Fermilab

Mu2e Solenoids

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L2 for the Mu2e Solenoid
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Mu2e Solenoids

- Perform many functions in the Mu2e Experiment
- One continuous field, generated by 3 unique superconducting solenoid systems
- Need superconducting magnets to achieve required fields
- Challenges associated with superconducting magnets
  - Cryogenic environment
    - LN2 and LHe
  - Large stored energies (over 100 MJ)
    - Has to be removed or absorbed once a quench occurs
  - High currents (many kA's)
  - High voltages when a quench occurs
  - Large magnetic forces (100 Ton axial forces between magnet elements)
  - Large material stress (on the order of 50 MPa)
  - Yet it doesn't take much of a disturbance to cause a quench..
    - ~100 mJ

Detector vs. Accelerator Magnets

Accelerator magnets (for circular accelerators)

- Dipoles and quadrupoles, (sometimes solenoids) Small aperture (100 mm), long (can be 20 meters)
- Often sets limit for beam energy (tunnel radius fixed) so designed for high fields ➔ small operating margins
- Magnets operated in both ramped and DC modes
- Coil immersed in liquid helium
- Many interchangeable magnets, pool of spares, relatively easy to swap out if one fails

Detector magnets

- Solenoids, toroids very large apertures (meters) and long
- Large volume ➔ coils usually conduction (indirectly) cooled
- Magnets operated in DC mode only
- One of a kind, non interchangeable therefore designed with large operating margins

Mu2e Magnets are somewhere in between (but more like detector magnets)

Interesting facts about charged particles in a solenoid field

Mu2e field is generated from a system of solenoid rings

- Charged particles execute a helical orbit in a uniform Solenoid Field
  - Radius proportional to Pperp
  - Radius Inversely proportional to Bfield
  - Helix sense given by particle charge

Non-uniform field

- With an axial gradient, Bz increasing,
  - Radius of helix decreases
  - Vperp increases, Vparallel decreases (V constant since no work)
  - under certain conditions the particle can actually reverse direction (magnetic mirror) Consequence of Div B = 0
- Conversely, if field decreases
  - Vparallel increases relative to V perp
- We use this to increase acceptance and minimize backgrounds

- See "Classical Electrodynamics" 2nd edition JD Jackson section 12.6

Sect. 12.6 **Dynamics of Relativistic Particles and Electromagnetic Fields** **591**

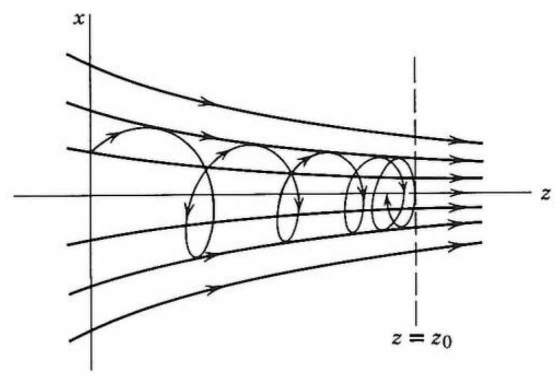


Fig. 12.6 Reflection of charged particle out of region of high field strength.

Non-uniform field II

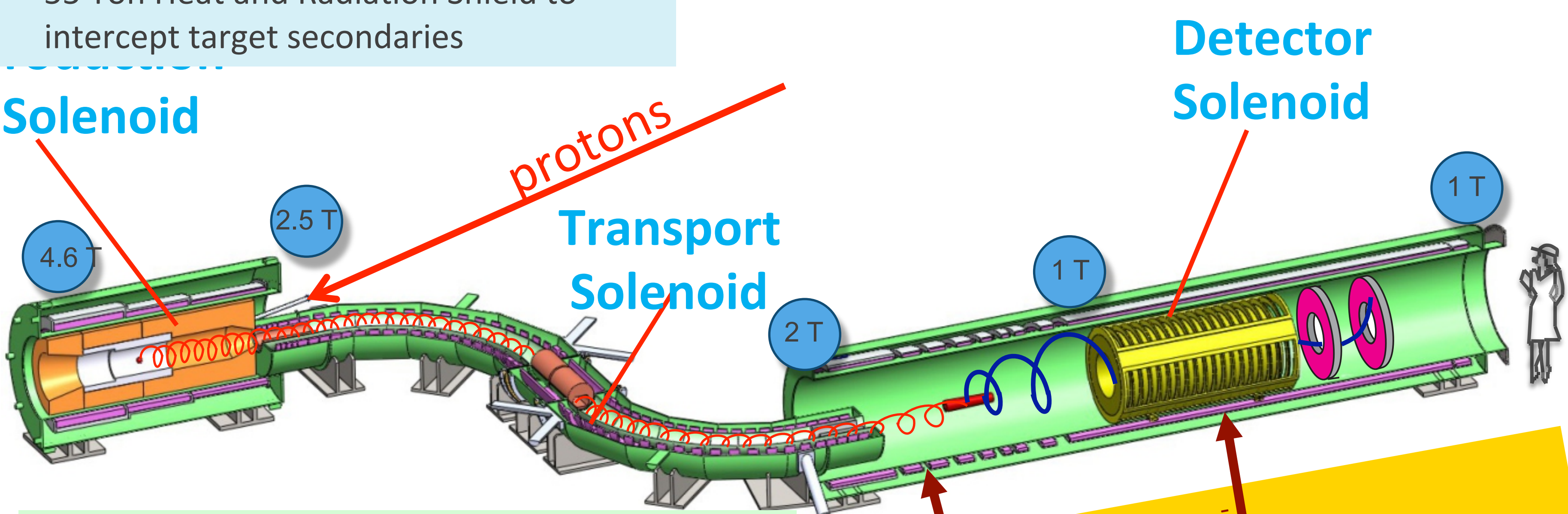
- In a "toroidal" field (with a horizontal orientation, and direction normal to the toroid is direction "s")
  - Particles tend to follow the field lines.. Helical centroid follows "s" direction of a curved solenoid…
  - The centroid of the helix will drift vertically, proportionally to sign and momentum
    - Problem for Toroidal Tokamaks
    - We exploit this to eliminate backgrounds

