Measurement of Small-Gap Insertion Devices

George Rakowsky

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Outline

- Motivation
- The Challenges of Small-Gap Measurement
- Review of Applicable Magnetic Measurement Techniques
- Recent Examples
- Prognosis

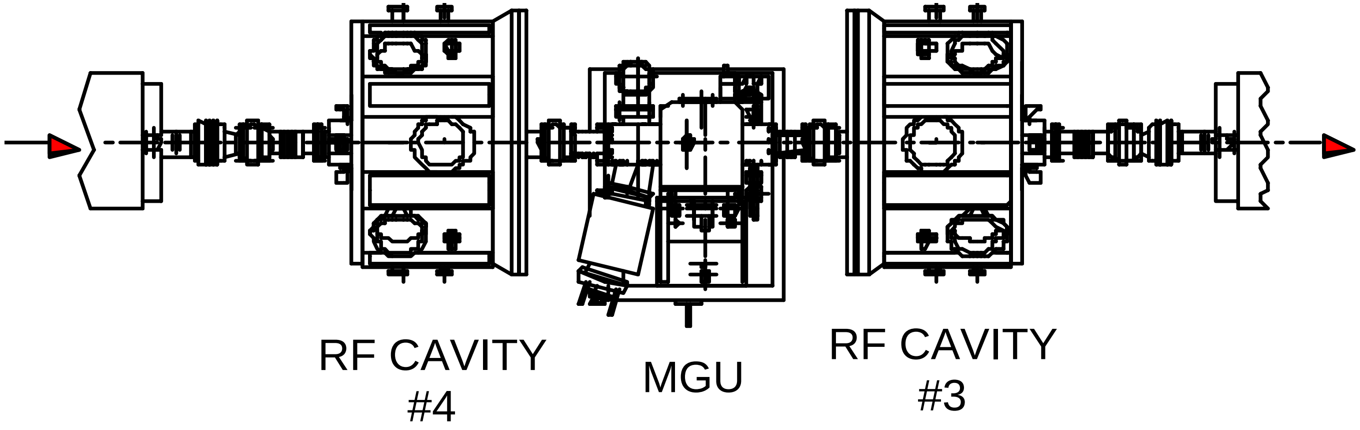
Motivation

- Insertion devices are being designed with ever-smaller gaps.
- Storage Rings:
  - Improvements in lattice designs have **reduced the vertical emittance**
  - Older (NSLS) and new machines (Swiss Light Source) are taking advantage of this by designing **ID's with smaller gaps**.
  - **In-vacuum ID's** allow further gap reduction (magnet gap = aperture)
  - Short, in-vacuum ID's are being squeezed into non-ID straight sections to create new beamlines in older machines (NSLS).
- Linac-Driven FEL's:
  - Photocathode RF guns now yield extremely **low emittance beams**.
  - Efficient beam transport designs **preserve this emittance**.
  - In-vacuum undulators with **small gap**, **short period** and **strong focusing** can reach saturation in much shorter length than previous designs. (VISA)

NSLS Small-Gap ID Development Program

	X13			X29
Device / Parameter	**PSGU** (1993)	**IVUN** (1997)	**MGU** (2002)	**MGU** (2003)
Type	Pure PM	Pure PM In-Vacuum	Hybrid PM In-Vacuum	Hybrid PM In-Vacuum
Period λ_u	16 mm	11 mm	12.5 mm	12.5 mm
No. of Periods	18	30.5	27	27
Nom.Mag.Gap	6.0 mm	3.3 mm	3.3 mm	3.3 mm
Peak Field B_u	0.62 T	0.68 T	1.0 T	1.0 T
K_{max}	0.93	0.7	1.17	1.17
Fund. Energy @ 2.8 GeV	3.2 keV	5.4 keV	3.5 keV	3.5 keV

NSLS “Finds” 2 New Undulator Straights



MGU’s will fit between pairs of RF Cavities at X29 and X9.
Result: 2 new Undulator Beamlines

The Challenges

- I.D. gaps ~ 3 mm (or less)
- I.D. periods ~10 mm
- Require field measurement with spatial resolution of ~0.1 mm
- Measuring devices must shrink
- I.D. must still meet performance requirements
- What measurement techniques can we use?

Magnetic Measurement Techniques

- Scanning Hall probe
- Scanning 1-period coil
- Scanning transverse wire
- Vibrating wire

DETAILED FIELD MAPPING

- Rotating long coil
- Translating long coil
- Moving wire

INTEGRATED MULTIPOLES

- Pulsed wire

- **TRAJECTORY IMAGING**
- **AXIS LOCATION**

Hall Probes - Conventional

Features

- Measure field at a point
- Measure single vector field component normal to chip
- Transverse probes ≥1.5 mm thick
- Axial probes ≥1.5 mm dia.
- Active area ≥0.5 mm dia.
- Angular alignment ±1°
- Linearity correctable to < 0.01%
- Various mountings available

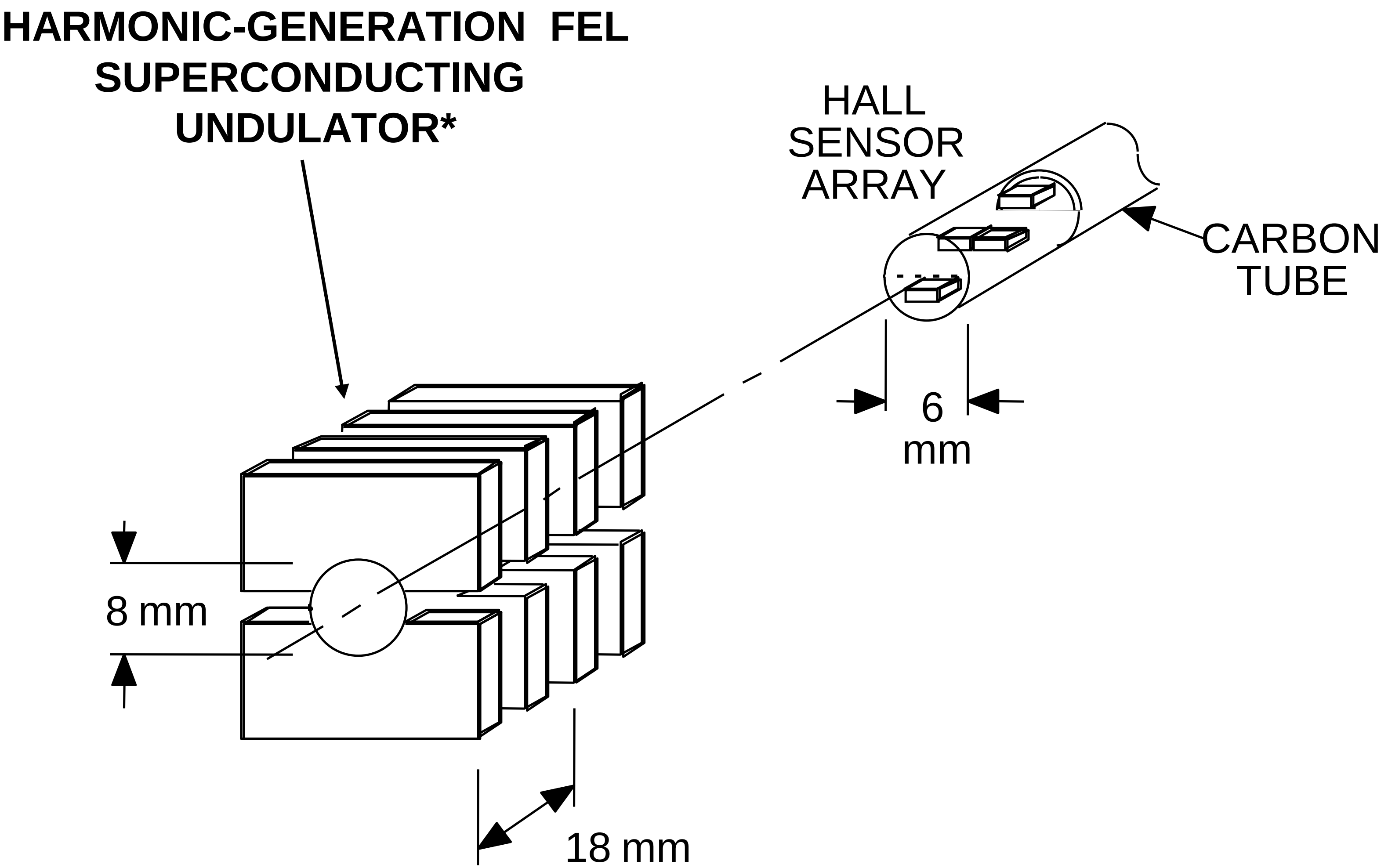
Advantages

- Detailed, high accuracy field measurement for computing K, trajectory, phase error, spectrum, flux, power
- Numerical integration cross-checks long-coil measurements
- Work down to 4°K

