A Proposed Extraction System for the Fermilab Booster

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Abstract
A modification is proposed for the beam extraction systems in the Fermilab Booster.

Introduction
At present, the Fermilab Booster synchrotron has two nominally identical vertical extraction systems located in long straight sections called Long 3 and Long 13. To be specific, the system used to extract beam at Long 13 will be described here. The current sheet septum of a pulsed septum magnet is located in the middle of the vertical aperture in the center of Long 13. A system of four magnets running DC in a dogleg configuration is used to steer the circulating beam below the septum during acceleration. Four vertical kickers located in Long 12 are fired to kick the beam above the septum, thereby extracting beam in a single turn. A three-bump magnet system called BexBump, with dipoles in Long 12, 13, and 14, is ramped so that the circulating beam clears the extraction septum during acceleration and then moves close to it to prepare for extraction.

A few years ago it was realized that the edge focusing of the dogleg magnets significantly distorts the lattice functions. To ameliorate these edge effects, the dogleg magnets were repositioned in order to increase their lever arms and thus reduce their bend angles. Significant operational improvements were realized, but beam losses in the extraction regions and lattice distortions resulting from edge focusing are still appreciable.

In the design proposed here, the DC dogleg magnets that displace the beam downward around the septum are replaced by a fast-rising orbit-bump system that displaces the beam upward, allowing the pulsed septum to be located outside of the aperture used by the circulating beam

The existing extraction systems

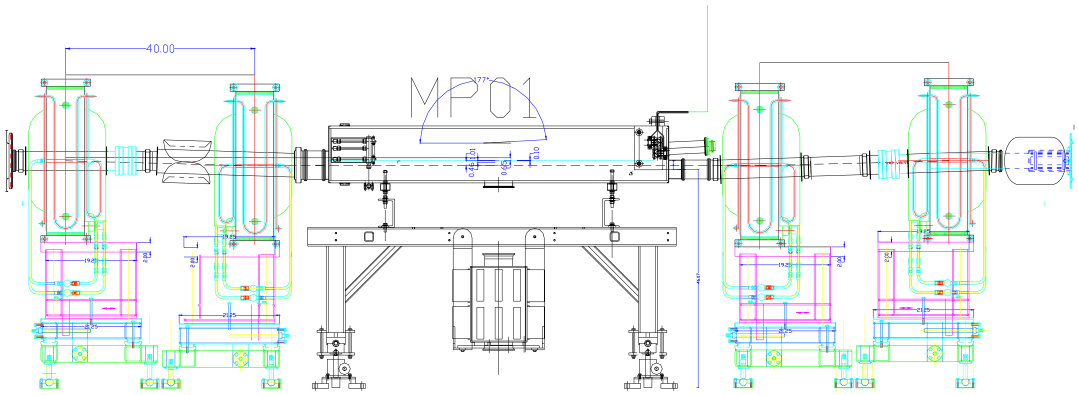

Figure 1. The present arrangement of the extraction components in Long 13

Figure 1 is a layout of long straight section 13. It shows the four dogleg magnets, a septum magnet called MP01, and the middle BexBump magnet, which is located between the first two dogleg dipoles.

Figure 2 shows a Trace3D simulation of four Booster cells including an extraction region. The horizontal and vertical beam envelopes are shown in blue and red, respectively. The heavy black line shows the vertical trajectory of the beam centroid with displacements generated by the BexBump system and the dogleg magnets; that is the design orbit just before the kickers are fired.

