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BEAM INTENSITY MONITORING FOR THE EXTERNAL PROTON BEAM AT LAMPF

by

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ABSTRACT

Three different intensity monitors have been tested in the external proton beam at LAMPF. These monitors enable one to measure the intensity over the entire range of beam currents available. A 800-kg Faraday cup was installed and was determined to measure the absolute intensity to better than 1% for beam currents up to several nanoamperes. A high gain ion chamber was used as part of the calibration procedure for the Faraday cup and was found to be useful when monitoring very small beam intensities. It is reliable down to the few picoampere level. A secondary emission monitor was also tested, calibrated, and found to be trustworthy only for beams of greater than 50 pA intensity.

I. INTRODUCTION

The Clinton P. Anderson Meson Physics Facility (LAMPF) external proton beam (EPB) is capable of delivering well-focused (2-mm-diam), low-emittance (<1 mr-cm) proton beams with a narrow momentum bite (± 3.5 MeV) in the energy region from 500-800 MeV. The beam intensity is variable from 1 pA to 100 nA.

The purpose of the work described below was to develop a versatile set of absolute and relative beam current monitors, which would not only cover the entire range of available intensities, but also provide enough redundancy so that, at almost any beam intensity, two instruments would be available to measure the beam current. A secondary purpose was to provide instrumentation which could be of use in tuning the beam. Three monitors were developed: a Faraday cup, an ionization chamber, and a secondary emission monitor, all of which have been demonstrated to work according to the design.

In the subsequent sections of the present report, detailed descriptions of each instrument are presented, along with discussions concerning the types of difficulties the user may expect to en-

counter. All of the monitors have been turned over to the LAMPF secondary beam lines group and are available to any user of the EPB.

II. FARADAY CUP

A general purpose Faraday cup has been constructed as part of an experiment to measure absolute proton-proton elastic scattering differential cross sections at LAMPF in the energy range up to 800 MeV. At these energies the effects of charged particle leakage due to inelastic nuclear processes had to be carefully considered in the design of the Faraday cup. In addition, the usual problems of secondary electron emission and electrical leakage have been minimized. The final results indicate that we have an instrument that has an absolute accuracy of better than $\pm 1\%$ over a range of currents up to several nanoamperes. Extension to higher beam intensities would only require that steps be taken to provide adequate cooling of the Faraday cup.

Previously, Faraday cups have been employed at several medium energy laboratories and our design

has been guided by the experience gained at the Berkeley 184" synchrocyclotron,¹ the Stanford medium energy electron linac,² and the Space Radiation Effects Laboratory (SREL) synchrocyclotron.³ A reasonable compromise between size and cost was made.

A. Design and Construction

Figure 1 shows the general design of the LAMPF Faraday cup. The LAMPF external proton beam, which has low emittance (<1 mr-cm) and energy spread (± 3.5 MeV), is virtually free of contamination from other charged particles. It enters the main body of the Faraday cup and is stopped by 45 cm of lead (range of 800-MeV protons in lead is 39 cm). The reentrant tube has an outside diameter of 35 cm, an inside diameter of 25 cm, and a length of 75 cm. The total length of the cup is 120 cm including the beam stop.

The probability of the beam coming to rest without undergoing nuclear inelastic collisions is only 11%⁴ so that we must be concerned with knock-on protons, particularly those produced by (n,p) reactions near the surface of the lead and then lost from the cup. A 1.25-cm-thick graphite shell surrounds the lead to reduce this effect by virtue of the much smaller $^{12}\text{C}(n,p)$ cross section. Elec-

tron pairs produced by gamma rays, being of opposite sign, should produce a negligible effect.

The 75-cm-long reentrant cavity was designed to capture secondary emission electrons produced when the beam strikes the inner surface of the lead cup. At 800 MeV the secondary emission efficiency is about 2.5% and, since the cavity is 85% enclosed, at most 0.4% of the proton beam current could be lost through secondary electron emission (the electron energies are <30 eV). In order to reduce this effect still further a small magnet produces a field of ~ 15 Gauss across the entrance port. Overall, the total electron loss is estimated to be less than 0.1%. Charge loss due to proton back-scattering is also calculated to be negligible.

