GENERATION OF A RECTANGULAR BEAM DISTRIBUTION FOR IRRADIATION OF THE ACCELERATOR PRODUCTION OF TRITIUM TARGET*

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Abstract

A scheme has been developed to produce, without beam scraping, a well-confined, rectangular beam-intensity distribution of greatly enhanced uniformity from an initially peaked intensity distribution such as a Gaussian or a parabolic distribution. This scheme employs a system of linear and nonlinear transport-line elements. The linear elements prepare the beam for the nonlinear focusing and govern the beam size at a downstream target. Uniformity is achieved with octupoles, and beam confinement is assured with duodecapoles. The scheme was applied to the target focus for the Accelerator Production of Tritium (APT) system. An initially Gaussian-distributed beam of 1.6-GeV protons was shaped into a rectangular 4-m by 2-m beam spot of acceptably uniform intensity at the tritium-production target. The scheme eliminates the need for sweeping the beam in a raster pattern to produce uniform target illumination. Details of the scheme are discussed.

Introduction

Uniform target illumination, either static or in a time-average sense, prevents target damage and optimizes target efficiency in high-intensity accelerator systems such as the APT system.[1] In this system, tritium production is achieved by interaction of energetic protons with a target composed of Pb pins and Li-Al pins. Neutrons are produced by spallation in the lead and interact with the lithium to produce tritium. The APT beam, with 250 mA of 1.6-GeV protons, has 400 MW of beam power. The maximum power density allowed in the production target is 100 W/cm^3. This dictates a beam at the target of approximately uniform intensity covering an area of 8 m^2. The desired beam footprint is a rectangle 4-m wide by 2-m high. Due to the high beam intensity, no significant fraction of the beam can be tolerated on the structural materials outside the target area, nor can the beam fringes be scraped.

Uniform target illumination in a time-average sense is achieved with sweep magnets, while static beam redistribution is accomplished with a beamline containing a combination of linear and nonlinear transport-line elements, henceforth called a beam expander.[2,3] For the APT geometry, a two-dimensional raster scan requires sweep magnets with unfeasible specifications for power and size. An alternative approach, a ribbon beam of uniform intensity, swept across the target in the direction orthogonal to the ribbon, requires a sweep magnet with achievable performance specifications, but with a peak reactive power of 20 MW. No sweep magnets are needed to run the two-dimensional beam expander.

Beam-Redistribution Method

The method for producing a ribbon beam is explained in detail elsewhere.[4] With an octupole one can affect the beam phase-space area in one transverse plane in such a way that, during subsequent transport, the beam fringes are folded into the core of the beam and the originally peaked projections of the beam-intensity distribution, in that plane, are transformed into projections of greatly enhanced uniformity. With the proper focus the other transverse plane is not affected and the projections of the distribution in that transverse plane remain peaked.

The method can be applied to both transverse planes. With the appropriate linear transport, this results in a folded horizontal and a folded vertical beam phase-space area at the target. Now the projections in all transverse coordinates, and in particular the x and y projections, are relatively uniform and the contour lines of the x-y intensity distribution are rectangles.

An acceptable beam distribution at the target cannot be produced with a single octupole. Due to the x-y coupling caused by the octupole, such attempts result in beams with distorted contour lines that display big lobes in the corners of the distributions, as illustrated in Fig. 1 for a Gaussian input distribution. Here, as for all figures of this type, an input distribution containing 10^5 particles was transported through the beam expander using the beam-transport code PATH,[5] and the resulting distribution was characterized by its x and y projections and by its 10%, 50%, and 90% contour lines.

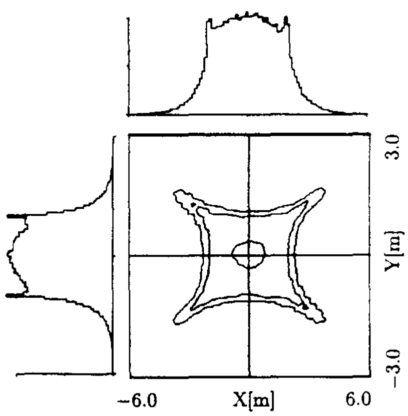

Fig. 1. Beam-intensity distribution obtained from a Gaussian input beam and a beam expander with a single octupole.

The following beam-expander components are needed to successfully produce a uniform rectangular beam distribution: a section to prepare the beam for the first octupole; a first octupole, where the beam is large horizontally and small vertically to manipulate the horizontal beam phase-space area without distorting the vertical beam phase-space area; a section to prepare the beam for the second octupole; a second octupole, where the beam is large vertically and small horizontally to manipulate the vertical beam phase-space area without further distorting the horizontal beam phase-space area; and a section to prepare the beam for the target.

The simplest beam expander for producing an acceptable beam distribution consists of two octupoles separated by a drift. Depending on the desired beam footprint at the target, more magnetic elements may be required. Adding a quadrupole between the two octupoles serves, at the second octupole, both to decrease the beam size in the transverse plane manipulated by

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the first octupole and to increase the beam size in the transverse plane manipulated by the second octupole. Adding a quadrupole after the octupoles serves to reduce the length of the final drift. Care must be taken when placing quadrupoles. Depending on position and polarity, a quadrupole will enhance, negate, or not affect beam folding.

