Superconducting Magnet R&D for the High Intensity Muon Beam Production in the COMET Experiment

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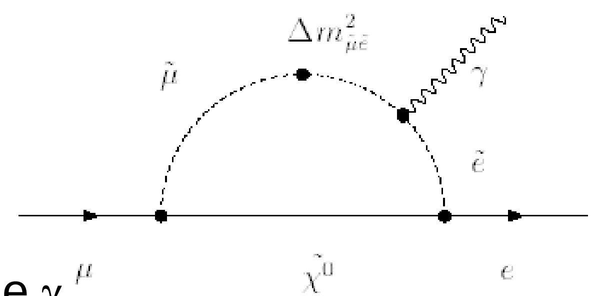
IPNS Seminar
Oct. 14th, 2011

Contents

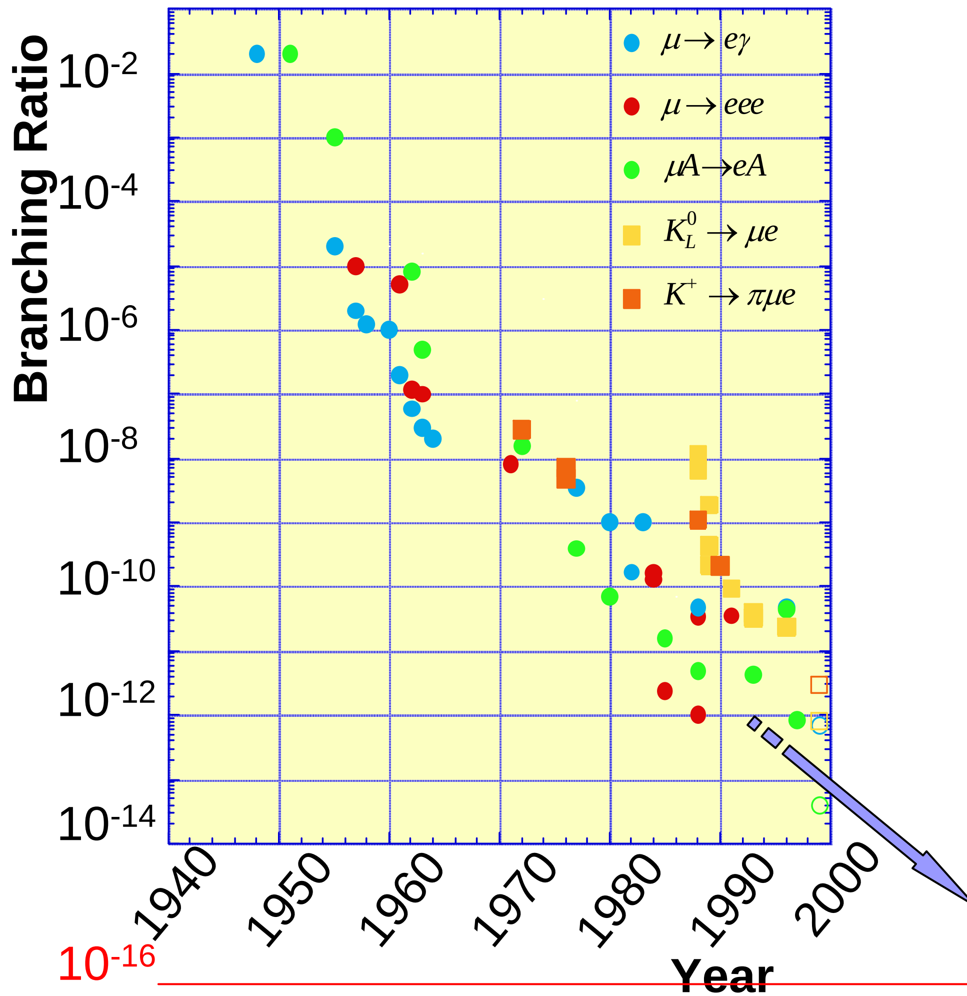
- The COMET experiment
- Superconducting magnet for COMET
- R&D status and prospects

Searches for Charged Lepton Mixing

- Lepton flavor violation → Beyond standard model
- Muon plays important role in the searches
  - Low mass → High statistics
  - Long life → easy to handle



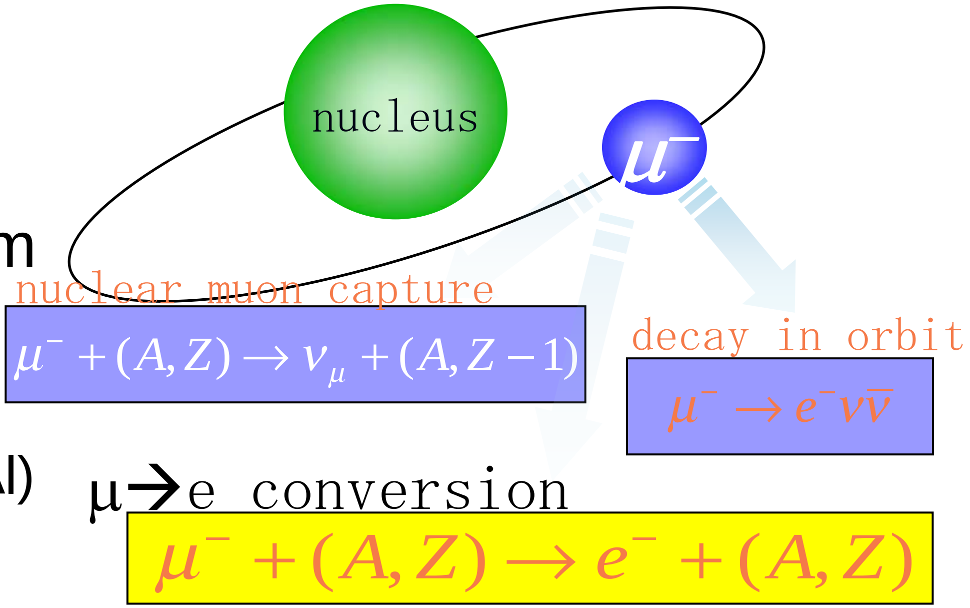
- $\mu \rightarrow e\,\gamma$
  $<2.4\times10^{-12}$(MEG2010) → O(10^{-13})
- μ N → e N
  1/400 (Al) of $\mu \rightarrow e\,\gamma$
  Awaiting searches for Br<10^{-16}

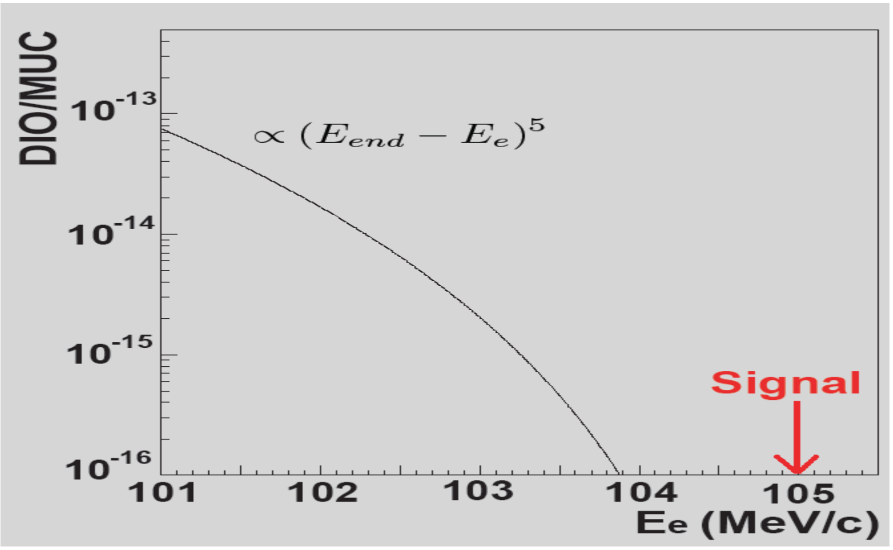


μ-e conversion

- stopping μ^- → Muonic atom
- Decay modes
  1. Muon Capture ~60%(Al)
  2. Muon Decay in Orbit ~40%(Al)
     - τ=0.88sec (Al)
  3. μ-e conversion

