The Strong-Focusing VISA Undulator for SASE FEL*

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Institutions Participating in the VISA Collaboration:

Brookhaven National Laboratory
Lawrence Berkeley Natioanl Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Stanford Linear Accelerator Center
University of California Los Angeles

Related papers:

R. Carr *et al.,* "The VISA FEL Undulator Design", FEL'98.

H-D Nuhn & P. Emma, "FEL Trajectory Analysis for the VISA Experiment", FEL98.

G. Rakowsky *et al.,* "Measurement and Optimization of the VISA FEL Undulator" PAC'99, Paper #THA35.

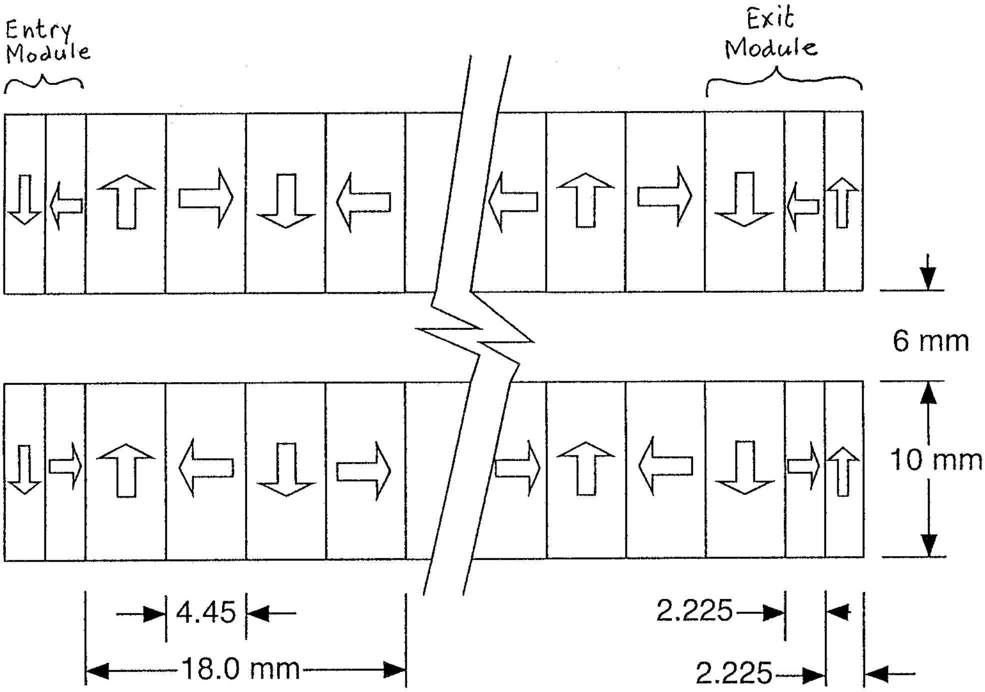
M Libkind *et al.,* "Mechanical Design of the VISA Undulator", PAC'99, #WEP93.

R. Ruland *et al.,* "Alignment of the VISA Undulator", PAC'99, Paper #TUA134.

Abstract :

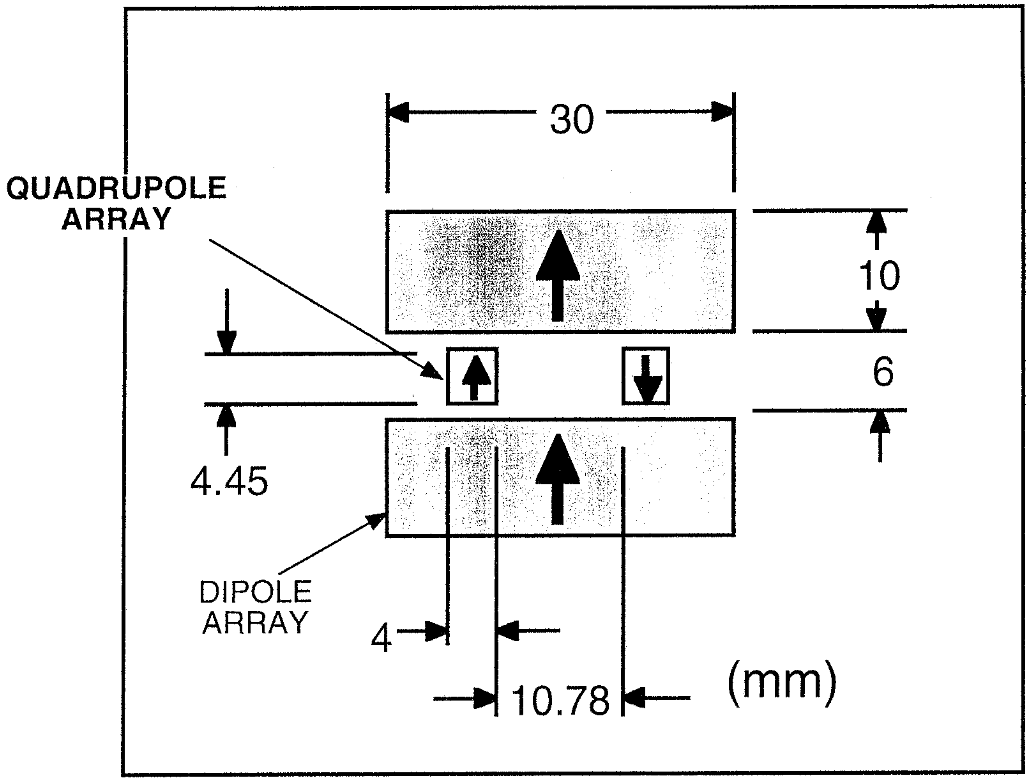
The Visible-Infrared SASE Amplifier (VISA) undulator is an in-vacuum, 4-m long, pure permanent magnet device, with a novel, strong focusing, permanent magnet FODO array included within the fixed, 6-mm undulator gap. The undulator magnet is constructed in 99-cm long segments, joined into a continuous structure. To attain maximum SASE gain requires establishing overlap of the 72 MeV electron beam and the 800 nm photon beams to within 50 μm rms. This imposes challenging tolerances on mechanical fabrication and magnetic field quality, and necessitates use of laser straightness interferometry for calibration and alignment of the magnetic axes of the undulator segments. This talk will describe the magnetic design, magnet sorting, trajectory measurement and correction, fiducialization and alignment using straightness interferometry. Future prospects and limitations will be discussed.

