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A SMALL-EMITTANCE, HIGH-INTENSITY PROTON BEAM

A. Maschke
National Accelerator Laboratory

ABSTRACT

The design of a collimated proton beam of intensity 10^{-3} of the external proton beam is considered.

Let us look at a method for obtaining a proton beam of intensity 10^{-3} of the initial beam.

At NAL, the beam emittance prior to the target is ≈ 0.04 cm-mrad. If focused to a spot of 1 mm, the total angular divergence would be ± 0.2 mrad. The proposal is to build a "collimator" to take a small portion of this beam.

The coulomb scattering in a target (1 mm), could be expected to about double the phase-space area of the beam, to ± 0.4 mrad say. Also, since the scattering is of the same order as the angular divergence in the beam, the central phase-space density will not be appreciably altered.

Now let us look at the phase-space transmission through a small rectangular collimator of length ℓ and aperture a. The phase-space acceptance in each plane is a^2/L.

For an attenuation factor of 1,000, we need about 30 in each plane; therefore

$$\frac{a^2}{L} = \frac{E_m}{30} \frac{0.04}{30} \text{ cm-mrad.}$$

Now stability criteria dictate the size of the aperture to be $\approx 1/\sqrt{30}$, or about 1/5 the beam size; therefore $a \approx 0.2$ mm, or 0.02 cm (8 mils, say). This determines $L = 0.0004 \times 30/0.04 \times 10^3 = 300$ cm.

Therefore, a collimator of 8 mils diameter, 10 feet long will give a beam intensity of 10^{-3} of the incident protons. The emittance of this beam will be ≈ 0.0013 cm-mrad. The maximum divergence will be $\pm 0.02/0.3 = 0.067$ mrad. After 400 feet, this means a beam size of ~ 1.5 cm.

Now it is interesting to look at the solid angle of this beam, $\Delta\Omega \approx 10^{-8}$ steradians. Also, the beam is only about 1/30 of the target size. The equivalent flux down the beam can be computed therefore by comparison to a beam of about 10^{-10} steradians.

It is interesting to compute the flux of diffracted protons which get down the hole.

$$\sigma_T = \frac{4\pi}{k^2}\ \mathrm{Im}\ f(0).$$

Assuming $f(0) \approx \mathrm{Im}\ f(0)$, we have

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2}\left(\frac{k^2\sigma_T}{4\pi}\right)^2 = \frac{k^2\sigma_T^2}{16\pi^2}$$

$$k^{-1} = \frac{\hbar c}{p} = \frac{2\times 10^{-11}}{2\times 10^5\ \mathrm{MeV}/c} = 10^{-16}\mathrm{m}$$

$$\frac{d\sigma}{d\Omega} = \frac{10^{+32}\times 30\times 10^{-27}}{160}\ \sigma_T.$$

If we assume a mean free path target, we get

$$\left.\frac{dN}{d\Omega}\right|_{\substack{\text{incident}\\ \text{proton}}} = 5\times 10^{+4}.$$

With the effective solid angle factor of 10^{-10} we get 5×10^{-6}/incident proton.

Now our previous calculation gave 10^{-3} proton/incident proton, so that the contamination of the beam by diffracted protons is 1 in 200. This is sufficient to show that contamination by other products (quasi-elastic protons, π's, etc.) is down by a much larger factor. An estimate of quasi-elastic protons, between 190-200 GeV, is down by a factor of 10^{-4}.

If extreme purity of the beam is desired, then a momentum analysis is called for. Since the beam has such a small angular spread (0.13 mrad), a bend of 13 mrad would increase the purity factor substantially to about 1 part in a million. Note that the energy spread in the primary proton beam is $\approx \pm 10^{-4}$ at any instant of time. A 1% bite would give a resultant beam spectrum as shown (see Fig. 1).

In the example considered, 30 times more beam entered the collimator hole than left it. It is of some interest, therefore, to see what happens to these. They will enter the collimator walls at angle of about 0.1 mrad on the average. They will coulomb scatter in the wall, and about half of them will random-walk back into the collimator hole. With a proper choice of materials, ~90% of the protons will have made strong interactions in the walls of the collimator. Since this still leaves 3 times more particles than desired, this process must be repeated in a "clean-up" collimator downstream from the phase-space collimator. The clean-up collimator is probably best located about 20 feet downstream of the PSC. This will probably reduce the phase-space noise by another factor of 10 (about 30% contamination). The final clean-up collimator (at ~200 feet, say) will clean the beam up by about a factor of 100.

Figure 2 shows the phase space accepted by the collimator compared with the phase space of the beam. Substantial "wobble" in either position or angle will not seriously affect the intensity of the beam.

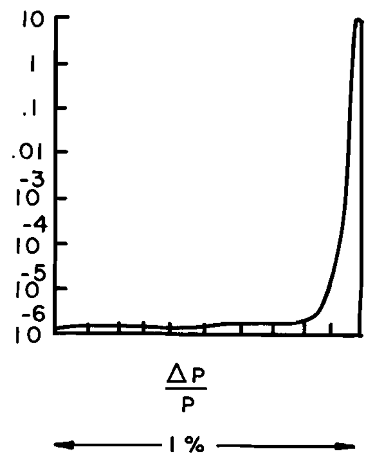

Fig. 1. Spectrum of beam contained in a 1% momentum interval.

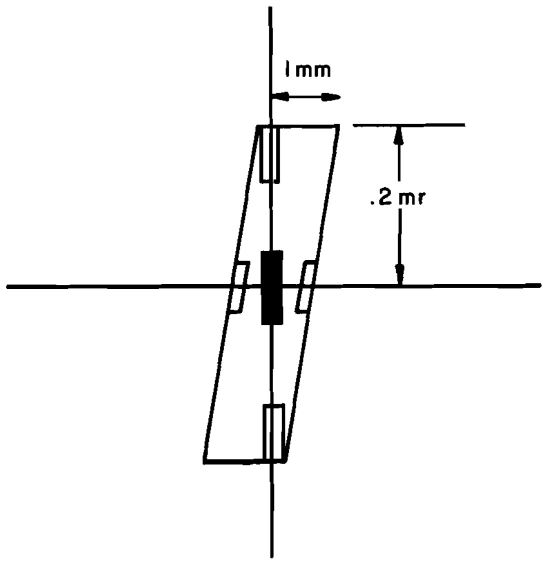

Fig. 2. Phase space about 10 ft downstream of the target.