# Mu2e Magnetic Measurements

# Introduction

- Physics & Detector
  - mu-e conversion
  - Mu2e and the LHC
  - Mu2e magnets
- Magnetic Measurements (concepts & ideas)
  - Measurement requirements and scope
  - In-Situ Sensors
  - Field Mapping
  - Electron Source Test
  - Safety

# What is mu-e conversion?

- Muon converts to electron in the field of a nucleus

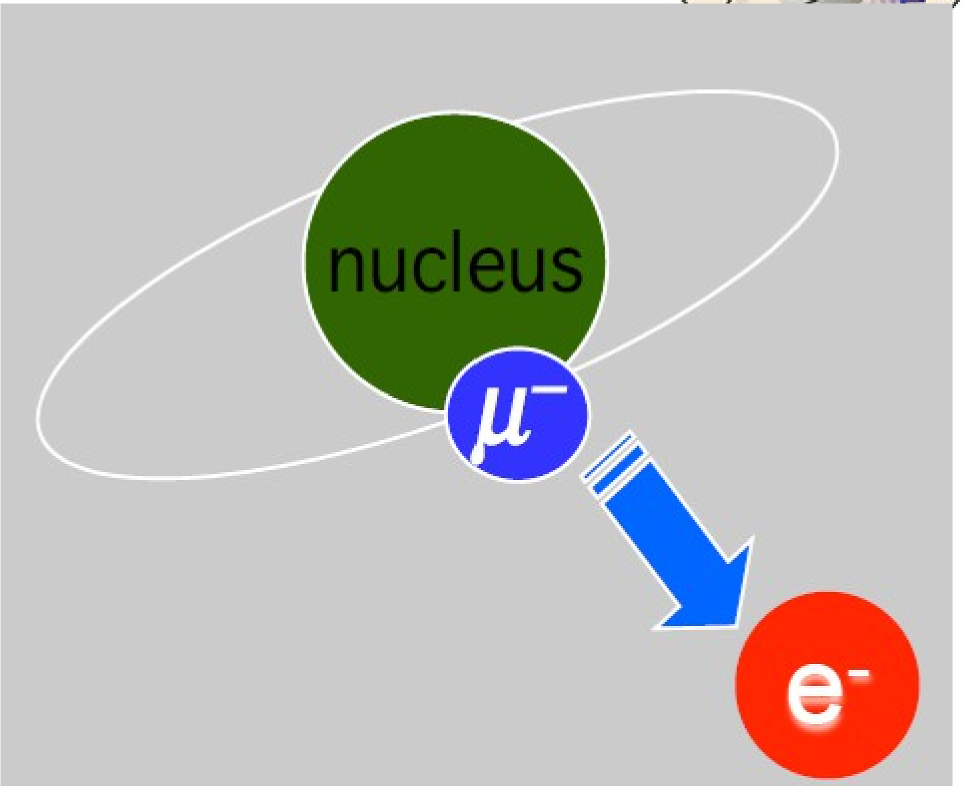
$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Standard Model Background of $10^{-54}$
- Charged Lepton Flavor Violation (CLFV) signal measurable with single-event-sensitivity (SES) of $2.5 \times 10^{-17}$
- Keep expected background <1 event

