Solenoid Magnet System for the Fermilab Mu2e Experiment

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Outline

- Fermi National Accelerator Laboratory
- Short description of the Mu2e Experiment
- Mu2e Solenoid System Design

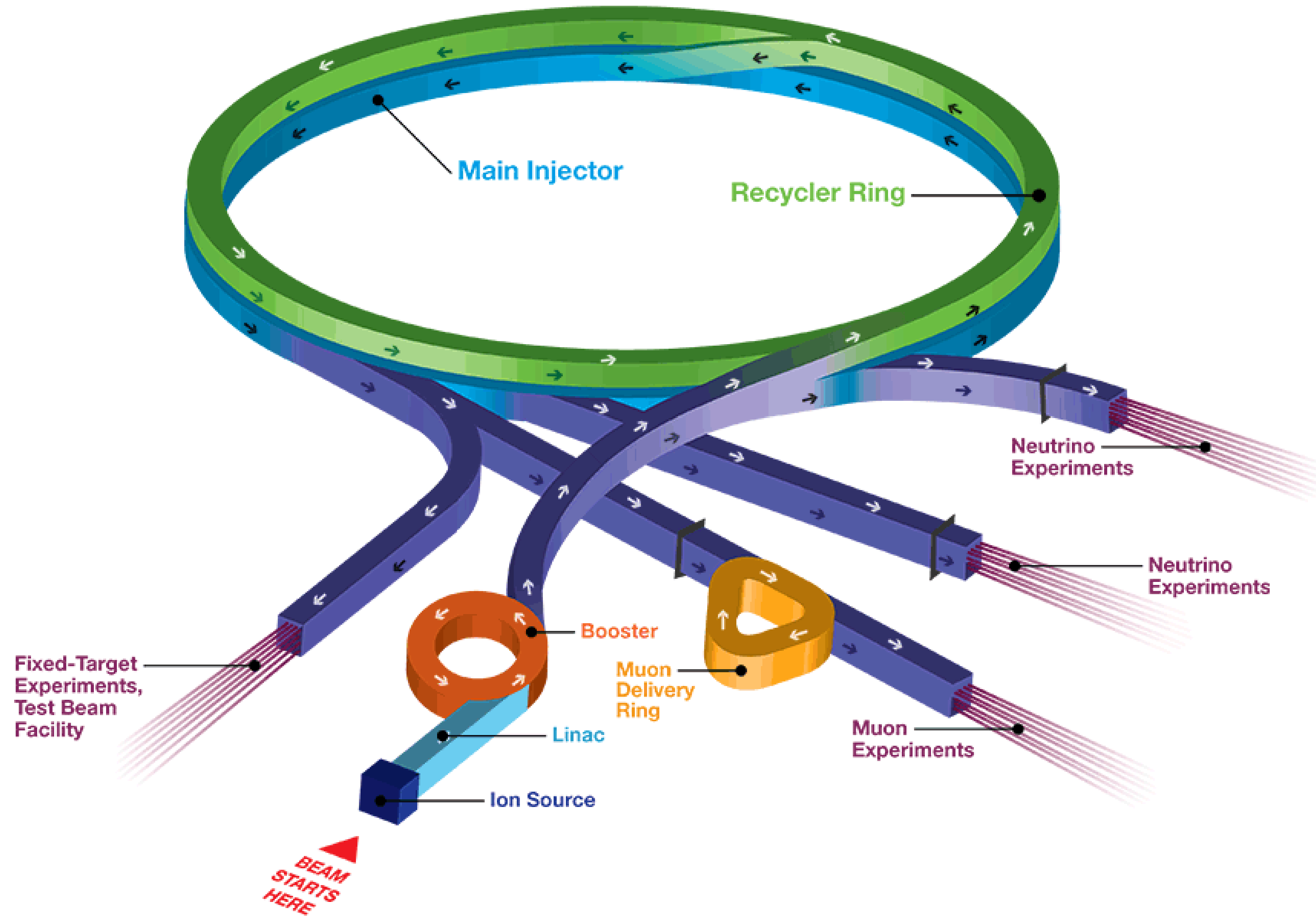
Fermilab

USA, Illinois west of Chicago
Particle Accelerator Complex

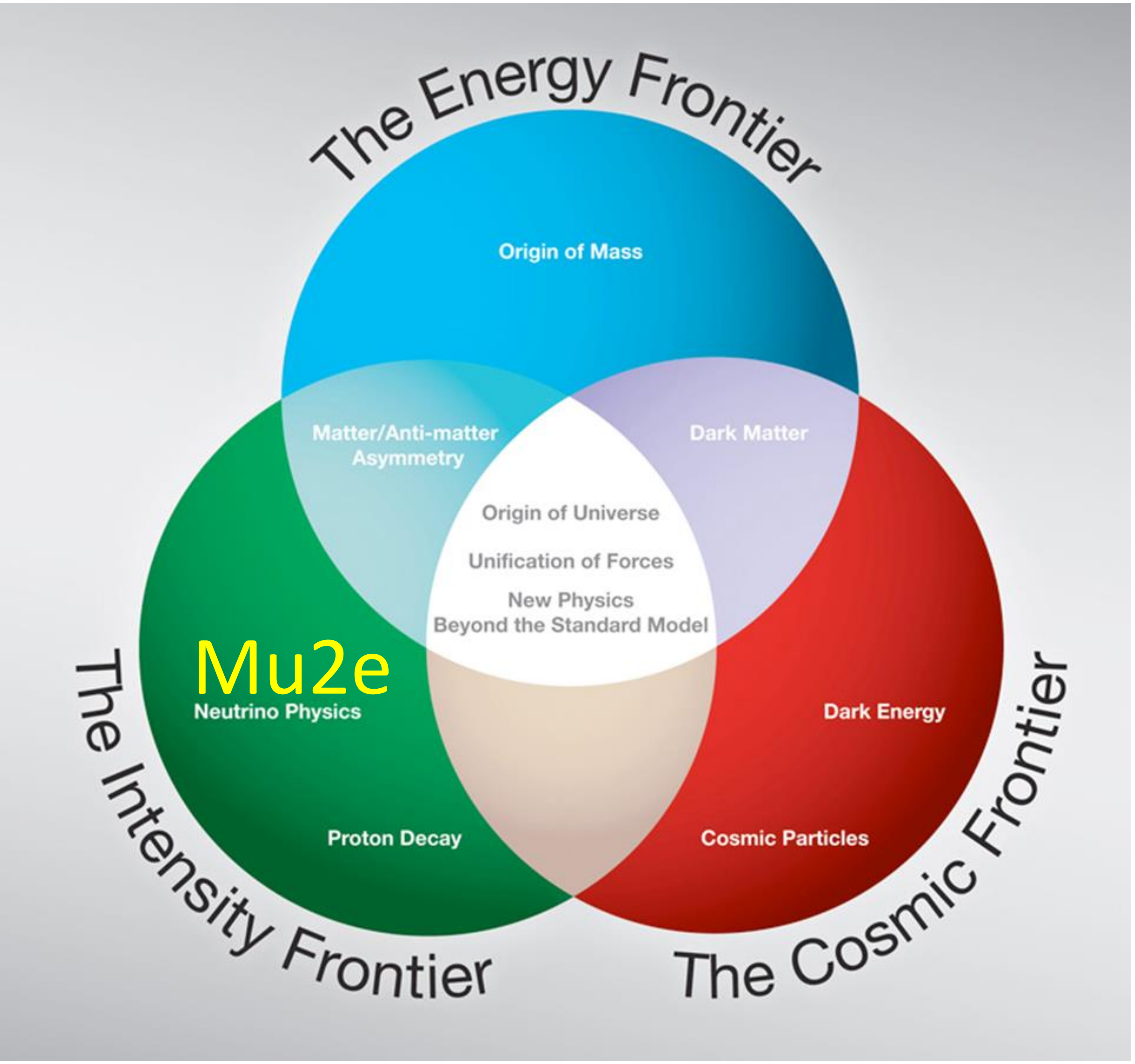
1965 JCAE and NAS approved 200GeV
1970 first proton beam
1972 Main Ring delivered 400 GeV
1974 Named after Enrico Fermi
1983 Energy Doubler – Tevatron approved
1986 Delivered 900 GeV

6800 acres of land
Herd of North America Bison in 1969
Restoration of the Prairie begin in 1971

Fermilab Accelerator Complex



The Frontiers in HEP



Fermilab was pushing the Energy frontier for more than two decades

Cosmic Frontier

Intensity Frontier

The Intensity Frontier at Fermilab

- One can probe the properties of the universe by looking for extremely rare processes
- Complementary alternative to using higher energies
- The medium-term future of accelerator-based particle physics on US soil is the intensity frontier:
  - Neutrino experiments (NOvA, LBNE, MINOS, MINERvA, and others…)
  - Precision measurements (g-2)
  - Rare decays (Mu2e)

Mu2e Collaboration

Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Lewis University
University of Massachusetts, Amherst
Muons Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Purdue University
Rice University
University of Virginia
University of Washington

Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce and Università del Salento
INFN Lecce and Università Marconi Roma
INFN Pisa
Universita di Udine and INFN Trieste/Udine