Pure Permanent-Magnet Halbach Structure with Displacement-Free Terminations



Dipole Array

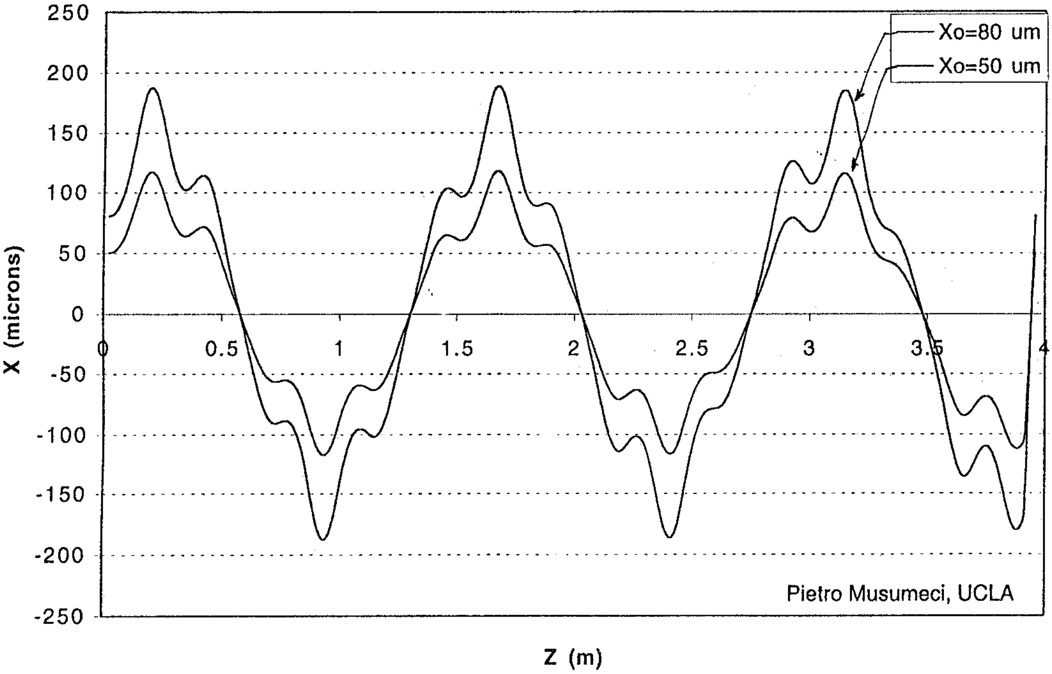
Type:	Pure PM Halbach, 4 blocks/period
Period:	18 mm
Gap:	6 mm, fixed
Peak Field	0.75 Tesla
Magnet Material:	NdFeB
Remanence:	1.25 Tesla
Intrinsic Coercivity:	>20 kOe
Block Dimensions:	30 w X 10 h X 4.45 t, mm
No. periods/section:	55
No. sections:	4 (ultimately 6)
Section spacing:	None
Total length:	4 m (6 m)
Total No. periods:	220 (330)
Terminations:	Non-steering, “zero-offset”



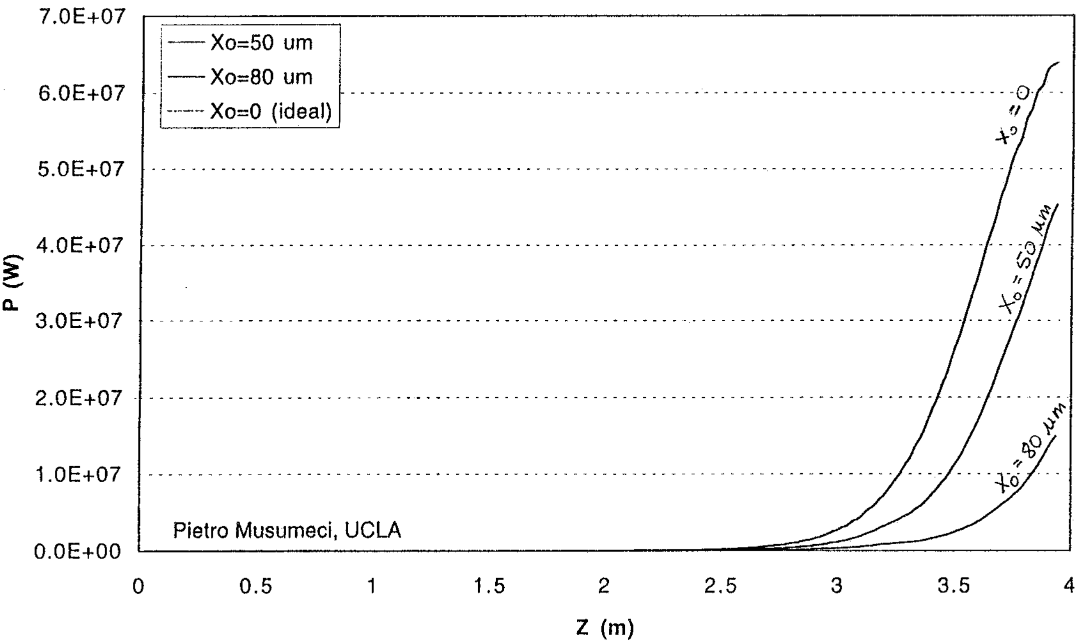
Quadrupole Array

Type:	**Pure Permanent Magnet**
Structure:	**2-block (see Figure 1.)**
Location:	**Within dipole gap**
Peak Gradient	**33 T/m**
Material:	**NdFeB**
Remanence:	**1.25 Tesla**
Intrinsic Coercivity:	**>20 kOe**
Block Dimensions:	**4 w X 4.45 h X 30 lg., mm**
Horiz. separation:	**10.78 mm**
Length of F, D modules:	**10 cm (9 cm effective)**
FODO period:	**24.75 cm**
No. periods/section:	**4**
Total FODO periods:	**16 (24)**

GENESIS Simulation of VISA Trajectories
With Launch Offset Errors



GENESIS Simulation of VISA Power
With Launch Offset Errors



ERROR BUDGET

Simulations show that SASE gain degrades when trajectory wander exceeds 50 μm rms. (The wiggle amplitude *a*. = 25 μm at 72 MeV.)

Error source	Budget (μm rms)		Achieved/ Probable (μm)
1) Magnetic centerline determination	**20**		
a) Trajectory straightness		14	**9**
b) Quadrupole axis location		14	**7**
2) Transfer onto Fiducials	**23**		
a) Wire finder calibration		10	**5**
b) Wire C/L determination		10	**5**
c) Measurement of fiducial offsets		18	**10**
3) Reference Undulators to Ref.Laser	**29**		
a) Laser finder calibration		20	**10**
b) Ref.Laser C/L determination		20	**10**
4) Undulator Positioning	**28**		**10**
TOTAL ERROR (quadrature sum):	**51 μm rms**		**24 μm rms**

ACHIEVING TRAJECTORY STRAIGHTNESS

DIPOLE ARRAY:

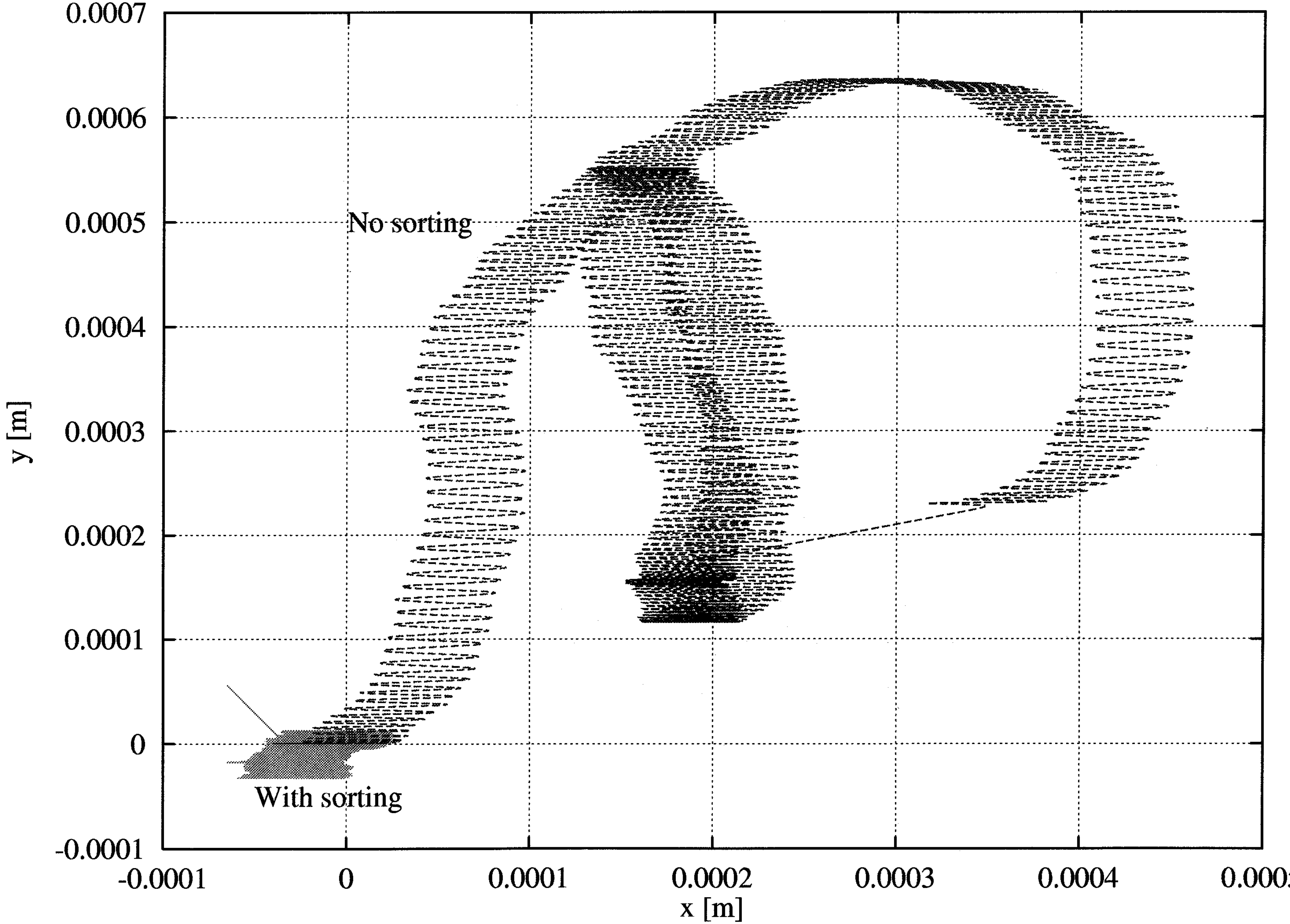
1) **Ordered magnet blocks with ±1.5%, ±1.5° magnetization tolerances.**
2) **Measured magnetic moments of each block in Helmholtz coil.**
3) **Sorted magnets using "Threshold Acceptance" algorithm to minimize rms field error. (Field error reduced to 1/14-th of random case.)**
4) **Installed magnets on ground surfaces with precision positioning.**

