Status of Superconducting Magnet Projects and R&D at KEK

Toru Ogitsu
On be half of KEK Cryogenics Science Center
and
J-PARC Center Cryogenics Section

Contents

- On going Projects
  - HL-LHC D1
  - COMET
  - g-2/EDM
- Future R&D
  - High Field Magnet
  - Radiation Hard Magnet
- Summary

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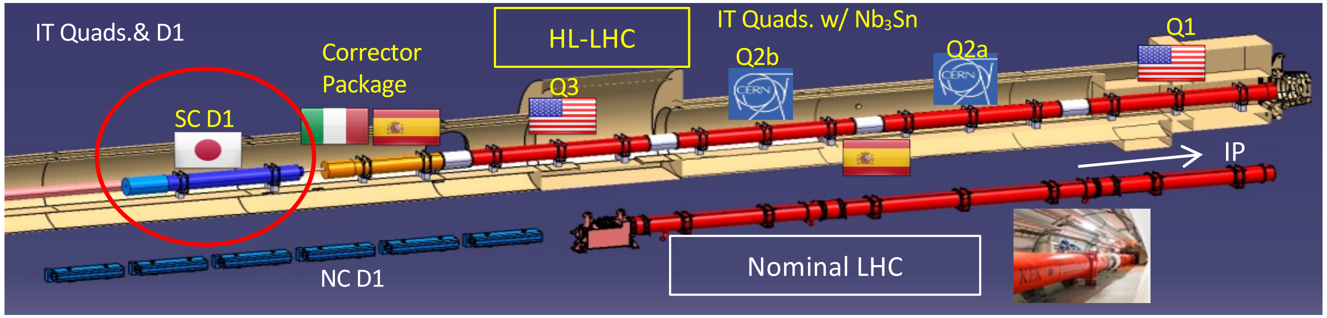
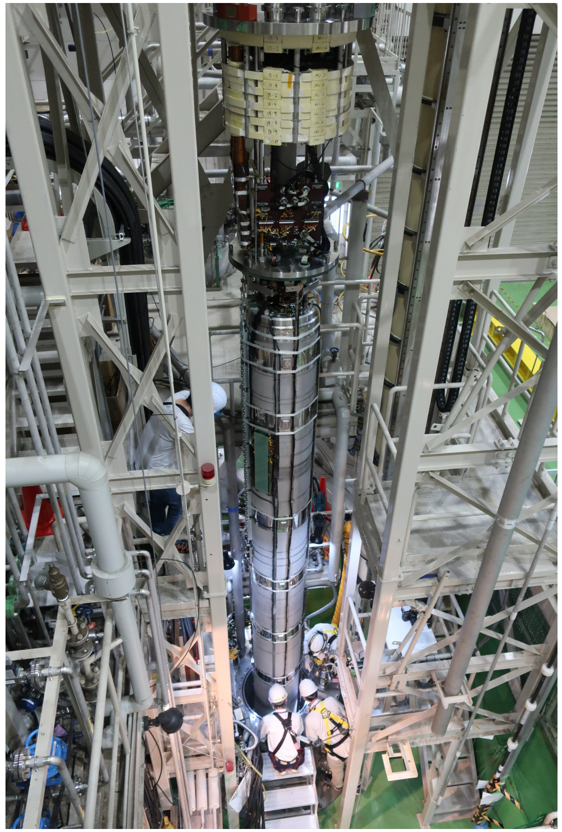
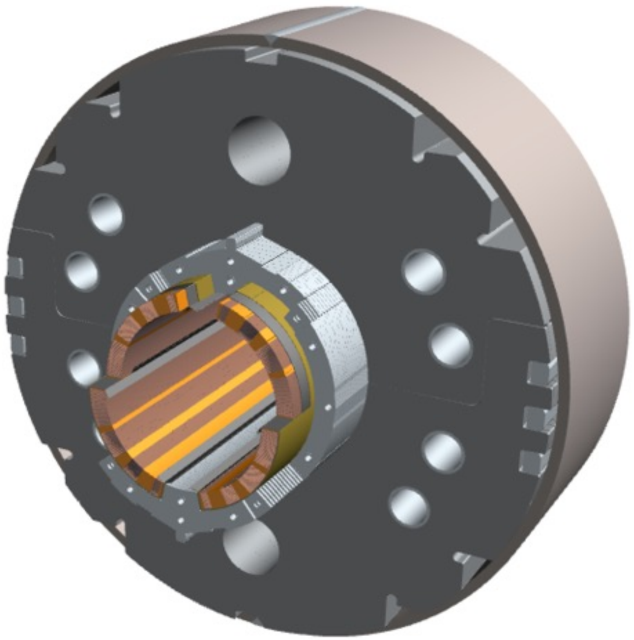
HL-LHC D1 Magnet





Beam Separation Dipole
KEK Contribution to HL-LHC

- Large Aperture 150mm, 6T Dipole

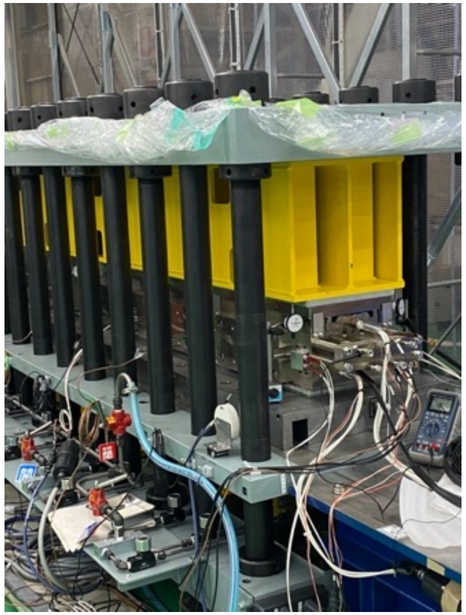


HL-LHC D1 Magnet

Sigh of MOU between CERN and KEK

Manufacturing of D1 Prototype

- Coil fabrication (LPT-1 and LPB-1 coils) started October 2, 2020.



- Azimuthal coil size measurement (evaluated as σ_{pole}) Target: 115 MPa
  - Top: L 113 MPa, R 112 MPa
  - Bottom: L 109 MPa, R 111 MPa
- The prototype coils achieved the coil size consistent with the model magnets and the sufficient pre-stress at the assembly can be expected.
- Dimension check: OK
- Electrical test: OK

Manufacturing of D1 prototype

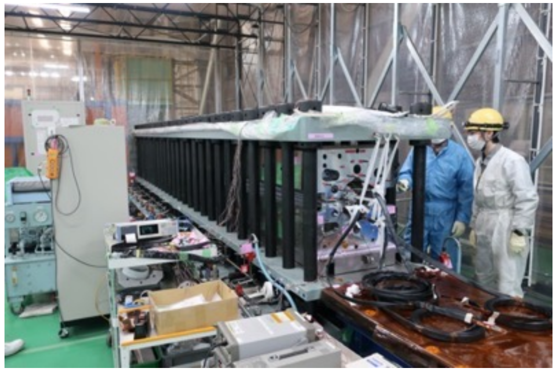
QPH, ground insulation wrapping

Top/bottom coil assembly

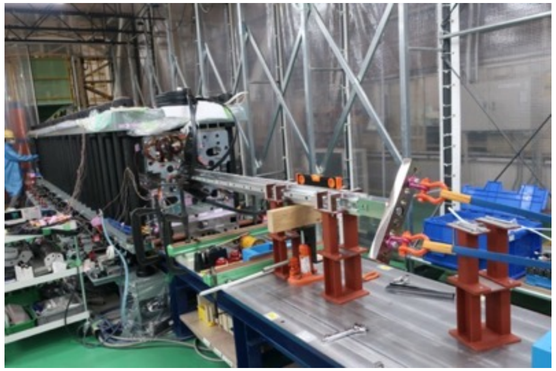
Brass shoe assembly

Collaring

Collared coil on bottom yoke



Yoking



Removal of collaring mandrel

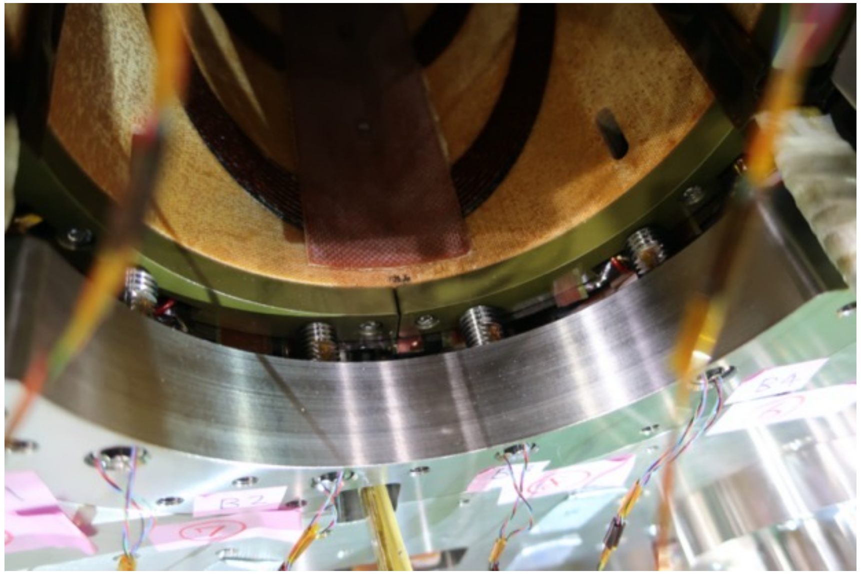
Shell welding

Welding of alignment markers

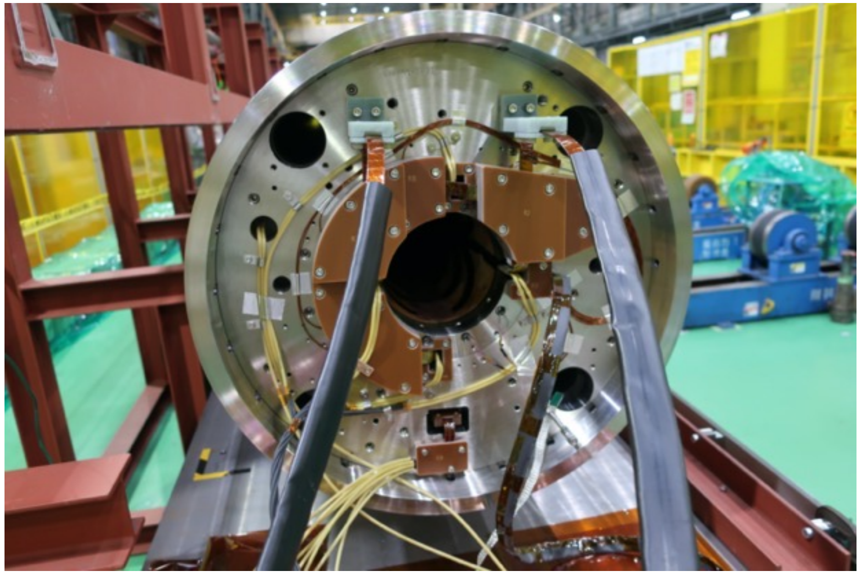
End ring welding

Manufacturing of D1 Prototype

- Axial compression on SC coils



- Splice work and bus-leads

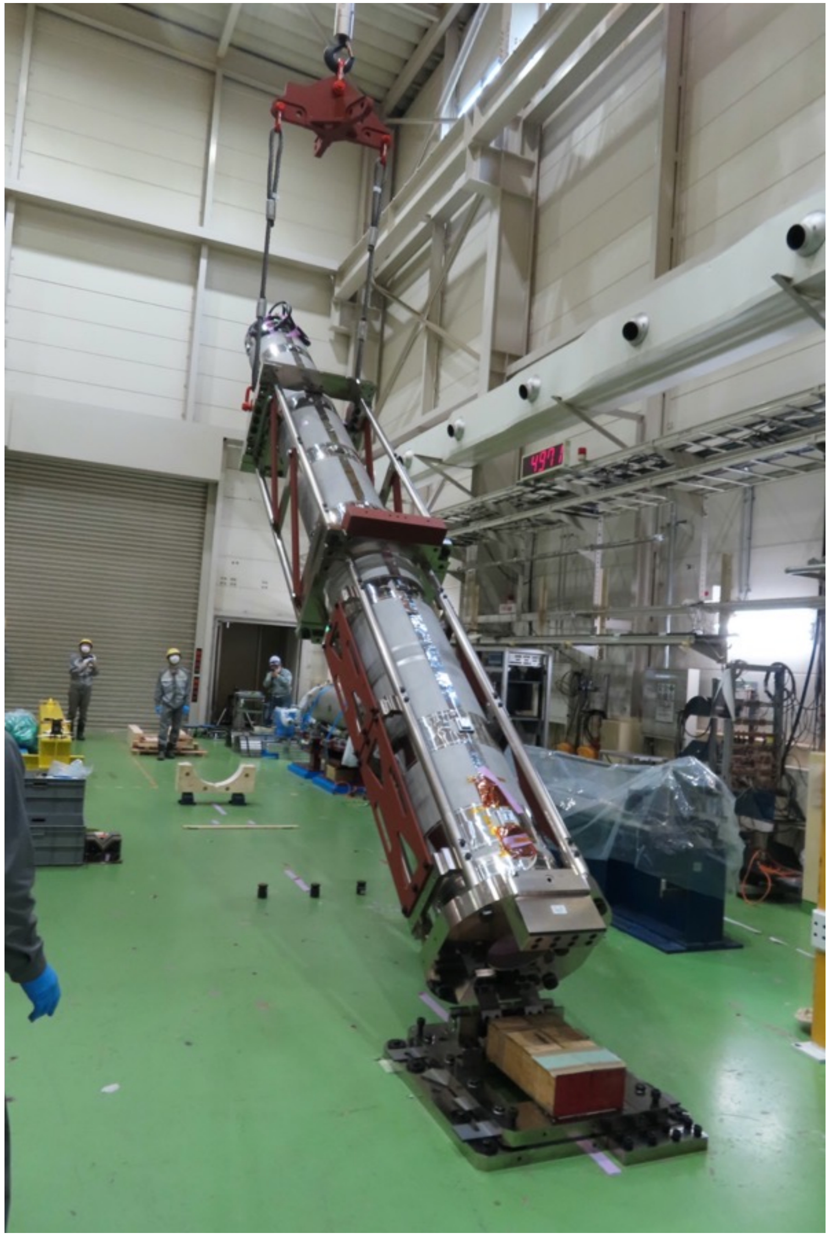


Manufacturing of D1 Prototype

- Completed D1 prototype magnet

Testing of D1 Prototype at KEK

- Lifting up the D1 magnet



- Insertion into vertical cryostat

Issue: Evaporated Gas and Voltage Limit

1st test cycle

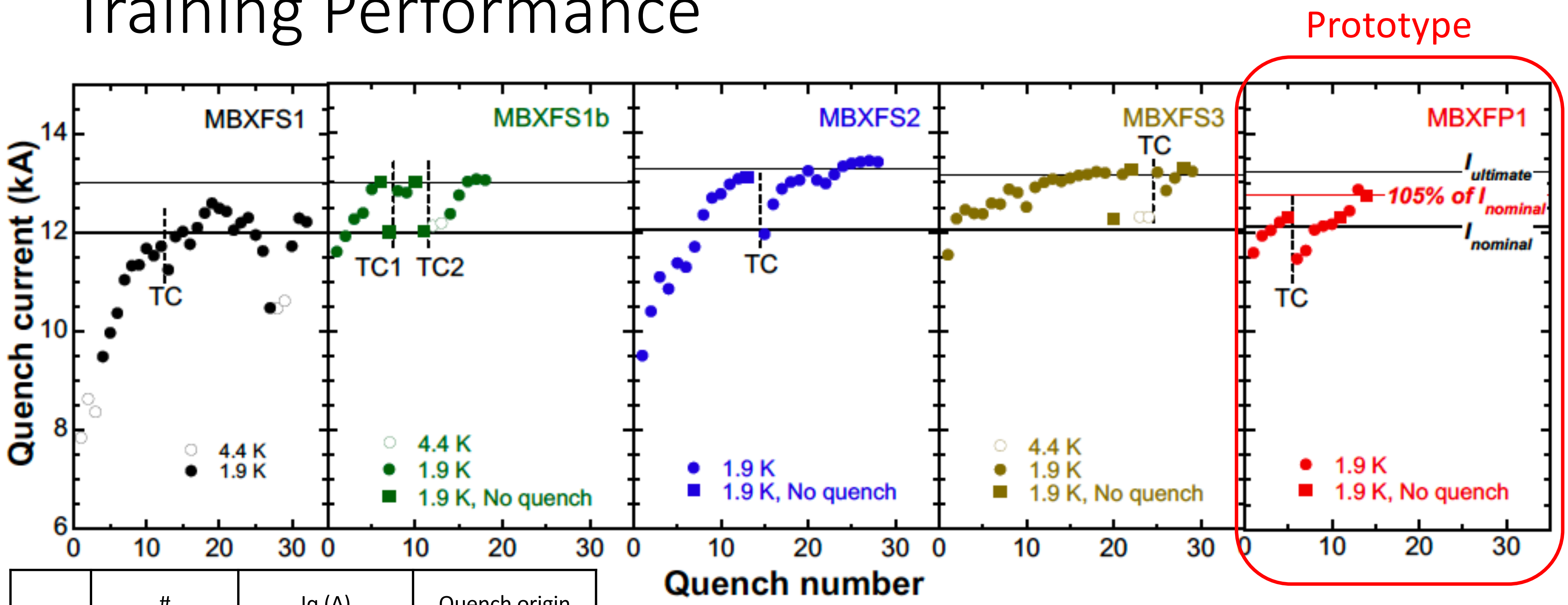
- R_{dump} of 25 mΩ for training quench was determined by voltage limit of DCCB.
- Due to a large energy dissipation in the cryostat and limited capacity of helium gas bag, it was impossible to recover the whole evaporated gas even at the nominal current.

2nd test cycle

- R_{dump} was increased to 50 mΩ for training quench to enhance the energy extraction.
- Thanks to that, the magnet was able to be energized up to **12.87 kA** while the helium gas was mostly recovered. But, the terminal voltage reached the DCCB limit and **we decided NOT to go beyond**.

