RESULTS FROM THE COMMISSIONING OF THE NSRL BEAM TRANSFER LINE AT BNL *

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Abstract

The NASA SPACE RADIATION LABORATORY (NSRL) has been constructed and started operations at the Brookhaven National Laboratory in 2003. The NSRL facility will be used by NASA to perform radiation effect studies on materials and biological samples for the space program. The facility utilizes proton and heavy-ion beams of energies from 50 to 3000 MeV/n which are accelerated by the AGS_Booster synchrotron accelerator. To date, ^{1}H, ^{12}C, ^{56}Fe, ^{48}Ti, and ^{197}Au ion beams of various magnetic rigidities have been extracted from the Booster, and transported by the NSRL beam transport line to the sample location which is located 100 m from the extraction point. The NSRL beam transport line has been designed to employ octupole magnetic elements [1] which transform the normal (Gaussian) beam distribution at the location of the sample into a beam with rectangular cross section, and with uniform distribution over the sample. When using the octupole magnetic elements to obtain the uniform beam distribution on the sample, no beam-collimation is applied at any location along the NSRL beam transport line and the beam focusing on the sample is purely magnetic. The main subject of this paper will be the performance of the octupoles (third order optics) in obtaining uniform beam distributions at the target location of the NSRL beam transport line.

INTRODUCTION

The NSRL facility has been constructed at BNL to be used by NASA and other scientific organizations to conduct irradiation experiments on materials and biological samples. The commissioning of the NSRL facility was completed in June 2003.

Some of the ion beams (see Table 1) which are available by the facility, have been accelerated by the BNL Booster, slow_extracted [2], and transported to the sample by the NSRL beam transport line which is the subject of this paper.

Unlike most of the beam transport lines which utilize only dipoles and quadrupoles magnetic elements for the beam transport and focusing, the NSRL beam transport line has a unique characteristic that employs octupole magnetic elements to generate uniform irradiation fields at the location of the sample. Uniform irradiation fields, over relatively large areas 20x20 cm^2, are often required when ion beams are used to irradiate materials or

Table 1: Some Ions Species that have been Transported at the Target Location of the NSRL Beam Transport Line

Species	Energy [MeV/nucleon]	Before stripping	After stripping
p	730	+1	+1
^{12}C	300	+5	+6
^{56}Fe	1000	+20	+26
^{48}Ti	1000	+18	+22
^{28}Si	600	+9	+14

biological samples. In other laboratories uniform beam distributions are obtained using various methods [3] depending of the ion beams. For protons and other light ions, uniform beams are obtained by increasing the angular divergence of the beam, by letting the beams passing through a layer of material that multiple scatters the beam to increases the beam divergence. For heavier ions that have higher rigidity, the multiple scattering technique in not effective therefore the “magnetic rastering” technique is used. In this method the beam is focused into a small spot at the location of the sample and the spot of the beam is sweeping the sample. The beam sweep is achieved by deflecting the beam horizontally and vertically using dipole magnets which are located upstream of the sample. Both methods, mentioned above, of generating uniform beam irradiation of the sample have disadvantages [4]. These disadvantages are eliminated by using octupole elements to modify the Gaussian beam distribution at the location of the sample to a uniform one. The first experimental “proof of principle” of this method appears in Ref. [5]. A detailed description of the theoretical aspect of this method appears in Ref. [2] and elaborate description of the NSRL beam transport line appears in Ref. [4]. In this paper we present results from the commissioning of the NSRL beam transport line which employs octupole elements to generate uniform beam distributions over the sample. The following aspects of the NSRL beam transport line are presented.

1. Description of the NSRL beam transfer line (magnet layout, beam envelop of the line using first order beam optics).
2. Results from the commissioning of the NSRL line.

2a) Measured beam parameters at the beginning of the NSRL line and experimental first order beam envelope.

2b) Beam distribution at the location of the target with and without the use of octupoles.

3c) Effect of the magnets instability on the beam uniformity at the sample.

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"NSRL" BEAM TRANSFER LINE

The layout of the magnetic elements of the NSRL beam transfer line is shown in Figure 1. The letters Q,D, and O in Figure 1 correspond to Quadrupole, Dipole and Octupole magnetic elements respectively.

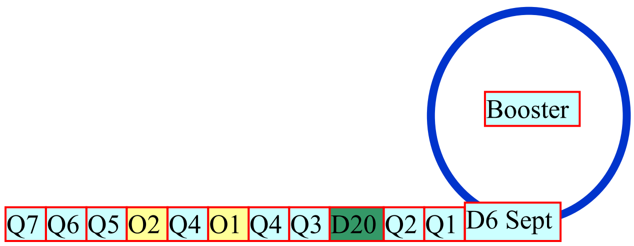

Figure 1: Schematic diagram for the layout of the magnetic elements of the NSRL transfer line.

