ACCELERATOR DEPARTMENT

Internal Report

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EFFICIENCY OF MULTIPLE TRAVERSAL TARGETS

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A proton traversing a thin target in an AG synchrotron such as the Brookhaven AGS will lose so little energy by ionization that, because of the strong momentum compaction, it goes around the machine again and can make another traversal. Ideally one might expect it to continue until it makes a nuclear collision in the target; on the average this will occur after it has traversed one mean free path of the target material. In actual fact, the proton may also be lost by hitting the vacuum chamber wall (or some other aperture stop), because (a) in every traversal, multiple Coulomb scattering in the target induces betatron oscillations which may build up to a sufficient amplitude to enable the particle to hit the wall; (b) the orbits drift inward (in a rising magnetic field with the rf off, or if the energy loss has kicked the particles out of the stable acceleration "bucket") and eventually drift past the inner edge of the target to the inner limit of the aperture. We shall neglect effect (b) here, which means that our results are valid only if the target is thick enough that the time necessary to make enough traversals for one mean free path is small compared to the time necessary to drift to the edge of the aperture.

We define the <u>target efficiency</u> F as the probability that a proton dies by making a nuclear collision in the target rather than by hitting the limit of the synchrotron aperture. Diffraction scattering by the nucleus or the nucleons in the nucleus is included in the definition of nuclear collision if the diffraction angle is large enough to cause the particle to hit the chamber wall.

According to the scattering theory of Blachman and Courant[1] the probability that a proton survives after traversing a given amount of target material is

$$P_o(x) = 2 \sum_{s=1}^{\infty} \frac{1}{\lambda_s J_1(\lambda_s)} e^{-\lambda_s^2 \langle\theta^2\rangle /4\theta_o^2} \tag{1}$$

where λ_s is the s-th root of the Bessel function $J_o(\lambda)$, J_1 is the first-order Bessel function, $\langle\theta^2\rangle$ is the mean square angle of multiple Coulomb scattering resulting from the traversal of thickness x of target material, while $\theta_o = A\nu/R$ is the scattering angle required to cause a particle to strike the wall of the aperture. Here A = semiaperture (more precisely, the minimum distance between the equilibrium orbit touching the target and the edge of the aperture of the accelerator); R is the radius of the orbit and ν the number of betatron oscillations per revolution, so that R/ν is $1/2\pi$ times the wave length of oscillations.

Equation (1) is valid in the absence of nuclear interactions. If the nuclear mean free path is L_n, the actual survival probability is (1) multiplied by

$$e^{-x/L_n}$$

and the fraction of particles that have undergone nuclear collisions up to traversal x is

$$F(x) = \frac{1}{L_n} \int_0^x P_o(x)\, e^{-x/L_n}\, dx. \tag{2}$$

[1] N.M. Blachman and E.D. Courant, Phys. Rev. 74, 140 (1948)

The mean square scattering angle occurring in (1) is, according to the Molière theory.

$$\langle \theta^2 \rangle = \left(\frac{15 \mathrm{Mev}}{E} \right)^2 \frac{x}{L_R} \tag{3}$$

where E is the particle energy (assumed relativistic), and L_R the radiation length in the target material.

Let us define the quantity

$$Y = \frac{1}{4} \quad \frac{\theta_1{}^2}{\theta_o{}^2} \quad = \quad \frac{225\ R^2 L_n}{4E^2 A^2 v^2 L_R} \tag{4}$$

where $\theta_1{}^2$ is the mean square scattering angle for the traversal of one mean free path. Integrating (2) to infinity (i.e. assuming that the geometry of the target permits a particle to keep traversing the target until it dies), we obtain the target efficiency

$$F = 2 \sum_s \frac{1}{\lambda_s J_1 (\lambda_s) \ (1 + \lambda_s{}^2 Y)} \tag{5}$$

which depends only on Y. A graph of this universal target efficiency function is given in Fig. 1.

To compute Y, and hence F, one must know the nuclear mean free path and radiation length in the given target material, as well as the effective net aperture of the accelerator. The latter quantity depends very much on how "bumpy" the particle orbits are, and also on the location of the target. In the attached table we show efficiencies for Be, Al, Cu and Pb targets, assuming semiapertures A of 1, 2 and 3 cm, for 15 and 30 Bev protons in the Brookhaven AGS. In computing these values we have taken the radiation lengths from the Barkas-Rosenfeld tables (UCRL 8030) distributed as pocket cards with a recent "Physics Today". Nuclear mean free paths were computed by assuming that the total nuclear cross section is 3/2 times the geometrical cross section $\pi r_o^2 A^{2/3}$ (r_o = 1.4 fermi). The basis for this assumption is that light nuclei are somewhat transparent, and therefore the diffraction scattering is only about half the absorption cross section; heavier nuclei are more opaque, but there a good part of the diffraction goes into angles small enough to permit the particles to survive in the accelerator. Clearly the resulting compromise factor of 3/2 is at best a guess.

Material	15 Bev efficiency			30 Bev efficiency		
	A = 1cm	A = 2cm	A = 3cm	A = 1cm	A = 2cm	A = 3cm
Be	.49	.88	.98	.88	.99	.995
Al	.19	.51	.72	.51	.89	.98
Cu	.08	.28	.49	.28	.64	.87
Pb (or W)	.03	.10	.21	.10	.33	.54

It is seen that for 15 Bev work beryllium is definitely superior to aluminum, especially if the net usable aperture is less than 3 cm (which is probably the case). At 30 Bev the superiority of Be over Al is less pronounced.

