Description of Injection in the APS Storage Ring

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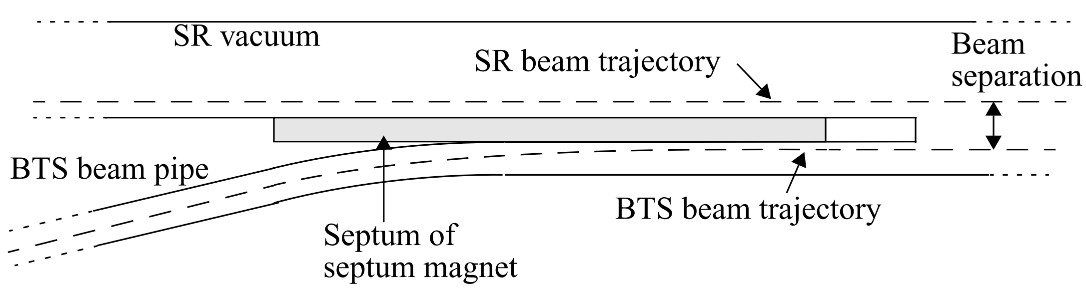
1.0 Introduction

The process of injection into the SR will be explained. Several plots will show the trajectories of the stored beam and injected beam under different conditions.

2.0 Layout of Injection Magnets

The BTS transport line brings the booster beam close to the storage ring beam in the SR injection straight section in a parallel trajectory. The booster beam is bent at the end of the beamline by a 1.75-m long thick septum of 74 mrad and then a 1.05-m long thin septum magnet of 33 mrad separated by 0.55 m of drift space. The last magnet, the thin septum is actually attached to the SR vacuum chamber. The magnet has the property that a magnetic field may exists on one side of a thin conductor wall (i.e. the actual septum part of the septum magnet) and none on the other side, which will prevent the perturbation of the stored beam. Figure 1 shows a schematic layout of the thin septum area of the injection straight section.

FIGURE 1. Layout of thin septum and BTS incoming trajectory. The BTS beam pipe is located inside the aperture of the thin septum magnet (below the septum shaded area), whose iron core in not shown for clarity.



The trajectories of the stored beam and the incoming beam are shown as dotted line. After the thin septum, the two beam pipes join into one and the two beams may oscillate freely about a closed orbit in the ring. The two beams have transverse size which requires a minimum distance from the walls, as it is important to minimize the particle loss at the walls to reduce the radiation production downstream.

Figure 2 is a schematic of the beam transverse dimension at the exit of the thin septum. The vertical dimensions of the beams are made larger for visibility. The stored beam is bumped in the straight section by a set of 4 kickers symmetrically arranged about the injection section as shown in Figure 3. Again, the two beams must stay a certain distance away the septum walls (or any metal covering the walls), but close enough to each other to minimize the betatron oscillation of the BTS beam. The particle coordinate distribution in the beams is gaussian, so a small number of particles at the tails will necessarily be lost and produce radiation downstream, hopefully in negligible amounts.

FIGURE 2. Schematic of particle distribution at X-Y plane cross-section at the end of the thin septum. Ellipse represents one sigma of distribution.

