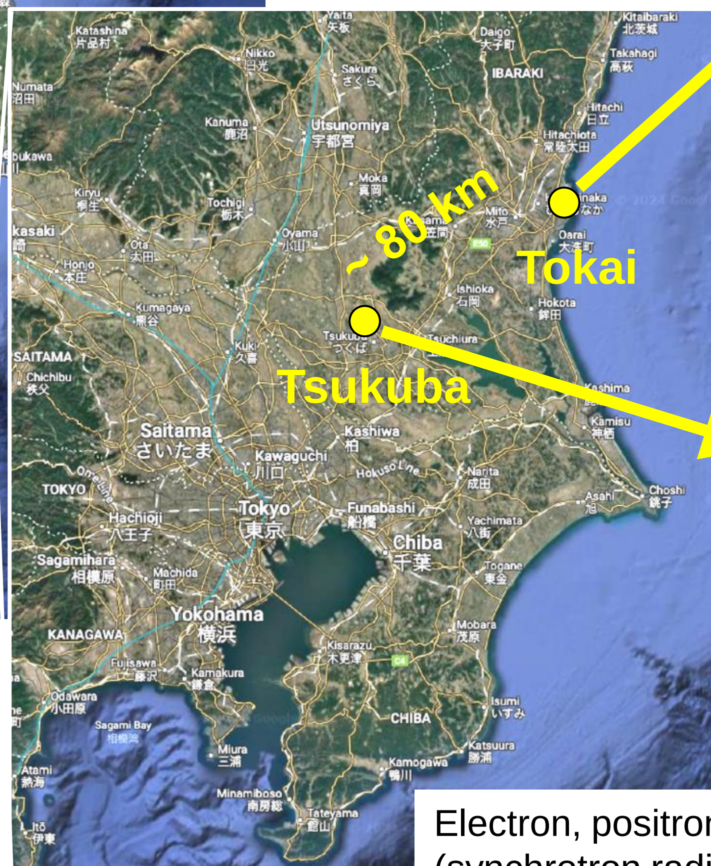
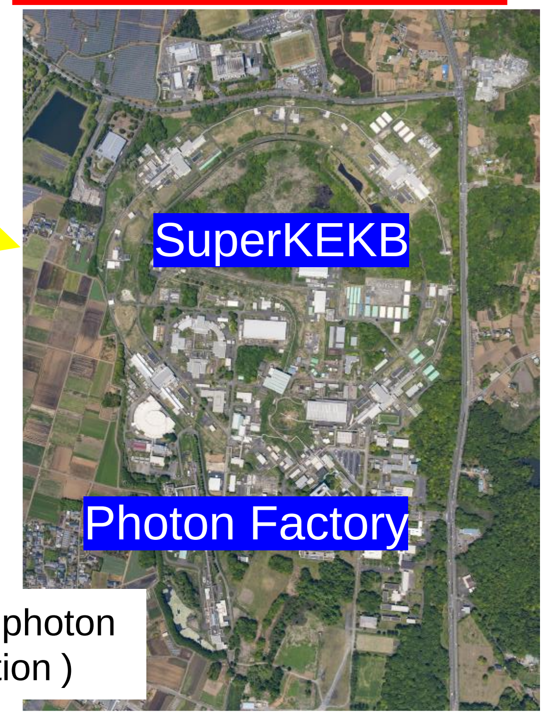
J-PARC Superconducting Magnets and Radiation Environments

Tatsushi NAKAMOTO

Cryogenics Science Center, KEK

KEK and Accelerators

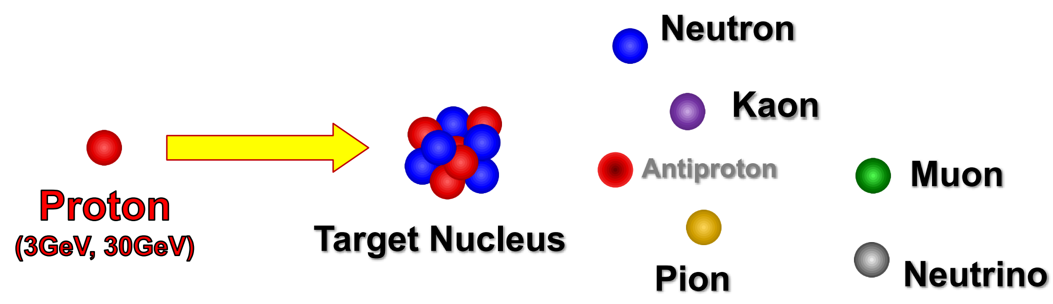


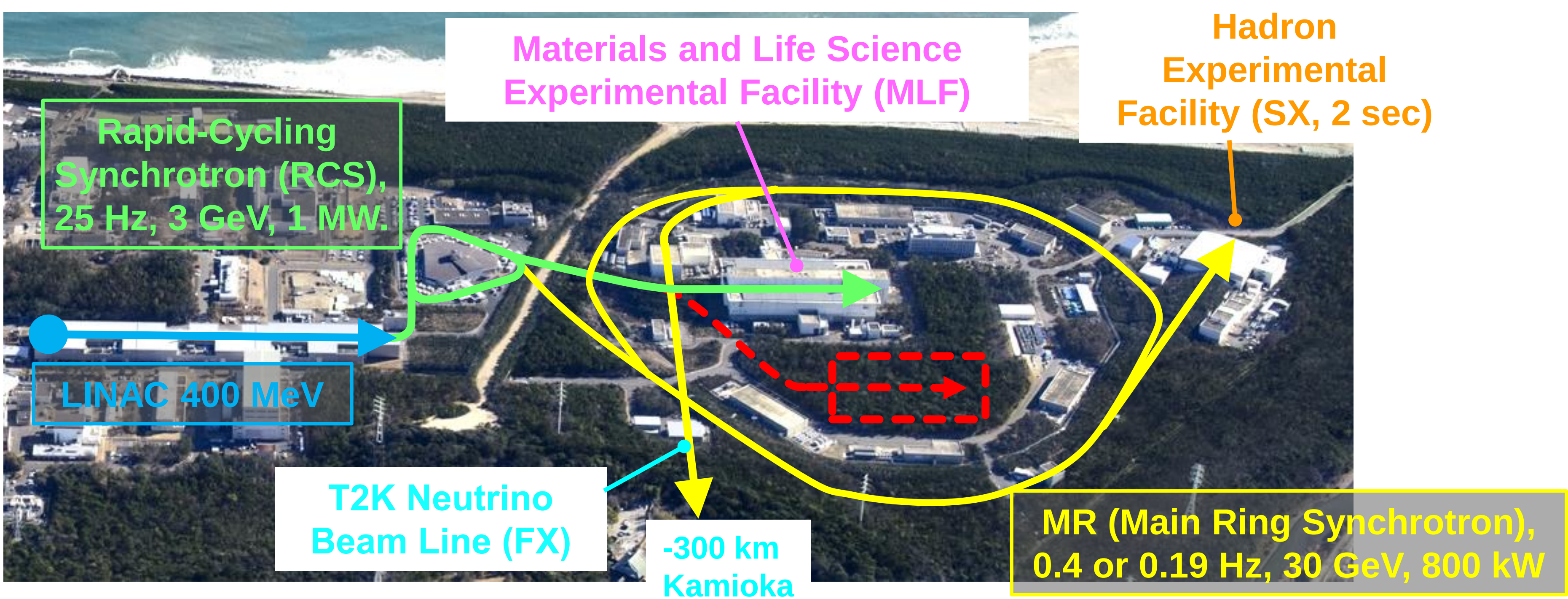


Electron, positron, photon
(synchrotron radiation)

