Superconducting Magnet Development for $\mu \rightarrow e$ Conversion Experiments

NuFACT 2012
July 23-28, 2012

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Outline

- Muon Conversion Experiments
- Magnet Elements
- Issues for Future Experiments
- Summary

Thanks to Makoto Yoshida (KEK) for slides on COMET magnets

Other slides from “Radiation Effects in Superconducting Magnet Materials” (RESMM’12) February 2012 see:
https://indico.fnal.gov/conferenceDisplay.py?confId=4982

Muon Conversion Experiments

μ N→e^- N experiments date back to the 1950's, making incremental improvements on observation limits:

Summary of "modern" experiments:

- Past (1990's) 10^{-13} sensitivity
  - SINDRUM II
- The Present (2010's) 10^{-17} sensitivity
  - COMET
  - MU2e
- The Future (2020's ?) ~10^{-19} sensitivity
  - PRISM
  - Project X-ERA at Fermilab

Magnetic Elements

Modern muon-electron conversion experiments all work on a similar principle:

1) Generate large number of “stop-able” muons

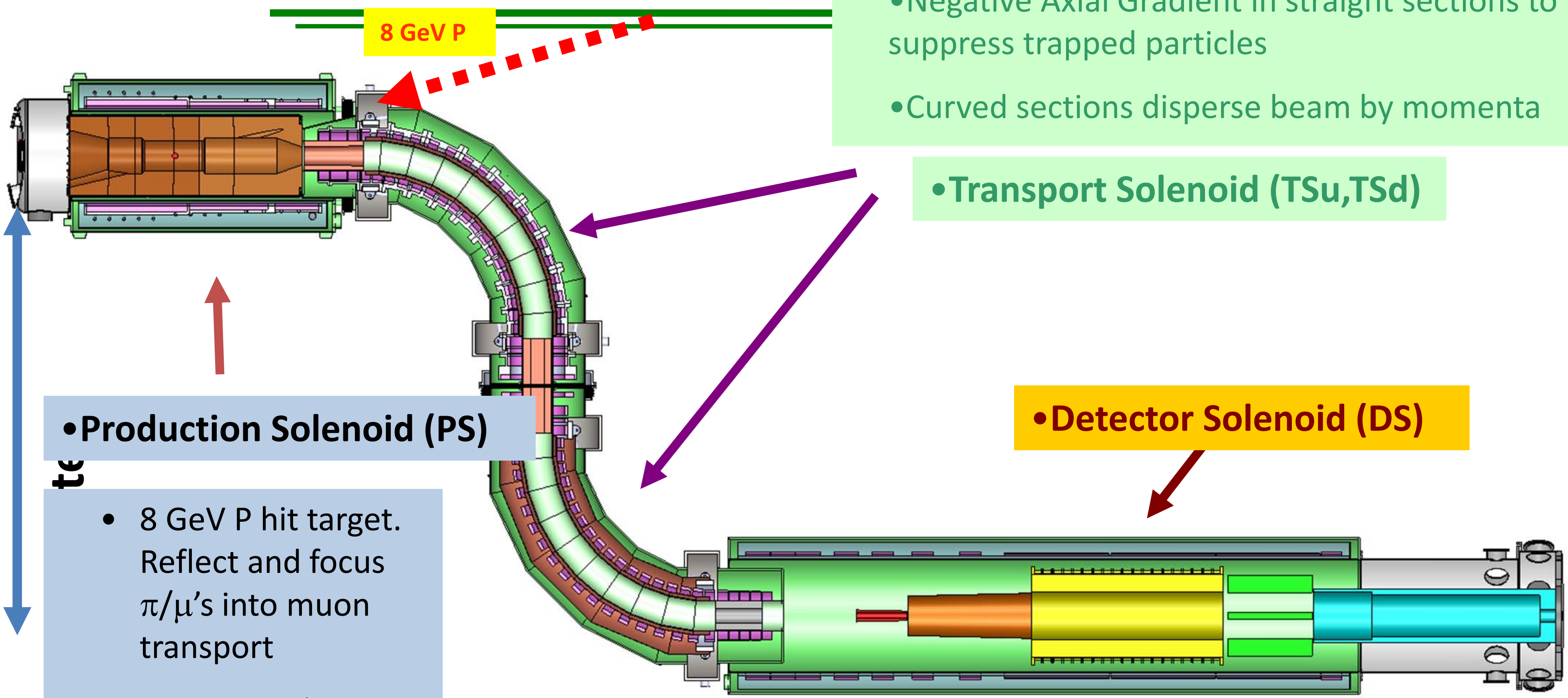
2) A mono-energetic 104 MeV conversion electron is created from the coherent process: μ N→e^- N

They utilizes three Basic Magnetic Elements:

- Capture Solenoid to collect pion and muon secondaries from primary target
  - Large aperture, highest possible fields
  - Heat and radiation from interaction secondaries
- Muon Transport
  - Maximum transports efficiency
  - Eliminate background
    - Eliminate Line of Sight for neutral background
    - Dispersion and collimation for momentum selection
  - Avoid trapped particles. Keep muons “in time”
- Muon Stopping Target and Electron Spectrometer
  - Efficient muon collection
  - Electron Momentum measurement with minimal background

Example: Mu2e

- Sign/momentum Selection
- Negative Axial Gradient in straight sections to suppress trapped particles
- Curved sections disperse beam by momenta



