# Magnetic Axis Determination of Pulsed Solenoids, with Application to the NDCX-II Accelerator

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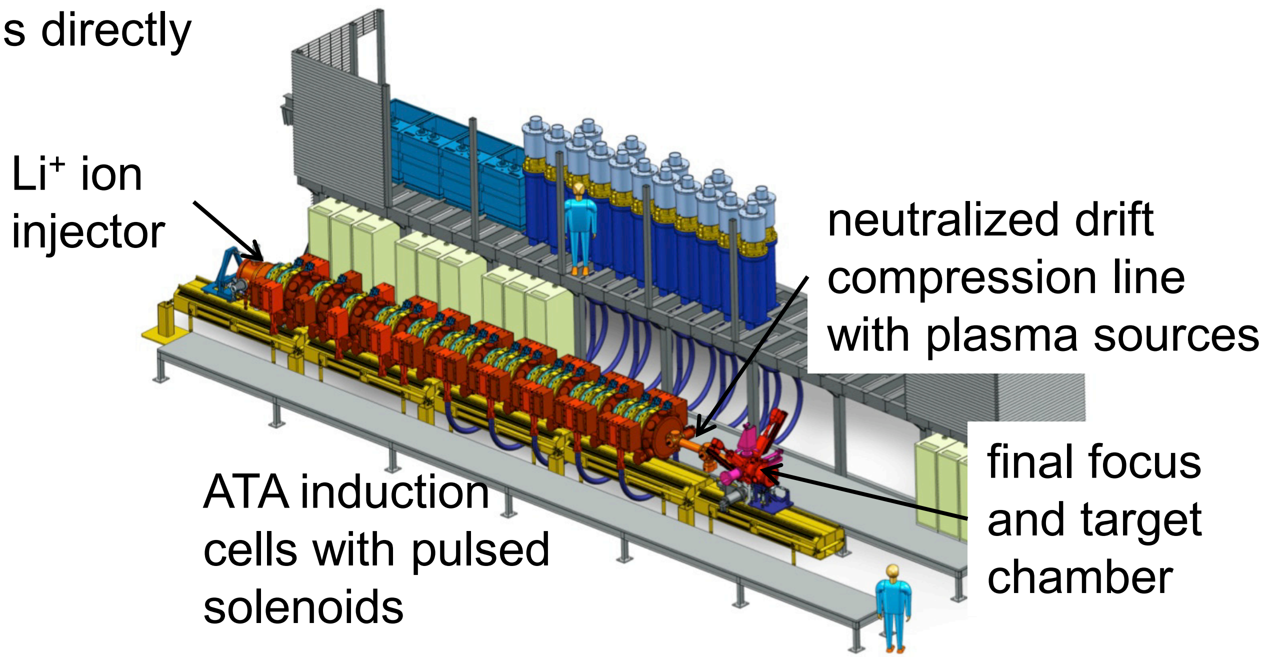
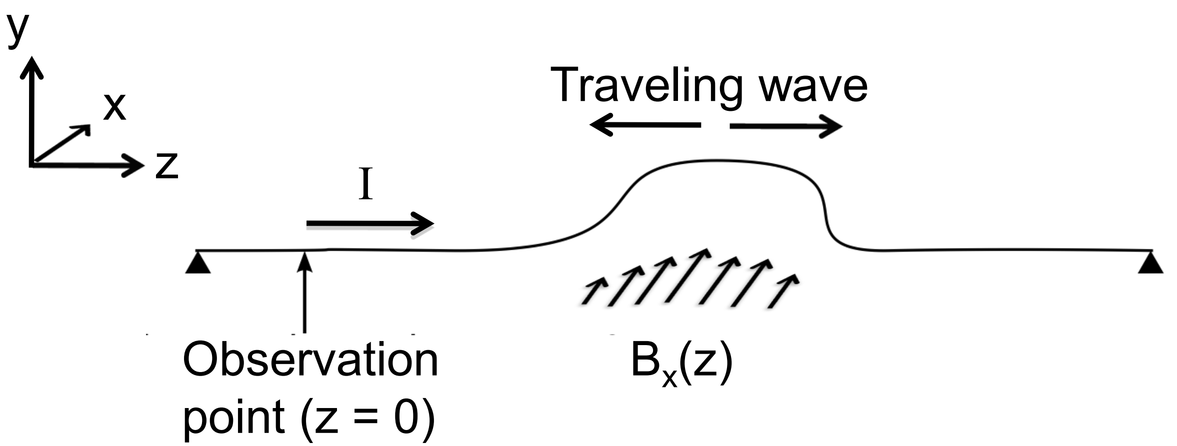
# NDCX-II Solenoid Alignment

