Dual AC Dipole Excitation for the Measurement of Magnetic Multipole Strength from Beam Position Monitor Data

IPAC11

JSA

Jefferson Lab

Office of Science
U.S. DEPARTMENT OF ENERGY

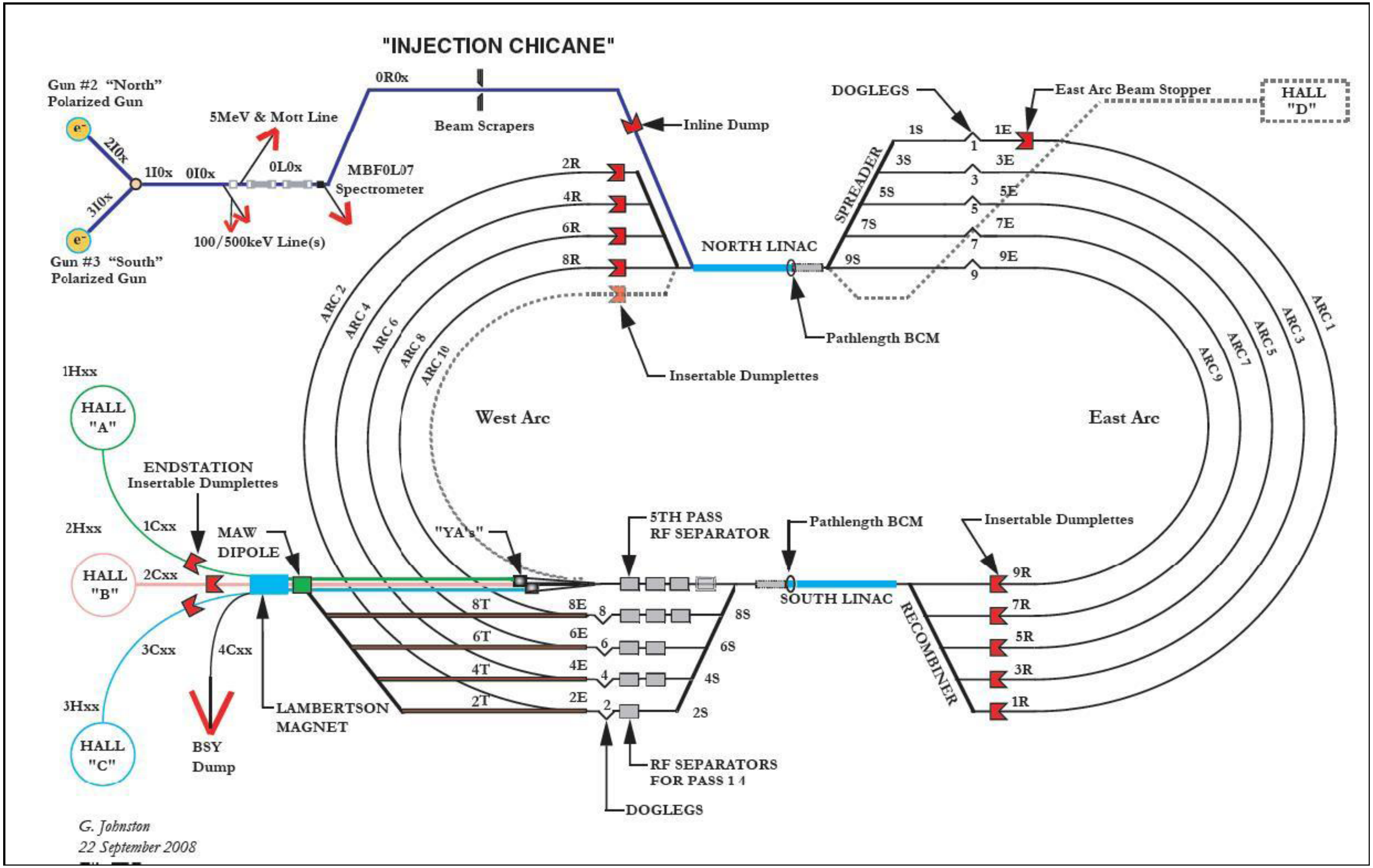
Outline

- CEBAF Overview
- Analytical Model
- Experimental Setup
- ARC1 Beamline
- Sextupole Measurements
- Beam Position Monitor Nonlinearity
- ARC1 Dipole Measurements
- Future Measurements
- Summary

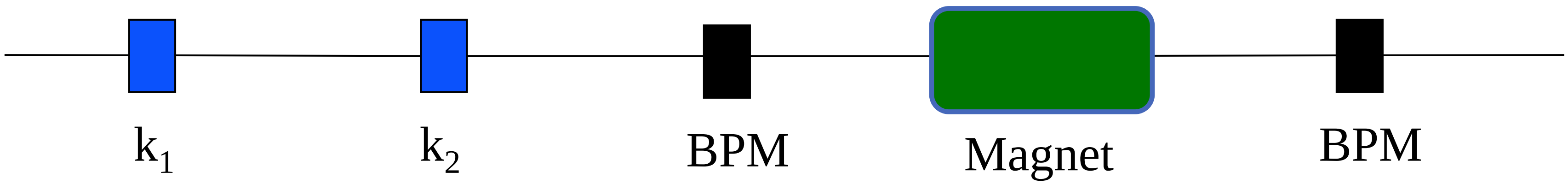
Aerial View

- 5-pass CW Electron Accelerator
- Three user facilities (A, B, C)
- CW Polarized Source
- >85% Polarization
- Two 1497 MHz Linacs
- Two Recirculation Arcs
- Operating at 6 GeV
- Now being upgraded to 12 GeV

CEBAF Overview

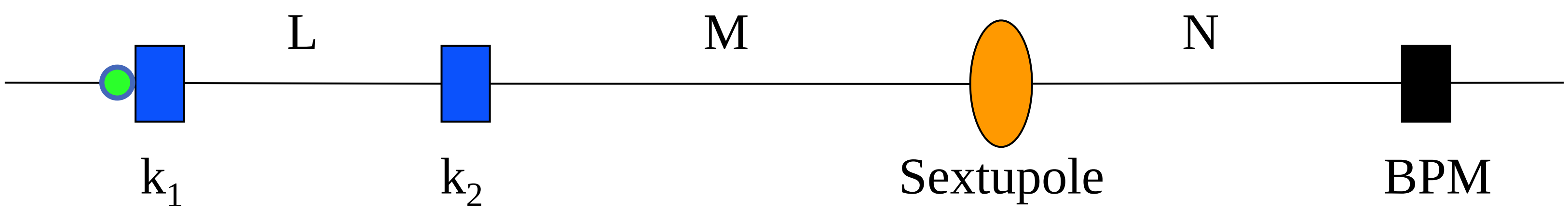


Introduction



- Modulate the beam with two AC dipoles at two different frequencies
- Record time domain data at 8 Beam Position Monitors within a CEBAF ARC
- Perform Fast Fourier Transform of BPM data
- Linear system will just have kick frequencies with amplitudes that depend on the phase advance of the lattice
- Nonlinear fields will produce harmonics of the kick frequencies

Analytical Model

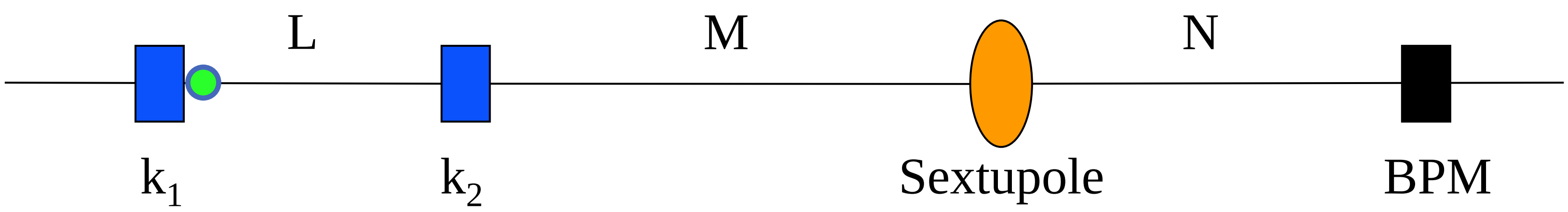


$$X_{k1-} = X'_{k1-} = 0$$

$$X_{k1+} = 0$$

$$X'_{k1+} = A_1 \cos \omega_1 t$$

Analytical Model

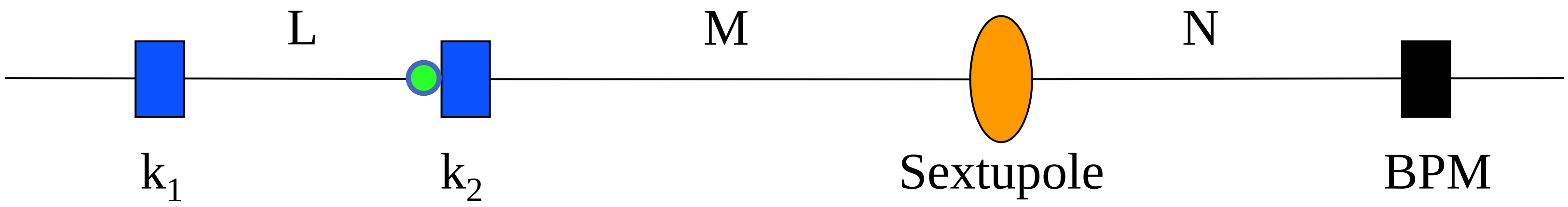


$$X_{k1-} = X'_{k1-} = 0$$

$$X_{k1+} = 0$$

$$X'_{k1+} = A_1 \cos \omega_1 t$$

Analytical Model

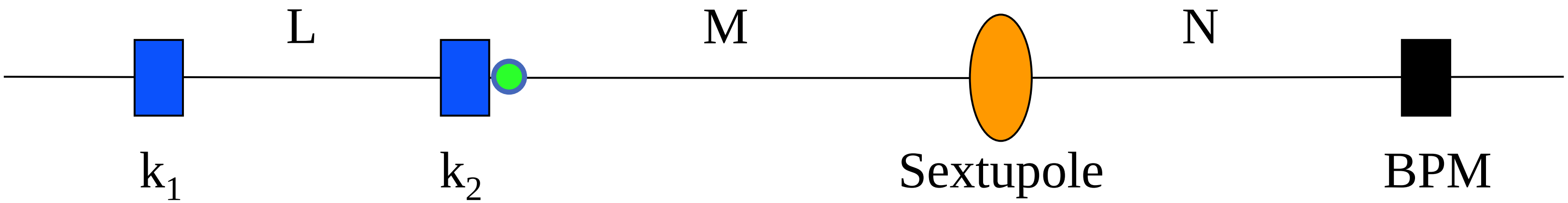


$$\begin{pmatrix} X_{k2-} \\ X'_{k2-} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} X_{k1+} \\ X'_{k1+} \end{pmatrix}$$

$$X_{k2-} = L_{12} A_1 \cos \omega_1 t$$

$$X'_{k2-} = L_{22} A_1 \cos \omega_1 t$$

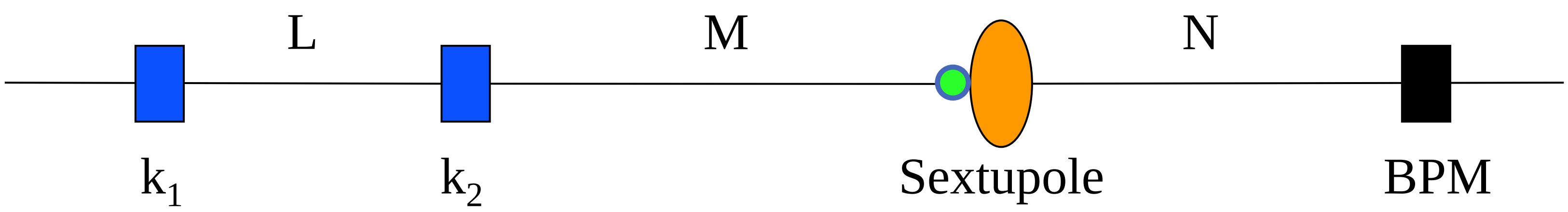
Analytical Model



$$X_{k2+} = L_{12} A_1 \cos \omega_1 t$$

$$X'_{k2+} = L_{22} A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$$

Analytical Model

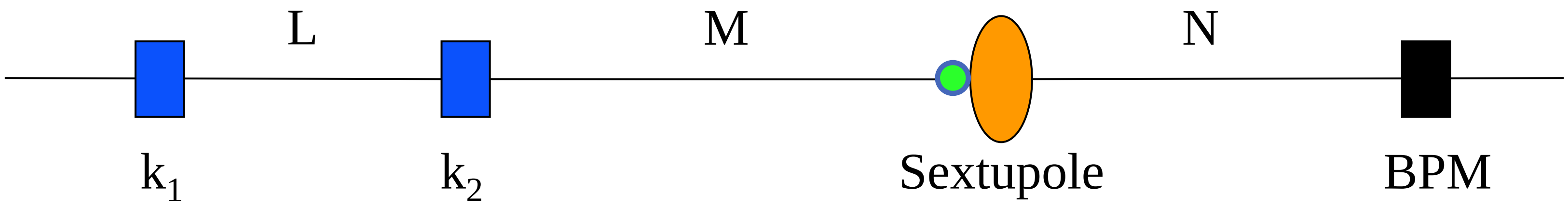


$$\begin{pmatrix} X_{s-} \\ X'_{s-} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} X_{k2+} \\ X'_{k2+} \end{pmatrix}$$

$$X_{s-} = (ML)_{12} A_1 \cos\omega_1 t + M_{12} A_2 \cos\omega_2 t$$

$$X'_{s-} = (ML)_{22} A_1 \cos\omega_1 t + M_{22} A_2 \cos\omega_2 t$$

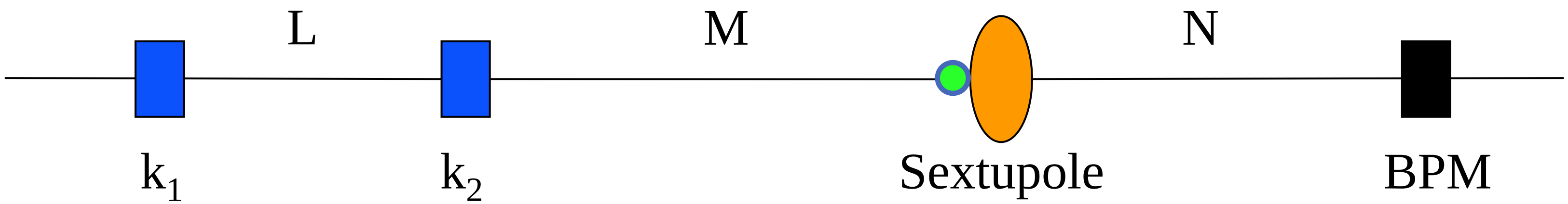
Analytical Model



$$B_x = \frac{2B_0}{a^2} xy$$

$$B_y = \frac{B_0}{a^2}(x^2 - y^2)$$

Analytical Model

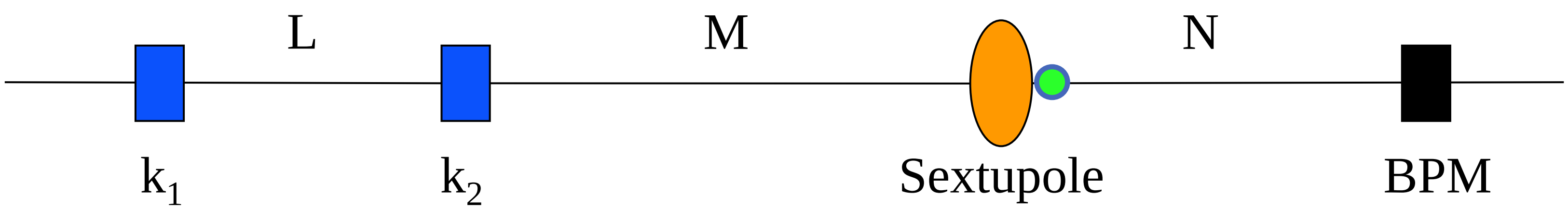


$$B_y = \frac{B_0}{a^2} x^2$$

$$\Delta\theta = 2.998x10^{-4} \frac{B_y(G)L(cm)}{E(MeV)}$$

$$\Delta\theta = \frac{2.998x10^{-4} B_0 L}{a^2 p_z} x^2 = SX_{s-}^2$$

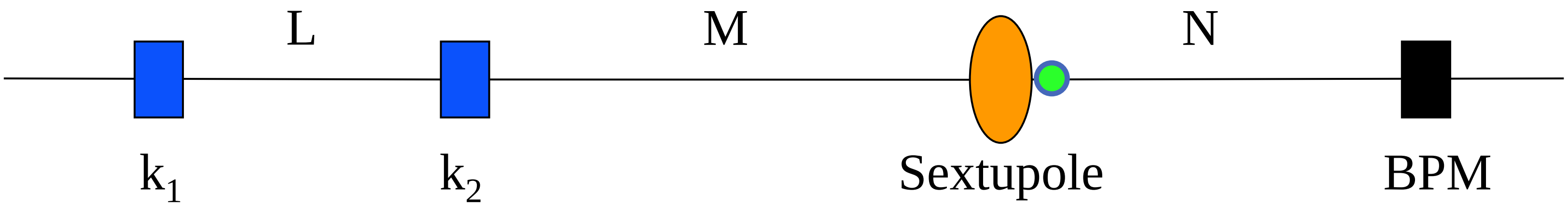
Analytical Model



$$X_{s+} = (ML)_{12} A_1 \cos\omega_1 t + M_{12} A_2 \cos\omega_2 t$$

$$X'_{s+} = (ML)_{22} A_1 \cos\omega_1 t + M_{22} A_2 \cos\omega_2 t + S\begin{bmatrix} ((ML)_{12})^2 A_1{}^2 \cos^2\omega_1 t + \\ 2(ML)_{12}(M_{12}) A_1 A_2 \cos\omega_1 t \cos\omega_2 t + \\ (M_{12})^2 A_2{}^2 \cos^2\omega_2 t \end{bmatrix}$$

Analytical Model



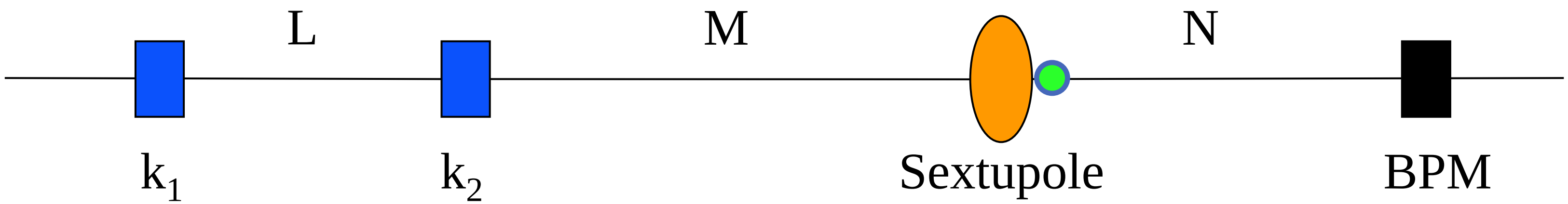
$$\cos(A+B)=\cos A\cos B-\sin A\sin B$$

$$\cos(A-B)=\cos A\cos B+\sin A\sin B$$

$$\cos A\cos B=\frac{1}{2}\left[\cos(A+B)+\cos(A-B)\right]$$

$$\cos^2 A=\frac{1}{2}\left[1+\cos 2A\right]$$

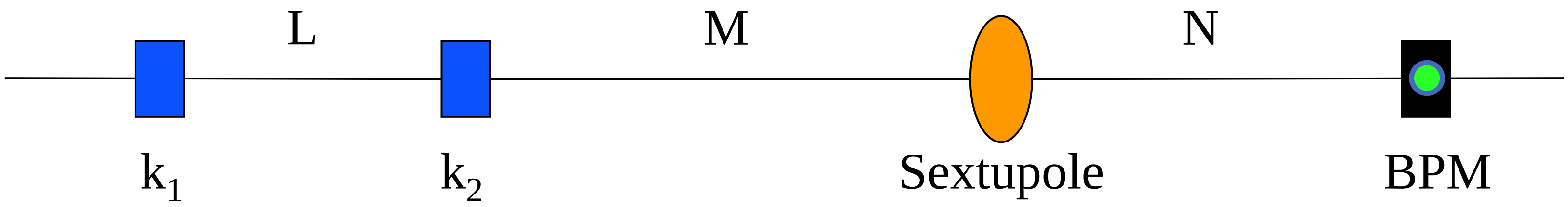
Analytical Model



$$X_{s+} = (ML)_{12} A_1 \cos\omega_1 t + M_{12} A_2 \cos\omega_2 t$$

$$X'_{s+} = (ML)_{22} A_1 \cos\omega_1 t + M_{22} A_2 \cos\omega_2 t + S\begin{bmatrix} ((ML)_{12})^2 A_1^{\,2}\,\tfrac{1}{2}\left[1+\cos 2\omega_1 t\right] + \\ (ML)_{12}(M_{12}) A_1 A_2 [\cos(\omega_1+\omega_2)t + \\ \cos(\omega_1-\omega_2)t] + (M_{12})^2 A_2^{\,2}\,\tfrac{1}{2}\left[1+\cos 2\omega_2 t\right] \end{bmatrix}$$

