Conceptual Design of COMET and Radiation Hardness

Makoto YOSHIDA
(KEK)

RESMM12
FNAL
Feb. 13th, 2012

Contents

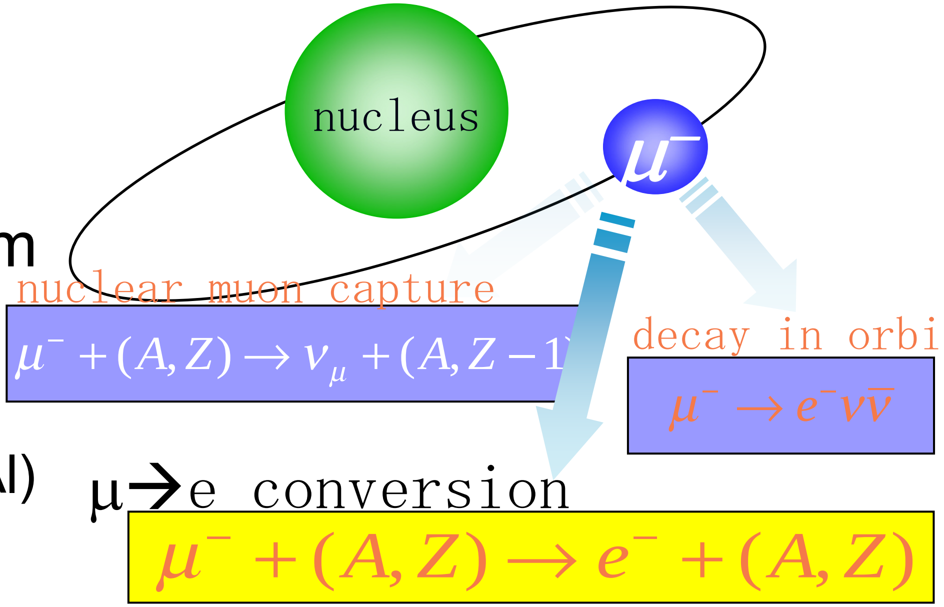
- The COMET experiment
- Superconducting magnets for COMET
- Radiation hardness

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

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

Detect monoenergetic electrons from μ-e conversion



nuclear muon capture

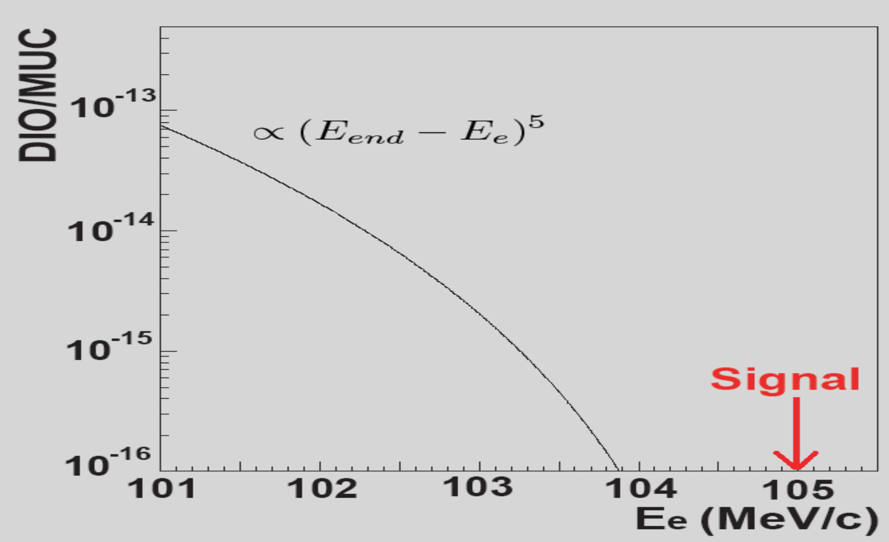
$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1$

decay in orbit

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

μ→e conversion

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



COMET Collaboration List

84 people from 20 institutes (August 2011)

Imperial College London, UK
A. Kurup, J. Pasternak,
Y. Uchida, P. Dauncey,
U. Egede, P. Dornan

University College London, UK
M. Wing, M. Lancaster,
R. D'Arcy, S. Cook

University of Glasgow
P. Soler

JINR, Dubna, Russia
V. Kalinnikov, A. Moiseenko,
G. Macharashvili, J. Pontecorvo,
B. Sabirov, Z. Tsamaiaidze,
and P. Evtukhouvich

BINP, Novosibirsk, Russia
D. Grigorev, A. Bondar, G. Fedotovich,
A Ryzhenenkov, D. Shemyakin

ITEP, Russia
M. Danilov, A. Drutskoy, V. Rusinov,
E.Tarkovsky

Department of physics and astronomy, University of British Columbia, Vancouver, Canada
D. Bryman

TRIUMF, Canada
T. Numao, I. Sekachev

Department of Physics, Brookhaven National Laboratory, USA
R. Palmer, Y. Cui

Department of Physics, University of Houston, USA
E. Hungerford, K. Lau

MPI-Munich
T. Ota

Tbilisi State University
M. Nioradze,
Ni. Tsverava
Y. Tevxadze

Institute for Nuclear Science and Technology
Vo Van Thuan, T.P.H. Hoang

University of Science, HoChi Minh
Chau Vau Tao

University of Malaya
Wan Ahmad Tajuddin

University Technology Malaysia
Md. Imam Hossain

Kyoto University, Kyoto, Japan
Y. Iwashita, Y, Mori, Y. Kuriyama, J.B Lagrange

Department of Physics, Osaka University, Japan
M. Aoki, T. Hiasa, T. Hayashi, S. Hikida, Y. Hino, T. Itahashi, S. Ito,
Y. Kuno, H. Nakai, T. H. Nam, H. Sakamoto, A. Sato, N.M.Truong

