluation criteria at the end of stress calculations.
- A temperature-dependent coefficient of thermal expansions was set with a conservative value of 3.5 $\cdot 10^{-6}$/°C at 200 °C, 4 $\cdot 10^{-6}$/°C at 500 °C and 4.5 $\cdot 10^{-6}$/°C at 900 °C.
- The thermal conductivity depends on the grain direction which is not known. However, considering that the heat is spread in all directions, it was opted for an average value of the lower bound for the two grain directions which is 145 W/mK at room temperature. Temperature-dependent and decreasing values of

Table 4
Properties for copper and stainless steel used in the ANSYS calculations.

Property	Value Cu	Value SSL
Density	8.3 g/cm^3	7.8 g/cm^3
Coeff. Thermal Expansion	18 $\cdot 10^{-6}$ /K	17 $\cdot 10^{-6}$ /K
Thermal Conductivity	401 W/K/m	15.1 W/K/m
Specific Heat	385 J/K/m	480 J/K/m

Table 5
Maximum temperature and equivalent (von Mises) stresses computed for the DTL1 FC foil and collector. The values (in MPa) within square brackets are negative (for the compression) or positive (in tensile). The stress in the vessel is negligible thus not listed.

	T^{max}_{foil} (°C)	T^{max}_{coll} (°C)	Stress (MPa)
A	95	120	Within allowable
B	477	615	[−30, 4.3]
C	240	317	Within allowable
D	135	150	Within allowable
E	805	1030	[−55, 8]

the thermal conductivity were implemented up to 1800 °C, for which the thermal conductivity is 31 W/mK.

- The Poisson ratio is 0.13.
- The Young's modulus for the graphite type of interest is not known, so a value of 11.5 GPa is conservatively assumed. The increase with temperature is expected to be moderate for temperatures below 1000 °C.

The cooling water temperature is conservatively assumed to be 35 °C, which is used as the ambient temperature at the pulse start. The heat conduction mainly occurs in the contact close to the clamping bolts sticking the collector to the copper body. The cooling pipes were brazed in a vacuum surface, therefore perfect contact is assumed in ANSYS simulations. The water flow is 1.2 m/s, with a corresponding heat transfer coefficient of 9 kW/m^2/ K [12]. The resulting maximum temperature values in the entrance foil and in the collector are provided in Table 5. In general, the temperature rise is greater in the collector than in the foil. Peak temperature of 1030 °C are found after just one 100 μs long pulse at the maximum proton current (case E). Such temperature value is well below the sublimation point of graphite, however the maximum compressive stress (of 55 MPa) in the collector would not exclude permanent deformation of the collector surface. Such incident did not occur during the DTL1 commissioning, but the MCNPX/ANSYS results predicted that such scenario would have been destructive for the DTL1 FC graphite components. On the contrary, a pulse of 100 μs and 6 mA current (case D) could be sustained. Case A is well below the engineering limits, therefore it is deduced that also 65 mA, 5 μs at 1 Hz is feasible. Case B is also expected to induce either permanent deformations or fracture of the collector, therefore the maximum pulse duration recommended during the commissioning is 20 μs when sending a 65 mA proton current at 1 Hz onto the DTL1 FC (case C). Table 5 points out the two cases (B and E) for which significant stresses are anticipated. In all the other cases (A-C-D), both maximum tensile stress and the compressive stress are below the evaluation criteria previously mentioned in this section. The results in Table 5 collect the impact of just one pulse; the impact of subsequent pulses was investigated and it was concluded that the steady-state is reached after 90 s, with an increase of the maximum temperature of 5–10 °C degrees with respect to the peak values written in Table 5.

2.2. MCNPX/CINDER'90 for activation and dose calculations

The materials of the components of the DTL1 FC were chosen not only to cope with the high-power proton-beam, but also to minimize the activation of the DTL1 FC itself and the residual dose nearby.