Disadvantages

- Precision carriage system req'd.
- Field sampled at discrete points
- Cross-field, planar Hall errors
- Field averaged over chip area
- At limit of spatial resolution

Cryogenic Multi-Element Hall Array



* L. Solomon & G. Ingold, 1993 PAC

Silicon “Vertical” Hall Sensor*

Features

- 1, 2 & 3-axis measurements with one chip
- Measures B_x & B_z parallel to chip
- B_y component normal to chip is derived from 2 parallel components
- Fabricated with IC technology
- Orthogonality of axes ±0.1°
- Sensor area ≥0.1x 0.1 mm
- Linearity to ±0.1%
- Low cross-coupling, planar-Hall

Advantages

- Same as Conventional Hall probe
- True 3-axis vector field measurement at common point
- Available probes ≥0.4 mm thick

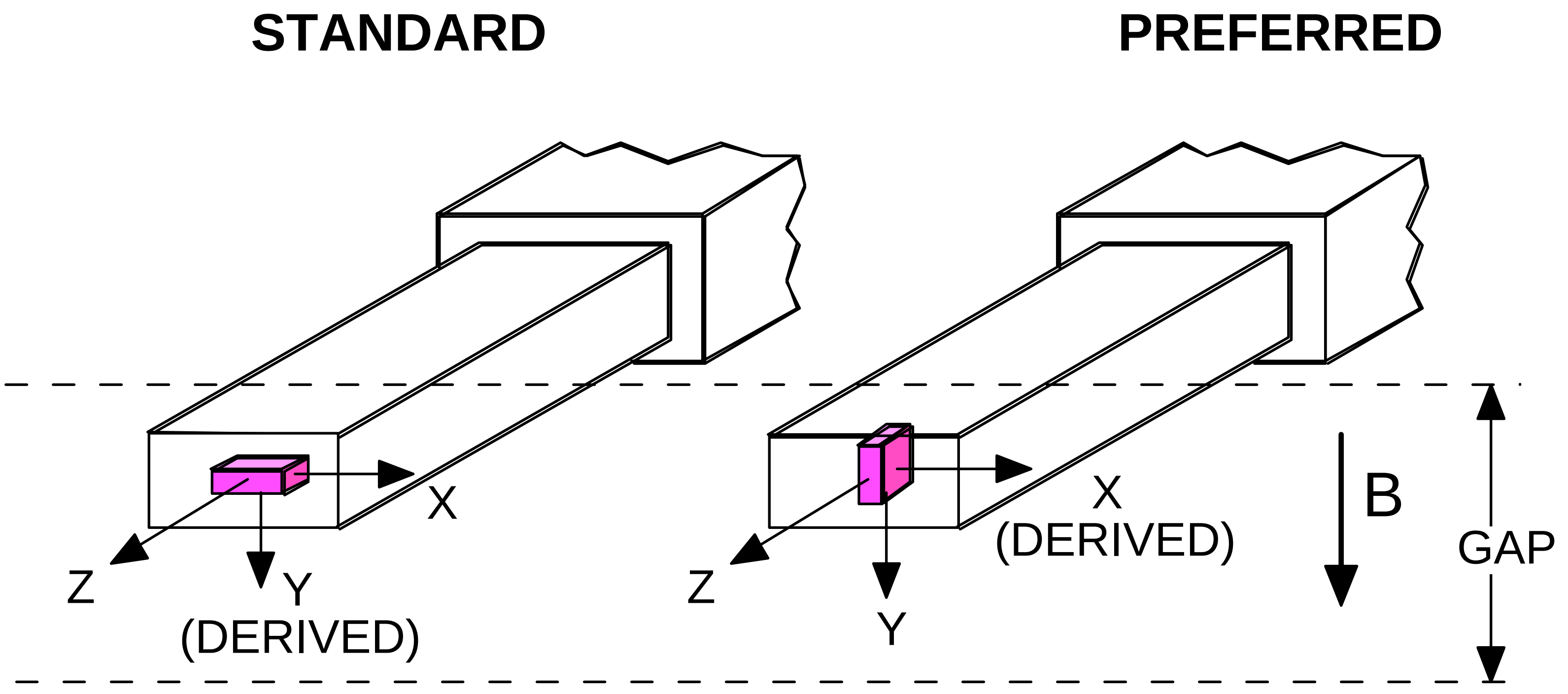
Disadvantages

- Same as Conventional Hall probe.
- Standard 3-axis probes oriented so *derived (worst) axis* measures principal undulator field

•C. Schott, et al., IEEE Trans. Instr. & Meas.,(46) 1997, 613-616.
Made by SENTRON AG, Zug, Switzerland

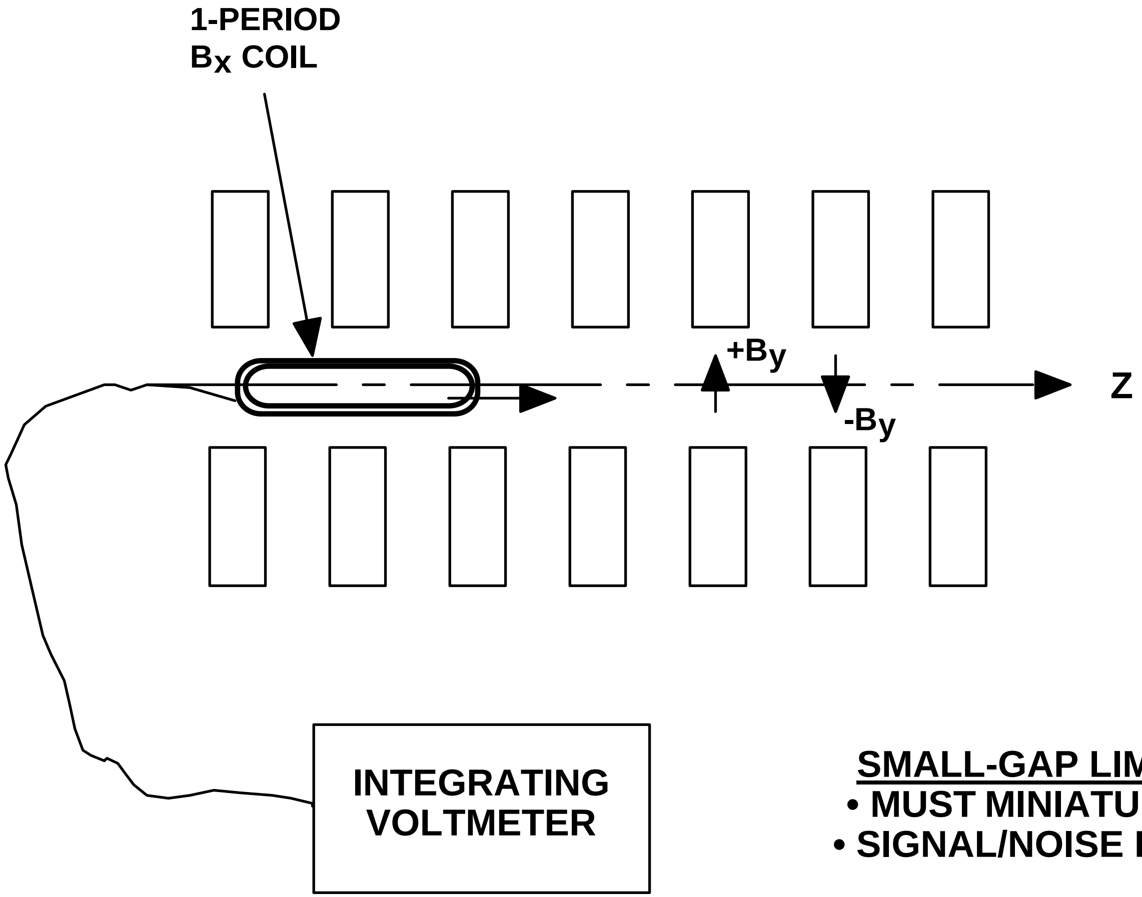
Vertical Hall Sensor Orientation

With exception of the “nude” tip probe, standard **3-axis** sensor mountings available from Sentron are not optimal for small-gap undulator mapping, because the least linear, noisiest, & slowest (Y) axis is oriented to measure the **principal** field component. We recommend the orientation shown at right.