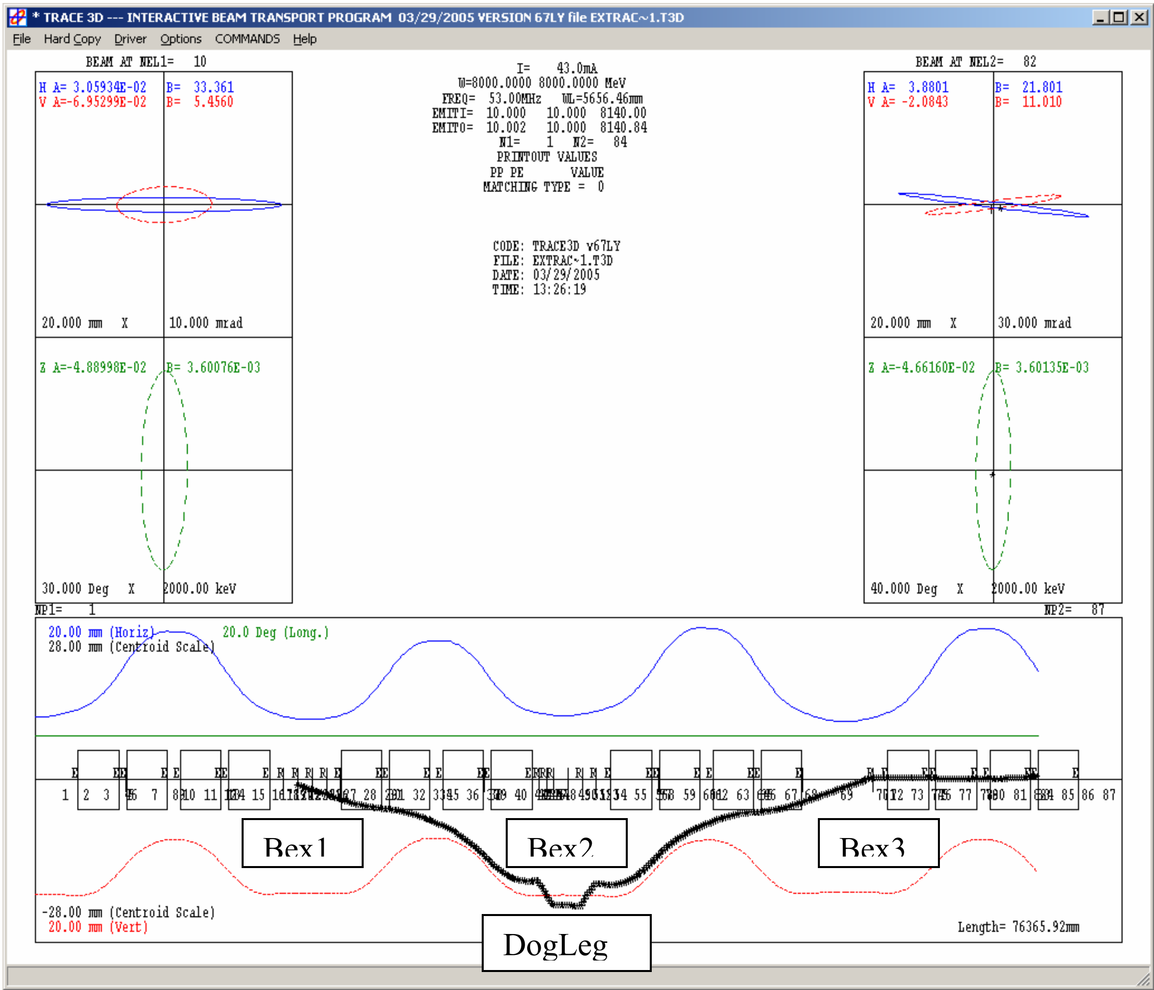

Figure 2. Trace3D results for one of the Booster extraction systems. The heavy black line shows closed orbit distortions caused by the BexBump and dogleg dipoles.

The next Trace3D simulation, presented in Figure 3, shows the vertical beam trajectories resulting from the firing of zero, one, two, three and all four kickers. The vertical bend generated by the septum magnet, which completes the extraction process, is not included in this simulation. The downward displacement generated by the dogleg system is still quite noticeable at extraction time. That is one of the reasons why it is hard to tune the circulating beam through the region and minimize the beam loss at extraction time. The downward dogleg displacement is necessary at injection time to snake the circulating beam around the extraction septum, but at extraction time an upward displacement would be more appropriate.