APT Beam Expander

Table I lists the elements of the APT beam expander, designed to produce a sufficiently uniform rectangular beam with the required 4-m by 2-m footprint. This beam expander represents one of many possible combinations of magnetic elements and drifts to achieve this goal. The pole-tip fields of all magnets are kept at or below 1.5 T, and the drifts are kept short. The design is not unique and further optimization is desirable before building the system.

TABLE I

APT beam expander to produce a uniform rectangular beam with a 4-m by 2-m footprint. The drift lengths between elements, and the element effective lengths, bore radii, and pole-tip fields are given.

type of element	length (m)	r_o (m)	B_p (T)
first octupole	0.50	0.020	0.768
drift	6.50		
focusing quadrupole	0.50	0.100	0.712
drift	2.19		
second octupole	1.00	0.134	0.914
drift	15.50		
defocusing quadrupole	2.00	0.356	1.499
drift	10.50		

The first octupole in the line manipulates the horizontal beam phase-space area. Once the beam is folded, the focusing quadrupole decreases the horizontal beam size and increases the vertical beam size at the second octupole while not affecting beam folding. The second octupole manipulates the vertical beam phase-space area. The defocusing quadrupole achieves the large footprint at the target, a very short distance away.

For the high-intensity APT beam, magnets with large apertures are desirable to avoid beam scraping. The magnets also must provide the fields dictated by the beam-transport calculations, and these fields are strong because the beam rigidity is large. It is thus impossible to dimension nonlinear beamline elements to have a substantial effect on the beam in the significantly populated beam fringes and not scrape the insignificantly populated far fringes of the beam. The APT beam expander was designed to clear 7σ (where σ is the rms beam size) of a Gaussian-distributed input beam. The radii given in Table I are those necessary to accept this beam.

Beam Distributions at the Target

The dimensions of the beam footprint at the target are fixed by the beam-expander configuration and the input-beam rms sizes and divergences, but the beam distribution at the target depends on the input beam distribution. For each input beam distribution there is a different nominal input beam, resulting in an acceptable beam distribution at the target.

Non-nominal input beams can result in unacceptable beam distributions. Non-nominal input beams caused by failures of accelerator quadrupoles or accelerator rf modules result in non-nominal but acceptable beam distributions. Varying the strengths of the beam-expander octupoles changes the beam distributions at the target as discussed below.

Nominal Beam Distributions

A Gaussian beam distribution provides the most realistic simple model for the distribution from the Coupled-Cavity Linac (CCL) planned for APT. A parabolic distribution, although often considered in beam-transport calculations, is not a good model for the CCL output beam. With an initially parabolic distribution one can achieve essentially uniform beams, while with an initially Gaussian distribution one cannot. Figures 2 and 3 show the beam distributions at the target for the nominal Gaussian and the nominal parabolic input beam, respectively.

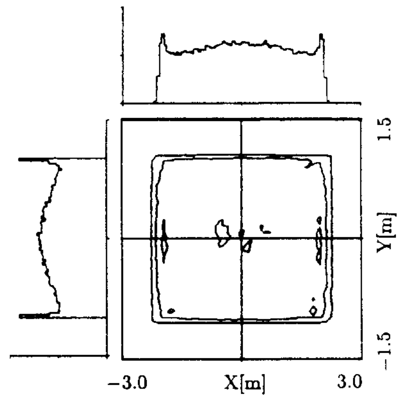

Fig. 2. Beam-intensity distribution at the target obtained from the APT beam expander and the nominal Gaussian input beam.

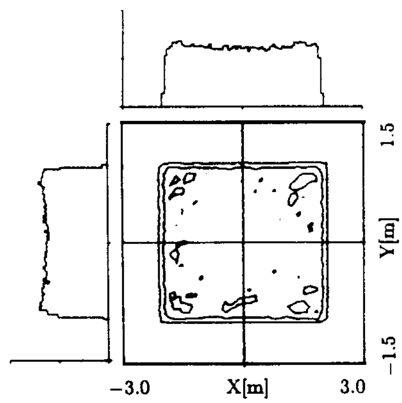

Fig. 3. Beam-intensity distribution at the target obtained from the APT beam expander and the nominal parabolic input beam.

Distribution Dependence on Octupole Strength

The dependence of the x projection of the beam-intensity distribution at the target on the strength of the first octupole in the APT beam expander is shown in Fig. 4, both for the nominal Gaussian and the nominal parabolic input beam. Only half of each symmetric projection is shown. Very weak octupoles influence only the far fringes of the beam, resulting in a beam that is similar to the input beam except for the tails of the distribution. Excessively strong octupoles fold the beam near the core, producing a beam with large spikes at the distribution edges.