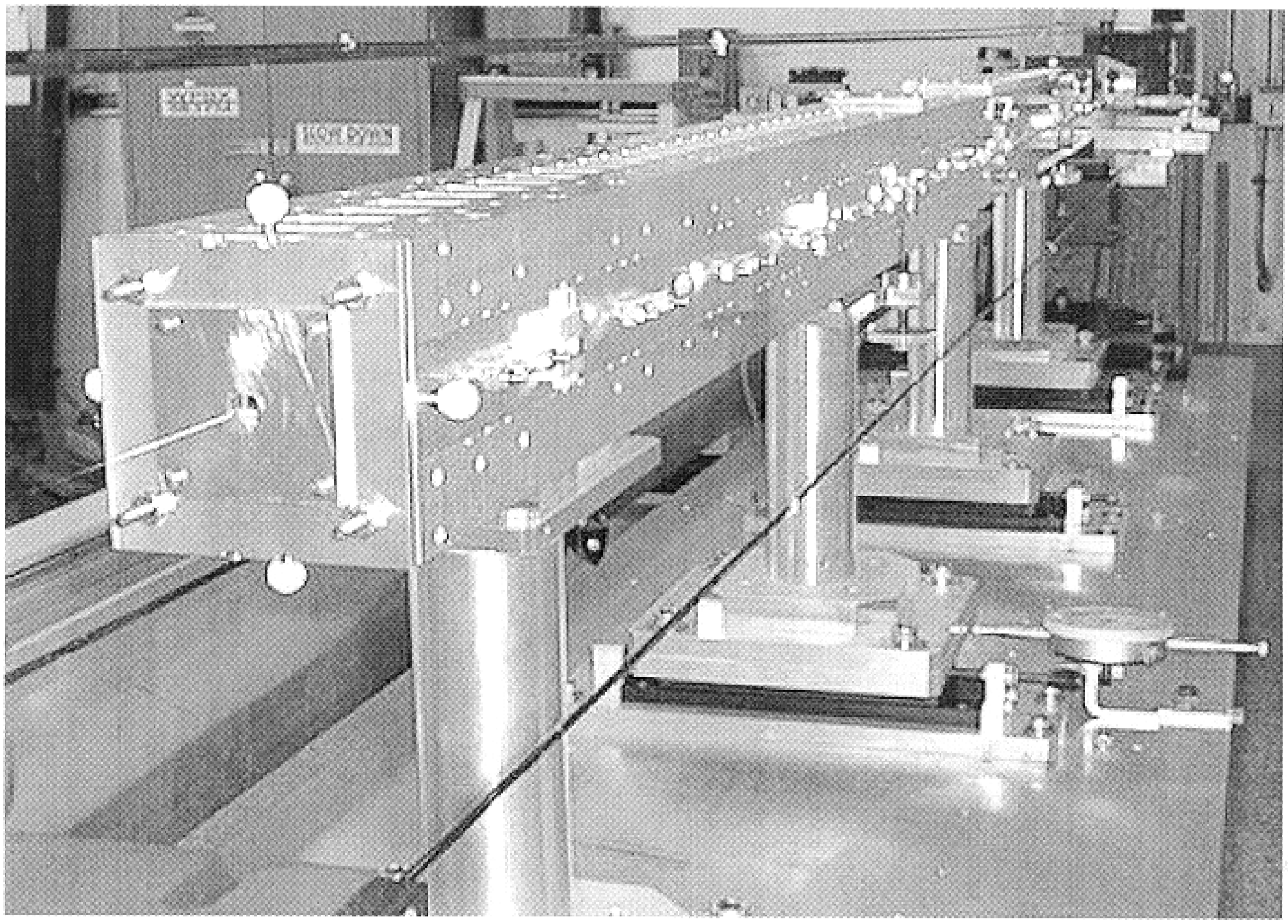
QUADRUPOLE ARRAY:

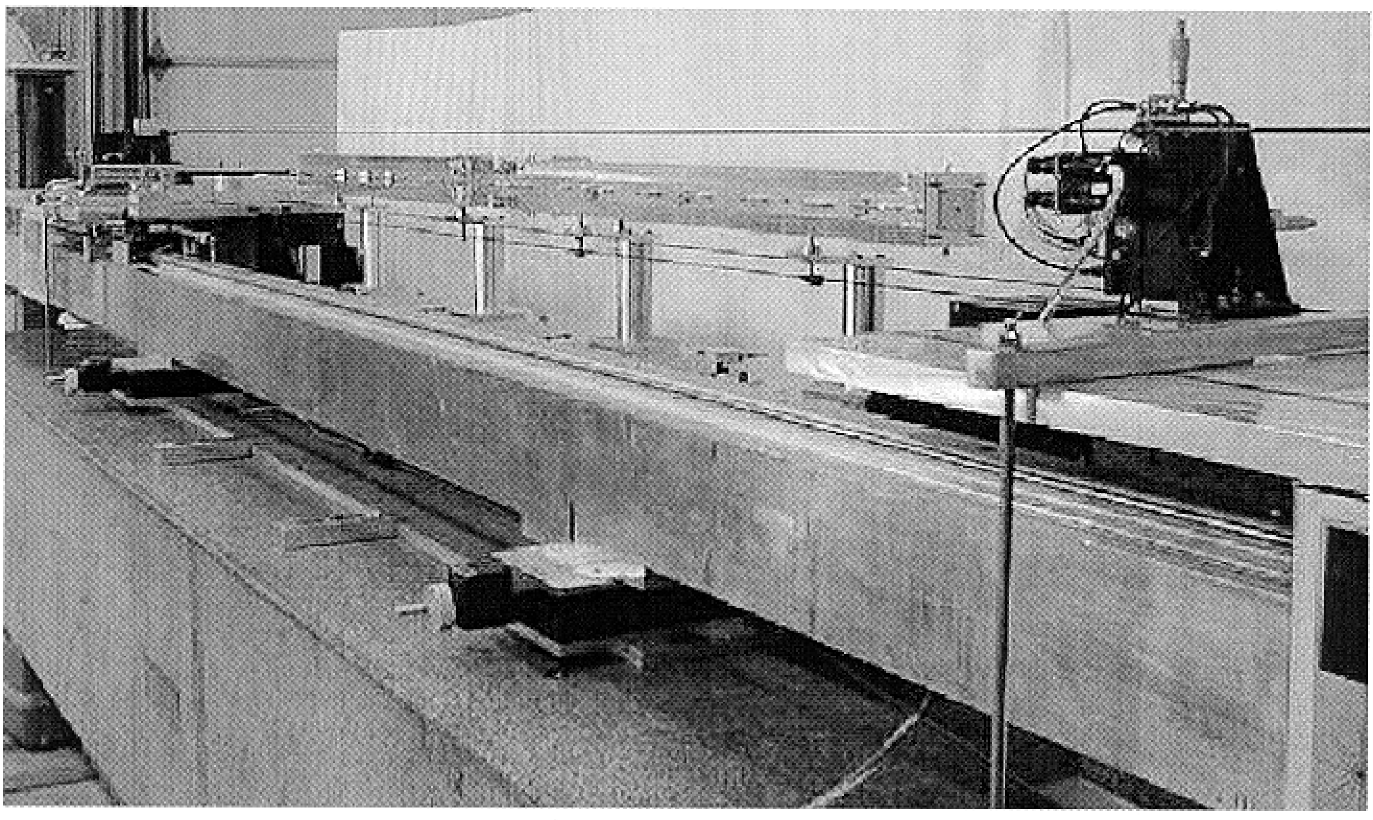
1) **Assembled quadrupole magnets in machined modules.**
2) **Installed & aligned in undulator using 1-m ground gauge bar.**

