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Energy interlock in the Booster to Storage Ring transfer line

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1 Introduction

Under normal operational conditions in NSLS-II the energy of the beam extracted from the Booster and transferred to and injected into the Storage Ring (SR) is 3 GeV. It was determined that for the commissioning purposes energy range of the beam reaching the SR is allowed to be 2 GeV - 3.15 GeV. While the upper limit of the beam energy is defined by the maximum possible settings of Booster dipoles at the top of the ramp, the lower energy limit has to be provided by magnet interlocks. Dynamic interlocks of the Booster dipoles would be an ideal solution, yet the constraints of time and resources do not allow providing such interlocks for commissioning stage of NSLS-II. Therefore, the static interlock of magnets in the Booster to SR transfer line (BSR) shall be used to build a required “energy filter”.

The goal of this exercise is to find a feasible solution for the BSR energy interlock that will be used at commissioning stage of NSLS-II accelerator.

2 Description of the BSR

The Booster to Storage Ring transfer line includes two beamlines BSR-P1 (phase 1) and BSR-P2 (phase 2). Figure 1 shows the beamlines under consideration.

Figure 1: BSR phase 1 and phase 2.

The phase 1 of BSR line (a.k.a. dump line) consists of five quadrupoles Q1, Q2, Q3, Q1BD and Q2BD (their respective engineering names are BS-Q1, BS-Q2, BS-Q3, BS-Q1BD and BS-Q2BD), and one bending magnet B1 (its engineering name is BS-B1). These magnets transport beam to the beam dump when bending magnet B2 is turned off. The BSR-P1 also includes pulsed septum magnet SP1 (its lattice file name is BRSP1SE and its engineering name is BR-XSSMP1), and DC septum magnet SP2 (its engineering name is BR-XSSMD1). These magnets are utilized for the extraction of the beam from the Booster into the BSR line.

The BSR-P2 includes magnets Q1, Q2, Q3 and B1, and additionally has quadrupoles Q4, Q5, Q6, Q7, Q8, Q9, Q11, Q12, Q13, Q14 (BS-Q4, BS-Q5, BS-Q6, BS-Q7, BS-Q8, BS-Q9, BS-Q11, BS-Q12, BS-Q13, BS-Q14 in engineering notation) and bends B2, B3 and B4 (BS-B2, BS-B3, BS-B4 in engineering notation). These magnets transport beam to the Storage Ring. Injection into the Storage Ring is performed with SP3 and IS, which are the DC and pulsed Storage Ring injection septa respectively. Their engineering names are BS-SP3 and SR-IS-SP1.

The detailed description of each of the beamlines elements is given in Ref. [1].

3 BSR energy interlock

The requirements to the energy interlock are straightforward. It has to be located as close to the beginning of the BSR as possible and its physical realization has to be as simple as possible. It is undesirable to interlock the quads from accelerator physics point of view. The first DC bend in the BSR is SP2. Yet, since it has a nonstandard power supply, interlocking this dipole is

questionable from engineering point of view. These considerations leave us with bends B1 and B2 as interlock devices of choice. These two bends are located at the very beginning of the BSR. They are close to each other and there is just one quad in between them. Therefore, in case that interlocking B2 only does not create a necessary energy filter, one can expect that adding an interlock on B1 would constructively raise the limit of beam energies passing the interlock. Finally, adding a few percent interlock to B1 or B2 power supplies is a trivial engineering task.

To explore various interlock options we perform beam tracking with a set of codes built specifically for that task. In all of these codes we utilize the following beam tracking algorithm. We start with the beam centroids phase space defined by the geometric acceptance of the drift upstream of BRSP1SE. In our simulations the initial phase space was populated with 2500 beam centroids. It was checked that increasing this number does not affect final results. The approach to creating such phase space is schematically demonstrated in Fig. 2.

Figure 2: The picture on the left schematically shows the beam centroids (red) originating at the upstream magnet and filling the drift upstream of BRSP1SE. The plot on the right shows the phase space available to the beam centroids at the entrance of BRSP1SE.

