Magnet Alignment Challenges for an MBA Storage Ring*

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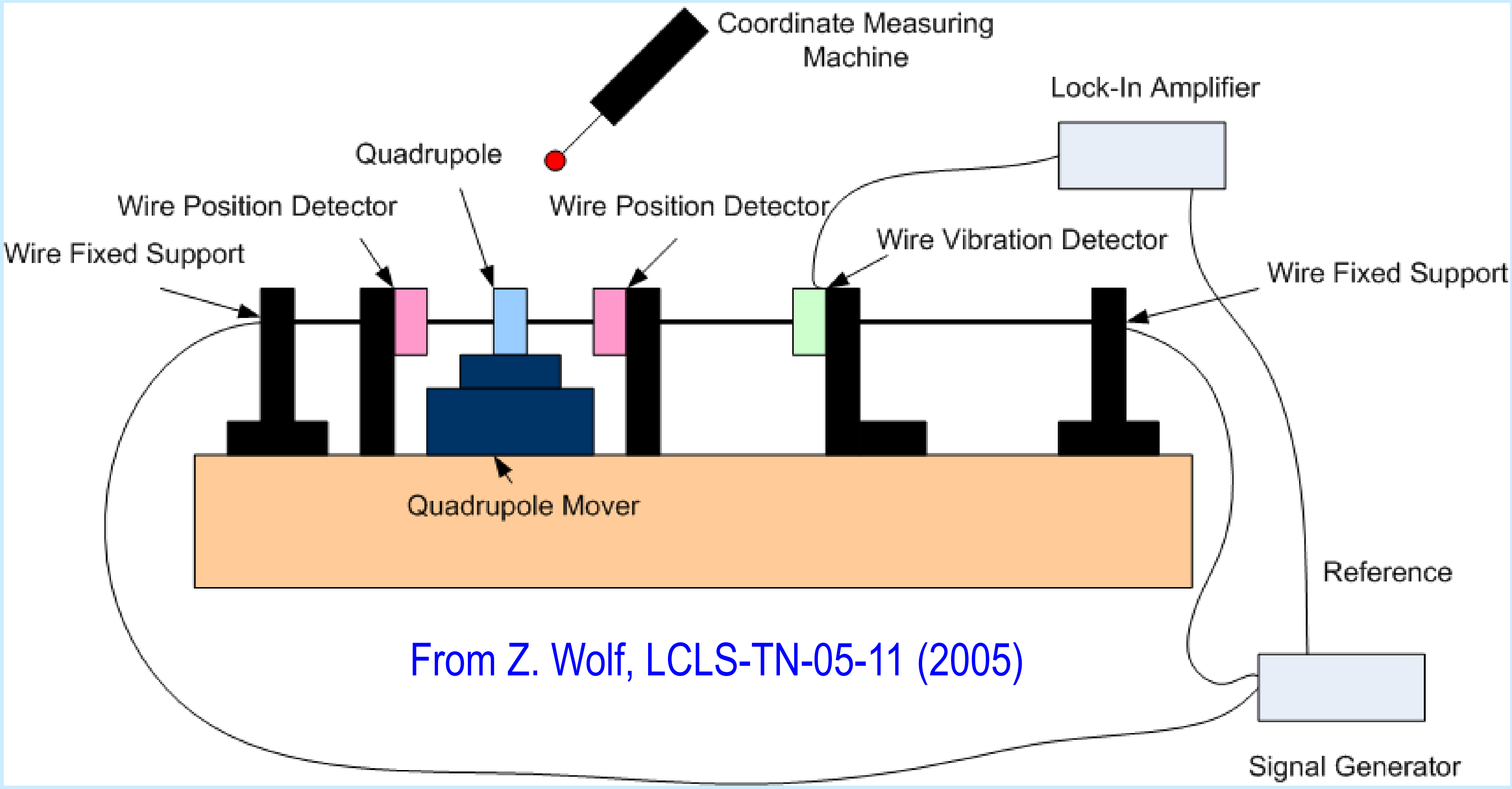
Outline

- Definition of “alignment” in the context of this talk:
  - The process of positioning multiple (>2) *physically disjointed* objects such that their magnetic centers lie on a desired curve.
- Alignment methods involving survey and/or mechanical precision, with or without the use of magnetic measurements:
  - Magnetic measurements to *fiducialize*, then survey to install
  - Magnetic measurements to *characterize*, then shim (?) to install
  - Alignment using manufacturing tolerances alone
- Direct alignment using magnetic measurements
- Special requirements for multi-bend acromat (MBA) storage rings.

Fiducialization of Magnetic Axis

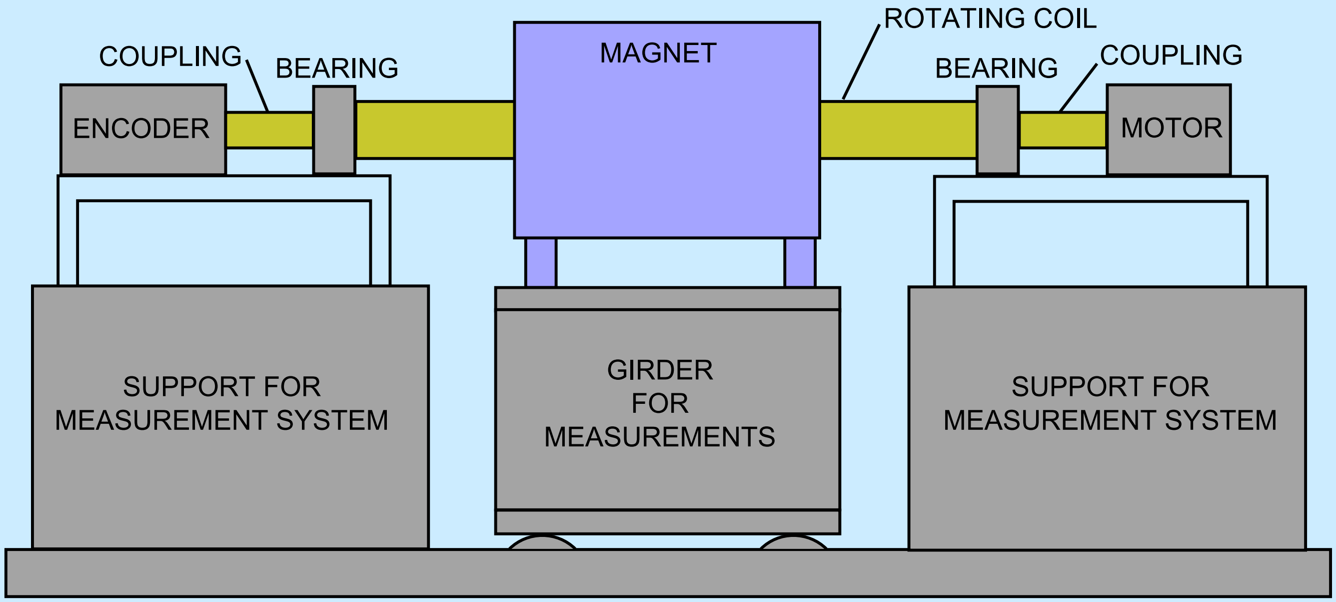
- Techniques such as rotating coils or wire based magnetic measurements (vibrating wire, stretched wire, …) of a single magnet element can measure the magnetic axis to within ±1-5 μm *in a coordinate system tied to the measurement probe*.
- But the probe itself must be located in relation to fiducials or reference surfaces of the magnet. This is typically carried out by survey. Errors may be ~10-25 μm, or more, depending on setup.
- Final installation may incur additional errors (e.g. by survey).
- Using magnetic measurements reduces uncertainty due to possible mismatch between the mechanical and magnetic axes.
- Stack up of errors may preclude alignment < ±25-30 μm. Still, the benefit is that no precise reference surfaces are needed.

