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Ionisation Chambers and Secondary Emission Monitors at the PROSCAN Beam Lines

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Abstract. PROSCAN, the dedicated new medical facility at PSI using proton beams for the treatment of deep seated tumours and eye melanoma, is now in the commissioning phase. Air filled ionisation chambers in several configurations are used as current monitors, profile monitors, halo, position and loss monitors at the PROSCAN beam lines. Similar monitors based on secondary emission are used for profile and current measurements in the regime where saturation deteriorates the accuracy of the ionisation chambers.

INTRODUCTION

Ref. 1 describes the diagnostics for the PROSCAN beam lines which were under development at that time. Here we discuss the realised devices, the production techniques and the performance reached up to now. This article should be read in conjunction with Ref. 1, since there the environment of the detectors, the evaluation techniques, saturation effects of air filled ionisation chambers, the cabling, the electronics [2], the alignment, etc. have been discussed.

The detectors discussed in the following are ionisation chambers filled with ambient air. Thin profile and current monitors based on secondary emission, which are realised by placing detectors of the same type in vacuum, are also mentioned.

THICK PROFILE MONITORS WITH VARIABLE STRIP CONFIGURATION

The detector consists of three thick-film coated ceramic plates which form two 4 mm long active volumes which are passed by the beam (Fig. 1). The two outer plates present bulk anodes to the horizontal and vertical strip patterns on the sides of the centre plate. The ceramic plates are made from 0.635 mm Al_2O_3 raw material, laser cut [3], thick film coated with 9 μm PtAu and supplied with Samtec connectors [4]. The guiding holes are laser cut to a dimension of 4.015 ±0.015 mm, with most of the samples in an even narrower margin. Dedicated control measurements during the setup of the printing process yield a positioning of the centre of the strip pattern relative to the guiding holes within a tolerance of ±0.03 mm, with most of the samples in an even narrower margin. Together with the alignment of the pressurized air actuator in a test bench and mounting with alignment rods, this resulted in an overall position deviation of the strip pattern relative to the alignment bores in the vacuum box of less than ±0.18 mm and a position uncertainty of ±0.1 mm. In addition the absolute position of the box is uncertain by ±0.1 mm from the surveying process.

The detectors will be used for beam currents up to 10 nA but have been operated up to 700 nA for several hours. No degradation was observed despite a yellow colouring of the originally white ceramic plates. No sparking takes place at the standard operation voltage of 600 V. With the smallest beam diameters, saturation was visible at currents above 2 nA (at 250 MeV). When the beam was switched off after a extended operation at high current, an afterglow was visible due to the activation of the detector itself. The signal current from this was at least three orders of magnitude below the signal due to the beam. No microphonic noise of the detector was observed in the range accessible with the electronics.