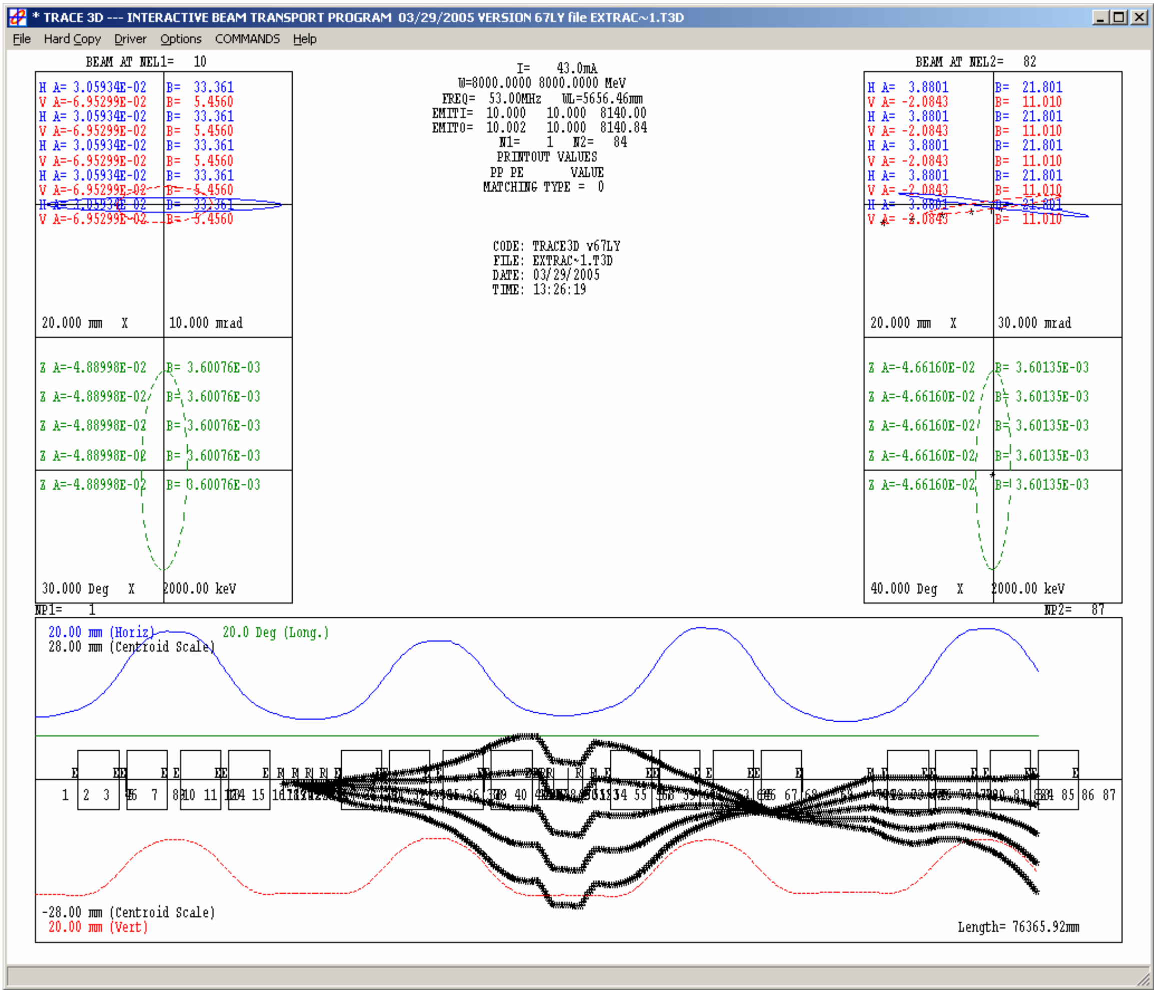

Figure 3. Trace3D simulation results showing the trajectories generated by firing one or more kicker magnets. The vertical bend of the extraction septum magnet is not included in this simulation.