Fiducialization: Vibrating Wire for LCLS



- Quadrupole is moved to align it with the wire (~ few microns)
- Wire is located to tooling balls on wire position detectors (~10 microns)
- Magnet fiducials are located to the wire (~15 microns)

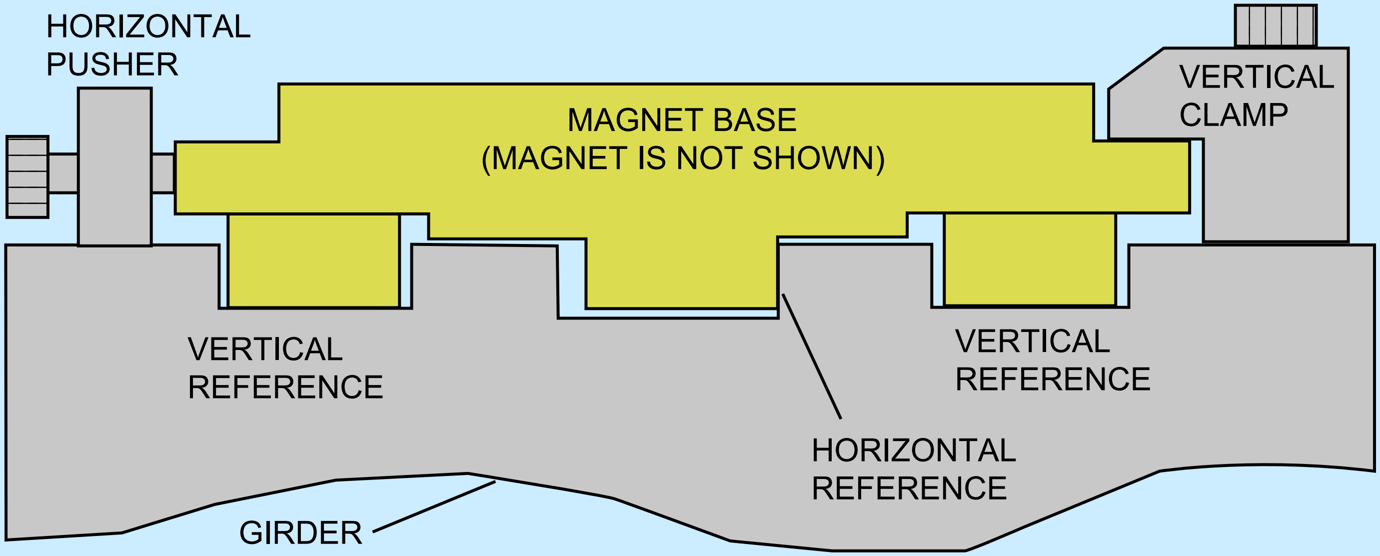
Characterization: Rotating Coil for SLS



Based on Antokhin et al., Nucl. Instrum. Meth. A 470 (2001) 11–17.

- Rotating coil axis precisely adjusted relative to reference surfaces on the girder.
- Magnet located to the girder using reference surfaces.
- Measurements verify that the magnetic axis is within specification.
- Mean offset of all magnets < 5 μm horizontal, < 10 μm vertical, Std. dev. < 20 μm.
- Several magnets installed on a girder using reference surfaces.

Alignment of SLS Multipoles on Girders



Based on Antokhin et al., Nucl. Instrum. Meth. A 470 (2001) 11–17.

- Magnet axis is verified to be within specification in relation to the reference surfaces by magnetic measurements.
- Installation of several magnets on a girder is done entirely based on reference surfaces. This allows easy alignment of several magnets.
- It is possible to use shims if the axis is found to be too far off from nominal.