- See "Classical Electrodynamics" 2nd Edition JD Jackson section 12.5

Mu2e Experiment

- Three solenoids, provide magnetic field for experiment

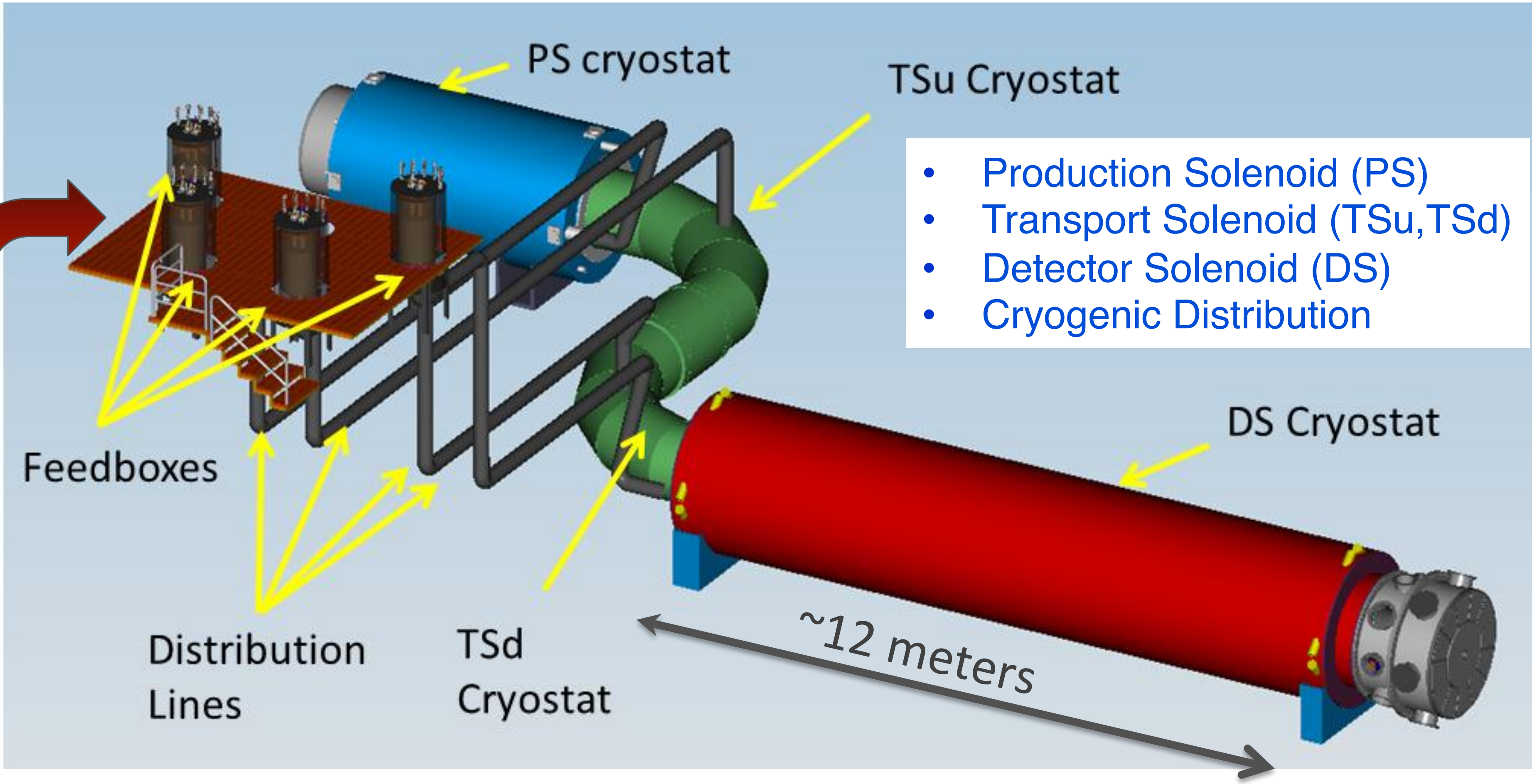
- Strong axial gradient. Reflect and focus (move along) π/μ's into muon transport
- 55 Ton Heat and Radiation Shield to intercept target secondaries



- Sign/momentum Selection
- Negative Axial Gradient in S.S. to suppress trapped particles

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

Mu2e Solenoid Scope



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

- Cryo distribution box
- Power Supply/Quench Protection

- Field Mapping
- Ancillary Equipment
- Installation and commissioning

Operational Requirements

- Reliable superconductor operation at full field life of experiment
  - Large temperature margin (>1.5K) and Jc margin (>30%) typical of detector solenoids.
  - Complex thermal mechanical design to obtain and maintain desired field
- Individual operation of magnets and cryostats
  - Cryostats cooled down and 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
- Operation due to radiation damage
  - 7 MGy over life of solenoid. (irreversible damage limit of epoxy)
  - **Conductor and stabilizer to operate for 1 year at nominal beam intensity without loss of performance, can be repaired by room temperature anneal**