Department of Physics, Saitama University, Japan
M. Koike, and J. Sato

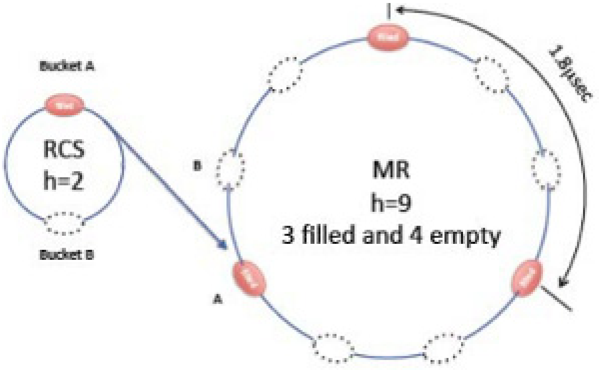
High Energy Accelerator Research Organization (KEK), Japan
Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto,
Y. Makida, S. Mihara, H. Nishiguchi, T. Nakamoto, T. Ogitsu,
C. Ohmori, Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchida,
A. Yamamoto, M. Yamanaka, M. Yoshida, M. Yoshii,
K. Yoshimura

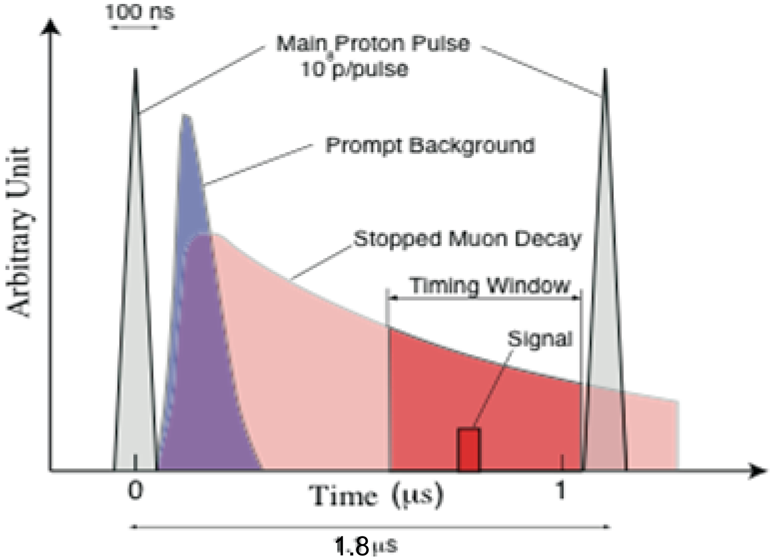
Requirements on Muon Beam

- 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

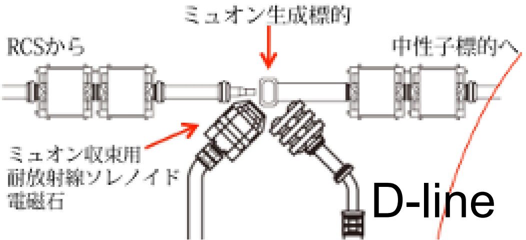
pulsed proton beam@J-PARC

- J-PARC E21
- Pulsed protons by slow extraction from MR
- 8GeV x 5~7microA
- Proton extinction $<10^{-9}$
    - ☐ $O(10^{-7})$x10^{-6}





Muon sources



D-line
(50mSr)

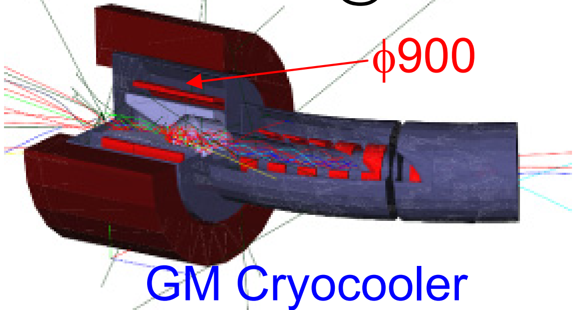
- Quadrupole
  - PSI, TRIUMF, RAL, J-PARC MUSE D-line (50mSr)
- Solenoid capture
  - Normal solenoid of SuperOmega
  - embedded target : MuSIC

Requirements for capture magnet

- Large aperture
- High magnetic field
- Radiation hardness

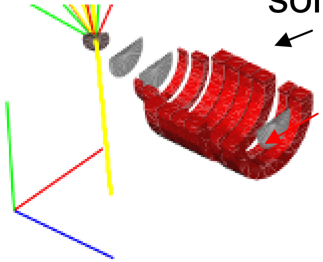
MuSIC

CW muon source@RCNP



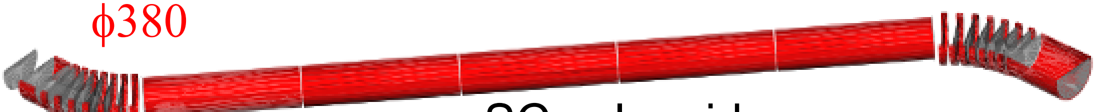
- 400W proton beam (100W on target)
- ~3x10^8 μ^+/s, ~10^8 μ^-/s