Analytical Model

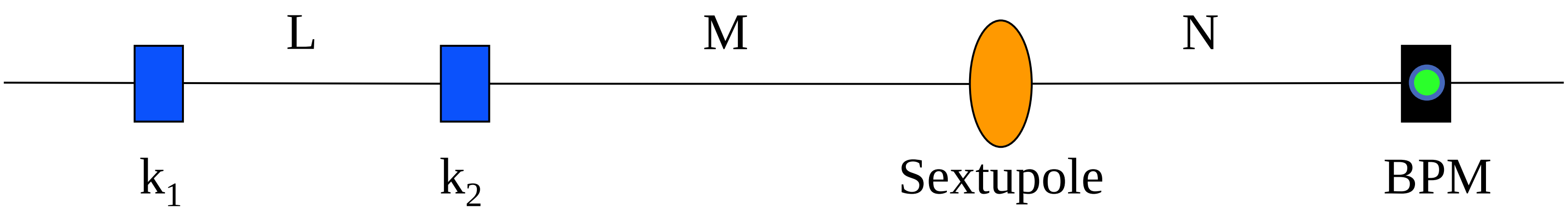


$$\begin{pmatrix} X_{bpm} \\ X'_{bpm} \end{pmatrix} = \begin{pmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{pmatrix} \begin{pmatrix} X_{s+} \\ X'_{s+} \end{pmatrix}$$

$$X_{bpm} = N_{11} X_{s+} + N_{12} X'_{s+}$$

$$X'_{bpm} = N_{21} X_{s+} + N_{22} X'_{s+}$$

Analytical Model

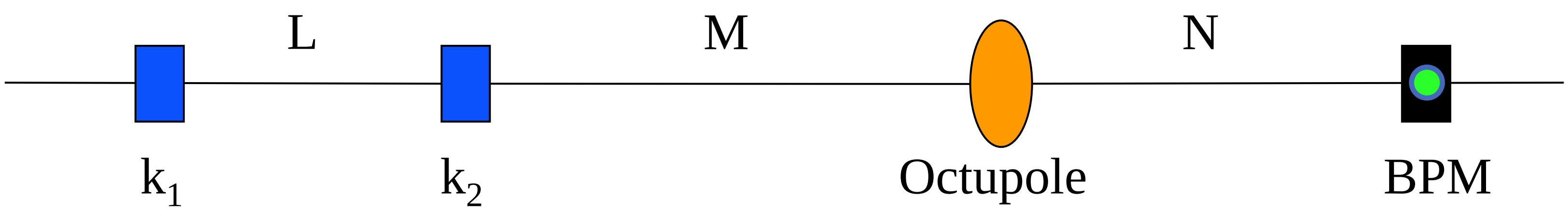


Kick frequencies for these tests were chosen to be 1 Hz and 21 Hz

Sextupole Frequencies

ω_1 = 1 Hz	ω_2 = 21 Hz
$2\omega_1$ = 2 Hz	$2\omega_2$ = 42 Hz
$\omega_1 - \omega_2 = 20$	$\omega_1 + \omega_2 = 22$ Hz

Analytical Model

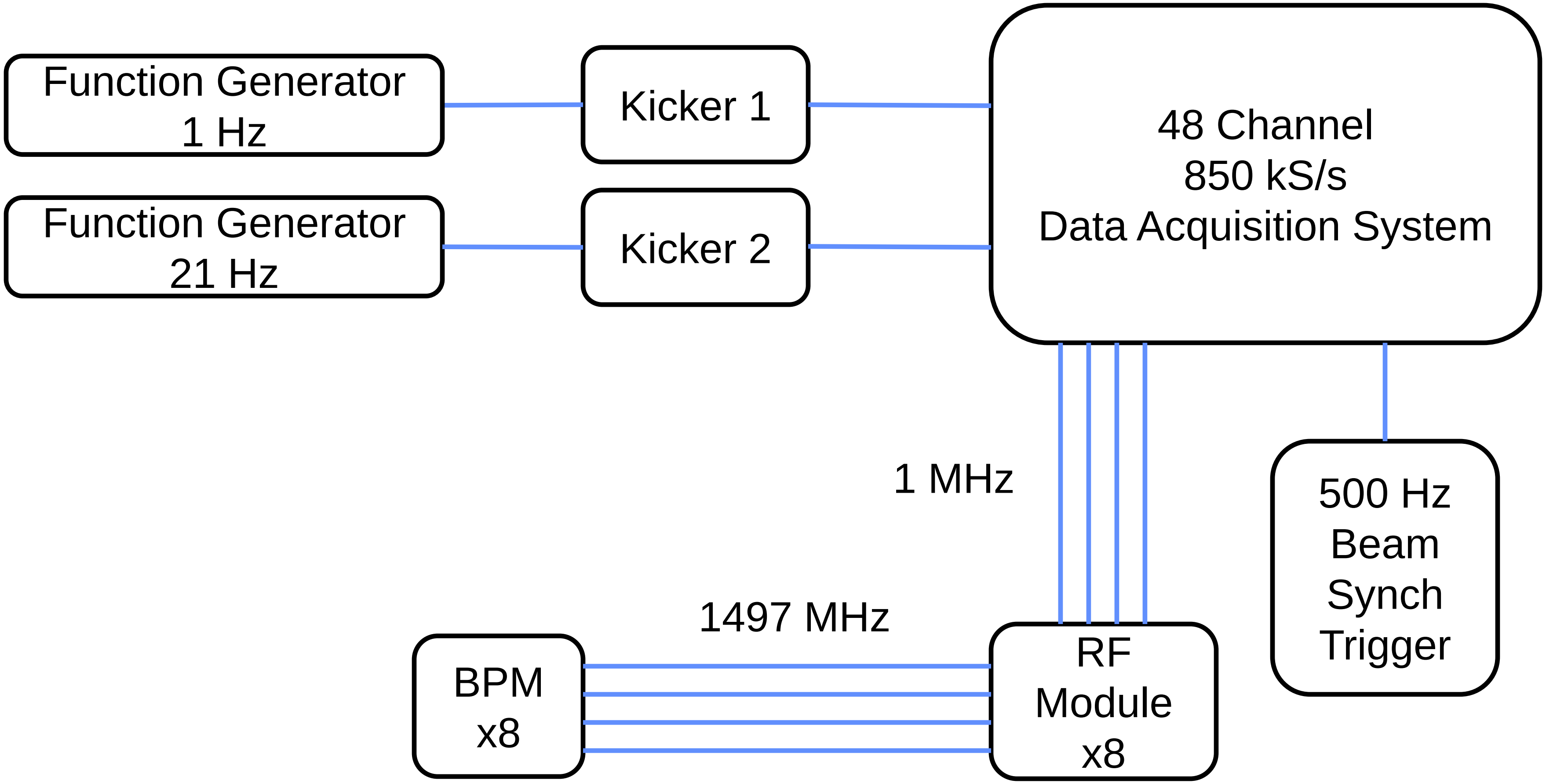


Kick frequencies for these tests were chosen to be 1 Hz and 21 Hz

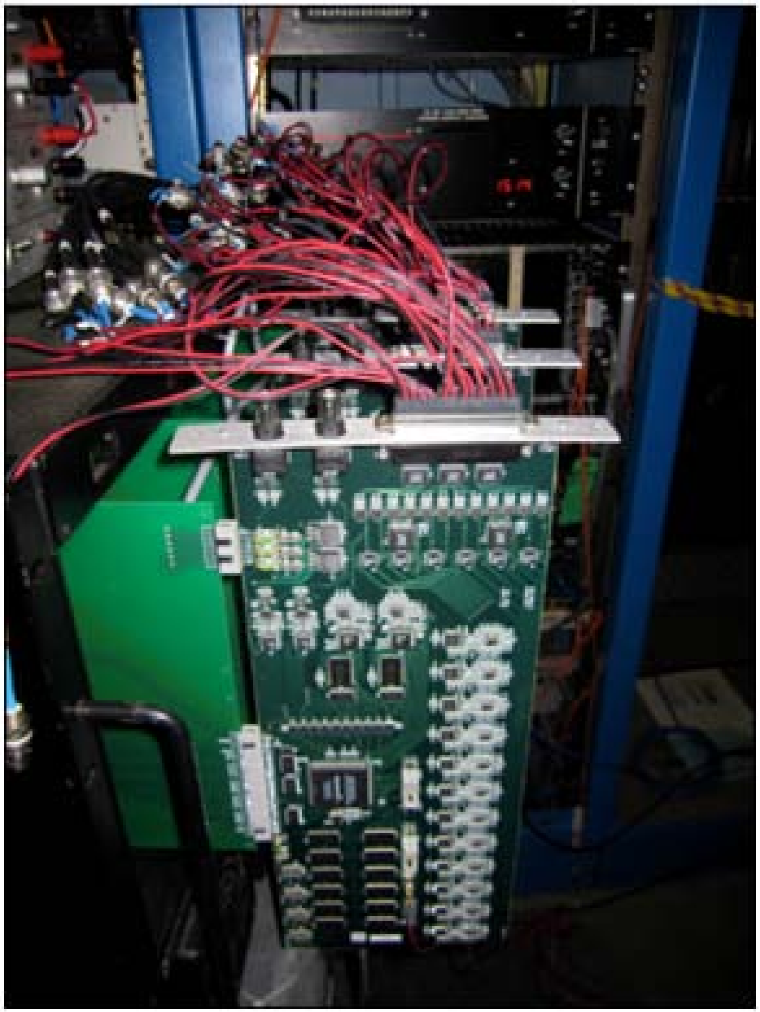
Octupole Frequencies

ω_1 = 1 Hz	ω_2 = 21 Hz
$3\omega_1$ = 3 Hz	$3\omega_2$ = 63 Hz
$\omega_2 + 2\omega_1 = 23$	$\omega_2 - 2\omega_1 = 19$
$2\omega_2 + \omega_1 = 43$	$2\omega_2 - \omega_1 = 41$

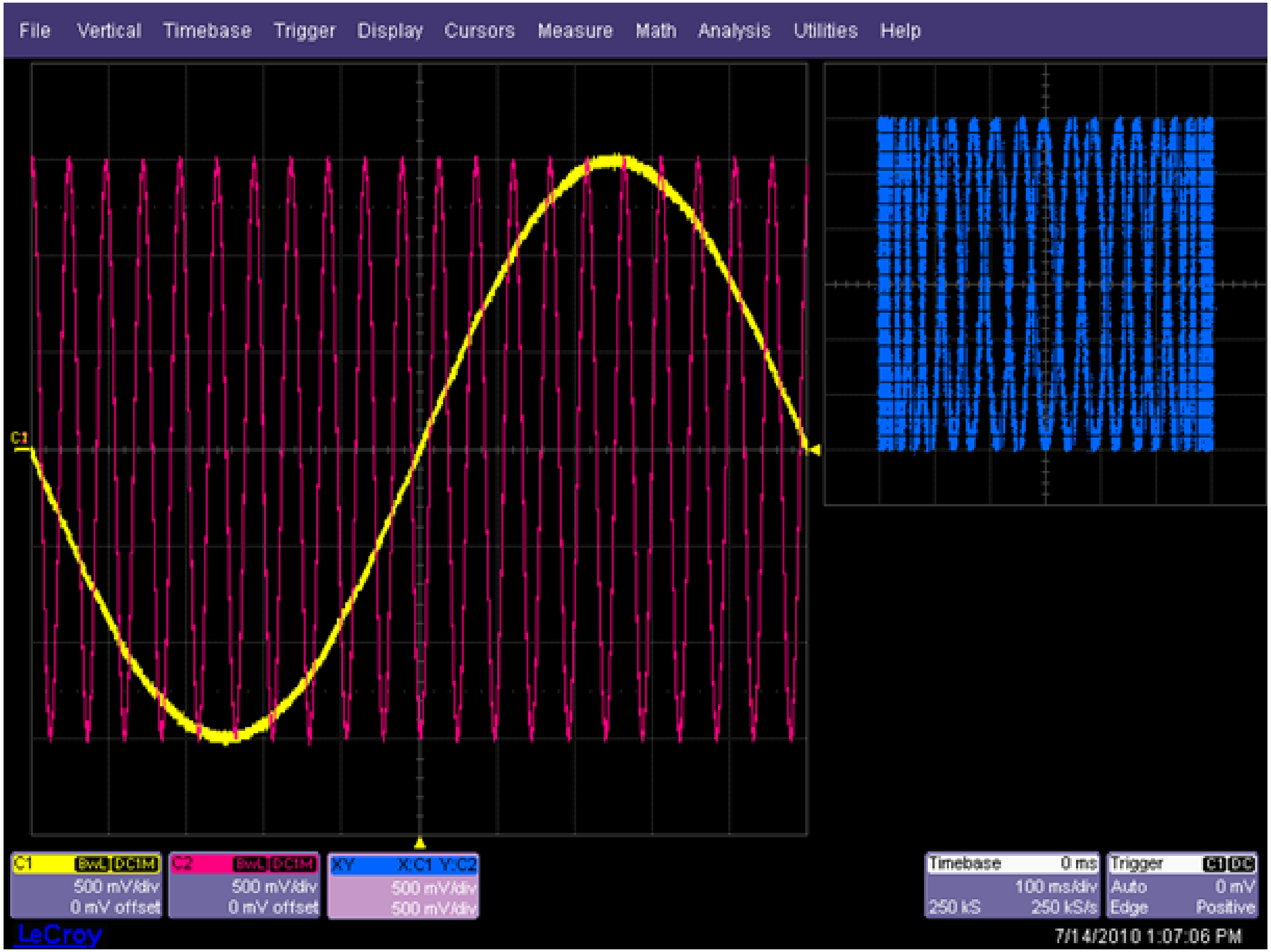
Experimental Equipment



Data Acquisition System

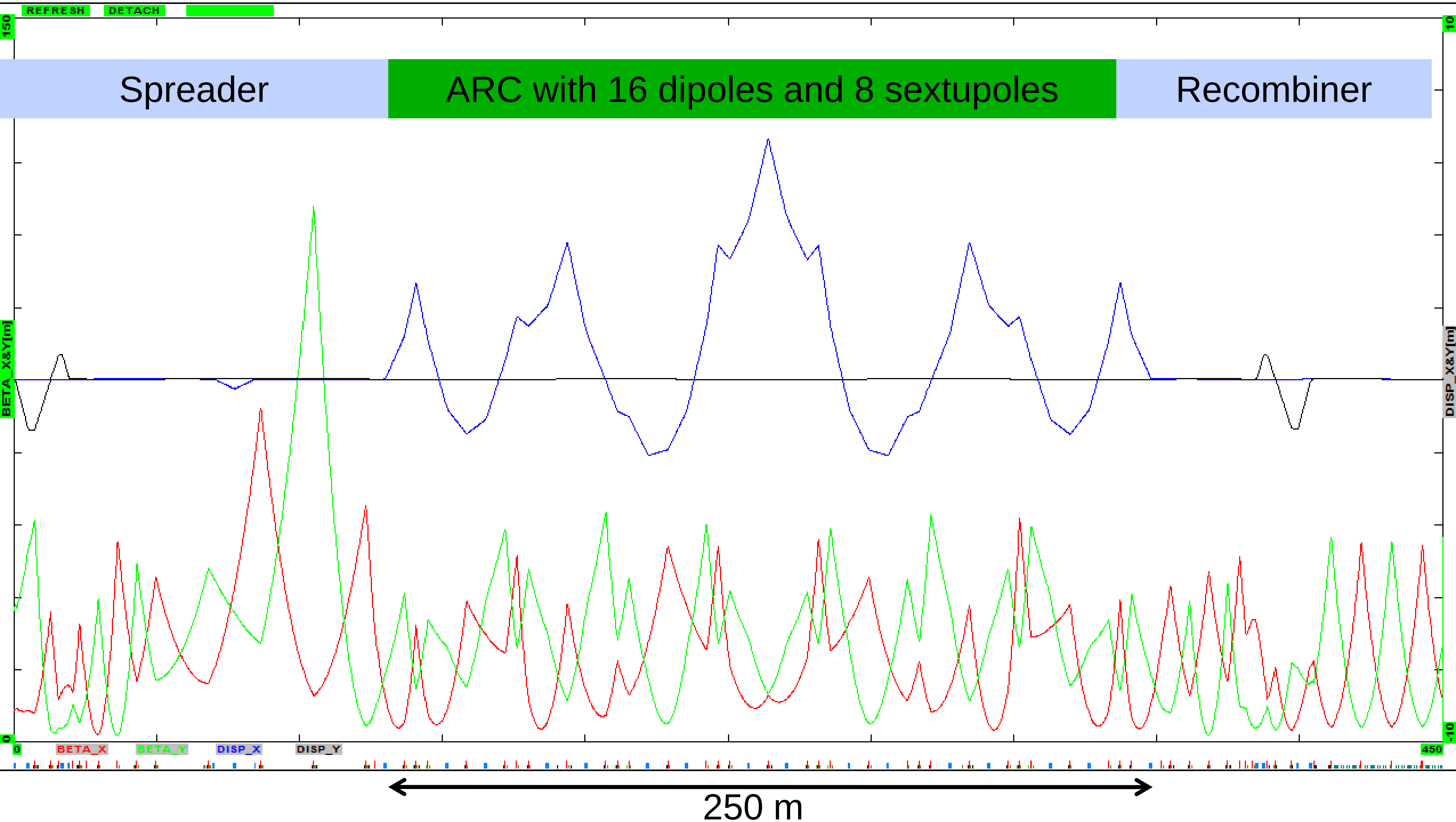


Kicker Magnets



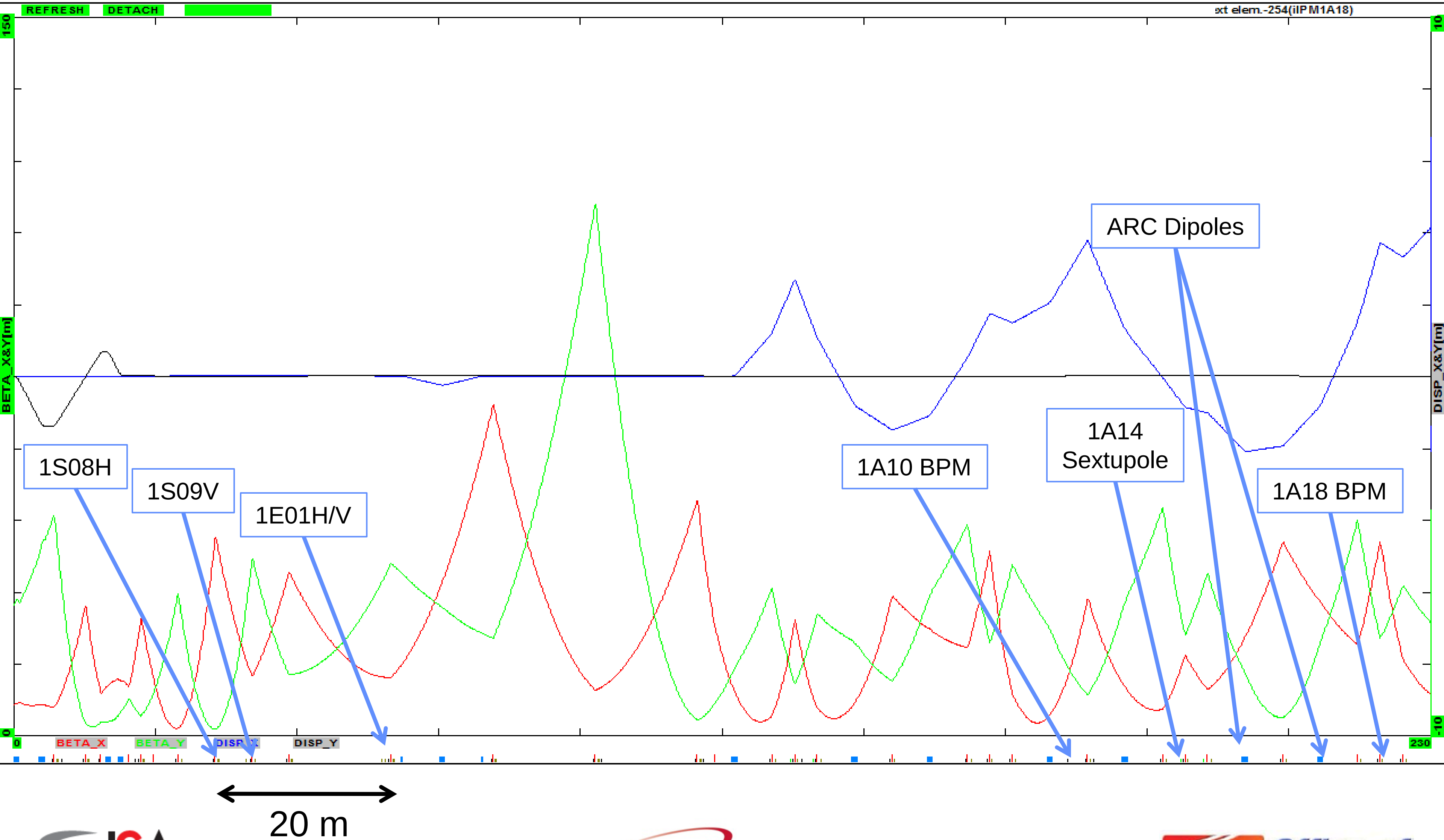
ARC1 Beamline

Arc1 Optics



REFRESH
DETACH
150
BETA_X&Y[m]
0
10
DISP_X&Y[m]
-10
Spreader
ARC with 16 dipoles and 8 sextupoles
Recombiner
0
BETA_X
BETA_Y
DISP_X
DISP_Y
450
250 m