Scanning 1-Period Coil

USED FOR TRANSVERSE FIELD MEASUREMENT IN PLANAR ID’S

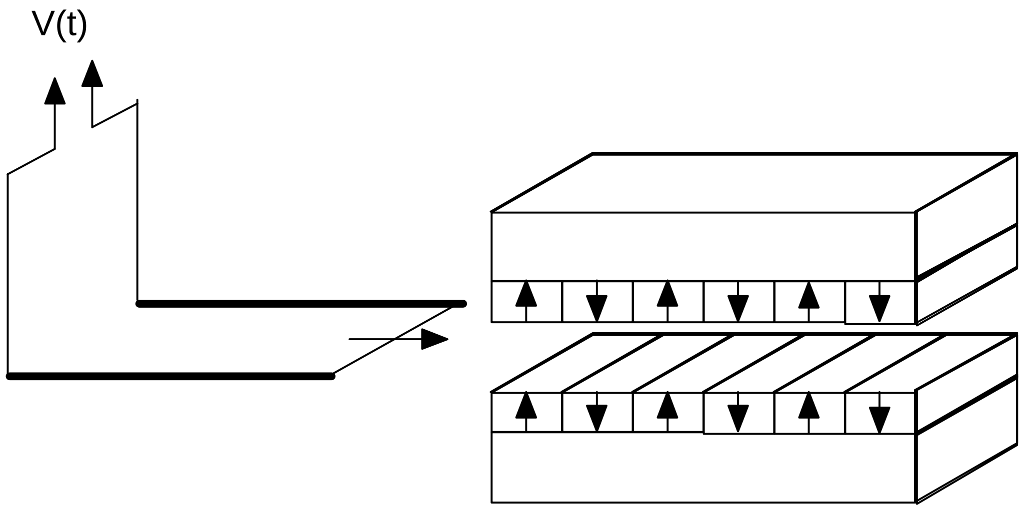


SMALL-GAP LIMITATIONS:

- MUST MINIATURIZE COILS
- SIGNAL/NOISE DECREASES

*Scanning Transverse Wire**

TO SCOPE OR
VOLTAGE
INTEGRATOR



- INDUCED VOLTAGE DUE TO Φ_y CUT BY WIRE
- TO GET B_y UNFOLD TRANSVERSE PROFILE (COMPUTE BY RADIA?)

ADVANTAGES

- FAST
- INSTANT B_y or $\int B_y\,dz$ MAP
- USED FOR GAPS < 1mm and PERIODS < 1mm

DISADVANTAGES

- NO DETAILS ON $B_y(x)$
- CAN'T MEASURE B_x

* R. Tatchyn, NIM A279 (1989) 655-664

Vibrating Wire Technique [1, 2]

(FREQUENCY-DOMAIN DUAL OF THE PULSED-WIRE TECHNIQUE)

- **Reconstructs fields from vibration amplitudes of wire driven by currents at frequencies of natural modes of the wire.**
- **Both B_x & B_y measured simultaneously**
- **Measures fields in inaccessible regions, in gaps < 1 mm**

REFERENCES

[1] A. Temnykh, “Vibtating Wire Field Measuring Technique”, PAC 1997, p.3218-3220.

[2] A. Temnykh, This Workshop

Integrating Coil & Moving Wire Techniques

Key Features:

- Measure total field integrals
- Measurement over a volume
- Obtain multipole components
- Resolution: ~ 1 gauss-cm
- Figure-8 coil can measure total 2nd integral

Advantages:

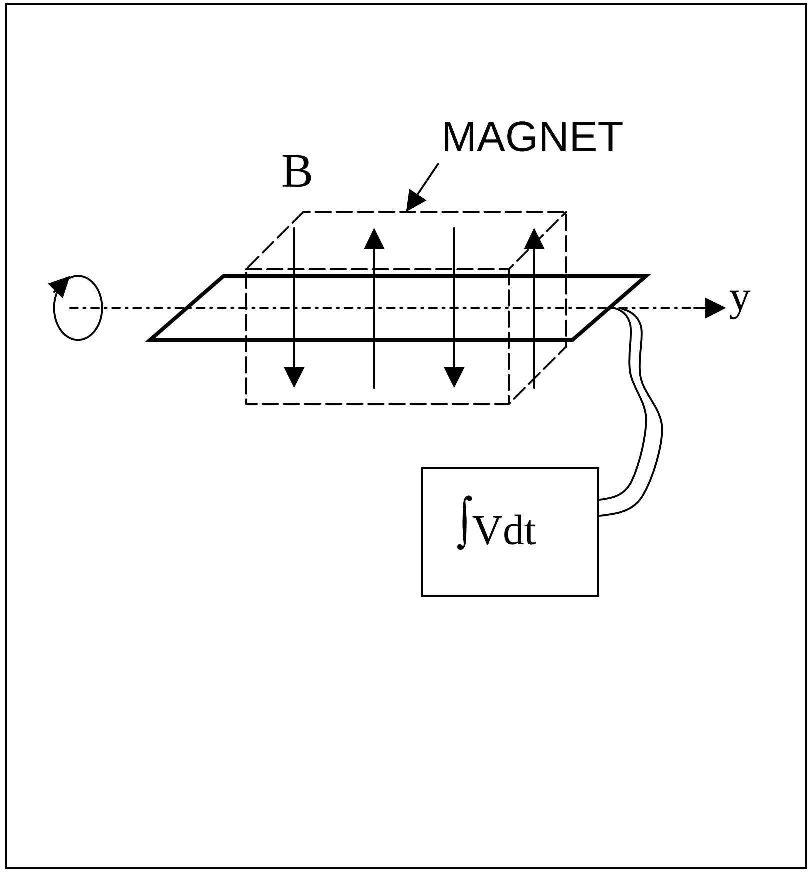
- No precision probe carriage
- No bucking coils needed for undulator measurement
- Sensitive near-null measurement

Disadvantages:

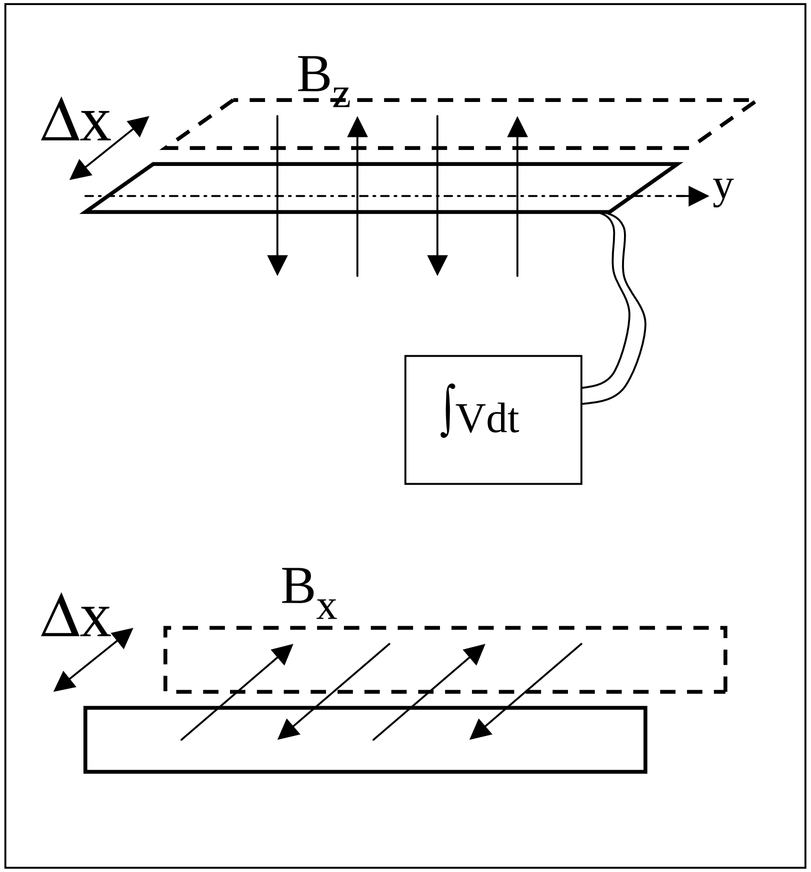
- No information on internal fields, local trajectory errors;
- Integrator drift error
- Length limited by sag

