Superconducting Magnets for J-PARC Physics Experiments

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On be half of J-PARC Cryogenics Section

Major Physics Projects at J-PARC with Superconducting Magnets

- Under construction
  - COMET (Coherent Muon to Electron Transition)
  - g-2/EDM experiment

- Being proposed
  - MLF 2nd Target Station

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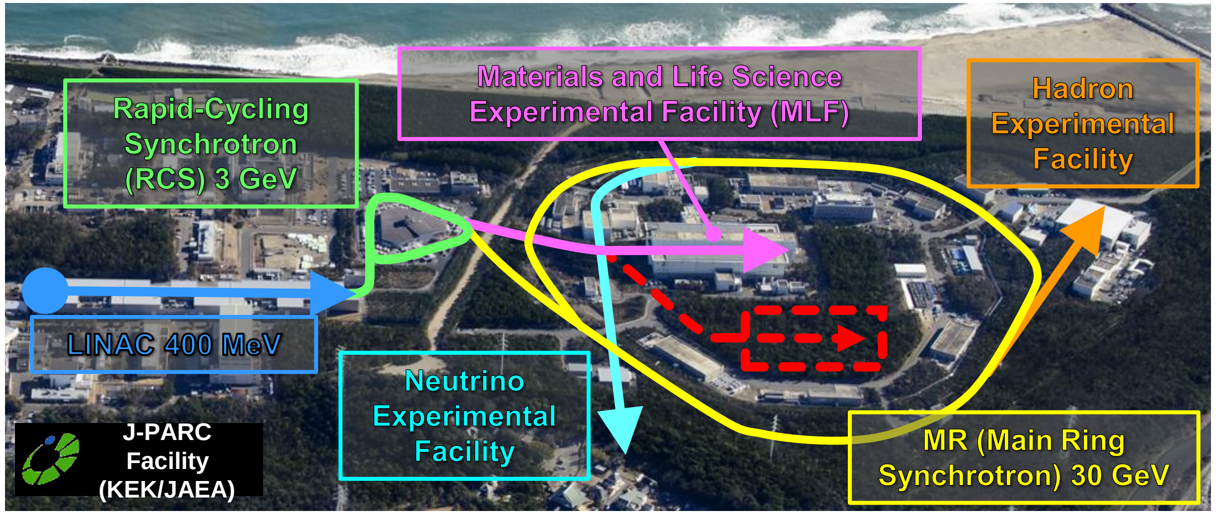

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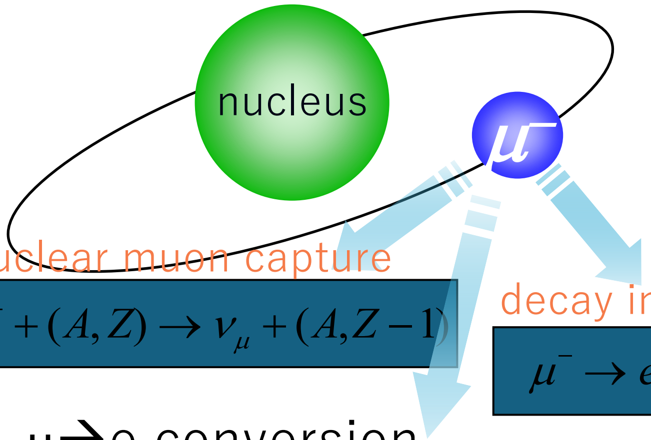
The COMET Experiment

- stopping μ^- → Muonic atom

$$B(\mu^- N \to e^- N) = \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \nu N')}$$



nuclear muon capture

$$\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$$

decay in orbit

$$\mu^- \to e^- \nu \bar{\nu}$$

μ→e conversion

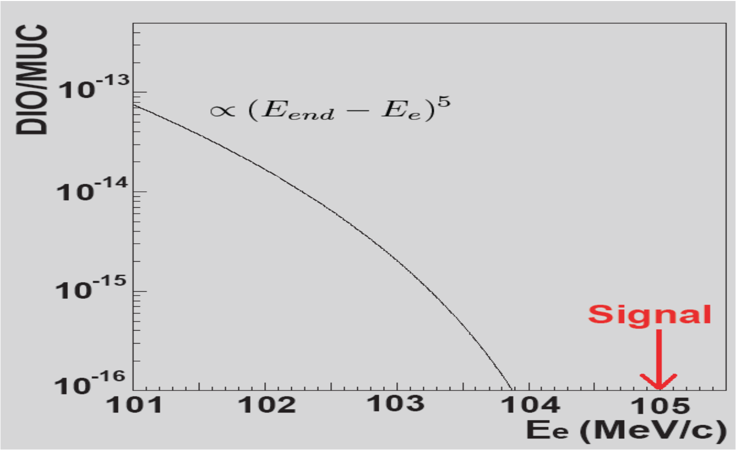
$$\mu^- + (A,Z) \to e^- + (A,Z)$$

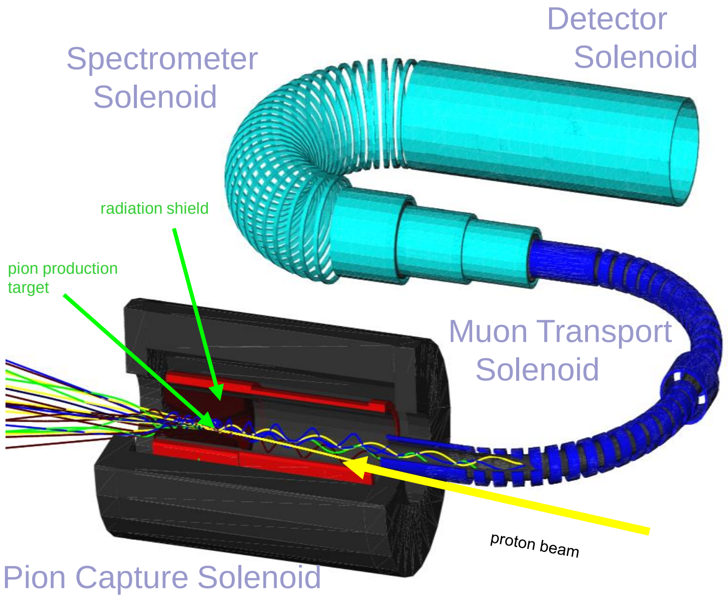
Detect monoenergetic electrons from μ-e conversion

Physics Reach: Br<10^{-16} (PhaseII)
<10^{-14} (PhaseI)

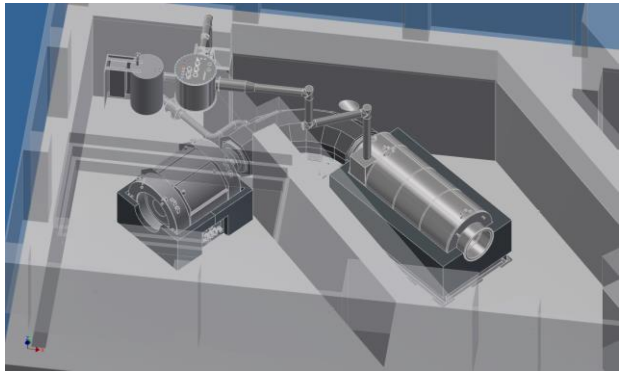
→ 2×10^{18} muon stops

→ 10^{11} μ^-/sec





COMET Phase II



COMET Phase I

Requirements for COMET magnets

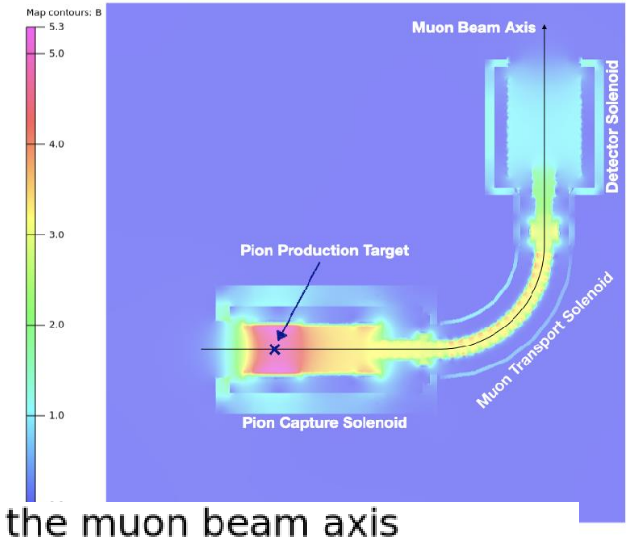
Goal: 10^{11} μ^{-}/sec

- Produce high intensity muon beam
  - Large acceptance to collect pions from production target
  - High field on pion production target
  - Graded field to focus pions forward
- Reduce pion contamination / high energy muons
  - Long solenoids from production to muon stopping target
  - Curved solenoid with dipole corrector to select momentum / charge
- Solenoid field for spectrometer
  - Large aperture for detectors

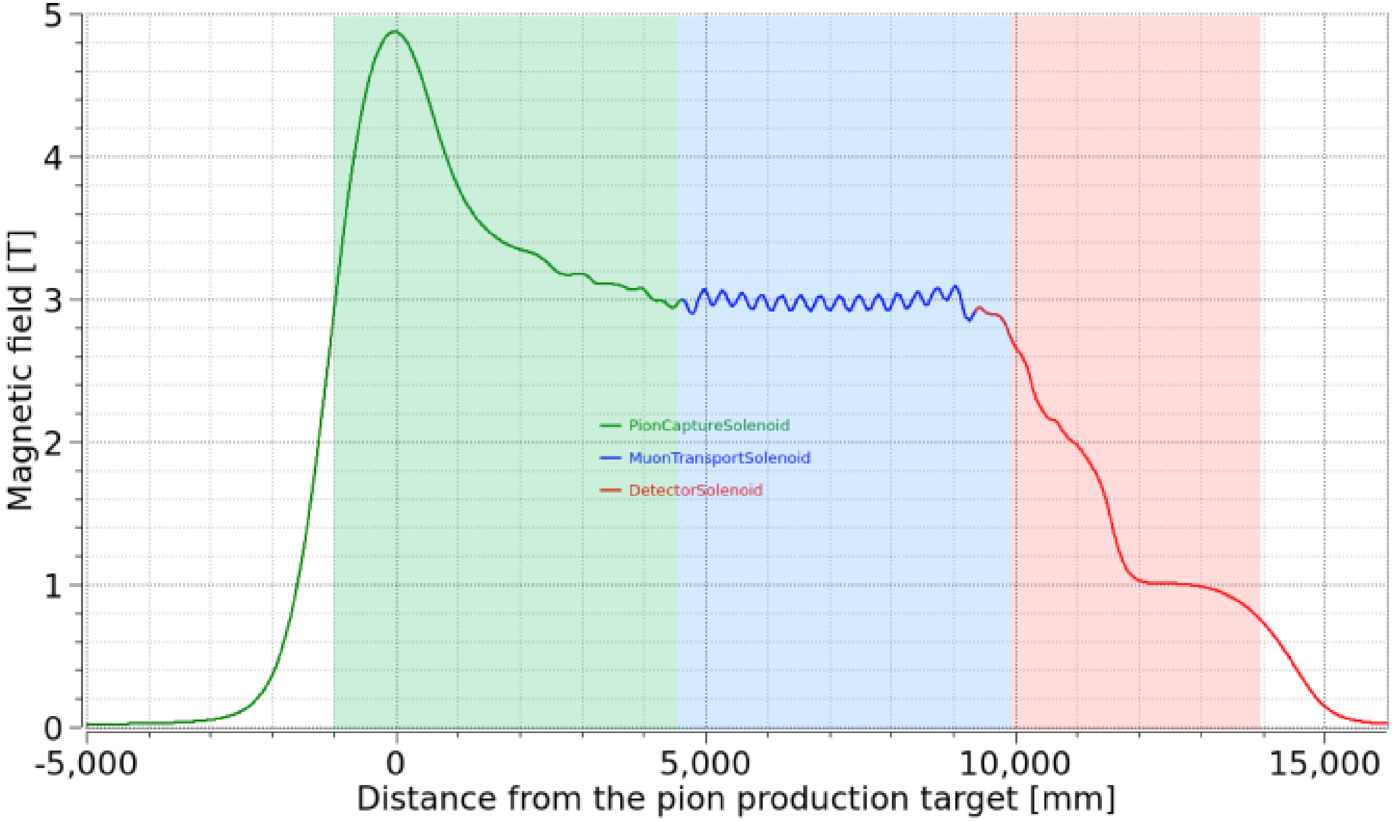
Magnetic Field Design (COMET phase-1)

- Pion Capture Solenoid
  - *5T on Target embedded in magnet bore*
- Muon Transport Solenoid
  - *3T curved solenoid*
  - *Correction dipole max. 0.07T*
- Detector Solenoid