MIC normal solenoids



SuperOmega

Ultra slow muon beam@J-PARC MLF

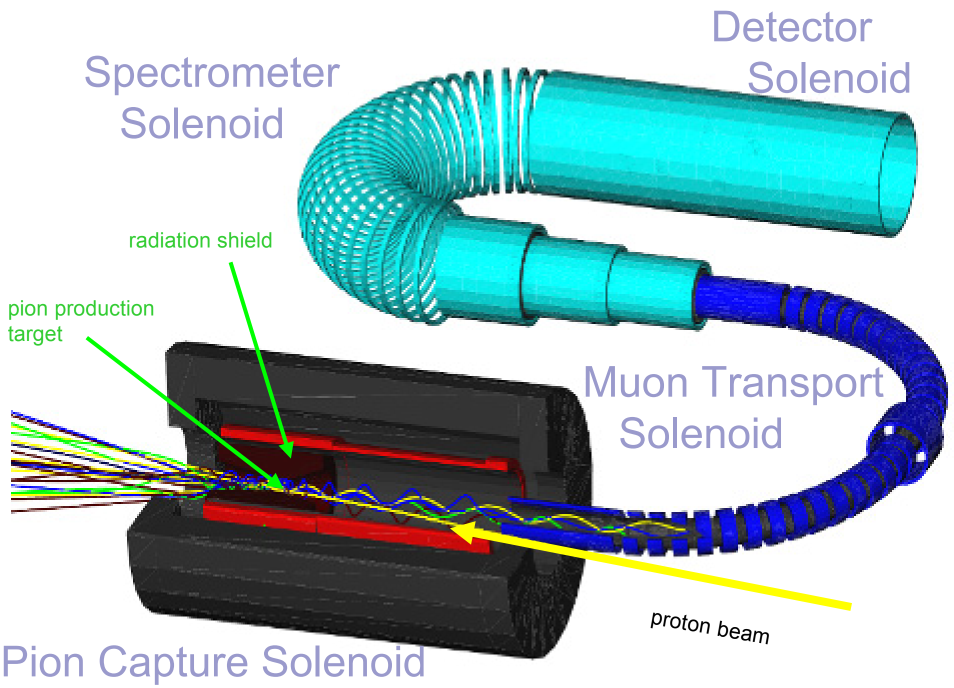


SC solenoids

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

COMET apparatus

- A series of long solenoids from end to end
  - pion capture & decay
  - muon transport
  - electron focus
  - spectrometer
  - detector



COMET Superconducting Magnet System

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

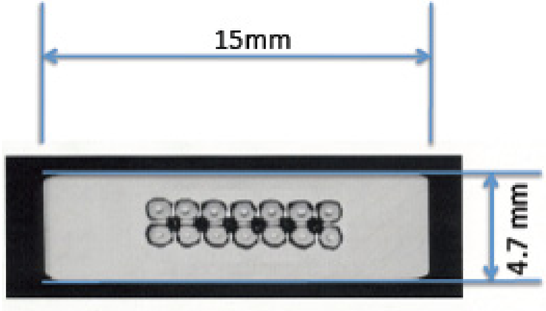
Fusion (ITER CS model)
Field: ~13T (Nb3Sn)
Cooling: Direct
cable in conduit