# Experimental Signal

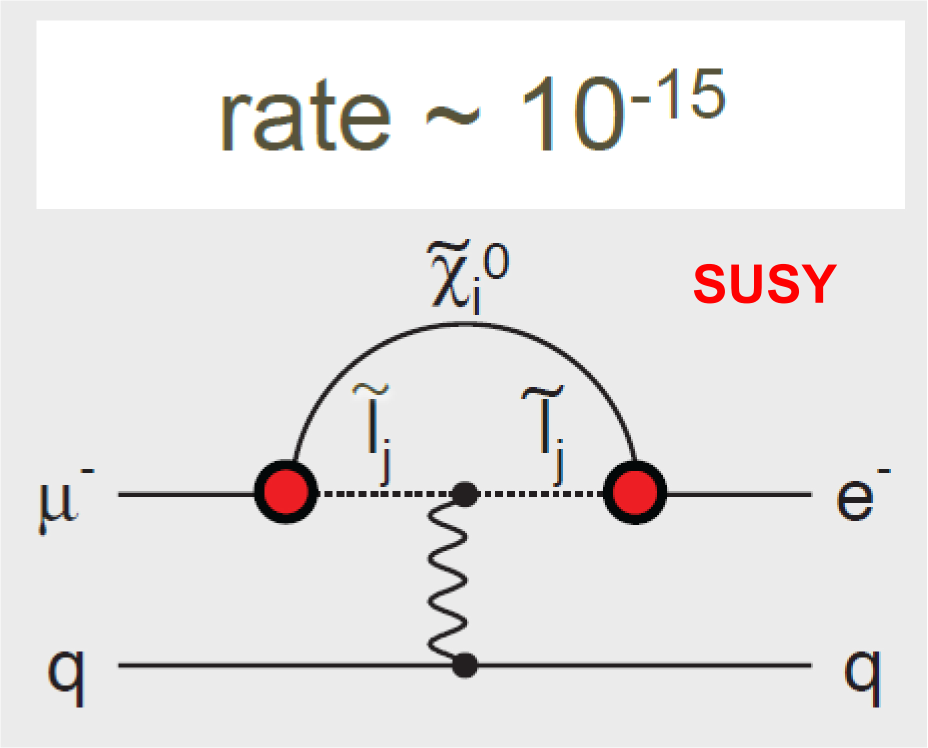
$$\mu^- N \to e^- N$$



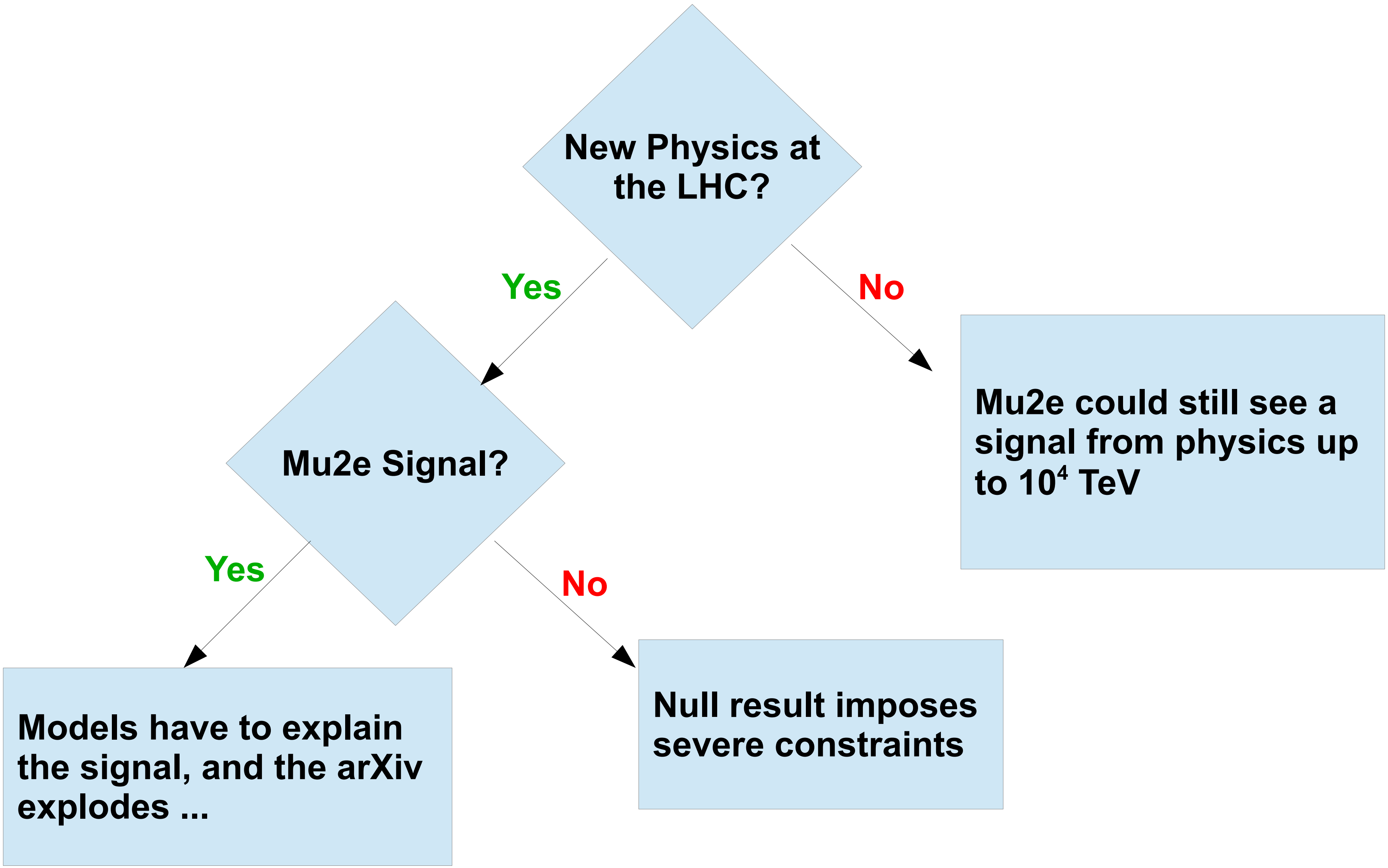

- A single mono-energetic electron
- For Aluminum stopping target, $E_e$ = 105 MeV
- Electron energy depends on Z of stopping target
  - Switch target Z to further discriminate models of underlying physics
- Nucleus coherently recoils off electron, no breakup

# Mu2e is a Discovery Experiment

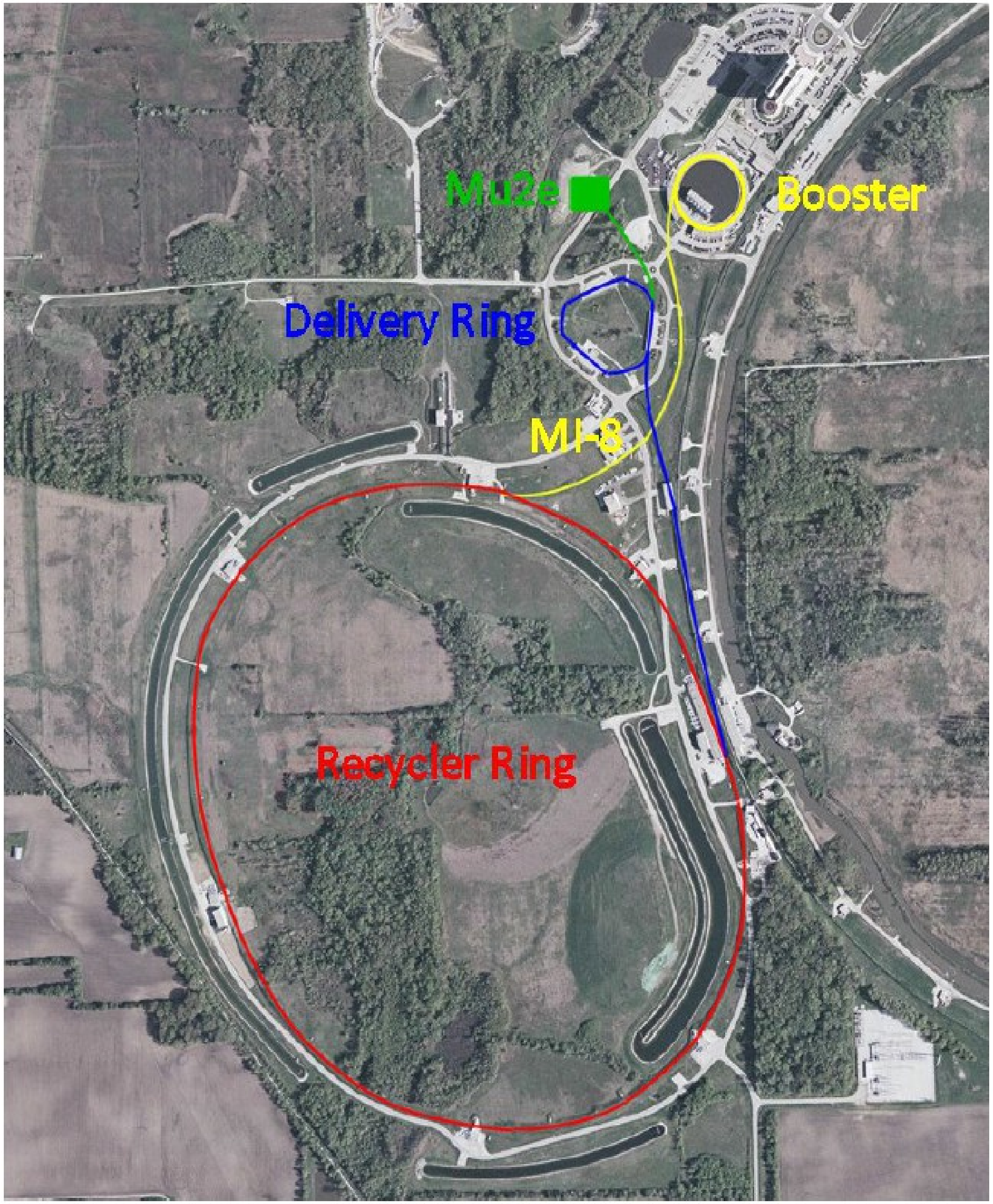
- Access SUSY through loops
- Compositeness
- Leptoquarks
- Heavy Neutrinos
- Second Higgs Doublet
- Heavy Z'
- ...