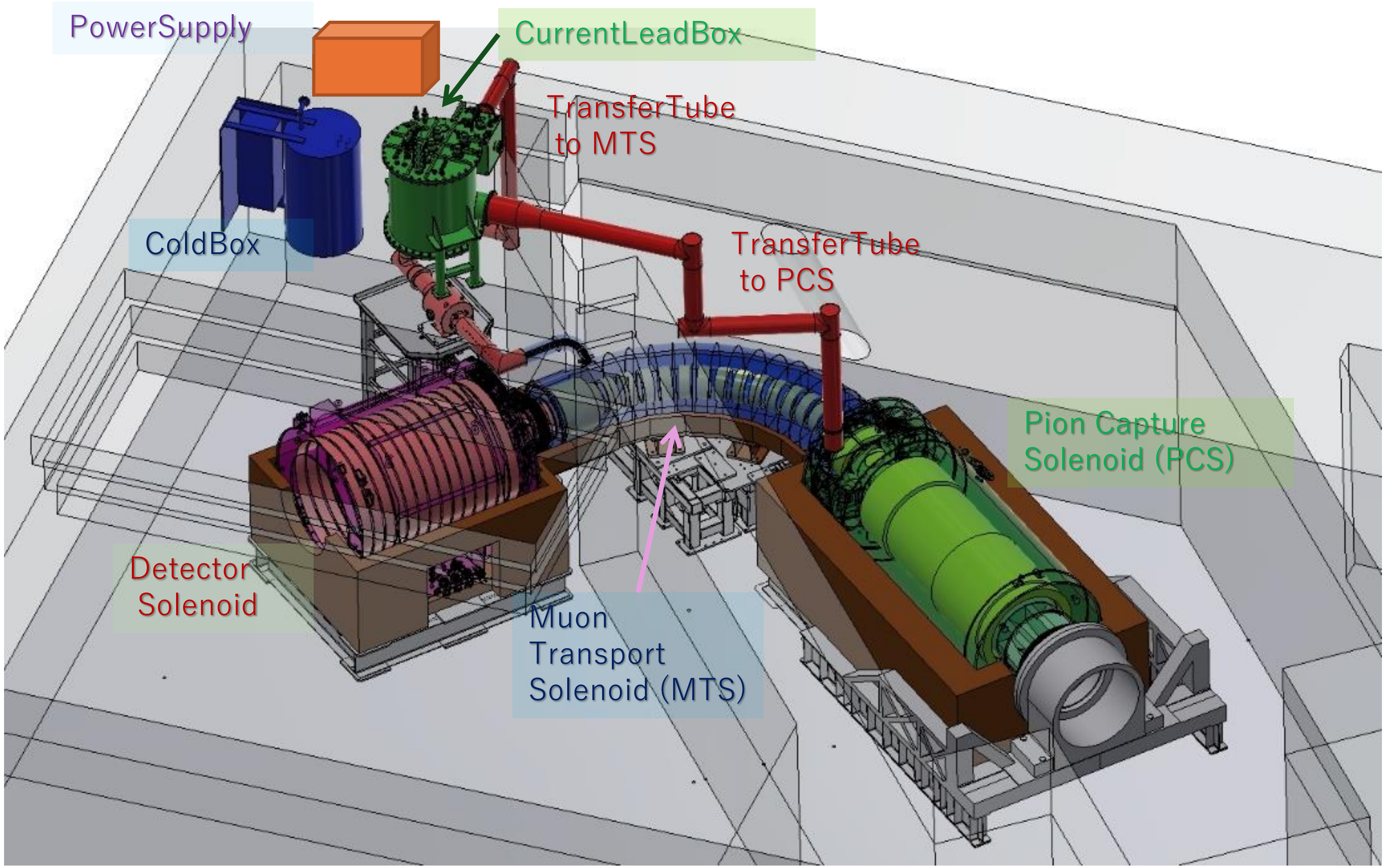
  +Bridge Solenoid
  - *graded field from 3T to 1T*



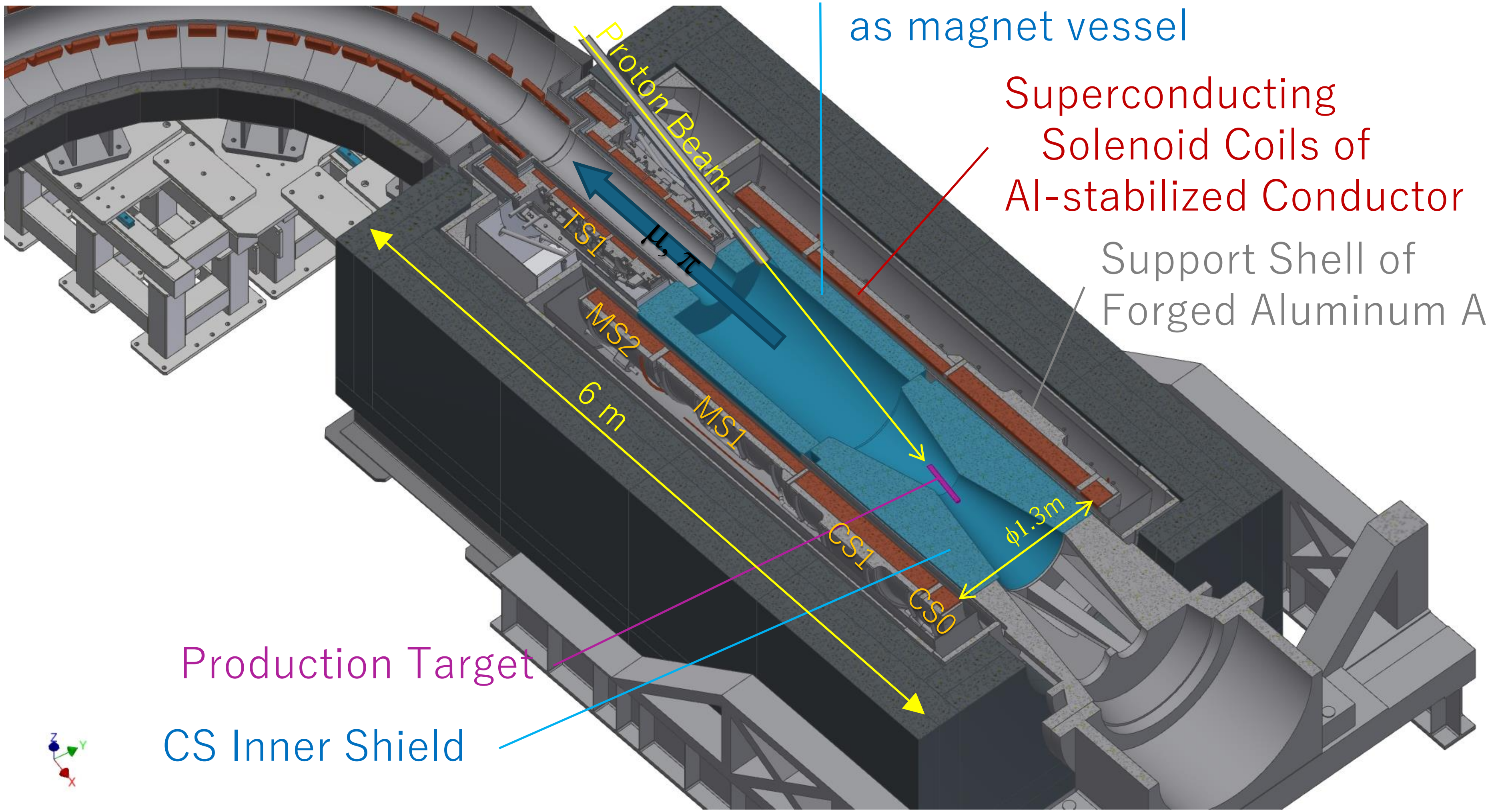
COMET Magnetic field along the muon beam axis



Superconducting Magnet System for COMET Phase-1



COMET Pion Capture Solenoid

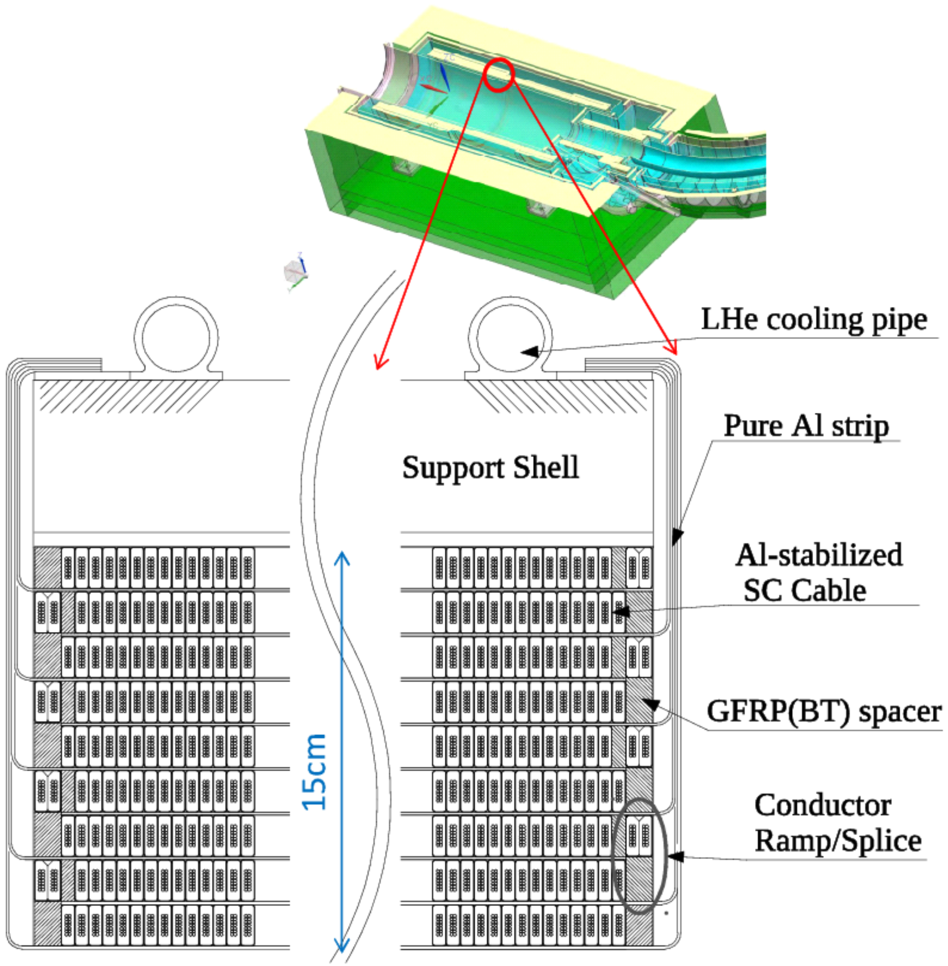


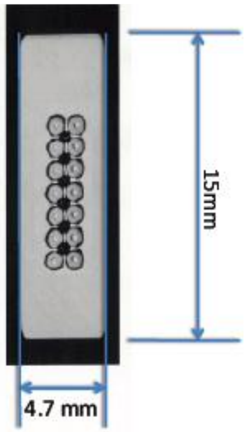
Coil Structure

- Aluminum stabilized SC cable
  - for less nuclear heating
- Radiation resistant insulator, resin
  - Polyimide film, Bismaleimide-Triazine resin
  - Boron-free glass in GFRP
- Pure aluminum strips in between layers
  - to cool down a coil inside

DESIGN PARAMETERS OF CAPTURE SOLENOID MAGNET

Item	Value
Conductor	Aluminum stabilized SC cable Al/Cu/NbTi = 7.3/0.9/1
Cable dimensions	15.0 × 4.7 mm^2 (without insulation) 15.3 × 5.0 mm^2 (with insulation)
Cable insulation	Polyimide film/Boron-free glass cloth/BT-Epoxy prepreg.
Magnet length	~6 meters
Num. of coils	10
Operation current	2700 A
Max. field on conductor	5.5 T (T_{cs} = 6.5 K) [a]
Stored energy	47 MJ
Coil inner diameter	1324 mm (CS0~MS2) 500 mm (TS1a~TS1e) 800 mm (TS1f)





