Magnets for the Mu2e Experiment at Fermilab

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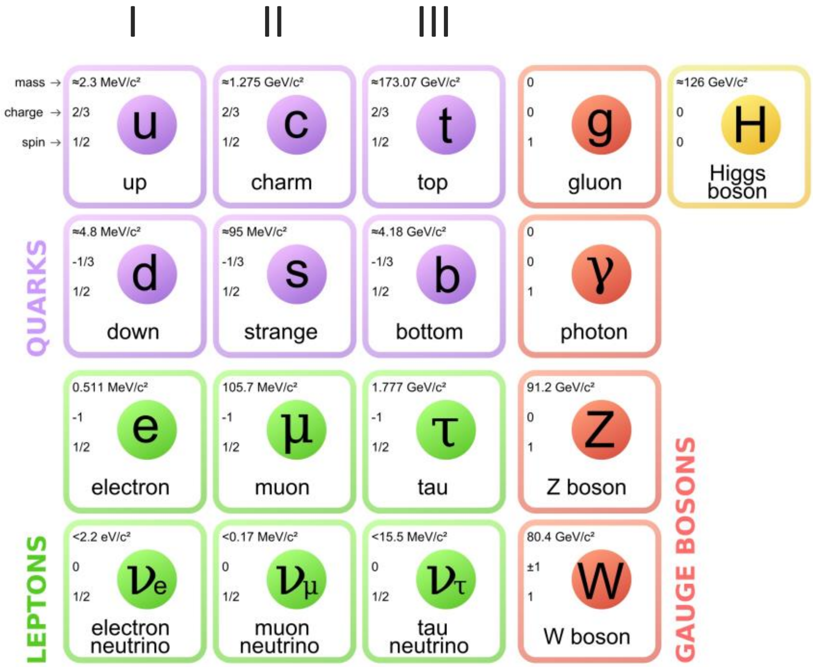
FRIB/MSU APES
11/17/23

Outline

- Brief Mu2e Physics Motivation
- Mu2e Experimental Setup
- Solenoids and Requirements
- Transport Solenoids
  - Fabrication
  - Testing
    - Room Temp
    - LHe “Cold”
  - Assembly
- Magnet Test Facilities at Fermi

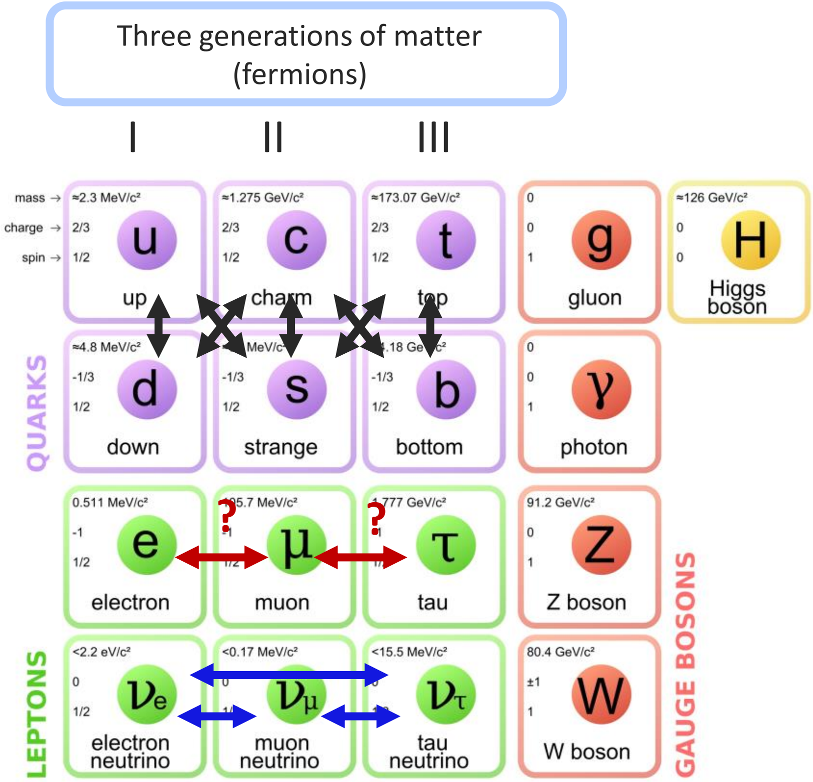
Standard Model

Three generations of matter (fermions)



- **Successful theory**
  - Discovery of SM-like Higgs particle
- **Incomplete!**
  - Gravity, Dark matter, Neutrino oscillations…
- Motivates a search for physics beyond the SM

Standard Model – is mixing allowed?



- Quarks mix → (Quark) Flavor Violation
- Recently (~last 15 years) found the neutrinos mix → Lepton Flavor Violation (LFV)
- Why not the charged leptons?
  - CLFV

Global interest in CLFV

Some of the CLFV Processes

Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \cdot 10^{-8}$	
$\tau \to e\gamma$	$\mathrm{BR} < 3.3 \cdot 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 4.4 \cdot 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \to \pi^+ e\mu$	$\mathrm{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \to e^+ e^- e^+$	$\mathrm{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \to e^- A$	$\mathrm{R}_{\mu e}^{\mathrm{Au}} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

Most sensitive CLFV measurements use μ

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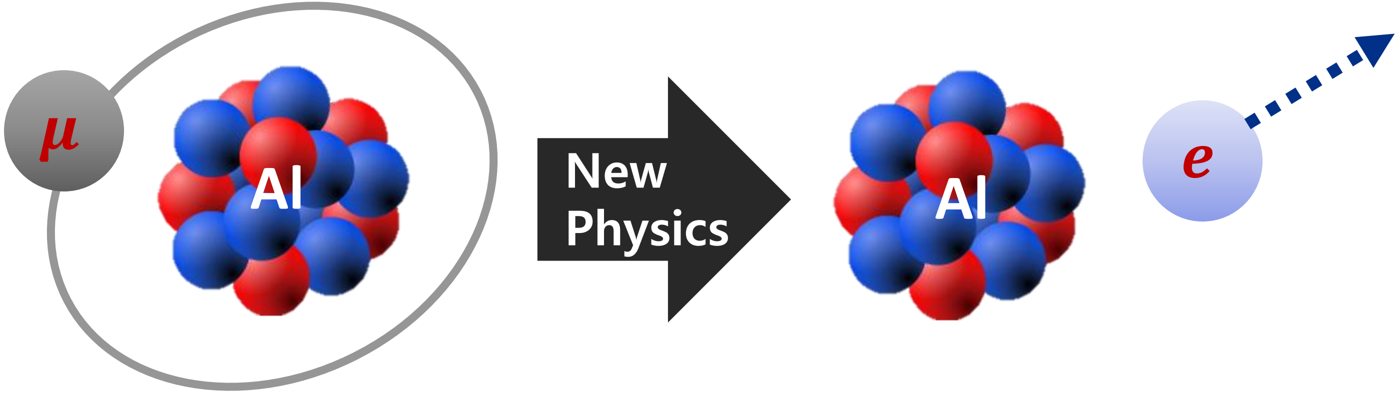
What is Mu2e?

Search for Charged-Lepton Flavor Violation (CLFV)

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



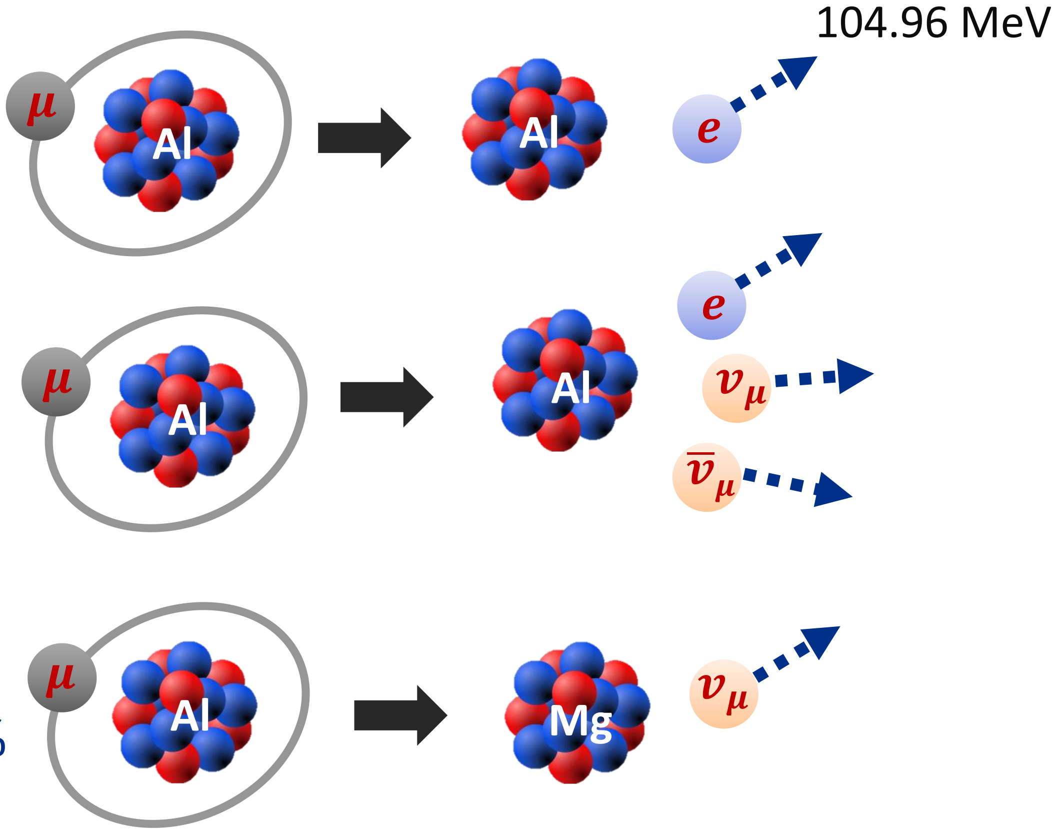
What is Mu2e measuring?

Muonic Al

Conversion < 10^{-12}

Decay In Orbit ~39%

Nuclear Capture ~61%



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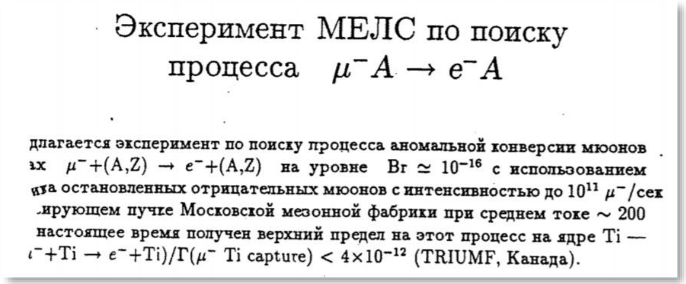
A Clever Idea


Эксперимент МЕЛС по поиску
процесса $\mu^- A \to e^- A$

длагается эксперимент по поиску процесса аномальной конверсии мюонов
ах $\mu^- + (A,Z) \to e^- + (A,Z)$ на уровне $Br \simeq 10^{-16}$ с использованием
ка остановленных отрицательных мюонов с интенсивностью до 10^{11} μ^-/сек
ирующем пучке Московской мезонной фабрики при среднем токе ~ 200
настоящее время получен верхний предел на этот процесс на ядре Ti —
$^- + Ti \to e^- + Ti)/\Gamma(\mu^-$ Ti capture) $< 4 \times 10^{-12}$ (TRIUMF, Канада).


