UNIFORM BEAM DISTRIBUTIONS AT THE TARGET OF THE NSRL BEAM TRANSFER LINE*

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Abstract

Uniform irradiation of biological or material samples with charged particle beams is desired by experimenters because it reduces radiation dose errors. In this paper we present results of uniform beams produced in the NASA SPACE RADIATION LABORATORY (NSRL) at the Brookhaven National Laboratory (BNL) by a method which was developed theoretically and was proven experimentally [1,2,3] at BNL. A similar method which requires collimation of the beam, and also lacks the flexibility of the present method to produce beam various beam sizes at the target, was patented[4] in the year 1988. The present method of producing uniform beam distributions on a plane transverse to the direction of the beam, is based on purely magnetic focusing of the beam and requires no collimation of the beam or any other type of beam interaction with materials. It can also generate uniform beam distributions of various sizes. The method is favorably compared with alternative methods [5] of producing uniform beam distributions and can be applied to the whole energy spectrum of the charged particle beams that are delivered by the BNL Booster synchrotron.

INTRODUCTION

A unique method of generating uniformly irradiated areas ranging from 10x10 cm^2 to 20x20 cm^2 is utilized by the NSRL facility at BNL. In brief, the method of producing uniformly distributed beams over a rectangular area normal to the beam direction is based on third order magnetic optics and employs octupole magnetic elements which are placed at specific locations along the beam line. The octupole elements transform the otherwise normally distributed beam at the target, into a beam with uniform distribution. The details of the method to generate uniform beam distributions at the target are presented in [1,2,3] and the first experimental proof of the method appears in [1]. In this paper we provide more experimental data on the uniform beam distributions obtained in the NSRL facility, and we explore the possibility of using dodecapole magnetic elements instead of octupoles to generate uniform beam distributions.

THE NSRL FACILITY

The NSRL facility has been constructed at BNL to be used by NASA and other scientific organizations to conduct experiments involving irradiation of materials and biological samples. The construction of the NSRL facility was completed in March 2003 and was commissioned in June 2003[6,7]. Part of the NASA's research effort is to use the facility to irradiate biological samples with a variety of ions similar to those that a spacecraft on a mission to Mars will encounter. The location of the NSRL facility in relation to the AGS Booster, the BNL Tandem, and the BNL LINAC is shown schematically in Figure 1.

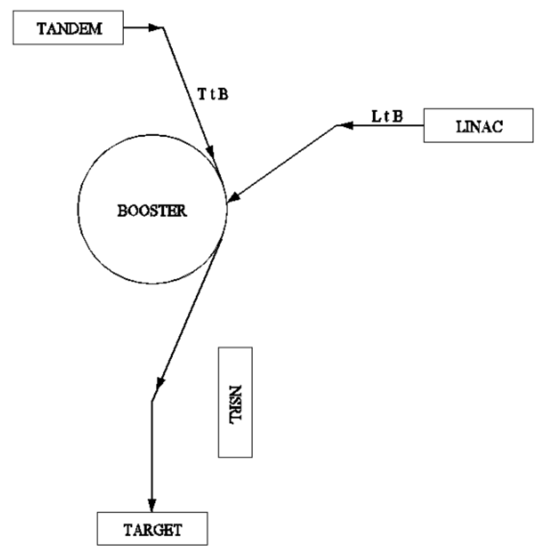

Figure 1: Schematic diagram of the NSRL line in relation to the Booster synchrotron, which accelerates the ions, the LINAC, which provides a proton beam, and the Tandem accelerator, which provides beams of many ions species.

The ion beams, used by the NSRL facility for the irradiation of the samples, are produced by the BNL Tandem (Van de Graaff), which provides light and heavy ion species, or the BNL LINAC which provides protons only. The ion beams are transported to, and accelerated by the BNL Booster synchrotron, and subsequently are slowly extracted [7], into the NSRL beam transport line which generates the uniform beam distribution at the target. Table 1 shows the ion beams that have been transported at the target of the NSRL line since the facility started operations. The second column of Table 1 shows the energies of the ion species transported at the target. Each ion beam is usually stripped of its electrons by a 0.051 [mm] thick copper foil which is located at the entrance of the NSRL line, and can be inserted and retracted automatically from the path of the beam. The third and fourth columns of Table 1 show the charge

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states of some of the ions before and after they are stripped of electrons respectively. The last column of Table 1 shows the typical number of ions delivered at the target per Booster cycle.

TABLE 1: Ion species that have been transported at the target of the NSRL beam transport line.