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



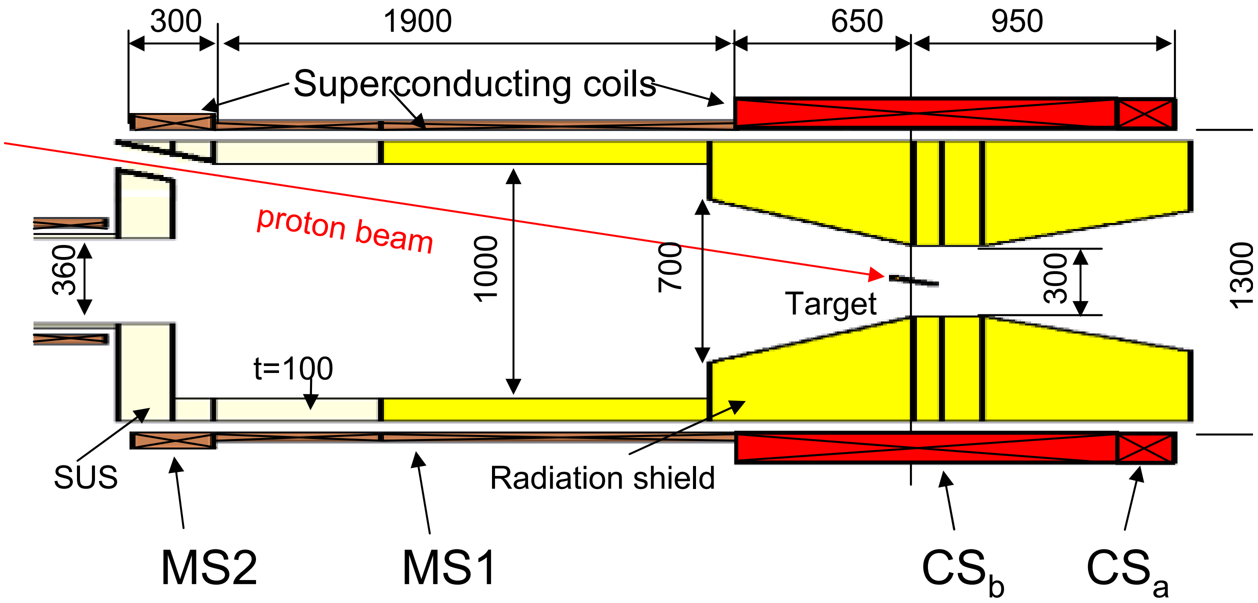
COMET design value

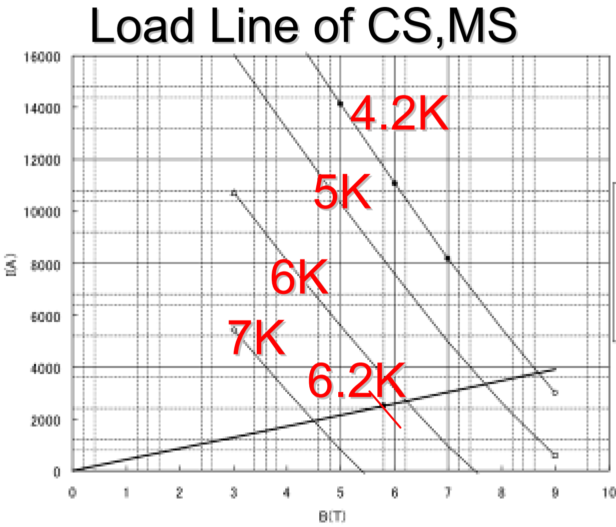
- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

Capture Solenoid Layout

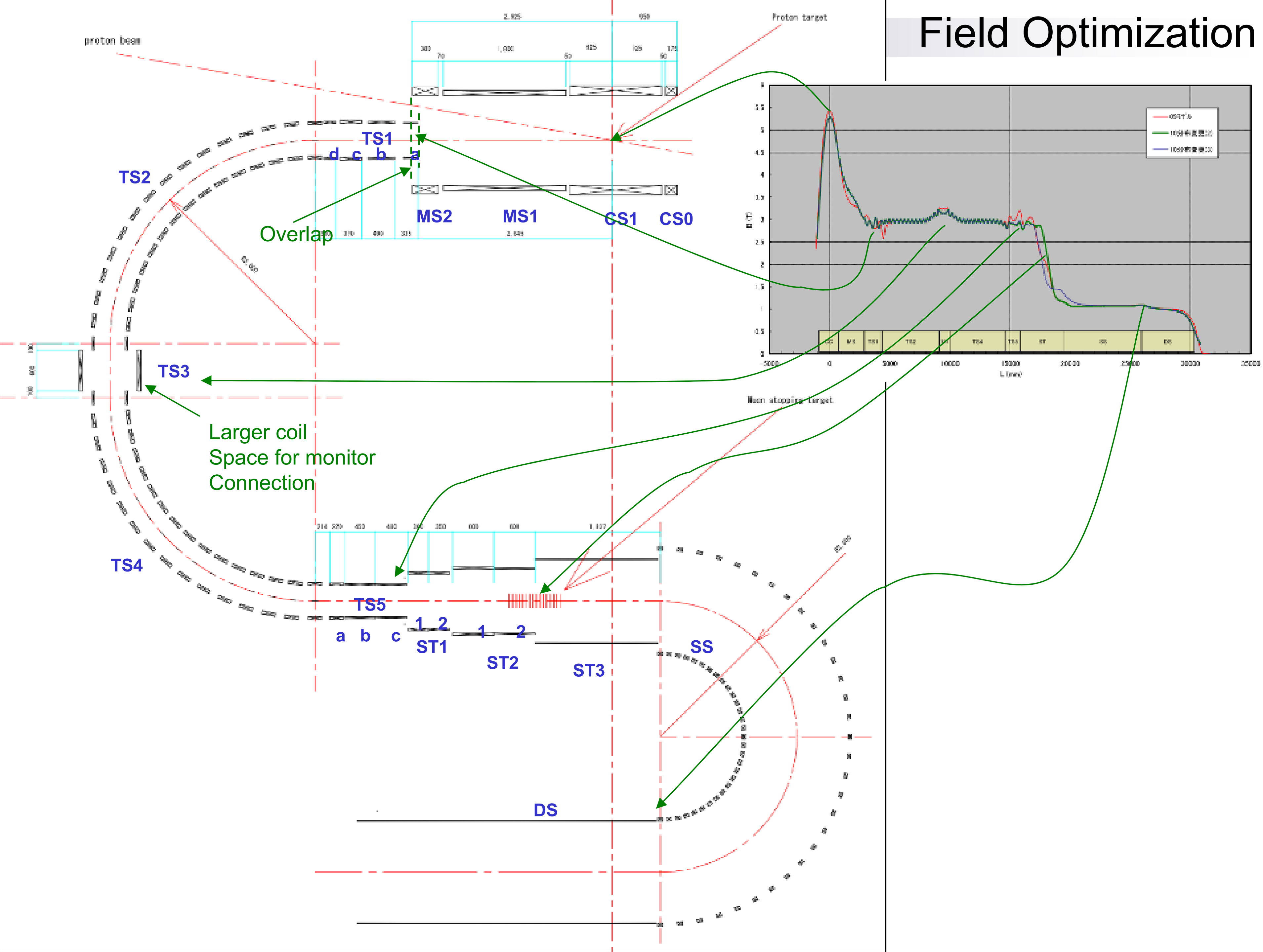
- Superconducting solenoid magnets with Al-stabilized conductor
- High field 5T to capture π^-
- Large bore 1300mm
- High radiation env.
- Decreasing field
- to focus trapped pions
- Thick radiation shielding 450mm
- Proton beam injection 10° tilted
- Simple mandrel

