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CONSIDERATIONS IN USING THIRD ORDER FOCUSING OF PROTON BEAMS FOR UNIFORM IRRADIATION OF EXTENDED TARGETS*

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ABSTRACT

The latest target designs for the National Spallation Neutron Source (NSNS) and Accelerator Production of Tritium (APT), require that the geometrical target cross-section (normal to the proton beam direction) be of rectangular shape with dimensions (10 cm x 30 cm) and (16 cm x 160 cm) for the NSNS and APT targets, respectively. These targets are to be irradiated with high-intensity proton beams. At present, plans are to use beam-expanded uniform intensities for the APT target, with possibly a small horizontal and vertical jitter superimposed. Although current plans for the NSNS target call for non expanded gaussian distributions, we nevertheless investigate the application of a beam expander to provide beam on that target. The high aspect ratios, 3:1 and 1:10 , currently proposed for the NSNS and APT targets prompt a feasibility study for the creation of uniform beams over such targets. This paper presents a beam-optics design of two proposed beam expanders which will generate a beam to irradiate uniformly the NSNS and APT targets. Both beam optics designs are representative only, and independent of any other "official" designs that may exist within the design groups of the APT or NSNS project. Recent experimental work on uniform beam profiles on the target of the Brookhaven Isotope Resource Center (BIRC) of the BNL-200 MeV-LINAC will also be presented.

I. INTRODUCTION

The theoretical background on the production of charged particle beams with uniform transverse distribution on a target was presented in a recent publication [1]. Although there are alternative methods of producing uniform beam distributions on targets (e. g., beam rastering), the method dealt with here makes use of a combination of quadrupole and octupole magnetic elements. There have been a few independent developments elsewhere of the basic principles involved in the production of beams with uniform distribution (see Ref. 2 and bibliography in Ref. 3) but the first practical realization of flat-field illumination by this method was accomplished at the BNL (200 MeV linac-driven) Radiation Effects Facility (REF) beam line [3].

Several applications are currently under consideration for neutrons produced via proton-induced spallation/evaporation in heavy metal targets. In this paper attention will be given to the production of uniform beam distributions on the APT and NSNS targets, by using the quadrupole/octupole focusing method. The most recent design of the APT target, has dimensions (transverse to the beam direction), of 16 cm in the horizontal and 160 cm in the vertical. The corresponding dimensions of the NSNS target, are 30 cm and 10.5 cm, respectively. Uniform beams with almost square cross sections have been theoretically calculated and experimentally produced using the quadrupole/octupole focusing method [1] . However uniform beams with rectangular cross-section having high aspect

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ratios, of 1:10 and 3:1 for the APT and the NSNS target, respectively, have not been reported. This paper presents and discusses a beam-optics design of the beam line section which expands and distributes the beam uniformly on the APT and NSNS targets. This beam-line section will be referred to in the text as the beam expander.

II. WHY USE A BEAM EXPANDER

The transport of a charged-particle beam to a target, maintains the Gaussian particle beam distribution on the target, assuming that only dipoles and quadrupoles (zero and first-order elements) are involved in the beam transport. It is always possible to focus a Gaussian beam entirely within the boundaries of a target. Such beam focussing, however, creates a nonuniform irradiation of the target with subsequent effects like nonuniform heat deposition, and nonuniform utilization of the target material in terms of neutron production. At the other extreme, it is also possible to expand the beam so that only the center of the Gaussian beam covers the target area, thus improving the beam *uniformity* over the target area, but with a significant fraction of the beam falling outside the target boundaries and being lost. A pictorial presentation of the above discussion which shows the Gaussian beam distributions on the target in both extremes, is presented in Ref. 1.

There are few ways to avoid these extreme situations which are caused when a Gaussian beam is used to irradiate a target. One method is the employment of the beam expander whose function is twofold. First, to confine the beam intensity within the target area, thus utilizing all the beam produced by the accelerator, and second, to create a more uniform beam distribution over the target area, thus eliminating any effects caused by nonuniform irradiation of the target. A pictorial comparison of two beams, one with Gaussian distribution, and the other with "uniform distribution", each irradiating a target with rectangular cross-section, is presented in Fig. 2. of Ref. 1. This figure shows that the non-Gaussian beam has far better uniformity than the Gaussian one.