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

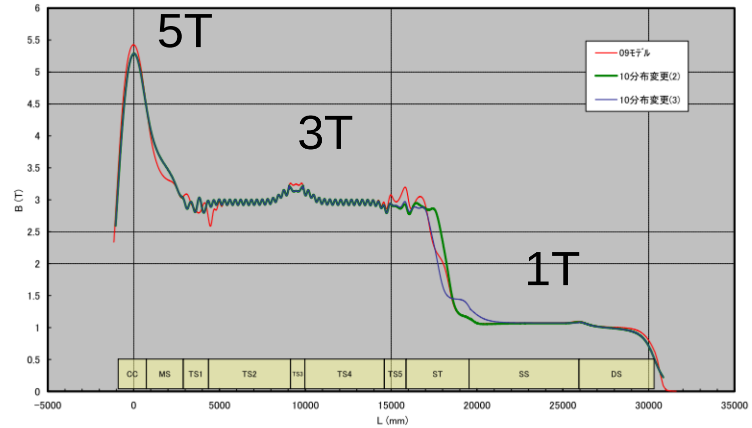


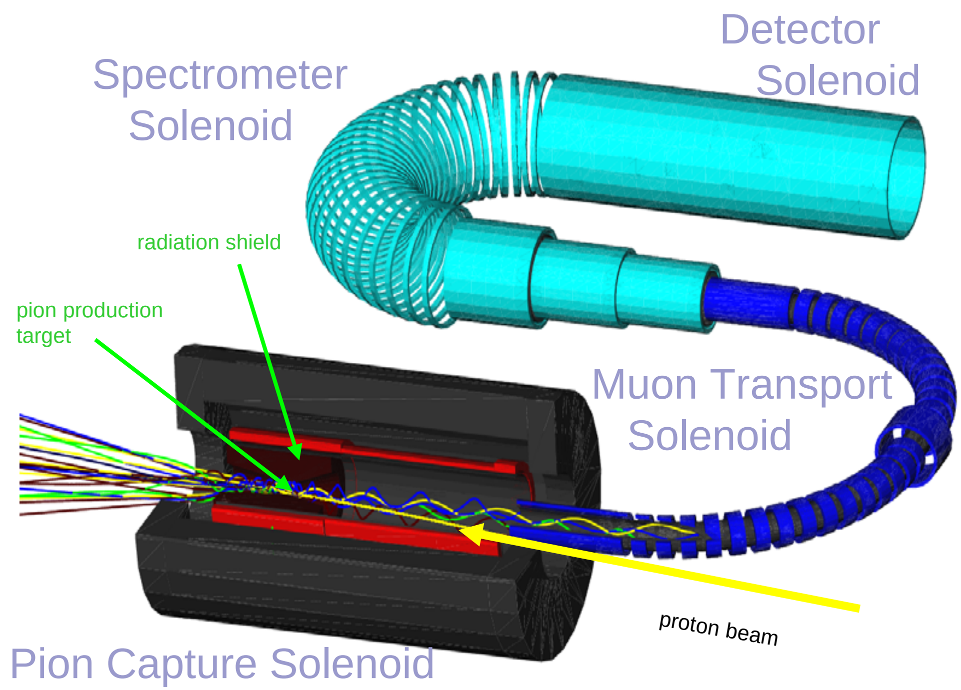


Detect monoenergetic electrons
from μ-e conversion

COMET

- J-PARC E21
- BR <10^{-16}
- A series of long solenods from end to end
  - pion capture & decay
  - muon transport
  - electron focus
  - spectrometer
  - detector





COMET Superconducting Magnet System

COMET Collaboration List

84 people from 20 institutes (August 2011)

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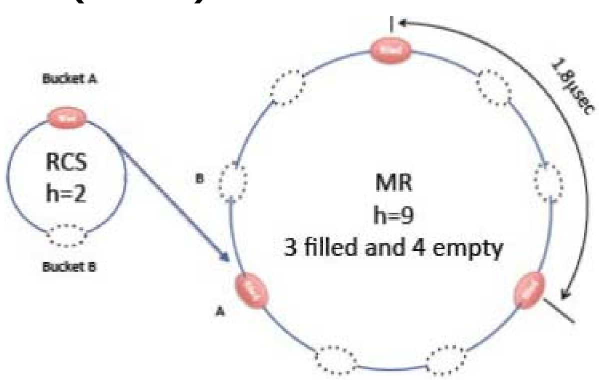
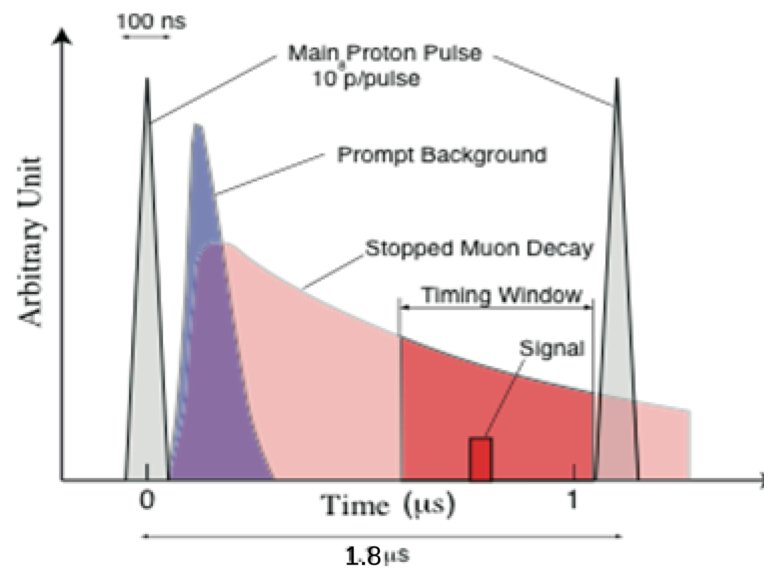
Requirements on Muon Beam

- Pulsed beam
  - Bunch spacing ~muon life
  - can mask prompt BG
- High intensity negative muon beam
  - Br<10^{-16} → 10^{18} μ^-
  - 10^{11} μ^-/sec for 2 year operation
- Low energy muons
  - <~70MeV/c
  - to form muonic atoms
  - to avoid Decay-in-Flight BG

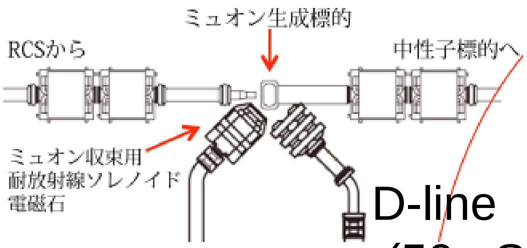
COMET@J-PARC

- Pulsed protons by slow extraction from MR
- 8GeV x 5~7microA
- Proton extinction <10^{-9}
  - $O(10^{-7})\times10^{-6}$





Muon sources



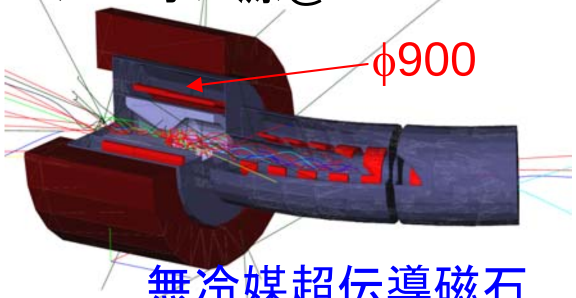
- Quadrupole
  - PSI, TRIUMF, RAL, J-PARC MUSE D-line (50mSr)
- Solenoid capture
  - Normal solenoid of SuperOmega
  - embedded target : MuSIC

Requirements for capture magnet

- Large aperture
- High magnetic field
- Radiation hardness

MuSIC

DCミューオン源@RCNP

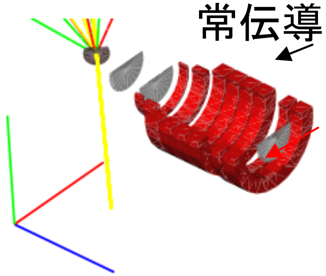


無冷媒超伝導磁石

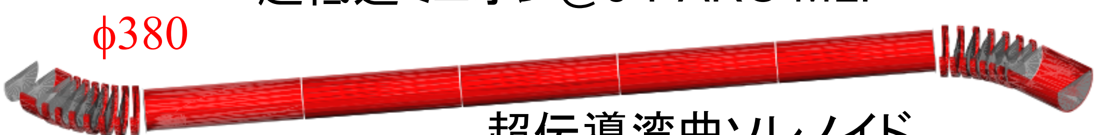
- 400W proton beam (100W on target)
- パイオン捕獲ソレノイド
- ~3x10^8 μ^+/s, ~10^8 μ^-/s

SuperOmega

常伝導ソレノイド



超低速ミュオン@J-PARC MLF



超伝導湾曲ソレノイド

- 1MW pulsed beam (50kW(5%) on target)
- 400mSr
- ~4x10^8 μ^+/s, ~10^7 μ^-/s

Large SC solenoids

Heat Load
~1W
Cost
~1M$

Heat Load
~100W
Cost
~10M$

Heat Load
~10kW
Cost
~100M$

MRI Magnets
Field: 1~4T
Cooling: He Free?