Beam Constraints along the NSRL Beam Transfer Line

The following constraints are imposed on the optics of the NSRL beam transfer line.

- The set of magnetic elements D6,Q1,Q2, and D20^{o} form an achromatic bend.
- The (x,x') beam particle coordinates at the location of the octupole (O1) should be highly correlated in the horizontal plane Ref [1] to facilitate the effect of the octupole which will generate the uniform beams at the target. Similar constraint should also apply for the beam coordinates (y,y') at the location of the second Oct. (O2).

First Order Beam Optics

Details on the first order beam optics that satisfies the constraints mentioned above appear in [1,4,6]. The TRANSPORT or MAD computer codes have been used for the first order beam optics.

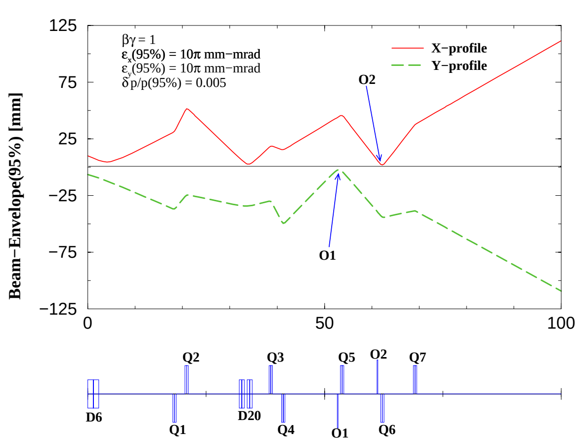

Figure 2: Half of the horizontal (red solid line) and half of the vertical (green dashed line) beam envelopes of the beam transported in the NSRL transport line.

The first order beam envelopes and the magnetic elements of the NSRL line are shown in Figure 2. The envelopes contain 95% of a beam with emittance of 10π [mm.mrad]. Note the horizontal and vertical beam sizes at the location of the octupoles shown in Figure 2.

THIRD ORDER BEAM OPTICS

The first order beam optics, that satisfies the beam constraints mentioned earlier, provides the beam conditions for the octupoles to transform the "normally" distributed beam on the target into a rectangular beam uniformly distributed over the rectangle. The theory that describes the action of the octupoles on the first order beam distribution, which is assumed to be "normal" in all of its coordinates, is described in details in ref. [1].

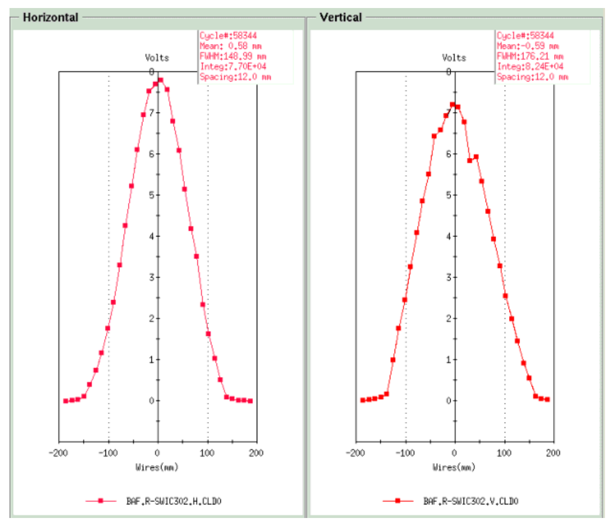

Figure 3: Horizontal and Vertical beam profiles at the target with both Octupoles OFF (first order beam optics).

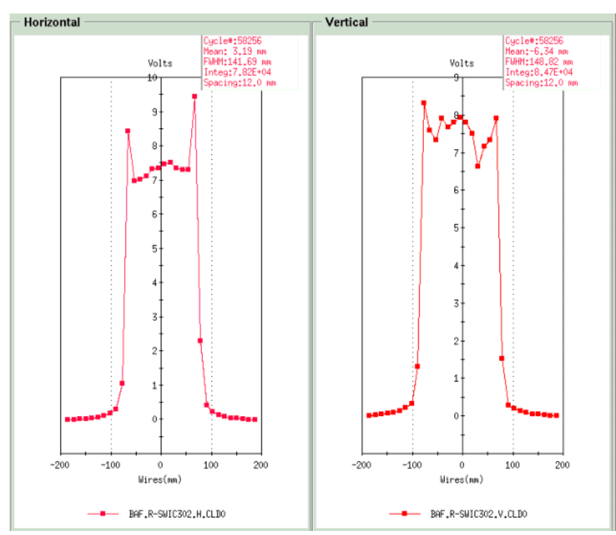

Figure 4: Horizontal and vertical beam profiles at the target with both octupoles ON (third order beam optics).