- The transverse focusing of the beam is achieved with 2.5 T pulsed solenoids
- Magnetic axis misalignments lead to corkscrew deformation of the beam and reduced intensity
- From beam dynamics calculations the total alignment budget has been set to 500 μm
- Pulsed wire technique was chosen after investigating several options
  - Good sensitivity for the 2.5 T solenoid measurements
  - Simplicity in positioning the wire
  - Wire defines an axis directly



# Pulsed Wire Description

- Tensioned wire between two points
- Part of the wire is in an external magnetic field
- Current is applied to the wire
- The wire is subjected to the Lorentz force
- A traveling wave moves along the wire
- The displacement at a given point is measured
- The displacement of the wire as a function of time is related to the spatial dependence of the magnetic field



# Analytical Solution

- Solution for the wire motion at a given location as a function of time
- A square current pulse with pulse width δt is assumed
- Result is obtained using the Green's function solution

$$\rho \frac{\partial^2 y}{\partial t^2} - T \frac{\partial^2 y}{\partial z^2} = -\rho g + B_x I$$

$$c = \sqrt{\frac{T}{\rho}}$$

ρ: wire mass per unit length

T: wire tension

c: wave speed

$\hat{y}(t)$ : wire position at z = 0 as a function of time

General solution:

$$\hat{y}(t) = \frac{I}{2T} \int_{z=0}^{z=ct} \int_{z=\eta-c\delta t}^{z=\eta} B_x(\xi) d\xi d\eta$$

DC current:

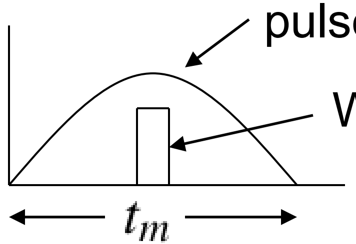
$$\hat{y}(t) = \frac{I}{2T} \int_{z=0}^{z=ct} \int_{z=0}^{z=\eta} B_x(\xi) d\xi d\eta$$

δt → 0:

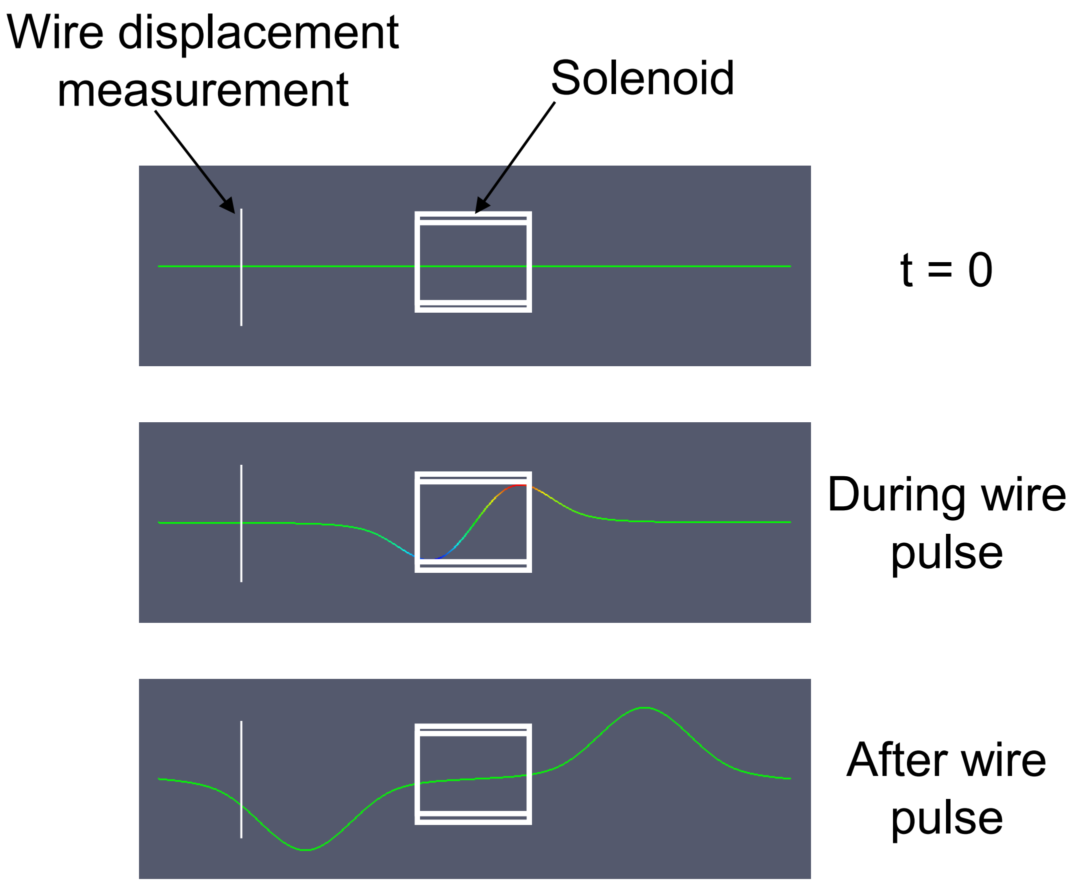
$$\hat{y}(t) = \frac{I c \delta t}{2T} \int_{z=0}^{z=ct} B_x(\xi) d\xi$$

