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FARADAY CUP FOR LOW-ENERGY, LOW-INTENSITY BEAM MEASUREMENTS AT THE USR

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Abstract

For destructive beam intensity measurements, electrostatic Faraday cups will be incorporated into the Ultra-low energy Storage Ring (USR) and its transfer lines at the Facility for Low-energy Antiproton and Ion Research (FLAIR). This multi-purpose machine will offer both slow and fast extracted beams resulting in a wide range of intensities and varying time structure of the beam. In this contribution, we present the particular challenges of measuring the beam intensity in the USR, results from numerical optimization studies, as well as the design of the cup.

INTRODUCTION

Faraday cups are commonly used for beam intensity monitoring due to their simplicity and reliability. Despite a destructive character of the measurements, they can provide accurate information on the beam current in a very straightforward manner: a conductive beam stopper is introduced in the beam path and the total charge carried by the particles is collected and measured by means of an ammeter connected to the device.

A number of issues need to be considered when designing a Faraday cup: the heat load together with a proper cooling system, a suitable current meter, and finally, the emission of secondary charged particles which could escape from the cup and affect the results. This is normally not a problem for most accelerators, but very important when an existing design needs to be optimised to specific beam parameters.

BEAM INTENSITIES AT THE USR

A novel electrostatic Ultra-low energy Storage Ring (USR) [1], being under development for the future Facility for Low-energy Antiproton and Ion Research (FLAIR) [2], will require ultra-sensitive instrumentation for its proper operation. The USR will store antiprotons and decelerate them from 300 keV to 20 keV. Due to the space charge limitations at such low energies, the expected total number of single-charge particles is about $2 \cdot 10^7$ corresponding to only 3.2 pC. In order to make a wide range of external experiments possible, the beam will be extracted in two modes: in a single shot lasting a few microseconds and in a quasi-DC manner with the particles released over a longer time scale [3]. The latter will result in as few as $5 \cdot 10^5$ - 10^6 particles per second. Consequently, a Faraday cup planned for the USR will have to cover intensities from about 1 μA down to the fA range.

SECONDARY PARTICLES

Whilst antiprotons are of the main interest at the USR, other particles, like protons or H^- ions, will be used for the initial commissioning of the machine. Ideally, all beams would be monitored with one device, but this may not be possible. Given that the Faraday cup accuracy will depend on the collection efficiency of the total charge carried by the beam, the secondary charged particles emission processes need to be well understood and no charge should be allowed to escape the detector.

In the case of a proton beam, only secondary electrons will be emitted from the surface of the beam stopper. The total electron yield varies proportionally to the inelastic stopping power of the projectiles in the target material. It increases with increasing proton energy, then reaches a maximum in the 100 keV range and decreases thereafter. The yield scales with the incident angle α, measured with respect to the surface normal, by a factor $1/\cos(\alpha)$ for protons [4]. The energy spectrum of the secondary electrons has a peak at a few eV with a spread at half height of the same order of magnitude, thus about 85% of emitted particles are below 50 eV [4]. The emission of these low energy electrons is a result of a cascade process, while the higher energy tail of the spectrum is due to direct energy transfer from the impinging particle to an electron of a solid body. However, the most energetic δ-electrons are expected to be emitted mostly in the forward direction. Electrons emitted backwards can be stopped by means of an electric field applied at the entrance of the monitor.

In the case of an antiproton beam, the use of the Faraday cup will be strongly limited. The reason for this is the creation of highly energetic charged particles being able to escape the device very easily. Following the annihilation of antiprotons on protons or neutrons, various combinations of pions will emerge at 100-MeV-scale energies. Due to momentum conservation, a nuclear recoil of a few tens of MeV, depending on the target material, will be also observed. In addition, a fraction of annihilations will induce the production of an unstable nucleus; the nuclear breakup will result in fragments emitted in all directions and ionizing surrounding atoms. All in all, many annihilation products will have energy hundreds of times higher than the primary keV beam, thus their stopping in the detector will be extremely difficult. Consequently, the MeV-scale pions and recoiling ions will leave the monitor and the charge measured will not reflect the absolute beam current. Despite this limitation, the cup

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will be very useful for the commissioning stage with protons or ions. In addition, it will be used for a comparison of the response to both protons and antiprotons of similar intensities.

MECHANICAL DESIGN OPTIMISATION

The initial design proposed for the Faraday cup is presented in Figure 1 [5]. The monitor consists of a cylindrical beam stopper with a conical cut-out, and a suppressing ring electrode. Both are electrically isolated from each other and shielded against external influences by means of a grounded casing. The primary proton beam, not shown in the picture, approaches from right to left. The colour-coded curves drawn in the figure are randomly generated tracks of secondary electrons emitted in the backward direction from different points of the cup. Due to insufficient suppressing voltage applied to the electrode in this illustration, some charge may eventually leave the monitor in its central part.