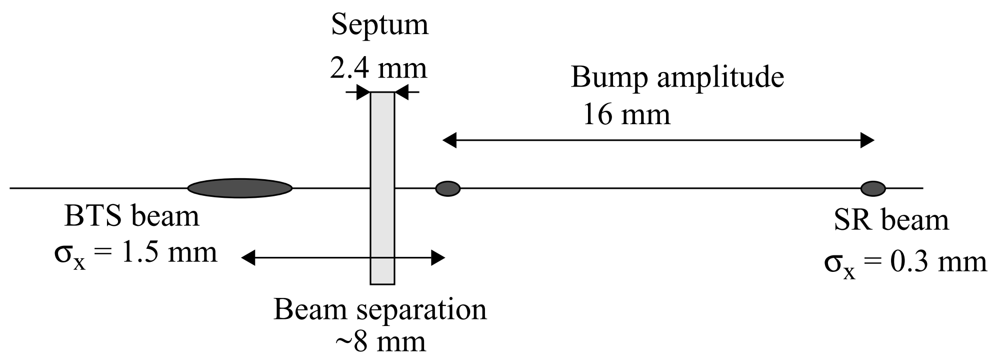
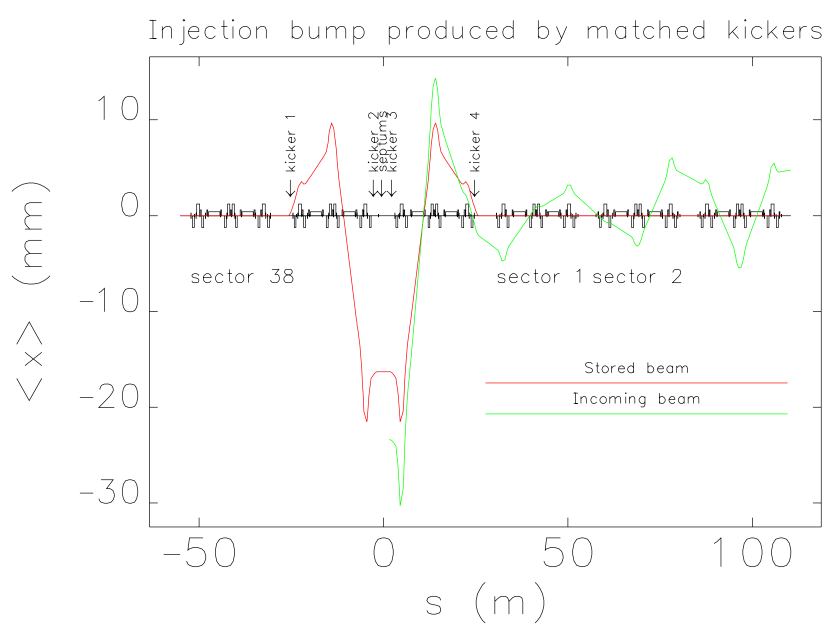


FIGURE 3. Off-axis injection trajectories in accelerator coordinates showing bumped stored beam centroid and injected beam centroid in 6 sectors around the injection point. Vacuum chambers apertures and septum wall not shown.



In the design layout ideally-aligned vacuum chambers and ideal magnets are assumed. In practice the bump amplitude and the BTS beam position must be adjusted to minimize the beam losses and the betatron oscillation of the injected beam. The bump amplitude is increased in small steps until losses occur from hitting the septum, then the amplitude is reduced by some amount for safety. The injected beam position at the end of the BTS is adjusted with the thick septum magnet setpoint and some upstream H corrector in the BTS line. The position which produces the best capture into the SR is what is used for operations.

The design beam separation at the end of the septum is about 8 mm, which is composed of several sigmas (3) of the stored beam + several sigmas (3) of the BTS beam + septum thickness. Figure 3 shows that for a 8 mm separation at the septum, one expects a betatron oscillation of about 5 mm measured at the straight sections. There is a demagnification effect due to the sextupoles in the injection bump.

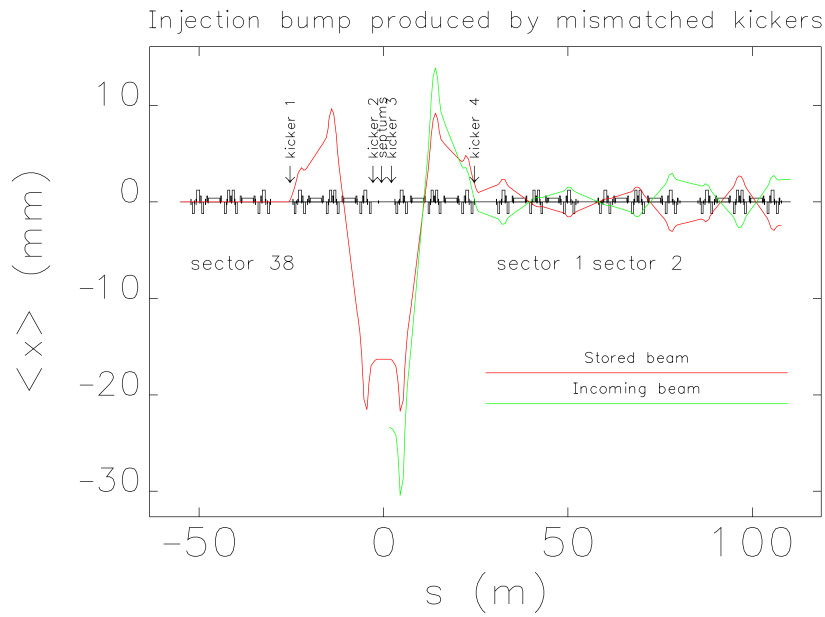
In order to accumulate for operations, the BTS beam must be injected with an offset relative to the closed orbit as shown in Figure 3. The beam separation in Figures 1 and 2 gives the amplitude of the horizontal betatron oscillation when the kickers are set up in a closed bump, i.e. when the stored beam returns to the closed orbit after passing though the 4 kickers. Actually particles in the BTS beam experience a distribution of betatron oscillation amplitudes. The largest amplitude being about 12.5 mm, assuming 3 sigmas of the distribution, and 8 mm of separation of the centroids. The physical aperture in the horizontal plane is 15 mm at ID3 where an elliptical chamber is installed. If there is any significant linear (or nonlinear) coupling, some of this horizontal amplitude may be transferred to the vertical plane where the physical aperture at ID3 is 2.5 mm, nominally, but 2.4 mm actually, and somewhat smaller due to beam steering and some misalignment. It is therefore important to reduce betatron oscillations (in both planes) of the incoming particles.

