COMET and J-PARC g-2/EDM

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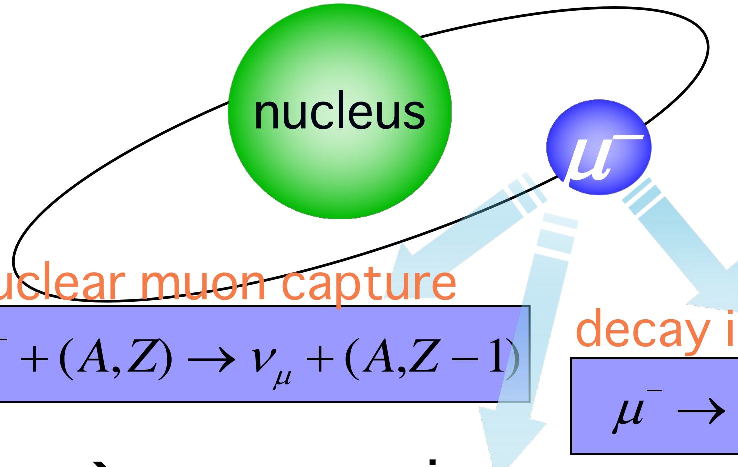
2022/09/12

COMET Superconducting Magnet

Slides by M. Yoshida

The COMET Experiment



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

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

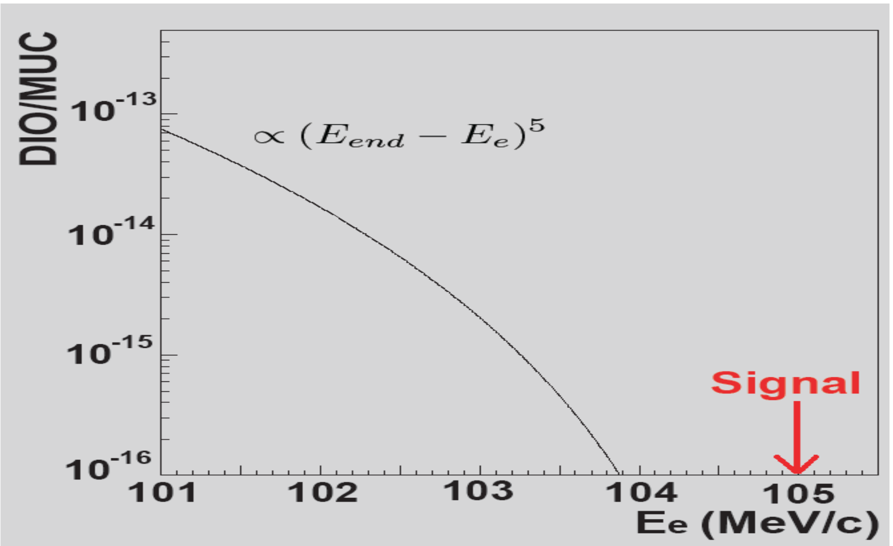
- stopping μ^- → Muonic atom in Al target

μ→e conversion

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

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

Detect monoenergetic electrons from μ-e conversion



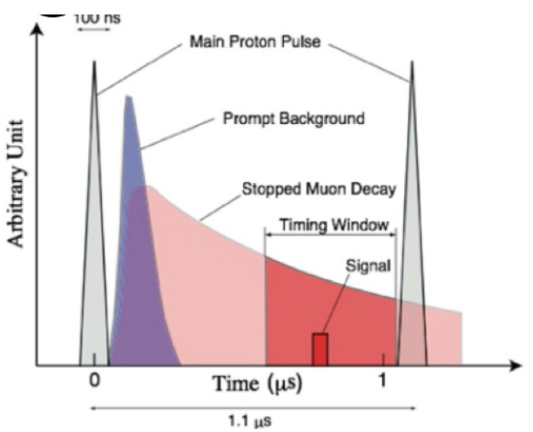
Physics Reach: Br<10^{-16} (PhaseII)
<10^{-14} (PhaseI)

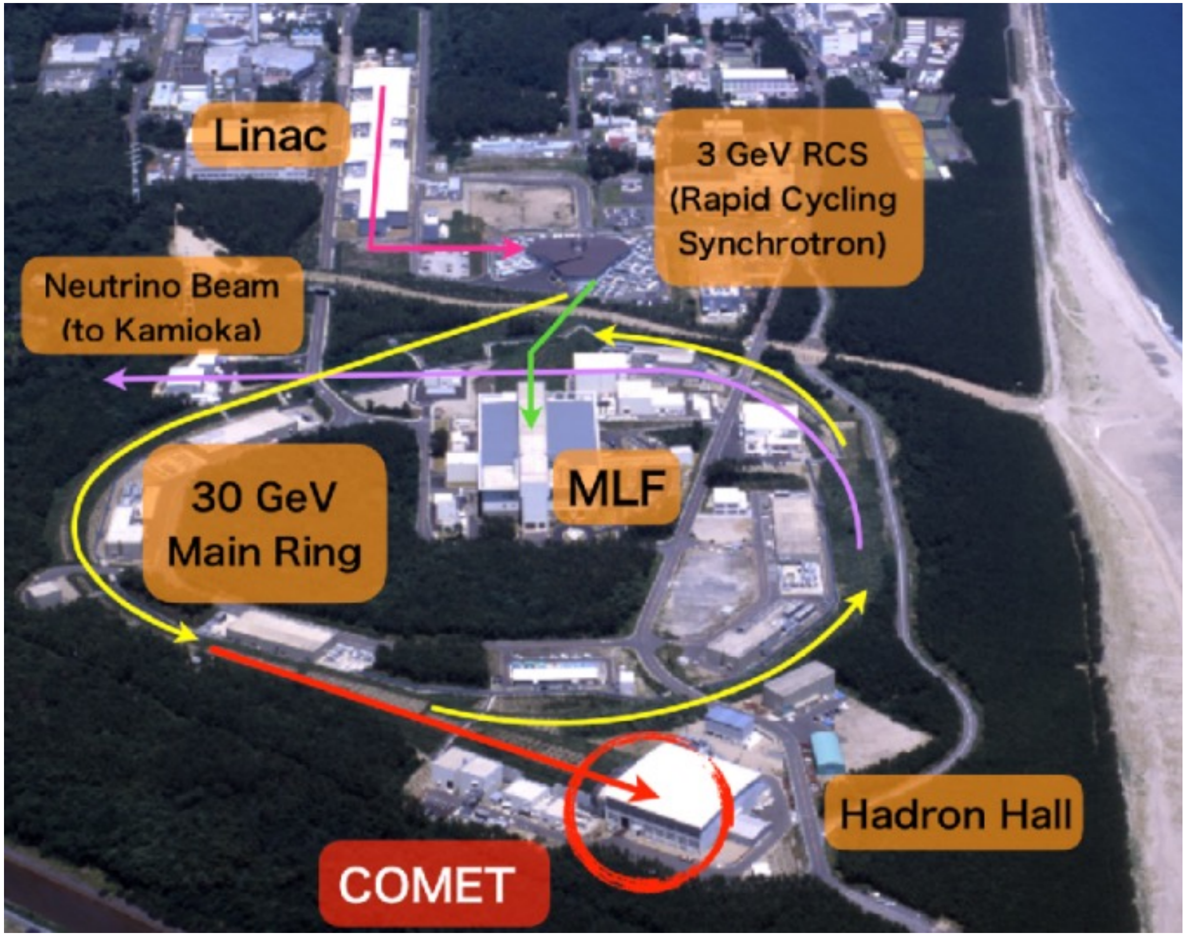
→ 2×10^{18} muon stops

→ 10^{11} μ^-/sec

COMET at J-PARC

- J-PARC E21
- Bunched slow extracted proton beam at 8GeV from Main Ring
- New muon beamline is under construction at Hadron Experimental Facility





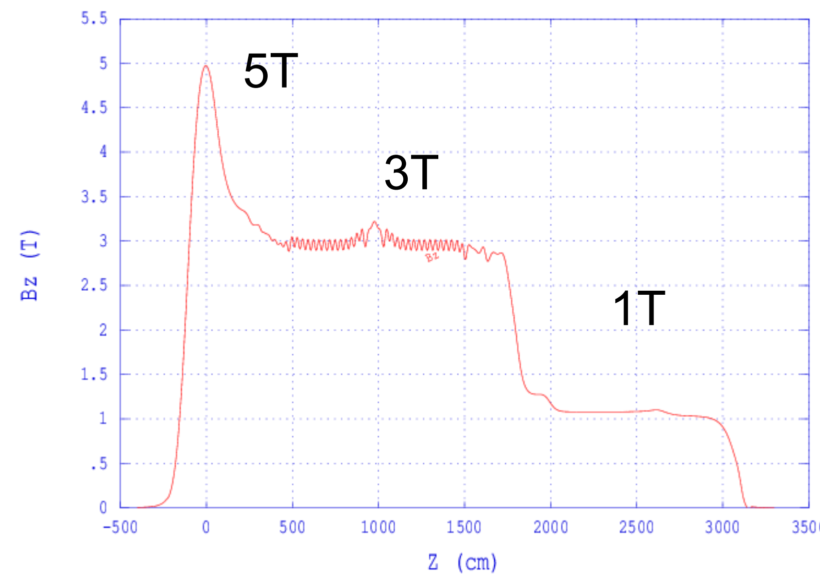
Goal: 10^{11} μ^{-}/sec

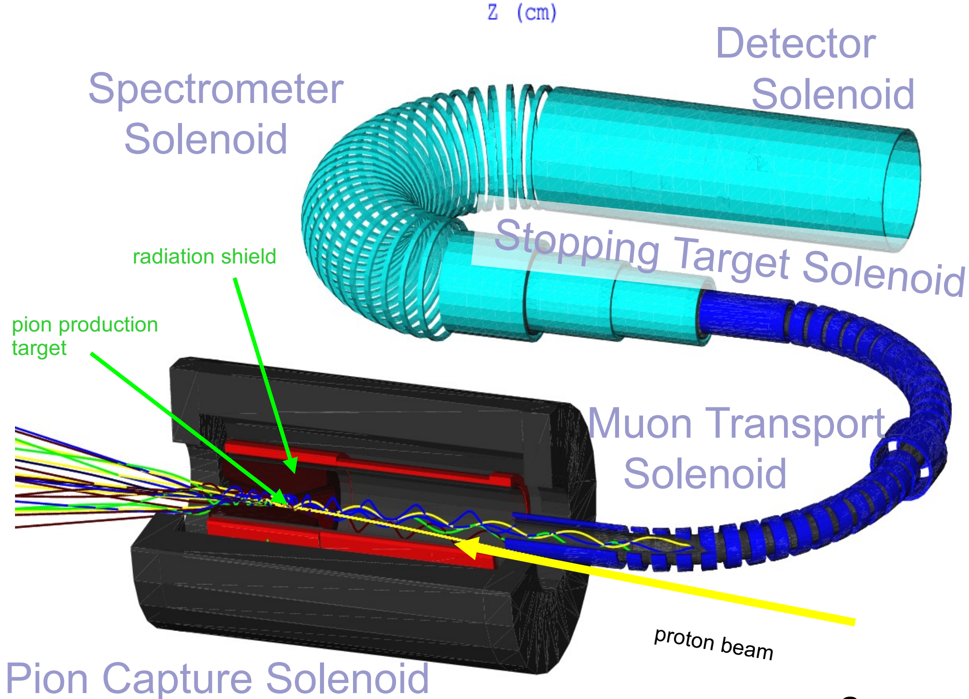
Requirements on muon beamline

1. Large acceptance to collect pions from production target
   - High field on pion production target
   - Graded field to focus pions forward
2. Reduce pion contamination / high energy muons
   - Long solenoids from production to muon stopping target
   - Curved solenoid to select momentum / charge
3. Large signal acceptance. Reduce decay-in-orbit BG
   - Graded field on muon stopping target
   - Curved solenoid to select 105MeV/c electrons