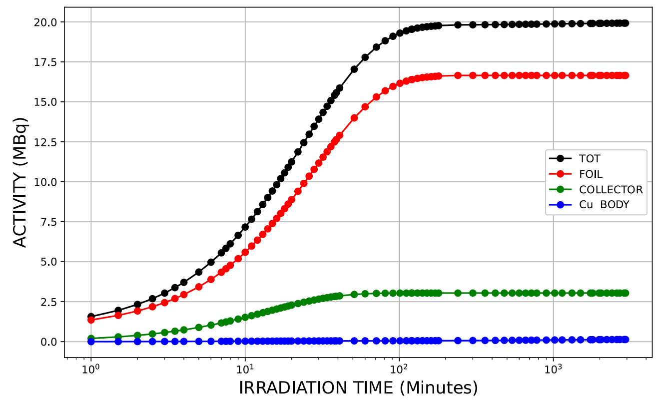

Fig. 4. Activation of the DTL1 FC components as a function of the irradiation time, assuming 21 MeV protons and an average current of 0.3 μA/h.

The activation of the DTL1 FC components was calculated in MCNPX/CINDER'90, following the method in [13]. The activation as a function of the irradiation time with 21 MeV protons are shown in Fig. 4, assuming an average beam current of 0.3 μA/h. The most activated component is the entrance foil, followed by the graphite collector and then the copper body.

The most abundant radionuclides are:

- In the graphite foil and collector: ^{3}H, ^{7}Be and ^{11}C.
- In the copper body: ^{3}H, ^{60}Co, ^{63}Ni and ^{64}Cu.

The total activation reaches saturation about five hours after the start of the proton irradiation. In order to allow daily maintenance and rapid access to the NCL area, as well as installation in the SCL area downstream, the DTL1 FC was surrounded by a dedicated radiation shielding (Fig. 5). The DTL1 FC shielding consisted of a carbon-steel core, surrounded by concrete blocks as outermost layer, with overall dimensions in (x × y × z) being (224 cm × 200 cm× 275 cm). The shielding structure is modular to facilitate installation, dismantling and expansion for other ESS beam dumps in future commissioning phases. While the beam was on and sent to the DTL1 FC, no one was allowed to access the tunnel. In the first set of dose calculations, it was assumed a commissioning period of 100 days with average current of 1 μA/h, leading to the following results:

- a residual dose rate of 10 mSv/h at contact of the FC, after no decay time,
- a residual dose rate below 1 μSv/h at 30 cm from the outer shielding surfaces, after no decay time.

During the commissioning, the measurements by the ESS Radiation Protection group confirmed that the dose was always below 1 μSv/h at 30 cm from the outermost surfaces of the shielding. In a second set of dose calculations, the residual dose-rate in the vicinity of the DTL1 FC were calculated after the actual irradiation time during the DTL1 commissioning: a total of 100 h at 0.03 μA/h during the first commissioning period, followed by a total of 40 h at 0.3 μA/h in the second and last phase. The residual dose-rate as a function of the decay time is shown in Fig. 6. Two main decay phases can be noticed:

1. A fast decay phase: in the first 4 h of decay and mainly due to ^{11}C.
2. A slow decay phase: due to long-lived isotopes and mainly due to ^{3}H, ^{60}Co and ^{63}Ni.

It can be noticed that the residual dose-rate is below 2 μSv/h after 16 h from the end of the commissioning, thus allowing the relocation of the DTL1 FC in its shielding and proceeding with the NCL installation the day after the DTL1 commissioning was over.

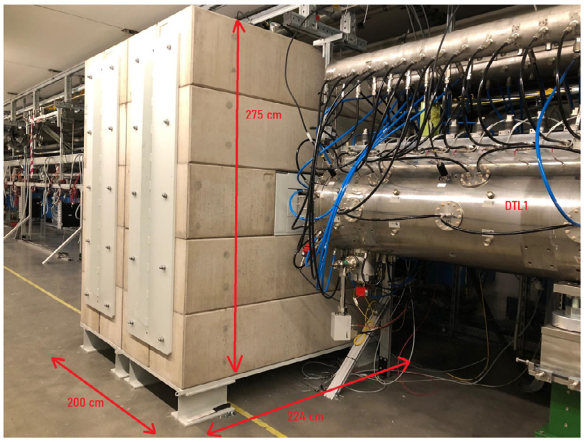

Fig. 5. The DTL1 FC shielding installed in the ESS accelerator tunnel.

