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Effect of energy interlock on possible beam losses 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 two bends in the Booster to SR transfer line (BSR) will be used [1] - the bends B1 and B2 will be interlocked within 5% of their nominal values.

The possible energy of the beam reaching each BSR magnet strongly depends on the details of interlock scheme. Thus, the possible beam losses in the BSR transfer line have to be calculated taking into account the particular energy interlock.

The purpose of this exercise is to determine the potential beam loss locations, for further identification of the radiation risks they impose outside the existing bulk shielding, and specification of the supplemental shielding design necessary to mitigate those risks.

We will present the beam systems description along with their planned operating ranges, which forms the basis of our analysis. Next, we will find the range of beam energy that can possibly be experienced by each BSR magnet. Finally, we will describe the method used to determine potential beam loss locations and we will present the results of our studies in a form of convenient to use table which includes all the information necessary for analysis of radiation risks induced by the determined beam losses.

In the following analysis we assume, unless the opposite is indicated in the clearest possible terms, that the accelerator is configured in any feasible way that its design allows.

2 Description of the beamlines

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

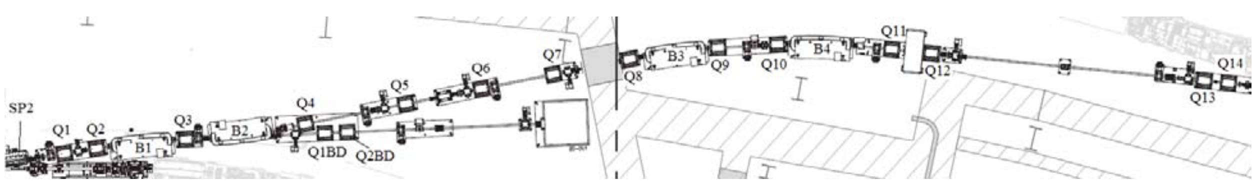

Figure 1: BSR phase 1 and phase 2.

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). This 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. [2].

3 Beam energy range for beamline elements

Since the 2 GeV energy filter will be obtained by interlocking B1 and B2 within 5% of their nominal current, the low energy beams starting at 150 MeV can be extracted from the Booster. Apparently the energy range for BRSP1SE, SP2, Q1 and Q2 is 150 MeV – 3.15 GeV. Here the upper energy limit is defined by the maximum energy that can be extracted from the Booster.

The same beam energy range is correct for B1. The difference of B1 from other magnets is that it is interlocked. In case the beam is directed to BSR-P1 the interlock configuration is the following. The B1 is set around its nominal value at 2 GeV (the width of B1 interlock window is +-5%) and the B2 is turned off. If the beam is directed to BSR-P2 then both B1 and B2 are interlocked around their nominal 3 GeV values with +-5% windows.

To determine the beam energy range for Q3 we follow the tracking procedure outlined below. We start with the beam centroids phase space determined by the geometric acceptance of the drift upstream of BRSP1SE. Next, we track this phase space at particular energy through the beamline down to the entrance to B1 varying each magnet settings in their full range. After each magnet the phase space is repopulated, so that the number of beam centroids stays the same throughout the whole tracking routine. Fig. 1 shows the phase space of 0.9 GeV beam centroids reaching the entrance of B1.

The obtained phase space is tracked then through B1 set at interlocked value. Plotting the result of tracking together with geometric acceptance of the drift downstream of B1 shows whether the beam of particular energy can reach Q3. Fig. 2 shows that there is marginal intersection of the phase space of possible 0.9 GeV beam centroids at the exit of B2 set to nominal 2 GeV setting -5% and the acceptance of B2-Q3 drift. This means that 0.9 GeV beams reach Q3.

It was checked that 0.8 GeV beams do not reach Q3. As an additional proof we also tracked the phase space of 0.9 GeV beam centroids through the whole BSR-P1 beamline varying all magnets except B1 in their full range, while B1 was varied in the range allowed by its interlock. The result of such tracking confirms that some of 0.9 GeV beam centroids reach Q3 (Fig. 3). Since both methods show that 0.9 GeV beams are barely touching Q3 it is reasonable to assume this energy to be a lower energy limit for Q3. Apparently, the upper Q3 limit is 3.15 GeV.