Countermeasures: New dump resistor (~~~40 mΩ or~~ Metrosil varistor) will be implemented in the energy extraction

Training Performance



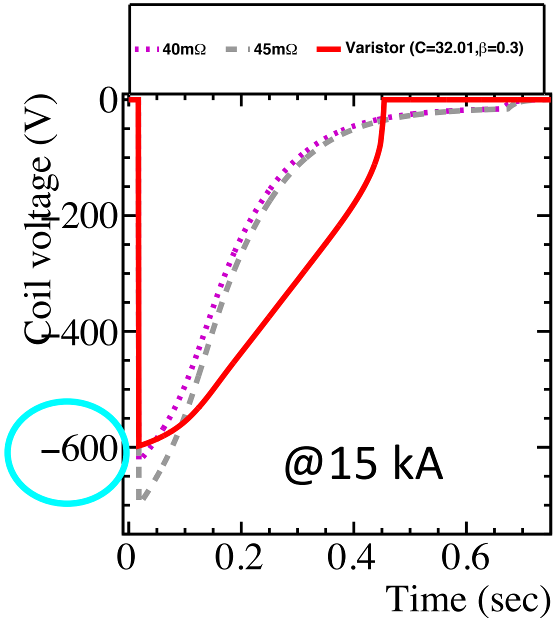
	#	Iq (A)	Quench origin
1st	1	11589	Top coil
	2	11934	Top coil
	3	12042	Bottom coil
	4	12209	Top coil
	5	12310	No quench
2nd	1	11466	Top coil
	2	11634	Bottom coil
	3	12052	Top coil
	4	12132	Bottom coil
	5	12169	Top coil
	6	**12310**	**No quench**
	7	12436	Bottom coil
	8	12866	Bottom coil

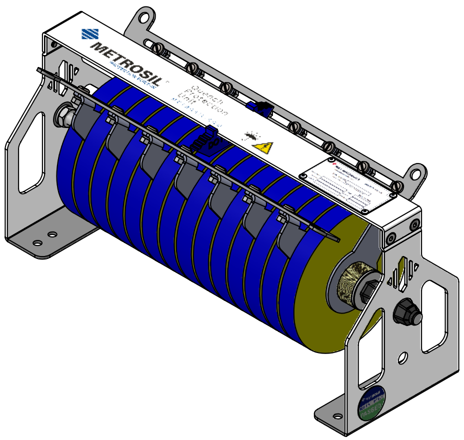
- The magnet needed 3 training quenches to reach the nominal (12.11 kA).
- The maximum current was 12.87 kA which was limited by allowable terminal voltage of DCCB.
- The magnet safely operated at 12.75 kA (105% nominal) for 4 hours.

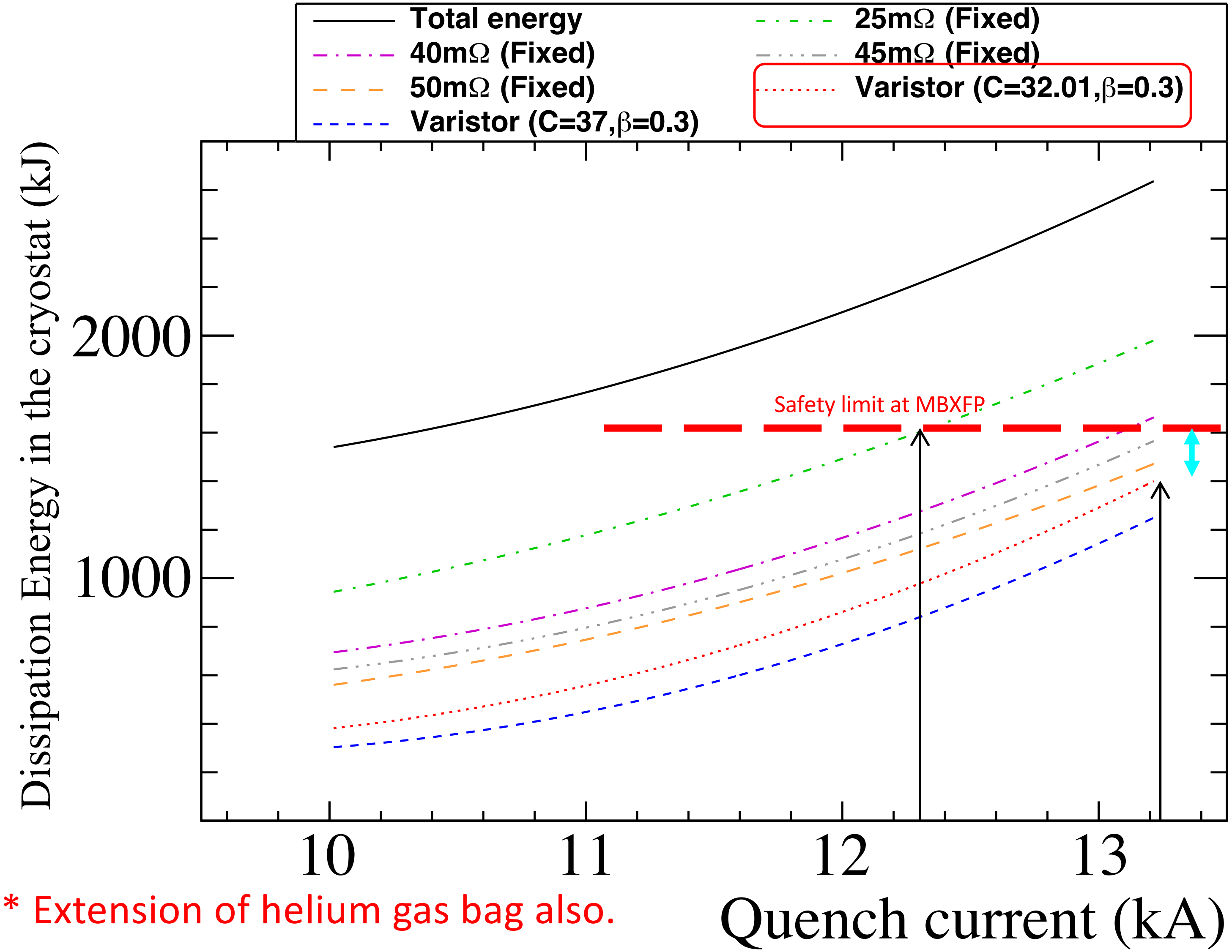
While the ultimate was not demonstrated, good performance in training behavior.

NCR: MBXFP1 Quench Performance EDMS2632162

Implementation of Varistor in EE system for the series magnets testing



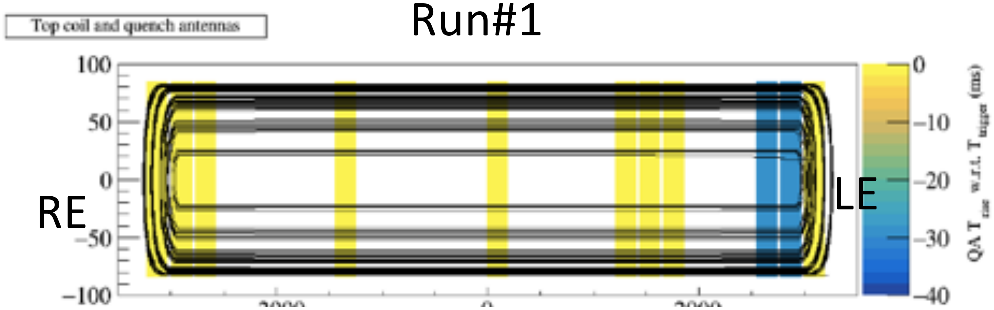




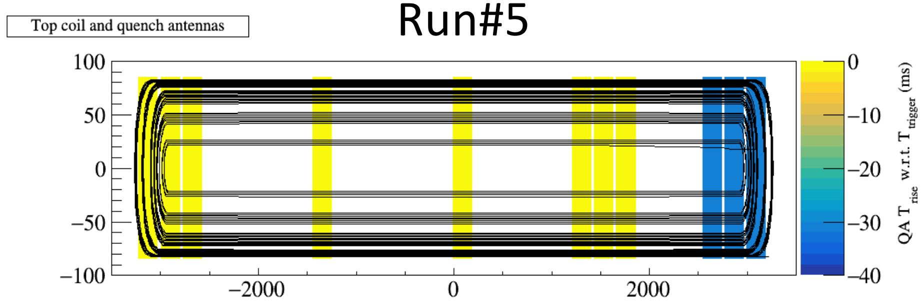
* Extension of helium gas bag also.

Quench location identified by antennas

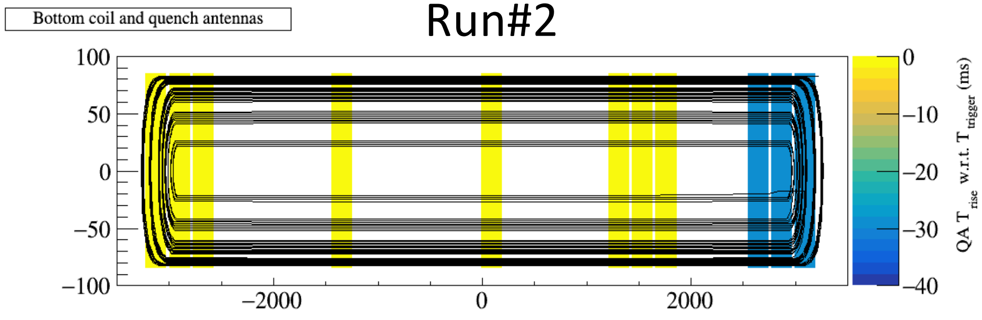
Run#1



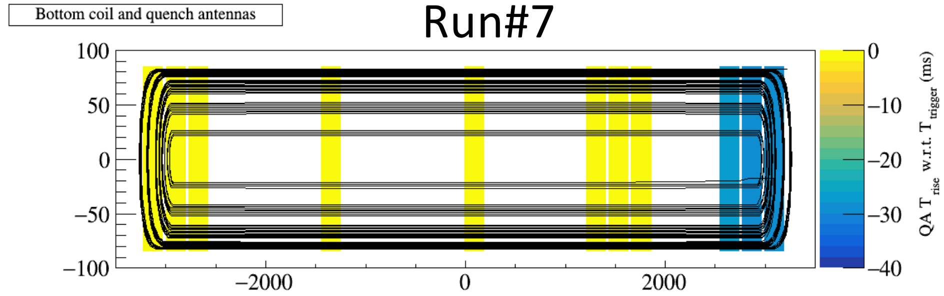
Run#5



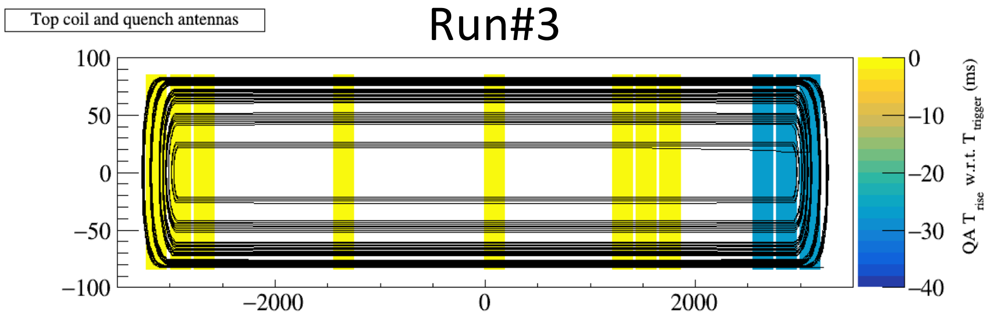
Run#2



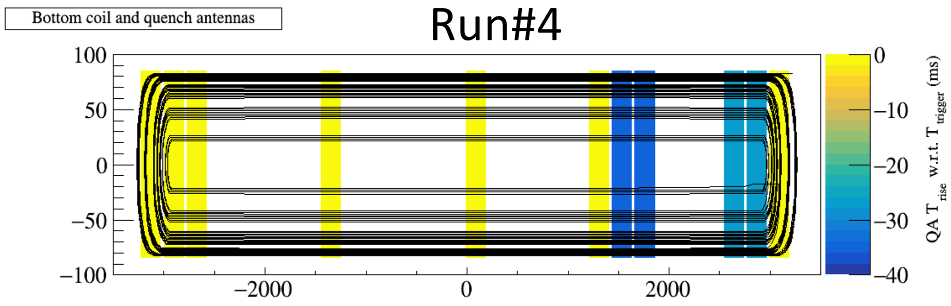
Run#7

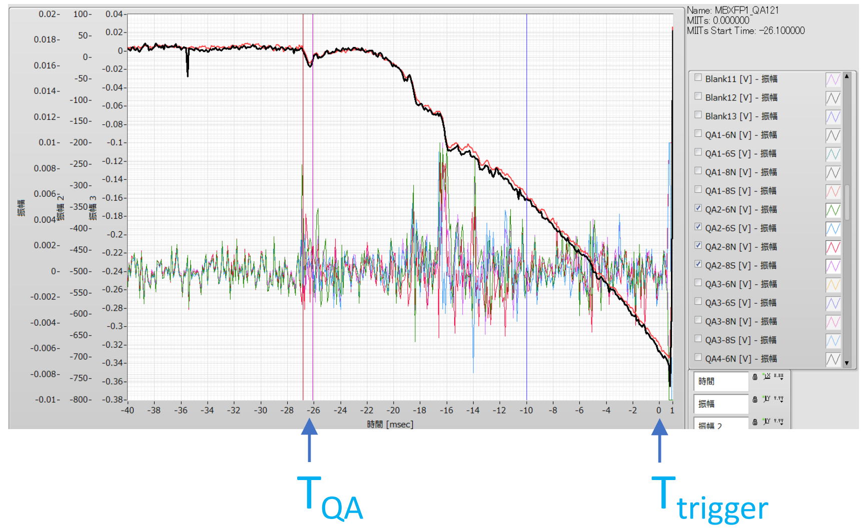


Run#3



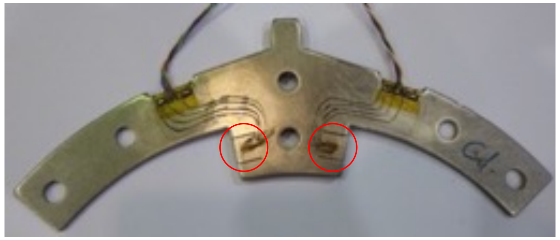
Run#4





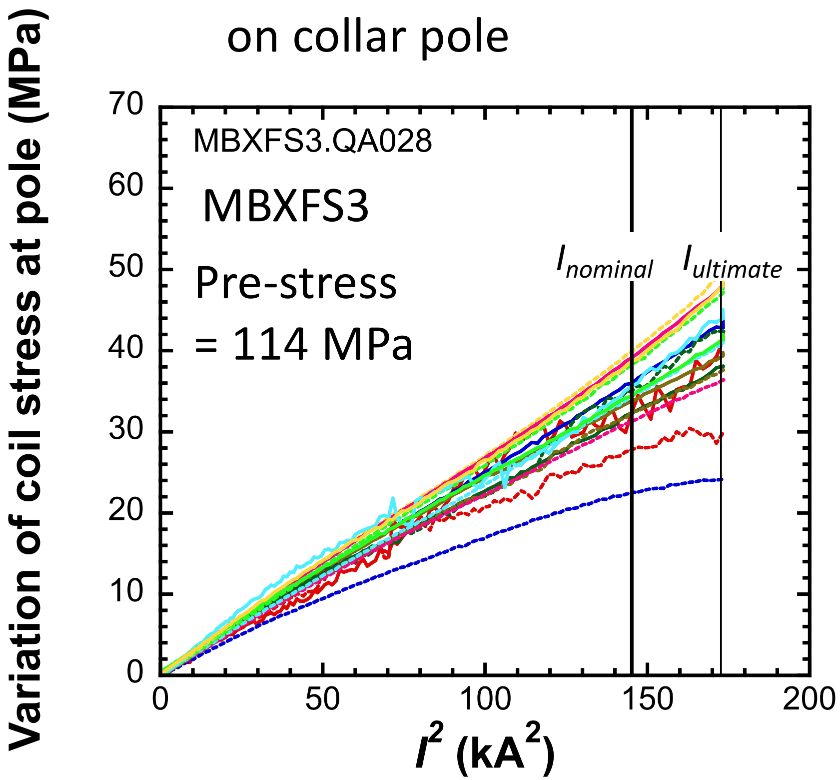
All the quench locations are confirmed to be around the LE region.

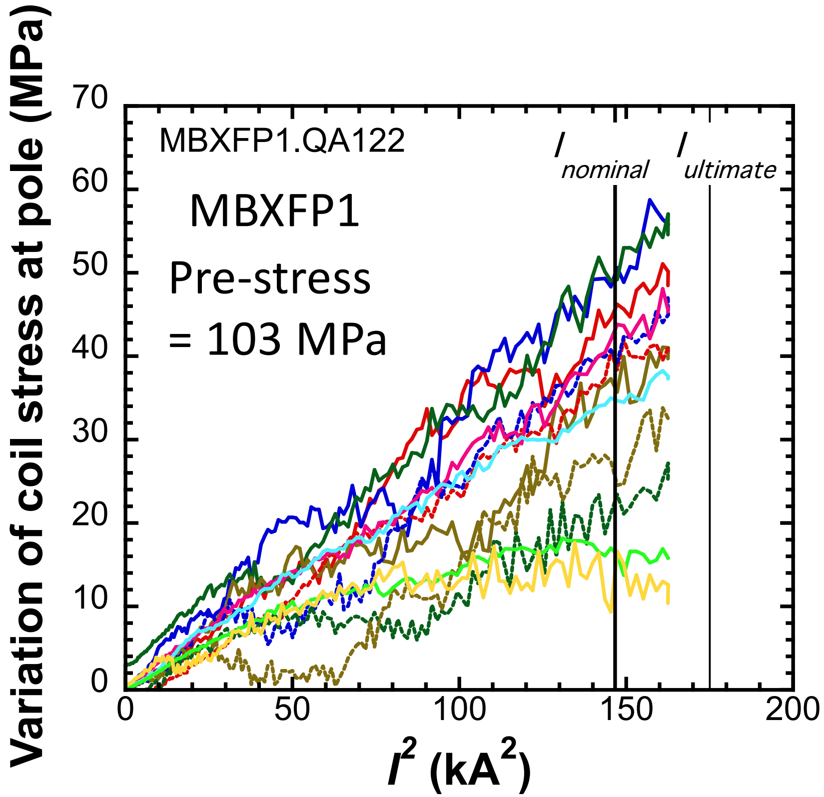
Coil stress at pole during excitation



Strain gauges on collar pole

Pre-stress is defined as azimuthal coil stress measured at collar pole after yoking.