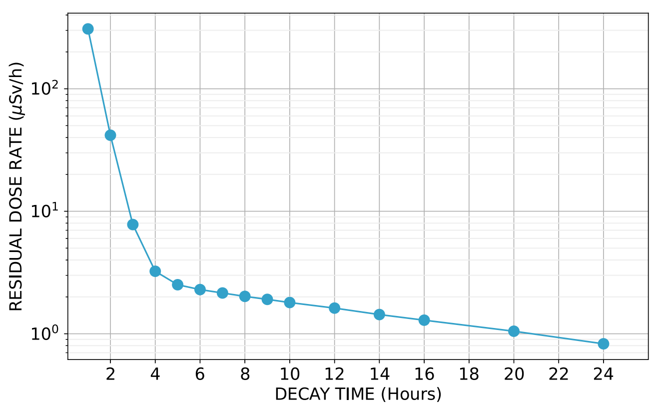

Fig. 6. Residual dose-rate around the DTL1 FC as a function of the decay time, at the end of the DTL1 commissioning.

3. Control system

The DTL1 FC control system relies on EPICS (Experimental Physics and Industrial Control System, in the e3 environment), which is a set of Open Source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments such as a particle accelerators, telescopes and other large scientific experiments [14].

The Micro Telecommunications Computing Architecture (μTCA) is the adopted technology for high speed processing and communication interfaces, being the μTCA Channel Hub (MCH) the fundamental module. The DTL1 FC control system includes three IOCs for Input/Output Control (IOC):

1. The EVR-IOC: to trigger the Struck board with the RTM module for the proton-current measurement. The ESS has a timing system that provides high-precision synchronization of the distributed control systems to ultimately achieve coordinated operation of the accelerator, target and neutron instruments.
   The timing system is synchronized to the accelerator power sources, broadcasting operational data, timestamps and trigger events to a large number of receivers including the DTL1 FC, with a deterministic nano-second accuracy.
2. The DAQ-IOC: to control the data acquisition (DAQ) for the proton-current measurement. The DAQ-IOC is synchronized to the ESS timing system through the EVent Receiver (EVR). The timing triggers are sent from the EVR to the Struck board. The acquisition engineering interface is the ADSIS8300 digitizer.

Table 6
Allowed beam modes on the DTL1 FC (with C = Commissioning, and T = Tuning).

Mode	Current (mA)	Pulse (μs)	Rate (Hz)
PROBE	6	5	1
FAST-C	6	5	14
RF-TEST	6	50	1
SLOW-C	65	5	1
FAST-T	65	5	14
SLOW-T	65	20	1

3. The MHV-IOC: to control the FC motion as well as the power supply for biasing the repeller ring. It also reads the status of the water-temperature and flow.
   The water temperature is measured on the cooling pipe exiting the cup with a PT100 sensor by Pentronic (Model 7400000, class A) that is connected with a PUR cable which is halogen free, flame and abrasion resistant. The water flow is also measured on the return, with Dk37-M8M -R-K1-SK by Krone. The MHV-IOC relies on the EtherCAT technology. The MHV-IOC does not have an interface with the EVR-IOC.
   Motion control utilities are based on Beckhoff modules and are controlled by the MHV-IOC, communicating with the EtherCAT master hosted by the μTCA CPU.

The EtherCAT crate is daisy chained with the other three Faraday cups in the ESS NCL, and connected to the concurrent CPU where the MHV-IOC runs. The DTL1 FC has external interfaces with:

- The NCL Vacuum system. An interlock between the DTL1 FC HV and the vacuum level prevents the operation of the DTL1 FC HV power supply in case there is no UHV.
- The Machine Protection System for the motion permission, as well as the interlocks on the water temperature and water flow.

The OPerator Interfaces (OPIs) in the ESS Main Control Room are developed in Phoebus, with three main OPI levels:

1. Operator OPI: including real-time display of the measured proton pulse, the history trend of the minimum, average and maximum current, and also the overall status of the cooling system.
2. Machine-Expert OPI: including details on the water cooling system, the motion control and actuation, and the HV settings.
3. Engineering OPIs: including all the DAQ settings and mainly intended for debugging.

Following the MCNPX/ANSYS results (in Section 2), and also because of the fact that no measurements of the beam sizes were performed in real-time, the operational limits were defined for the DTL1 FC. The full list of allowed beam modes during the DTL1 commissioning can be found in Table 6.