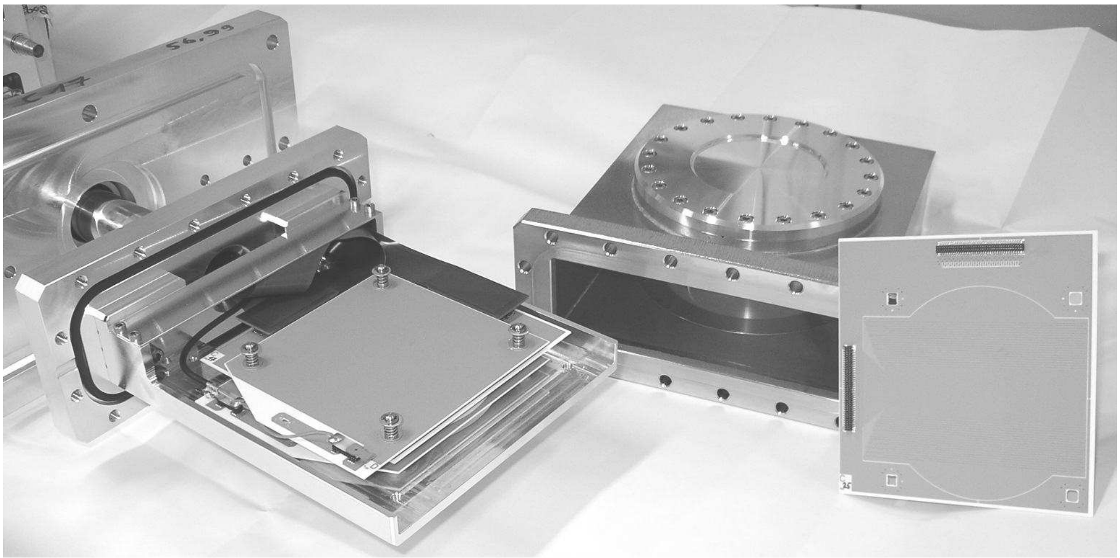

FIGURE 1. Thick profile monitor with pressurized air actuator. To the right: centre plate with vertical strips (the horizontal strips are on the reverse side).

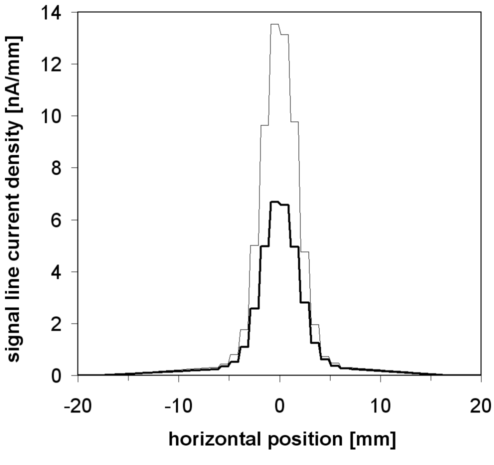

FIGURE 2. Momentary beam profiles at an average beam current of 1 nA (beam energy 230 MeV). All 16 currents of one profile are sampled synchronous to a few ns.

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Fig. 2 shows two beam profiles, one measured 0.2 ms after the other. Due to the large current fluctuations (white noise) of the ion source, the signal level has changed drastically. Hence a synchronous measurement of all points of a single profile is essential.

THICK PROFILE MONITORS WITH PIXEL ROW

In order to measure 2-dimensional beam profiles, the centre plate of a thick profile monitor was replaced by a 4-layer FR4 printed circuit board (PCB) providing a horizontal row of quadratic pixels in addition to the horizontal and vertical strip pattern (Fig. 3). The pixels are connected by the inner layers of the PCB. The current to each pixel is measured when the monitor is moved vertically into the beam. The actuator speed was therefore slowed down to ~130 mm/10 s. 2 of the 32 channels of the current measurement electronics were used to read the vertical position information and reference voltage from a potentiometer. The device was tested at low beam currents and performed as expected. No artifacts due to an interaction of the beam with the inner connecting layers were observed.

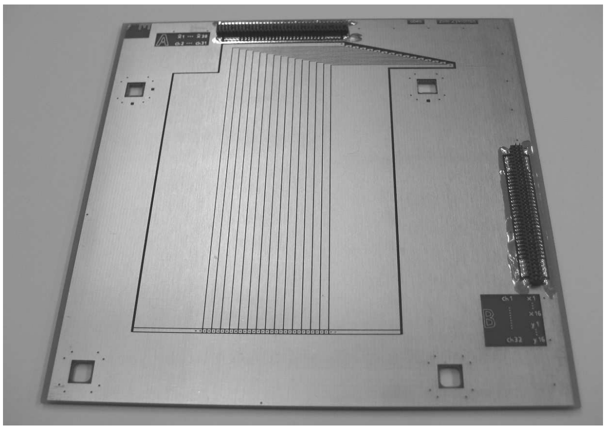


FIGURE 3. Centre plate with a row of 28 quadratic pixels with 1 mm separation and two broader outer "pixels".