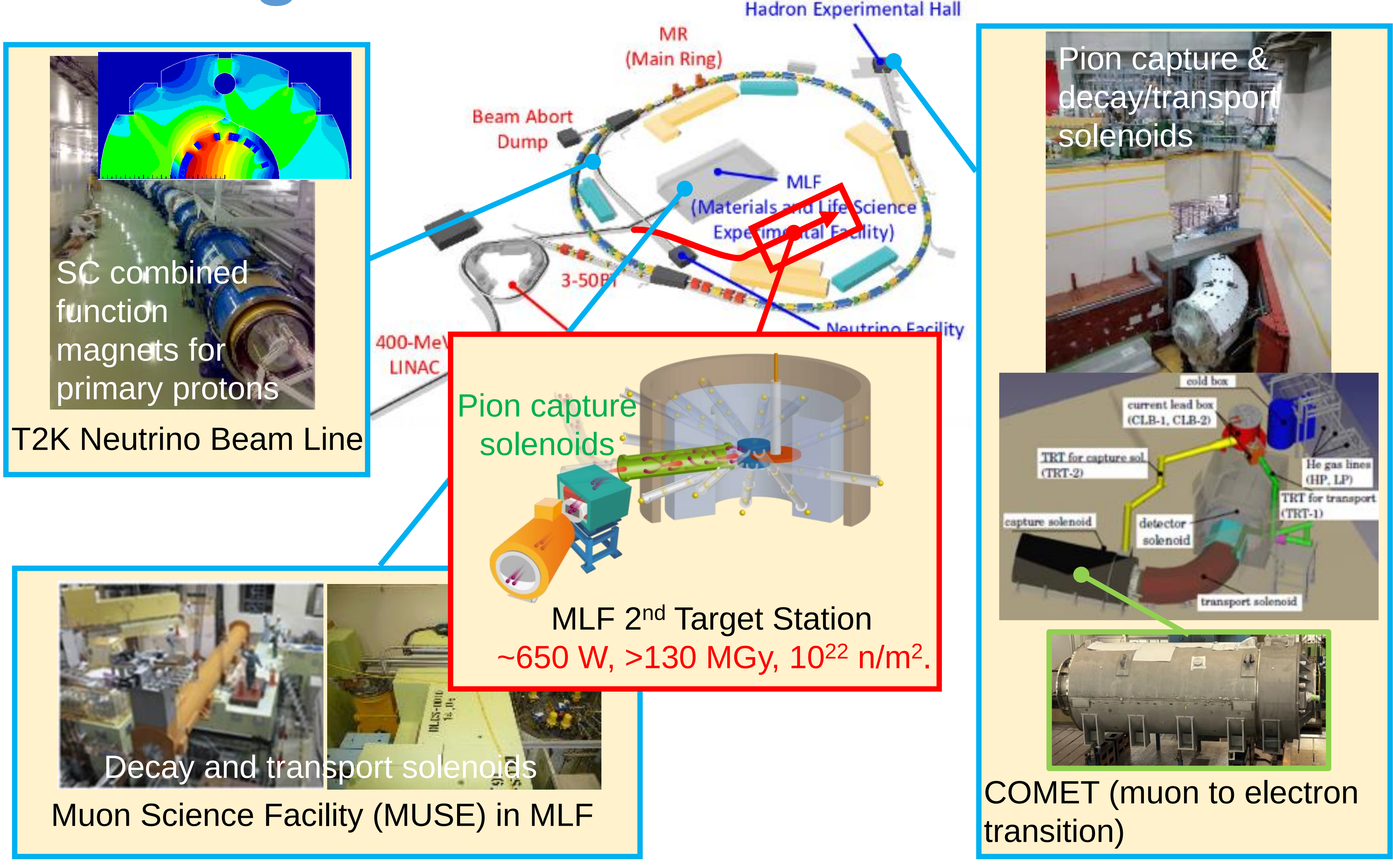
KEK and J-PARC

- J-PARC (Japan Proton Accelerator Research Complex) has been jointly operated by JAEA and KEK since 2007.
- A variety of experiments has been carried out using secondary beams of pions, muons, neutrinos and other particles generated by proton beam with a power of several hundreds of kilowatts from 3 GeV Rapid Cycle Synchrotron and 30 GeV Main Ring.





SC Magnets in J-PARC



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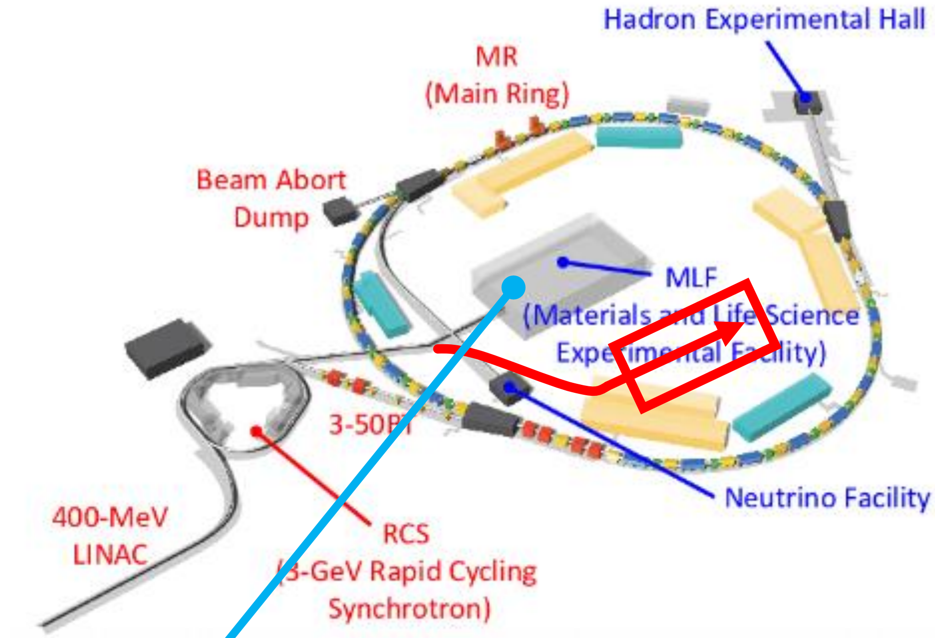
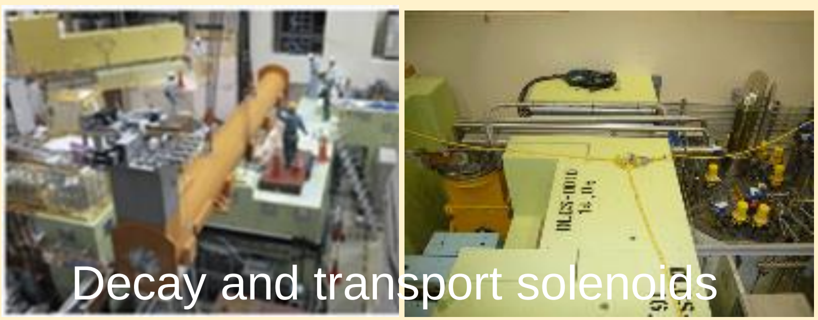




Muon Science Facility (MUSE) in MLF

Muon Science Facility (MUSE)

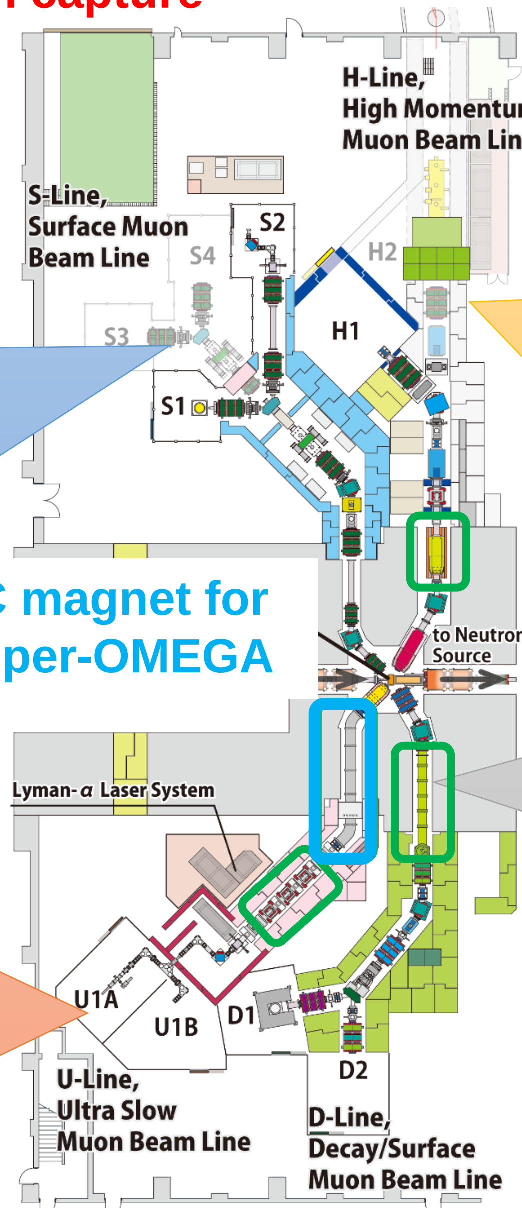
- 5 % of proton beam (3 GeV, 800kW) is used for pion/muon production.
- NC magnets for pion capture

S-line **μ^+**

Surface muon（4 MeV）
dedicated to bulk μSR
in 4 experimental areas
w/ various sample env:
- ultra-low temperature
- high magnetic field
- pulsed excitations *etc.*

H-line **μ^+/μ^-**

High-intensity surface
and high-energy cloud
muon（<4 - 50 MeV）
for general purpose
“fundamental physics”
- requiring high precision,
- high sensitivity



SC magnet for Super-OMEGA

SC magnets in MUSE

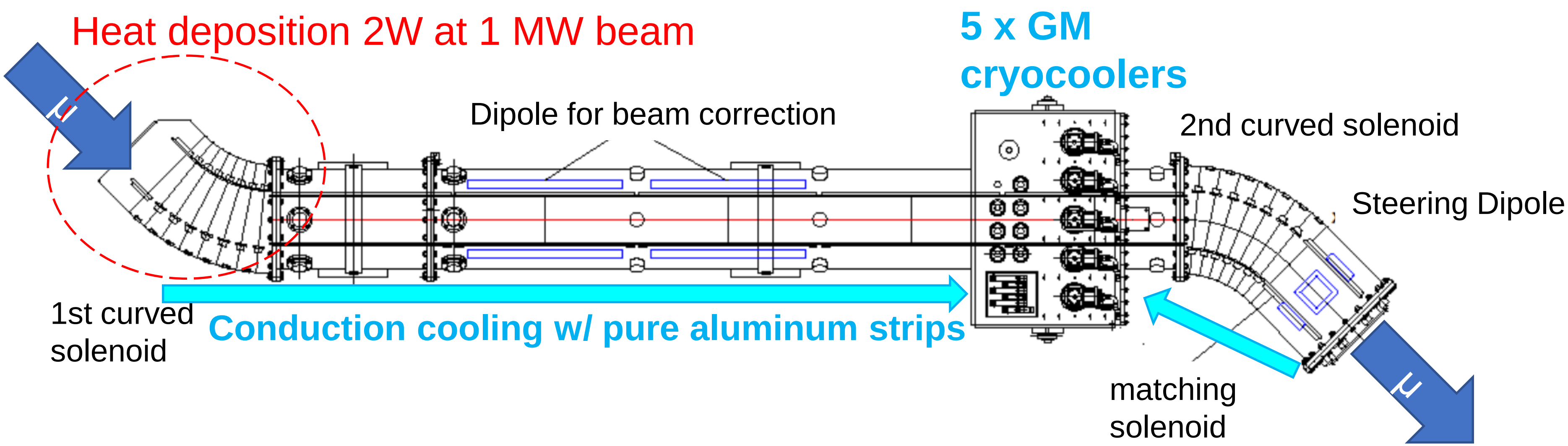
U-line **μ^+**

Ultra slow muon
（0.1 - 30 keV）
surface/sub-surface
/interface sciences (U1A)
Test-bench for TμM
(U1B)