# Mu2e and the LHC

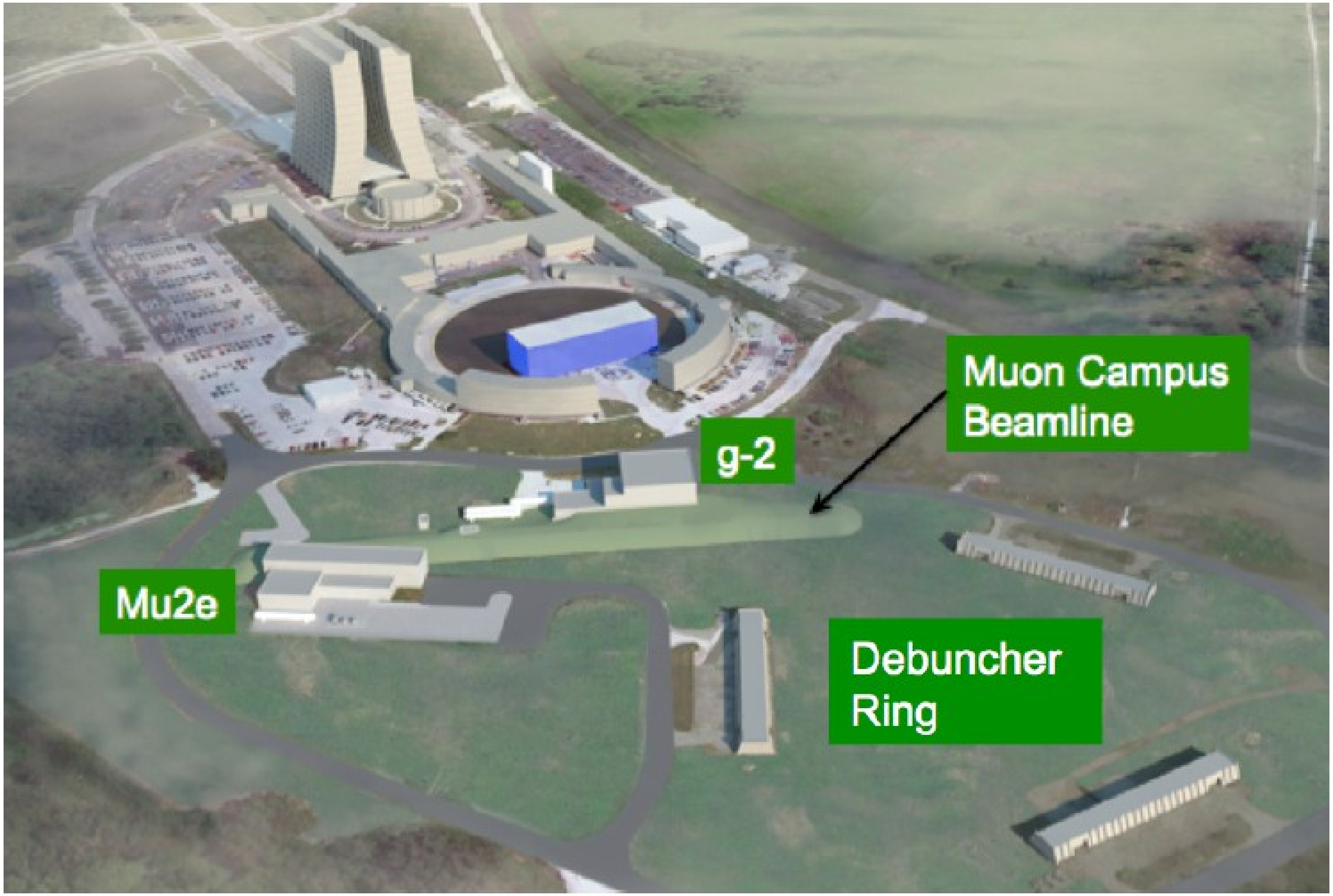


# Mu2e at Fermilab (1)

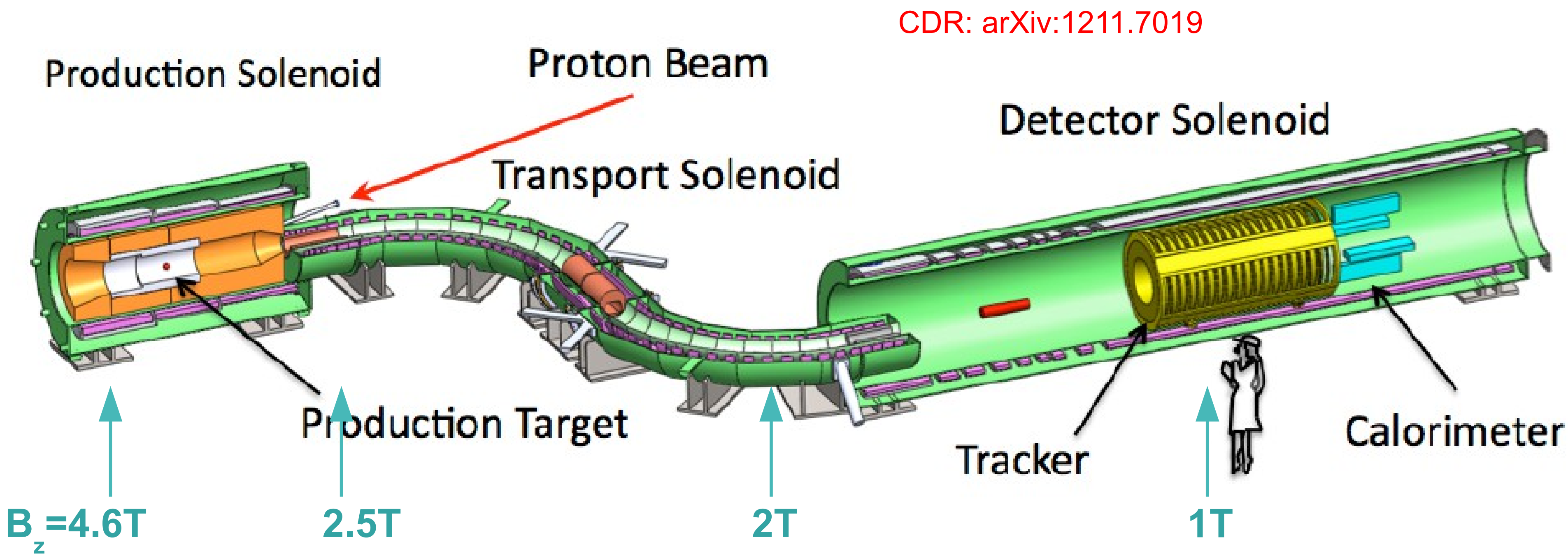



- Proton batches from Booster to Recycler Ring for re-bunching
- Transfer to Delivery Ring
- Resonant extraction system to deliver high intensity and pulsed proton beam to Mu2e
  - 8GeV protons
  - 200ns pulse width
  - 1695ns pulse spacing
  - 8kW beam power on target
  - $3 \times 10^7$ protons/pulse