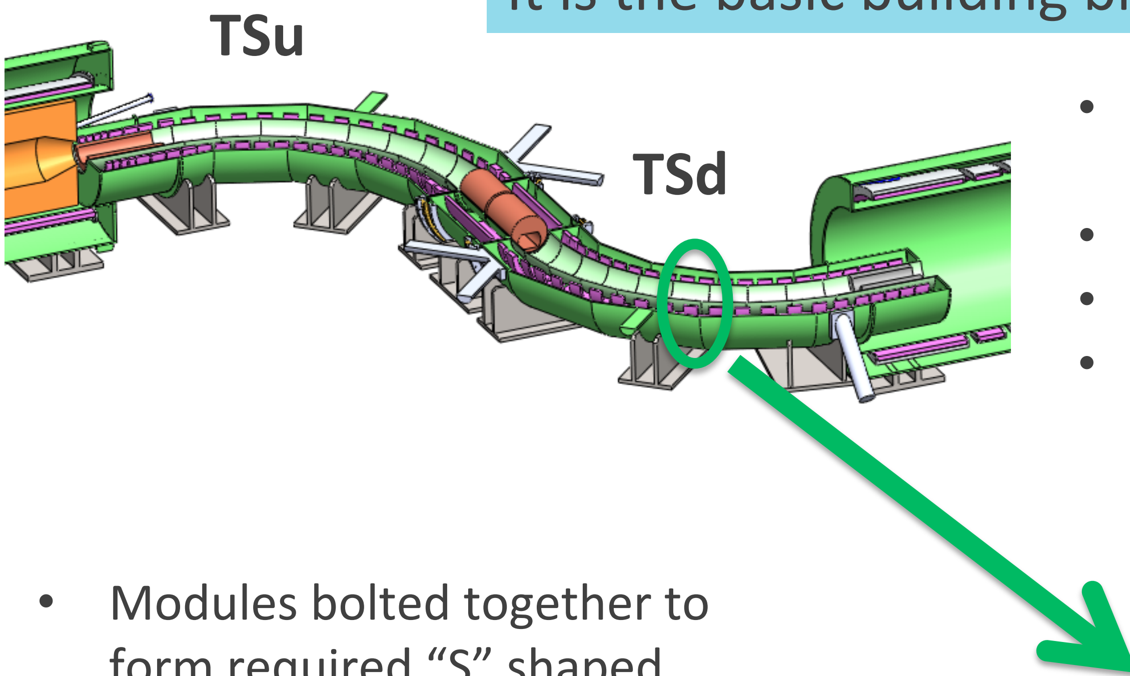
Solenoid Design Features

Solenoid have common design features:

- Consist of multiple "solenoid coil modules". Use Al-stabilized NbTi cable wound either in the "easy way" or "hard way". Length and # of layers to achieve desired field.
- Module has an outer support structure made of Al 5083-O to manage the forces. Cooling tubes, electrical connections located on the outer surface
- Coils are "indirectly" cooled with liquid helium. Helium thermally connected to coil through aluminum straps and through structure
- The shells are bolted together to form a cold mass assembly.
- The coil modules are installed inside of cryostat using axial and transverse supports.