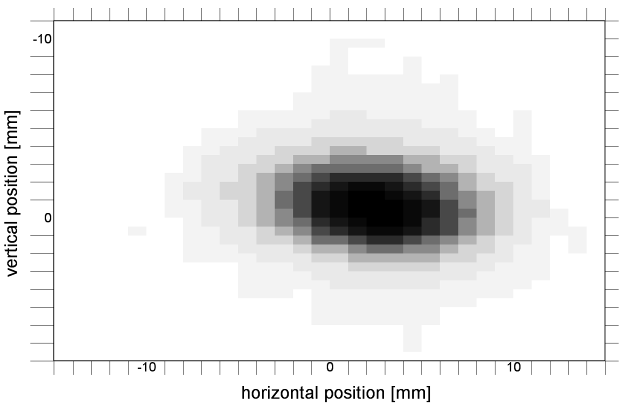


FIGURE 4. 2-dimensional beam profile. (Beam current 1 nA, beam energy 110 MeV.)

THIN PROFILE AND CURRENT MONITORS

Thin monitors placed at locations with large beam divergence and small beam diameter allow for a continuous observation of the beam with a limited increase of beam emittance due to scattering.

Monitors In Front Of The Degrader

These detectors consist of a stack of 6 μm thick titanium foils which are individually pretensioned and soldered to thick film (AgPd) coated [4] ceramic frames [3] (Fig. 5). A strip pattern with 1 mm pitch was etched [5] in some of the raw titanium foils [6]. The foils were sonic cleaned in acetone, 50% acetone - 50% isopropyl alcohol, isopropyl alcohol, demineralized water baths (2 minutes each) and then removed slowly from the water bath with the water film retracting gradually. After drying, they were locally sputtered with 0.27 μm $Ni_{75}V_{25}$ and 0.6 μm Ag to allow for soldering with solder paste [7]. During sputtering, the foil must stay at low temperatures to avoid bimetallic deformation.

At a separation between the planes of 2 mm, the active length between two anodes (with the measurement electrode in between) is again 4 mm. Two bulk current measurement foils, a horizontal and a vertical strip foil together with 5 anode foils and two outer grounded foils form a detector. Similar monitors equipped with actuators are located shortly after the cyclotron.

FIGURE 5. Thin profile monitor in front of the degrader. When used as MSIC, it is equipped with a hood with 50 μm titanium windows. Left: a single frame with strip foil.

Measures have to be taken to prevent fast venting of the beam line in order to protect the detector foils. A N_2-inlet via a needle valve was installed leading to a venting time of ~8 minutes. Together with an adapted flooding procedure this also prevents the titanium windows of the housing of the MSIC from folding back and thereby inducing fatigue.

Ionisation Chamber Monitors

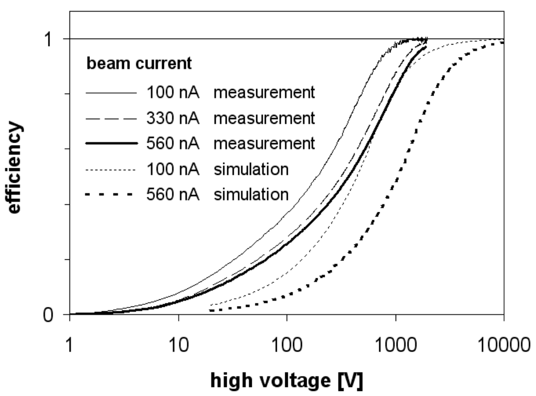
The ratio of signal to beam current was roughly determined to be 48 at a beam energy of 250 MeV and small beam currents.

With the operating voltage of 2000 V, saturation effects are much less severe than estimated from theory (Fig. 6 left), even at high beam current and the most focused beam. The difference can neither be explained by the rough assumption on the beam density distribution nor by possible measurement errors of up to 10 % due to calibration errors of the pre-series current measurement electronics. In addition, the strong beam current fluctuations caused by the ion source (Fig. 6 right) should even further increase saturation effects.

When switching on the beam to a high current, the signal of the ionisation chamber decreases over the first 20 seconds relative to the current readings of the secondary emission monitor and the following beam stopper (e. g. ~3% at 565 nA). This can be attributed to an increase of the temperature of the air in the chamber. Cooling down after switching off the beam takes roughly the same time.

The "afterglow" due to the activation of the detector was much less than with the thick monitors.

