A CARBON FILAMENT BEAM PROFILE MONITOR
FOR HIGH ENERGY PROTON–ANTIPROTON STORAGE RINGS

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Contributed to the "Workshop on Intensity Limitations in Storage Rings"
at Brookhaven National Laboratory on July 14th–27th 1979

* CERN
** FNAL
1. Introduction

The measurement of the evolution of the transverse profile of the stored beams in high energy proton storage rings such as the p-p colliders at CERN and at FNAL is of considerable importance. In the present note, a simple monitor is discussed which will allow almost non-destructive measurement of the profile of each individual proton and antiproton bunch separately. It is based on the "flying wire" technique first used at C.E.A.\(^1\) and more recently at the C.P.S.\(^2\). A fine carbon filament is passed quickly through the beam, acting as a target for secondary particle production. The flux of secondary particles is measured by two scintillator telescopes, one for protons and one for antiprotons, having an angular acceptance between 30 and 100 mrad. Measurements of secondary particle production performed at FNAL in this angular range show that a very respectable flux can be expected.

2. General considerations

In the SPS proton-antiproton collider the protons and antiprotons will be stored in two counter-rotating beams at 270 GeV/c. Each beam consists of 6 bunches of \(10^{11}\) particles per bunch. The wire diameter should be sufficient to give a reasonable flux in the detector in the tails of the beam. The displacement speed should be such that the wire moves at least by one diameter during one revolution period of the machine i.e. \(v = \frac{d}{\text{rev}}\), where \(d\) is the wire diameter. On average, each proton then traverses the material only once. The emittance blow-up and particle loss should be small and therefore a low Z material is required. In addition, the thermal properties should be compatible with the heating and thermal shock experienced during traversal of the beam. All of these conditions are satisfied by carbon filaments, and they have already been used in the more hostile environments of the CPS\(^2\) and the FNAL main ring\(^3\).

The following parameters are assumed.

| Beam \(^4\) |
|-------------------|-------------------|
| Maximum intensity | \(1.2 \times 10^{12}\) particles |
| Energy            | 270 GeV/c          |
| \(E_{\text{p}}\)  | proton emittances  |
| \(E_{\text{v}}\)  | at 270 GeV/c       |
| \(3.5 \times 10^{-8}\ \pi \text{ rad m} \) | \(6.9 \times 10^{-8}\ \pi \text{ rad m} \) |
| \(E_{\text{\tilde{p}}}\) | antiproton emittances |
| \(E_{\tilde{v}}\) | at 270 GeV/c       |
| \(1.9 \times 10^{-8}\ \pi \text{ rad m} \) | \(3.8 \times 10^{8}\ \pi \text{ rad m} \) |
| \(\delta_{\text{H}}\) | betatron functions |
| \(\delta_{\text{v}}\) | at wire location   |
| 50 m              | 50 m               |
WIRE

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbon Filament</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Density</td>
<td>2.3 grams/cc</td>
</tr>
<tr>
<td>Displacement Speed</td>
<td>4.3 m/sec</td>
</tr>
<tr>
<td>Radiation Length</td>
<td>42.7 grams/cm²</td>
</tr>
<tr>
<td>dE/dx</td>
<td>1.78 MeV cm²/gram</td>
</tr>
<tr>
<td>Total Cross Section</td>
<td>40 millebarns/nucleon</td>
</tr>
<tr>
<td>Heat Capacity</td>
<td>0.24 Cal/gram °C at 400 °K.</td>
</tr>
</tbody>
</table>

3. Emittance blow-up

The average thickness of the wire of diameter d is d/4. The average r.m.s. projected scattering angle due to multiple coulomb scattering is

\[
\delta \theta = \frac{0.015}{270} \left( \frac{\pi d}{4} \times \frac{2.3 \text{ grams/cm}^2}{42.7 \text{ grams/cm}^2} \right)^{\frac{1}{2}}
\]

= 1.1 μrad for d = 0.1 mm.