- **Transport Solenoid (TSu,TSd)**

- **Production Solenoid (PS)**

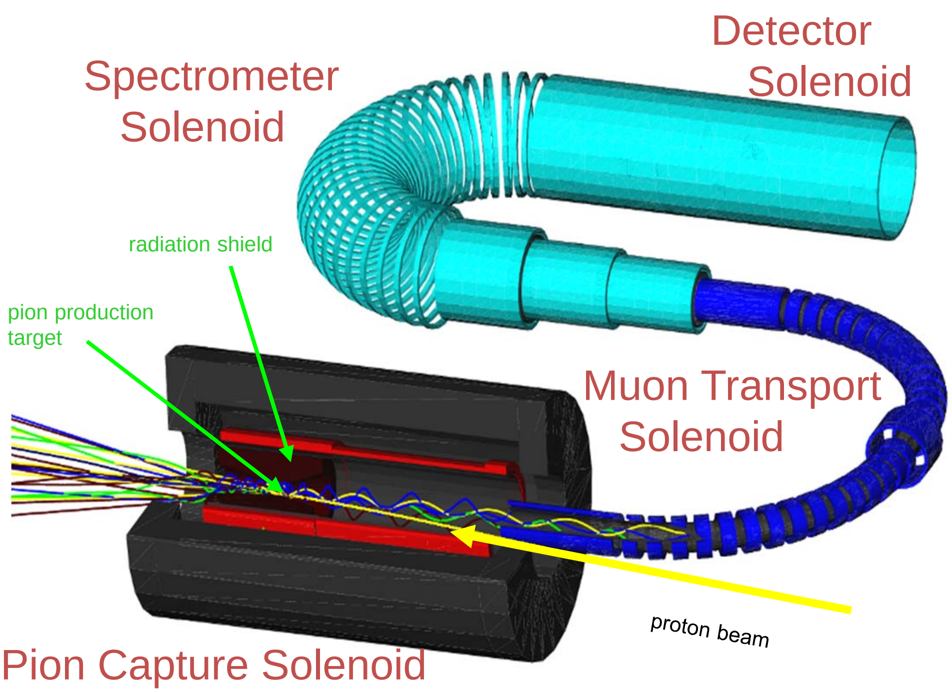
- 8 GeV P hit target. Reflect and focus π/μ's into muon transport
- Strong Axial Gradient Solenoid Field

- **Detector Solenoid (DS)**

- Graded field to collect conv. e^-
- Uniform field for e^- Spectrometer

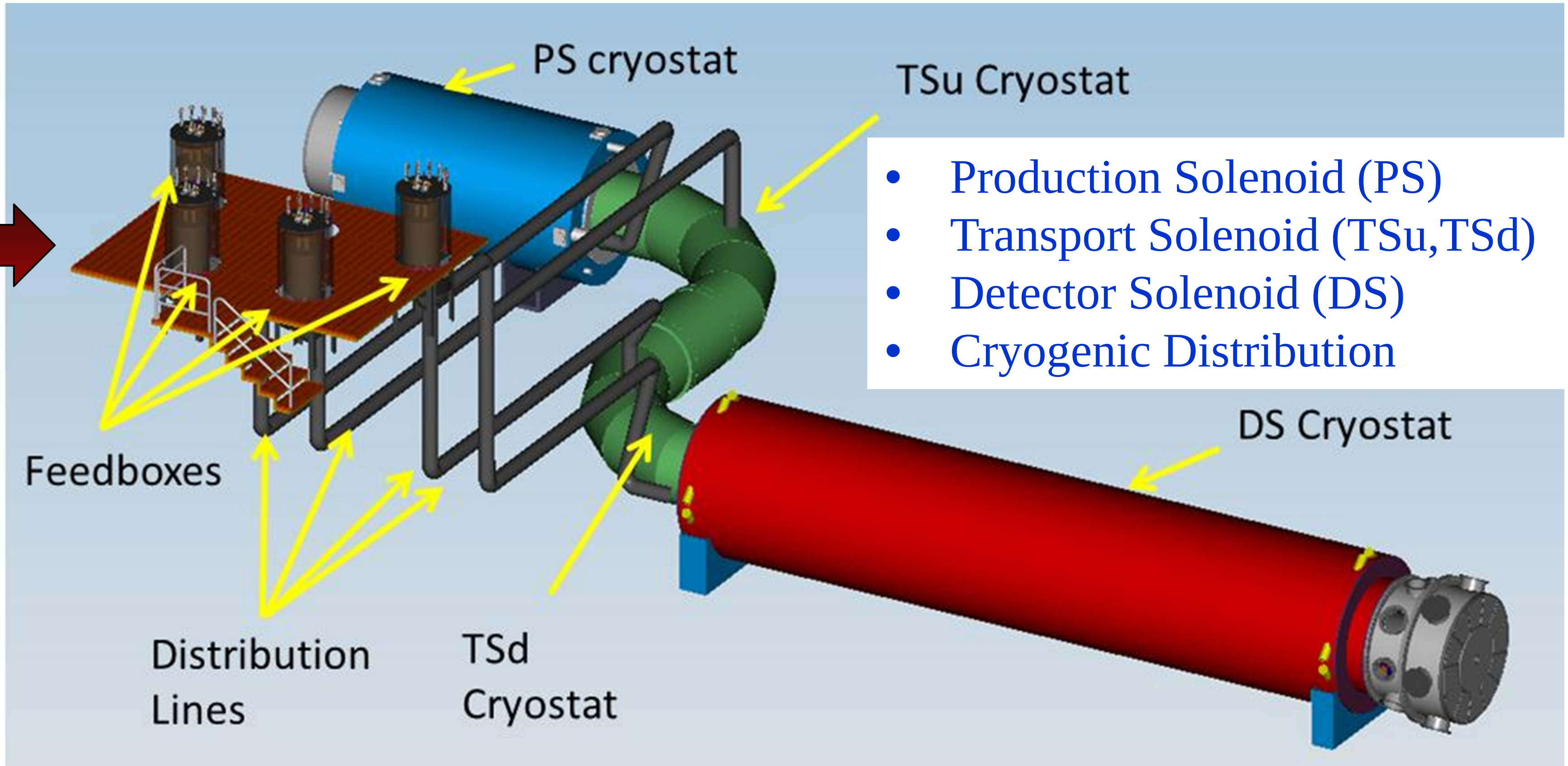
Example : COMET apparatus

- A series of long solenoids from end to end
  - pion capture & decay
  - muon transport
  - electron focus
  - spectrometer
  - detector



COMET Superconducting Magnet System

Mu2e Solenoids and Supporting Infrastructure



- Production Solenoid (PS)
- Transport Solenoid (TSu,TSd)
- Detector Solenoid (DS)
- Cryogenic Distribution

