Plans for Measurement of Field Straightness in the Solenoids for the Electron Lens System for RHIC*

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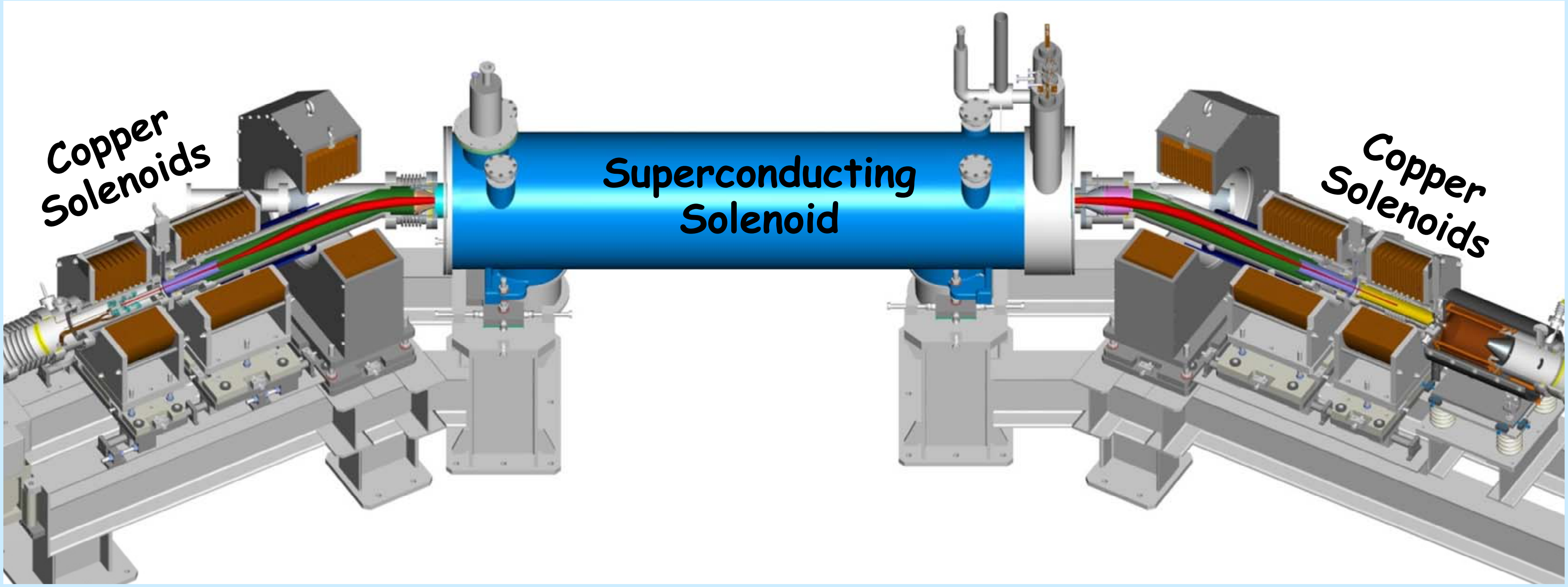
Introduction

- The Head-on Beam-Beam Compensation Project for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) requires two superconducting 6 T solenoids.
- These 2.5 m long, 200 mm aperture solenoids were designed, and are now under construction, at BNL.
- The electron and proton beams must remain aligned to each other within <50 microns as they pass through the solenoid.
- This places stringent requirement on the straightness of field lines in the solenoid, at least near the axis and away from ends.
- Precise measurements of the field straightness are required to characterize the magnets, and to make the corrections.

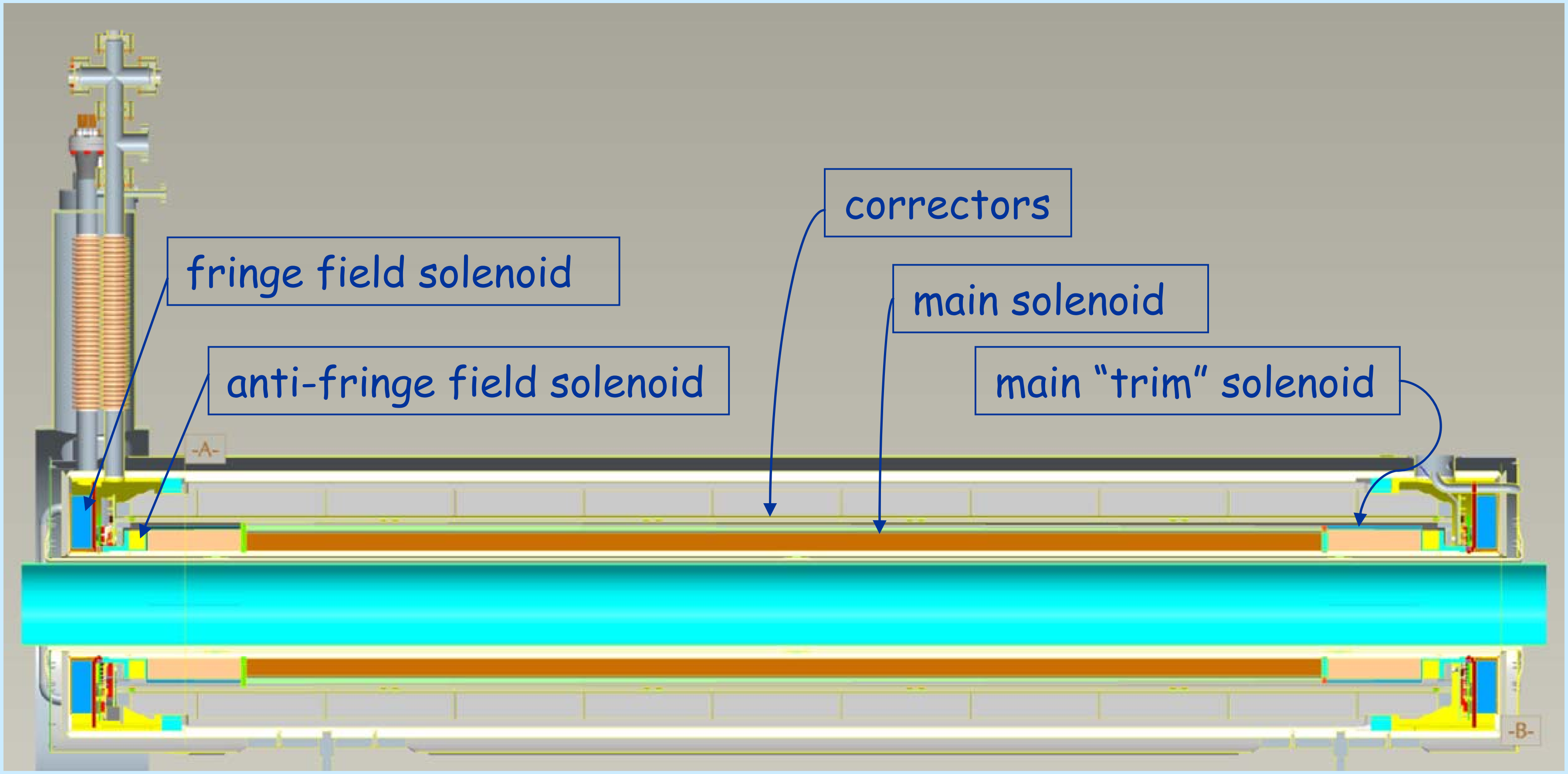
Layout of the eLens Solenoid System



Electron beam goes through the copper and the superconducting solenoids

The proton beam goes straight through the superconducting solenoid.

