Multi-pole fields in MPØ2

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Introduction

This write-up describes the effort to evaluate quadrupole and sextupole content of Booster extraction septum magnet MPØ2 by analyzing orbit data taken during the November start-up study. Surprisingly strong multi-poles were found to be present. The implicated field uniformity appeared consistent with the write-up by B. Brown [1]. Tracking simulation to see the effect of these multi-pole fields are also included.

The 1-bump data

About the only way to move beam position around at MPØ2 is to use the Booster extraction kickers MKS05, 06, 07, and 08, which kicks beam vertically. At 8-GeV there is no available horizontal orbit control in Booster. The voltage of four extraction kickers were varied at a range of ±0.5 KV to cause displacement at MPØ2. Figure 1 shows the expected vertical orbit down MI8 line at +1.0 KV. By studying the down-stream beam position responses it is possible to estimate the fields in the septum magnet.

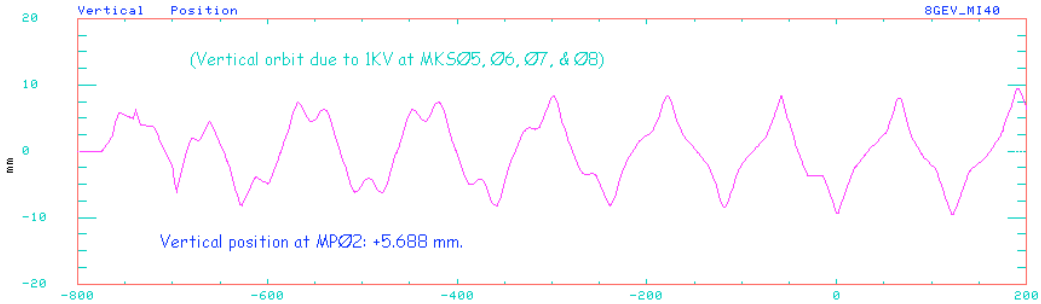

Figure 1. Expected vertical orbit in MI8 line for +1 KV kick from the Booster extraction kickers MKS05, 06, 07, & 08.

Analysis

Harmonic orbit decomposition

Figure 2 shows examples of the ***on-plane***, i.e. in this case the kicked vertical plane, positions as a function of kicker voltage at VP802C, MW810 and VP107. Figure 3 shows examples for the ***off-plane***, i.e. horizontal, positions at MW800, MW802, and HP816. The position responses are clearly not linear in either on-plane or the off-plane data.

The second order polynomial fit, also shown with each plot, provides the means to turn position data into first and second order response orbits, in the on-plane and in the off-plane as well. Linear vertical response orbit, constructed with first order coefficients

from vertical plane data, is used to diagnose quadrupole error. Second order vertical response gives information on the skew sextupole fields. Linear horizontal orbit response implies the existence of skew quadrupole components. Second order horizontal orbit implies the existence of normal sextupole components.

Third order polynomial fit was not attempted as there were no apparent justification in the data and the accuracy of the data may not support it.