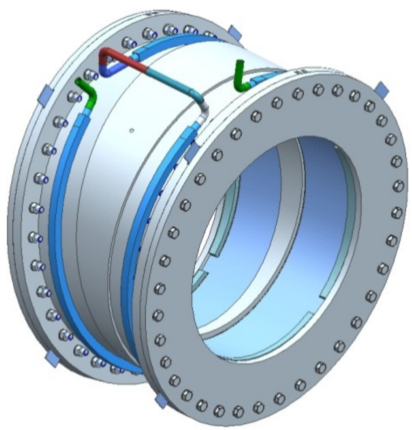
TS Module Overview

It is the basic building block of Transport Solenoids

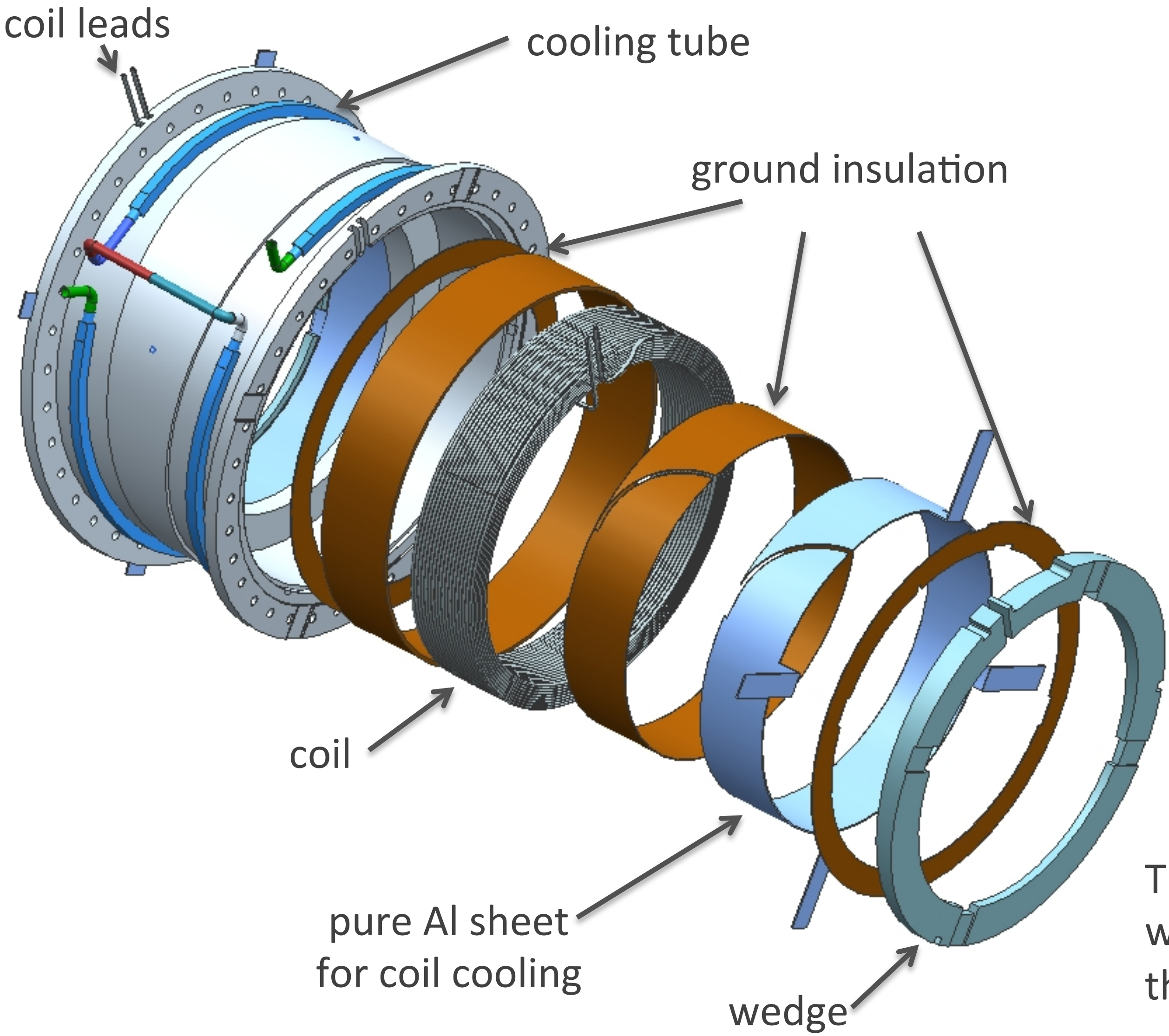


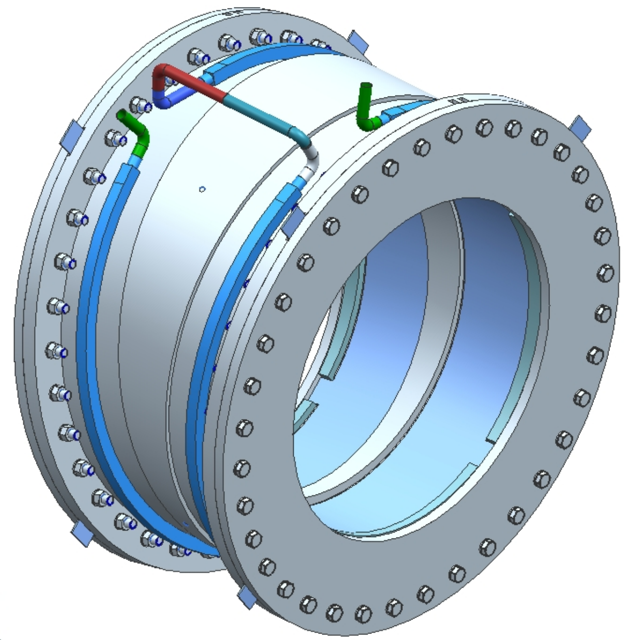
- Typically 2 superconducting solenoid rings per module
- Outer aluminum support shell
- Coils indirectly cooled with LHe
- 27 modules in total
  - 13 in TSu
  - 14 in TSd

- Modules bolted together to form required "S" shaped geometry. Geometry defines the magnetic field