Ion	Energy [MeV/n]	Q_{bs}	Q_{as}	Ions/cycle 10^9
p	2500, 730 500, 200	+1	+1	34
^{12}C	300	+5	+6	12
^{16}O	1000	+7	+8	5
^{28}Si	1000, 300	+9, +13	+14	3
^{39}Cl	550	+14	+17	2
^{48}Ti	1000, 300	+18	+22	0.8
^{56}Fe	1000, 600 300	+20	+26	2

THE NSRL BEAM TRANSPORT LINE

Figure 1 shows the layout and the names of the magnetic elements of the NSRL line which starts at the "slow extraction" point of the Booster which is located just upstream of the D6 extraction septum, and ends at the target which is located 100 [m] downstream. The arc at the bottom of the Fig. 2 is part of the Booster synchrotron ring. The beam line is comprised of eight quadrupoles (Q1 to Q8), two Octupoles (O1,O2), one septum magnet (D6), two 20^{o} bend magnet (D1,D2), five horizontal (TH0, TH4) and five vertical (TV0,TV4) corrector dipoles. Five instrumentation packages (IP) have been installed [8] at specified locations along the beam line, and the relative location of the IP's is shown in Fig. 2. Each IP is equipped with an Ionization Chamber (IC) which measures the beam intensity, and a Segmented Wire Ionization Chamber (SWIC) which measures the horizontal and vertical beam profiles. Additional beam diagnostic devices are the phosphor Visual Flags (VF) which, when inserted into the path of the beam, can measure the beam distribution as well as the horizontal and vertical beam profiles. Visual Flags are located 0.75 [m] upstream of each instrumentation package, and also at the end of the beam transport line, (R300 in Fig. 2) and at the target location.

BEAM OPTICS OF THE NSRL LINE

The set up of the "first order" beam optics is essential for the octupoles to transform the beam distribution at the target into one, with a rectangular shape, which is uniformly distributed over the rectangle. The beam constraints that the first order beam optics has to satisfy are discussed in [2,3]. The first order beam parameters of the beam which satisfies these constraints are shown in Fig 3. When the octupoles of the line are excited, the beam distribution at the target acquires a rectangular shape, and the beam distribution becomes uniform over the rectangle. Fig. 4 shows a beam distribution over a 20x20 cm^2, rectangular area. The brightness along the perimeter of the beam's distribution, indicates that the beam intensity is increased along the perimeter.

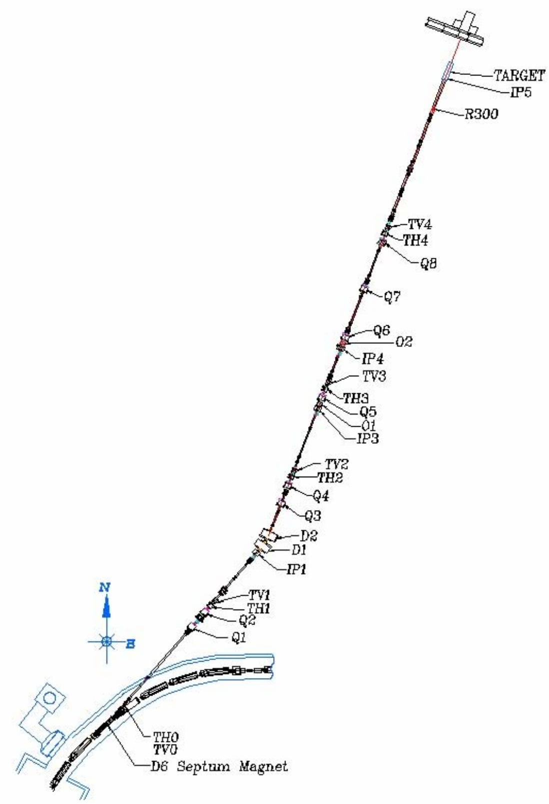

Figure 2: Drawing of the NSRL line. Shown are the main magnets and corrector magnets and the instrumentation packages (IP).

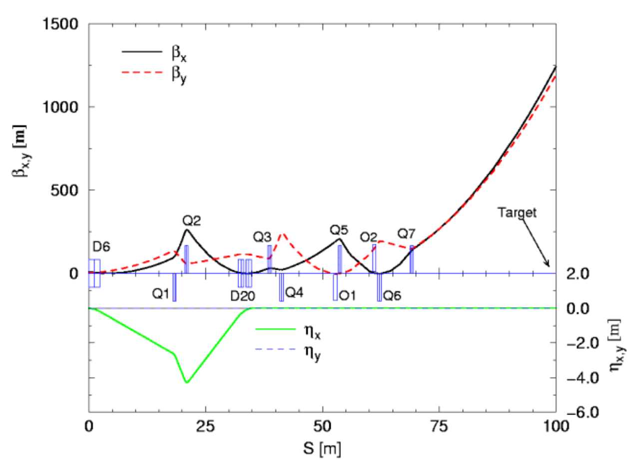

Figure 3: The horizontal- and vertical-beta ($\beta_{x,y}$) and dispersion ($\eta_{x,y}$) functions along the NSRL beam transport line. The rectangular blue boxes in the figure correspond to the magnetic elements of the line. The label D20 in the figure designates the two dipoles D1 and D2 of Fig.1.