Microphonic noise is only significant as long as eigenmodes of the foils are excited by nearby moving actuators. Current oscillations of ~1 kHz with amplitudes corresponding to beam currents of up to ~0.2 nA_{pp} are introduced by moving the degrader actuator.



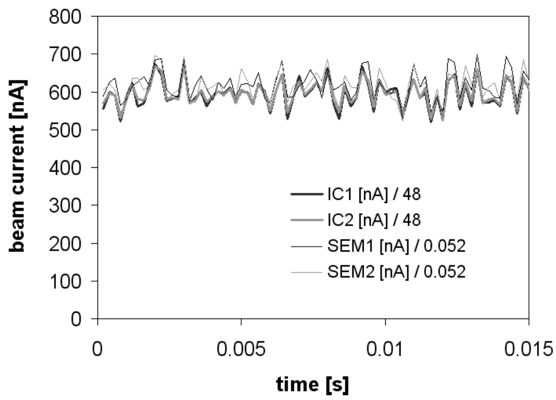


FIGURE 6. Left: Saturation curves of thin ionisation-chamber current monitor measured at a proton beam of 250 MeV and a beam diameter of ~2.4 mm full width quarter maximum. For the simulation according to Mie [8] a homogeneous beam diameter of 2.4 mm was assumed. Right: beam current fluctuations caused by the ion source. The signal is averaged over 0.2 ms by the measurement electronics and hence the actual fluctuations are probably larger. Similar noise fractions are present at lower beam currents.

Secondary Emission Monitors

When used as secondary emission monitors, a ratio of signal to beam current of 0.052 was measured. This ratio changes reproducibly as much as 5% by moving the beam over the detector.

An anode voltage of 30 V is sufficient to catch the bulk of the secondary electrons. A further increase to 300 V results in a signal drop of ~3%, independent of beam current. This is not understood.

Microphonic noise is similar to that of the ionisation chamber monitors, but is more aggravating due to the 1000 times lower beam signal level. Current oscillations of ~1 kHz with amplitudes corresponding to beam currents of up to ~25 nA_{pp} are excited by the omnipresent ground vibrations. Driving the nearby degrader actuator increases the noise level to ~60 nA_{pp} (at an anode voltage of 30 V).

Current Monitor In Front Of Gantry 1

A simpler set-up with an active diameter of only 12 mm is installed at the "control point" in front of Gantry 1. It is located behind a collimator of 8 mm diameter (Fig. 7). 6 µm thick titanium foils are glued to PCBs (Fig. 8). Two types of boards are used to provide high voltage, measurement and guard electrodes. The use of commercially available board thicknesses resulted in a foil separation of 2.5 mm corresponding to an active length of 5 mm. With the low beam currents used, saturation is not critical. Nevertheless, an anode voltage of 2000 V is applied to get a fast response. No microphonic noise was observed as expected for the small surface area.