COMET Magnet (Phase2)

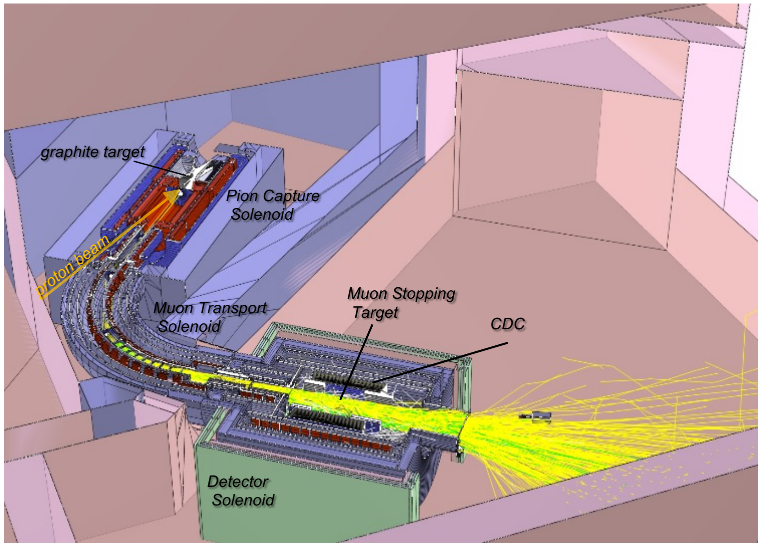
- Pion Capture Solenoid
  - *5T High field on Target*
  - *Tungsten shield inside*
- Muon Transport Solenoid
  - *3T curved solenoid*
  - *Correction dipole 0.03T~0.06T*
- Stopping Target Solenoid
  - *3T→1T graded field*
- Spectrometer Solenoid
  - *1T curved solenoid*
- Detector Solenoid
  - *1T curved solenoid*





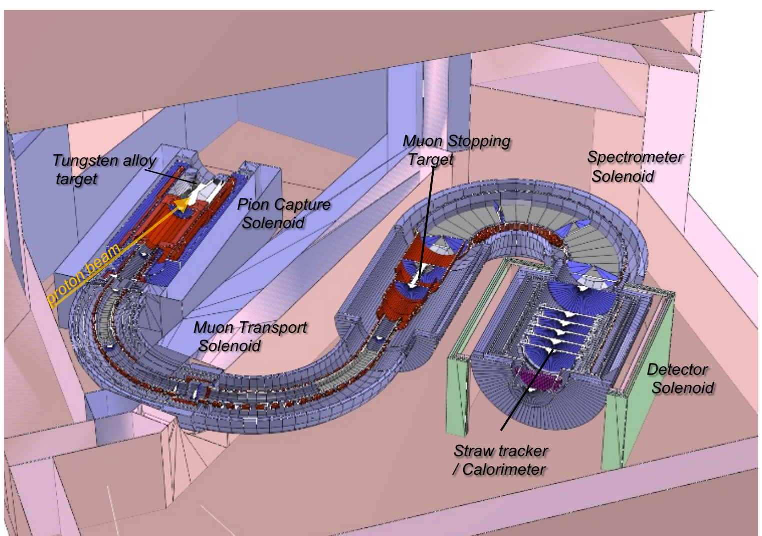
COMET Superconducting Magnet System

Staging Approach



Phase-I

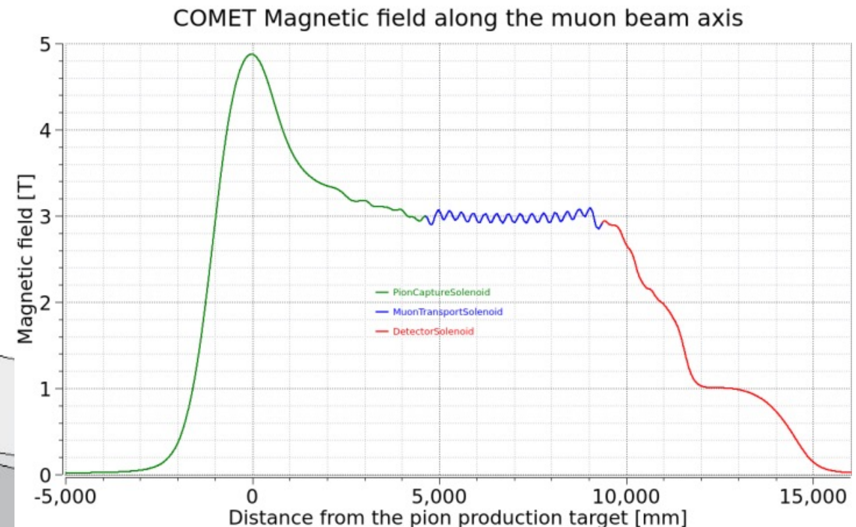
- 3.2kW proton beam (8GeVx0.4μA)
- Sensitivity Br<10^{-14}
- Graphite target
- Pion Capture Solenoid + 90deg curved solenoid
- Cylindrical drift chamber + trigger hodoscope