A 50-cm-diam, 0.32-cm-thick stainless steel electrostatic shield surrounds the cup, as shown in Fig. 1, with Lucite standoff insulators isolating the cup from the shield. The cup and the shield have separate electrical output leads through the outer vacuum vessel. The entire assembly was connected directly to the accelerator vacuum system, maintained at a pressure of the order of 10^{-6} torr (as measured at an ion pump 12 m from the cup). This vacuum level reduced the possibility of positive

Fig. 1. Design of the LAMPF-CWRU leaky Faraday cup for the external proton beam.

ions produced by radiation fields in the gas surrounding the Faraday cup to essentially zero. No dark currents due to the ion pump, as observed at SREL,³ were measured in our system. We believe this is due to the considerable distance to the ion pump as well as the baffle installed on the pump to prevent ions from migrating down the beam pipe.

The charge collected by the Faraday cup was fed through ~40-m-long coaxial cables to an ORTEC 439 charge digitizer located in our electronics trailer. Charge leakage due to insufficient impedance to ground may occur in either the Faraday cup, the cables, or the associated electronics. A known current source was connected in parallel to the Faraday cup and the leakage current was found to be less than 1 pA. Dark current can also be induced through pickup from rf fields associated with the accelerator. The grounded shield and an rf filter at the input to the digitizer kept dark currents generally below the 1 pA level.

B. Calibration and Tests

The ORTEC 439 was checked a number of times to find the absolute digitizing efficiency (pico coulombs per pulse). Two precision current sources known to better than $\pm 0.3\%$ were used to calibrate the system over a range of currents from 10 pA to 15 nA. These results indicate that the charge collected is known to better than $\pm 0.2\%$, except for possible efficiency losses in the Faraday cup itself. In order to determine the absolute cup efficiency, two methods were employed.

In the first method the cup was calibrated relative to the Ar-CO₂ ion chamber. Data were obtained at energies of 500, 650, and 800 MeV. At each energy the ratio of the integrated charges from the ion chamber and the Faraday cup was compared with the calculated ion chamber gain (see Section III).

Results shown in Table I indicate that the calculated gains agree with the measured gains to well within $\pm 3\%$ accuracy, assuming the Faraday cup has 100% collection efficiency. Thus, these results show that the Faraday cup has an efficiency of $(100 \pm 3)\%$ over this energy range.

A second and more accurate method of determining the charge collection efficiency of the Faraday cup takes advantage of the characteristics of our H⁻ beam. It is possible to compare positive and

TABLE I
COMPARISON OF CALCULATED AND
OBSERVED ION CHAMBER GAINS

T_p (MeV)	Q_{IC}/Q_{FC}	Calculated I. C. Gain	Deviation (%)
500	146	149*	2.0
650	151	153	1.3
800	140	145	2.1

*The ion chamber used in the 500-MeV test was different from the one used for the 650- and 800-MeV tests.

negative charges collected in the cup by simply inserting a thin stripper foil in the H⁻ beam to convert it to H⁺. The two measurements should be equal and opposite in sign unless there is a charge loss due to secondary protons emitted in the inelastic scattering of the 800-MeV proton beam stopped in the lead cup. The sensitivity of this test is a factor of two Δ , since the H⁺ measurement would be decreased by an amount Δ and the H⁻ measurement increased by the same amount Δ (Δ is the fraction of secondary protons emitted).

Measurements should be made relative to a monitor insensitive to nuclear effects such as a toroid. However, at the beam intensities available on EPB this was not possible, so that we depended upon the beam remaining reasonably constant over the intervals when H⁺ and H⁻ were compared. We repeated the measurements with alternate runs taken with the stripper inserted and extracted, with each cycle lasting about 2 min. This experiment was repeated several times throughout an 8-wk period. The results presented here are from the runs during which the beam intensity (about 1 nA) showed the smallest fluctuation. All data obtained were consistent with the final results quoted below. A typical set of data is shown in Fig. 2 for a 1-nA beam. The average elapsed time for H⁺ and H⁻ was 11.22 and 11.25 s, respectively. The quantity we are interested in is δ , the difference in elapsed time for two alternate runs. A total of 48 separate values of δ were determined yielding an average value

$$\delta = (0.04 \pm 0.087) \text{ s}$$

This corresponds to a charge loss of $0.2 \pm 0.4\%$.