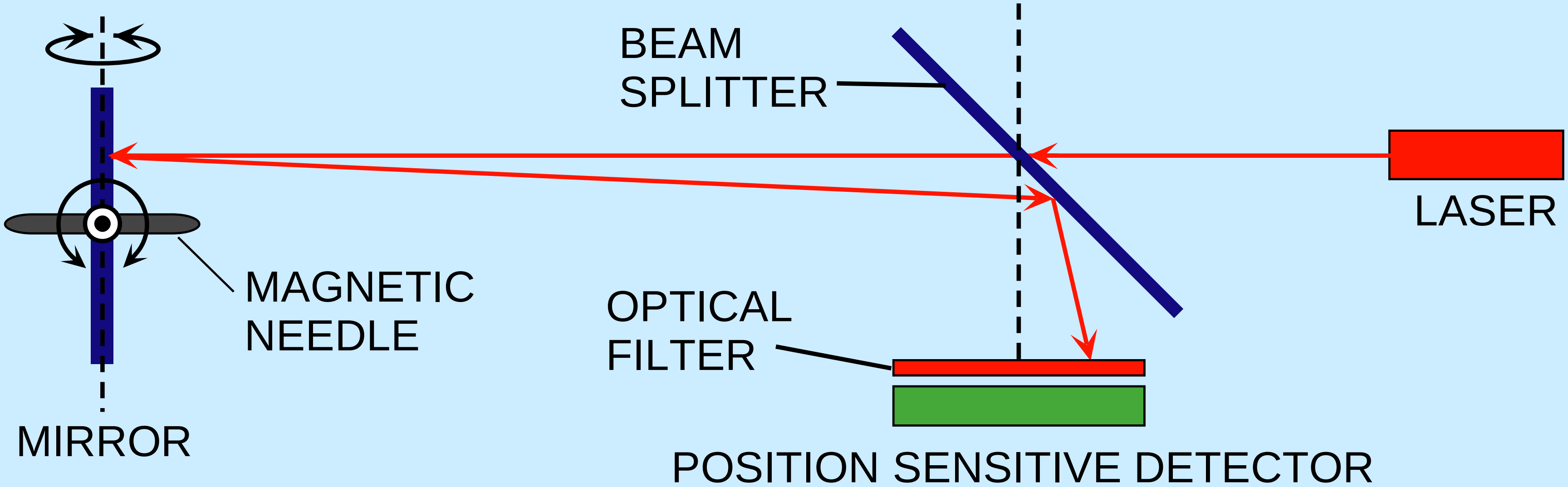
eLens Superconducting Solenoid



Fringe field solenoids provide >0.3T field outside solenoid to guide the electron beam between the copper solenoids and the main superconducting solenoid.

The anti-fringe field solenoids preserve field uniformity inside the main solenoid.

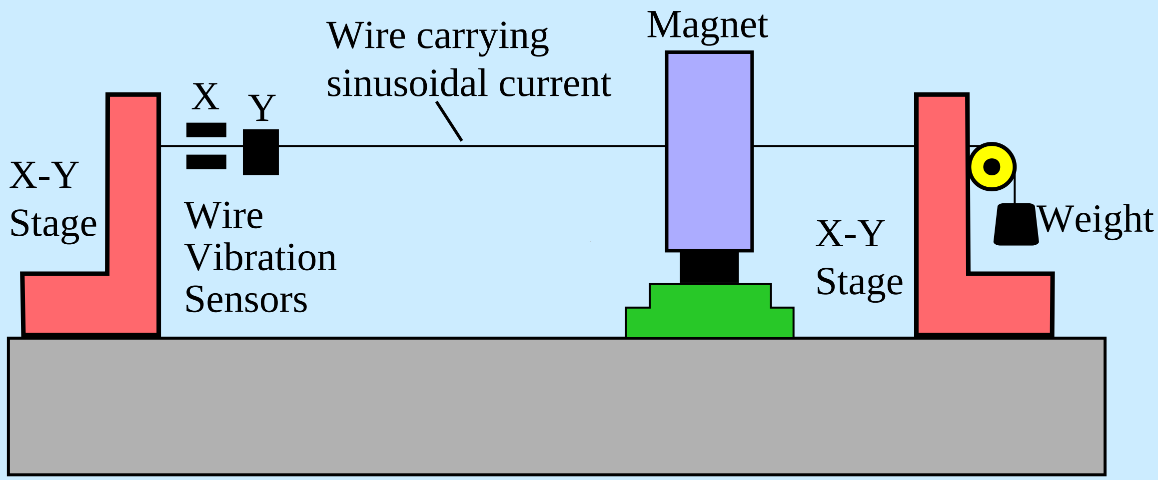
Measurements of Field Straightness



(Based on *C. Crawford et al., FNAL and BINP, Proc. PAC'99, p. 3321-3*)

- “Needle-and-mirror” method has been used in the past at other laboratories, but there was no experience at BNL in using this.
- Our initial plan was to develop the vibrating wire technique, well established for multipoles, for straightness measurements.

The Vibrating Wire Applied to Solenoids: Basics



- An AC current is passed through a wire stretched axially in the magnet.
- Any transverse field at the wire location exerts a periodic force on the wire, thus exciting vibrations.(in solenoids: Offset, Tilt, **Bending of field lines**.)
- The vibrations are enhanced if the driving frequency is close to one of the resonant frequencies, giving high sensitivity.
- The full profile of transverse field as a function of axial position can be reconstructed by measuring amplitudes for many modes of vibration.