The Proposed Extraction Scheme

In the scheme proposed in this note, the DC dogleg magnets are replaced by a fast-rising local four-bump system so that the pulsed septum can be moved outside of the circulating beam aperture. The current proposal improves upon a similar scheme suggested a few years ago by Chuck Ankenbrandt and analyzed by Jim Lackey. Compared to that proposal the current proposal gets by with weaker magnetic fields (by about a factor of two) in the fast-rising local bump system.

The proposed scheme works as follows. At the end of the acceleration cycle, a three-bump system like BexBump, with dipoles in Long 12, 13 and 14 as at present, displaces the beam downward by 1.5 cm at the upstream end of Long 13. Just prior to extraction, a fast-rising local four-bump system, with all four magnets in Long 13, displaces the beam upward by 3 cm at the exit of the second magnet. The third magnet of this four-bump is a special magnet with two apertures separated by a pulsed current-sheet septum. The lower aperture bends the circulating beam downward, and the upper aperture bends the extracted beam upward. At extraction time the four kickers in Long 12 displace the beam 2.4 cm upward so that the kicked beam enters the upper region of the third magnet, whence it is deflected into the extraction line.

The Trace3D simulations illustrated below in Figure 4 show three trajectories. The lowest one is the circulating orbit just before the kickers are fired. The uppermost trajectory is that of the extracted beam kicked by the kickers and bent upward in the extraction channel of the septum magnet. The middle trajectory, for reference, is a hypothetical orbit if the third magnet did not have a septum and an extraction channel.