The Solenoid Muon Capture System
for the MELC Experiment

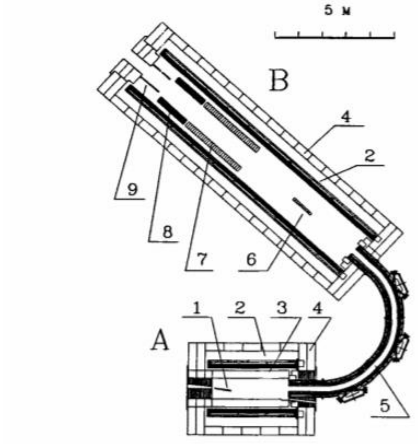
Rashid M. Djilkibaev and Vladimir M. Lobashev

Institute for Nuclear Research, Russian Academy of Sciences,
60-th Oct. Ann. 7a, Moscow 117312, Russia

- Proposed in a 1989 by V. Lobashev & R. Djilkibaev in the Soviet Journal of Nuclear Physics

  - Pulsed proton beam

  - Solenoids to capture muons

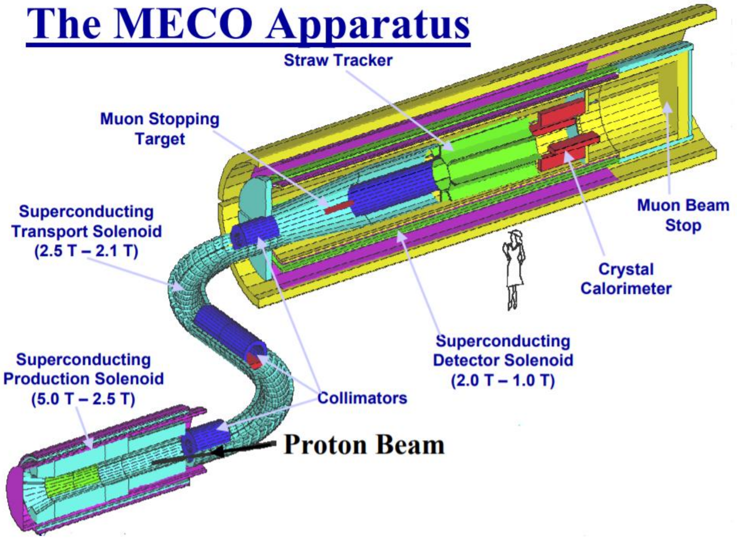


A Clever Idea…proposed at BNL

A Search for $\mu^- N \rightarrow e^- N$ with Sensitivity Below 10^{-16}

Muon – **E**lectron **CO**nversion

Proposal to Brookhaven National Laboratory AGS



- Proposed at Brookhaven in 1997
- Mu2e is essentially the MECO experiment moved to Fermilab to take advantage of the accelerator complex

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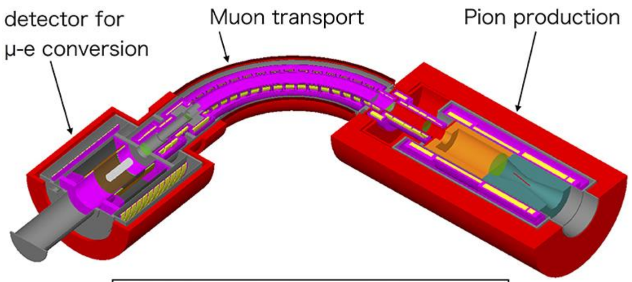
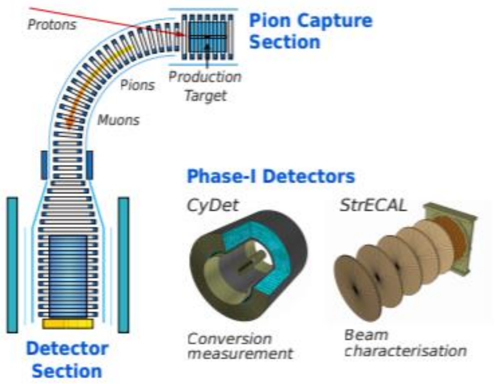
A Clever Idea…also in Japan

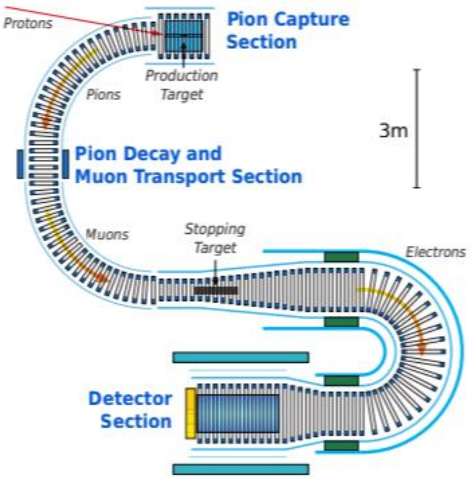
- COMET is currently under construction at J-Parc in Japan
- Phase-II will provide the same sensitivity as Mu2e



COMET Phase-I Layout



Phase I



Phase II

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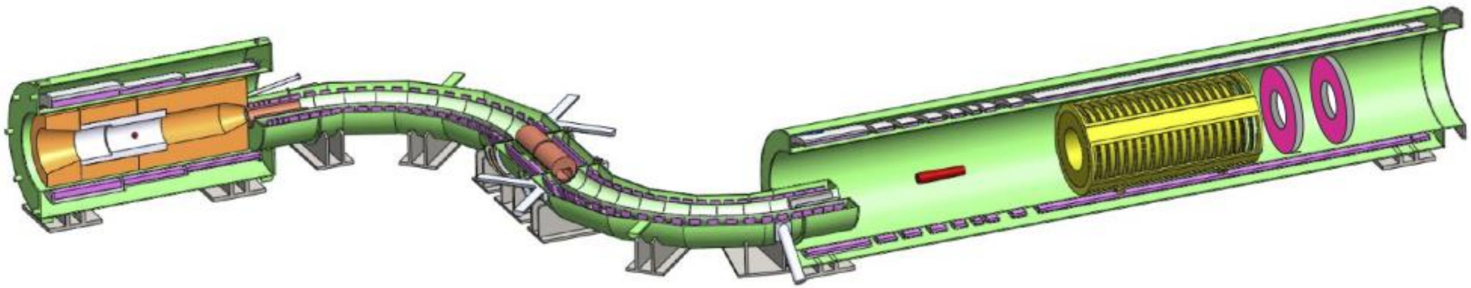
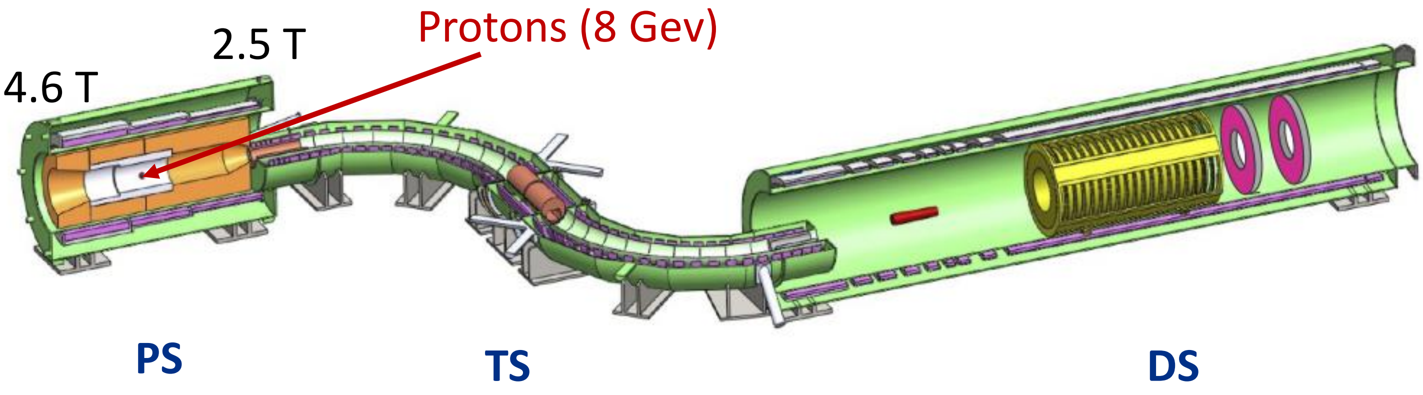
Mu2e Goals



- Produce 10^{18} Muonic Al atoms
  - This is on the order of the number of grains of sand on all the world's beaches!
- Suppress Backgrounds
- Detection system with tracking and calorimetry
  - Conversion electrons of 104.96 MeV

Mu2e Experimental Layout

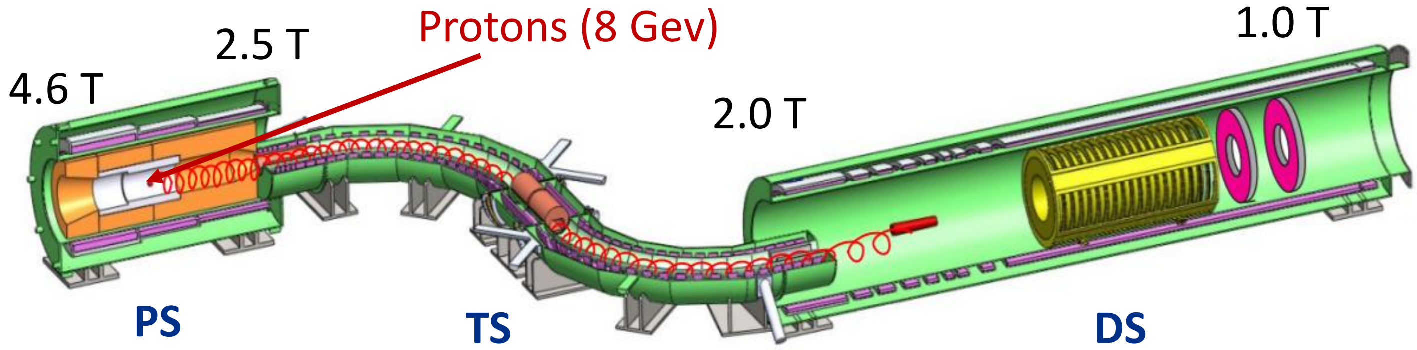


Experiment consists of 3 solenoid systems

Production Solenoid (PS)

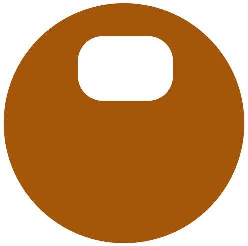
- 8 GeV protons interact with a tungsten target to produce, among other things, μ^-(from pion decay)
- Magnetic field gradient encourages pions and muons to travel toward the stopping target

Mu2e Experimental Layout



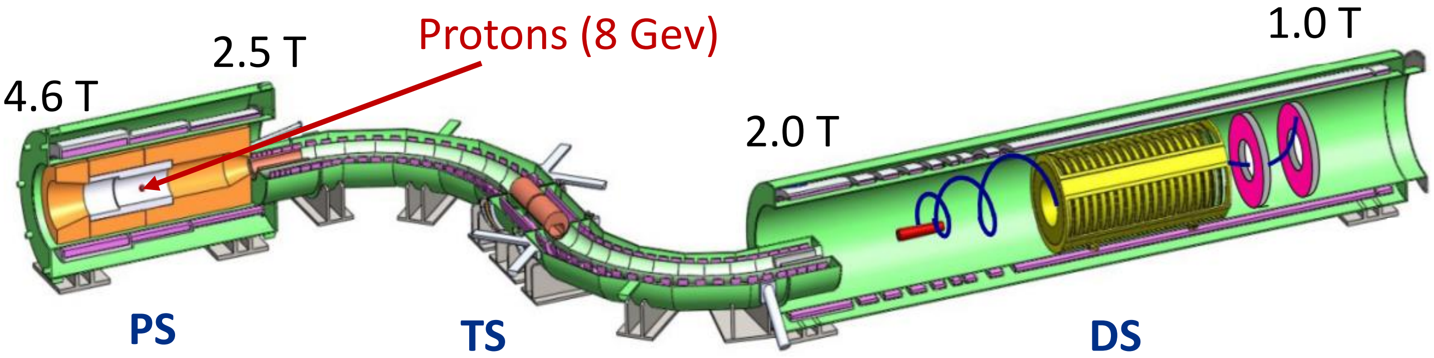
Transport Solenoid (TS)

- Magnetic field gradient encourages pions and muons to travel toward the stopping target
- S-shape
  - Eliminates line of sight
  - Minimize positive and neutral particles
  - Allows for momentum and sign filtering
- Absorb anti-protons in a thin window



Collimator between TSU and TSD

Mu2e Experimental Layout



Detector Solenoid (DS)