# Mu2e at Fermilab (2)

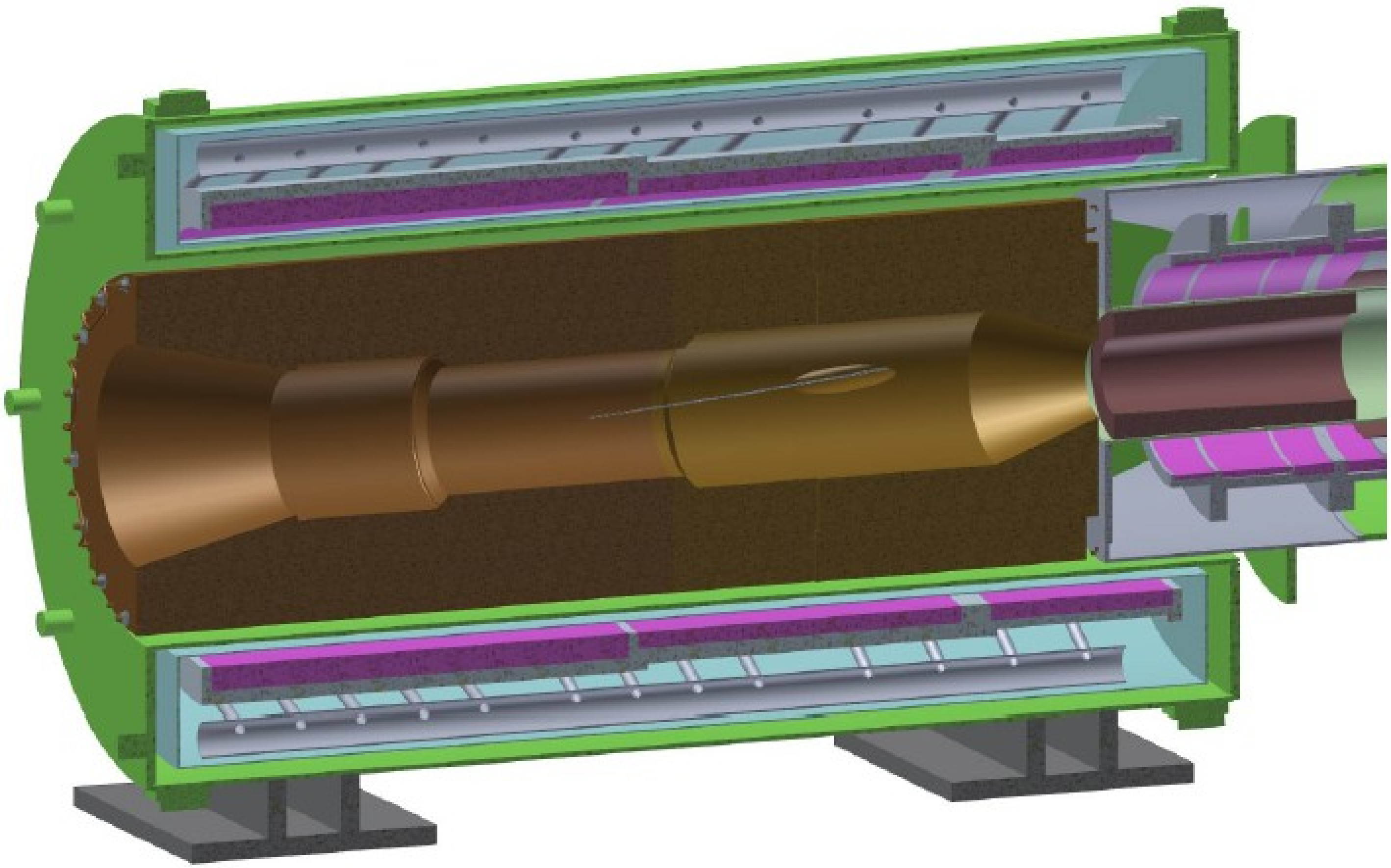


# The Mu2e Detector



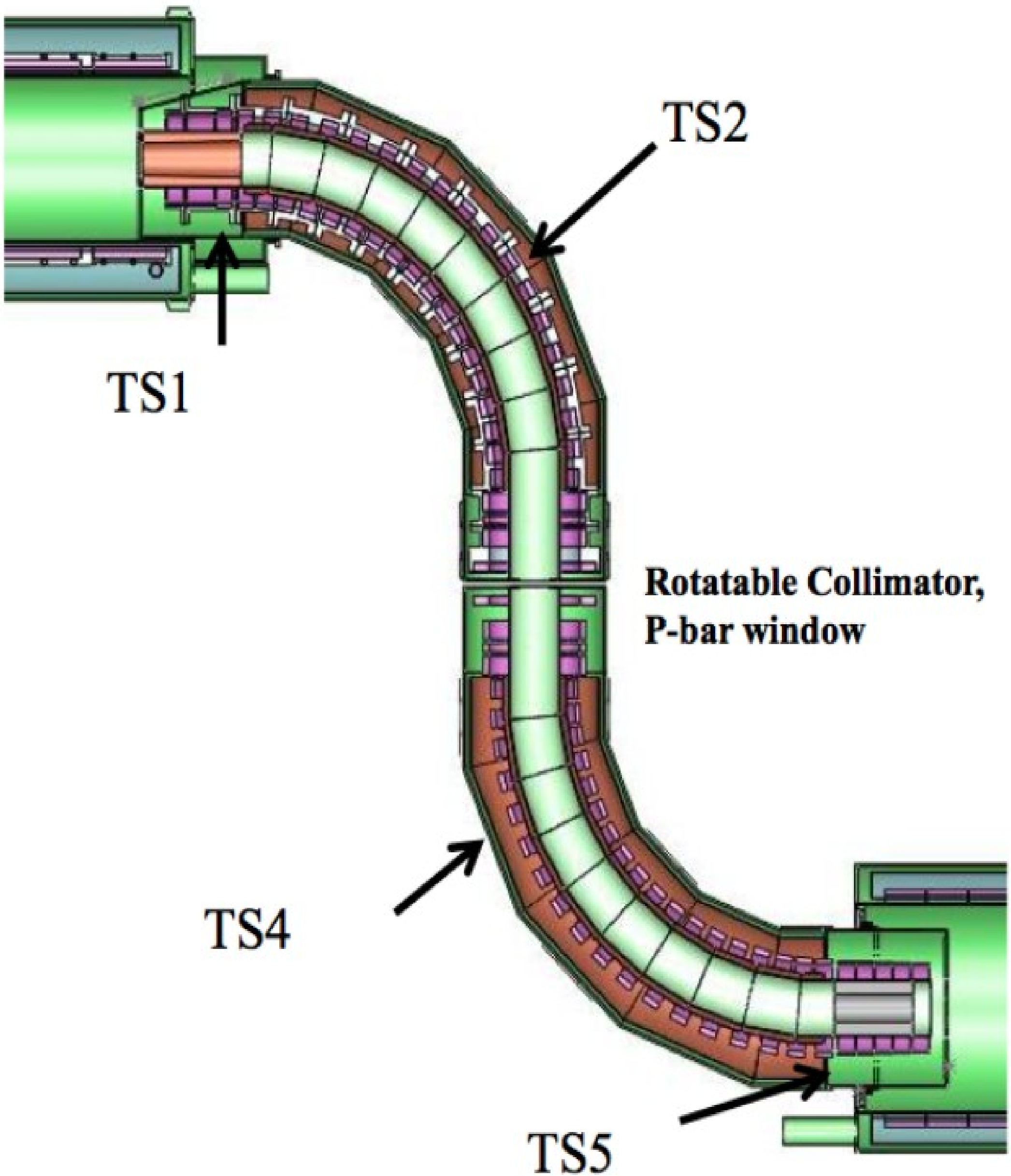

- Target protons at 8 GeV inside superconducting solenoid (Production Solenoid)
- Capture muons and guide through S-shaped region (Transport Solenoid) to Al stopping target (Detector Solenoid)
- B-field gradient: $B_z$=4.6T (Prod. Sol.) to 1 T (Det. Sol.)

# Mu2e Production Solenoid (PS)



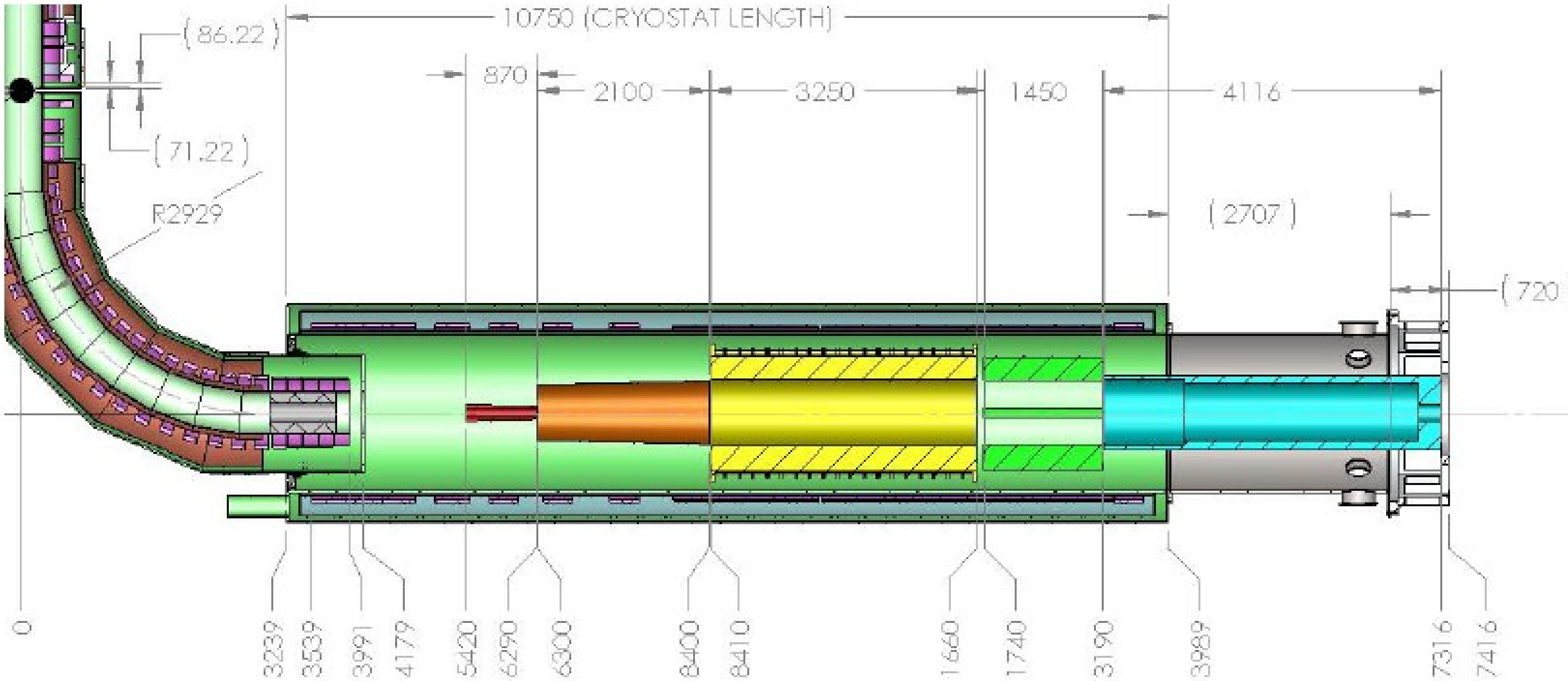
- 1.6m aperture, 4m long
- Operating current ~9kA
- 8GeV protons hit target
- Strong axial gradient solenoid field
  - 4.6T to 2.5T
- 3 solenoid coils with 3, 2, and 2 layers of Al-stabilized NbTi superconducting cable
- Magnetic field deflects traps charged pions and moves them towards TS as they decay to muons

# Mu2e Transport Solenoid (TS)




- Set of superconducting solenoids and toroids to form magnetic channel
- Transmits low energy negatively charged muons from PS to DS
- Absorbers and collimators eliminate high energy neg. charged particles, pos. charged particles, neutrals
- Selection of neg. muons using the fact that a charged particle beam traversing a toroid will drift perpendicular to toroid axis
- Maintaining a negative gradient for magnetic field is crucial to minimize late arriving particles

# Mu2e Detector Solenoid (DS)




- 1.8m aperture, 10m long, operating current ~6kA
- Contains muon stopping target (Al) and detectors to analyze conversion electrons
- Stopping target resides in graded field (2T to 1T) to deflect electrons towards detectors
- Detectors reside in uniform field region: tracker & calorimeter