III. OUTLINE OF THE BASIC PRINCIPLES FOR PRODUCING BEAMS WITH UNIFORM DISTRIBUTIONS

As mentioned above, a beam with a Gaussian distribution, which is transported and focussed on a target by means of dipole and quadrupole magnetic elements, can only lead to a beam with Gaussian distribution. Mathematically, this is a consequence of the linear transformation of the beam ellipsoid as it goes through the various magnetic elements [4]. The introduction of higher-order multipoles modifies the Gaussian distribution of a beam to a non-Gaussian distribution. An octupole for example, placed in the path of the particle beam, mixes the horizontal (x,θ) particle coordinates with the vertical ones (y,ϕ). This coordinate mixing, which is also referred to as "beam coupling", results in a beam distribution on target which is not a Gaussian, and most likely not a useful one. In order to take advantage of the octupole effect on the beam and gain control of the beam distribution on the target, the beam coupling must be reduced to a minimum. The beam coupling due to the octupoles can be significantly reduced by shaping the Gaussian beam at the location of the octupoles using the quadrupole focussing only [1]. Subsequently, by turning on the octupoles one can modify the beam distribution on the target. There should be at least two octupoles in the beam expander, the "horizontal octupole" and the "vertical octupole", which, respectively, modify the horizontal and vertical beam distributions on the target. More specifically at the location of the "horizontal octupole", the first-order beam focussing should

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confine the beam on a horizontal plane to the maximum extent that the vertical beam emittance allows. Similarly, the beam at the location of the "vertical octupole" should be confined by the first- order optics on the vertical plane. Such a beam shape minimizes the beam coupling, allowing the manipulation of the horizontal beam coordinates almost independently from the vertical ones. An additional requirement that the beam should fulfill at the location of each of the octupoles is the high correlation of the horizontal (x,θ) coordinates at the "horizontal octupole" and of the vertical (y,ϕ) coordinates at the "vertical octupole". The high correlation of the horizontal coordinates (x,θ), along with the beam confinement at the horizontal plane at the location of the "horizontal octupole", reduces the independent beam coordinates (to a good approximation) to only one coordinate (x), thus making the " horizontal octupole" seemingly act on an almost horizontal planar diverging beam. Similarly the beam coordinates at the location of the "vertical octupole", depend on the y coordinate only with the "vertical octupole" to act on an almost vertical planar diverging beam. Thus, by independently adjusting the strength of the "horizontal" and "vertical" octupoles one can independently modify the beam distribution at the target location. A quantitative analysis of the above discussion, with simple examples, is presented in Ref. 1.

IV. PROCEDURE FOLLOWED IN THE DESIGN OF A BEAM EXPANDER

The beam expanders for the APT and potentially the NSNS designs, would consist of six quadrupoles, and two octupoles. The first four quadrupoles are used to produce the required beam shape (see previous section) at the location of the "horizontal" and "vertical" octupoles, and the last two quads are used to produce a beam on target with horizontal and vertical sizes having standard deviations close to the one half of the horizontal and vertical dimensions of the target respectively. The above tasks are accomplished using first-order beam optics. Subsequently, the octupoles are turned on to confine the beam within the target, and also improve the beam uniformity over the target area. The strength of the various quadrupoles and of the two octupoles, set to produce the required beam shape at the location of the octupole and at the target, depends on the shape and orientation of the six-dimensional beam ellipsoid at the entrance of the beam expander. In this paper the beam ellipsoid used is assumed to be the same for both the APT and NSNS beam expanders, and corresponds to a 95% beam emittance of 0.24π (cm)(mrad) for both the vertical and horizontal planes.

