

# Portable Faraday cup for nonvacuum proton beams

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**A portable Faraday cup design is described for the accurate measurement of large-diameter, low-current, and high-energy proton beams traveling in air. The unit has been tested with protons from 4 to 300 MeV. The unit has an accuracy of 10% for beams of 1 pA, improving to about 2% accuracy for ion currents of 20 pA to 1  $\mu$ A.**

## Introduction

We know of only three scientific papers on the design of Faraday cups to measure high-energy ion beams in air [1-3]. Such beams are rarely used in scientific studies; however, they are widely used in various applications such as material analysis of art and archeological objects [4-6], radiation treatment in medicine [7, 8], and the accelerated testing of LSI components and systems for sensitivity to cosmic rays [9].

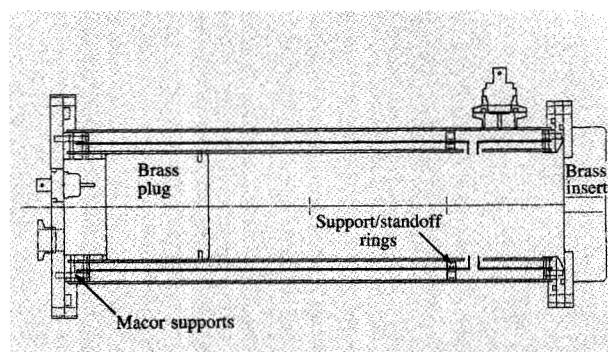
In these application papers, Faraday cups were sometimes used to calibrate the nonvacuum beams, although the design of these systems appears not to have been reported. For the accelerated testing of LSI parts, the Faraday cup is particularly critical, since this application requires very low currents, typically 10-100 pA ( $1 \text{ pA} = 6 \times 10^6$  protons/s), operating in an electronically noisy accelerator environment.

One requirement for our Faraday cup design was for portability, i.e., low weight, which precluded the use of magnetic field suppression. The cup is designed to operate with electrostatic fields only.

The unit described in this paper was the third major design attempt we made over a period of five years. Our first attempt was to design an open-air Faraday cup which did not have an entrance window or an internal vacuum. This would have allowed us to measure very low-energy proton beams (note that protons lose about 2 MeV energy in the thinnest windows which will support an air/vacuum interface over a wide aperture,  $>70$  mm). There is significant ionization of room air by a nonvacuum proton beam, and its magnitude and drift appear to be dramatically influenced by humidity and room convection currents. For 50% humidity, air ionization drift noise is of the order of 50-200 pA. Typical room convection currents of 400-1000 cm/min were observed, even in rooms without forced air exchange, and the magnitude of these currents had a significant effect on the Faraday spurious current [10, 11]. We were unable to find a combination of magnetic and electrostatic suppression which would reduce the system noise to allow beam measurements below 50 pA in an atmospheric Faraday cup. The reason, we would guess, was that the polarization of the air was constantly changing because of humidity and convection currents, and Faraday cup suppression was erratic.

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**Figure 1**

The Faraday cup for nonvacuum ion beams consists basically of three coaxial cylinders, with a gap between the right-hand suppressor section and the left-hand Faraday-cup section. The diameter of the inner active cylinder is 75 mm, allowing the cup to measure rather broad beams. Shown at the beam entrance to the cup, at the right of the above diagram, is a removable aperture which, when in place, allows the measurement of the current density ( $A/cm^2$ ). Just inside this removable aperture is the vacuum window described in the text. The unit is designed to be used for proton beams from 4 to 300 MeV. The lower energy limit is probably because of lateral scatter of the beam exiting the window (which absorbs 50% of the beam energy at 4 MeV). The upper energy limit is because the range of protons exceeds the depth of the brass plug at the bottom of the Faraday cup.

### Faraday cup construction

Our final Faraday cup design is shown in **Figure 1**. In overview, the Faraday cup has five different sections:

1. The beam entrance to the Faraday cup is at the right of the figure. The object called the *brass insert* in the figure is an optional brass collimator which can be placed at the entrance to the Faraday cup to restrict the beam size so that the central current density ( $A/cm^2$ ) may be measured.
2. Just inside this removable collimator is the thin foil entrance window (not shown).
3. The next section is the suppression stage, which acts both to suppress electron showers from the entrance foil and to suppress electrons coming from the beam absorber at the bottom of the Faraday cup.
4. The longest section of the Faraday cup is the cup itself, ending with a brass plug which captures the beam. A 10-cm-long plug is adequate to stop up to 300-MeV protons.
5. Finally, at the far left are most of the electrical connections as well as the vacuum pumping port.

