CONF-901116--5

LA-UR -90-3293

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: **PRODUCTION OF UNIFORM AND WELL-CONFINED
BEAMS BY NONLINEAR OPTICS**

AUTHOR(S): Barbara Blind

AT-3

LA-UR--90-3293

DE91 000210

SUBMITTED TO: Eleventh International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 5-8, 1990

Received
OCT 04 1990

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

RECEIVED

28

PRODUCTION OF UNIFORM AND WELL-CONFINED BEAMS BY NONLINEAR OPTICS*

Barbara Blind

MS H811, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

Particle beams with uniform and well-confined intensity distributions are desirable for medical treatment, food irradiation and ion implantation. Moreover, such beams are essential in the development of high-intensity accelerators to prevent target damage and optimize target efficiency. One accepted method for beam redistribution employs nonlinear beamline elements, in particular octupoles and to a lesser degree magnets of even higher odd multipolarity. The method is not limited to the production of uniform beam distributions. The development of this field is reviewed. Beam redistribution is explained and the degree of uniformity and confinement achievable under various conditions is discussed. A method for tuning the size of the irradiation area is presented. A possible alternative to the use of combined-function multipoles is given. The effect of beam jitter on the distribution is considered. Applications of the method are given as examples throughout.

Introduction

The possibility of sterilizing food and medical apparatus with electron beams was recognized many years ago.¹ The need was then recognized to convert the peaked transverse intensity distribution typical of an accelerator output beam into a more uniform distribution over the irradiation area. This was accomplished by linearly defocusing the beam into a large oblong spot covering several times the width of the objects to be irradiated and moving the objects across the beam on a conveyor belt. However, the possibility of using nonlinear beamline elements for beam redistribution was then also discussed.

For tumor treatment, beams with uniform and well-confined distributions are required and are customarily obtained either in a time-average sense with a raster scanning system, or by letting the beam interact with materials, achieving uniformity by multiple nuclear elastic scattering and collimation.²

In high-intensity applications, such methods are often not viable. The Accelerator Production of Tritium (APT)³ beam carries 400 MW of beam power and the full beam must impinge on the target. The configuration is such that, for a two-dimensional raster scan, sweep magnets with unfeasible specifications for power and size are required. For a ribbon beam of uniform intensity, swept across the target in the direction orthogonal to the ribbon, a sweep magnet with achievable performance specifications but with a peak reactive power of 20 MW is required. The preferred method to achieve uniform target illumination thus is static beam redistribution with linear and nonlinear beamline elements.⁴ Other high-intensity applications where beam redistribution is considered are the Laser Sub System (LSS)⁵ and the International Fusion Materials Irradiation Facility (IFMIF)⁶.

Beam-Redistribution Method

The method for producing a ribbon beam by nonlinear optics is explained in detail elsewhere.⁷ With a nonlinear beamline element of odd multipolarity, one can shape 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. At the nonlinear beamline element the beam is focused into a spot with a large aspect ratio to avoid the x - y coupling normally caused by this device. Then, the peaked intensity distribution of the input beam is transformed into a distribution of greatly enhanced uniformity in the manipulated plane while retaining its peaked character in the other plane.

The method can sequentially 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. The distribution thus is of greatly enhanced uniformity in both planes and the contours of the x - y projection of the intensity distribution are rectangles.

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

While nonlinear beamline elements initiate the process of beam redistribution, sections containing linear transport line elements are necessary to let the beam evolve. These sections can be long, which poses a problem for applications with tight space constraints.

In accelerator systems with highly energetic particles, it is impossible to dimension nonlinear beamline elements so that they have a substantial effect on the significantly populated near beam fringes, and, at the same time, do not scrape the insignificantly populated far beam fringes. In high-intensity accelerator systems such losses have to be kept to a minimum. Therefore, beam redistribution is largely accomplished in these cases with the lowest order nonlinear element of odd multipolarity, the octupole.

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 beam loss downstream of the octupoles. Addition of an appropriately dimensioned duodecapole to the octupole counteracts this effect. Thus, duodecapoles are necessary for beam-fringe control in cases where even a small amount of beam spill cannot be tolerated.

The simplest beamline for achieving two-dimensional beam redistribution consists of two octupoles separated by a drift. Depending on the desired irradiation area, more magnetic elements may be required. Adding quadrupoles between the two octupoles serves to reduce x - y coupling by, at the second octupole, both decreasing the beam size in the transverse plane manipulated by the first octupole, and increasing the beam size in the transverse plane manipulated by the second octupole. Adding quadrupoles after the octupoles serves to reduce the length of the final drift. One or more quadrupoles downstream of the octupoles are also useful for varying the size of the ir-

*Work supported by the US Department of Energy, with Los Alamos National Laboratory Program Development funds.

radiation area. Care must be taken when placing quadrupoles. Depending on position and polarity, a quadrupole will enhance, negate, or not affect beam folding.