MuSIC
SuperOmega

Detector Solenoids
Field: 1~5T (NbTi)
Al Stabilized Cable
Cooling: Indirect
with cooling pipes

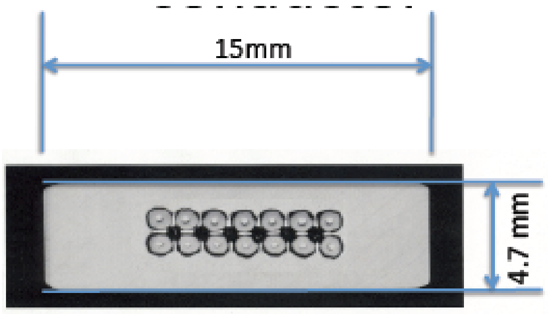
COMET

Fusion (ITER CS model)
Field: ~13T (Nb3Sn)
Cooling: Direct
cable in conduit

NF/MC

Al-stabilized superconductor

- NbTi Rutherford cable with aluminum stabilizer
- "TRANSPARENT" to radiation
  - Less nuclear heating
- Doped, cold-worked aluminum
  - Good residual resistance
    - RRR~500 (ρ_0=0.05nΩm@4K)
  - Good yield strength
    - 85MPa@4K



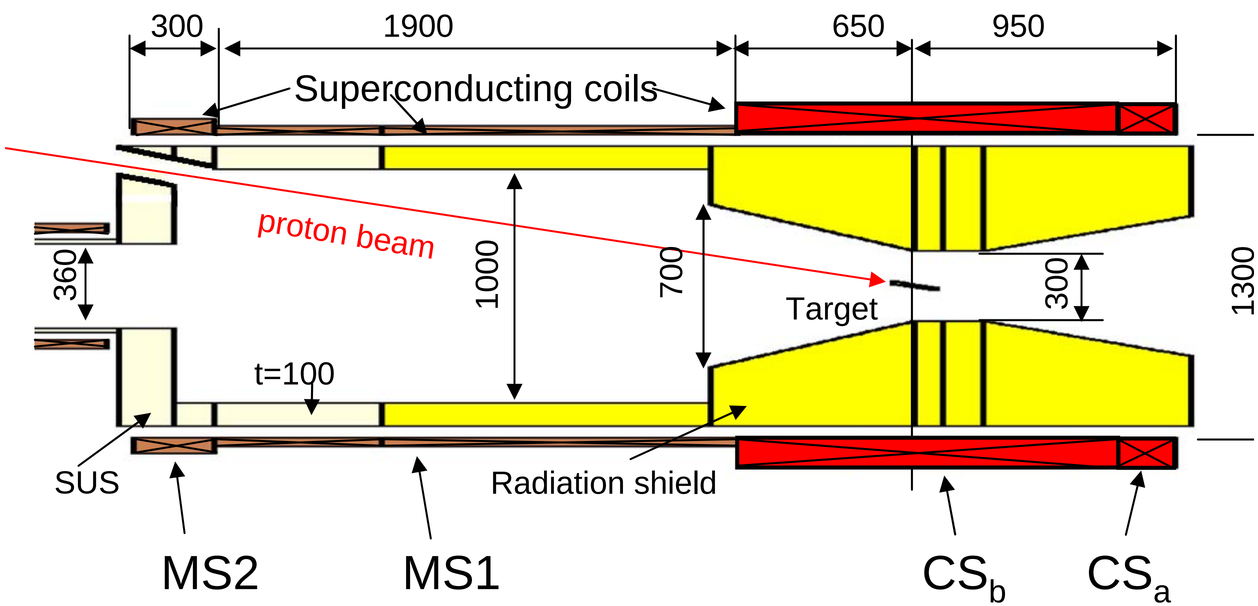
COMET design value

- 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.

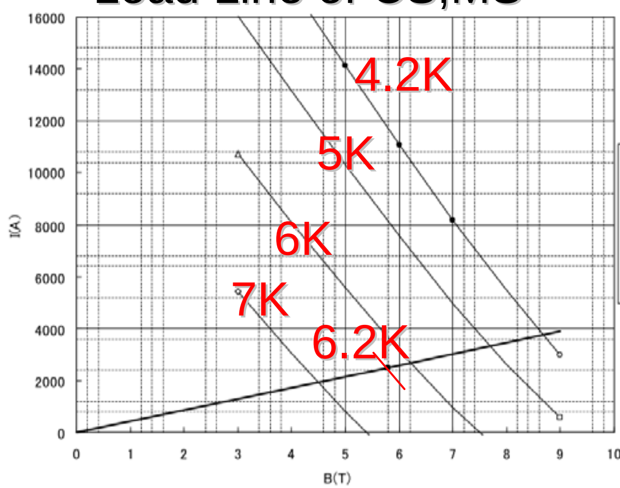
Capture Solenoid Layout

- Superconducting solenoid magnets with Al-stabilized conductor
- High field 5T to capture π^-
- Large bore 1300mm
- High radiation env.
- Decreasing field
- to focus trapped pions
- Thick radiation shielding 450mm
- Proton beam injection 10° tilted
- Simple mandrel

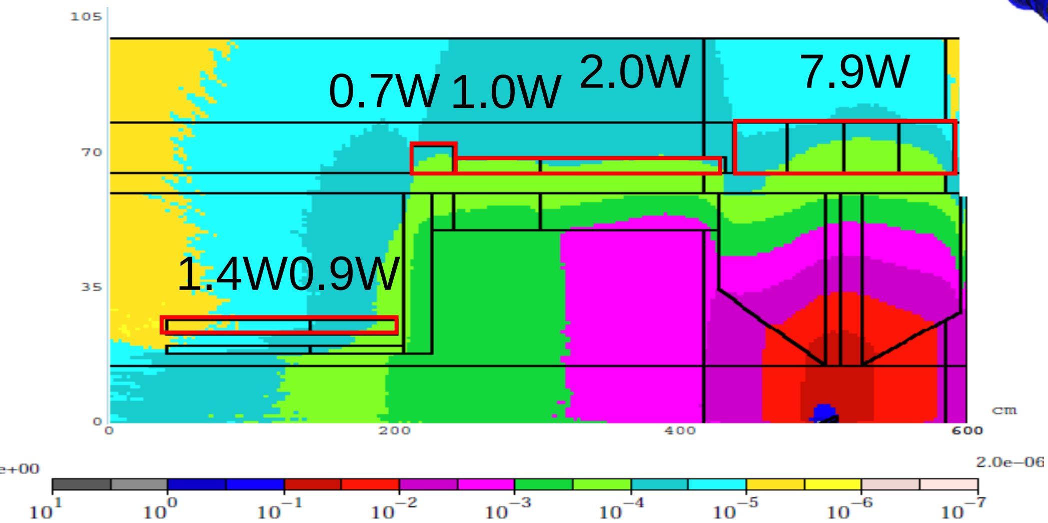
	CS	MS1	MS2
Length (mm)	1600	1900	300
Diameter (mm)	1300	1300	1300
Layer	8 layers	4 layers	8 layers
Thickness (mm)	120	60	120
Current density (A/mm^2)	42	42	42
Maximum field (T)	5.8	4.8	4.2
Hoop stress (MPa)	73	100	38



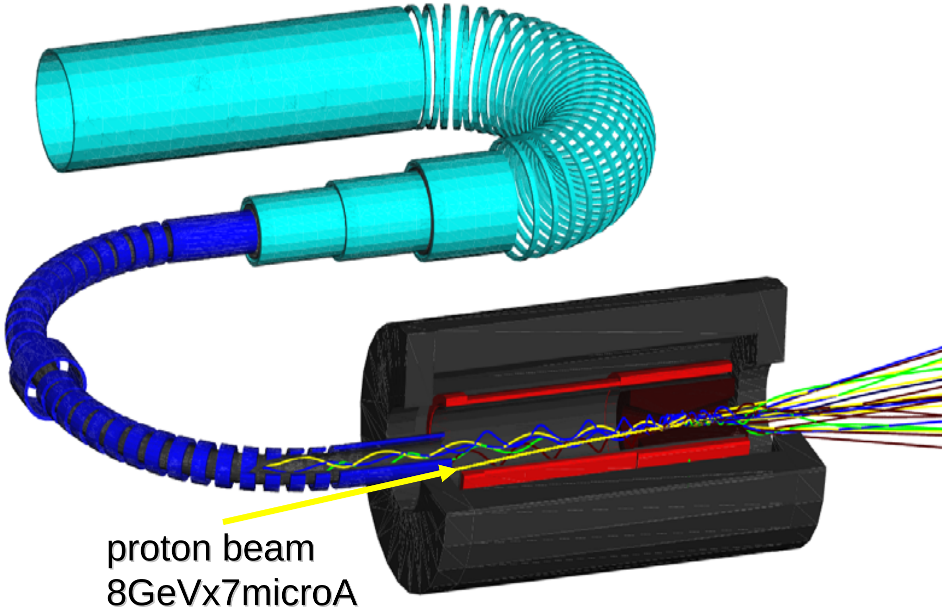
Load Line of CS,MS



COMET
Capture Solenoid



Neutron flux (n/cm2/proton)



- Maximum heat deposit
  - 10 mW/kg
- Maximum dose
  - 0.07 MGy/10^{21}p
- Neutron flux
  - 1×10^{21} n/m^2/10^{21}p
  - fast neutrons 6×10^{20} n/m^2/10^{21}p (>0.1MeV)

Neutrons penetrates thick 45cm tungsten shield surrounding the target

Neutron fluence for experimental life-time (~10^{21} p) approaches a level of ITER magnets (ITER requirement: 10^{22} n/m^2)

Superconducting Magnet R&D

- Feasibility of Aluminum stabilized conductor
  - Optimize strength vs. RRR
    - Additives, cold work
  - industrial production, coil fabrication
    - Size, Details of coil structure

- Radiation Hardness
  - Availability of rad-hard insulator
  - Check electrical/thermal degradation of stabilizer, thermal links

- How fabricate a series of solenoid magnets with various function from proton target to detector

Superconductor R&D

in US-Japan Collaboration

- In JFY2009
  - Replicate aluminum conforming technology
  - Confirm yield strength of aluminum with various additives
  - Successful trial production of 200 meter cable
    - 15mmx4.7mm (COMET design)
- In JFY2010
  - Test of RIKEN test coil in FNAL
  - Test of ATLAS short sample stack in FNAL
  - Trial production of larger conductor
    - 30mmx6.5mm (Mu2e design)
- In JFY2011
  - Plan to fabricate a test coil with 15mmx4.7mm conductor in FNAL
    - small diamter
  - Plan to fabricate a test coil with 30mmx6.5mm conductor in Japan
    - 1.3 m diameter
    - radiation hard insulator

