Mass Separation in a Proton Analog of a 5 MeV Electron Beam

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Introduction

To support studies of beam transport and design of transport elements for medium energy electron cooling, a proton analog is being built at Fermilab. This approximately 12.5 keV proton beam has the same rigidity as a 5 MeV electron beam. If prepared with the same geometric emittance and a scaled-down current, the beam trajectory should be identical to the electron beam.

This requires a clean, stable source of 12.5 keV protons. The duoplasmatron ion source which we plan to use generates and emits a number of different mass clusters (H^+, H_2^+, H^{+2}, etc.) For certain operating conditions, the desired H^+ species can be swamped by some of the other species.

Basic Design

Some sort of mass separation is needed to filter the output of the ion source. Separation of two beams of different mass but the same energy cannot be done with a static electric field alone; it requires a magnetic field to introduce dispersion. This can be done either with a simple magnetic bend, which acts as a momentum selector, or with a Wien filter, which acts as a velocity selector. We chose to use a magnetic bend, since it is simpler, and chose a spare Antiproton Debuncher trim dipole for this purpose.

The mass difference is so large (a factor of two) that mass separation is relatively easy, and does not require a very large bend angle. Because of focusing and fringe field effects which are difficult to estimate, we decided to limit the bend angle to 45°. For non-relativistic beams of equal energy, $r \propto \sqrt{m}$ in a constant magnetic field. If mass 1 goes through a 45° angle, mass 2 will go through about 31° in the same magnet, assuming the magnet has parallel ends. It will emerge with a 14° angle relative to the mass 1 beam, or a slope of about 1/4. It will strike the wall of a 6" beam pipe about a foot downstream of the bend magnet. These estimates will be modified slightly, but not significantly, by use of a field index and by edge focusing.

Such a bend magnet has significant focusing effects. For a magnet with no index and parallel ends, there is a focusing in x (the betatron phase advance is equal to the bend angle) and virtually no focusing in y (the little y focusing that exists is due to fringe field effects). It was decided to make the focusing roughly the same in the two planes by either giving the magnet an index or by slanting the ends. Since it was desired not to permanently modify the magnet, so it could still be used as a spare for the Antiproton source if necessary, we decided to give the magnet a field index by constructing two wedge-shaped, removable pole pieces, with slopes of about 1:30.

Measurements and Fringe Field Effects

The magnet pole length is about 18". The width is about 12". The gap, with pole pieces installed, is about 4.5". Because of the large magnet gap relative to the other dimensions, fringe field effects are a significant perturbation to beam focus and beam trajectory. In the design process, it was necessary to make estimates of these fringe field effects. However, these estimates were somewhat in error.

After the pole pieces were completed and installed, the field was mapped. An excitation of 10 A produced a central field of 385 G. From a simple integration of the field data in a straight line along the center of the magnet, I find that the effective edge of the magnet[1] is about 10.8" from the center, or about 1.8" beyond the magnet pole edge[2]. Thus the magnet is effectively 21.6" long, and the effective bend radius for 45° is 28.2".

A beam behaves roughly as if it were in a field-free region until reaching the effective edge, then behaves as if it were in a region of full field. This approximation to the field and trajectory gives the correct bend angle. However, the extended nature of the fringe fields causes the beam to begin bending earlier than this approximation would imply, and the actual trajectory falls inside of that implied by this approximation. As a better approximation, the "effective trajectory" may be found by another integral of the fringe

[1]Harald A. Enge, "Deflecting Magnets," in *Focusing of Charged Particles,* vol. 2, ed. Albert L. Septier, §4.2.3 (New York: Academic Press, 1967); John J. Livingood, *The Optics of Dipole Magnets*, ch. 1, (New York: Academic Press, 1969).
[2]This value is less than the typical value of about one half-gap, or about 2.25", which was assumed in the design stage. In our case, the field falls off faster than normal because of the relatively narrow pole width as compared to the magnet gap.

field, similar to a first moment calculation, given by the integral I_1 of Enge[3] (similar to I_2 of Wollnik[4]):

$$I_1 = \int_{-s_1}^{\infty} ds \int_{-s_1}^{s} (h_0 - h) ds \qquad 1)$$

where $h=B/B_0$, B_0 is the field well inside the magnet, s is distance along the particle trajectory (normalized to the magnet gap, and measured outward from inside the magnet). s_1 is an arbitrary point well inside the magnet (I used the center of the magnet), and h_0 is a step function which is equal to 1 inside the effective edge, and 0 outside the effective edge (i.e. it is the value of h for the idealized sharp-cutoff approximation).

When this is done, the integral is found to be about 0.17 for our data[5]. The beam's effective trajectory has an offset at the effective edge given by[6]:

$$\Delta y = \frac{D^2 I_1}{r \cos\theta} \qquad 2)$$

where D is the magnet gap, θ is the incidence angle of the beam (the angle which the effective trajectory makes with the normal to the edge; 22.5° in our case), and r is the radius of curvature in the magnet. For our magnet, this offset is about 0.14" toward the inside of the bend (fig. 1).

