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BEAM PROFILE MONITORS FOR FAST AND SLOW EXTRACTED
PROTON BEAMS

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Introduction

This paper describes two beam profile monitors based on the principle of secondary emission (SEM) from thin foils, and a profile indicator based on luminescence from inorganic screens.

These profile monitors have been designed for the Beam Transfer System of the 28 GeV - Intersecting Storage Rings which are at present under construction at CERN¹.

Types

The first type SEM monitor is called "SEM-grid profile monitor". It uses a grid of 15 horizontal and 15 vertical narrow aluminium foils which measure the beam intensity profile in the x and y plane.

The second type SEM monitor, an "SEM - probe beam scanner" consists of thin secondary emission probes driven by stepping motors, which scan along the two main axes, of the beam profile. The probes can be programmed in two ways: a) to find the beam edges in both beam planes, b) to make a plot of the intensity distribution.

The third monitor, a "Screen Profile Indicator", uses screens of activated lithium glass fibres or thin discs of the same material, which are observed by a TV camera.

The functional difference between the first and the third type of profile monitor is that the SEM grid monitor produces electrical signals proportional to the horizontal and vertical beam intensity distribution while the screen gives direct visual indication of the beam cross-section. The visual indication is more useful in showing irregularities in the shape of the beam cross-sections.

The SEM - beam probe scanner requires much time to measure the beam profile but has attractive possibilities as a "limit switch" of drift in the position of the beam.

Requirements

Criteria set for the SEM profile monitors described in this paper demand the following additional features: a) they must operate with fast-extracted beam pulses (2.1 μ s) or with single bunches (10 ns) and with slow-extracted beam pulses (a few hundred msec); b) the control and the output signals should be in a digital form in order to be able to use the control computer for certain operations.²

All three profile monitors have to operate in ultra-high vacuum (10^{-10} Torr) in some areas, and must therefore be bakeable at 150 to 250° C.

The Beam Transfer System which has a total length of about one mile consists of four complicated beam transport channels. The many focussing and bending magnets are powered by about 100 magnet supplies.

In order to set up and analyse the beams in these channels a comprehensive beam observation system is required.³ The functions of the profile monitors in this system are the following:

Twenty-four SEM - Grid profile monitors are required a) for adjusting the beam, b) for emittance measurements and c) for matching the phase space ellipses of the beam to the phase space ellipses of the four transport channels and of the two storage rings.

Four SEM - probe beam scanners are required, primarily to check on drift in (slow-ejected) beam position.

The luminescent screen profile indicators (about 22) will be used for adjusting the beam in locations where the beam shape is of interest and near narrow passages in the vacuum chamber such as the gap of the inflectors.

The beam observation system will, besides the monitors described in this paper also employ 7 pick-up electrodes and 7 current transformers to measure in each channel respectively, drift in beam position and possible beam intensity loss. These monitors operate on fast-ejected beam pulses only.

In the following paragraphs, the principles, the construction and the performance of the three profile monitors are described.

SEM - Grid Profile Monitor

Principle

The SEM - grid profile monitor consists of a row of 15 horizontal and 15 vertical foils mounted individually on two ceramic frames (Fig. 1). The aluminium foils are 2 mm wide, 0.02 mm thick and 5 mm apart. Each foil is connected to an amplifier. A signal is produced by low energy secondary electrons emitted from both sides of the foils by traversing protons with an efficiency of about 4%. The secondary electrons are trapped by three positive collector electrodes (Fig. 1).

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The positive charge left behind on each foil is proportional to the number of protons which traverse the foil during a beam pulse. The charge is collected on 100 pF cable capacitance and measured by a sampling amplifier with 10^{11} ohm input impedance. The output of the amplifiers are switched sequentially into a cable for display on a CRT (Fig. 2).

The foil assembly is mounted on a pendulum mechanism by which it can be moved in and out of the beam (Fig. 3).

Multiple scattering

The two outer collector electrodes are ring shaped and do not intercept the beam. A third electrode, consisting of a 5 micron thick aluminium foil is placed between the 2 frames. The function of this electrode is not only to act as a collector, but also as a screen between the horizontal and vertical signal foils, and for applying a test pulse which is picked up capacitively by the signal foils.

The average density of the material placed in the beam path by this electrode and the signal foils is $5,7 \text{ mg/cm}^2$. The multiple scattering angle for 28 GeV/c protons varies between $4 \cdot 10^{-6}$ rad. and $1.2 \cdot 10^{-5}$ rad., depending on whether they traverse one, two or three foils.

Resolution

The spatial resolution, which is 5 mm for the foil assembly shown in Fig. 1 can be improved by one or more interpolation measurements. The pendulum arm, therefore, is mounted at an angle of 45 degrees (Fig. 3), so that the foils can be moved simultaneously in the x and y plane by, for example, 2,5 mm for a displacement of the arm by $2,5 \sqrt{2}$ mm. The displacement takes place in the time gap between two beam pulses.