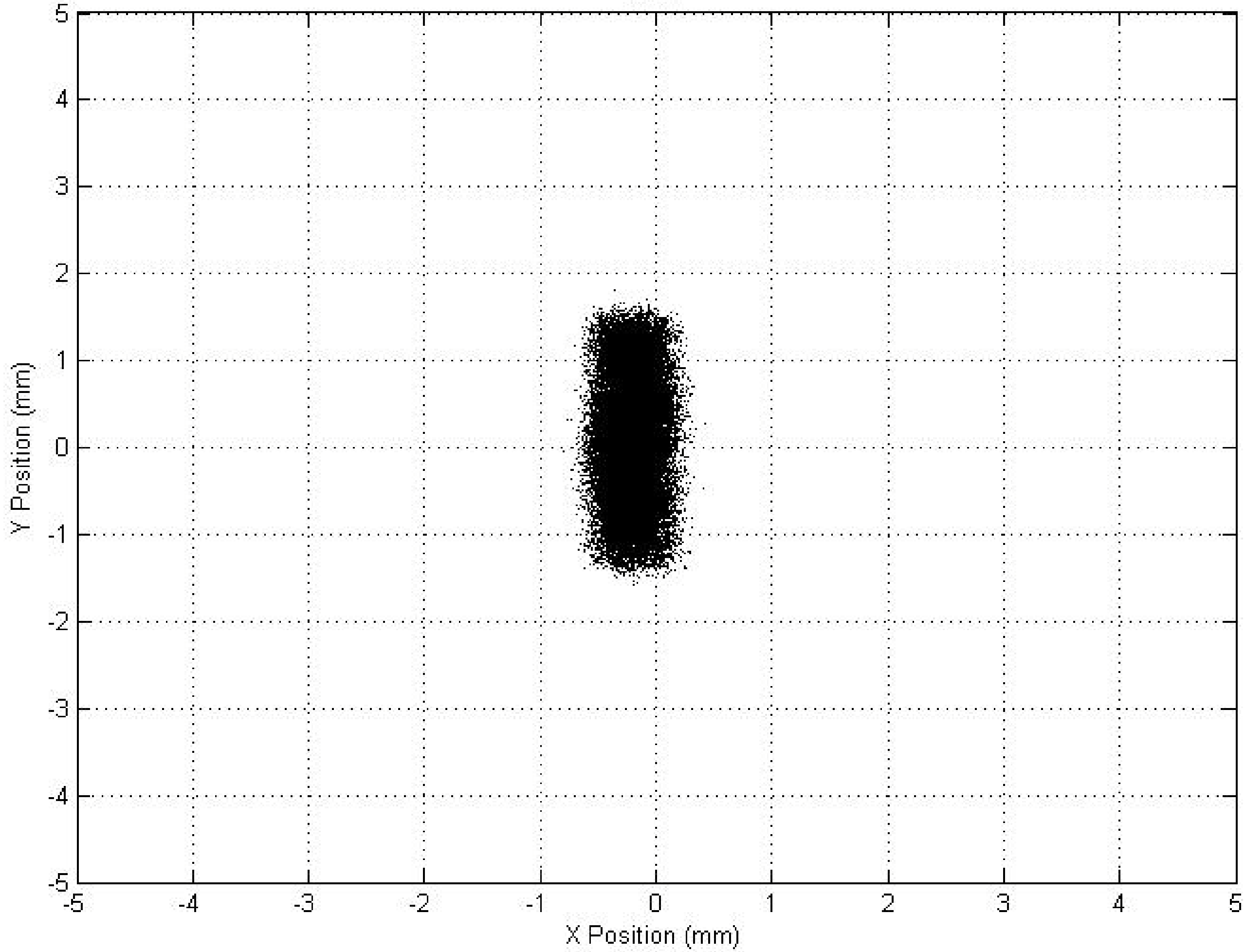
Arc1 Optics



REFRESH
DETACH
xt elem.-254(iIPM1A18)
150
BETA_X&Y[m]
0
10
DISP_X&Y[m]
-10
230
BETA_X
BETA_Y
DISP_X
DISP_Y
ARC Dipoles
1A14 Sextupole
1A10 BPM
1S08H
1S09V
1E01H/V
1A18 BPM
20 m