The Faraday cup is essentially three coaxial cylinders, broken into two parts: the Faraday cup on the left, and the suppressor section on the right in the figure. The outer cylinder, of stainless steel, acts as the vacuum chamber

wall. The inner two coaxial cylinders are made of copper. The middle cylinder is the ground shield of the system, and is not biased. The inner cylinder of the Faraday cup is electrically connected to the brass plug, and is the electrically active part of the unit. The inner cylinder of the suppressor is biased as described below. Of significant importance are the two grounded guard rings which separate the Faraday cup from the suppressor cylinder. These rings are essential to terminate the suppressor fields.

The dimensions of the Faraday cup shown in **Figure 1** are to scale, with the overall length being 38 cm (flange-to-flange OD, not counting the brass insert), the overall vacuum tube OD being 11.4 cm, and the inner tube ID being 7.6 cm. The brass plug shown was one used for 150-MeV protons; it was 7.3 cm long. A 10-cm-long brass plug was used for beams up to 300 MeV.

Three construction items should be carefully noted:

1. The various insulating supports were made of a machinable glass-ceramic with the trade name of Macor (Corning Glass Company product no. 9658). Various materials were tried for this supporting function, including bakelite, TEFLON<sup>®</sup>, and plexiglas<sup>®</sup> (lucite<sup>®</sup>). These materials were quite unsuitable, because they slowly polarize under bias and induce false currents into the Faraday cup output. For example, with TEFLON supports, when 100 V bias was applied to the suppressor inner cylinder, there was a spike of current in the Faraday output which would settle to about 80–150 pA in about a minute. This induced current would slowly decrease, so that by 24 hours later it would be at about 10 pA. A period of about three days was required for the current to reduce to <2 pA. The other insulating materials were worse than this. Only Macor showed a tolerable polarization, with the induced Faraday current dropping below 5 pA within about two minutes of a change in suppressor voltage.
2. The foil at the entrance window has to sustain 47 kg (104 lb) from air pressure. We used two layers of 76- $\mu$ m aluminized MYLAR<sup>®</sup> foils for this window. A double layer was used to seal any foil pinholes and to prevent catastrophic implosion if one foil had thin spots. The inner surface of the flange holding the foil was rounded and polished so that the foil would have minimal edge stress. Later, we also tried a transparent conductive plastic, 75  $\mu$ m thick, manufactured by 3M Company (foil no. 2100). This material appears equally effective and durable. (This is the material from which "antistatic" bags for electronic parts are made.)
3. The middle cylinders of the suppressor stage and the Faraday cup are used as noise shields, and are electrically grounded. The Faraday middle cylinder is connected to the triax connector leading to the current meter. The

suppressor middle cylinder is connected to the suppressor bias-supply ground.

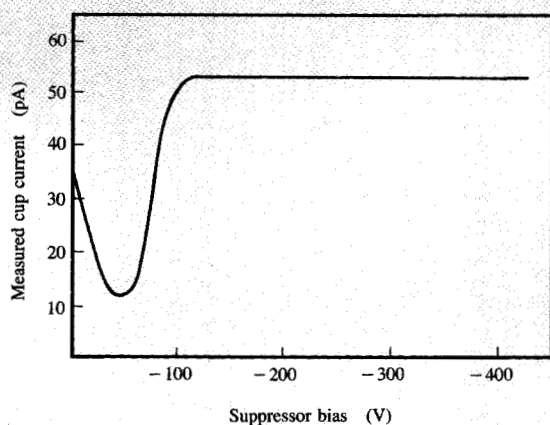
The current output from the Faraday cup was via a triax cable, with the outer shield attached to the unit's vacuum cylinder, the inner shield attached to the middle cylinder, and the inner wire attached to the Faraday cup. The current was measured using a Keithley Model 617 digital ammeter with a triax input.

### Testing the Faraday cup

The Faraday cup was extensively tested to determine the suppressor voltage required to give accurate and consistent results. Further, since the unit was to be portable, it was also tested to find the smallest vacuum pump which would be required to give accurate results.