The design procedure is summarized in the following steps:

a) The TRANSPORT computer code [5] with its first-order optimization capabilities is used to produce the required beam shape at the location of the octupoles and on the target.

b) Subsequently the octupoles are turned on to a given strength, and the aberration coefficients, up to the third-order are calculated using the third order version of the TRANSPORT computer code.

c) Using the aberration coefficients of the beam expander as calculated in step (b) above, a set of 100,000 rays are randomly selected from the beam ellipsoid (which extends three standard deviations in any of its coordinates) at the entrance of the beam expander and the coordinates of each ray at the target are computed [1] and then histogrammed and plotted. This step is accomplished using a computer code under the name NSC [6].

d) The plots of the beam profiles on the target, which are obtained from step (c), are visually examined. A return to step (b) may be required if further improvement of the beam profile on the target is needed.

V. A PROPOSED DESIGN OF A BEAM EXPANDER FOR THE "APT" TARGET

The cross section of the APT target (normal to the beam direction) is rectangular with horizontal and vertical dimensions of 16 cm and 160 cm, respectively. The objective of the beam expander is to confine the beam which irradiates the target within the area of the target with the beam having the best possible uniformity.

This section details a proposed design of a beam expander for the APT project and presents the beam shape on the APT target. Throughout this discussion it is assumed that the expanded beam is optimally focused in the plane coinciding with the face of the target. For a discussion of the effects of placing the focal plane at different positions throughout the extended target, see Ref. 7.

The beam at the entrance of the beam expander is described with a six-dimensional beam ellipsoid (Gaussian distribution). The physical quantities which describe the shape and orientation of the beam ellipsoid are given in TABLE I. For the description of the beam ellipsoid the notation of Ref. 6 has been adopted. Thus, in TABLE I, the beam ellipsoid is characterized by the momentum of the central ray, and the standard deviations of the various particle-beam coordinates. The assumed value of the momentum spread ($\delta p/p = 0.05\%$) appearing in TABLE II does not make any significant contribution in the beam shape on target when the third-order calculations are performed.

The magnetic elements of the proposed APT beam expander, which are used to focus the beam on the target are shown in TABLE II in the sequence they appear in the beam line. The label "DRIF" in TABLE II represents the distances in meters between the centers of the consecutive magnetic elements which in turn are labeled "QUAD" for quadrupoles and "OCTU" for octupoles. The quadrupoles and octupoles used to focus the beam on the target, are characterized by their corresponding integrated strength expressed in Tesla for QUAD and Tesla.m^{-2} for OCTU. One can use these quantities as input data in various higher-order beam-transport codes, like TRANSPORT [5], RAYTRACE [8] or any other codes available and reproduce the beam shape on the APT target. Indeed, the third-order version of the computer code TRANSPORT was used to calculate the third-order transport matrices of the beam expander with magnetic elements listed in TABLE II under the title APT. Subsequently, 100,000 particles were randomly selected from the ellipsoid described in TABLE I and then raytraced through the beam expander,

TABLE I

Phys. Quantity	Value
P (momentum)	1.696 Gee/c
$\delta p/p$	0.05%
T (Kin.En.)	1.0 Gee
x (stand. dev.)	0.063 cm
θ (stand. dev.)	0.633 mrad
r_{12} (x,θ correlation)	0.019
ε_x (x-emittance)	0.04πcm.mrad
y (stand. dev.)	0.561 cm
ϕ (stand. dev.)	0.544 mrad
r_{34} (y,ϕ correlation)	0.991
ε_y (y-emittance)	0.04πcm.mrad

TABLE I. The physical quantities which characterize the beam ellipsoid at the Entrance of the beam expander.

using the third-order transport matrix elements, to obtains the beam coordinates of the particles at the target location.

TABLE II

Elmnt Name	APT	NSNS
DRIF_1	2.250	2.250
QUAD_1	-1.6953	-1.8578
DRIF_2	2.500	2.500
QUAD_2	4.1934	4.8628
DRIF_3	3.250	3.250
QUAD_3	-3.7466	-3.8297
DRIF_4	2.454	2.447
OCTU_1	1152.0	1646.4
DRIF_5	1.040	1.059
QUAD_4	4.8062	4.1921
DRIF_6	1.899	2.410
OCTU_2	2496.0	1392.0
DRIF_7	1.000	1.160
QUAD_5	5.3333	-2.0267
DRIF_8	1.000	1.000
QUAD_6	-0.4333	2.9833
DRIF_9	22.550	11.35

TABLE II. The Drift spaces (DRIF) and the Strength of the magnetic elements (QUAD, OCTU) of the proposed beam expanders for the APT and NSNS targets.

