Solenoid Capture Systems for MuSIC and COMET

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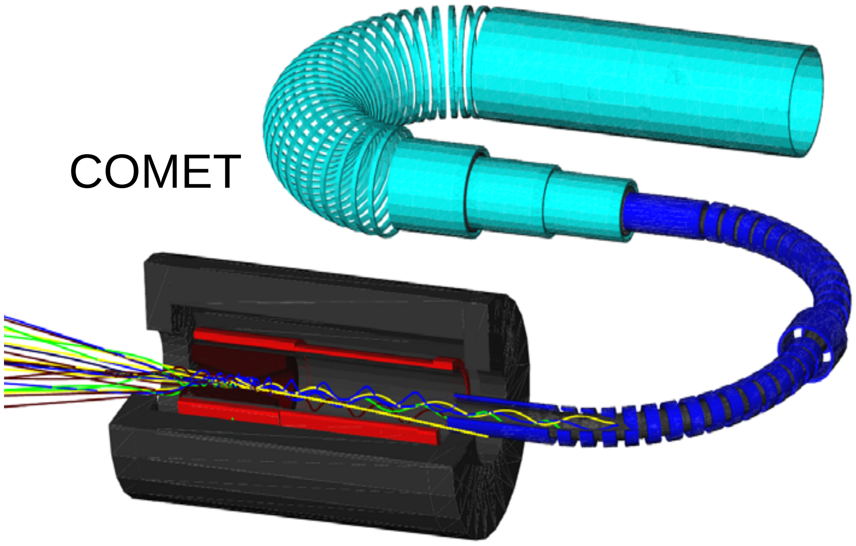
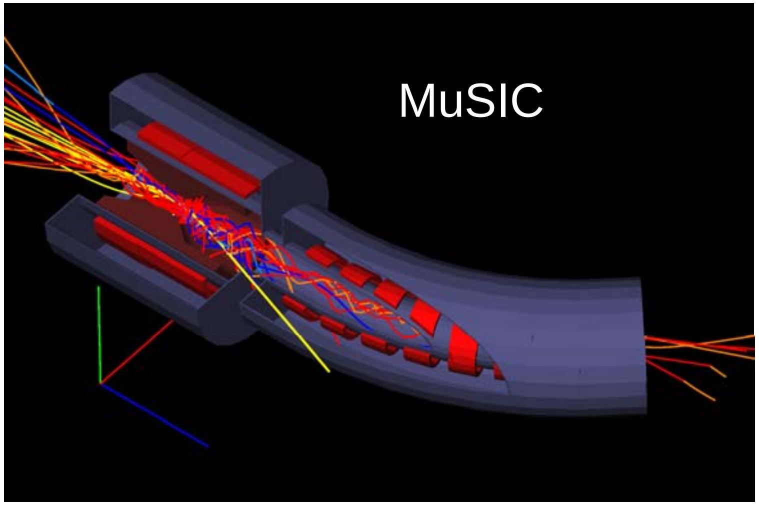
Solenoid Capture Workshop at BNL

Nov. 30, 2010

Contents

- MuSIC
  - The first of solenoid capture scheme
  - 3.5T
  - 0.4GeVx1μA cyclotron
  - miniature of COMET
- COMET
  - 5T
  - high power 8GeVx7μA proton beam at J-PARC
  - High radiation environ.
- Preliminary results from neutron irradiation test at KUR





Large aperture SC solenoid magnets

Heat Load
~10kW
Cost
~100M$

Heat Load
~100W
Cost
~10M$

Heat Load
~1W
Cost
~1M$

Fusion (ITER CS model)
Field: ~13T (Nb3Sn)
Cooling: Direct
Cable in Conduit

Detector Solenoids
Field: 1~4T (NbTi)
Al Stabilized Cable
Cooling: Indirect
With Cooling pipes