LOCATING MAGNETIC AXIS & CORRECTING TRAJECTORY

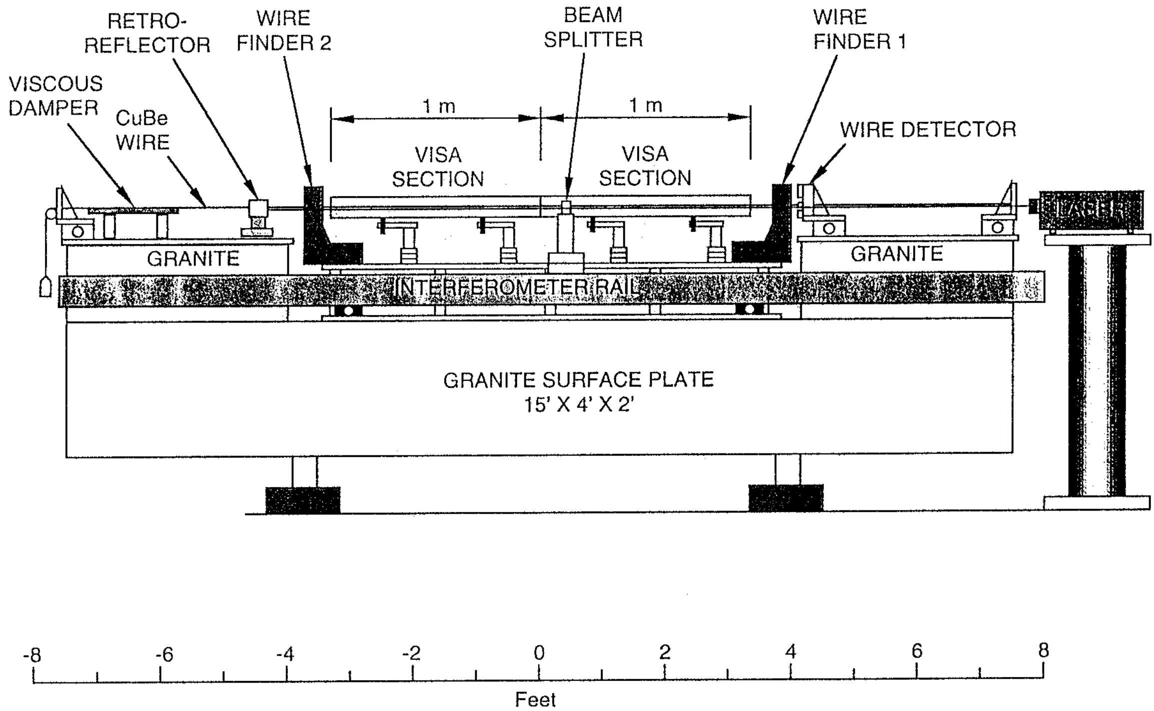
1) **Set up section(s) on Pulsed Wire Bench for best straightness.**
2) **Corrected X-steering errors first by repositioning quadrupoles in X.**
3) **Corrected Y-steering errors by external magnet blocks.**
4) **Fine-tuned trajectories by inserting small trim magnets (in sets of 4) via back-side access ports.**
5) **Rotated sections 90°, rechecked Y-trajectory in horizontal plane (avoids error due to wire sag.)**


0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
y [m]
-0.0001
0
0.0001
0.0002
0.0003
0.0004
x [m]
No sorting
With sorting





