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BMAD BASED PARTICLE TRACKING SIMULATION FOR SLOW RESONANT EXTRACTION*

B. Dhital†, K.A. Brown, Brookhaven National Laboratory, NY, USA
E. Hamwi, G.H. Hoffstaetter, W. Lin, D. Sagan, Cornell University, NY, USA

Abstract

Slow resonant extraction plays a crucial role in delivering a high-quality continuous beam to experiments. Simulating the extraction and transport of charged particle beams requires a process of careful modeling and experimentation. In this work we have used long-term tracking based on the Bmad ecosystem to run a third integer resonant extraction simulations of beams of various ion species in the booster synchrotron at Brookhaven National Laboratory. In this paper, we will present results of detailed slow extraction, multi-particle tracking simulations.

INTRODUCTION

The use of a resonant slow extraction scheme allows the continuous extraction of particles from a synchrotron ring over a large number of turns. Slow extraction is a dynamic process that can be described by combining the different phase-space properties that characterise particle behaviour in a synchrotron with a horizontal betatron tune close to a third-integer resonance [1, 2]. At Brookhaven National Laboratory (BNL), this technique is used to extract beams of various ion species from the Booster synchrotron to the NASA Space Radiation Laboratory (NSRL) [3, 4]. The Booster facility provides heavy ion beams of different ion species at different energy ranges.

In this paper, a long-term tracking program, based on Bmad [5, 6], is used to simulate slow extraction via a one-third integer resonance in the Booster ring with further tracking down the NSRL transfer line.

ACCELERATOR OVERVIEW

The Booster is a 201.78 m circumference separated function alternating gradient synchrotron that can operate up to a maximum rigidity of 17 Tm [4]. Three sources: LINAC (protons only), the Tandem Van de Graaff (certain ions and protons), and the Electron Beam Ion Source (EBIS) (any ion except protons) provide beams which are injected into the Booster synchrotron where they are further accelerated to reach the final energy and delivered to NSRL [4]. For one-third resonance extraction from the Booster ring to the NSRL beamline, we have five extraction bump magnets (C7, D1, D4, D7, and E1), two septa magents (D3 and D6), and two families of sextupoles (not shown in Fig. 1) placed at certain location in the Booster ring. These sextupole magnets are different than those sextupole magnets being used to correct the chromaticity in the ring [7–9]. The layout of the portion of the Booster ring is shown in Fig. 1.

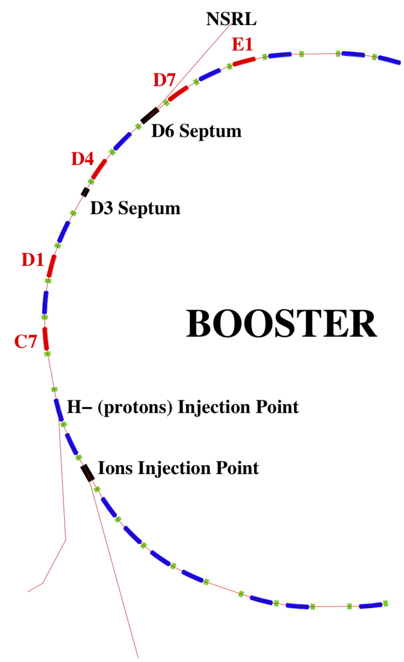

Figure 1: Layout of the portion of the Booster ring showing five extraction bump magnets (C7, D1, D4, D7, and E1) along with two extraction septa magnets D3 and D6 [4].

The schematic layout of the NSRL beam line is shown in Fig. 2. The line consists of three dipole magnets forming a 20° bend, eight quadrupoles (Q1–Q8) magnets, and two octupole (Oct1, and Oct2) magnets respectively. The two octupoles, one upstream of Q5 and the other upstream of Q6, can be adjusted to achieve a uniform rectangular distribution of beam on target. The optics of the line is designed to make an achromatic beam after the two dipoles. This is crucial towards achieving good quality uniform beams since momentum dependent motion at the entrance to the octupoles will affect the uniformity.

LONG-TERM TRACKING

The long-term tracking program is for long term (over many turns) tracking of a particle or a beam in a ring. The long-term tracking program can track spin as well as simulate such things as element misalignments, wake fields, higher order mode cavity resonances, energy ramping, beta squeezing, etc. The output of the program will be such things as turn-by-turn particle tracks or beam statistics including