Design – TS Module





The coils are epoxy impregnated with the ground insulation and the Al sheet.

Phase diagram for NbTi

- From "Superconducting Magnets", Martin N. Wilson

- Superconducting condition when conductor is below "critical surface"
- Conservative operating conditions using state of the art NbTi Conductor
  - 5 K
  - 5T
  - 2000 A/mm^2

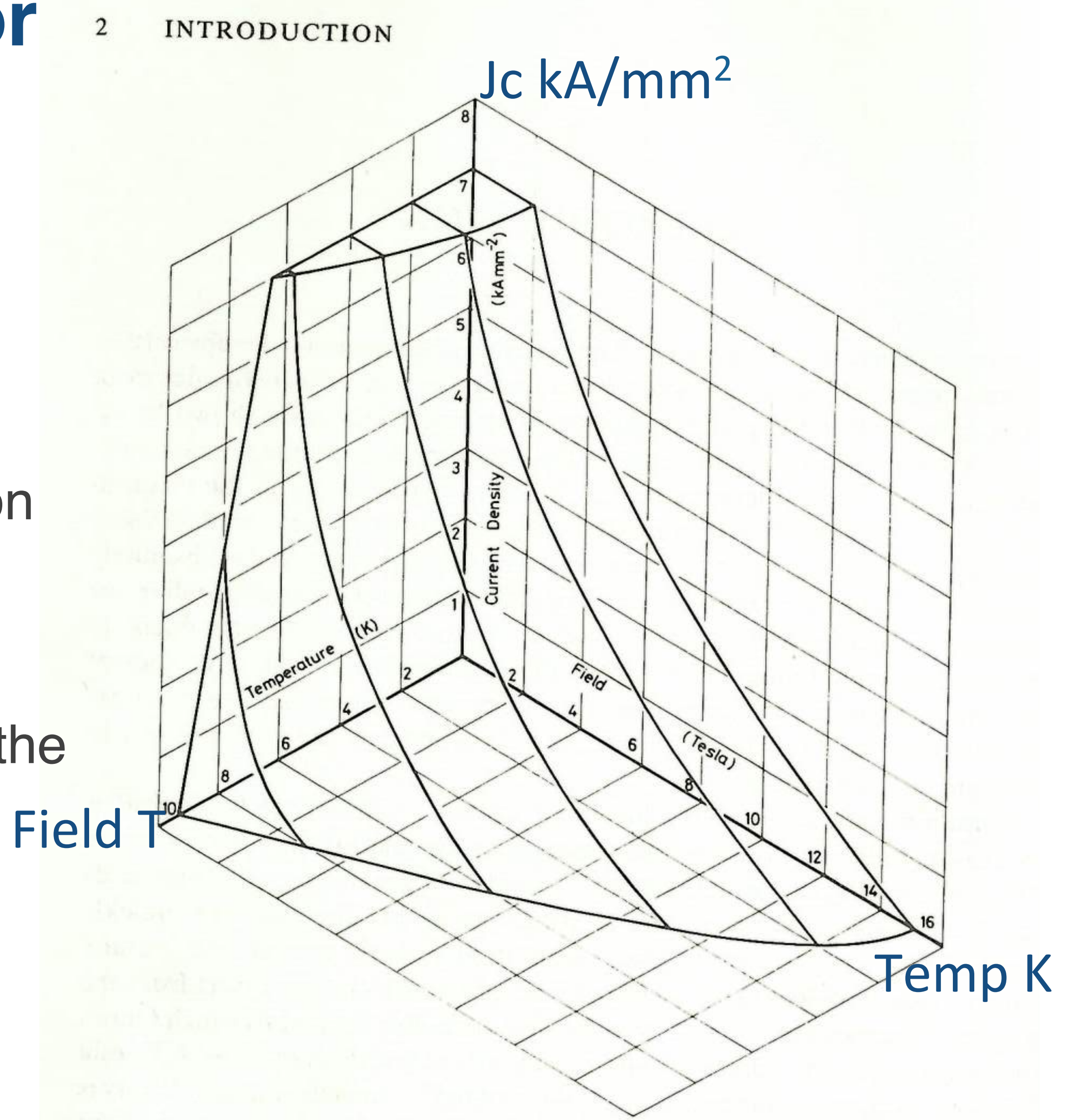
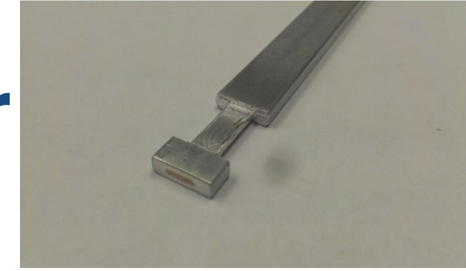
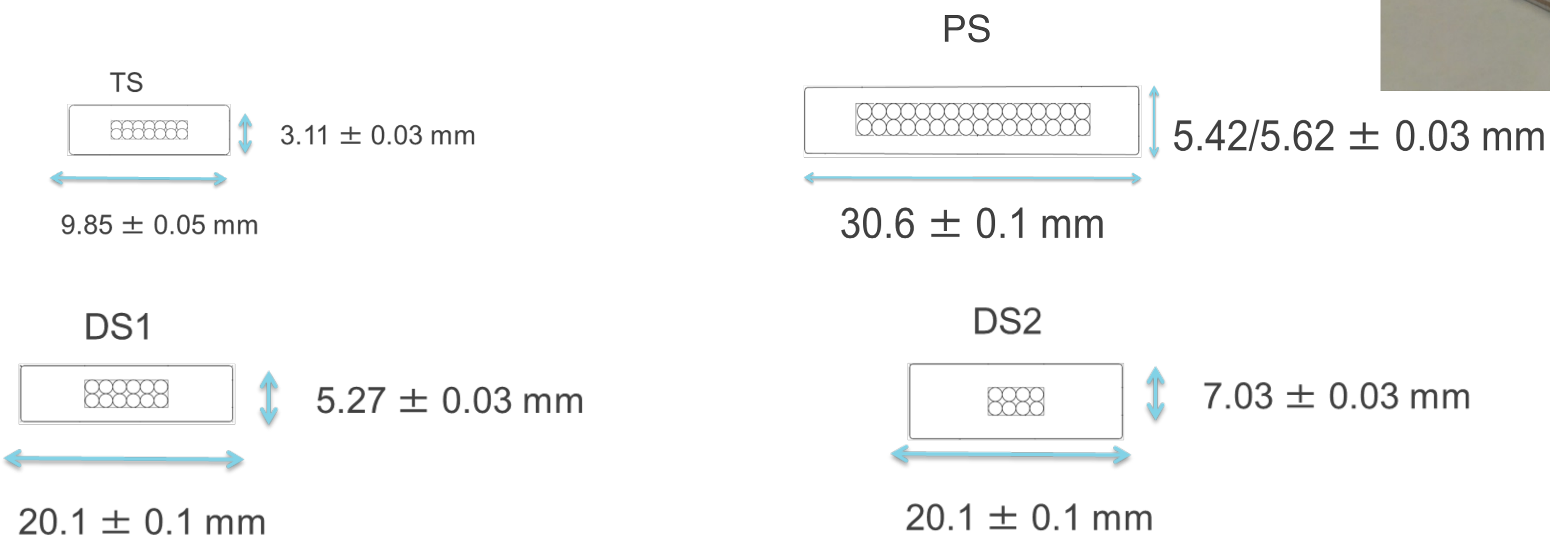