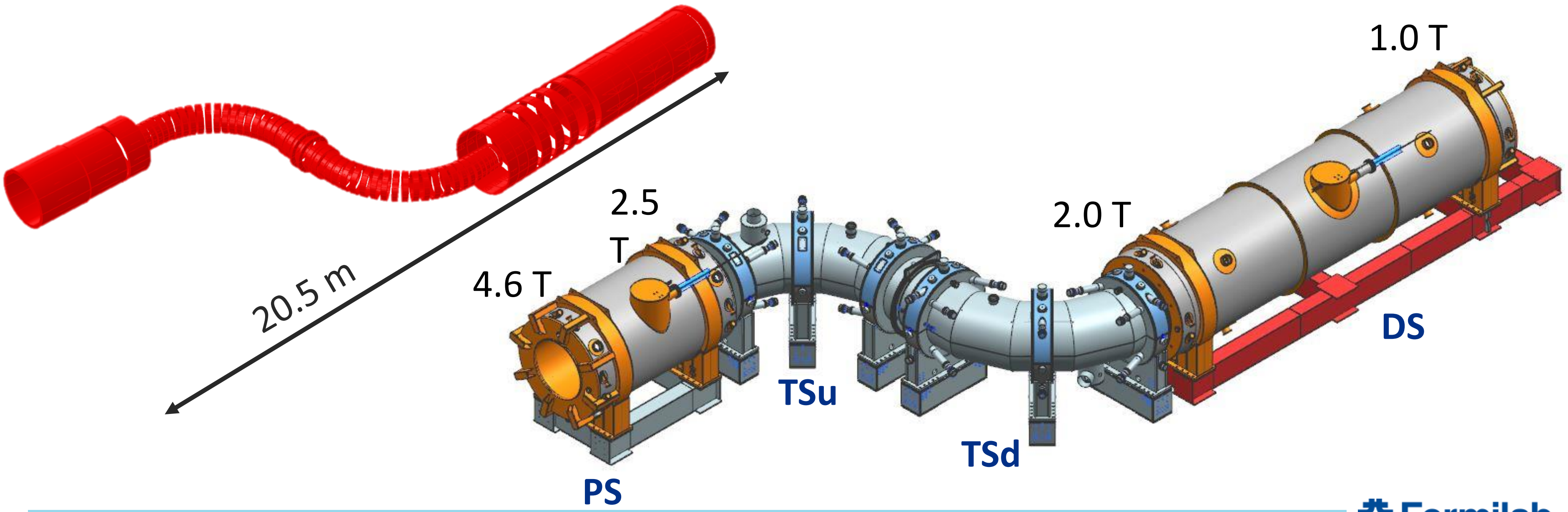
- Aluminum stopping target
- Magnetic field gradient in the target regions en … l toward the detector
- Uniform field in detector region
  - Tracker
  - Calorimeter

PS bore tube

DS bore tube

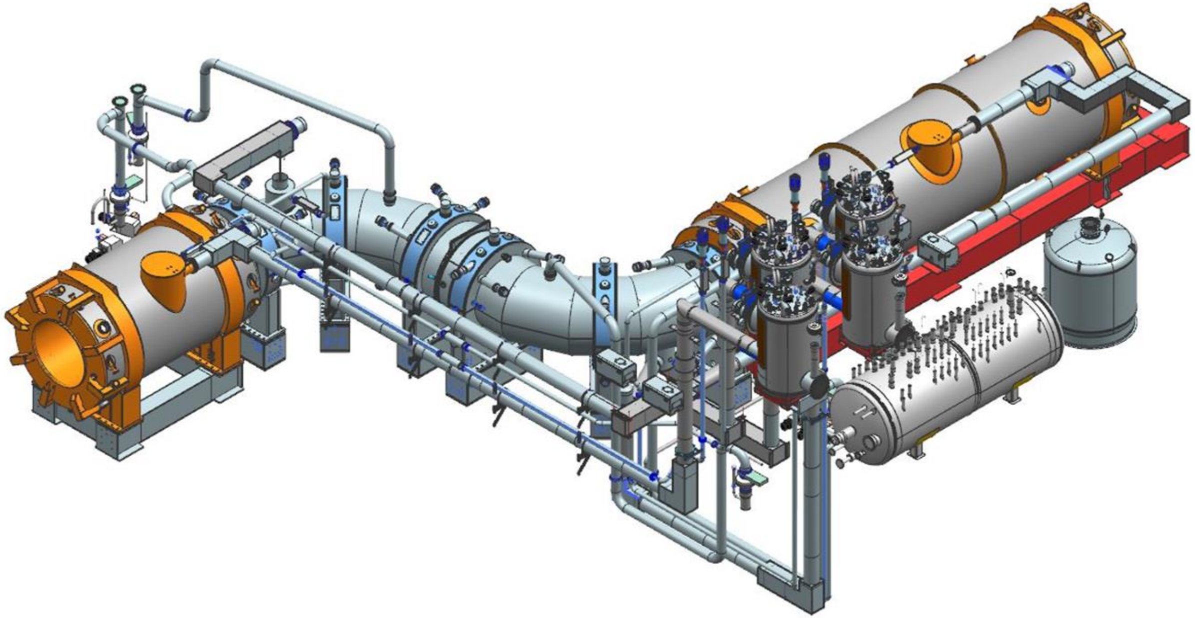
Mu2e Magnet System

- 66 superconducting solenoids
  - Production Solenoid(3), Transport Solenoid(52), Detector Solenoid(11)
  - TS is divided into an upstream(TSU) and downstream(TSD)
- 4 cryostated magnets- individually cooled and powered



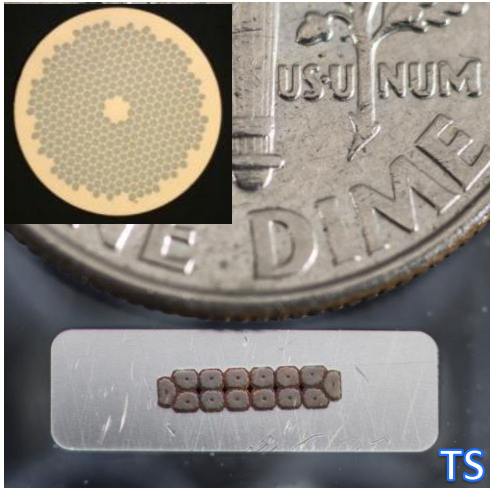
Solenoid System

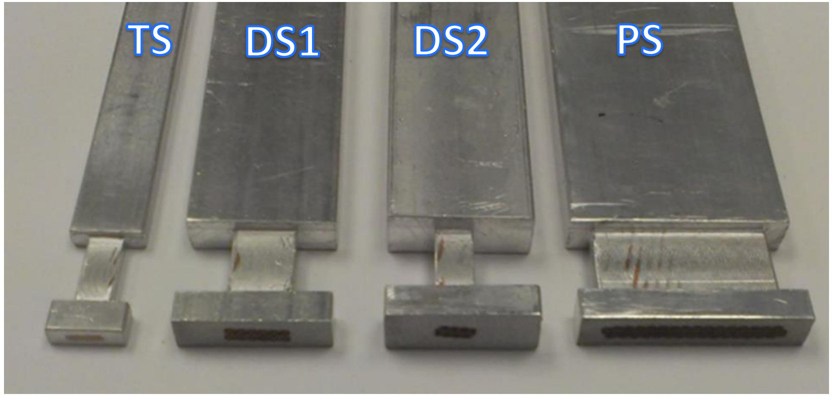
- Power Supplies
- Cryogenic System and Piping
- Quench Detection
- Vacuum Pumps



NbTi Superconductor

- All coils are made of Al-stabilized NbTi superconductor
  - PS 9200A
  - DS 6000 A
  - TS 1750 A
- DS and TS used 99.998% pure Al (5N)
- PS uses 5N doped with 0.1wt% Ni
- ~ 75 km of cable required
- Coils are conduction cooled using liquid He
  - NbTi critical temperature ~10 K in zero magnetic field





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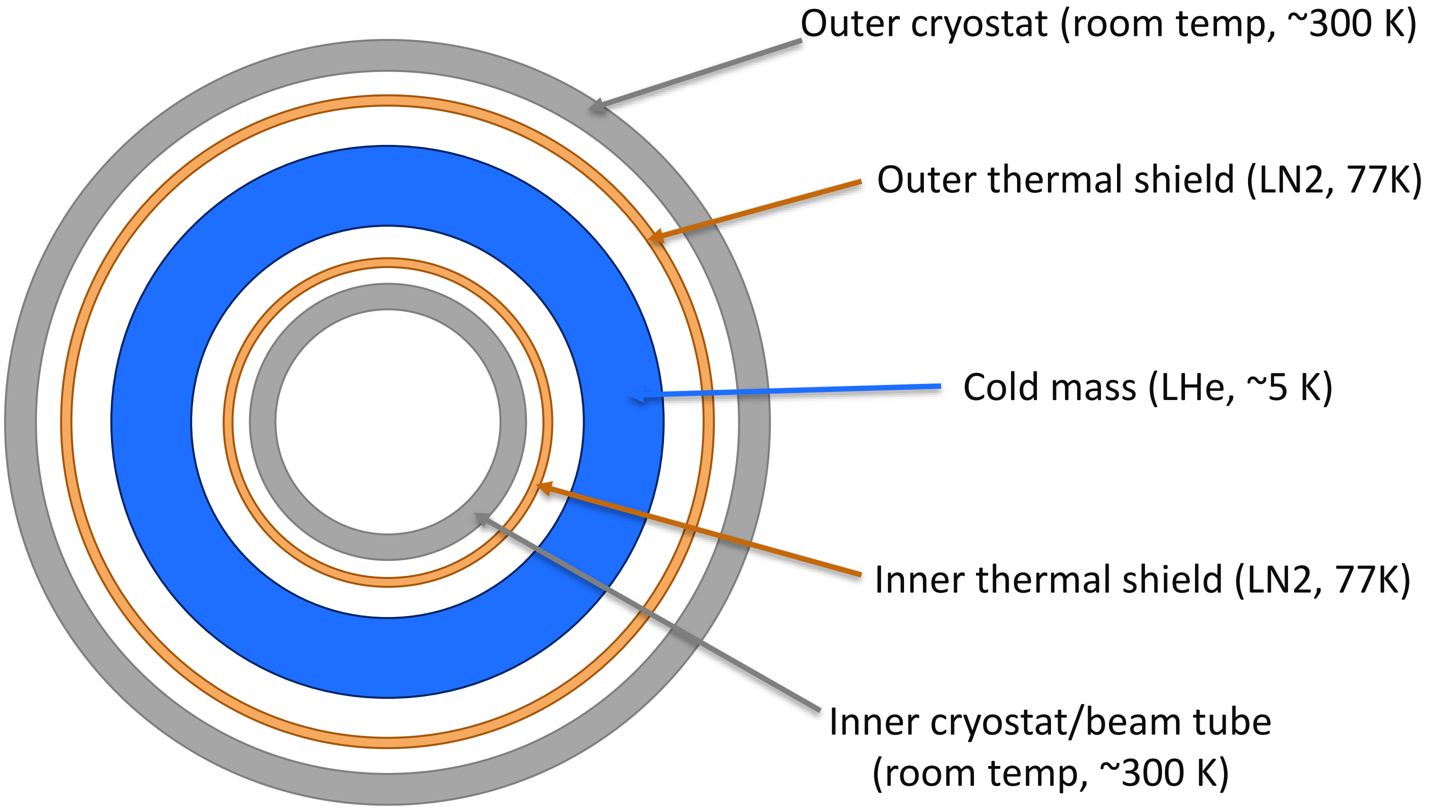
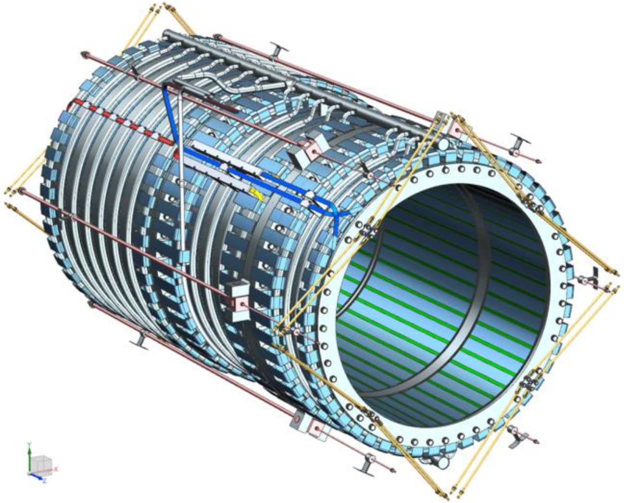
Anatomy of a Mu2e Solenoid



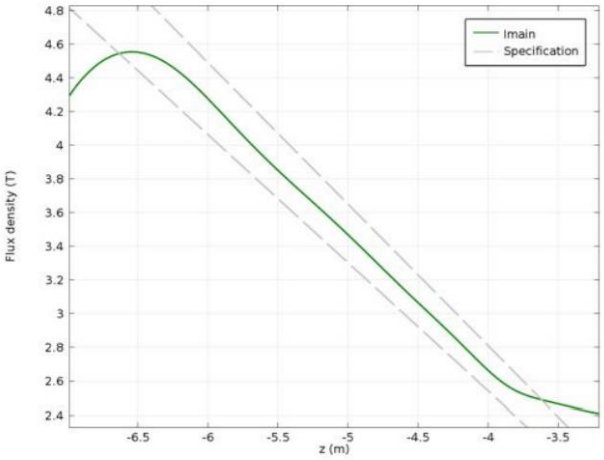
Production Solenoid

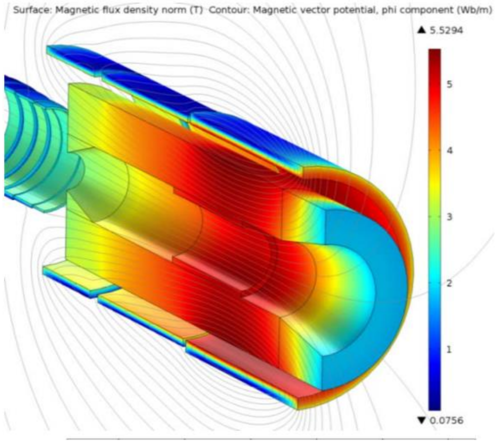
- Highest magnetic field region, ~4.5 T down to 2.6 T
- Being fabricated in industry, will be delivered fully cryostated and ready to install early next year