D-line **μ^+/μ^-**

Decay and surface muon
（100 keV - 50 MeV）
to answer a variety of
users’ demands with
μSR spectrometer (D1)
general purpose (D2)

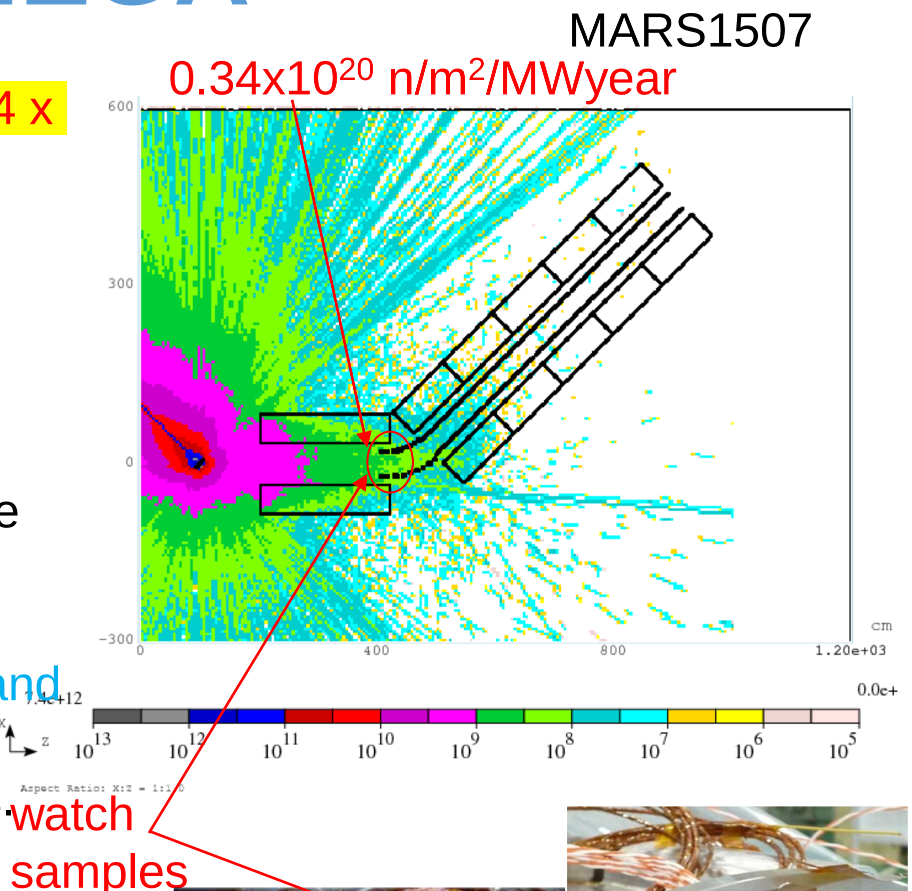
SC Curved Solenoid for Super-OMEGA

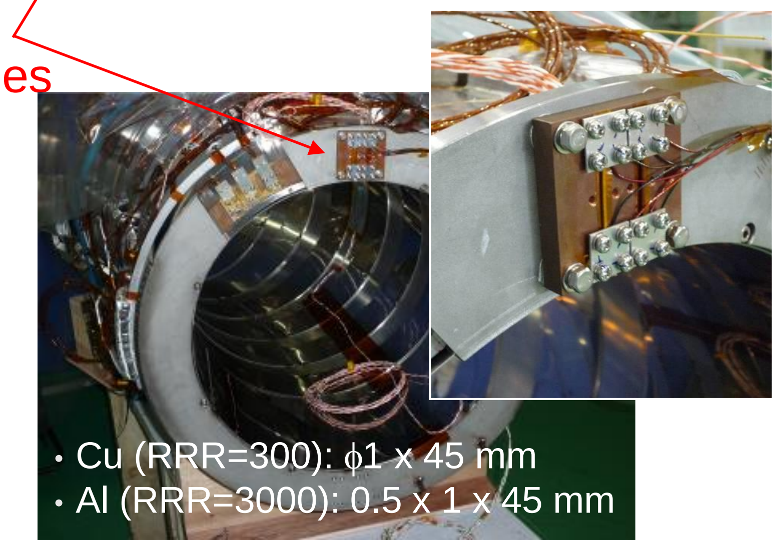


Length	7 m
Coil ID	300 ~ 360 mm
Central / Peak Fields	2 T / 3.1 T
Inductance	400 H
Operational Current	83 A

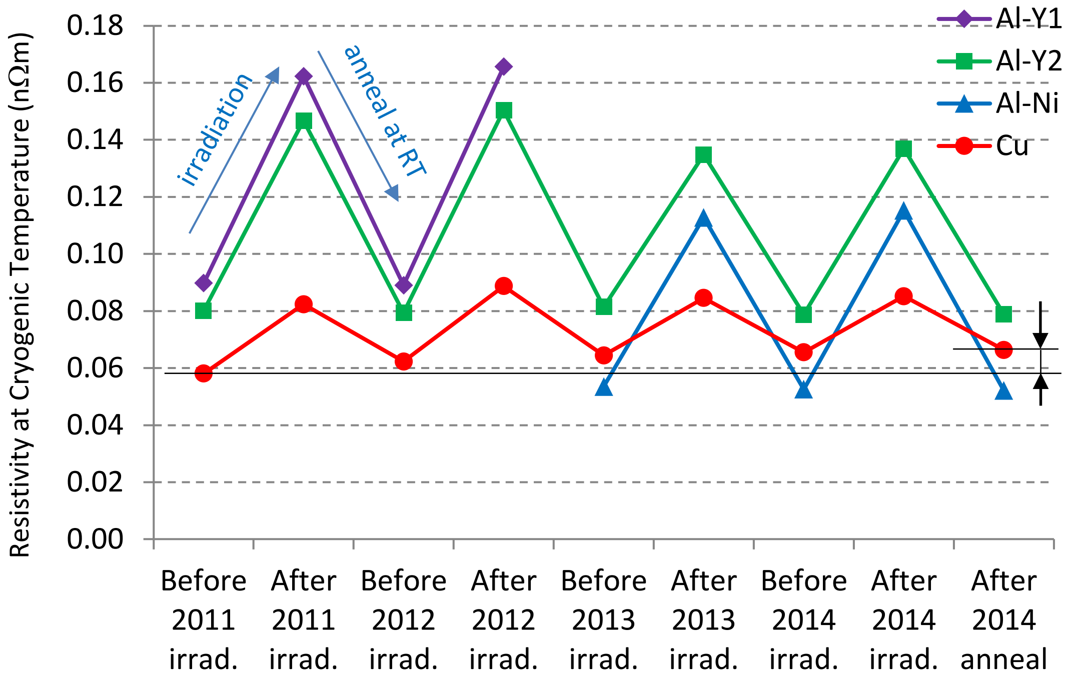
Radiation at Super-OMEGA

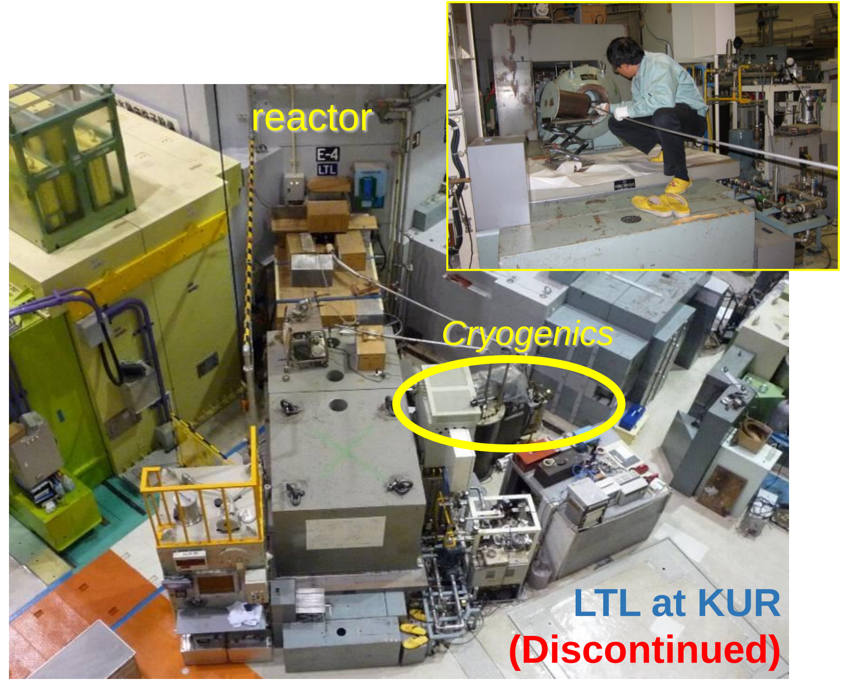
- Heat deposition of 2 W and neutron fluence of 0.34 x 10^{20} n/m^2/MWyear in the SC coil.
  - ➢ **Modest, but non-neglegible radiation.**
- Design concept
  - ➢ 5 x GM cryo-coolers
  - ➢ Conduction cooling with pure aluminum strips
  - ➢ Radiation resistant materials for the front coil: BT (Bismaleimide triazine) resin and Polyimide MLI.
- Concerns about radiation damages in thermal conductors and stabilizers: temperature increase and degradation of quench protection.
  - ➢ Degradation rates determined by experiments.
    - Aluminum: 0.03 nΩ.m for 10^{20} n/m^2
    - Copper: 0.01 nΩ.m for 10^{20} n/m^2
  - ➢ Expected degradation after 1 MWyear operation
    - RRR(Al) = 2000 → 1130
    - RRR(Cu) = 100 → 98
- "Watch samples" are attached to the SC front coil to monitor the degradation during the beam operation.