Al stabilized SC cable

- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

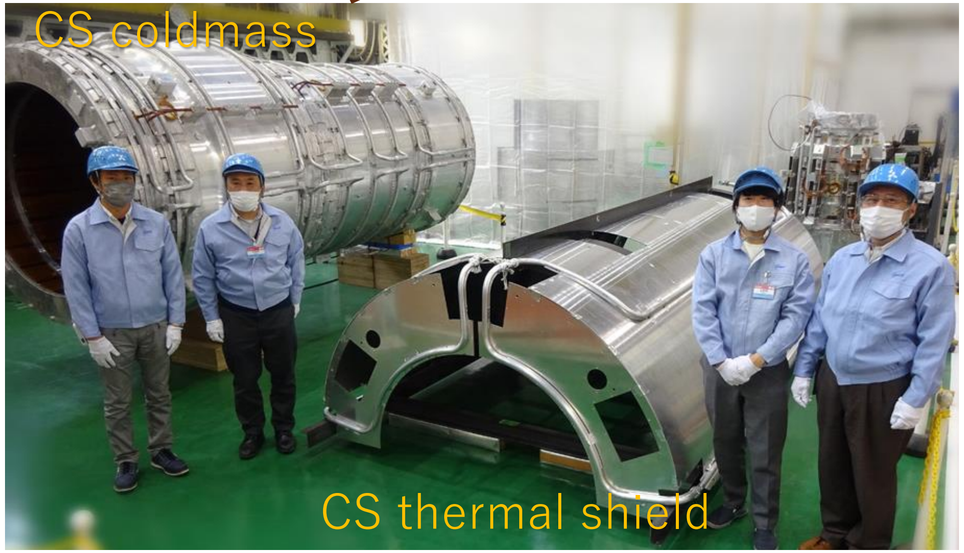
Coldmass Fabrication

Support shell of forged A5083

heat curing

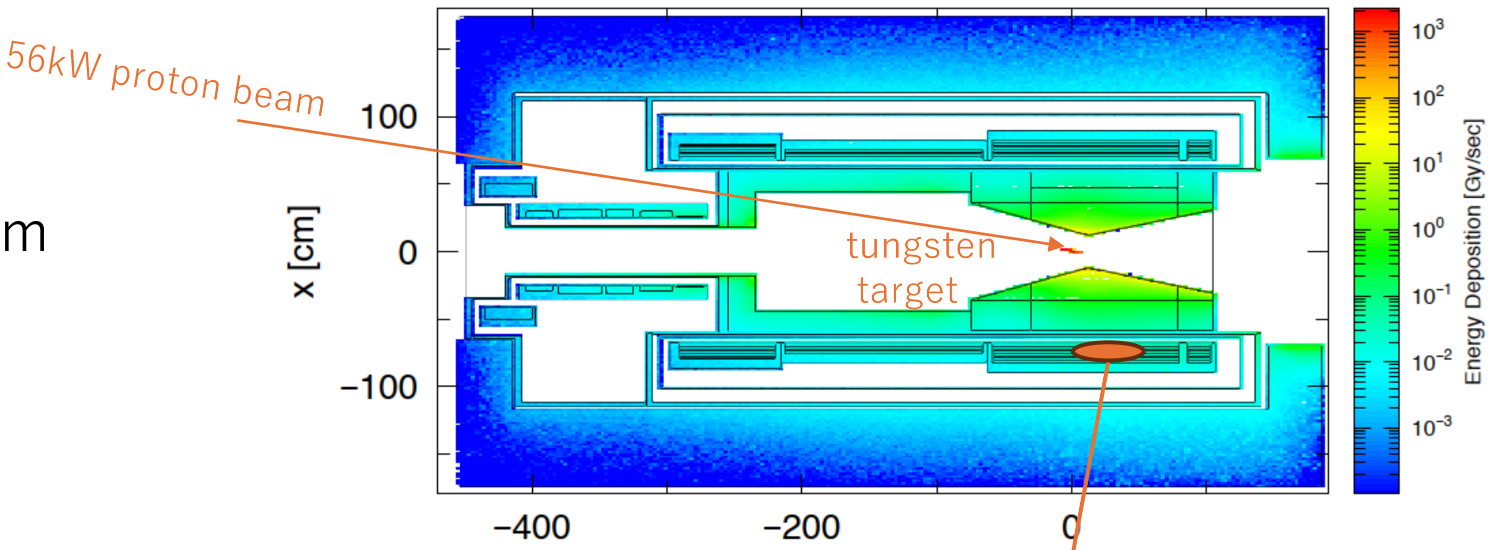
Impregnation with BT+Expoxy

Wet winding with BT+Epoxy resin

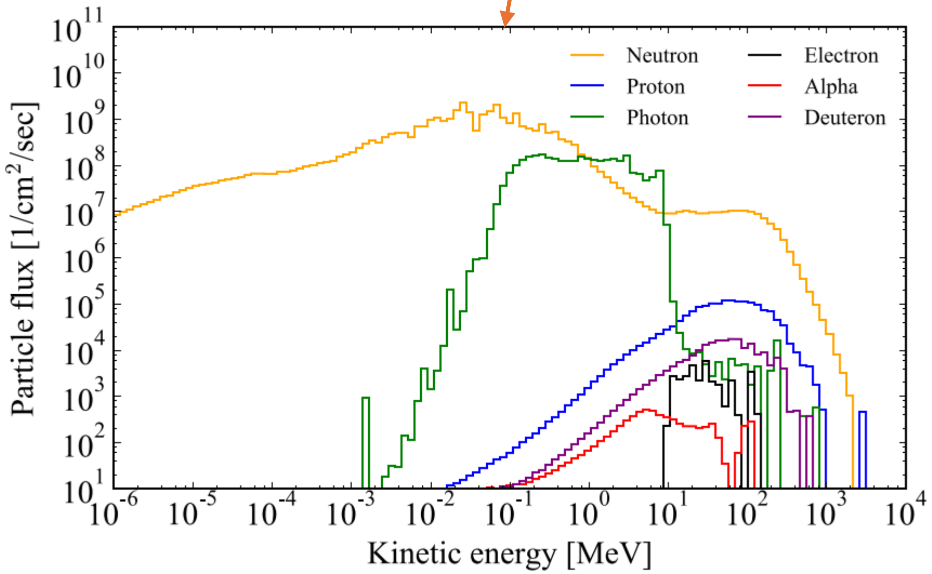


Radiation Environment for Pion Capture Solenoid

- COMET Phase-2
  - 56kW 8GeV proton beam
  - Tungsten target
  - Tungsten shield

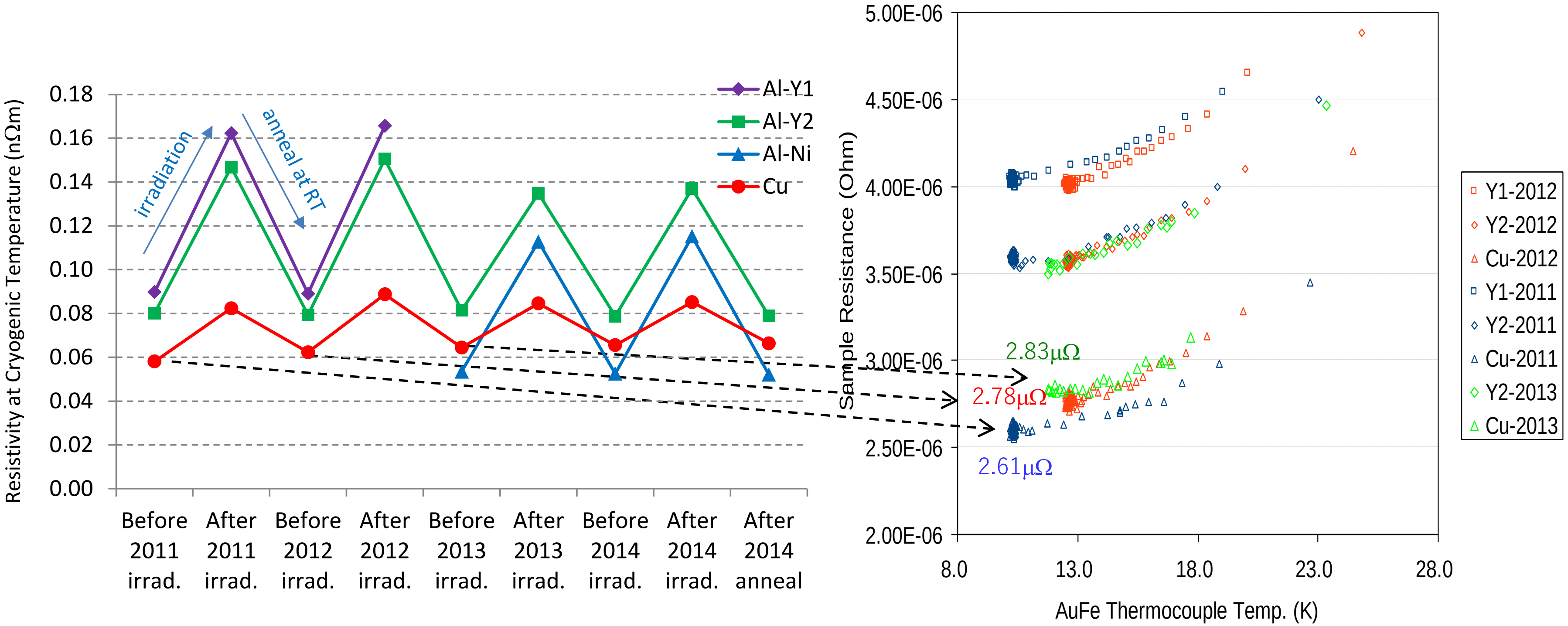


- Peak heat deposit
  - ~40 mW/kg
    → 1MGy for 300day operation
- Peak neutron flux
  - ~4×10^{14} n/m^2/s
    → 10^{21} n/m^2 for 30day operation



Radiation-tolerant magnet is mandatory

Neutron Irradiation / Annealing Effect in Electrical Resistance of Stabilizer

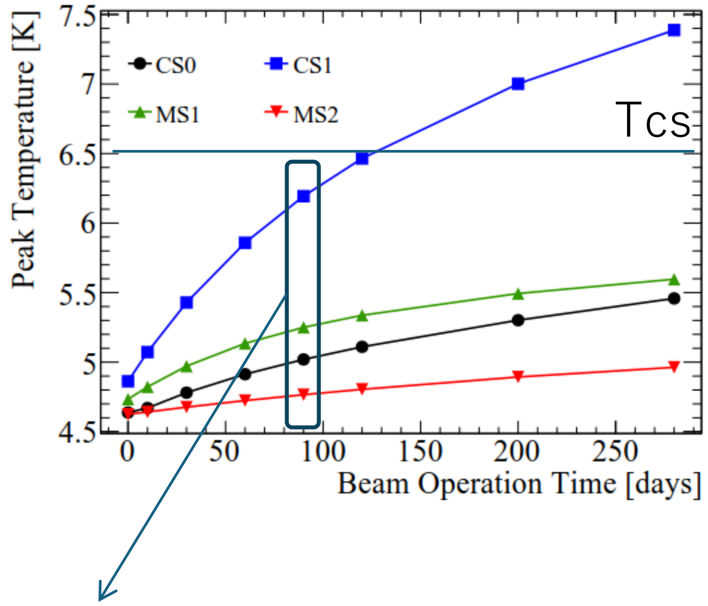


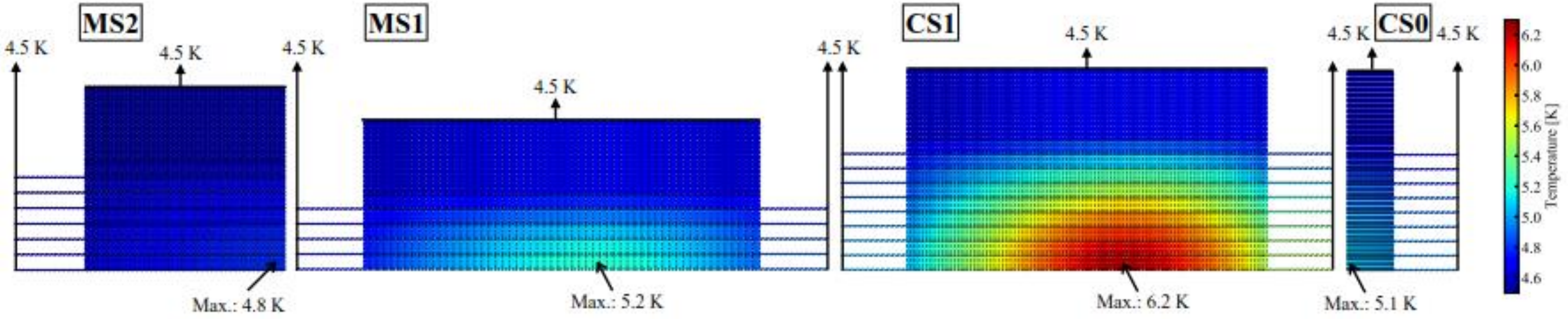
- Al: 0.03 nOhm.m for 10^{20} n/m^2
- Cu: 0.01 nOhm.m for 10^{20} n/m^2
- All Al samples show "full" recovery of electrical resistivity after thermal cycle to RT.

"Repetitive Irradiation Tests at Cryogenic Temperature by Neutrons and Protons on Stabilizer Materials of Superconductor," M. Yoshida et al., *IEEE Trans. Appl. Supercond,* 32(6), 7100405 (2022); doi:10.1109/TASC.2022.3178944

Coil Temperature during Beam Operation (phase-2)

- Simulation including heating by irradiation
- Peak temperature in coil is estimated assuming irradiation by 56kW beam operation
- Temperature will rise as thermal conductivity degrades by irradiation
- Irradiation damage in aluminum can be recovered perfectly by thermal cycling to room temperature.