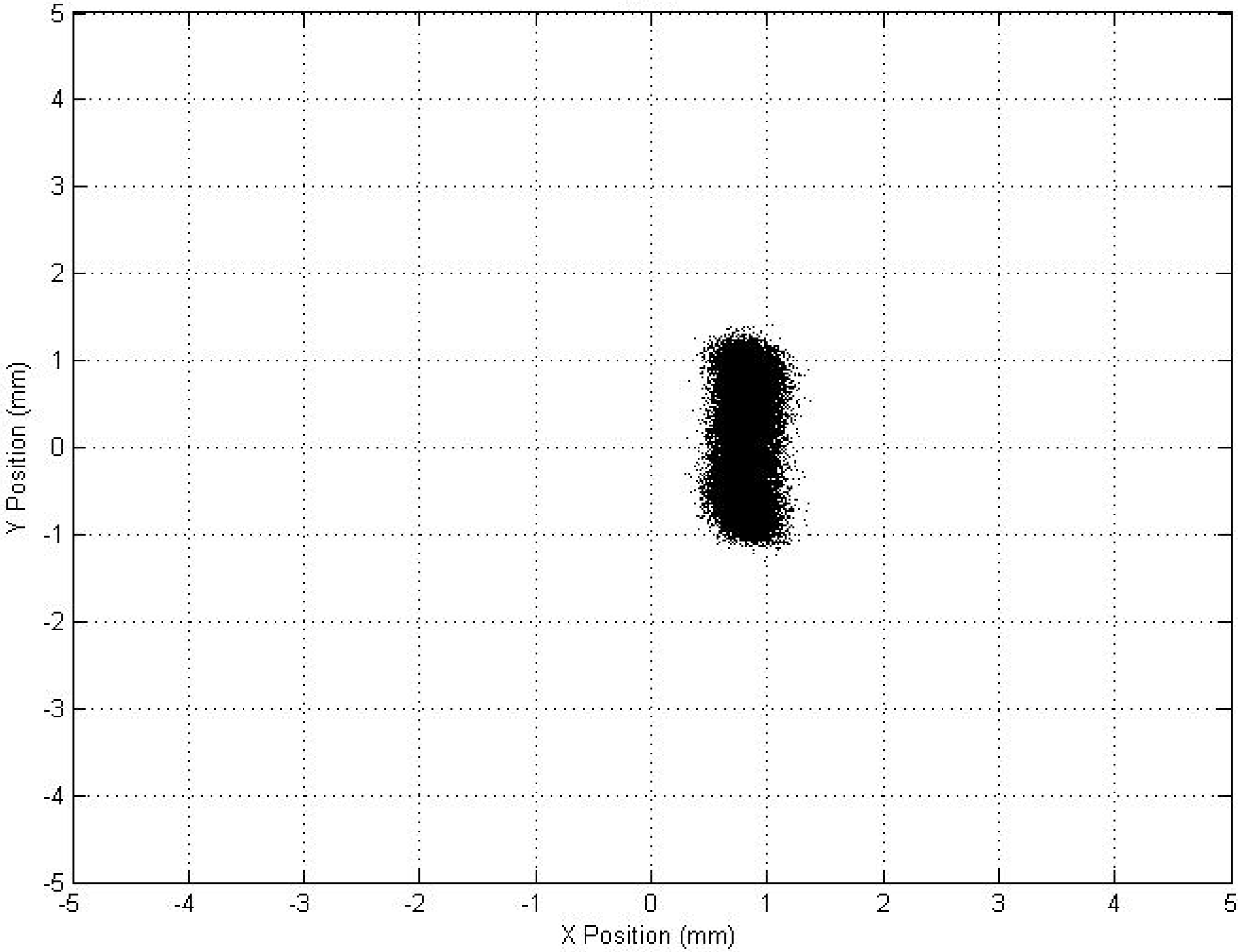
X-Y Beam Profiles

1A10 BPM Before Sextupole



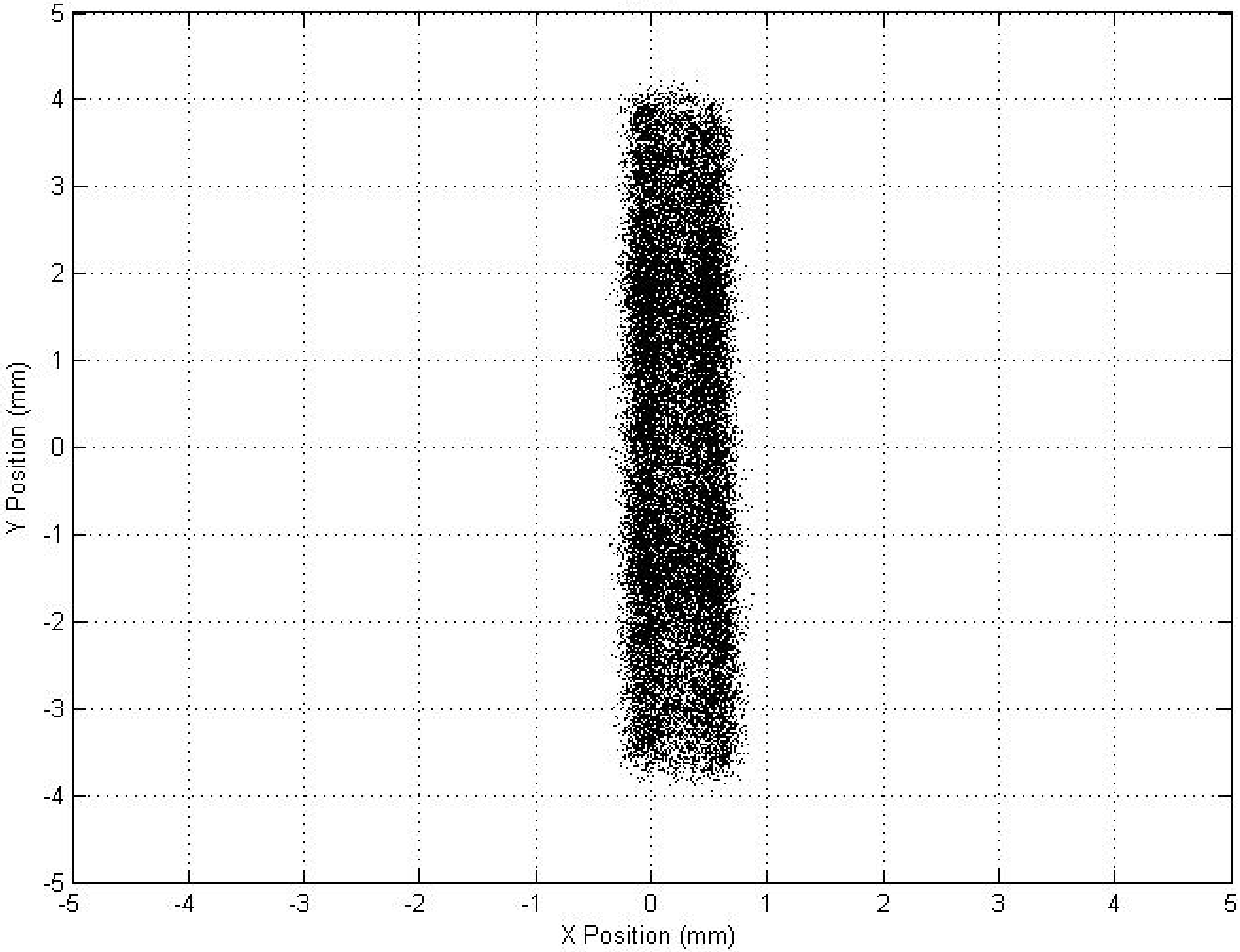
X-Y Beam Profiles

1A11 BPM Before Sextupole



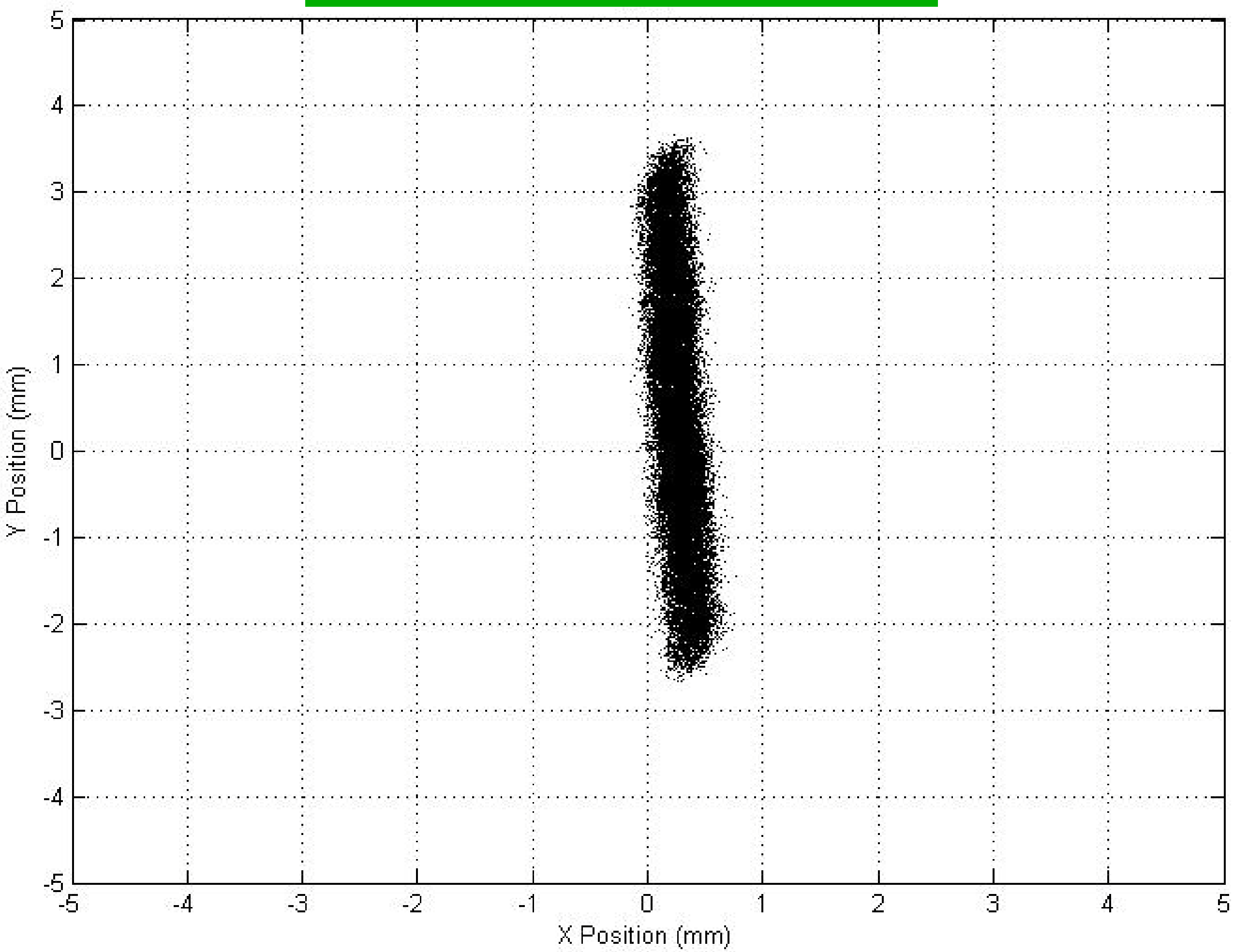
X-Y Beam Profiles

1A13 BPM Before Sextupole



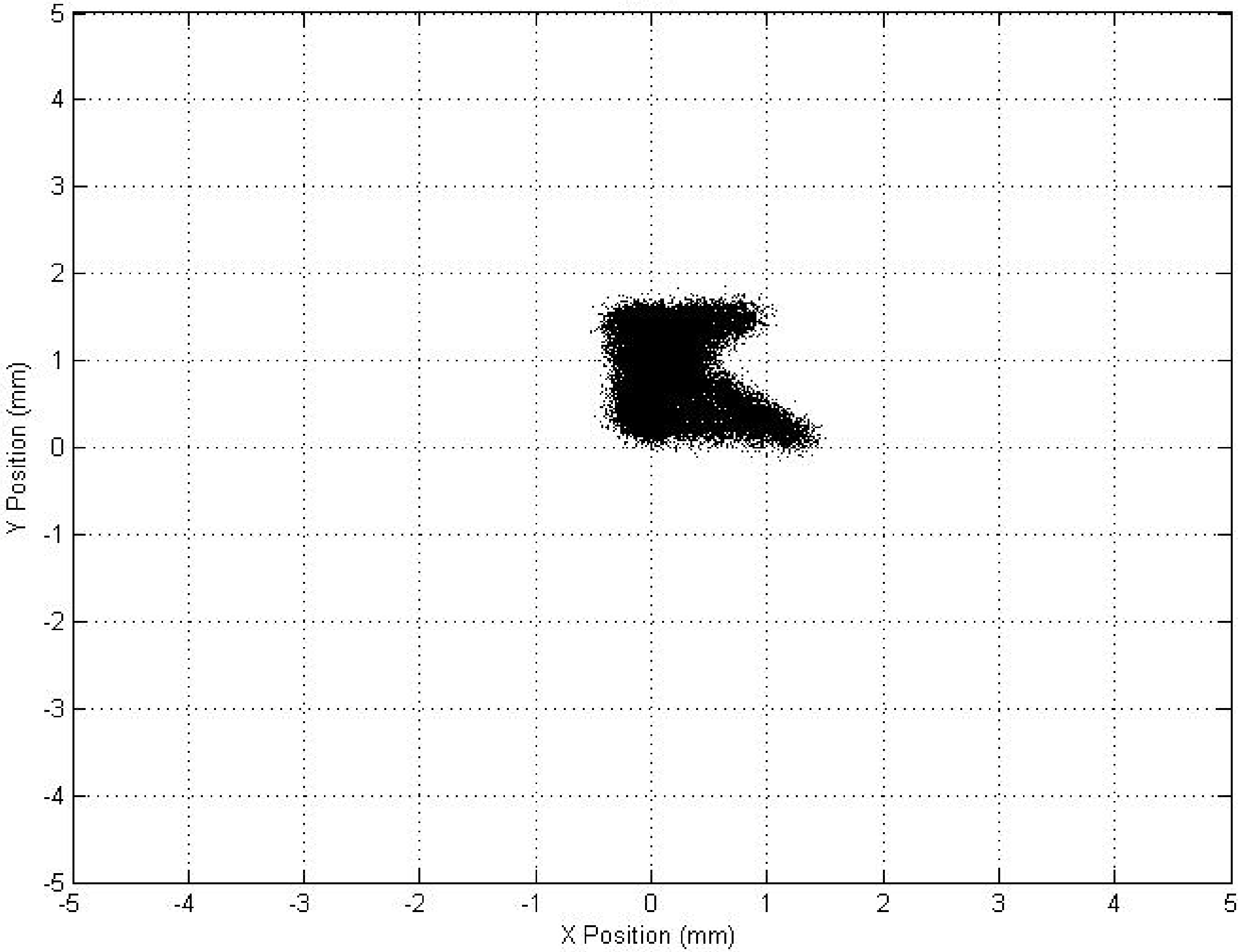
X-Y Beam Profiles

1A14 BPM Before Sextupole



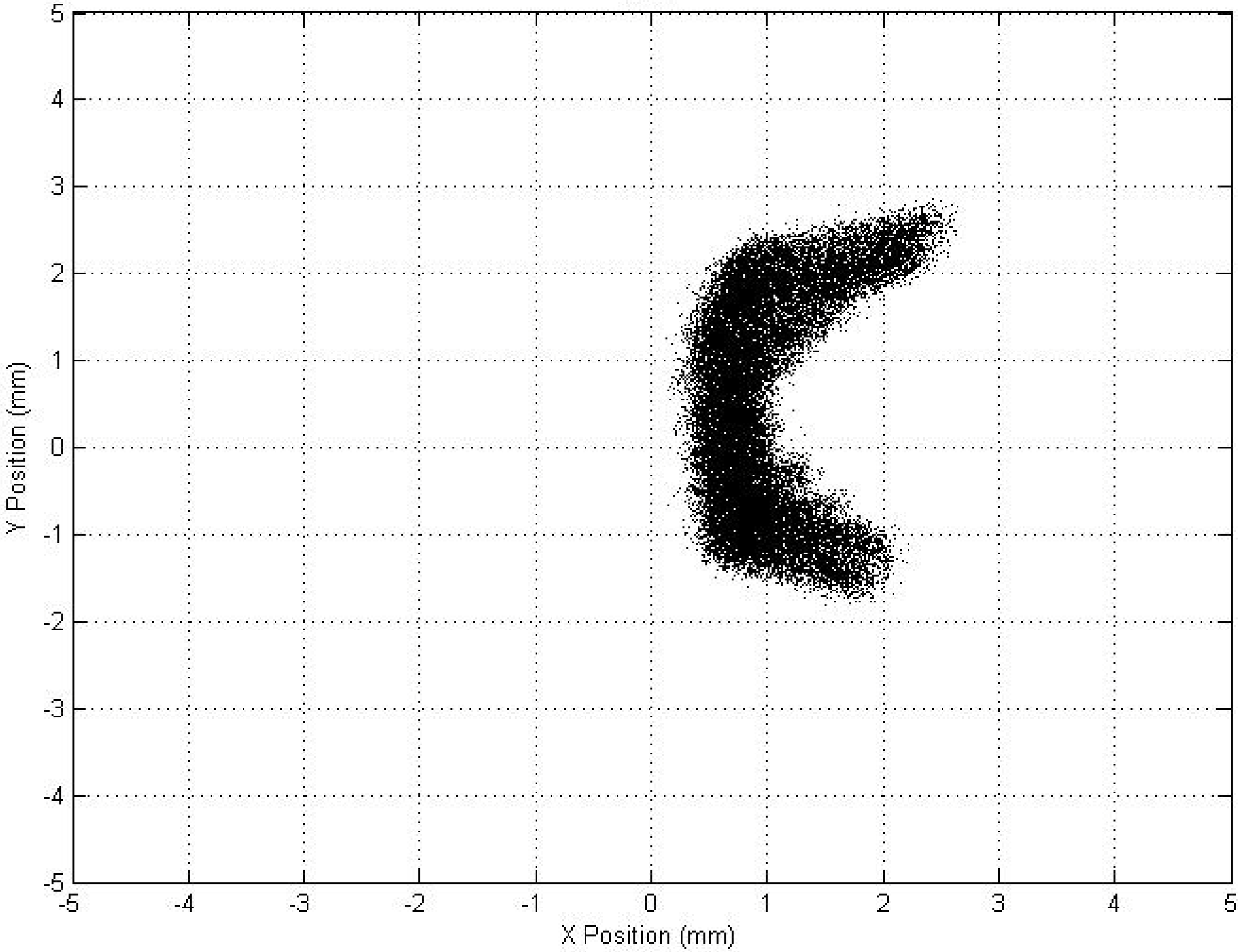
X-Y Beam Profiles

1A16 BPM After Sextupole



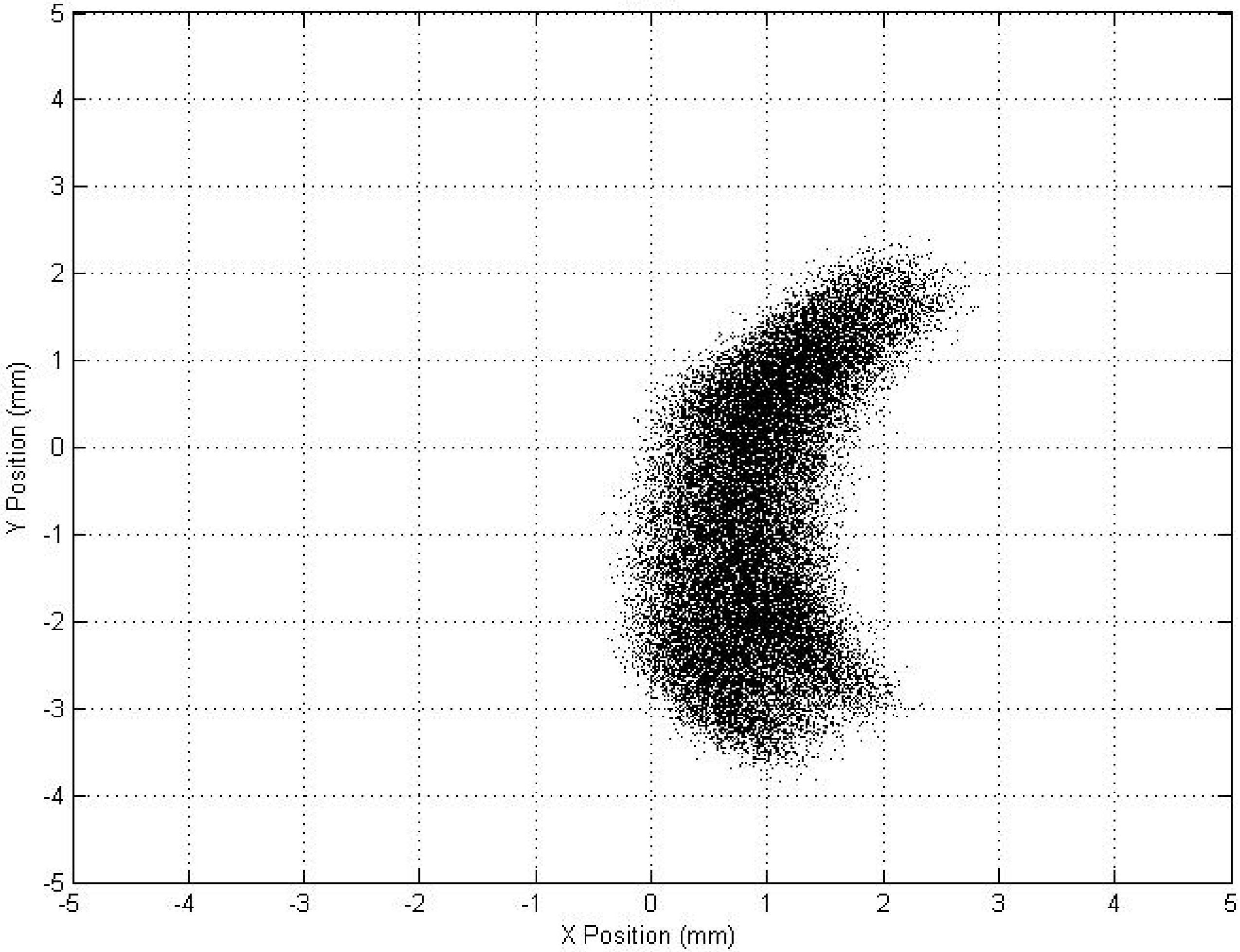
X-Y Beam Profiles

1A18 BPM After Sextupole

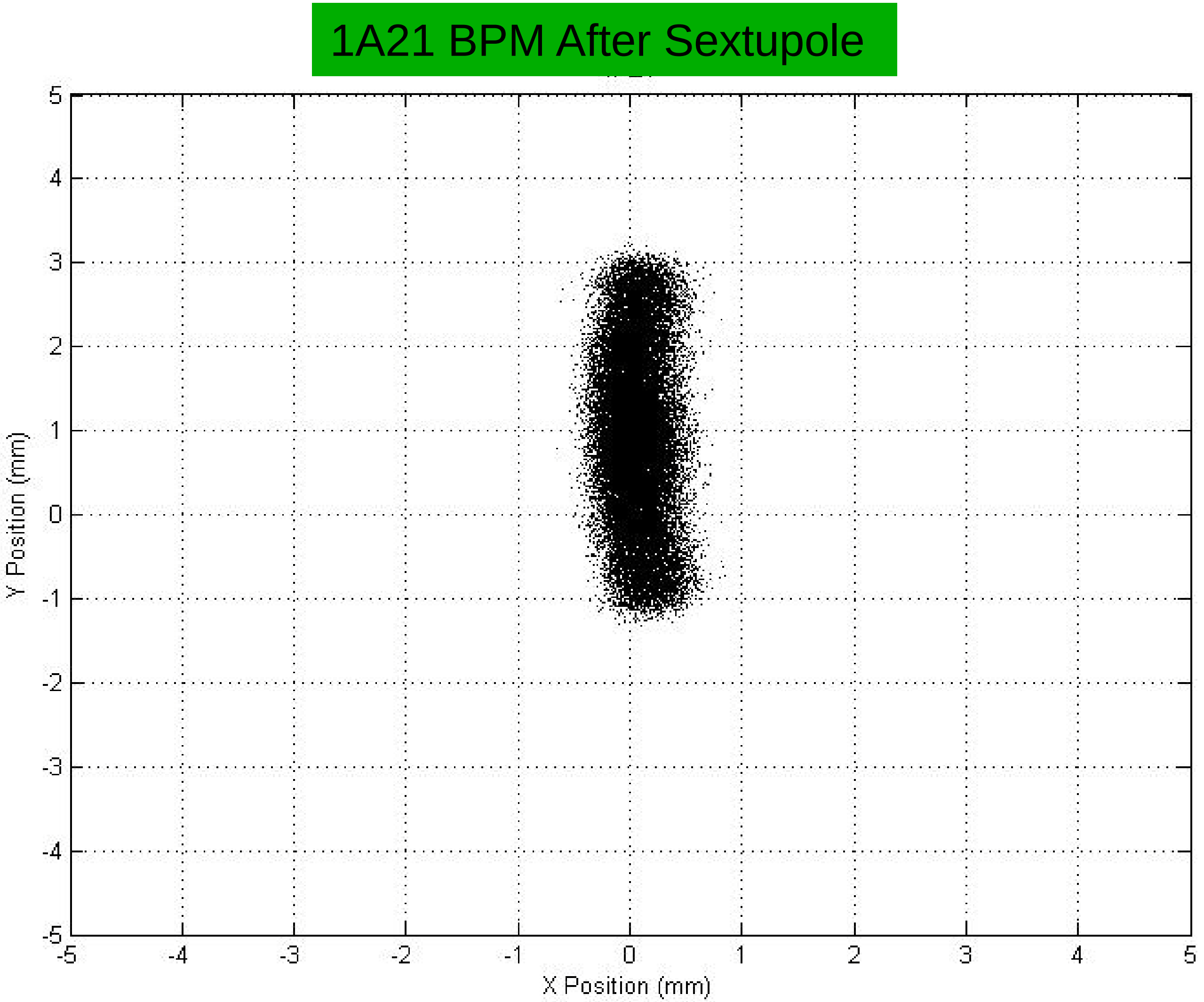


X-Y Beam Profiles

1A19 BPM After Sextupole

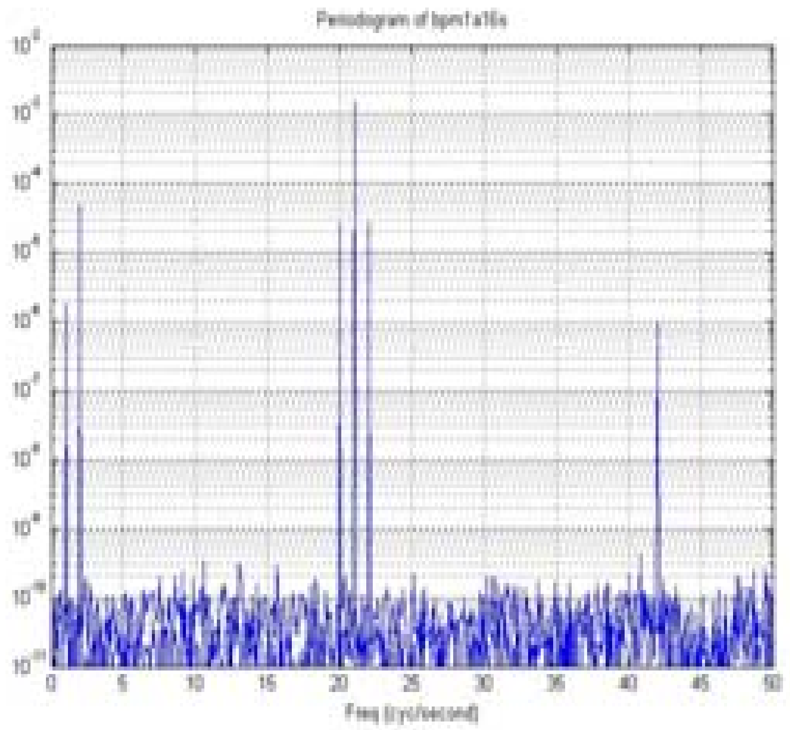


X-Y Beam Profiles