	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

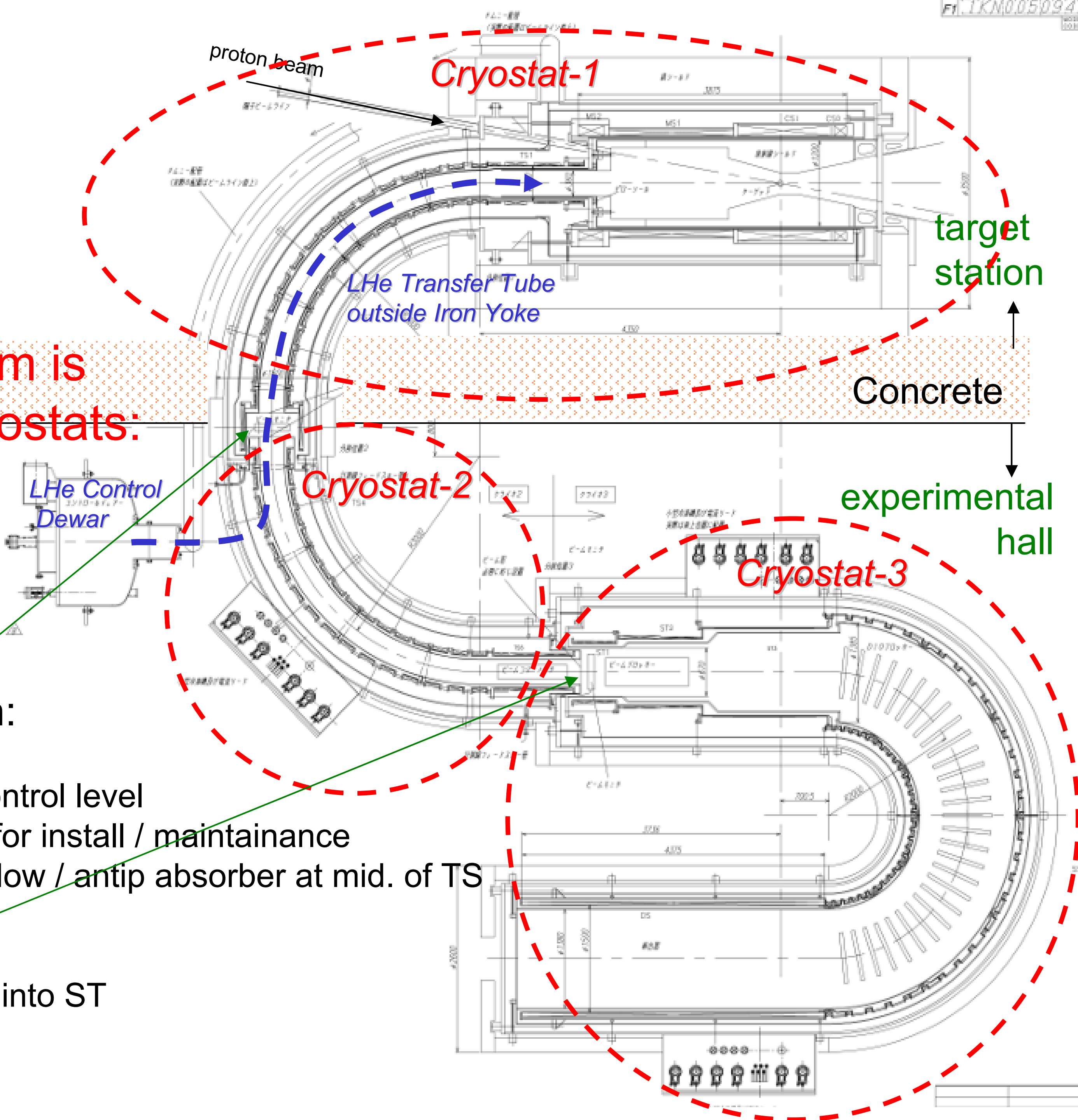




Field Optimization



Magnet Design



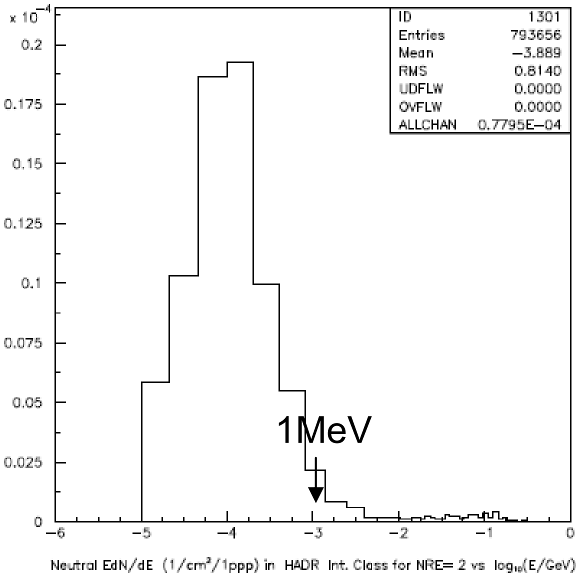
The magnet system is separated in 3 cryostats:

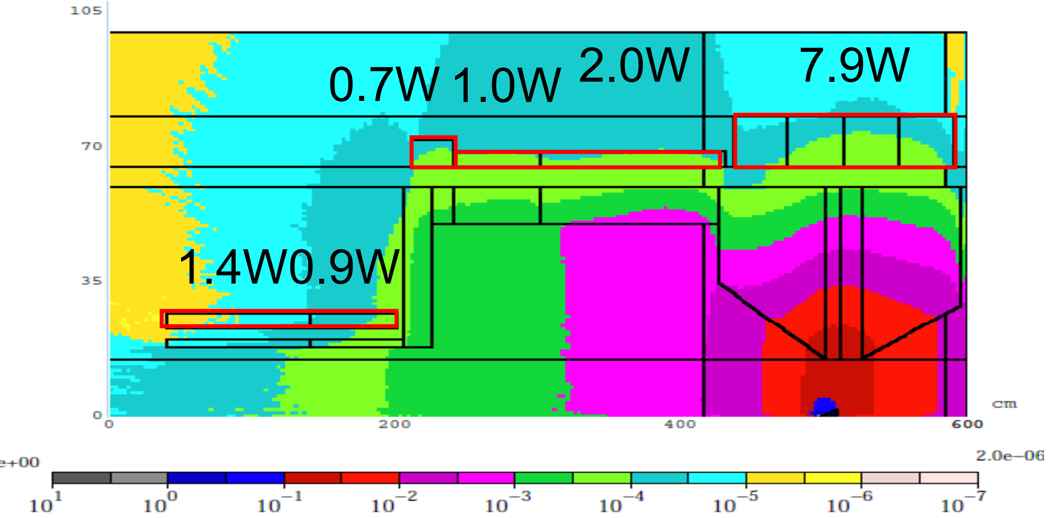
Cryostat-1: CS+UpstreamTS
Cryostat-2: DownstreamTS
Cryostat-3: ST+SS+DS

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

Radiation on CS





Neutron flux (n/cm2/proton)

- Maximum heat deposit
  - 10 mW/kg
- Maximum dose
  - 0.07 MGy/10^{21}p
- Neutron flux
  - 1x10^{21} n/m^2/10^{21}p
  - fast neutrons 6x10^{20} n/m^2/10^{21}p (>0.1MeV)

Neutrons penetrates thick 45cm tungsten shield surrounding the target

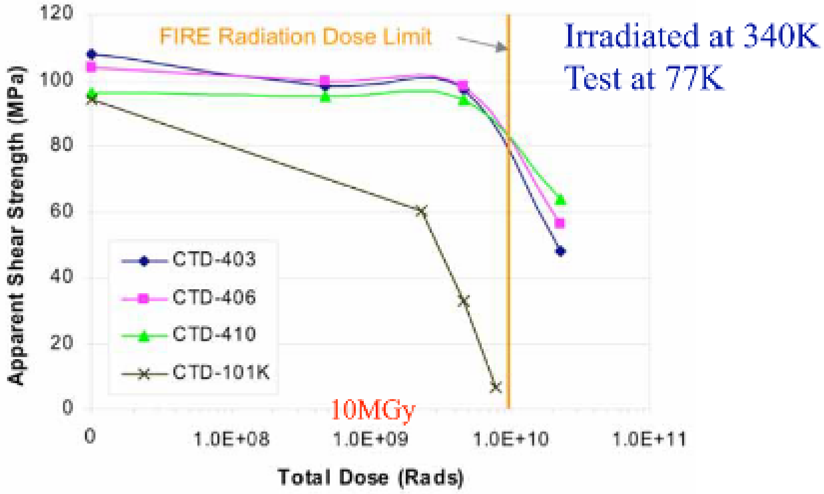
Neutron fluence for experimental life-time (~10^{21} p) approaches a level of ITER magnets (ITER requirement: 10^{22} n/m^2)

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

Resin

- Epoxy can be used <1MGy
- BT resin is good candidate
  - ☐ J-PARC accelerator magnet
  - ☐ Top part of the SuperOmega solenoid
- Also Cyanate ester
- Kapton-BT prepreg tape



Fabian and Hooker et. al., presented at "HHH-AMT, Topical Meeting on Insulation and Impregnation Technologies for Magnets"

Problematic components

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

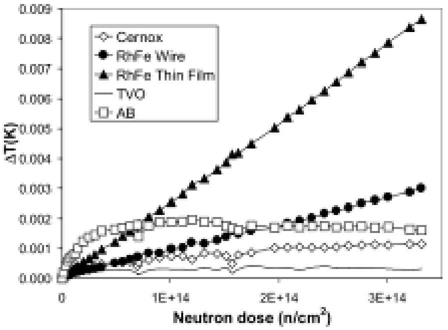


Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

LHC Project Report 209

- 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

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]
    - ρ_i=0.02nΩ.m for 10^{20} n/m^2
  - ☐ Perfect recovery by anneal at RT
- pure Cu (RRR=2280)
  - ☐ ρ_i=1.2nΩ.m [1]
  - ☐ 10% damage remains after annealing at RT