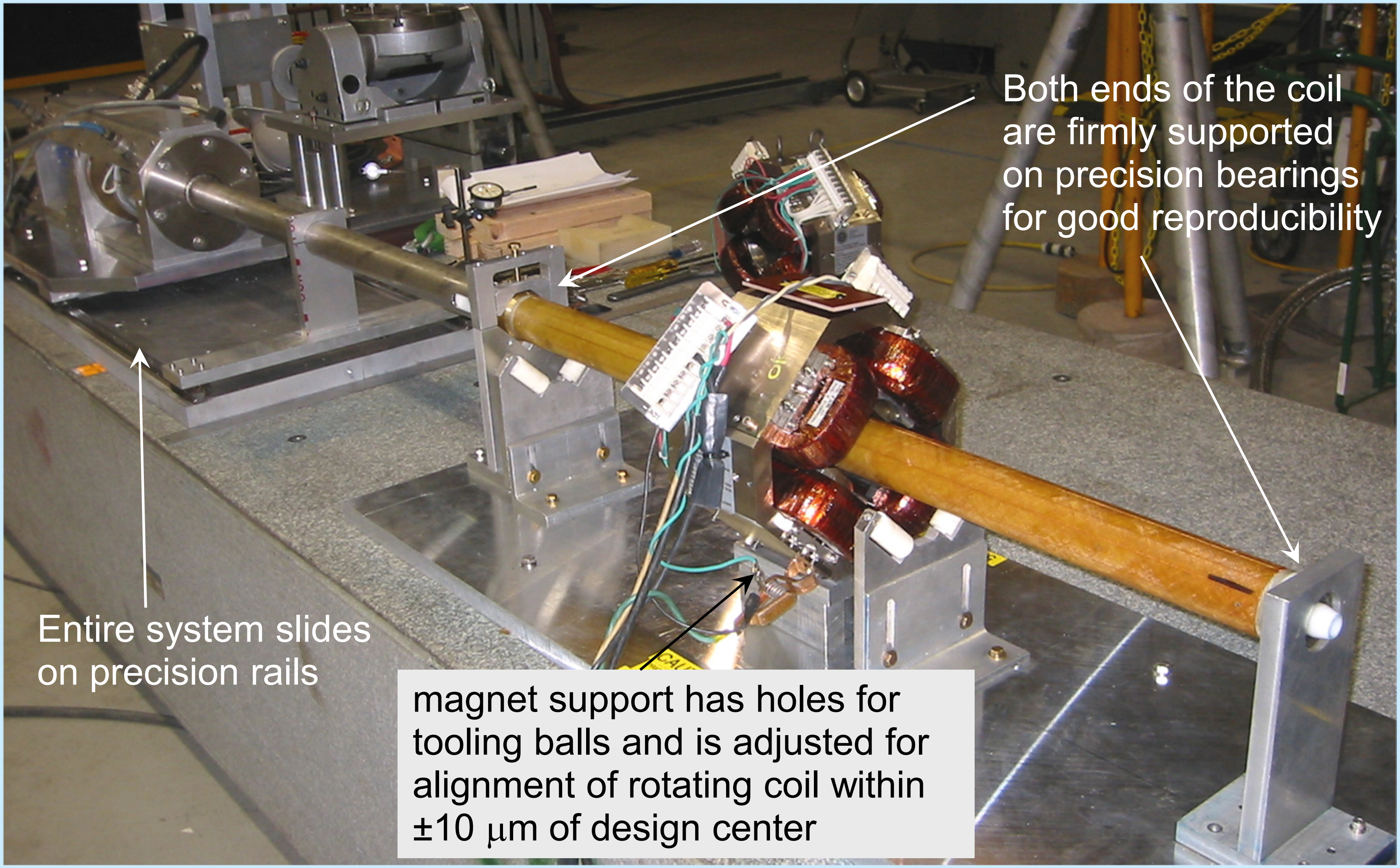
Purely Mechanical Alignment

- It may be argued that in a well built magnet (good field quality), the magnetic and mechanical axes must coincide.
- It should, therefore, be possible to skip fiducialization, or a verification using magnetic measurements.
- A purely mechanical alignment does require precision machined surfaces on all magnets, as well as on long and massive support structures, similar to those used for SLS.
- Since magnets are to be machined to high precision anyway, it may not be too expensive to add precision reference surfaces.
- Surfaces with ~10 μm accuracy over long lengths, however, may add significant cost and limit the pool of possible vendors.