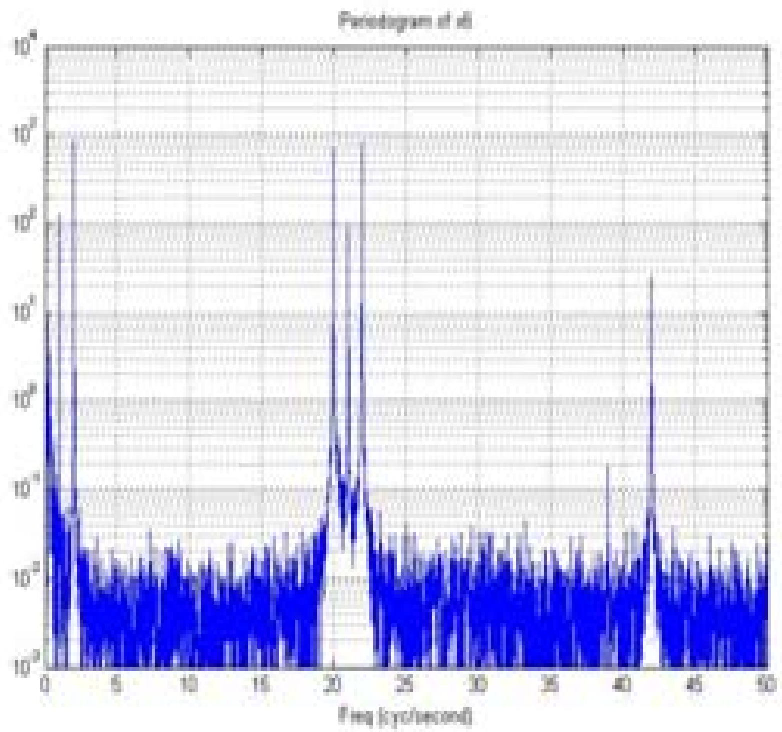


Simulation and Measurements

Elegant Simulation



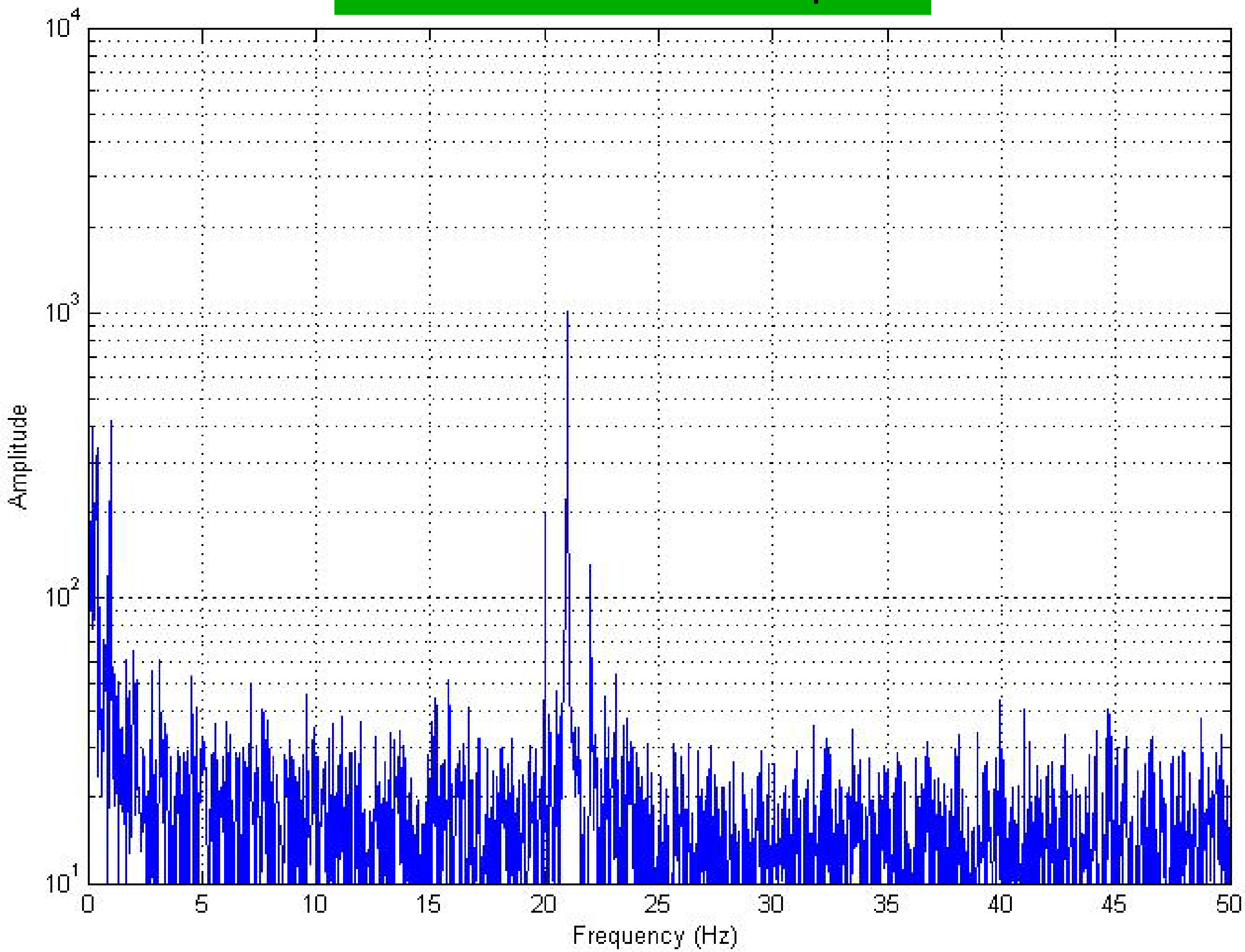
Beam Measurement



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

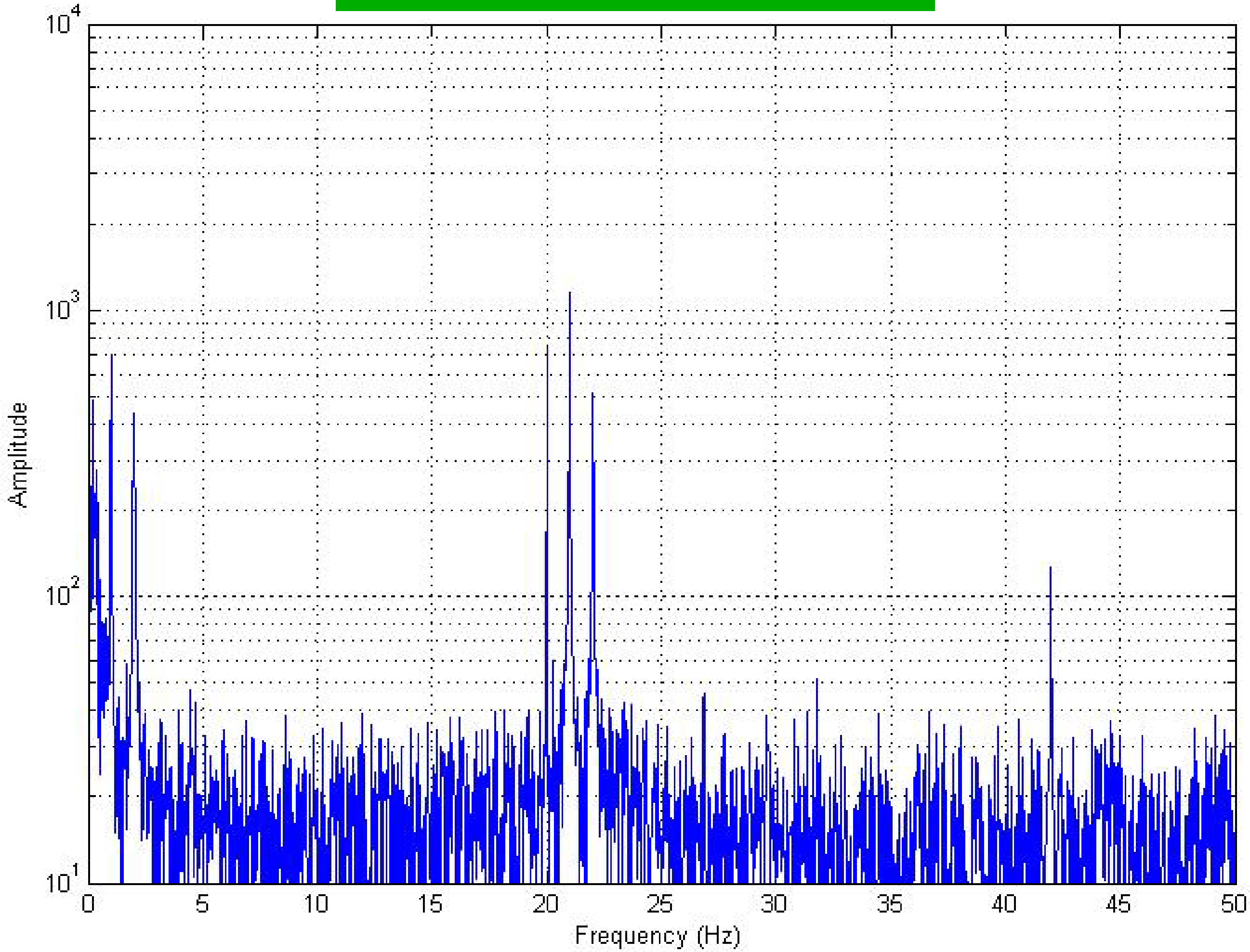
0 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

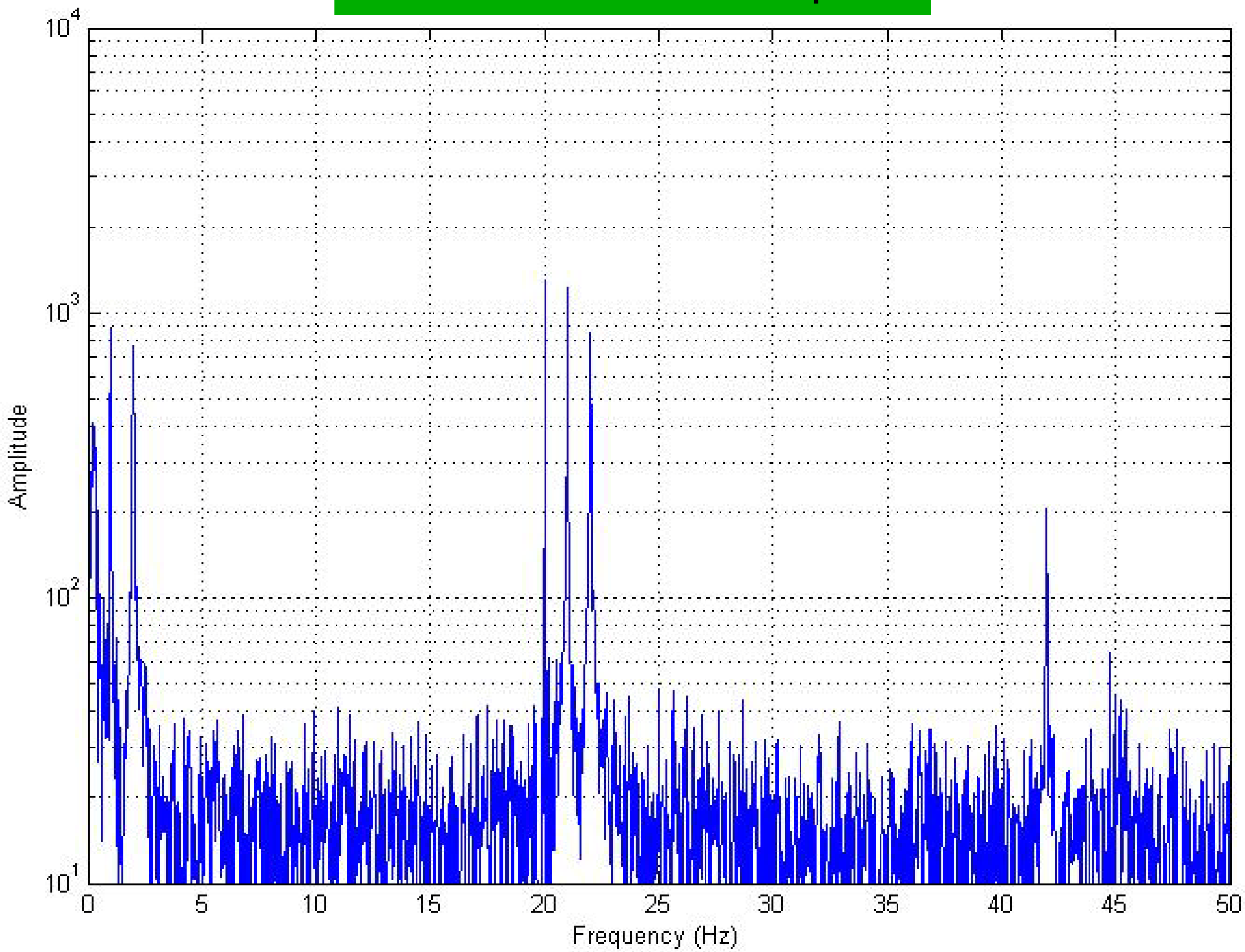
100 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

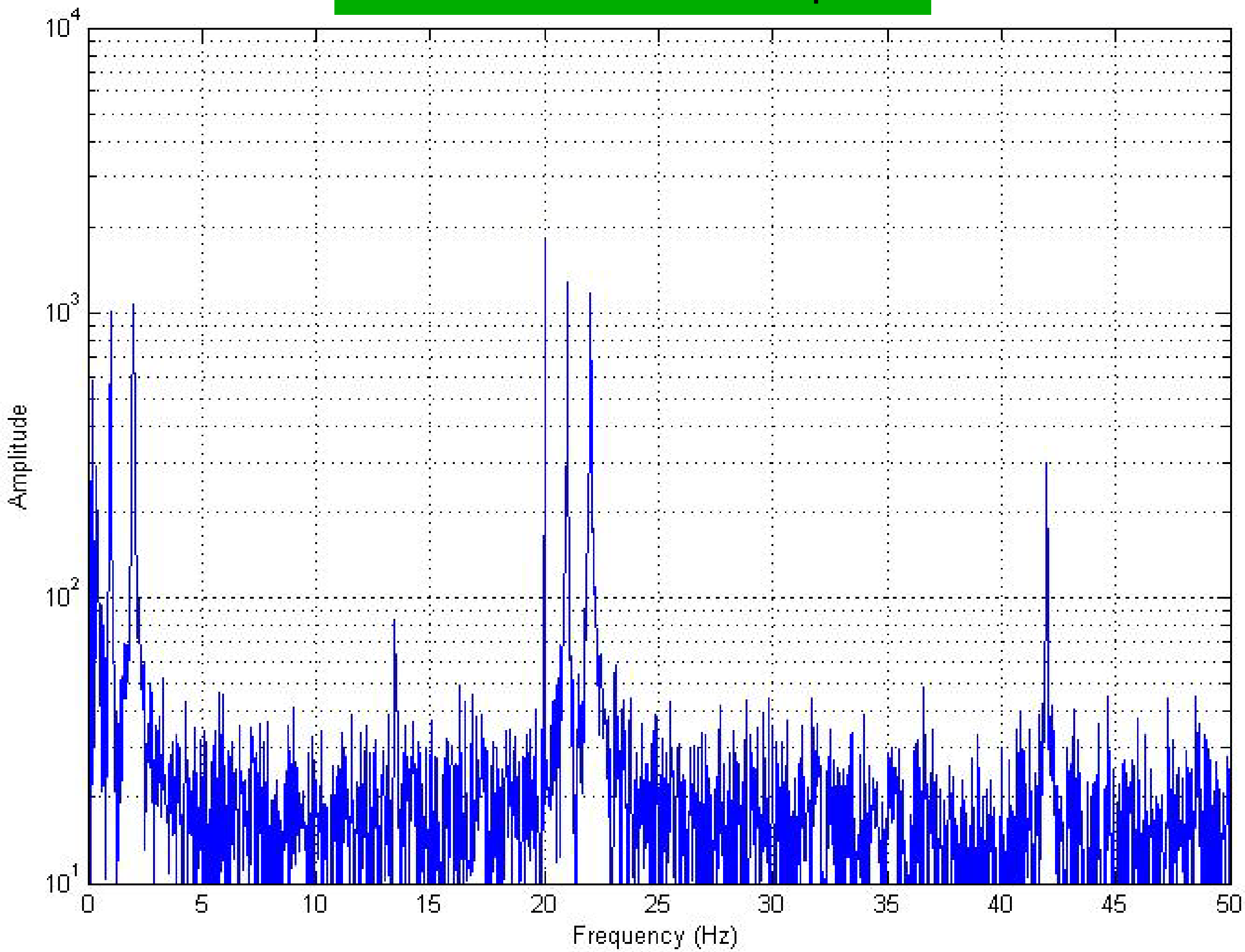
200 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

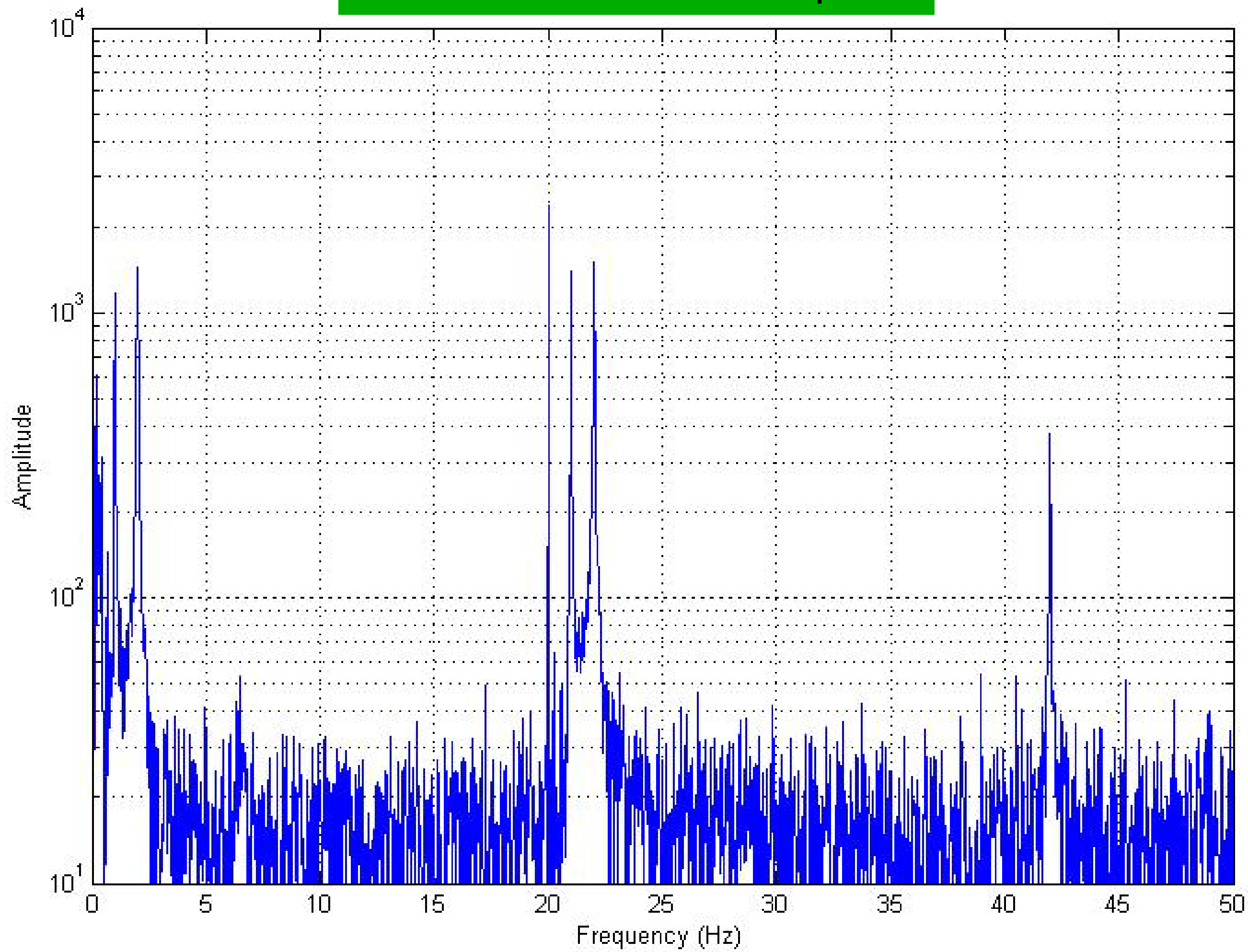
300 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

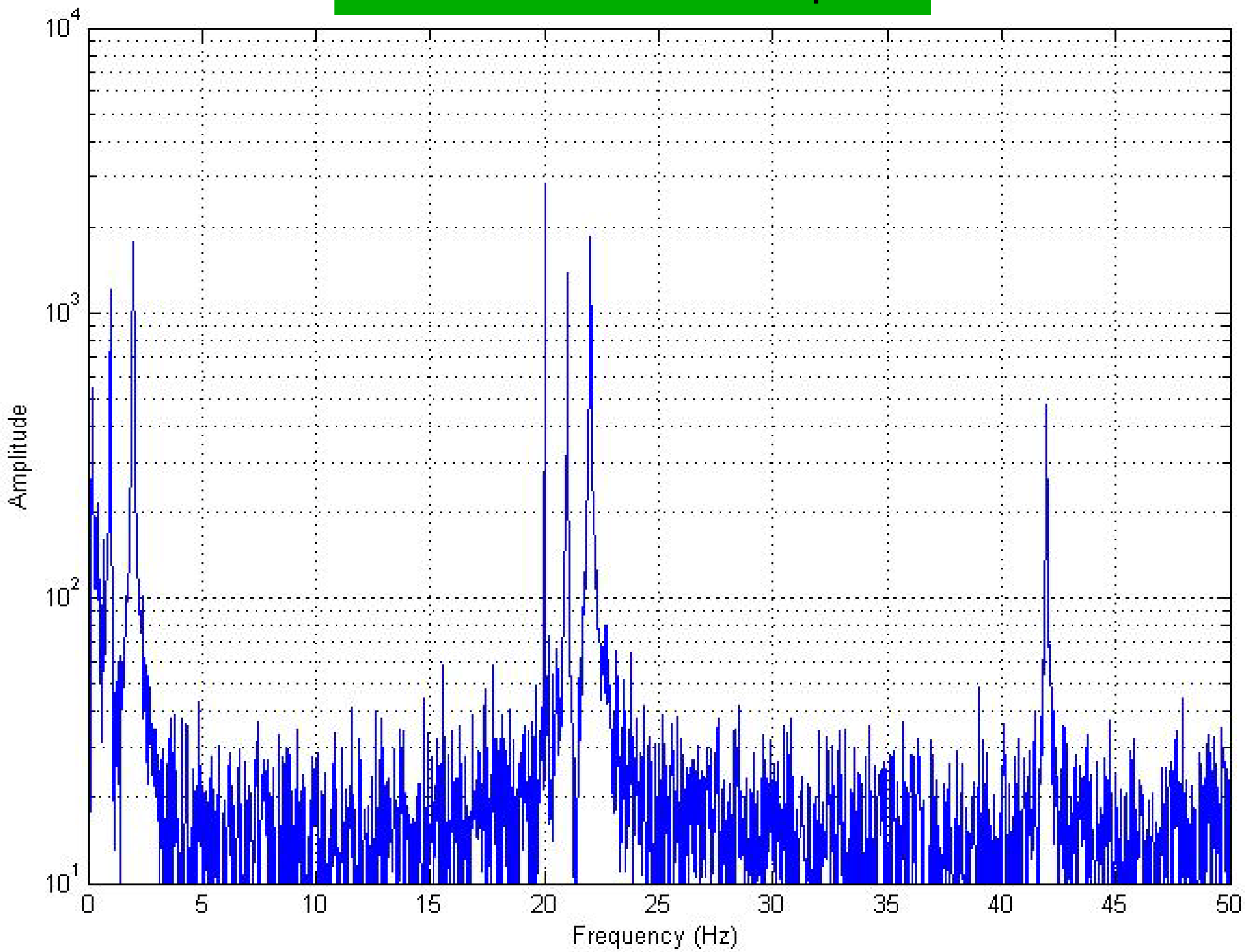
400 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