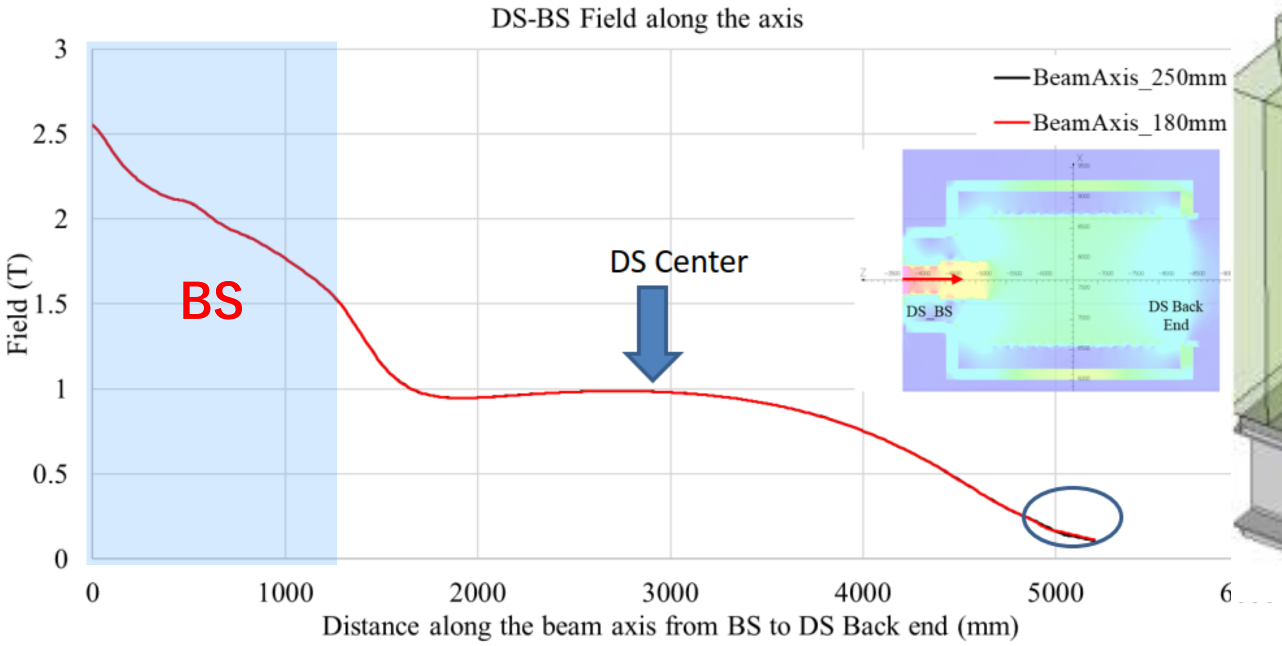


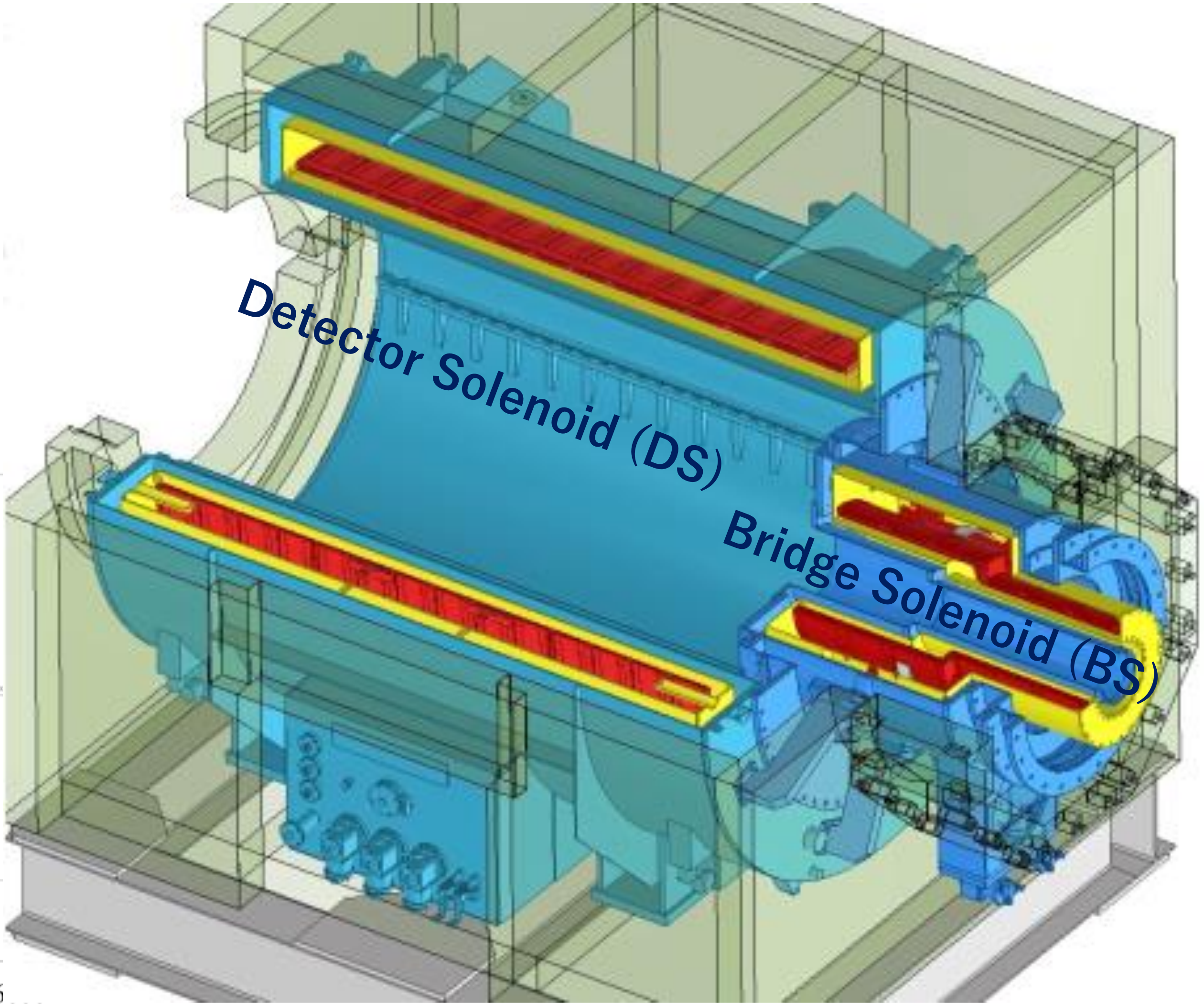


Y. Yang et al., IEEE Trans. App. Supercond., 28(3), 4001405 (2018).

DSBS assembly

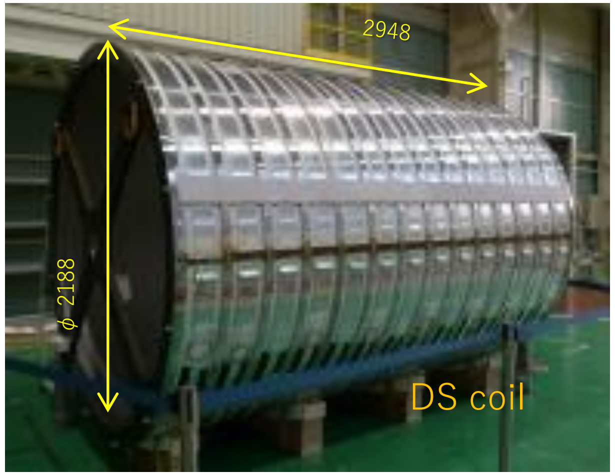
- Field bump between MTS and DS can be tuned by BS

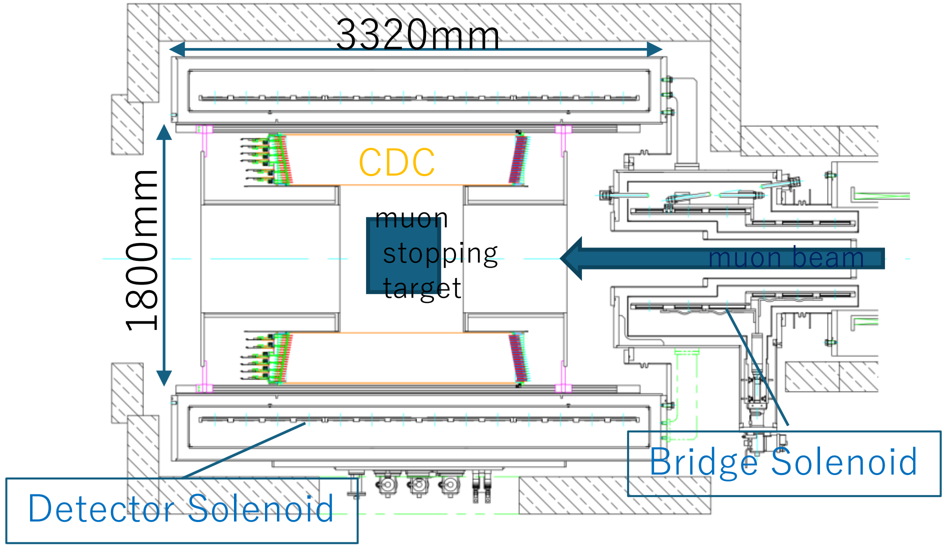




Detector Solenoid

- 1 Tesla on the muon stopping target
- Large aperture for CDC and trigger hodoscope
- Cyogen-free magnet
  - Cooled by 3 GM cryocoolers



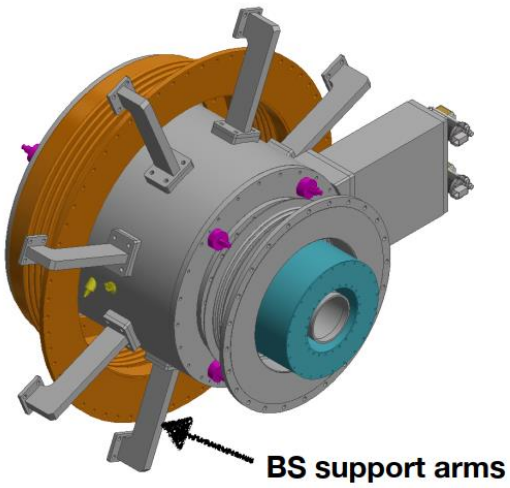


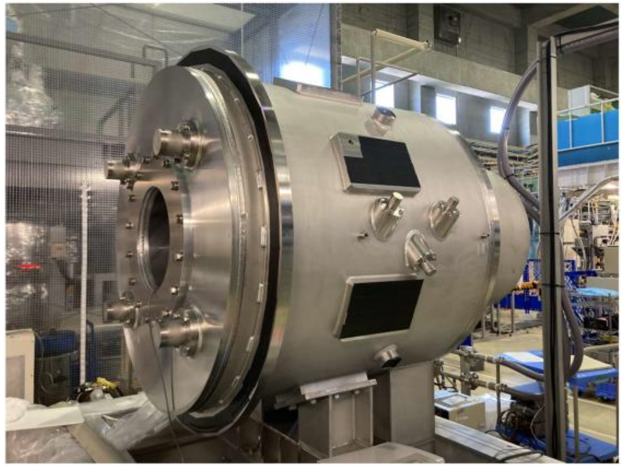
SPECIFICATION OF THE BRIDGE SOLENOID AND DETECTOR SOLENOID

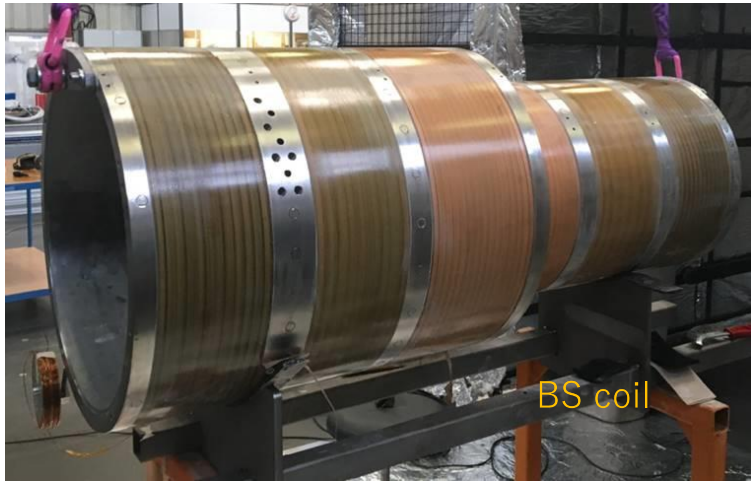
	Bridge Solenoid	Detector Solenoid
Conductor	NbTi/Cu monolith wire Cu/NbTi = 4	
Strand dimensions	ϕ1.2 mm (without insulation) ϕ1.3 mm (with insulation)	
Cable insulation	PVF	
Coil inner diameter	460, 620 mm	2140 mm
Total coil length	1.4 m	2.9 m
Operation current	155 A	189 A
Magnetomotive force	1.9 MAT	2.5 MAT
Field on axis	3 T - 1 T	1 T
Inductance	29.1 H	236 H
Stored energy	0.35 MJ	4.2 MJ
Refrigeration	conduction cooling by GM 2 × 1.5W	conduction cooling by GM 3 × 1.5W
Quench protection	external dump resistor	semi-active quench back heater

Bridge Solenoid

- To be installed between DS and MTS
- Magnet vessel is mounted on DS end flange, due to space limitation
- Need supports for large magnetic force and vacuum sealing
  - 200kN with DS,MTS
  - 430kN with MTS
  - 240kN with DS







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COMET SCM Summary

- Superconducting Magnets
  - Capture Solenoid
    - Construction completed
    - Soon to be installed to the experimental hall
    - Connection to the cryogenics and cold testing in next year
  - Transport Solenoid
    - Construction and Installation Completed
    - Cold testing and field measurements also completed
  - Bridge and Detector Solenoid
    - Construction completed
    - Now waiting for installation

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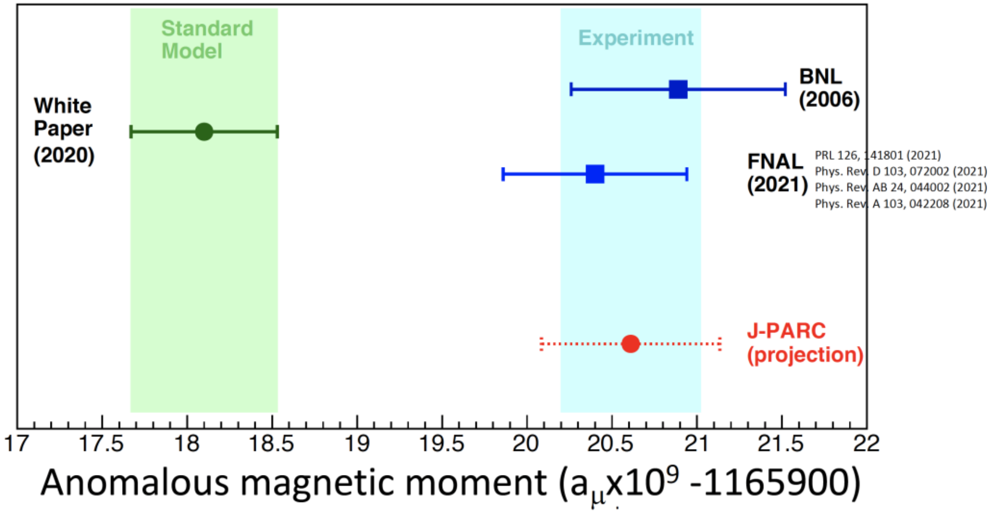
- Being proposed
  - MLF 2nd Target Station