Acceptable Non-Nominal Beam Distributions

Failure of an accelerator quadrupole causes a doubling of the transverse emittances of the CCL output beam. Instead of the nominal beam, a larger beam passes through the beam expander, and therefore the distribution at the target exhibits large spikes at the edges, characteristic of a beam subjected to excessively strong octupoles. The footprint dimensions are unchanged, and the distribution remains acceptable. Increased beam loss in the beam expander occurs.

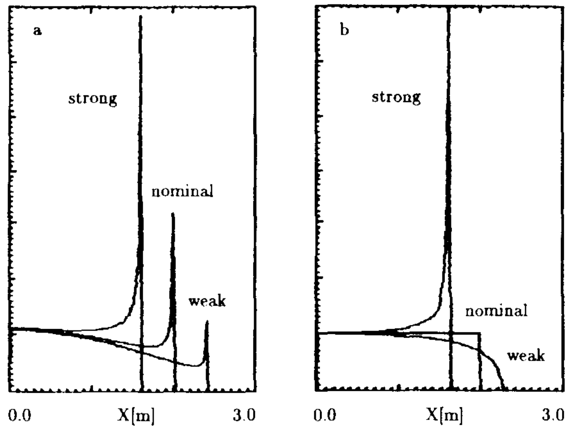

Fig. 4. Horizontal projection of the beam-intensity distribution obtained from the APT beam expander with a weak, nominal, and strong first octupole and (a) the nominal Gaussian and (b) the nominal parabolic input beam.

Failure of an rf module at or above 320 MeV causes a shift in the energy of the CCL output beam by up to ±10 MeV. The resulting non-nominal input beams yield different but acceptable target beam distributions and footprint dimensions.

Beam Jitter

For the APT beam expander, the rms beam sizes and divergences at the target are orders of magnitude larger than those at the exit of the CCL. Jitter of the beam centroid by one rms at the exit of the CCL would result in jitter by one rms at the target without octupoles and thus in only slightly less than one rms with octupoles, because these are dimensioned to have little effect on the core of the beam. Unless severe, jitter does not affect the footprint dimensions. On the other hand, jitter does have noticeable effects on the beam-intensity distribution.

Jitter control to 0.1 rms is feasible, and 0.1 rms of jitter can be tolerated for APT, as is illustrated in Fig. 5. For Fig. 2, a Gaussian-distributed input beam traversed the beam expander with its centroid on axis. For Fig. 5, the same beam traverses the beam expander with its centroid shifted by 0.1 rms. The previously symmetric contour lines and projections of the beam-intensity distribution at the target have become skewed.

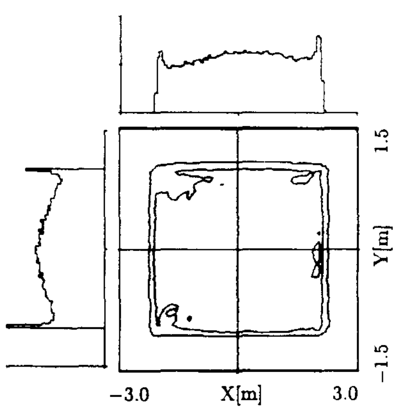

Fig. 5. Beam-intensity distribution at the target obtained from the APT beam expander and the nominal Gaussian input beam with a 0.1-rms centroid shift.

Beam-Fringe Control With Duodecapoles

Octupoles dimensioned to cause beam redistribution have the desired effect on the particles in the near beam fringes but an undesirably large effect on the particles in the far beam fringes. This results in intolerable beam loss downstream of the octupoles. Addition of appropriately dimensioned duodecapoles to the octupoles counteracts this effect.

The duodecapoles to be added to each of the two APT beam-expander octupoles are specified in Table II.

TABLE II

Duodecapoles to be added to the APT beam-expander octupoles for beam-fringe control.

type of element	length (m)	r_o (m)	B_p (T)
first duodecapole	0.50	0.020	0.538
second duodecapole	1.00	0.134	0.678

In Fig. 6 the beam footprint at the target of a Gaussian-distributed input beam populated to 7σ is shown for the APT beam expander without and with duodecapoles. Without duodecapoles, the far fringes of the original distribution have been folded into the core and actually protrude from the opposite distribution edges. With duodecapoles, the fringe particles to 7σ are totally contained in the core of the beam.

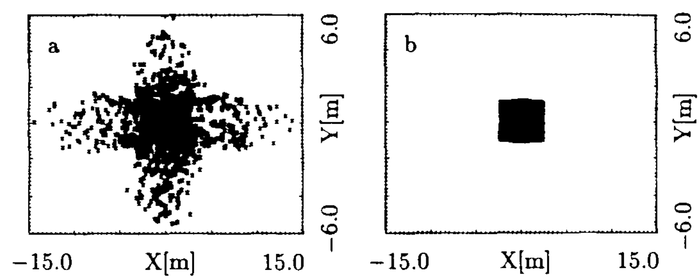

Fig. 6. Beam footprint obtained with the nominal Gaussian input beam populated to 7σ and the APT beam expander (a) without duodecapoles and (b) with duodecapoles.

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