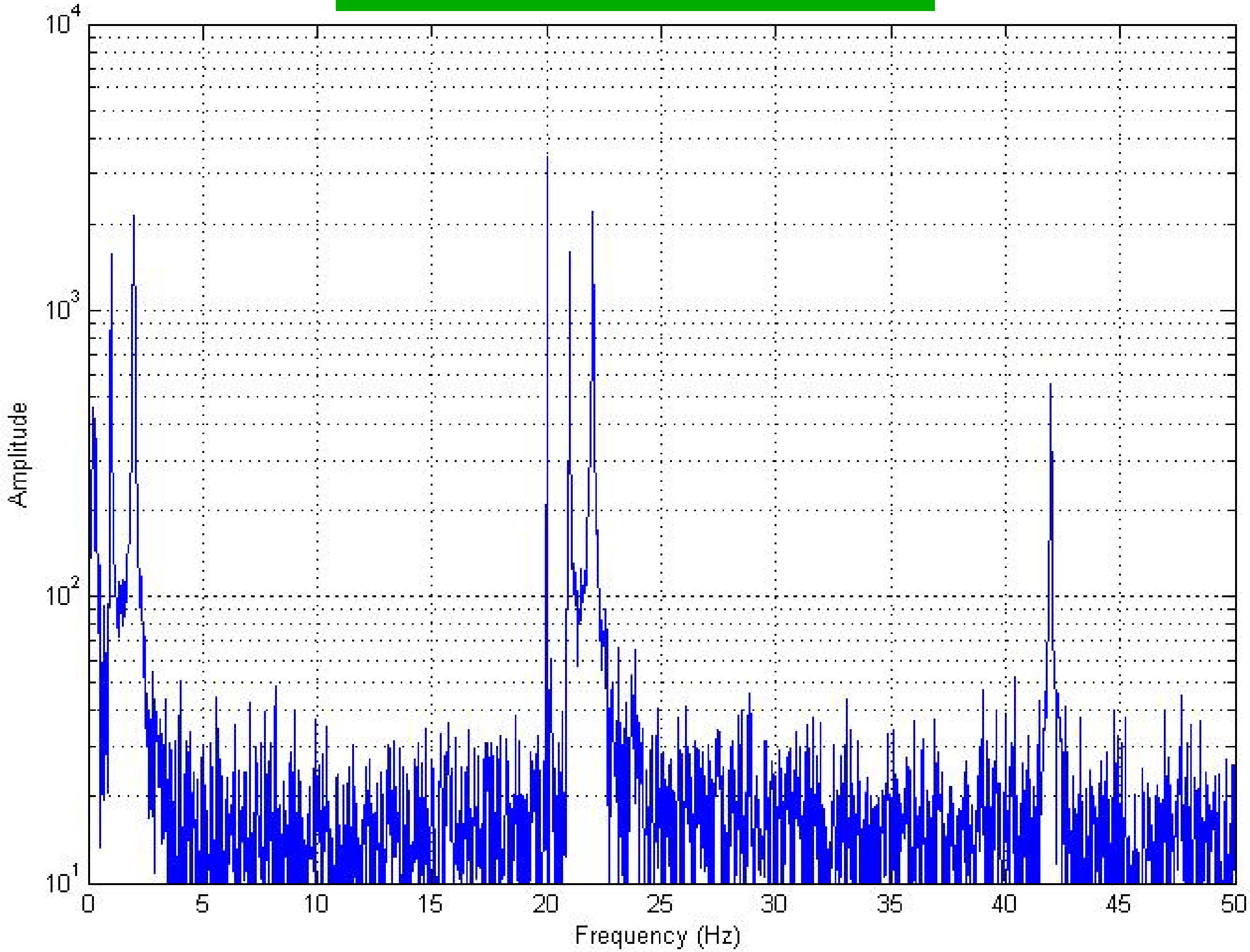
500 G/cm



Spectrum vs. Sextupole Strength

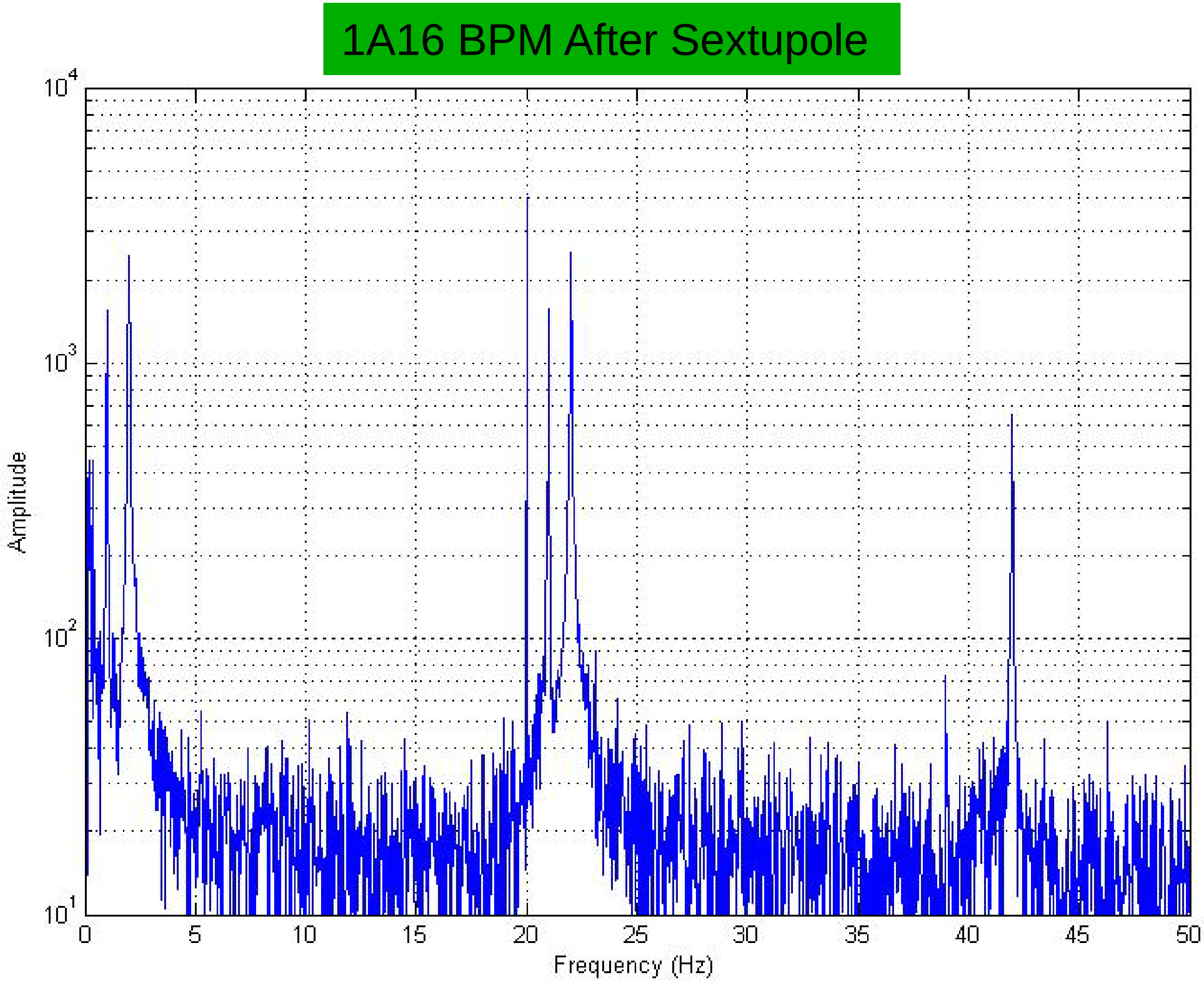
1A16 BPM After Sextupole

600 G/cm



Spectrum vs. Sextupole Strength

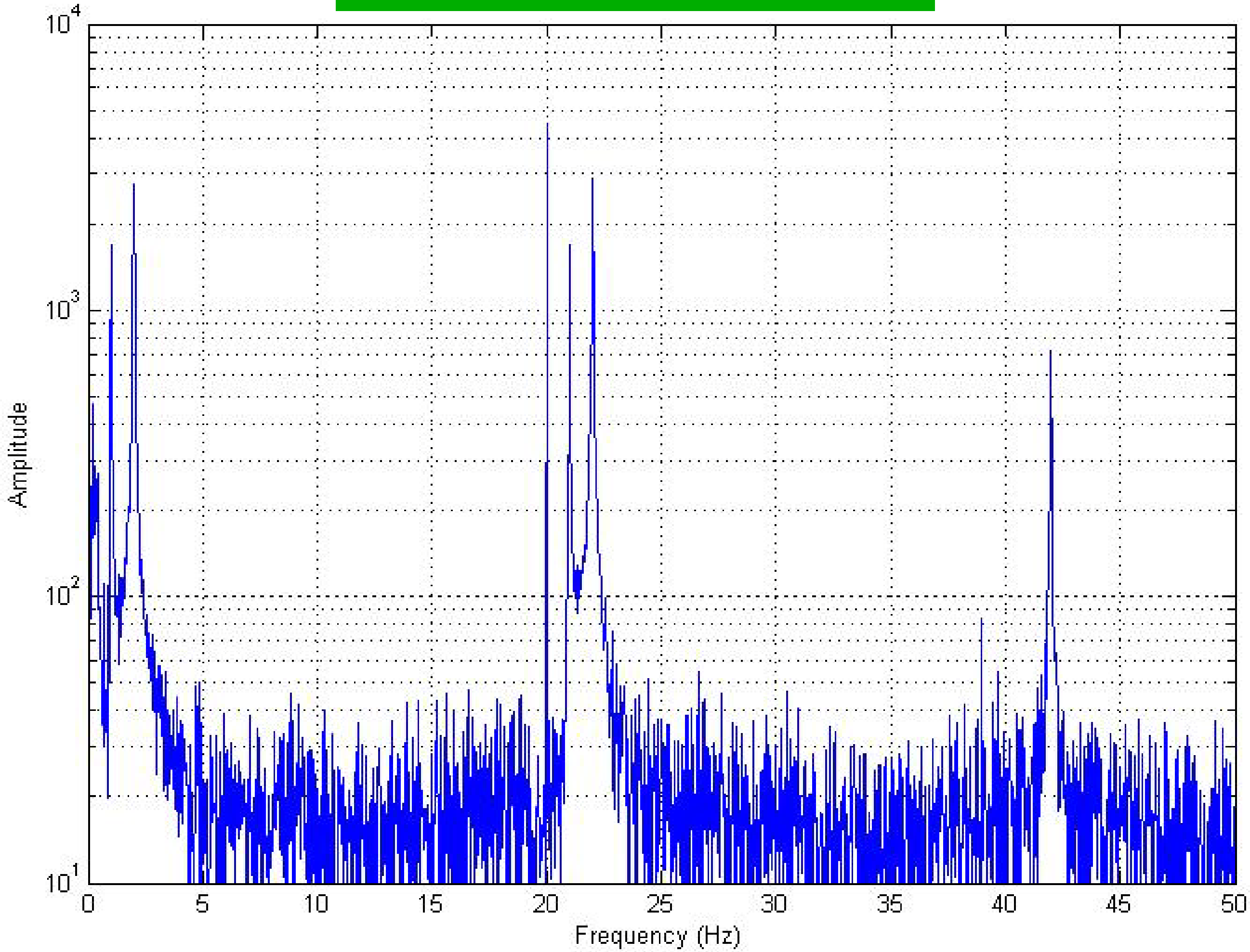
700 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