Long Coil for Integrated Multipole Measurement

ROTATING COIL



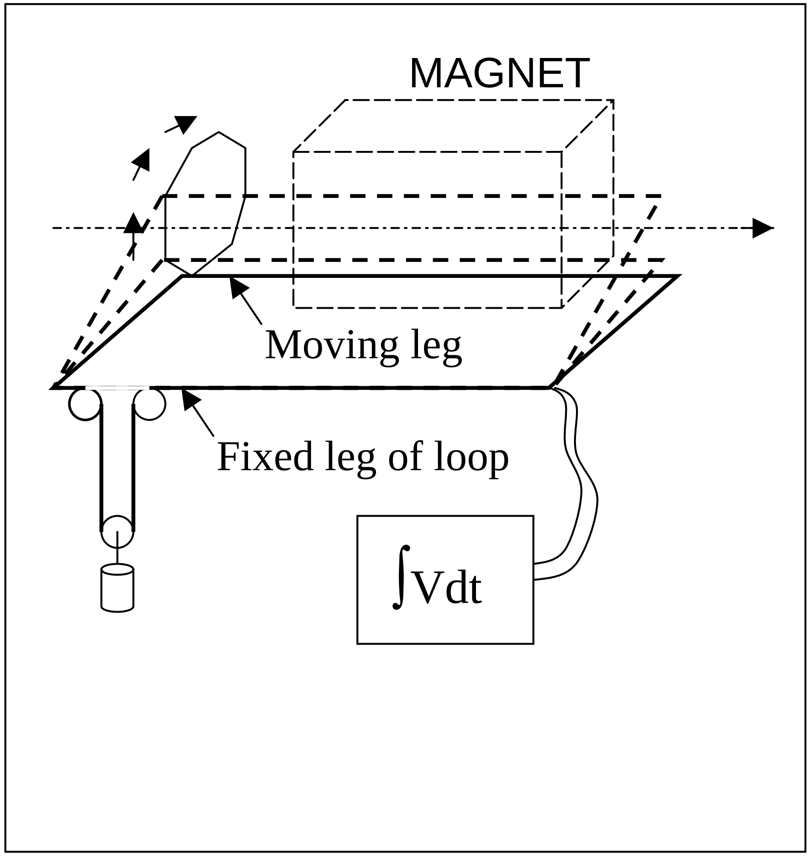
TRANSLATING COIL



Small gap limits diameter or height of coil, --> lower signal/noise

Moving Wire Integrated Multipole Measurement

Ref.: D. Zagrando, R.P. Walker, “A Stretched Wire System for Accurate Integrated Magnetic Field Measurement in Insertion Devices”, NIM, 1996.



- **Integrates field over area cut by moving leg of loop.**
- **Move one leg of loop along circle of radius r, in steps $\Delta\theta = 2\pi/2^n$. Obtain *n* multipoles by FFT.**
- **No details of fields inside loop.**
- **Multiple moves needed to average integrator drift.**
- **Same GAP HEIGHT limitations as rotaing & translating coil.**
- **Stretched wire subject to sag.**

*** If wire only moves in mid-plane, we get multipoles of By, but not of Bx.**

Measurement of 2nd Integral of Field

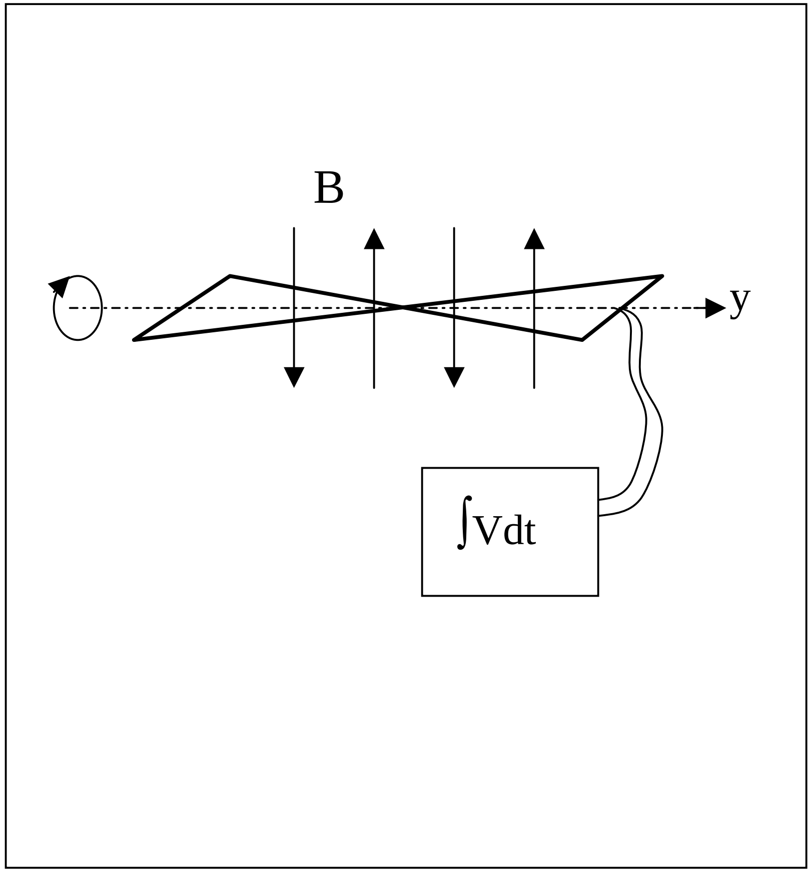
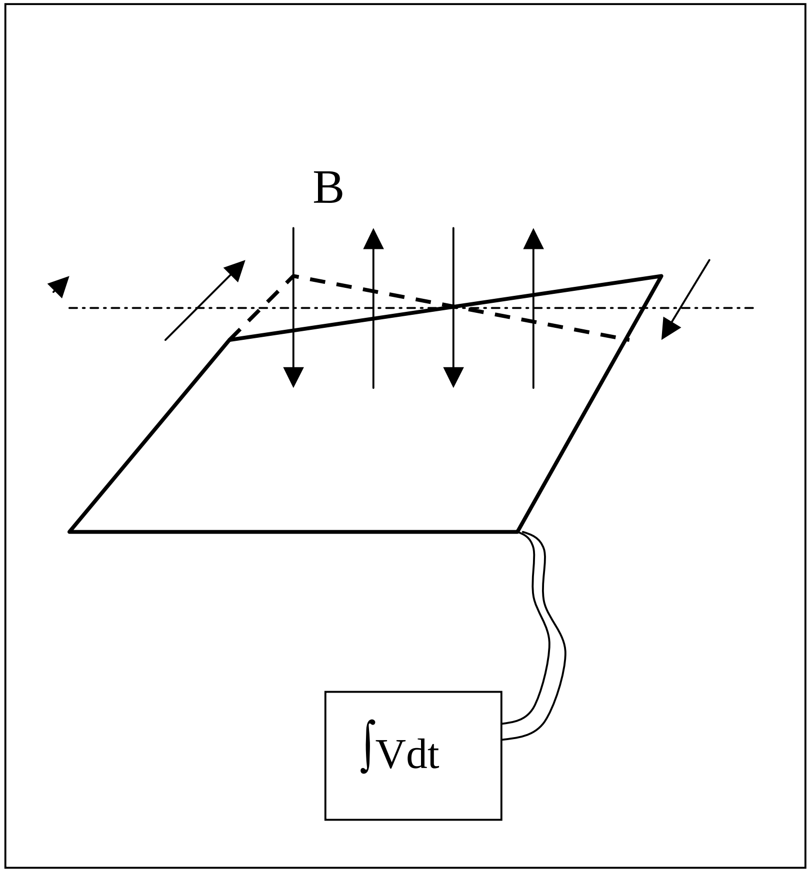


Figure-8 Integrating Coil



Move wire about mid-point

Same height limitation as long coils

Pulsed Wire Technique [1, 2]

Ref.: [1] R.W. Warren, NIM A272 (1985) 257; [2] G. Moritz, Proc. IMMW 11, BNL, 1999.
[3] T.C. Fan, PAC 2001

Key Features:

- **Measure 1st or 2nd field integral along a line (volume of wire)**
- **Get “snapshot” of trajectory**
- **Fast, qualitative information**
- **Use for gaps < 1mm**