Neutron Irradiation / Annealing Effect in Electrical Resistance of Stabilizer



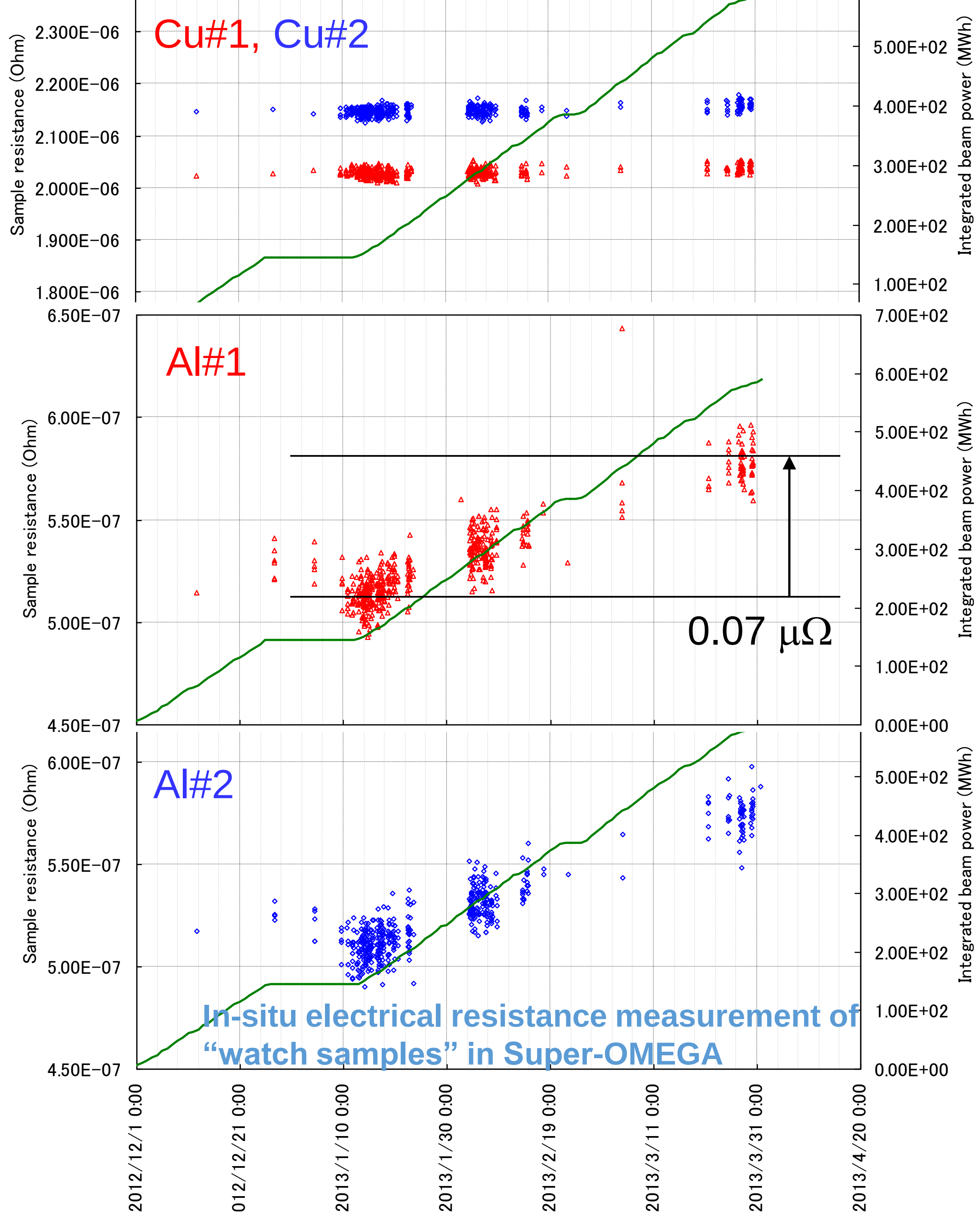


- Al: 0.03 nOhm.m for 10^{20} n/m^2
- Cu: 0.01 nOhm.m for 10^{20} n/m^2
- All **aluminum** samples show **"full" recovery** of electrical resistivity after thermal cycle to RT.
- But, **copper** samples show "partial" recovery after thermal cycle: accumulation of degraded resistivity should be considered in design and operation.

"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

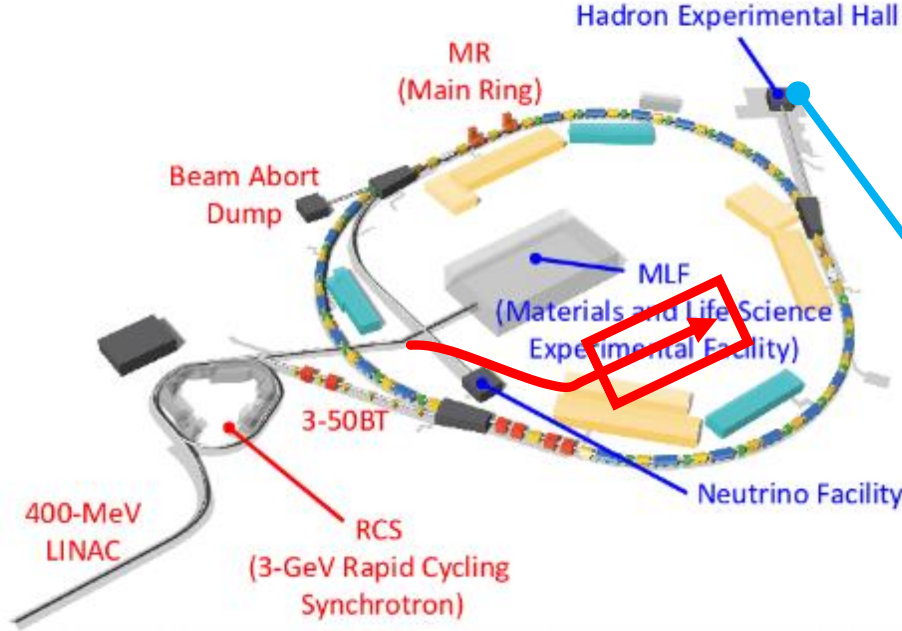
Degradation in Operation

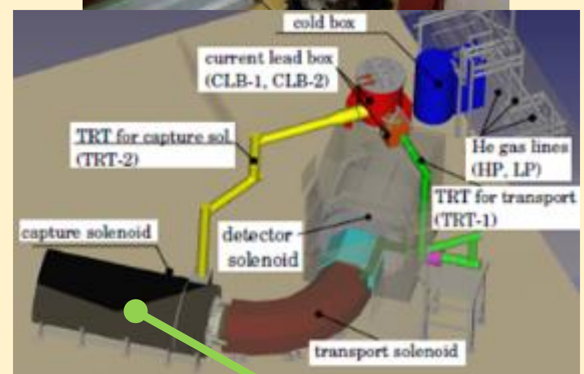
- “Watch samples” were monitored during the beam operation in 2012.
- Predicted degradation rates for 1MWyear
  - ➢ Aluminum: 0.088 nΩ.m
  - ➢ Copper: 0.029 nΩ.m
- Actual degradation after 600MWh (0.0685MWyear)
  - ➢ Aluminum: ΔR=0.07 μΩ (prediction 0.039 μΩ)
  - ➢ Copper: ΔR= non-measurable (prediction 0.008 μΩ)
  - ➢ Predictions were fairly comparable to measurements.
- Electrical resistance increases during the beam operation were recovered by warming up to room temperature during the downtime.
- So far, Super-OMEGA SC magnet has been successfully operated.



In-situ electrical resistance measurement of “watch samples” in Super-OMEGA

SC Magnets in J-PARC



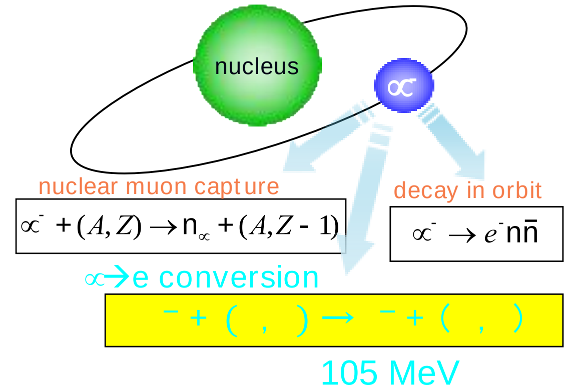


COMET (muon to electron transition)