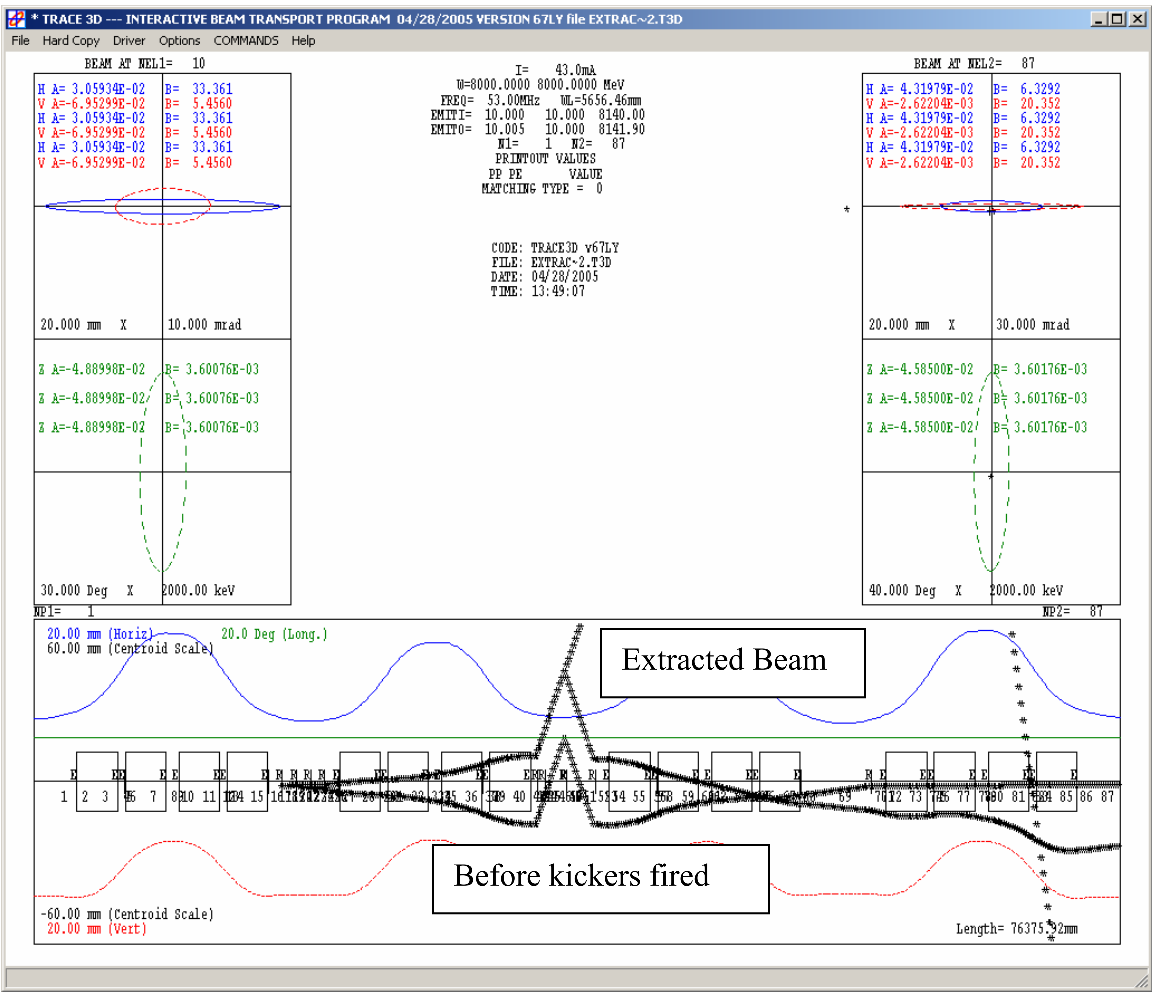

Figure 4. Trace3D simulation results showing the trajectories generated by the pulsed magnet four-bump and by the firing kicker magnets

The lower part of Figure 5 shows the extraction section with four pulsed magnets (blue boxes) in addition to the main lattice magnets (green boxes) at the beginning and end of the straight section. The red line is the center of the beam pipe, and the dotted lines indicate the beam pipe. Three beam trajectories are shown:

- Just before the start of the four-bump pulse (BexBump magnets are on)

- At the peak of the four-bump pulse (just before firing kickers)
- During beam extraction (the kickers are on)

The upper part of Figure 5 represents the cross section of the beam pipe, showing the positions and size of the beam at the entrance of each pulsed magnet.