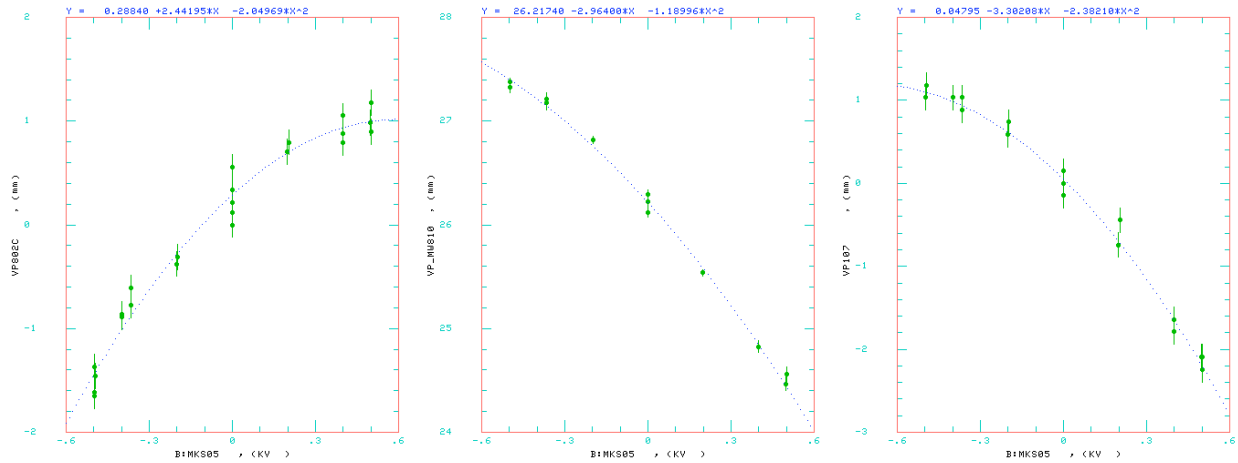

Figure 2. Examples of vertical positions as a function of Booster extraction kicker voltage of MKS05, 06, 07, and 08. From left are data at VP802C, MW810 and VP107 in Main Injector. The fitted polynomial is shown with its equation at the top and as dotted line on the plot.

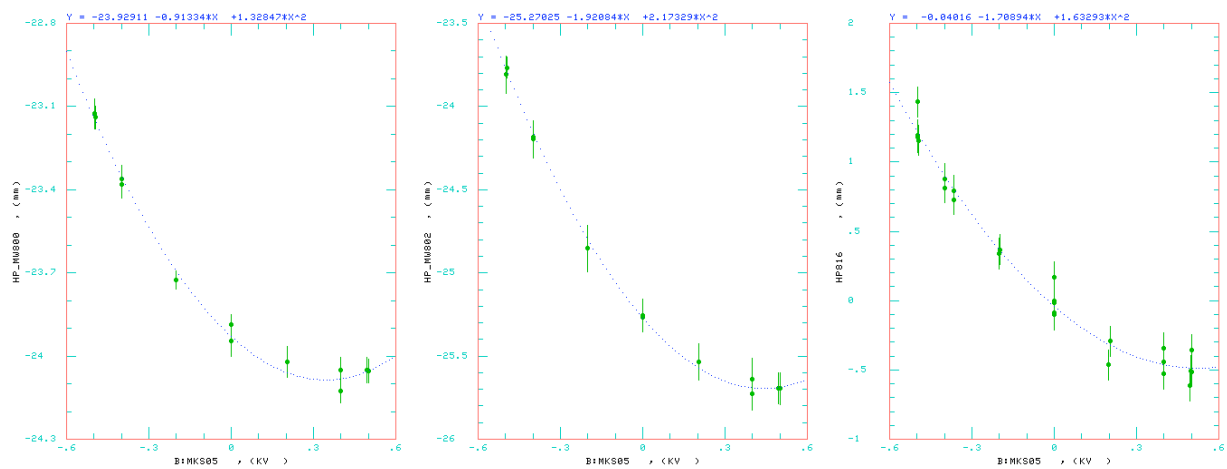

Figure 3. Horizontal position examples from MW800, MW802, and HP816 in MI8 line as a function of the voltages at Booster extraction kickers MKS05, 06, 07, and 08. The second order polynomial fit results are also displayed.

First order orbit

The vertical plane linear orbit is shown as top plot of Figure 4 with calculated orbit in magenta trace. This is the orbit response when each of the four kickers is set to 1.0 KV higher than nominal. In addition to kicks from extraction kickers the calculation also included a -30 amp vertical kick at MPØ2. With orbit displacement at MPØ2 estimated

to be 5.69 mm this translates to a quadrupole field of -2.32 KG/M, i.e. a vertically focusing field. The strength of MPØ2 at 22757 amp was measured to be 0.44 G/amp using position data from multiwire MW800, about 10% lower than the published strength [1]. Figure 5 shows the data and the strength calculation.

