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Particle Beams with Uniform Transverse Distribution

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Abstract: A successfully tested method is described which achieves a more uniform illumination of an extended flat target by the charged particle beam from an accelerator, by proper use of a combination of quadrupole and octupole magneto-optical elements.

Particle beams having a uniform distribution transverse to the beam direction are desirable for irradiating spallation neutron targets, as well as for other technical or medical applications, in order to minimize target temperature excursions and to utilize the beam more efficiently. The charged particle beam exiting an accelerator typically has a transverse distribution resembling a Gaussian out to a few σ (standard deviations). A small "full-width at half-maximum" (FWHM) for the lateral dimensions of the beam is usually considered a favorable figure of merit in accelerator design. There are, however, applications (spallation neutron generation, isotope manufacture, medical applications) for which uniform irradiation of an extended target is highly desirable or even necessary for the above reasons. For such applications there is a need to match the lateral dimensions of a beam exiting the accelerator (a few mm for a LINAC) to a target whose extent might be 1 to 2 meters (the frontal dimensions of the spallation target design for the accelerator production of tritium, "APT" project). Until recently the options available for producing a uniform beam on an extended target were limited. The simplest basic choice that was available is illustrated in Figs. 1a and 1b: To (de)focus the beam on the target to either accept the whole Gaussian beam within the borders of the target, which results in grossly inhomogeneous target irradiation, or to utilize just the central portion of the Gaussian, which results in greater uniformity but at the expense of much wasted beam. A thick absorber placed in front of the target to spread the beam by multiple Coulomb scattering has also been used to achieve uniformity at least in the neighborhood of the beam axis but is wasteful of accelerator energy and creates unwanted radioactivity. Another approach to irradiation uniformity is "rastering," i.e., sweeping the beam repetitively over the target in a prescribed pattern. This however requires large amounts of power for beam deflection magnets, and there is also concern that a failure in the sweep system would allow a disastrous concentration of beam power on a small area of the target. Moreover, some time-dependent phenomena require simultaneous irradiation of the whole target area. Combining a "pixel by pixel" modulation of the beam with rastering overcomes only some of the problems, but also requires active online control of the beam, increasing the system complexity and opportunity for failure.

The passive method of achieving a flat field illumination of an extended target to be described here has been independently thought of elsewhere,[1] but to our knowledge, the first physical realization of the method was at BNL in connection with studies of the effects of charged particle irradiation on whole missiles and on large area electronic assemblies, such as circuit boards.[2] It has since then also been employed at BNL for the design of a spallation target irradiated by a 1 GeV LINAC,[3] and to an isotope production target irradiated by a 200 MeV LINAC beam.[4]

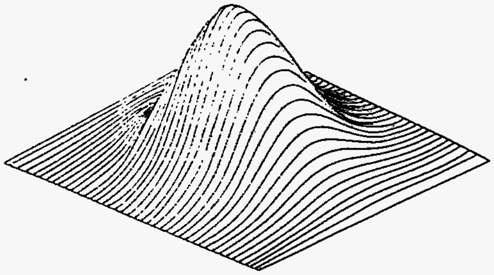


Figure 1a

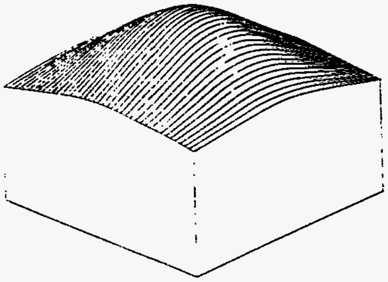


Figure 1b

Figs. 1a and 1b. Fitting a Gaussian Distribution to a Rectangular Target

The description below is a verbal prescription for the design procedure: In the following, a charged particle beam (or any particular particle in it) will be described by a rectangular coordinate system (x,y,z) with the positive z-axis corresponding to the central ray of the beam, and the (x,y) coordinates describing the position of the beam or particle transverse to the z-axis. The direction of the beam or particle with respect to the z-axis as measured in the (x,z) plane will be measured by the angle θ, in the (y,z) plane, by the angle ϕ.