Joint Institute for Nuclear Research, Dubna
Institute for Nuclear Research, Moscow

Mu2e Experiment

Mu2e is searching for rare decays: Charge Lepton Flavor Violation

$$\mu \rightarrow e\gamma \quad \mu \rightarrow e^+e^-e^+ \quad K_L^0 \rightarrow \mu e \quad B^0 \rightarrow \mu e$$

$$\tau \rightarrow \mu\gamma \quad \tau \rightarrow \mu^+\mu^-\mu^+ \quad D^+ \rightarrow \mu^+\mu^+\mu^-$$

Muon to electron conversion experiment: muon converts to electron in the presence of a nucleus

Experimental Goal

Single-event-sensitivity

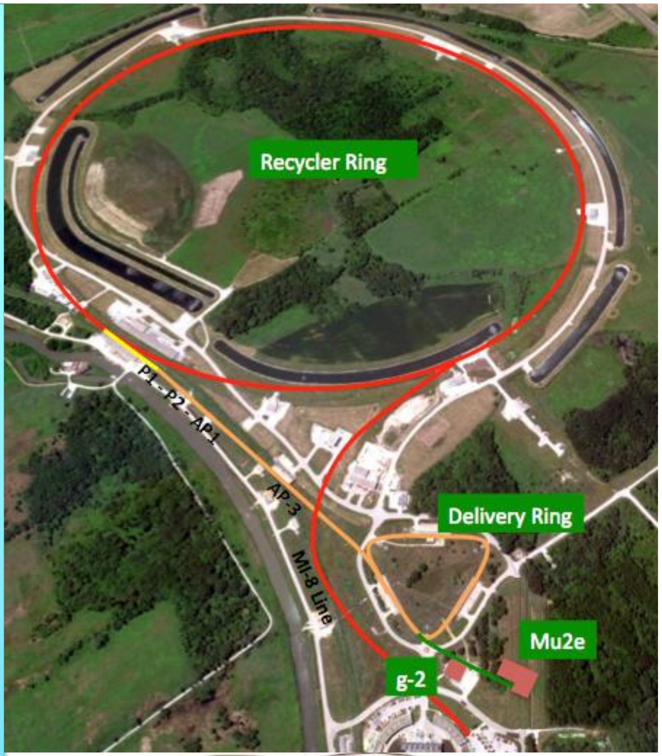
$$\mu^- N \rightarrow e^- N$$

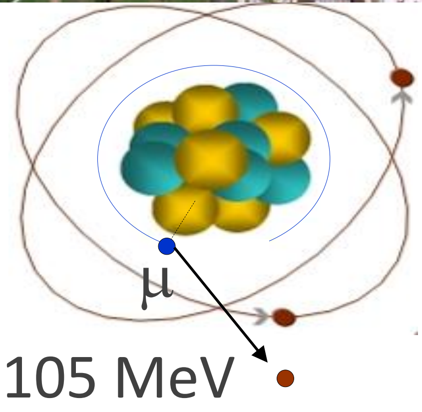
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

expected limit of 7 x 10^{-17} @ 90% CL

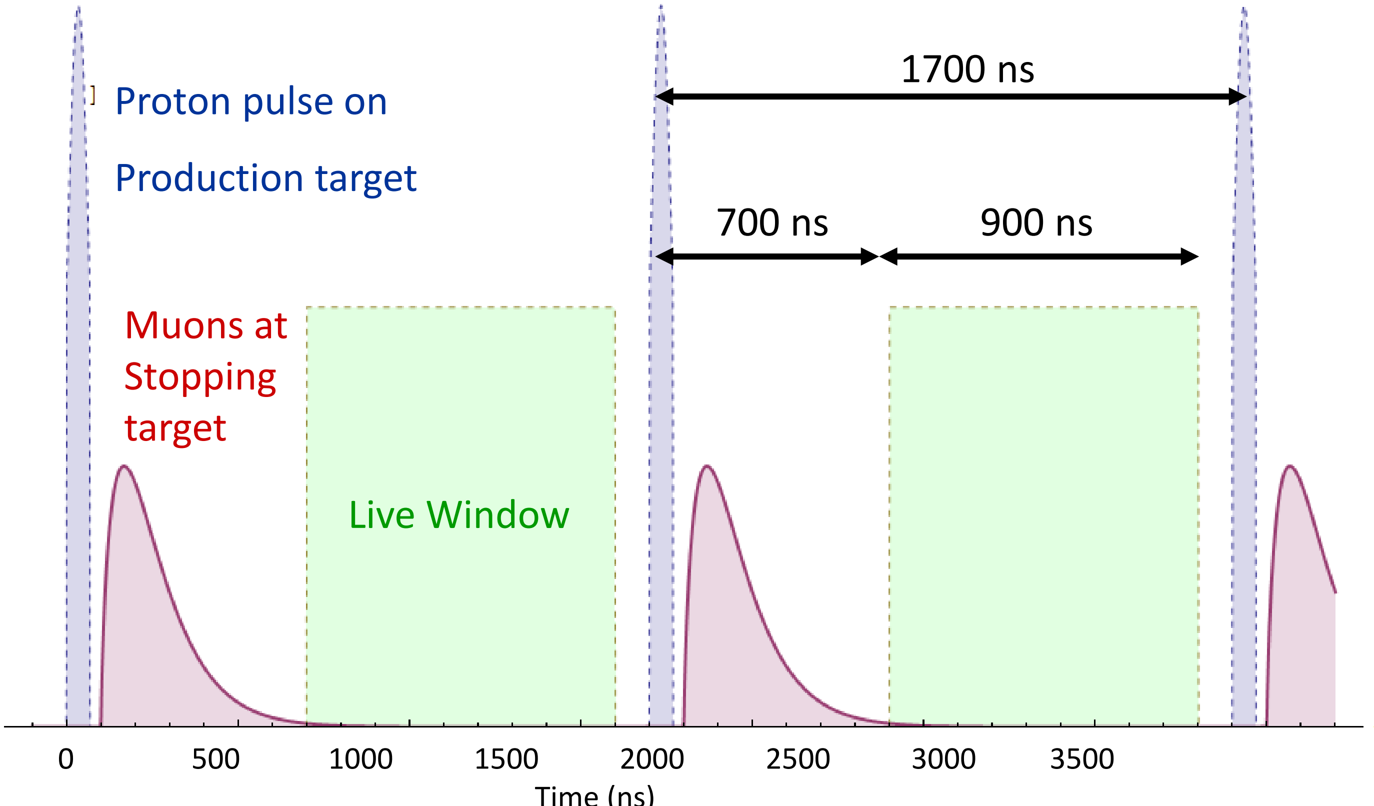
Mu2e Strategy

- Generate a beam of low momentum muons
  - Use 8 GeV protons from existing Fermilab complex – 8 kW beam power
- Stop the muons in orbit around a nucleus
  - We plan to use aluminum stopping target; μ^- captured; 1s state
  - the Bohr radius is ~ 20 fm, the μ^- sees the nucleus (~4 fm)
  - In orbit around aluminum τ_μ^{Al} = 864 ns
  - Important in discriminating background
- Look for events consistent with the signal
  - 105 MeV electron emanating from target; nucleus coherently recoils off outgoing electron, no breakup
  - Clean experimental signature, separate from electrons from muon decay