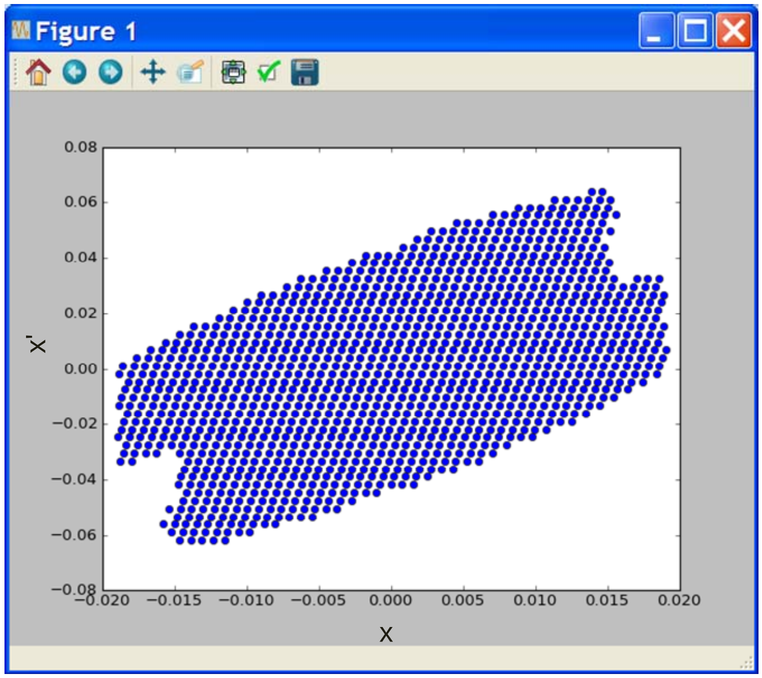

Figure 1: The phase space of 0.9 GeV beam centroids at the entrance to B1.

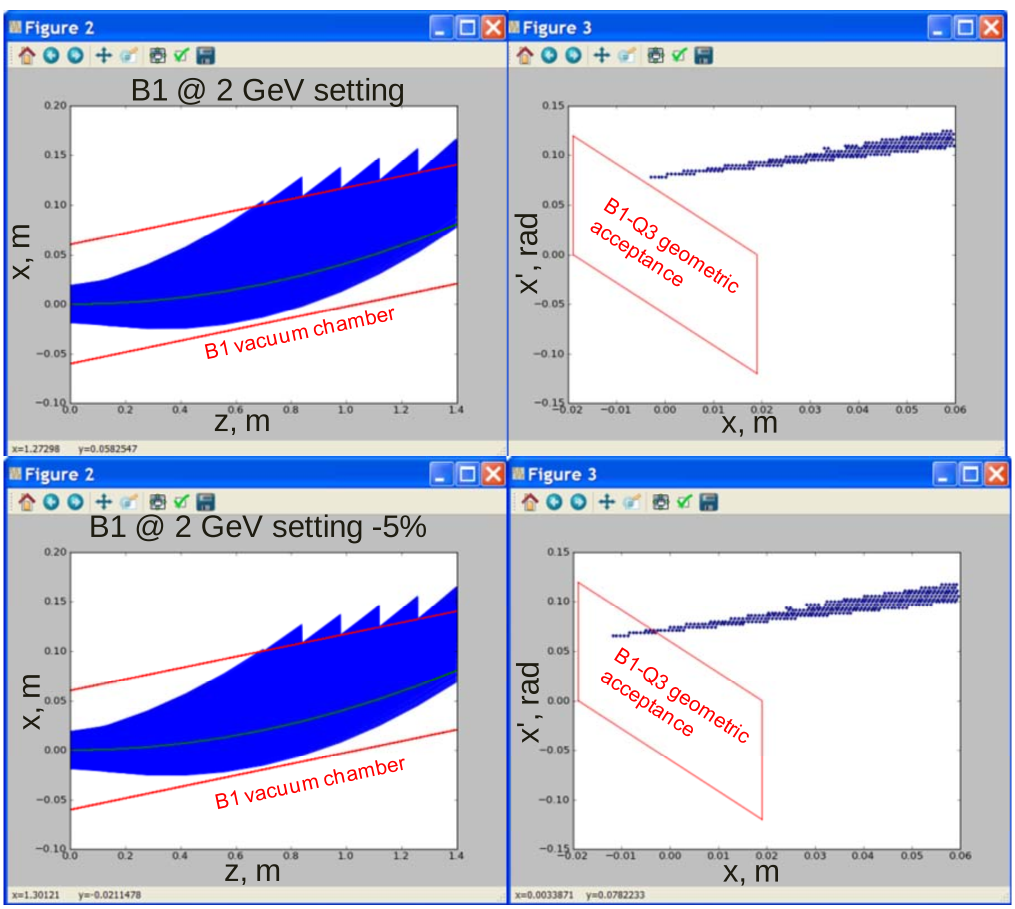

Figure2: Tracking the phase space of 0.9 GeV beam centroids through B1.