Accordingly, the Faraday cup charge collection efficiency is

$$(99.8 \pm 0.4)\%$$

This result, in excellent agreement with the ion chamber calibration method, indicates that the absolute calibration of the Faraday cup has a maximum uncertainty of less than $\pm 1\%$ due to possible charged particle emission produced through nuclear interactions.

III. ION CHAMBER

A high gain Ar-CO₂ ion chamber has been constructed and tested on the EPB. The ion chamber is inside a vacuum-tight box with foil windows and mounted on an actuator so that it may be inserted into or removed from the beam by remote control.

The ion chamber consists of three aluminum foils spaced 0.84 cm apart (see Fig. 3). The two outer foils are maintained at negative voltage so that electrons are collected on the center foil, which has a guard ring around it (to ensure a uniform field at the edge). The current signal is taken from this center foil and integrated with a current digitizer. The ion chamber has been constructed as three pairs of 0.79-mm-thick G-10 fiber boards separated by Lucite spacers and held together with nylon screws. The G-10 boards have copper-clad strips for electric circuit paths (including the center foil guard rings). The aluminum foils

were mounted on the G-10 boards of each pair with tape and epoxy and the pairs then epoxied together. The separation of the two outer foils was carefully measured with micrometers.

The ion chamber has been operated with a 99% Ar, 1% CO₂ mixture at ambient pressure. This mixture was allowed to flow slowly through the chamber, although this is judged to be usually unnecessary. The voltage applied between the center and outer foils has been limited to less than 600 V (due to the voltage capability of the coaxial cables in the actuator). From the measured spacing of the foils, the gas pressure and the temperature, along with the reported value for the energy loss per ion pair in argon,⁵ we have calculated the absolute gain of the ion chamber. Table II shows that for a pressure of 58.9 cm of Hg and a temperature of 19°C we obtain

TABLE II
ION CHAMBER GAINS

Proton Energy	Calculated Gain	Gain Normalized to Faraday Cup
497	167	164
647	153	151
800	143	140

The calculated gains are believed to be accurate to $\pm 3\%$ absolute and the normalized gains (i.e.,

Fig. 2. A typical set of data of measurements of beam intensity for both H⁺ and H⁻ beams with the LAMPF-CWRU Faraday cup.

Fig. 3. Design of the LAMPF-CWRU Ar-CO₂ ion chamber for the external proton beam.

the measured gains) to $\pm 2\%$, with one very important qualification. The ion chamber gain will begin to drop due to space charge buildup somewhere between 100 and 800 pA of beam current, depending on the EPB spot size. We have observed that this fall-off will start when the current density reaches approximately 10.2 pA/mm^2 ($\pm 30\%$). The effect is shown in Fig. 4.

This ion chamber was found to be particularly helpful for runs at low beam currents. It performs well to a 10-pA proton beam. Although an rf filter on the output of the chamber can help considerably, a small dark current usually exists. This dark current rarely exceeds an equivalent of 0.5 pA of proton beam, although it is often of that magnitude (the dark current disappears when the accelerator is off).

Some of the important parameters of the chamber are listed in Table III.

TABLE III
ION CHAMBER PARAMETERS

Parameter	Value
Active area	7.30-cm diam
Total gap (2 spacings)	$1.692 \pm 0.005 \text{ cm}$
Foils	19- μm aluminum
Gas mixture	99% Ar - 1% CO_2
Voltage	-600 V
Guard ring around center foil (gd. Pot.):	
Width	1.0 cm
Separation from center foil	1.6 mm
Vacuum box:	
Window size	7.62-cm diam
Window material	1-mil titanium

Fig. 4. Ion chamber gain as measured with the Faraday cup vs beam current for two different external proton beam spot sizes.