How about cold-worked Al-stabilizer
→ tests at KUR

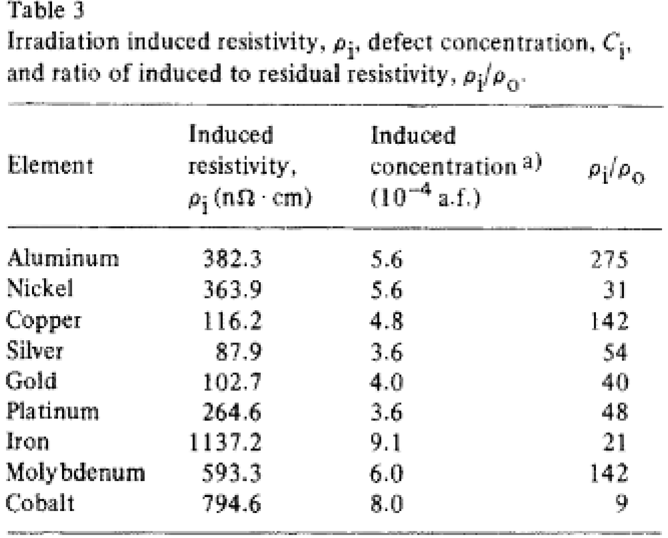
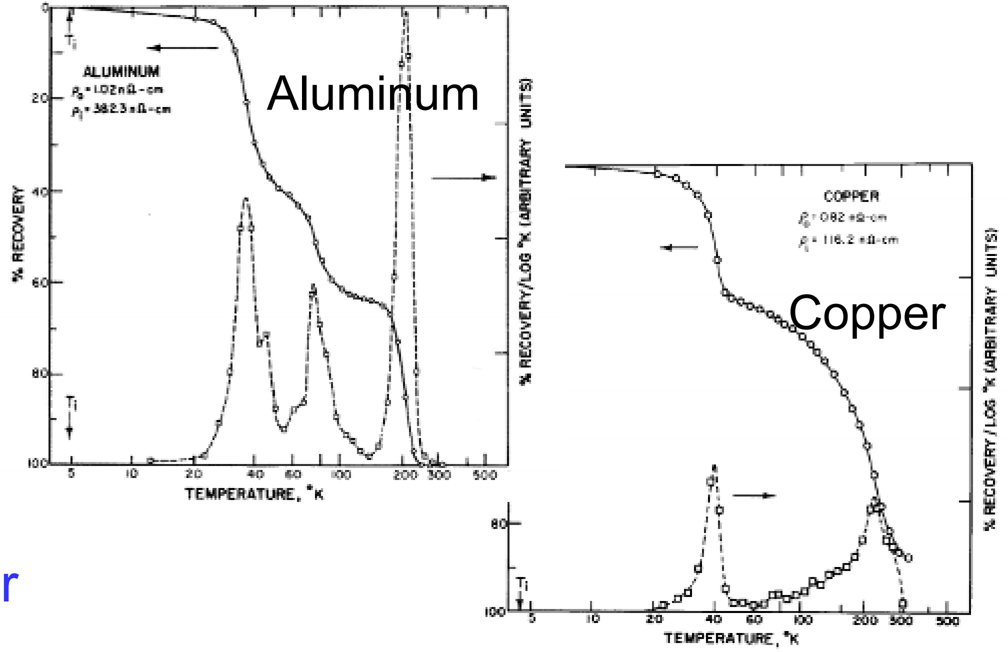


Table 3

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)



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

Cooling in high radiation

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

→ 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)

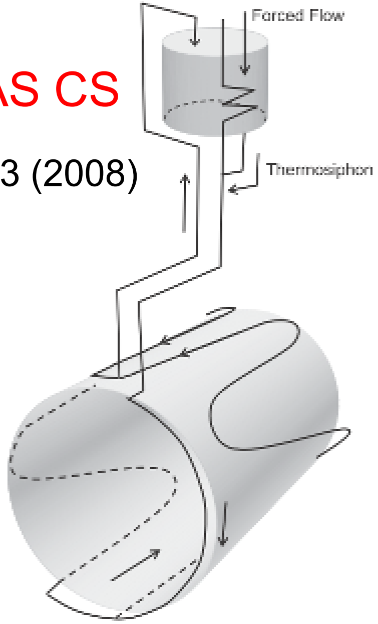
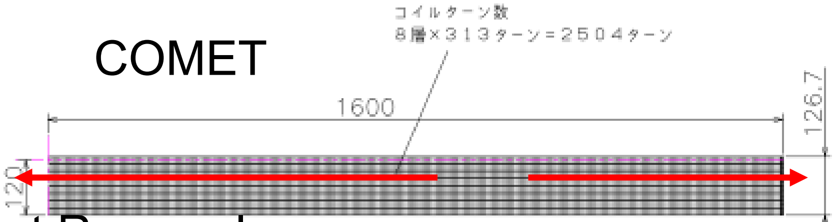
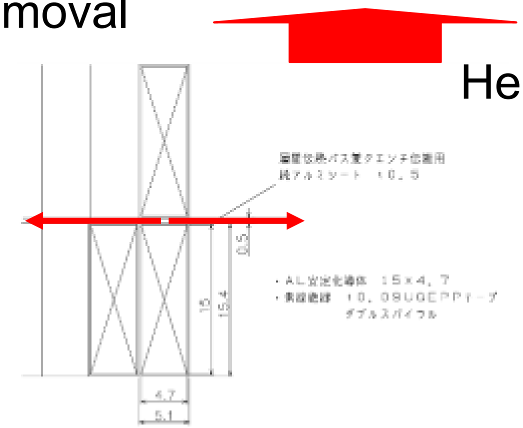


Fig. 11. Sketch showing the showing the concept of the thermosiphon and indicating where the cooling pipes are fixed to the cold mass.