- Coil stress in a straight section was measured at 12 points at collar pole.
- Coil stress at pole continues to change at most of the measured points up to 105% of the nominal current suggesting that pre-stress still remains.

Summary of MFM at the Magnet Center

(Units)

	MBXFS2		MBXFS3		MBXFP	
	3 kA*	12.05 kA*	3 kA*	12.05 kA*	**3 kA***	**12.11 kA**
b_3	20.84	35.94	24.05	37.28	**-3.06**	**-8.51**
b_5	-1.98	1.61	-1.82	2.01	**3.03**	**6.68**
b_7	-0.16	-0.83	0.03	-0.58	**1.24**	**0.98**
b_9	0.05	0.40	0.08	0.50	**0.79**	**1.35**
b_{11}	0.20	0.21	0.21	0.23	**-0.02**	**-0.06**
b_{13}	-0.50	-0.53	-0.51	-0.52	**-0.90**	**-1.03**
b_{15}	-0.96	-1.02	-1.01	-1.10	**-1.31**	**-1.52**

Large offset was significantly reduced.

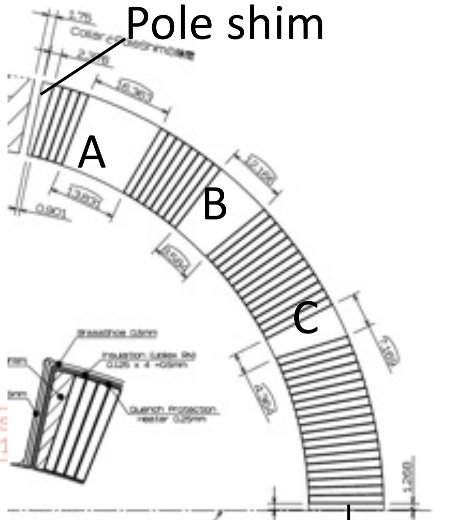
Induced by the unexpected cross section change of MBXFP1 due to increased cable thickness.

(*) Average of ramp-up/down

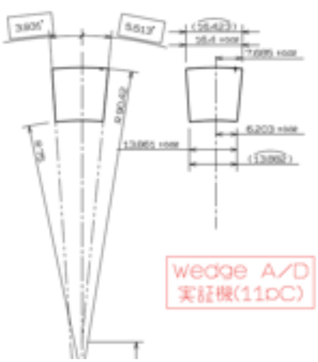
Change of the wedge size

EDMS 2612909

Wedge used in MBXFP

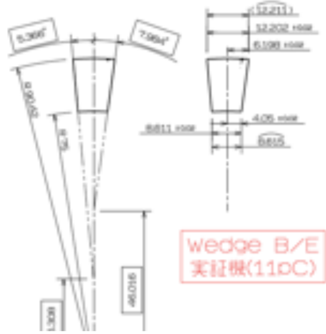


Wedge A



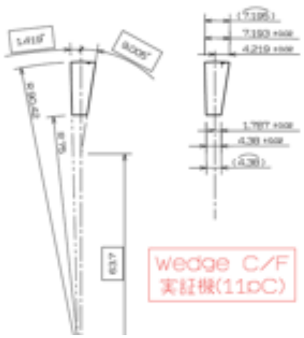
R_{in} : -170um
R_{out}: +145um

Wedge B



R_{in} : -151um
R_{out}: -143um

Wedge C



R_{in} : -294um
R_{out}: -253um

Pole shim

R_{in} : +554um
R_{out}: +179um

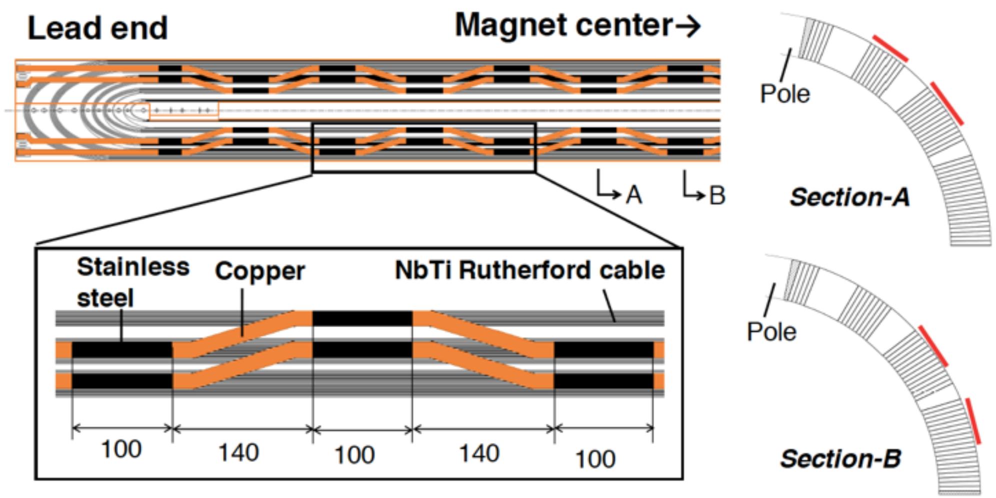
MP shim

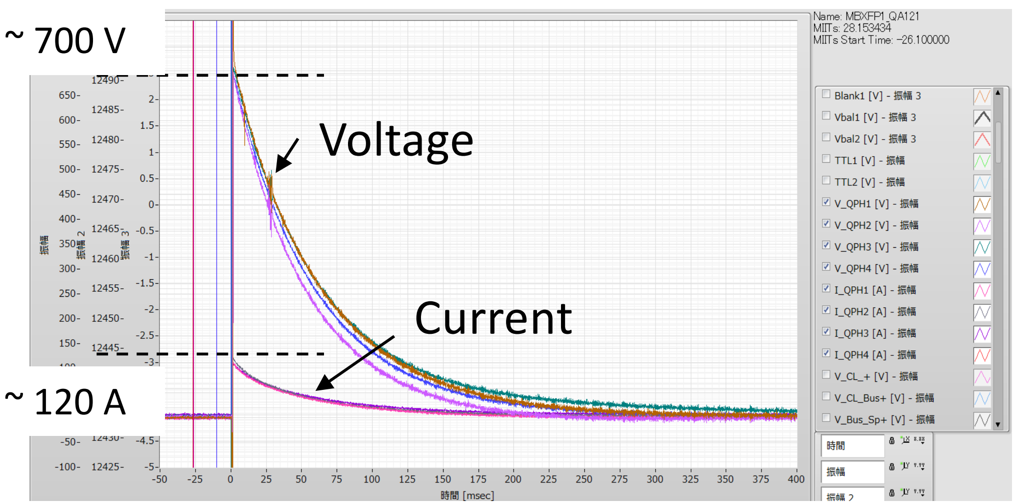
+58um

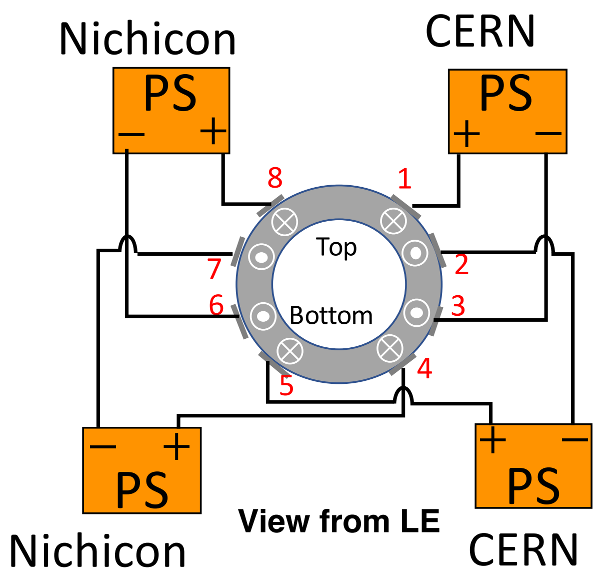
Wedge for MBXF series

Quench Protection of D1 magnet

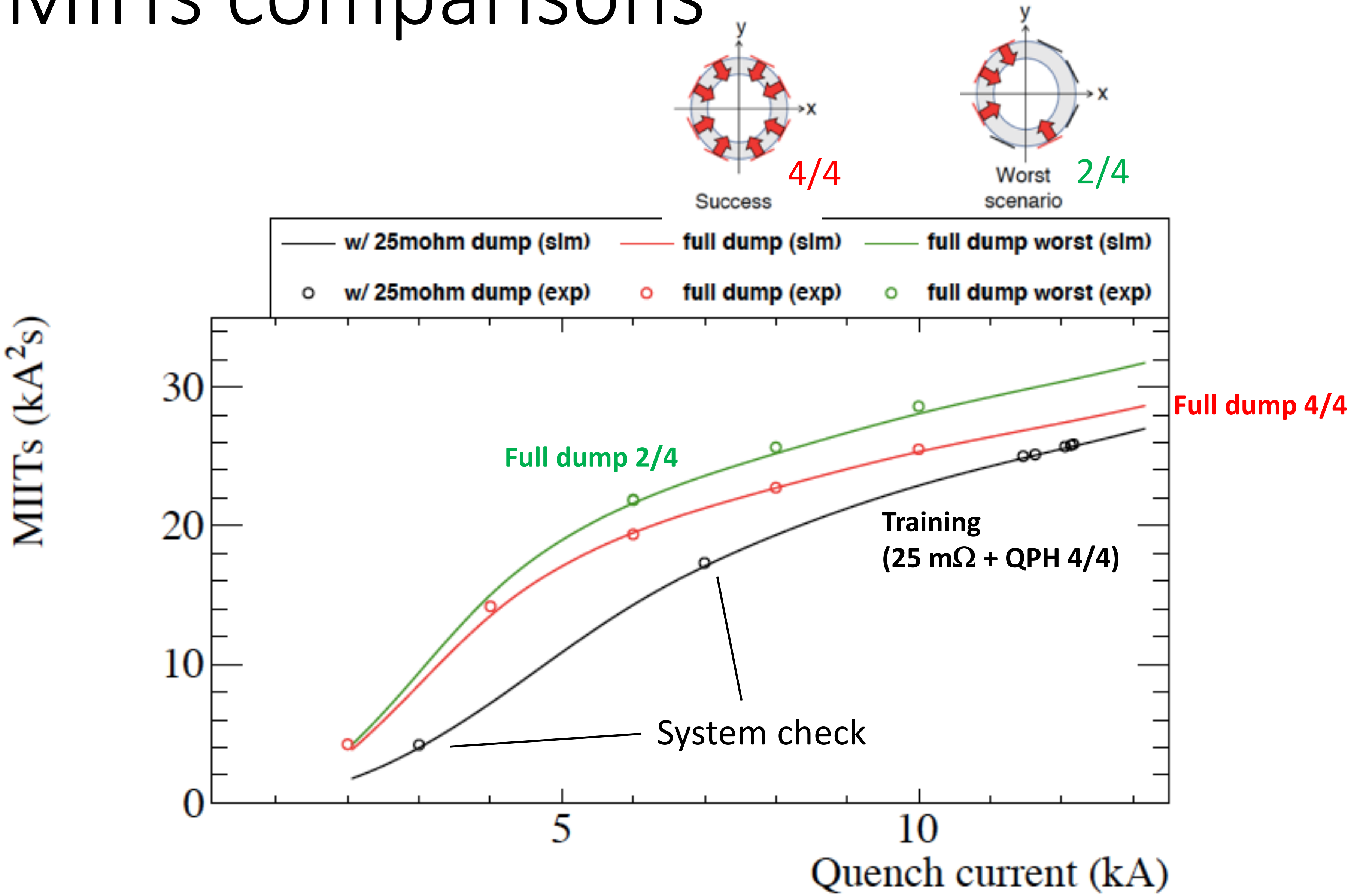
- MIITs (Quench Integral): index to evaluate peak temperature in the quenched coil.
- Baseline of the D1 magnet protection in case of quench: Quench Protection Heaters
  - ➢ Designed by the KEK's simulation code.
  - ➢ Verified with 2-m long model magnets so far.
- **First validation with a 7-m long full-scale magnet.**







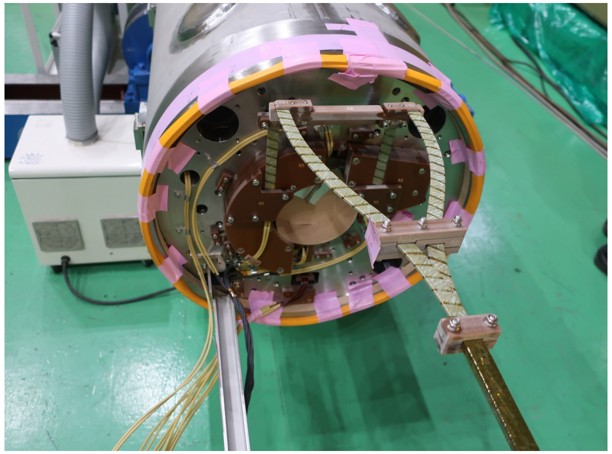
MIITs comparisons



- Measured MIITs are in good agreement with simulated ones

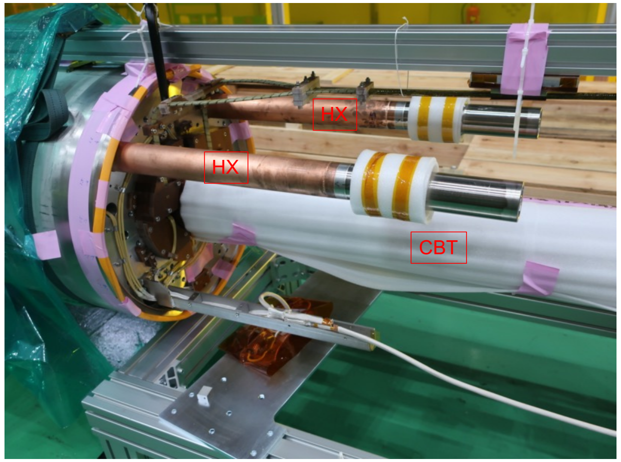
Validating both D1 heater performance and KEK's simulation code

D1 Final Assembly at Hitachi



Splice Work

Beam Tube Insertion



Heat Exchanger Insertion

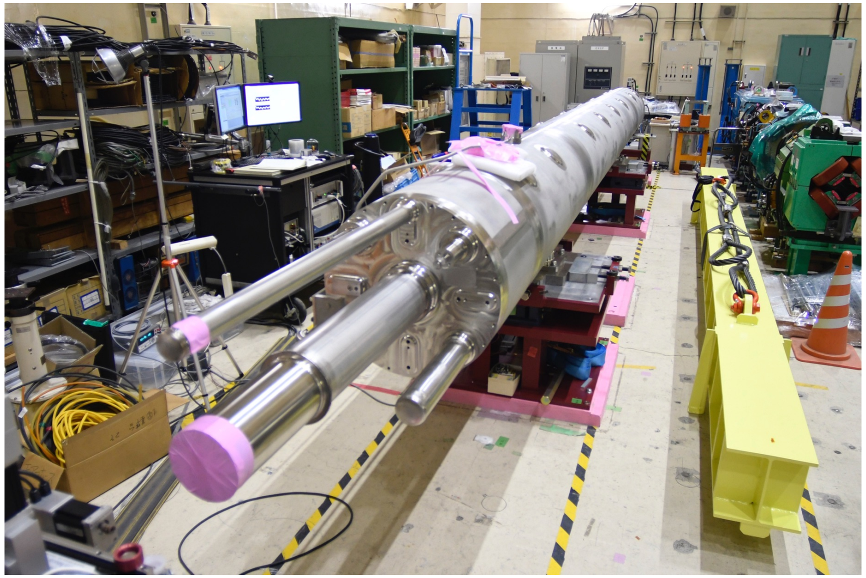
End Dome Welding

After Welding

Capillary Tube Assembly

D1 Proto-Type Final Procedures

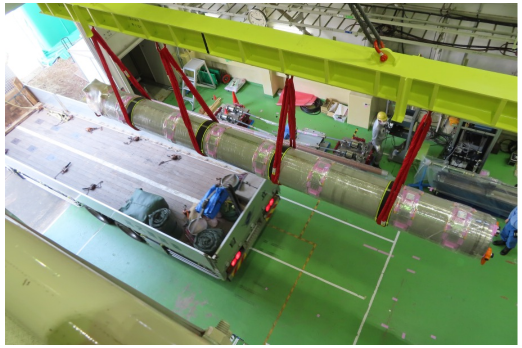

Preparation of Leak Check

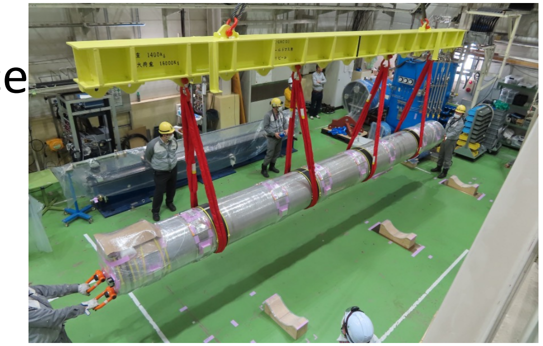

Field Angle Measurement at KEK


Final Leak Check


Shipping Preparation

Summary D1





- Model Magnet (since early 2010s)
  - 3 Model Magnets
    - 1^{st} model rebuilt due to insufficient preload
    - 1^{st} rebuilt and 2^{nd},3^{rd} showed good training performance
    - Field qualities are not good > modified for Prototype
- Prototype Magnet (since 2018)
  - Quench performance were good enough
    - Test stand needed to be upgraded
  - Field quality needed to be optimized for production
    - Small change in wedges
- Production Magnet (since 2021)
  - **1^{st} production arrived to KEK CSC last Thursday**
  - Following magnets
    - Delayed due to assembly troubles