SC Magnets for COMET

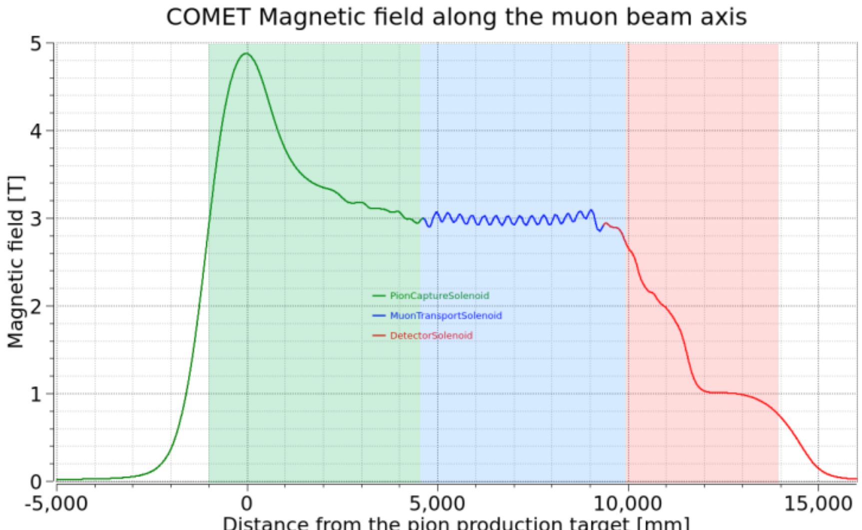
<COMET experiment>

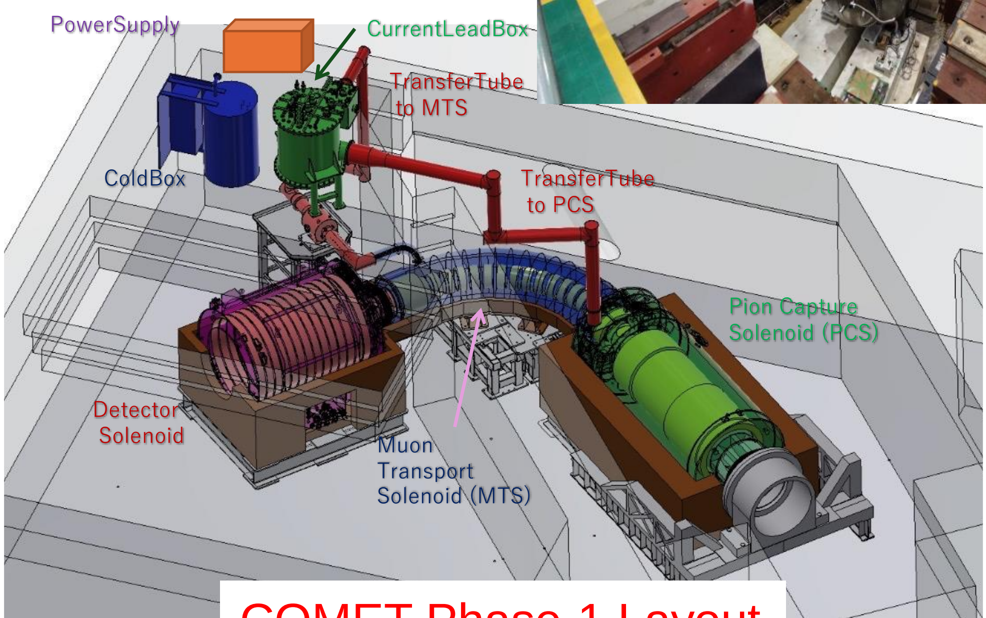
- Coherent neutrino-less conversion of a muon to an electron, μ^{-}+ N(A, Z) → e^{-} + N(A, Z).
  - ➢ Phase-1 (8 GeV proton, 3.2 kW, 150 days)
  - ➢ Phase-2 (8 GeV proton, 56 kW, 180 days)



<SC Magnets for COMET>

- Pion Capture Solenoid
  - ➢ *max. 5 T on Target*
- Muon Transport Solenoid
  - ➢ *3T curved solenoid*
  - ➢ *Correction dipole max. 0.07T*
- Detector Solenoid + Bridge Solenoid
  - ➢ *graded field from 3T to 1T*

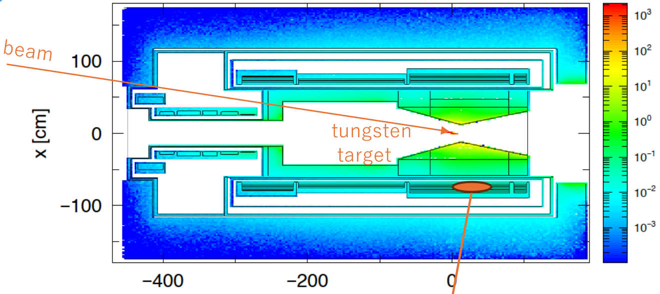


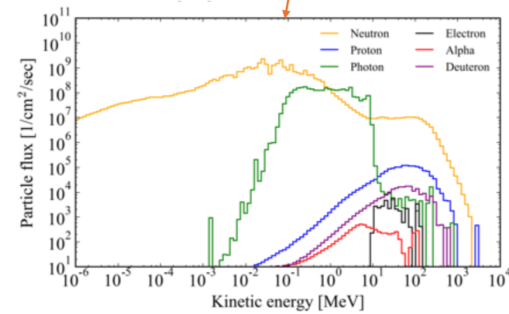


COMET Phase-1 Layout

Radiation Environment of PCS

PHITS simulation



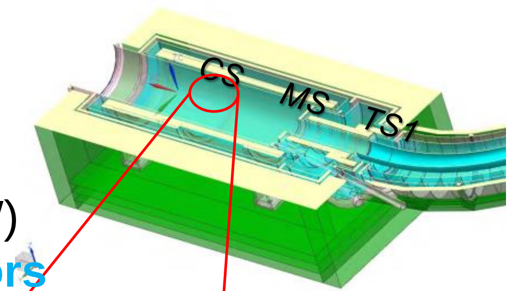


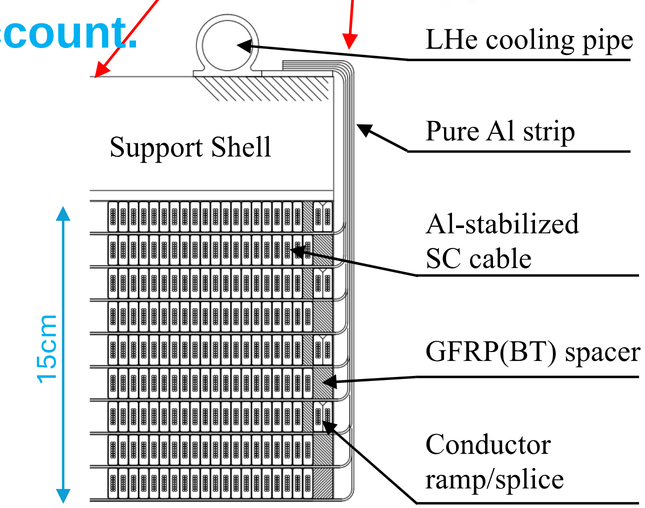
- PCS with tungsten radiation shield against radiation from the target at 56 kW proton incidence for 180 days.
  - ➢ Heat deposition: ~40 mW/kg >> 0.6 MGy
  - ➢ Neutron fluence: 6.2 x 10^{21} n/m^2

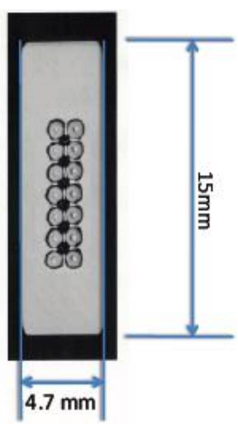
Radiation tolerant magnet is mandatory.

<Design concept>

- Aluminum stabilized SC cable for less heat deposition.
- Radiation resistant insulator, resin.
  - ➢ BT resin, Polyimide MLI.
  - ➢ New GFRP (BT, boron free S glass fiber)
- Helium refrigerator (130W)
- Conduction cooling by pure aluminum strips between coil layers. (Total heat load will be ~75W)
  - ✓ **Radiation damages in thermal conductors and stabilizers are fully taken into account.**





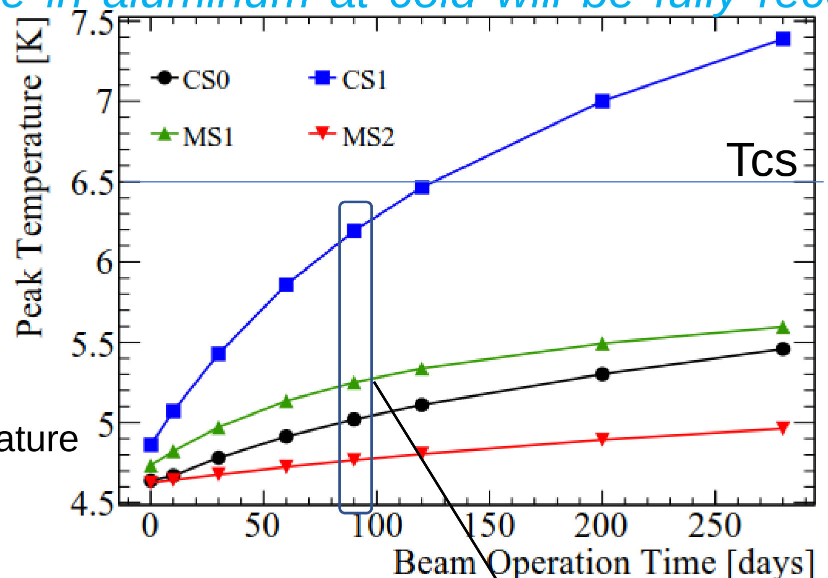


Al stabilized SC cable

- 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.