4. Commissioning results

The commissioning up to the DTL1 FC started on the first day of June 2022 at ESS. All the commissioning results are saved in the .hdf5 format in Jupyterlab and analyzed in Python (version 3.7.12). A pilot beam of (3 mA, 5 μs, 1 Hz) was sent and detected in the DTL1 FC.

The proton beam current was readily ramped up in steps of 5–10 mA to the maximum on the first day of July 2022. The historical plot with the peak current on the DTL1 FC, as a function of the time, is visible in Fig. 7. During the ramp-up period, the rise in the beam line pressure due to additive outgassing from the heated beam pipe and FC had no effect on the line pressure. The temperature of the DTL1 FC cooling water remained below 21 °C during the ramp-up as well as throughout the commissioning period.

During the overall ESS DTL commissioning, the cavity RF field amplitude and phase must be set to the design value for each DTL section.

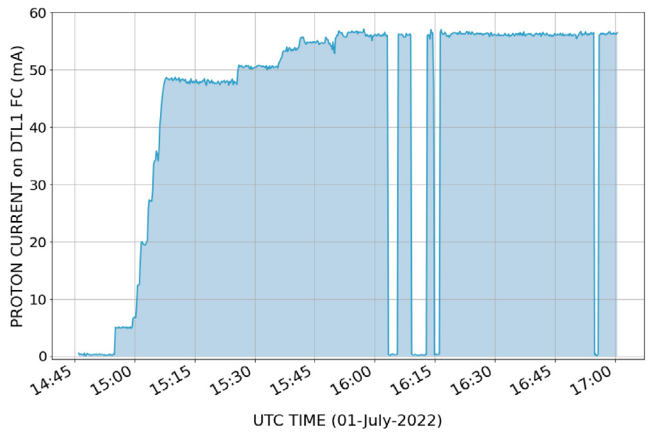

Fig. 7. First current ramp-up on the DTL1 FC, as a function of the time.

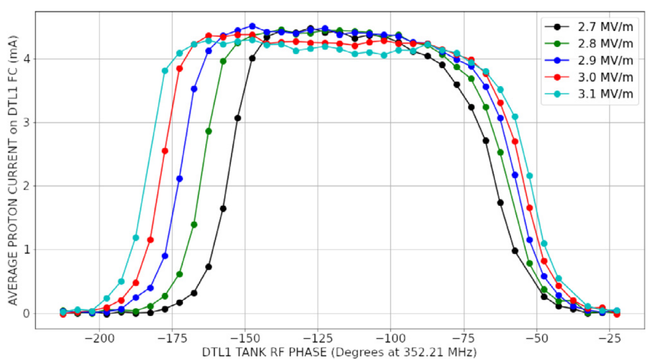

Fig. 8. Average proton current measured by the DTL1 FC, as a function of the DTL1 RF phase, with five different values of the electric field between 2.7 and 3.1 MV/m.

The acceptance scan is one of the possible methods to determine the set points [15], by exploiting the entrance foil of the DTL1 FC. In fact, in addition to increase the beam size at the collector, the entrance foil is also useful to stop those particles not accelerated by the DTL1 cavities. From MCNPX simulations, it is known that the entrance foil indeed acts as an energy degrader, stopping protons with energy less than 20.3 MeV. This ensures that phase and amplitude scans are measured without interference from not properly accelerated protons.

Fig. 8 shows the result of the very first acceptance scans performed with the DTL1 FC, with five different values of the electric field in the DTL1, between 2.7 and 3.1 MV/m. More information on the accelerating field requirements can be found in [16]. In Fig. 8 it can be noticed that the higher the amplitude of the electric field, the larger the phase. In the next commissioning phase, the acceptance scans will be repeated when the DTL1 FC will be installed in the DTL2 intertank; the results will be compared with the model from multi-particle simulations as well as with phase scans performed with other beam diagnostics devices upstream the DTL1 FC.