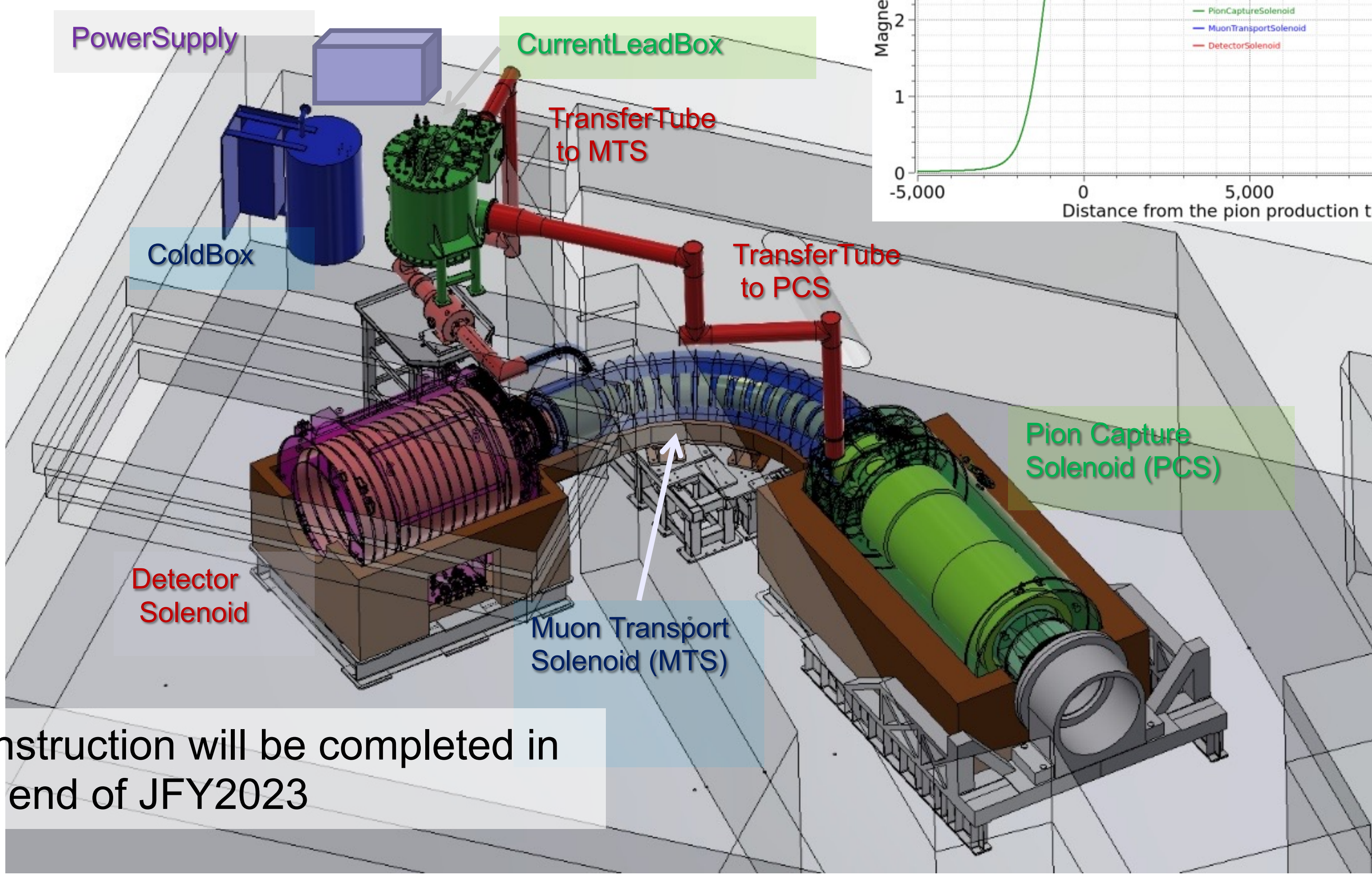


Phase-II

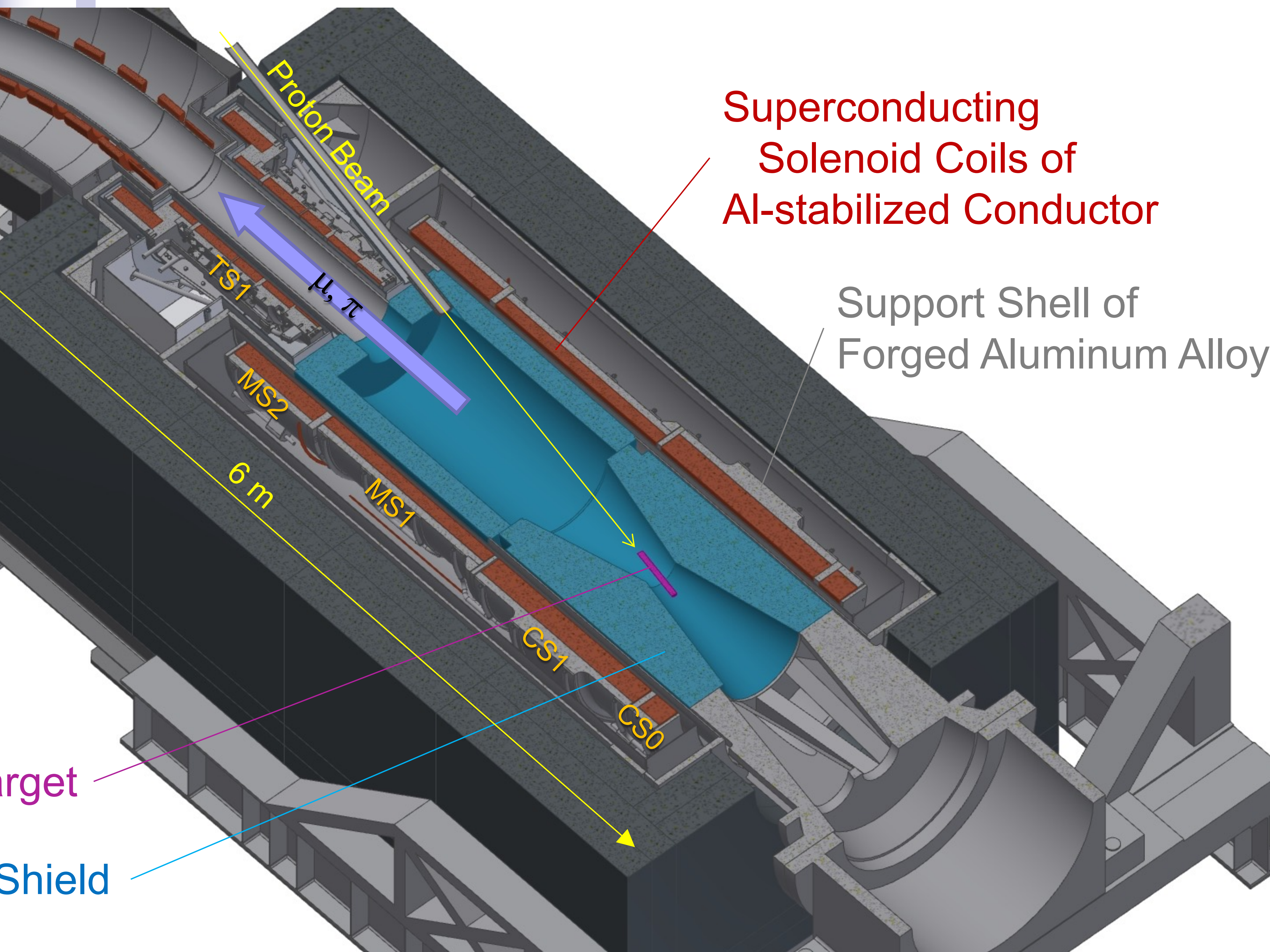
- 56kW proton beam (8GeVx7μA)
- Sensitivity Br<10^{-16}
- Tungsten alloy target
- Pion Capture Solenoid + 180deg curved solenoid + Spectrometer Solenoid
- Straw tracker + calorimeter

COMET Magnet System (Phase-I)





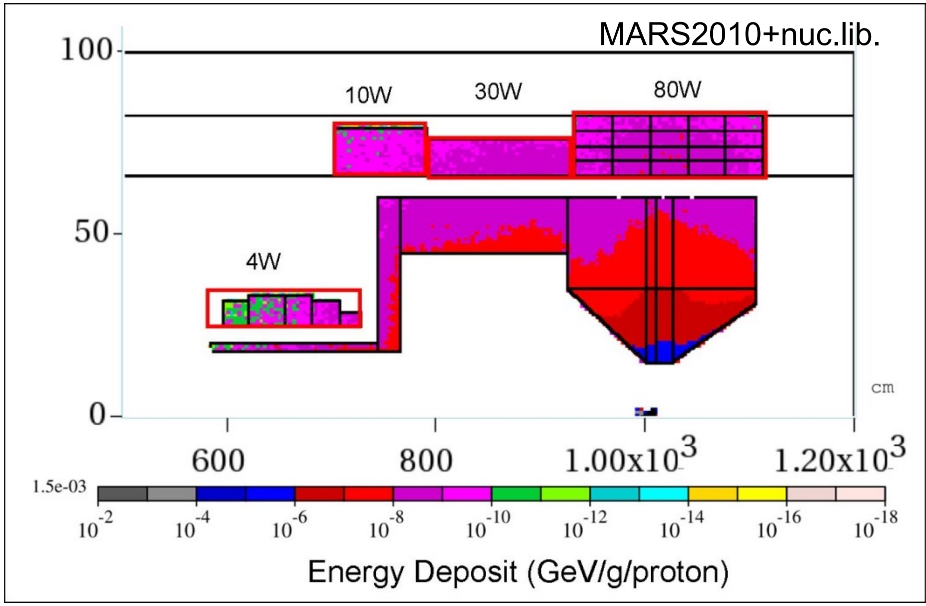
Construction will be completed in the end of JFY2023

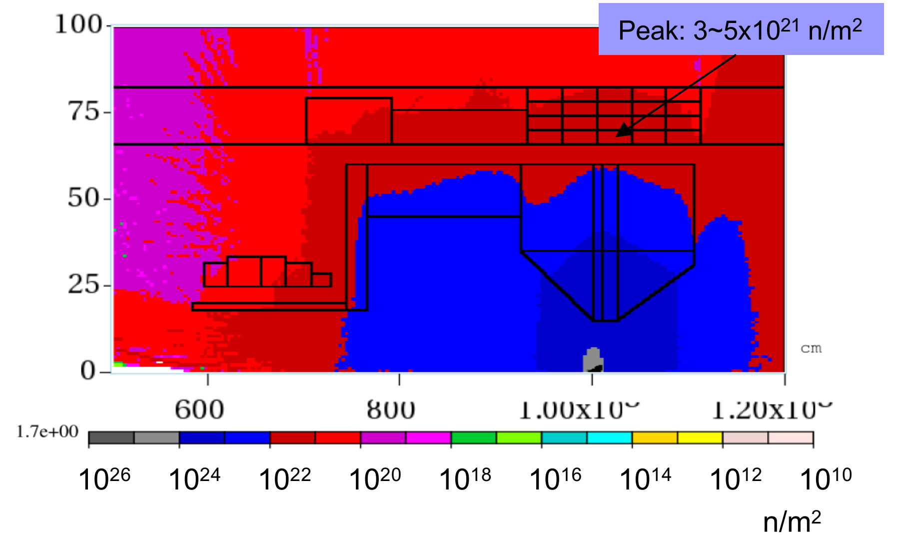

Proton Beam
Superconducting
Solenoid Coils of
Al-stabilized Conductor
Support Shell of
Forged Aluminum Alloy
TS1
μ, π
MS2
MS1
6 m
CS1
CS0
rget
Shield

Key Issues on PCS

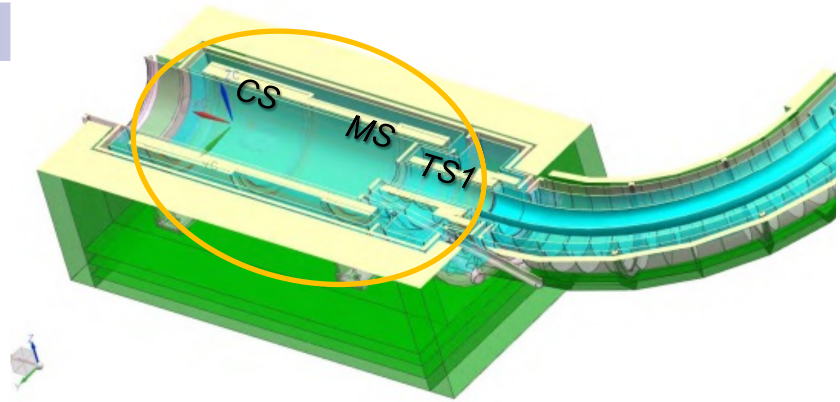
Nuclear Heating : >100W
Peak dose rate in Al : ~1MGy
Neutron fluence : >10^{21} n/m^2

- Radiation tolerance of magnet materials
  - Organic material
    - Strength
    - Out gas
  - Metal
    - Electrical conduction
    - Thermal conduction





Coil Structure (Pion Capture Solenoid)

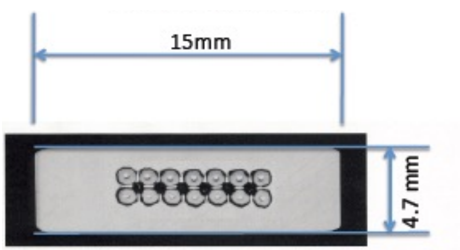


- Aluminum stabilized SC cable
  - for less nuclear heating (max. 35mW/kg)
- Radiation resistant insulator, resin
- Pure aluminum strips in between layers
  - to cool down a coil inside

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)
Coil length	~1.6 m (CS0+CS1) ~1.4 m (MS1), ~0.7m(MS2), ~1.6 m (TS1a~TS1f overall)
Coil layers	9 (CS0+CS1) 5 (MS1), 7 (MS2) 1~6 (TS1a~TS1f)
Quench protection	active quench back heater

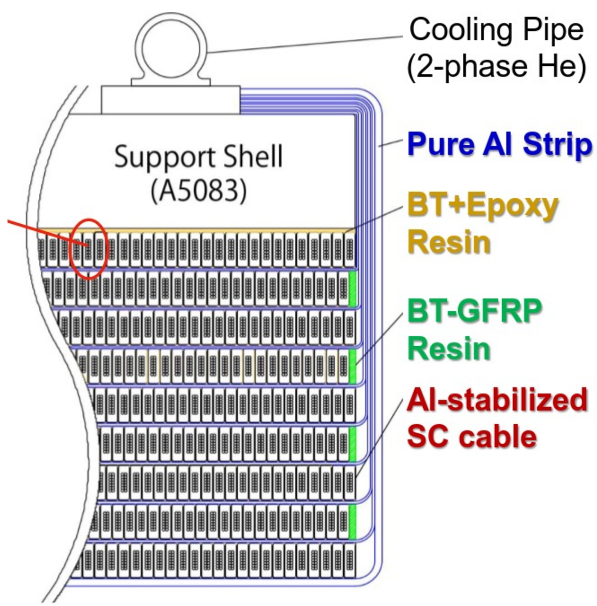
[a] T_{cs} is critical temperature at the maximum temperature.



Al stabilized SC cable

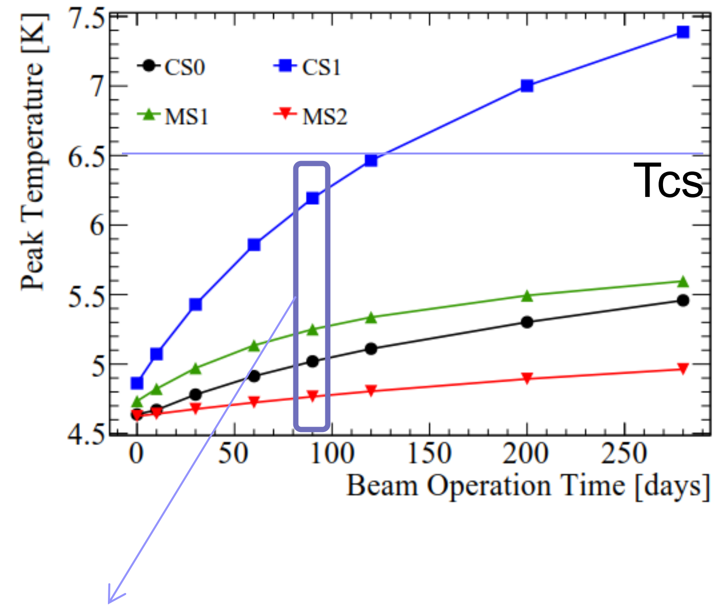
- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

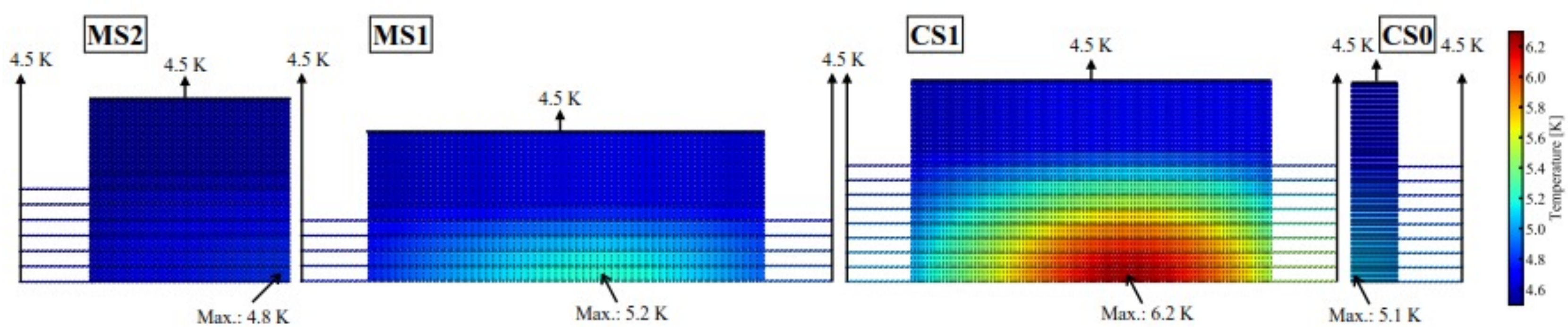
CS coil structure



Coil Temperature during Beam Operation

- Coils in Pion Capture Solenoid will be heat up by irradiation (max. 35mW/kg)
- Peak temperature in coils 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).