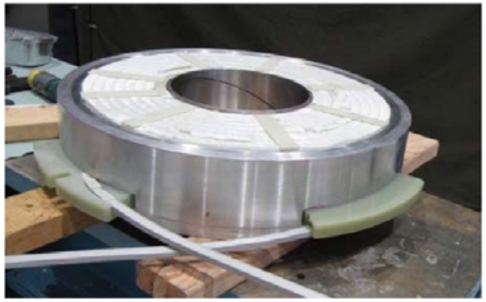
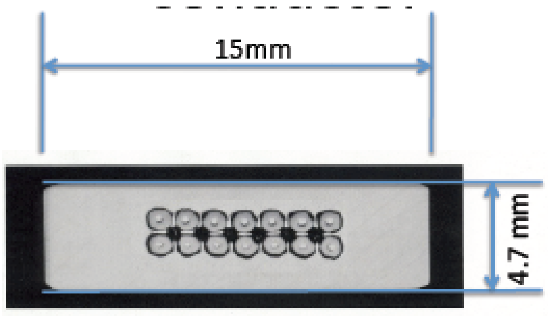
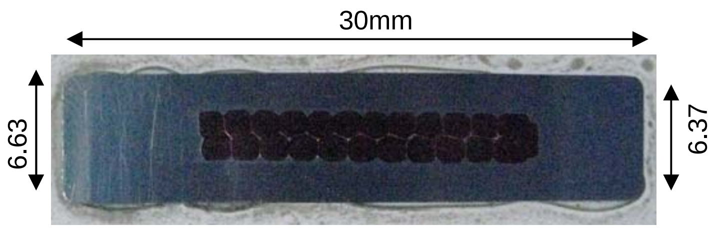


Figure.3.2.1: Test Coil with the outer aluminum ring and G-10 lead insulators, installed on the bottom aluminum flange.



COMET conductor (2009):

- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >450
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.
- Ic@4.3K > 11 kA@6T



Mu2e-design-based conductor (2010):

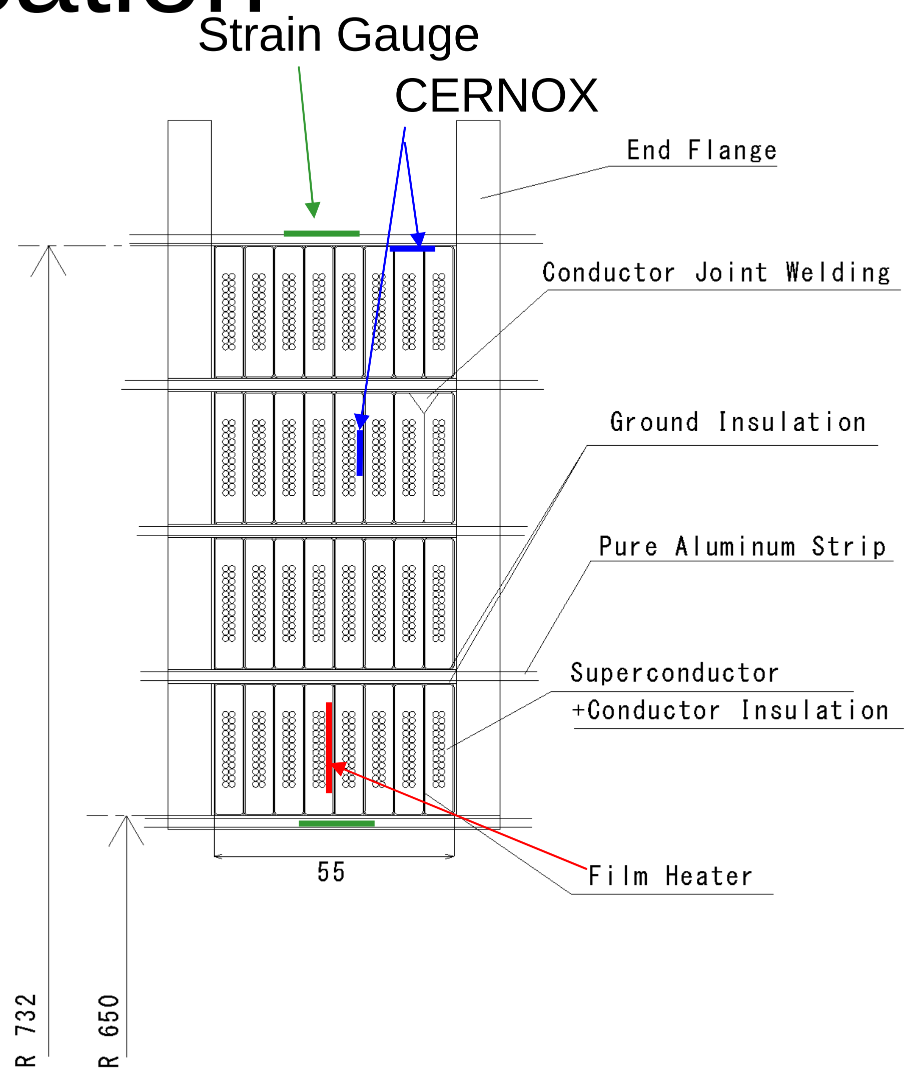
- Size: 6.5x30mm
- Al/Cu/SC: 9.2/1.3/1
- 24 SC strands: 1.43mm dia.
- Ic@4.3K > 29 kA@6T

Bending Tests of a Wide Conductor (ATLAS cable)

No problem was found in R=650

Test Coil Specification

- Coil dimensions
  - 4 layers
  - 8 turns
- Al-stabilized Conductor
  - 6.5mmx30mm
  - test underway
- Conductor Insulation
  - Upilex/Glass*
  - Double spiral wrapping
- Ground Insulation
  - GUG*
  - Double spiral
- Resin
  - BTresin
- Thermal propagator
  - 2mm thick pure aluminum strips in between each lay
  - coverage 50%(*)
- Conductor joint welding for R&D
- Film heater for quench test
- End piece or flange (GFRP) to be attached to supports

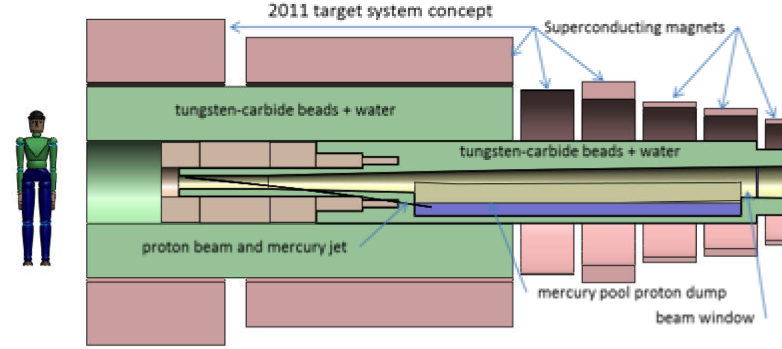


* may be changed in engineering design

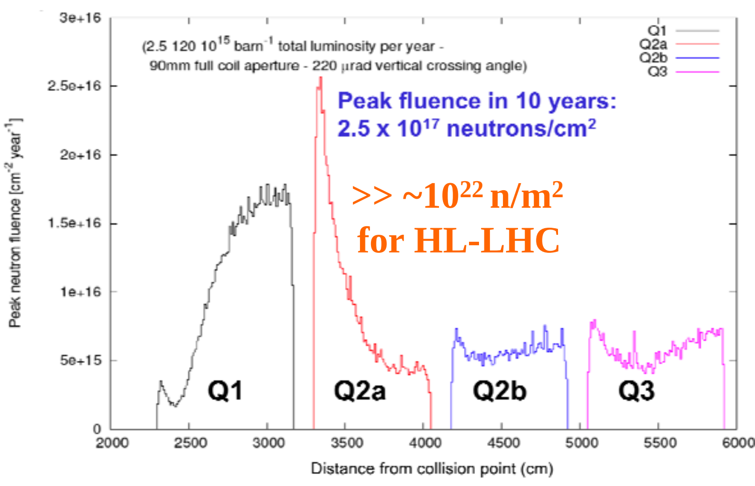
Radiation-resistant SC magnet

- Neutron fluence $>10^{21\text{-}22}$ n/m^2
- Dose >>1 MGy

- High field application needs radiation resistant superconducting magnets
  - High intensity muon source
    - MuSIC, COMET, Mu2e and next
  - Synergy to the next generation accelerator
    - Muon colliders, LHC upgrade ...