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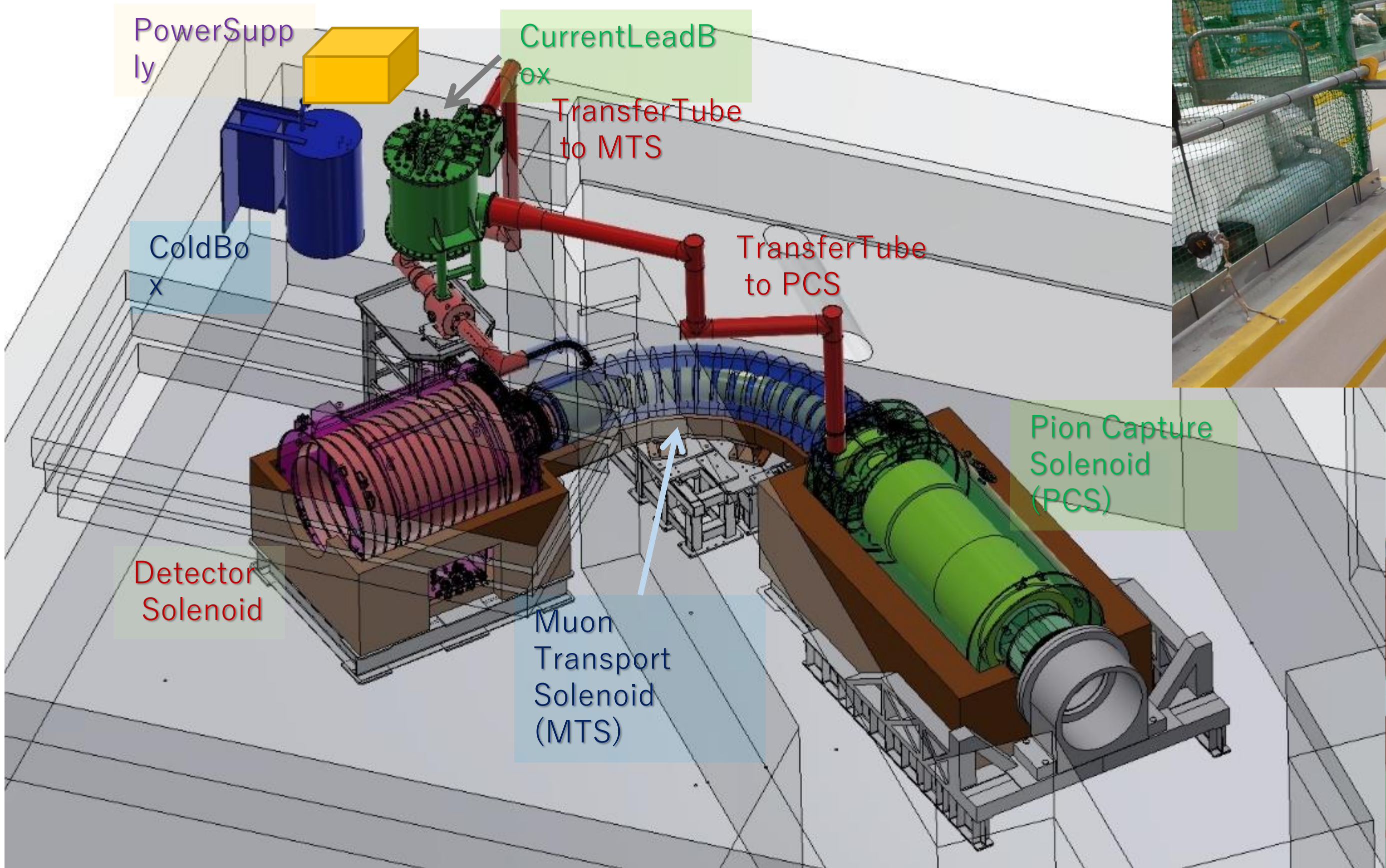
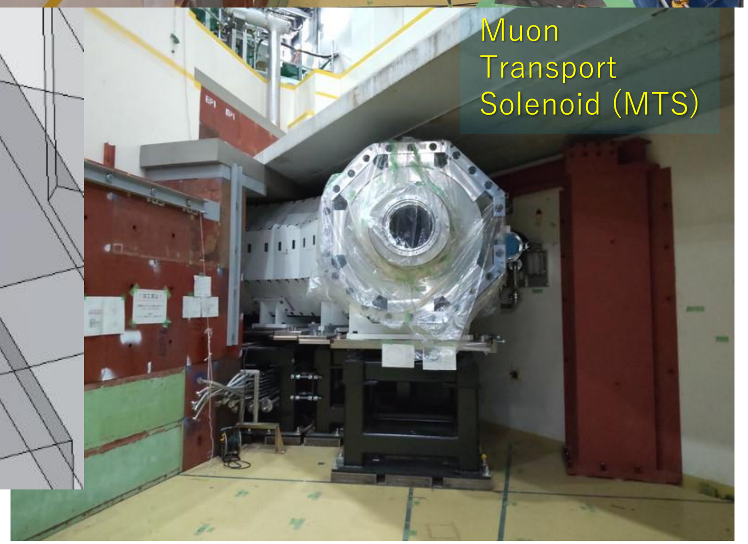
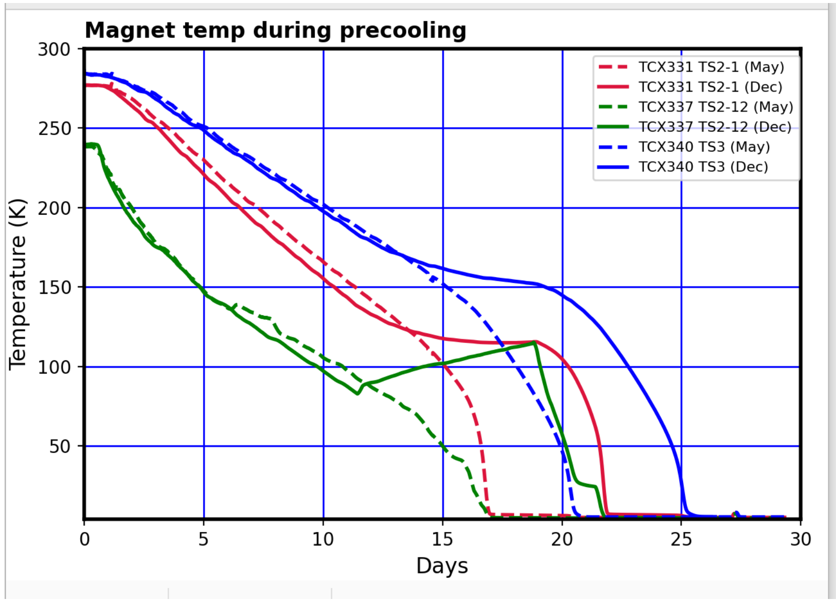
Superconducting Magnet System (COMET Phase-1)





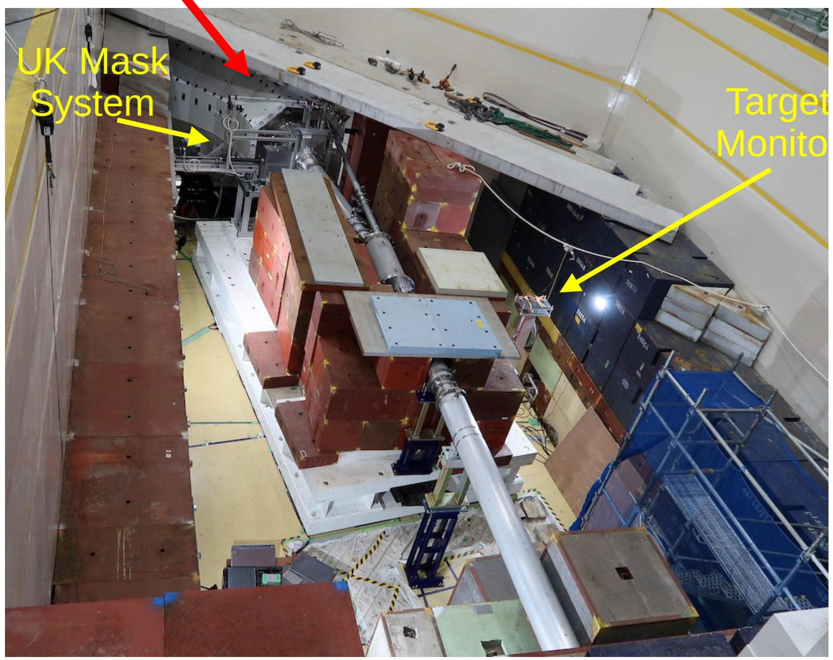
Phase α Operation

- Trial Beam Operation without production solenoid
  - 1.5T operation for transport solenoid
  - Muon beam detected at the exit of the transport solenoid



Transport Solenoid

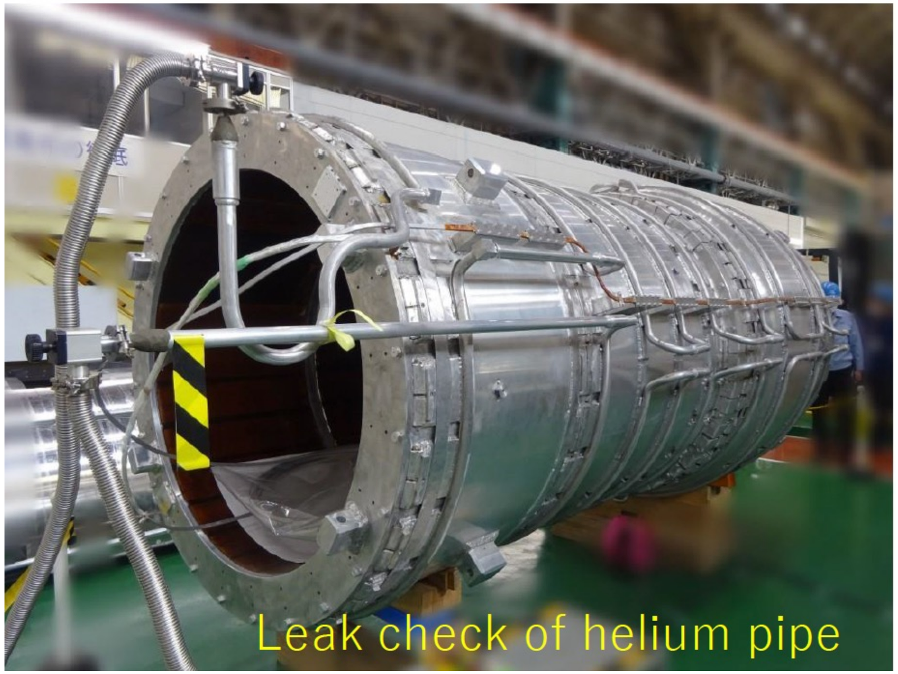
Down stream with detector



UP stream with target

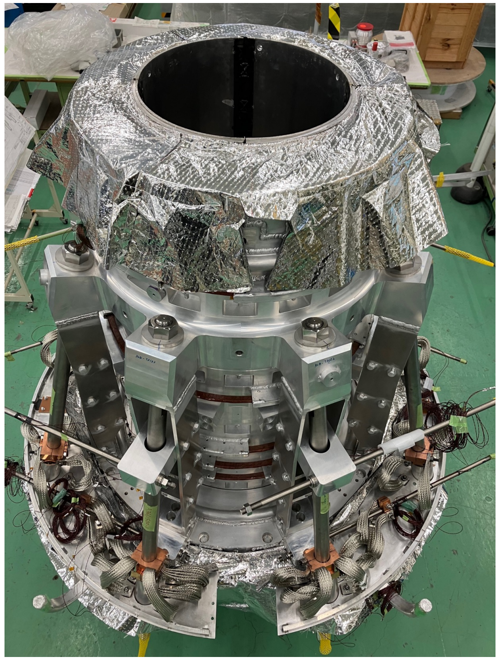
Other magnets

- Production Solenoid
  - CS solenoid: Insulation failure detected during high pot test
    - Recovery procedure is now under discussion
- Detector Solenoid
  - Bridge solenoid cold mass completed



CS solenoid

Bridge solenoid



TS1 solenoid

Summary COMET

- Phase α Operation
  - Beam operation completed, now under analysis
- Production Solenoid
  - Final assembly on going
    - Electric Insulation failure detected for CS coil
      - Recovery procedure is now under discussion
- Detector Solenoid
  - Bridge solenoid cold mass completed
  - Detector solenoid???

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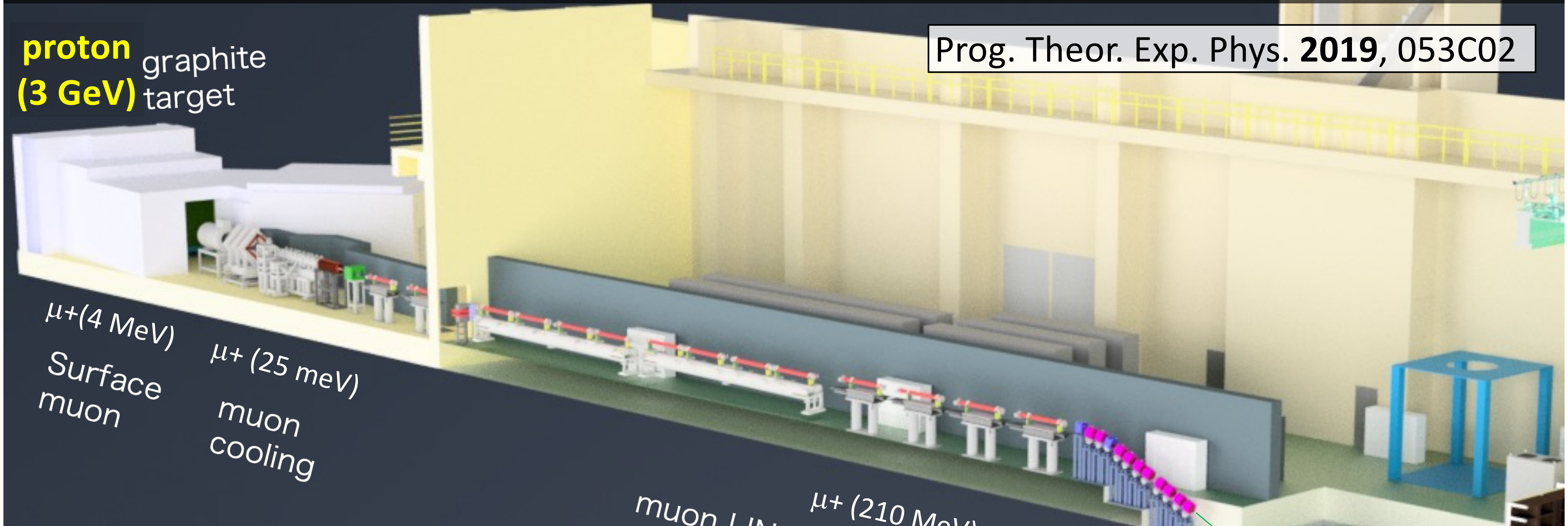
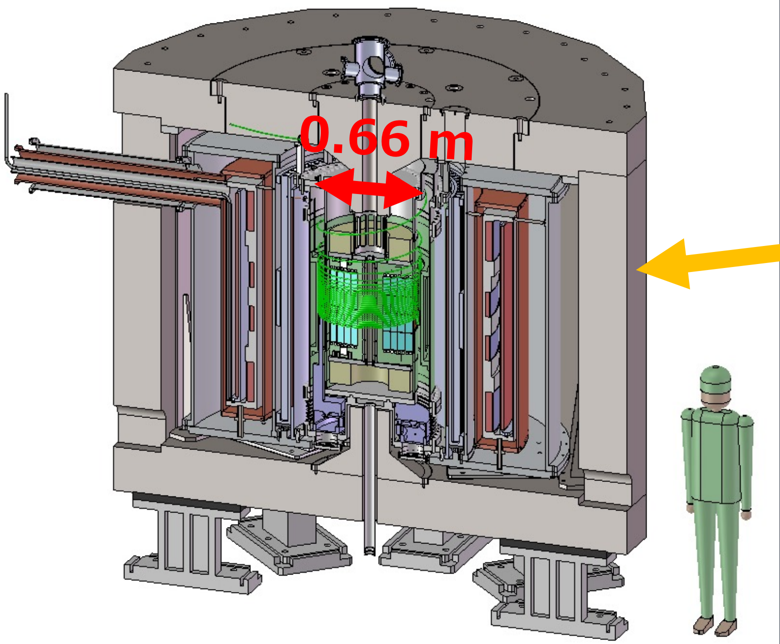
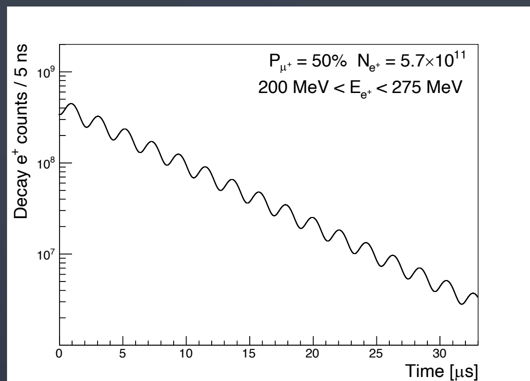
Muon g-2/EDM experiment at J-PARC





muon storage magnet



Goals:

g-2 450 ppb (~ BNL/FNAL run 1)

EDM 1.5 x 10^{-21} e・cm (x70 better)

History

Date	Events
July, 2009	LOI submitted to PAC8
Jan, 2010	Proposal submitted to PAC9
Jan, 2012	CDR submitted to PAC13, Milestones defined.
July, 2012	Stage-1 status recommended by PAC15, granted by the IPNS
May, 2015	TDR submitted to PAC
Oct, 2016	Revised TDR submitted to PAC and FRC
June, 2016	**Selected as a KEK-PIP priority project**
Nov, 2016	Focused review on technical design
Dec, 2017	Responses and Revised TDR submitted to PAC
Nov, 2018	**Stage-2 status granted by the IPNS director**
Jan, 2019 **Mar, 2019**	**Stage-2 status granted by the IMSS director** **KEK-SAC endorsed the E34 for the near-term priority**
June, 2020	**Grant-in-aid “specially prompted research” (2020-2025)**
April, 2022 **(June, 2022)**	**KEK allocated a budget for preparation for construction** **Funding request to MEXT**