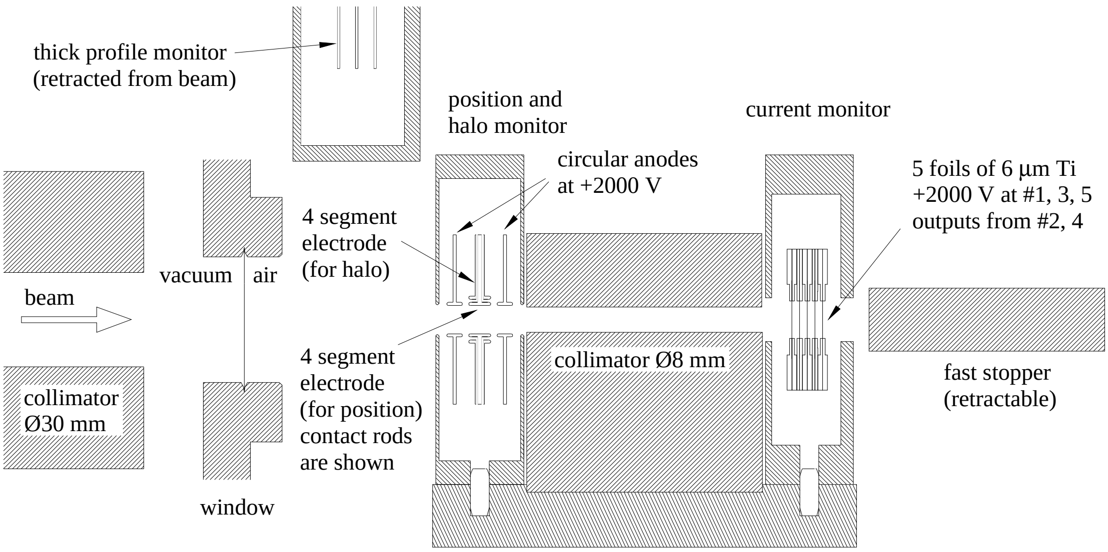


FIGURE 7. Set-up at the "control point" in front of Gantry 1.

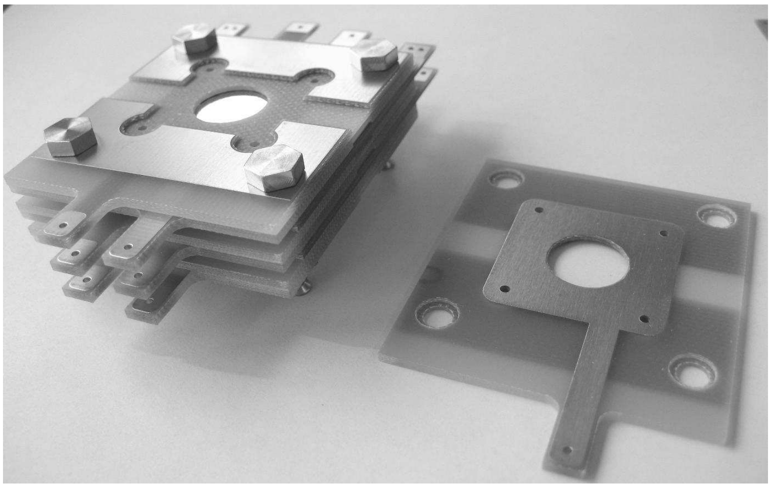


FIGURE 8. Thin current monitor in air. (Housing with high-voltage filter removed.) The four small holes allow the application of epoxy glue for the fixation of the foil. Electrical contact is provided by pressing the foil between the gold coated copper cladding of the FR4 boards.

POSITION MONITOR IN FRONT OF GANTRY 1

At the "control point" in front of Gantry 1 (and later also before Gantry 2 and Optis) the position of the beam is controlled by a segmented ion chamber with no electrodes intersecting the beam core (Fig. 9). (A second position measurement ~1 m in front is used to control the beam direction. This is provided by a stripline bpm. Nevertheless, its accuracy and bandwidth are limited due to the small signal to noise ratio at beam currents of below 1 nA.)

The positive ions created inside an active volume of 16 mm length and 9 mm diameter are pulled in the electric field configuration to four electrodes ("position monitor"). The surrounding volume is covered by another four electrodes which intercept the beam halo ("halo monitor"). The beam position is determined from the signal currents I_{left}, I_{top}, I_{right}, I_{bottom} as

$$x = (x' + y')/\sqrt{2} \quad , \quad -y = (y' - x')/\sqrt{2} \tag{1}$$

with $$x' = k_{\backslash} \frac{-I_{left} - I_{top} + I_{right} + I_{bottom}}{I_{left} + I_{top} + I_{right} + I_{bottom}} \quad , \qquad y' = k_{/} \frac{-I_{left} + I_{top} + I_{right} - I_{bottom}}{I_{left} + I_{top} + I_{right} + I_{bottom}}$$

and $k_{\backslash}$, $k_{/}$ a measure for the beam width in both diagonal directions. With the assumption $k_{\backslash} = k_{/} = k$ the equations simplify to

$$x = k\sqrt{2}\,\frac{I_{right} - I_{left}}{I_{left} + I_{top} + I_{right} + I_{bottom}} \quad , \qquad -y = k\,\sqrt{2}\,\frac{I_{top} - I_{bottom}}{I_{left} + I_{top} + I_{right} + I_{bottom}} \tag{2}$$

The beam positions determined according to Eq. (1) with position and halo monitor are compared to the 1. moments of the distributions which were measured simultaneously by a thick MSIC profile monitor. For this the beam was swept horizontally over the monitors by a steering magnet (Fig. 10). $k_\backslash$ and $k_/$ are fitted by requiring horizontal slopes in the points of symmetry which define the monitor axis. Offsets between the readings of ~1 mm in both directions were observed although all monitors were aligned within 0.1 mm. Azimuthal asymmetry of the 2-dimensinal beam profile is a possible explanation. The noise of the position readings is of the order of 0.2 mm_{pp}.