In this paper we only present experimental results from the measured beam distributions at the target with the octupoles OFF, shown in Figure 3 and octupoles ON shown in Figure 4. These beam profiles were measured using Segmented Wire Ionization Chamber (SWIC).

The two dimensional beam profile of the beam at the target when both octupoles are ON is shown in Figure 5.

This profile was obtained by a light emitting material which is inserted at the target location with the beam ON. The beam uniformity at the region of the irradiation has been measured ±2%. Experimental observations of the beam profiles on the target [4] show that the excitation of a single octupole, affects only the distribution of the beam in one plane, with the distribution of the beam in the other plane remaining Gaussian. This is an indication that the octupoles do not "couple" significantly the horizontal and vertical coordinates of the beam.

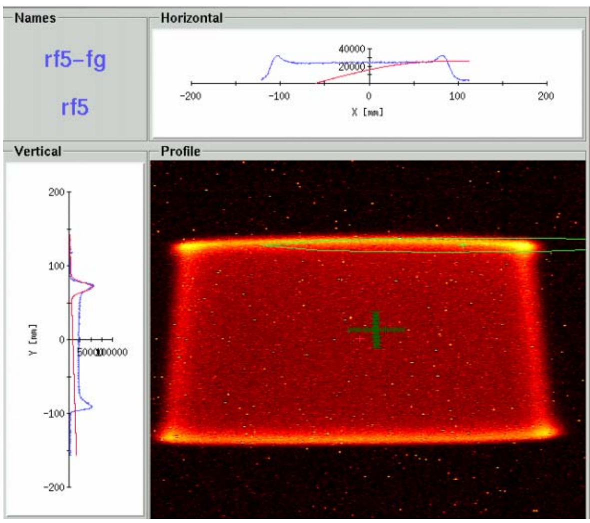

Figure 5: Two dimensional beam profile at the target. The horizontal and vertical projections of the beam distribution is also shown.

EFFECT OF THE BEAM MISALIGNMENTS

During a regular setup of the NSRL beam line for uniform beam irradiation of the target, it is possible that the beam distribution on the target is not uniform and its projection on the horizontal or vertical plane or both my look like the profiles shown in Figure 6. Such a distribution as shown in Figure 6 indicates that the central trajectory of the beam does not line up with the magnetic axis of the octupole. This misalignment can be easily corrected by exciting a horizontal corrector magnet which places the beam on the magnetic axis of the octupole. A vertical corrector magnet can be used to correct for vertical misalignments. Proof of the above statement is based in computer simulations, and appears in ref. [4].

FURTHER DEVELOPMENTS

Although the octupoles can generate a beam distribution which is uniform over a rectangular area, the edges of the rectangle show an increase of the beam intensity "batman ears". Preliminary theoretical studies, using duodecapole magnets instead of octupoles, show that the duodecapole magnets generate beam distribution on the target with equally good uniformity but with the added benefit of smaller "batman ears".

Few of the two dimensional beam profiles like the one shown in Figure 5 exhibit a uniform distribution but with "curved" instead of straight boundaries. Preliminary results, obtained from computer modelling of the beam transport line indicated that the curved boundaries is the result of higher order aberrations of the octupoles acting in a beam which deviates from the normal distribution as it enters the NSRL beam transport line.

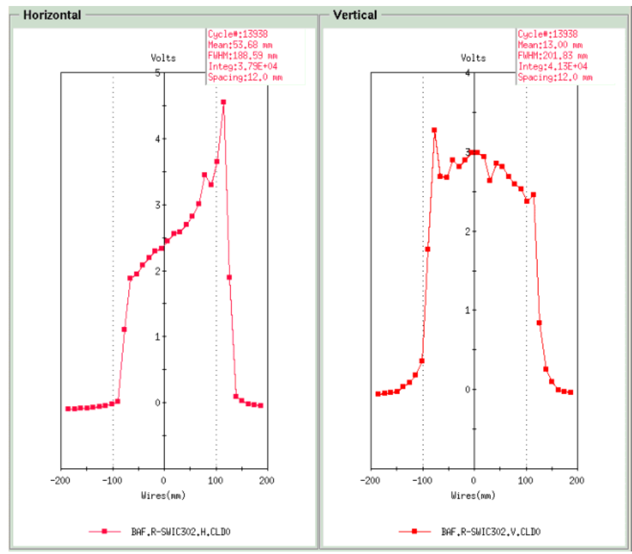

Figure 6: Beam misalignments at the entrance of the horizontal (O1) or Vertical (O2) octupoles affect the uniform beam distribution at the target. A horizontal corrector magnets can be used to correct such beam misalignments.

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