5. Conclusions and outlook

The commissioning of the ESS proton accelerator started in 2018; the commissioning up to the first ESS DTL section occurred in June and July 2022. The DTL1 Faraday cup was a key device during the DTL1 commissioning, acting as beam dump, measuring the proton current and contributing to the first acceptance scans. No incidents nor failures of the DTL1 FC system and its shielding occurred during the DTL1 commissioning. In view of the future 24/7 operation of the ESS accelerator, critical spare components will be procured as well as an entire spare device will be produced and stored if a quick replacement will be needed. In this paper, the design of the DTL1 FC was detailed. The actual cup is compact (less than 27 mm in thickness) and made of a copper–graphite assembly. The DTL1 FC was installed under UHV in a vacuum pipe connected to the DTL1, locked in the inserted position and within a dedicated shielding. The DTL1 FC detected 21 MeV protons with current up to 62.5 mA; the average power of the proton beam was up to 100 W. The DTL1 FC was designed and optimized at ESS in Lund via MCNPX/ANSYS simulations, in order to guarantee the integrity and functionality while dumping the high power ESS proton beam, with volumetric power densities in the MW/cm^3 order.

The DTL1 FC as well as spares of critical components were manufactured by RadiaBeam in the USA. Low activation and residual dose-rates were predicted in MCNPX/CINDER'90 calculations, allowing quick access to the tunnel for maintenance during the commissioning, as well as the uninstallation of the DTL1 FC and its shielding right after the end of the DTL1 commissioning.

In view of the next ESS commissioning phase up to the DTL4 section, the diagnostics device will be relocated within the DTL2 intertank. Given the permanent nature of the installation and also the higher proton energy in the DTL2 intertank (i.e. 39 MeV protons, which lead to lower beam power density with respect to 21 MeV protons, while considering the same beam size), the entrance foil and the collector will be replaced and manufactured of SIGRAFINE® R7550 [17]. In particular, such type isostatic and fine grain graphite was chosen especially for its higher density (to keep the compact size of the collector), high purity, long-term stability and the repeatability of the manufacturing process that will be necessary for spare items to be produced in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] The European Spallation Source, available at https://europeanspallationsource.se.
[2] R. Garoby, et al., The European spallation source design, Phys. Scr. 93 (2018) 0140011, 21 pp.
[3] T. Shea, et al., Overview and status of diagnostics for the ESS project, in: Proc. of IBIC17, Grand Rapids, MI, United States, 2017, p. MO2AB2.
[4] C. Plostinar, et al., Status of the normal conducting Linac at the European spallation source, in: Proc. IPAC 2022, Bangkok, Thailand, 2022, WEPOTK001.
[5] RadiaBeam Technologies, LLC. 1735 Stewart Street, Suite A, Santa Monica, CA 90404, Contact: info@radiabeam.com.
[6] P. Strehl, Beam instrumentation and diagnostics, in: Particle Acceleration and Detection Serie, Springer, Darmstadt, 2006.
[7] Carbon (graphite) - C-00-FL-000160 batch 9, GoodFellow datasheet, 2022.
[8] D.B. Pelowitz (Ed.), MCNPX Users Manual Version 2.7.0, LA-CP-11-00438, 2011.
[9] ANSYS (version 2019.R1), available at http://www.ansys.com.
[10] The ESS DMSC (Data Management and Software Center of the European Spallation Source), available at https://https://europeanspallationsource.se/data-management-software-centre.
[11] I. Bustinduy, et al., Design of the ESS MEBT Faraday cup, in: In: Proc. IBIC 2018, Malmoe, Sweden, 2018, p. MOPP014.
[12] J.P. Holman, Heat Transfer, eight ed., McGraw-Hill, New York, 1997.
[13] F.X. Gallmeier, et al., The CINDER transmutation code package for use in accelerator applications in combination with MCNPX, in: Proc. ICANS XIX Conference, 2010.
[14] EPICS - Experimental Physics and Industrial Control System, available at https://epics.anl.gov/.
[15] A.W. Chao, et al., Handbook of Accelerator Physics and Engineering, World Scientific, Hackensack, 2013.
[16] R. De Prisco, ESS dtl RF modelization: Field tuning and stabilization, in: Proc. IPAC 2013, Shangai, China, 2013, p. THPWO070.
[17] SIGRAFINE® R7550 datasheet, 2022, available at https://www.sglcarbon.com/pdf/SGL-Datasheet-SIGRAFINE-R7550-EN.pdf.