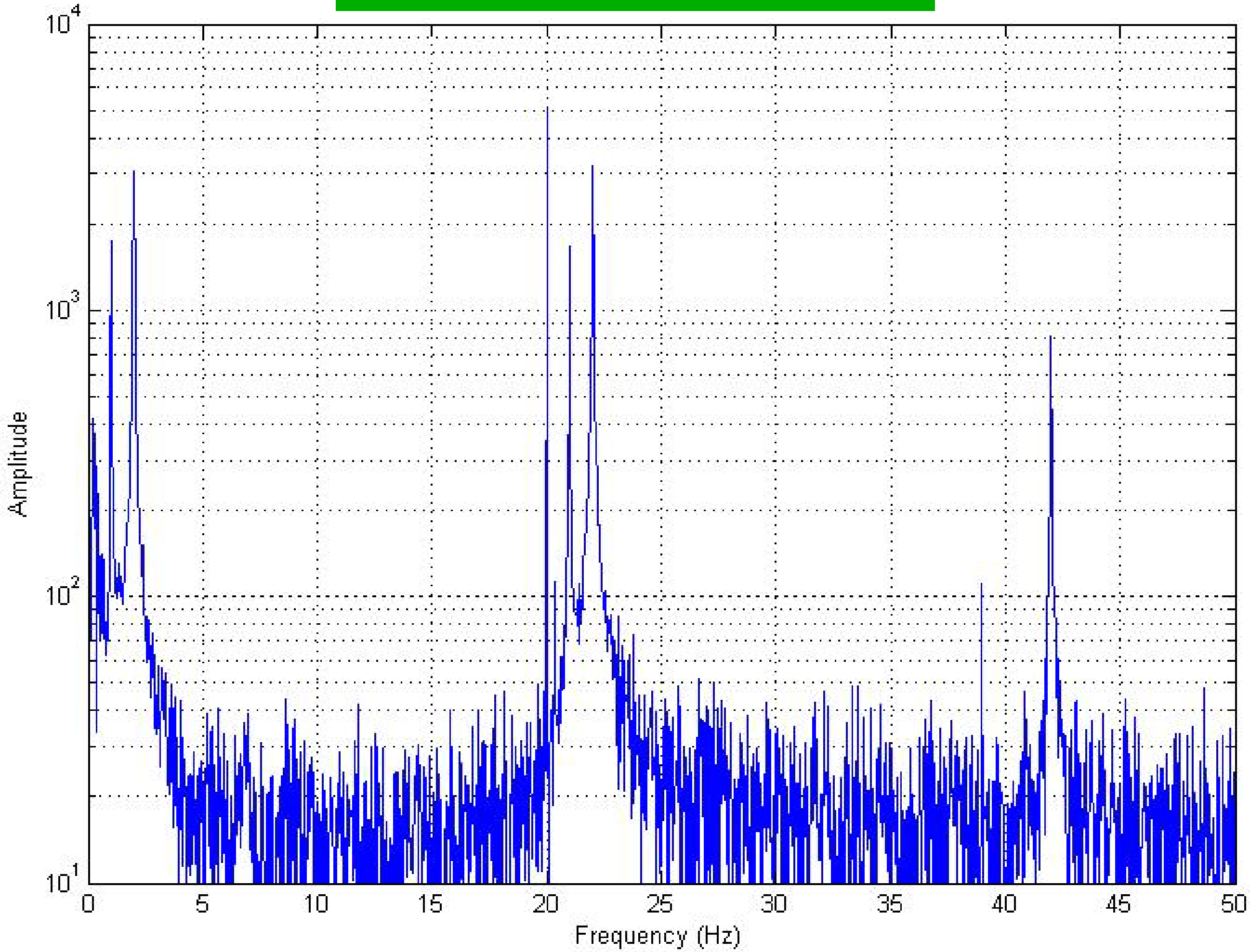
800 G/cm



Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

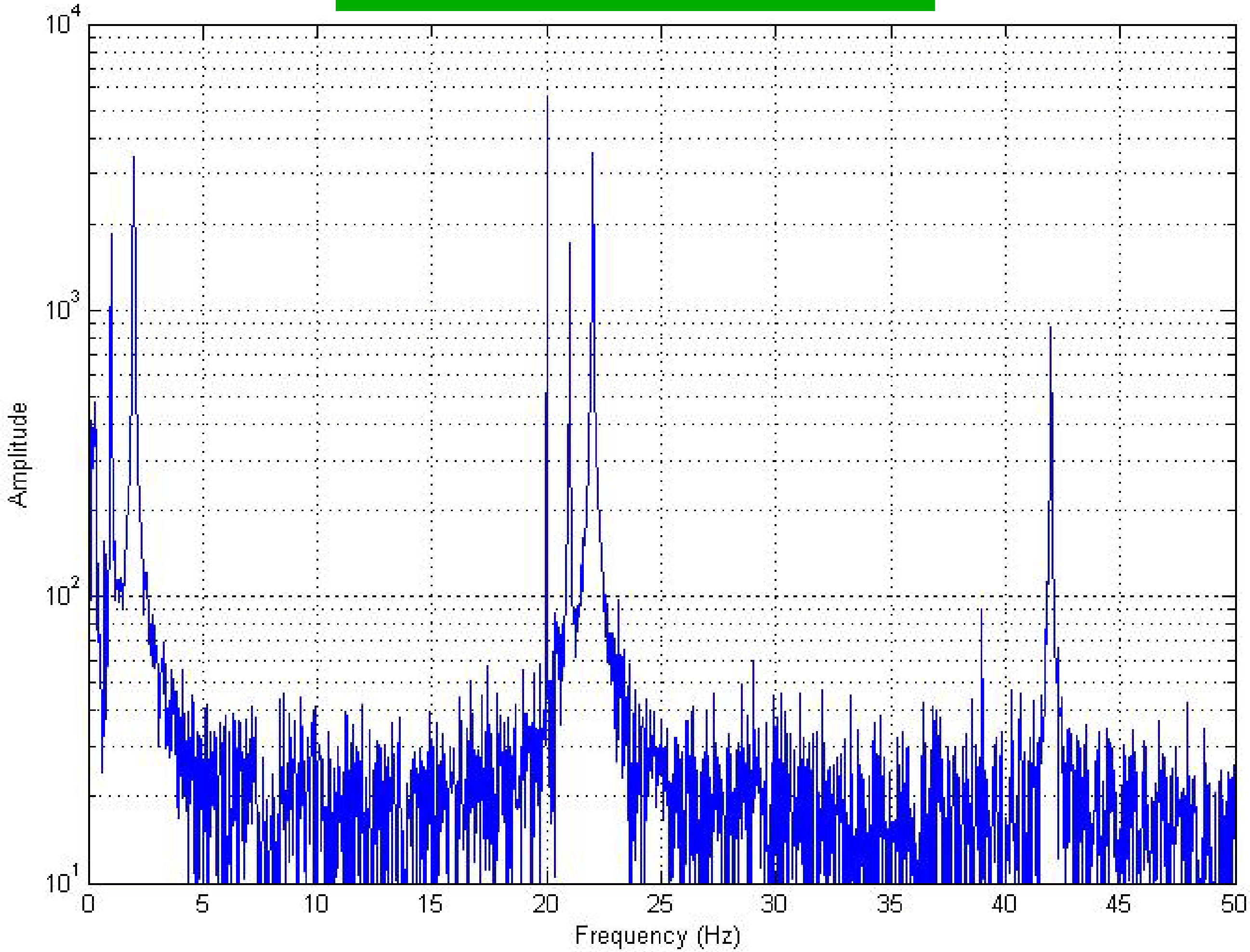
900 G/cm



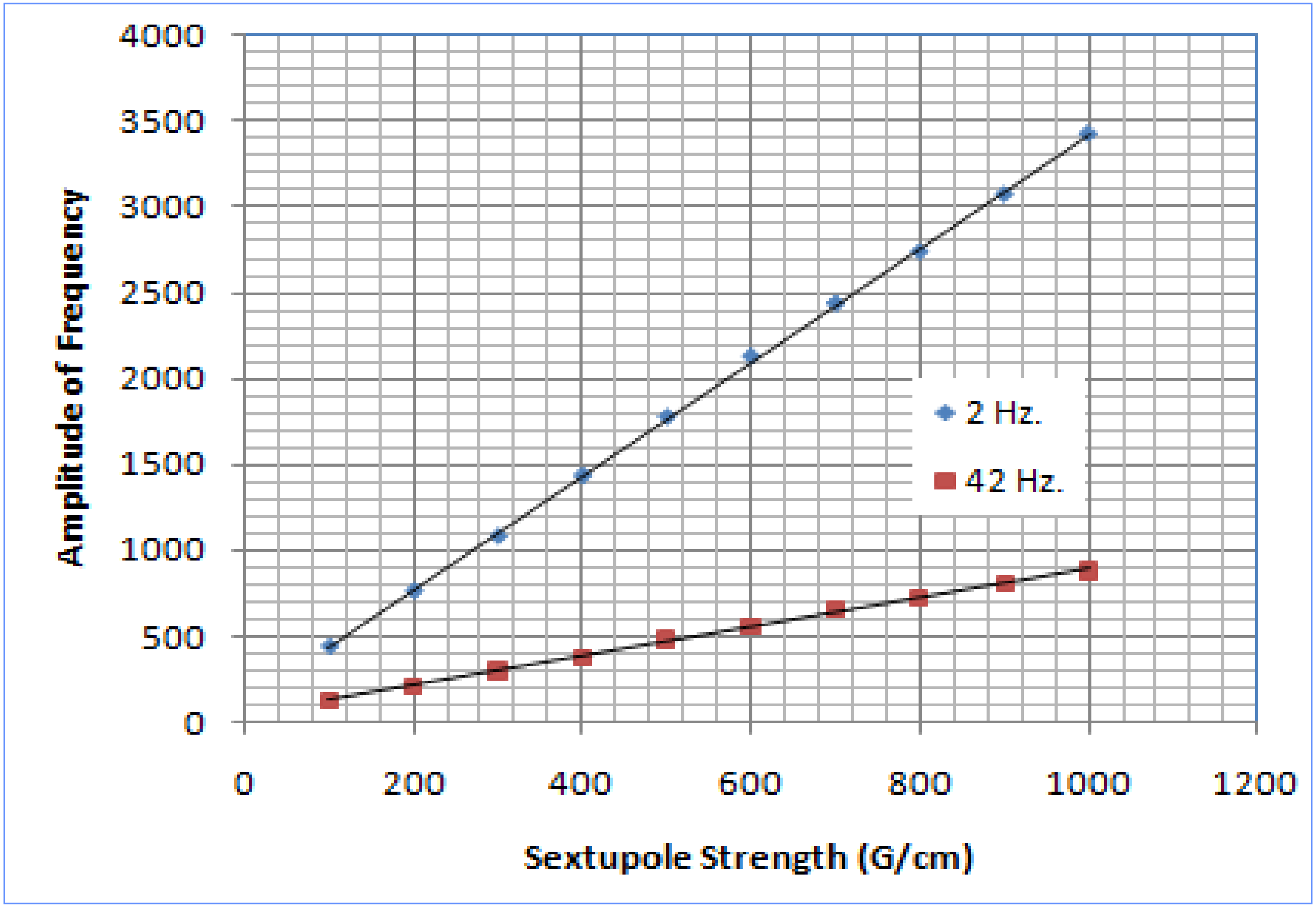
Spectrum vs. Sextupole Strength

1A16 BPM After Sextupole

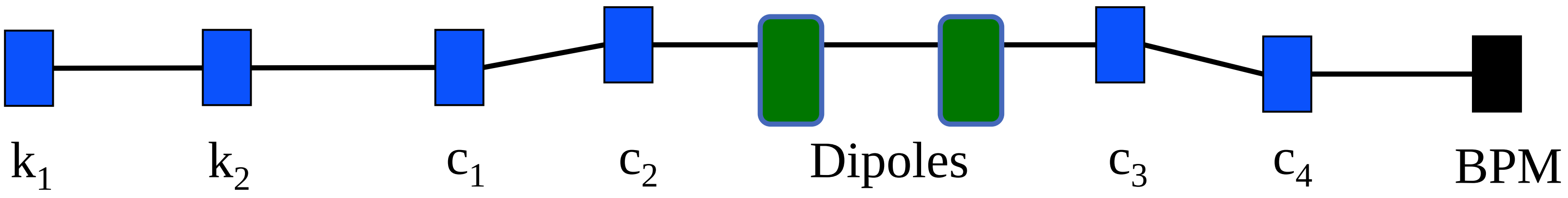
1000 G/cm



Amplitudes vs. Sextupole Strength

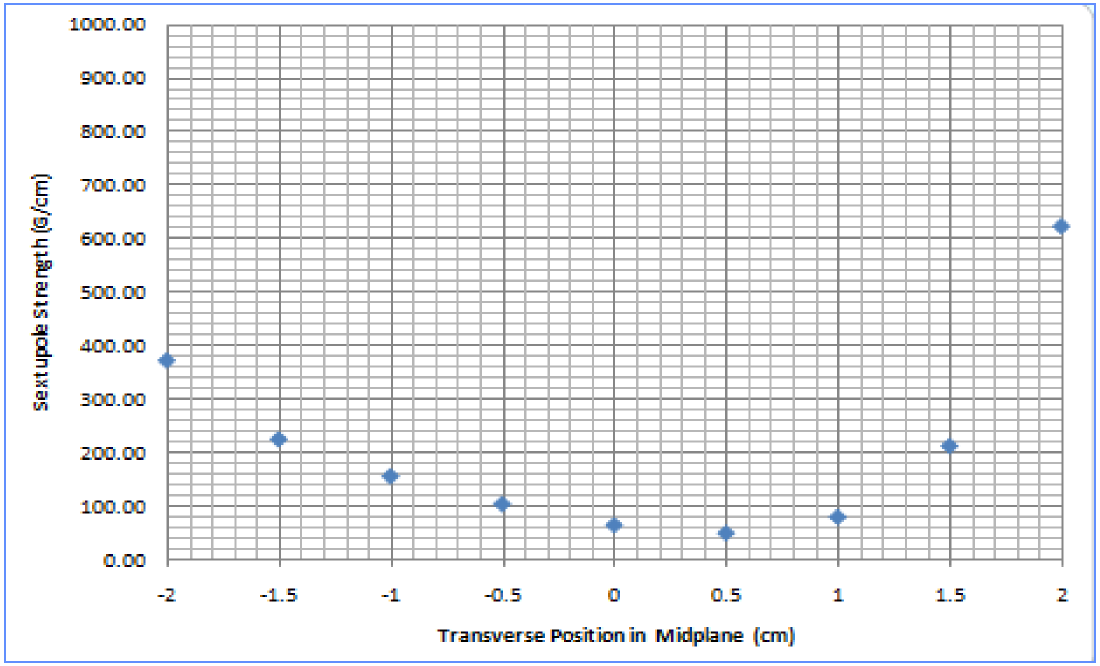


Dipole Measurements



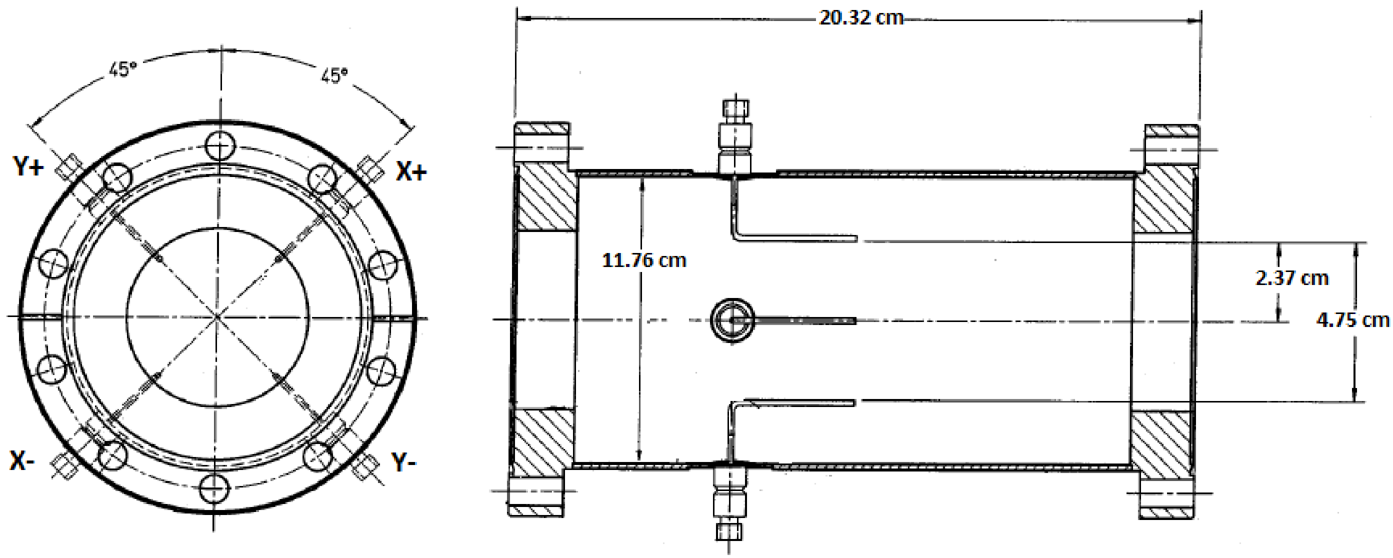
- Local orbit bump to offset the beam within the dipoles
- Measurements made at 1 mm steps in transverse direction from the reference orbit out to 1 cm

ARC1 Dipole Hall Probe Data



- Dipoles also measured at the Magnet Measurement Facility with a Hall Probe stepper
    - 21 tracks through the dipoles at 0.5 mm spacing
    - Measurements made every 2 mm along the tracks to create a grid of points
    - Multipole fields calculated along curved trajectories

Beam Position Monitor Nonlinearity



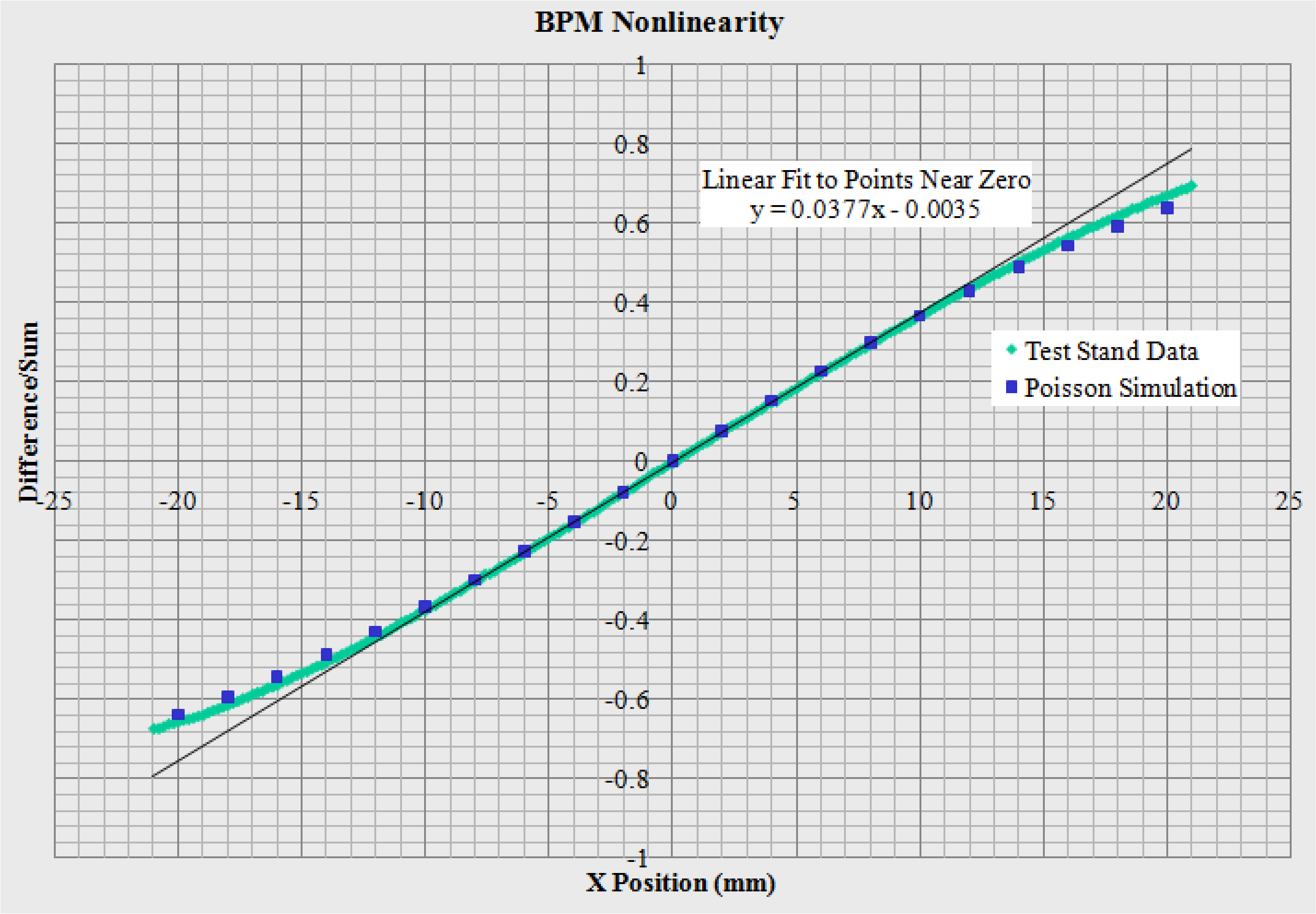
$$X_{rot} = k_x \frac{\left(X^+ - X^+_{off}\right) - \alpha_x \left(X^- - X^-_{off}\right)}{\left(X^+ - X^+_{off}\right) + \alpha_x \left(X^- - X^-_{off}\right)}$$

$$Y_{rot} = k_y \frac{\left(Y^+ - Y^+_{off}\right) - \alpha_y \left(Y^- - Y^-_{off}\right)}{\left(Y^+ - Y^+_{off}\right) + \alpha_y \left(Y^- - Y^-_{off}\right)}$$

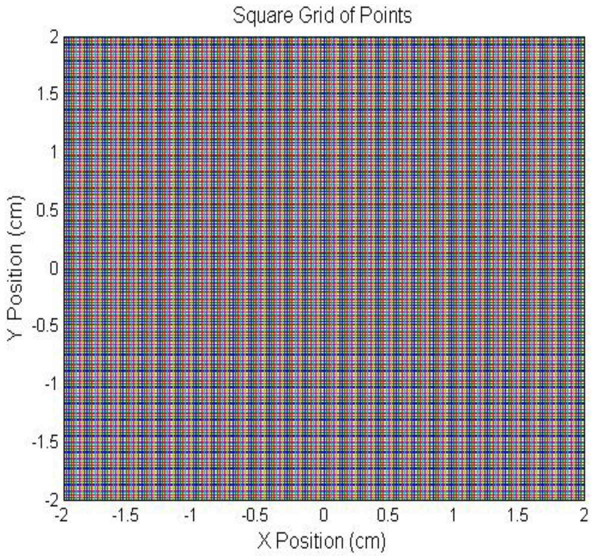
$$X = \frac{1}{\sqrt{2}}\left(X_{ROT} - Y_{ROT}\right)$$

$$Y = \frac{1}{\sqrt{2}}\left(X_{ROT} + Y_{ROT}\right)$$

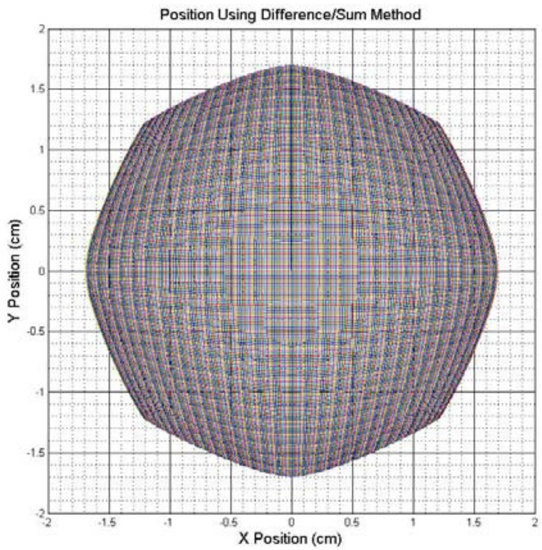
Beam Position Monitor Nonlinearity



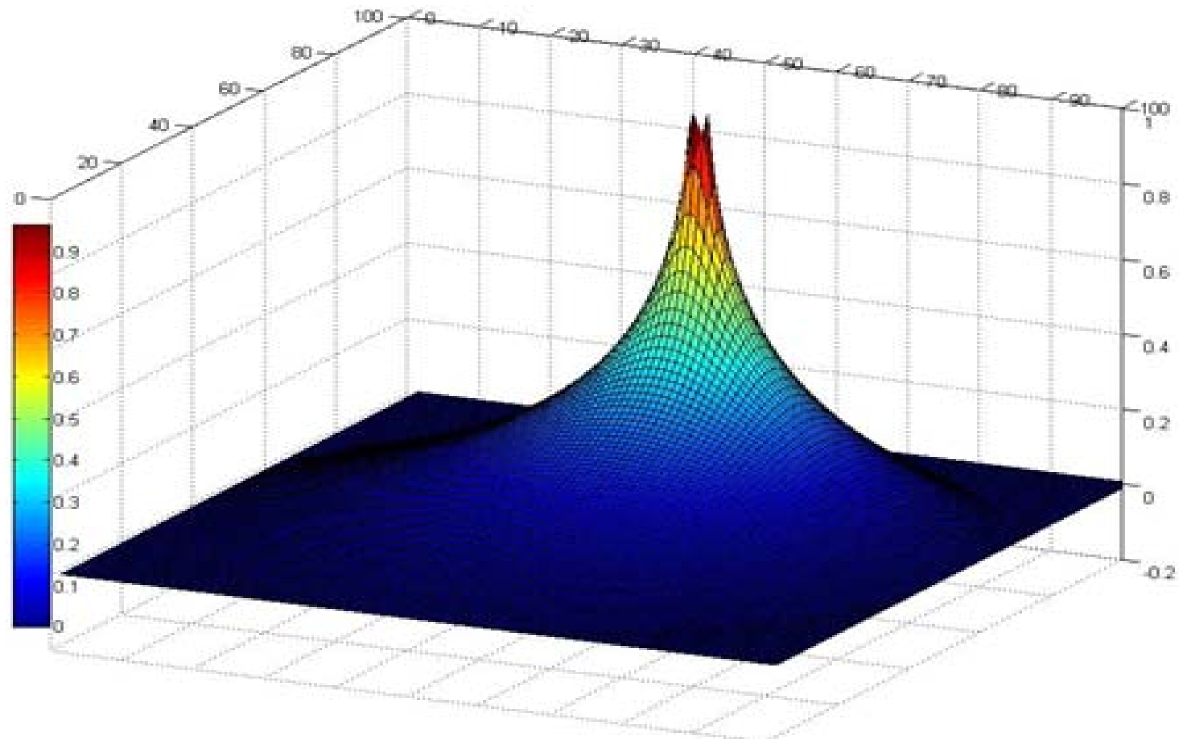
Beam Position Monitor Nonlinearity



Difference/Sum Method

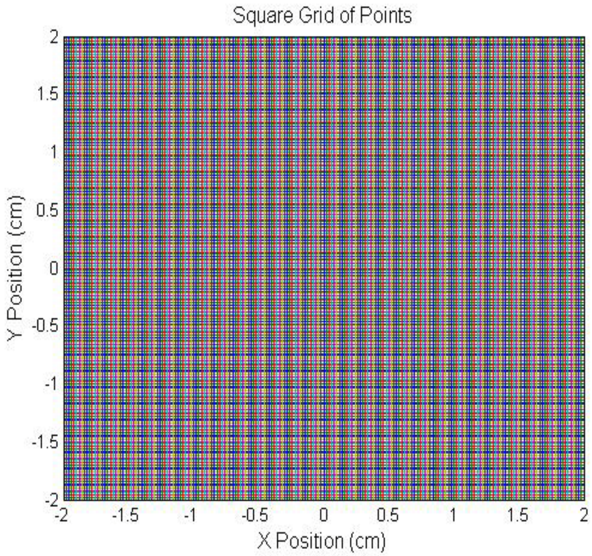


Beam Position Monitor Nonlinearity

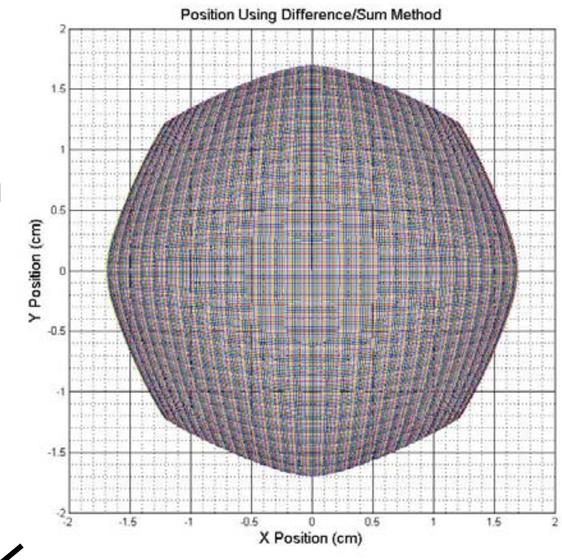


Poisson potential map of a single wire used to calculate coefficients for a two-dimensional polynomial correction of BPM data