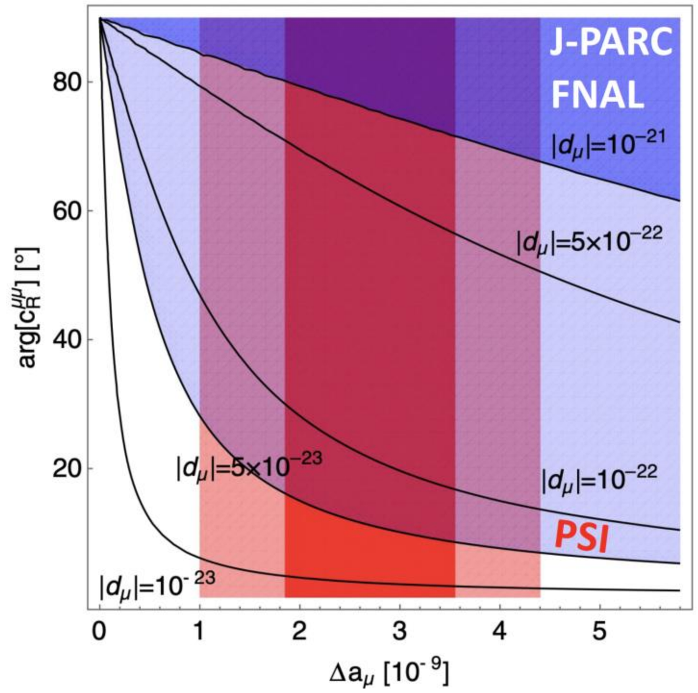
Background

- Muon anomalous magnetic moment (g-2)
  - 5.0 σ discrepancy between FNAL measurement and prediction
  - Measurement (FNAL): 116 592 055(24) × 10-11 (200 ppb)
  - SM prediction : 116 591 810(43) × 10-11 (370 ppb)
  - Can be a contribution from new physics
- Muon EDM
  - Upper limit given by BNL : 1.8 × 10-9 e・cm (95% C.L.)
  - EDM and g-2 can be induced by the same new physics



$$c_R^{\mu\mu} = -\frac{e}{4m_\mu}a_\mu - i\frac{1}{2}d_\mu$$

A. Crivellin et al., PRD 98, 113002 (2018)



muon g-2/EDM measurements

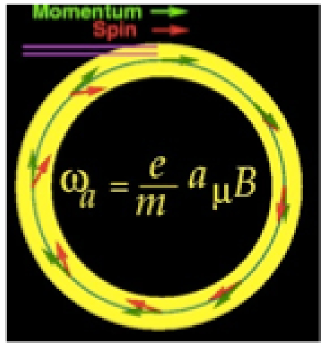
Anomalous magnetic moment (g-2)

a_μ = (g-2)/2 = 11 659 208.9 (6.3) x 10^{-10} (BNL E821 exp) **0.5 ppm**

11 659 182.8 (4.9) x 10^{-10} (standard model)

Δa_μ = Exp - SM = 26.1 (8.0) x 10^{-10} **3σ anomaly**

In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0



general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL E821 approach
γ=30 (P=3 GeV/c)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Continuation at FNAL with 0.1ppm precision (E989)

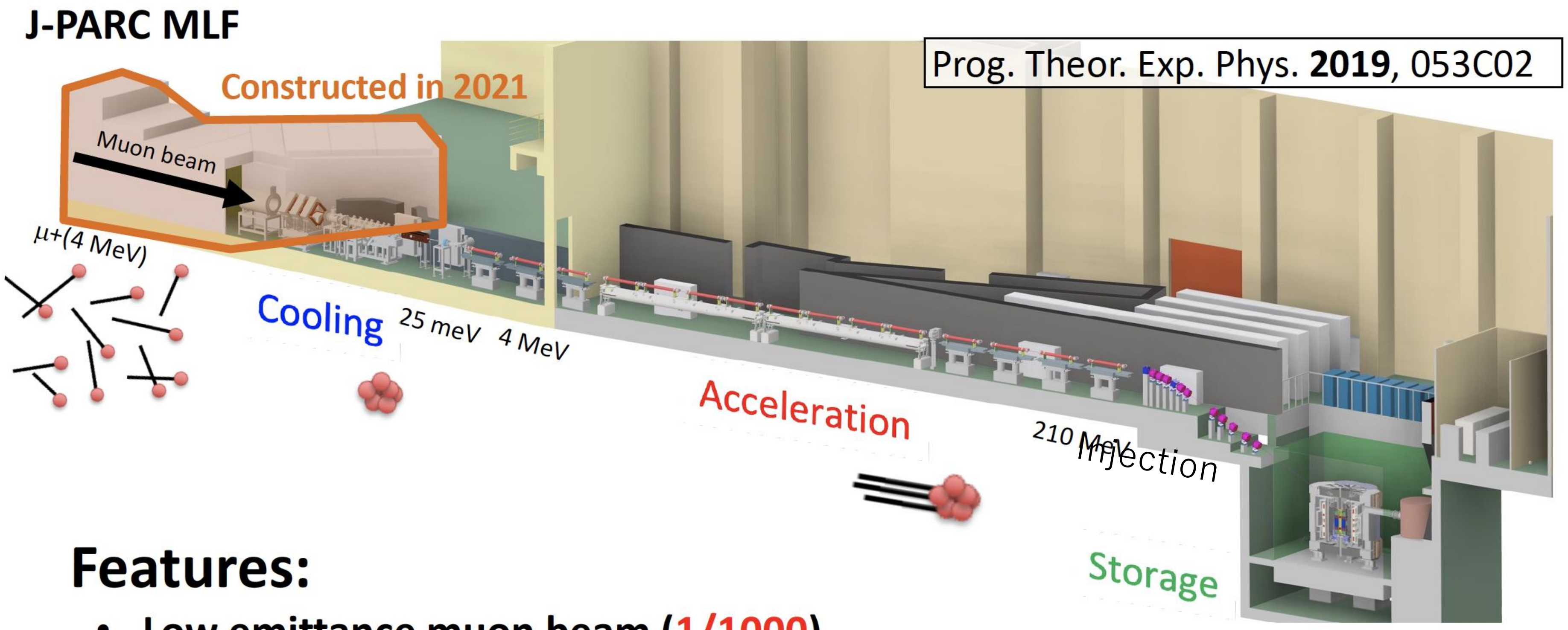
J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

Proposed at J-PARC with 0.1ppm precision (E34)

Slide by Mibe

J-PARC muon g-2/EDM experiment



Features:

- Low emittance muon beam (1/1000)
- No strong focusing (1/1000) & good injection eff. (x10)
- Compact storage ring (1/20)

The only experiment to check FNAL/BNL *g*-2 results

Excellent sensitivity to **muon EDM** about **100 times** better than the previous limit (sensitivity : 1.5 E-21 ecm)

Muon storage magnet ~ SC solenoid

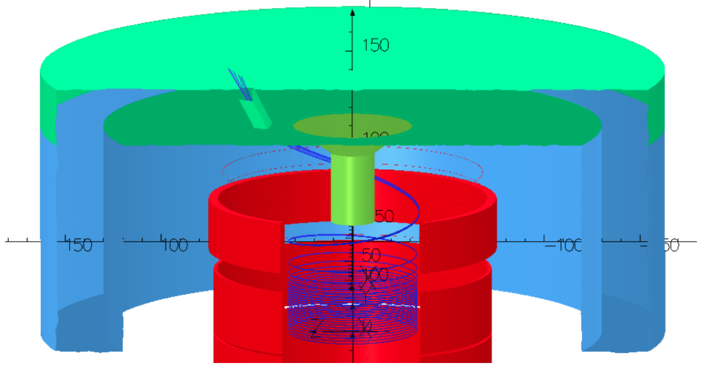
- Important requirement for muon storage region
  - Storage region :
    - radius : 33.3±5.0 cm
    - height : ±10 cm
  - Field strength 3 T
  - Spatial and temporal homogeneity : ±0.1 ppm

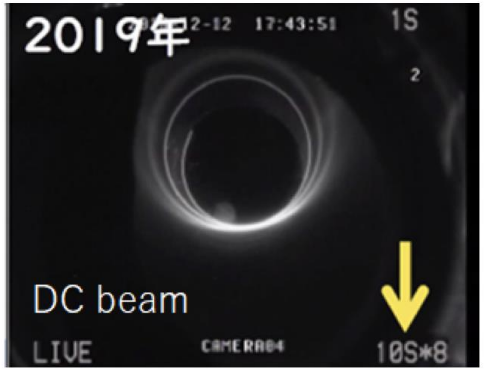
MRI magnet technology !

- <u>How to inject muons to the storage region in the center of SC solenoid</u>

Spiral injection scheme

- Inject the beam from magnet end
- Spirally down to magnet center
- Apply vertical kick field to the beam around magnet center (storage region)
- Apply weak focus field to store the beam in to the storage region





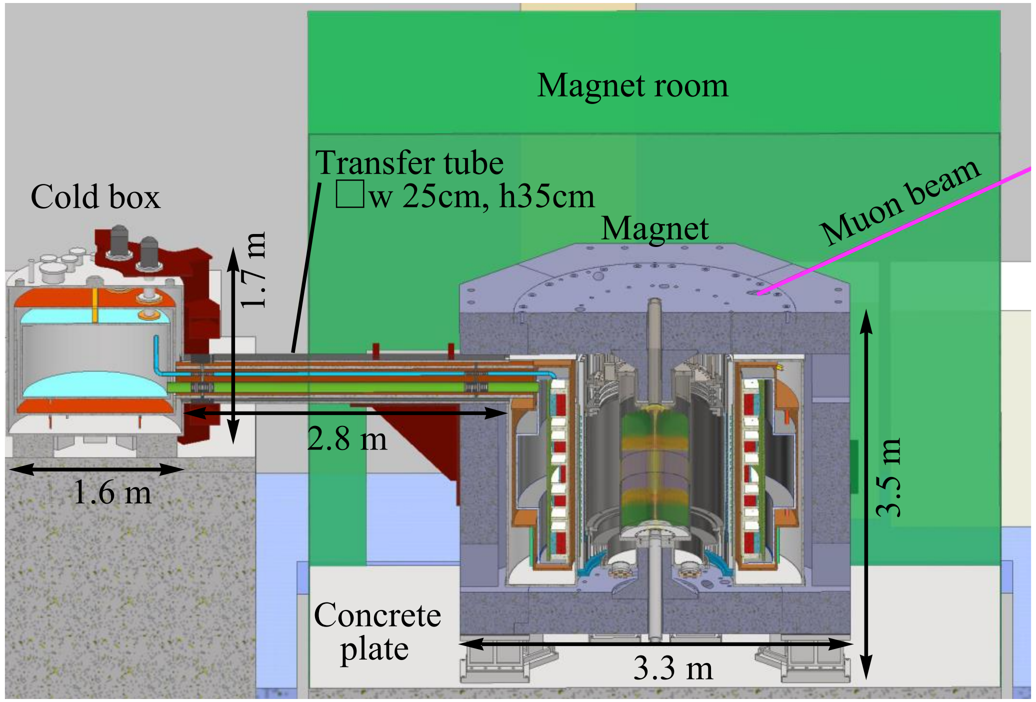
Demonstration of spiral injection with DC beam ->

Specifications

- Storage region :
  - radius : 33.3±1.5 cm, height : ±5 cm
  - Field strength : 3T
  - Bz uniformity : ±0.1 ppm (Azimuthal integral)
- Injection region :
  - Smooth field for beam injection
- Weak focus field:

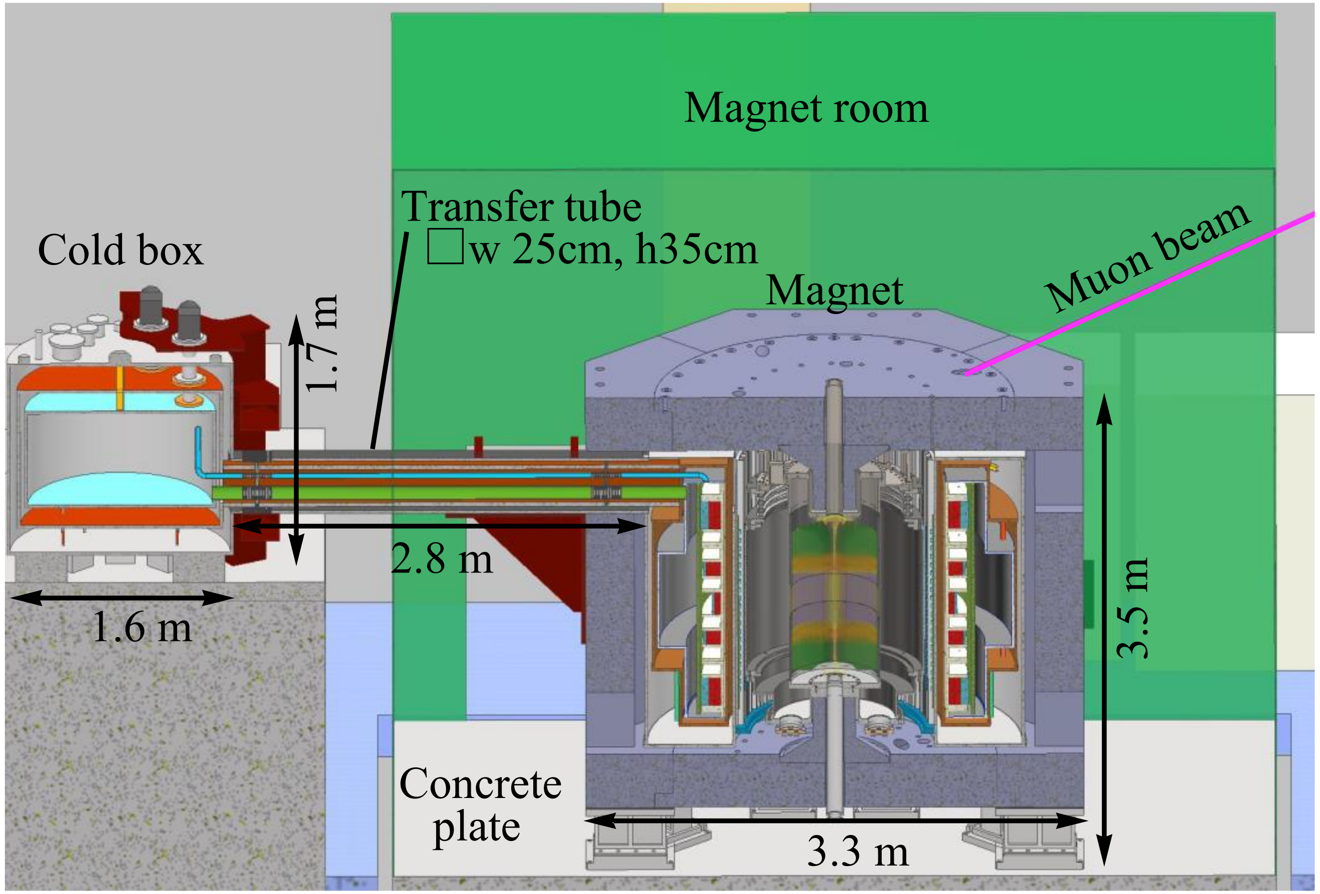
$$B_r = -n\frac{B_{0z}}{R}z$$

n: $1.0\times10^{-4} – 2.0\times10^{-4}$



Overall Design

- Superconducting coils : NbTi
  - Main solenoid coil
    - Persistent current operation
  - Weak focusing coil
    - Power supply operation
  - Shim coils
    - Power supply operation
- Field tuning system using iron pieces
- Iron yoke
  - Adjust field shape
- Cooled by liquid Helium
  - Cryocoolers to recondense LHe
- Separated cold box from magnet cryostat
  - Isolate vibration
- Vibration isolation/control system