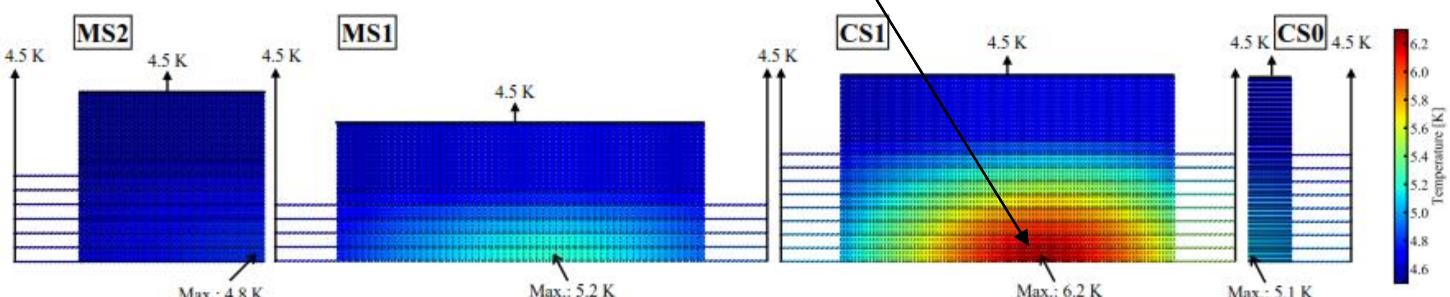
Coil Temperature Increase at Beam Operation

- Peak temperature in coil is estimated assuming irradiation by 56 kW beam operation.
  - ➢ Constant heat deposition: ~40 mW/kg at max.
  - ➢ Degradation of thermal conductance in proportion with beam operation time. (Assuming a damage rate of *0.03 nΩm for 10^{20} n/m^2)
- A runtime of COMET Phase-2 will be limited < 90 days in view of the coil temperature increase of PCS.
- *Note: irradiation damage in aluminum at cold will be fully recovered by thermal cycle to room temperature *.*



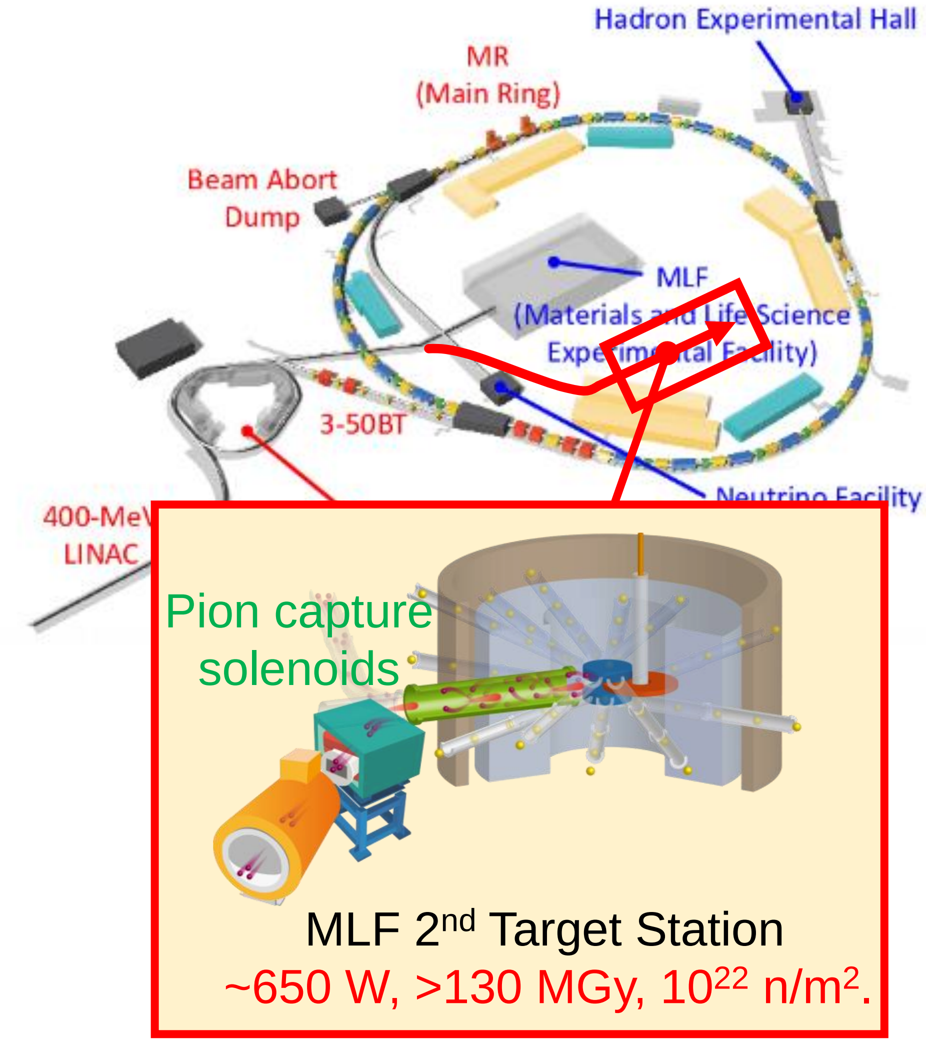
*"Repetitive Irradiation Tests at Cryogenic Temperature by Neutrons and Protons on Stabilizer Materials of Superconductor," M. Yoshida et al., *IEEE Trans. Appl. Supercond,* 32(6), 7100405 (2022); doi:10.1109/TASC.2022.3178944

Time evolution of coil temperature as a function of beam time.



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

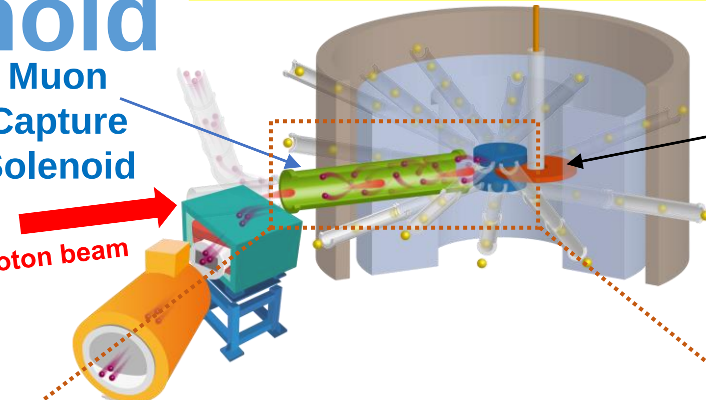
SC Magnets in J-PARC



Plan:
MLF 2nd Target Station and Pion Capture Solenoid

Integrated neutron and muon target

10 (target) x 5~10 (Muon capture solenoid)
→ 50 ~100 times gain of muon flux

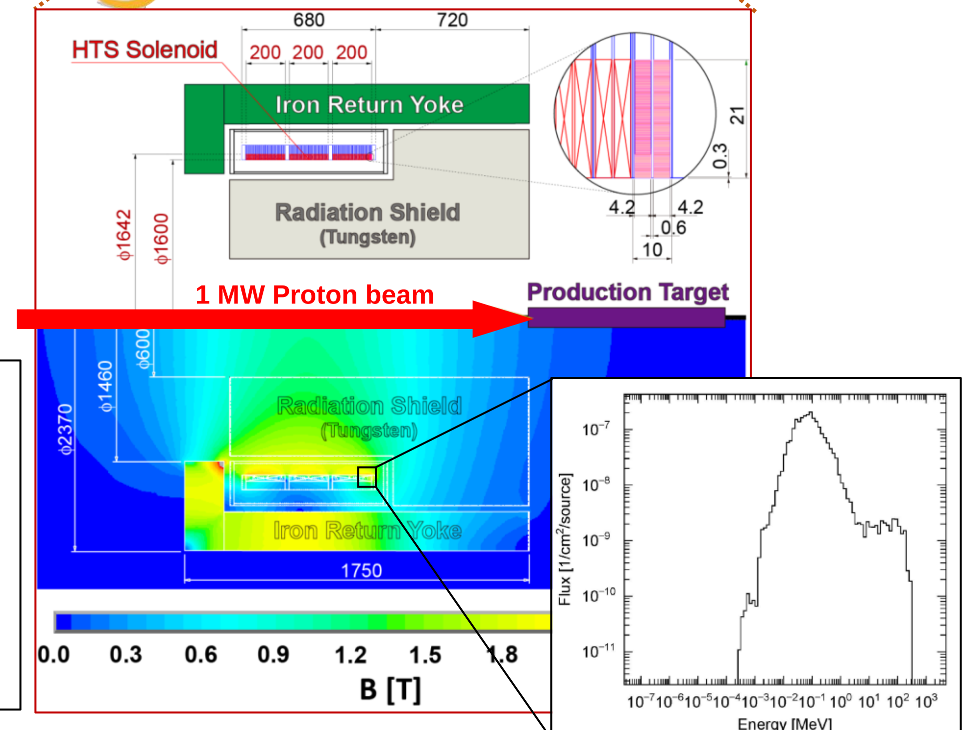


Radiation environment of TS2 Capture Solenoid
(10 years operation)

- Heat deposition: ~ 650 W
- Neutron fluence: 7.7 x 10^{21} n/m^2
- Absorbed dose: > 130 MGy

< Design concept>

- Central field of 1.1 T.
- Beam aperture of 600 mm and a massive tungsten radiation shield (t400): coil ID of 1600 mm.
- ***HTS coil to be operated at 20 K.***
  - 2.3 T at coil, 200 A, load line ration of 48 %.



neutron flux at HTS coil 7.74 × 10^{20} n/m^2/year (@1 MW)

R&D for HTS PCS

<Studies on radiation resistance>

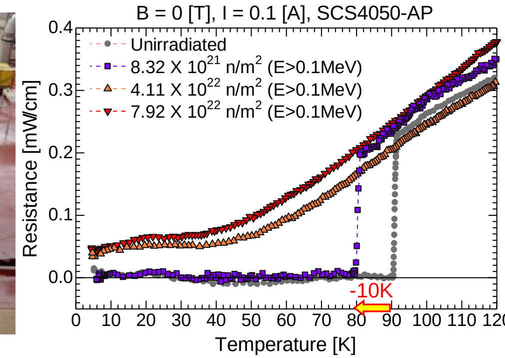
- Neutron irradiation on (Gd, Eu, Y)BCO tapes, ceramic coating, BT-GFRP at BR2, JRR3.
- Gamma-ray irradiation on REBCO tapes, ceramic coating at QST-Takasaki.
  - ✓ Collaboration with CERN, LBNL for screening of conventional resins and GFRPs (~2021)*.