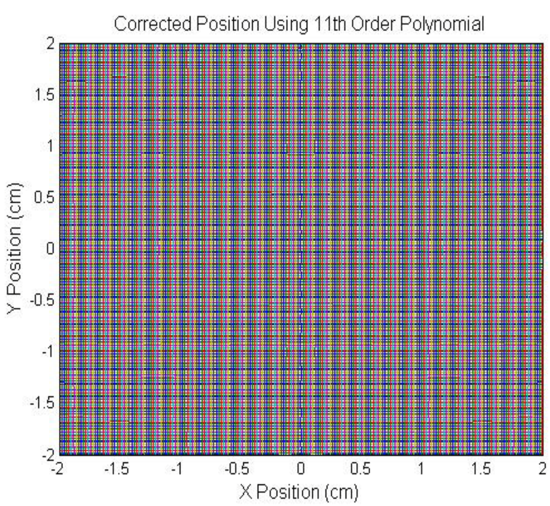
Beam Position Monitor Nonlinearity



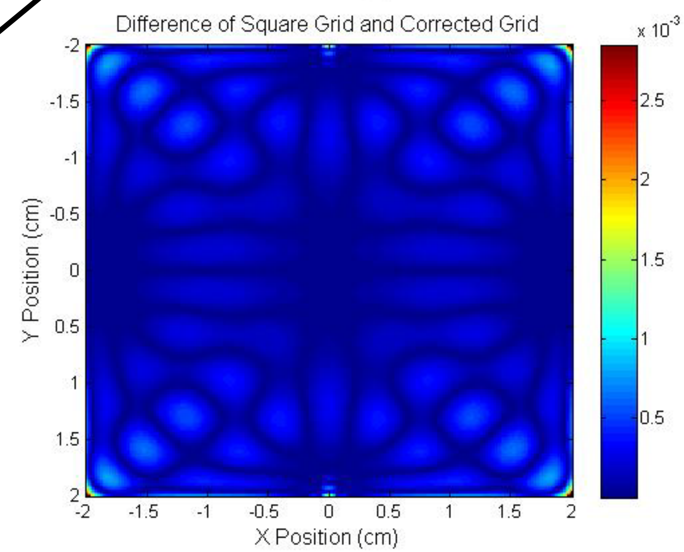
Difference/Sum Method



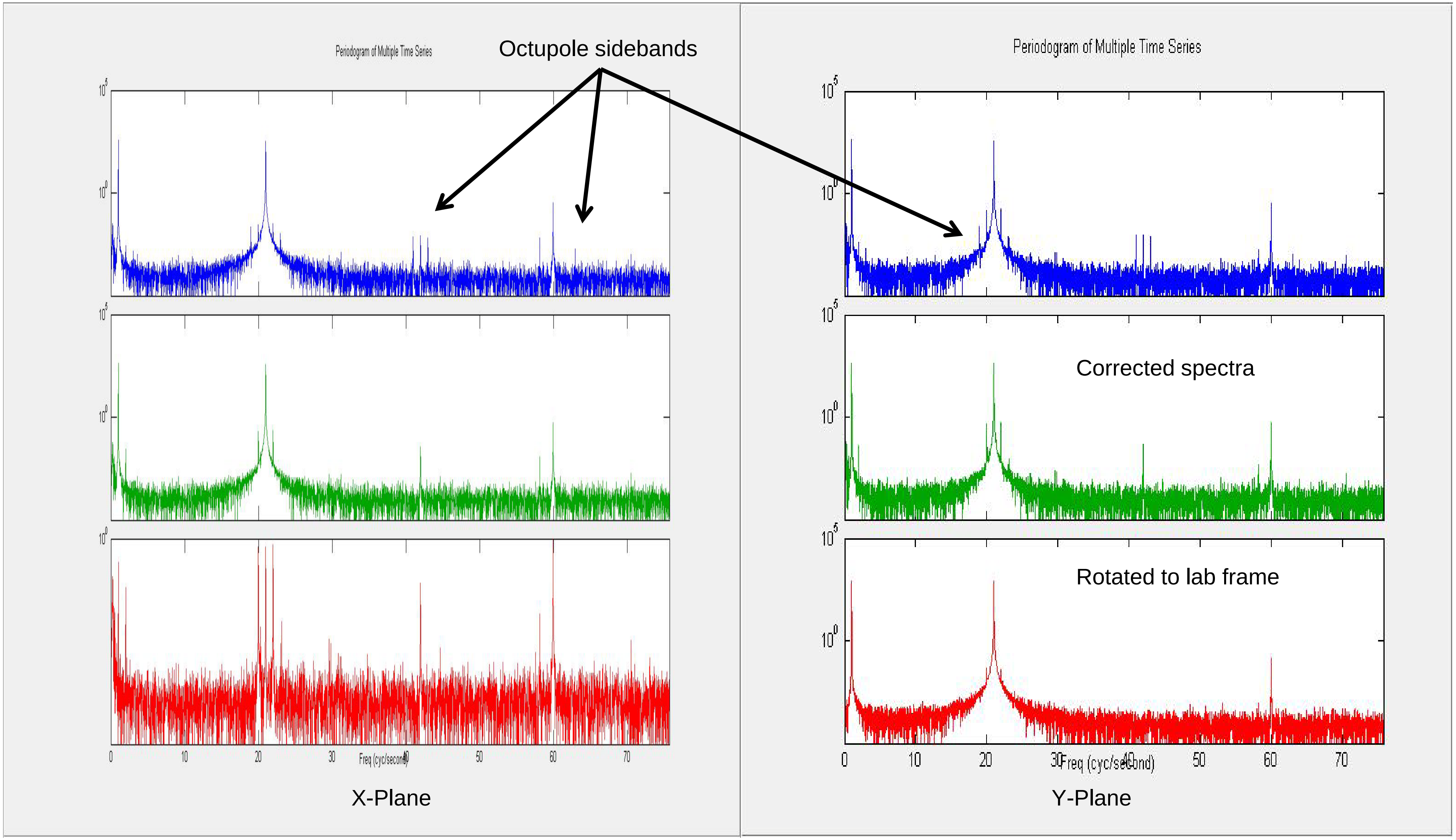
11th Order Polynomial



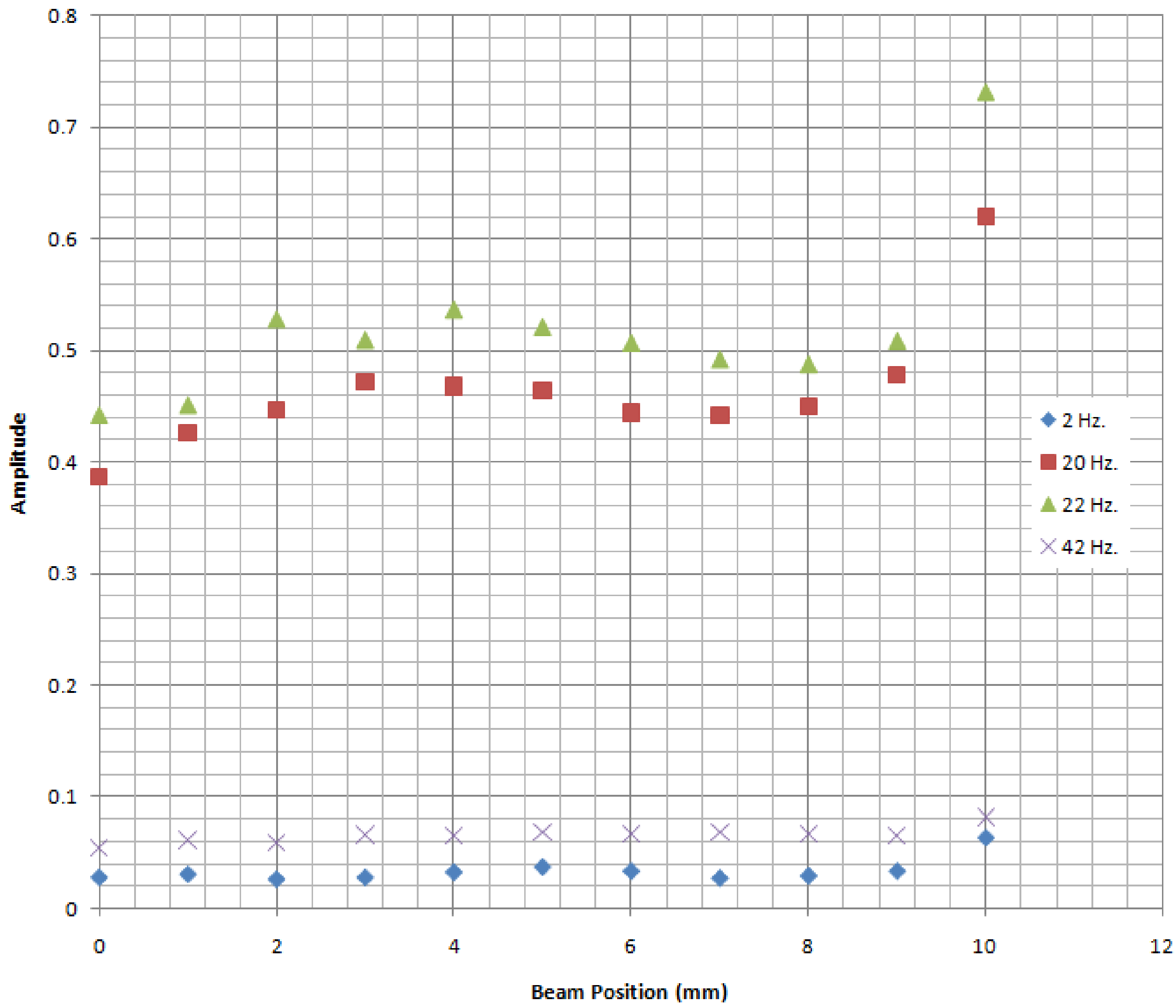
Correction to 100 microns



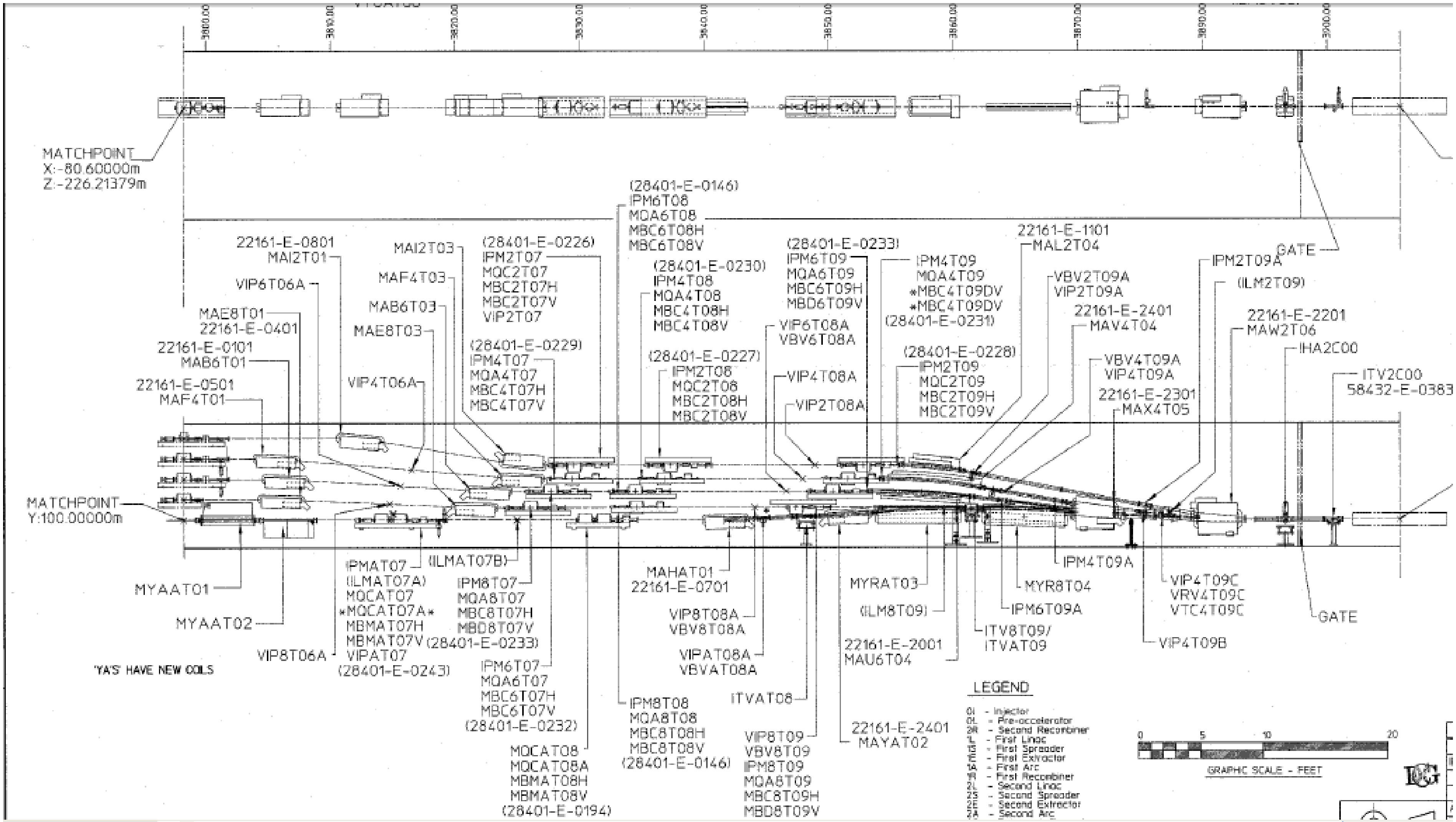
Spectra Correction



Dipole Measurements



BSY Recombiner Elevation View



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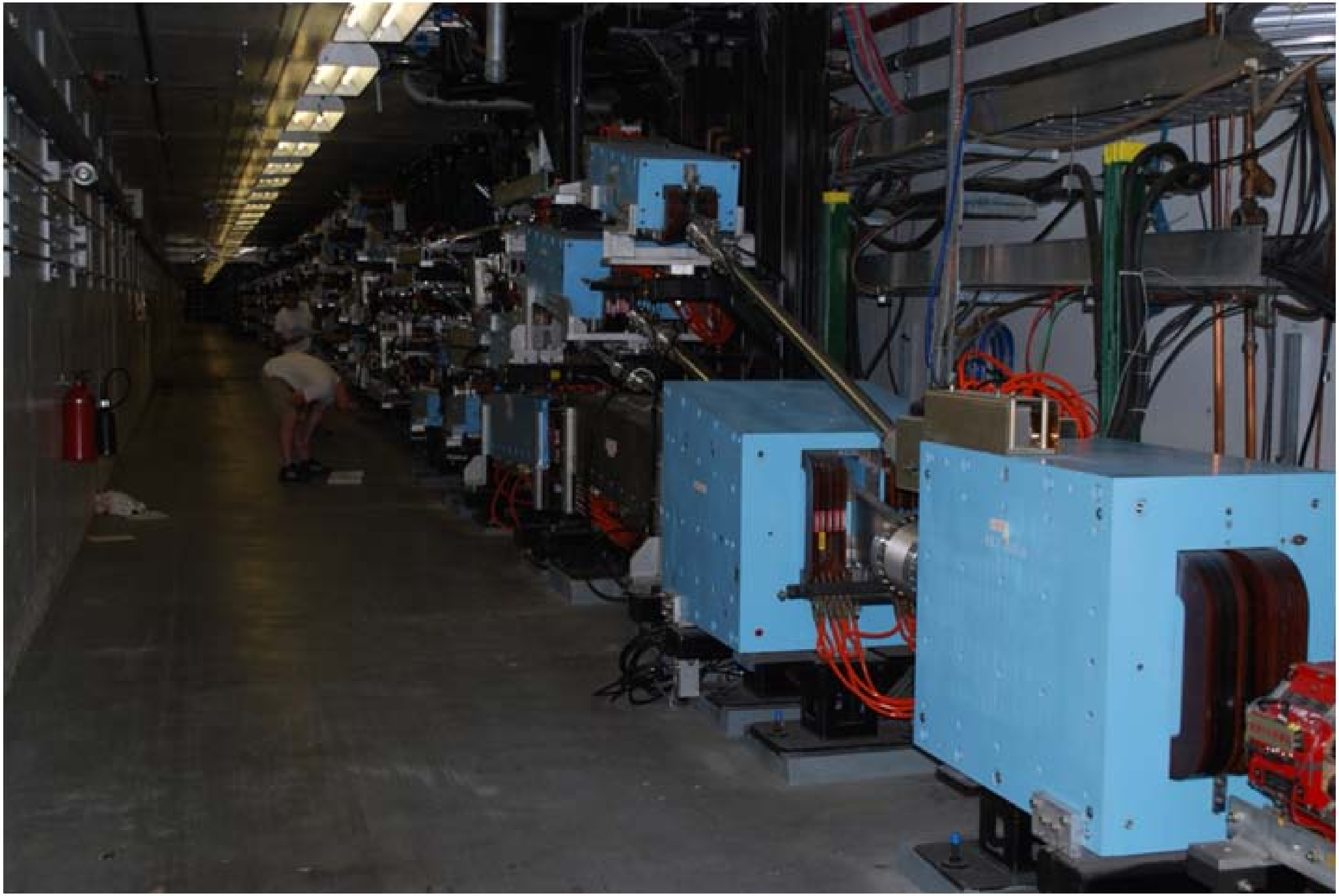
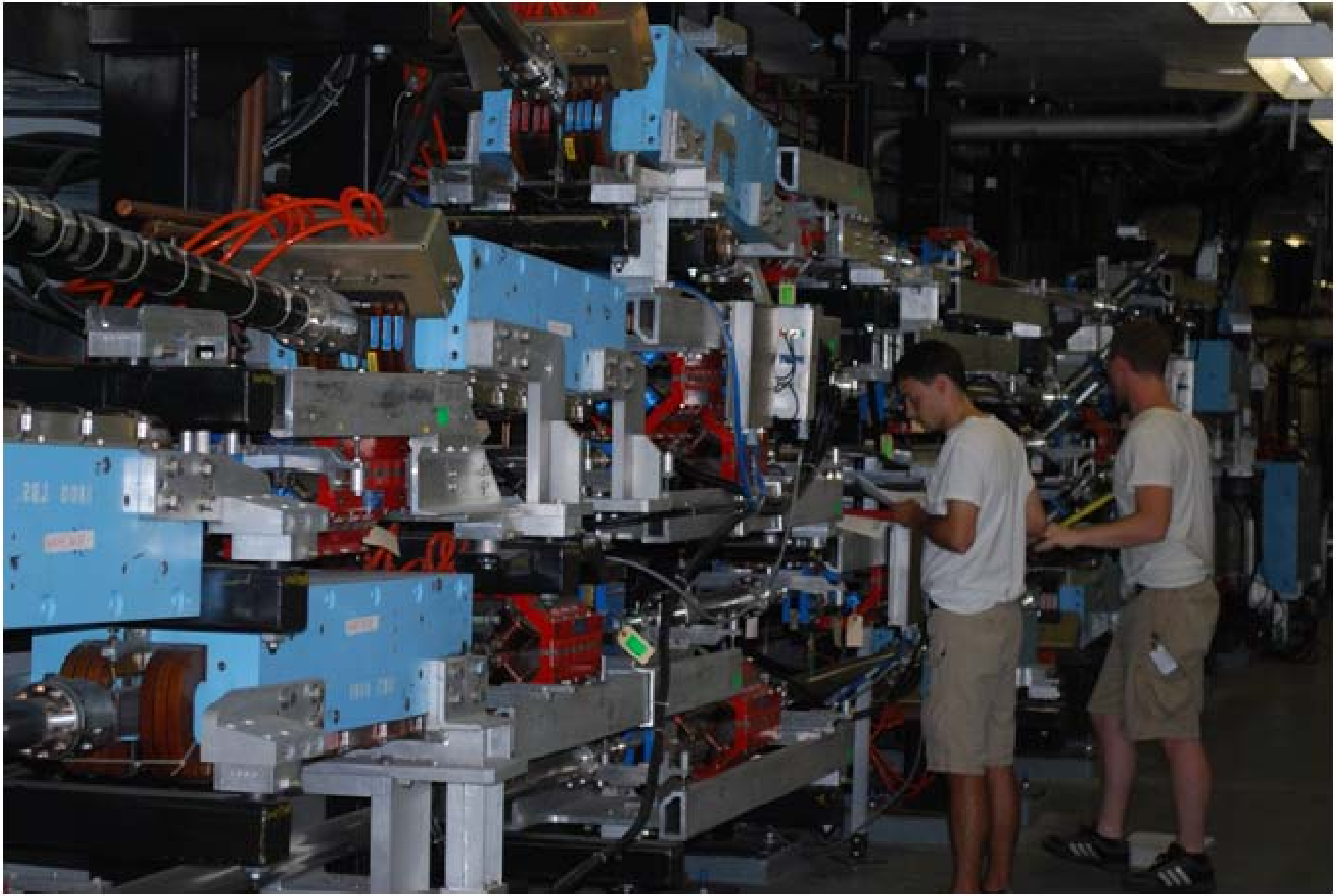
Recombiner Beamline



Recombiner Beamline



Summary

- Dual AC dipole magnets were used to measure nonlinear fields
- Sextupole measurements were made to develop a calibration standard
- Measurements of dipole nonlinearity versus position within the dipole were perfromed
- Will be ready to characterize new beamlines as the 12 GeV machine is commissioned

Thanks!