The emittance blow-up is

\[
\frac{\delta \varepsilon}{\varepsilon} = \frac{2 \pi \beta \delta \theta^2}{\varepsilon}
\]

If the device is placed somewhere near the centre of a lattice half-period where \( \beta_H = \beta_V \sim 50 \), then for the smallest foreseen emittance (antiprotons in the vertical plane) we have

\[
\frac{\delta \varepsilon}{\varepsilon} = 0.6\%
\]

4. Heating

The total energy deposited in the wire is

\[
1.2 \times 10^{12} \text{ protons} \times 1.78 \frac{\text{MeV cm}^2}{\text{gram}} \times \frac{2.3 \text{ grams}}{\text{cm}^3} \times \frac{\pi d}{4} \text{ cms} \times 1.6 \times 10^{13} \frac{\text{joules}}{\text{MeV}}
\]

= 6.3 \times 10^{-3} \text{ joules}
Assuming that all bunches have the vertical emittance of the antiprotons, the vertical beam size is about 2 mm at the position of the wire. The mass of material into which the heat is deposited is then $3.6 \times 10^{-5}$ grams. Assuming no conduction or radiation loss during the passage through the beam, the temperature rise is

$$\Delta T = \frac{6.3 \times 10^{-3} \text{ joules}}{3.6 \times 10^{-5} \text{ grams}} \times \frac{1 \text{ calorie}}{4.18 \text{ joules}} \times \frac{1 \text{ gram}}{3.24 \text{ calories}}$$

$$= 174 \degree C.$$  

5. **Particles lost**

The probability that a particle will be lost in traversing the filament is

$$40 \times 10^{-27} \frac{\text{cm}^2}{\text{nucleon}} \times \frac{\pi d}{4} \frac{\text{cms}}{\text{cm}} \times 2.3 \frac{\text{grams}}{\text{cm}^2} \times 6.02 \times 10^{23} \frac{\text{nucleons}}{\text{grams}}$$

$$\sim 4.4 \times 10^{-4}$$

i.e. 0.04% per scan

6. **Detector**

Measurements at 400 GeV/c with a similar target at FNAL \(^3\) in the range 350 to 1700 mrad have shown that for a single counter (veto counter in figure 3 of the reference), the differential cross section per nucleon can be fitted by

$$\frac{d\sigma}{d\theta} = \frac{67}{(0.1 + \theta)^2} \text{ millibarns per nucleon per steradian}$$

Thus, if we have an annular detector around the beam pipe with an angular acceptance between 30 and 100 mrad, the cross section would be

$$2\pi \int_{0.1}^{0.1} \frac{67}{(0.1 + \theta)^2} \sin \theta \, d\theta \ \sim \ 67.2 \text{ mb/nucleon}$$

0.03

For a gaussian beam distribution, the number of particles per bunch passing through the wire a distance $x$ from the beam centre is

$$N(x) = \frac{N_0}{\sqrt{2\pi}} \cdot \frac{24}{\sqrt{\varepsilon B}} \cdot \frac{e^{-\frac{x^2}{\varepsilon B}}}{\sqrt{\varepsilon B}}$$
Where $N_0$ in the total number of particles per bunch. The number of counts in the detector would then be

$$N_c(x) = \frac{N_0}{\sqrt{2\pi\sigma}} \cdot \frac{\pi \sigma d^2}{2} \cdot A \cdot e^{-\frac{2x^2}{\varepsilon \beta}}$$

where $A = 1.38 \times 10^{24}$ nucleons/cm$^2$

$\sigma = 67.2 \times 10^{-27}$ cm$^2$/nucleon

For an emittance $\varepsilon \beta \gamma = 100$ mm.mrad(protons with a factor of 5 blow-up) this would give $1.3 \times 10^6$ particles through the detector in the beam centre and $1.7 \times 10^5$ at 2 standard deviations for $10^{11}$ protons per bunch. This flux is too low for secondary emission detectors and marginal for an ion chamber, which also has clearing problems. Therefore we propose a simple scintillator telescope (figure 1). Due to the strong forward peaking of particle production, two separate telescopes can be used (for protons and one for antiprotons).

Each bunch produces a burst of secondary particles of less than 5 nanoseconds duration. The integrated pulse height from the photo multiplier anode would be digitised and stored in a memory in the time interval between bunches ($\sim 3.8$ $\mu$sec). In this way the profile of each individual bunch can be built up.

7. Conclusion

The carbon filament beam scanner linked to a scintillator telescope offers a simple, almost non-destructive method of measuring the profile of each individual bunch in the SPS $p\overline{p}$ collider. The estimated particle flux in the telescope is sufficient to provide a spatial resolution of better than 0.1 mm well into the tails of the beam.

References

2. P. Lefèvre, PS/DL/Note/78-8 (1978)
Figure 1

Schematic diagram of double scintillator telescope