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† bdhital@bnl.gov

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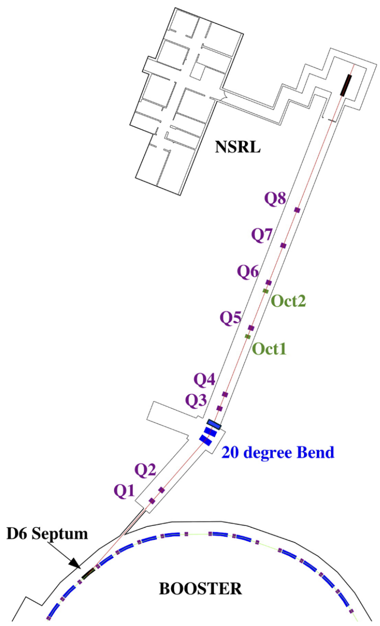

Figure 2: Layout of the NSRL beam line starting at D6 septum and going downstream to the NSRL target [4].

beam sizes and polarizations. The long-term tracking program is built atop the Bmad software ecosystem. Bmad is a subroutine library for charged–particle and X-Ray simulations in accelerators and storage rings. Bmad can be used to study both single and multi–particle beam dynamics as well as X-rays [6].

EXTRACTION SIMULATION

In an extraction simulation based on long-term tracking, particles are initially tracked for a certain number of turns within a ring, followed by tracking through an extraction line. We employ tune ramping in these simulations, where the strengths of horizontal quadrupoles in the machine are continuously varied over time. For the Booster slow extraction system, the one-third resonance horizontal tune is 4.33, and we select a machine tune just above this value. The tune ramping with quadrupoles gradually brings the machine tune close to the resonance tune of 4.33, causing tracked particles to fall into resonance and become unstable. This instability leads to the stable elliptical horizontal phase space becoming unstable and forming a triangle, as depicted in Fig. 3.

There are basically two simulation “modes” in a long-term tracking program to run particle tracking in the ring and the transfer line. They are: “SINGLE" and “INDIVIDUAL" tracking simulation modes respectively.

Single Mode

In a “SINGLE" mode, a single particle is tracked for a large number of turns in the ring. A particle with a given amplitude is tracked for many turns until lost or until the maximum number of turns set by user is reached. The output file has particle positions at every n turns set by the user. The transverse phase space (x, px) shown in Fig. 3 is at D3 septum location in the Booster ring for five particles with different amplitudes being tracked using “SINGLE" mode in a long-term tracking code. D3 septum in the ring is described as a “marker" element and we set this marker as a stop element where all particles position for every n turns are recorded. All particles extracted and crossing D3 septum (represented by red vertical line at 0.07 m) get a kick from D3 magnet and particles move downstream towards D6 septum and finally to the NSRL transfer line.

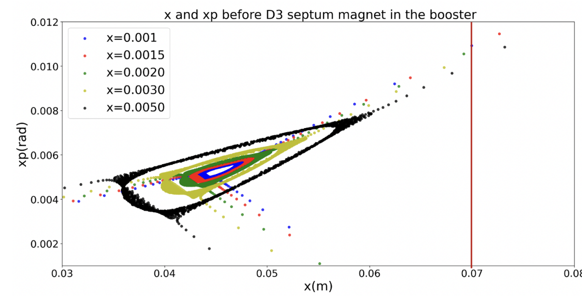

Figure 3: Horizontal phase space of five particles with different amplitudes at D3 septum location using “SINGLE" mode.

Individual Mode

With the "INDIVIDUAL" simulation mode, it is assumed that there is a septum and that particles that are outside of the aperture set for the septum are to be tracked through the extraction line. Extraction tracking starts with particles that have hit the septum having their state switched from dead to alive and vice-versa for the other particles. Figure 4 shows the particles that are outside of the D3 septum. In this case, D3 septum is treated as a horizontal kicker magnet that gives a certain kick (3 mrad in our case) to the particles hitting the thin septum wire at D3 location. Those particles switching their state from “dead" to “alive" will be tracked through D3 septum to the line going downstream through D6 septum and finally to the NSRL transport line until particles reach the NSRL target location.

Starting in the Booster synchrotron, we track the particles along the transfer line. This is possible in Bmad using the features like *Branch, Fork* and *Patch*.

BRANCH, FORK AND PATCH

A fork element marks the point where multiple lines can merge or branch off from. Patch element on the other hand shifts the reference orbit. Two red circles in Fig. 5 shows the fork elements used to connect with different branches. The first fork element (at START_OF_BEXT) connects the Booster ring with a branch starting at D3 septum and going downstream to D6 septum location. At D6 septum location, there is another fork (FORK_TO_NSRL) element to connect with the NSRL line. At this location, we also use a patch element to shift the reference orbit providing offset in the

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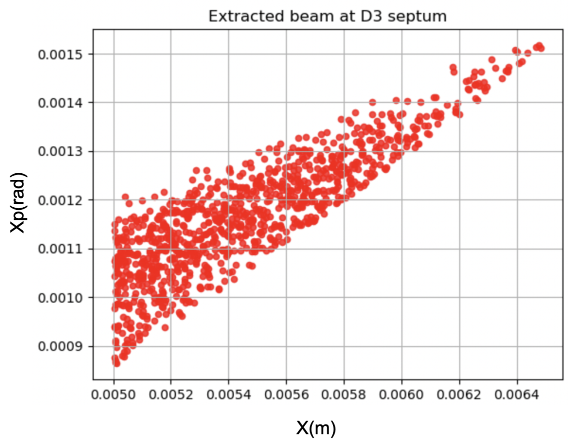

Figure 4: Horizontal phase space for 1000 particles hitting D3 septum which is at 5 cm from the beam center using “INDIVIDUAL" tracking mode.