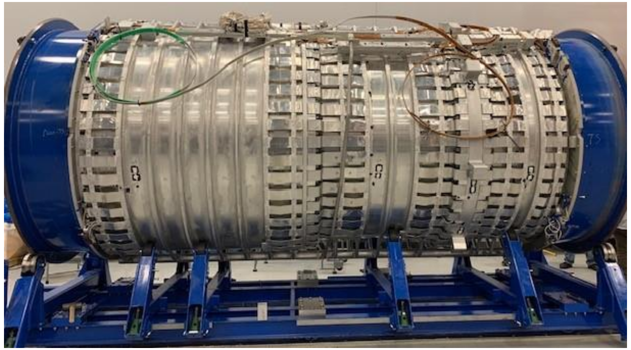
PS Cold Mass Design

PS Magnetic Field Requirement





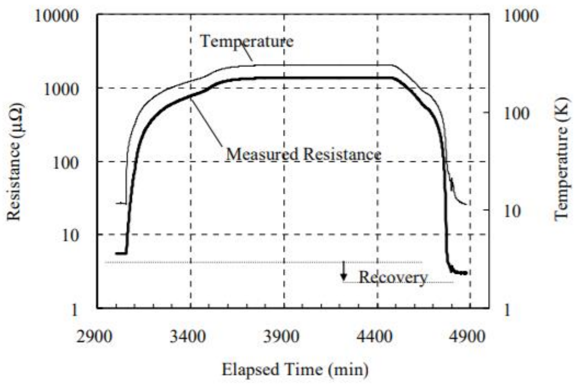
V. Kashikhin et al., IEEE Trans on Applied Superconductivity, Vol 3, No 3



PS Cold Mass Assembly

Production Solenoid

- Large heat and radiation environment
  - Mitigated by heat and radiation shield
  - Heat conductively removed through Al stabilizer and thermal straps
  - Radiation reduces the thermal conductivity over time (~2.5×10^{-5} /year DPA)
  - RRR sensors to measure resistance
    - relationship between electrical and thermal conductivity
  - Room temperature thermal cycle to anneal Al ~1/year

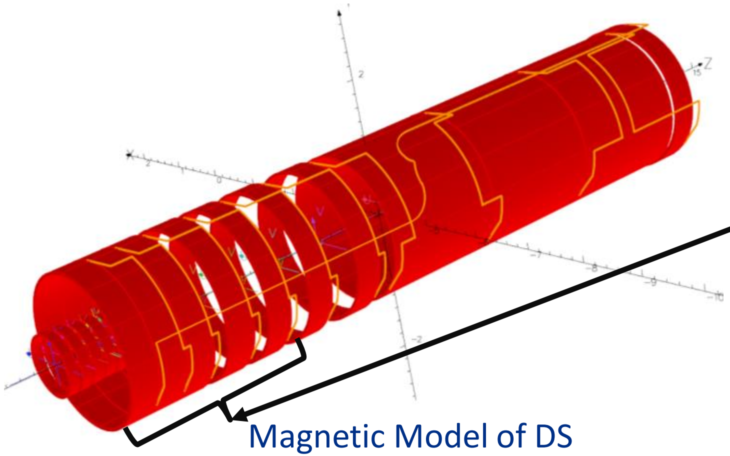


M. Yoshida et al., AIP Conference Proc. 1345, 167

PS installed in outer cryostat (11/16/23)

Detector Solenoid

- Field gradient 2 T down to a uniform 1 T in the detector region to transport electrons from the target to the detector
- Two conductor cross sections were required to meet the field requirements while operating at the same current
- The DS is also being fabricated in industry, will be delivered fully cryostated and ready to install next year



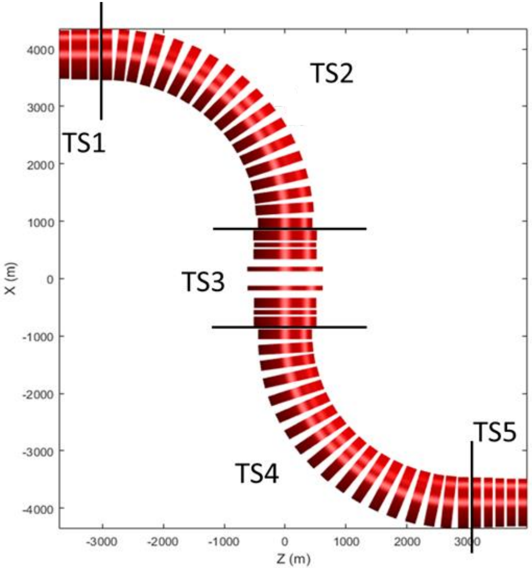
Magnetic Model of DS

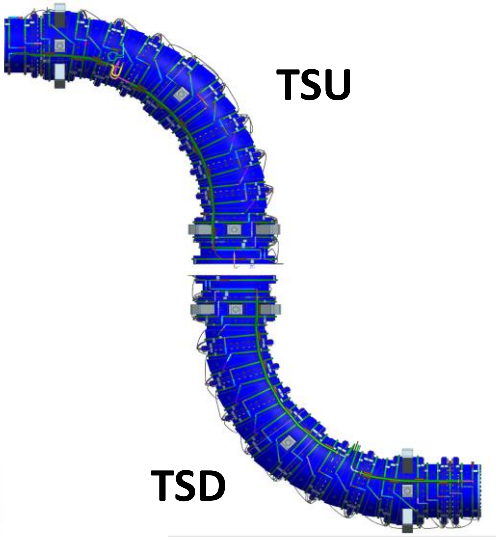
DS1-4 Assembled

Transport Solenoid

Transport Solenoid Magnetic Requirements

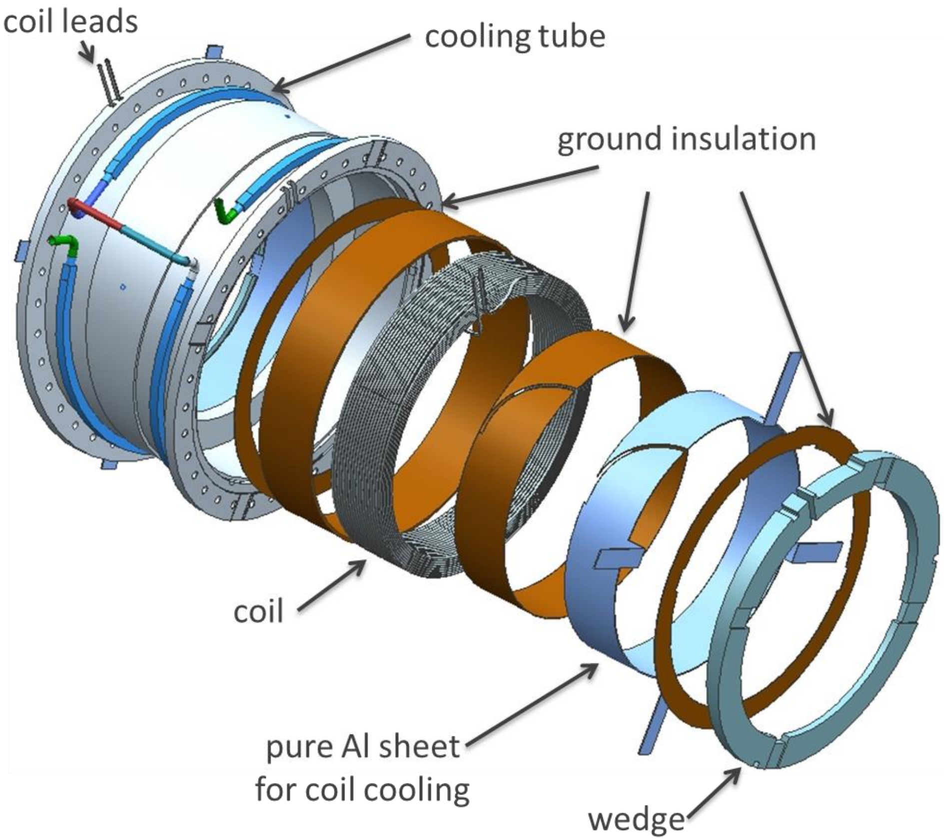
Region	B Initial/Final ±5% (T)	dBs/ds (T/m)	dBs/dr (T/m)	Ripple (T)	Location* (m)
TS1	2.50/2.40	< -0.02	NA	NA	r=0, r=0.15
TS2	NA	NA	> 0.275	±0.02	r < 0.15
TS3	2.40/2.10	< -0.02	NA	NA	r=0, r=0.15
TS4	NA	NA	> 0.275	±0.02	r < 0.15
TS5	2.10/2.0	< -0.02	NA	NA	r=0, r=0.15

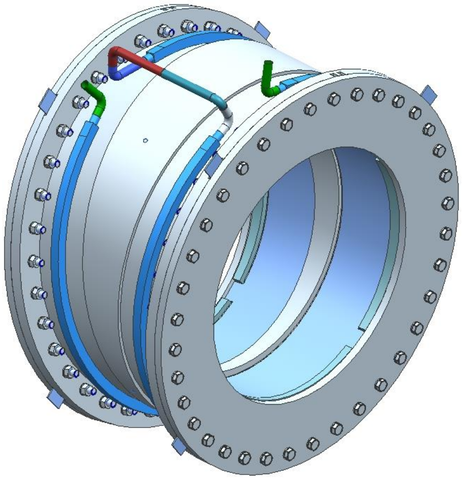




- Consists of 52 coils grouped into the TSU(25) and the TSD(27)
- The straight sections require a gradient to prevent trapped particles and direct muons toward the detector solenoid
- The curved sections have a limit on the radial gradient and the ripple due to the coil spacing

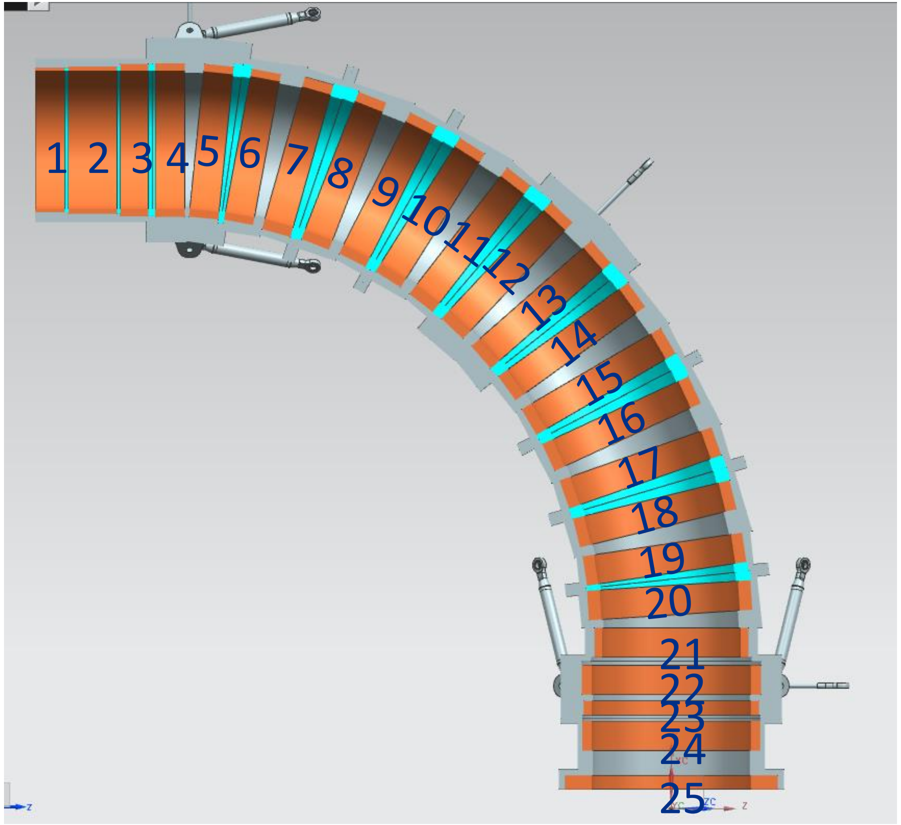
Transport Solenoid Module





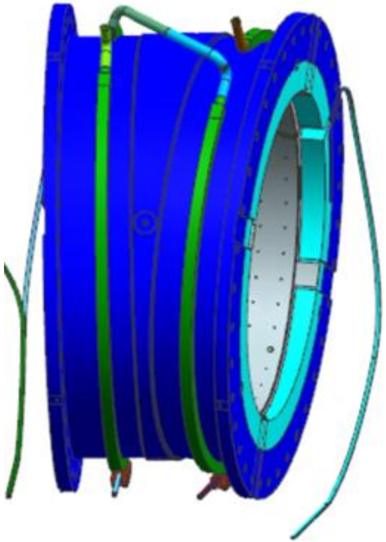
Coils inserted through shrink fit process