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

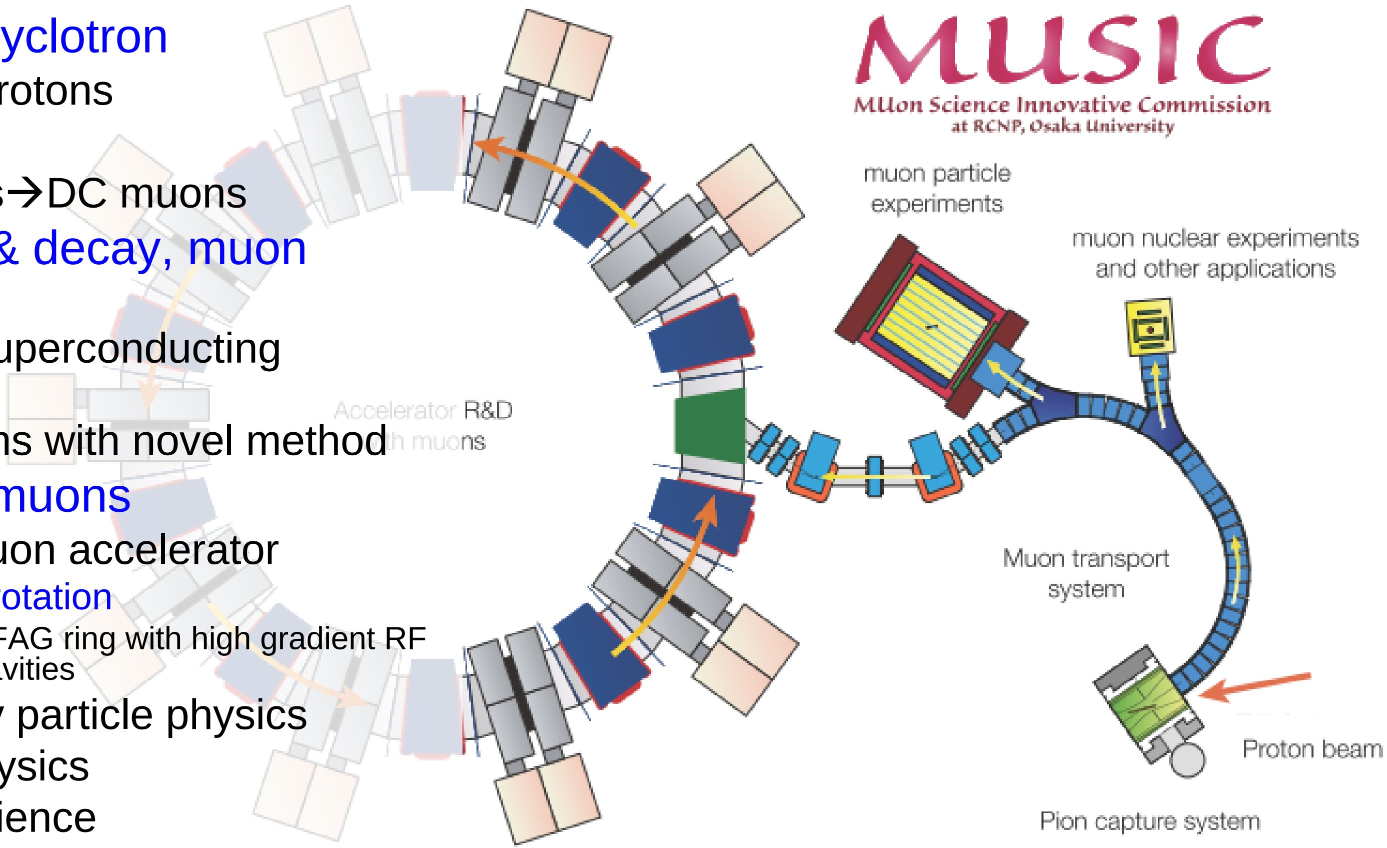
MuSIC
SuperOmega

COMET

Less heating in aluminum

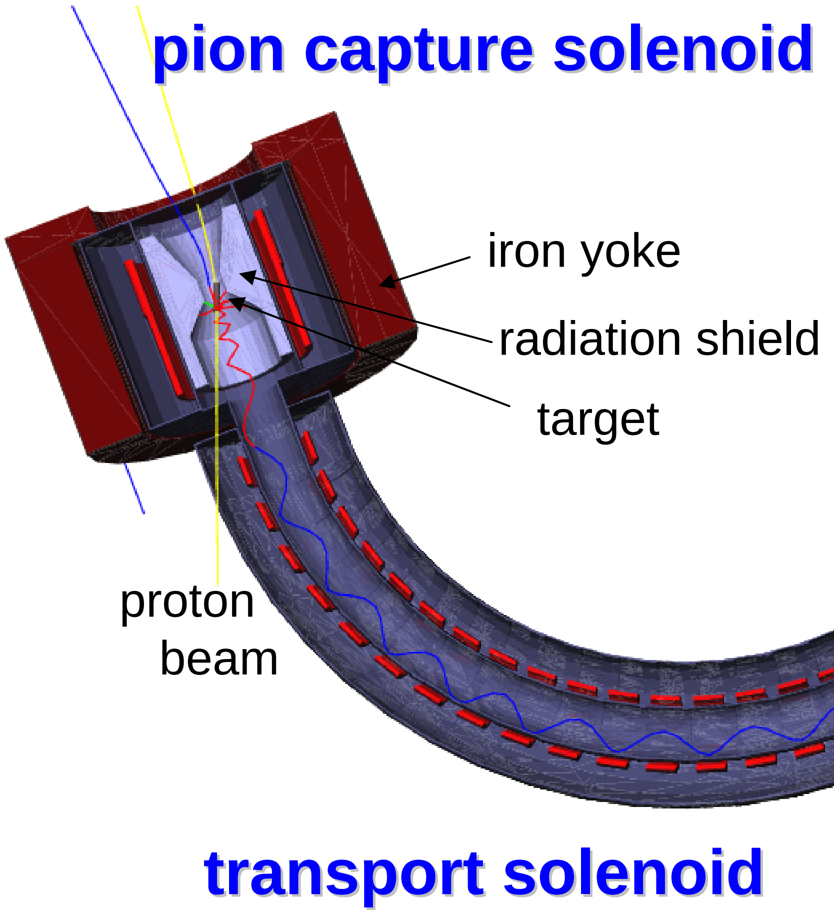
MuSIC – Muon Channel at RCNP

- RCNP Ring Cyclotron
  - 400 MeV protons
  - 1 μA
  - DC protons→DC muons
- Pion capture & decay, muon transport
  - Series of superconducting solenoids
  - Collect pions with novel method
- Science with muons
  - R&D on muon accelerator
    - Phase rotation
      - FFAG ring with high gradient RF cavities
  - Elementary particle physics
  - Nuclear physics
  - Material science
  - …



Requirements to SC magnets

- Strong magnetic field on pion production target
  - Trap pions in 3.5T
  - Superconducting coil surrounding the target
- Long solenoid channel with big aperture
  - Decay pions and transport muons in 2T
  - 360mm dia. bore
  - ~10m long
  - Correction field
    - drift in toroidal field
- Compact and low cost
  - Adopt MRI magnet technologies
- LHe free refrigeration
  - Conduction cooling by GM cryocoolers
  - Heat load should be < a few Watts
  - Heat deposit by neutrons etc.

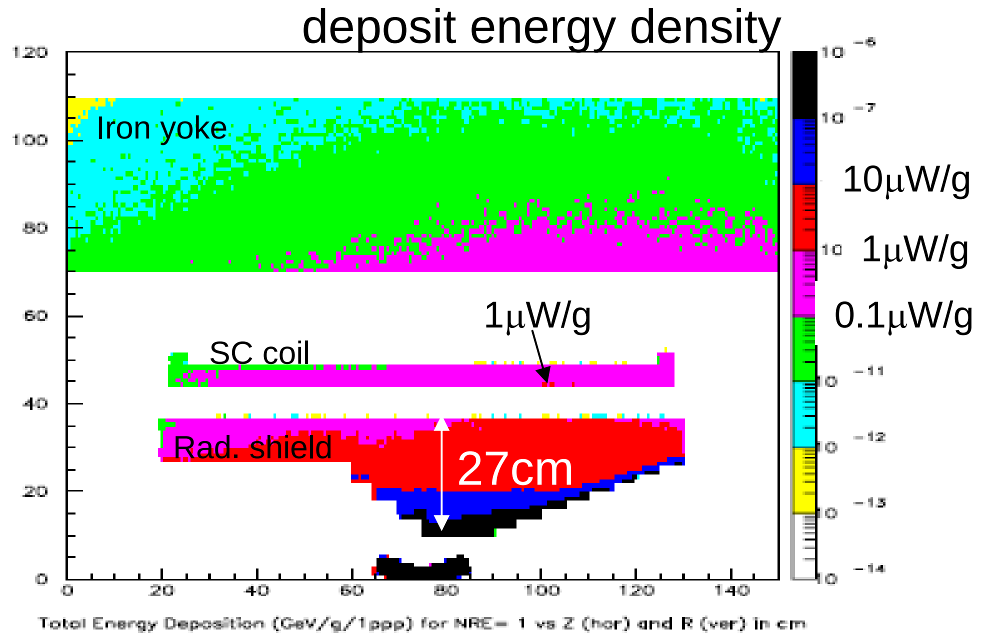


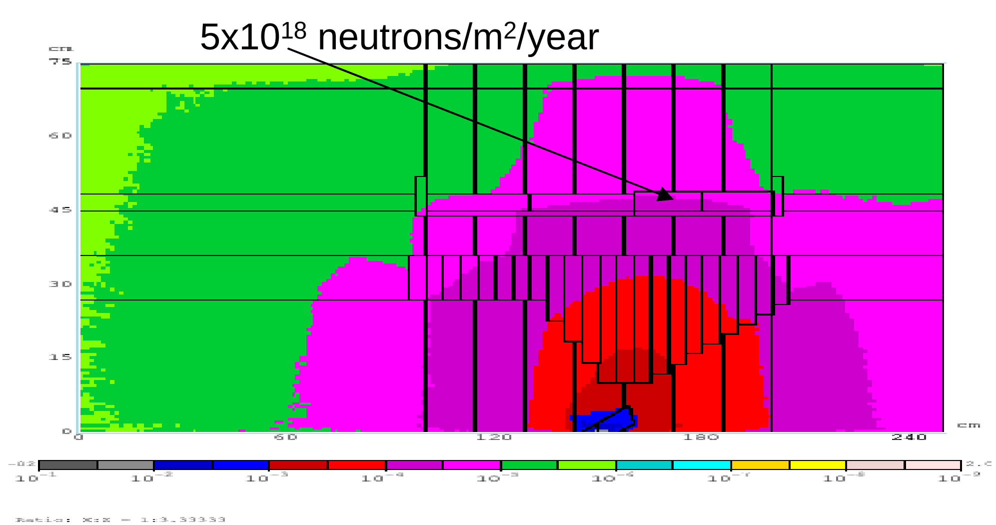
Radiation dose

- Irradiation on coil should be controlled to meet conditions:
  - Heat deposit < ~1W
  - Dose < 1MGy
    - for insulator, glue, …
  - Neutron flux < 10^{20} n/m^2
    - avoid degradation of stabilizer of SC wire