PULSED WIRE BENCH



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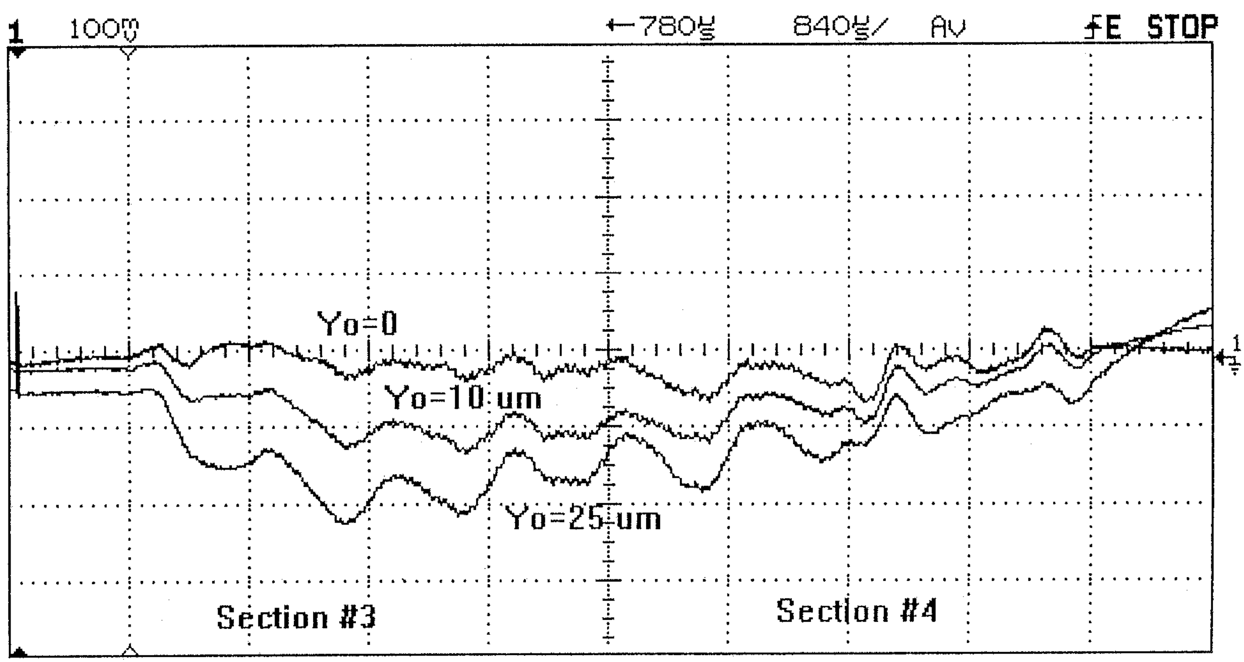
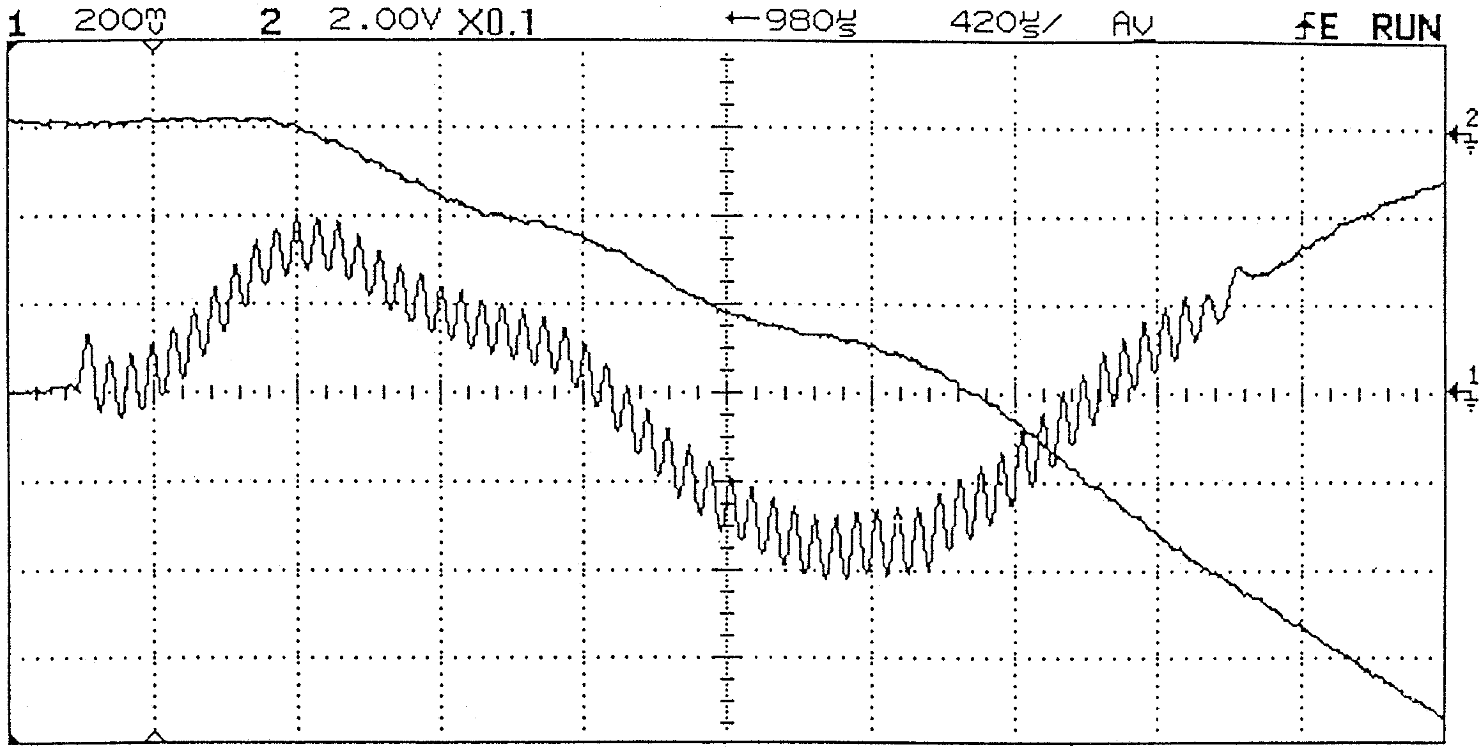
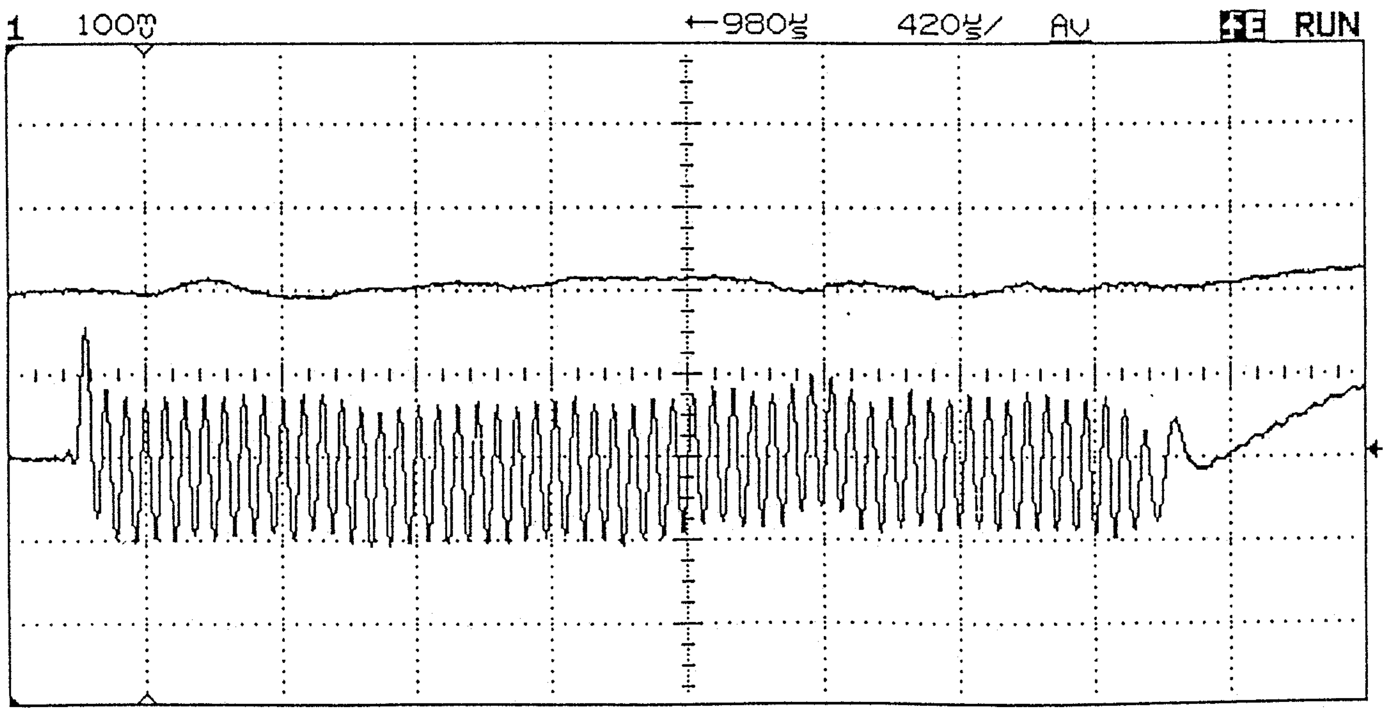