MC/NF capture system
by K. McDonald@Nufact11



Radiation hardness of magnet materials

- Insulator, resin
  - BT resin, Cyanate ester
  - Polyimide/Glass composite
- Thermal insulator
  - Al-coated polyimide film ← Less outgas
- Support structure
  - GFRP, Titanium rod
- Superconductor
  - NbTi, Nb3Sn would be OK up to 10^{22} n/m^2

Problematic components

- Stabilizer
  - Aluminum alloy
  - Copper
- Thermal conductor
  - Pure aluminum
  - Copper
  - Aluminum alloy
- Thermo sensor
  - No experience at 10^{21} n/m^2

- Fast-neutron irradiation induces defects in metal.
- Defects could be accumulated at Low temperature,
- and causes degradation of electrical/thermal conductivity

- Problems in
  - Quench protection, Stability
  - Cooling

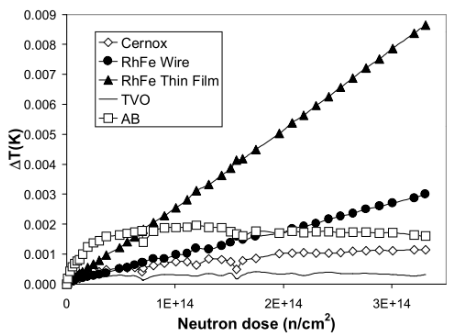
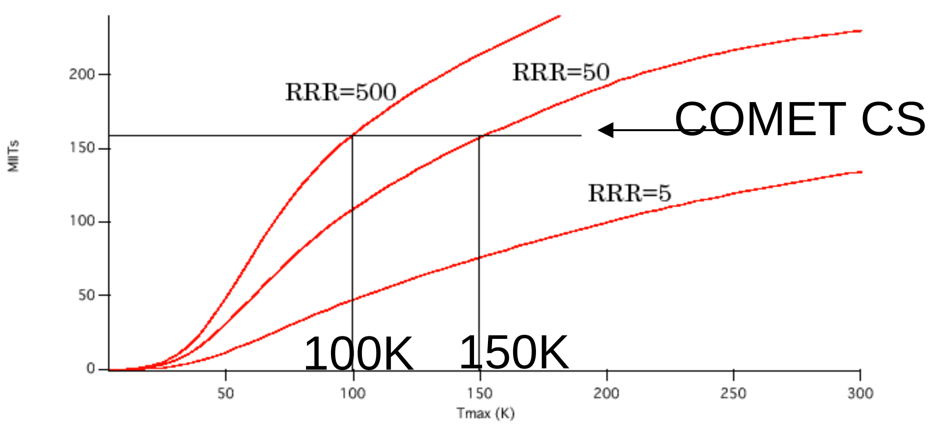


Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

LHC Project Report 209



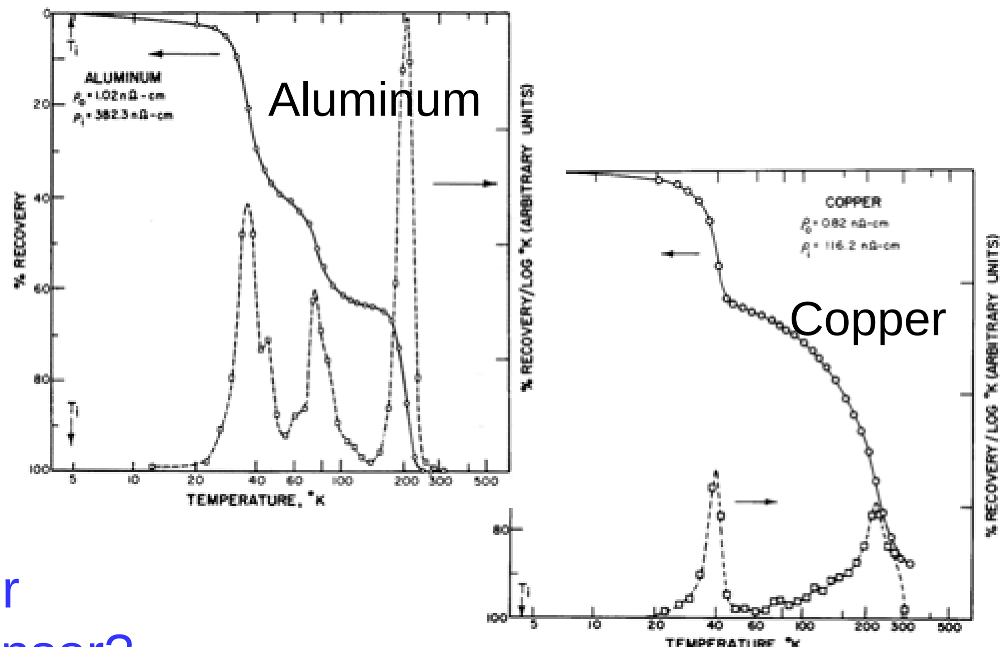
Irradiation effects on Al, Cu in literature

- pure Al (RRR=2286)
  - Fast neutron 2×10^{22} n/m^2 Induces ρ_i=3.8nΩ.m [1]
  - Perfect recovery by annealing at RT
- pure Cu (RRR=2280)
  - ρ_i=1.2nΩ.m [1]
  - 10% damage remains after annealing at RT

Table 3
Irradiation induced resistivity, ρ_i, defect concentration, C_i, and ratio of induced to residual resistivity, ρ_i/ρ_0.

Element	Induced resistivity, ρ_i (n$\Omega\cdot$cm)	Induced concentration a) (10^{-4} a.f.)	ρ_i/ρ_0
Aluminum	382.3	5.6	275
Nickel	363.9	5.6	31
Copper	116.2	4.8	142
Silver	87.9	3.6	54
Gold	102.7	4.0	40
Platinum	264.6	3.6	48
Iron	1137.2	9.1	21
Molybdenum	593.3	6.0	142
Cobalt	794.6	8.0	9

Recovery after irradiation 2×10^{22} n/m^2 (E>0.1MeV)



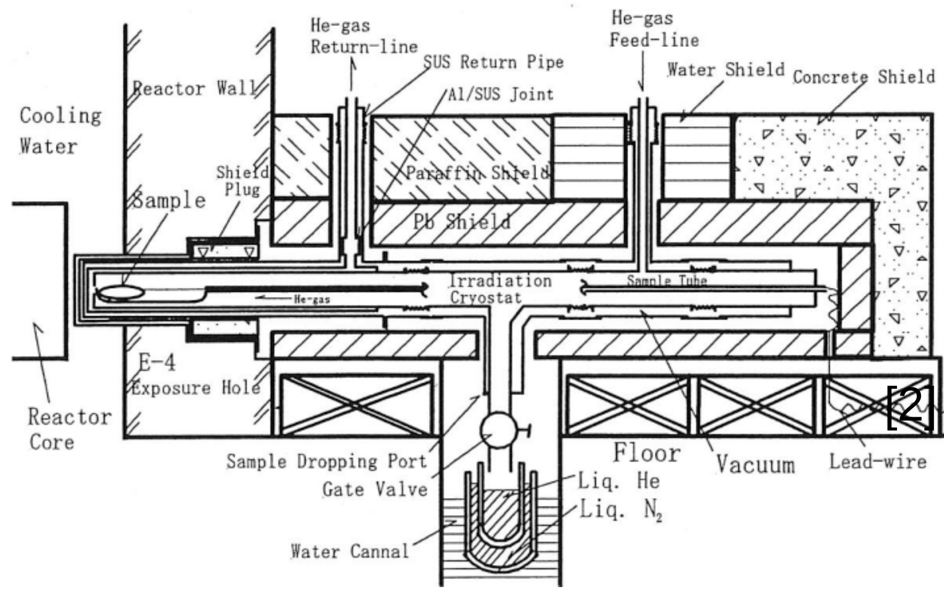
How about cold-worked Al-stabilizer and CERNOX sensor?

[1] J.A. Horak and T.H. Blewitt, J. Nucl. Materials, Vol. 49 (1973) p161

Low Temperature Irradiation Facility

- Kyoto Univ. Research Reactor Institute
- 5MW max. thermal power
- Cryostat close to reactor core
- Sample cool down by He gas loop
  - 10K – 20K
- Fast neutron flux(>0.1MeV)
  - 1.4×10^{15} n/m^2/s@1MW

[2] M. Okada et al., NIM A463 (2001) pp213-219



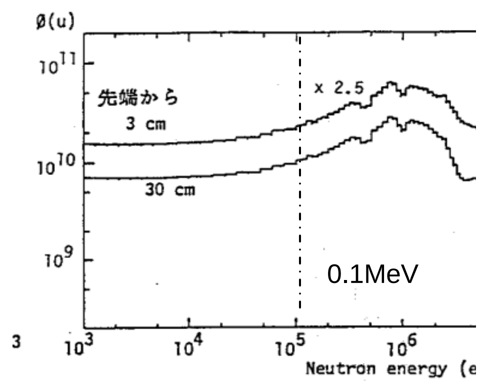


Fig. 15 Neutron energy spectrun in LTL of KUR for ordinary core (above 1000 eV)

KUR-TR287 (:

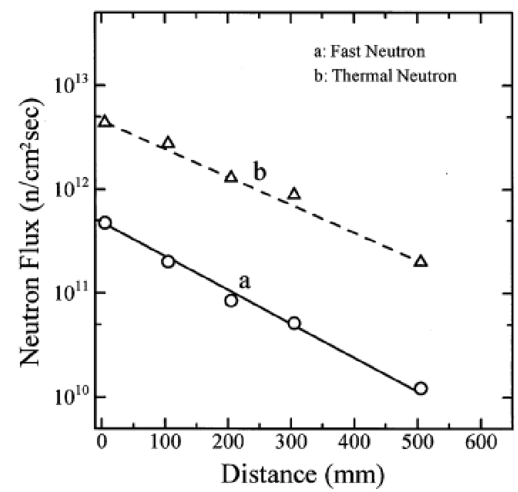
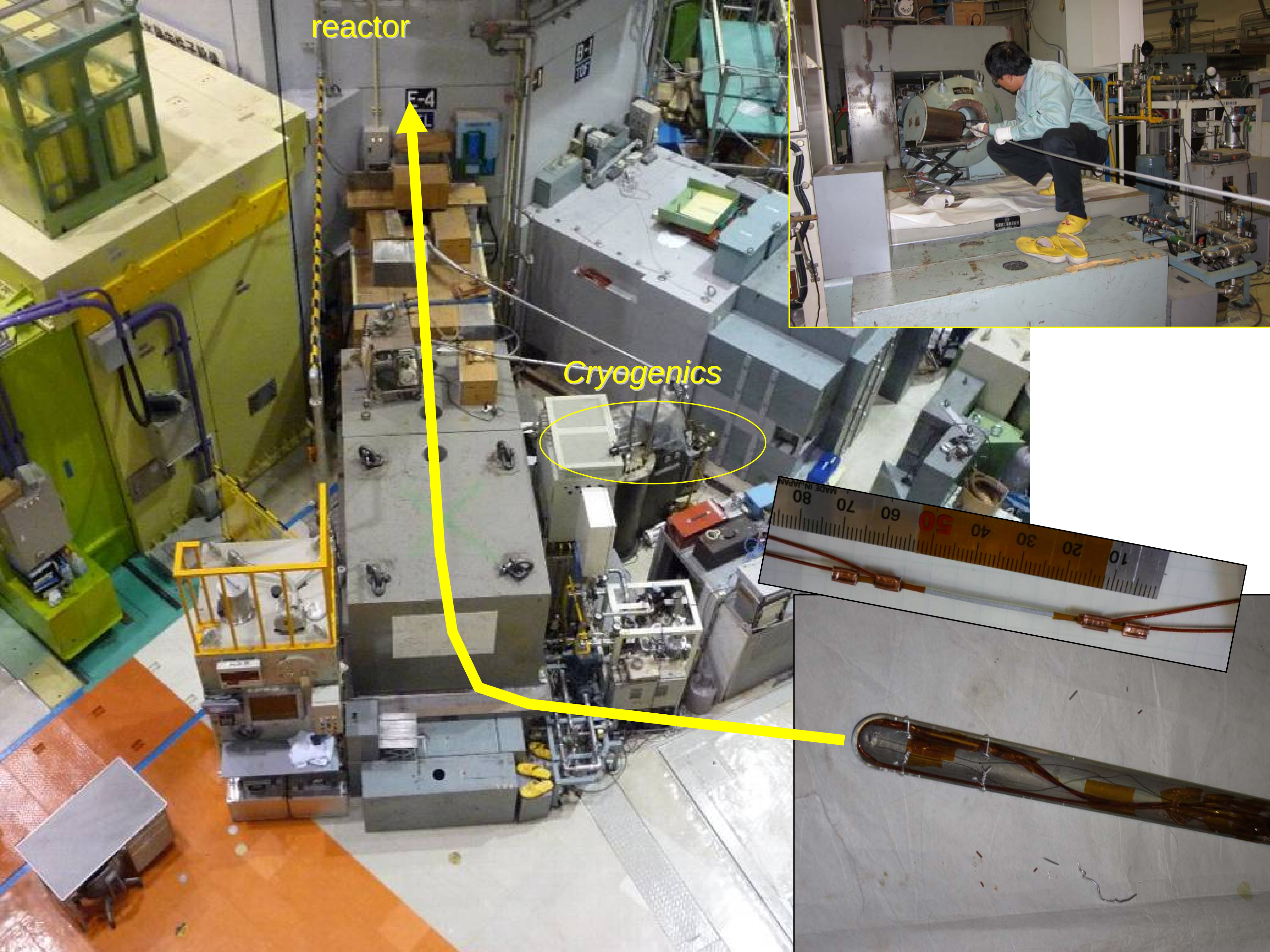


Fig. 7. Neutron flux distribution as a function of distance from top of sample chamber, (a) fast-neutron and (b) thermal neutron.

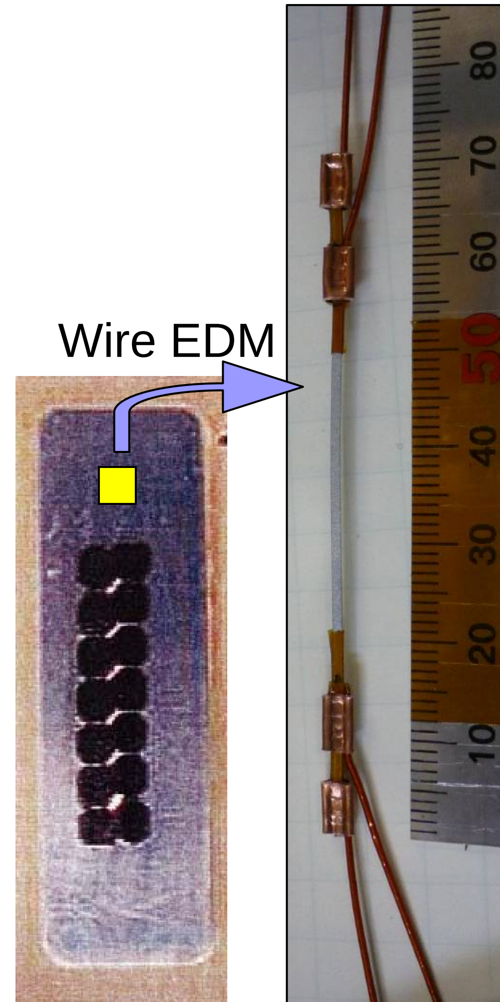

reactor
Cryogenics

Irradiation sample

- Aluminum stabilizer sample from the superconductor by wire electrical discharge machining in KEK
  - Keep defects by cold-work
- Size: 1mmx1mmx70mm
- Voltage taps with 45mm spacing
- 4 wire resistance measurement by nano-voltmeter
- CERNOX CX-1050-SD close to sample temperature (also irradiated)

Irradiation sample

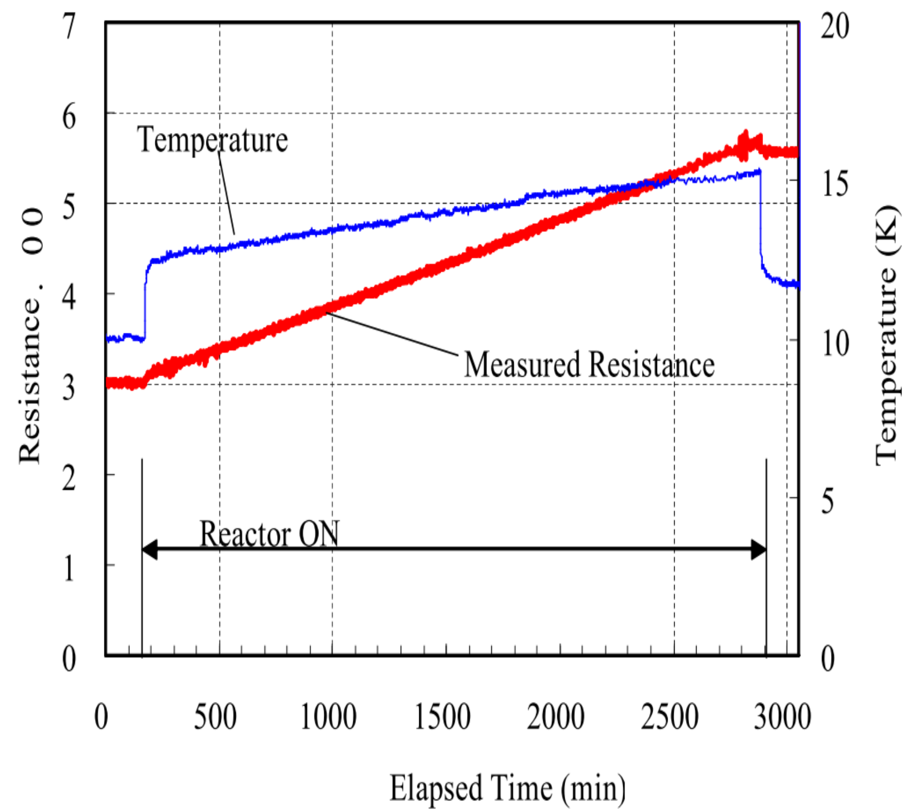
- 5N aluminum + Cu, Mg with 10 % cold work
- RRR=450
  - 1.35mΩ @RT, 3$\mu\Omega$ @10K



Result

- Fast neutron exposure at 12K
- Resistance increased in proportional to neutron fluence
  - No threshold at low neutron fluence10^{19}-10^{20} n/m^2
- Observed ρ_i = 0.056 nΩ.m for 2.3x10^{20} n/m^2 (>0.1MeV)
  - Good agreement with pure aluminum results (cf. [1])
- In COMET life time (2 year operation), resistivity of stabilizer will increase by a factor of 4 for neutron fluence of 6x10^{20} n/m^2