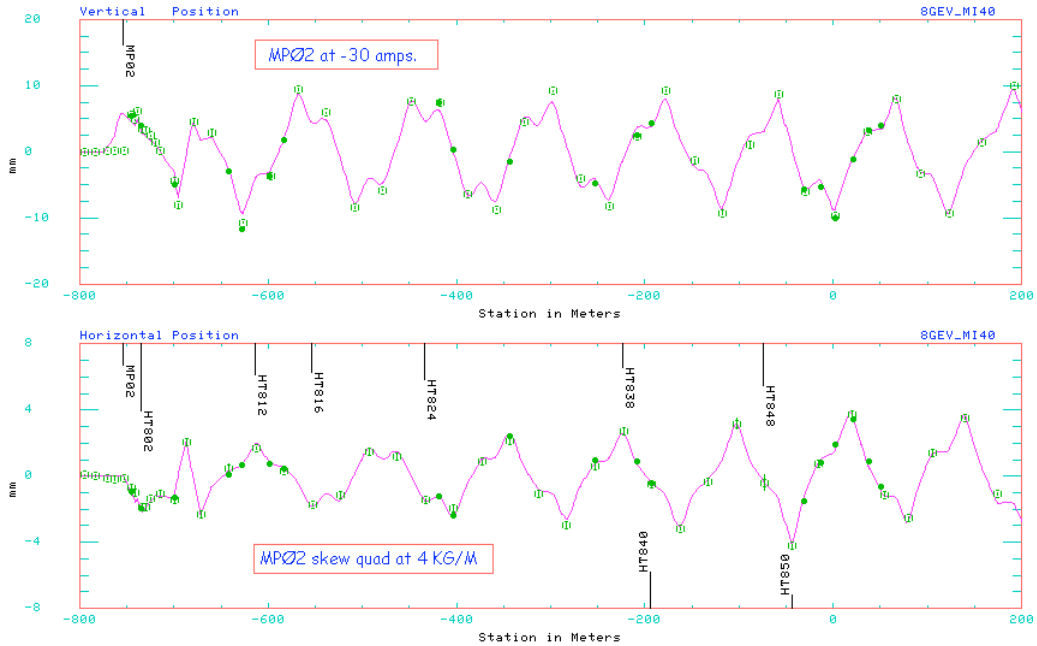

Figure 4. Linear horizontal and vertical orbit response, with +1.0 KV in the Booster Long-3 extraction kickers. The need for a -30 amp kick at MPØ2 to reproduce vertical MI8 line orbit is attributed to quadrupole focusing. A skew quadrupole of 4 KG/M at MPØ2 was also needed to provide horizontal kick to match into upstream MI8 line orbit. .

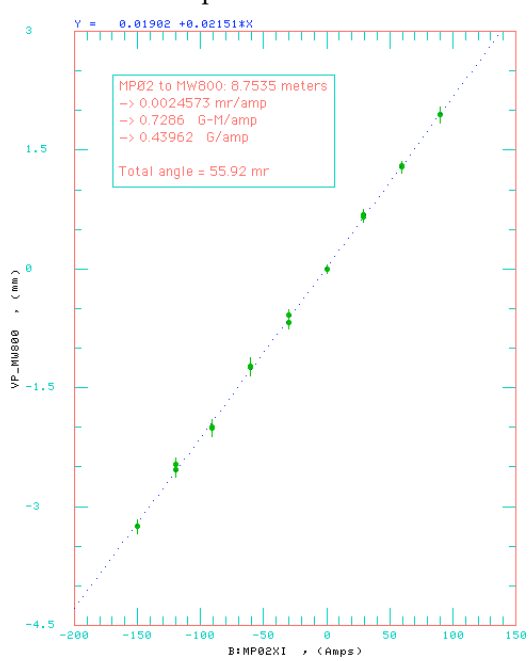

Figure 5. The kick strength of MPØ2 was calculated using the position data from multiwire MW800, which is immediately down-stream of MPØ2 and before the first quadrupole Q800.

The bottom plot of Figure 4 shows the off-plane horizontal linear response orbit. A skew quadrupole field of 4 KG/M at MPØ2 was included in the calculation to generate a horizontal kick needed to match the observed position responses at the upstream end of MI8 line. Note that only the very beginning of MI8 line orbit, i.e. up to HT802, was needed to determine the strength of skew quadrupole. Small horizontal corrections, with trim dipoles as marked by labels, were used for the purpose of finding coupling sources in MI8 line and are un-related to the topic of this write-up.