Using the calculated beam coordinates at the target, the beam shape at the target is presented as a histogram of the projected particle

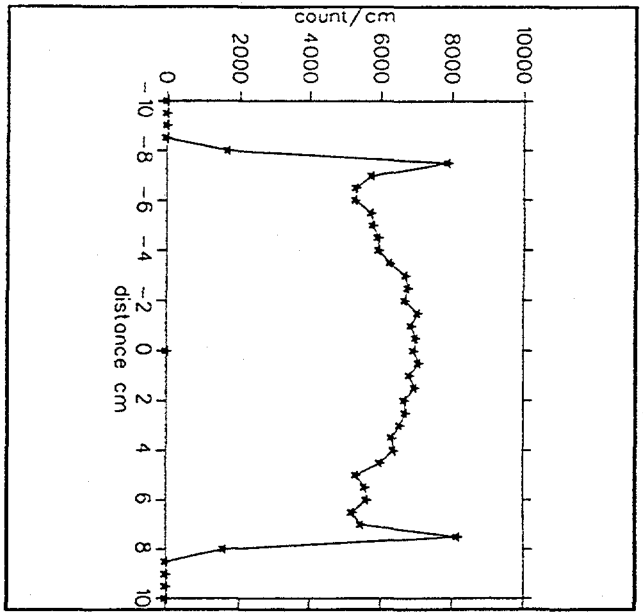

Fig. 1a. Histogram showing the beam profile of the horizontal particle coordinates at the APT target.

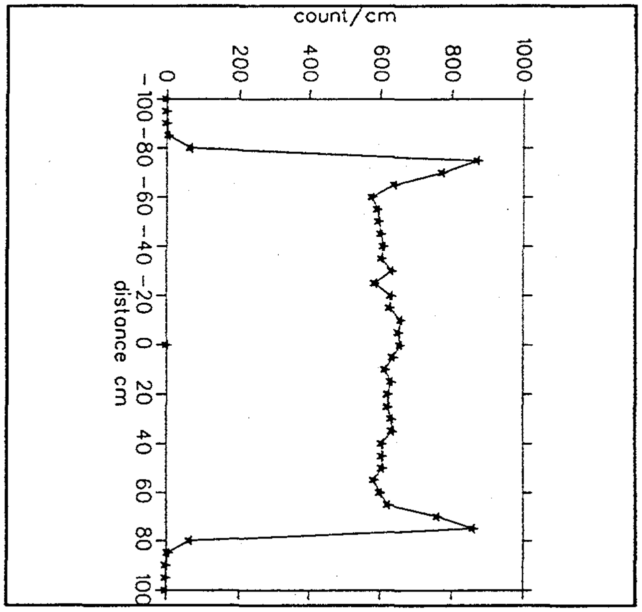

Fig. 1b. Histogram showing the beam profile of the vertical particle coordinates at the APT target.

coordinates on the x-plane (Fig. 1a) and the y-plane (Fig. 1b).

One can notice from figures 1a and 1b the improvement of the beam uniformity on the target as compared with that of a beam having a Gaussian distribution.

A scatter plot of the x and y coordinates of the beam particles at the target is shown in Fig. 1c.