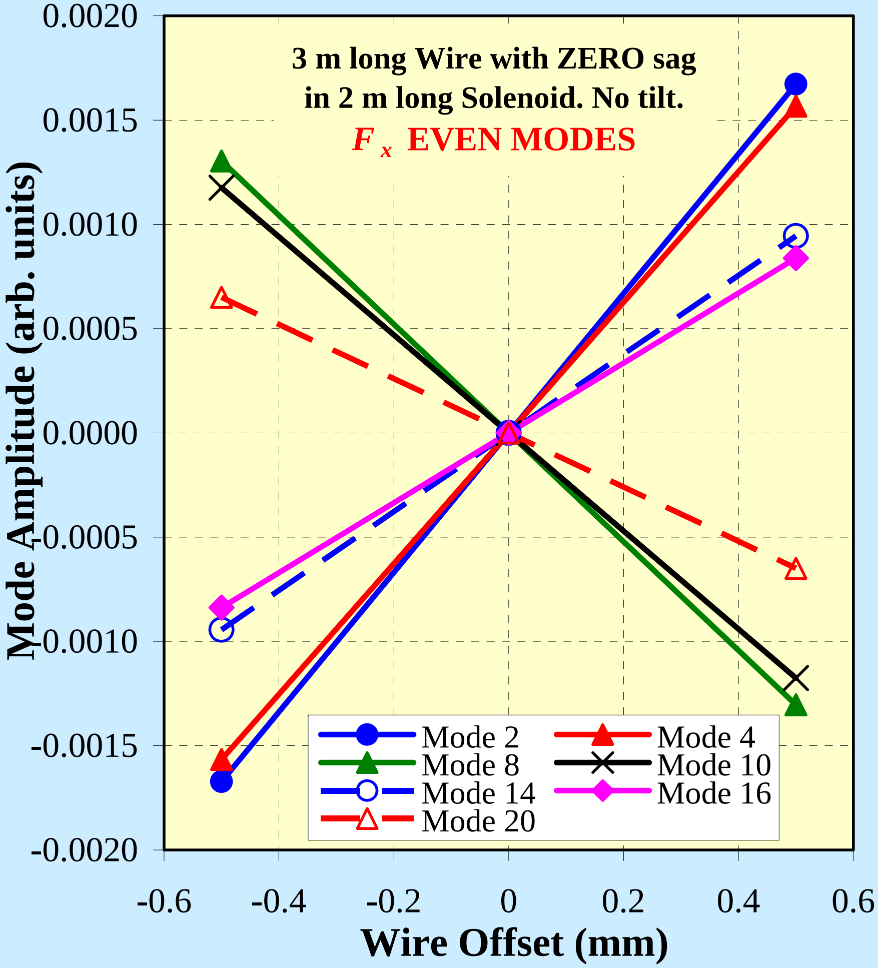
Vibrating Wire in Solenoids

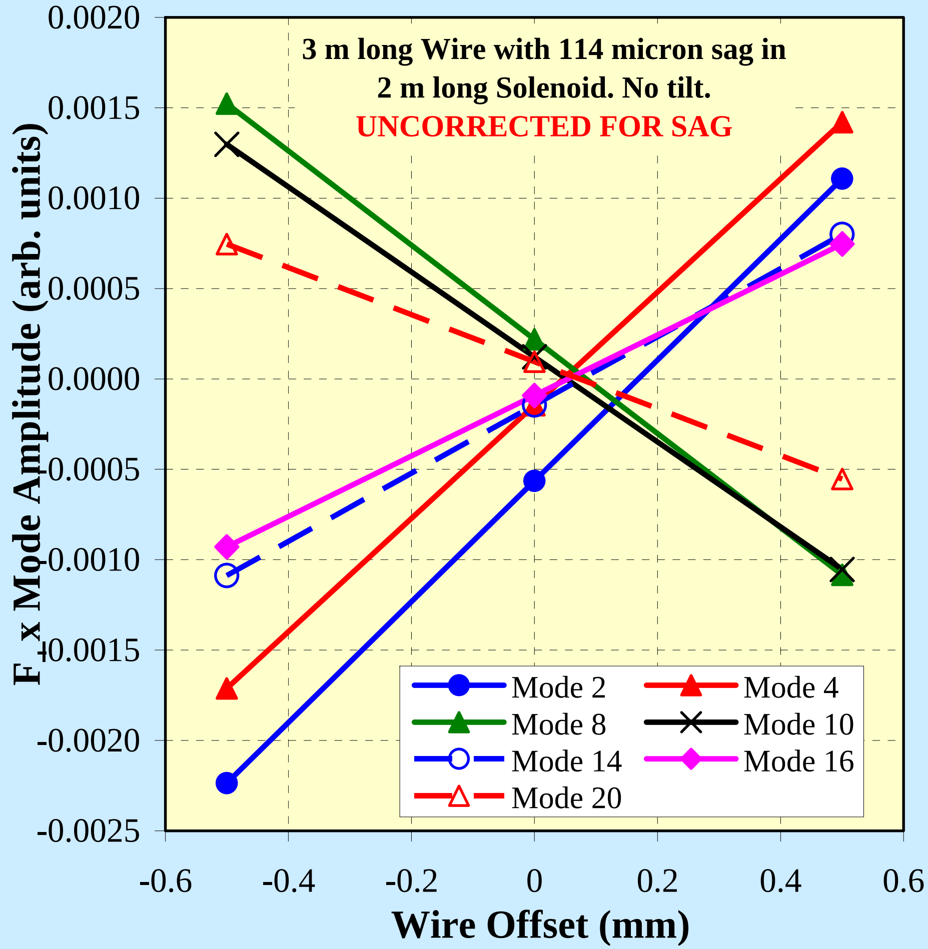
- The concept of using the vibrating wire in solenoids is not new.
- Finding axis of short solenoids (~0.3 m long) has been reported as early as IMMW14 (2005) by A. Temnykh of Cornell University.
- A precision of ~10 microns in offset and 0.2 mrad in tilt has been demonstrated, corresponding to transverse fields of well below 1 micro-Tesla. (or < 1 μrad in >1 T field!)
- Despite potentially very good resolution, application to the electron lens solenoid for RHIC poses many new challenges:
  - Effect of large sag (~300 microns) of ~5 m long wire
  - Very high order modes are needed to measure the full profile
  - How to separate offset/tilt/sag from a local bending of field lines?
  - Large fringe field outside the solenoid.

Simulations to Study Difficulties

- To help understand, and quantify the nature of potential difficulties in using the vibrating wire technique, simulations were carried out in solenoid fields both with and without field straightness errors, and both with and without wire sag.
- These studies were carried out very early in the program, and are not with the final design of the solenoid, or wire length. However, the general conclusions should still be valid.
- Transverse force profile was computed analytically along the wire (with or without sag), and decomposed into modes.
- Solenoid with errors was modeled as a sequence of 50 short solenoids, each with a different offset and tilt in such a way that a long solenoid with known bending (~±0.2 mm max) was generated.

Solenoid Axis: Perfect Solenoid

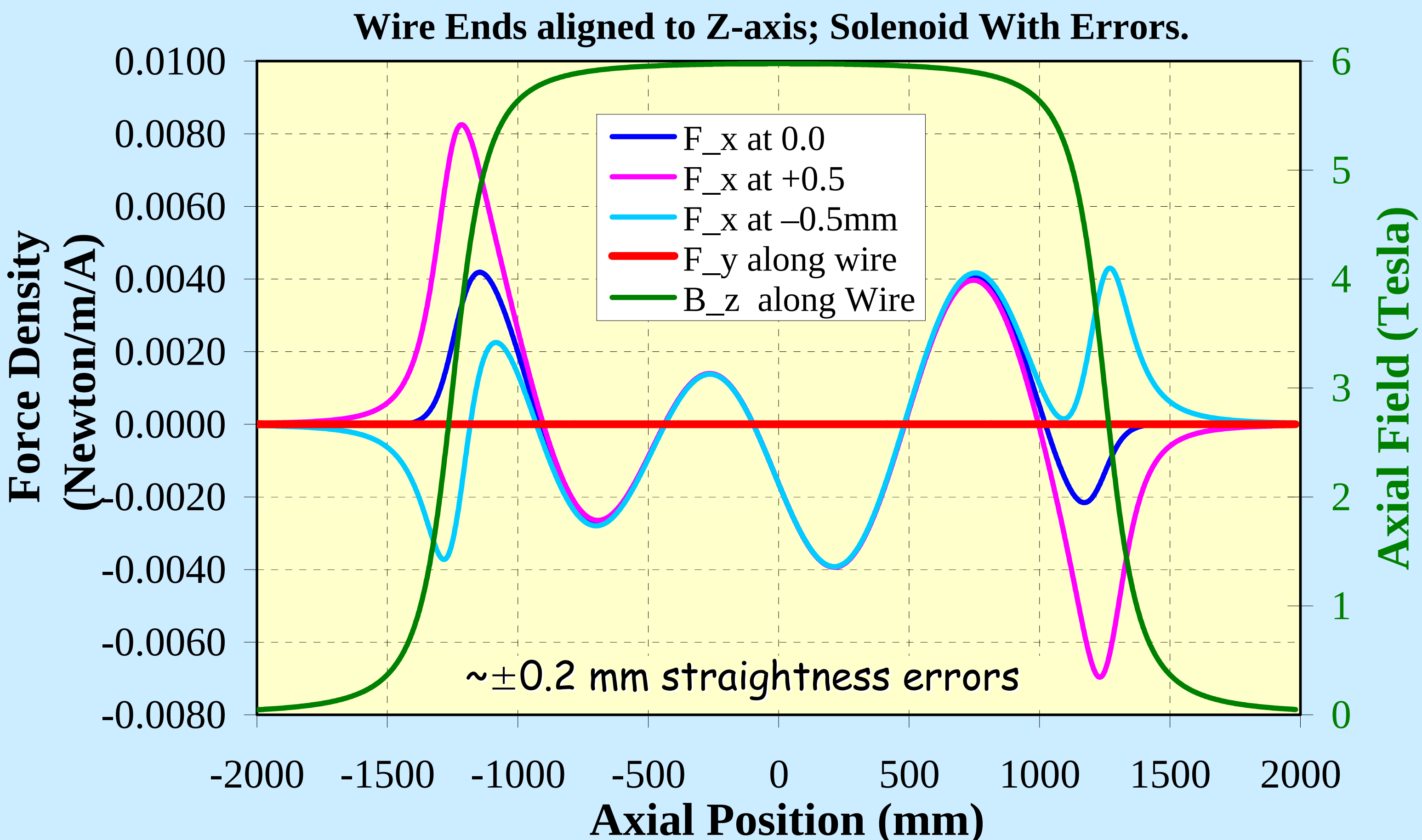




Solenoid axes found from different modes are inconsistent in presence of sag!
Must compute, and then correct for the effect of the sag. How to do this?