Main coil parameters

- 5 coil blocks

DIMENSIONS OF MAIN COIL BLOCKS

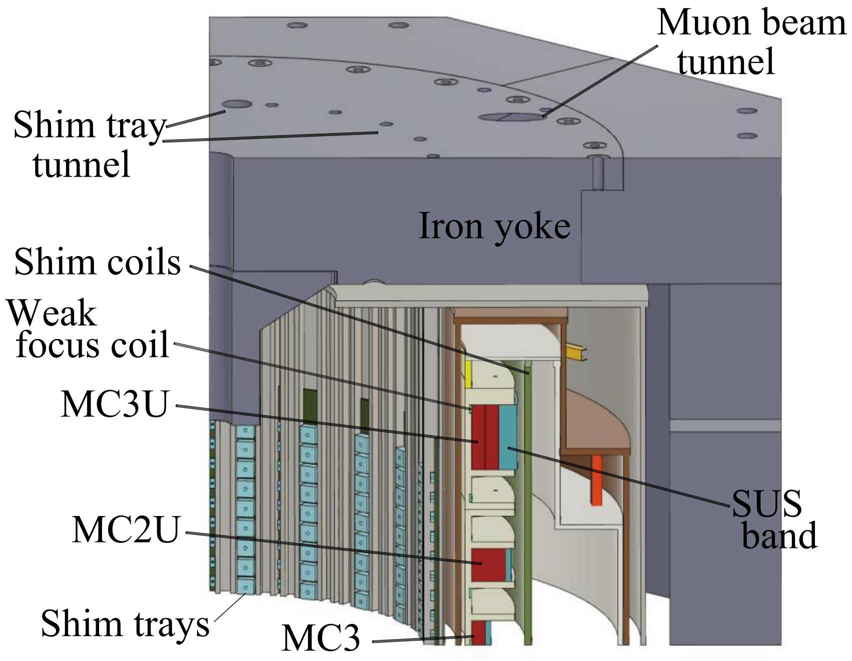
	MC1U/MC1L	MC2U/MC2L	MC3
Inner radius	801.5 mm	801.3 mm	799.6 mm
Width	54.9 mm	53.9 mm	33.5 mm
Coil center z position	+/-632.7 mm	+/-228.5 mm	0 mm
Height	235.6 mm	96.9 mm	114.5 mm
Turns/Layers	107/36	44/36	52/22
Peak B field	5.4 T	4.6 T	3.9 T
Hoop stress	1.3e7 N	5.0e6 N	3.8e6 N

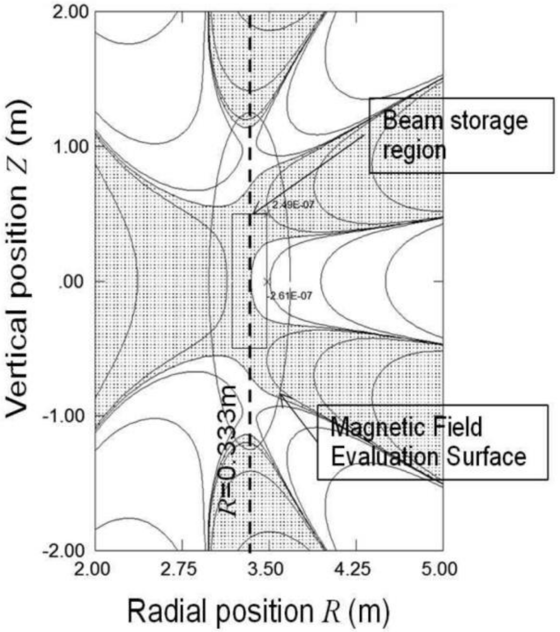
MAGNET MAIN PARAMETERS

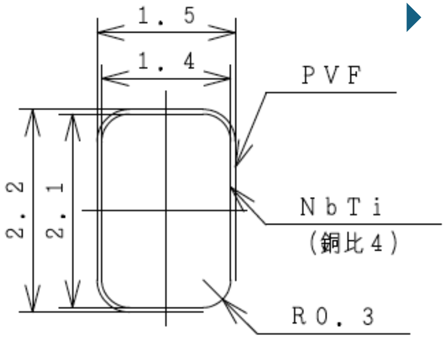
Item	Value	Unit
Nominal central field	3.0	T
Nominal current	417.5	A
Stored energy	14.6	MJ
Inductance	166.9	H
Peak field on strand	5.4	T

Total weight~150 ton

*Persistent current operation







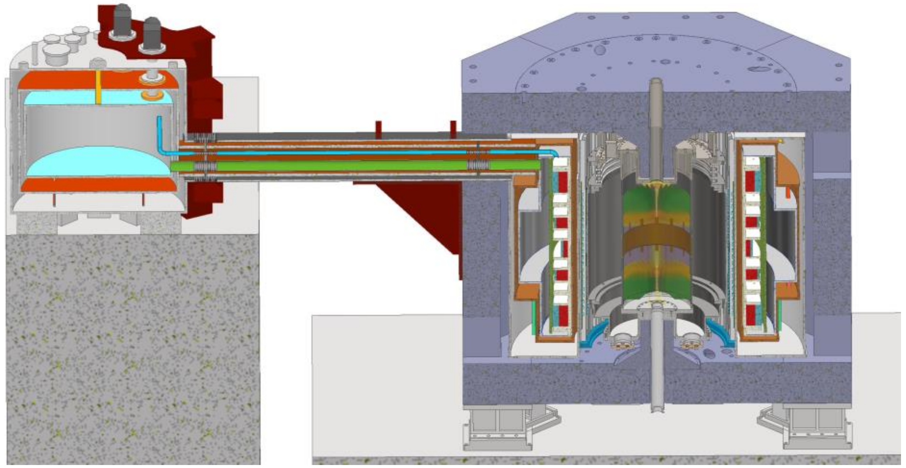
- SC strand
  - NbTi with Cu Stabilizer
  - Cu/Sc = 4
  - Cu RRR ~100
  - Load line :~65%
- Expected homogeneity <u>*±0.085 ppm*</u>

Cryogenics

- Basic concept
  - LHe pool boiling
  - GHe re-condensation system
  - Cold box with GM cryocooler separated from magnet
  - Open dewer (GHe recovery)

<- Temperature stability

<- Vibration damping

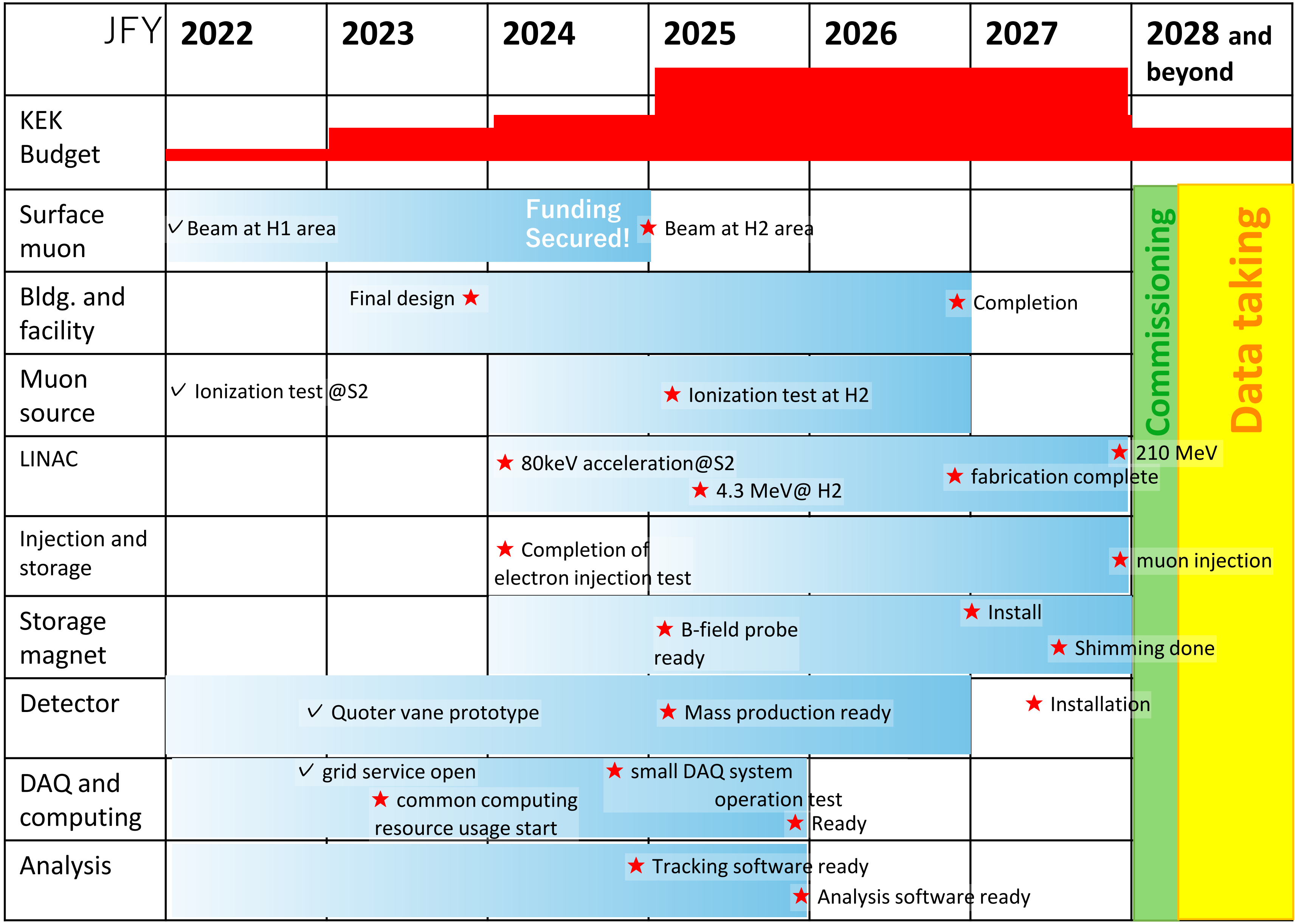


Other conditions

- Main coils : persistent current mode
- Weak focus coil and shim coils
  - driven by individual PS
  - 100 A HTS lead x 2
  - 10 A HT lead x 24

- Cryocoolers
  - 2 stage 1.8W GM : ~4
  - 1 stage 160W GM : 1

Schedule (Mar. 2024)



✓ might be delayed, depending on budget approved by government

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  - **MLF 2nd Target Station**