Next, we track this phase space at particular energy through the beamline down to the entrance of the dipole of interest varying each magnet settings in their full range. In the studies described below each magnet goes through 10 settings spanning the range of possible magnet values. It was determined that the chosen number of magnet settings is ample since 10 resulting beam centroids phase spaces at magnet exit overlap well enough to exclude the possibility of any missed centroids.

While tracking, the vacuum chamber dimensions in both magnets and drifts are taken into account, and the beam centroid hitting the chamber is considered to be lost. At the downstream end of each beamline element the phase space is repopulated, to exclude exponential growth of the number of beams and to ensure that the number of beam centroids stays approximately the same throughout the whole tracking routine. The method of repopulating the phase space, a so-called phase space “sand molding”, is described in Fig. 3. In our studies the number of beam centroids in the “sandbox” was 2500. It was checked that increasing this number does not affect final results.

Figure 3: In sand-molding technique we obtain repopulated phase space by “imprinting” the original PS on the “sand box” of beam centroids.

To study the case of interlocked B1 and B2 we track the phase space of possible 2 GeV beam centroids through the beamline upstream of B2 with B1 fixed within $\pm 2\%$ of its nominal value and all other magnets varied in their full range of strengths at 2 GeV. The respective magnets ranges and nominal setting are shown in Table 1.

element name	PS max current [A]	B or B' max [T] or [T/m]	B or B' nom [T] or [T/m]	θ_{nom} [rad] @3 GeV	K1nom [1/m ²] @3 GeV
BRSP1SE	11242	0.88	0.80	0.048	
SP2	500	0.98	0.87	0.104	
Q1	175	29.92	-5.69		-0.853
Q2	200	34.03	11.69		1.754
B1	375	1.34	0.55	0.115	
Q3	175	29.97	0.93		0.140
B2	375	1.34	-0.73	0.154	
Q4	175	29.99	-6.39		-0.958

Table1: Nominal settings and ranges of magnets at the beginning of the BSR.

Next, we track obtained phase space through B2 interlocked at its nominal 3 GeV setting and compare the phase space at B2 exit with acceptance of the rest of the BSR. The acceptance of B2-SR beamline is obtained from backtracking of the phase space of all possible beam centroids in SP3-IS drift to the exit of B2.

Results of the study are presented in Fig. 4.

Figure 4: Studies of B1-B2 interlock. The phase space at the entrance to B2 was obtained by tracking all possible beam centroids through the BSR line with B1 interlocked at its nominal value with $\pm 2\%$ window. The green trace in the middle plot shows B2 reference trajectory.

As one can see, although some of the beam centroids will reach Q4, none of them will be transported to SR injection septum. Varying the B2 settings within $\pm 2\%$ window doesn't change this conclusion. That means that interlocking B1 and B2 with $\pm 2\%$ window around their nominal 3 GeV values provides required energy filter.

To double-check this result we perform additional tracking through the BSR. We track 2 GeV beam centroids with B1&B2 fixed within $\pm 2\%$ of their nominal values and rest of the magnets varied within their full range. As can be seen from Fig. 5, beam centroids do not propagate farther than Q4. A few centroids passing through Q4 are lost in Q4-Q5 drift.

Figure 5: Tracking the phase space of 2 GeV beam centroids through the BSR. Dipoles B1 and B2 are interlocked at their nominal settings with $\pm 2\%$ window.

We followed described procedures to study the case of interlock including B2 only. It was discovered that even 0% window interlock on B2 does not filter out beam energies below 2 GeV.

Finally, we explored B1-B2 interlock with various widths of interlock windows. We found that the window width above 10% does not provide necessary energy filter. Therefore we suggest using B1-B2 interlock with $\pm 5\%$ window. Such settings are easily achievable from engineering point of view and are comfortably far from the interlock window width that limits applicability of the filter.

Conclusion

We found that the BSR bends B1 and B2 interlocked at their nominal 3 GeV settings with $\pm 5\%$ window filter out the beam energies below 2 GeV.

References

- [1] S. Seletskiy, Analysis of localized beam losses in the Booster extraction straight section and the Booster to Storage Ring transfer line, BNL-101037-2013-IR.