IV. SECONDARY EMISSION MONITOR (SEM)

Secondary emission is a phenomenon through which electrons, liberated from their atomic bonds by the passage of energetic charged particles through matter, can escape from the surface of a body. These electrons are very low in energy and therefore must originate in the thin region within $0.01 \mu\text{m}$ of the surface of the material in order to escape. The secondary emission efficiency, which is defined as the ratio of the number of electrons emitted from a surface to the number of incident charged particles, varies with the energy of the incident particle and measures ~ 0.03 per surface for 800-MeV protons. The loss of electrons induces a charge on the surface and by integrating this charge electronically, one can obtain an accurate determination of the total number of charged particles incident on the body.

This effect has been utilized with great success for monitoring high-intensity charged-particle beams.⁶⁻⁹ In general, secondary emission monitors have been constructed with several thin foils in order to multiply the gain. The choice of foil surface has a significant influence on the gain, but for reasons of reliability and long-term stability, one should be careful to choose a surface whose properties are not readily susceptible to change. Since the emission efficiency can vary markedly due to absorption or emission of gases from the surface, secondary emission monitors should be thoroughly outgassed in a high vacuum prior to making any beam intensity measurements.

The SEM described here consists of nine foils; five emitters and four collectors. The construction allows for easy replacement of foils. It is designed to be operated in the vacuum of the beam tube and can be inserted into the beam remotely by means of an actuator. In general, a potential of -300 V is applied to the emitters and the signal is taken from the four collectors.

The SEM is most useful as a relative intensity monitor for beams of greater than 50 pA. This lower limit is due to the fact that the monitor has a net gain of about 0.25, and will produce a current of only 12 pA with a 50-pA incident beam. It is difficult, although not at all impossible, to accurately integrate currents of the order of 12 pA. The

allowable upper limit on beam intensity for this instrument is well above that attainable in the LAMPF EPB.

Using the SEM as an absolute monitor requires calibration against the Faraday cup or ion chamber and should be rechecked at least each time the foils are replaced. Since the foil surfaces may change with time, calibrations should be performed more often for accurate absolute performance. One such absolute calibration has been performed at a proton energy of 500 MeV, and the gain was found to be 0.25 (0.032 per surface). This result is in qualitative agreement with previous measurements made at the Argonne National Laboratory ZGS, using proton beams of 3.6 GeV/c (0.027 per surface) and 12.6 GeV/c (0.030 per surface), see Table IV.

V. PRECAUTIONS

As always, multiple scattering, beam steering and other effects may introduce grave systematic errors. Any user should convince himself that the various problems are resolved for his setup. The following list is not guaranteed to be complete:

1. Multiple scattering in the target, SEM, or ion chamber may cause some beam to miss entry into the Faraday cup. Remember that a multiple scattering distribution is not Gaussian and has long angular tails. We calculate the multiple scattering rms angular width for the devices in this paper to be: ion chamber = 0.024° and SEM = 0.015° .
2. Misalignment of the beam tube or steering distortions may cause incomplete beam collection.
3. Radiations, possibly intermittent, from other areas may cause a background in the ion chamber.
4. The above discussions for the ion chamber and SEM are for an H^+ beam incident upon them. If the beam has not been stripped at least several feet upstream of either device, its response may be altered.
5. The vacuum must be maintained at 10^{-6} torr or better after a calibration of the SEM, and then it may still slowly change with time.
6. In order to obtain absolute normalizations to $\pm 2\%$ with the ion chamber (at low intensities only, of course), one must know the temperature and pressure to $\pm 1\%$ each.

TABLE IV
SEM PARAMETERS

Parameter	Value
Active area	7.62-cm diam
Gap spacing	5.56 mm
Foils	8.5- μ m aluminum
Foil surfaces: 5 emitters 4 collectors	Aluminum oxide Gold plate
Voltage	100 V
Sign	Negative

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