The physical basis for obtaining uniform transverse beams is the fact that the deflection produced by a quadrupole lens depends upon the first power of the distance from axis of the charged particle entering the field of the lens, while for an octupole lens, the deflection behaves as the cube of the particle entrance distance from the axis. This difference in the dependence of the deflection on the off-axis position of beam particles is utilized to produce, for a proper positioning of quadrupoles and octupoles along the z-axis, with the proper respective strengths and deflection senses, a situation where the off-axis particle impact points on a downstream target plane will be limited to prescribed maximum values (not necessarily the same) in each of the two perpendicular x and y directions. Octupoles suitably introduced into a previously properly configured magnetic system consisting of quadrupoles will take the extreme tails of the beam distribution (that would have existed for the quadrupoles alone and extended past the target boundaries) and create a new distribution in which the tails of the original distribution are effectively folded over towards the beam axis. The limits of the new distribution are fairly sharp, and can be arranged to coincide with the limits of a rectangular area, so that essentially no particles are wasted outside of the designated target. The new distribution, because of the tendency of the folded-over tail to fill in where the previous distribution was low in amplitude, will also be found to be much more uniform then the original.

The following is the procedure developed at BNL for setting up the magneto-optical system:

> Usually a set of at least four quadrupoles is first employed to create a condition such that the beam comes to a line focus along the x direction at some downstream point z_1 and to a line focus along the y direction at some other point z_2. Also, a high correlation (ideally a linear relation) should be established between x and θ, and between y and ϕ, at, respectively, z_1 and z_2. At the same time, the $\pm\sigma_x$ and the $\pm\sigma_y$ dimensions of the beam on the target plane should match the desired final size of the beam on that plane. These goals are accomplished by applying a "first order" raytracing program to the set of quadrupoles. (It is assumed that the parameters of the beam from the accelerator are known and available for input into the raytracing code.) This is a trial and error calculational process carried out by the computer code in which the locations and distances between the quadrupoles, and their magnetic strengths, are varied until an acceptable solution is attained. It may be necessary to employ one or two additional quadrupoles in order to obtain a satisfactory solution and to accept compromises for economic or beamline space availability reasons. Having set up these conditions on the quadrupole positions and strengths, the next step is to place an octupole at z_1, and another octupole at z_2. The strengths of these are then varied using a raytracing program capable of "third order" optics (i.e., including octupole magnetic elements) until all the beam falls only within the desired target area

The results of applying the above process are illustrated for a real design calculation:[3] Fig. 2 shows the first order optics calculation of the horizontal and vertical beam envelopes for an 18 m long beamline carrying 1 GeV protons intended for a 1.4 m x1.4 m target. The arrows indicate the appropriate locations for the octupoles., namely a place where the x dimension of the beam envelope is large and the y dimension is small and another place where the reverse is true. Figs. 3a and 3b illustrate how the originally Gaussian-like beam (with the octupoles not active) is converted to the sharp-edged distribution almost totally confined within 140 cm. Figs. 4a and 4b indicate the effect of the octupoles for a different choice of the first order beam optics and different octupole strengths for the above beamline. The sharp confinement of particles within the boundaries is the same but the increased flatness of the distribution throughout most of the distribution is accompanied by more pronounced peaking near the boundaries. (All these figures were generated by a Monte Carlo selection of initial position and direction of individual particles sampling from a Gaussian distribution in the variables and allowing the raytracing codes to generate the actual trajectories until impact on the target, and gathering the statistics on impact points; typically 50,000 case histories are involved.) Figs. 5a and 5b show actual wire harp generated beam profiles illustrating the conversion of a 200 MeV proton beam distribution, ±3 cm x ± 5 cm base-to-base, into a fairly uniform rectangular distribution ±2 cm x ±3 cm from boundary to boundary.

The effect of slight misalignments on the field flattening has only begun to be investigated. For the 18 m long beam line referred to above, there was the surprising result that the distribution became noticeably skewed for only a small misalignment (a 0.25 mm shift of a magnet perpendicular to the beam line) yet the beam remained completely within the original boundaries (Fig. 6).