COMET



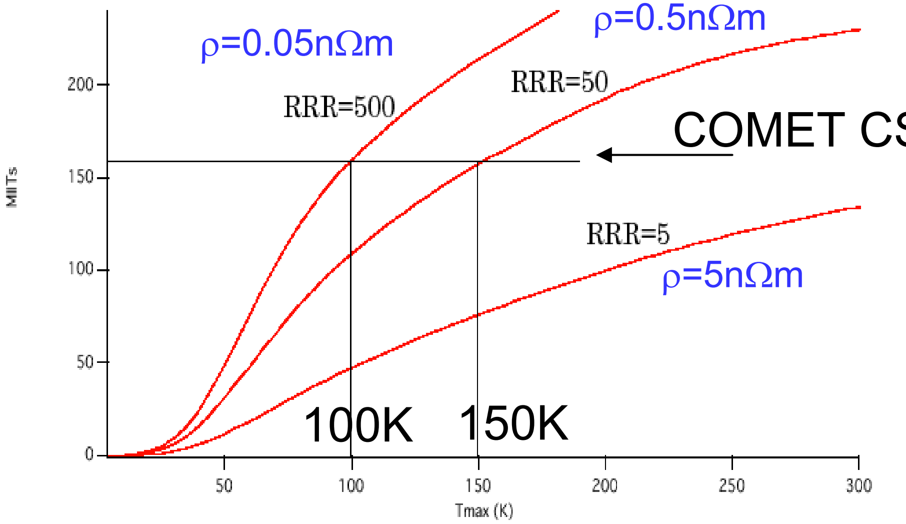
Heat Removal



Heat Load

Quench protection

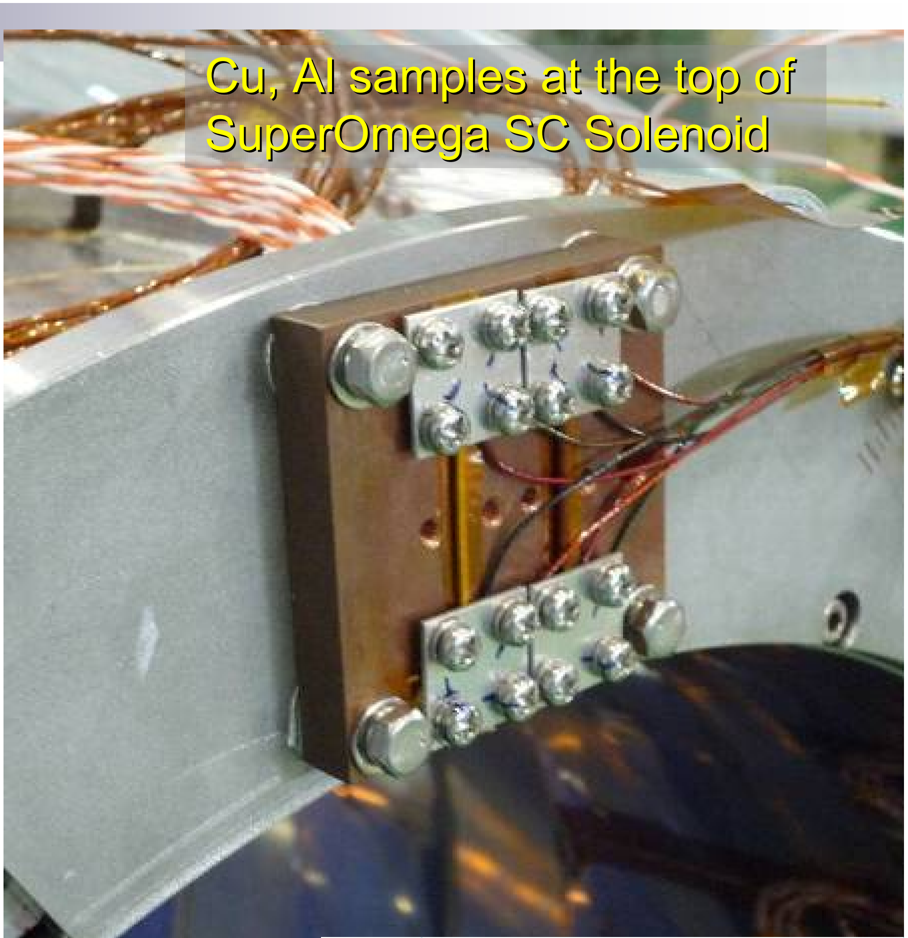
- Aluminum stabilizer
- Induced resistivity by neutrons
  - ρ_i = 0.02-0.03 nΩ.m for 10^{20} n/m^2
- Should keep ρ<0.5nΩm
- Thermal cycle to RT every a few x 10^{20} n/m^2



Watch Sample

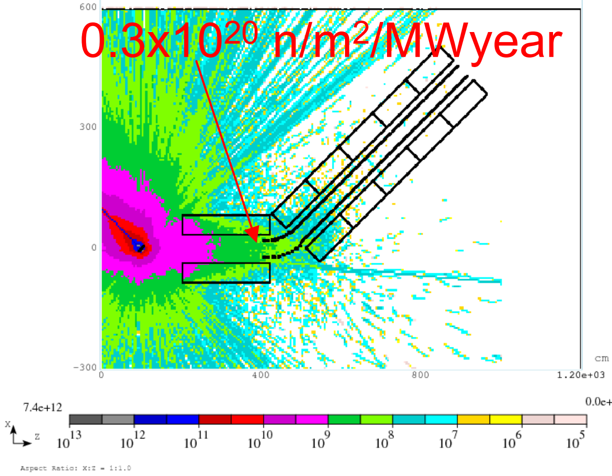
- Monitor degradation of electric resistance during irradiation
- Specimens made of same material as SC stabilizer, thermal conductor

- If degradation is detected during magnet operation



Cu, Al samples at the top of SuperOmega SC Solenoid

- Magnet would be warmed up
  - ☐ Annealing at RT



0.3×10^{20} n/m^2/MWyear

- Cu (RRR=300)
  - ☐ ϕ1mm x 45mm (28mm for Vsense)
- Al (RRR=3000)
  - ☐ 0.5x1 x 45mm (28mm for Vsense)

Summary

- Conceptual design of COMET superconducting solenoid magnets has been performed
- Solenoid capture scheme is employed to realize the intense negative muon beam
- Pion Capture Solenoid is operated in severe radiation
- Radiation hardness of magnet material is inspected and is taken into account in the COMET magnet design
  - Stabilizer
  - Thermal conductor
  - Thermosensor can be degraded?