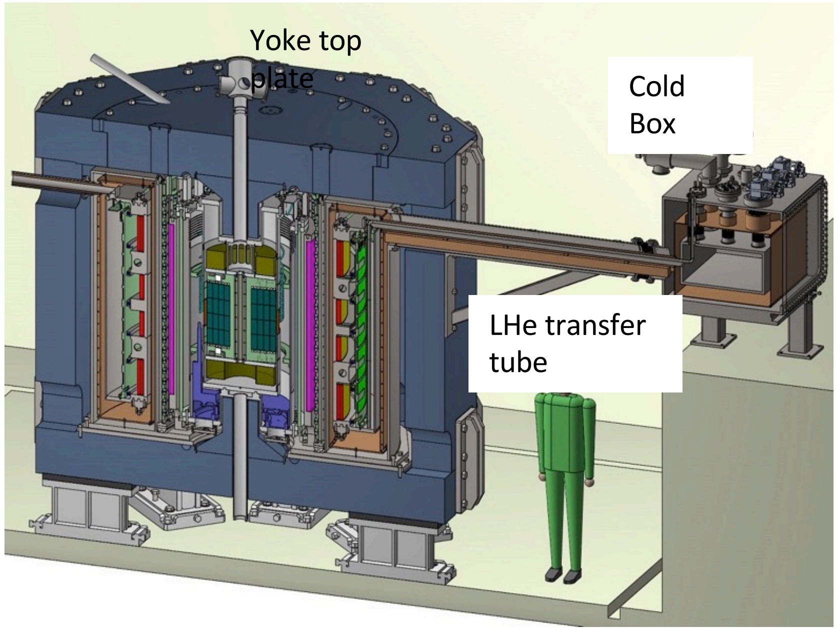
The Magnet

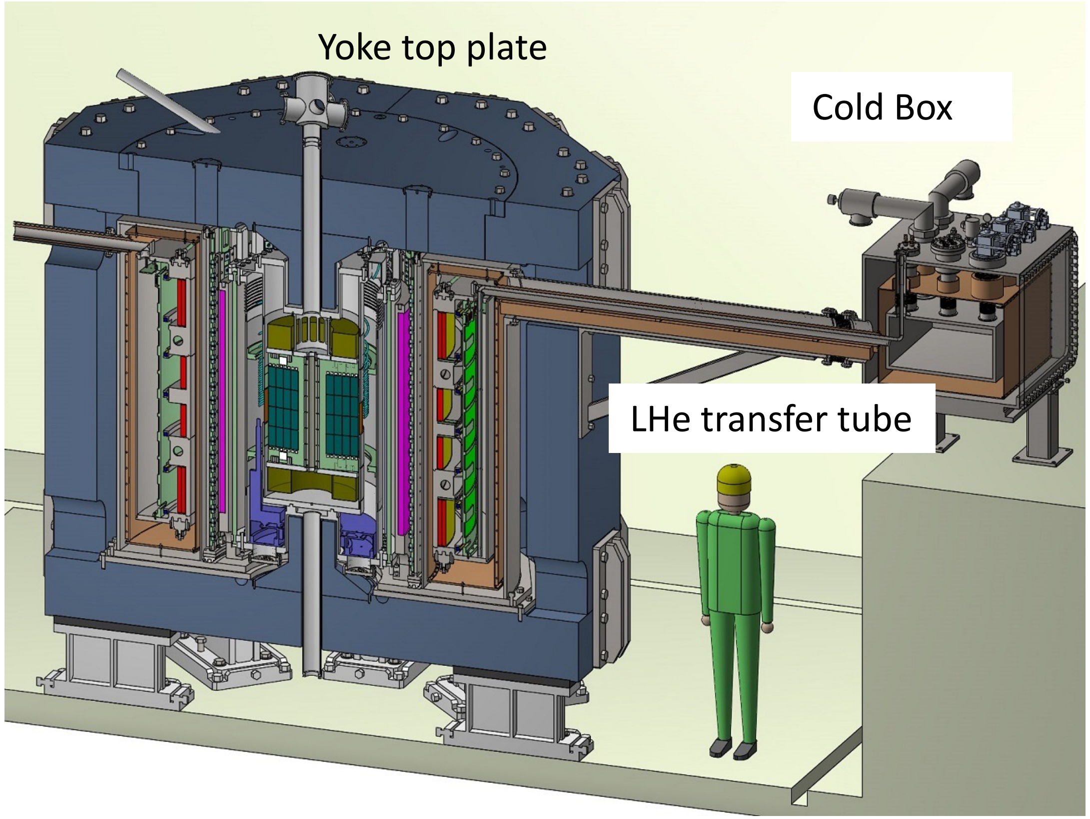
- Storage region :
  - radius : 33.3 ± 1.5 cm
  - height : ± 5 cm
  - Field strength : 3T
  - Uniformity : 0.1 ppm (Azimuthal integral)
- Injection region :
  - Smooth field for beam injection
- Weak focus field: -5e-4 T/m of Br at maximum

Adopt MRI technology

Superconducting solenoid system

- Current model of the magnet



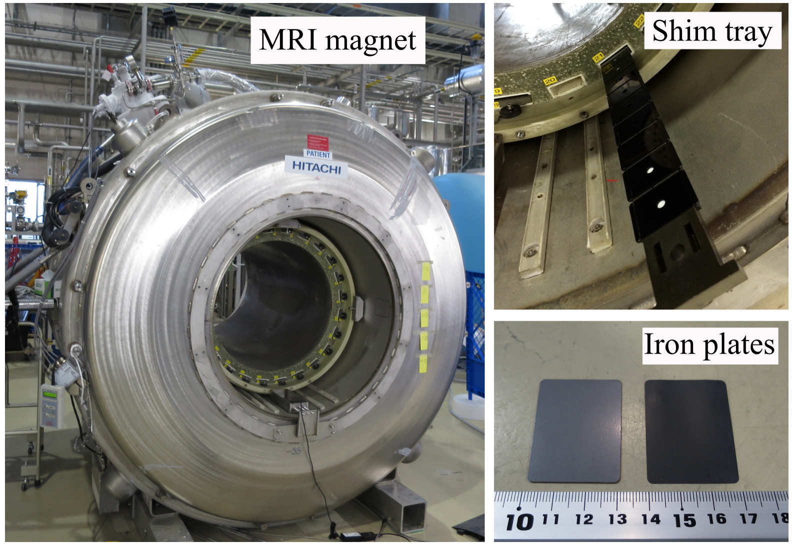


- Superconducting coils : NbTi
  - Main solenoid coil
    - Persistent current operation
  - Weak focusing coil
    - Power supply operation
  - Shim coils
    - Power supply operation
- Cooled by liquid Helium
  - Cryocoolers to recondense LHe
- Separated cold box from magnet cryostat
  - Isolate vibration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

- Mag. field monitoring system
  - CW-NMR probe : < 0.1 ppm accuracy
    - Mapping probe
    - Drift monitoring probe
    - Standard probe

Study on shimming scheme

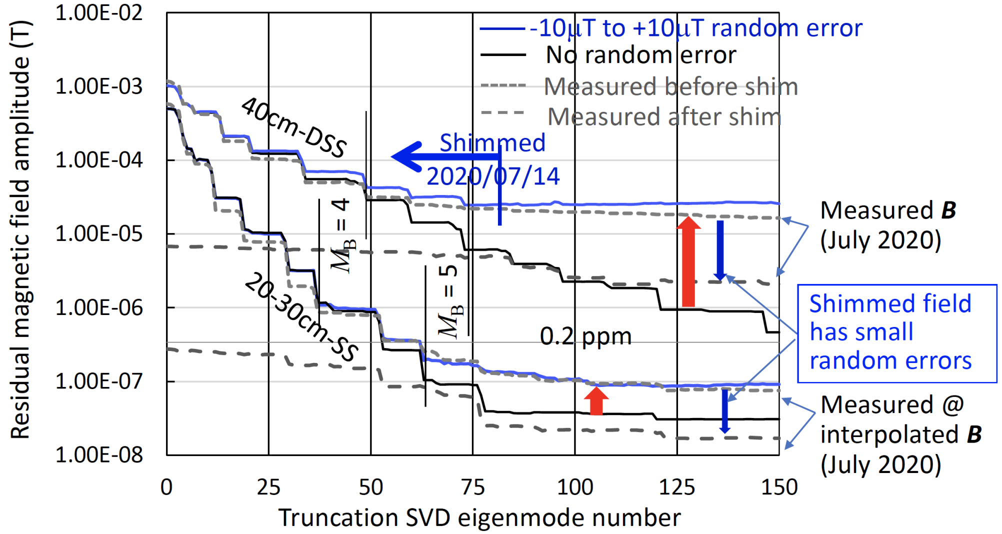
- Studying the shimming scheme : MuSEUM magnet
  - Different magnet
    - Developed process can be applied to g-2



- Simulation study
  - Optimum area for shimming calculation
  - Effect of error field due to massive iron outside the magnet
  - Accuracy of magnetic field interpolation
  - Effect of random measurement error

✓ Random error
  ✓ result in worse homogeneity

➢ Require
  ➢ precise measurement
  ➢ previous rough shimming



- Continue the study to explore the best shimming process

Study of cryocooler vibration effect

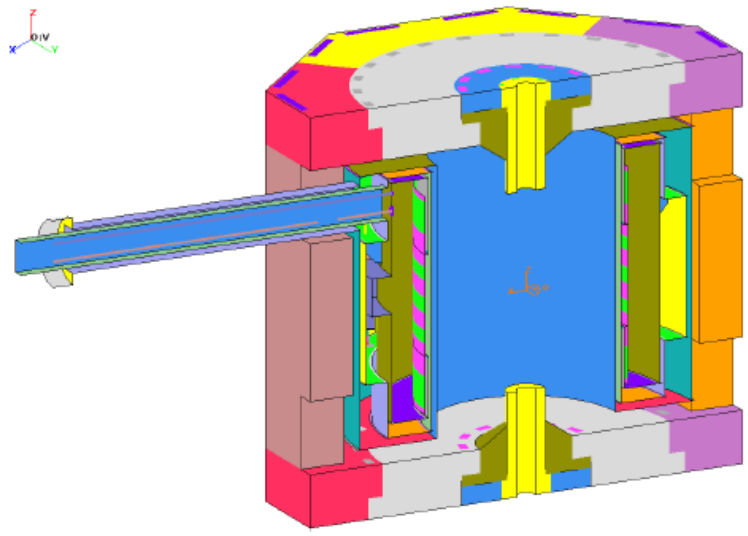
- Vibration source
  - Ground vibration
  - GM cryocoolers

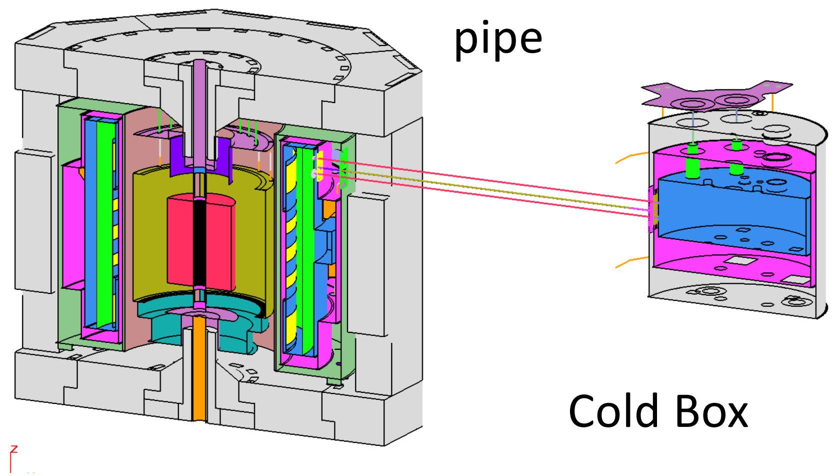
- Ground vibration
  - Magnet : 2019
    - With practical mechanical design
    - Apply measured ground vibration

expect : ~ 0.33 ppm@14.3 Hz

Need vibration isolation system

- GM cryocoolers
  - Cold box : 2020
  - Overall : 2021





Study of cryocooler vibration effect

- Frequency response analysis with ANSYS

Normal vibration modes
1) 20.48 Hz
2) 21.48 Hz
3) 41.67 Hz
4) 53.38 Hz
5) 53.68 Hz
6) 60.74 Hz
:

10 N each

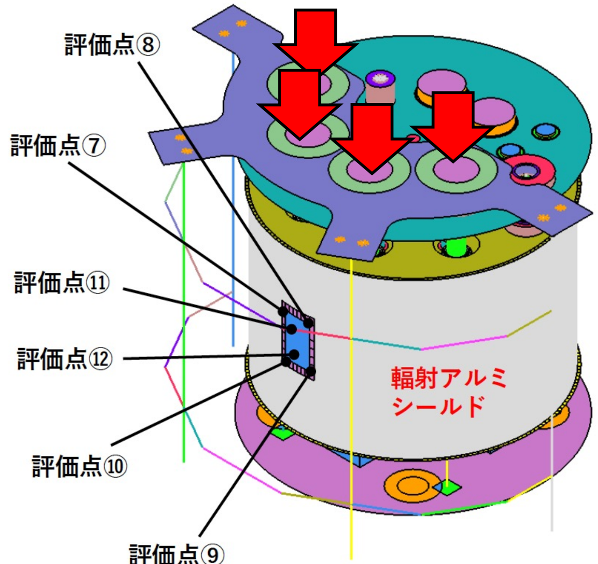
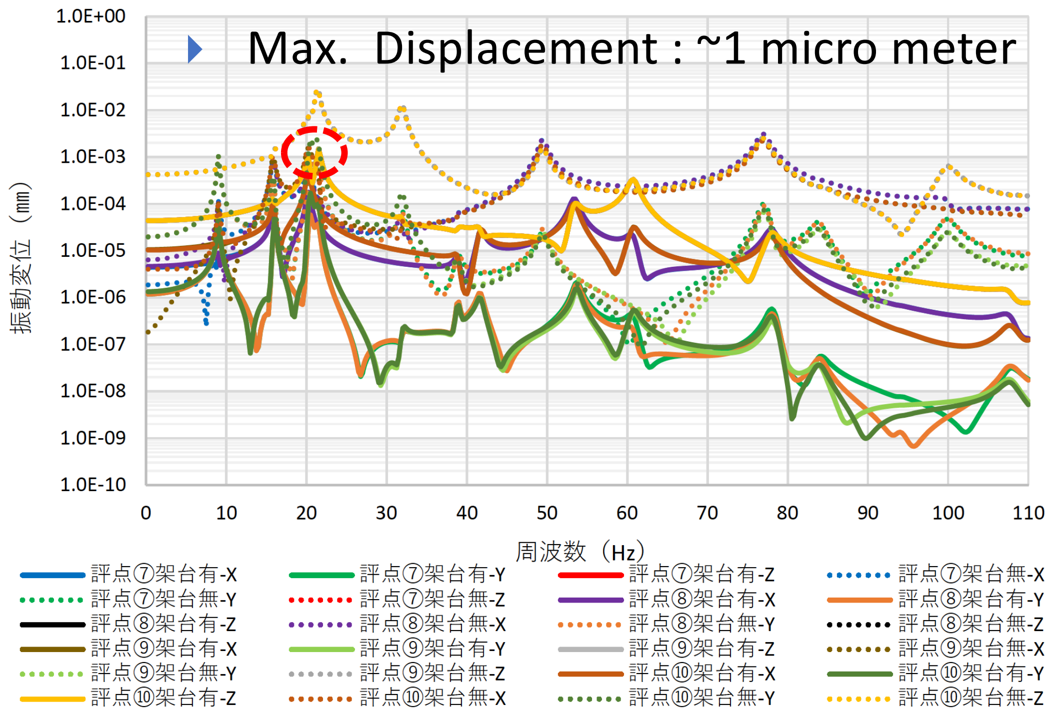
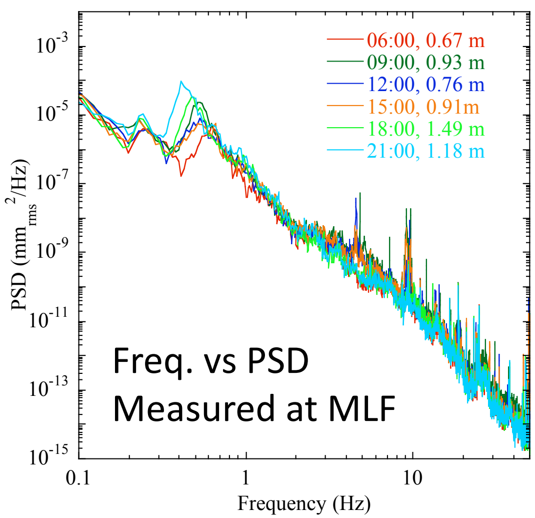


図2.2 変位量評価点





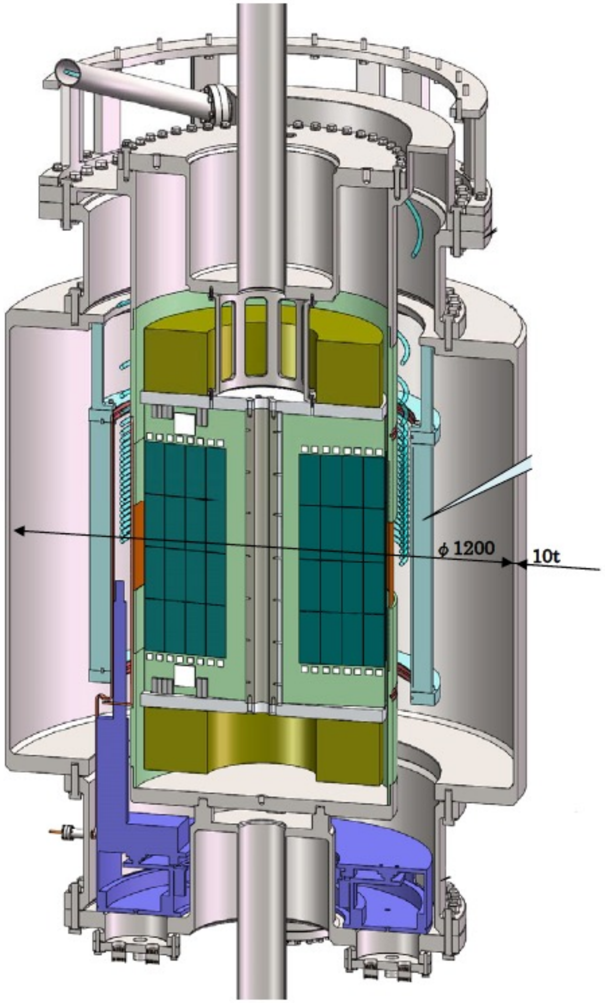
- Max. Displacement : small enough
- Ground vib. : off resonant