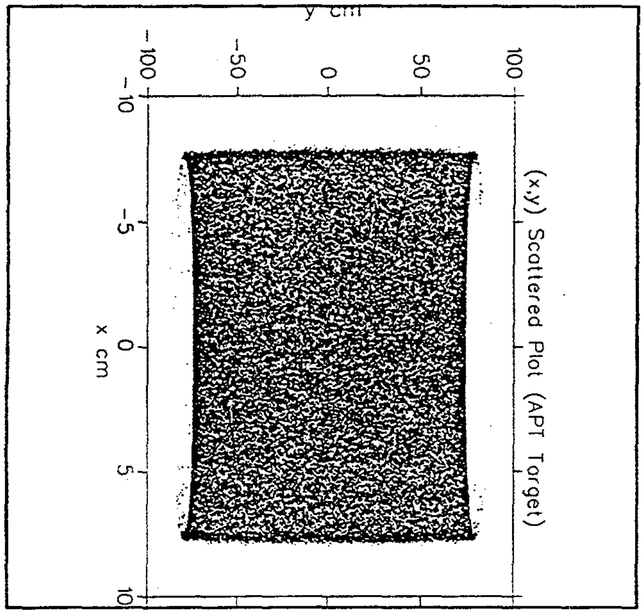

Fig. 1c. Scatter plot of the x,y particle coordinates on the APT target. Each dot represents a single particle. There are 100,000 dots.

The beam confinement within the geometrical limits of the target can be seen in Fig. 1c.

In this proposed design of the APT beam expander, the strength of the quadrupoles and octupoles is modest and easily achievable with warm magnet technology. Higher octupole strength can be achieved with cold magnets, thus improving the beam uniformity on the target [1].

VI. A PROPOSED DESIGN OF THE BEAM EXPANDER FOR THE "NSNS" TARGET

The cross section of the NSNS target (normal to the beam direction) is rectangular with horizontal and vertical dimensions of 30 cm and 10.5 cm, respectively. As in the design of the beam expander for the APT project, the task is twofold. First to confine the beam within the target area, and second, to improve the beam uniformity. In this design the beam ellipsoid entering the beam expander is identical to the one used in the corresponding design of the beam expander for the APT project and its parameters appear in TABLE I. The layout of the magnetic elements and the drift spaces of the beam expander are shown in the third column of Table II. The beam shape at the NSNS target for an x and y expander scenario is shown in Fig. 2a. (horizontal beam profile), 2b (vertical beam profile), and 2c (scatter plot) of the x and y coordinates of the 100,000 particles which were retraced through the beam expander.

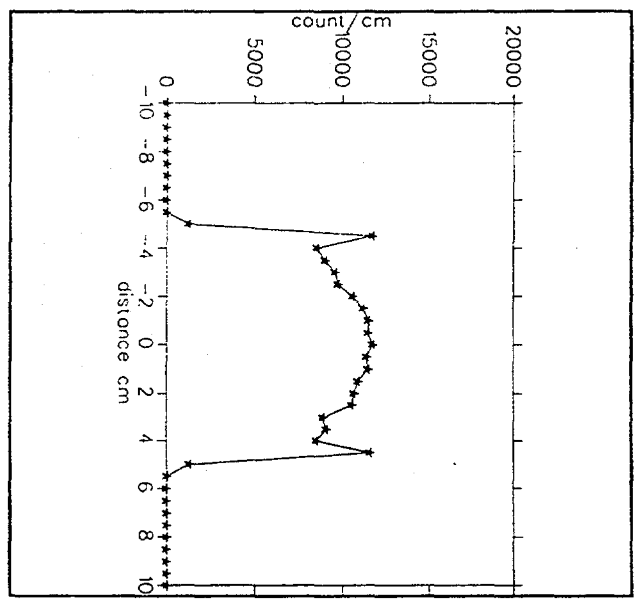

Fig. 2a. Histogram showing the beam profile of the horizontal particle coordinates at the NSNS target.

As indicated before, the current choice for the beam shape for the NSNS target is a gaussian