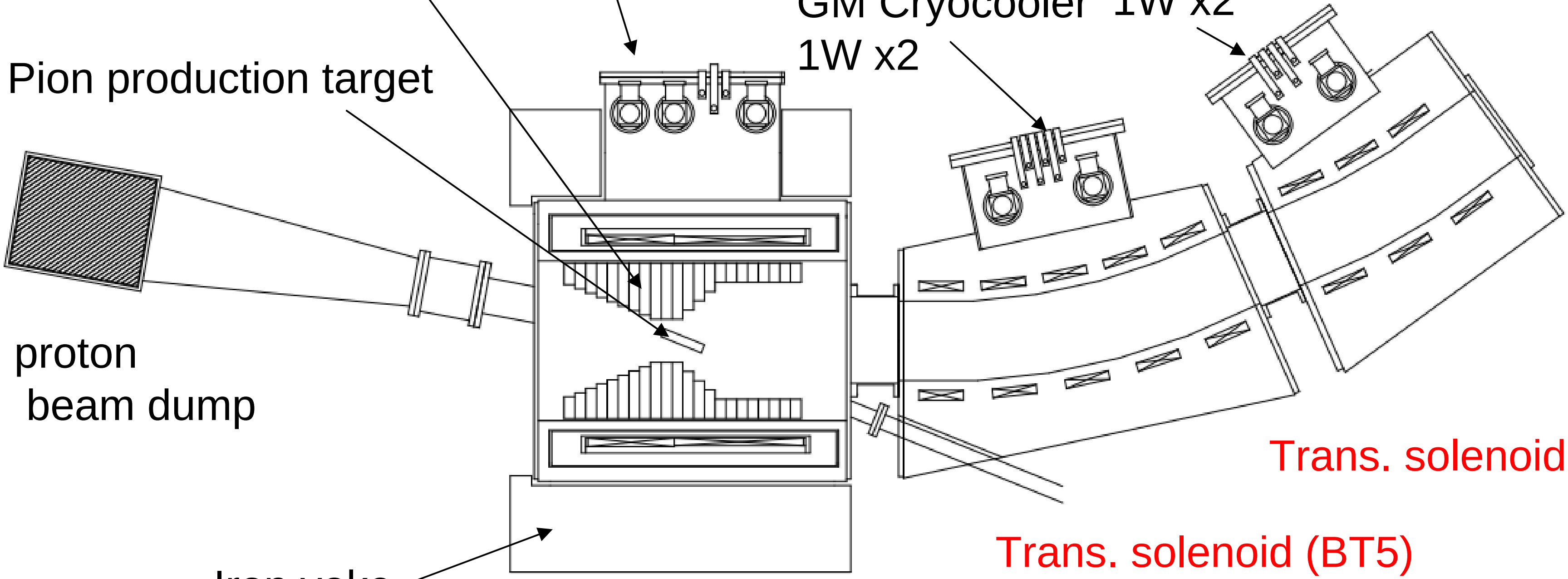
- Layout of pion capture solenoid has been optimized.
- 27cm thick stainless steel around the target

- Radiation dose on SC coil ~10kGy/year
- Heat deposit 0.6W
  - 0.4W in coil (~1ton)
  - 0.2W in coil support
- No degradation is expected in SC
- Power supply, quench protection diodes are placed at 30m away





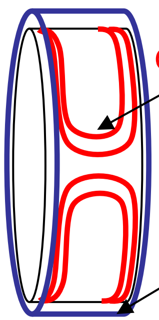
Magnet layout in 2010



Coil parameters

Capture solenoid coil

Conductor	ϕ1.2mm NbTi/Cu wire
Operation current	145A
Max field on axis	3.5T
Bore	ϕ900mm
Length	1000mm
Inductance	400H
Stored energy	5MJ
Quench back heater	Cu wire ~1Ω@4K



Element coil of Trans. solenoid

Transport solenoid coils

Operation current	145A
Field on axis	2T
Bore	ϕ480mm
Length	200mm x8Coils
Inductance	124H
Quench back heater	Cu wire ~0.05Ω/Coil@4K

Correction dipole coils

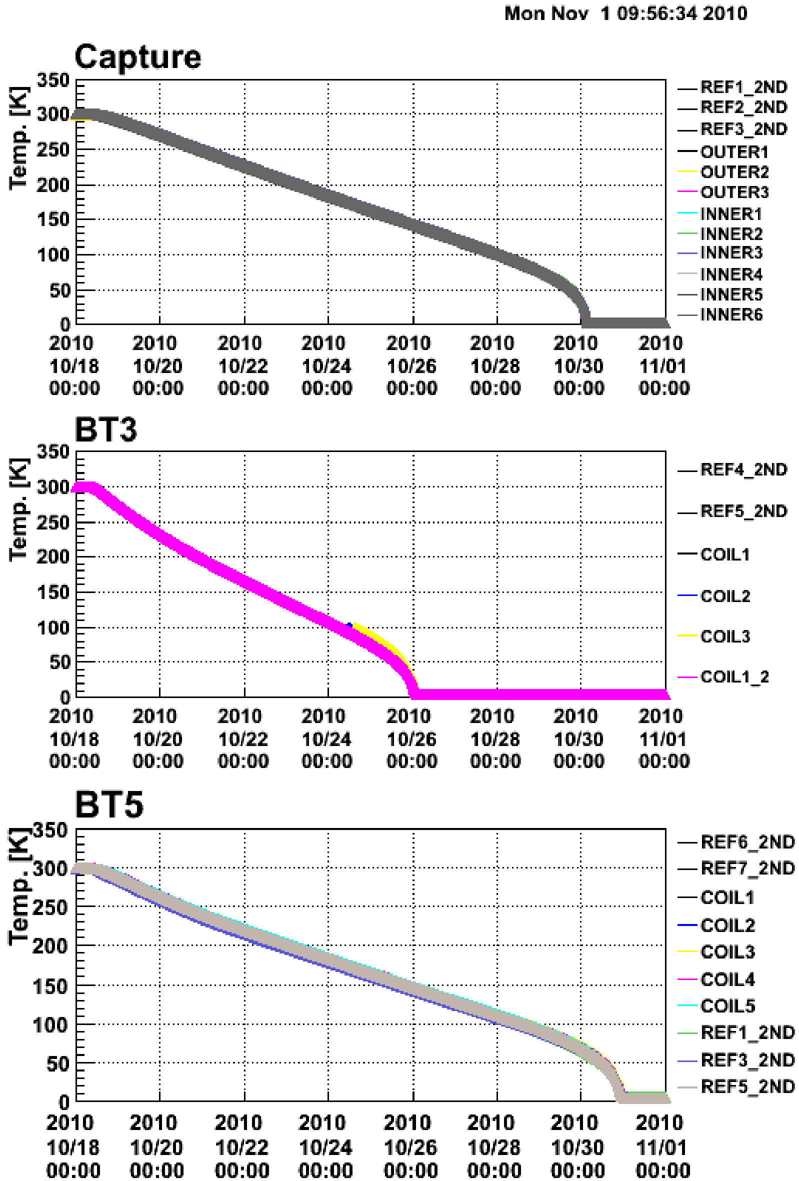
Coil layout	Saddle shape dipole
Current	115A (Bipolar)
Field	0.04T
Aperture	ϕ460mm
Length	200mm

Refrigeration

- Conduction cooling by GM cryocoolers
- Can be cooled down by GM cryocoolers in 2 week