# Pulsed Wire Measurements on Pulsed Solenoids

- Ion beam moves across the solenoid in a narrow window at the peak of the pulse
- Axis location can vary as a function of time due to eddy currents
- Apply a short wire pulse at the peak of the solenoid pulse

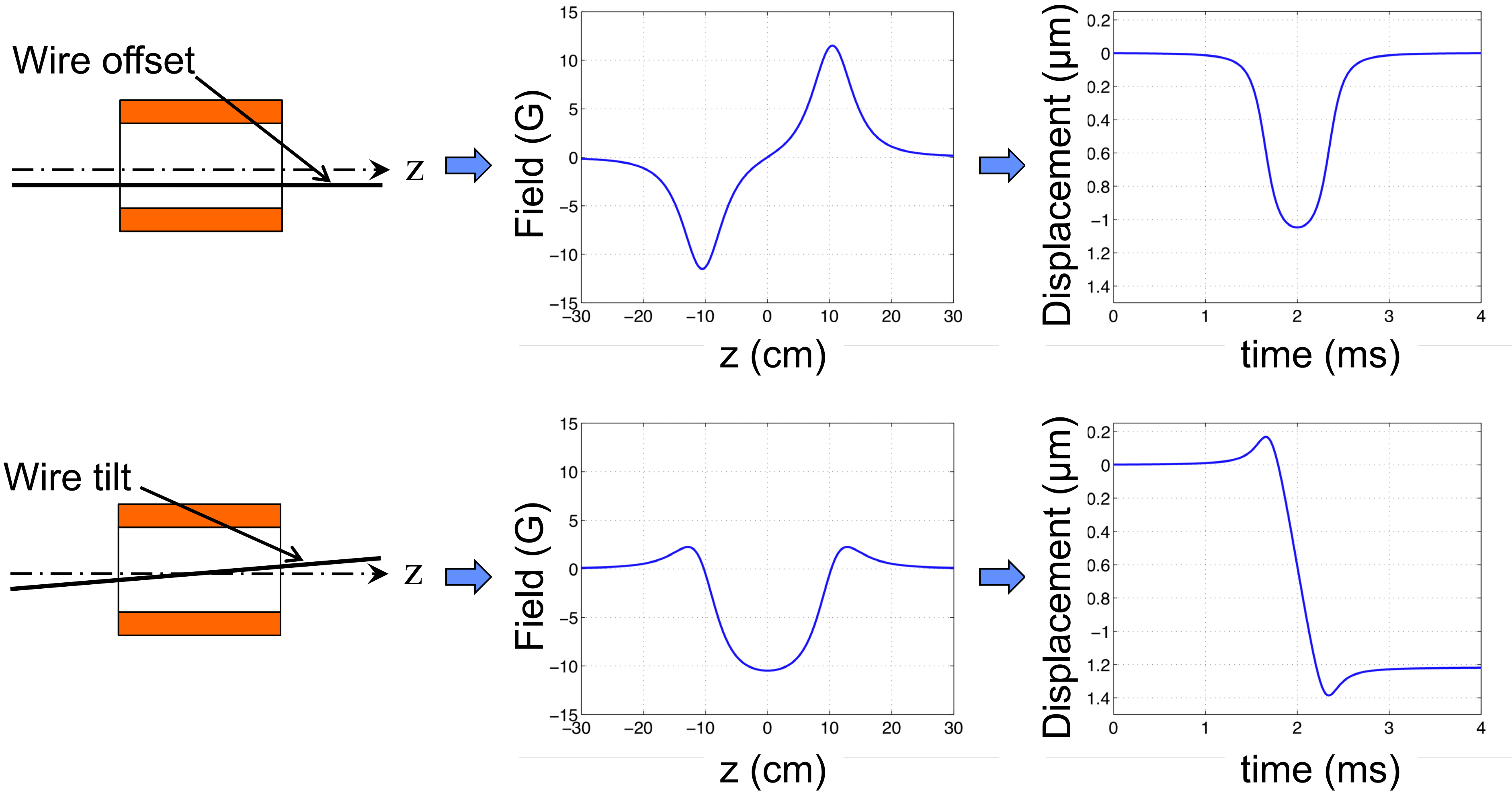



$t_m$ ~ 3 ms