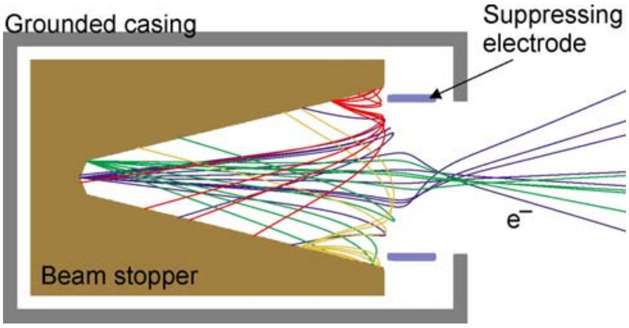

Figure 1: Simplified model of the Faraday cup produced with SIMION [6] (a cylindrical symmetry of the device around its horizontal axis is assumed).

The shape of the beam stopper was chosen in order to optimise the secondary electrons collection efficiency. Since they are not simply emitted from a surface perpendicular to the primary beam, their escape solid angle is greatly reduced in the proposed geometry. In addition, a larger area of the material is exposed to the incident beam, therefore the heat load per mm is lowered. However, the heat performance as such is not a problem in the USR due to low intensities and low energies of the available beams. Considering the energy of 300 keV and the instantaneous beam current of 1 μA, the peak beam power will not exceed 300 mW. This corresponds to 14.5 mW/mm for a 28° cut-out cone surface and a beam of 5 mm diameter, and is 15 times smaller for a 20 keV beam. As for the material, the oxygen-free high thermal conductivity (OFHC) copper was chosen. It is suitable for vacuum and has medium atomic number which is important since backscatter increases with Z. The thickness of the beam stopper is much larger than the sub-mm penetration depth of 300 keV protons.

The suppressing electrode made of stainless steel is used to prevent secondary electrons from leaving the monitor. A ring shape instead of a grid was chosen in order to avoid losses of the already few primary particles hitting anything else than the beam stopper. In the given geometry, protons can freely enter the cup and their energy is low enough not to produce very high energy electrons which could be difficult to stop afterwards. The shape of the ring was optimised as compared to the setup in Figure 1. By increasing the length of the electrode by only a few mm, the potential on the axis of the suppressor was decreased by about 20%.

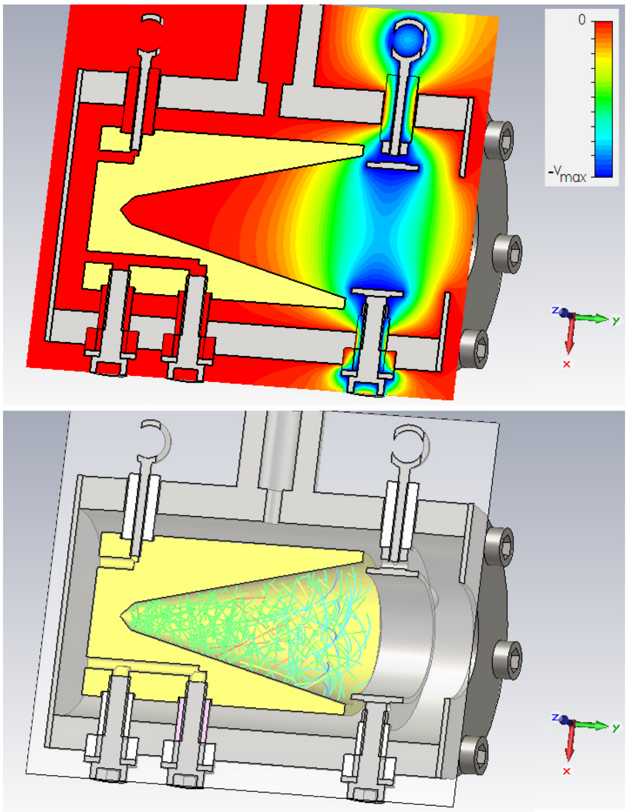

Figure 2: Simulations of the field distribution (top) and the secondary electron emission (bottom).

A more detailed model of the Faraday cup was prepared and studied in terms of electric field distribution and electron collection efficiency. Figure 2 shows numerical calculations made with the CST Studio package [7]. As expected, the critical point of the cup is at the central axis of the electrode where the electric field is reduced due to the finite length of the suppressor. By implementing the known secondary electrons emission model, it was shown that the majority of the particles are kept inside the monitor. Only high energetic electrons emitted in a very narrow solid angle covering the central axis of the suppressor may be able to escape the cup. Due to small probability, this will have only a minor effect on the measurement accuracy.