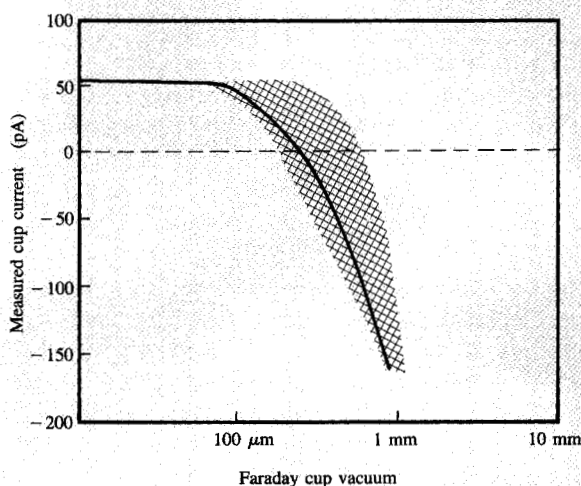
#### • Testing of suppressor voltage

Though a suppressor on a Faraday cup is a standard feature, its effect on a cup with an entrance foil has been discussed only once [2]. The shower of electrons from the entrance foil requires the use of much higher suppressor voltages. Since the voltages may induce charge in the Faraday cup, terminating guard rings are installed between the suppressor cylinder and the Faraday cylinder (see Figure 1). Shown in Figure 2 is the performance of the Faraday cup as a function of suppressor voltage. The test shown was one of the more severe tests, using a 4-MeV proton beam which lost about 2 MeV going through the air/vacuum window. As shown, the unit stabilized at about



**Figure 2**

Current measured for a constant 53-pA proton beam (at 4 MeV) as a function of suppressor voltage. For suppression below (more negative than) -120 V, the unit showed constant current.



**Figure 3**

Sensitivity of the Faraday cup to a constant 53-pA beam of 4-MeV protons as a function of Faraday vacuum (torr). The Faraday cup operated accurately up to a pressure of 100  $\mu$ m of vacuum. Above this pressure, the current dropped until, at vacuums above 200  $\mu$ m, the current went negative. This negative current could be traced to currents from the suppressor cylinder, which exactly matched the negative currents induced in the Faraday cup.

-120 V, with adequate suppression. Other tests were run with proton beams up to 150 MeV, with the required suppression voltage stabilizing between 40 and 120 V. Higher-energy proton beams required less suppression voltage. The unit was finally operated at -200 V to maintain a safety margin.

#### • Testing for sensitivity to vacuum

Shown in Figure 3 is the Faraday current as a function of the unit's vacuum. A constant beam current of 53 pA was maintained with 4-MeV protons. The suppressor was at a constant bias of -200 V. The actual Faraday current measured for vacuums from 100  $\mu$ m to 1 mm varied considerably from run to run, as indicated by a crosshatched region in the figure. The changes in the Faraday current were found to scale with the current drawn by the suppressor circuit. It was determined that a vacuum of <10  $\mu$ m was necessary for reliable operation. This vacuum required only a small portable roughing pump (Sargent Welsh Company vacuum pump no. 8804, 0.9-cfm capacity). Once the system was pumped down to 1  $\mu$ m, it would stay below 10  $\mu$ m for 24 hours without continued pumping.

In an attempt to eliminate the need for a vacuum pump, we filled the cup with room-pressure helium. There was

significant negative current induced in the Faraday cup when bias was applied to the suppressor, and this current did not decrease over the one hour of the test. The current was not constant, but changed erratically in the region of 10–40 pA. (During these tests there was no beam into the cup.) Similar results were found after the cup was filled with argon at room pressure.

#### • Other tests of the Faraday cup

**Sensitivity to beam position** The unit was tested for lateral displacement of the beam by collimating the beam to about one cm and then moving the Faraday cup so that the beam entered 2 cm from the coaxial axis. The current change was less than 1% for all tested displacements.

**Comparison to other Faraday cups** The Harvard Cyclotron Laboratory has used a single nonvacuum Faraday cup for 30 years [2]. This cup was designed and built by A. Koehler in 1964. We attempted to duplicate this cup, but our exact copy was hopelessly poor because of polarization currents when we biased the internal suppression rings. We presume that this effect was not present in the Koehler cup because its bakelite insulating supports had been under continuous vacuum for almost all of those 30 years, and this material was not the same as newly machined bakelite. Our final cup was tested against the Koehler cup, and they were found to be within 3% of each other for proton energies from 50 to 150 MeV, and currents from 2 pA to 60 pA. The difference between the two Faraday cups was constant, with the Koehler cup reading slightly below our cup in all cases.

In a separate experiment, the accuracy of the unit was also tested by placing it at the exit of a normal vacuum beamline, downstream of a withdrawable-beamline Faraday cup. Proton beam currents from 1 pA to 1  $\mu$ A were sent down the line. The two Faraday cups measured within 2% of each other over the entire current range.

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