# Characteristic Wire Motion for Tilt and Offset Errors

| Alignment error type | Magnetic Field Transverse to the wire | Wire Displacement |
| --- | --- | --- |



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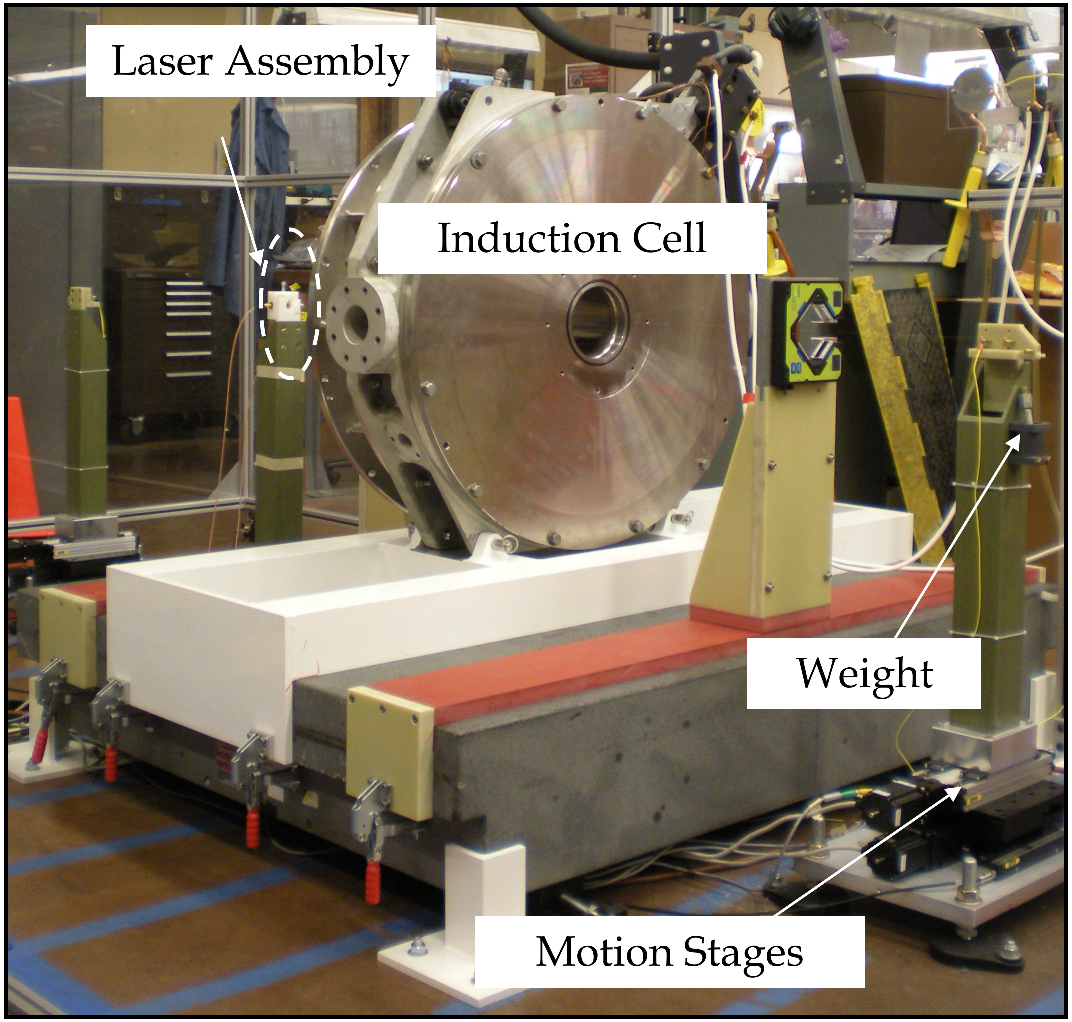
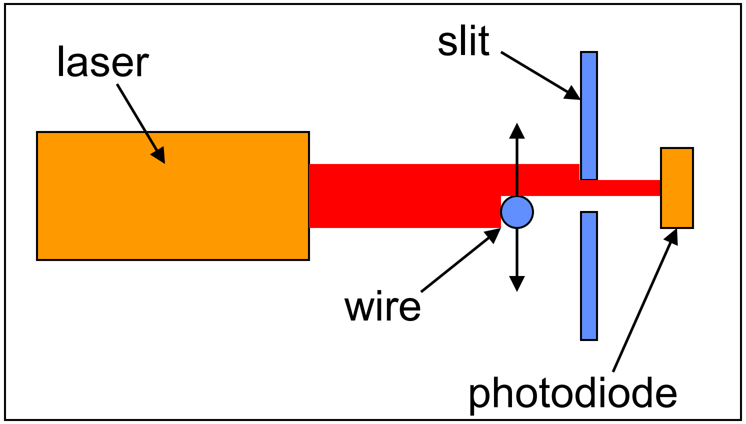
# Measurement Facility