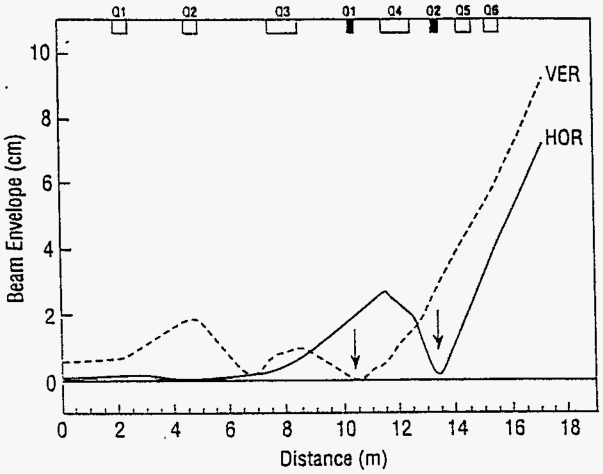
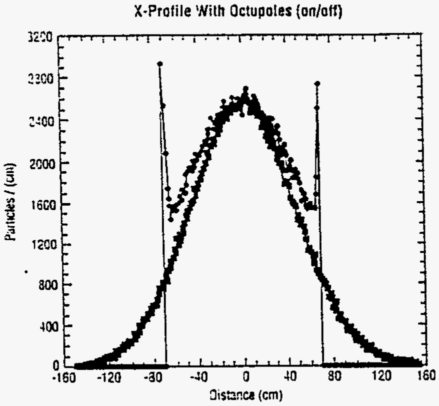
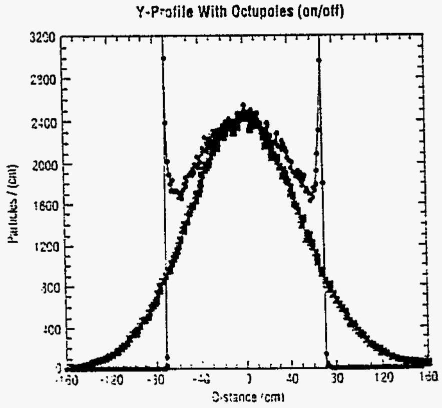
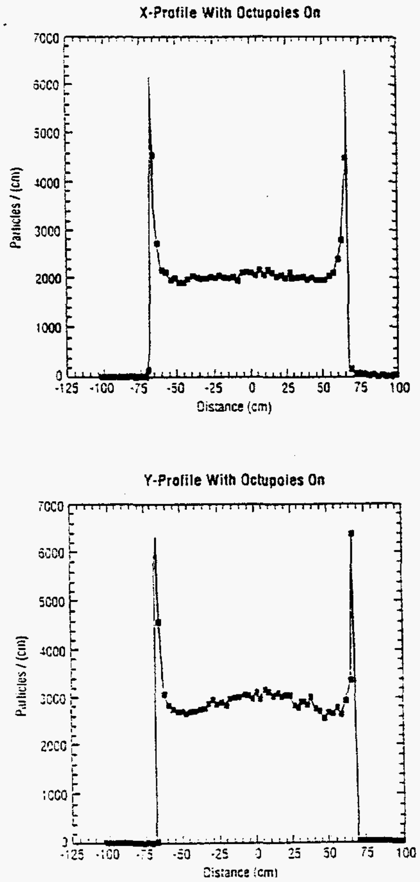


Fig. 2. Horizontal and Vertical Beam Envelopes (1σ, first order)





Figs. 3a and 3b. A First Solution for the Given Beam Line
(Expansion to 1.4 m x 1.4 m, in 18 m length)



Figs. 4a and 4b. An Alternate Solution for the Same Beam Line as Figs. 3a and 3b (Expansion to 1.4 m x 1.4 m in 18 m length)