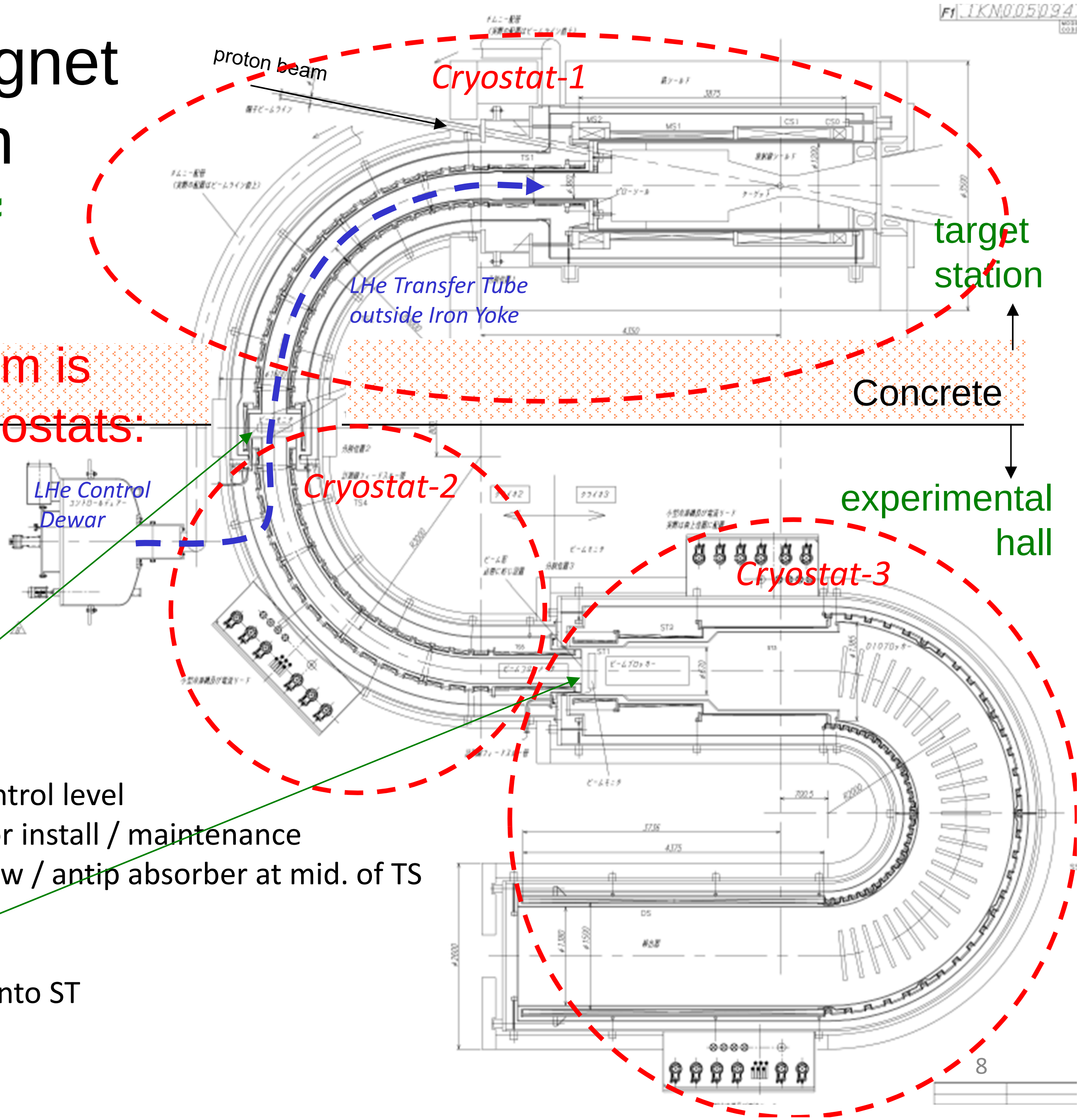
- Power Supply/Quench Protection
- Cryoplant

- Field Mapping
- Ancillary Equipment
- Installation and commissioning

Comet Magnet Design

The magnet system is separated in 3 cryostats:

Cryostat-1: CS+UpstreamTS
Cryostat-2: DownstreamTS
Cryostat-3: ST+SS+DS

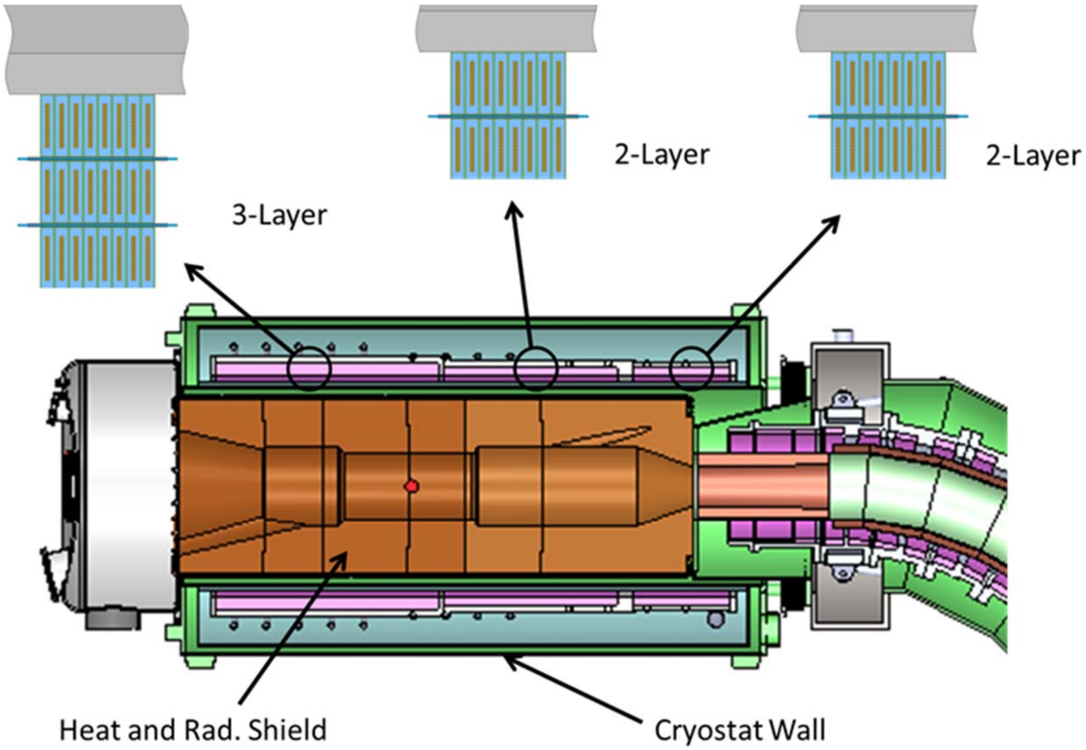


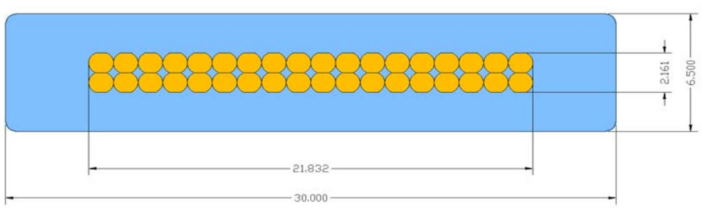
Purpose of separation:

- At concrete wall
  - Different radiation control level
  - Movable Cryostat-2 for install / maintenance
  - Vac. separation window / antip absorber at mid. of TS
  - Beam monitors
- At stopping target
  - inject electron beam into ST
  - Muon beam monitor

Mu2e Production Solenoid Concept

4.6T➔ 2.5 T Axial Gradient





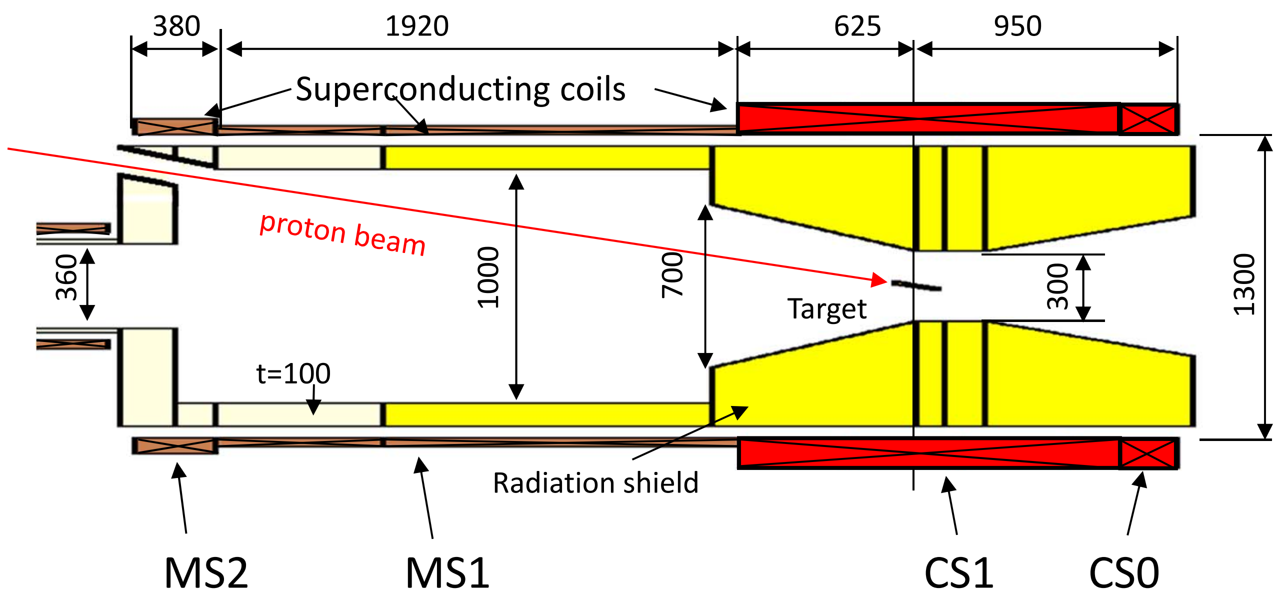
Features:

- 1.6 m aperture, 4 m long
- Operating current ~9kA
- 3 coils "3-2-2" layers
- High strength aluminum stabilized NbTi superconductor (similar to ATLAS Central Solenoid)
- Aluminum outer support shells
- Thermal Siphon Cooling
- Mechanically supports Heat and Radiation Shield