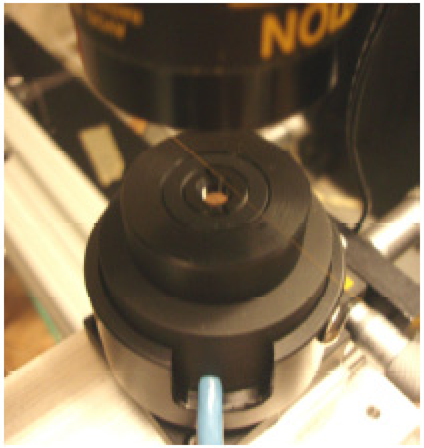


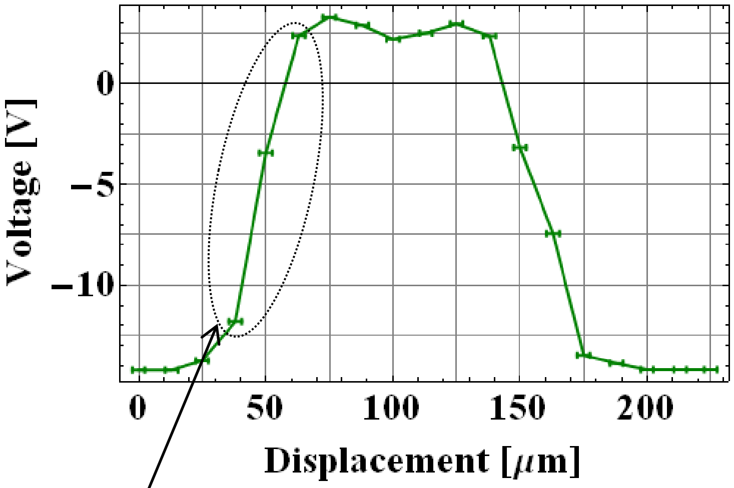

Measurement Bench Parameters:

- Adjustable wire position
- Vertical and horizontal motion sensors
- Laser micrometers to determine wire position
- Laser tracker
- Wire: 75 µm Be-Cu
- Length = 2.8 m
- Wire pulser: I < 4 A