Solenoid with Errors: Zero Sag

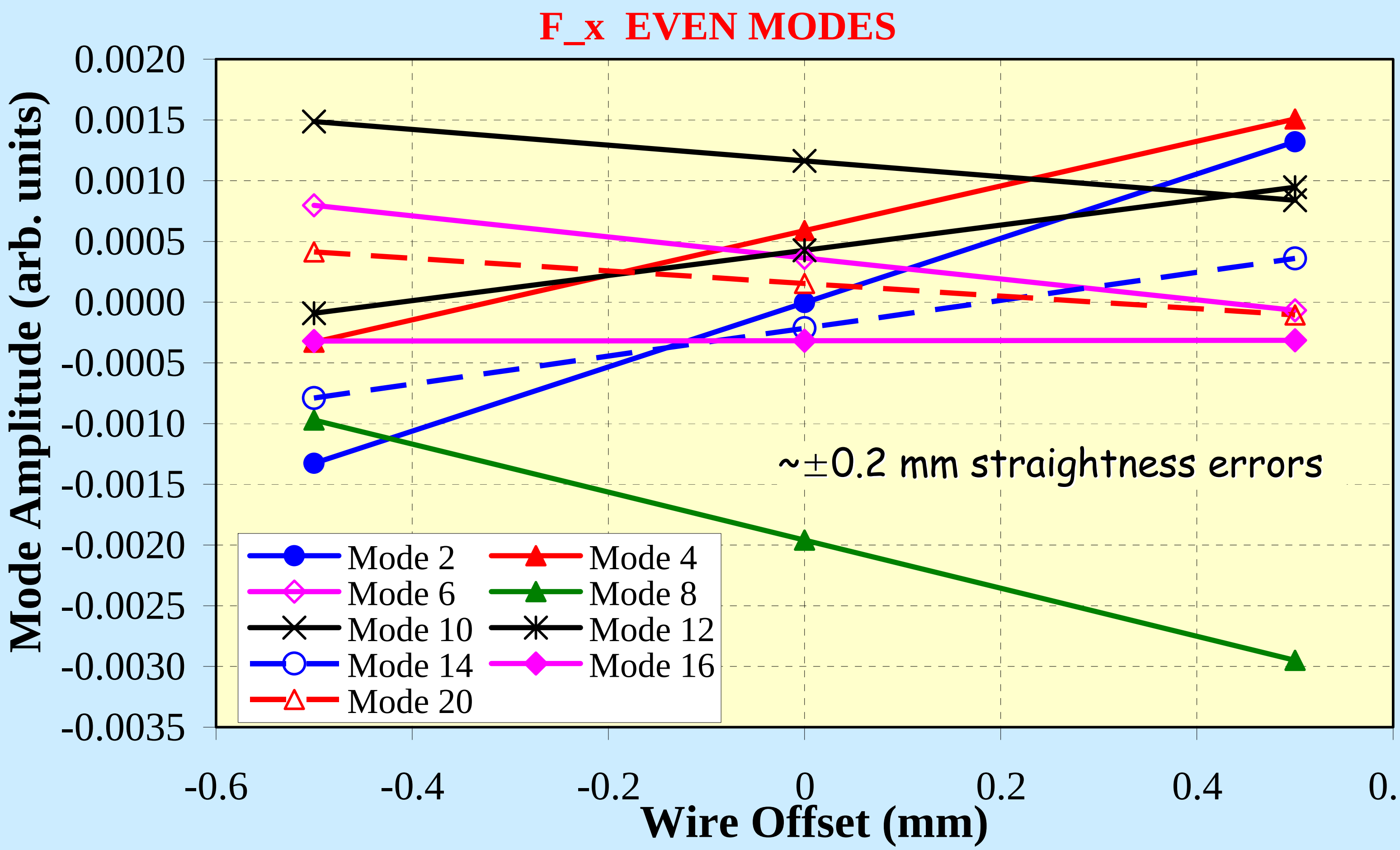
Force Components along a wire with ZERO sag; 2.5 m, 6 T, 270mm ID solenoid



Even with zero sag, the force profile loses its symmetry if the solenoid axis is not perfectly straight. This causes various even modes to have non-zero amplitude, even when the wire is aligned to the solenoid "on-an-average".

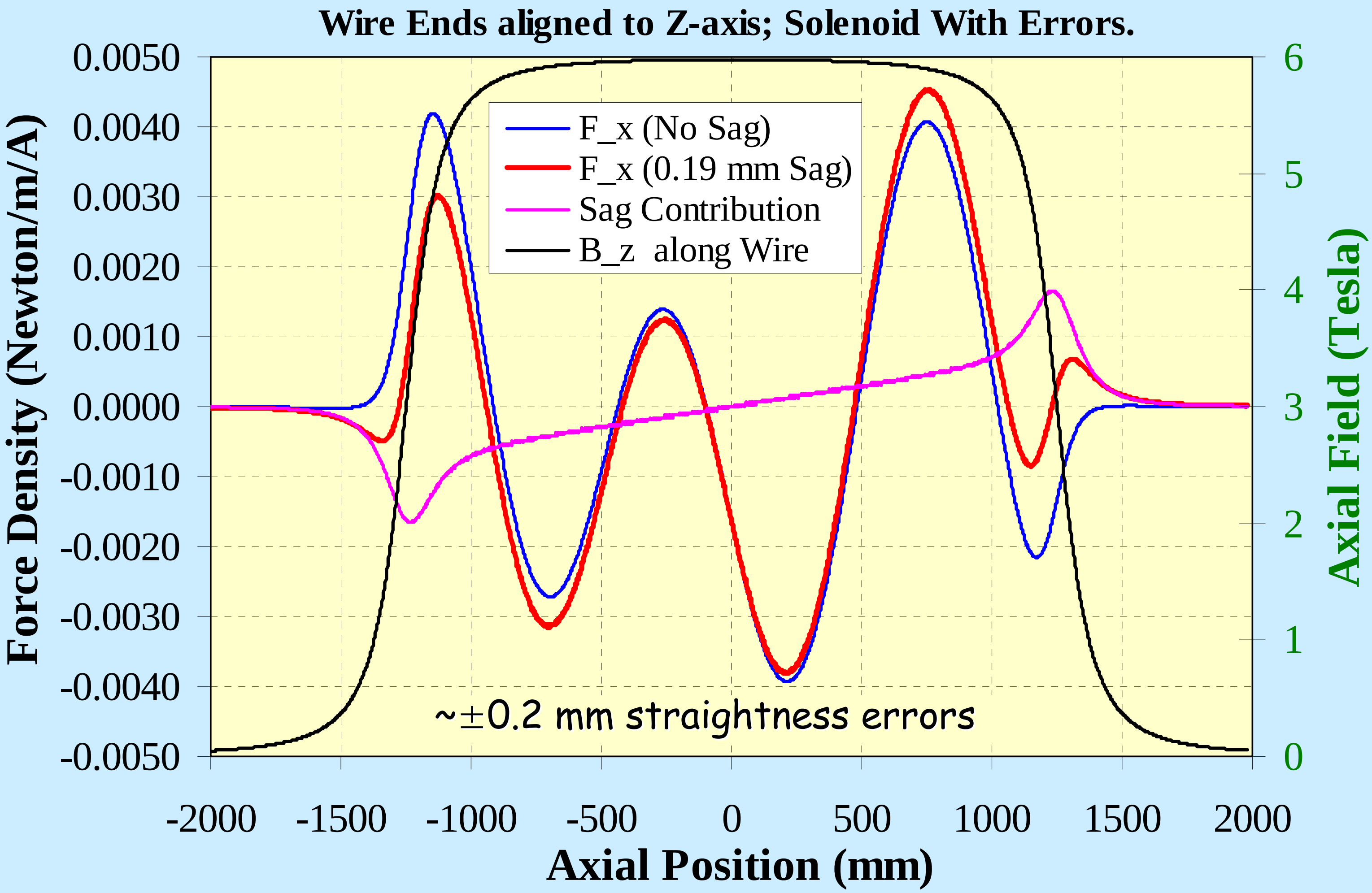
Solenoid with Errors: Zero Sag

4 m long Wire with ZERO sag in 2.5 m; 6T; 270 mm ID Solenoid. No tilt.