Simulation of Temperature Rise at Quench

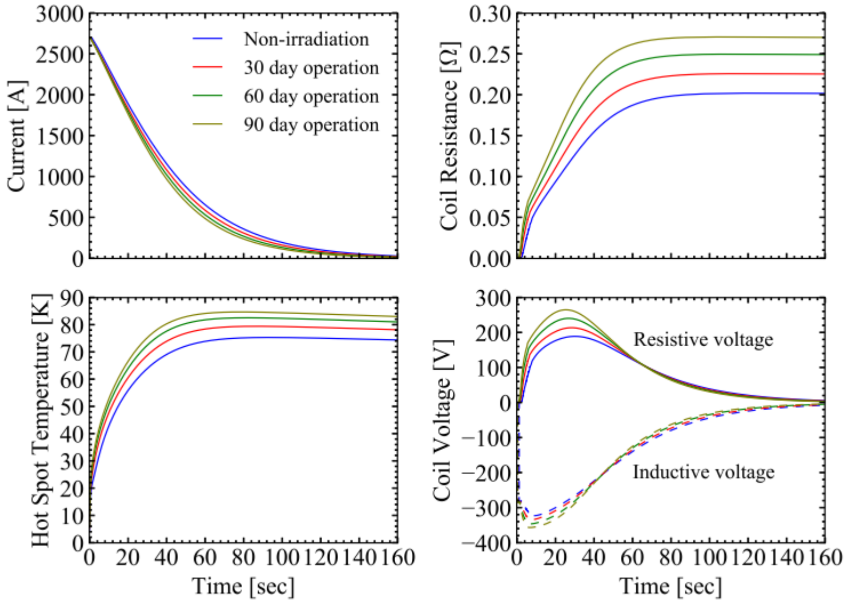


Fig. 5. Predicted current, coil resistance, temperature at hot spot and coil voltage after a accidental quench is occurred at varied beam operation time. The dashed line indicates the inductive voltage.

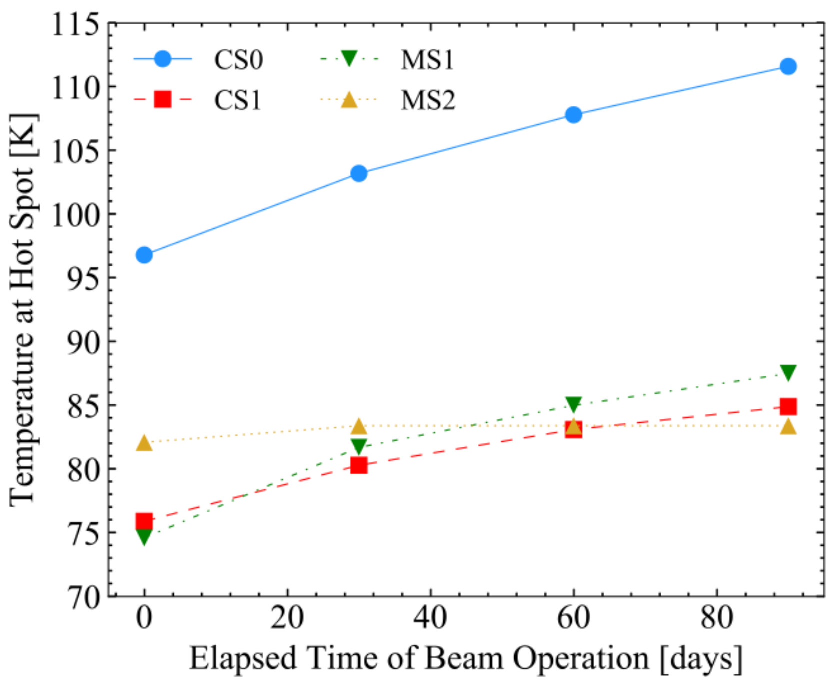


Fig. 6. Maximum temperature at hot spot for CS0 (blue line), CS1 (red line), MS1 (green line) and MS2 (golden line) coil as a function of beam operation time.

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

Coldmass Fabrication

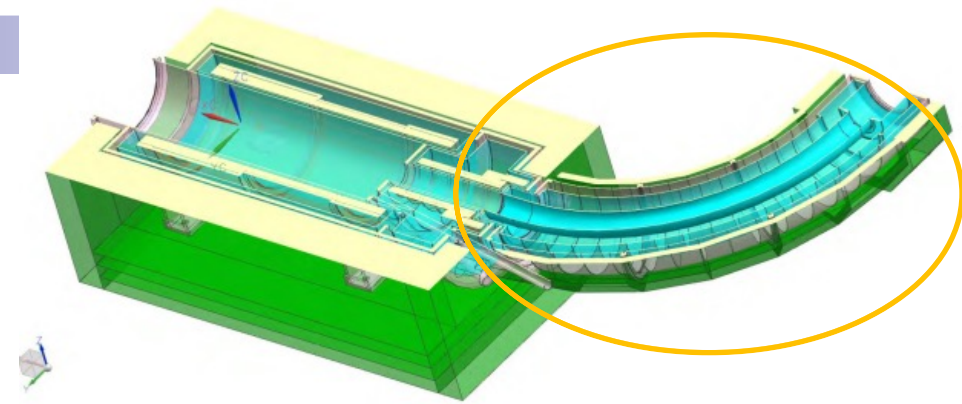
Support shell of forged A5083

heat curing

Wet winding with BT+Epoxy resin

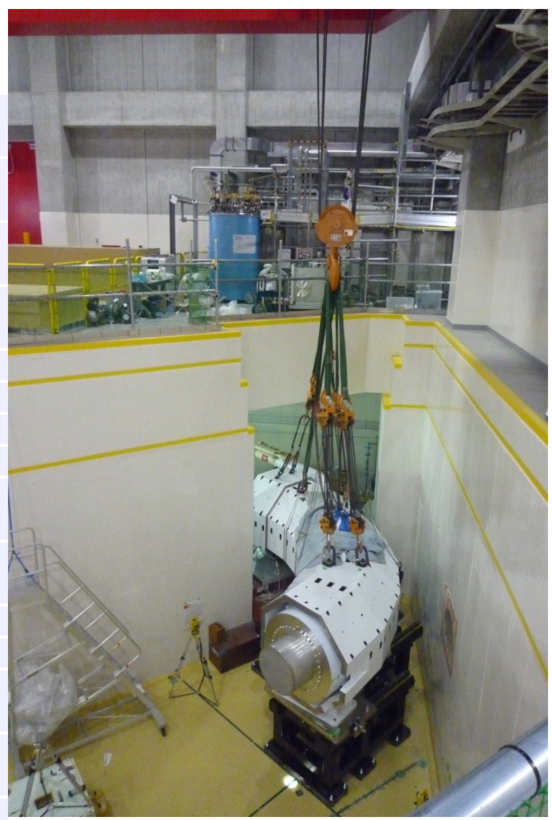
Impregnation with BT+Expoxy

Muon Transport Solenoid



- Curved solenoid with correction dipole

Magnet already delivered at J-PARC.

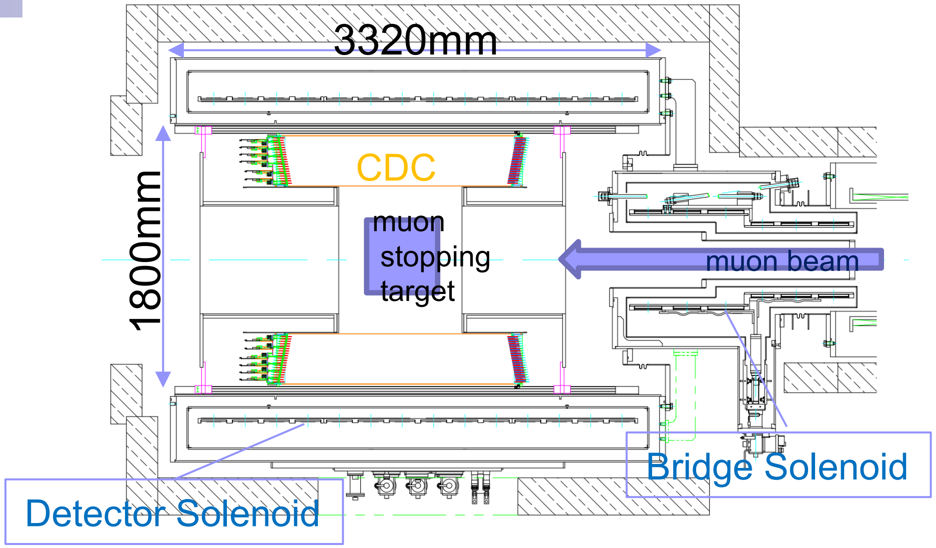


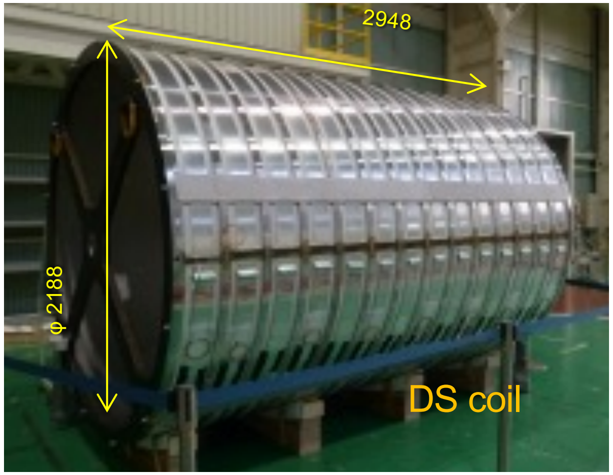
Design Parameters of Transport Solenoid

Conductor	NbTi/Cu monolith wire Cu/NbTi = 6
Cable dimensions (Solenoids)	ϕ1.5 mm (without insulation) ϕ1.56 mm (with insulation)
Cable dimensions (Dipole coils)	ϕ1.2 mm (without insulation) ϕ1.3 mm (with insulation)
Cable insulation	Polyamide-imide enamel (AIW), PVF (TS2-15,16, TS3)
Magnet length	~6 meters
Curvature Radius	3 meters
Num. of solenoid coils	18
Num. of dipole coils	16 pairs
Operation current	210 A (solenoids) 175 A (dipole coils)
Field on axis	~3 T (solenoid) ~0.056 T (dipole)
Stored energy	5.6 MJ
Total inductance	254 H
Coil inner diameter	468 mm (TS2a~TS2-16) 600 mm (TS3)
Refrigeration	conduction from forced flow 2-phase LHe piping (7~10 g/s)
Quench protection	semi-active quench back heater