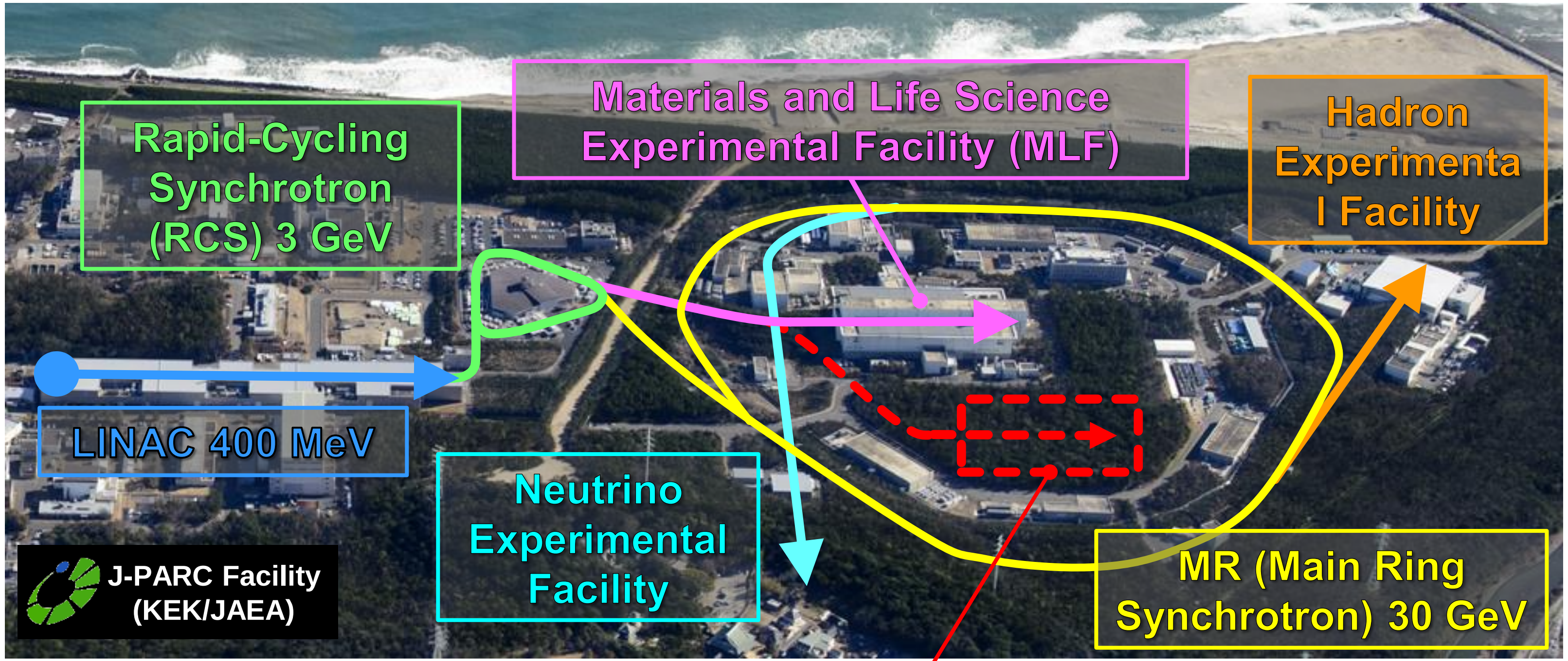
J-PARC MLF 2nd Target Station TS2

TS2-Pion Capture Solenoid

(10 years operation)

- Heat Deposit: **~450 W**
- Neutron fluence: **7.8 x 10^{21} n/m^2**
- Absorbed Dose: **> 100 MGy**

Requirements for operation in high radiation environments



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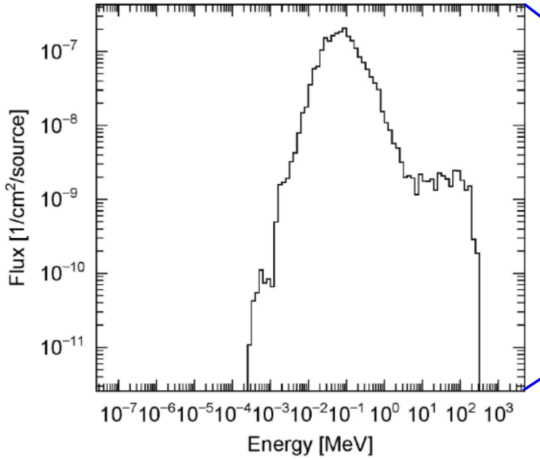
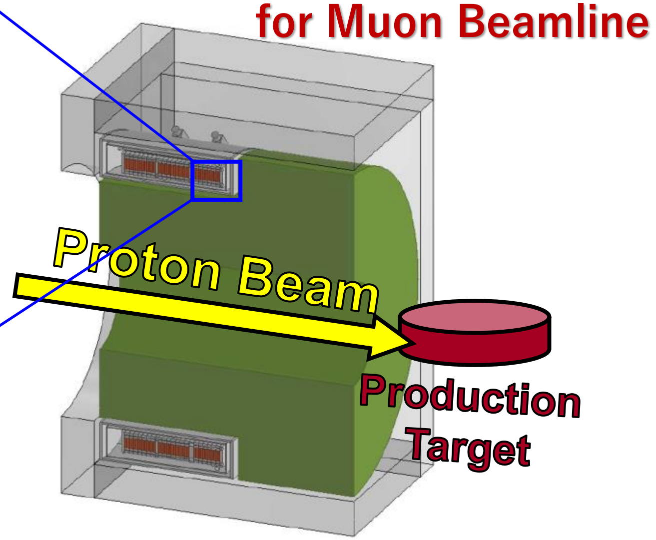
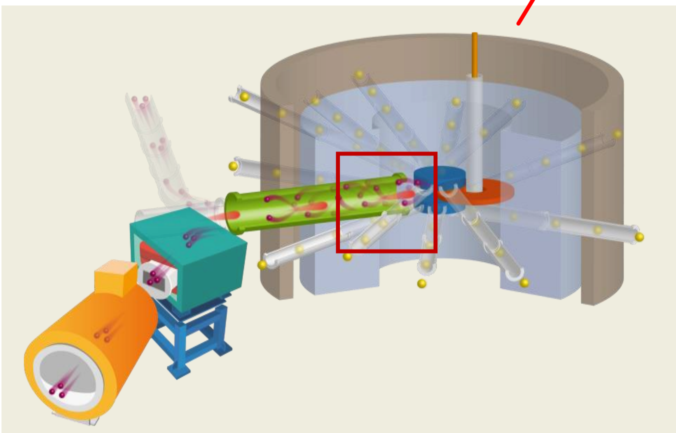
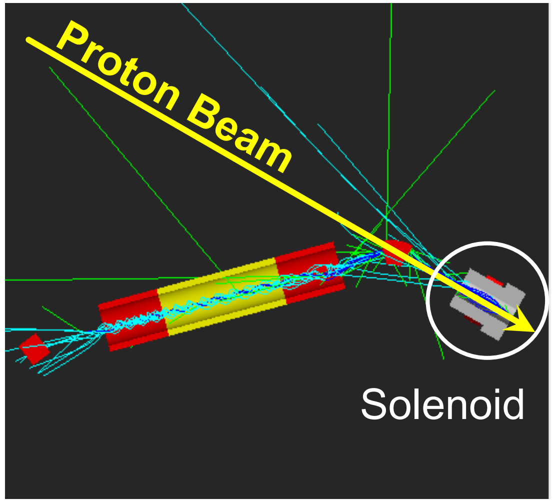


AVG. flux at the top 100 mm of the coil

Pion Capture Solenoid (PCS) for Muon Beamline







Simulation for muon beam transportation

Challenging issue 1: Conductor

- It is difficult to maintain the 5K temperature range of the LTS conductor under a heat load caused by nuclear heat of over 450 W.

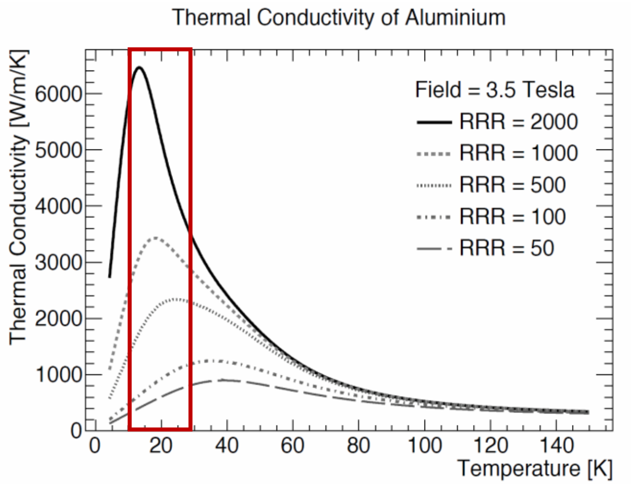
REBCO coated conductor

High temperature margin (T_C=93 K)

- Conduction cooling operation in the temperature range of 20 K

High magnetic field tolerance of Ic

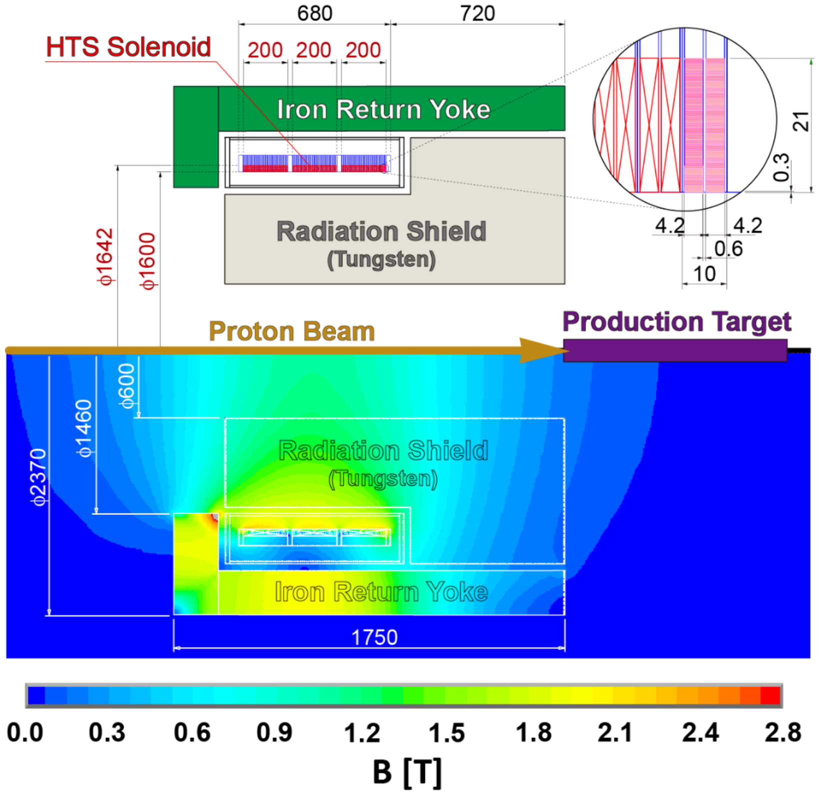
- Potential for 20T class high field magnet



R&D have been performing to realize a conduction-cooled solenoid at 20K based on REBCO conductors.

Stack of double pancake coil

- ID=1600 mm, T=21 mm, L=10 mm, **70** turns/layer
- Number of double pancake coils: **60** (20 x3)
- Conductor : **REBCO**, W=4 mm, T=0.1 mm
- Insulation: Mineral, t=0.1 mm
- Operation Temperature: **20 K** (He gas cooling with pipe)
- Transport current: **200 A** (Load line ratio: 0.48)
- Peak Field: **1.11 T** at center, **2.25 T (B//c)** at coil (200 A)



Design case study of conductor and magnet

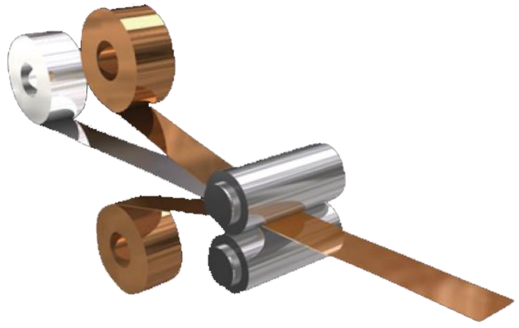
- TS2-solenoid quench protection is difficult due to its large inductance (~36 H)

Conductor Width	mm	12.0	**6.0**	4.0
Operating Current	A	1200	**600**	400
Allowable coil voltage	V	500	**500**	500
Inductance	H	4	**16**	36
Dump Resistor	W	0.42	**0.63**	1.25
Decay Time Constant	sec	9.6	**19.2**	28.8
Quench detection time	sec	1.0	**1.0**	1.0
Current Square Integral	$MA^2.s$	8.4	**3.8**	2.5

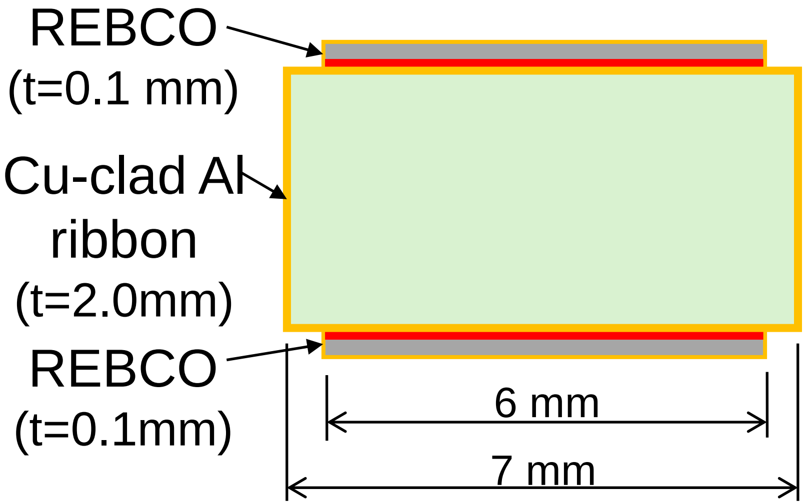
KEK has begun development of REBCO conductors with increased stabilizer content