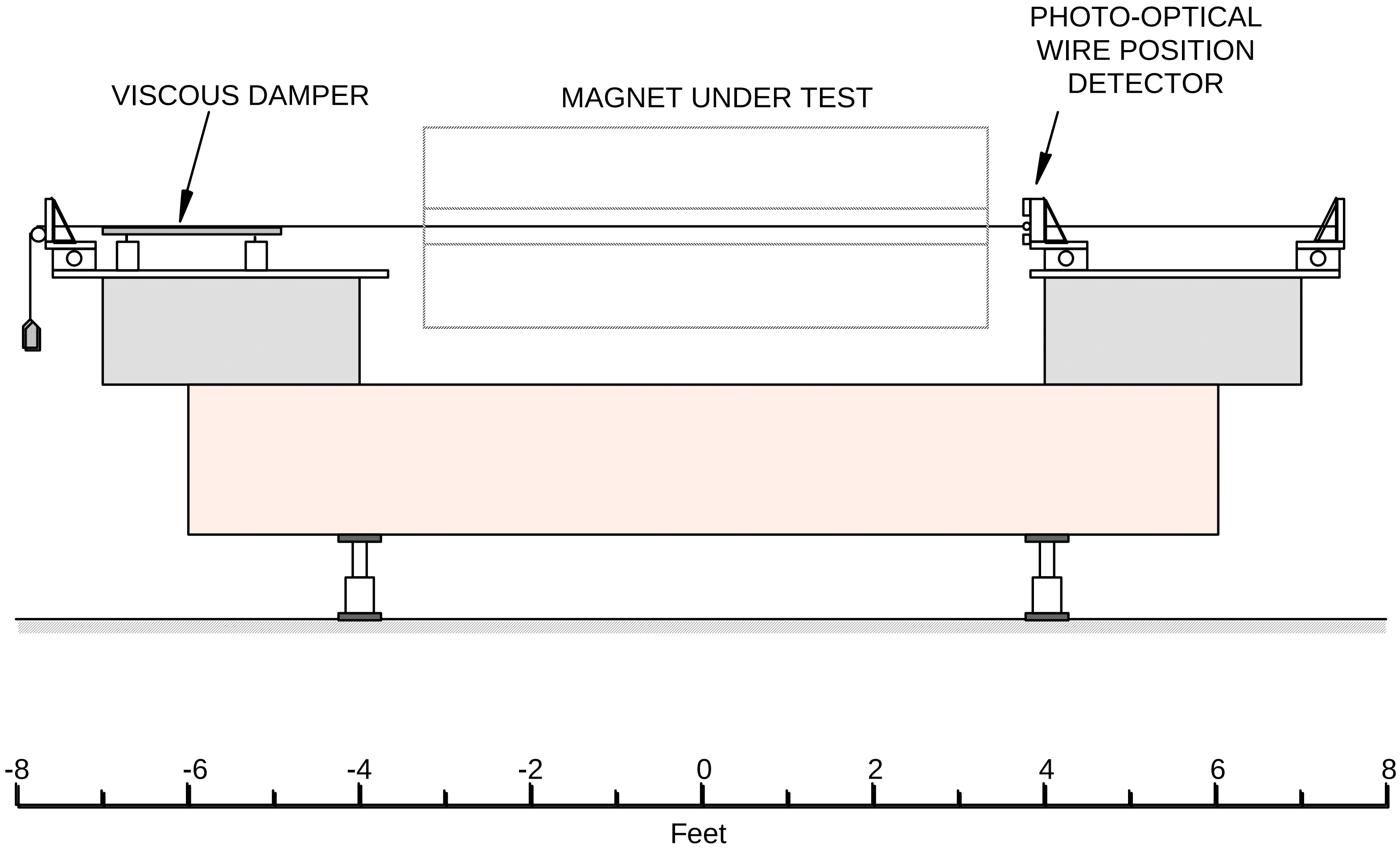
Disadvantages:

- **No information on multipoles**
- **Distortion due to dispersion** [3]
- **Length limited by wire sag**
- **Motion not scaled to energy**
- **No direct field measurement**

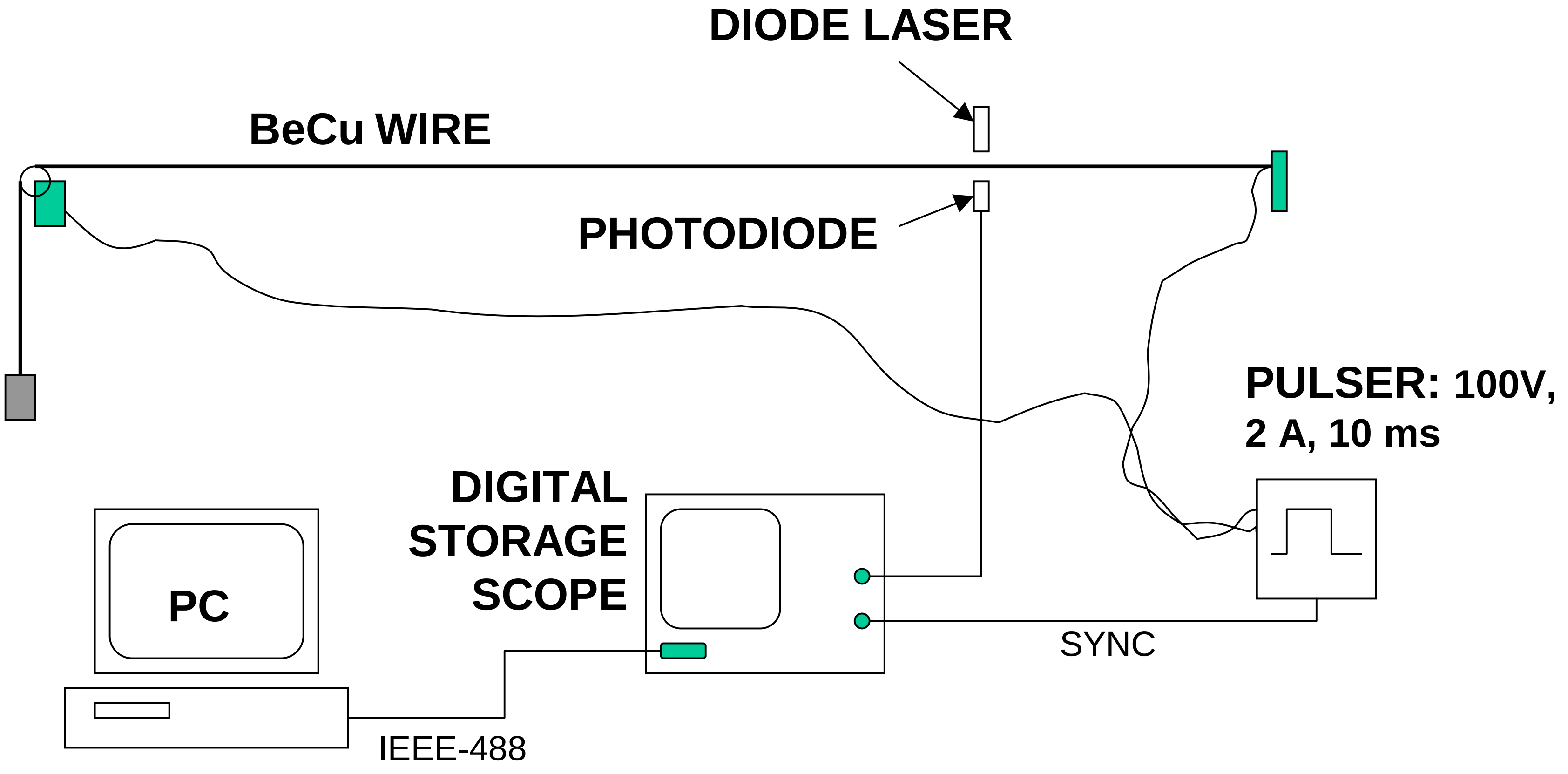
Advantages:

- **Simple instrumentation**
- **Access confined spaces**
- **No precision probe carriage**
- **Local trajectory errors visible**
- **Distinguish systematic, local errors, end effects**
- **Real-time feedback eases tuning**
- **Sensitive null measurement**
- **Find magnetic axis to ~10 μm**
- **Wire provides reference for fiducialization**