3.0 Mismatched injection bump

This is the standard way to inject in the APS. One or both of the last two kicker angles are increased in order to reduce the betatron oscillation amplitude of the incoming beam. This results in some betatron excitation of the stored beam. This is acceptable for normal injection operations as long as all particles in the stored beam survive.

Figure 4 shows the trajectories of the strored beam and injected beam under these conditions. The betatron oscillation amplitude is now about half of that in the matched bump case. Actually, the IK3 and IK4 setpoints have been optimized to minimize the amplitude of the injection beam and stored beam at the same time. The oscillations of the stored beam is exactly out of phase with the oscillation of the injected beam. Since the injected beam is wider than the stored beam one could adjust the kickers to make the stored beam oscillation larger than that of the injected beam to make better use of the available aperture.

FIGURE 4. "Optimized" unclosed bump condition. Off-axis injection trajectories in accelerator coordinates showing bumped stored beam centroid and injected beam centroid in 6 sectors around the injection point without vacuum chambers and septum wall.

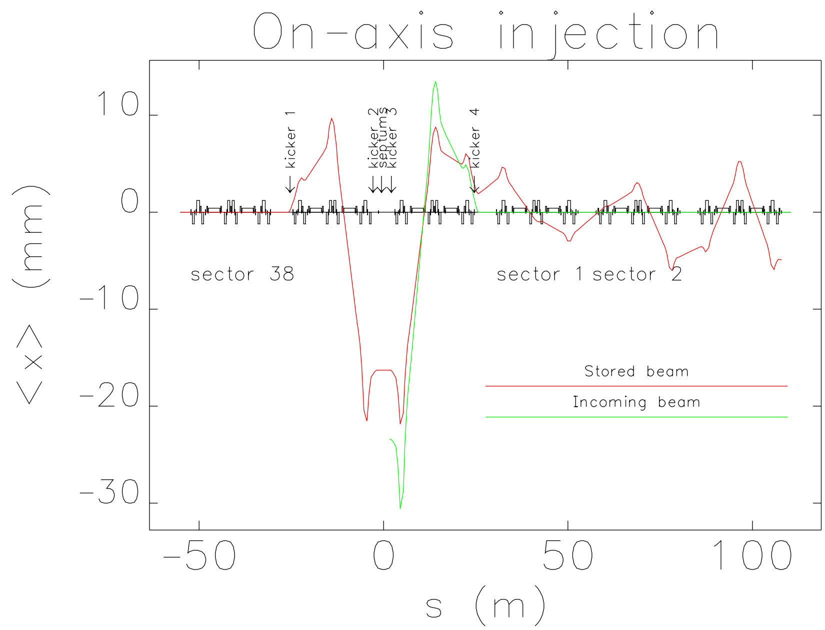


4.0 On-axis Injection

This is the simplest mode of injection where there is no betatron oscillation of the injected beam. It is used in some machine physics measurements of a new lattice, such as initial correction of orbit or tunes when only a small amount of charge can be captured because of low dynamic aperture. Figure 5 shows how the BTS trajectory joins the SR closed orbit with the downstream two kickers set to moderately higher values.

If there is stored beam present then the stored beam gets a betatron oscillation of about 5 mm (in the straight sections). Therefore, it would still be possible to accumulate, generally.

FIGURE 5. Trajectory of BTS beam with on-axis injection.