The use of Eq. (2) with an only roughly estimated k leads to a distortion of the curves around the points of symmetry. Nevertheless, this "position" information can still be used as input to a beam centring procedure.

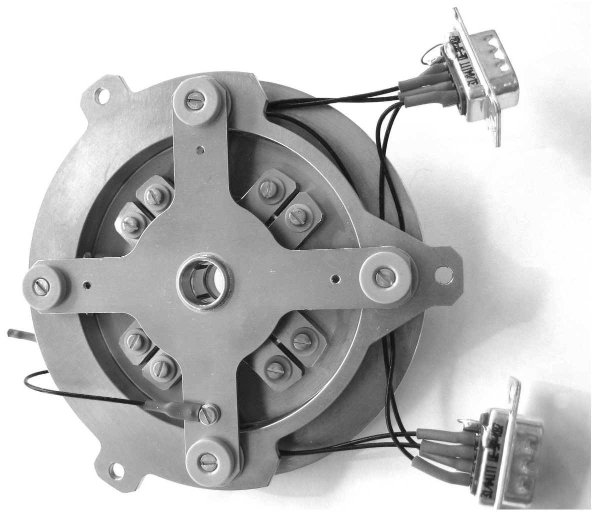


FIGURE 9. Position and halo monitor at the control point in front of Gantry 1. (Housing with high-voltage filter removed.) Anode voltage 2000 V.

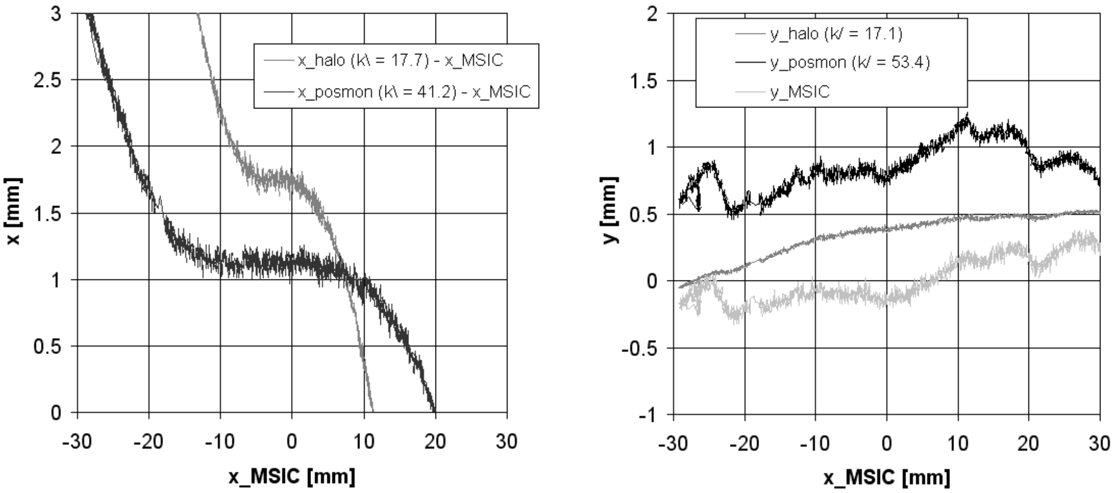


FIGURE 10. Comparison of position information of position and halo monitor with MSIC. Beam current 1.8 nA. Beam energy 220 MeV. Beam width horizontally ~12 mm and vertically ~7 mm full width quarter maximum (beam not fully focused). Strip pitch of MSIC 1 mm. Integration time of all currents 20 ms.