→Seasonal warm-up would be enough to recover



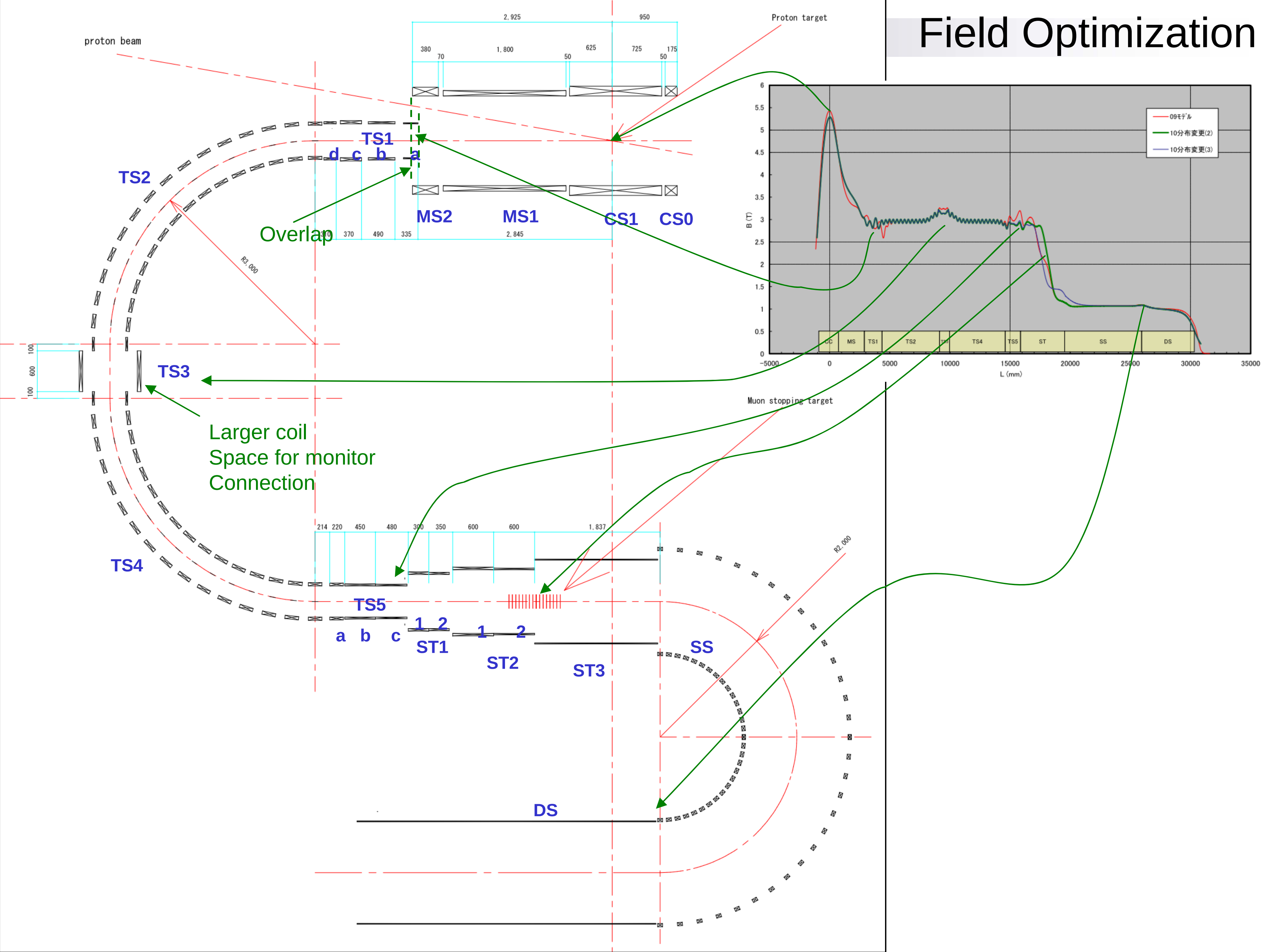
M. Yoshida et al., ICMC2011

- Perfect recovery was observed by thermal cycling to RT
- Temperature drift due to CERNOX sensor degradation?

Design Study

- So far
  - Coil layout for field optimization
  - Conceptual design of cryostat
  - Estimation of cryogenics
- To do
  - Interface to contents;
    - Proton target, Beam monitor, Collimator, Stopping target, Detectors
  - Remote handling, installation/disassembly procedure
  - Coil structure → test winding (conductor R&D)
  - Cryogenics design
    - Optimize refrigerator
    - LHe piping
    - Thermal links
    - Thermal cycling procedure

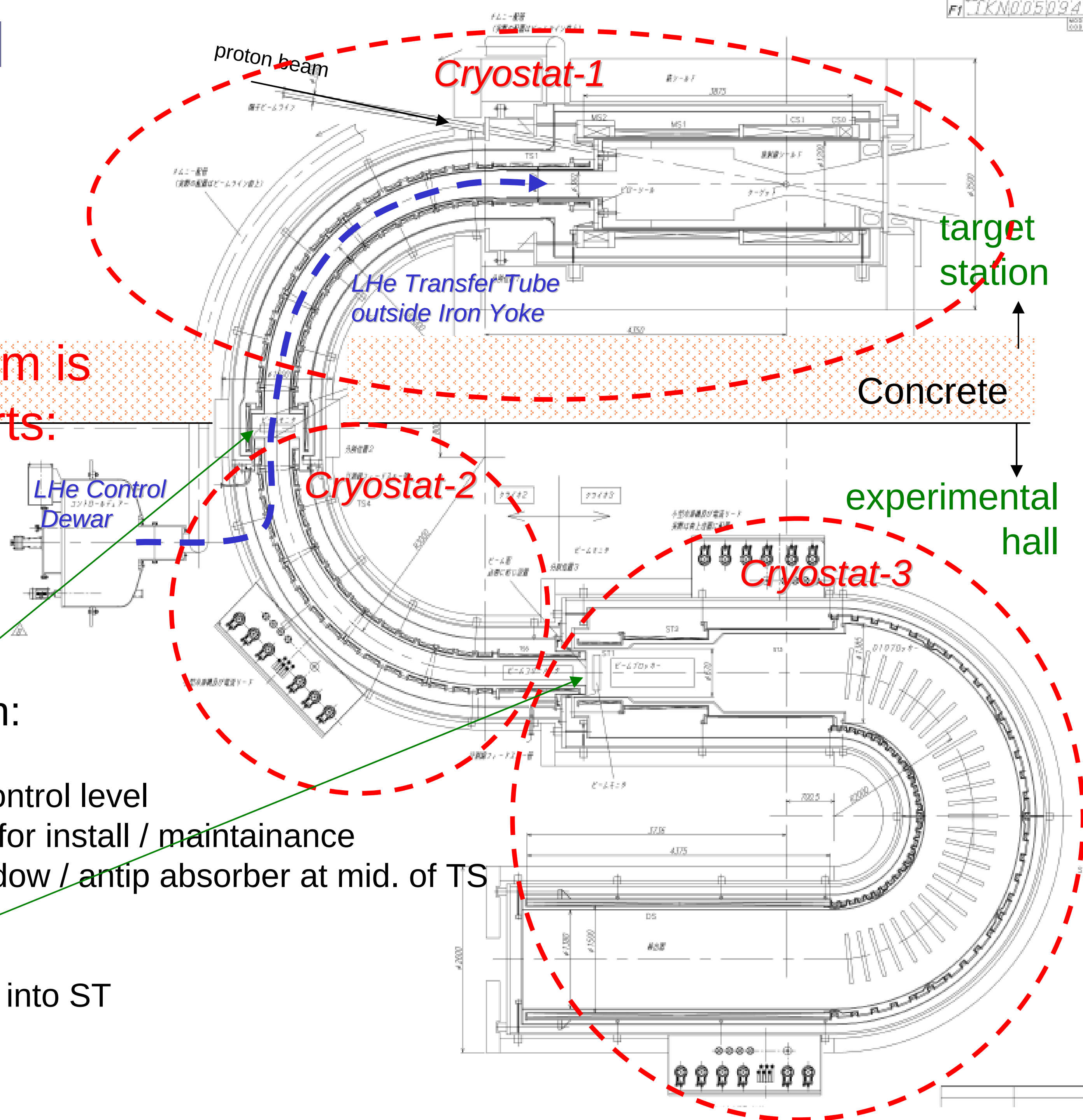
Field Optimization



COMET Magnet Design

The magnet system is separated in 3 parts:

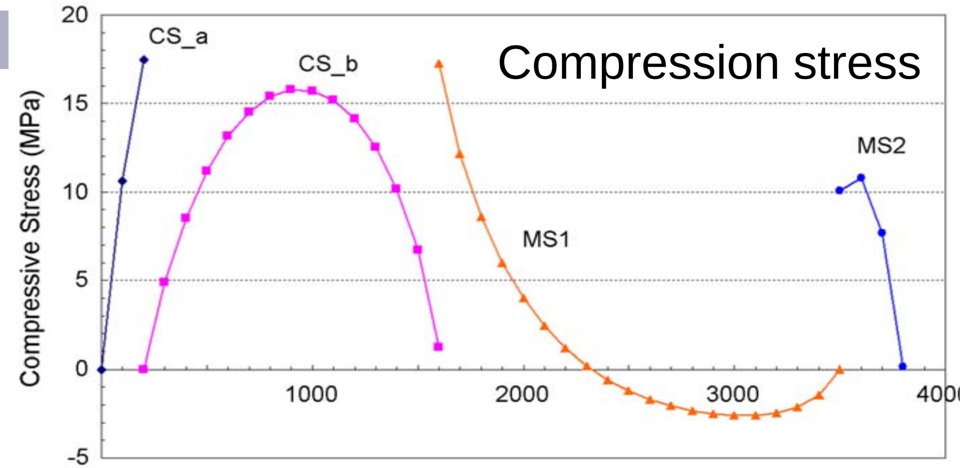
Cryostat-1: CS+UpstreamTS
Cryostat-2: DownstreamTS
Cryostat-3: ST+SS+DS