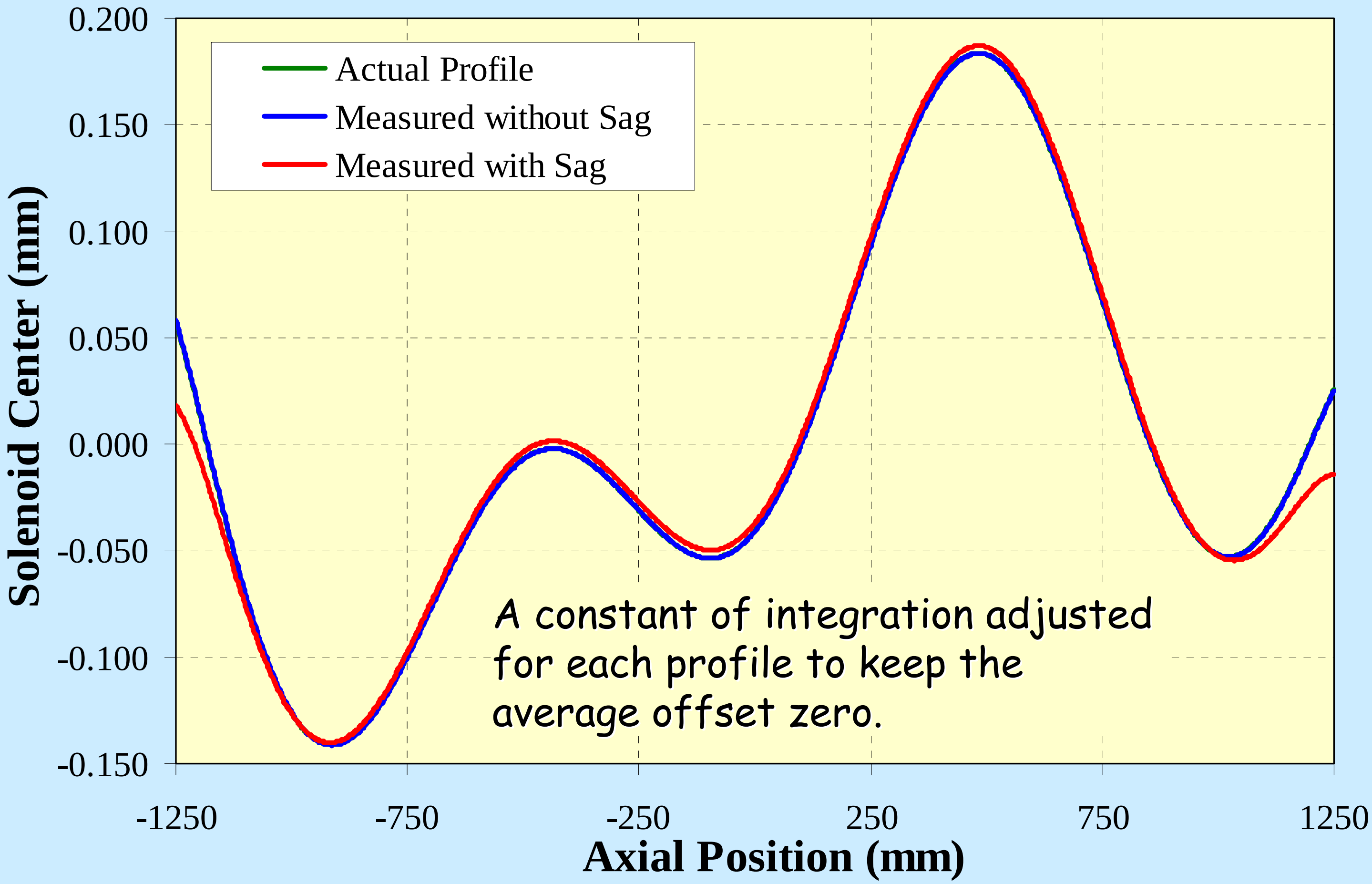
Even with zero sag, the force profile loses its symmetry if the solenoid axis is not perfectly straight. This causes various even modes to have non-zero amplitude, even when the wire is aligned to the solenoid "on-an-average".

Solenoid with Errors: With & Without Wire Sag



If the sag contribution can be computed from the *known* wire sag and *known* axial field profile, then it can be subtracted from the measured profile to obtain the true transverse field profile due to solenoid errors.

Computed Profiles of the Solenoid Axis



Even though the presence of wire sag and solenoid errors makes the definition of the solenoid axis quite difficult, in the end, the computation of solenoid axis has noticeable errors only near the magnet ends. **Very promising!!**