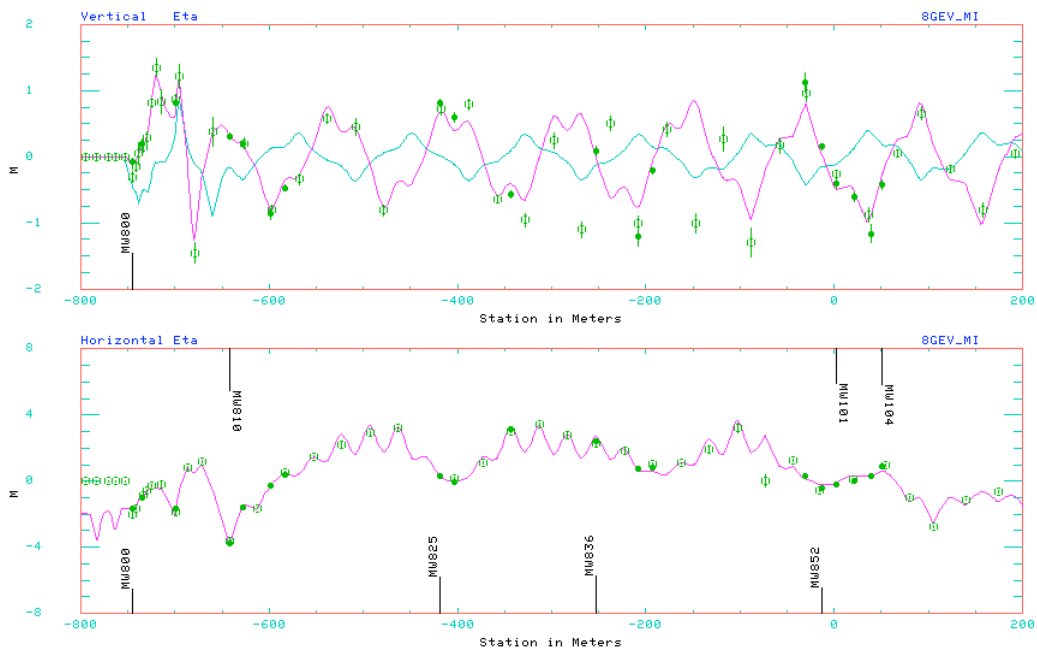

Figure 6. Dispersion function measurement result from study of March 2004, with calculation in magenta. Bottom plot is the horizontal plane and top plot the vertical plane. In calculating vertical dispersion function a skew quadrupole field of 4 KG/M was inserted in the Booster extraction septum MPØ2. The calculation without skew component is shown as cyan trace.

This estimated quadrupole field strength is consistent with the conclusion from a prior study in March of 2004 [2]. In that study it was found that a 4 KG/M skew quadrupole component in MPØ2 could explain the anomalous vertical dispersion function observed in MI8 line. Figure 6 shows horizontal and vertical dispersion functions as measured from that study and the calculation results. While the horizontal dispersion function calculation was straight forward the vertical dispersion function calculation was not. The magenta trace in the top plot shows the vertical dispersion function calculated with 4 KG/M skew quadrupole component in MPØ2. The calculation without skew component is shown in cyan trace. It is the most likely source of anomalous vertical dispersion function, observed ever since the new MPØ2 septum was installed.

Second order orbit

Shown in Figure 6 are horizontal and vertical second order orbit responses, using the second order coefficients from the fitted polynomials. For either plane the calculation needed only one single kick at MPØ2 to reproduce the observed second order orbit responses in the MI8 line, with amazingly good agreements. It is encouraging that no other visible second order error source is present in the MI8 line.