R&D of moving stage

- 3D moving stage
  - to get field map in the muon storage region

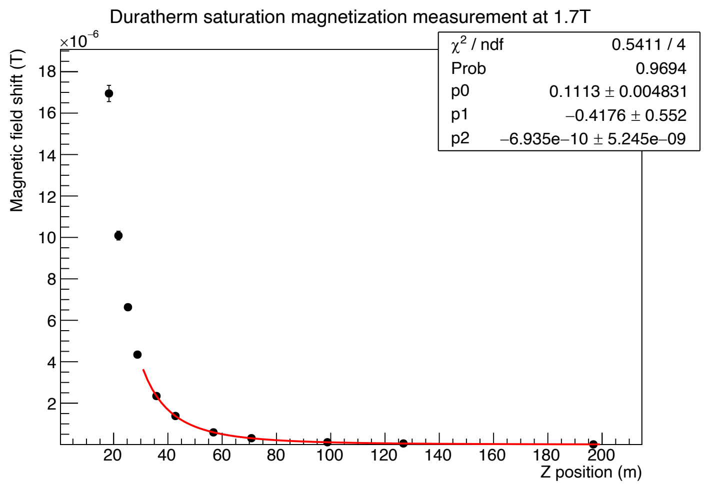
- Need azimuthal moving stage with large diameter
  - Non-magnetic -> Low-magnetic
- Discuss with German company (FRANKE)

✓ Crossed roller bearings



Magnetization check

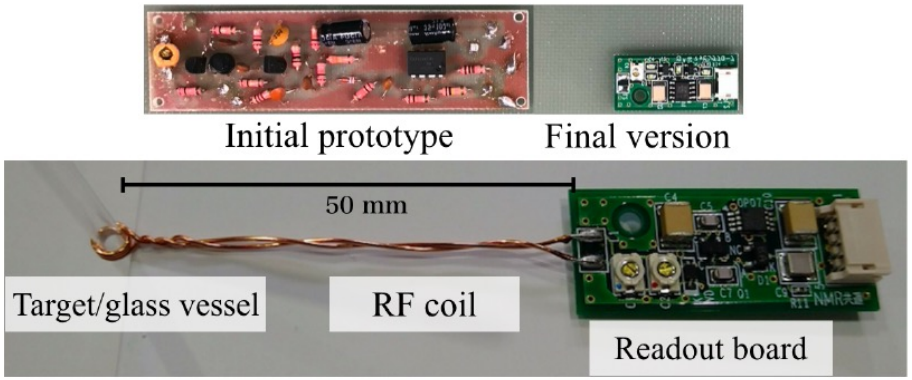
	Magnetic moment (Am^2/g)
Duratherm	0.00316092
Ni	0.05468 (measured)
SUS304[*1]	~0.01



Magnetic field mapping system ~ 1ch

by H. Tada & S. Oyama

- Study of probe configuration
  - Material of RF coil
    - Cu wire, Non-mag. wire
  - Diameter of Glass tube
    - 3 mm or 5 mm
  - NMR sample
    - Water or MgCl2 Solution



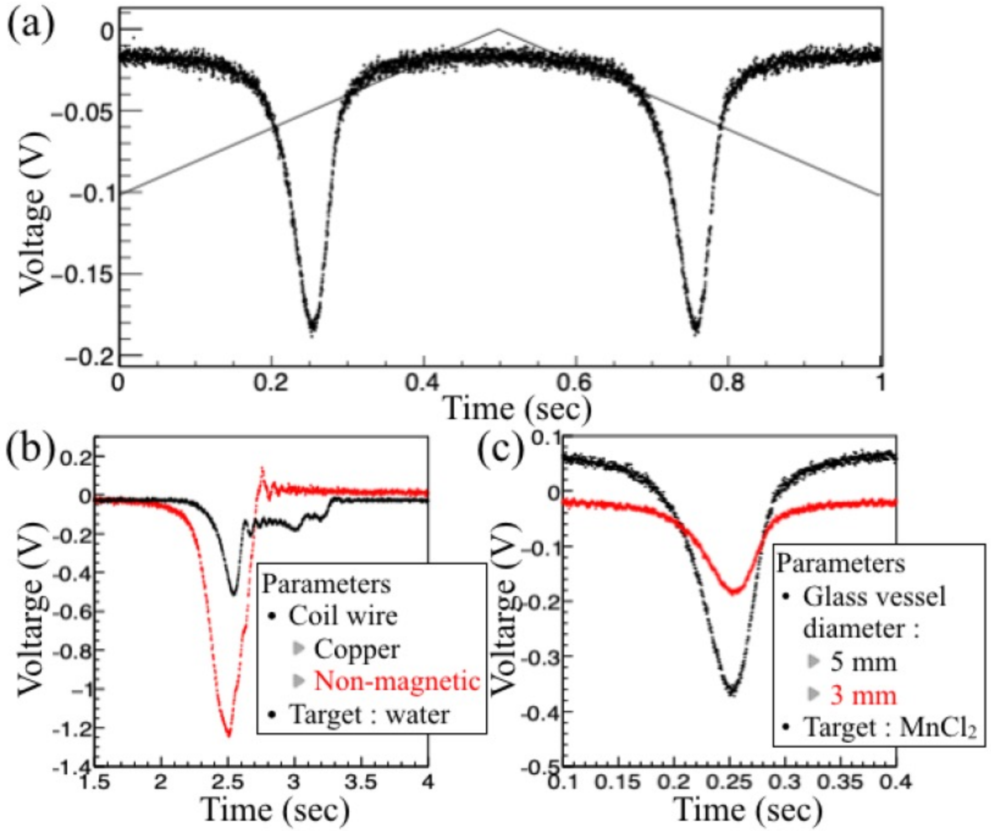


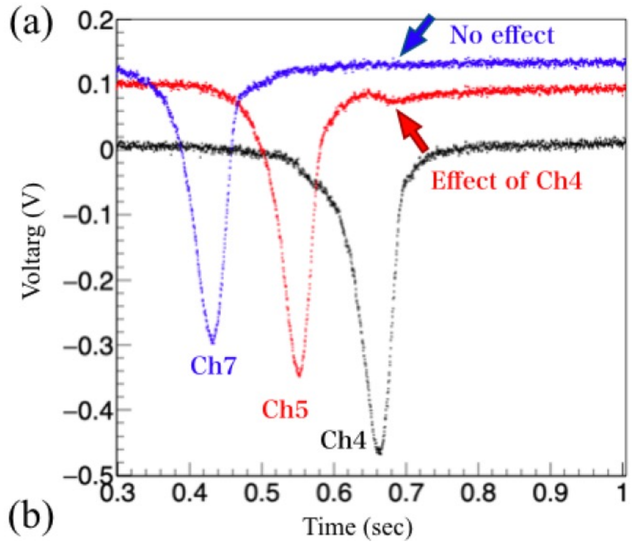
Fig. 4. (a) Data sample: The RF frequency is swept with the triangular frequency modulation. (b) Comparison of coil wires (sample: water), (c) Comparison of glass tube diameters (sample: manganese chloride solution).The blue line indicates the same frequency sweep range.

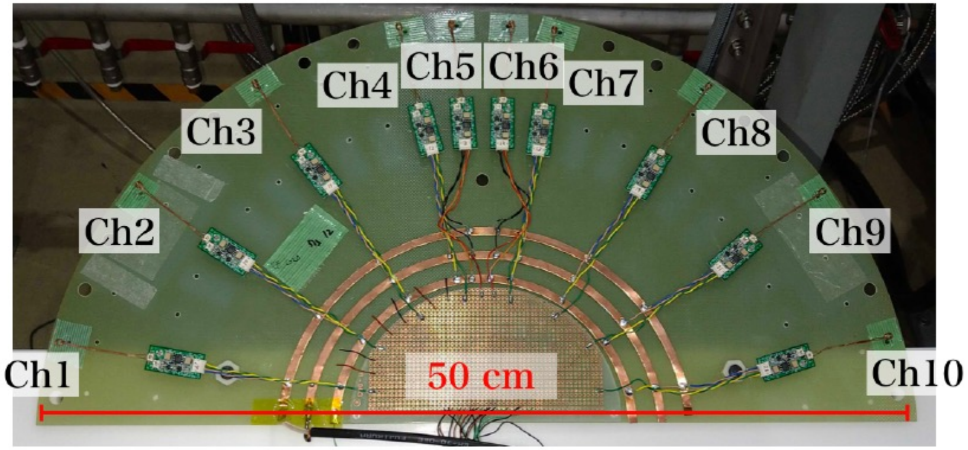
✓ Non-mag. wire
✓ ϕ 3 mm tube
✓ Use water and solution properly according to the homogeneity

Magnetic field mapping system ~ 8 ch

- Goal : 24 ch probe system
  - prototype : 10 ch system
    - verify the multi-ch. operation

✓ Cross talk btw channels



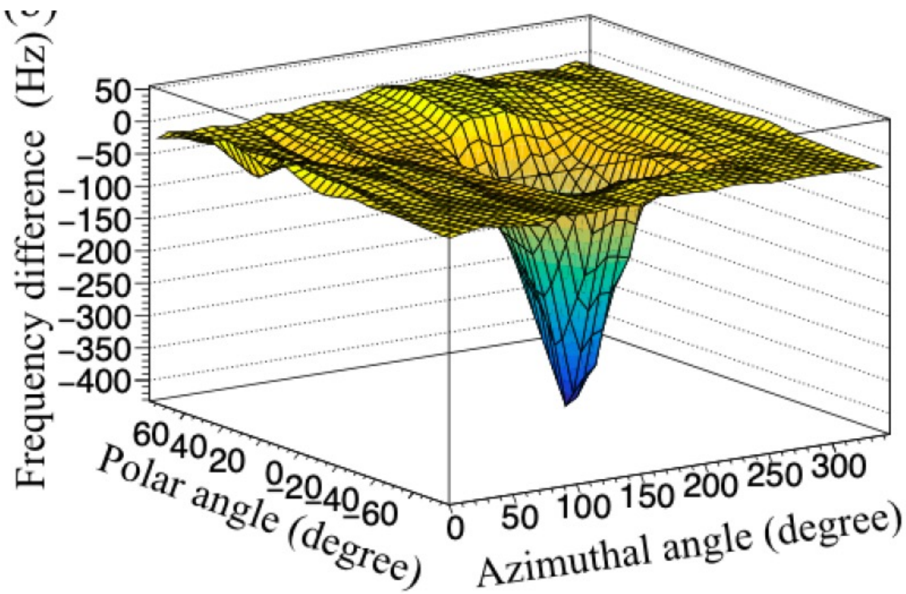


✓ Estimate uncertainty due to the crosstalk
➢ ~2 ppb

＊Depends on the magnitude of crosstalk

◆ Measurement sequence test

✓ Signal peak due to iron
✓ Meas. : -430 +/- 10 Hz
✓ Calc. : -467 Hz

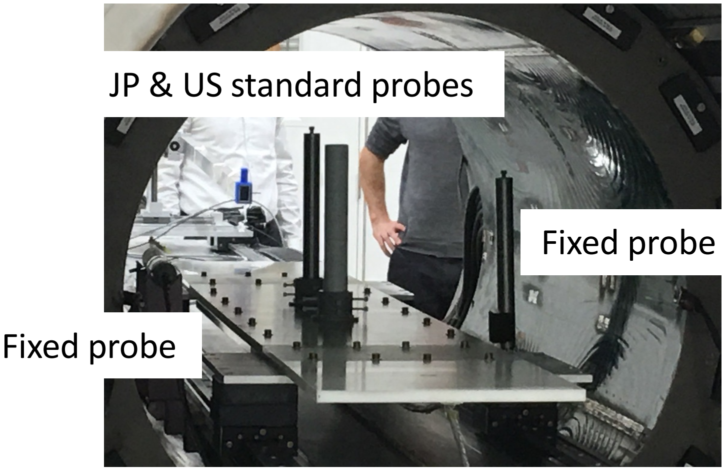


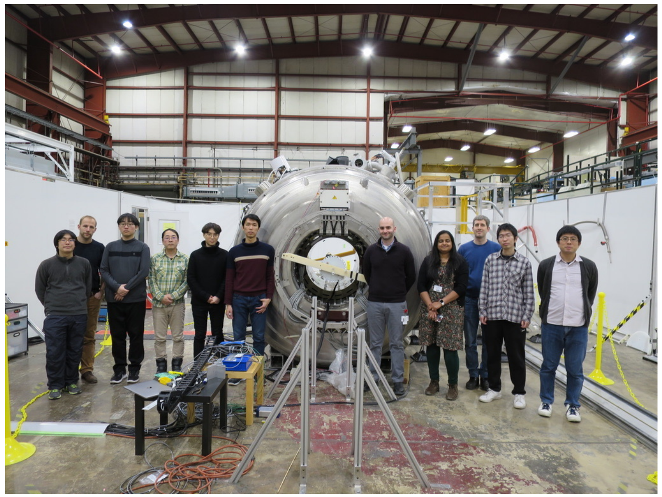
Cross calibration in US-JP collaborative framework

- Check consistency btw J-PARC and FNAL probes
  - increase the robustness of magnetic field measurement
  - collaboration with ANL and UMass group
  - at 1.45, 1.7 and 3.0 T

✓ measure magnetic field of single magnet at the same location with different probes

- Performed tests at 1.45 and 1.7 T in 2019





- planned 3 T test in 2020 <- postponed
- Analyzed the data at 1.45 T and 1.7 T with blind offset

Summary g-2/EDM

- Updates of magnet design
  - Optimized main coil size
  - Systematic and statistical study of manufacturing error on the magnetic field error -> on going
  - Study of shimming scheme -> on going
  - Study of magnet system vibration -> on going
- Field monitoring system
  - R&D of moving stage
    - material study of rotating bearing
  - Multi channel probe system
    - made 10 ch. prototype, checked cross-talk and meas. scheme
  - Cross calibration analysis
    - found the difference : 40 ~ 55 ppb -> further study is underway
  - He3 probe
    - made cells, checked discharge performance
    - preparing laser room to do the test in J-PARC

Contents

- On going Projects
  - HL-LHC D1
  - COMET
  - g-2/EDM
- **Future R&D**
  - **High Field Magnet**
  - Radiation Hard Magnet
- Summary

Nb3Sn conductor R&D structure

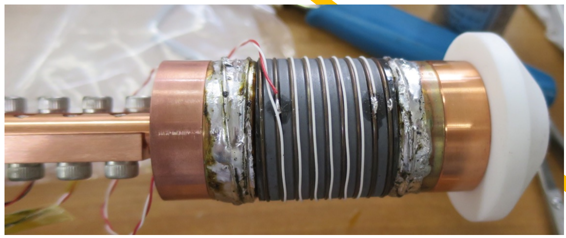
Design and Characterization

KEK — **CERN**

CERN
- In-depth characterization
  HT, J_c, composition, d_{eff} ...

- **Program coordination**
- **Defining specification**
- **Conceptual design**

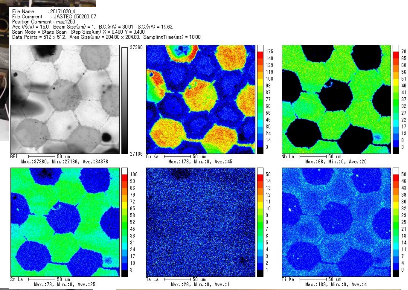
KEK

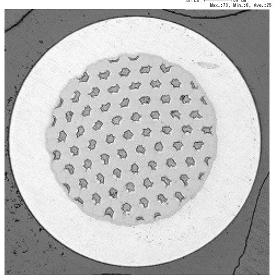


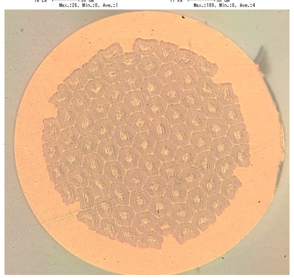
- Evaluation of J_c, B_{c2}
- Mechanical property

Tokai University — **Tohoku University**

Tokai University
- Optimization of HT condition
- Microstructure observation
- Compositional analysis

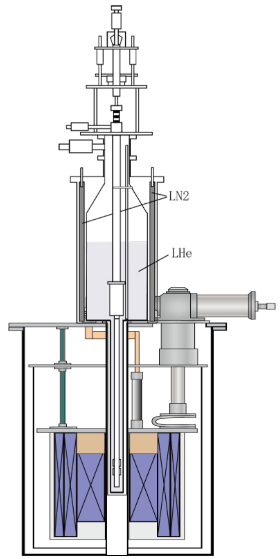






Tohoku University
- High field magnet facility
- Evaluation of d_{eff}

28 T HM



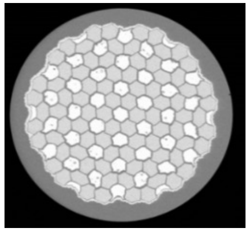
Spec, design ⇕ R&D billets ⇑

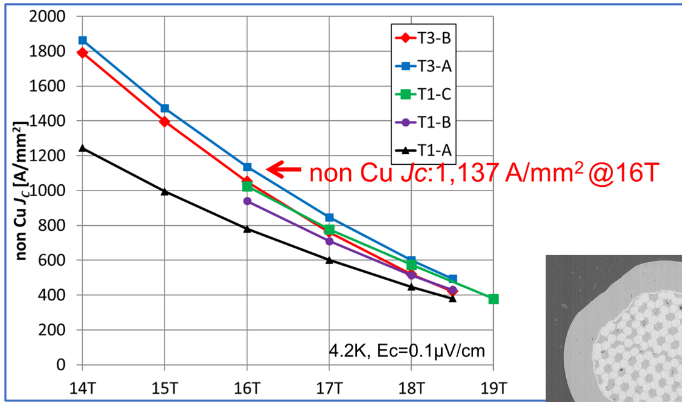
Fabrication

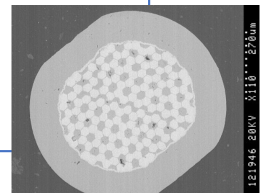
Kobe Steel / JASTEC

Furukawa Electric

Status of Nb3Sn conductor R&D

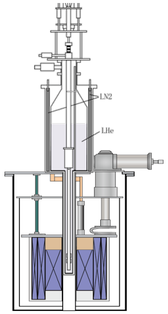


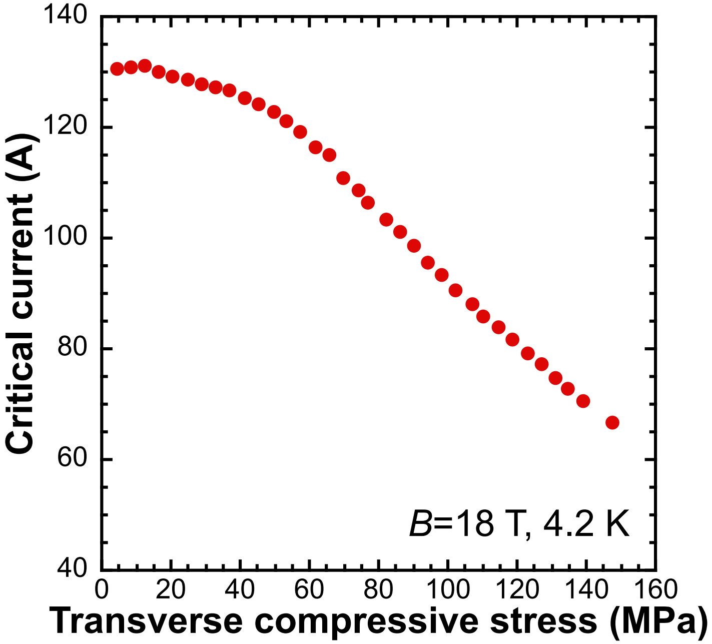




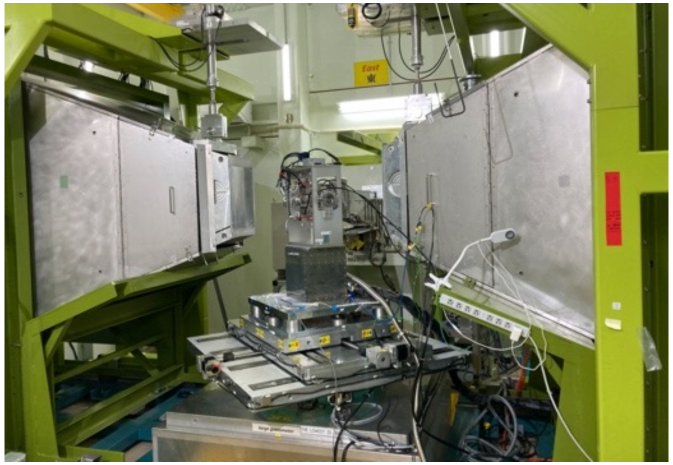
- DT wire
  - non Cu J_c @16T 1,100 A/mm^2
  - reasonable results in d_{eff} (~50μm)
  - and rolling test (Ic/Ic0>95%, RRR>100 @ 10% roll)
  - Production of 5 km wire is completed (1.2 mm dia.)
- New Plan
  - Industrialization of DT wire
  - Mechanical reinforcement (DT with Nb-rod-process)
  - Jc enhancement (DT and Nb tube)