NSLS Pulsed Wire Bench



Pulsed Wire Instrumentation



DIODE LASER

BeCu WIRE

PHOTODIODE

PULSER: 100V, 2 A, 10 ms

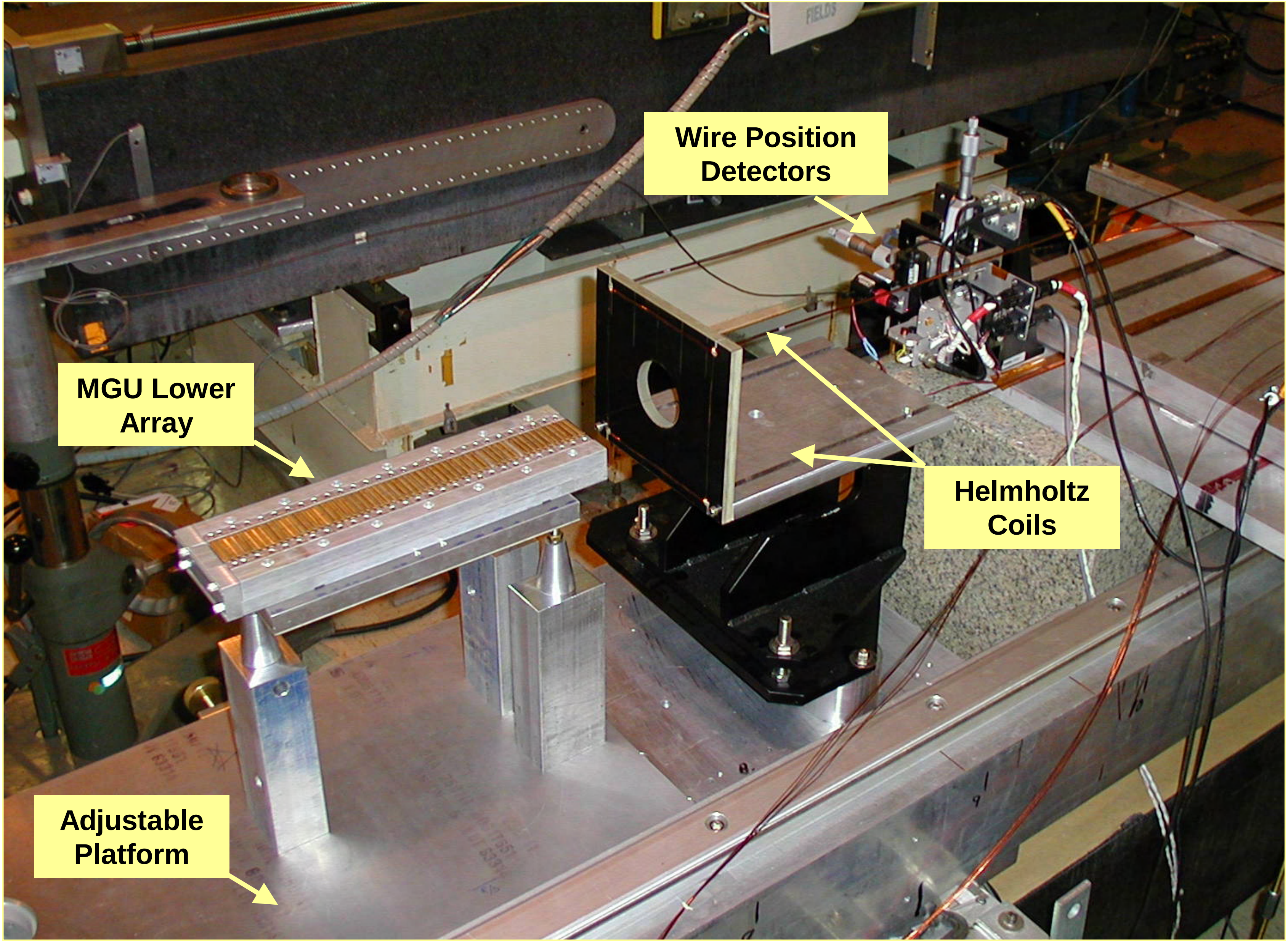
DIGITAL STORAGE SCOPE

PC

SYNC

IEEE-488

MGU Lower Array on Pulsed Wire Bench



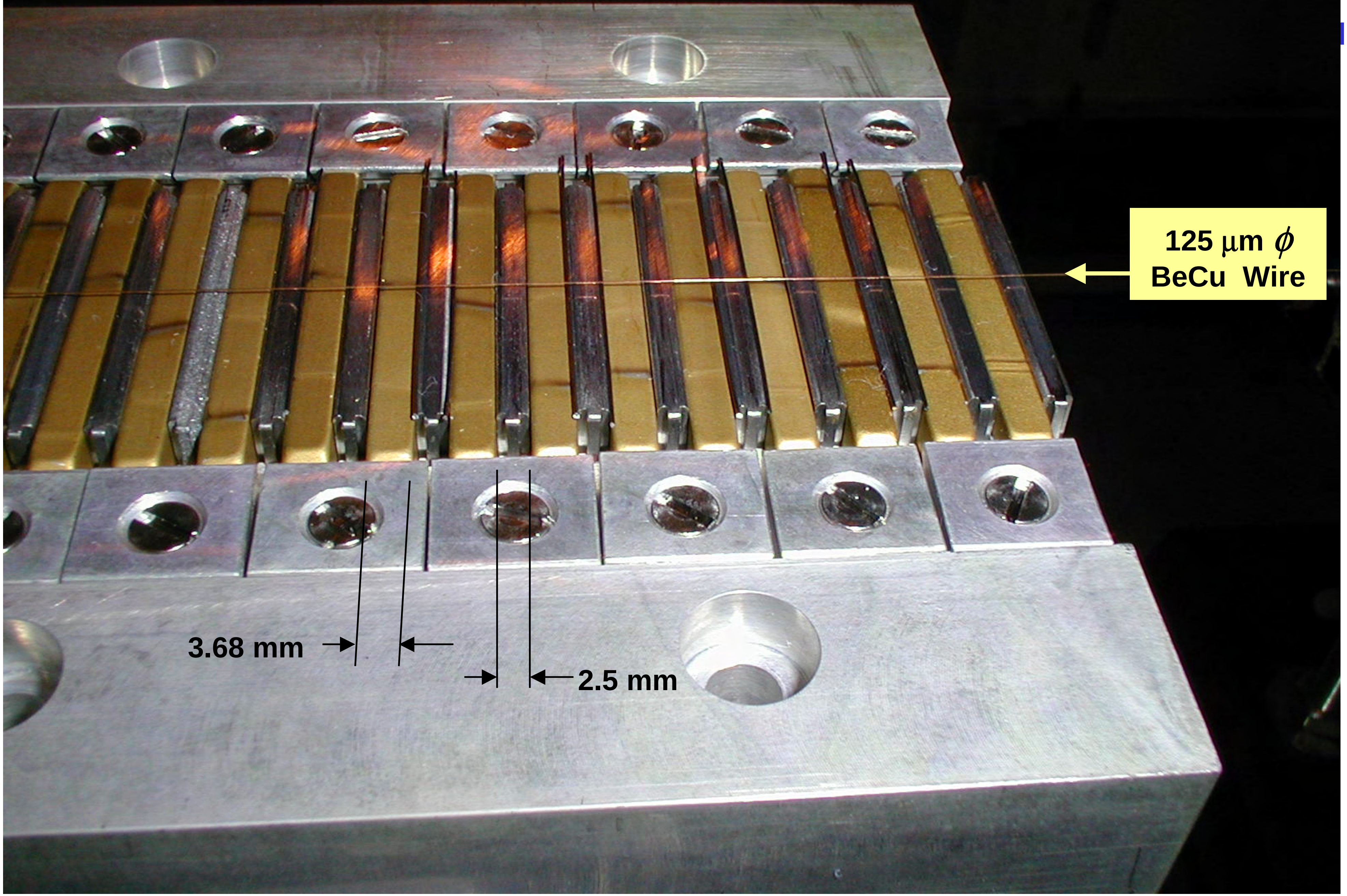
Wire Position Detectors

MGU Lower Array