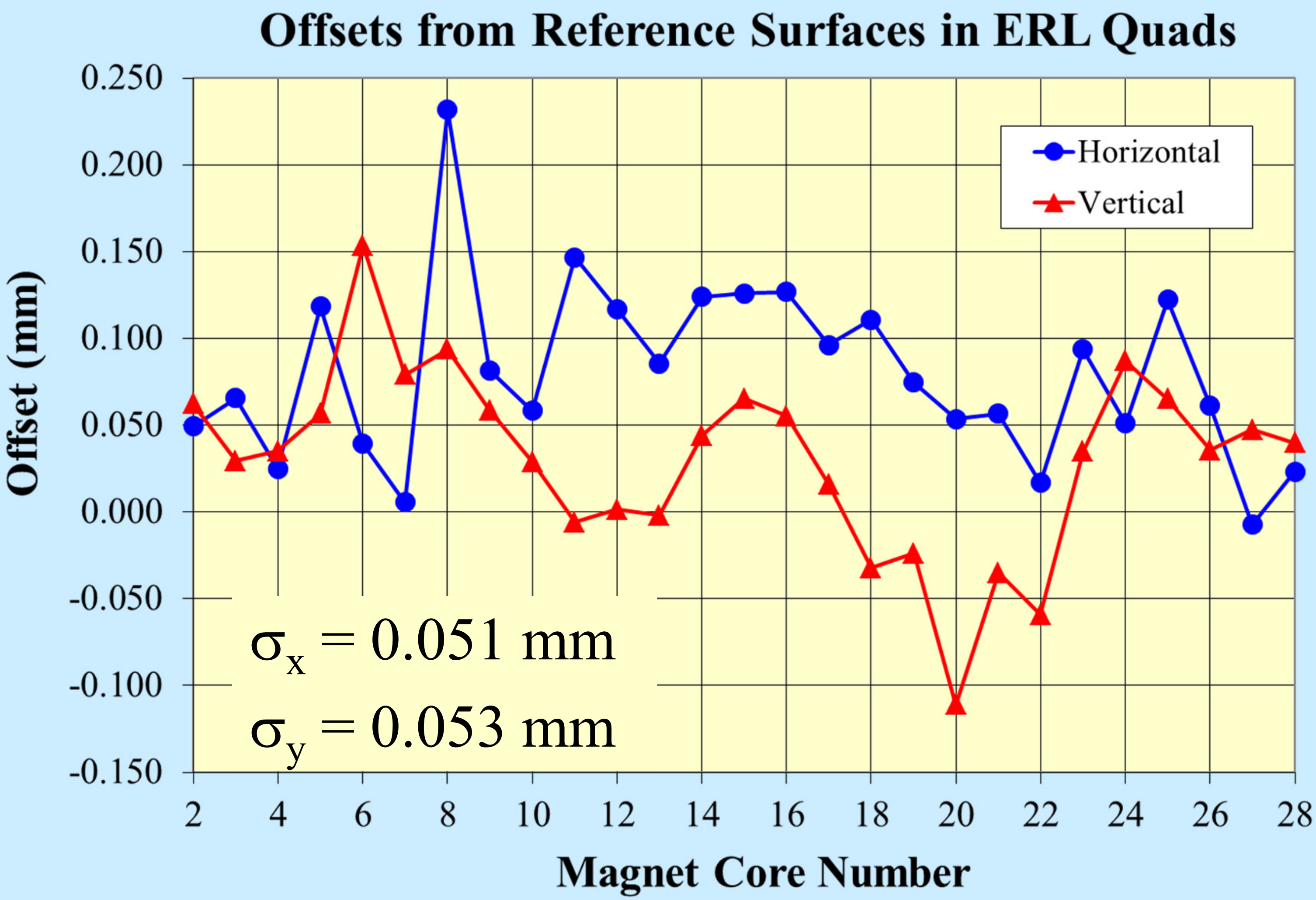
Mechanical Vs. Magnetic Axes

- While the definition of magnetic axis is less ambiguous, there is no unique definition of the mechanical axis of an as-built magnet
  - Option 1: Define as a fixed offset from reference surfaces
    - Easy to use; no ambiguity; but really only pole positions matter
  - Option 2: Define somehow based on survey of individual poles
    - Tedious; complex pole profiles not very suitable to work with; subject to data analysis procedures; not too useful for aligning.
- While good agreement between mechanical and magnetic axes is reported in some cases (e.g. SLS), counter examples exist.
- It may be prudent to confirm the validity of this agreement in a specific production before deciding on a purely mechanical alignment, specially if tight alignment tolerances are needed.

Example: Quadrupoles for BNL ERL

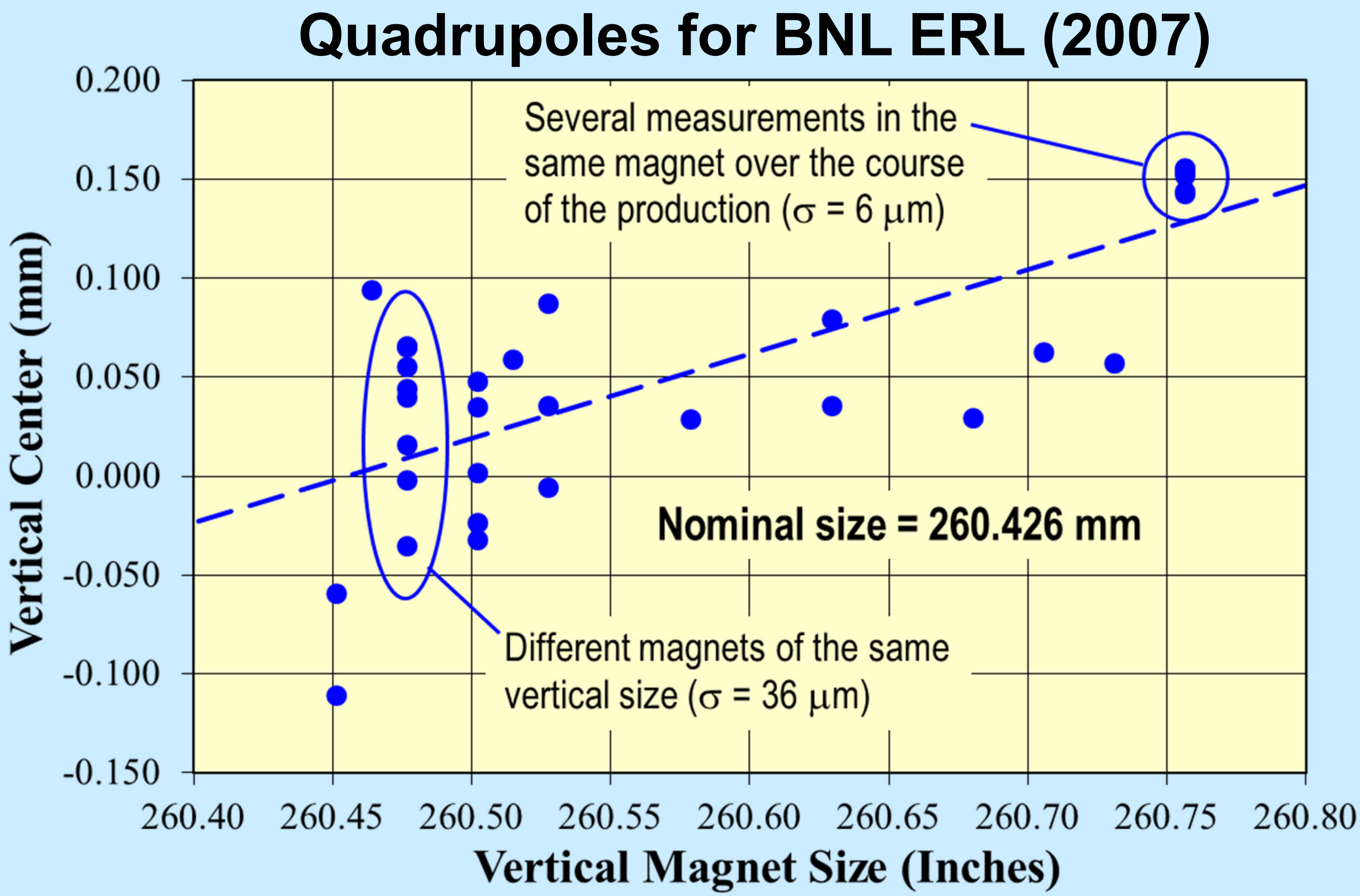


Measured Offsets in ERL Quadrupoles



The vertical offset shows some correlation with magnet vertical size

Y-Offset Vs. Magnet Vertical Size



Summary: Mechanical/Survey based Alignment

- Alignment using survey:
  - Does not require special precision machined reference surfaces.
  - Requires the magnet fiducials to be related to the magnet center (either magnetic or mechanical).
  - Alignment at ~30 μm level of several elements on a common support spanning several meters may be possible, but not easy.
- Alignment using precision reference surfaces:
  - Aligning several elements on a common support is straightforward.
  - Requires precision machining of each magnet element as well as of long, massive support structures that should not deform easily.
  - Magnetic and mechanical axes must show good agreement.