- Pion capture solenoid
  - 4K: 1W+nucl. heating 0.6W
  - 3 x GM cryocoler
    - 1.5Wx2+1Wx1 @4K
- Transport solenoid
  - 4K: 0.8W
  - 2 x Cryocoolers on each cryostat (BT5,BT3)
    - 1Wx2 @4K

- Achievable temperature
  - Pion capture solenoid : 3.7K
  - Transport solenoids : 4.2K-4.5K(BT3), 4.5K-5.8K(BT5)

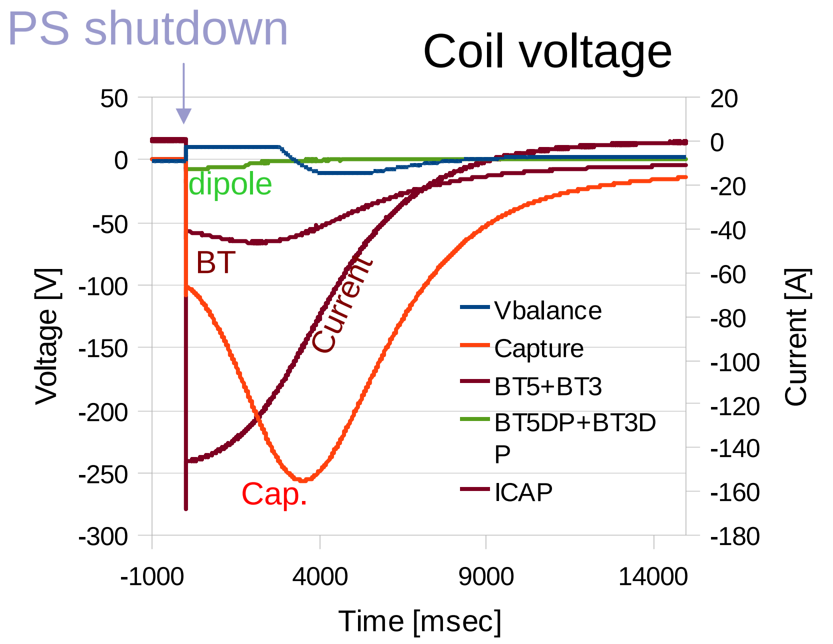


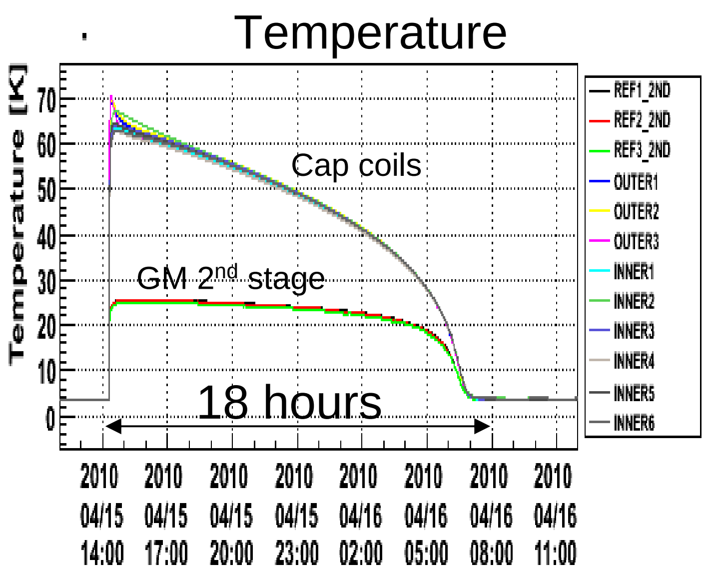
SC magnet commissioning

- Feed current to all solenoid coils in series
- Bipolar PS for correction dipole coils
- Quench back with Cu wire wound on the mandrel

- PS shutdown after feeding 145A
  - current is introduced in Cu wire
- Temp. rise up to 70K (Cap.) , 40K(Trans.)
- Can recover within 18 hours

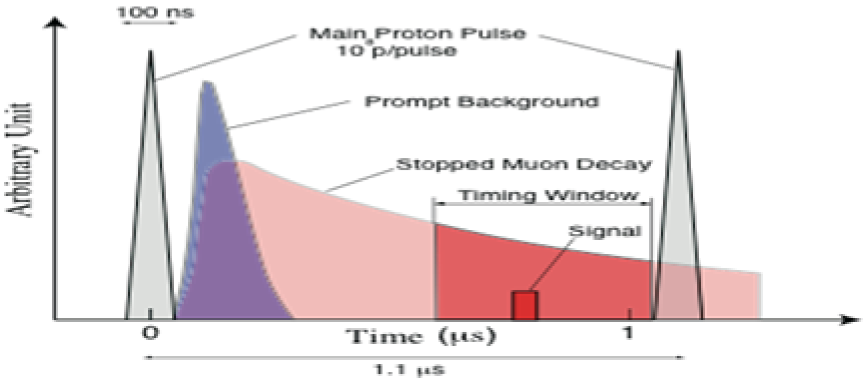
- Proton beam ~1nA successfully injected in July, 2010.
- Stable operation in 2 day beam time.





COMET at J-PARC

- Proton synchrotron at J-PARC, Tokai, Ibaraki
- Bunched slow extraction, 1.6×10^{13} ppb
- 100ns bunch width in ~1μs spacing
- 8 GeV x 7 μA = 56kW
  - avoid pbar production



COMET Collaboration

51 people from 14 institutes (Jan. 2010)

