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DEVELOPMENT OF A FARADAY CUP FOR THE FETS-FFA

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Abstract

The proposed FETS-FFA would exhibit high-intensity operation of a Fixed-Field Alternating Gradient (FFA) accelerator, as a demonstrator for a spallation neutron source driver. Faraday cups are planned to be installed in the injection straight to investigate injection efficiency and infer beam-position during early commissioning stages; and in the extraction line to inspect extraction efficiency. The chosen Faraday cup design must be suitable for the 3 - 12 MeV proton energy range, the average beam power of the FETS Linac and the FETS-FFA's extracted beam.

Thermal aspects of this design will be introduced, including cooling water flow-rate calculations and an approximate method of simulating this flow with equivalent convective cooling. The 3D tracking for a secondary electron suppressor will also be presented, as well as calculations to estimate the required suppression voltage.

INTRODUCTION

ISIS-II is a proposed MW-class pulsed neutron and muon source currently in the design phase, with three options being considered for its driving accelerator: a Rapid Cycling Synchrotron (RCS), a high-energy linear accelerator with an accumulator ring (AR), and a Fixed-Field Alternating Gradient (FFA) accelerator [1]. RCS and AR machines have already demonstrated MW operations [2, 3], but the FFA option has not. The FETS-FFA (Front End Test Stand - FFA), has therefore been proposed to demonstrate aspects of high-intensity operation of an FFA, using its beams of 3-12 MeV protons [4].

As with the RCS and AR options, charge-exchange injection will be used to inject a beam of H^- ions into the FFA ring through a stripper foil. A Faraday cup (FC) has been proposed to measure injection efficiency and align the beam during commissioning. A second FC in the extraction line has also been proposed to measure extraction efficiency. The feasibility of producing a FC that is suitable for both the injected and extracted beams will be studied in this paper.

This study has focused on two challenging aspects of FC design: managing the heat load imparted by the incident proton beam, and emission of low-energy secondary electrons which can cause systematic measurement errors.

MATERIAL AND GEOMETRY

Copper has been chosen for the FETS-FFA FC, because of its good thermal and electrical properties (see Table 1), as well as its relatively low secondary electron yield (SEY) [5]. A schematic of the cross-sectional view of the FC's geometry is shown in Fig. 1. A conical cutout has been adopted to reduce secondary electron emission (SEE) [7] and to spread heat load over a larger volume. The copper will have a minimum thickness of 5 mm, which was found from SRIM simulations [8] to prevent almost all 12 MeV protons from penetrating through the cup.

Table 1: Copper Properties Close to Room Temperature [6]

Thermal Conductivity [W/cm/K]	4.01
Electrical Resistivity [10^{-8} Ωm]	1.725
Specific heat capacity [J/g/K]	0.385
Melting point [°C]	1084.62

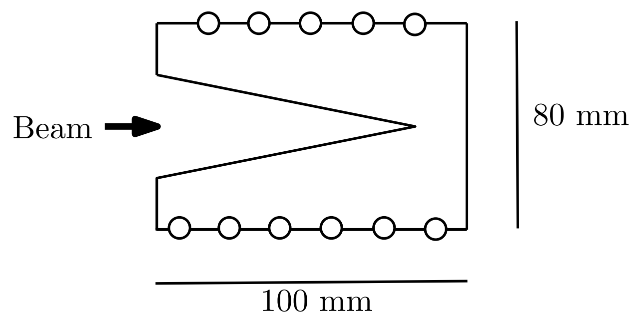

Figure 1: Schematic cross-section of the FC model, with the beam directed into a conical cutout. Circles represent pipes for cooling water wrapped around the outer cylinder.

THERMAL ANALYSIS

The maximum instantaneous temperature rise of the FC due to thermal load imparted by the beam was calculated, as well as its steady-state temperature. The latter of these was found using the steady-state thermal simulation of ANSYS Mechanical (2024 R2 version) [9].

Instantaneous Temperature Rise

The real-space transverse distribution of the FETS beam was assumed to be a round, 2D Gaussian with $\sigma_x = \sigma_y = 1.5$ mm. The peak energy density was estimated using the product of maximum protons density for a single injected pulse (i.e. 2.12×10^{10} protons/mm^2) and peak stopping power per ion (dE/dx/ion) obtained from SRIM. The temperature rise due to a single injected pulse inside the FC was calculated using

$$\Delta T = \frac{E'}{\rho c}, \tag{1}$$

with E' as highest energy density, ρ being material density and c as the specific heat capacity. The calculated temperature rises, listed in Table 2, suggest that if the diffusion

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Table 2: Highest Energy Density and Maximum Instantaneous Temperature Rise in Copper Resulted From the Impact of Single FETS Beam Pulse

	3 MeV	**12 MeV**
Highest Energy density [J/mm^3]	0.585	0.331
Maximum Temperature rise [ΔK]	170.07	96.34

of heat through the cup's volume is neglected, the melting temperature of copper would be reached in around 6 injected pulses. Options for active cooling were therefore explored.