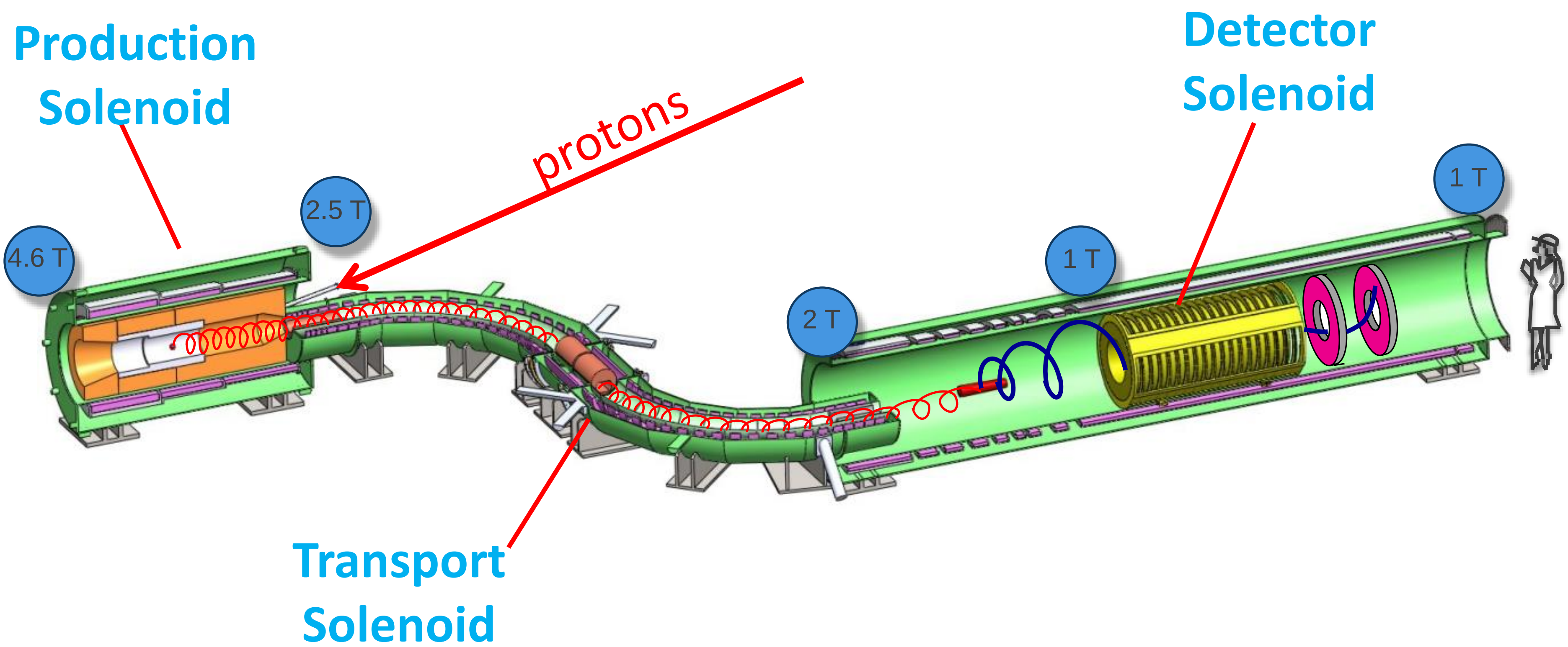
Mu2e Concept



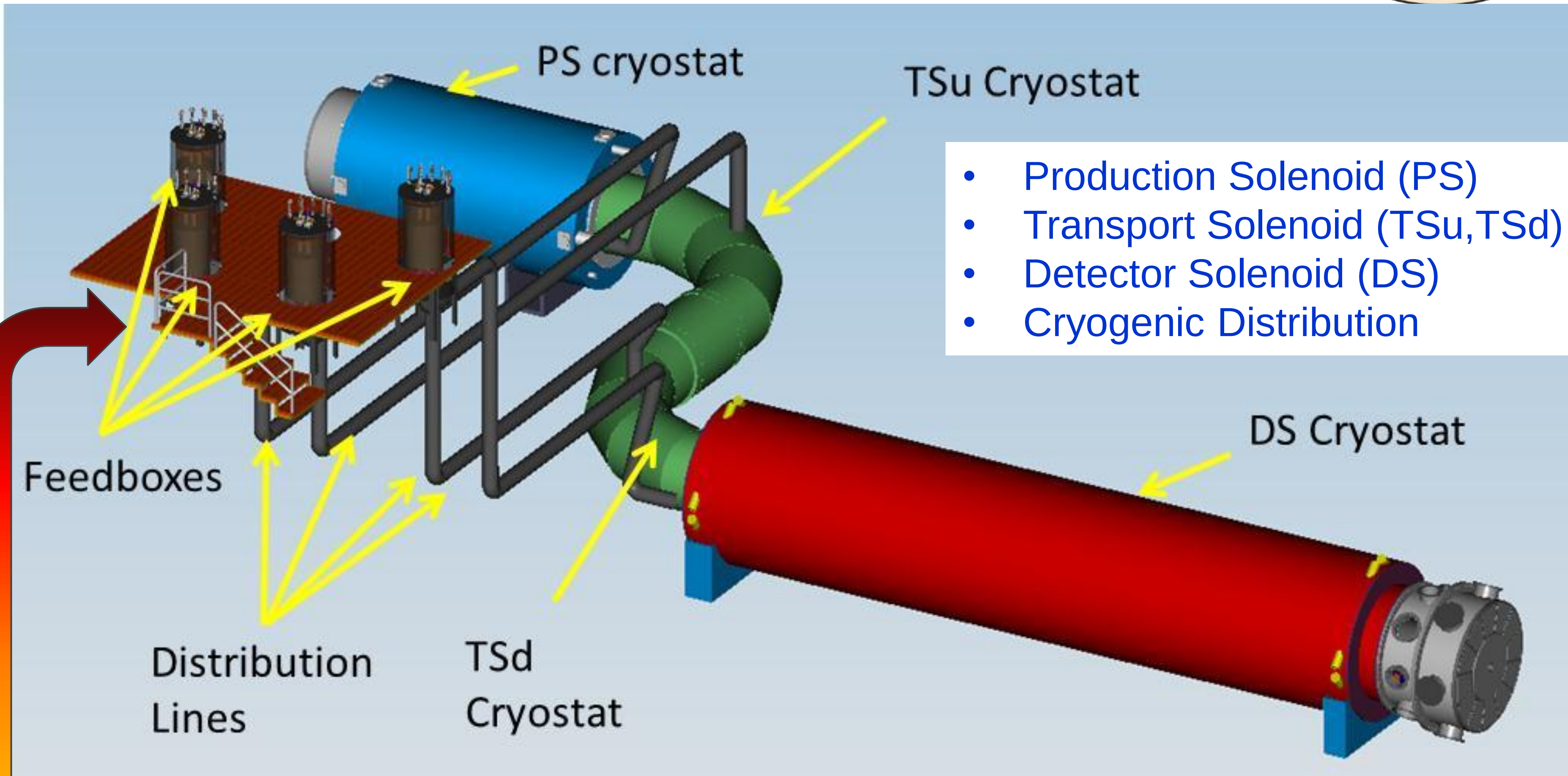
- Mu2e will use a pulsed proton beam (250 ns width, 3 x 10^7 P/pulse) and a delayed live gate to suppress prompt background
- Out of time muons are a potential source of background
- Total of 10^{20} proton on target, 10^{18} stopped muons

Mu2e Solenoid System

- Three solenoids provide magnetic field for experiment



Mu2e Solenoids Scope



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

- Helium and LN2 Supply
- Power Supply/Quench Protection Electronics

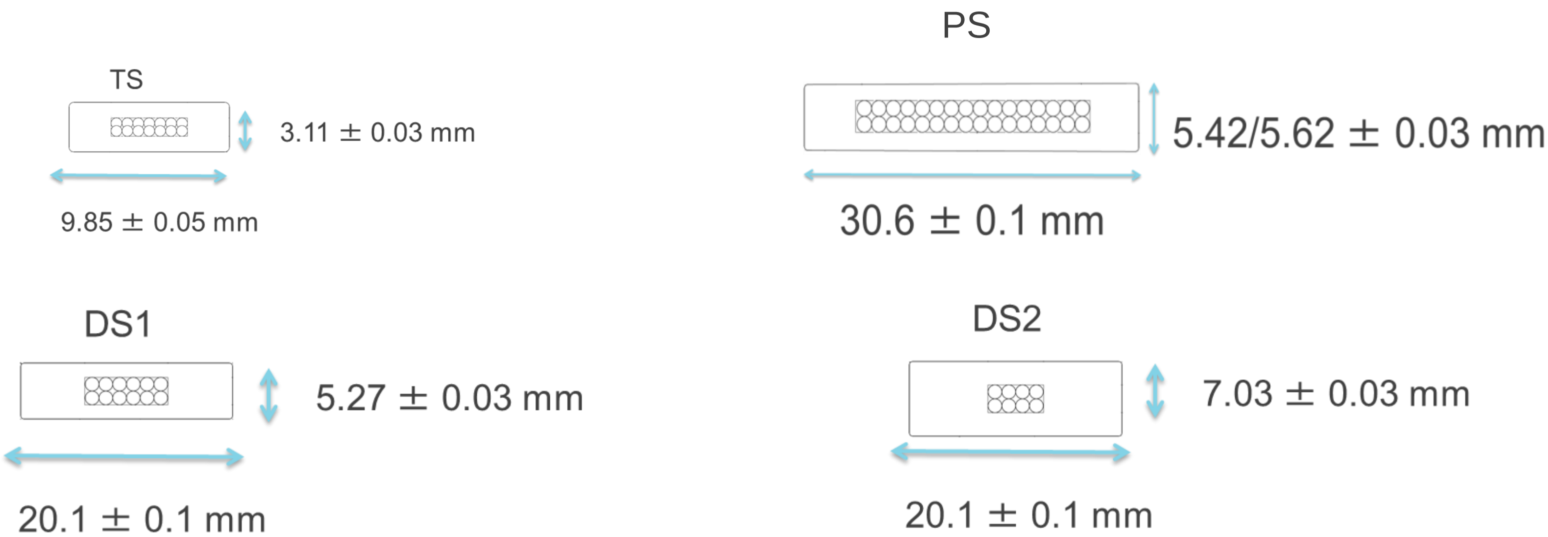
General Solenoid Requirements

- Magnetic field requirements are complex. Generally speaking field must meet the following:
  - Straight Sections
    - Negative monotonic axial gradient to prevent trapped particles. (potential source of backgrounds)
  - Toroidal Sections
    - Matched to central collimator geometry for muon momentum selection
  - Spectrometer Section
    - 1 Tesla field matched to tracker and calorimeter geometry for measurement of conversion electron momentum, energy and particle identification
- To verify that the solenoid system meets the field performance standards
  - Generate field maps from coil packs using fabrication tolerances
  - Field maps are vetted with collaboration for muon transmission, background generation and tracking efficiency and resolution