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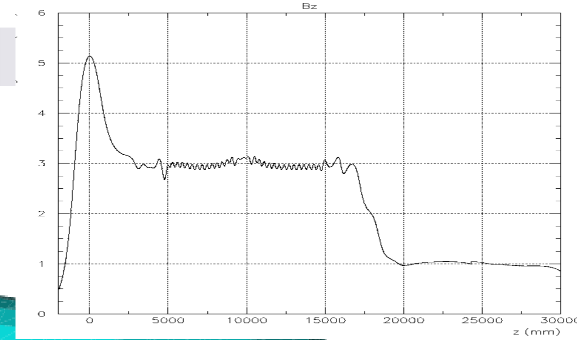
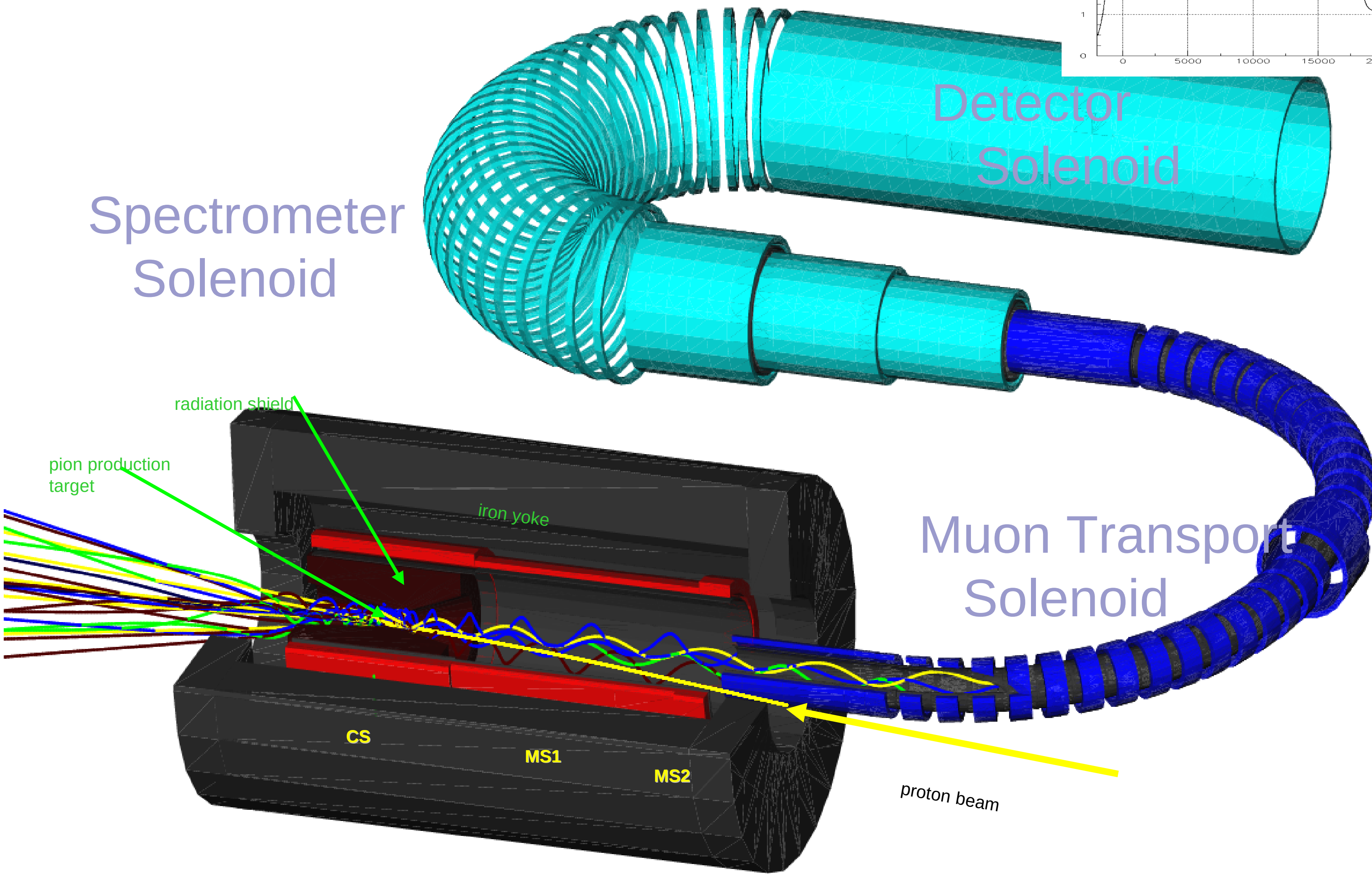
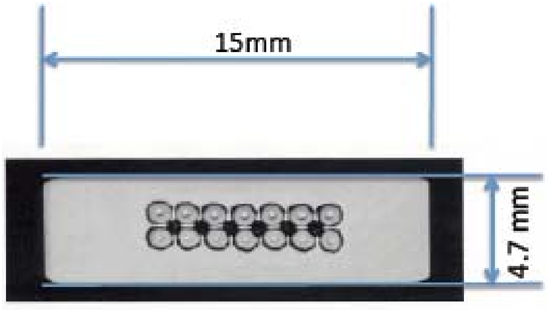
COMET SC Magnets





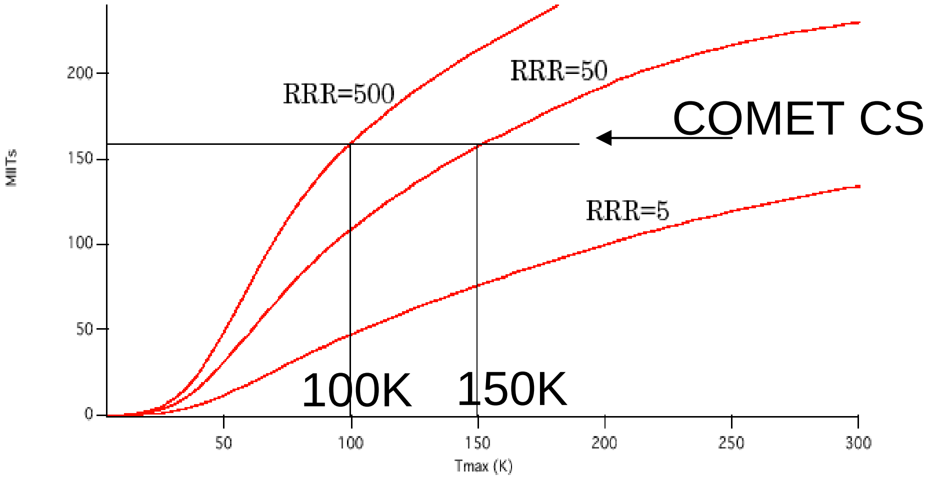
Pion Capture Solenoid

Al-stabilized conductor



- COMET pion capture solenoid is exposed to severe neutron radiation
- The coil should be "transparent" to radiation.
- Aluminum stabilized conductor is able to reduce heat load compared to Copper stabilized conductor
- Better recovery is expected in Aluminum.

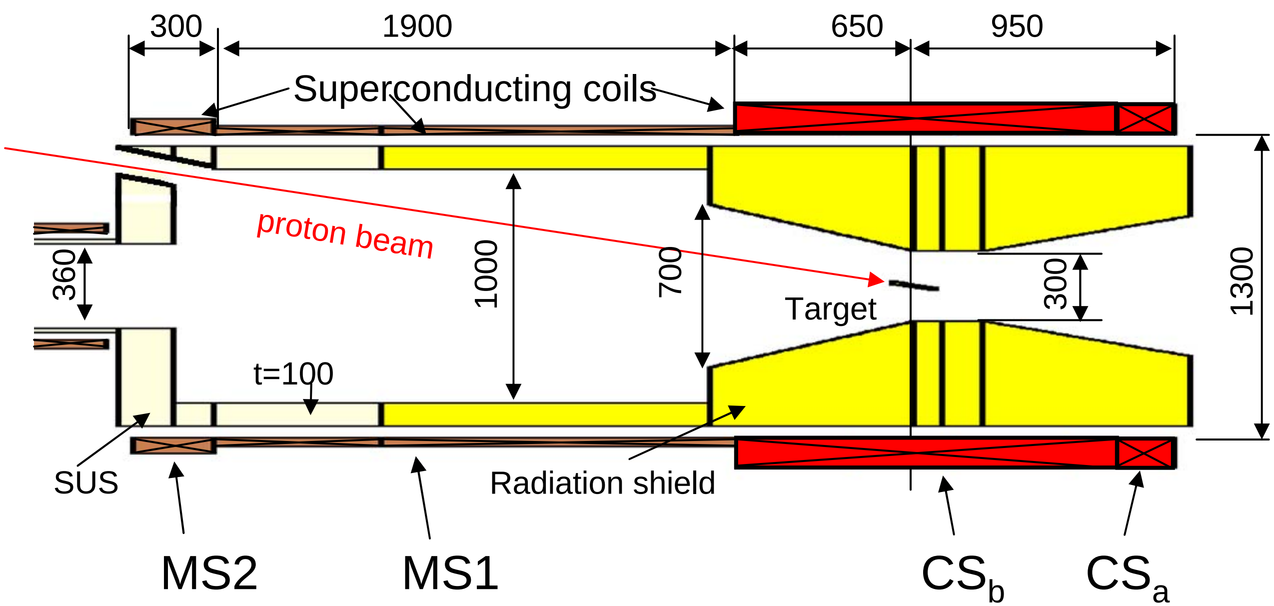
- Size: 4.7x15mm
- Offset yield point of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.