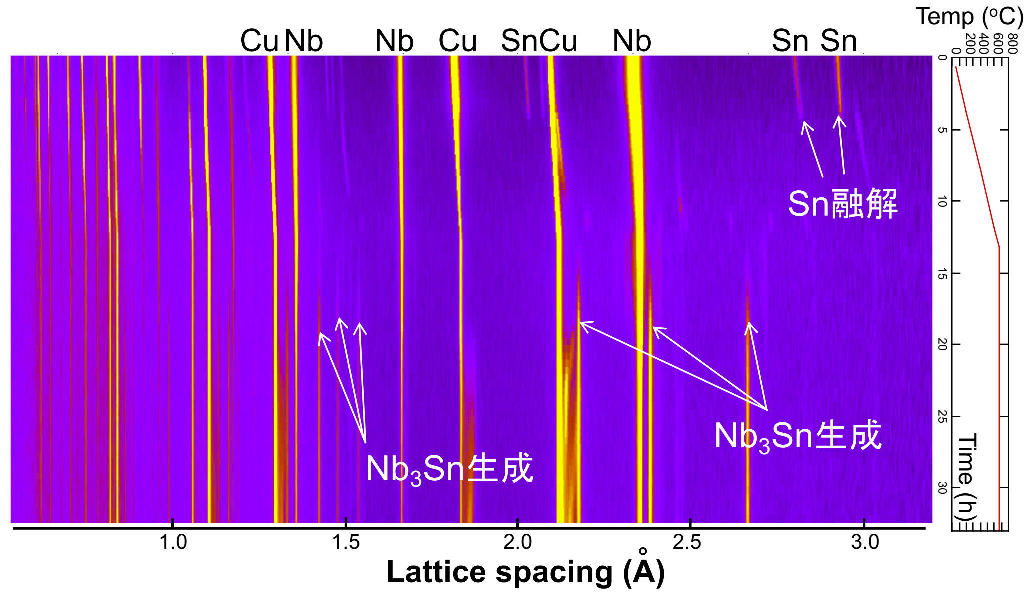
Nb_3Sn Recent Progress





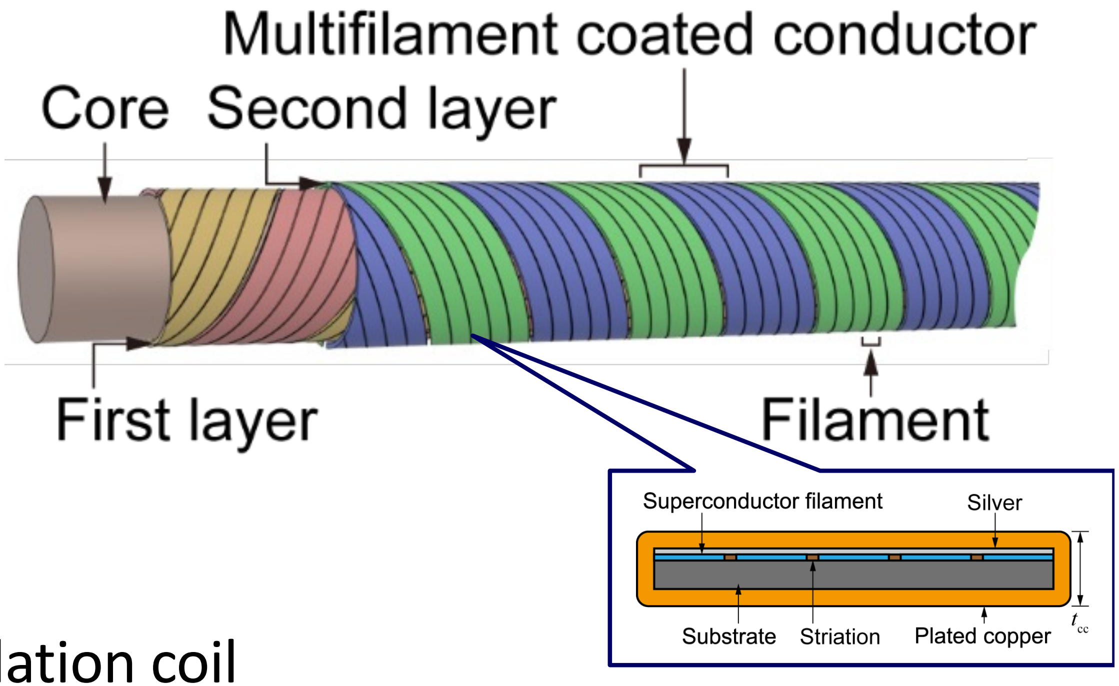
Ic Measurement with
Transverse Stress at Tohoku U.



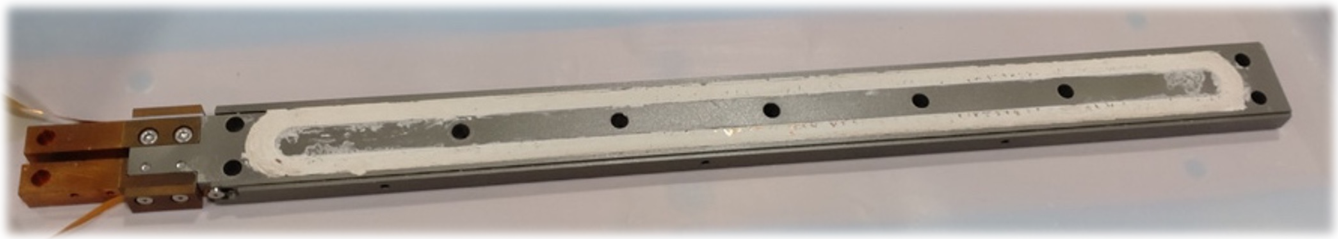


In-situ Material Analysis during Heat Treatment
at J-PARC Neutron Beam Line

HTS Study



- US-JAPAN
  - SCSC cable by Kyoto Univ.
    - Prof. Amemiya's Lab.
  - 10T test of inorganic insulation coil
    - With BNL test stand

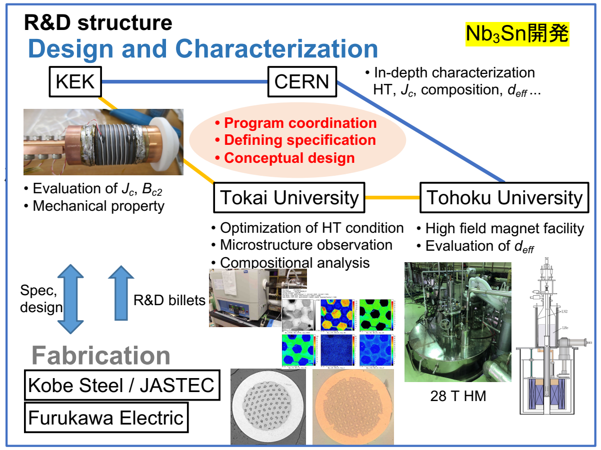


- Tohoku-Kyoto-KEK Collaboration (JSPS)
  - Study on 3d mechanical properties of HTS conductor
    - Tension, compression, peeling, sharing…
    - Effect of striation

Future Magnet Development with Large Funding (Proposal submitted..)

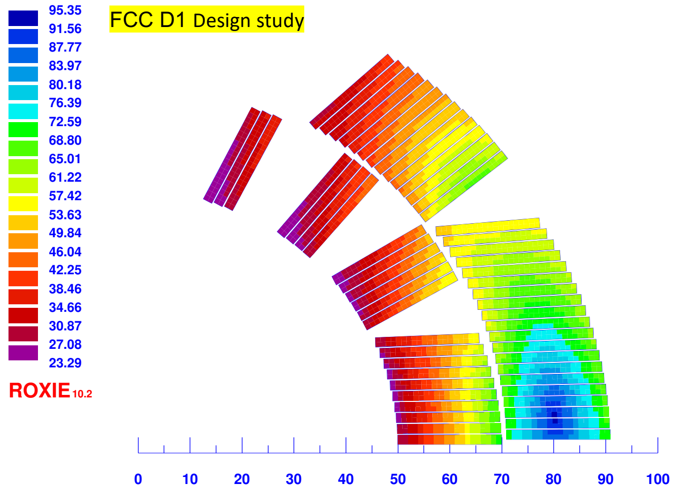
Magnet Manufacturing Experience

Advanced Conductor Development



Infrastructure

Magnet Design

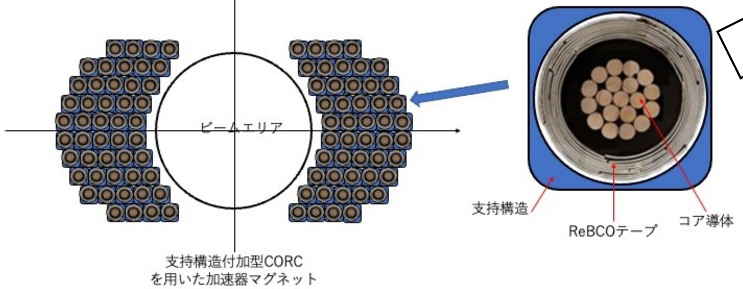


Large Aperture 12T Magnet

16-20T Magnet

4-8T Insert Coil

HTS Coil Development



New JSPS Funding with Tohoku and Kyoto

High Field Magnet for Future Accelerator

Contents

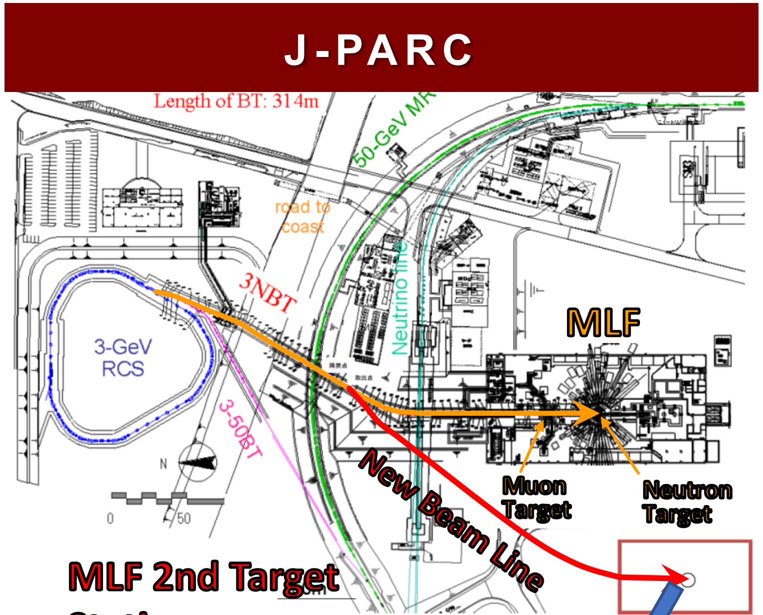
- On going Projects
  - HL-LHC D1
  - COMET
  - g-2/EDM
- **Future R&D**
  - High Field Magnet
  - **Radiation Hard Magnet**
- Summary

J-PARC Future Muon Source

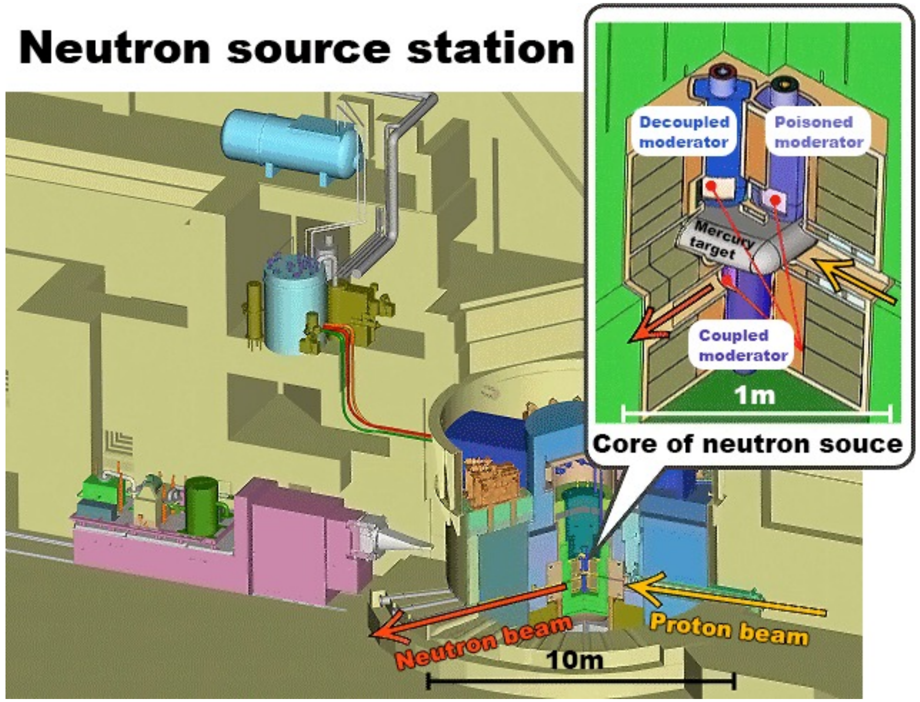
J-PARC MLF 2nd Target station

- Solenoid covering production target

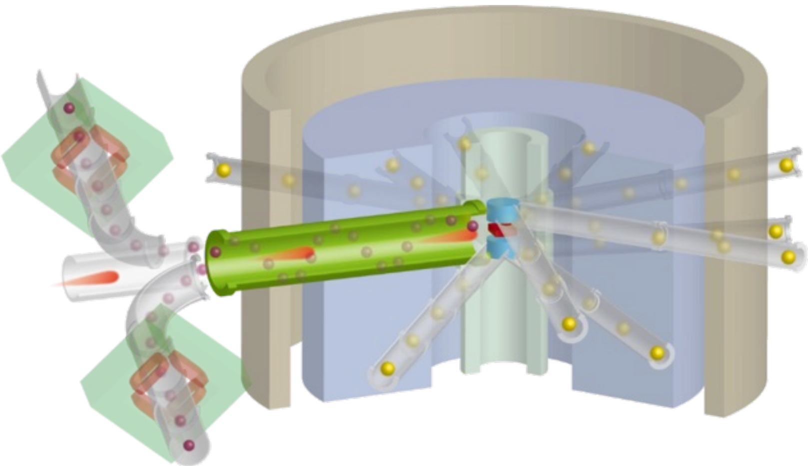
→ Absorbed Dose: 130 MGy???