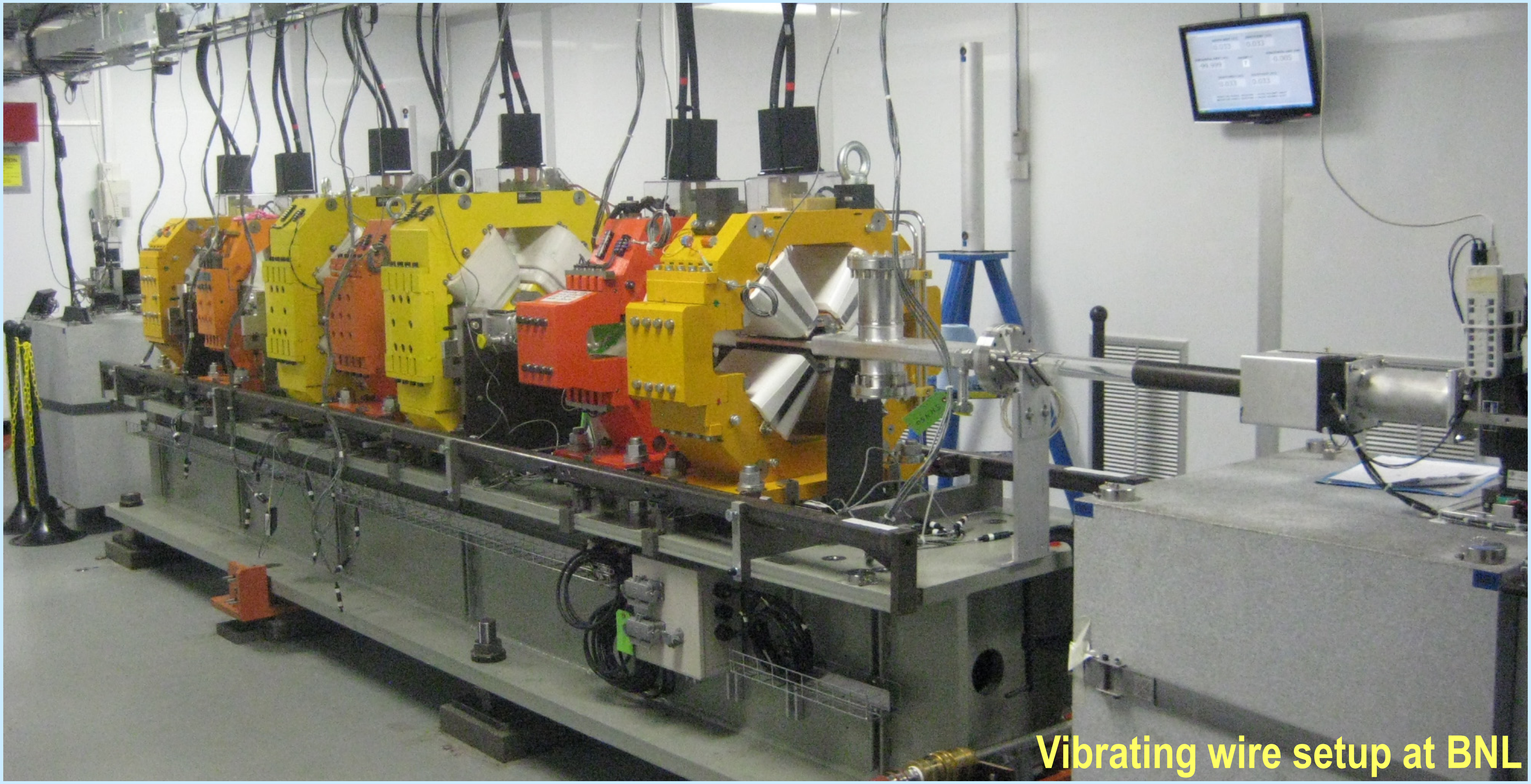
Direct Magnetic Alignment

- Magnets may be aligned directly to each other using magnetic measurements. This offers some advantages:
  - No need to fiducialize magnets, no stack up of errors
  - No need for precision reference surfaces
  - Support structure requires no precision manufacturing (cheap)
  - Mechanical vs. magnetic axes is irrelevant (less R&D & monitoring)
- Requires a wire based measurement technique, and is thus most suitable for straight assemblies up to ~5 m long.
- Requires temporary fixtures to move and secure magnets.
- Most frequently voiced concern is that it is too expensive, or too time consuming (not necessarily well founded!)

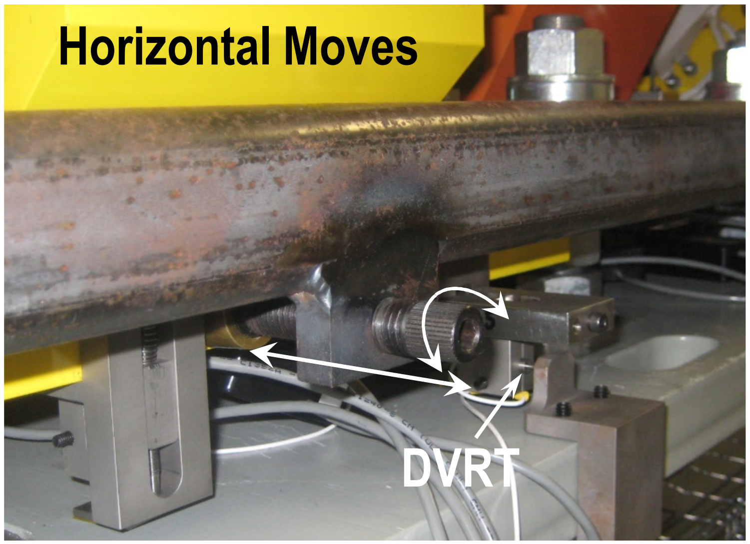
Wire Based Measurement Techniques

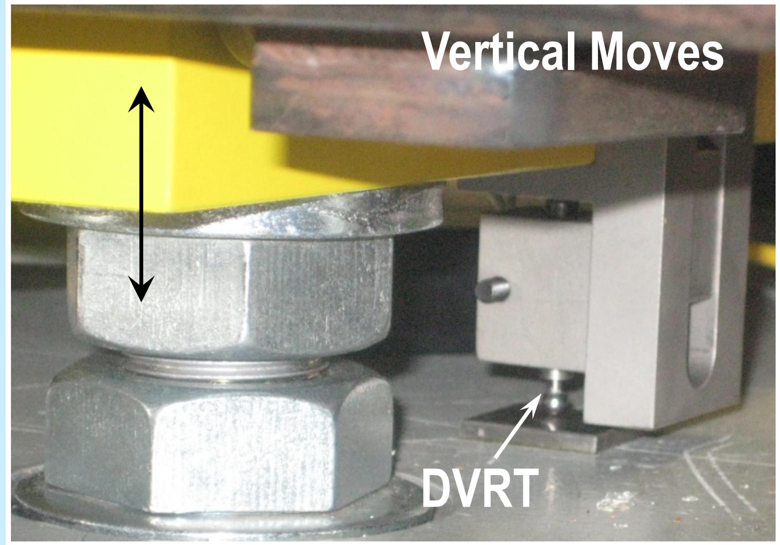
- Stretched Wire
  - The wire is moved across the aperture and the change in flux is measured. The axis is derived from a set of measurements with different wire motion paths. (Accuracy ~2-5 μm; time ~ ½ hr)
- Vibrating wire
  - An AC current of a frequency matching a resonant mode of the wire is passed through the wire. This causes the wire to vibrate with an amplitude proportional to the field strength.
  - Vibration amplitudes are analyzed as a function of wire position to derive the magnetic axis. (Accuracy ~2-5 μm; time ~ ½ to ¾ hr)
- Rotating wire (not yet well established, but promising)
  - A single wire is used as a rotating coil. (Accuracy ?; time ~ ¼ hr)