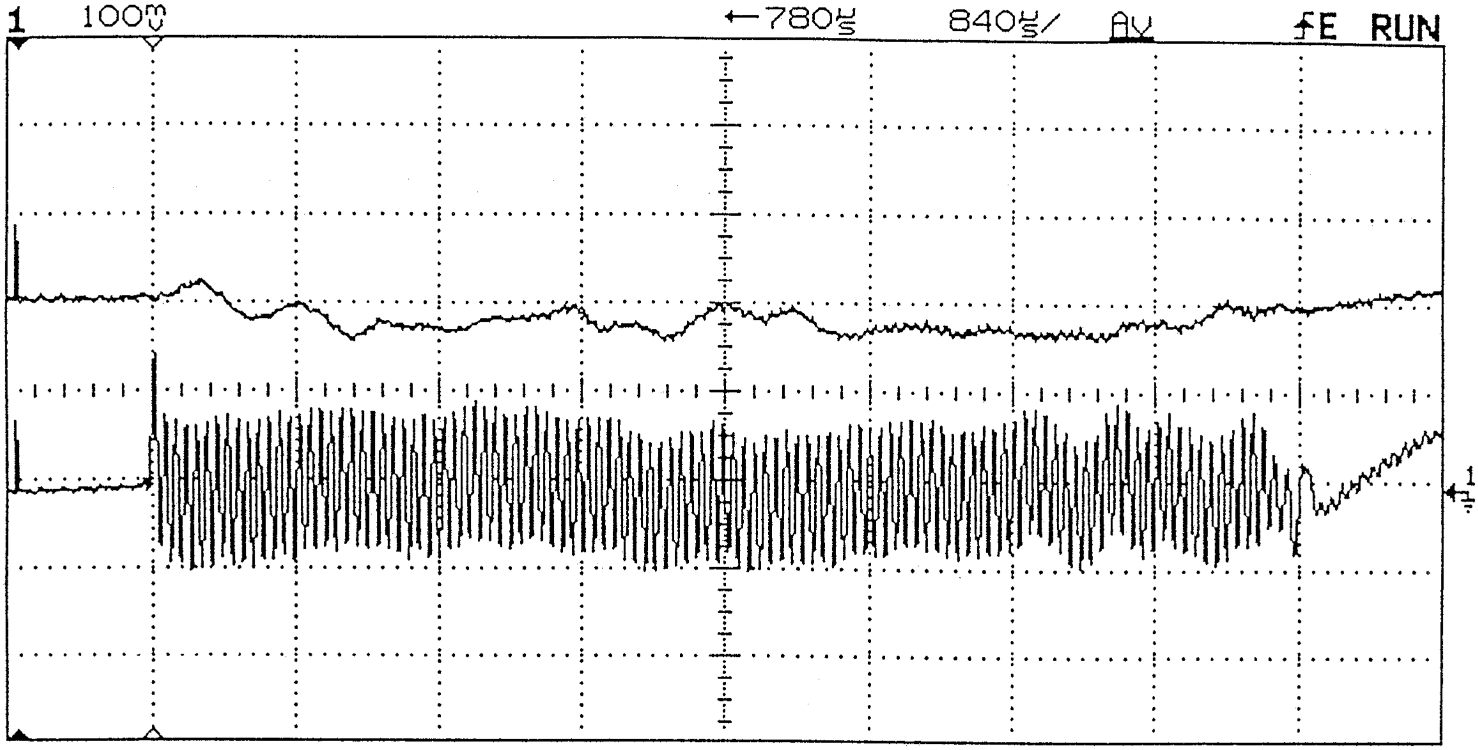
VISA Sections #3 and #4; 90 deg. orientation (roll ccw.)
Y trajectory vs. Y offset.



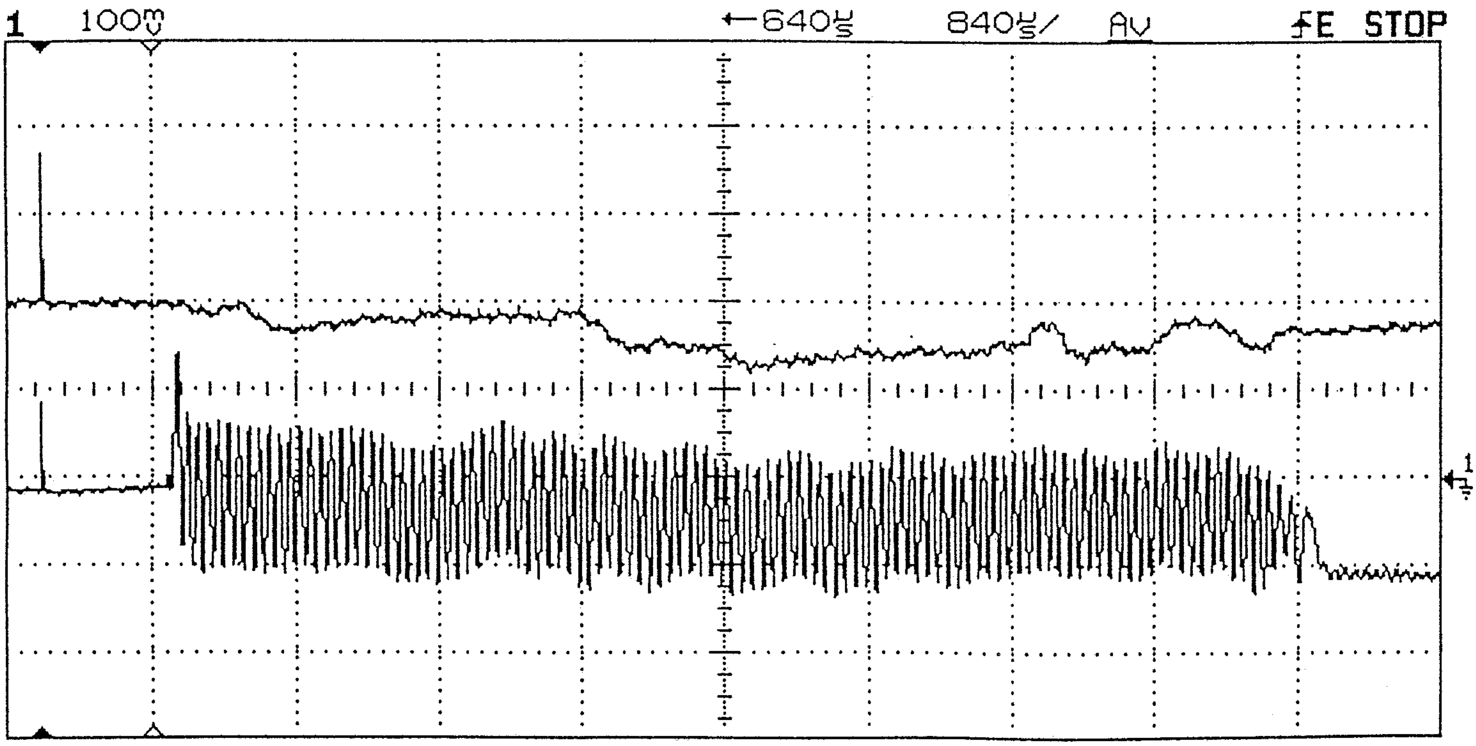
VISA Section #3; Normal Orientation.
X and Y trajectories before shimming.



VISA Section #3; Normal (upright) orientation.
X and Y trajectories after shimming.



VISA Sections #2 and #3; Normal orientation.
X and Y trajectories after final shimming.



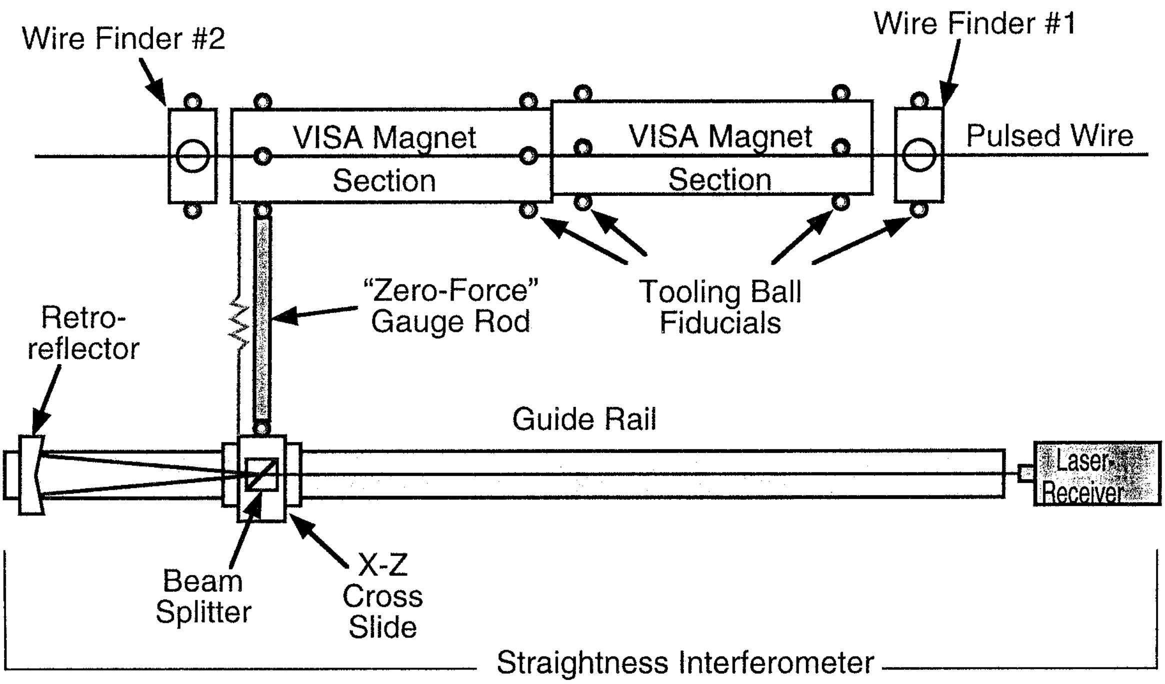
VISA Sections #3 and #4; Normal orientation.
X and Y trajectories after final shimming at joint.