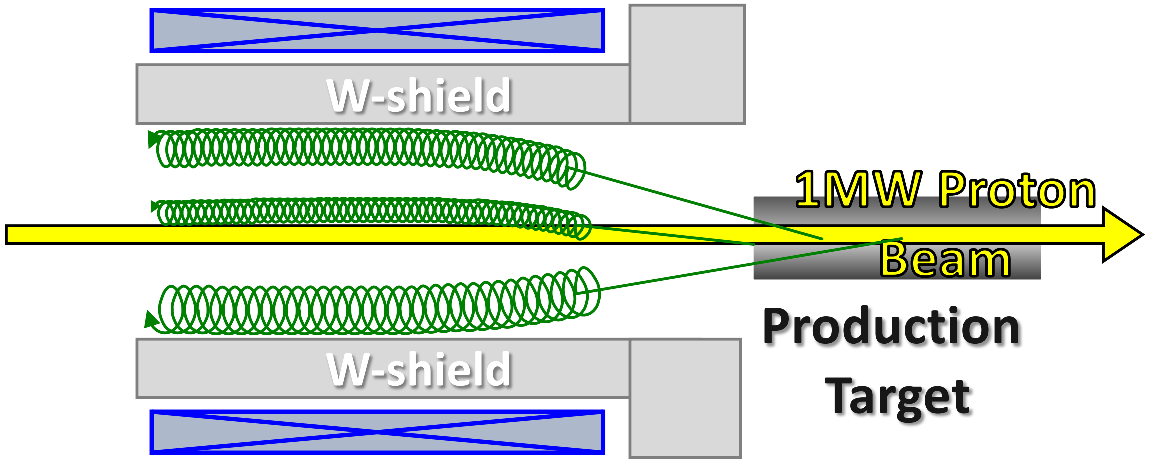


MLF 2nd Target Station

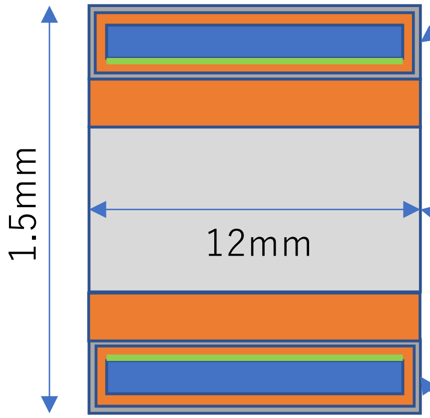


Share Helium Refrigerator for Neutron Moderator: 20K 6~8 kW





Al Stabilized HTS by Clad Metal

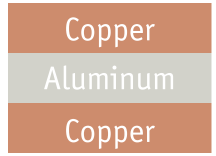


HTS Tape
12mm wide tape
30µm thick Hastelloy
5µm thick Copper Plating
4µm thick Solder Plating

Copper Clad Aluminum
Copper: 60µm thick each
Aluminum: 1.1 mm thick
Solder Plating: 4µm each

HTS Tape
12mm wide tape
30µm thick Hastelloy
5µm thick Copper Plating
4µm thick Solder Plating

Copper Clad Aluminum



Width (in)	0.125 – 25.000
Thickness (in)	0.005 – 0.120
Outer layer ratio %	5% – 30%
Core material	Alum alloy
Layer material	Copper alloy

Engineered Materials Solutions
Wickeder Group

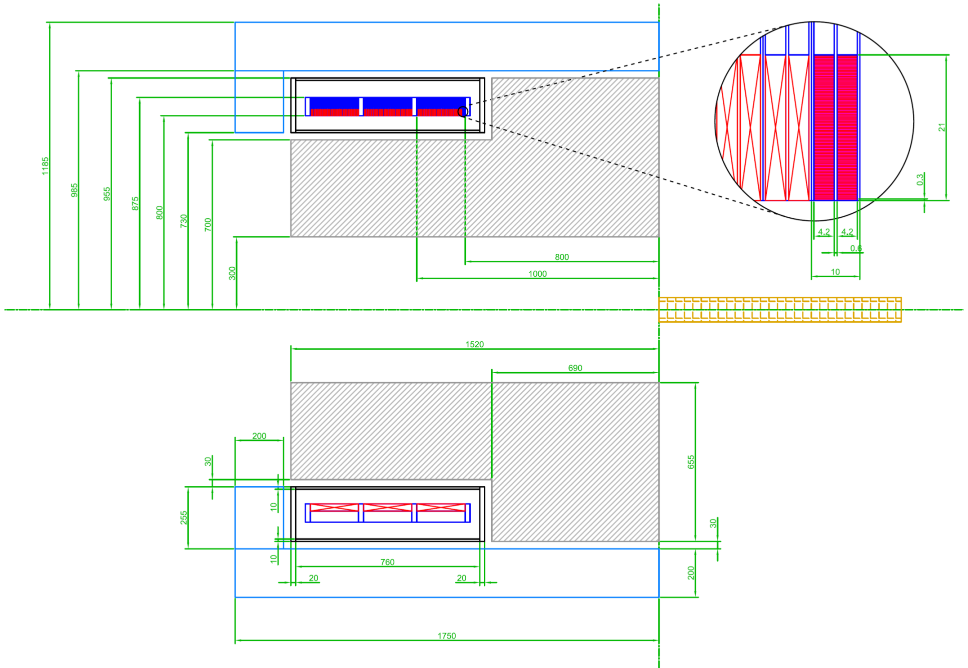
Material Ratio
Thickness: ~1.3mm
Aluminum: ~85% (2.7)
Copper: ~10% (8.9)
Hastelloy: ~5% (8.9)
Av. Density:= 3.6 g/cm^3

Operation Condition
Field: 3T
Temperature: 30K
Operation Current: 1200A
Margin: ~50%
Current Density: ~77 A/mm^2

Coil Configuration

Series of pancake coils

Parameter	Value
Coil Inner Diameter	1600 mm
Coil Thickness	55 mm
Double Pancake coil	
Number of Turns	70 (35 each)
Width	30 mm
Number of DP Coils	20
Operation Current	1200 A
Peak Field @solenoid axis	1.12 T
Peak Field @coil	2.41 T
Peak Field B//ab	2.09 T
Peak Field B//c	2.25 T
Inductance	~4 H
Total conductor length	~7km



Schematic of capture coil (drawing is old version)

Quench protection by 0.4Ω dump resister
Shutdown time constant: 10sec
Magnet terminal voltage: 500V

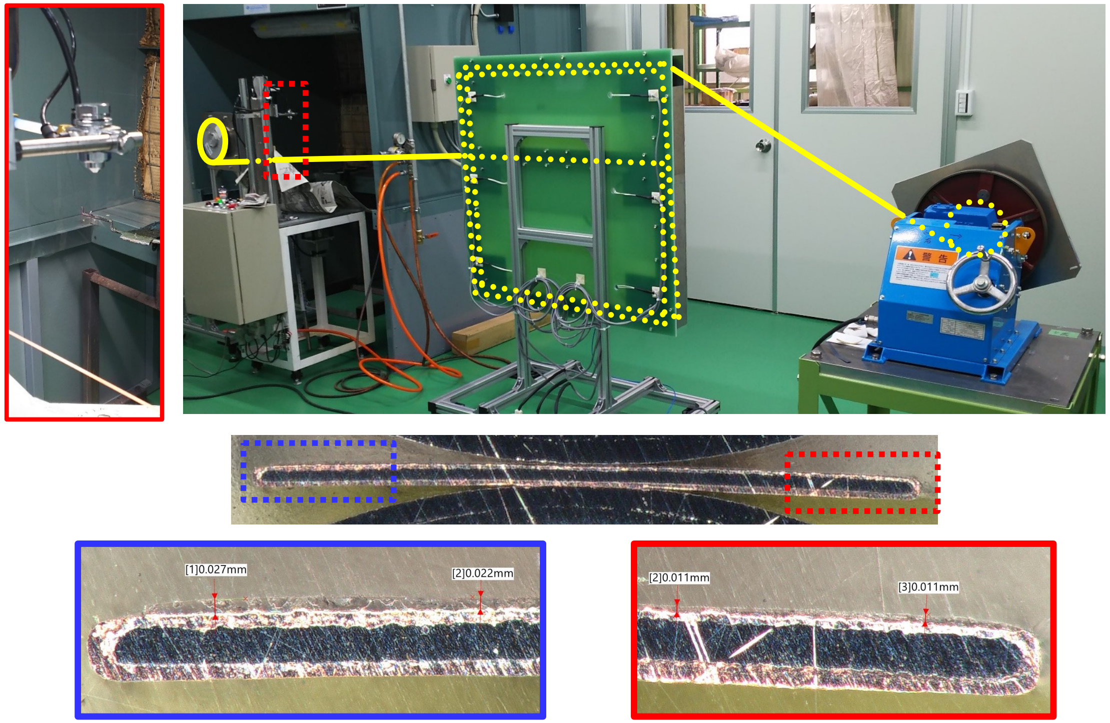
Conductor additional cost: ~ 2M$
Cost saving in refrigerator > 3M$

Cost saving only if coil survive more than 10 years

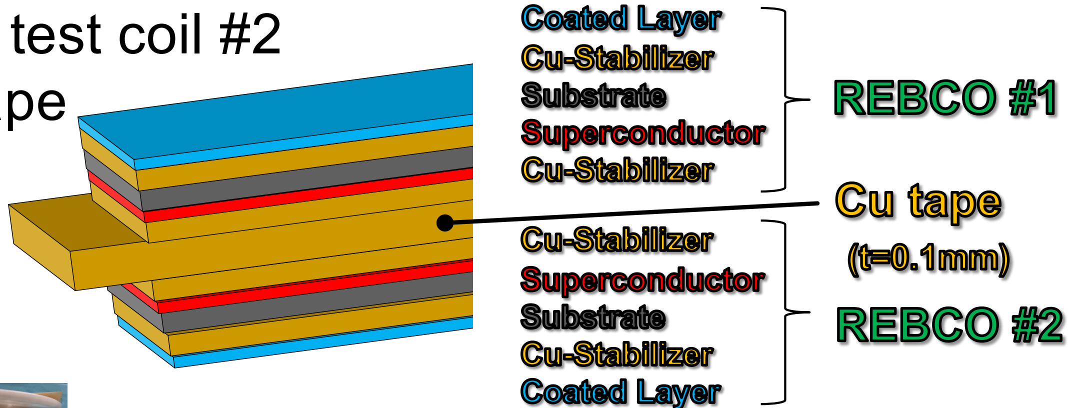
Inorganic Insulation HTS coil

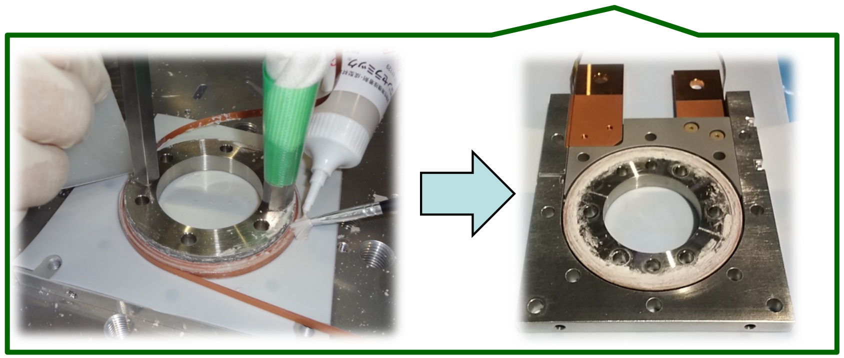
R&D of continuous coating on long tapes by real to real insulation machine is in progress.

Although continuous coating is successful, difference in thickness of ~16 μm in the width direction is confirmed.



Preparing the winding of the circular test coil #2 with co-winding 2 REBCO and Cu tape (same shape as **Test coil #1**)

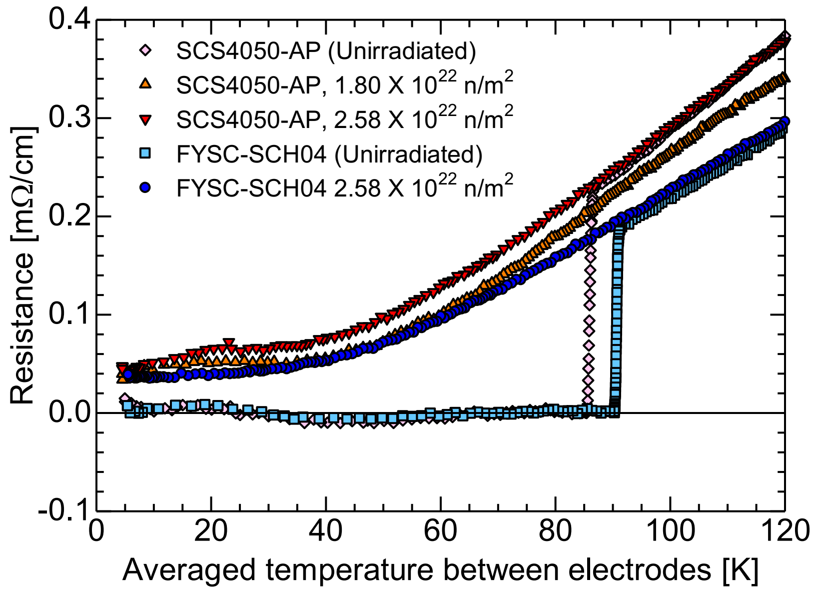




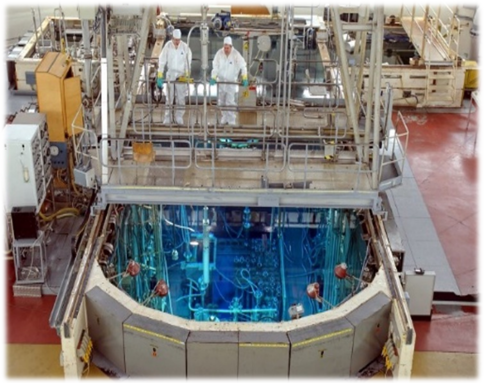
Wires identified and shipped from LBNL to KEK for testing KEK's new ceramic coating insulation on Nb_3Sn and Bi-2212 wires.

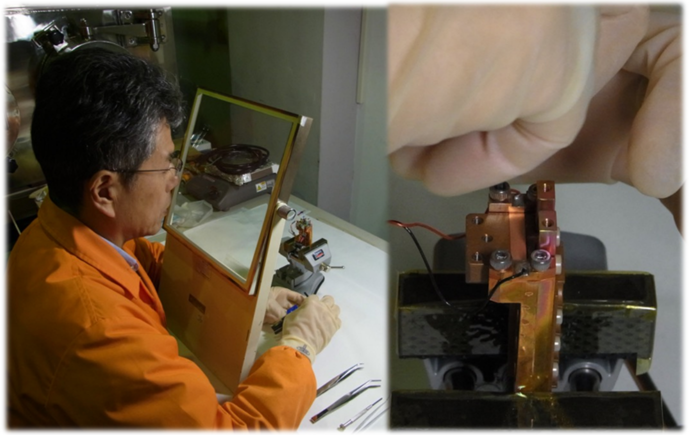
Neutron Irradiation to HTS

- Neutron Irradiation
  - Belgium BR2, JR3 at JAEA Tokai
    - ReBCO (Re = Gd or Eu or Y)
- Post Irradiation Experiment (PIE)
  - Hot Labo at Tohoku Univ. Oarai Center
    - Ic measurements
  - UC Berkeley
    - Further analysis using TEM etc



BR2 @Belgian nuclear research center



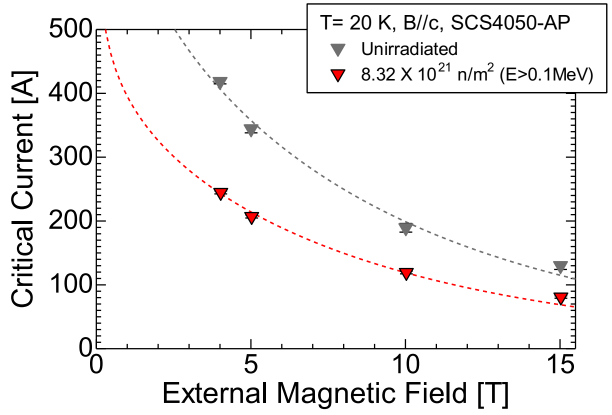


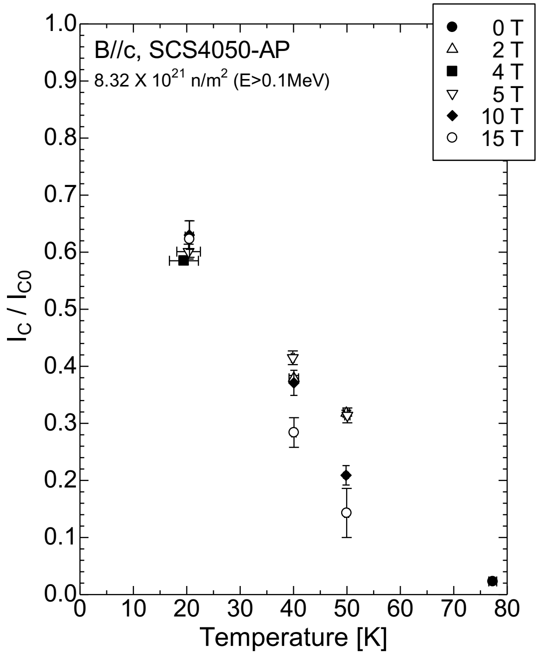
PIE Sample preparation

Ic Measurement Magnet

Neutron irradiation to HTS

PIE of GdBCO samples with neutron flux of 1.80, 2.58x10^{22} n/m^2

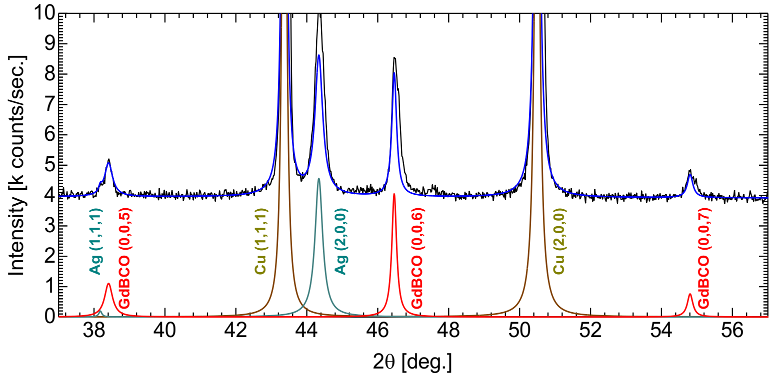




Neutron irradiation effect on Tc
***influence of Cd foil for SuperPower SCS4050**

D. X. Fischer, et al., Supercond. Sci. Technol. 31 (2018) 044006

- **No significant degradation in shielded HTS tape at 0.6 x 10^{22} n/m^2.**
- **But, reduction of Tc by 5 K in unshielded sample.**



X-ray diffraction patterns of the unirradiated GdBCO tape as a preliminary study.

☐ **Degradation is confirmed**

Further study

- **PIE of GdBCO samples of target fluence 1x10^{21}, 5x10^{21} n/m^2**
- **Fast neutron irradiation by shielding of samples with Cd foil**
- **Irradiation of EuBCO & YBCO samples to confirm the contribution of Gd**
- **Materials analysis of irradiated samples at UC Berkeley**

Summary

- On going Project
  - HL-LHC D1
  - COMET
  - g-2/EDM
  - Also some user experiments at J-PARC
  - Too many projects for not enough resources
- For future projects
  - We still need R&D for new technologies (Nb3Sn, HTS…)
  - Can we make it?
    - Collaboration!: Universities (Tohoku, Kyoto, Berkeley), Laboratories (NIMS, LBNL, FNAL, BNL, CERN..)
  - Need Funding
    - Collaboration!: US-JP, CERN-KEK, Joint Proposal with Physics Group and/or Universities
- For survival: widen collaborations and applications