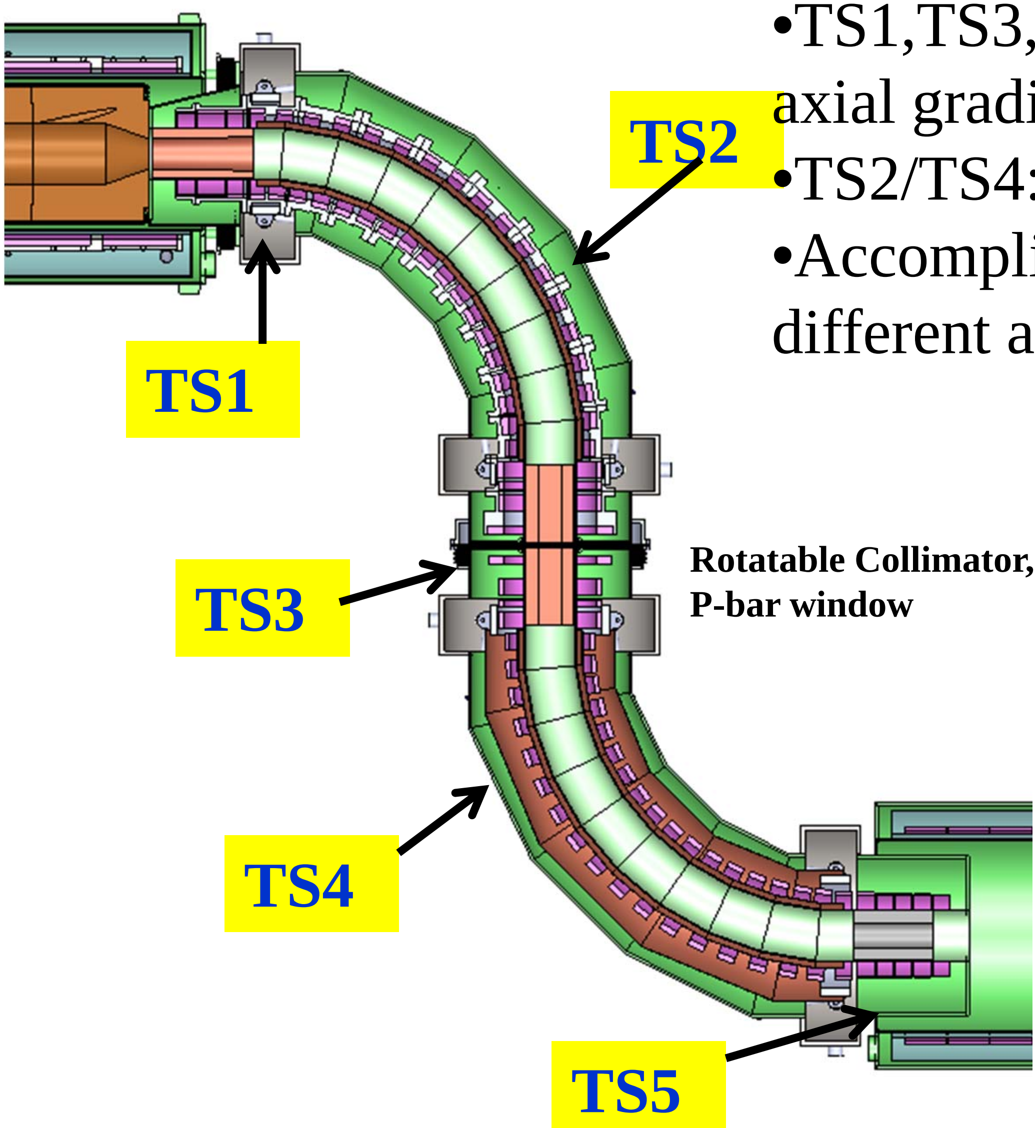
Comet Capture Solenoid Layout

- Superconducting solenoid magnets with Al-stabilized conductor
- High field 5T to capture π^-
- Large bore 1300mm
- High radiation env.
- Decreasing field
- to focus trapped pions
- Thick radiation shielding 450mm
- Proton beam injection 10° tilted
- Simple mandrel

	CS0	CS1	MS1	MS2
Length (mm)	175	1350	1800	380
Diameter (mm)	662	662	662	662
Layer	9	9	5	8
Thickness (mm)	144	144	80	128
Current density (A/mm^2)	35	35	35	35
Maximum field (T)		5.7	4.0	3.9
Hoop stress (MPa)		59	51	30

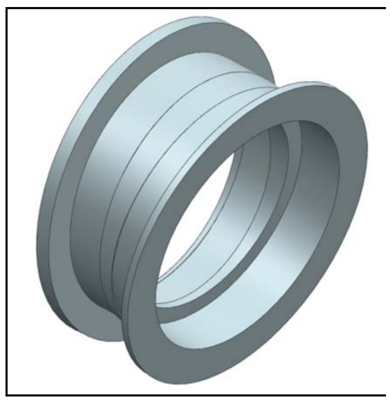


Mu2e Transport Solenoid



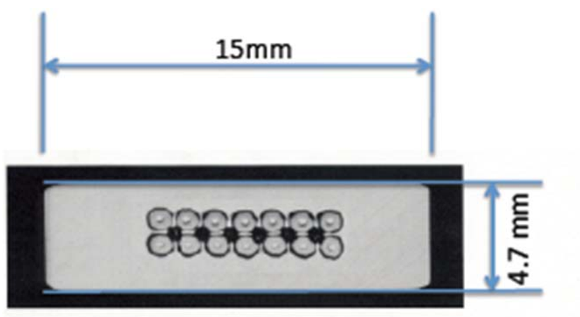
- TS1,TS3,TS5: Straight sections with axial gradient
- TS2/TS4: approximate toroidal field
- Accomplished by 52 solenoid rings of different amp-turns

- Two cryostats: TSu, TSd
- TS3: ➔ TS3u, TS3d. Wider coils to compensate for gap
- Coil fabrication similar to MRI coils

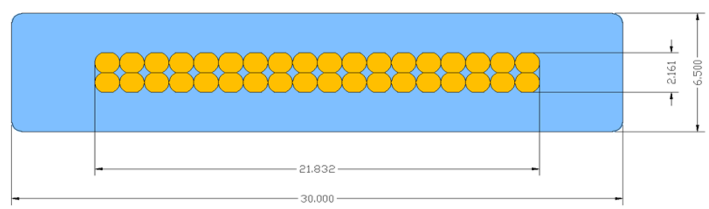


Al-stabilized superconductor

- NbTi Rutherford cable with aluminum stabilizer
- “TRANSPARENT” to radiation
  - Less nuclear heating
- Doped cold worked aluminum
  - High RRR (>500) and
  - High offset yield point at 4K > 85 MPa



30 mm x 5.5 mm



COMET design value for Capture Solenoid

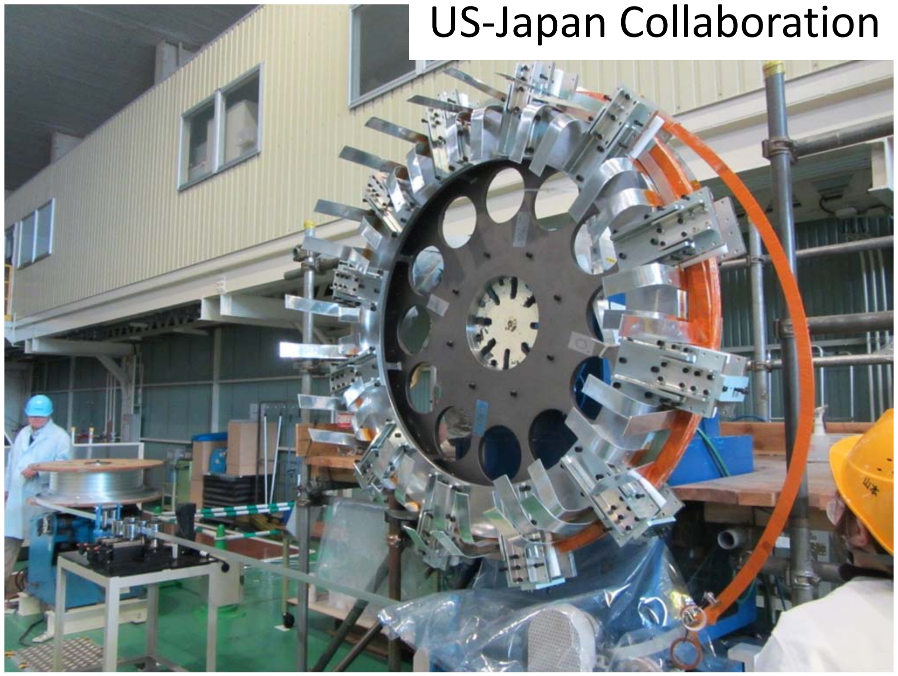
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