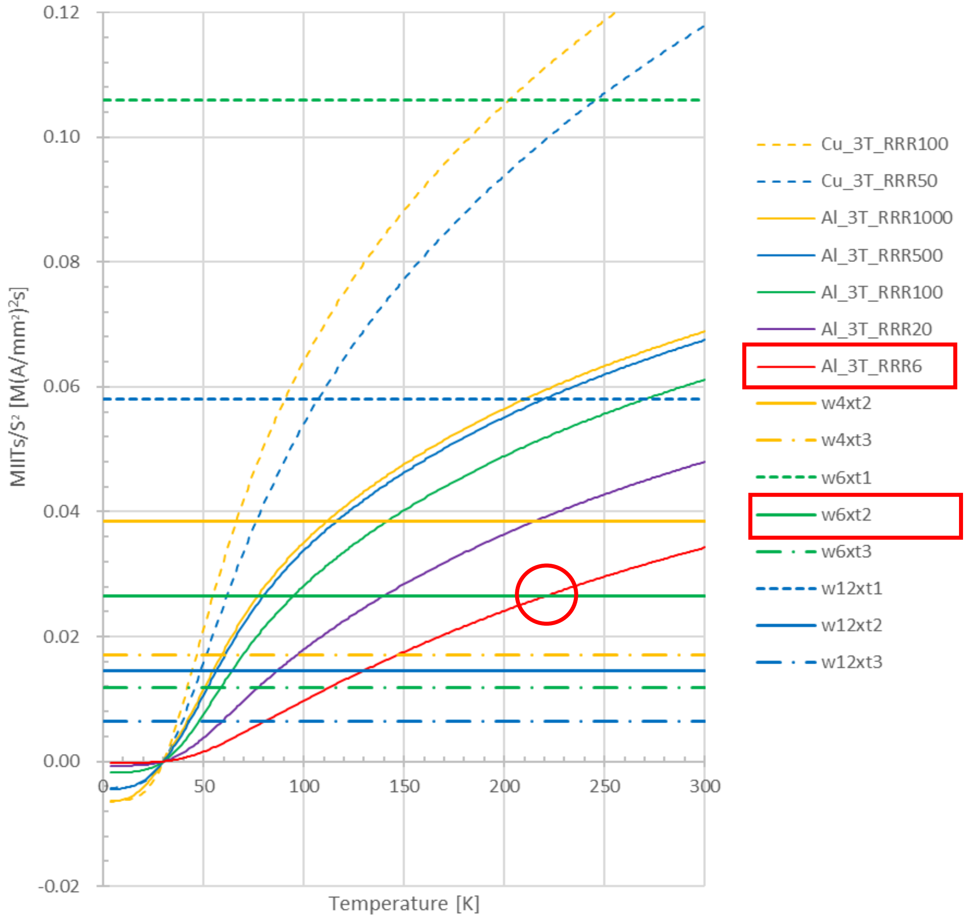
Al-stabilized HTS conductor

- Integration REBCO tapes and CCA ribbon by soldering
- REBCO tapes with their superconducting layers facing each other



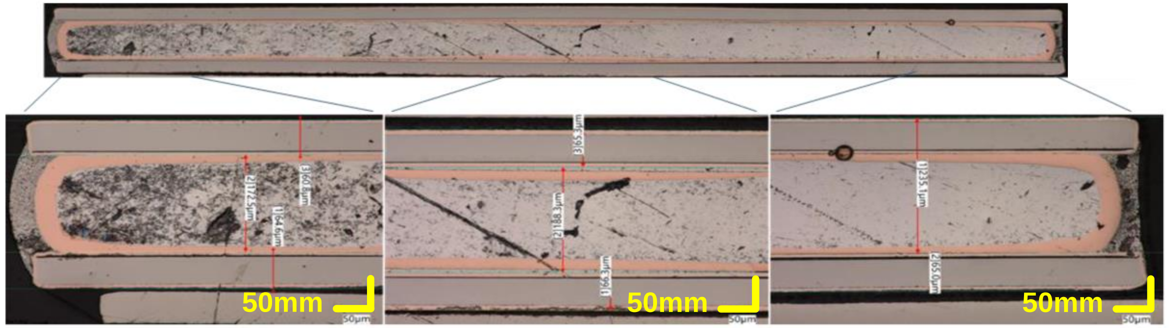
Copper-clad Aluminum (CCA)



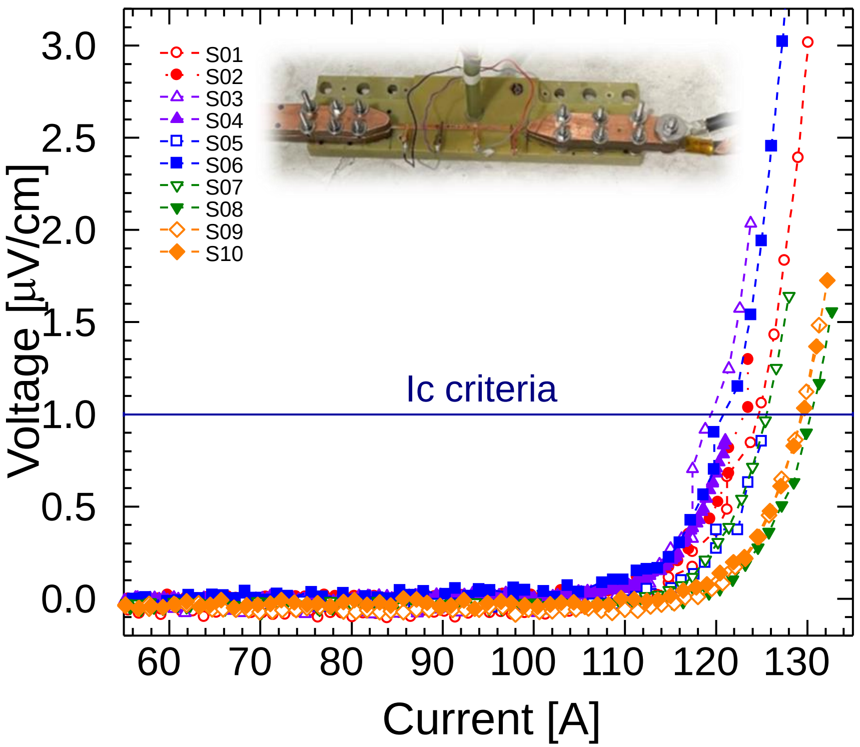


Jointing test on short samples

- CCA flat wire : **0.17 mm thick, 4 mm wide**
  (T_{Cu}=0.015-0.02 mm, Al: 8030 Alloy)
- REBCO: YBCO with AP **x2**
  (SCS4050HM, W4mm, **Ic= 70A**)
- Joint length: 200 mm
- Temperature conditions:
  195℃-2min / 210℃-2.5min / 220℃-4min
- No. of trials: **39** **(25 successes / 14 failures)**



- ☐ REBCO and CCA are successfully joined by soldering
- ☐ All 17 failures are caused by the tilt of the press jig
- ☐ I_C decrease of about 20% has been observed
- ☐ Mechanical testing is underway
- ☐ After further short sample Jointing tests, long tapes will be tried with reel to reel system

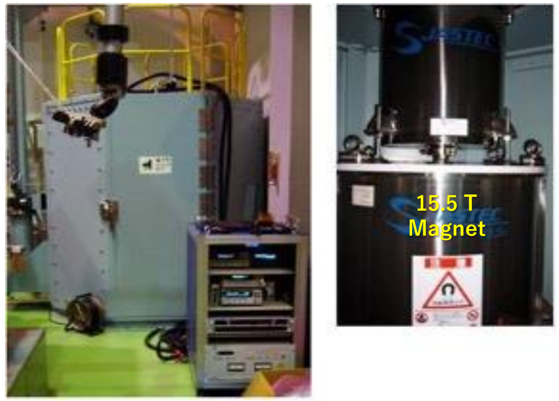


MLF TS2 Summary

- MLF Second Target
  - Now under consideration
  - First proposal is intensively discussed
  - Basic technology research for superconducting magnet is started
    - HTS solenoid under high radiation environment
    - Aluminum stabilizer for quench protection
    - Radiation hardness of the magnet
      - Irradiation tests of various HTS conductors
      - Development of inorganic insulation

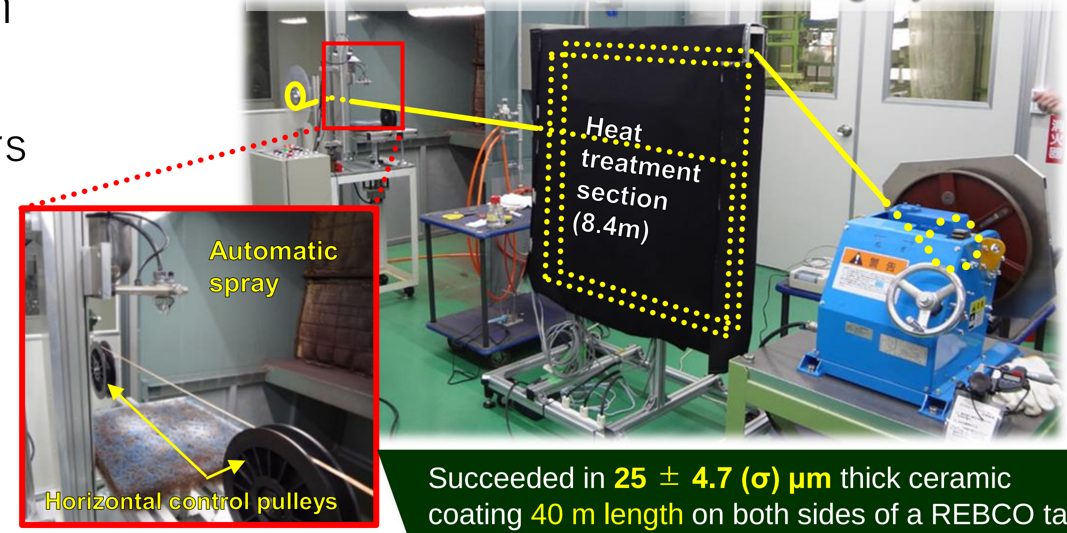
HTS Irradiation Effect Measurements

BR2 @Belgian nuclear research center



Ic Measurement Magnet in Hot Lab.

Reel to Reel Ceramic Coating System



Succeeded in **25 ± 4.7 (σ) μm** thick ceramic coating 40 m length on both sides of a REBCO tape

One more thing

- ITDC Workshop
- Superconducting magnets for Accelerator Sciences
  -Prospects and Issues-
- https://kds.kek.jp/event/51828/timetable/#20240925.detailed

Wednesday, 25 September

13:30 → 13:34 WS information — 1 F大会議室

13:35 → 15:45 Detector magnet (solenoid) — 1 F大会議室

13:35 **Introduction** 10m
開催のあいさつ：粒子検出器の構成と超伝導磁石への期待
Speaker: Makoto TOMOTO (KEK IPNS)

13:45 **Thin solenoid type detector magnet ~ past and future ~** 30m
薄肉超伝導ソレノイド技術と将来計画
アルミ安定化超伝導線にも軽く触れるが、伝導冷却などほかの技術要素の説明もする。将来計画の磁石についても触れる。
Speaker: Dr Yasuhiro MAKIDA (KEK IPNS)

14:15 **Rebuilding production technology on the Aluminum-stabilized conductors for superconducting magnet** 30m
アルミ安定化超伝導線の製造体制再構築
現在CERNに協力して進めようとしているアルミ安定化超伝導線の製造体制再構築について。
Speaker: Makoto YOSHIDA (KEK IPNS)

14:45 **Additional talk (TBD)** 30m

15:15 **Request : Big and strong magnets demanded by dark matter axion searches** 30m
超伝導マグネットの作り出す強力な磁場は加速器のみならず、いわゆる「非加速器物理学」分野での探索でも非常に重要な役割を果たしてきた。今後も超伝導マグネットの要請は高まるものと考えられる。このような例の1つが、暗黒物質アクシオンの探索である。本公演では、現在、世界で行われているアクシオン探索とそこで利用されている超電導磁石を紹介する。そして、将来計画で検討されているマグネット述べた後、今後、日本で暗黒物質アクシオン探索で必要になるマグネットについて議論する
Speaker: Dr 康宏 岸本 (東北大学)

15:45 → 17:10 SC magnet for target / capture secondary particles — 1 F大会議室

15:45 **J-PARC MLF secondary target project** 30m
J-PARC 第2MLF/第2ターゲット計画
ミュオンなど二次粒子生成標的の基本構成、磁場利用、将来計画
Speaker: Naritoshi KAWAMURA (KEK IMSS MSL)

16:15 **SC magnet for target** 30m
耐放射線ターゲット用超伝導磁石の開発
ミュオンなどの生成標的に隣接する超伝導磁石の耐放射線性確保に関する開発状況
Speaker: Dr Mukesh DHAKARWAL (KEK / J-PARC)

16:45 **High-temperature superconducting application/high field magnet** 25m
高温超伝導応用・強磁場磁石
20 Tを超える高磁場生成への高温超伝導線応用
Speaker: Satoshi AWAJI (Tohoku University)

19:00 → 21:30 **懇親会** 2h 30m — むらさき (つくばセンター地区)
むらさき https://maps.app.goo.gl/vUjB4jpxZkSapCHx7
つくばセンター Biviの３階です。
会費 ５０００円です。

Thursday, 26 September

10:00 → 13:30 SC magnet for accelerator — 1 F大会議室

10:00 **SC magnet for accelerator** 15m
加速器計画における超伝導磁石
SuperKEKB
Speaker: Tadashi KOSEKI (KEK ACCL)

10:15 **Super KEKB Nb3Sn focusing magnet** 30m
Speaker: Yasushi ARIMOTO (KEK ACCL)

10:45 **Development of HTS Accelerator magnet for SuperKEKB** 30m
高温超伝導線材（REBCO）による6極磁石の開発状況
Speaker: Xudong WANG (KEK ACCL)

11:15 **Development of wire for strong magnetic field accelerator magnets** 30m
強磁場加速器磁石の線材開発
加速器応用に向けたNb3Snなどの高磁場・高電流密度線材開発状況
Speaker: Michinaka SUGANO (KEK ARLCRYO)

11:45 **Current status and prospects for accelerator applications of high-temperature superconductors** 30m
高温超伝導応用・加速器応用への課題
高温超伝導線の加速器応用への現状と展望
Speaker: Dr Naoyuki AMEMIYA (Kyoto University)

13:30 → 14:30 Discussion / Site visit — 1 F大会議室