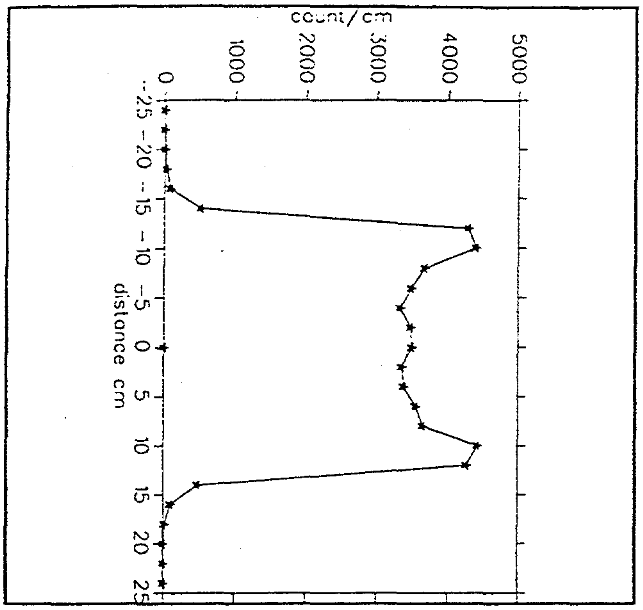

Fig. 2b. Histogram showing the beam profile of the vertical particle coordinates at the NSNS target.

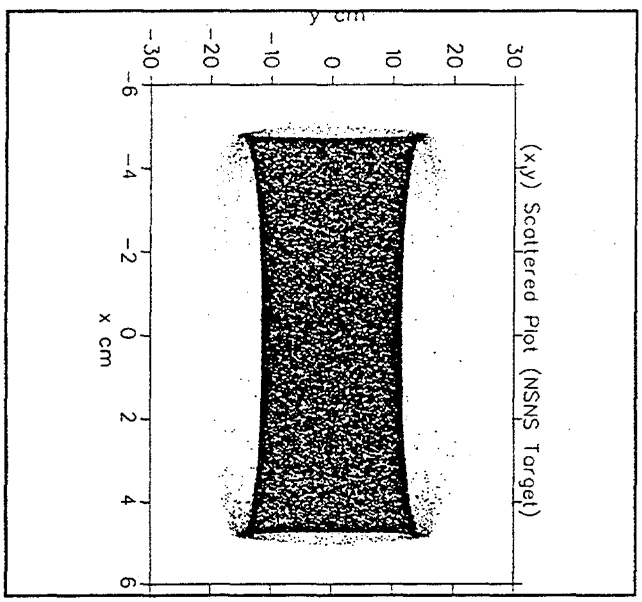

Fig.2c. Scatter plot of the x,y particle coordinates on the NSNS target. Each dot on the plot represents a single particle. There are 100000 dots.

distribution in both x and y, and not the two-dimensional beam expander.

It is interesting to speculate that another potential configuration might provide for more optimal heat dissipation and neutron generation. In this scenario the beam could be expanded uniformly along the longer x direction using the x octupole, but not expanded in the vertical dimension, leaving it gaussian and increasing the peak intensity in the middle of the target.

VII. EXPERIMENTAL WORK ON PRODUCING UNIFORM BEAM DISTRIBUTION ON THE "BIRC" TARGET

The recent upgrade of the 200-MeV linac at BNL included redesigning the optics of the transfer line to the Brookhaven Isotope Resource Center (BIRC), formerly known by the acronym BLIP, to produce a uniform beam on target [9]. The approach with quadrupole/octupole magnets was used. A schematic layout of the BIRC beam line, the beam optics and the implementations of the octupoles to produce uniform beam distribution, are discussed in more detail in Ref. 8.Each of the two octupoles used in the beam line has a radius of 7.6 cm, a magnetic effective length of 33.7 cm, and a maximum integrated strength of 475 $T.m^{-2}$. Final commissioning of the line has been slow because beam profiles at the target can only be measured by activation methods which have a turnaround time from several hours to several days, and opportunities for studies are few and far between.