Electronics

The electron emission from the foils produces positive potentials on the 100 pF capacitors with levels varying between 5 and 1000 mV. The 10^{11} ohm input impedance of the sampling amplifiers connected to each capacitor assure a time constant of 10 seconds, which is long enough to make measurements on slow-ejected beams.

The output signals of the amplifiers are sequentially switched into a cable at a rate of 20 kc/s, and can in principle be displayed directly on a memoscope as a histogram (Fig. 2).

Between each measurement the capacitors are discharged by reed relays. The timing of the reed relays and of the signal switching at the output of the amplifiers can be adjusted such that a beam profile of a slow-ejected beam can be measured as a function of time. The best time resolution in this mode is about 10 ms.

Fig. 1 - SEM - grid foil assembly

Fig. 2

Histogram of hor. and vert. beam profile

Signal handling and display

A commercial analogue-digital recorder/generator from E.H. Research Laboratories (Model 702) will be used in the final system to interface all the 24 monitors to the computer and the CRT displays.

This recorder-generator can read and store 1000 analogue signals at a maximum rate of 100 kc and reproduce them in analogue or digital (BCD) form. It can read back the signals at any convenient speed and display a histogram or a smooth curve on a low priced CRT display (rather than the memoscope mentioned above) or a curve tracer.

The recorder-generator is ideally suitable for mixing the signals obtained from two sequential beam pulses if an interpolation measurement is made.

Design details

The aluminium foils are spring loaded to avoid breaking for example due to differential expansion during baking. The ceramic (magnesium silicate) support pieces are machined before firing. After firing they have excellent out-gassing properties which are comparable to stainless steel. Thorough cleaning is required

of the ceramic parts and of the 32 bakeable feedthroughs in order to obtain 10^{12} ohm insulation, and to avoid gas release. The 30 foils are connected to the feedthroughs via spot-welded stainlesswires (not yet completed in Fig. 3). The device is cleaned in an ultrasonic bath before assembly. Units to be used in the UHV region, will be baked and pumped down to 10^{-10} Torr on a test stand before installation.

Performance

A prototype has been tested in slow-and fast-extracted beams at the PS. The sensitivity is just high enough to measure single PS bunches with a density of about $2 \cdot 10^{10}$ protons/cm². The profile of the PS slow-ejected beam was measured as a function of time, showing an increase in size by more than a factor of two over 100 ms.

SEM - Probe Beam Scanner

Principle

The probe of the scanner consists of an aluminium cylinder with a diameter of 4 mm and 0,02 mm wall thickness. The signal, which is produced by secondary emission, is proportional to the number of protons which traverse the probe.

The probe is driven by a stepping motor. The digital drive circuits for the stepping motor are triggered by the repetition rate of the ejected beam pulses (once every second to once every 3 seconds) in such a way that the probe is always moved to its new position between two beam pulses.

This monitor, with one probe for each beam axis, is capable of providing the same information as the SEM grid monitor but is much simpler to construct.

However, the disadvantage of the probe scanner is that it requires 9 consecutive beam pulses to find the beam edge and another 10 to 20 to measure the beam intensity profile. During this time the beam must remain stable.

Scanning action

The angle α over which the probe can move, starting at the rest position (see Fig. 4), corresponds to 512 steps of the stepping motor. When the command "SEARCH BEAM EDGE" is given, the logic and control box applies 256 pulses to the stepping motor, which moves the probe over an angle $\alpha/2$ into position 1. If the probe does not detect a signal in this position on the next beam pulse, it will be moved in the same direction over an angle $\alpha/4$ (128 steps) to position 2.

If the probe is now in the beam in this position, it will pick-up a signal which, after amplification, sets switch "S" to position "OUT". This causes the probe to move back before the following beam pulse over an angle $\alpha/8$ (64 steps) to position 3 at which point, it is again out of the beam. Next, it will move in again over an angle $\alpha/16$ etc.

This scanning action occurs during 9 consecutive beam pulses until the probe is located at the edge of the beam. The coordinate of this beam edge will then be read and recorded from a calibrated signal on a helipot with sinusoidal characteristic.

Now the "SCAN" command can be given to measure the intensity profile along this axis. The resolution of the scanning can be selected by driving the motor one or more steps every beam pulse. The signals from the amplifier and the helipot can be used to draw the intensity profile on an x - y plotter or on a memoscope. The signals can also be read into the recorder-generator discussed in the previous section.

Limit switch feature

This monitor can also be used as an adjustable limit switch to detect drift in beam position. In this application, the probe will first be given a command to find the beam edge as described above and will then be moved away from the beam edge for example by one cm. A warning signal will then be produced if the beam drifts one cm or more. This feature is particularly useful for slow-ejected beams.