Operational Requirements

- Reliable superconductor operation at full field life of experiment
  - Large temperature margin (>1.5K) and critical current density margin (>30%) typical of collider detector solenoids
- Individual operation of magnets and cryostats
  - Cryostats cooled down and solenoids powered independently
  - Individual magnets do not rely on mechanical support of adjacent magnets
- Cryogenic operation
  - Liquid Helium Indirect cooling
  - One Fermilab Satellite refrigerator for steady state operation (600 W cooling capacity at 4.5K)
- Operation due to radiation damage
  - 7 MGy over life of solenoid. (irreversible damage limit of epoxy)
  - NbTi damage is not a serious issue
  - Aluminum stabilizer to operate for 1 year at nominal beam intensity without loss of performance, with damage being repaired by room temperature anneal

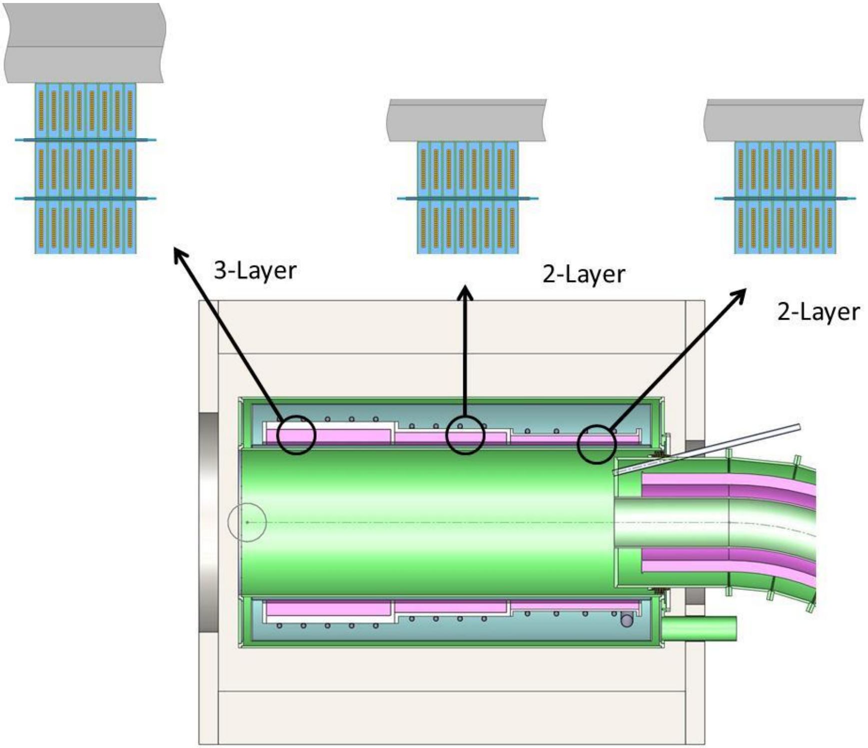
PS/TS/DS Conductor



- NbTi Rutherford cable with aluminum co-extruded stabilizer
- Aluminum vs. Copper
  - Lower dynamic heating, better recovery from radiation damage, lighter weight
- SC content sized for specific magnet requirement for current and temperature margins
- TS/DS: 99.998% aluminum for high electrical and thermal conductivity
- PS, use special Ni Doped Aluminum Alloy developed for Atlas Central Solenoid, for high strength and high conductivity
- ~75 km of conductor required for project

Production Solenoid Design

4.6T➔ 2.5 T Axial Gradient



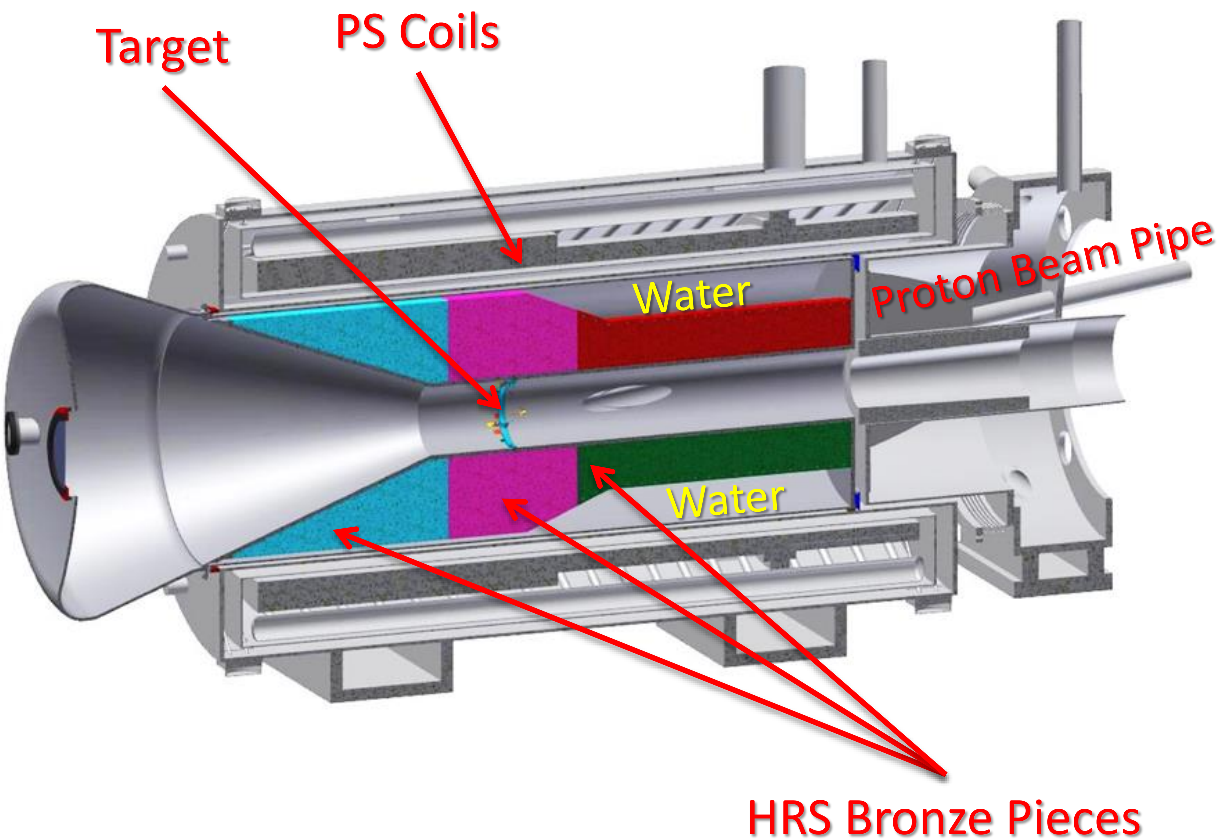
Features:

- 3 axial coils same turn density, different lengths and # of layers
- 1.6 m diameter, Iop=9.2 kA
- Aluminum outer support shell sized for expected coil stress
- Indirect Cooling (Thermal Siphon)
  - Tubes welded to outer support structure
  - Tubes connected to inner and outer surface of coil via pure aluminum thermal bridges
- Heat and Radiation Shield in magnet bore (next slide)

Heat and Radiation Shield (HRS)

Purpose:

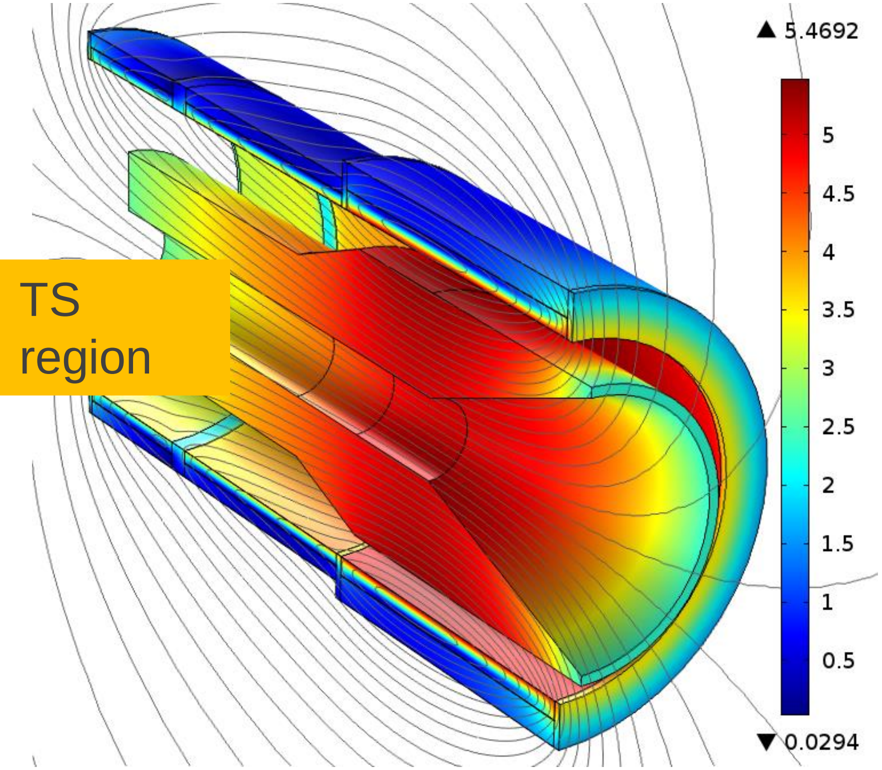
- Limit Production Solenoid (PS) thermal exposure from heat radiated from target to acceptable levels
- Limit radiation dose and radiation damage to the Production Solenoid superconducting coils to acceptable levels