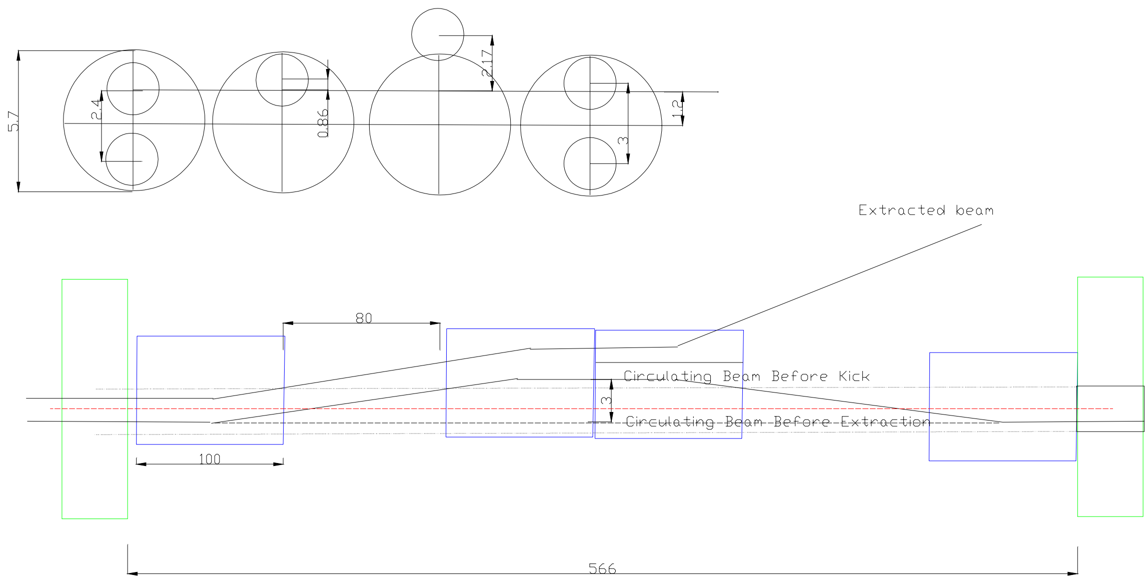

Figure 5. The extraction long straight section. The blue boxes represent the pulsed magnets. The green boxes represent the Booster lattice magnets at the ends of the straight section. The red line is the center line of the beam pipe.

The pulsed four-bump magnets have a magnetic field of about 5 kGauss created by 22 kA current. The whole system needs about 350 microseconds to reach peak field.

Table 1 shows some of the parameters of the four-bump magnets.

Field (kGauss)	4.89
Magnet length (meter)	1
Bending Angle (rad)	0.017
_AmpereTurns (kAmps)	22.1
Magnet Gap (cm)	5.8
Pole tip width (cm)	9.
Rise Time per magnet (microsec)	59.
Assumed Voltage(kVolt)	1

All four magnets can have the same properties in their circulating beam apertures. One magnet has an additional current sheet septum as shown below.

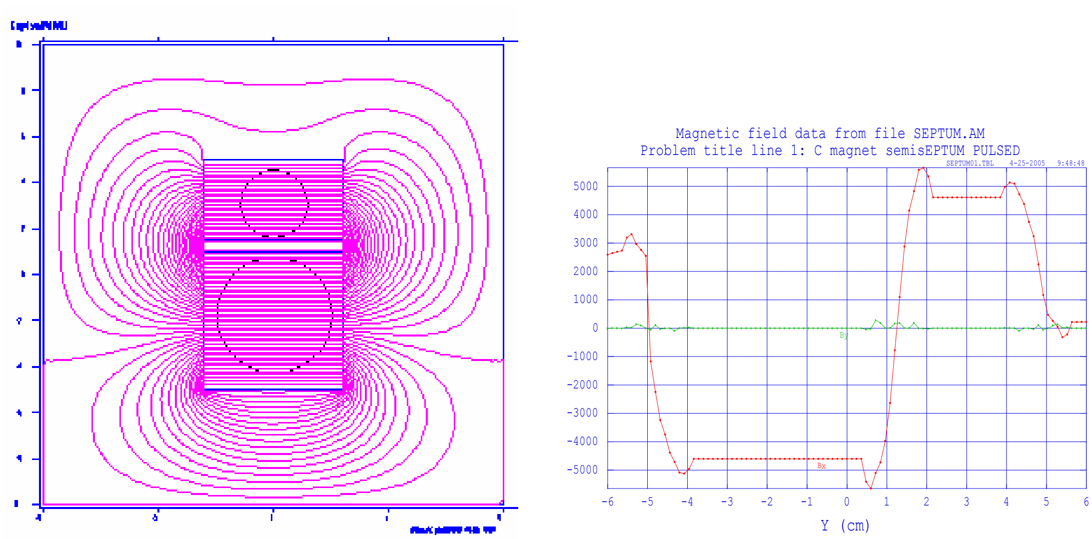

Figure 6. These results of a Superfish simulation show the field in the two regions of the septum magnet. The magnet field in the graph is along the vertical line in the center of the magnet.

The drawing and the graph in Figure 6 show the result of Superfish calculations. The two circles represent the allowed beam size at injection and extraction. The red lines are field contours. The magnet has three current sheets. The two at the top and bottom of the aperture carry half of the full current in the same direction, and the middle sheet carries the full current in the opposite direction. In this simulation there was no effort to optimize the shape and thickness of the conductors or the iron frame.