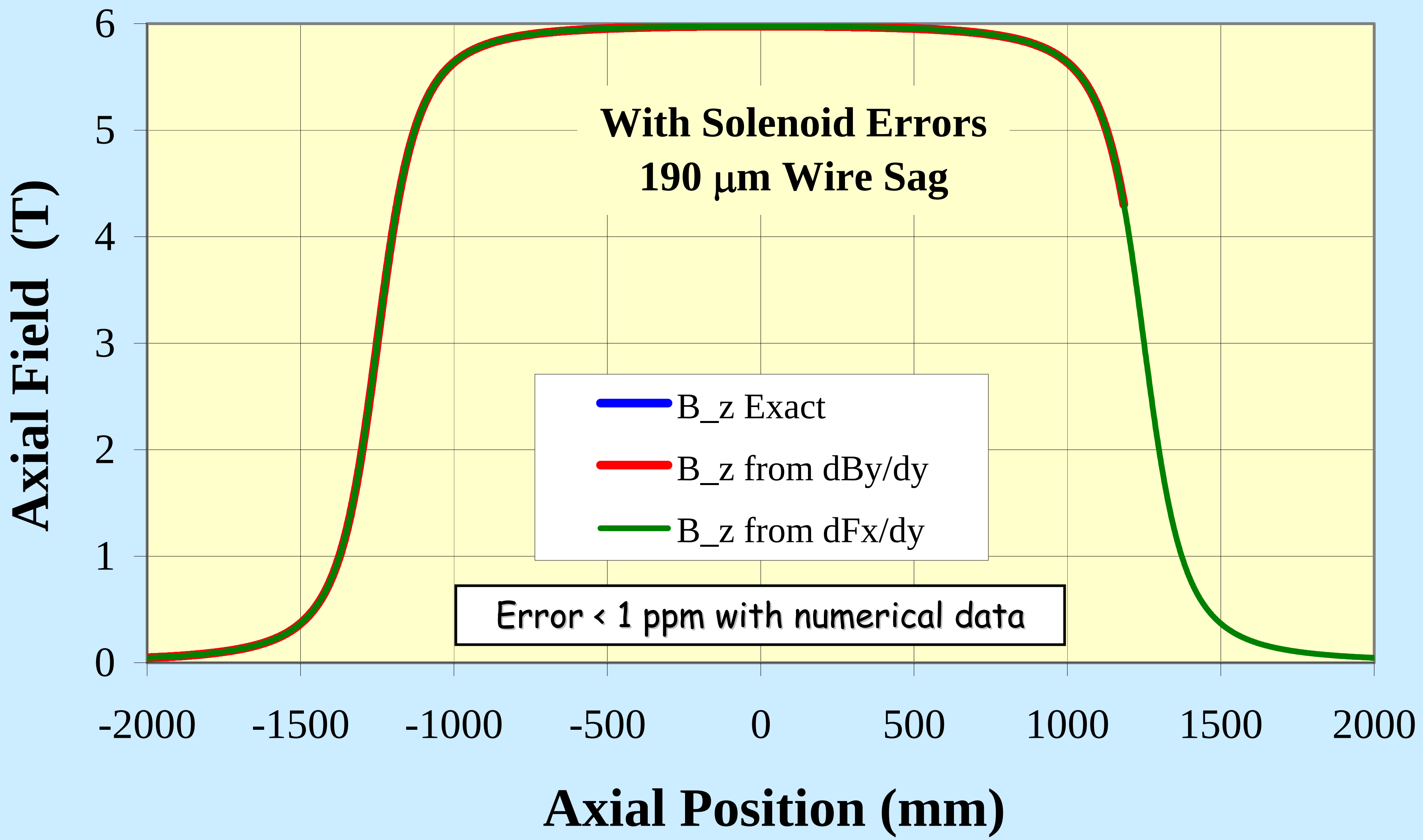
Estimating Sag Contribution

- Estimation of the sag contribution requires the knowledge of the wire sag, and the axial component of the field as a function of position.
- The wire sag is known from the measured resonance frequency of the wire, and is a byproduct of the vibrating wire measurements.
- The axial field profile can be measured independently using Hall probe, for example.
- Hall probe measurements are in absolute units (Tesla), whereas the vibrating wire results are generally in arbitrary units.
  - Calibrate the vibrating wire results in absolute units
  - Obtain the axial field profile also using (uncalibrated) vibrating wire:

$$\text{Assume: } \frac{dB_x}{dx} = \frac{dB_y}{dy} \text{ (Axial symmetry in solenoid)}$$

$$\frac{dB_z}{dz} = -2\frac{dB_x}{dx} = -2\frac{dB_y}{dy}; \text{ Get } B_z \text{ Vs. } z \text{ by integration.}$$

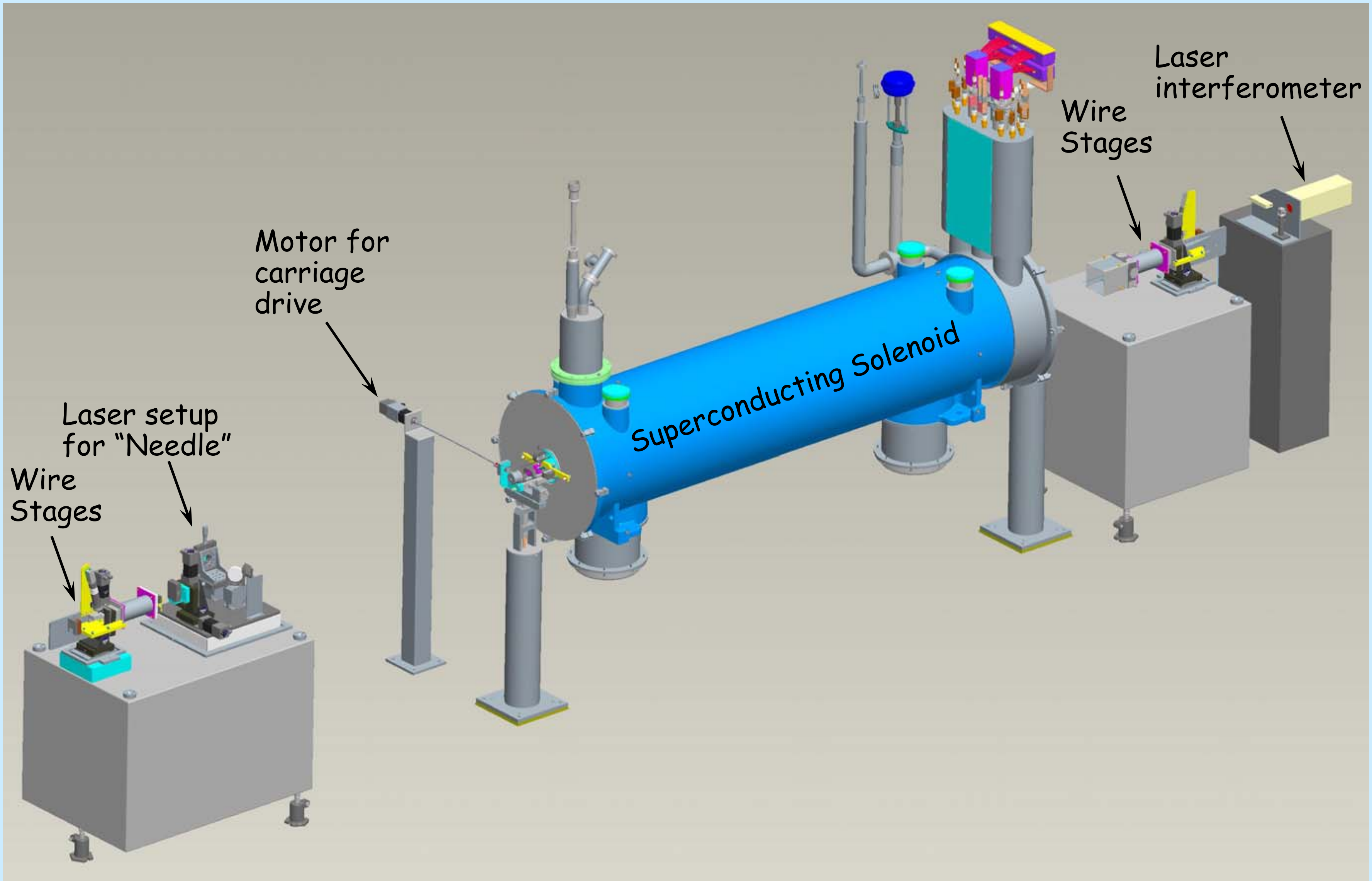
Axial Field Derived from Transverse Field