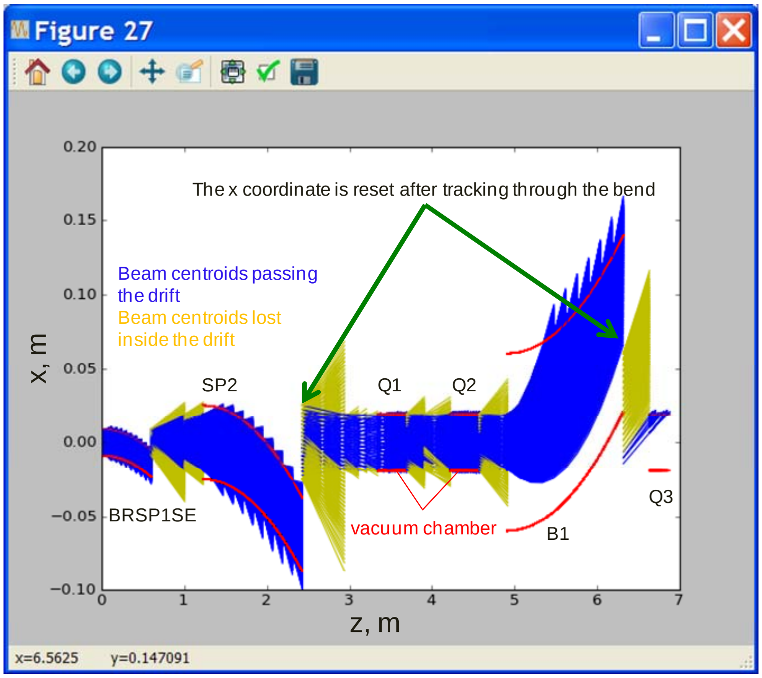

Figure3: Tracking the phase space of 0.9 GeV beam centroids through BSR-P1. A few beam centroids reach Q3, and none of them make it through this quad.

The same technique was applied to determine the lower energy limit for Q1BD, Q2BD and B2. For both quads the limit is 1 GeV, while for B2 the lower energy limit is 1.8 GeV when B1 is interlocked at its 3 GeV nominal setting.

To find the beam energy range for Q4, we apply the routine described above, with the only difference that both B1 and B2 are interlocked at their nominal 3 GeV settings with +-5% window. The results show that while very few of the possible 1.9 GeV beam centroids reach Q4, none of them pass through the quad. At the same time a few of 2 GeV beams pass through Q4.

In conclusion, the beam energy ranges for the BSR magnets are the following:

1.) BRSP1SE, SP2, Q1, Q2: 150 MeV- 3.15 GeV;
2.) B1: 150 MeV- 3.15 GeV;
3.) Q3: 800 MeV – 3.15 GeV;
4.) Q1BD and Q2BD: 1 GeV – 3.15 GeV;
5.) B2: 1.8 GeV – 3.15 GeV;
6.) Q4: 1.9 GeV – 3.15 GeV.

For the rest of the BSR magnets the beam energy range is 2 GeV – 3.15 GeV.

4 Analysis of possible lost beam angles in the BSR

The thorough analysis of the possible angles of the beams lost in the BSR for the case of 2 GeV lower energy limit is given in [2]. Here we will present such analysis for only those BSR magnets, which lower energy limit is below 2 GeV.

We start with defining the possible beam centroids phase space at the entrance of each magnet by the geometric acceptance of the respective upstream drift. This technique, although it results in overestimates of the lost beam angles provides a bullet-proof guarantee that all possible beams entering the magnet are considered. The described method is illustrated in Figure 4.