Steady-state Temperature Rise

Water cooling is often used on Faraday cups, but different methods have been used to thermally couple the coolant pipes to the FC body. The increased surface area of a helical pipe, wrapped around the outside of the cup, provides a better thermal contact than a pipe mounted at the back of the cup. The helical cooling pipes that have been chosen for this FC are shown schematically in Fig. 1. This geometry has been modelled in the ANSYS Steady State Thermal Solver, with the water cooling modelled with an equivalent convective heat sink.

To simulate the flowing water as an equivalent convective cooling, the cooling pipes are not included in the geometry, and instead a cutout was made where the water is expected to flow. To calculate the equivalent convection coefficient, the Reynolds and Nusselt numbers were first determined [10].

The Reynolds Number (Re) represents a ratio of inertial to viscous forces within fluid and is defined as

$$Re = \frac{\rho v D}{\mu}, \tag{2}$$

with v as the water flow rate, D as inner diameter of tube, μ being viscosity of coolant.

The Nusselt Number (Nu) is a ratio of the total heat transfer to conductive heat transfer at a boundary in a fluid, and was calculated using the following equations [10]

$$Nu = \left[\left(3.66 + \frac{4.34}{a}\right)^3 + 1.16\left(\frac{Re\,(D/C)^{1/2}}{b}\right)^{3/2}\right]c, \tag{3}$$

where,

$$a = \left(1 + \frac{927(C/D)}{Re^2 Pr}\right), b = \left(1 + \frac{0.48}{Pr}\right), c = \left(\frac{\mu}{\mu_s}\right)^{0.14}, \tag{4}$$

C is bend diameter of helical tube and Pr is the Prandtl number [10].

Convection coefficients (h) were estimated for various pipe inner diameters (see Fig. 2) using

$$h = \frac{Nuk}{D}, \tag{5}$$

where the thermal conductivity of water at 295 K, k is taken to be 0.606 W/m/K, $Pr = 6.62$, $C = 80$ mm and $\mu = \mu_s$ was assumed [10].

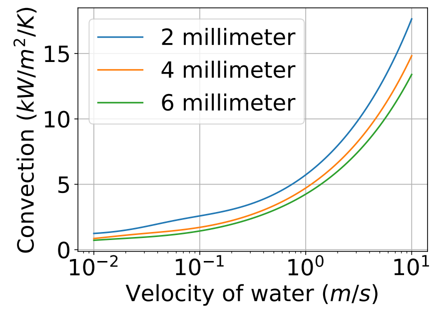

Figure 2: Convection coefficients for three inner diameters.

A transverse Gaussian beam distribution was modelled by defining annular regions with heat flows based on the particle density. The sum of these heat flows was equivalent to the overall heat contribution from the FETS beam of 32 W. The radii of these regions, listed in Table 3, were selected to contain specified fractions of the total beam. The innermost regions were made more dense to improve accuracy where the peak temperature was expected.

Table 3: Percentage of Particles Used to Define the Heat-Flow Segment Radii

Particles [%]	**Radial range [mm]**	**Heat flows [W]**
5	0 - 0.5	1.6
12	0.5 - 1	3.84
20	1 - 1.5	6.4
63	1.5 - 4.5	20.16

Initial and ambient temperatures were specified as 22 °C and 35 °C respectively, which is considered conservative. Simulation results for each inner pipe diameter, and different numbers of cooling pipe turns are listed in Table 4. Even with an inner diameter of 2 mm, a flow rate of 0.01 m s^{-1} and only 3 turns, the steady-state temperature did not rise more than ∽ 15 °C from the ambient value.

Table 4: Results of ANSYS Thermal Simulations, Convection Coefficients Were Taken From Fig. 2

	Inner diameter = 2 mm	
Turns	Water velocity [m/s]	Temperature range [°C]
3	0.01	49.552 - 45.629
5	0.1	41.622 - 37.825
	Inner diameter = 4 mm	
8	0.1	39.943 - 36.215
8	1	38.909 - 35.301
	Inner diameter = 6 mm	
5	0.1	40.45 - 36.635
5	1	39.058 - 35.374

It is expected that the FC's peak temperature will be similar to the peak instantaneous temperature rise added to this

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steady-state temperature, giving ~195 °C, which is well below the melting point of Copper. It is therefore concluded that the FETS-FFA Faraday cup is feasible provided active water cooling is used.

SECONDARY ELECTRON SUPPRESSION

Secondary electron emission (SEE) can occur when a beam strikes the Faraday cup and a large number of low-energy electrons are liberated from its surface. Electrons which escape the cup can be a source of systematic error, so it is common to reduce SEE with a negative potential applied to a suppressor. Since this suppressor should not intercept the beam, a circular ring has been adopted for the FETS-FFA FC, but the voltage and exact geometry should be optimised.