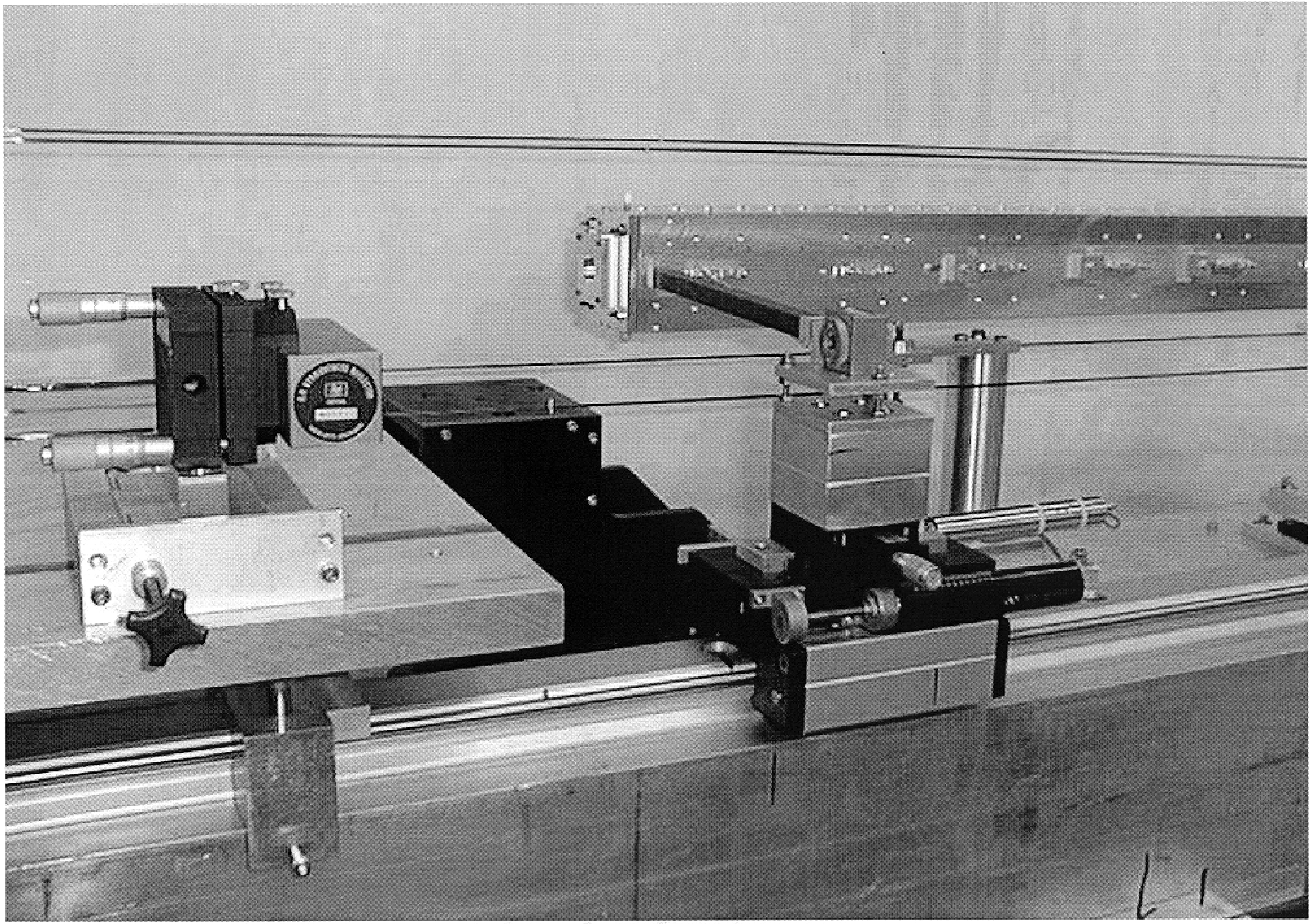
MEASURING MAGNET POSITION w.r.t. WIRE

- Calibrate Wire Finder.
- Set up Straightness Interferometer parallel to wire, at same height.
- Locate wire centerline.
- Using "force-free" gauge bar, measure x-offset of tooling balls on both wire finders and on each end of magnet sections(s).
- Calculate offset of each magnet tooling ball from wire center.
- Rotate magnet 90°, re-align magnetic center to wire. Repeat procedure to measure y-offsets of vertical tooling balls (avoiding wire sag).