Detector Solenoid for phase1

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

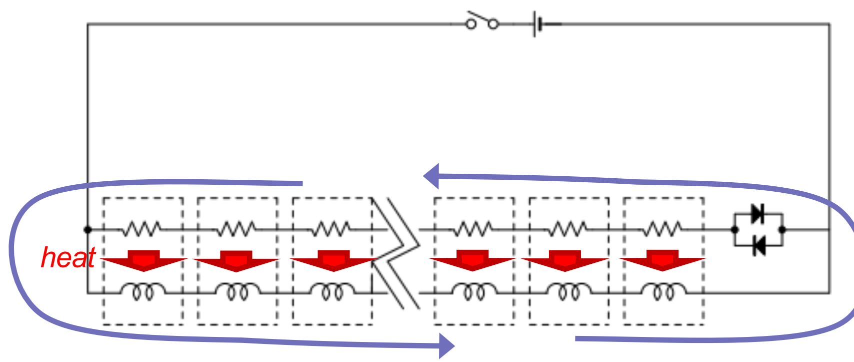


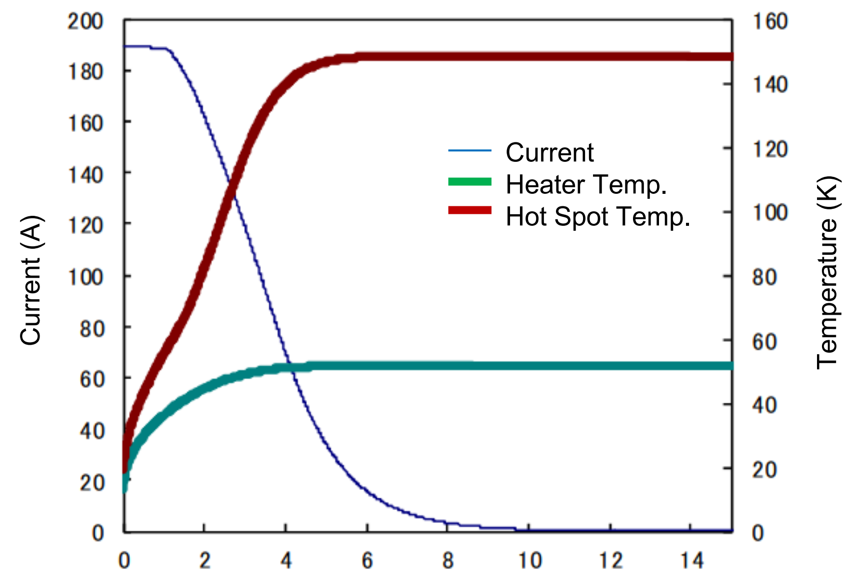


Item	Value
Conductor	NbTi/Cu monolith wire Cu/NbTi = 4
Strand dimensions	ϕ1.2 mm (without insulation) ϕ1.3 mm (with insulation)
Cable insulation	PVF
Magnet length	~1 m (BS), ~2.5 m (DS)
Operation current	210 A
Field on axis	3~1 T (BS), ~1 T (DS)
Stored energy	~14 MJ
Coil inner diameter	460~620 mm (BS), 2140 mm (DS)
Refrigeration	conduction cooling by GM refrigerators
Quench protection	active or semi-active quench back heater

Quench Protection in MTS, DS

- Semi-active quench back system is employed in MTS and DS.
- Heater coils are wound on superconducting coils
- The heater warms up each coil by making circuit from coils to heaters via diodes
- Stored energy will be dumped in the magnet





Calculated temperature of hot spot and heater of DS.

Summary ~ COMET

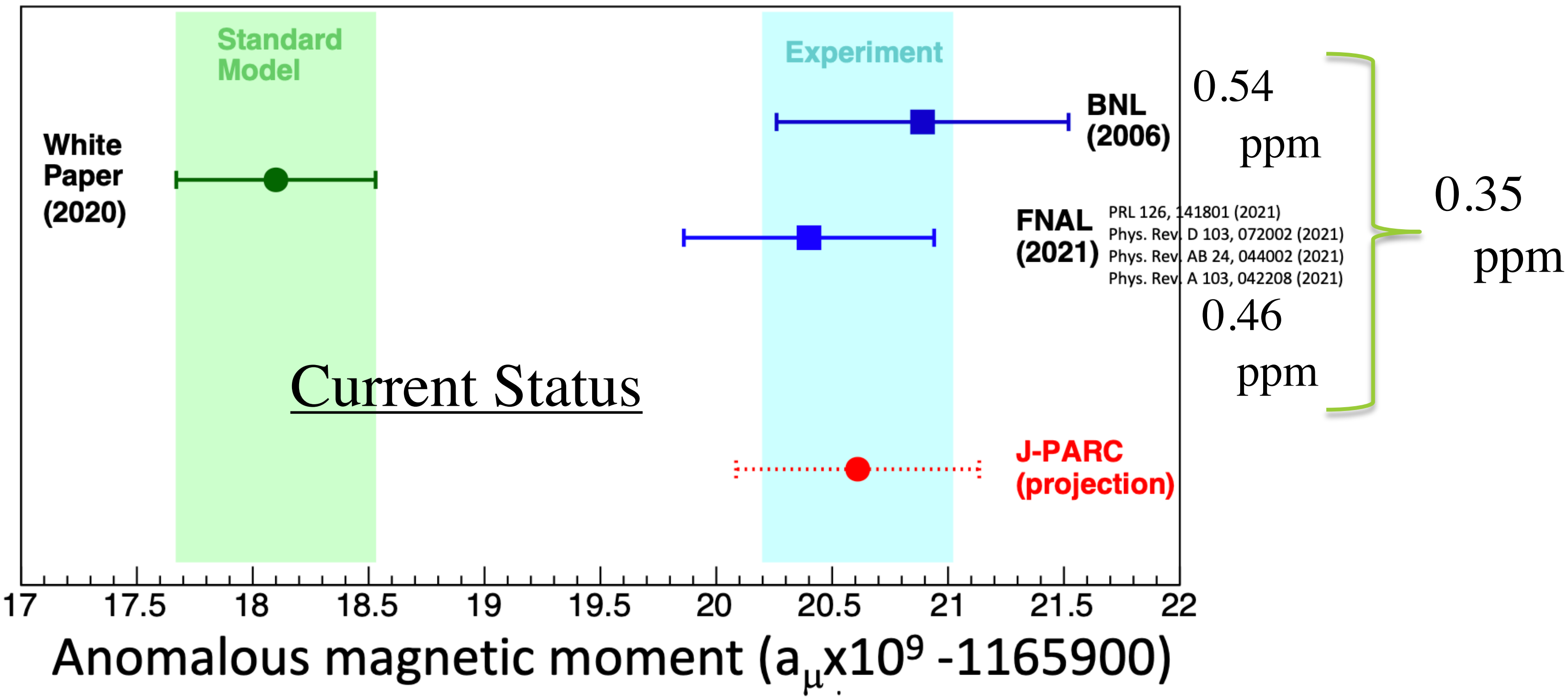
- Construction of COMET superconducting muon beamline for Phase I is underway
- Construction will be finished in the end of JFY2023.
- Magnet commissioning and beam run will start in JFY 2024.

J-PARC g-2/EDM

Ken-ichi Sasaki

Objective of J-PARC muon g-2/EDM experiment

- Measure muon anomalous magnetic moment (g-2) precisely



The FNAL run 1 result

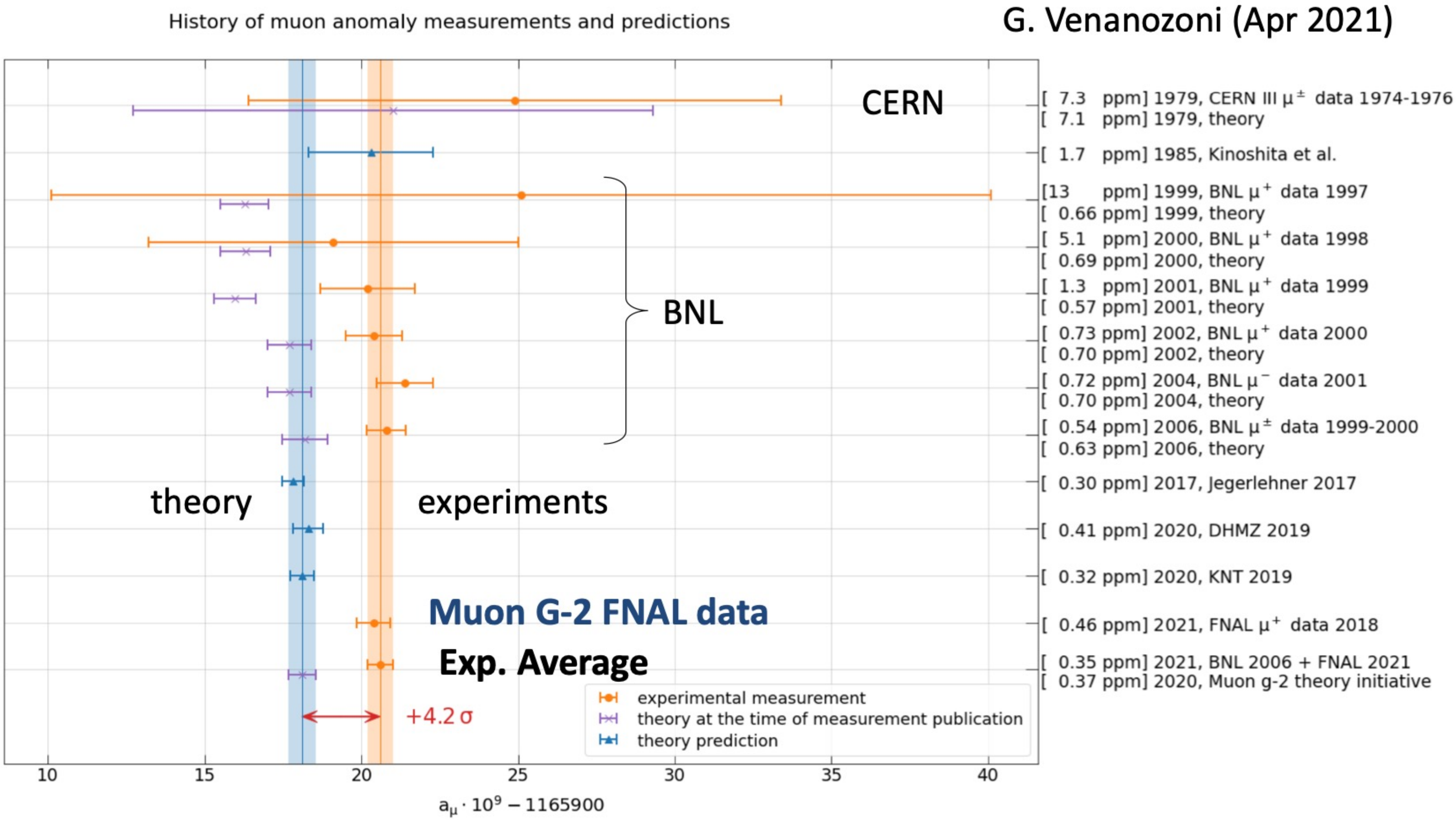
(1) Confirmed previous BNL result
(2) Deviation from the SM became 4.2σ (was 3.7σ)

- J-PARC
  - Stage 1: < +/- 0.45 ppm   Stage 2 : < +/- 0.1 ppm

Slide by Mibe

Why new experiment?