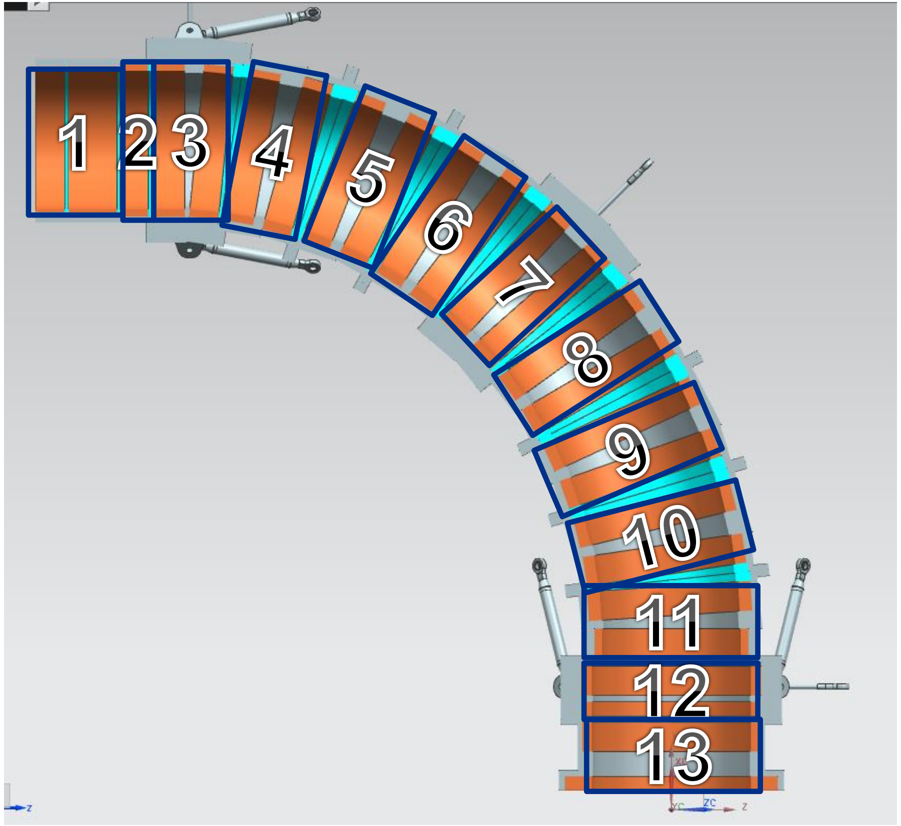
Transport Solenoid-TSU Coils



Transport Solenoid – TSU Modules

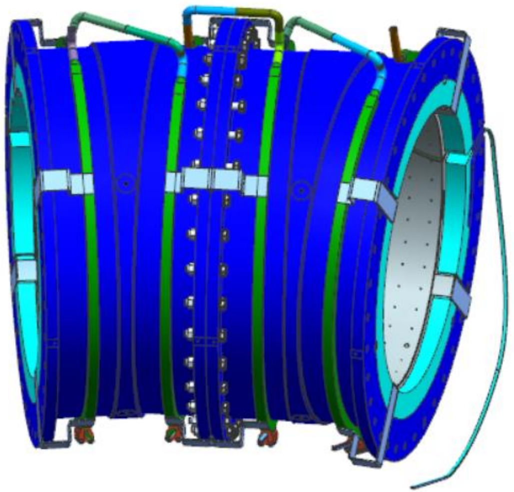
Typically 2 coils per module

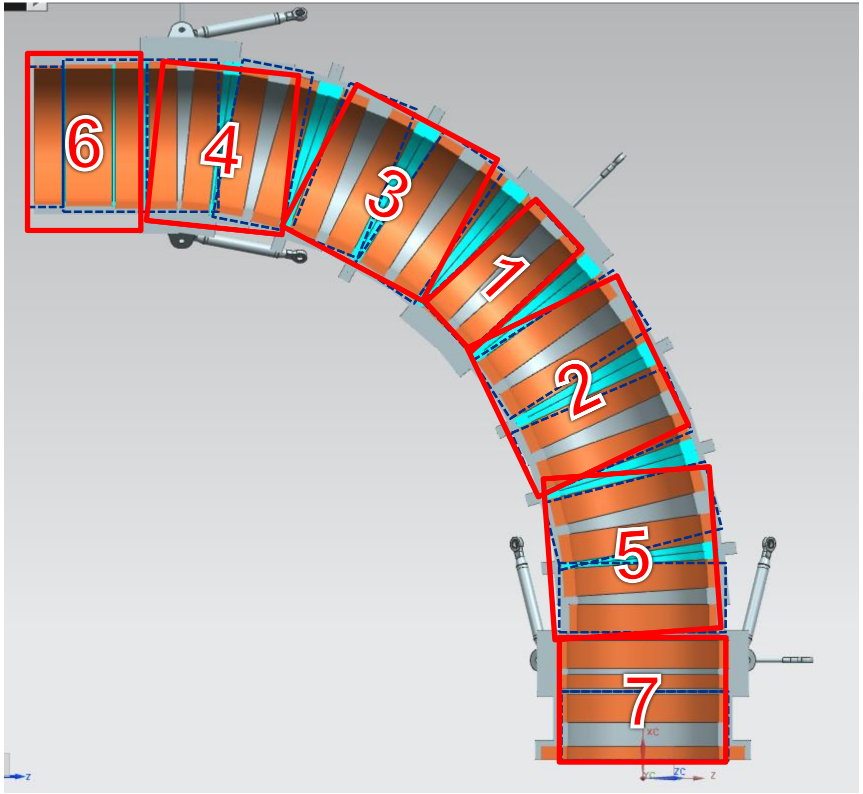




Transport Solenoid – TSU Units

1-3 modules per unit



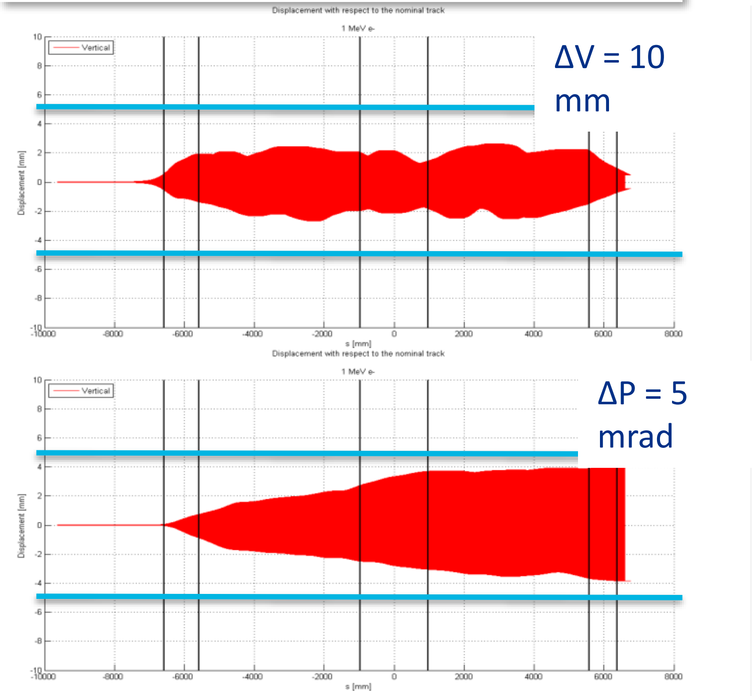


Units are fabricated at a vendor and shipped to Fermilab for testing and assembly

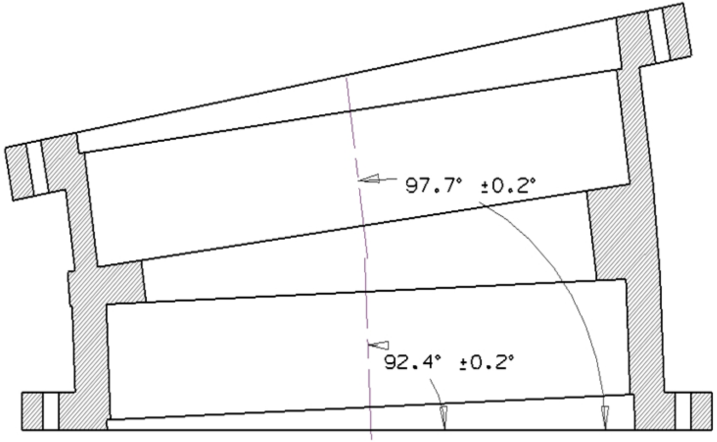
Tolerance

Tolerance studies of the Mu2e solenoid system

M. L. Lopes, G. Ambrosio, M. Buehler, R. Coleman, D. Evbota, S. Feher
M. Lamm, V. Kashikhin, G. Moretti, T. Page, M. Tartaglia, *Fermilab*,
J. Miller, *Boston University*
J. Popp, *York College CUNY*
R. Ostojic, *CERN*



- Mu2e requires efficient muon transmission and no trapped particles
- Error studies helped set the tolerances for fabrication and assembly
- Transmission was found to be sensitive to the angle between coils



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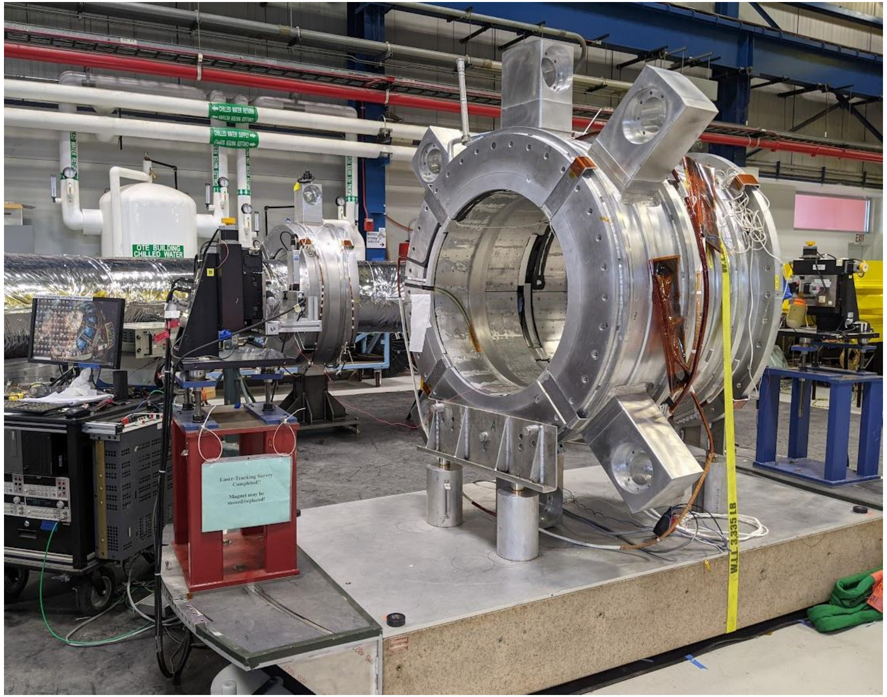
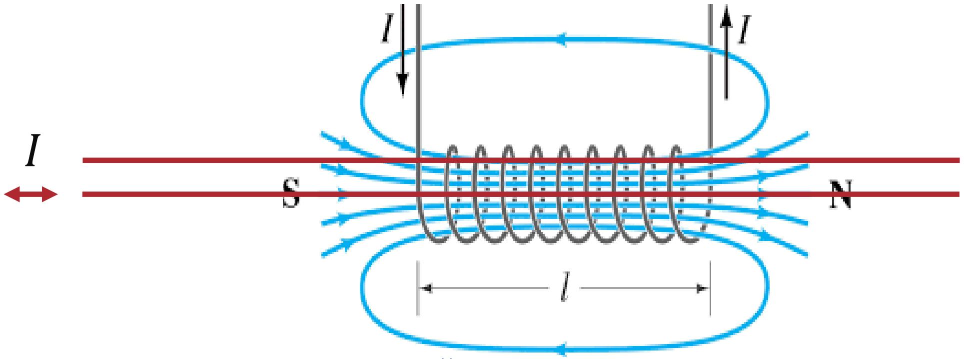
Room Temperature Testing