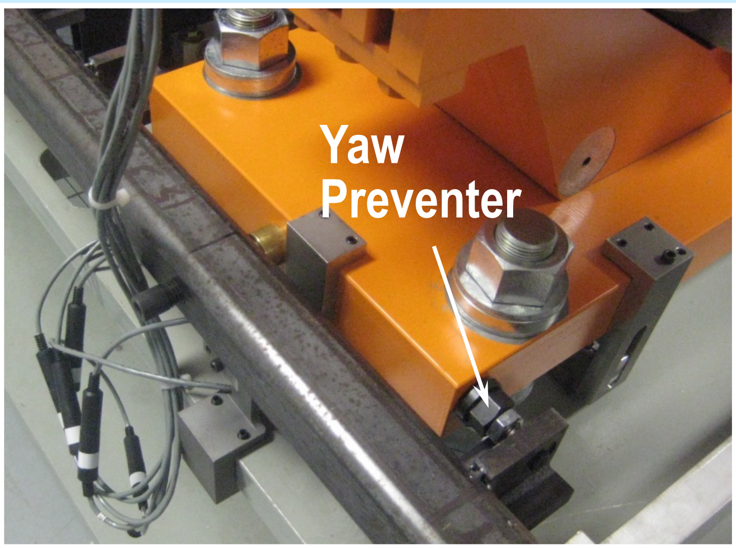
A NSLS-II Girder Undergoing Alignment

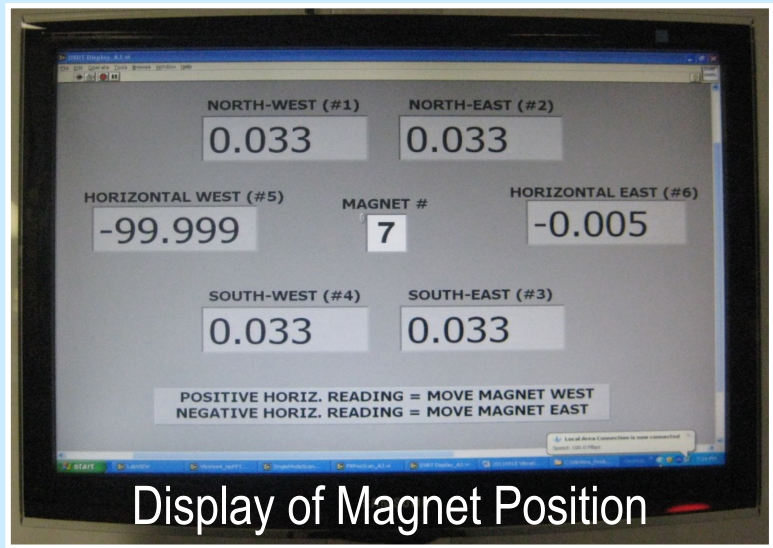


Adjusting Magnet Position









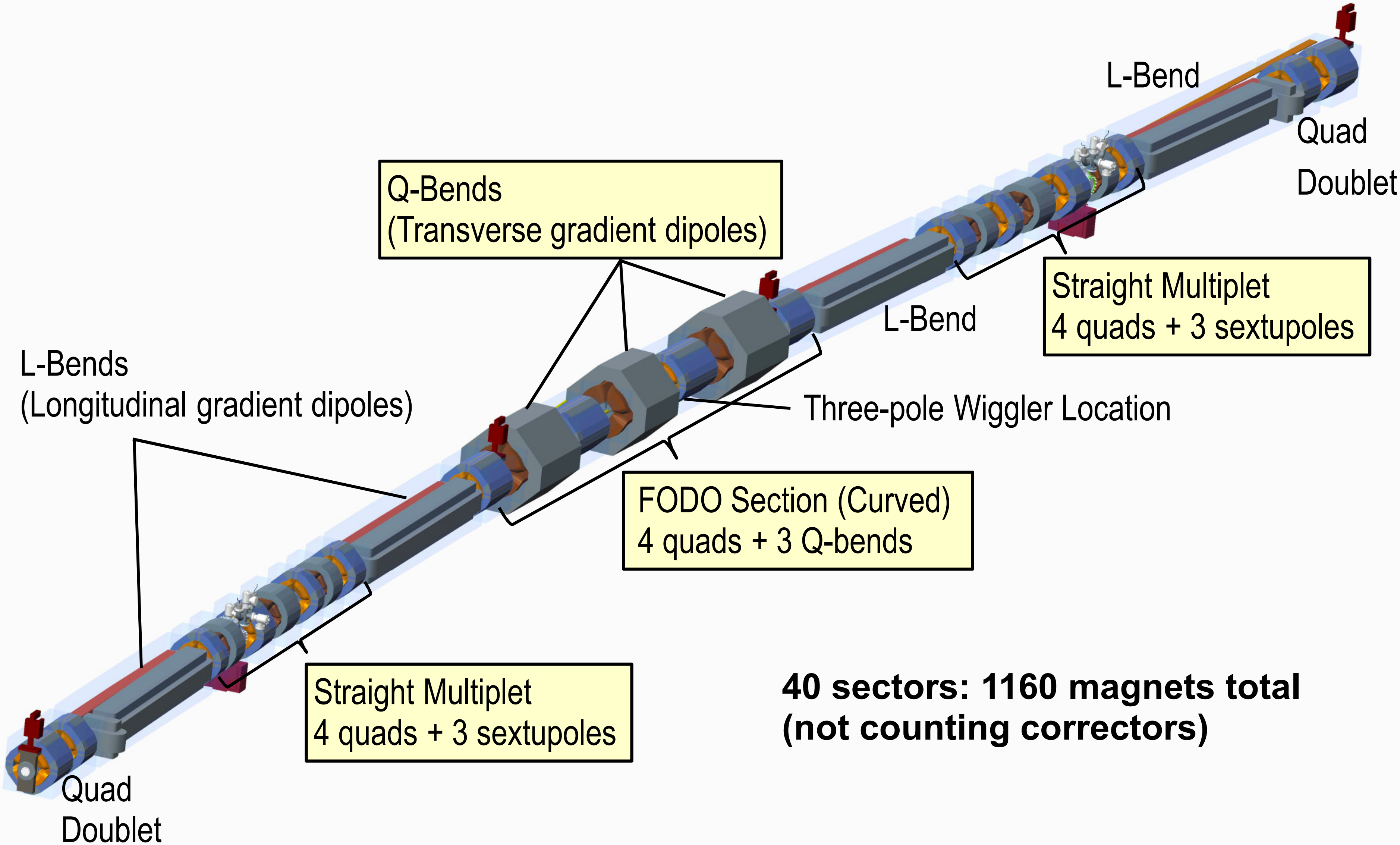
Summary of Magnetic Alignment

- Magnetic alignment provides the best assurance that magnets are aligned to the required tolerance, or better.
- Direct alignment using a wire based technique saves the effort to fiducialize individual magnets, or the cost of precision reference surfaces. It also avoids error stack up.
- But there are a few drawbacks:
  - Measurements can be time consuming (can be reduced significantly by developing techniques such as a rotating wire).
  - Moving magnets precisely and securing them to the girder requires small moves, and could be time consuming for large moves.
  - Girder must be very rigid, or the profile must be reproduced.
  - Readily applicable to straight assemblies only.

Multi-bend Acromat Storage Rings

- Multi-bend acromat (MBA) designs for the low emittance rings contain several bending elements per cell, and a large number of magnets packed closer together.
- One obvious challenge is that there are many magnet elements to align, and any technique used must be cost effective.
- The presence of many bending elements may mean that not all magnets within a “logical group” are arranged in a straight line.
- The MBA designs also feature combined function magnets where both the field and the field gradient are very high. These magnets pose a unique alignment challenge, not encountered in the traditional Double Bend Achromats (DBA).