# Wire Displacement Sensor

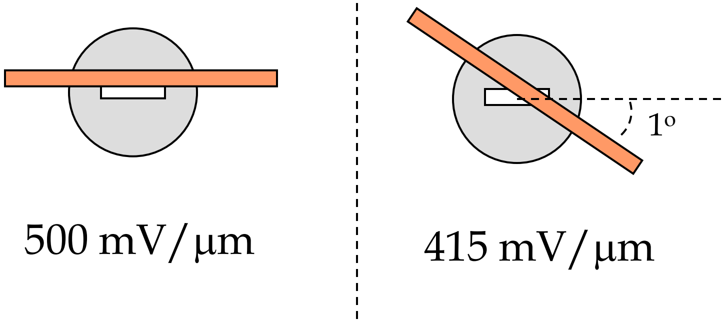


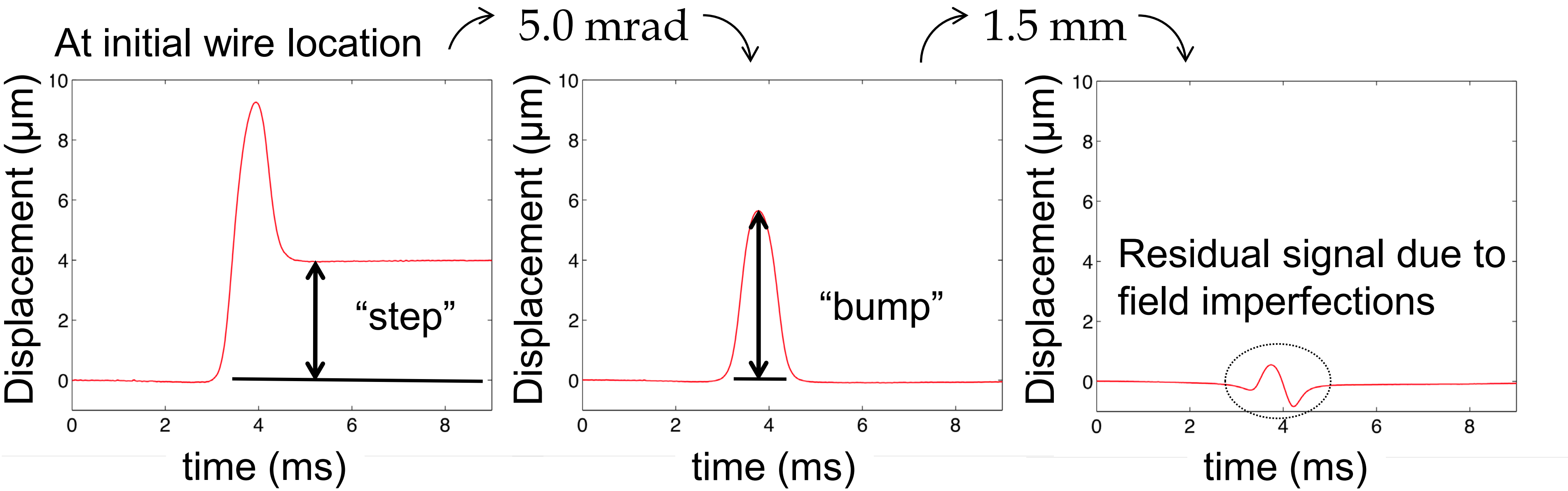



Region of interest:
500 mV/μm (mean value)

Sensitivity depends on angle between slit and wire



# Locating the Axis




## Magnetic axis definition:

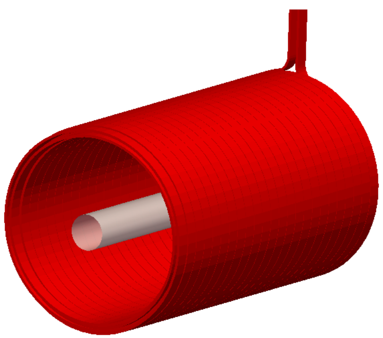
- Zero "step" wire motion (i.e. zero net first field integral)
- Zero total integral of the wire motion (i.e. zero net second field integral)

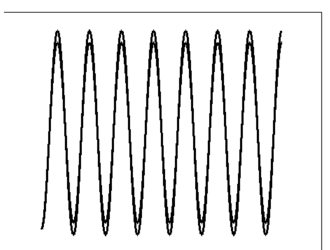
# Field Imperfections

## Possible field imperfection sources:

- Current leads
- Solenoid end transitions
- Winding imperfections
- Asymmetric eddy current effects