# Field Measurement Requirements

- Production Solenoid:
  - Maintain strong axial gradient
- Transport Solenoid
  - Straight sections: Negative monotonic axial gradient to prevent trapped particles
  - Toroidal sections: Matched to central collimator geometry for muon momentum selection
- Detector Solenoid:
  - Field uniformity near tracker <1% dB/B, measured to ~1 part in $10^4$ for conversion electron energy determination
  - Field uniformity near calorimeter reduced to 5% dB/B

# Field Mapping Scope

- Design and build a precisely positioned array of Hall probes for measuring magnetic field profile of each TS coil module during cold testing
- Design and build a system of fiber optic displacement sensors to measure TS coil end positions and angles wrt to the cryostat at each TS interface (TS1, TS3u, TS3d, TS5)
- Design and build field mappers to precisely position Hall & NMR probes and measure PS, TS1, TS5, DS fields in final magnetic configuration; also to measure PS field after HRS installation
- Design and build precisely positioned arrays of Hall (NMR) probes, for installation in the muon beamline regions at TS1, TS3, TS5, (DS3) to monitor field profiles during operation
- Design and build a low energy electron source, with positioning & detection systems, to test electron transport through TS channel

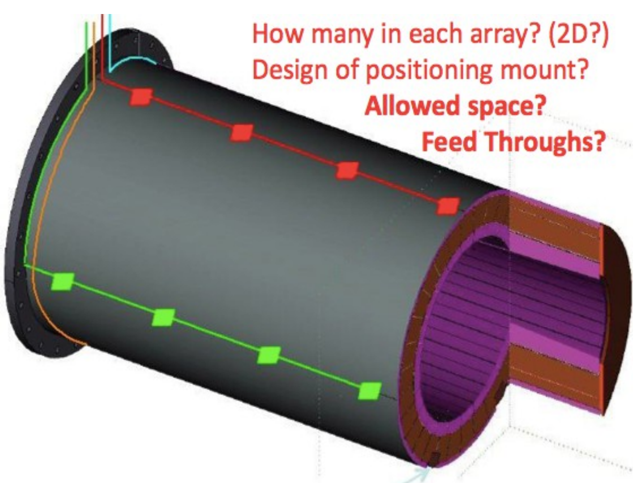
# In-Situ Sensors: Displacement

- Displacement sensors
  - Monitor the TS coil positions and angles
    - especially during commissioning
    - Coils will move: warm to cold, unpowered to powered
    - Axial and radial motions, up to 25 mm
    - Supports will allow some coil position adjustment
  - Preferred solution: Fiber optic (Philtec)
    - Used in MRI (work in vac, cryo, high B)
    - Length of fibers? Local amplifier/digitizers? (TBD)
    - Radiation issues: feed-through, fiber changes (TBD)
    - Alternative: capacitive displacement sensors?

PHILTEC
FIBEROPTIC SENSORS
DISTANCE | DISPLACEMENT | VIBRATION

# In-Situ Sensors: Hall-Probes

- Hall Probe Arrays (and Temp. sensors)
  - Measure field axial, radial components at interfaces
    - In “final magnetic configuration”
      - Negative gradient dB/ds through straight collimator regions
      - Radial gradient dBr/ds and radial field Br through these
      - TS1, TS5 will also be mapped in baseline plan
      - TS3 can only be measured this way in final configuration
    - Monitor stability (polarity) of fields during (initial) operation
      - Radiation will affect probe sensitivity in unknown ways over time
  - Conceptual solution:
    - Measure field at discrete points using linear arrays
    - How many are needed, in which locations? (TBD)
      - 4-wire devices, wired into current chains to reduce # feedthroughs
    - What is the best location for these?
      - Radiation shielding; well-known positions



# In-Situ Sensors: NMR

- NMR Probes
  - Measure field stability in DS uniform tracker region
  - Absolute field at nominal and reduced current (calib)
- Conceptual solution:
  - Two probe ranges needed (Inom, Ical)
  - Mount to ends of tracker frame
    - Sensitive to change of field due to tracker position changes
  - Mount to inner wall of DS bore
    - Distinguish actual field changes due to current or coil changes
    - If neutron absorber, would need small cutout regions
  - Co-axial IFB Feedthroughs
    - 8, each (5 or) 8-pin lemo + BNC
- RemoteElectronics
  - How will power, signal, control cables be routed?
    - How long do they need to be?
  - Do we need some equipment in the Mu2e hall?
    - Amplifiers, digitizers close to the magnets

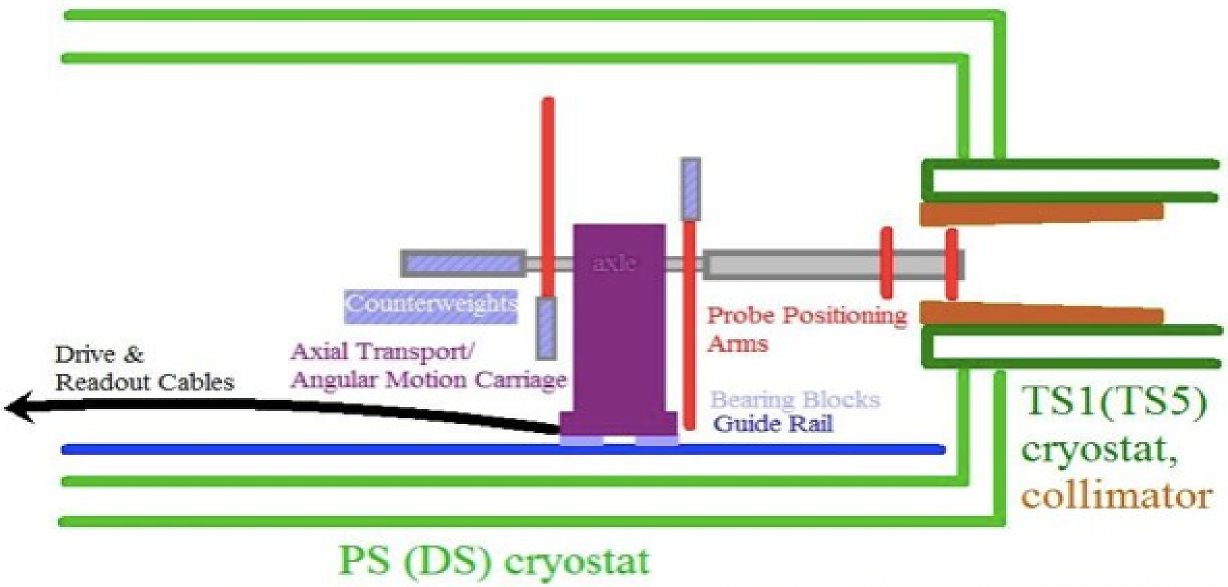
# Field Mappers (1)