COMET Capture Solenoid Layout

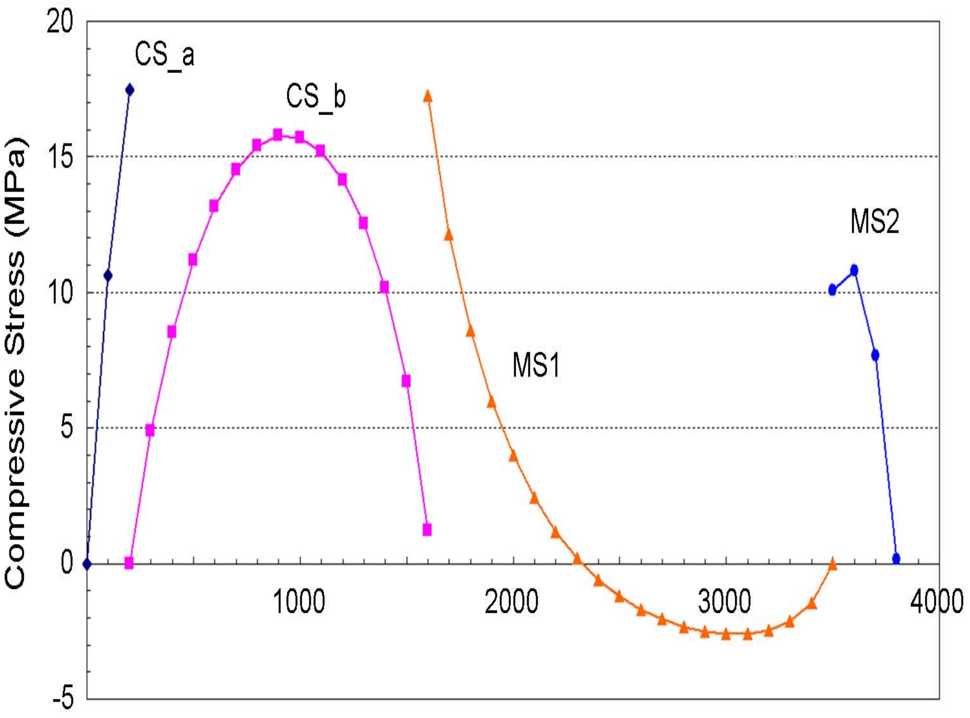
- Superconducting solenoid magnets with Al-stabilized conductor
- High field 5T to capture π^-
- Large bore 1300mm
- High radiation env.
- Decreasing field
- to focus trapped pions
- Thick radiation shielding 450mm
- Proton beam injection 10° tilted
- Simple mandrel

	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



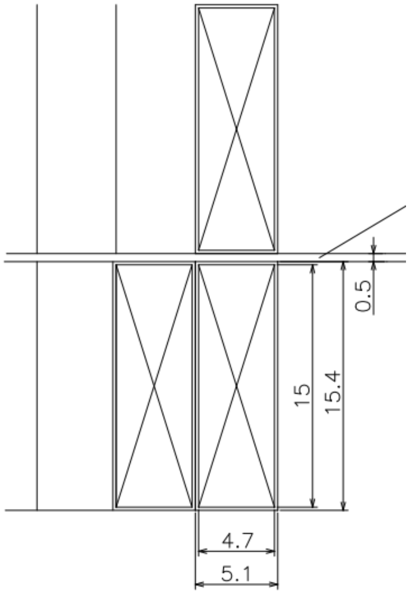
Stress on coils

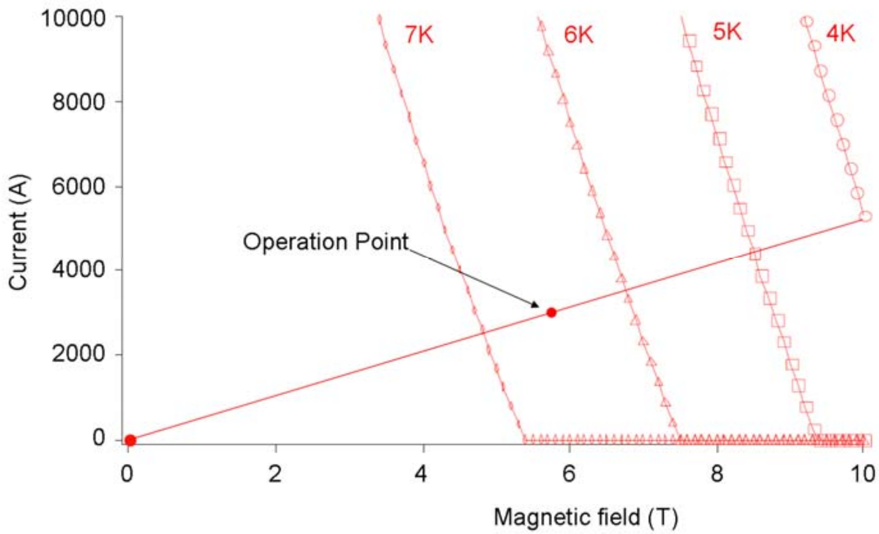
- Solenoids CS+MS1+MS2 are pull by 100tons
- Hoop stress exceeds Al strength
  - Outer support cylinder
- Axial compressive stress
  - Divide coils, put support partition
- Design studies ongoing



Cooling

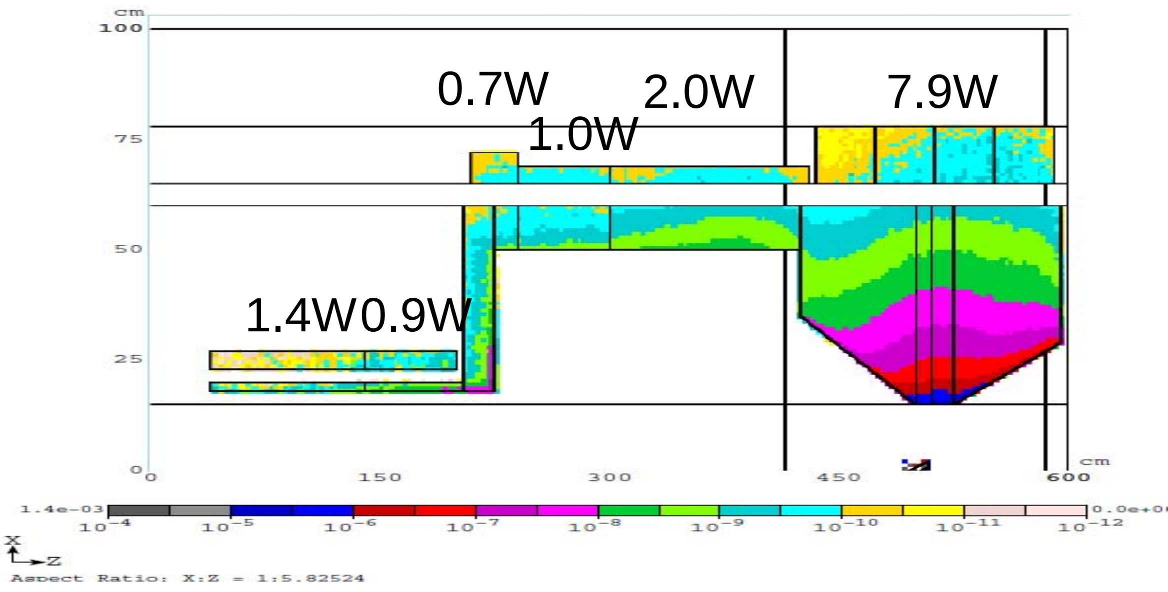
- Edgewise winding
- Pure aluminum strips between layers for heat transfer and removal
- Cooling pipes at the end of the coils and outer cylinder
- removes total ~30W