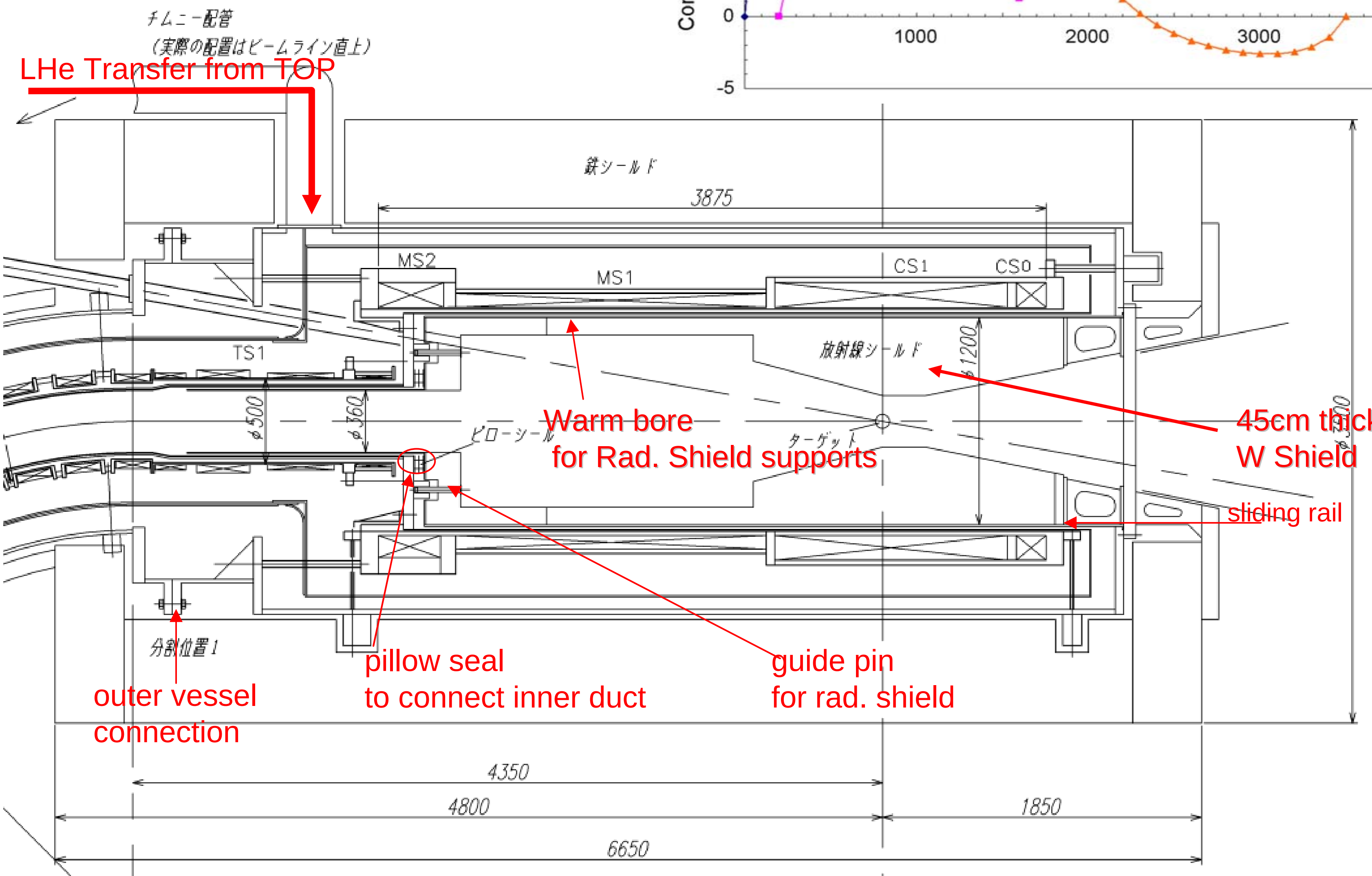


Purpose of separation:

- At concrete wall
  - Different radiation control level
  - Movable Cryostat-2 for install / maintainance
  - Vac. separation window / antip absorber at mid. of TS
  - Beam monitors
- At stopping target
  - inject electron beam into ST
  - Muon beam monitor

Pion Capture Solenoid





Indirect Cooling of Capture Solenoid

- Bath cooling could cause helium activation
  - Tritium production by $^{3}He(n,p)^{3}H$

→ Conduction cooling
  - Remove nuclear heating (max. 20W) by pure aluminum strip in between coil layers

- Thermal conduction can be degraded by neutron irradiation

- Temperature gradient in coil
  - 0.5mm thick, λ=4000W/m-K (RRR=2000) → ΔT=0.12K
  - If irradiation degrade λ=400W/m-K → ΔT=1.2K
- Taking into account margin for irradiation damage, thick aluminum will be used
  - 2mm, λ=400W/m-K → ΔT=0.3K

ATLAS CS

NIMA584, p53 (2008)

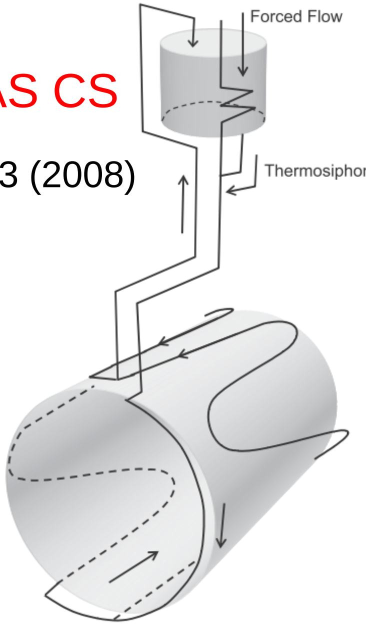
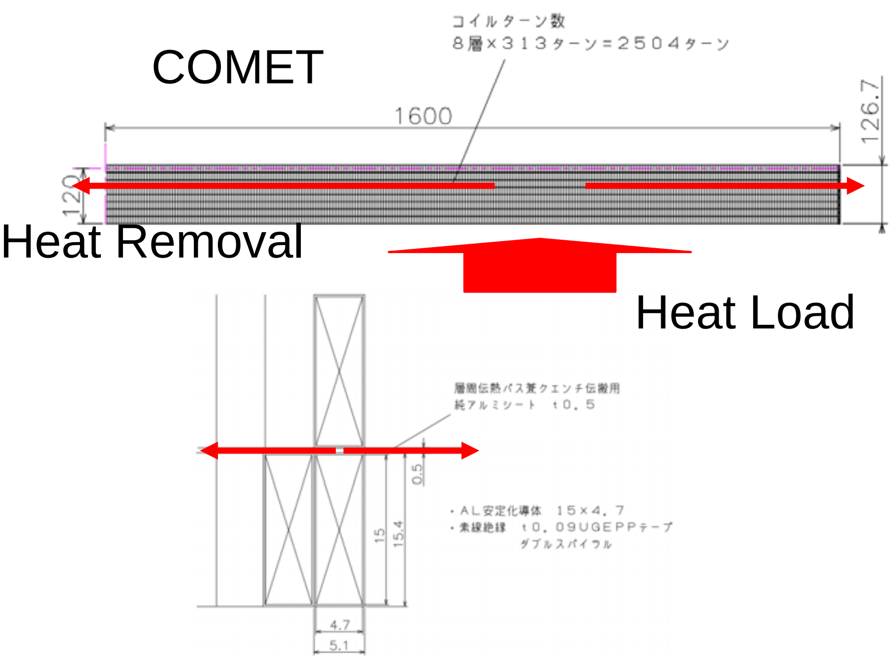


Fig. 11. Sketch showing the showing the concept of the thermosiphon and indicating where the cooling pipes are fixed to the cold mass.



Design Study

- So far
  - Coil layout for field optimization
  - Conceptual design of cryostat
  - Estimation of cryogenics
    - 200W refrigerator for upstream magnets
    - 30W GM cryocoolers for downstream magnets
- To do
  - Interface to contents;
    - Proton target, Beam monitor, Collimator, Stopping target, Detectors
  - Remote handling, installation/disassembly procedure
  - Coil structure → test winding (conductor R&D)
  - Cryogenics design
    - Optimize refrigerator
    - LHe piping
    - Thermal links
    - Thermal cycling procedure

Summary and Prospects

- Solenoid capture scheme is adapted for high intensity muon source in NF/MC, mu-e conversion experiments

- Radiation issues are most important for the feasibility
  - Irradiation effects on electrical and thermal properties
  - Indirect cooling
  - Radiation hard organic materials
- Steady R&D on irradiation effects is underway
  - First test successfully done in 2010
  - Degradation of electric resistivity of Al-CuMg was observed from ~10^{20} n/m^2.
  - Full recovery by thermal cycle to room temperature was also confirmed.
  - Will investigate different additives, copper, pure aluminum for thermal conduction.
- Feasibility of proposed coil structure will be checked in the test coil using large Al-stabilized superconductor.

- Detailed design will take into account the R&D results.