HALO AND LOSS MONITORS

Beam losses are detected in two ways. Near each quadrupole doublet or triplet where the beam diameter is large, a halo monitor is installed. This 4-segment ionisation chamber protrudes circumferentially 5 mm into the beam pipe and measures directly the beam halo (Fig. 11). With an active length of 9.4 mm and a sensitivity of the current measurement of ~10 pA, beam fractions of down to 0.1 pA can be detected. On the other hand, external ionisation chambers of 2 litre active volume are placed at the exits of the dipole magnets. All monitors are sensitive only if the beam passes through directly or is lost nearby (Fig 12).

As opposed to high-power machines, the loss and position information of these monitors is not used primarily for machine protection but as an additional check of the correctness of the set "beam tune".

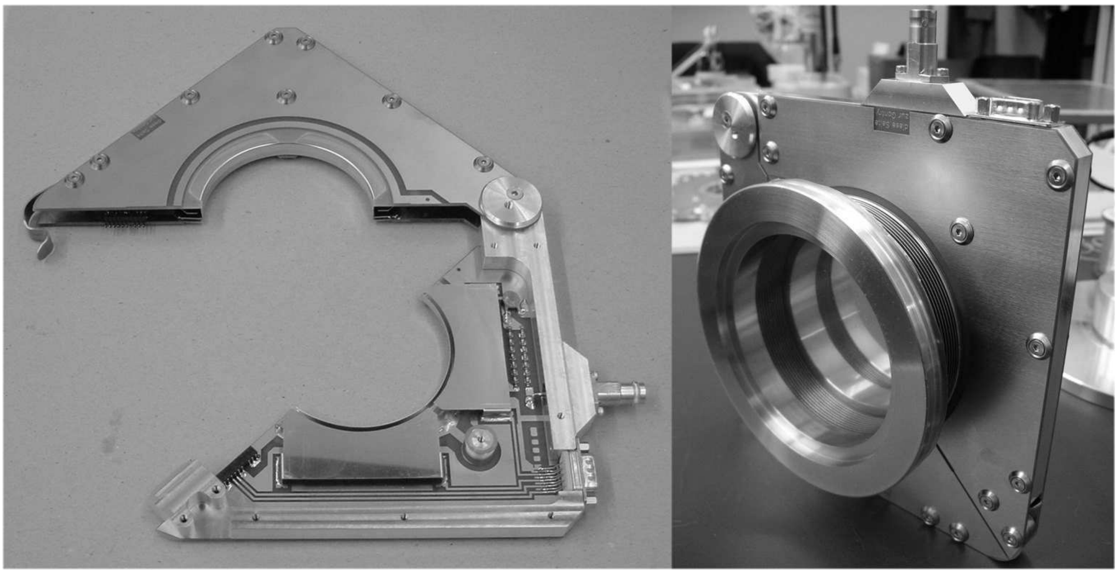


FIGURE 11. Halo monitor.

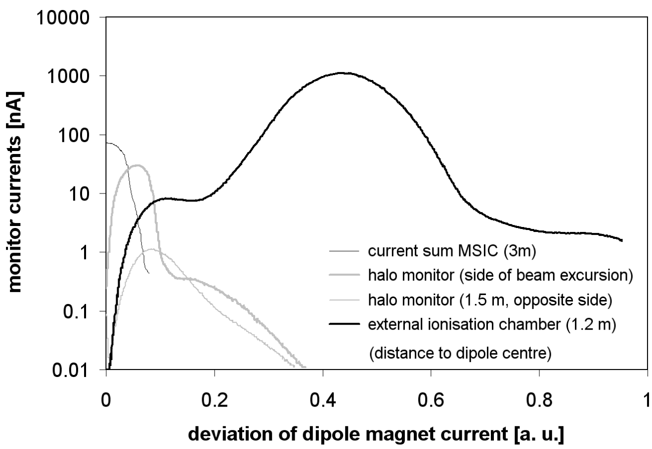


FIGURE 12. Signal levels of several monitors when the beam is steered far off-axis. Beam current 1.4 nA. Beam energy 230 MeV.

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