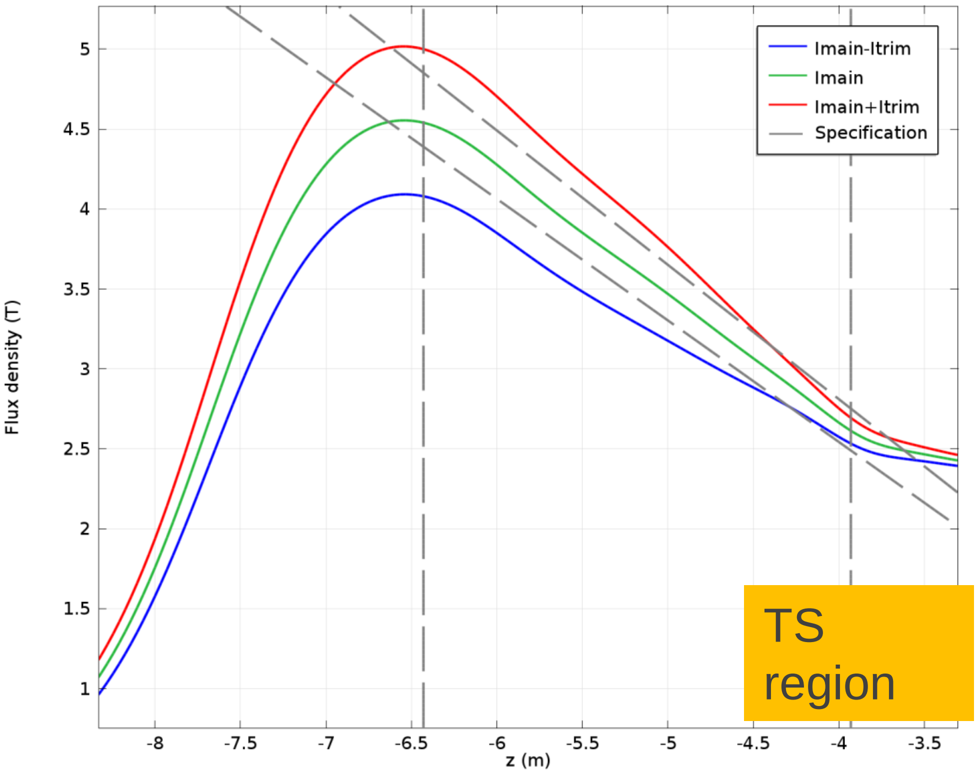


Performance:

- Dynamic heat load to superconducting coils limited to 24 Watts
- Peak Displacement per Atom (DPA) damage: 2.4 x 10^{-5}/year
  - Warm-up cycle to repair DPA damage only needed once/year

PS Magnetic field



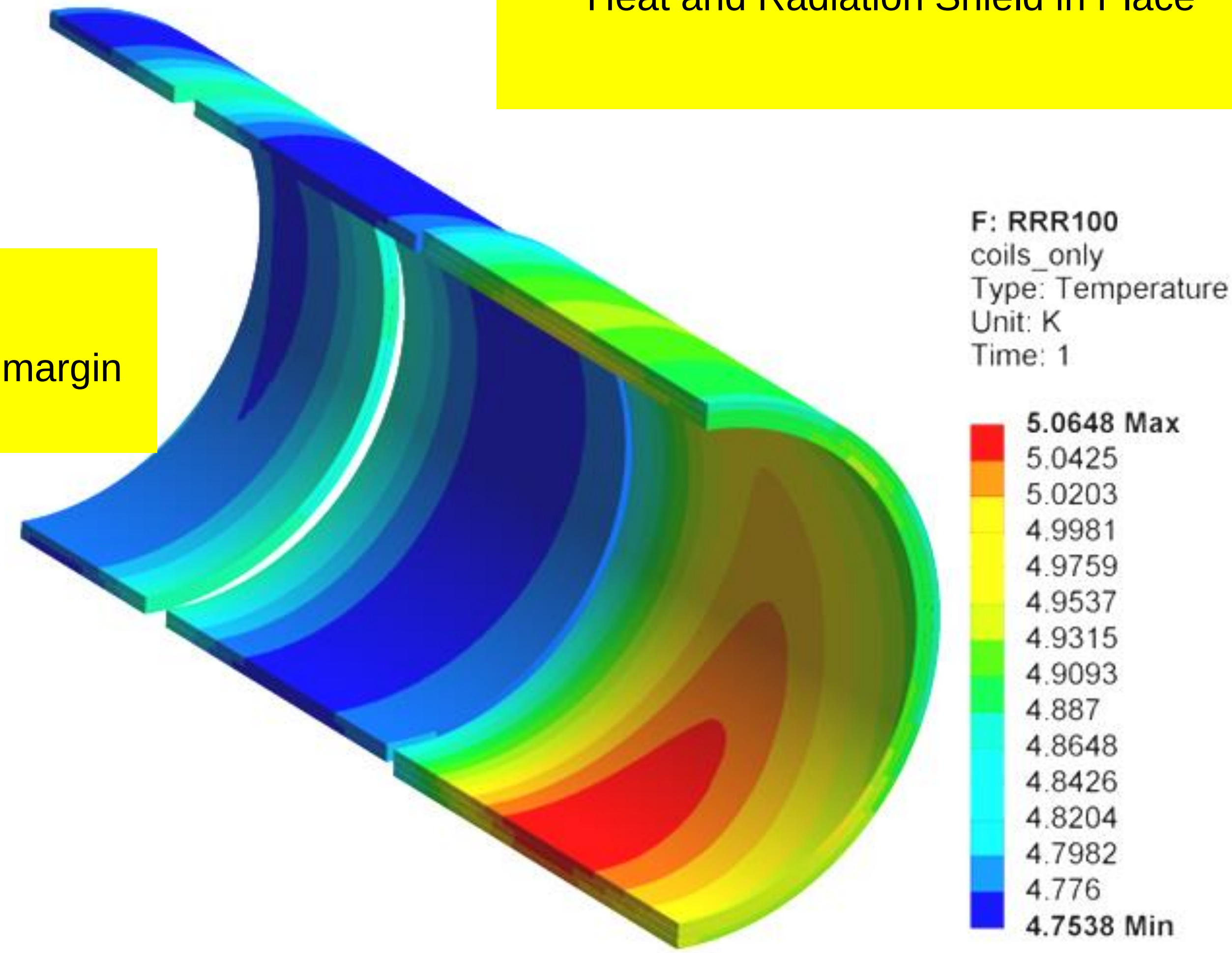


- Center profile (right plot) is nominal field which meets specification (dashed lines)
- Different field profiles correspond to variation of the current by ±1 kA;
- HRS shield (left plot) is made of high-resistivity bronze (with magnetic permeability of 1.04).

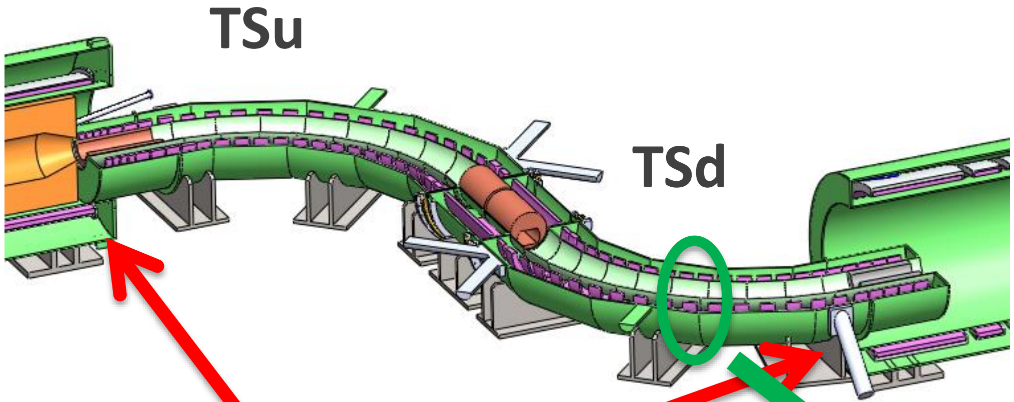
PS Coil Temperature Profile with HRS

Assumes:
- Nominal beam intensity
- 4.7 K input temperature
- Heat and Radiation Shield in Place

Performance
- Peak temperature is ~5.07K
- Meets the 1.5 K temperature margin requirement