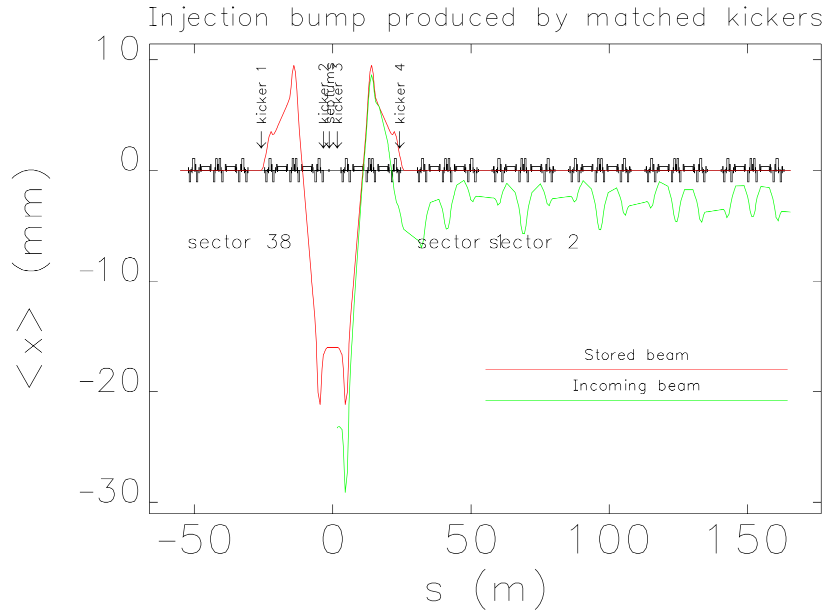


5.0 Longitudinal Injection

Longitudinal injection is injecting an off-momentum beam into a storage ring, with the betatron oscillation replaced by an energy (or phase) oscillation. A special lattice with high dispersion in the injection straight section is required. The kickers are still pulsed to produce a closed bump for the storage ring. The initial trajectory of the injected beam follows a dispersion orbit after passing through the SR kickers. This injection is useful in situations with small transverse betatron oscillation acceptance.

Figure 6 shows the trajectory of the injected beam in a longitudinal injection lattice with a closed bump for the stored beam. To produce the figure, the initial coordinates was only approximately matched, as the large trajectory through sextupoles affects the dispersion in the injection straigth section.

FIGURE 6. Trajectories in a longitudinal injection lattice with 0.3 m dispersion in straight section, and a -2% momentum error injected beam. Initial conditions approximately optimized.



The injected beam ideally follows the dispersion orbit on the first few turns, and then an energy oscillation will become apparent. The energy will oscillate with frequency of about 2 kHz while being damped at 5 ms time constant.

6.0 Possible Problems

Several things can prevent proper injection into the storage ring:

1. Wrong initial coordinates of the injected beam, i.e. pulsed magnet jitter or misteering of BTS line. For a positive coordinate change the beam may scrape against the septum defelcting particles (in horizontal and vertical planes), which will get transported to the smallest vertical or horizontal aperture and produce radiation. For a negative coordinate change the beam will clear the septum, but the betatron oscillation will be larger and some particles may scrape directly on the smallest horizontal aperture and produce radiation.
2. Aperture obstruction at the septum, which forces a steering of the injection beam away from the septum. The betatron oscillation will be larger and create some particle at the smallest aperture.
3. Small dynamic aperture which prevents off-axis injection of too large an amplitude.
4. Vertical beta function mismatch between BTS transport line and storage ring. This will cause a vertical beamsize modulation everywhere in the ring and at every turn for a fixed position in the ring.

Figure 7 shows what would happen if the BTS beam were steered 5 mm away from the septum. The betatron oscillation is much larger compared to that in Figure 3 (9 mm vs about 4 mm). The particles of the injected beam may risk scraping at the small horizontal apertures of the ID VC. They may also risk scraping against the chamber at S1A:Q2 (the first triplet in the ring seen by the injected beam) where the aperture is 42 mm.

Figure 8 shows how one would respond to a BTS beam steering with a re-matching of the IK3 and IK4 kickers to allow both the injected beam and stored beam to survive through the 15-mm horizontal apertures in two of the straight sections. The maximum centroid amplitude is about 5 mm at the straight sections.

FIGURE 7. Example of much larger BTS beam offset of 29 mm in closed bump kicker configuration.