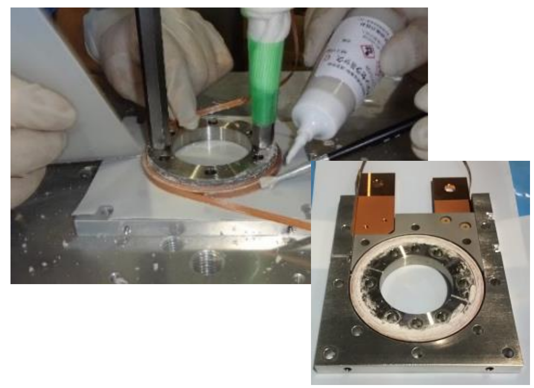
<Technology development of ceramic coating and bonding>

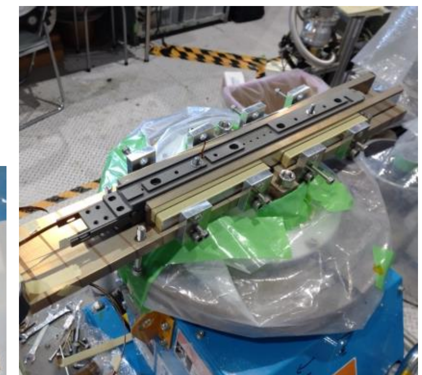
- Ceramic coating on REBCO coils.
- Demonstration of coil fabrication w/ ceramic adhesive.
- Excitation test at cold.

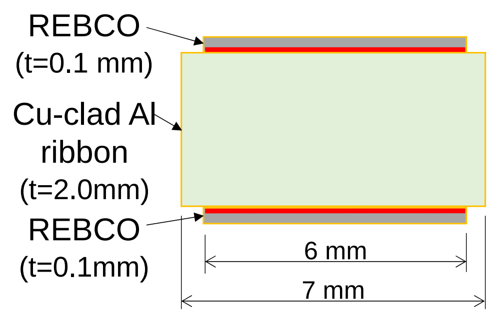
<Development of Al-stabilized HTS conductor>

*Andrea Musso, et al., "Characterization of the Radiation Resistance of Glass Fiber Reinforced Plastics for Superconducting Magnets", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 6, SEPTEMBER 2022, 7700405.





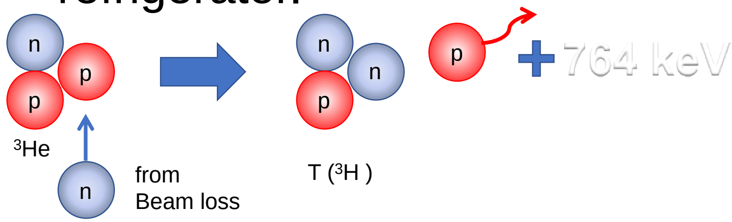


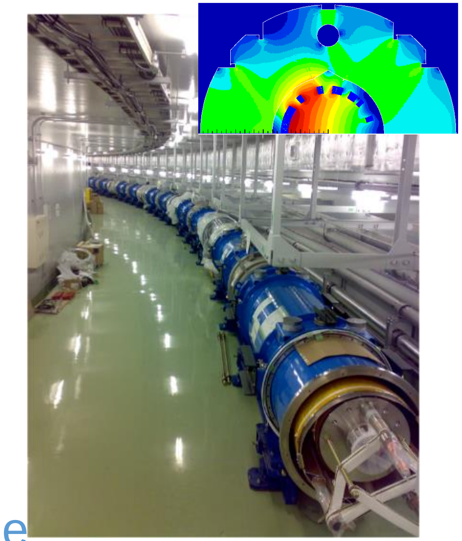


Cross section of Al-stabilized HTS conductor

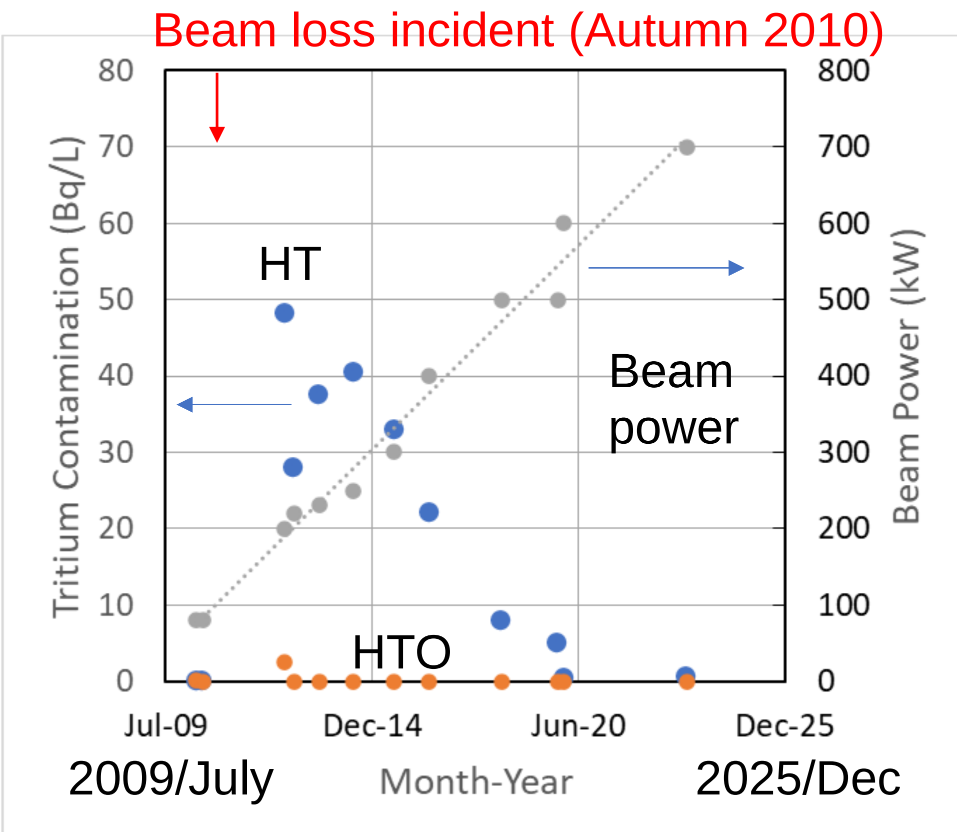
Tritium in T2K Neutrino Beam Line

- 28 units of 3.6 m long SC combined function magnets for T2K neutrino beam line: 30 GeV, 800 kW.
- Cooling by SHe (4.5 K, 0.4 MPa, 300 g/s) with 1.5 kW helium refrigerator.





- ➢ Abundance ratio of ^{3}He is ~1.4 ppm.
- ➢ Reaction cross section of ^{3}He for thermal neutrons is 5.3×10^3 barn.



Tritium production is negligible unless a beam loss incident occurs.

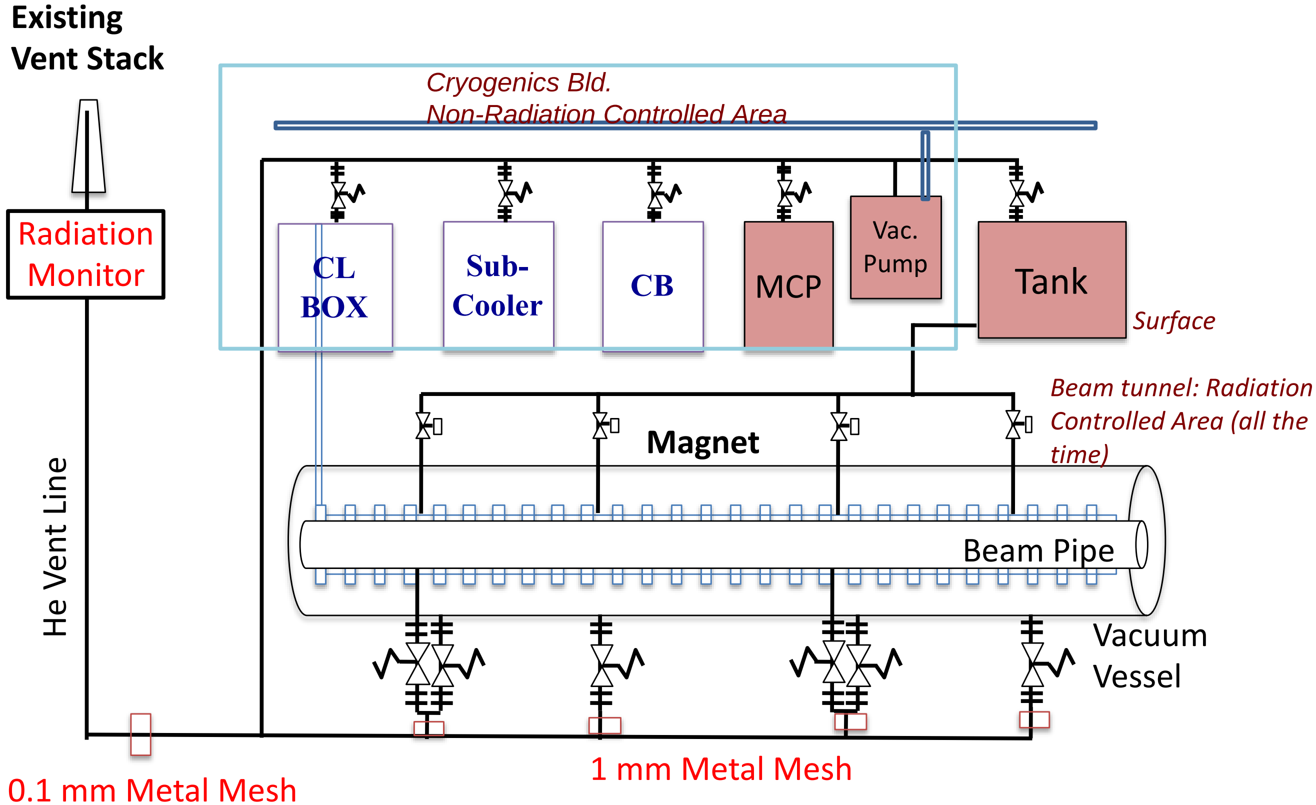
"Act on the regulation of Radioisotopes, etc."
(based on ICRP90)

^{3}H allowable limit (Bq/L) in discharging gaseous waste	
Hydrogen (HT)	**70000**
Methane	700
Water (HTO)	5
Organic Matter	3

Actual amount of tritium is much lower than the allowable limit. But…

Tritium in T2K Neutrino Beam Line

- Radiation Management Policy in J-PARC became much stricter **after the beam accident in 2013 (https://j-parc.jp/en/topics/HDAccident20130531.pdf).**
- Gaseous waste must **be vent through authorized vent stack and be quantified by radiation monitor**.
  - ➢ Even small amount of gas vent from maintained equipments must follow the guideline.
- **The work place**, where gaseous waste is vent, **shall be set as "a radiation controlled area" with a seal temporally** even if the expected amount of tritium is much lower than the allowable limit.