The above table is approximately valid under the following assumptions:

(1). The target is thin enough so that the probability of nuclear interaction in a single traversal is less than the efficiency computed from the table. In the case of a thick target (such as the tungsten target used in the current separated beam setup) the efficiency is still $1 - e^{-x/L_n}$, since the scattering in the first traversal does not affect the probability of nuclear collision in that same traversal. However, it is necessary that the target be well enough aligned to permit the beam to traverse all of it. - Note that even 1 inch of aluminum qualifies as a "thin" target in this sense.

(2). The target must not be so thin that the beam spirals to the limit of the aperture before it has traversed a nuclear mean free path. At 15 Bev the beam spirals in at the rate of about 10^{-3} cm per turn; at 30 Bev this rate is halved. With 2 cm of aperture available, this condition means that the target must be at least 1/2000 mean free paths thick (or about 50 mg/cm^2); at 30 Bev the minimum thickness is 1/4000 mean free paths or 25 mg/cm^2. This limitation, however, does not apply if the target is operated during a "flat top", or if the rf remains on and makes up the ionization energy loss.

(3). The radial width of the target must be sufficient so that the particles still traverse it after they have lost about 200 Mev by ionization, which brings them to smaller radii due to the finite momentum compaction coefficient. This width is 2 cm at 15 Bev and 1 cm at 30 Bev.(At these widths the efficiency will be reduced somewhat from the values in the table, but not by more than 1/3). This limitation still applies for flat-top operation; however, it does not apply for thin foil targets if the rf makes up energy losses.

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Distr: AD, B1,B2,B3
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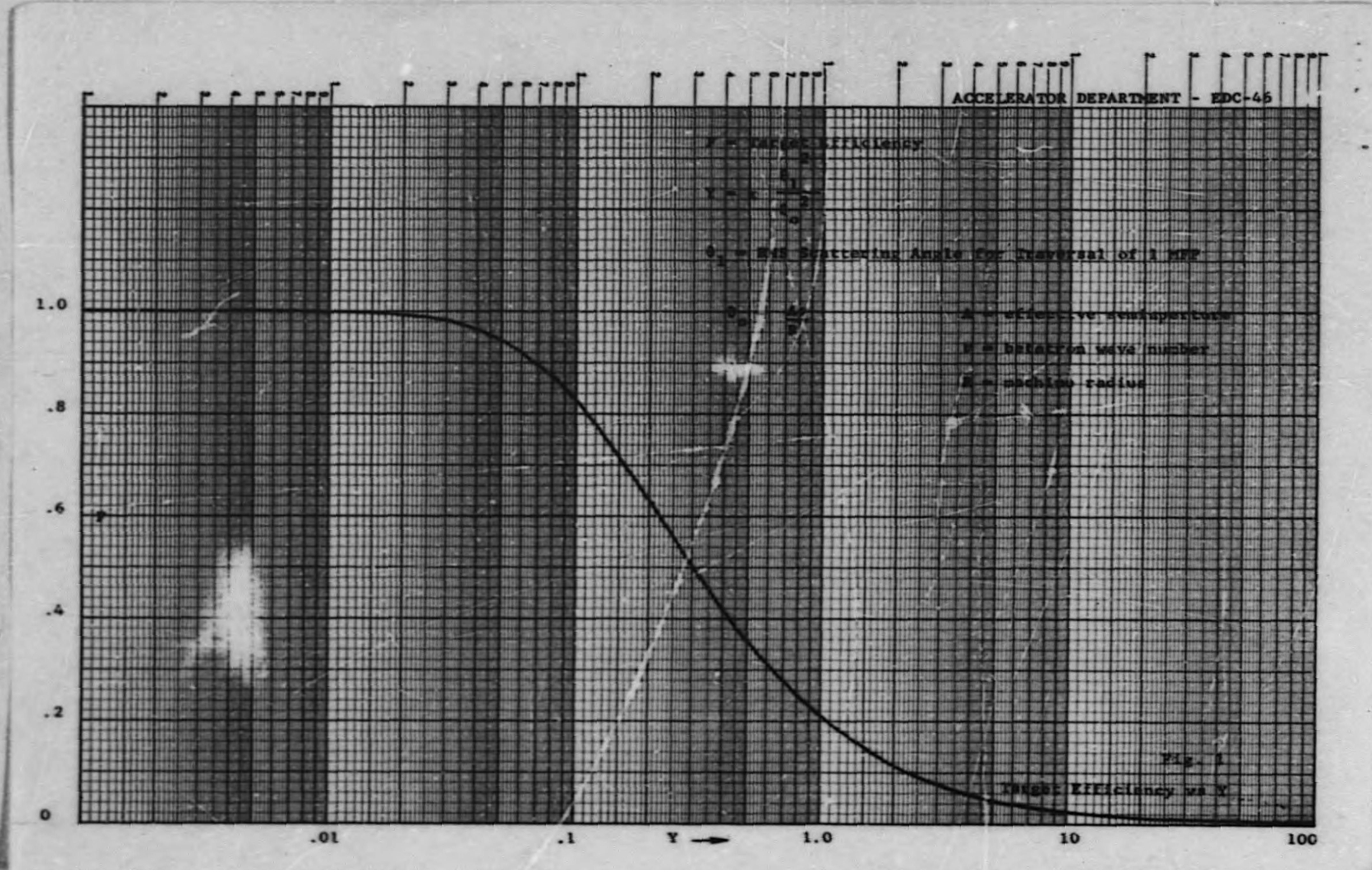
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.2
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F
.01
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Target Efficiency vs Y

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