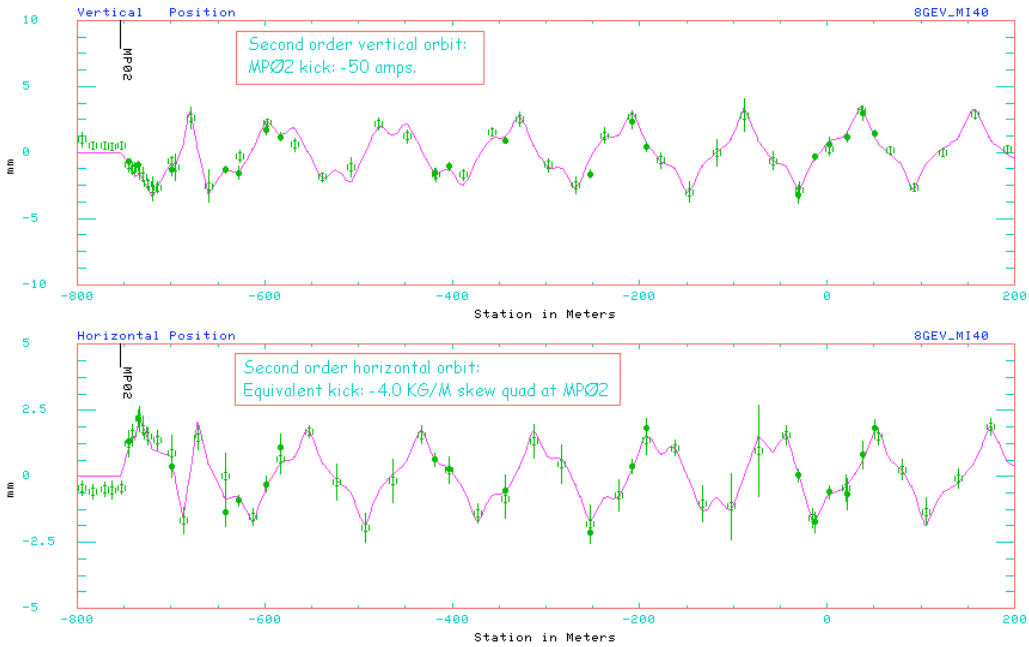

Figure 7. The second order orbit response per 1KV in the Booster Long-3 kickers. In both plane the only second order kick source needed in the calculation is at MPØ2.

The horizontal plane second order orbit is shown in bottom plot of Figure 7. The kick needed at MPØ2 was simulated with a skew quadrupole of -4.0 KG/M, given vertical beam position of 5.69 mm due to 1.0 KV in the extraction kickers. This implies that B_y at $y = 5.69$ mm is -22.75 Gauss. For a normal sextupole this means a strength of 1406.5 KG/M^2, or equivalently 0.454 KG at 1-inch.

Shown in the top plot of Figure 7 a -50 amp vertical kick at MPØ2 was needed for the vertical plane second order orbit. This implies a B_x of -22.0 Gauss at 5.69 mm and translates into a skew sextupole strength of -1358.8 KG/M^2, or 0.438 KG at 1-inch.

Table 1. The estimated strength of quadrupole and sextupole component in Booster extraction septum magnet MPØ2.

	Normal	Skew	
Quadrupole	-2.3	4.0	KG/M
Sextuple	1406	-1359	KG/M^2

Result and simulation

The field strengths as estimated are summarize in table 1. The resulted magnetic field as a function of vertical position for three different horizontal positions are shown in Figure 8 for both B_x and B_y. Comparing the curve of B_x at x = 0 with figure 1 of reference [1] the amount of field drop-off at 10 mm vertically is very comparable.

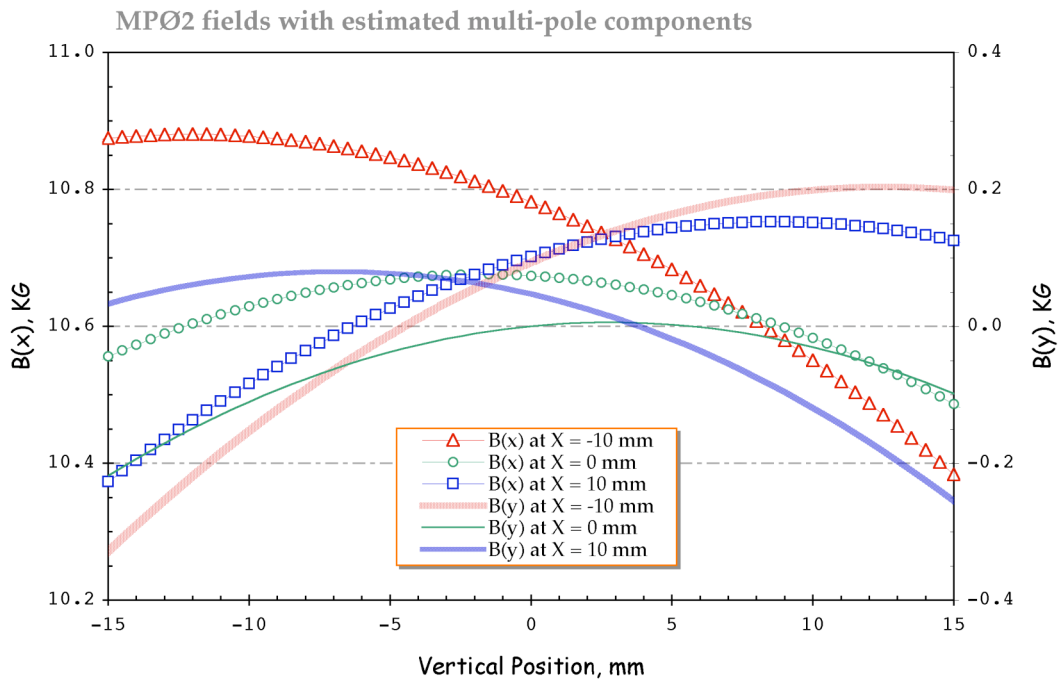

Figure 8. The plot of magnetic fields in MPØ2 as a function of vertical (y) positions for three different horizontal (x) positions. The B_y fields are plotted with marker and reference to left vertical axis. The B_x fields are plotted without marker and referenced to the right vertical axis.