- Visual inspection
- Shipping shock log data
- Pressure and leak testing
- Voltage tap and RTD installation
- Electrical checkouts
  - Resistance
  - AC,DC inductance measurements
  - Instrumentation checkouts
- Polarity check
- Vibrating stretched wire on each coil



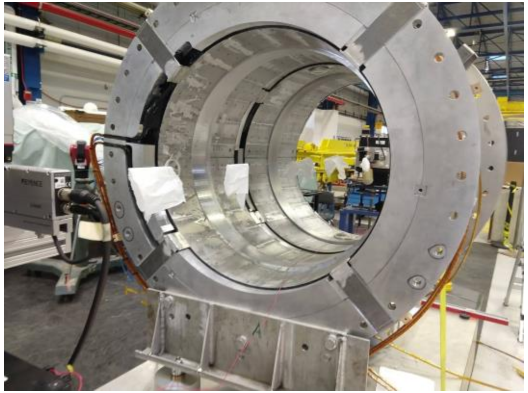
Stretched wire setup

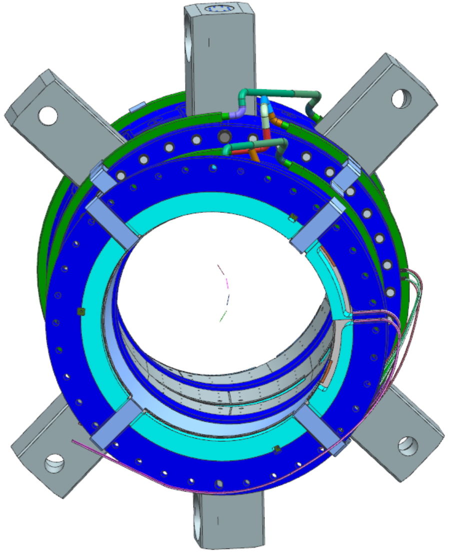
Magnetic Axis



https://www.miniphysics.com

$$F = Il \times B \neq 0$$
$$F = Il \times B = 0$$

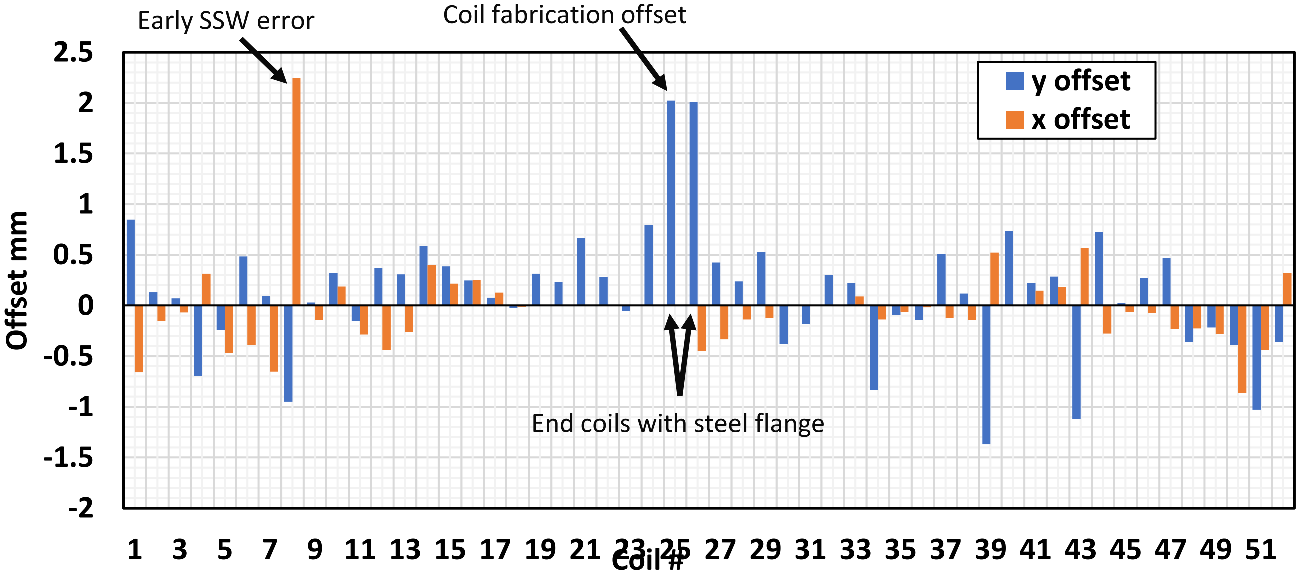




- Vibrating stretched wire measurement to find the magnetic axis for each coil, both position and angle
- Position measured with respect to fiducials on the shell and wire system, translated to the Mu2e coordinate system
- As-built values fed back into magnetic model to ensure magnetic requirements are met

TS Magnetic Measurements

- Magnetic center measurement of all 52 coils
  - After wire center located with vibrating stretched wire system, Metrology locates wire in the Mu2e coordinate system
  - ~ 1 coil/week
- Acceptance tolerance on coil position <1 mm, but tolerance was tighter than needed, can tolerate up to about 10 mm offset



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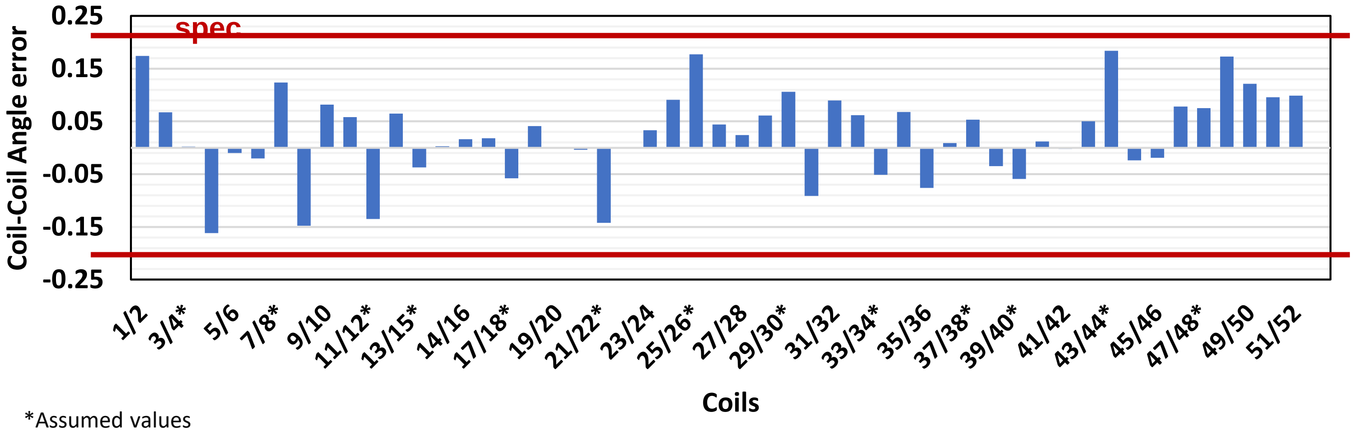
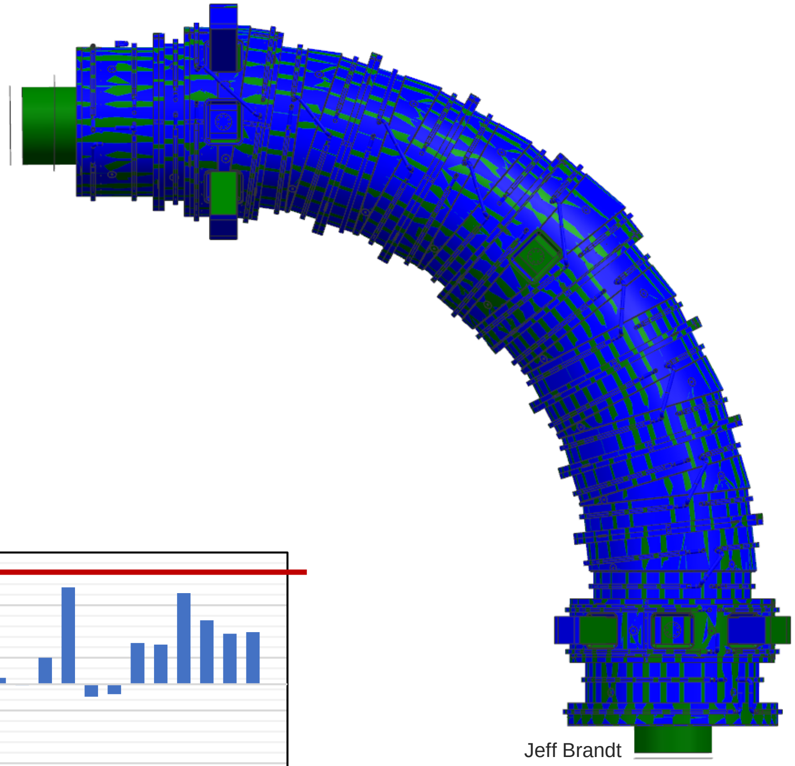
TS Magnetic Measurements

- Previous tolerance studies showed muon transmission was most sensitive to coil-to-coil angle errors
- A strict fabrication tolerance was set on coil-to-coil angle of < 0.2 degrees
- This also set tight fabrication tolerances on the mating module surfaces
- Very good agreement between model and as-built assembly



*Assumed values



CAD compare. Designed vs as-built.

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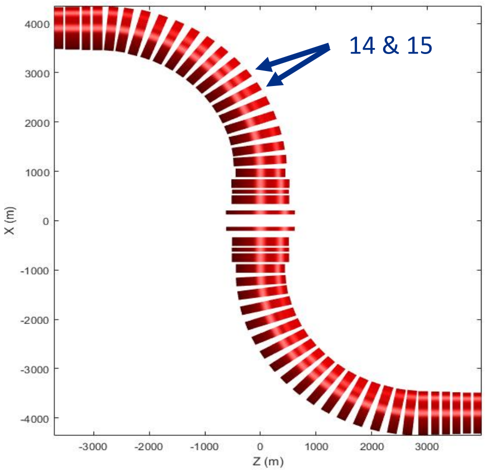
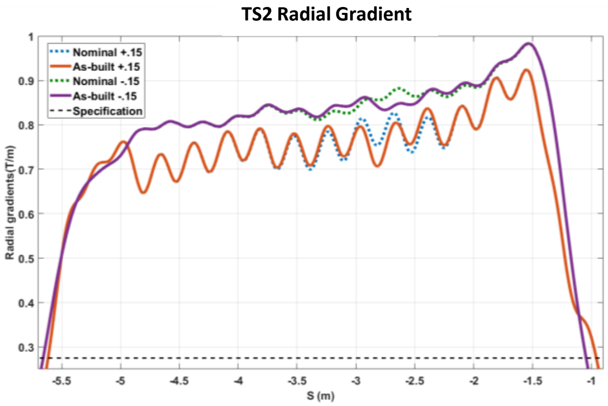
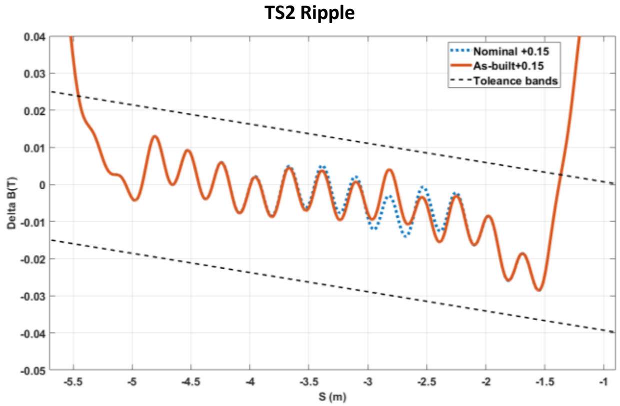
Swapped Coils 14 & 15

- Due to a vendor fabrication error, we investigated the feasibility of swapping coils 14 and 15
- The coil lengths and inner diameter are the same, so the coil center position and angles remained at nominal
- Coil 15 has one additional layer of conductor, this increases the axial field at 14 and decreases at 15
- Magnetic requirements were still met, so we accepted the coil swap