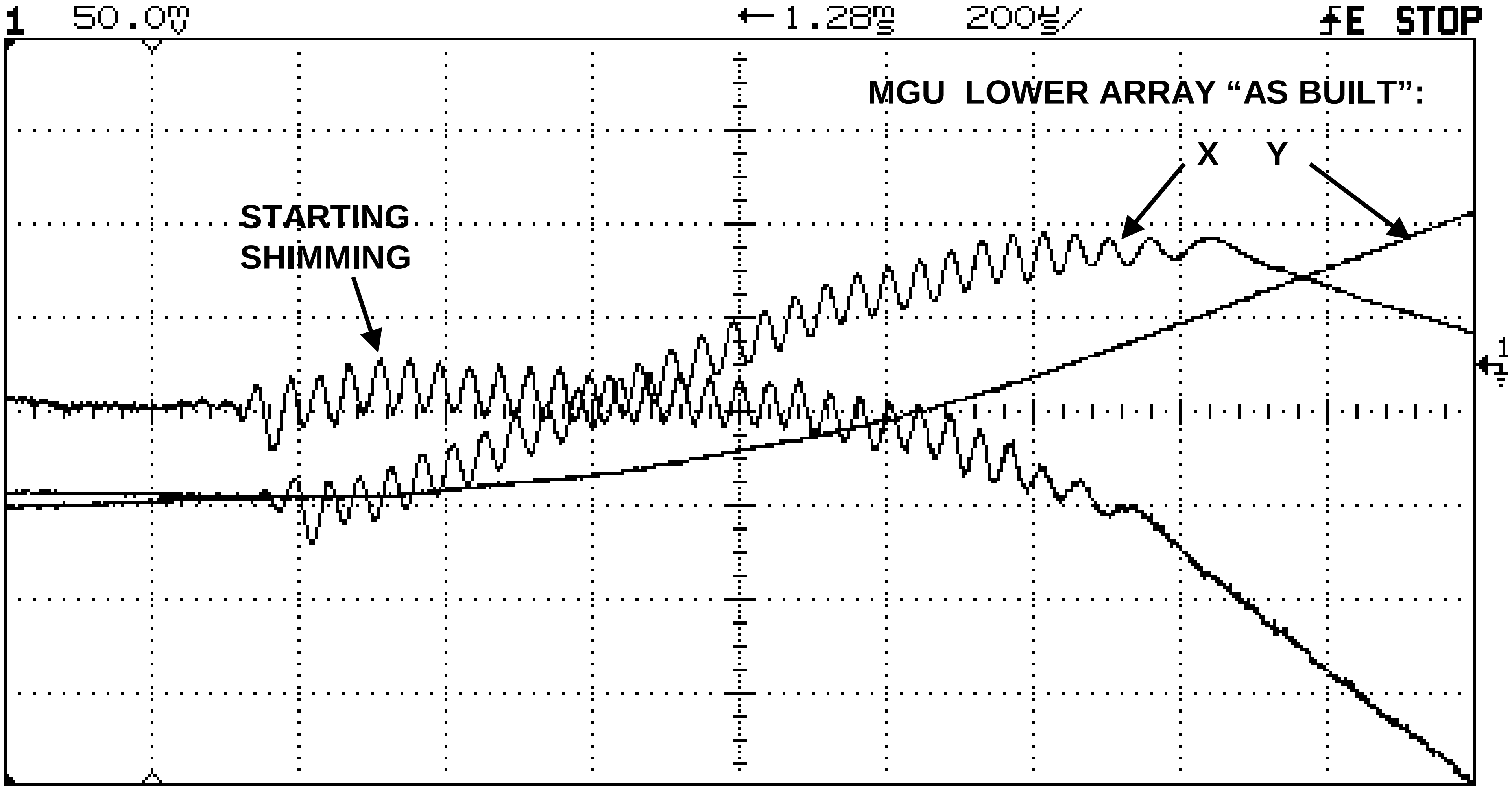
Helmholtz Coils

Adjustable Platform

Mini-Gap Undulator Magnet Array

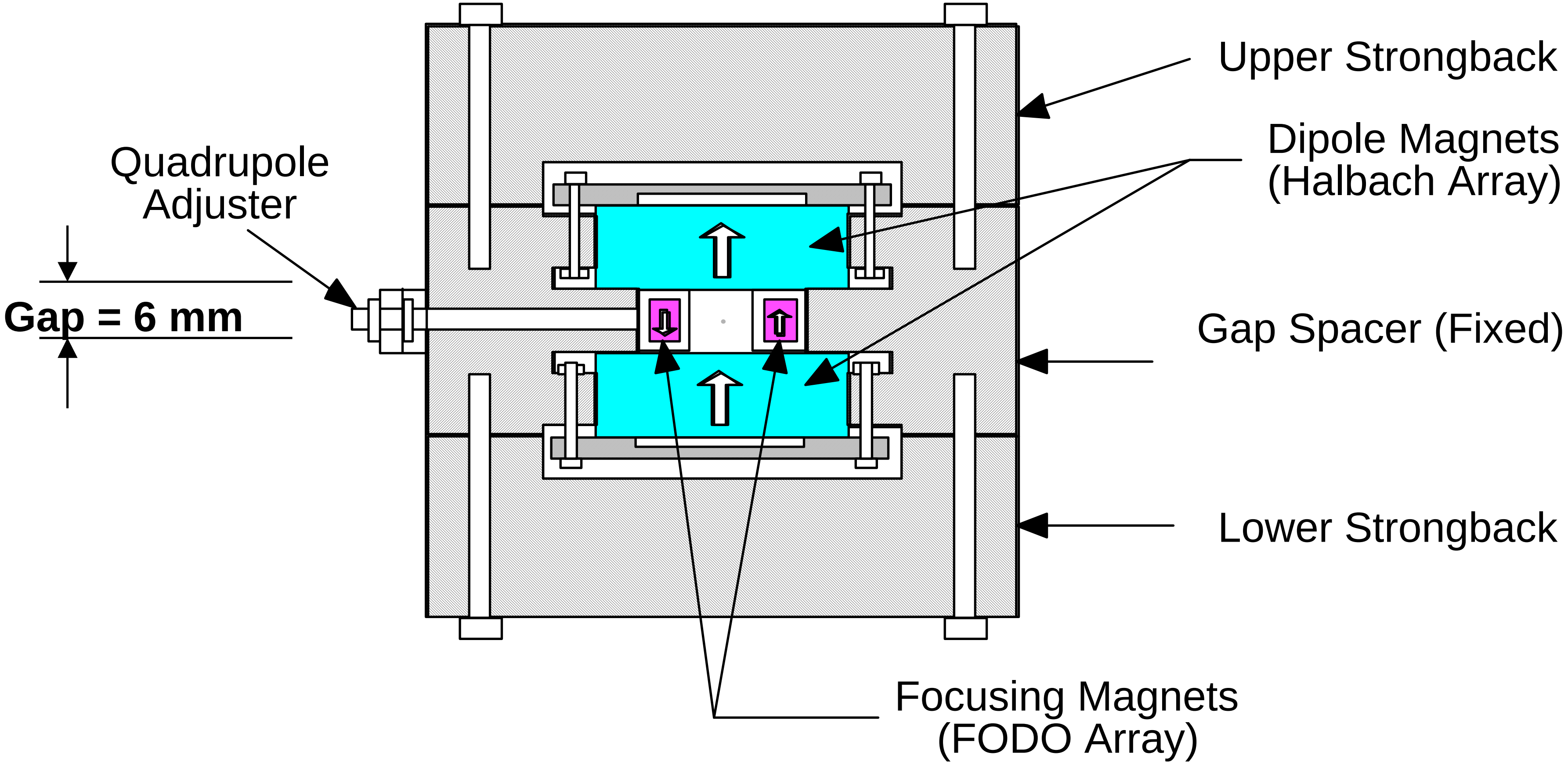


Pulsed wire allows quick first look and initial shimming



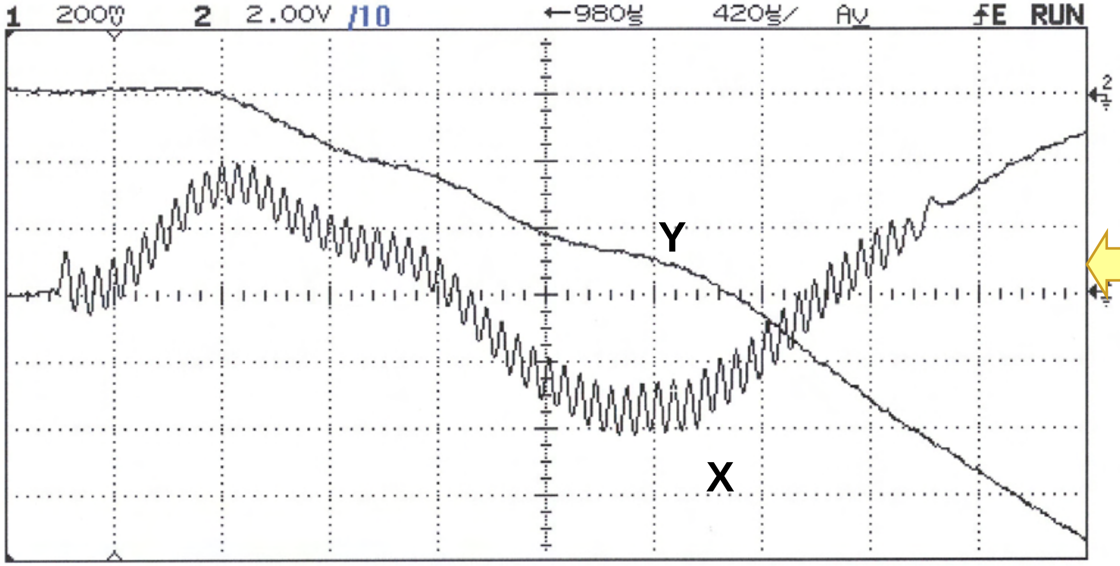
VISA Undulator’s aperture accessible only by stretched wire