Tracking simulation can help in visualizing the impact of the multi-pole fields from MPØ2. First set of tracking was done with a 20-π normalized 95% initial emittance in the horizontal plane and zero in the vertical plane. Figure 9 shows two color coded scatter-plots of horizontal phase space at up-stream and down-stream of MPØ2. The green dots are tracking results with extraction kickers at nominal setting, magenta dots with kickers at -1.0 KV from nominal, and gold dots with kickers at +1.0 KV from nominal. The effect of different vertical position can be seen at the down-stream end of MPØ2. Shown in Figure 10 are scatter-plots of vertical phase space at down-stream end of MPØ2 and at multiwire MW813. With zero initial vertical emittance it is easy to see the effect of coupling at down-stream of MPØ2 in kicks and at MW813 in beam size. The result of similar tracking calculation, but with initial emittance set to 20-π in vertical plane and zero in horizontal plane, are shown in Figure 11 and 12. In this case the extraction kickers were oriented horizontally so as to cause horizontal displacement at MPØ2.

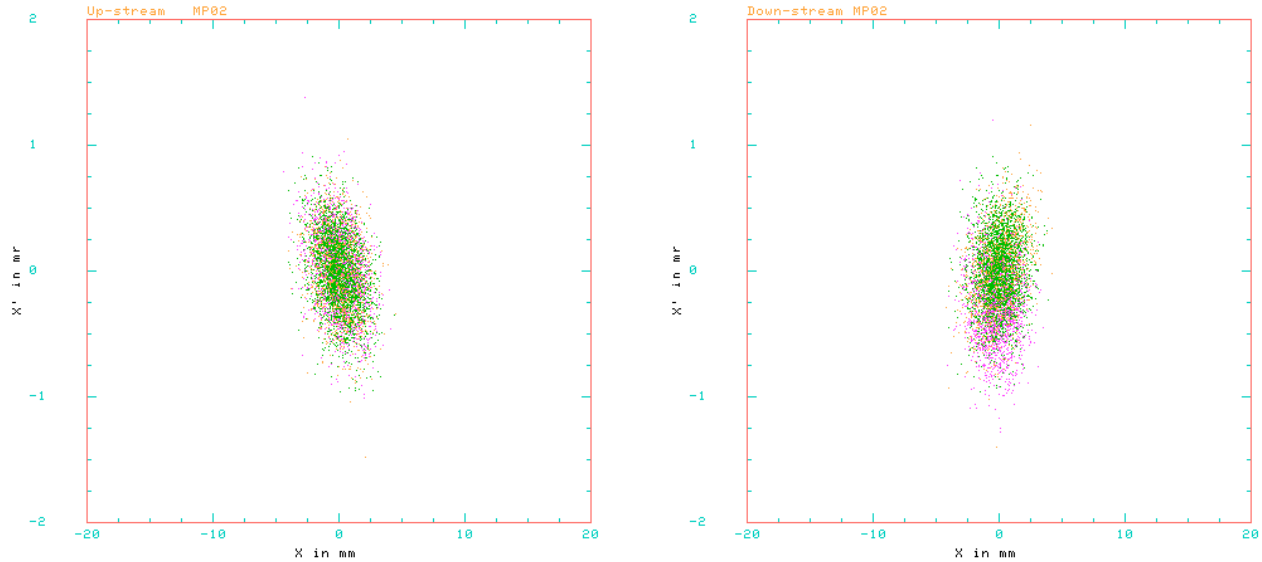

Figure 9. Horizontal phase space at up-stream (left plot) and down-stream of MPØ2 extraction septum. A 20-π 95% normalized emittance for horizontal plane was used. Green dots are results with extraction kickers at nominal setting, magenta dots with kickers at -1 KV, and gold dots with kickers at +1 KV. Approximately 2000 particles were tracked in each category.