Fig. 1.1 Critical-current surface for a commercial superconducting alloy of niobium–titanium. (Based on recent measurements at 4.2 K, together with earlier measurements at variable temperature by Hampshire, R., Sutton, J., and Taylor, M. T. (1969).)

Design: PS/TS/DS1/DS2 Conductor



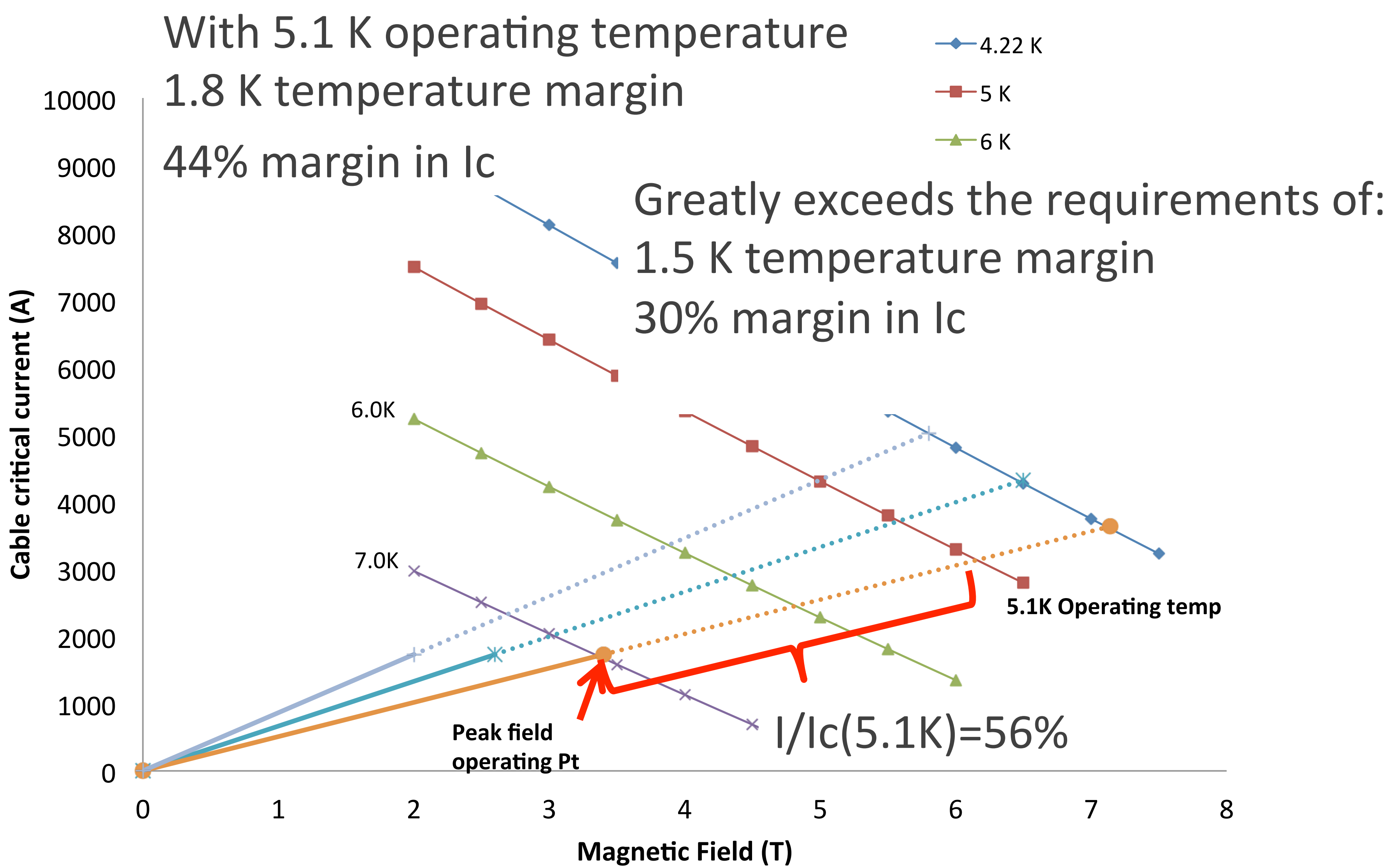


- **NbTi Rutherford cable with aluminum co-extruded stabilizer**
  - SC content sized for Specific Magnet Requirement for Current and Temperature Margins
  - TS/DS: 99.998% aluminum for high electrical and thermal conductivity
  - PS: use special Ni Doped Aluminum Alloy developed for Atlas Central Solenoid, for high strength and high conductivity
  - ~75 km of conductor required for project
- **Prototype conductor program successfully completed, production program in progress**

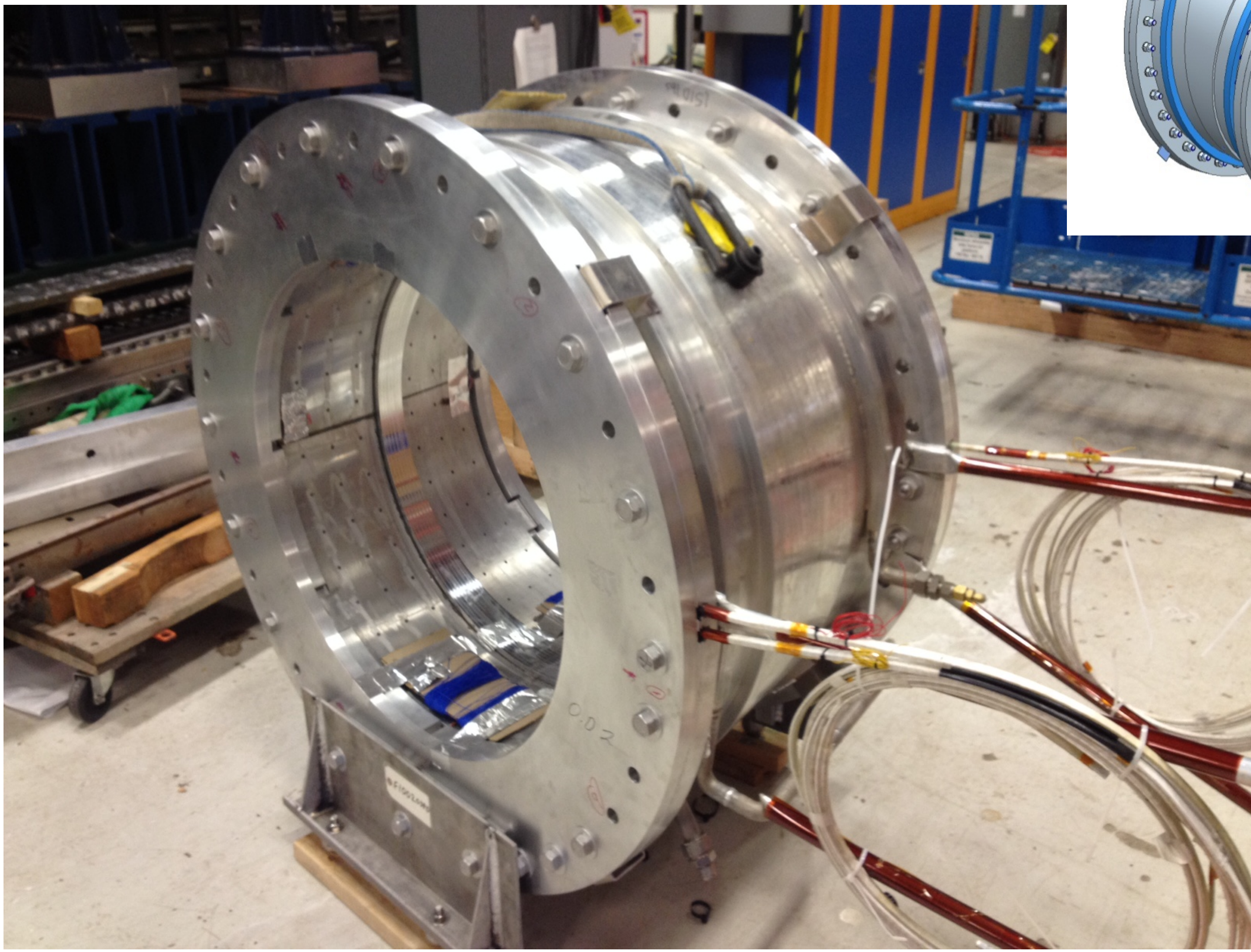
Magnet Quench

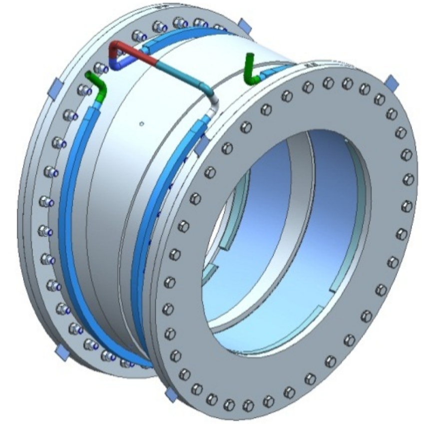
- A quench is an abnormal termination of magnet operation that occurs when part of the superconducting coil enters the normal (resistive) state. (Wikipedia)
- Resistive state usually occurs due to a local rise in temperature past the critical surface due to a mechanical disturbance (also beam induced heat…)
  - If disturbance is small enough, thermal conductivity and electrical conductivity may be sufficient to recover
  - Otherwise… runaway (quench) condition
    - Potentially very dangerous state for magnet
    - Must have very reliable quench detection and subsequent plan for dealing with stored energy

Design magnets to operate well below Critical Surface



TS Prototype Coil Module





TS Prototype Coil

TS Prototype Insertion into Cryostat at CHL

TEST COMPLETED

PASSED!