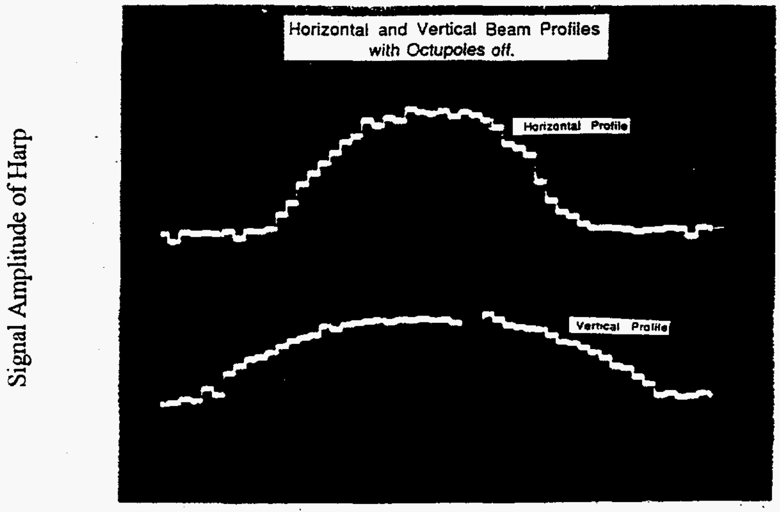


Fig. 5a. Harp Signals Illustrating the Effect of Octupoles for Uniform Irradiation (No octupoles activated)

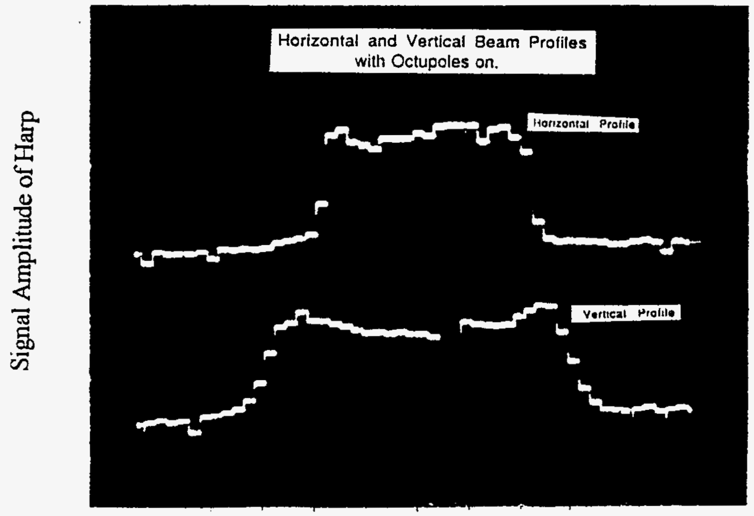


Fig. 5b. Harp Signals Illustrating the Effect of Octupoles for Uniform Irradiation (octupoles activated)

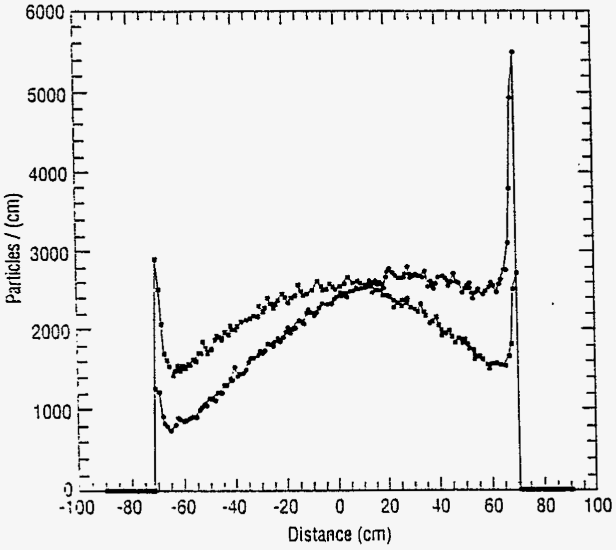


Fig. 6. Horizontal Profile With and Without Alignment Error of 0.25 mm

Further questions remain to be answered, such as the depth-of-field, and whether there could be any further worthwhile improvements through use of higher multipole fields.

Acknowledgement

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[4] A. Kponou, Brookhaven National Laboratory AGS report (to be published).