G. Venanozoni (Apr 2021)



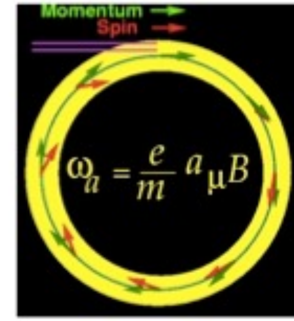
Dominated by the magic gamma experiments (BNL+FNAL).

→Independent measurements are important.

Slide by Mibe

Experimental approach ~ FNAL vs J-PARC

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)

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

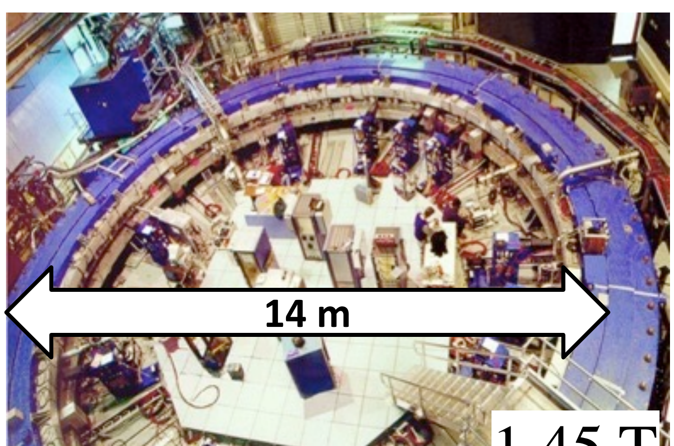
Continuation at FNAL with 0.1ppm precision (E989)

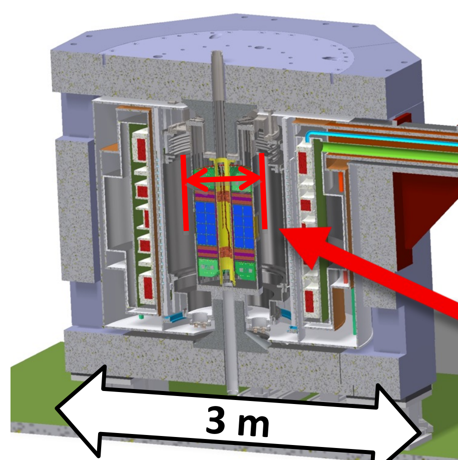
J-PARC approach
E = 0 at any γ

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

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

14



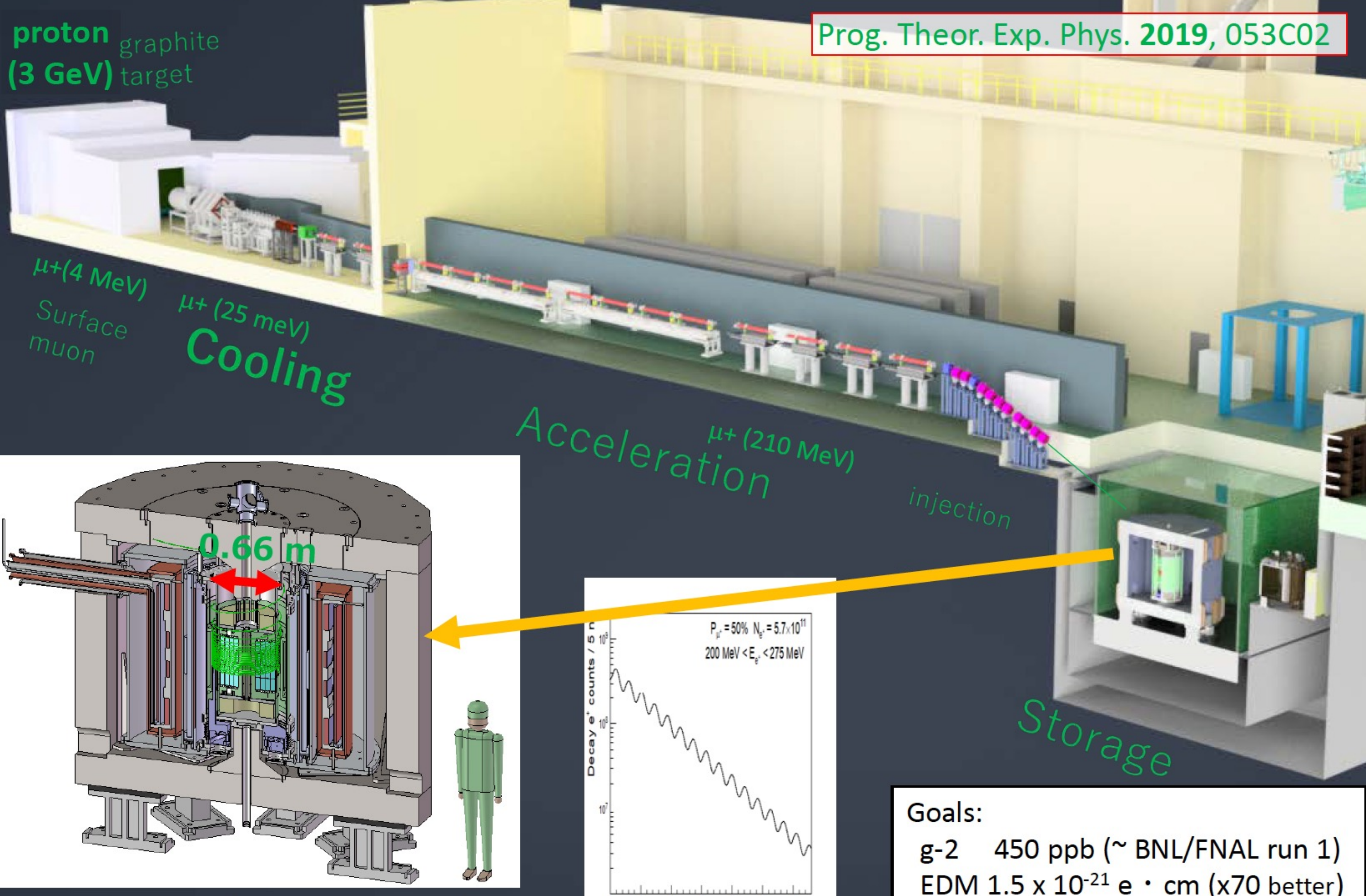


Low emittance muon beam

Muon orbit diameter
66.6 cm at 3 T

Muon g-2/EDM Experiment at J-PARC: overview

Prog. Theor. Exp. Phys. **2019**, 053C02

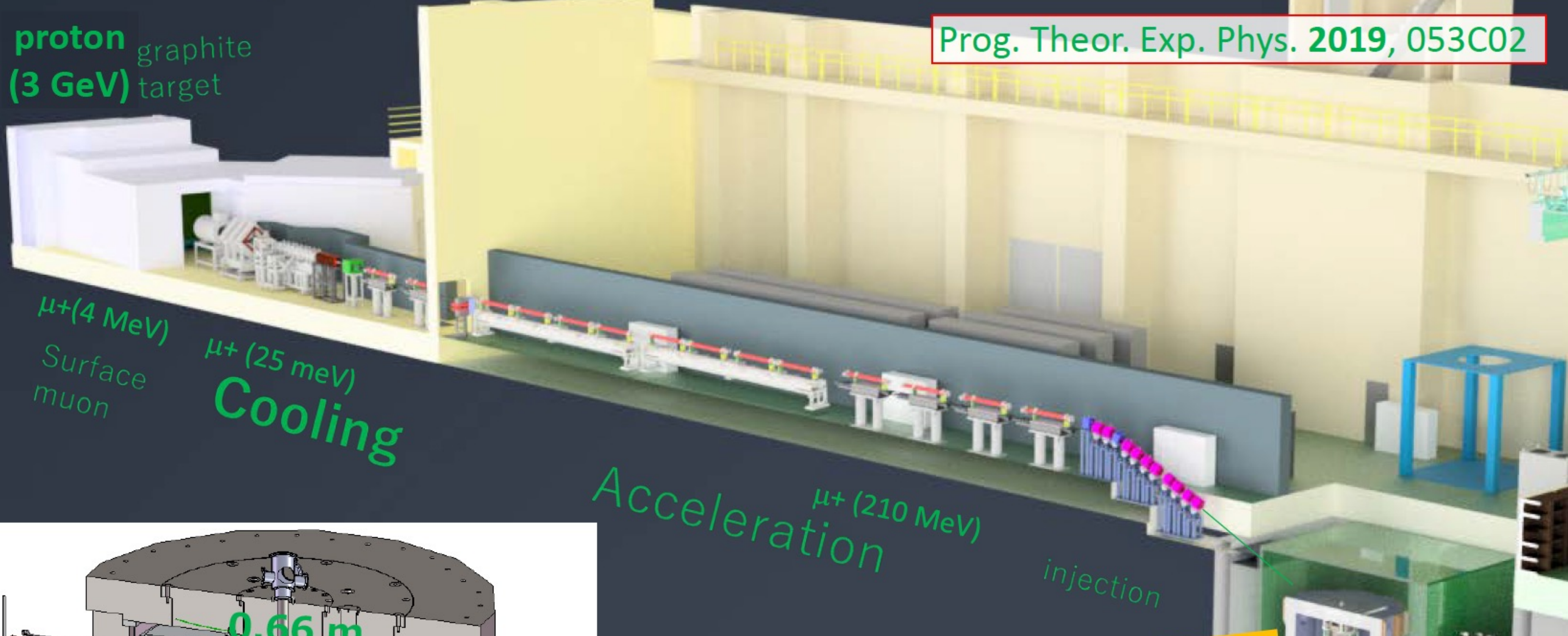


muon storage magnet

Goals:
- g-2 450 ppb (~ BNL/FNAL run 1)
- EDM 1.5 x 10^{-21} e・cm (x70 better)

Muon g-2/EDM Experiment at J-PARC: overview

Prog. Theor. Exp. Phys. **2019**, 053C02



Features:

- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

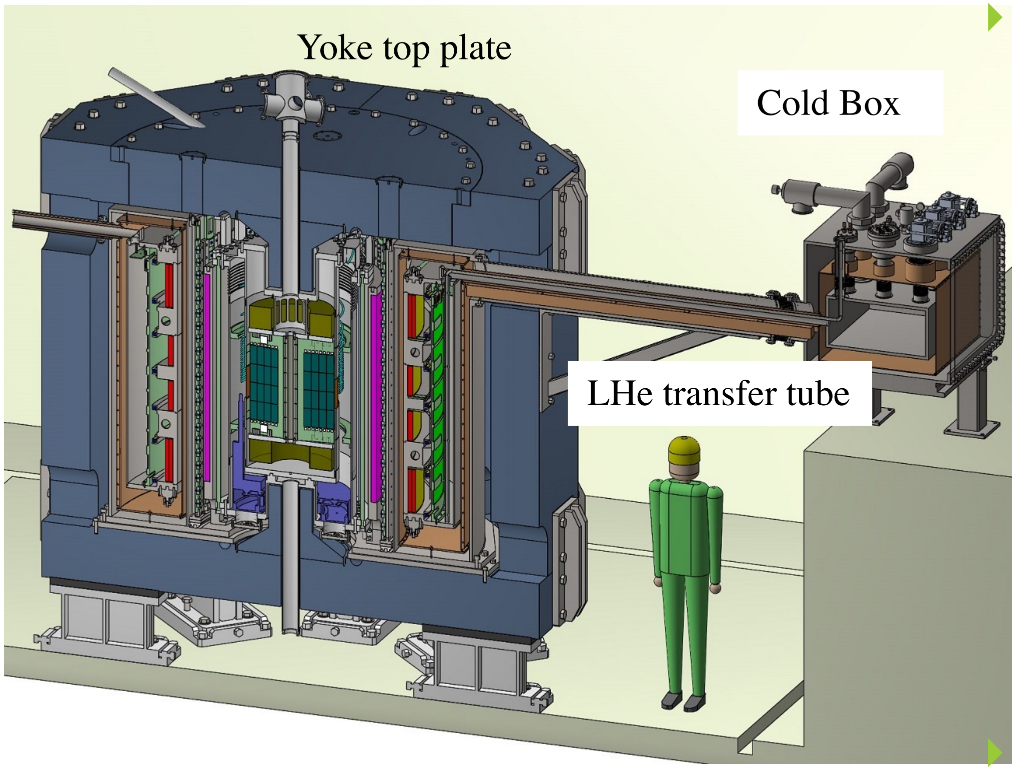
muon storage magnet

BNL/FNAL run 1)

cm (x70 better)

Time [μs]

SC magnet for J-PARC g-2/EDM



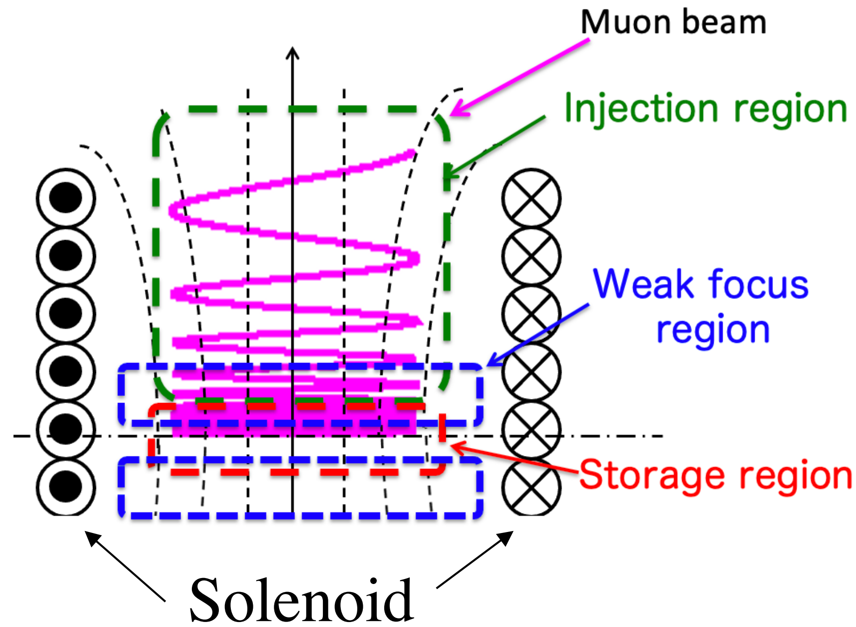
- Superconducting coils : NbTi
  - Main solenoid coil
    - Square wire : 1.4 x 2.1 mm
    - Persistent current operation
  - Weak focusing coil
    - Round wire : ϕ 0.8 mm
    - Power supply operation
  - Shim coils
    - Round wire : ϕ 0.8 mm
    - Power supply operation
- Iron piece shimming system
- Iron yoke

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

- Cooled by liquid Helium
  - Cryocoolers to recondense LHe
- Separated cold box from magnet cryostat
  - Isolate vibration
- Vibration isolation/control system

Requirement for magnetic field design

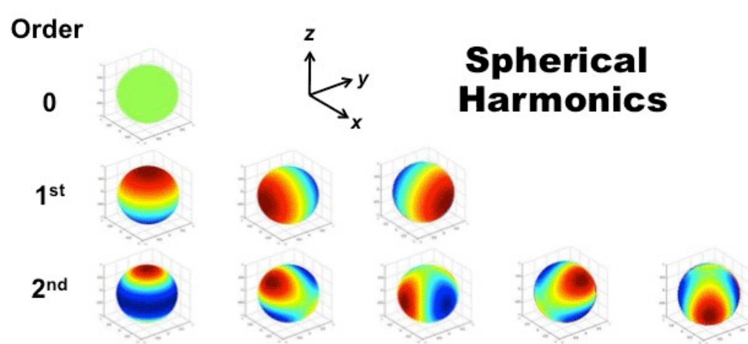
- Three functions
  - Storage region
    - Field strength : 3 T
    - Homogeneity: ±0.1 ppm (average in azimuthal direction)
    - Size : radius: 33.3 cm ± 1.5 cm height: ±5 cm
  - Injection region
    - $B_r \times B_Z > 0$
    - *Br* has to change smoothly along the beam orbit
  - Weak Focus field
    - $B_r = -n \frac{B_{0z}}{R} z$ n: 5×10^{-5} - 2×10^{-4}



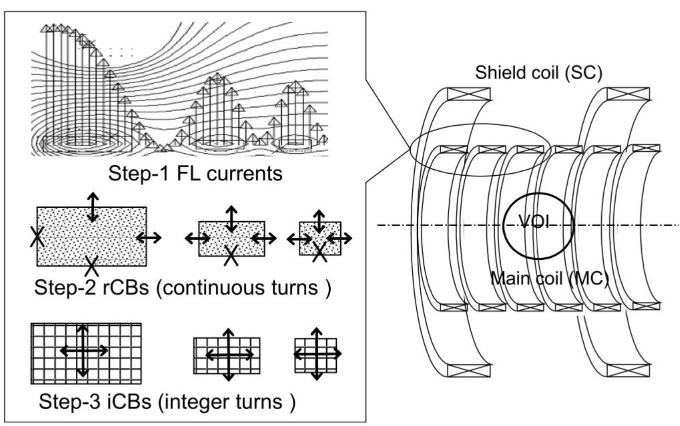
- Important point
  - Spatial control of magnetic field distribution

Study of magnetic field design

- Develop
  - New magnetic field calculation code
    - truncated singular value decomposition method *1
  - Conventional MRI magnet
    - Spherical harmonics deconvolution method



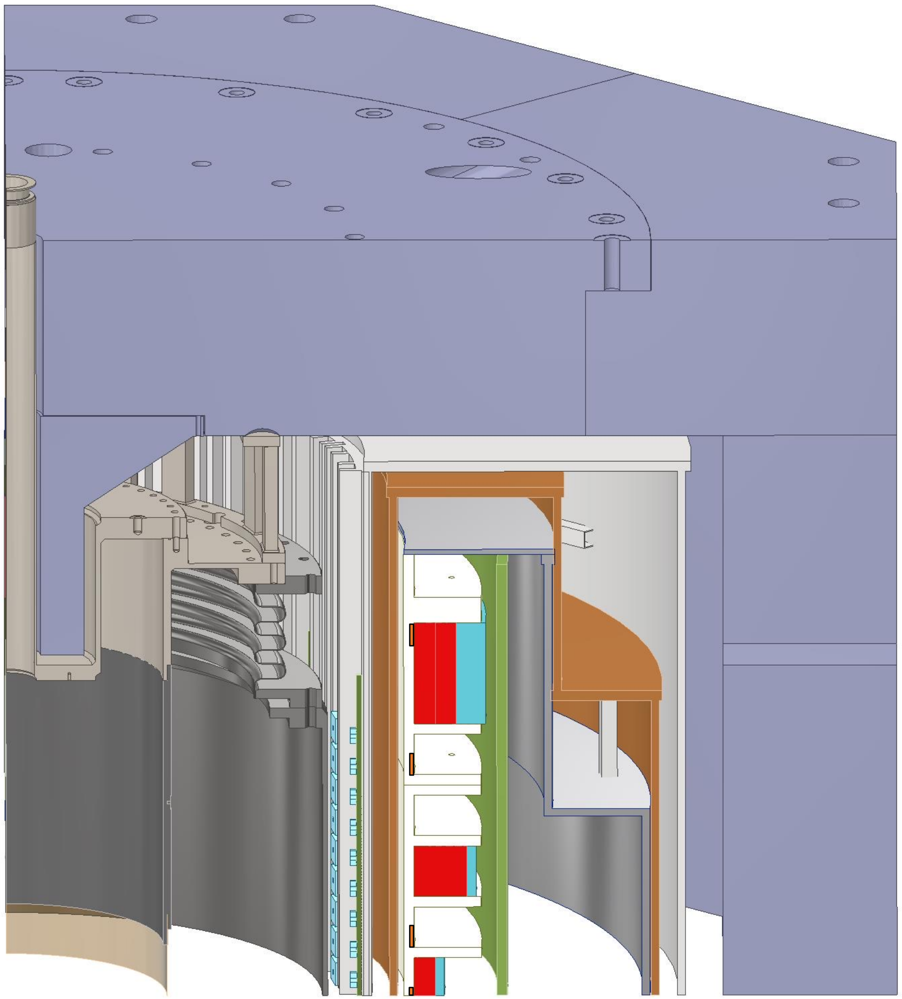
- Proven technique
- Target : Spherical Volume
  - too much volume



- New method
  - could optimize arbitrary volume
  - Coil size could be downsized

*1 M. Abe *et al.*, “Coil Block Designs with Good Homogeneity for MRI Magnets Based on SVD Eigenmode Strength," *IEEE trans. Magn.* Vol. 51, 7002713 (2015)

SC main coil design



- 1/8 model

Superconducting coils : NbTi

- Main solenoid coil
  - Square wire : 1.4 x 2.1 mm
  - Persistent current operation
- Weak focusing coil
  - Round wire : ϕ 0.8 mm
  - Power supply operation
- Shim coils
  - Round wire : ϕ 0.8 mm
  - Power supply operation

Study on Error Field

- Requirement for magnetic field homogeneity : < 0.1 ppm

  it's easily disturbed by any sources at this level

- Possible error source

- Static error source
  - Error from manufacturing error
    - Coil misalignment/deformation
  - Yoke shape
  - Magnetic Materials
    - Inside magnet
      - chamber, detector, etc.
    - Outside the magnet
      - beam line magnet, car, etc…
  - Non-uniformity of yoke permeability