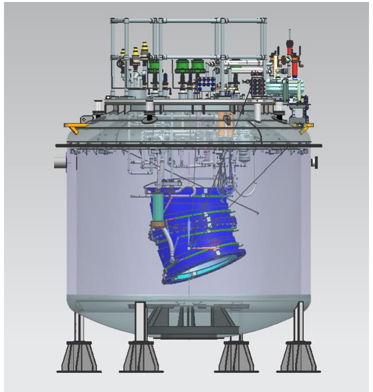


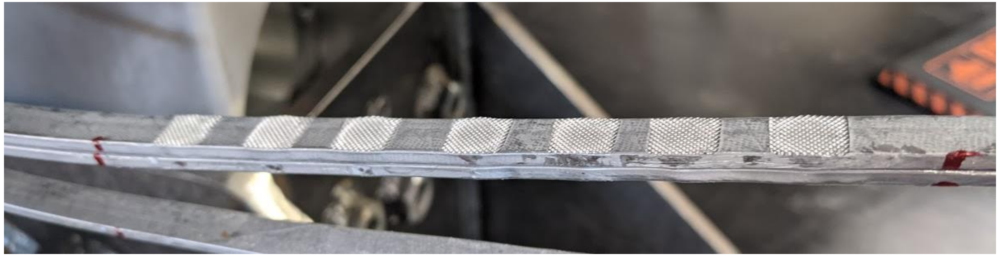




LHe/Cold Test Setup

- Unit-to-unit leads are ultrasonically spliced together and secured in splice boxes
  - Ultrasonic weld used to avoid damaging the superconductor
- Voltage tap connections made with an ultrasonic welder
  - Voltage taps used to detect quenches
- Temperature sensors installed
- Long unit-to-unit leads mechanically supported and soldered to dished head power leads



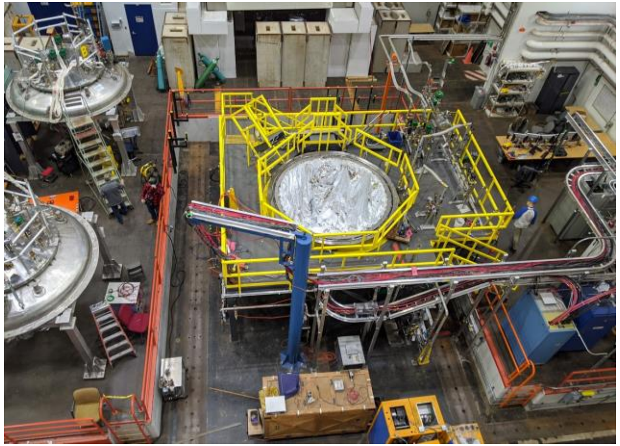


Ultrasonic splice

Unit mounted to the dished head

LHe/Cold Testing

- Dished head and unit craned over to the cryostat
- Vacuum pump down to 10^{-5} Torr
- Controlled cooldown ~1 week
- Hipot performed before, during, and after the cold test
- Final leak check after the cold test

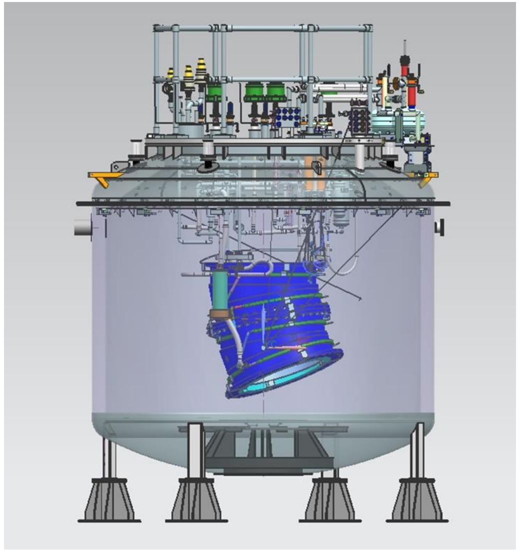


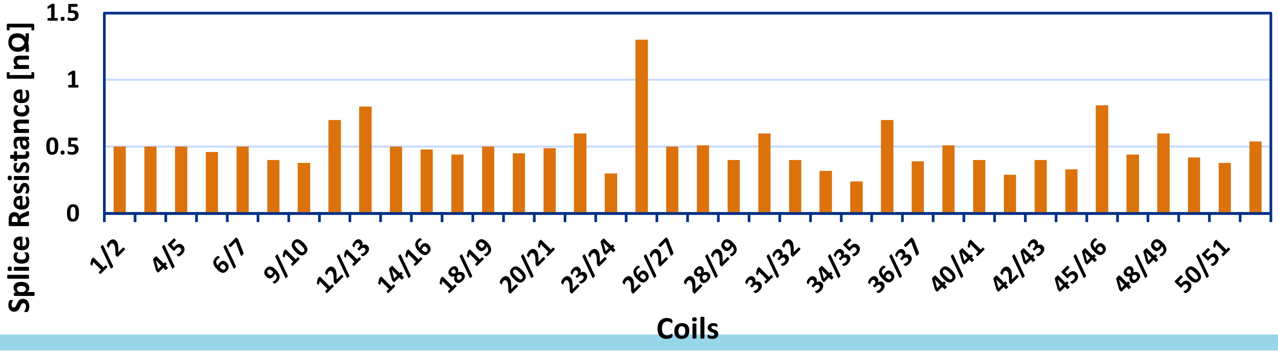
Cryostat and staging area

Unit transferred to cryostat

Cold Testing

- Each unit is cooled to ~5 K
  - Controlled cooldown and warmup to minimize delta T between the coil and shell
  - ~week to cooldown and warm up
- Powered to 2100 A (120% of operating current) to produce fields seen in the experiment
- Quenches in long unit-to-unit leads, no quenches in the coil
- Splice resistance under the required 2 nΩ





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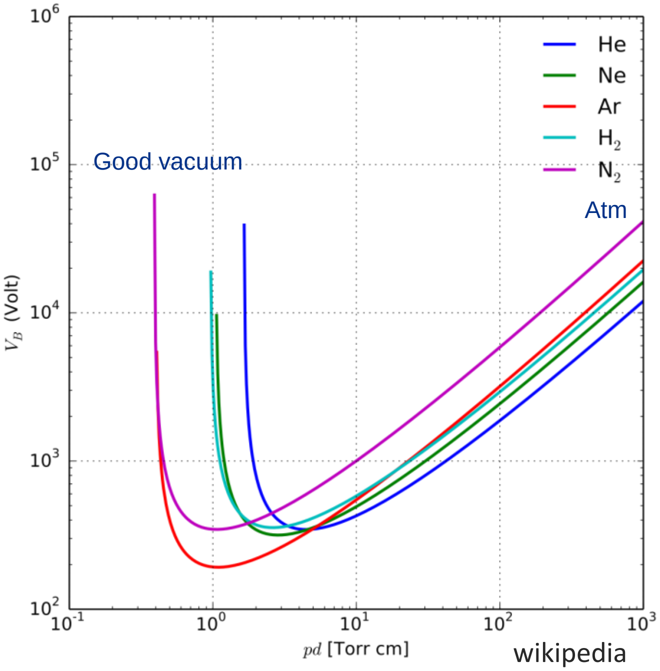
Aside on Paschen Breakdown

- Pressure and distant dependent breakdown
- An issue when performing hipot in poor vacuum or when developing a voltage from a quench
  - Can be overcome by improving the vacuum or eliminating the exposed voltage
- Extensive campaign to Paschen-proof the transfer lines, magnet cables, and feedbox leads

Power leads Paschen testing



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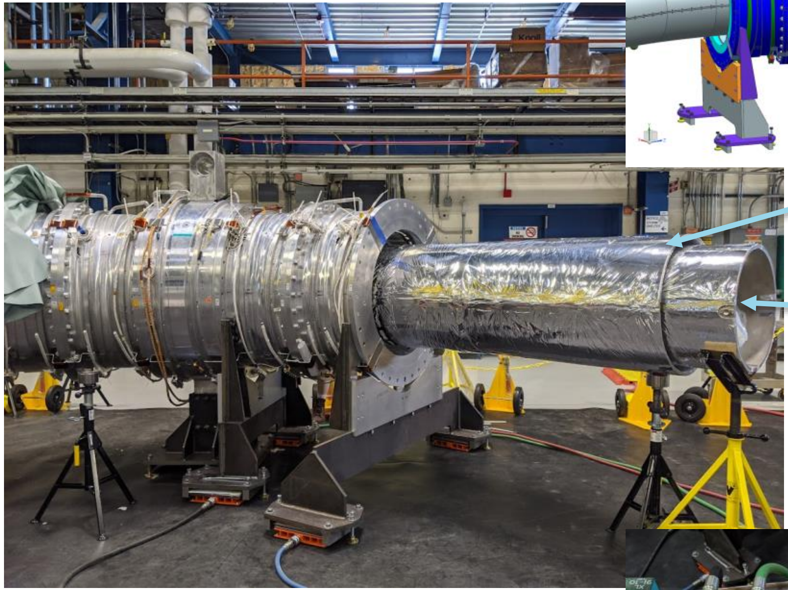
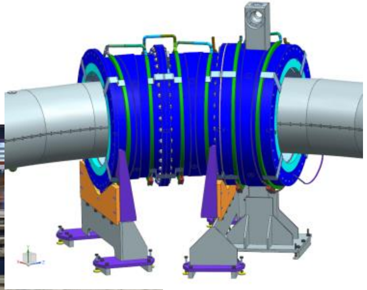
TS Unit Assembly

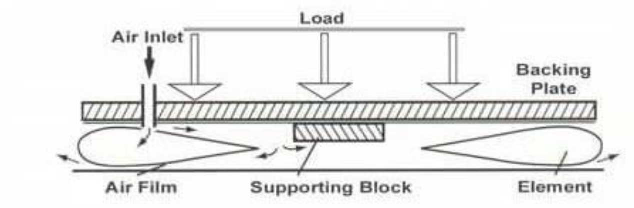




Inner thermal shield

Inner bore

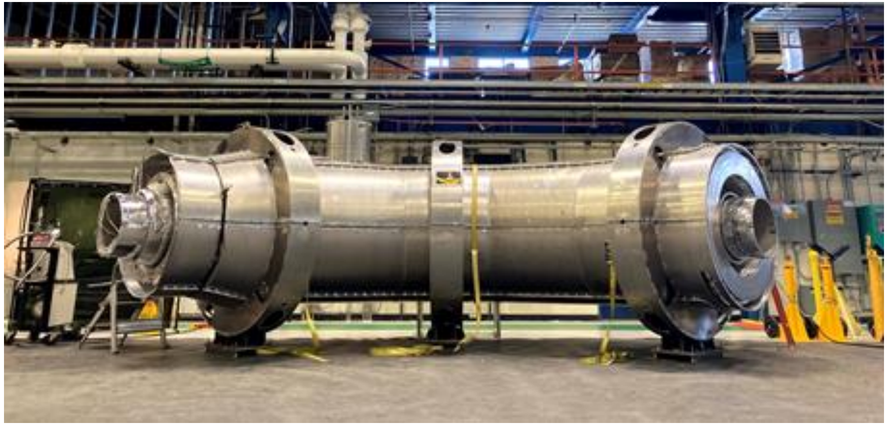
- Special assembly tooling
- Units moved into place on air bearings