- DS (1 to 2T, DZ~11m )
  - Measure field in DS/TS5 interface region, to r=0.15m
  - Measure field in DS gradient region, to r=0.7m
  - Measure field in DS uniform tracker region, to r=0.7m
- PS (2 to 5T, DZ~5m)
  - Measure field in PS/TS1 interface region, to r=0.15m
  - Measure field in PS volume prior to HRS installation, to r=0.7m
- Common Conceptual solution:
  - Volume map on a cylindrical grid of points
    - Detailed comparison against Opera3D magnetic model
    - Analytical fit (to function satisfying Laplace equation)
  - CMS-style transporter to position probes in {r,z,q}
    - 3D Hall Probes, NMR ref probe, at fixed R,q along “propellers”
    - Propellers rotate in azimuthal angle steps at each z position
    - Cantilevered extension to move probes into collimator region
  - Axial motion along precision rails
    - Drive mechanism (e.g., pneumatic or non-mag. cable?) TBD
    - Precision linear encoder
    - continuous survey of targets during map

# Field Mappers (2)

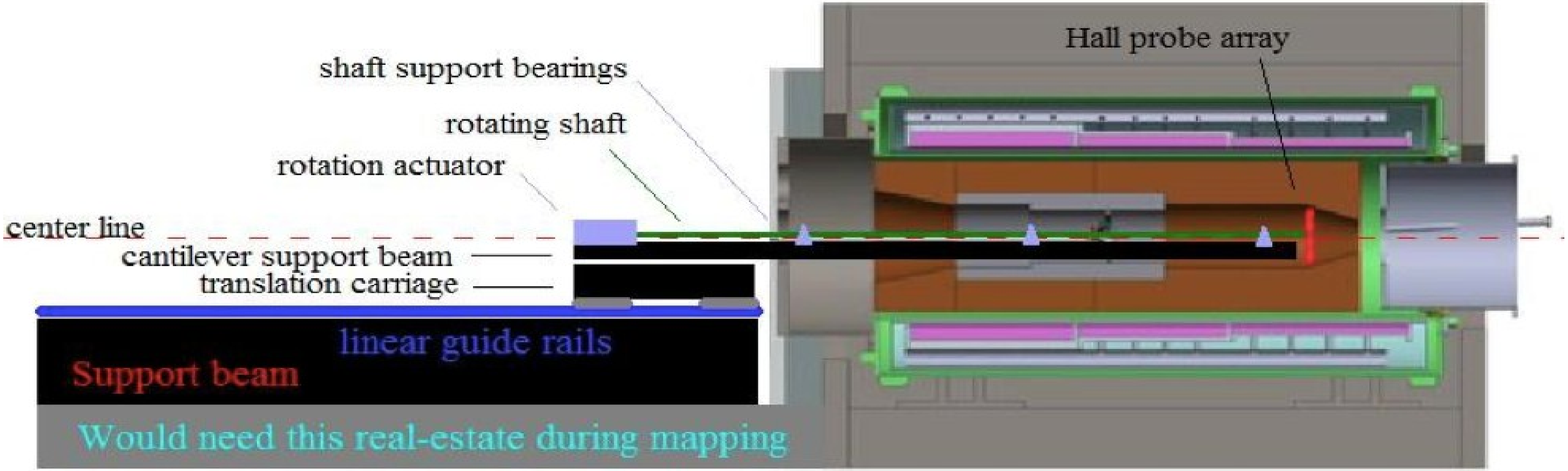
CMS System: R=1.72m
Mu2e System: R=0.70m

- PS/DS Field Mapping System:
  - Transport mechanism on guide rails pneumatic or non-magnetic cable driven
  - Probes on propeller arms (large volume map) low mass extension (collimator map)
  - Same system has to be used in two places
    - Can not map PS and DS simultaneously
    - May need to move/setup multiple times
    - Re-survey for each new setup after adjustments



# Field Mappers (3)

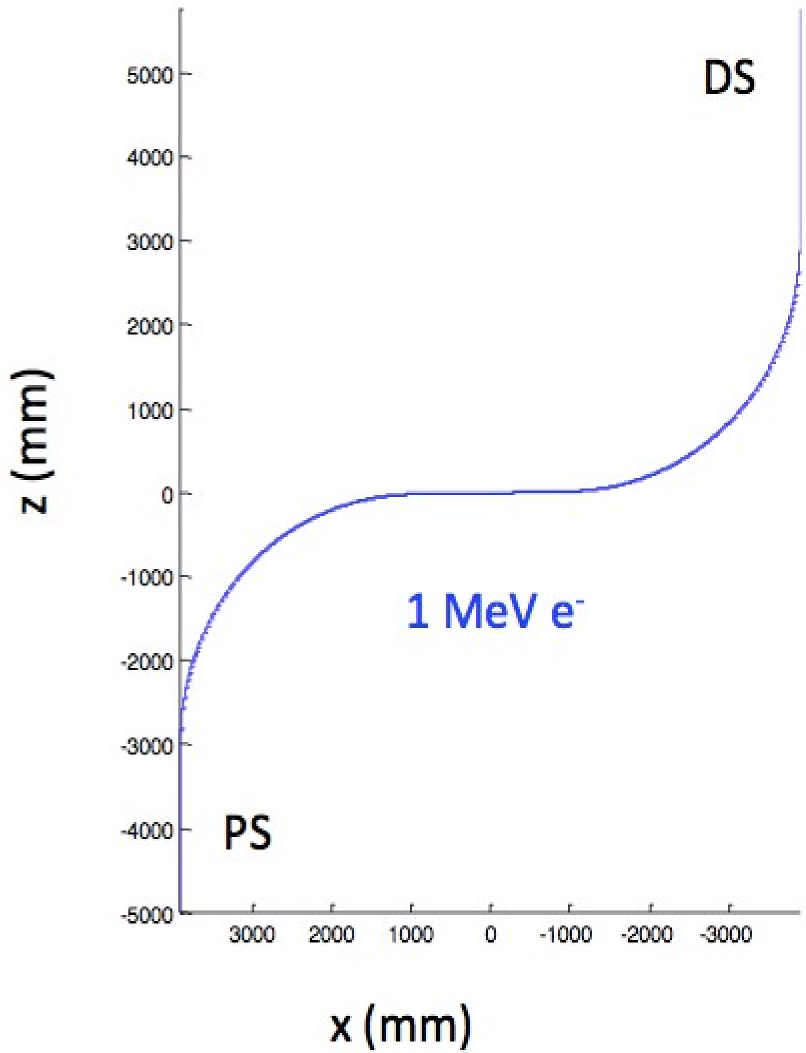
- Alternative PS Conceptual solution
  - Stiff beam with rotating shaft, cantilevered propeller(s)
  - External base with rails, transport and drive system
  - Method used for CDF, BABAR ("rotoTrack")
  - Electronics could, in principle, still be shared with DS mapper
- Dedicated system stays (roughly) in place for all measurement phases (moves for HRS installation)
- Large and small "propellers" with Hall probe arrays for mapping outer radii without HRS; inner radii with HRS
- Long enough to extend probes through TS1 collimator (or add extension to front end of shaft)