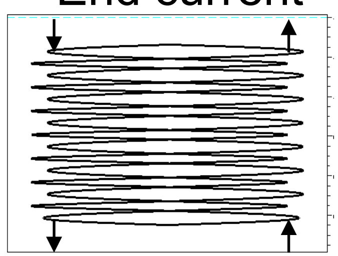
Geometric Model with Realistic Windings





Side

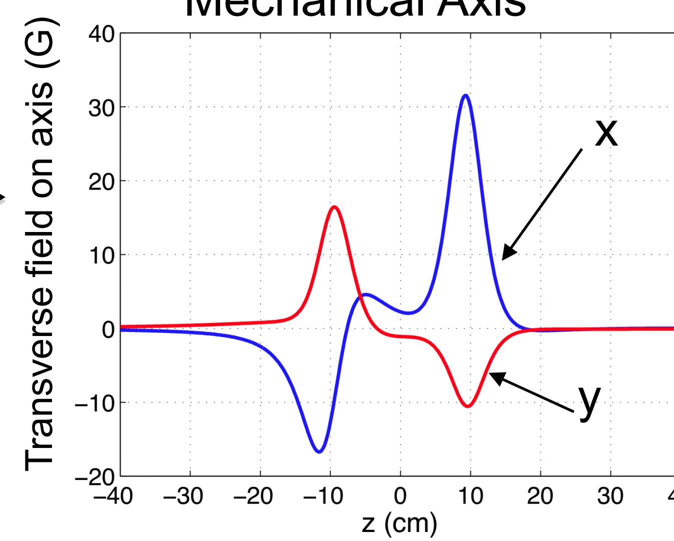
End current



Top

Biot Savart Calculation

Calculated Field on Mechanical Axis



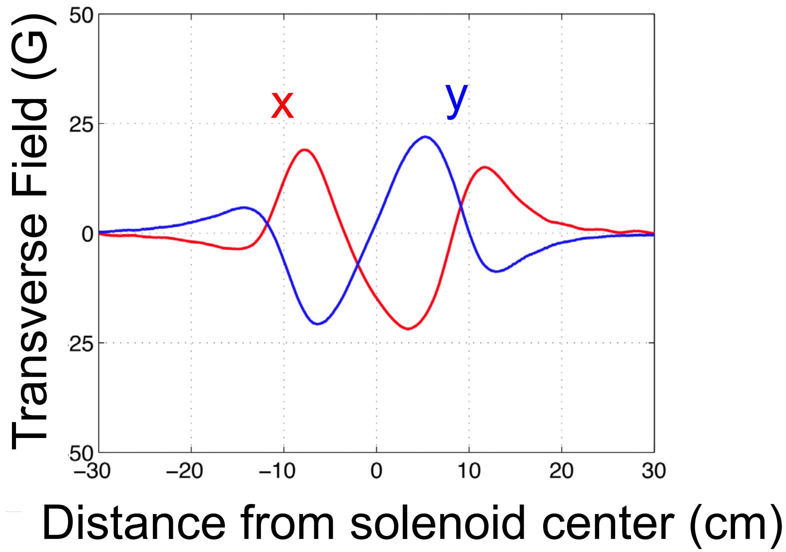
# Magnetic Field Measurements

## Transverse Magnetic Field:

$$B_T \propto \frac{d\hat{y}}{dt}$$

$$z = ct$$

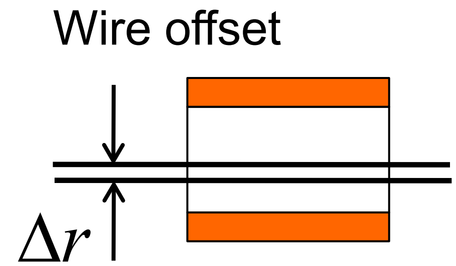
### Error Field Profile on Axis



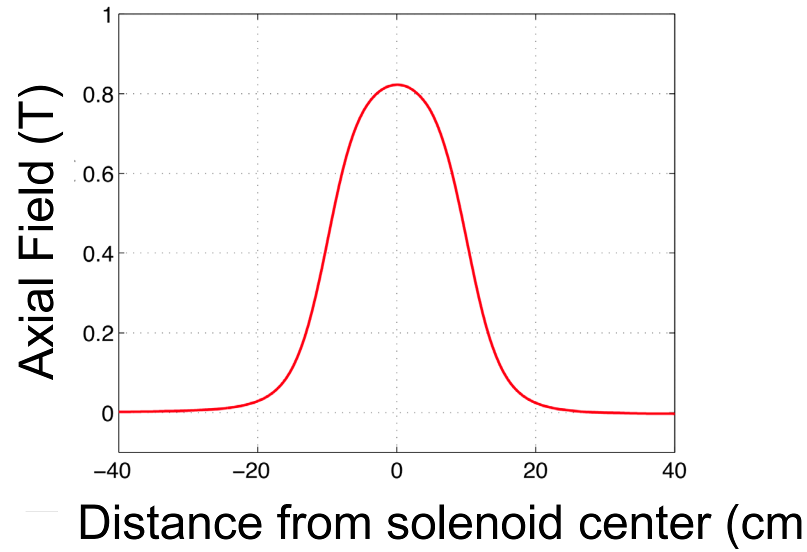

## Axial Magnetic Field:

$$\nabla \cdot B = 0$$

$$B_z \propto \frac{\Delta\hat{y}}{\Delta r}$$



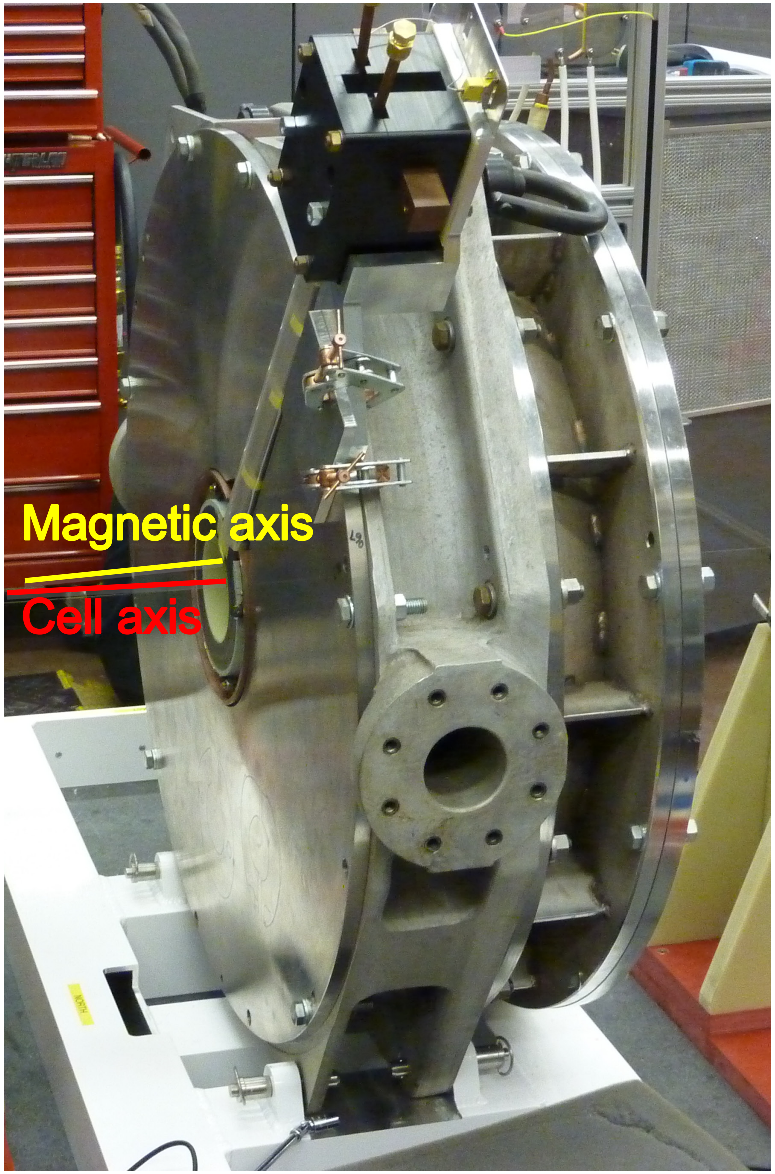

### Solenoid Axial Field Profile



# Solenoid Alignment

Fiducial location measurements performed with a laser tracker

1. Cell coordinate system is defined at the center and normal to the face of the cell
2. Magnetic axis coordinate system is defined using the measured wire locations and the fiducials on the solenoid
3. Magnet position is adjusted until the magnetic axis and the cell axis coincide
4. Proper alignment of the solenoid inside of the cell is verified through magnetic measurements



# Conclusions

- The pulsed wire method has proven to be effective for the alignment of the NDCX-II pulsed solenoids
- Measurement resolution is 25 μm for offset errors and 0.1 mrad for tilt errors after averaging only a few samples
- Solenoids can be aligned to the cell axis with an accuracy better than 100 μm
- Both the axial and transverse magnetic field profiles can be derived from the pulsed wire measurements