Example: APS Upgrade Sector Layout



40 sectors: 1160 magnets total (not counting correctors)

Straight Sections in MBA Lattice

- If only multipoles are to be aligned on a straight line, these assemblies are similar to existing machines and any of the alignment techniques described earlier may be used.
- The choice of which method to use depends on several factors:
  - Prior experience and resources available for magnetic alignment.
  - Level of agreement between mechanical and magnetic axes.
  - Availability and cost of high precision (~10 μm) machining.
- Perhaps a good compromise could be (?):
  - Align based on precision reference surfaces, but verify magnetically (also gives "assembly axis"); shim only larger than acceptable offsets (> 30 μm, say; hopefully in rare cases).

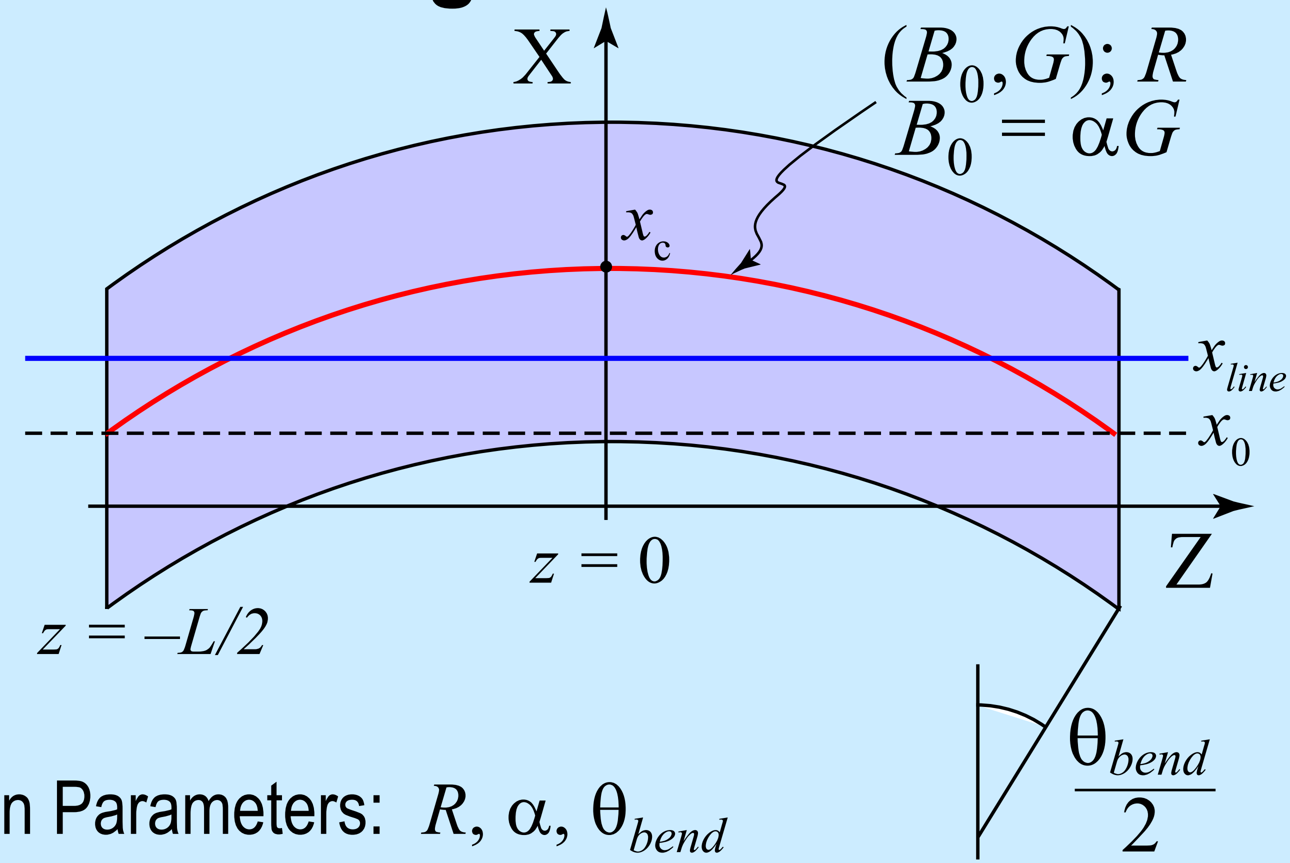
Curved Sections in MBA Lattice

- Several bending and focusing elements are closely interleaved in some sections, e.g., the central FODO section for the APS upgrade. The bending elements may have strong gradients too.
- An assembly of reasonable length may consist of at least one bending element.
- The alignment of the bending element may also be critical due to strong transverse gradients:
  - Example (APS-U): 100 μm misalignment ~ 0.8% bending error
- There is no well established technique to find the axis of a curved magnet at the level of precision needed (~10-15 μm).
- R&D is needed to develop procedures for curved magnets.