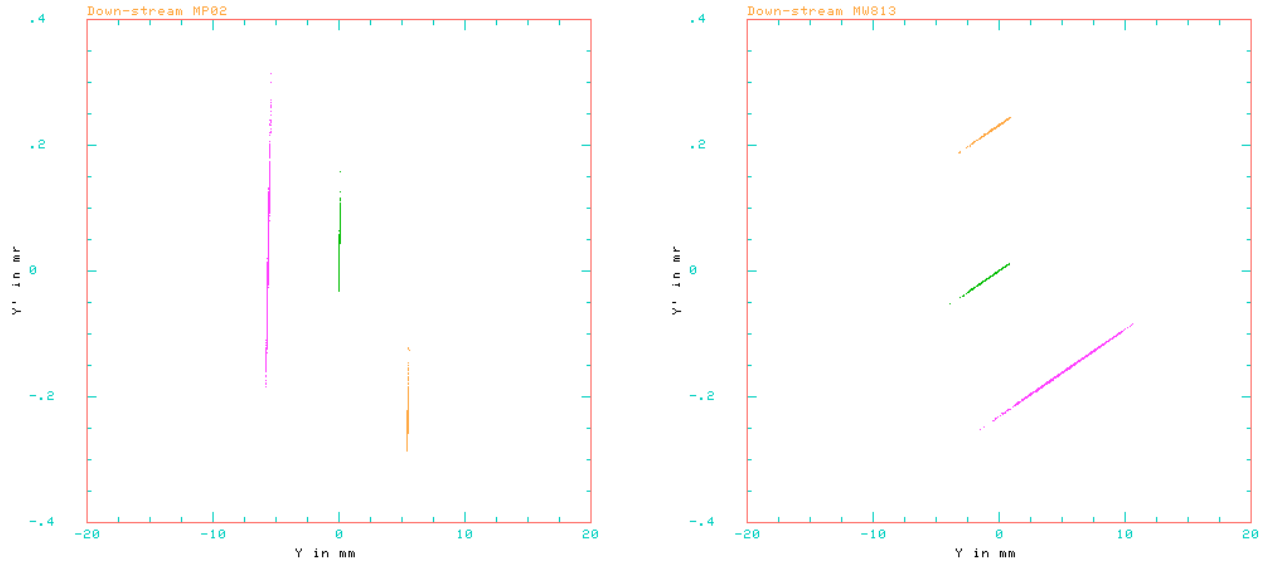

Figure 10. Vertical plane phase space at MPØ2 down-stream (left plot) and multiwire MW813 from the same tracking run as in Figure 9. To show the effect of coupling more straight forward the initial vertical plane emittance was set to 0. The left plot shows the amount of vertical kicks due to coupling at MPØ2, for the three different vertical beam positions. The right plot shows the resulting beam position spread due to coupling at MW813.