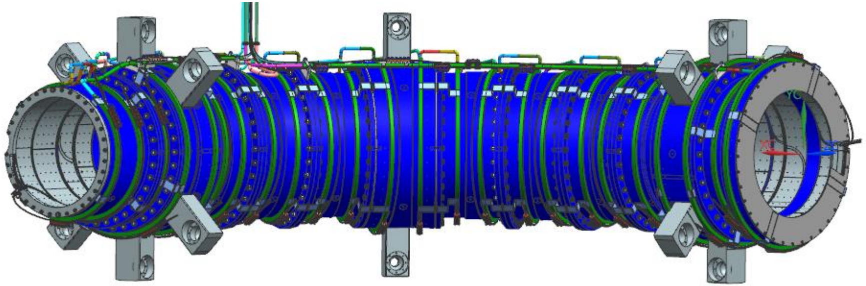
https://www.hovair.com/airbearing/

Assembly

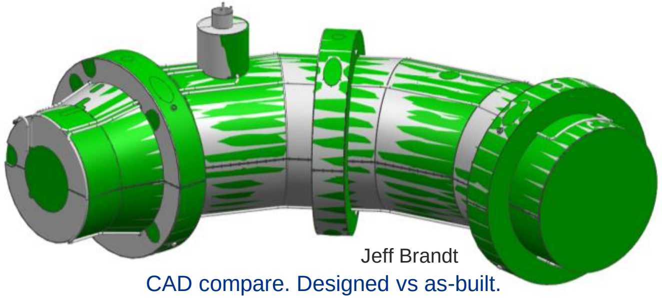
Assembled TSU coldmass



TSU outer thermal shield



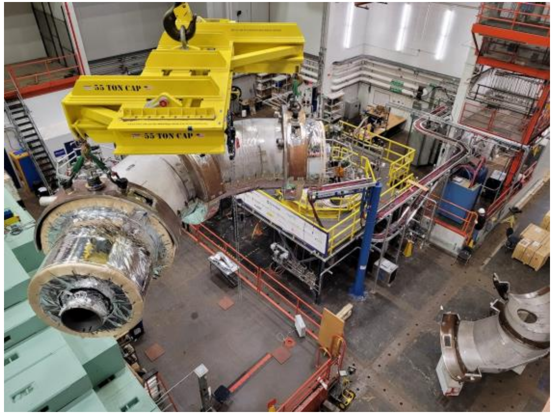
TSU coldmass model



Good agreement between designed and as-built thermal shield

TSU Cryostat/Vacuum Vessel -Video

TSD Cryostat/Vacuum Vessel- Pictures



TS Current Status

TSd shipping early next year

TSu shipping in Dec

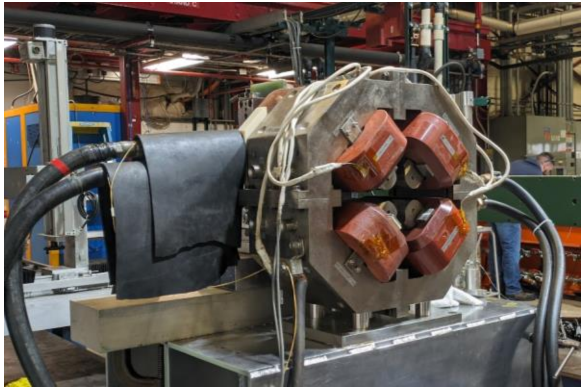
Magnet Test Facilities at Fermilab

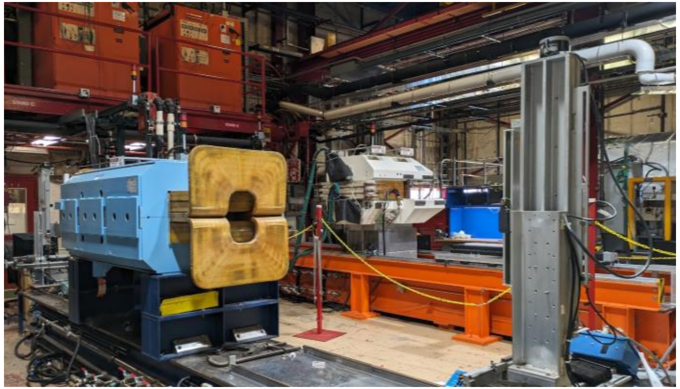
- Resistive/Normal Conducting Magnet Test Stands
  - Stands A-C
- Superconducting Test Stands
  - Vertical Magnet Test Facility (VMTF)
  - Stand 4
  - High Field Vertical Magnet Test Facility (HFVMTF) coming soon!

Stands A-C

- Magnets from Fermi accelerator, for PIP-II, ORNL PPU, …
- Resistive and permanent magnets
- Current up to 5000 A with LCW water for cooling

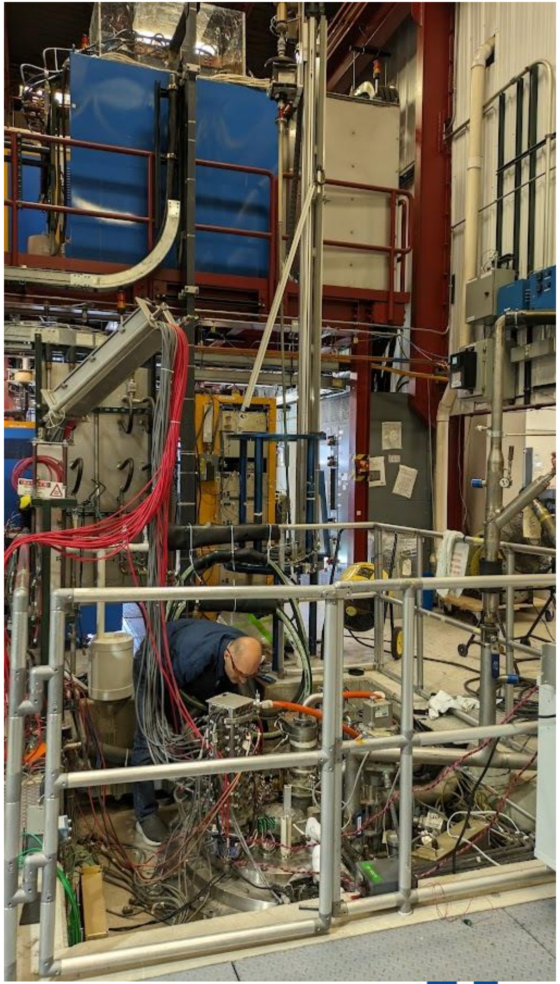
Sample of magnets from the past month:





Vertical Magnet Test Facility - VMTF

- For testing cold masses
- Min temperature of 1.9 K LHe
- Current up to 30 kA
- Max Cold mass dimensions – 3.7m length and 62 cm diameter
- Supporting HF SC Magnet R&D and test for MDP program



Stand 4

- Testing fully cryostated magnets
- Min 1.9 k LHe
- Max current 18 kA
- Length of the cryostats ~ 11 m
- Dedicated to CERN HiLumi AUP

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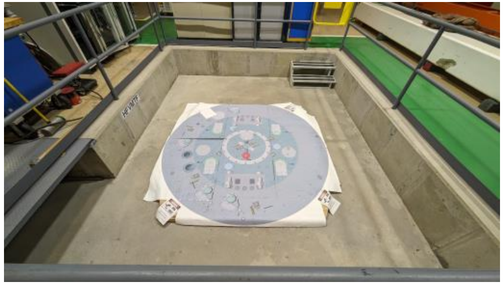
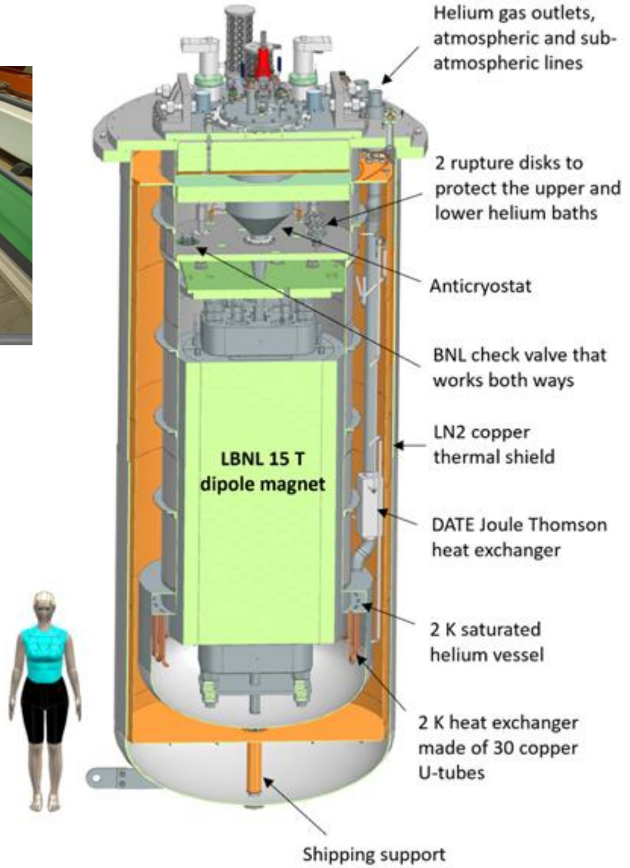
HFVMTF High Field VMTF – Under construction



- Background dipole field
  - 15 T
  - Down to 1.9 K
  - 20 kA power supply
- Cold masses up to 1.3 m diameter and 3 m long
- Test sample
  - temperature between 4.5-50 K
  - 100 kA
- Collaboration between High Energy Physics and Fusion Energy Sciences



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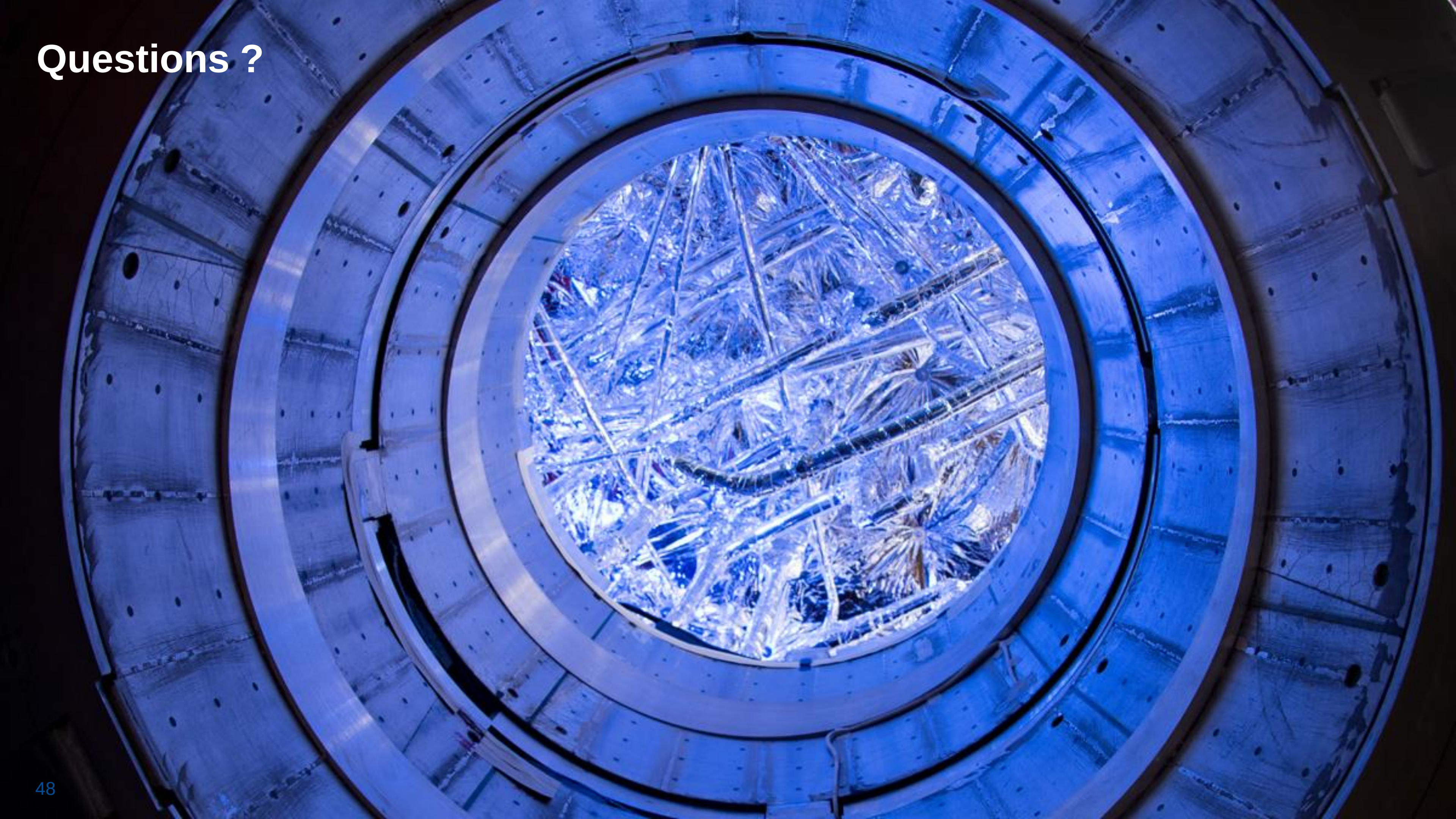
Concluding Remarks

- Accelerators need magnets and magnets need you
  - Scientists (high energy, material, accelerator)
  - engineers (mechanical, electrical, cryogenic, …)
  - technicians (mechanical, electrical, vacuum)
  - …
- Exciting time to be part of Mu2e!
  - Project is currently under construction
  - Magnets shipping to the experimental hall soon
  - Interested in learning more? Mu2e.fnal.gov

Questions ?



Improving on the previous experiment

- Current world's best limit on $\mu N \rightarrow eN$
  - $R_{\mu e}(\mu N_{Au} \rightarrow eN_{Au})$ < 7x10^{-13} at 90% CL
  - Sindrum-II Collaboration, 2006

- The previous measurement was limited by
  - Backgrounds from prompt pions
  - Stopped μ)