Performance

A prototype was tested successfully at the PS in the 2.1 μ s fast-ejected beam pulse with 20 bunches, with a single bunch, and in a slow-ejected beam.

Screen Profile Indicator

Luminescent screens placed in the beam path and observed via a TV camera are commonly used for beam observation. They are very convenient for setting up the beams and give a good appreciation or irregularities in the beam cross-section.

Screen materials

Usually, a 0,03 to 0,1 mm thick layer of activated ZnS is applied with a suitable binder (sodium silicate, collodion or epoxy) to a thin aluminium foil. Such screens, however, become inactive after exposure to about 10^{17} protons/cm² and they are unacceptable in ultra-high vacuum. Therefore, we tested various inorganic materials. In particular, the performance of cerium activated lithium glass (e.g. type NE 901 from Nuclear Enterprises), sapphire and quartz were compared with a ZnS screen.

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Values on the minimum visible beam current for these materials observed with a Vidicon TV camera and with a 4.5 lens under optimum conditions are shown in the following table:

	ZnS	NE 901	Sapphire	Quartz	
	.1 mm layer	1 mm disc	.2mm fibres	1 mm disc	1 mm plate
na/cm ² (d.c.)	10	20	70	40	140
protons/cm ² (per pulse)	10 ¹⁰	2.10 ¹⁰	9.10 ¹⁰	5.10 ¹⁰	1.8.10 ¹¹
price index (dollars)	5	100	30	150	20

D.c. beam current values are given in nA/cm² and for pulsed beams in protons/cm². We estimated from tests that the average pulsed beam current required to produce a certain brightness on the TV monitor was 20% of the current required with a d.c. beam.

Lithium glass: (NE 901) seems the most suitable material for the beam densities encountered in the beam transfer system. A 1 mm thick NE 901 disc is only two times less sensitive than ZnS. This plate showed some browning after exposure to 2.10¹⁵ electrons of 2 MeV per cm². However, the browning did not affect the light output, and was released easily. For example a brown spot practically disappeared in a few minutes when the electron beam, depositing only about 20 mW in the plate, traversed the plate at a position 2 cm away from the spot.

The multiple scattering angle for a 1 mm plate is of course considerable ($\approx 10^{-4}$ rad. for 28 GeV/c) but this can be reduced with the fibre screen as shown in Fig. 6. This screen is made of 0,3 mm thick fibres spaced at 4 mm intervals, and causes only (7.5%) of the beam to be scattered over an angle of 5.10⁻⁵ rad.

Sapphire (Al₂O₃) is two times less sensitive than NE 901 and the discs are more expensive. Browning starts only after exposure to 8.10¹⁷ protons/cm². Unexplained effects, such as: changes in sensitivity and light rings outside the beam spot, were observed with this material after the browning was released in a baking cycle.

Quartz is not very sensitive. It is suitable for use in high intensity beams where thermal shock becomes a problem.

Construction details

Fig. 6 shows a spindle holding three different screens each of which can be moved into the beam at an angle of 45 degrees. The spindle is rotated from outside the vacuum housing via a rotary feedthrough. The fourth position of the spindle is not occupied and

allows the beam to pass freely. One mm thick lithium glass discs will be used to observe low intensity beams (it is hoped that a large part of machine development work can be done with single bunches) and the fibre screen for normal beam intensities. The third position (shown holding another disc in Fig. 5) is actually a spare position which may eventually be equipped with a second grid with thicker fibres and a wider spacing.

Reference marks will be provided on the screens. They can be illuminated via the vacuum window (Fig. 7) with a lamp of variable intensity. An adjustable mirror mounted on the housing will direct the light into a mirror telescope and TV camera mounted as shown.

A mirror telescope is chosen rather than special lenses of stabilized glass which would otherwise be needed to overcome radiation browning. An additional benefit is that a telescope collects more light than a lens on account of its larger diameter (e.g. D = 100 mm), and provides a larger magnification at the same distance, because of its larger focal distance (e.g. f = 250 mm).

The windows for the monitors in the normal beam transfer vacuum (10⁻⁶ Torr) are made of lead glass clamped with an indium seal. Bakeable windows for the UHV monitors are made of Pyrex for the larger diameters, sapphire for the smaller ones. Pyrex browns under radiation but this can be released by exposure to an ultra-violet lamp, or by baking at a temperature higher than 200° C.

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References

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Fig. 3 - SEM - grid monitor

Secondary emission probe beam scanner

Fig. 4

Fig. 5 - SEM - probe scanner (prototype)

Fig. 6 - Screen profile indicator

Luminescent screen profile indicator

Fig. 7

 