The uniformity achievable with a beamline consisting of quadrupoles for the proper first-order focus, octupoles for beam redistribution and duodecapoles for beam-fringe control depends on input beam distribution. One can achieve essentially uniform final distributions with initially parabolic, but not with initially Gaussian, distributions. Gaussian distributions present a much better model of the beams coming from linear accelerators than parabolic distributions. With initially Gaussian distributions one can achieve uniform final distributions only when scraping a substantial fraction (20%-30%) of the beam tails.⁸

With initially Gaussian distributions one can achieve uniform final distributions with only a modest amount (5%) of beam scraping in beamlines containing combined-function magnets which are dimensioned so that all their components contribute to beam redistribution.⁹

Example of One-Dimensional Beam Redistribution

For the proposed high-flux, high-energy IFMIF system, two 250-mA, 35-MeV deuteron beams impinge on two liquid-lithium jet targets oriented at right angles to each other to provide a large test volume of uniform neutron-flux levels for fusion materials and technology testing. The beam impinging on a target is shaped into a 4-cm-long ribbon of uniform intensity perpendicular to the direction of lithium flow, with a 1-cm-rms Gaussian projection perpendicular to the ribbon. This is accomplished with a single octupole, followed by a drift. The horizontal beam phase-space area is being manipulated by the octupole. Figure 1 shows the beam distribution at the target for an initially Gaussian-distributed beam. Here, as in all plots of this type, the 1%, 10%, 30%, 50%, 70% and 90% contour lines of the distribution and the x and y projections of the distribution are shown. An initially Gaussian beam distribution containing 10^5 particles was transported through the beamline using the beam transport code PATH.¹⁰

Fig. 1. Beam-intensity distribution at the IFMIF target.

Example of Two-Dimensional Beam Redistribution

For the APT system, a 4-m-wide by 2-m-high irradiation area is desired. Beam losses from the 250-mA, 1.6-GeV proton beam must be kept to a minimum. The beamline to achieve this consists of two octupoles and two quadrupoles.¹¹ A first octupole manipulates the horizontal beam phase-space area. Once the beam is folded, a focusing quadrupole decreases the horizontal beam size and increases the vertical beam size at a second octupole. This second octupole manipulates the vertical beam phase-space area. A defocusing quadrupole then achieves the large illumination area at the target a very short distance away. Figure 2 shows the distribution at the target for an initially Gaussian-distributed beam.

Fig. 2. Beam-intensity distribution at the APT target.

Each of the two octupoles has a duodecapole component to control the beam losses otherwise caused by the octupoles. Figure 3 illustrates this point. A Gaussian input distribution, populated to 7σ , was sent through the beamline, once without duodecapoles and once 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 beam-fringe particles to 7σ are totally contained in the beam core. The particles outside the desired irradiation area would actually be lost upstream of the target, due to the finite pipe sizes.

Fig. 3. Beam-particle positions at the APT target, a) without and b) with duodecapoles.

Irradiation-Area Tunability

In tumor treatment, as well as other applications, it might be desirable to vary the size of the irradiation area. With some care, a matching section consisting of one or more quadrupoles accomplishes this much like a matching section in any beamline would govern the beam spot sizes downstream of it.

The point is illustrated with an example of one-dimensional beam redistribution using a beamline containing an octupole to manipulate the horizontal beam phase-space area, followed by a quadrupole to govern the length of the ribbon beam at the target. The manipulated beam is a 200-MeV proton beam. The same Gaussian-distributed input beam enters the beamline in all cases and the octupole strength is fixed. In Fig. 4, the beam distribution at the target is shown for the defocusing quadrupole at zero, at half its maximum gradient and at its maximum gradient. The ribbon length is more than doubled in the process. If desired, the width of the ribbon beam could remain constant by changing the vertical beam parameters into the beamline with an upstream matching section.

Two-dimensional irradiation-area tuning works analogously, by varying the gradients of two quadrupoles.

Alternative Nonlinear Beamline Elements

Beam redistribution is customarily achieved with magnets which are a combination of odd multipoles. Since beam redistribution is accomplished one transverse plane at a time the field distribution necessary is only needed along either axis. Thus, other configurations for producing the desired nonlinear fields are manifestly possible.