Options for Curved Sections

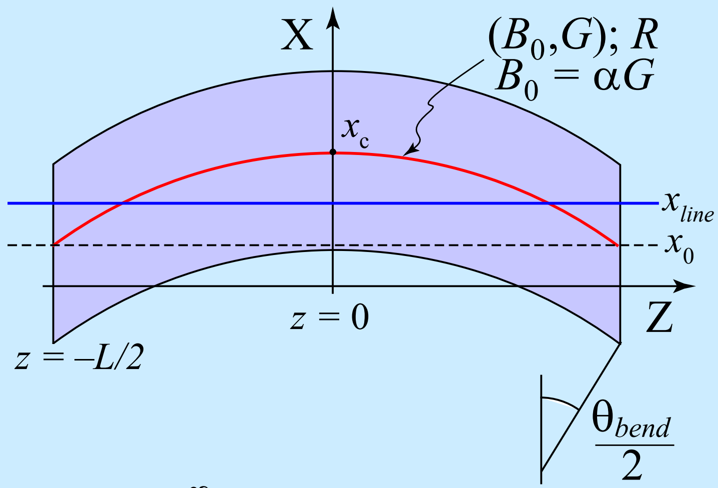
- Standard technique applicable to measurement of curved sections is to use a Hall probe system with precision stages.
- Hall probe element can be located in the stage coordinate system using a magnetic pin, for example. But this involves accurate knowledge (survey) of the pin location.
- The magnet can be mapped using Hall probe, and the axis derived, provided there is easy access for the Hall probe holder.
  - Easier to do with an open side design (e.g. ESRF design)
  - Achievable accuracy may not be sufficient; also time consuming.
- Another option is to measure along straight lines using a wire, and apply appropriate offset (to be developed, ESRF inspired).

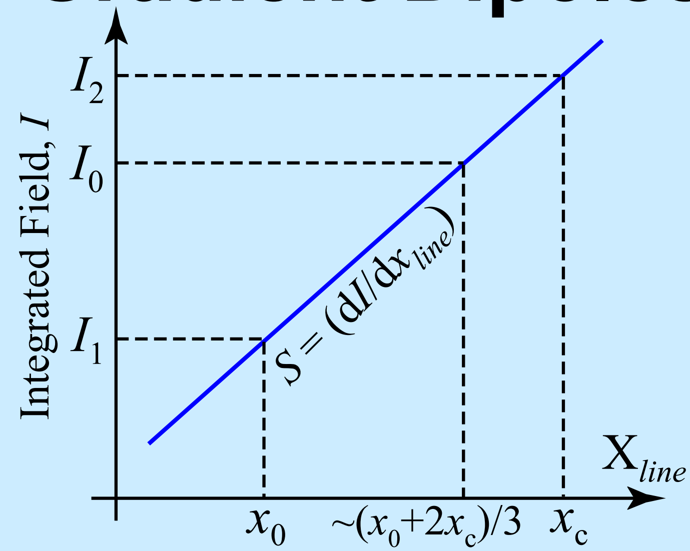
Straight Line Integration in Gradient Dipoles



- Known Parameters: R, α, θ_{bend}
- Integration path assumed parallel to tangent at x_c (General case is to be investigated)
- Goal is to locate the point x_c for a given magnet setting.

Straight Line Integration in Gradient Dipoles





$$I(x_{line}) = \int_{-\infty}^{\infty} B_y(x_{line}, z) \cdot dz$$

$$I = S\left[x_{line} - x_0 + \alpha + R\left\{\cos\left(\frac{\theta_{bend}}{2}\right) - \frac{\theta_{bend} + \sin\theta_{bend}}{4\sin(\theta_{bend}/2)}\right\}\right]$$

$$I_1 = S\left[\alpha + R\left\{\cos\left(\frac{\theta_{bend}}{2}\right) - \frac{\theta_{bend} + \sin\theta_{bend}}{4\sin(\theta_{bend}/2)}\right\}\right] \approx S\left[\alpha - \frac{R\theta_{bend}^2}{12}\right]$$

$$I_2 = S\left[\alpha + R\left\{1 - \frac{\theta_{bend} + \sin\theta_{bend}}{4\sin(\theta_{bend}/2)}\right\}\right] \approx S\left[\alpha + \frac{R\theta_{bend}^2}{24}\right]$$

Integral along curved trajectory:

$$I_0 = S\frac{\alpha\theta_{bend}}{2\sin(\theta_{bend}/2)}$$

$$\approx (S\alpha)\left[1 + \frac{\theta_{bend}^2}{24}\right]$$

Fiducializing Curved Gradient Dipoles

- Install magnet on a wire based measurement bench such that the wire is parallel to the tangent to the nominal trajectory at the axial midpoint of the magnet.
  - Based on mechanical measurements or reference surfaces
- Measure integrated field (e.g. using rotating wire) as a function of transverse position. The slope of a straight line fit gives roughly the integrated gradient (may correct for finite bending).
- Compute the integrated field expected when the wire is tangent to the nominal trajectory, and interpolate the tangent point (x_c).
- Use this information to install the magnet by survey, or to align to adjacent multipoles using the same wire setup.

Summary

- Alignment methods used in the past range from purely mechanical to purely magnetic alignment.
- Mechanical alignment offers ease of installation, but requires precision machined surfaces on all magnets, as well as on long support structures. Magnetic alignment is not guaranteed.
- Direct magnetic alignment offers the best assurance of good alignment without requiring precision machined surfaces.
- Multi-bend achromats contain many more magnets. Method used should be the fastest, while ensuring alignment tolerance is met.
- Curved gradient dipoles pose the maximum alignment challenge, requiring new alignment procedures to be developed.