Will be removed from test cryostat in ~2-3 weeks

Future Mu2e-like experiments….

Need to significantly increase muon yield….

- More intense proton beam.. more heat/radiation to production solenoid (PS) from production target secondaries
- Higher field PS to improve collection efficiency

➔ More stress on PS!

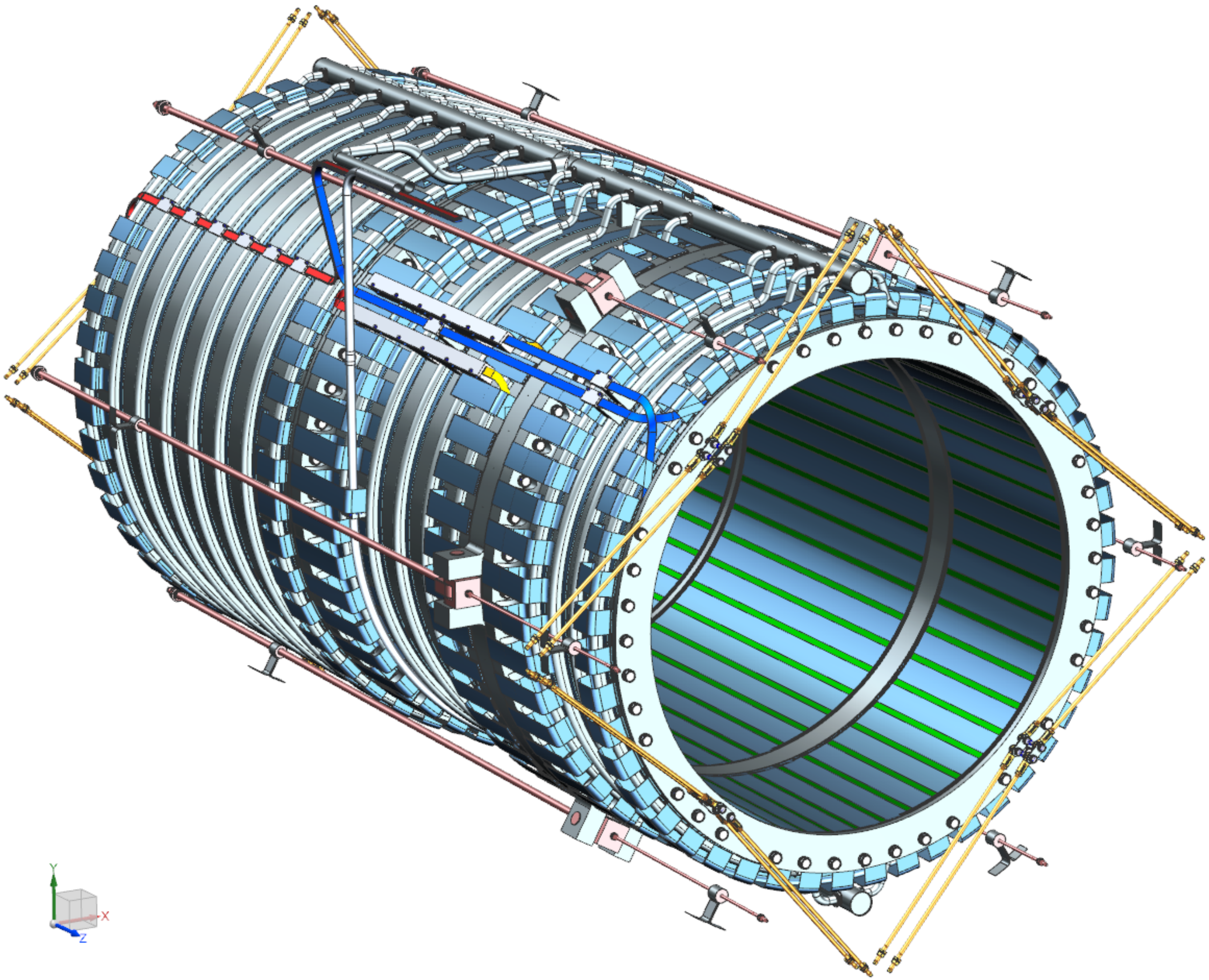
If we are limited by our present PS only options are to

- Use better (also more expensive) secondary beam absorber (probably Tungsten)
- Lower LHe temperature
  - Counteract increased heat load from secondary
  - Perhaps allow us to increase current
- Eventually we will be limited by rad harness of epoxies and insulation and aluminum stabilizer

May consider a new PS made with High Temperature Superconductor (HTS) which can operate at a higher temperature