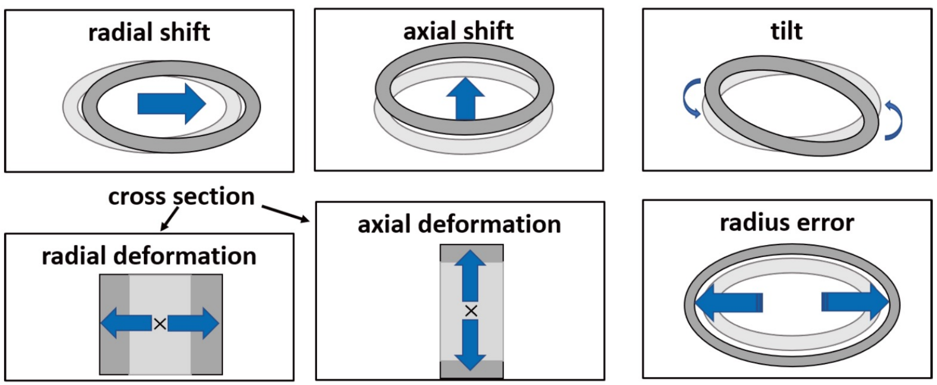
- Dynamic error source
  - Temperature change
  - Characteristics of Superconductor
    - Magnetization
    - Strand coupling current
    - Persistent current operation
  - Mechanical vibration
    - Cryocooler, Seismic vibration

Important : Evaluate the magnitude of error field
Check feasibility of shimming

Error field study ~ manufacturing error

ex: Manufacturing error

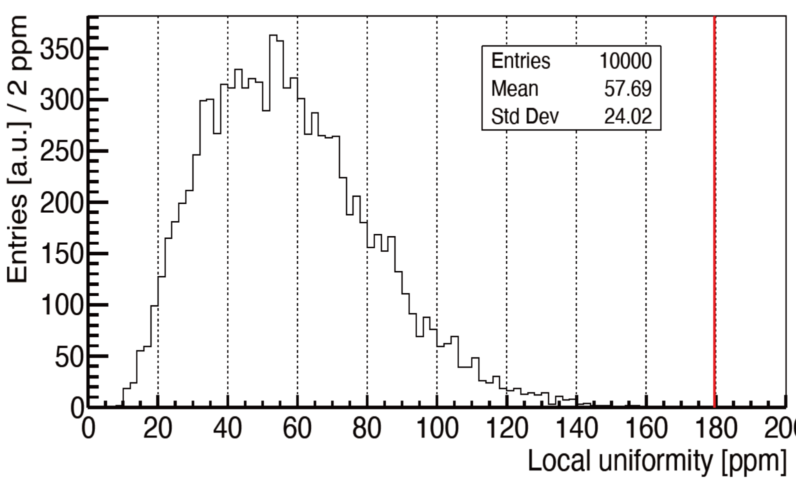
Coil deformation



Assumed : ±0.1 mm / 0.1 mrad

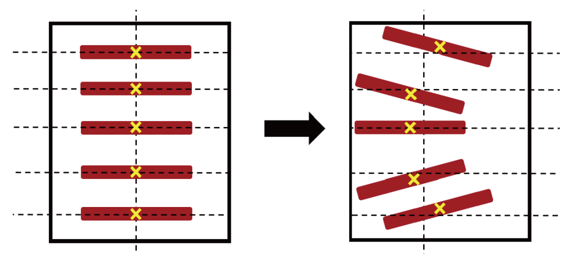
- Degrees of freedom : 40

Monte-carlo simulation



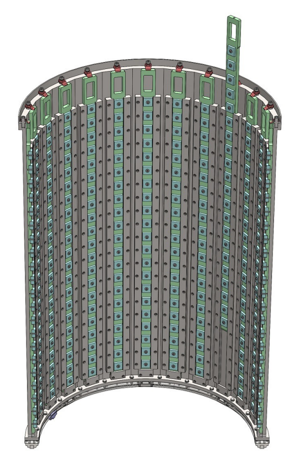
Simulation results

- Worst case of deformation pattern



~180 ppm

- Could be shimmed by shimming system

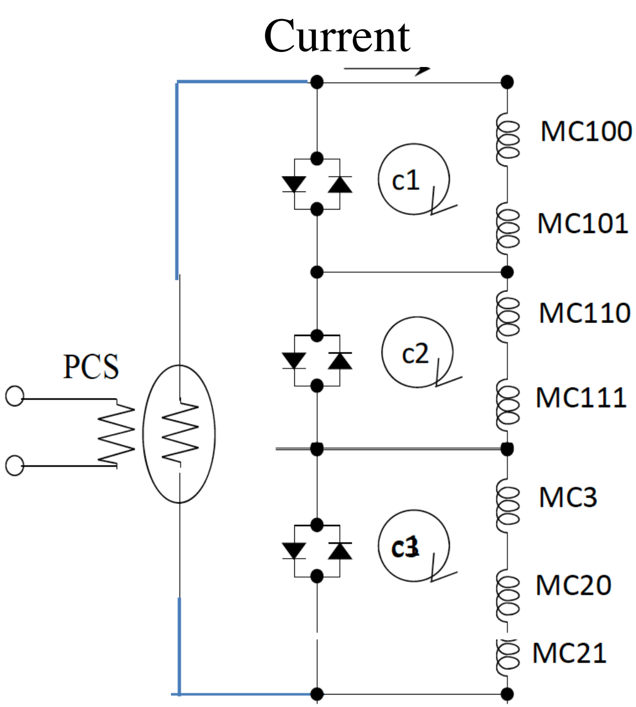


Quench protection study

- Simulation
  - Coupled analysis of electrical circuit and heat conduction
    - Coil peak voltage
    - Coil peak temperature

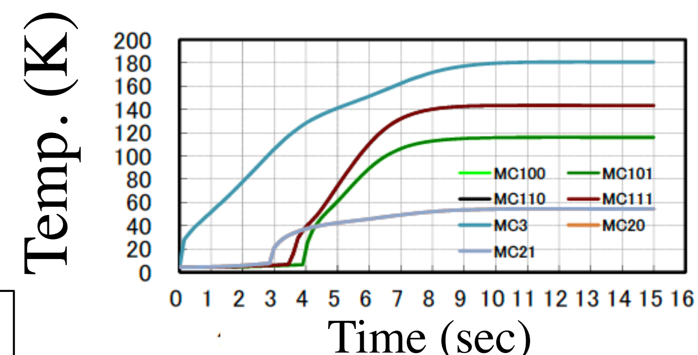
} < 1~2 kV
} < 300 K

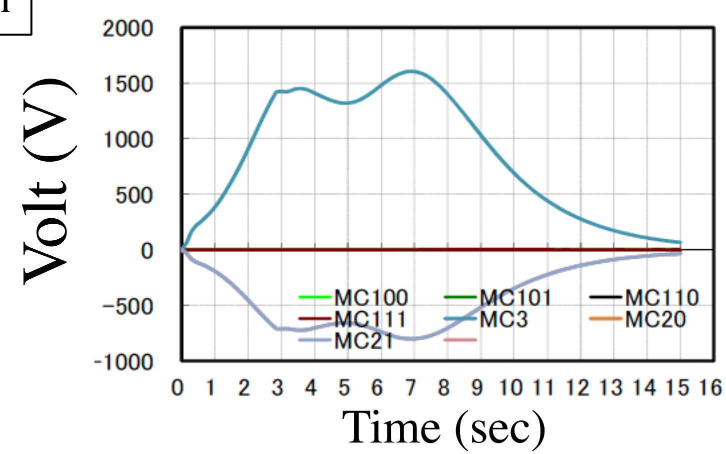
✓ Persistent current mode -> dissipate stored energy IN the magnet



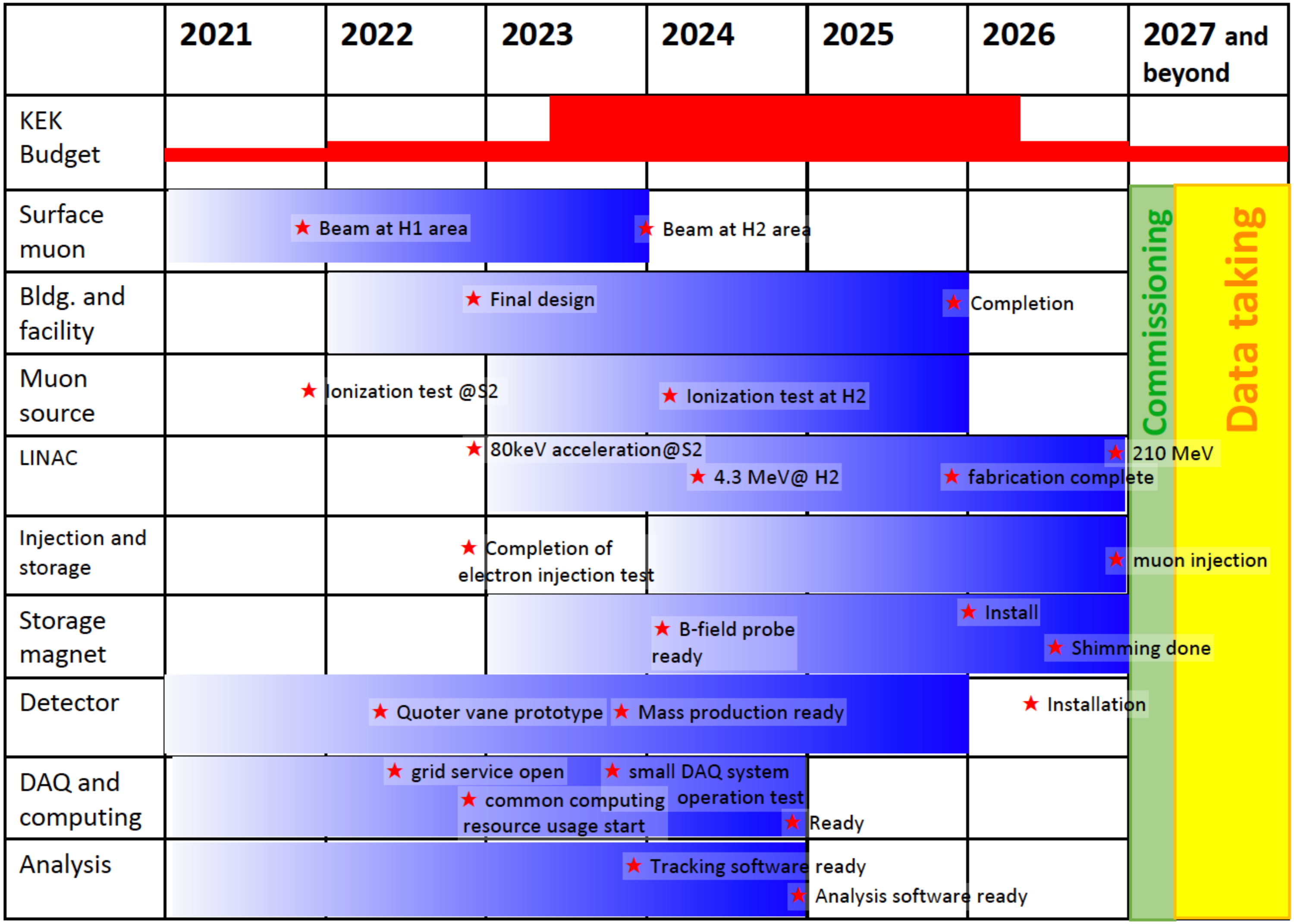
Circuit model

MC30 Quench





Intended plan



- Requesting the funding to the government

Summary

- COMET
  - Construction of COMET superconducting muon beamline for Phase I is underway
  - Construction will be finished in the end of JFY2023.
  - Magnet commissioning and beam run will start in JFY 2024.

- J-PARC *g*-2/EDM
  - Design stage
    - Basic design was finished -> Engineering design
  - Physics run will start n 2027, (hopefully).