REF**.:** R. Carr *et al*., “The VISA FEL Undulator”, Proc. FEL-98, North Holland, p. II-79
G. Rakowsky, *et al*., “Measurement and Optimization of the VISA Undulator”, PAC-99



Trajectory Tuning Using Pulsed Wire

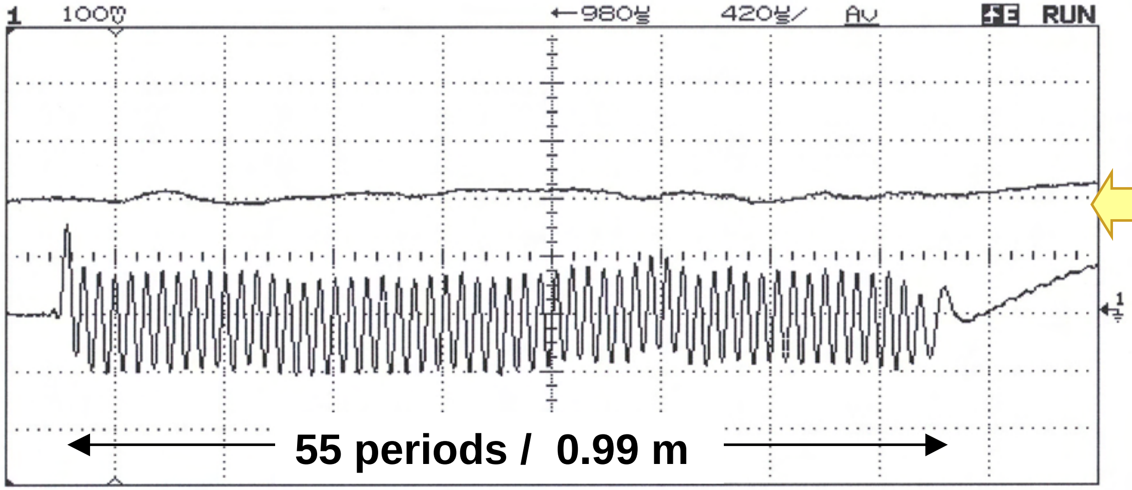
Pulsed Wire provides instant "snapshot" of trajectory in X & Y.



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

X & Y trajectories in typical VISA section (#3) as received from SLAC, after "best" centering.

***NOTE*: Dominant source of trajectory error was *Quadrupole misalignment*.**



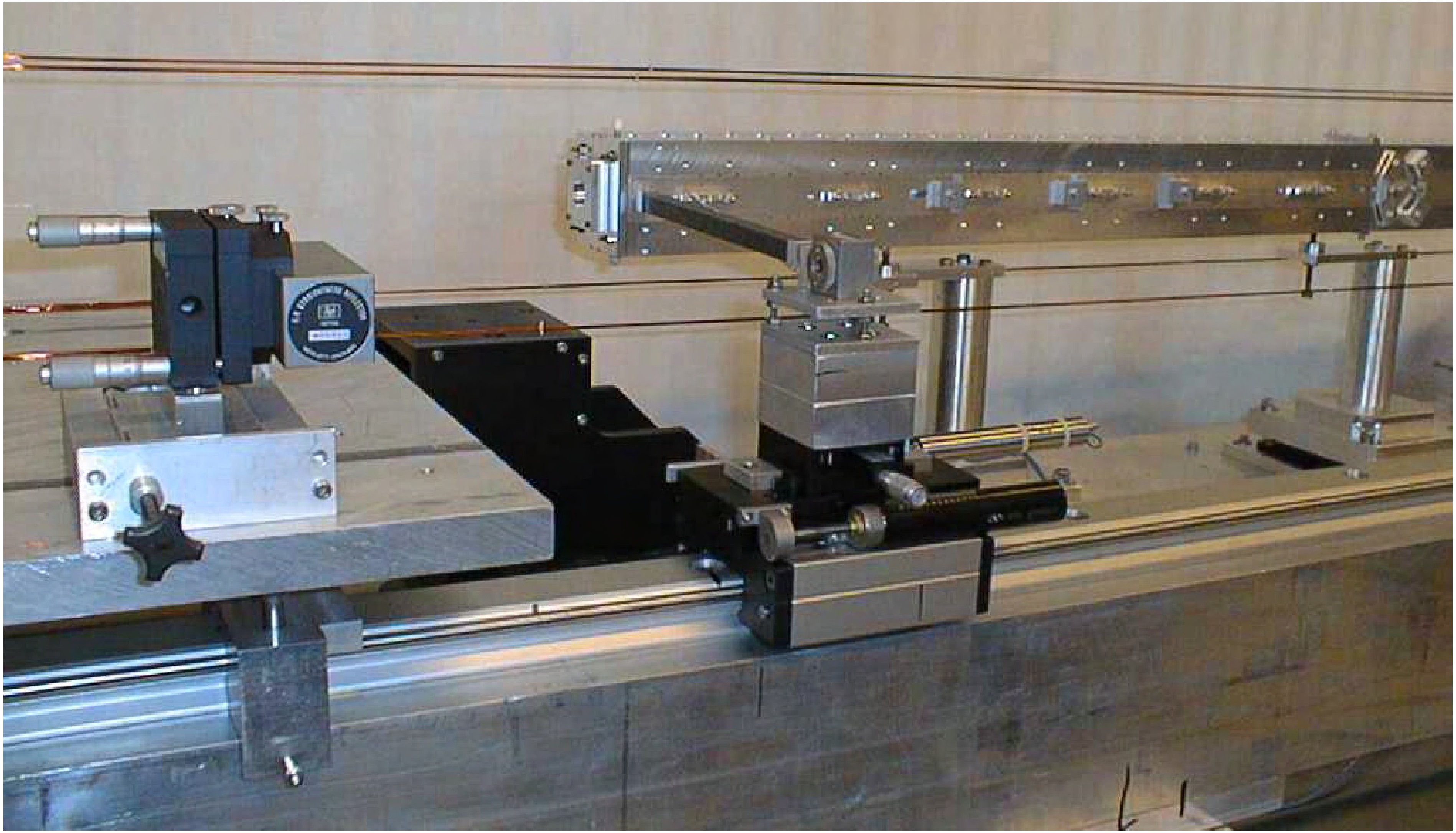
VISA Section #3; Normal (upright) orientation.
X and Y trajectories after shimming.

X & Y trajectories in VISA Section #3 after aligning Quadrupole modules (X) and shimming with external magnet blocks (Y).

For gradients of ~30 T/m, easily achieved centering accuracy of ±10 µm!

Fiducialization of VISA Sections Using Straightness Interferometer

REF.: R. Ruland, Proceedings IMMW-11, BNL, 1999



CONCLUSIONS

- As gaps of Insertion Devices approach mm scale, some magnetic measurement techniques become unworkable, due to size of devices. (Example: Integrating Coils)
- “Vertical” Hall sensors offer accurate, 3-axis, point field measurement in sub-mm probe geometries.
- Stretched-wire techniques (both TIME and FREQUENCY domain) can image 1st & 2nd integrals (angle & trajectory), and reconstruct the field along a line, in mm-scale apertures.
- Pulsed wire is a fast diagnostic of trajectory error, useful for trajectory shimming, end tuning (but not phase shimming).
- Pulsed wire can precisely locate magnetic axis of quadrupoles and higher multipoles, solenoids.