Horizontal focusing at the magnet edges is not affected by the fringe fields; there is an apparent (defocusing) thin lens at the effective edge with a focal length of $r/_{\tan\theta}$. In the vertical plane, in the absence of fringe fields, there would be an apparent (focusing) thin lens of the same focal length. The vertical edge focusing, however, is modified by fringe field effects. This is calculated by another integral of the field, I_2 of Enge[7] (similar to Wollnik's I_3[8]):

$$I_2 = -\int_{-s_1}^{\infty} dh \int_{s}^{\infty} h ds \qquad 3)$$

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[3]Enge, §4.2.3.
[4]Hermann Wollnik, *Optics of Charged Particles,* §7.1.1 (New York: Academic Press, 1987).
[5]This is an unusually low value (0.3 to 0.5 is more typical, and was assumed in the design stage). This is again due to the relatively narrow pole width as compared to the magnet gap.
[6]Enge, §4.2.3.
[7]Enge, §4.2.3. Note that there seems to be a sign error in Enge's equation.
[8]Wollnik, §7.1.3.

For our case, I_2 is about 0.34[9]. The effective edge angle for vertical focusing becomes[10]:

$$\theta_{eff} = \theta - \frac{DI_2\left(1+\sin^2\theta\right)}{r\cos\theta} \qquad 4)$$

A linear fit to field data taken across the width of the magnet gives a field index, defined as $n = \frac{dB}{dx}\Big/\frac{B}{r}$, of 0.58. Putting this value and the I_2 value into MacTransport, we find that the x and y focusing are not equal, and the beam has more y than x focus. This can be addressed either by adding a separate quadrupole lens to adjust the focus, or by reducing the slope of the pole pieces to 3/4 of their present value. It may also be possible to modify this slightly by moving the magnet in x, causing the beam to go over a slightly different area of the fringe field, which will cause the fringe field sextupole component to feed down and modify the focusing. For flexibility, and because I do not completely trust these simulation results[11], I would recommend addition of a weak quadrupole lens, e.g. one of the cos-2θ quadrupoles designed for the achromatic bends.

For our 12 keV proton beam, a field of 220 G is needed to bend with a 28.2" radius. This requires a magnet current of 5.7 A, in the present magnet.

Status

The magnet is complete with pole piece inserts. A power supply is available to drive the magnet. Two beam tubes have been completed. The first follows an incorrect trajectory due to bad assumptions of the field integrals; the second follows a corrected trajectory based on field measurements. Beam steering in y has not yet been addressed. In x, steering can be done by changing the magnet current. For steering in y, a small deflection coil will need to be added.

Bibliography

Enge, Harald A. "Deflecting Magnets." In *Focusing of Charged Particles,* vol. 2, ed. Albert L. Septier, Ch. 4.2. New York: Academic Press, 1967.

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[9] This value is slightly lower than usual, again because of the relatively narrow pole width as compared to the magnet gap. A value of 0.4 to 0.5 is more typical, and this was assumed in the design stage.

[10] Enge, §4.2.3.

[11] The field integrals have all been done in a straight line, rather than following the beam trajectory. In addition, the field index is non-constant along the trajectory (a constant index would require conical pole tips, rather than wedge-shaped).

Livingood, John J. *The Optics of Dipole Magnets.* New York: Academic Press, 1969.

Wollnik, Hermann. *Optics of Charged Particles.* New York: Academic Press, 1987.

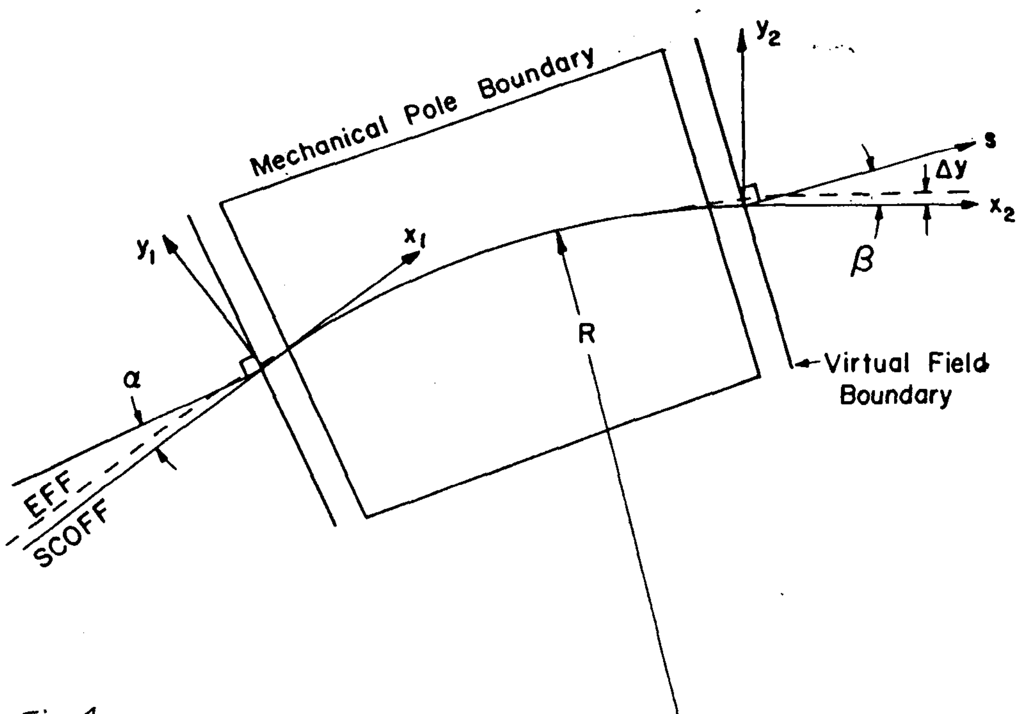

Fig. 1

~~FIG. 18.~~ Particle trajectories in sharp cutoff fringing field (SCOFF) and extended fringing field (EFF). (From Enge)