Transport Solenoids (TS) Features



Two cryostats TSu and TSd

Separate cryogenic lines

Separate power system

52 short solenoid coils
Typically 2 coils per module

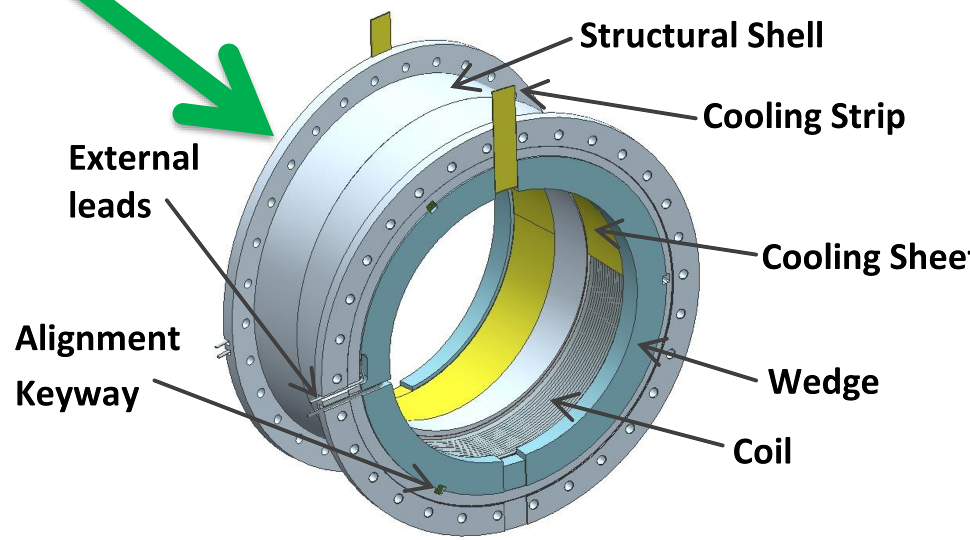
Vacuum and Magnetic interface

with PS and DS

Once bolted together defines coils

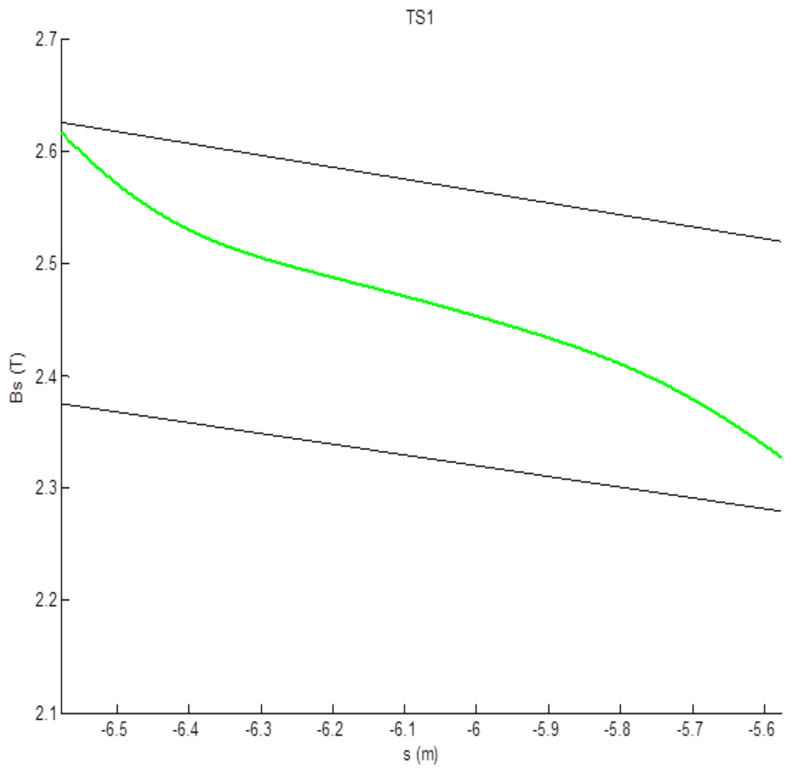
placement➔magnetic field

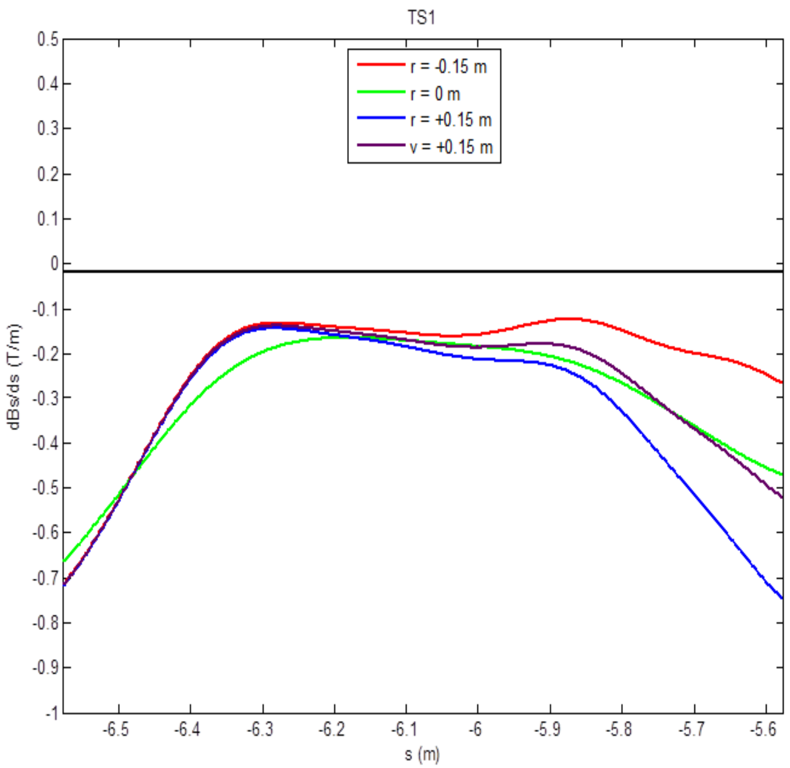
Modules will be built in Industry



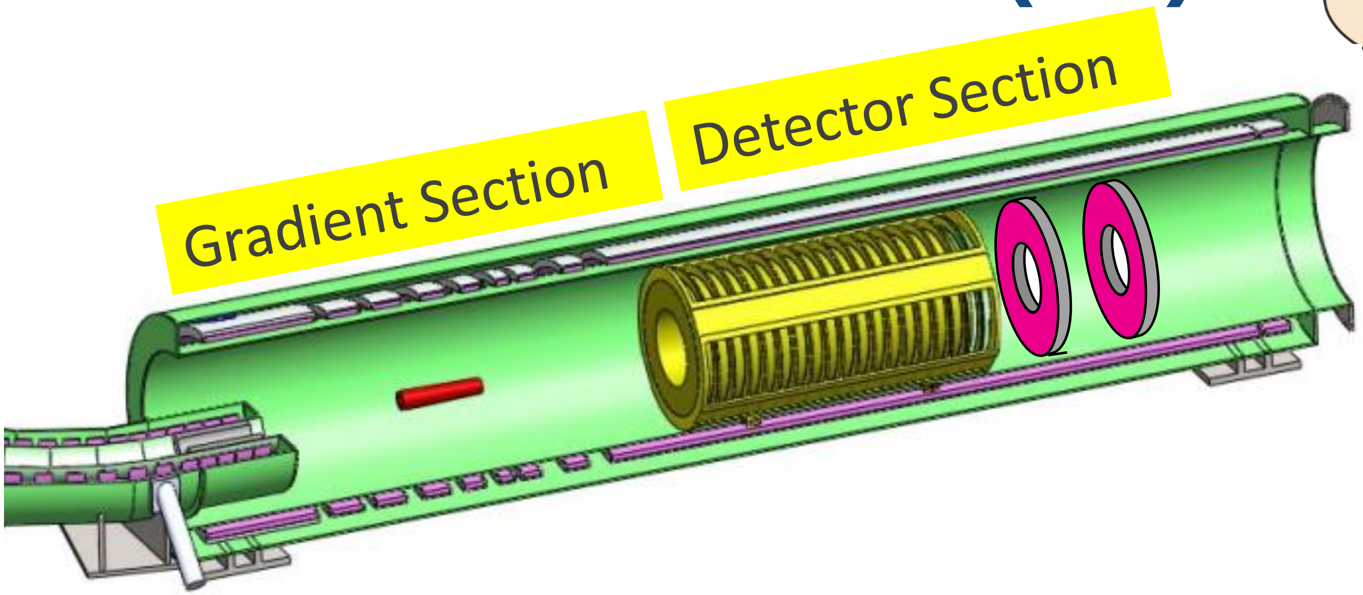
TS Field Profile

- Require negative axial gradients in straight sections to avoid trapped particles (potential source of background)
- Absolute fields within defined limits
- Magnetic Design is robust under random and systematic coil positioning errors