An efficient magnet configuration in this respect is shown in Fig. 5. Here, a pair of oppositely directed dipoles produce an appropriate nonlinear field near the origin but a constant field at large x . Thus, such a dipole pair has the substantial effect on the near beam fringes provided by an octupole, does not have the undesirably large effect of a pure octupole on the far beam fringes and affords the beam essentially unlimited clearance in the manipulated plane.

Figure 6 shows $B_y(y=0)$ both for an octupole and for the equivalent dipole pair. The field of the dipole pair has been obtained by conformal transformation.¹² In a preliminary calculation where the on-axis fields were used to calculate the forces on all particles, similar final x and y projections were obtained for the APT beamline with the two types of elements as is illustrated in Fig. 7.

Beam Jitter

In typical applications, the rms beam sizes and divergences at the target are orders of magnitude larger than those at the exit of the accelerator. Jitter of the beam centroid by one rms at the exit of the accelerator would result in jitter by one rms at the target without octupoles and thus in only slightly less than one rms at the target with octupoles, since these are dimensioned to have little effect on the core of the beam. Unless severe, jitter does not affect the dimensions of the irradiation area. On the other hand, jitter has noticeable effects on the beam-intensity distribution.

The effect of a particular case of 0.25 rms jitter in the APT input beam centroid is given as an example in Fig. 8. For Fig. 2, a Gaussian-distributed input beam traversed the beamline with its centroid on axis. For Fig. 8, the same beam traverses the beamline with its centroid shifted by 0.25 rms. The previously symmetric contour lines and projections of the beam distribution at the target have become skewed, but the irradiation area remains unchanged.

Fig. 4. Ribbon-beam tuning with a quadrupole. The beam-intensity distribution at a target is shown when the quadrupole is a) off, b) at half its maximum gradient, and c) at its maximum gradient.

Fig. 5. Cross section of a dipole-pair configuration for producing nonlinear fields for manipulating the horizontal beam phase-space area. The magnetic potential is given for each pole. A pole at zero magnetic potential has been placed in the center to bring the field gradient to zero at the origin. Beam direction is into the paper.

Fig. 6. On-axis field $B_y(y = 0)$ for an octupole and for the equivalent dipole pair.

Fig. 7. Horizontal and vertical projections of the APT intensity distribution, achieved with a) two octupoles and b) the equivalent dipole pairs.

Fig. 8. Beam-intensity distribution at the APT target. The Gaussian input beam has a 0.25 rms centroid shift.

References

1. M. C. Crowley-Milling, "Improvements Relating to the Irradiation of Substances by Electronic Bombardment," British Patent no. 834540 (1960).
2. Information gathered during the PTCOG Workshop on Proton Gantry and Beam Delivery Systems, May 7, 1990, Loma Linda, California.
3. G. P. Lawrence, "New Applications for High-Power Proton Linacs," to be published in *1990 Linear Accelerator Conference Proceedings*.
4. P. F. Meads, Jr., "A Nonlinear Lens System to Smooth the Intensity Distribution of a Gaussian Beam," *IEEE Trans. Nucl. Sci.* 30 (4), 2838 (1983).
5. E. A. Wadlinger, Los Alamos National Laboratory, private communication.
6. G. P. Lawrence, G. L. Varsamis, T. S. Bhatia, B. Blind, F. W. Guy, R. A. Krakowski, G. H. Neuschaefer, N. M. Schnurr, S. O. Schriber, T. P. Wangler, and M. T. Wilson, "A High-Flux Accelerator-Based Neutron Source for Fusion Technology and Materials Testing," *Journal of Fusion Energy*, Vol. 8, Nos. 3/4, 201 (1989).
7. A. J. Jason, B. Blind, and E. M. Svaton, "Uniform Ribbon-Beam Generation for Accelerator Production of Tritium," 1988 Linear Accelerator Conference Proceedings, CEBAF Report 89-001, 192 (1989).
8. E. Kashy and B. Sherrill, *Nucl. Inst. and Meth.* B26, 610 (1987).
9. B. Sherrill, J. Bailey, E. Kashy, and C. Leakeas, "Use of Multipole Magnetic Fields for Making Uniform Irradiations," *Nucl. Instr. and Meth.* B40/41, 1004 (1989).
10. J. A. Farrell, "PATH - A Lumped Element Beam Transport Simulation Program with Space Charge," *Proc. of Berlin Conf. on Computing in Accel. Design and Operation*, W. Busse and R. Zelany, Eds., Springer Verlag, Berlin, 267 (1984).
11. B. Blind, "Generation of a Rectangular Beam Distribution for Irradiation of the Accelerator Production of Tritium Target," to be published in *1990 Linear Accelerator Conference Proceedings*.
12. A. J. Jason, Los Alamos National Laboratory, private communication.

END

DATE FILMED

10 / 22 / 90