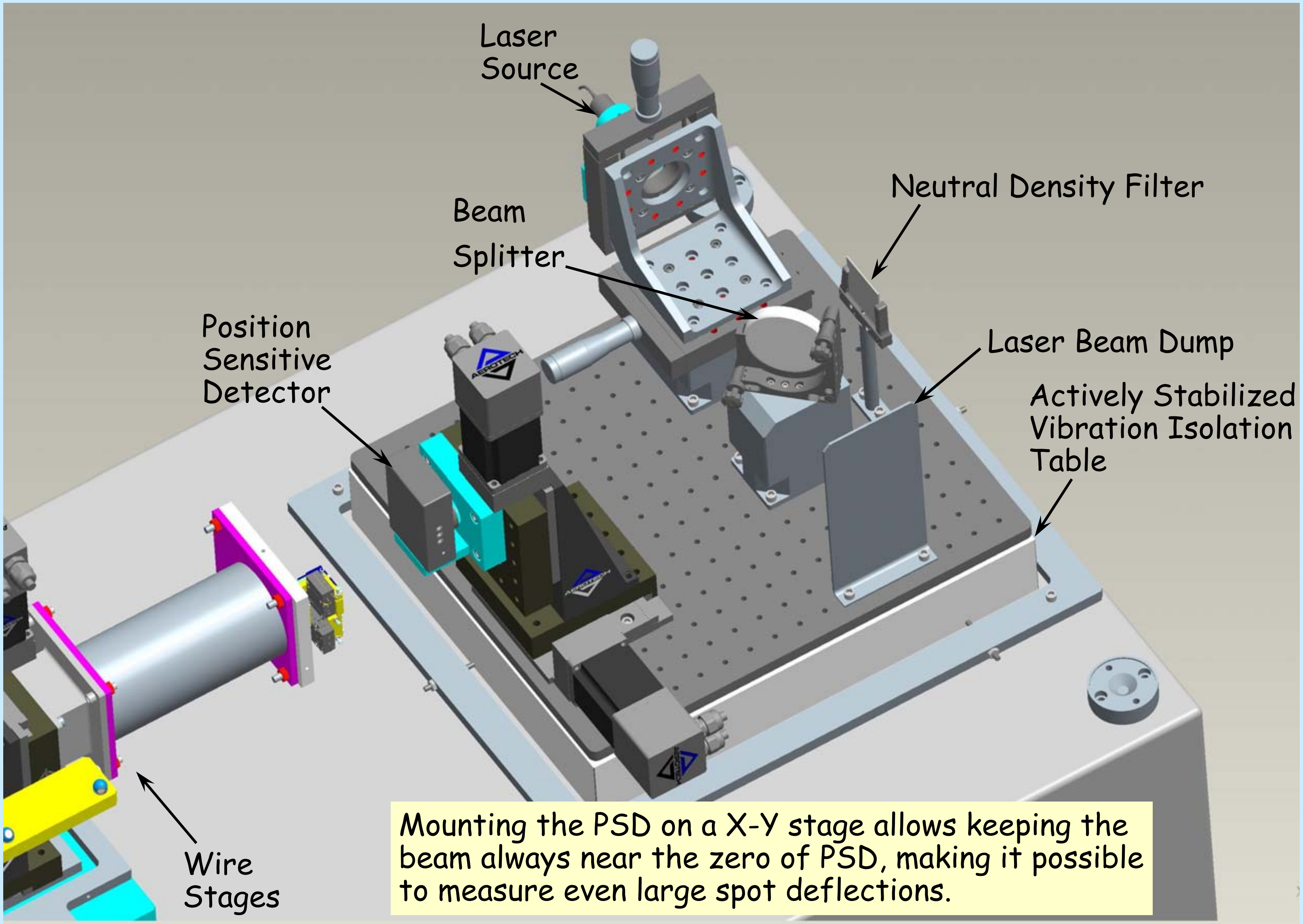
Equipment for Straightness Measurements

- Based on simulation studies, it appears feasible to carry out field straightness measurements with the required precision in the electron lens solenoid using the vibrating wire technique.
- Despite potential promise, there is a risk that it may not work as well in practice, specially because large sag contributions have to be estimated and corrections applied to the measured data in order to obtain very small transverse fields (e.g., after solenoid field correction using the correctors), and also due to large fringe fields.
- To minimize the risk to the project, while at the same time keeping the option open to further advance the vibrating wire technique, it was decided to build a new measurement system which will be capable of measuring the straightness using both the vibrating wire, as well as the traditional “needle-and-mirror” method.

Measurement Setup on Test Bench

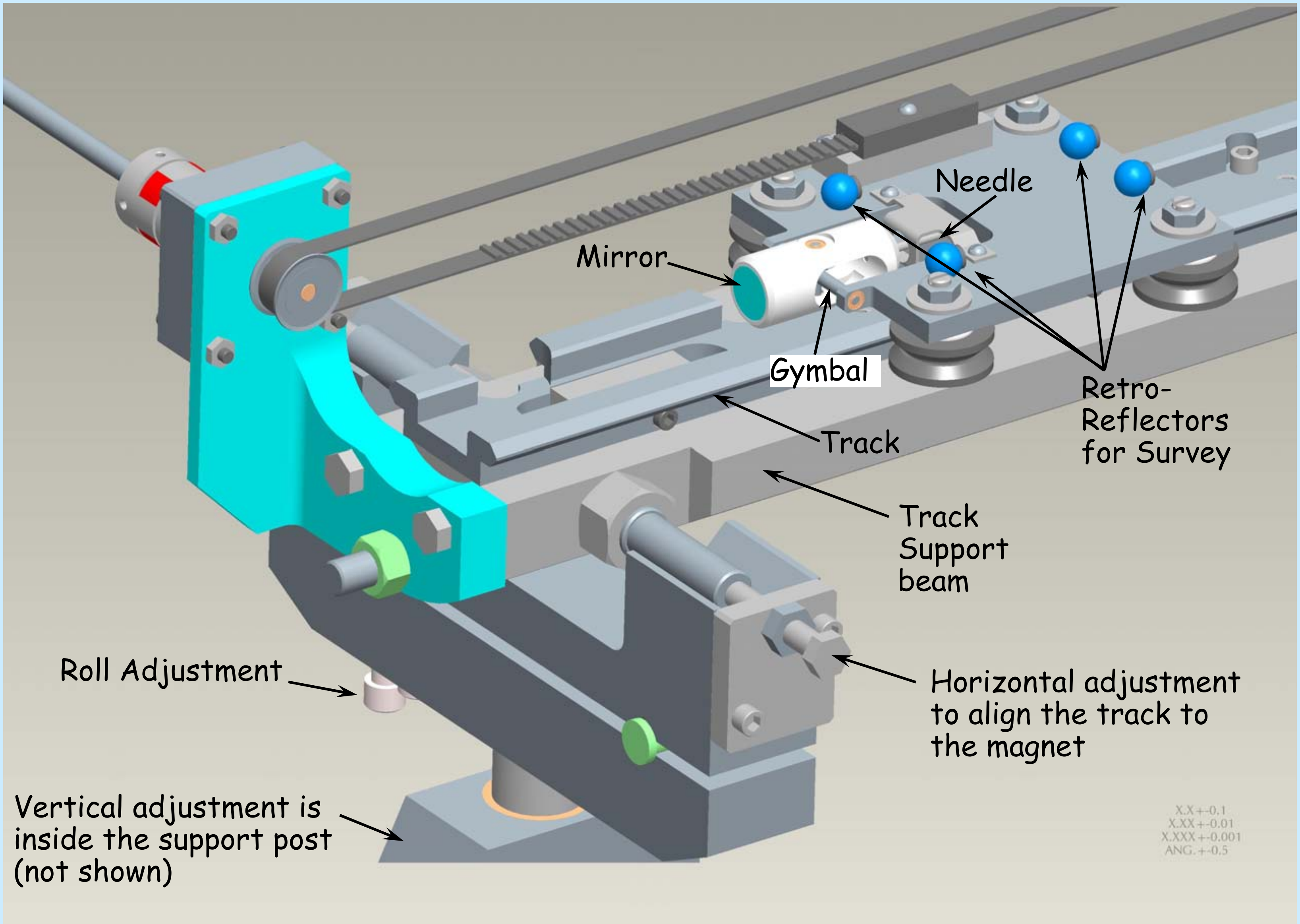


Details of the Laser Setup



Mounting the PSD on a X-Y stage allows keeping the beam always near the zero of PSD, making it possible to measure even large spot deflections.