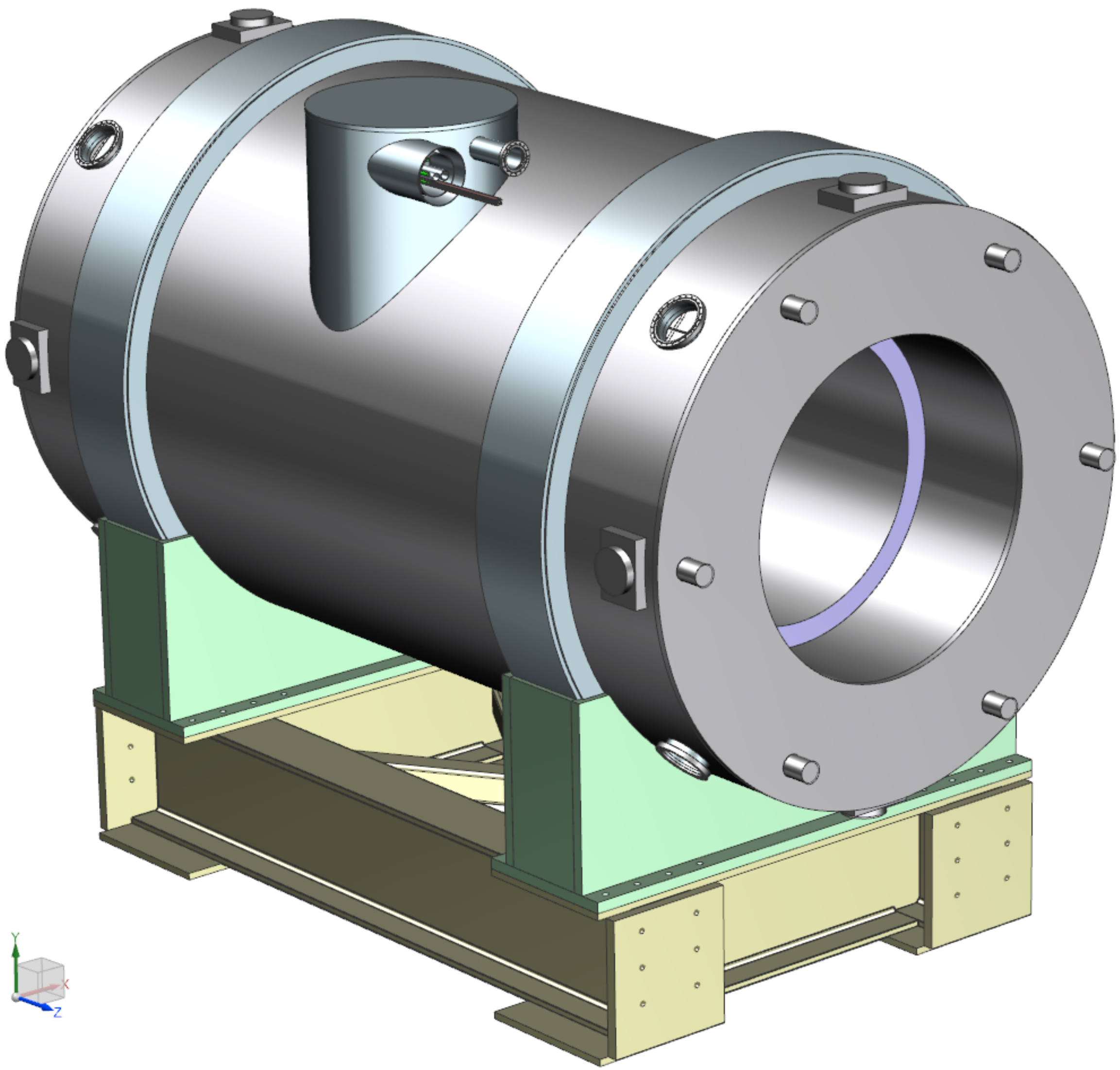
Additional slides

PS Design - cold mass suspension system



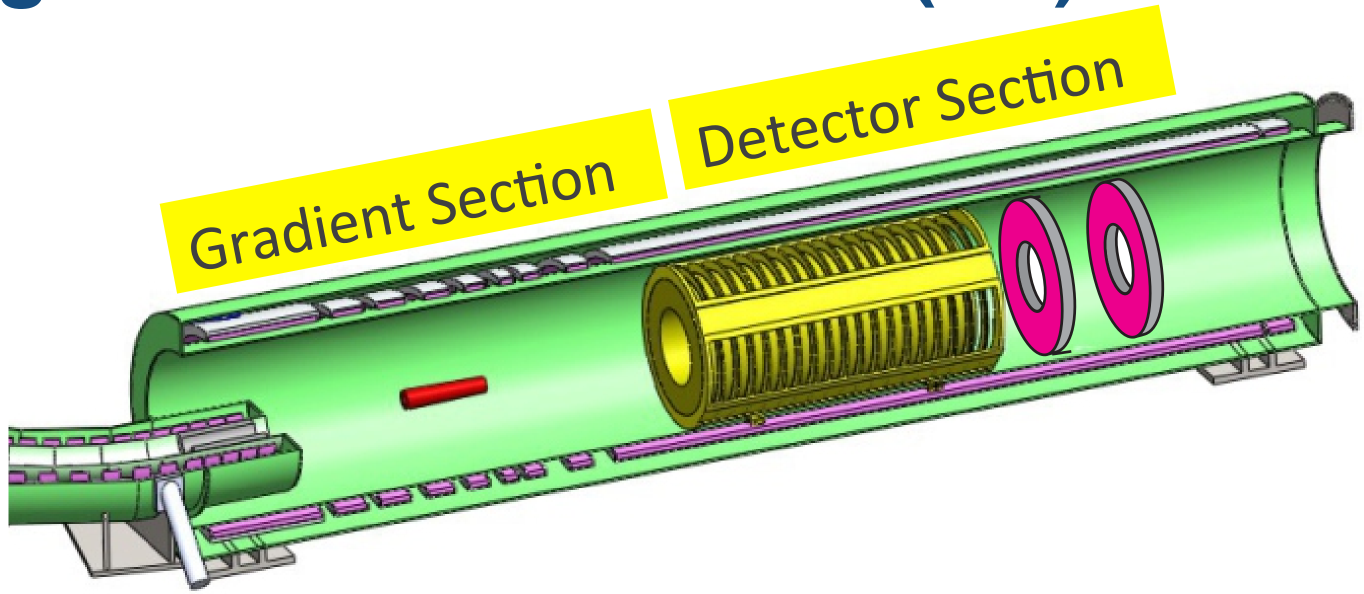
- Axial suspension:
  - 6 asymmetric pairs of Inconel-718 rods;
  - Belleville springs at each rod's end to compensate the thermal contraction.
- Radial suspension:
  - 4 pairs of Inconel-718 rods at each end;
  - Half of the rods is loaded through the Belleville springs to compensate the thermal contraction.

Design: vacuum vessel & support frame



- Provides insulating vacuum and attachment points for all components (in and out);
- Transfers all loads to ground:
  - Cold mass and LN_2 shield weight through the radial supports;
  - Lorentz forces through the axial supports;
  - HRS weight through the inner shell (~55 tonnes);
- Provides interfaces to:
  - HRS upstream, downstream;
  - Transport solenoid;
  - Transfer line;
  - Instrumentation line;
  - Vacuum system.

Design: 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
- **PS uses similar fabrication technology**

General Solenoid Requirements

- Magnetic field requirements, described in the Mu2e Technical Design Report and in supporting documents, 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
- To verify that the solenoid system meets the field performance standards
  - Generate field maps within coil fabrication tolerances
  - Field Maps are vetted with collaboration for muon transmission, background generation and tracking efficiency and resolution

Solenoid Schedule

CD-3a Conductor

CD-3b Building and TS Coil Modules

CD-3c Everything Else….