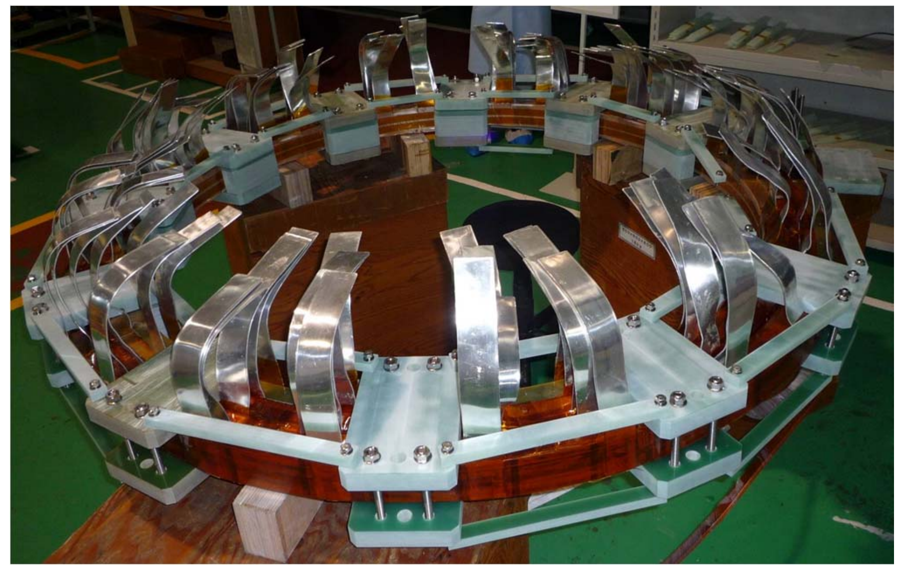
Mu2e design value for PS

- Al/Cu/SC: 6.0/0.9/1
- 36 SC strands: 1.30 mm dia.

Ongoing R&D

US-Japan Collaboration





PS demonstration coil at Toshiba

- 4-layer 8 turns using prototype cable
- Al-Al internal joint
- To be tested at Fermilab in 2013