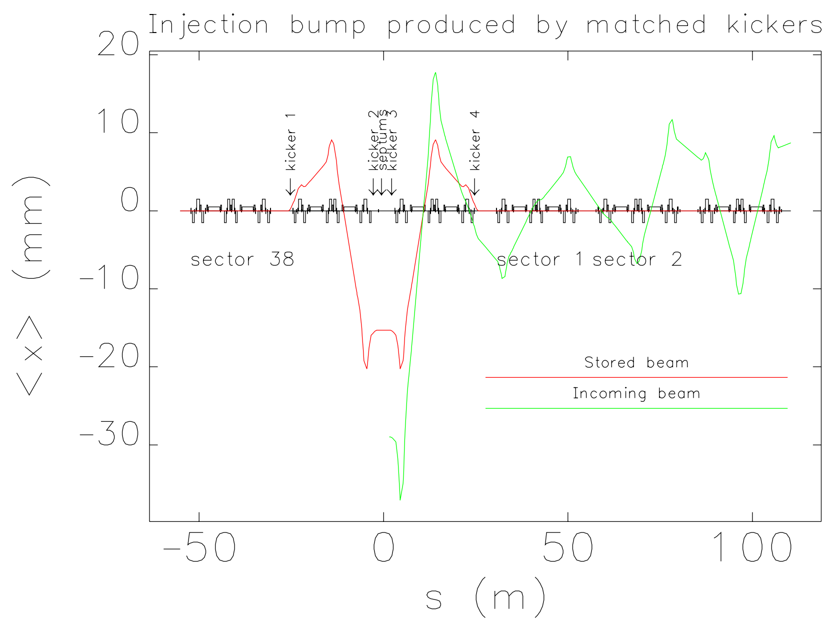
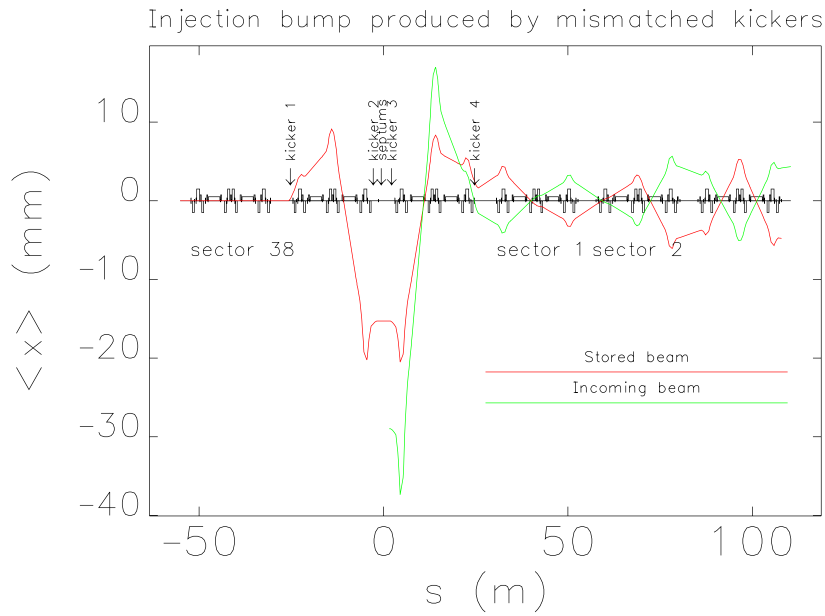


FIGURE 8. Large BTS beam offset with kicker mismatch to maximize the aperture.



7.0 Modelling

These calculation are helpful in modeling the actual injection in the storage ring. The position of the beam in the bump is not accurately known since the bpms work only within a range of 10 mm or so, while the bump amplitude is of the order 16 mm. Also there are no bpms in the BTS line at the exit of the septum.

Several procedures can be used to estimate the actual trajectories. First the closed bump condition can be enforced by adjusting the 4 kickers to produce a null result in the bpm histories outside the bump. The readback of B:P5 bpms in sector 39 and 40 can be recorded during a kick and related to tracked kicker bump models of various amplitudes. Here we must make sure that the correct sextupole fields are used in the model. It is also good to adjust the bpm readings with calibration gain values obtained by some other means.

Once the kickers for a closed bump is established, we inject the BTS beam for one turn only, allowing the bpms to trigger repeatedly on single passes of the injected beam. Averaging is required to reduce the electrical noise and to remove the jitter of the angle of the septums. The profile of readbacks of consecutive bpms is plotted with an overlay of the trajectory models of various BTS beam offset trajectories. In one recent measurement we found an absolute coordinate of 29 mm for the injected beam while the closed bump was measured at 15 mm. This indicate a separation of 14 mm between the two beam while the design value was 8 mm. It is obviously desirable to reduce this by steering the BTS beam back towards the septum. If this produces beam loss, then a bad aperture somewhere in the injection area may be present.

One can also estimate the BTS beam offset by setting up on-axis injection by adjusting the IK3 and IK4 kickers. The kickers angles can be calibration from the results of the bump closure procedure. The angles are then tracked backwards in a ring model to obtain the initial coordinates.

There is one cerenkov detector at every ID straight section, at the septum, and at the scrapers. They are useful in confirming improved injection conditions, and indicate any special problems with injection. For example, injecting on-axis should produce no particle loss until the beam is dumped. However we do see a beam loss signal at some of the smallest apertures, which we don’t understand at this time.