Fiducializing Magnetic Axis of Undulator

after aligning each undulator's magnetic axis to wire

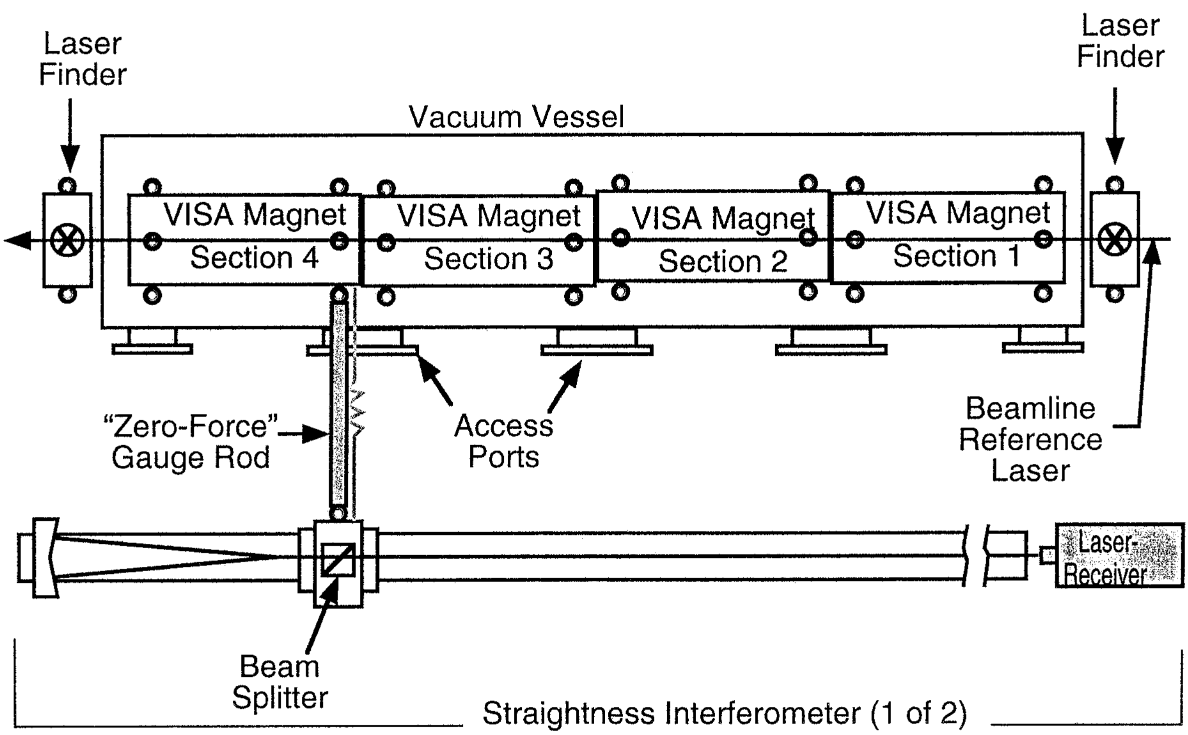




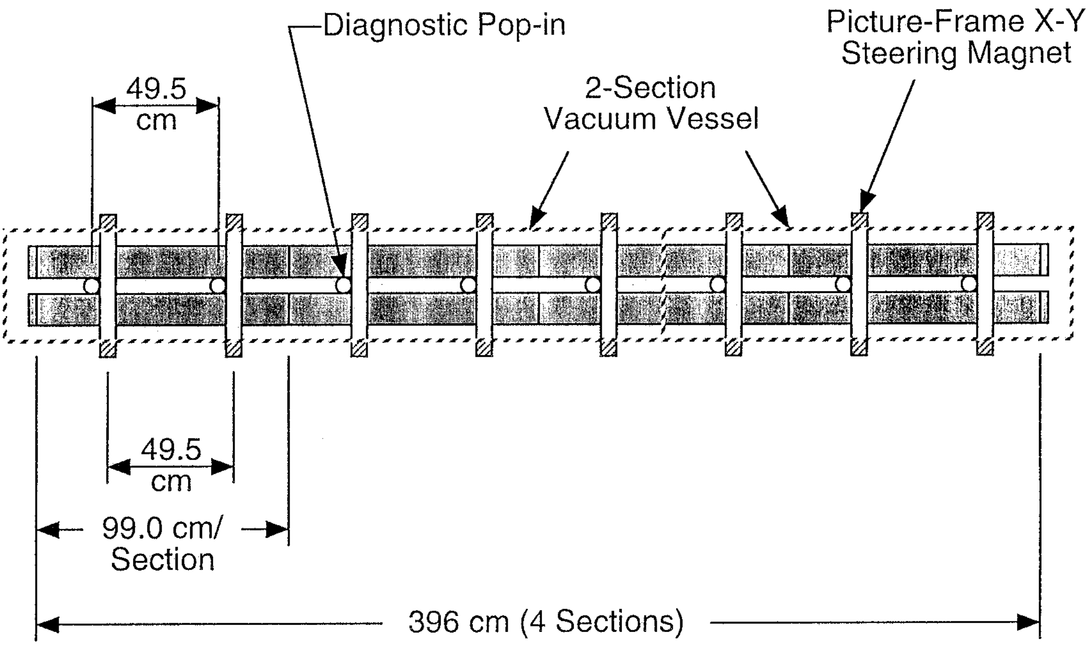
ALIGNING UNDULATOR SECTIONS w.r.t. BEAMLINE REFERENCE LASER

- Calibrate Laser Finder.
- Locate beamline reference laser centerline.
- Set up X and Y Straightness Interferometers parallel to beamline axis.
- Using "force-free" gauge bar, measure x-offset of tooling balls on both laser finders and on each end of magnet sections(s).
- Adjust X and Y position of undulator sections to reproduce offsets measured w.r.t. wire.

Aligning Undulator to Beamline Reference Laser



Schematic Layout of Diagnostics and Steerers



Beam Position Monitors

- Pop-in YAG Beam Position Monitors (BPM's) are located every 49.5 cm.
- YAG crystal images the beam via periscope to CCD camera
- Frame-grabber and image analysis software determine beam centroid.
- BPM's are calibrated with Beamline Reference Laser.

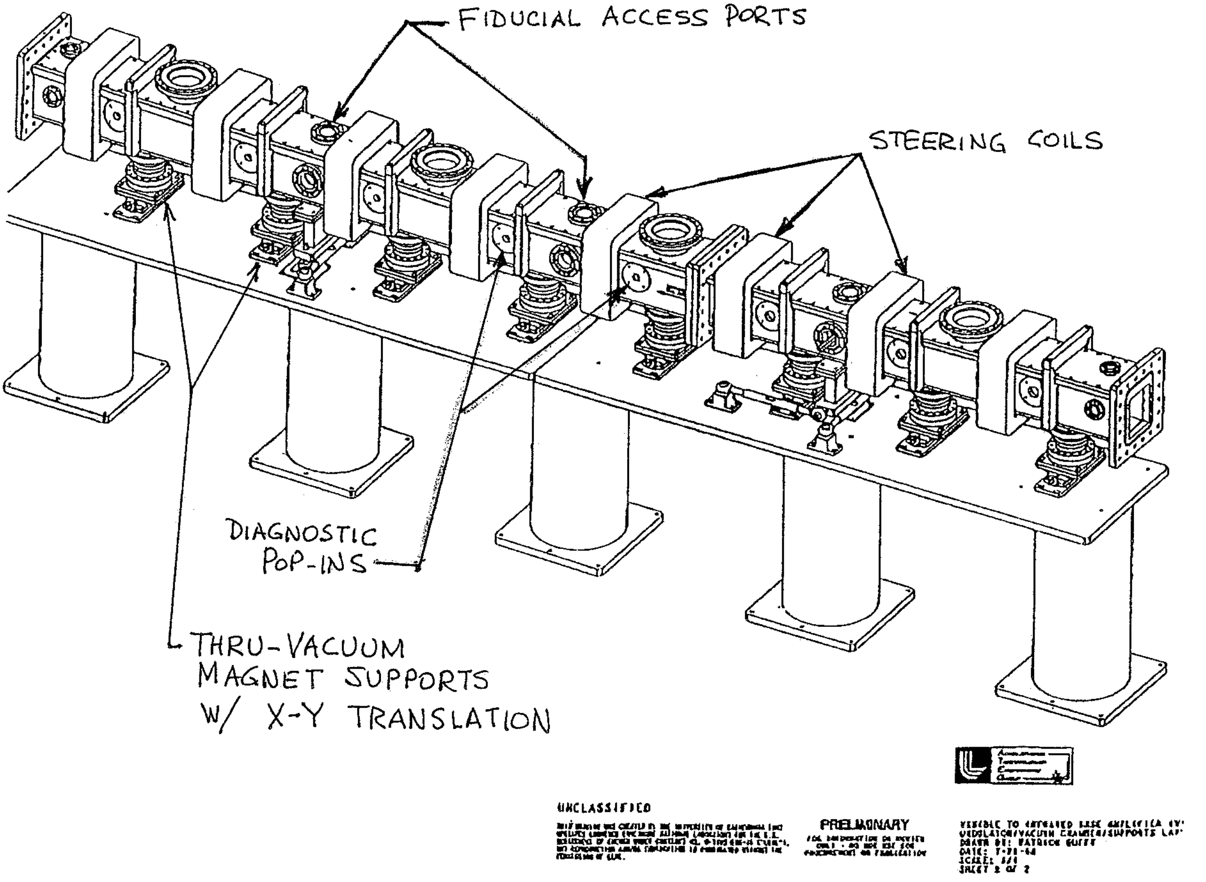
Steering Correctors

- Iron-core picture-frame magnets external to vacuum vessel.
- Must be carefully degaussed.
- Can compensate Earth's field (calibrate on Pulsed Wire Bench)

Limitations

- Beamline Ref. Laser pointing stability, setup repeatability.
- Errors in calculation of beam centroids (spot distortion, overfilling)
- Resolution limited by pixel size.

VISA VACUUM CHAMBER



Observations

- Alignment to <25 μm should make VISA usable into UV (e.g., 100 nm).
- Wiggle amplitude ***a*** of wire in VISA was <1 μm. (a = 25 μm @ 72 MeV) Therefore, we can achieve straightness of <***a*** @ 2.5 GeV!
- Uncertainties in locating magnetic axis, fiducialization and alignment are independent of energy.
- Trajectory straightness at higher energies limited by BPM resolution.
- Requirement on trajectory straightness is <u>per re-steering interval</u>, i.e., 50 μm/50 cm (not 50 μm/4m).
- Disadvantage of PM quadrupoles: can't locate axis by varying strength and observing beam steering.
- Can introduce energy-tapering with fixed gap by adding longitudinal phasing of upper vs. lower array.