# Electron Source Test (1)

- Motivation
  - TS curved sections cannot be mapped
  - Concern about potential backgrounds, and magnetic drifts in TS curved sections (e.g, systematic coil angles)
    - Will “good” particles get through the collimators
    - Will “bad” particles get stopped by the collimators
  - Test low energy electron transport through channel
- General Concept
  - After “rough” field mapping is completed (PS/TS1,TS5/DS are OK)
  - Install low Energy electron source in region of production target
  - Install electron detector at DS stopping target
    - Other detectors already tile upstream faces of TS3u, TS5 collimators
  - Reduce the transport channel pressure (gas mass)
  - Operate Solenoids in final magnetic configuration
    - (do we need to do this in both polarities?)
  - As a function of electron source position, detect electrons at key locations downstream
  - Since electrons will all show up where they are supposed to:
    - Remove e-source and DS e-detector
    - No need to remove those on collimator front ends
  - Can now install targets, pbar window, shielding, detector, do exp!

# Electron Source Test (2)



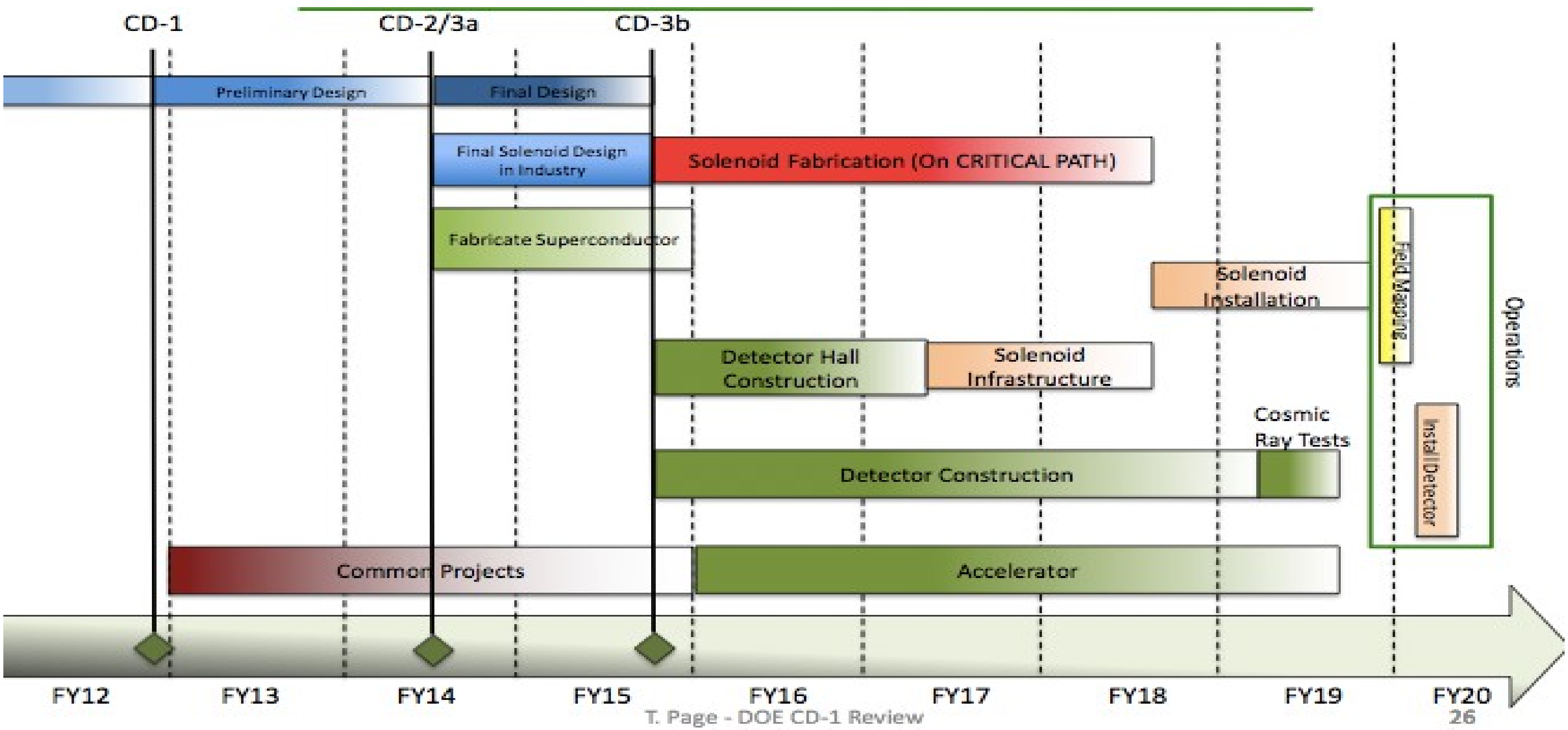

Opera simulation (M. Lopez)

- Electron source options:
  - electron gun (~10 keV) or beta source (1-2 MeV)
  - Source transverse positioning method
    - Needed to explore position dependence
    - Single beta source mounted on x,y positioning stage
      - 2D ceramic/piezo stage will work, but expensive (~$25k)
      - Advantage of fine position control
    - "Several" Individually powered electron guns (cheap) » (or, could one use shutters or mask to select?)
- Need low level vacuum for low energy electrons to pass through the channel
- Electron detector options
  - Want some level of segmentation (TBD; $/# channels)
  - Must work in ~2 T magnetic field
  - Low E electrons won't penetrate far
    - Light detection, segmented Phosphor screen/scint
    - Charge collection electrode array?
    - Re-use some old silicon detectors?

# Safety Issues

- High Magnetic Field Hazard:
  - No access to personnel during powered operation: fully remote control and data acquisition.
  - Possibility of laser survey operation with field on (at least in DS)
- Cryogenic
  - Cryogenic magnet operation probable when mapper is installed, surveyed, removed: ODH considerations will apply
- Radiation:
  - We don't anticipate to measure after irradiation
  - However, what if there is a potential problem and the experiment wants to investigate the field? Should at least keep it in mind.

# Summary




- Mu2e magnetic measurements will be on the critical path
- Interesting challenges ahead
- The clock is ticking ...

# Backgrounds

- Decay-in-orbit (DOI)
- Radiative Muon Capture
- Processes that are delayed because of particles that spiral slowly down the muon beam line
- Prompt processes where the detected electron is nearly coincident in time with the arrival of a beam particle at the muon stopping target (e.g. radiative pion capture, RPC)
- Electrons or muons that are initiated by cosmic rays
- Reconstruction errors