Ongoing R&D

Part of the US Japan Collaboration

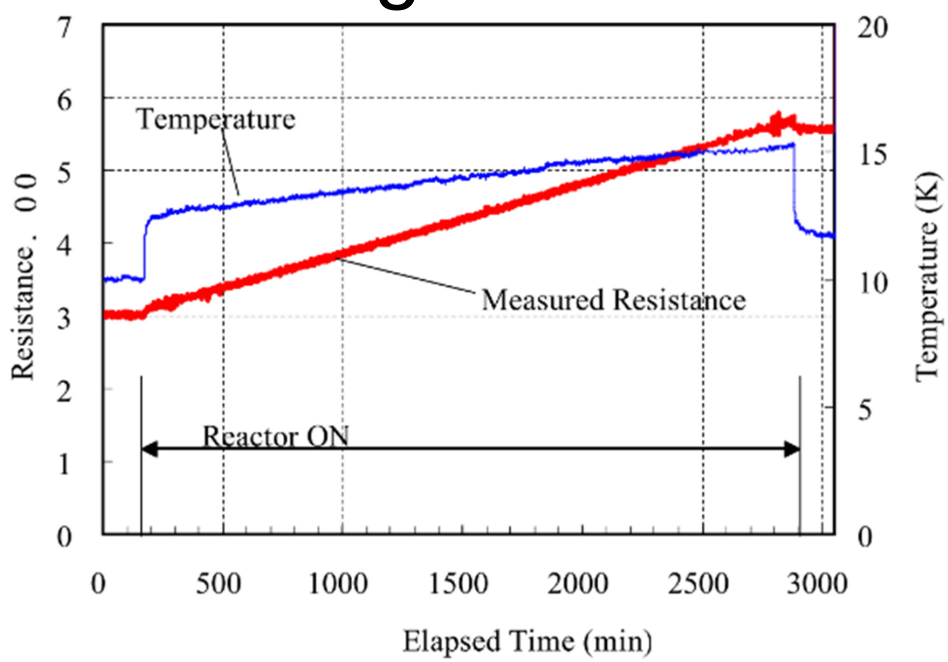
Splice Tests

- Chemically removed Al stabilizer
- NbTi-NbTi splice joint

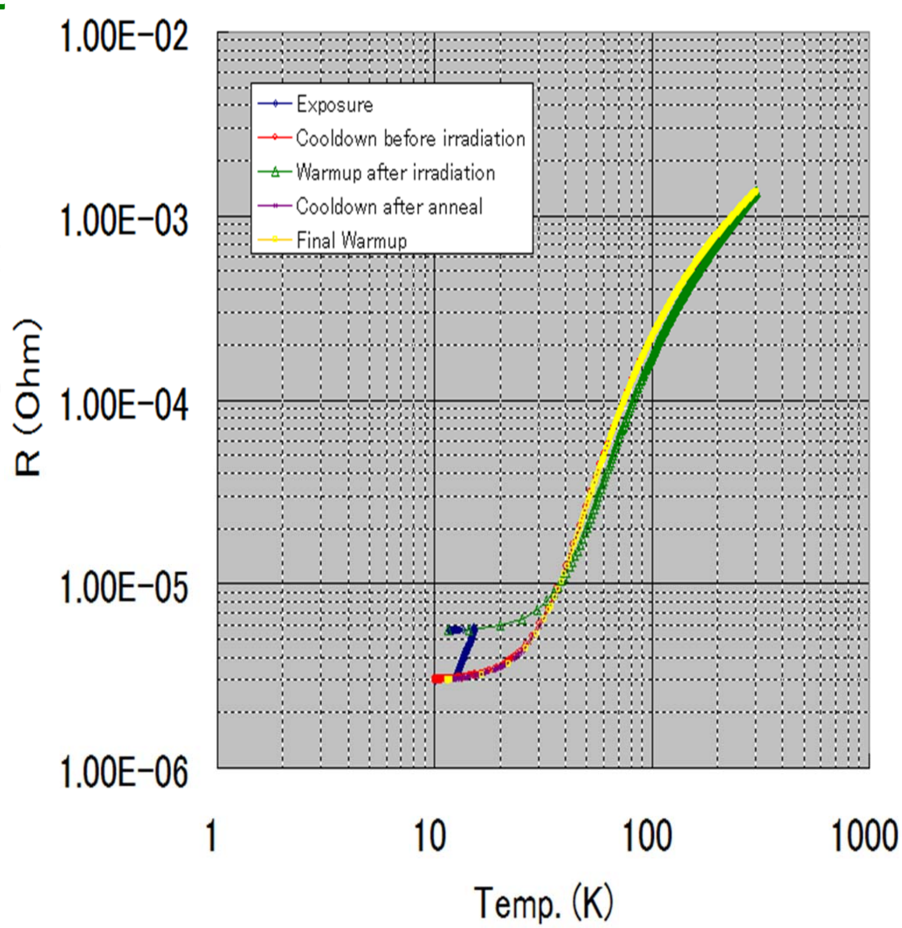
M. Yoshida et al, ICMC2011

Radiation Studies at KUR

Al-Cu-Mg



Resistivity change with accumulated dose



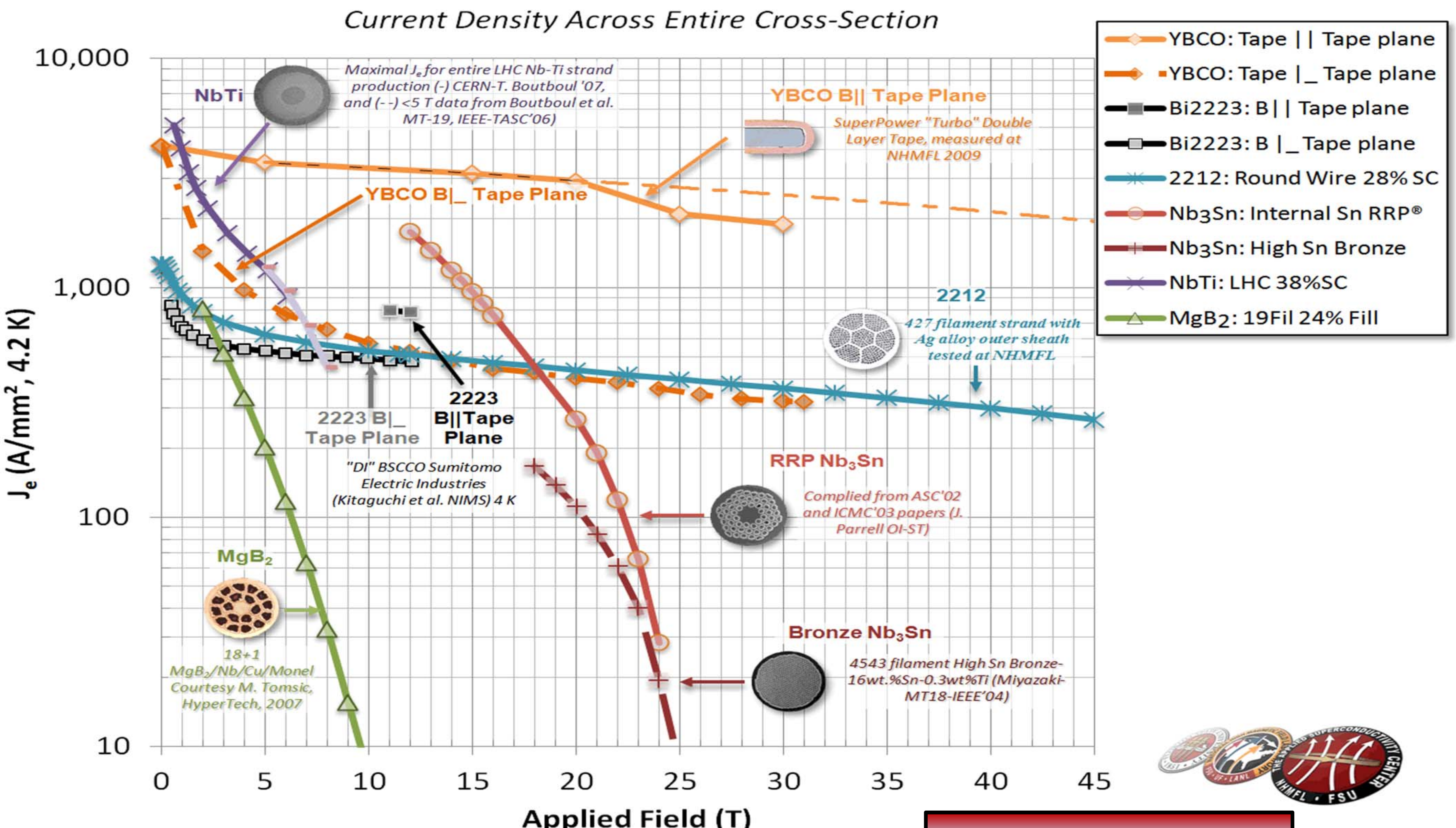
Fully recovered with room temp. anneal

Mu2e will have to warm up ~1/year to repair aluminum stabilizer

Issues for Future Experiments

- Higher intensity muon beams will be required to increase limit sensitivity/discovery.
- More Demands on the Pion Capture Solenoid
  - Higher intensity primary proton beams
  - Increase capture efficiency with larger aperture, higher field➔ higher field on superconductor
  - Larger flux of secondaries➔ higher heat load + high radiation on coil (superconductor, stabilizer and insulation)