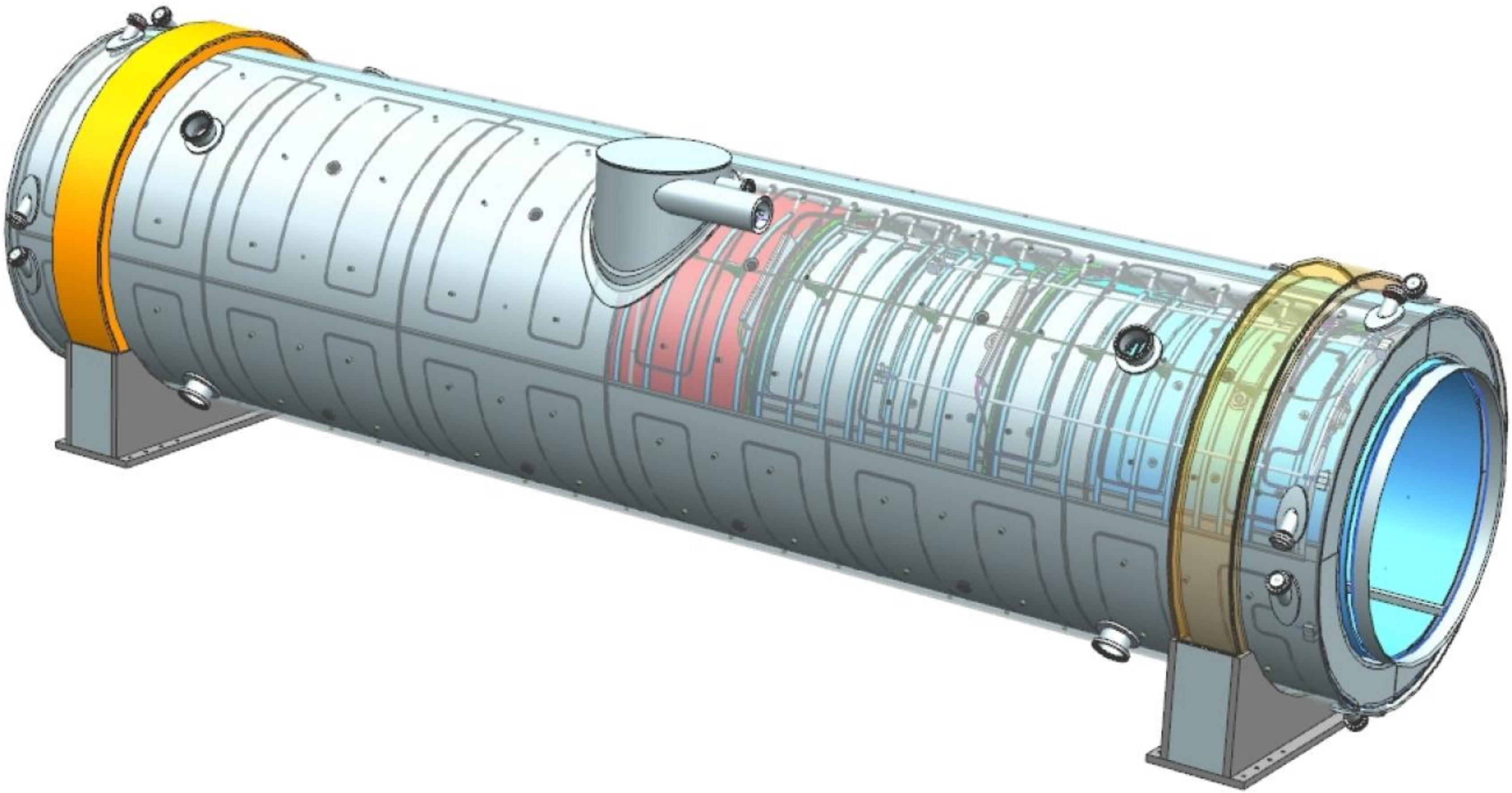


Detector Solenoid (DS)



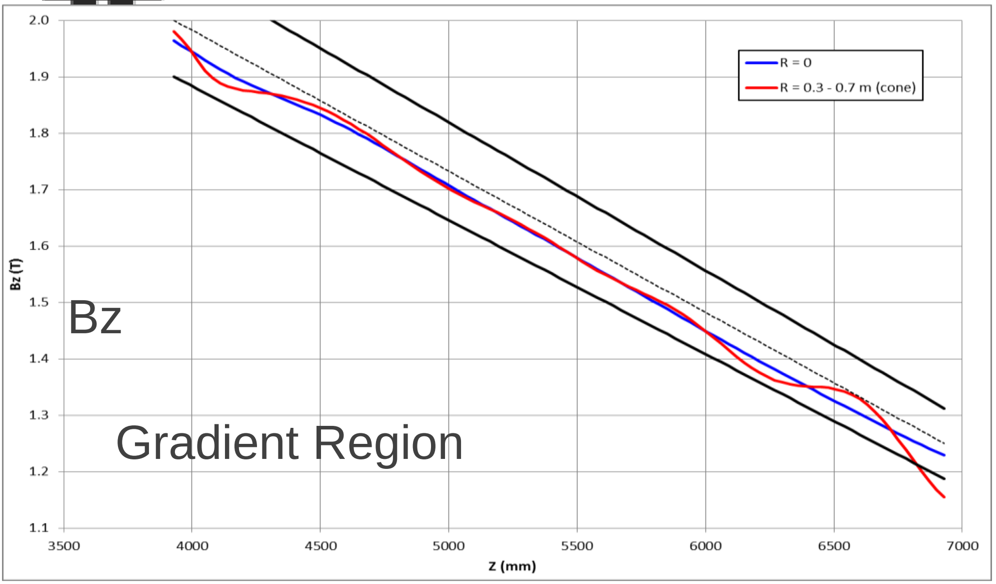
- 1.8 m Aperture   Operating Current ~6kA
- Gradient section 2T➔ I T field
- Spectrometer section 1 T field with small axial gradient superimposed to reduce backgrounds
- 11 Coils in total
  - Axial spacers in Gradient Section
  - Spectrometer section made in 3 sections to simplify fabrication and reduce cost

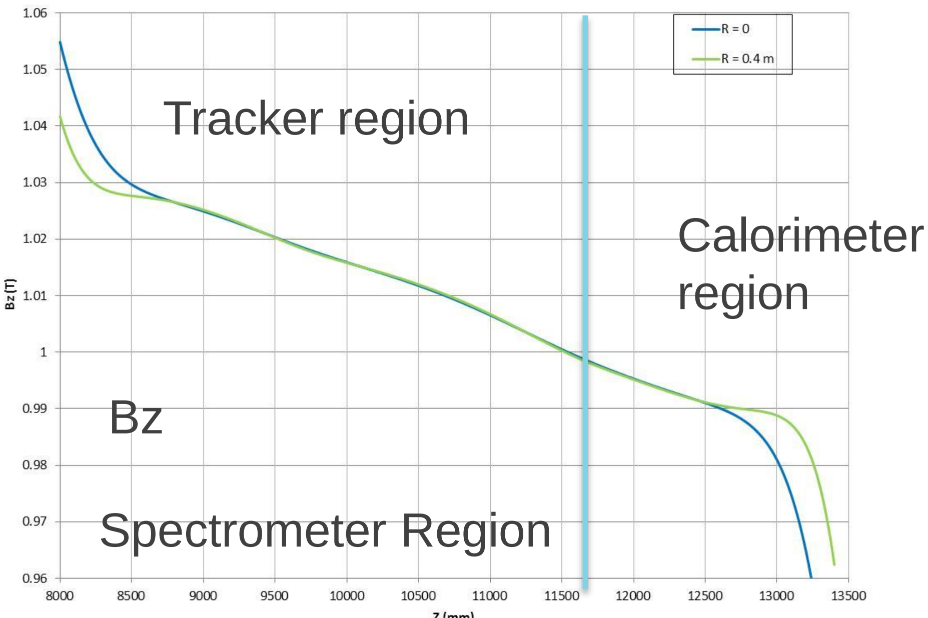
Solid Model of Detector Solenoid



- **Coil, coldmass, suspension system and cryostat very similar to PS**
  - Aluminum Stabilizer NbTi
  - Outer aluminum support structure
  - Coils units bolted together…

Magnetic Design & Performance





- Gradient Region: Black lines represent the limits for the field uniformity (dB/B) using the gradient of -0.25 T/m.

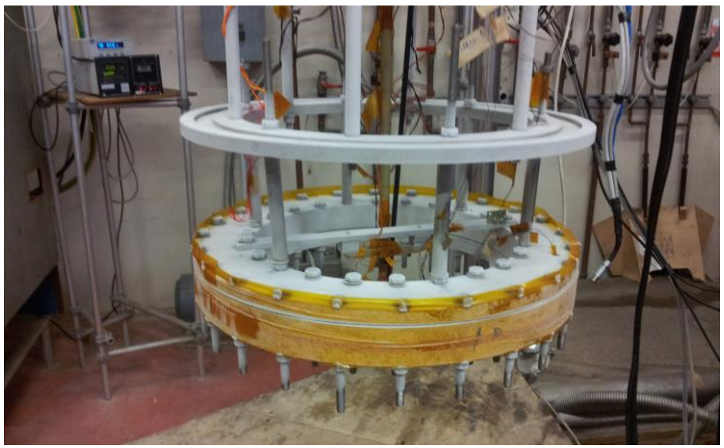
- Spectrometer Region: Field distribution in detector region for different radii. Field is monotonically decreasing in tracker region for R≤ 0.4 m.