The outer grounded casing is made of stainless steel and additional ceramic insulators ensure the electric isolation of the cup components. The entrance bore is 21 mm in diameter which also determines the maximum beam size that can be measured. The whole device is about 8 cm in length and about 5 cm in diameter. It will be mounted on a pneumatic actuator with a 75 mm stroke, and will fit into a DN100 CF cross chamber. The final design of the Faraday cup is presented in Figure 3.

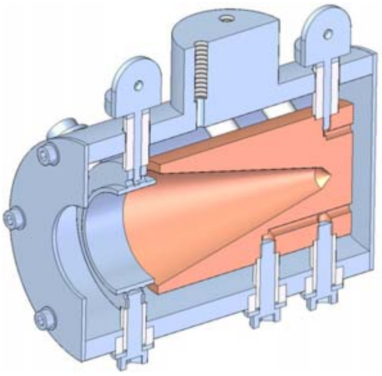

Figure 3: Section view of a CAD-based model.

LOW CURRENT MEASUREMENTS

Beam current monitoring in the USR will be a challenging task. Intensities in the fA range are extremely difficult to measure already in the simplest setups due to theoretical and practical noise limitations. The situation is far more complicated in a real accelerator where many noise sources, like vacuum-to-air feedthroughs, long cables or vibrating vacuum pumps, cannot be eliminated. In addition, the USR extraction schemes will lead to a variable time structure and different peak beam intensities.

To overcome the difficulties with measurements under the different beam delivery schemes, a variable gain transimpedance amplifier DLPCA-200 from FEMTO was bought. It offers several gain and bandwidth settings of which three are summarized in Table 1. The gain of either 10^6 or 10^7 V/A is sufficiently high for sub-µA bunches while the rise/fall time is short enough to sample the inner bunch structure. For sub-pA quasi-DC beams, the highest sensitivity can be achieved with 10^{11} V/A and an internal low-pass filter with the upper cut-off frequency of 10 Hz. The two possibilities are presented in Table 1 as the fast and slow mode respectively.

Table 1: Transimpedance amplifier parameters

Parameter	**Fast mode**		**Slow mode**
Gain setting [V/A]	10^6	10^7	10^{11}
Upper cut-off [kHz]	500	400	1.1 (0.01)
Rise/fall time [µs]	0.7	0.9	300
Input noise [fA/√Hz]	1800	450	4.3

For ultra-low current measurements, low noise triaxial cables should be used. Double screening reduces noise caused by ground loops and other parasitic effects. Such cables and feedthroughs, however, are not available for the ultra-high vacuum (UHV) of about 10^{-11} mbar under which the Faraday cup will be operated. For this reason, a custom-made 50 Ω Kapton-coated cable with an additional stainless steel screen was prepared. It includes a special connector for a floating BNC vacuum feedthrough. The components are presented together with the assembled cup in Figure 4.

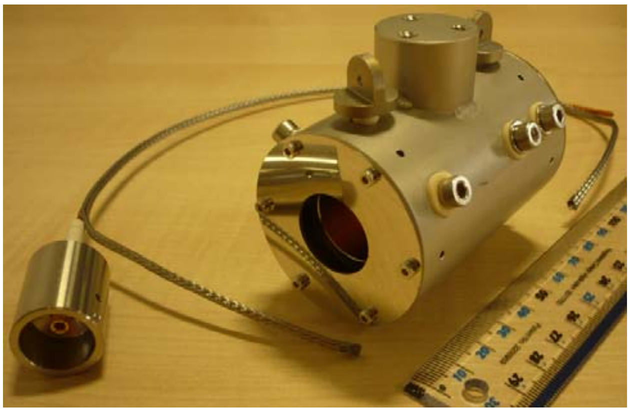

Figure 4: Assembled Faraday cup together with a double shielded cable equipped with a floating shield connector.

OUTLOOK

The Faraday cup will be incorporated into the USR as a reference monitor for a range of beam currents. A compact UHV test bench will soon be built and initial detector tests will be run with an electron gun. Should the variable gain current-to-voltage converter be not sensitive enough for the lowest intensities, a separate narrowband amplifier dedicated for sub-fA DC measurements will be used.

The flexible design of the cup and wide operating range of the amplifier project triggered collaboration with the Clatterbridge Centre for Oncology where the Faraday cup will be tested with 62 MeV protons.

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