HTS Needed for High Fields



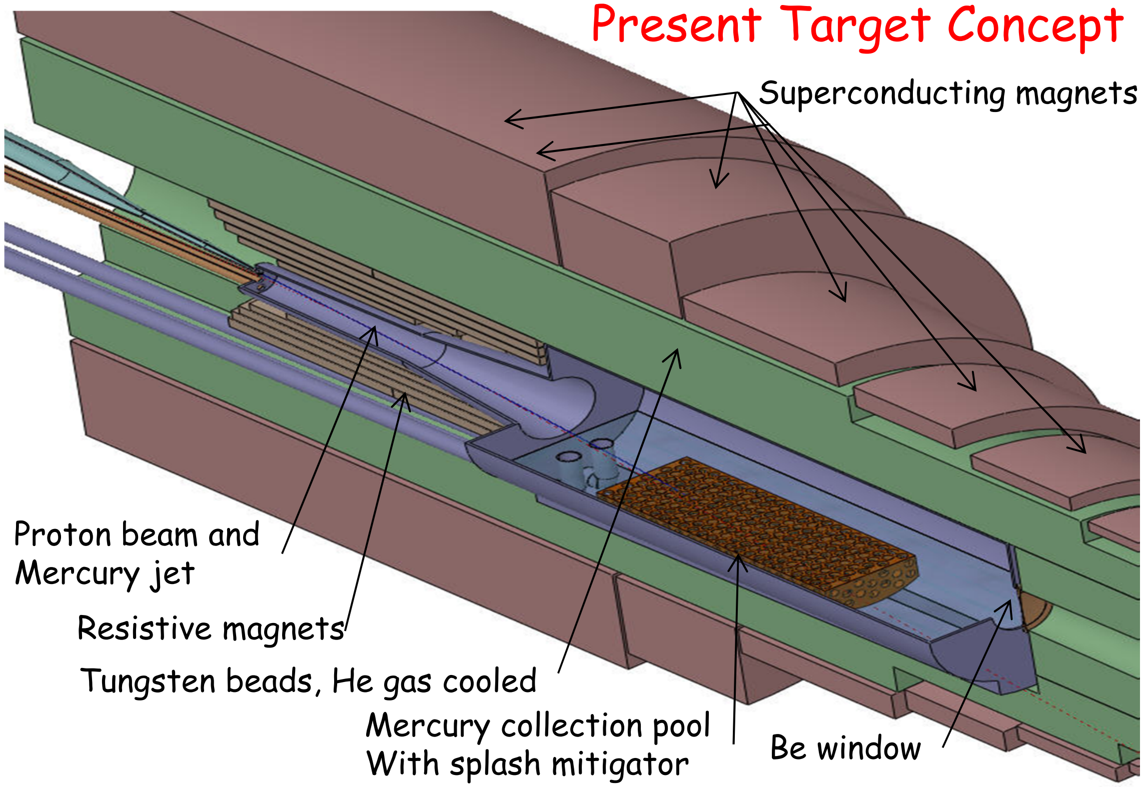
Peter Lee, FSU-NHMFL

Mu2e and Comet Capture Solenoids are near the limit in several areas

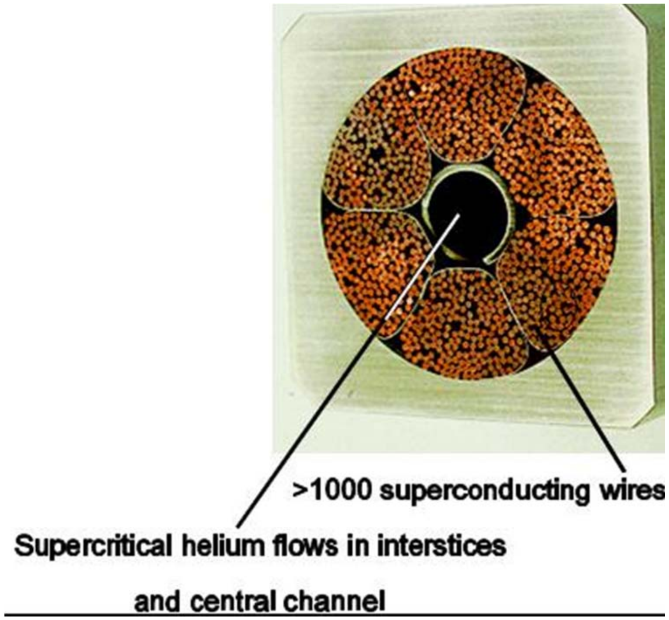
- Peak field on conductor is >5.5 T. Limited SC phase space especially since experiment demands large temperature and thermal margin for quench-free operation
  - Near the limit of what is practical with NbTi
  - Nb3Sn or HTS conductor is a possible upgrade path
    - Brittle conductor
    - Generally Nb3Sn solenoids are possible because of simpler mechanical forces, may not be true in this case.
- Radiation limits on stabilizer and insulation will demand more effective heat shield in bore of magnet
    - Tungsten ($$$$) replaces copper
    - Frequent room temperature anneals to repair stabilizer

  - Consider radiation resistant epoxies (cyanide ester)
  - HTS is purported to have good radiation qualities

Future Capture Solenoids may resemble muon collider concepts



Kirk McDonald RESMM'12



5-T copper magnet insert; 15-T Nb_3Sn coil + 5-T NbTi outsert.
Desirable to replace the copper magnet by a 20-T HTC insert.

Summary

- The conceptual design for the Mu2e and COMET solenoids has been completed
  - Both use indirectly cooled NbTi conductor stabilized with Aluminum
  - Designs are appropriate for sensitivity goals
- Peak Fields and dynamic heating are near the limit of what can be practically achieved with NbTi.
- Future experiments will likely require magnets built with Nb3Sn, HTS and radiation hardened insulators.