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Note the shape of the beam distribution, shown in Fig. 4, is not a rectangle but the two sides, left and right, are curved. Both, of these effects, increase of intensity and curvature of the sides, are explained in ref. [3]. The beam uniformity within the area defined by the outer tic marks shown in Fig. 4, is ±2%. Fig. 5 is another uniform beam distribution of a ^{48}Ti beam at energy of 1 GeV/nucleon. This is a smaller beam in size over an area of 10x10 cm^2 and the beam uniformity within the inner tic marks is also ±2%.

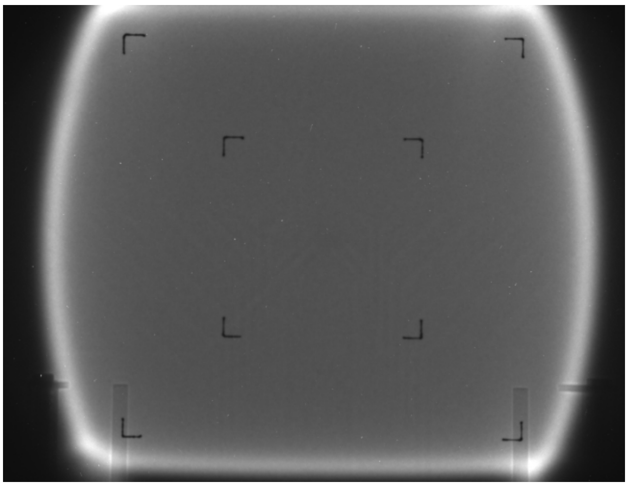

Figure 4: A uniform beam distribution at the target. The inner and outer tic marks correspond to distances of 10 cm and 20 cm respectively.

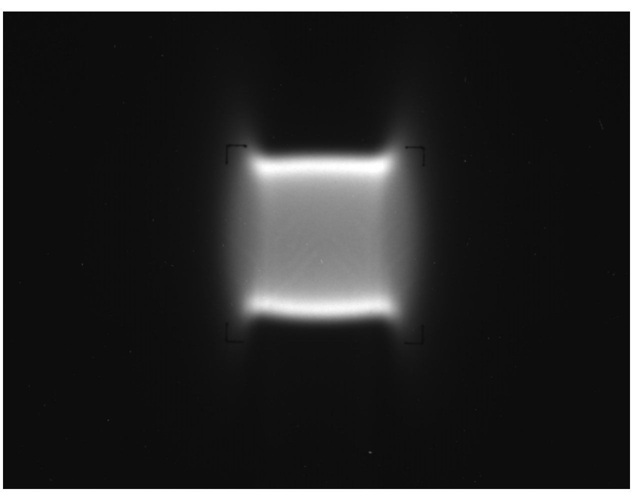

Figure 5: A uniform beam distribution at the target. The size of the area where the beam is uniform is ~8x8 cm^2.

UNIFORMITY WITH DODECAPOLES

Dodecapole magnetic elements can also generate uniformly distributed beams at the target. Figure 6 compares the projected horizontal and vertical beam distributions generated by octupole magnetic elements to those generated by dodecapole ones. The comparison shows no advantage in using duodecapole elements to improve the beam uniformity. The simulations to produce uniform beam distributions, assumes no fringe fields in either, octupoles or duodecapoles.

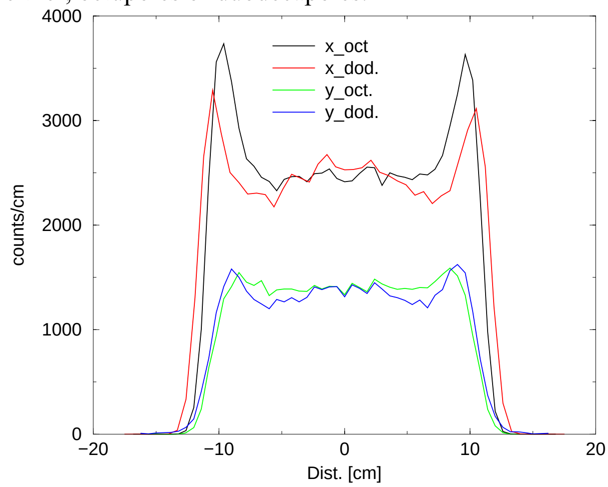

Figure 6: Calculated horizontal and vertical projections of the beam distribution at the target; with octupoles (black/green) and dodecapoles (red/blue). The counts for the vertical distributions have been scaled down by a factor of 2, for the curves to be separated for clarity purposes.

CONCLUSIONS

The NSRL facility at BNL has delivered uniformly distributed ion beams of various ion species at the target location of NSRL beam transport line. The beam cross section at the target is rectangular and the beam uniformity over the interior area of the rectangle is measured to be ±2%.

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