The CST Particle tracking solver [11] was initially used to investigate proton-induced SEE by applying negative potentials to the suppressor, as shown in Fig. 3. It was found to be too computationally intensive to gather the required statistics for this problem.

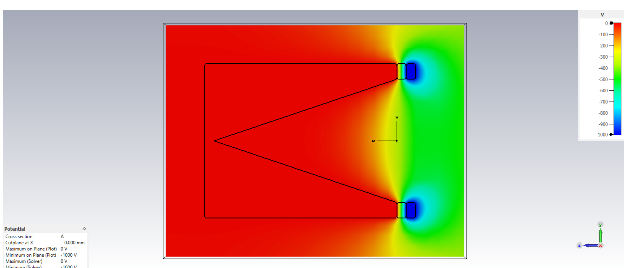


Figure 3: FC modelled in CST, showing negative potential applied to the electron suppressor.

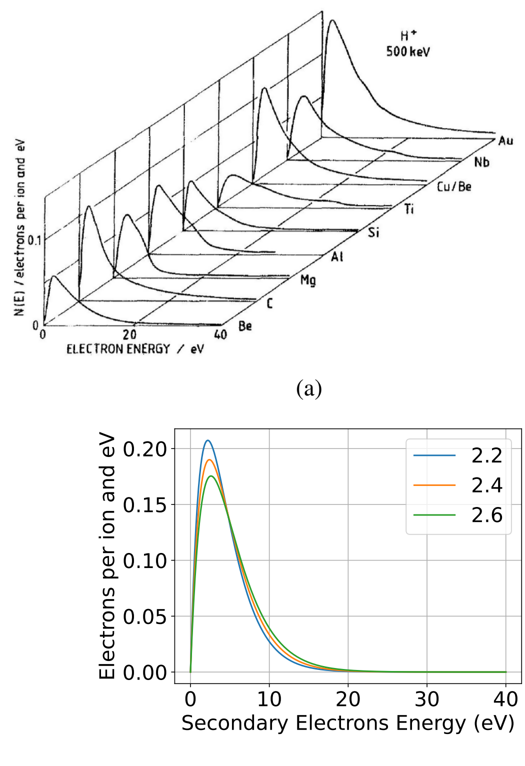
As an alternative method, the function used by CST

$$f(E) = \delta(E_0, \theta_0)\frac{E}{T^2}\exp\left(-\frac{E}{T}\right)P^{-1}\left(2, \frac{E_0}{T}\right), \quad (6)$$

to generate the SE energy spectrum was used, where E is electrons' energy, E_0 is incident proton energy, T is the temperature at which the spectrum peaks, P^{-1} is incomplete gamma function, and $\delta(E_0, \theta_0)$ is material's SEY at the given incident energy and angle. It was found that this function predicted a spectrum with the same order of magnitude, and general distribution as published experimental results, see Fig. 4 [12]. As the emission spectrum is expected to be almost independent of the incident energy [13], it was assumed that this formula remains valid for 12 MeV protons.

Equation (6) was then used to estimate the secondary electron spectra, but since the temperature is not well defined, values on the order of 10 eV were investigated, which is expected to over-estimate the average electron energy [12]. It was then assumed that any electron emitted with an energy sufficient to escape the minimum potential barrier of the suppressor was lost.

This minimum potential, typically along the cup's axis, was found to be −300 V from CST electrostatic simulations



(a)

(b)

Figure 4: Proton-induced SEs energy spectrum obtained from experiment (a) [12] and using Eq. (6), (b). Proton energy for Fig. 4 (b) was taken as 500 keV and numbers quoted in legends are temperature values in eV.

with −1 kV applied to a suppressor which was 5 mm away from the front face of the cup. The number of secondary electrons to escape the cup for each temperature value are listed in Table 5, and were found to be compatible with a 1 % accuracy for temperatures up to 20 eV. It was therefore concluded that a potential of close to −1 kV is sufficient for the FETS-FFA FC.

Table 5: Outcomes of Numerical Analysis of the SEs Energy Spectrum, The Number of Escaped Electrons Were Determined Per FETS-FFA Beam Pulse, With 3×10^{11} Protons

Temperature	Escaped SEs	Ratio of escaped SEs
10 eV	0.87	2.9×10^{-12}
20 eV	1.5×10^{6}	4.9×10^{-6}
50 eV	5.2×10^{9}	0.0174

CONCLUSION

It was found that a steady-state temperature rise of ≈ 10 K is expected for a conical FC with helical water cooling. Since the instantaneous temperature rise is not more than 170 K, it is concluded that a practical FC is feasible if it is constructed from copper. It was also concluded that SEE can be reduced to less than 1 %, with a −1 kV electron suppressor, which is also considered feasible. Any future studies should investigate the issues of thermal stress and signal processing.

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