However, the efficacy of the octupoles has been demonstrated in studies in which the beam was focused at a multiwire detector about 3 m upstream of the target. One such experimental result, along with the theoretical result obtained by modeling the BIRC beam line using the TRANSPORT/TURTLE computer codes [10] is shown in Fig. 3a, which shows the experimental

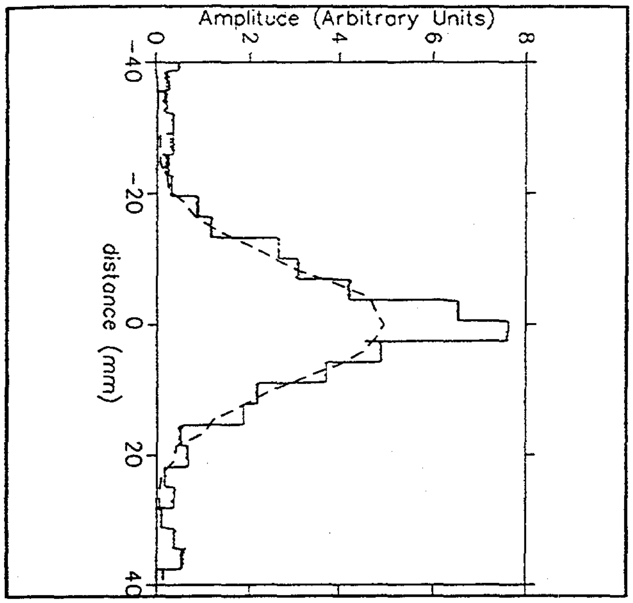

Fig. 3a. Experimental (solid line) and theoretical vertical beam profiles at the multiwire detector, with octupoles of the BIRC line turned off.

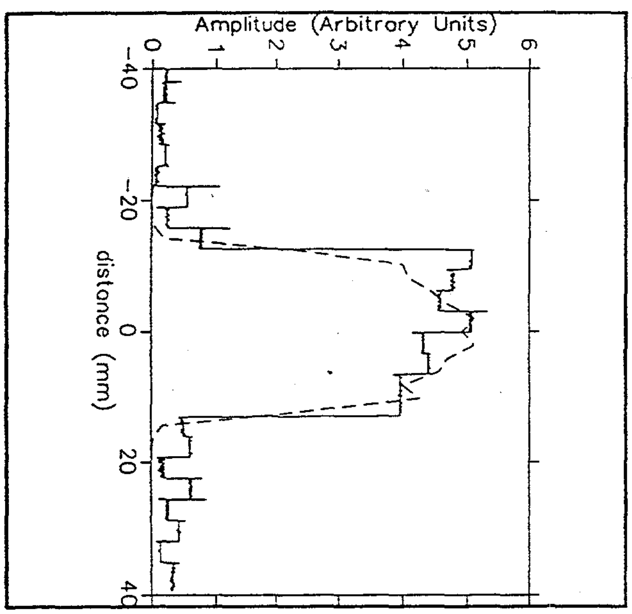

Fig. 3b. Experimental (solid line) and theoretical vertical beam profiles at the multiwire detector, with octupoles of the BIRC line turned on. Signal outside ± 15 mm is unsubtracted detector/electronics noise.

(solid line) and the theoretical (dashed line) vertical beam profile at the multiwire detector with octupoles of the BIRC line off, and Fig. 3b, which shows the experimental (solid line) and the theoretical (dashed line) vertical beam profile at the multiwire detector with octupoles of the BIRC line turned on.

The tilt in the flat top showing the experimental data (Fig. 3b) of the vertical distribution, is due to a slight missteering of the beam going through the octupoles, and can be reproduced theoretically. This missteering could be altered by adjusting the steering dipoles of the beam line.

For a more-detailed presentation of the effects of missteering on beam profiles, the reader is directed to Ref. 1.

IIX. CONCLUSIONS

There is sufficient experimental work [3,9] to support the quadrupole/octupole method of producing rectangular uniform beams. The theoretical results presented here for both the "APT" and "NSNS" beam expanders shows that the quadrupole/octupole method would work well. It is however suggested that more work is done on the beam optics of beam expanders to determine the sensitivity of the beam profiles to such variants as magnetic field strength errors and misalignments of the various magnetic elements of the beam expanders. The sensitivity study would allow better optimization for various applications. It would also providethe working knowledge of expander characteristics that will be needed to design the suite of sensors and the feedback diagnostics that will make up the required dynamic beam control system. Such tasks fall within the jouristriction of the groups in charge of the projects since they have the capability to experiment with the optics of the beam line systems.

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