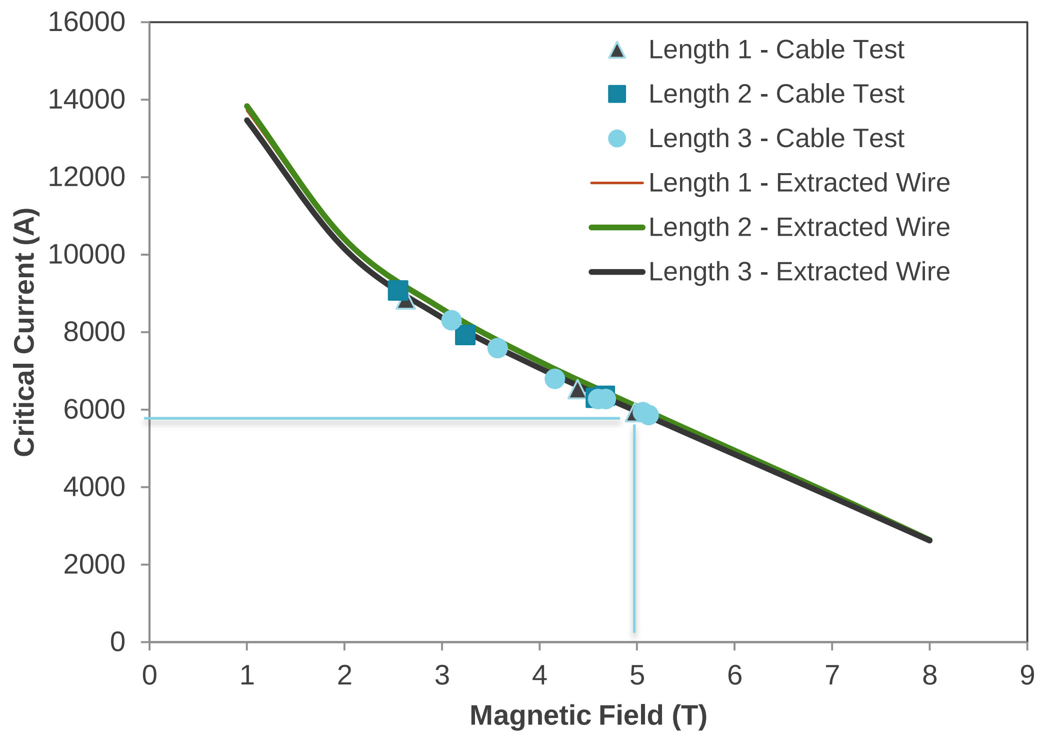
Prototyping

- Superconductor (completed)
  - Prototypes of Solenoid Conductor has been fabricated: Furukawa Electric and Hitachi Cable
  - Extensive testing at vendor and Mu2e project
- Transport Solenoid Module (in progress)
  - Built in industry
  - With Mu2e-supplied conductor and coil parts
  - Oversight from INFN-Genova Collaborators

TS – Prototype Cable Performance

Samples from each one of the three TS prototype lengths were sent to INFN Genova where the full cables were tested for critical current. The critical current measured on the three piece lengths is found to be very reproducible and in line with data collected via extracted strand from the stabilized cables.

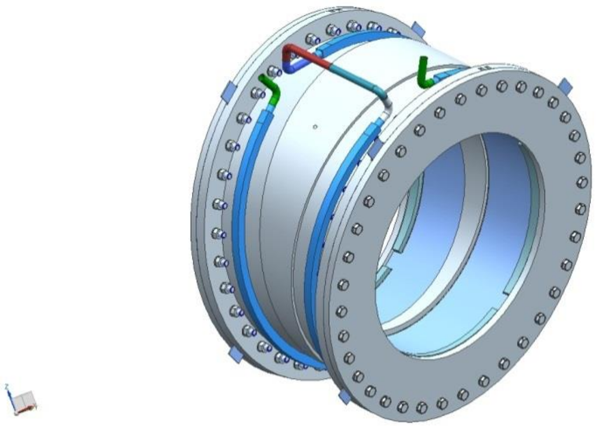




Strand data FNAL
Cable data INFN Genova

TS Prototype Collage

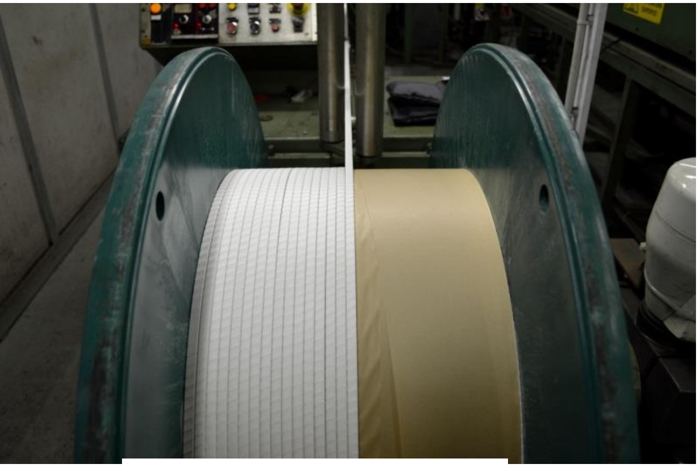
Completed in November 2014



Computer model of outer support cylinder

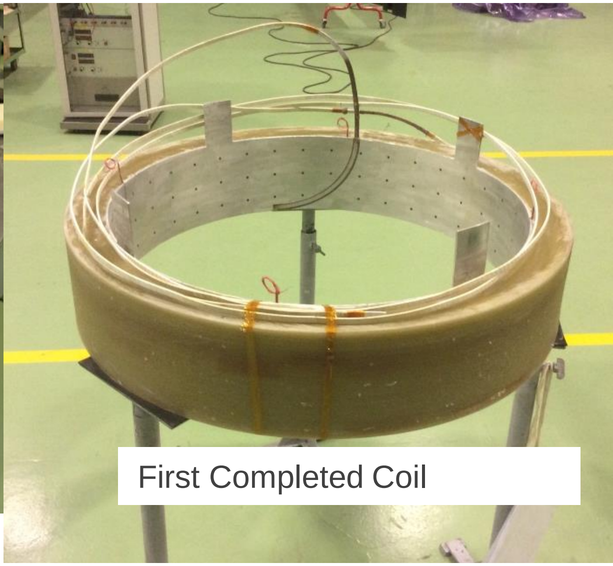
Outer support cylinder casting pre-machined

Machined shell ready for inspection



Cable Insulation

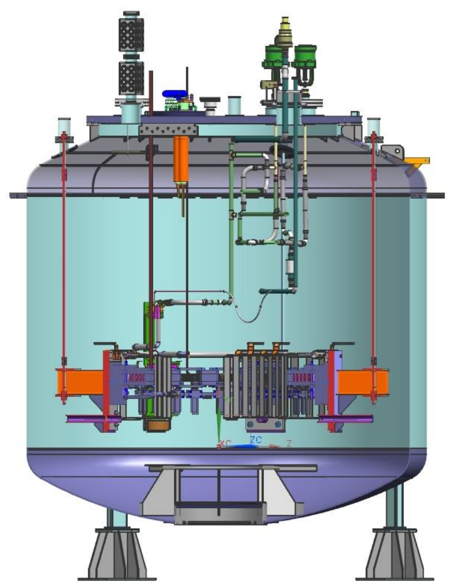
Assembly Mandrel

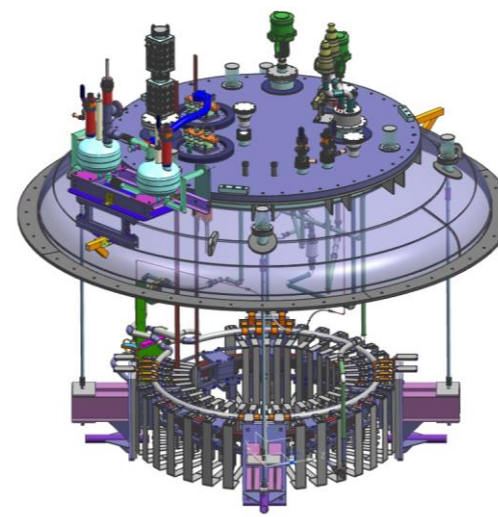


First Completed Coil

New Test Facility at Fermilab (SolTF)

- To test large indirectly cooled solenoids
  - Up to 2.4 m in diameter, 1.8 m long
  - Current capacity up to ~10kA
- Used first to test MICE coils
- Near term test plans
  - US/Japan Model made by Toshiba
  - Transport solenoid prototype coil being made by ASG
- Longer term
  - Test Transport solenoid production coil modules





Procurement and Fabrication

Strategy

- Superconductor, Production and Detector Solenoids will be fabricated in industry
- TS coils and cryostat will be fabricated in industry, final assembly at Fermilab
- Other components “build to print”, fabricated in industry

Status

- Placing orders for production lengths of superconductor
- In the final stages of selecting vendors for the Production and Detector Solenoids
- Transport Solenoid coil module order to be placed within the next 9 months

Summary

- Solenoid designs meet physics requirements
  - Close interplay between magnet designers and experiment
- Solenoid designs are well understood
  - Detail magnetic, mechanical, thermal, quench analyses
- We have well along on the procurement of the major components of the Solenoids:
  - Have are ordering long lead time conductor
  - Final stages of selecting PS and DS vendor
  - On track to place orders for TS coil modules
- Solenoids operational by the end of the decade