’XZ’ coordinates so that we match the reference coordinates at the beginning of the NSRL beamline. Patch element provides the offset to the co-ordinate system whereas Fork element just connect one branch to another.

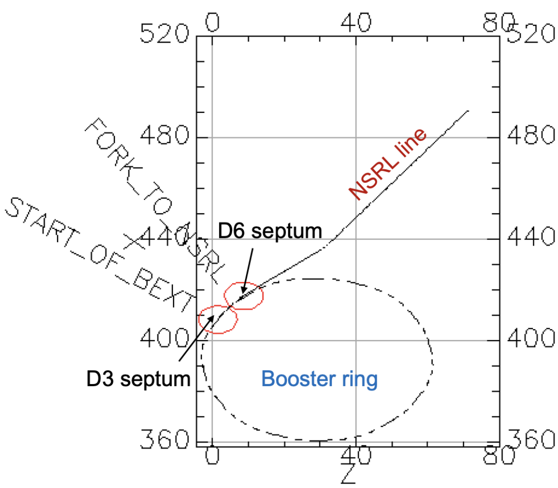

Figure 5: Connecting Booster ring with the NSRL transfer lines using fork and patch elements in Bmad.

FOIL ELEMENT

A foil element represents a planar sheet of material capable of stripping electrons from a particle. Consequently, there will be scattering of the particle, altering its trajectory along with an associated energy loss [5]. The foil is positioned just before the D6 septum at the start of the NSRL beamline to obtain the Gaussian beam, as depicted in Fig. 6. The foil element in Bmad has been implemented and tested for the first time in a slow resonant extraction simulation in Bmad. This is one of the notable features that sets Bmad apart from other available accelerator-based software.

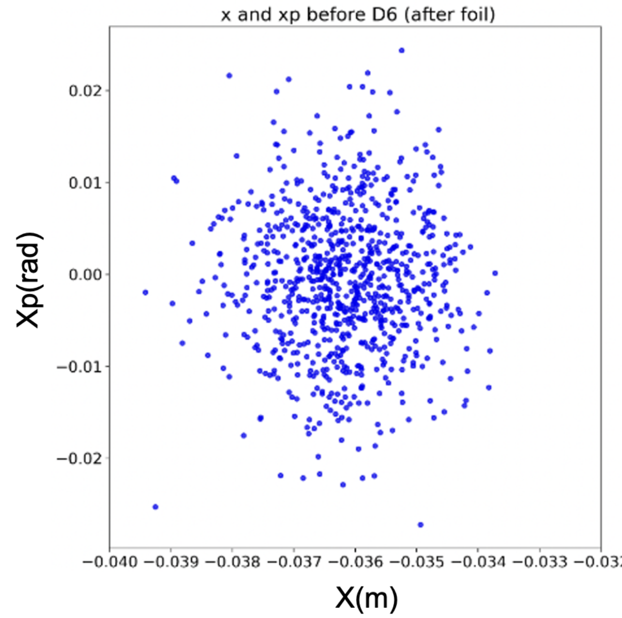

Figure 6: Horizontal phase space (x, xp) before D6 septum after passing through foil at the beginning of NSRL transfer line. 1 GeV proton beam with 1000 particles are being used to run the long-term tracking simulation.

FUTURE WORK

The future work will entail further enhancing the one-third resonant slow extraction simulation using long-term tracking code in conjunction with Bmad. Our focus will be on optimizing the NSRL beamline to generate highly correlated beams in the transverse planes in front of two octupoles, as well as creating a uniform beam at the NSRL target.

CONCLUSION

The Bmad-based long-term tracking code for slow one-third resonant extraction offers us greater flexibility to conduct single and multi-particle tracking simulations. Bmad includes unique features such as branch, fork, and patch, making it a special tool for running complete resonant extraction simulations from the Booster synchrotron to the end of the NSRL transfer line, which is connected to the Booster ring at the D3 septum. Additionally, the foil element in Bmad is a new feature that generates a Gaussian beam at the beginning of the NSRL transfer line, fulfilling a requirement for creating a uniform beam at the NSRL target.

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