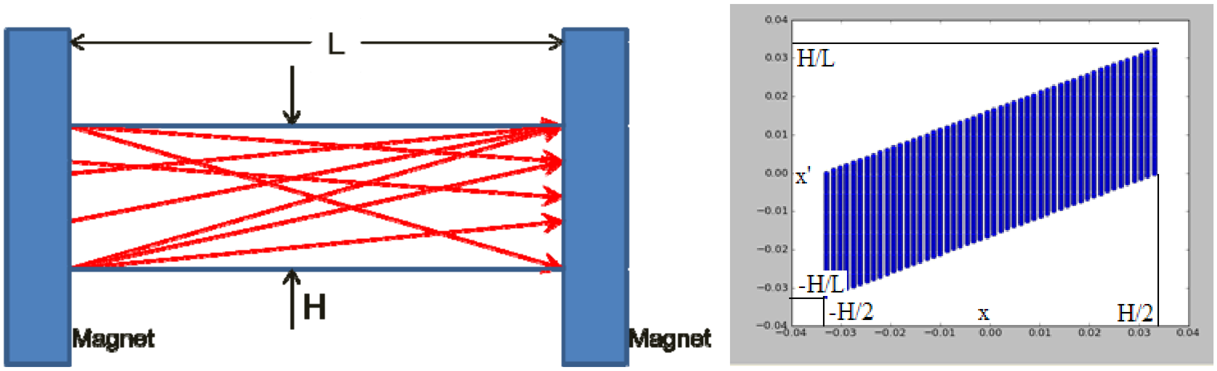

Figure 4: The picture on the left schematically shows the beam centroids (red) originating at the previous magnet and filling the drift upstream of the magnet under consideration. The plot on the right shows the phase space available to the beam centroids at the entrance of the considered magnet.

Starting with the beam centroids phase space described above we track each beam centroid through the magnet. We stop tracking the beam if it hits the magnet yoke and record the angle at which such beam was “lost”. Here, by the lost beam we mean that it is not a bright electron beam traveling towards the concrete wall anymore.

Each beam centroid is tracked through the magnet at its nominal, maximum and minimum possible settings. Finally, we determine the maximum angles of the beams lost inside the magnet as well as the maximum angles of the beams exiting the magnet both to the left and to the right direction with respect to the direction of beam motion.

We assume that the quadrupoles can switch polarity and can be set in the full range of their power supply currents. The two bends (B1 and B2) are interlocked as described in Section 3.

This procedure is performed for the lowest beam energy that can reach any particular magnet. Apparently, the maximum possible angles of lost beams are obtained at such energy.

The results of performed analysis are summarized in Table 1.

References

[1] S. Seletskiy, Energy interlock in Booster to Storage Ring transfer line, BNL-101365-2013-IR.

[2] 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.

	Geometry				Magnetic Element Data						Lost Beam Angles				
element name	S @ magn. entr. [m]	Magnetic L [m]	Vacuum chamber H app [mm]	Ref. traj. to yoke dist. [mm]	PS max current [A]	B or B' max [T] or [T/m]	B or B' nom [T] or [T/m]	θnom [rad]	bending direction	K1nom [1/m^2]	θmax R [rad]	θmax L [rad]	θmax R inside [rad]	θmax L inside [rad]	Minimal Beam Energy [GeV]
BRSP1SE	0.00	0.6	16	9	11242***	0.88	0.80	0.048	L		0.053	0.070	0.126	0.273	0.15
SP2	1.23	1.2	30	140	500	0.98	0.87	0.104	L		0.164	0.735	N/A *	0.898	0.15
Q1	3.34	0.35	38	20	175	29.92	-5.69			-0.853	0.149	0.149	0.394	0.394	0.15
Q2	4.22	0.35	38	20	200	34.03	11.69			1.754	0.156	0.156	0.281	0.281	0.15
B1****	4.92	1.4	45	221	375	1.34	0.55	0.115	R		0.657	0.116	0.818	N/A	0.15
Q3	6.63	0.35	38	20	175	29.97	0.93			0.140	0.081	0.081	0.135	0.135	0.80
B2****	7.59	1.4	45	221	375	1.34	-0.73	0.154	L		0.103	0.121	N/A	no hits **	1.80
Q4	9.87	0.35	38	20	175	29.99	-6.39			-0.958	0.047	0.047	0.055	0.055	1.90
Q1BD	10.36	0.35	38	20	175	29.90	0.00			0.000	0.050	0.050	0.058	0.058	1.00
Q2BD	10.96	0.35	38	20	175	29.80	0			0.000	0.079	0.079	0.164	0.164	1.00

* "N/A" - No magnet yoke in this direction

** "no hits" - None of the possible beam trajectories cross the yoke of the magnet

*** Nominal 10220 [A]+10%

**** Magnet is interlocked

1.) "R" stands for deflection to the right w.r.t. beam direction, "L" stands for deflection to the left w.r.t. beam direction

2.) All deflection angles are given w.r.t. beam direction downstream of the magnet

Table 1: Maximum possible angles of lost beams and beams exiting the BSR magnets at various energies. The 12^{th} and 13thcolumns give angles at magnet exit. The 14^{th} and 15^{th} columns give angles of the beams lost inside the magnet.