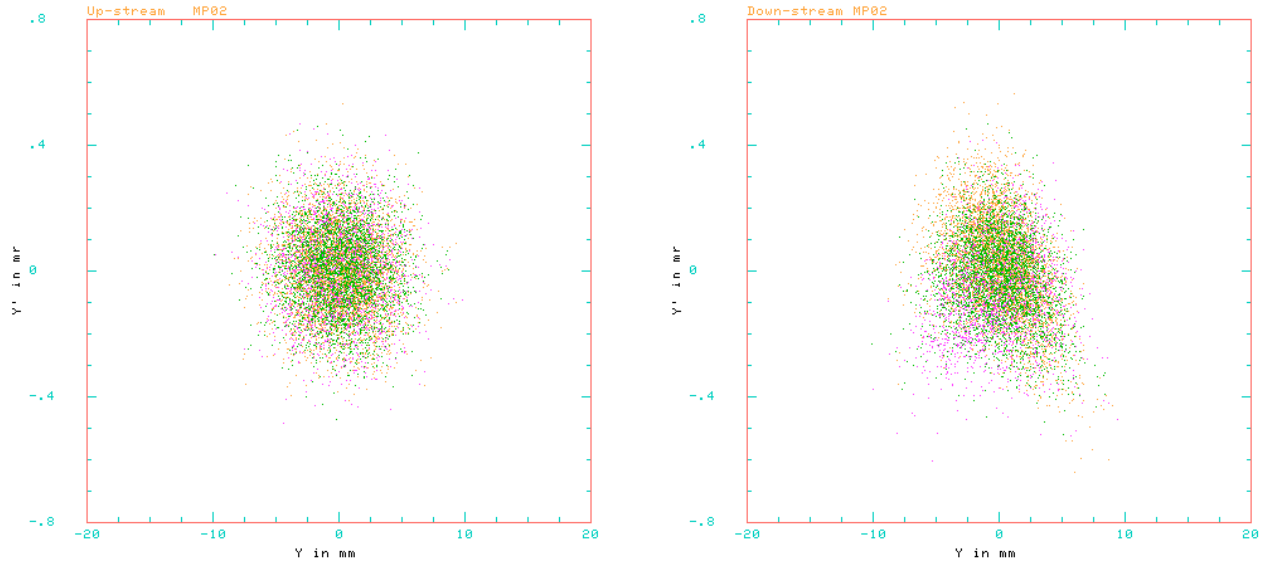

Figure 11. Vertical phase space at the up-stream (left plot) and down-stream of MPØ2. A 20-π 95% normalized initial emittance for vertical plane was used. Green dots are results with nominal horizontal position, magenta dots are with kickers at -1 KV and oriented horizontally, and gold dots are with kickers at +1 KV. The amount of horizontal displacement at MPØ2 can be seen in Figure 11. Approximately 3000 particles are in each category.

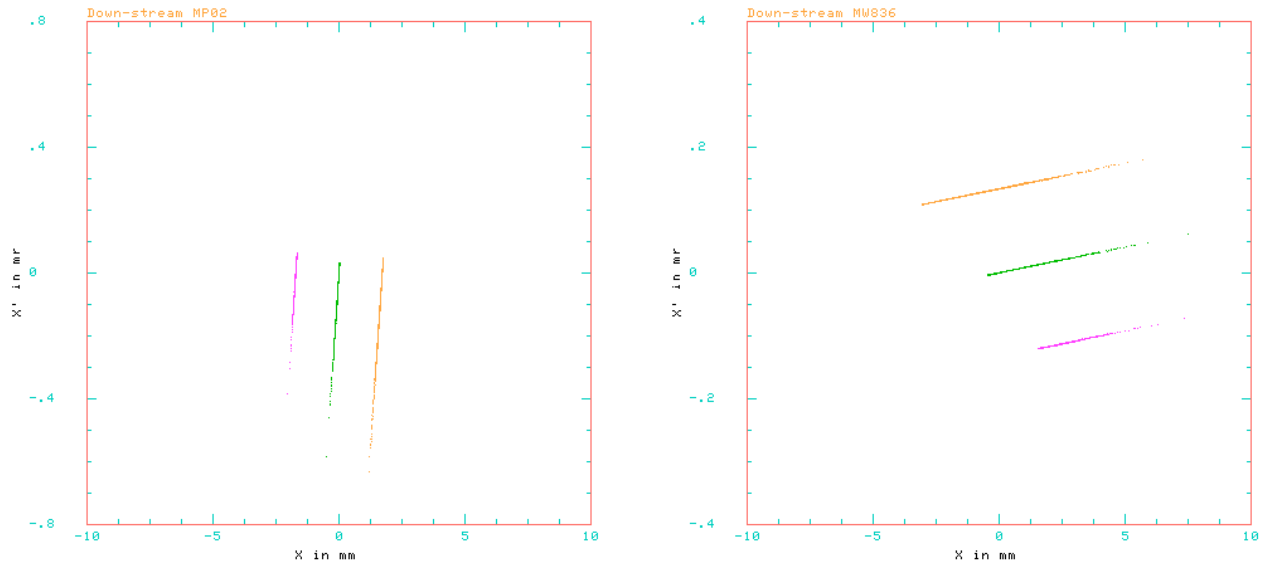

Figure 12. The horizontal phase space plot at down-stream of MPØ2 (left plot) and at MW836. The initial horizontal emittance was set to zero. The kicks due to coupling effect can be seen at MPØ2 in kicks and at MW836 in the beam size.

Conclusion

It is clear that the Booster extraction septum magnet possesses multi-pole fields much stronger than had been anticipated, according to the result of this analysis. The amount of emittance growth is substantial and there could be other undesirable effect

not yet visualized. More study in the future will be useful to gain confidence on the analysis result.

As a new septum magnet similar to MPØ2 is currently being built it is important that a new technique capable of measuring all field components be designed and used to ascertain the quality of the magnet.

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[1] Bruce C. Brown, "Focusing Properties of The Booster Extraction Septa", Fermilab Accelerator Division, beams-doc-462.

[2] Ming-Jen Yang, "MI8 line optics and source of anomalous vertical dispersion, March 2004", Fermilab Accelerator Division, beams-doc-1394.