Carriage for Needle-and-Mirror



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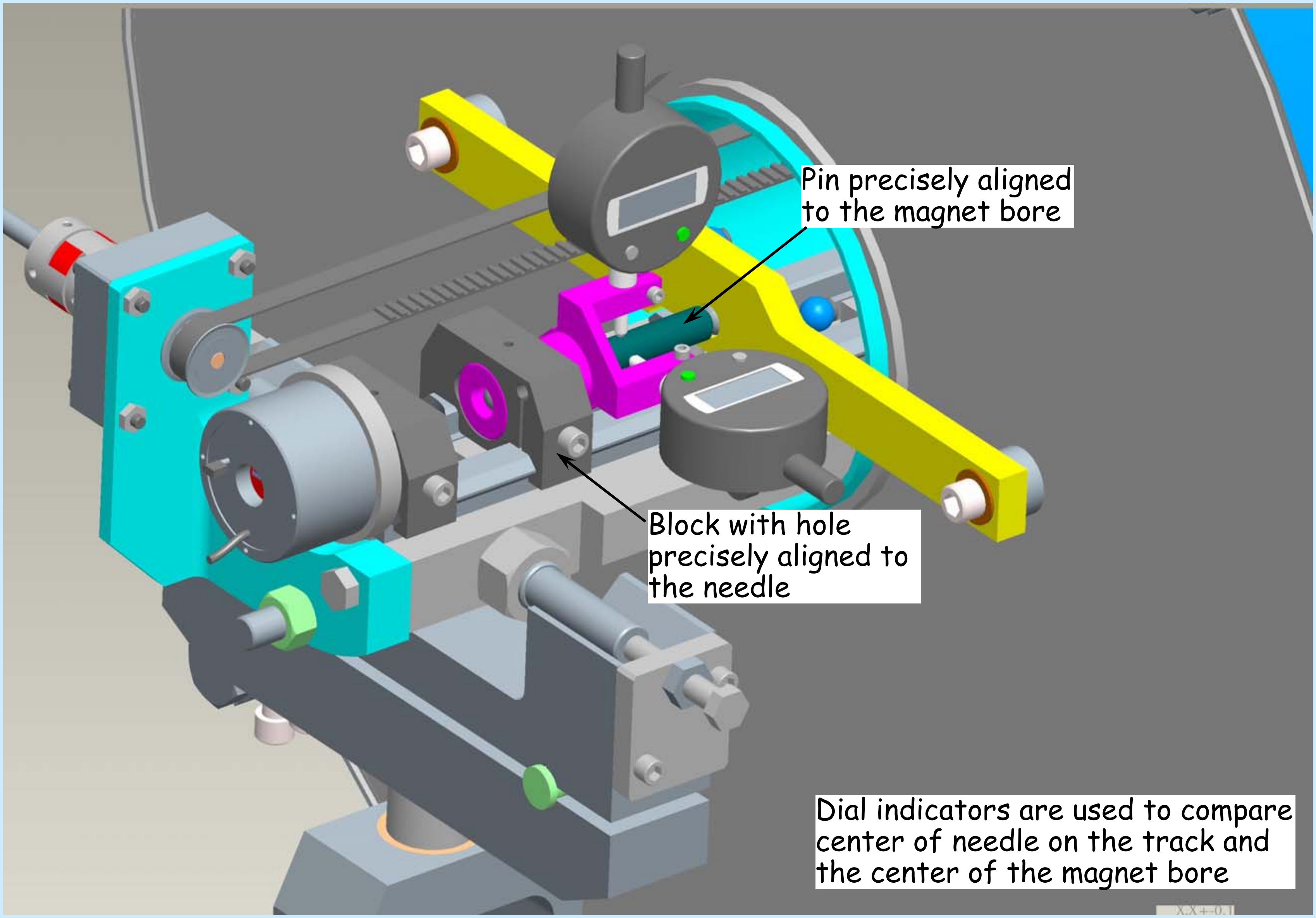
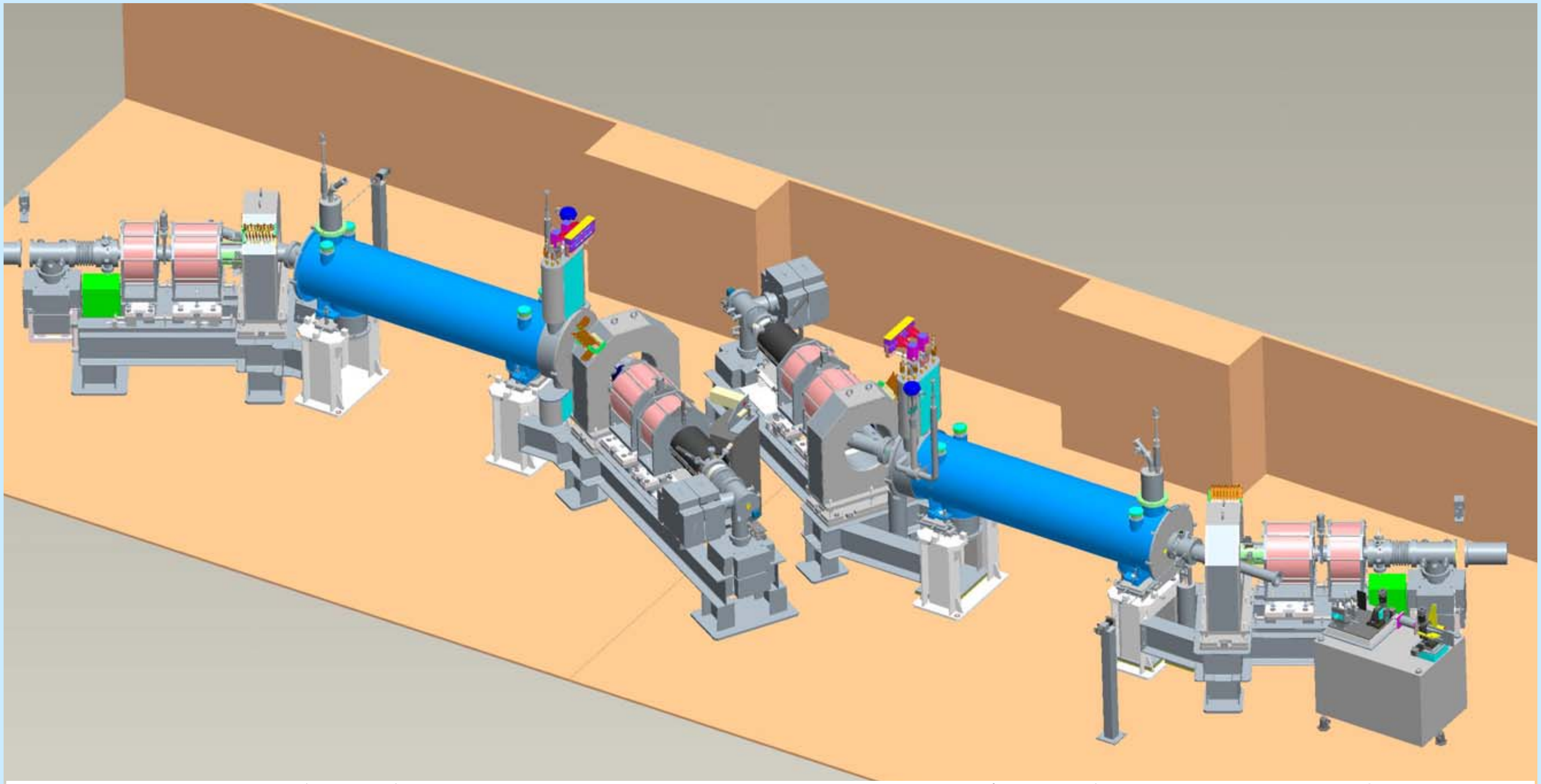
Alignment of the Track to the Magnet Axis



Measurement Setup in RHIC Tunnel



It is important that the measurement system be useable in the RHIC ring after installation of the magnets there.

Due to space constraints, only the Needle-and-Mirror system can be used in the tunnel. This system will be validated against the vibrating wire technique on the test bench prior to use in the tunnel.

Summary

- Measurement of field straightness in the electron lens solenoid is challenging due to several reasons.
- Problems anticipated in using the vibrating wire technique have been studied using simulations.
- Simulation results are very encouraging, but there may still be risks involved in real-life application.
- A safe approach is followed by designing the measurement system to use both the vibrating wire, as well as the traditional needle-and-mirror method.
- If successful, these measurements may provide the first ever direct verification of the needle-and-mirror method against another independent method to measure solenoid straightness.