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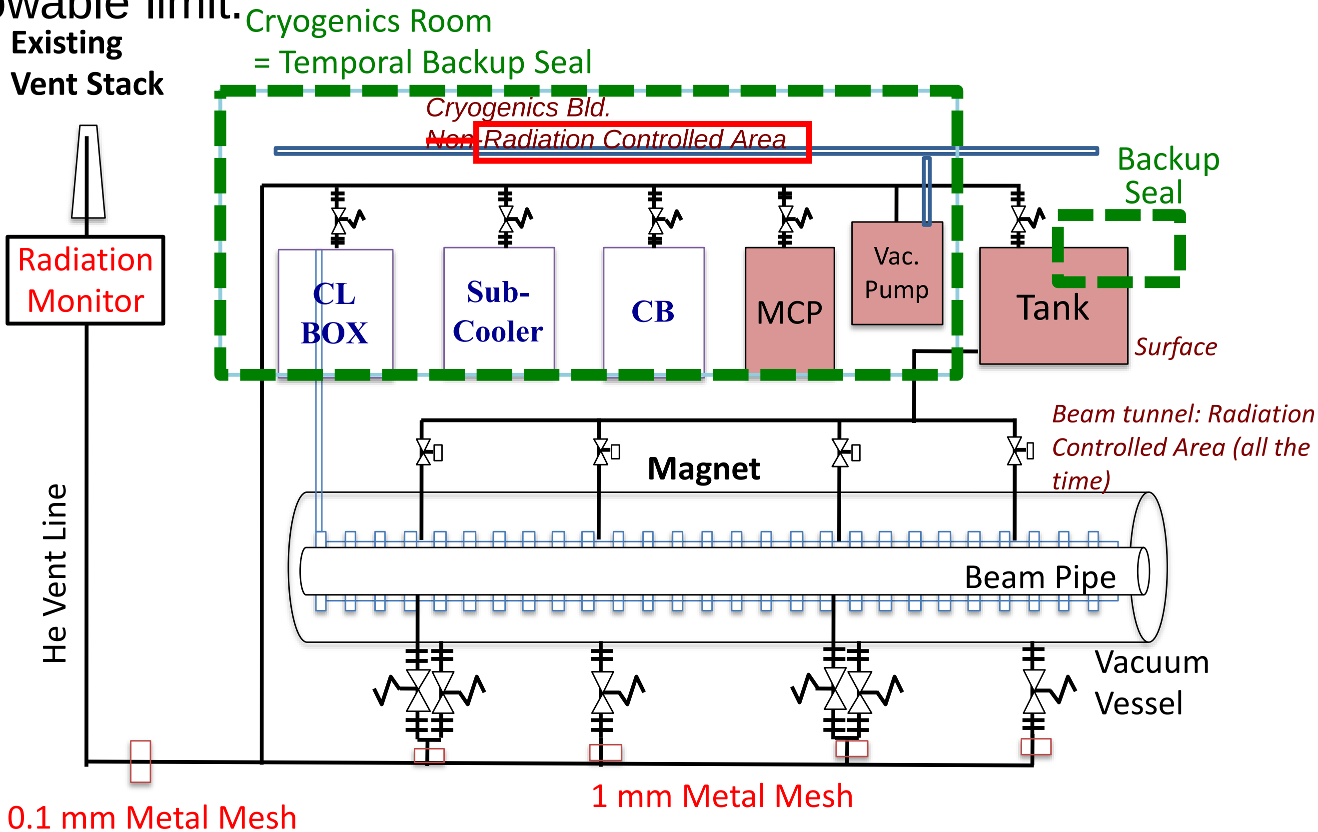

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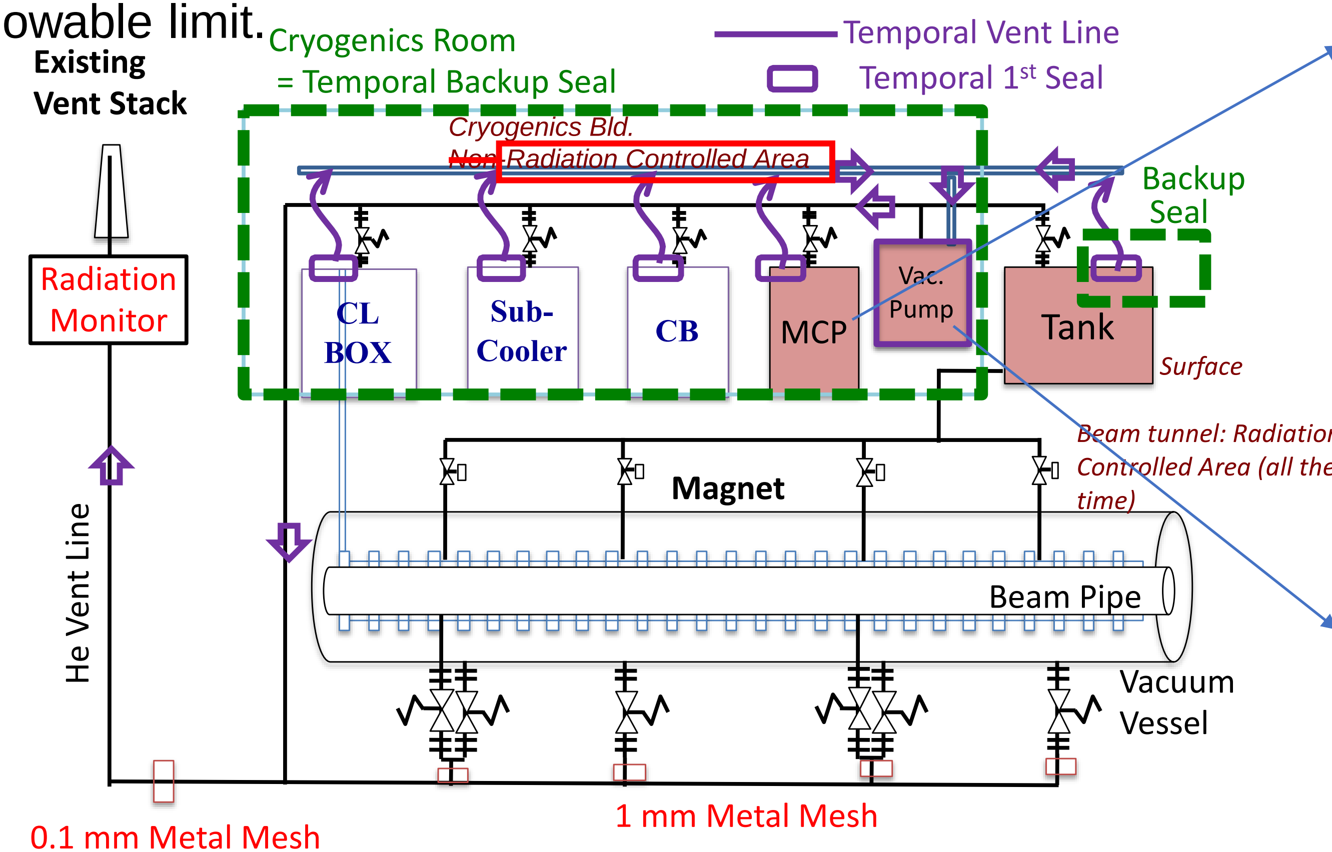

<1st seal>
Oil Separator Unit of MCP is covered by an air-tight plastic sheet room for maintenance work.

<Backup seal>
Cryogenics Room becomes radiation controlled area.

Vacuum pump (400m3/h) exhausts air from the room to the vent line.

Summary

- SC magnets in J-PARC and their radiation environments were introduced.
  - ➢Proton beam transport for T2K neutrino beamline.
  - ➢Muon facilities.
  - ➢Design and R&D for pion capture solenoid MLF 2nd Target Station.

- Issues of treatment of tritium at J-PARC.
  - ➢Highly appreciated if you kindly share the experience and the measures at your facility.

- Several presentations from J-PARC as listed in the next page.

Presentations from J-PARC in This Workshop

Overview

- J-PARC superconducting magnets and radiation environments
  - ➢ Tatsushi Nakamoto (J-PARC/ KEK), 15 January 2025 14:55

Radiation resistant magnets for COMET

- Design of COMET capture solenoid and shielding system
  - ➢ Makoto Yoshida (J-PARC/ KEK), 17 January 2025 11:00

R&D for HTS Magnets

- Irradiation Studies on HTS Materials in Japan: Results and Future Directions
  - ➢ Mukesh Dhakarwal (J-PARC/ KEK), 16 January 2025 14:00
- Research and development of ceramic-insulated HTS magnets for high-radiation environments
  - ➢ Masami Iio (J-PARC/ KEK), 17 January 2025 19:50

Modeling and experiment of irradiation

- DPA modeling in the PHITS code
  - ➢ Yosuke Iwamoto (JAEA), 16 January 2025 12:15
- Proton beam irradiation facility plan at J-PARC and activity on displacement damage study
  - ➢ Shin-ichiro Meigo (J-PARC/JAEA), 16 January 2025 14:25