Radiation dose

- Maximum heat deposit
  - 10 μW/g
- Maximum dose
  - 0.07 MGy/10^{21}p
  - 3×10^{-6} DPA/10^{21}p
- Neutron flux
  - 1×10^{21} n/m^2/10^{21}p
  - 6×10^{20} n/m^2/10^{21}p (>0.1MeV)



Neutron irradiation on Aluminum

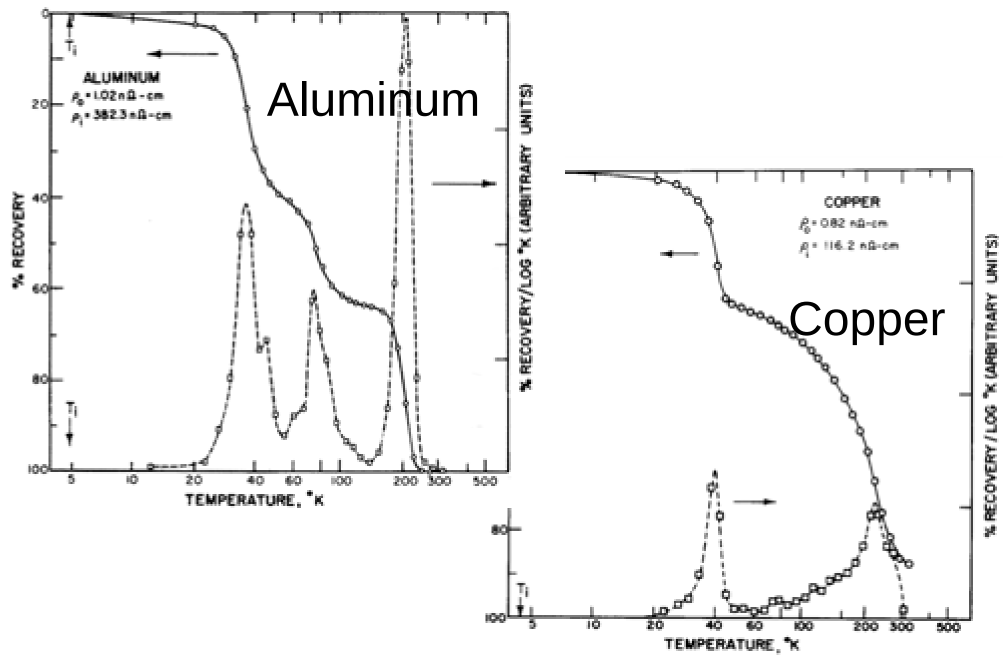
Table 3
Irradiation induced resistivity, ρ_i, defect concentration, C_i, and ratio of induced to residual resistivity, ρ_i/ρ_0.

Element	Induced resistivity, ρ_i (nΩ · 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
Cobalt	794.6	8.0	9

pure Al: 23.3 nΩ.m@RT
3.8 nΩ.m by irradiation 2x10^{22} n/m^2

- Damage at 10^{21} n/m^2 would be comparable to residual resistivity
  - difficulties on quench protection, cooling ...
  - Same for high strength aluminum?
- Need great care on conductor damage
  - measure RRR to judge
  - If necessary, thermal cycle to room temperature
- Check degradation and recovery of high yield strength aluminum

Recovery after irradiation 2x10^{22} n/m^2 (E>0.1MeV)



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

Low temperature irradiation facility at Kyoto Univ. Research Reactor Institute

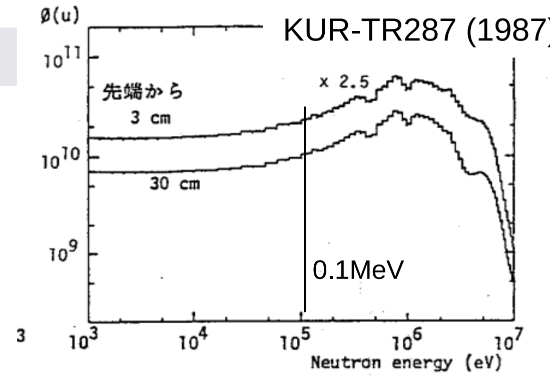
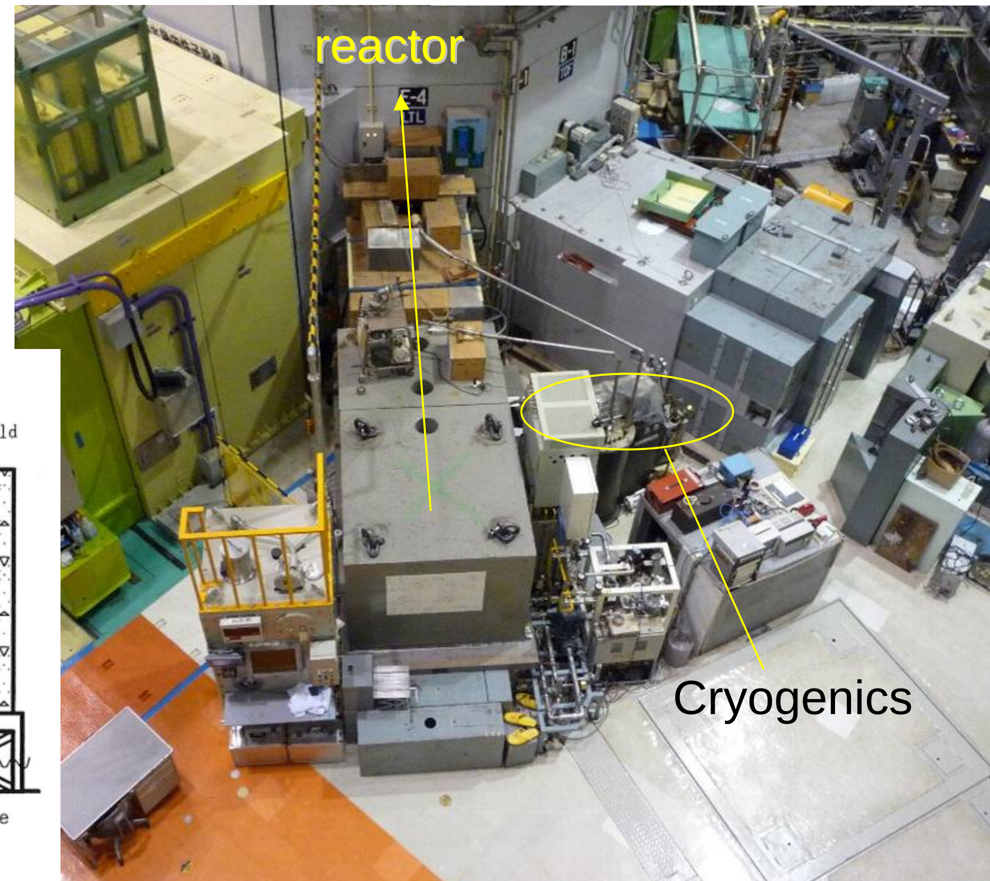
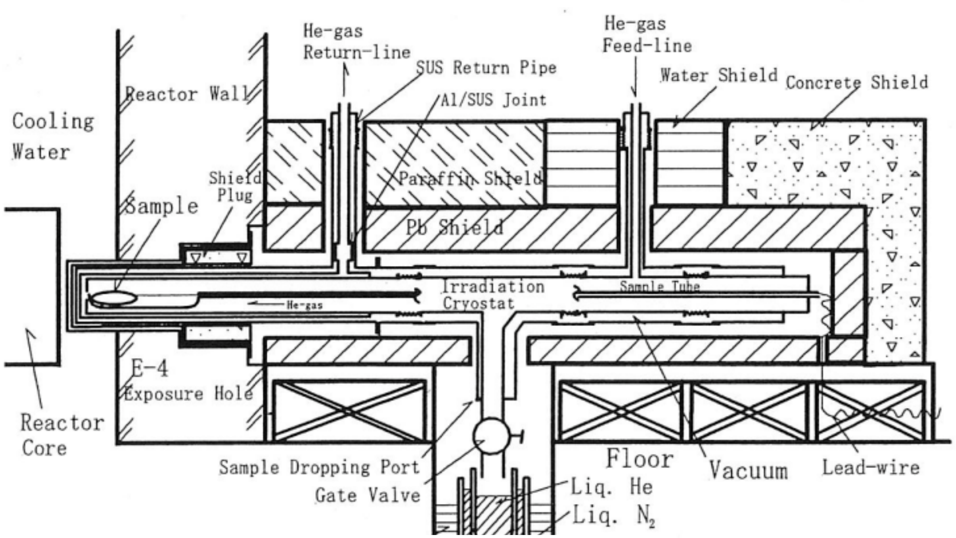


Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV)

- Low Temp. Lab. at Kyoto University Research reactor (KUR-LTL)
- Cooled by He gas down to 10K-20K
- Operated in 46 hours with 1MW power
  - Nov. 16-18, 2010
- Expected neutron flux
  - ~10^{20} n/m^2 (with large uncertainty)
  - measure with ^{58}Ni(n,p)^{58}Co reaction

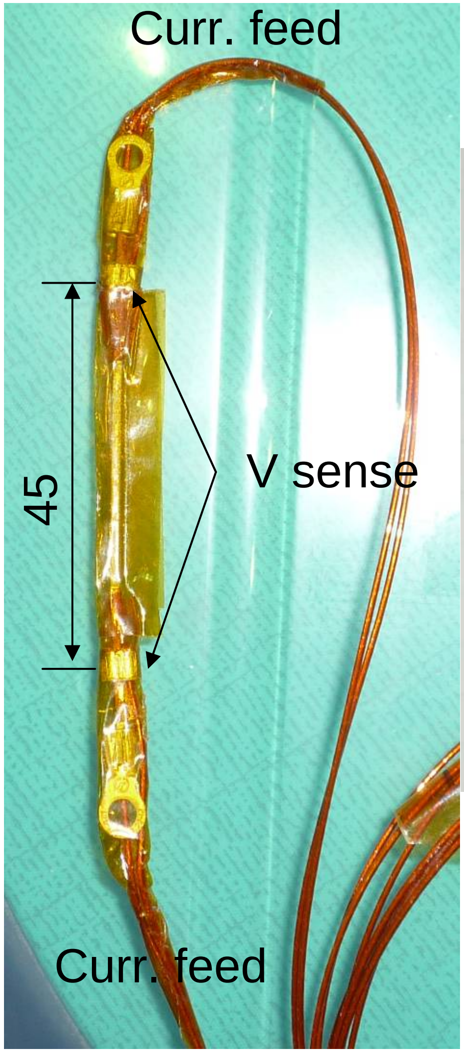


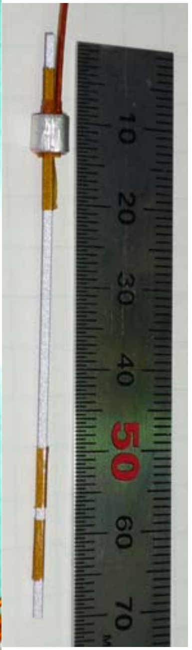


M. Okada et al., NIM A463 (2001) pp213-219

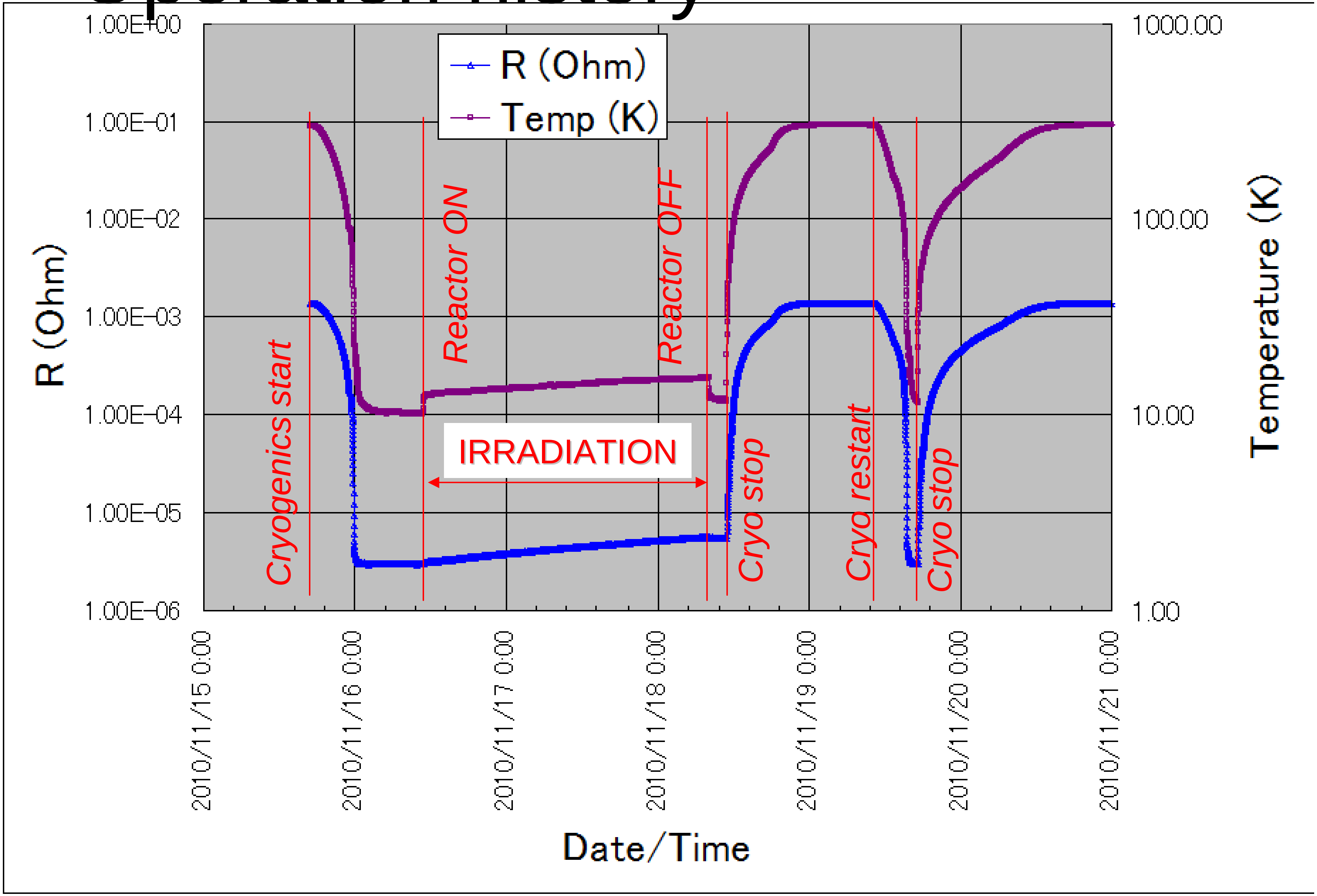
Equipments

- Aluminum sample; cut from Al-stabilized SC cable manufactured last year.
- 4Wire resistance measurement with
  - Keithley 6221+2182A
- 1mmx1mmx70mm
- 45mm between voltage sense
- 1.35mΩ@RT

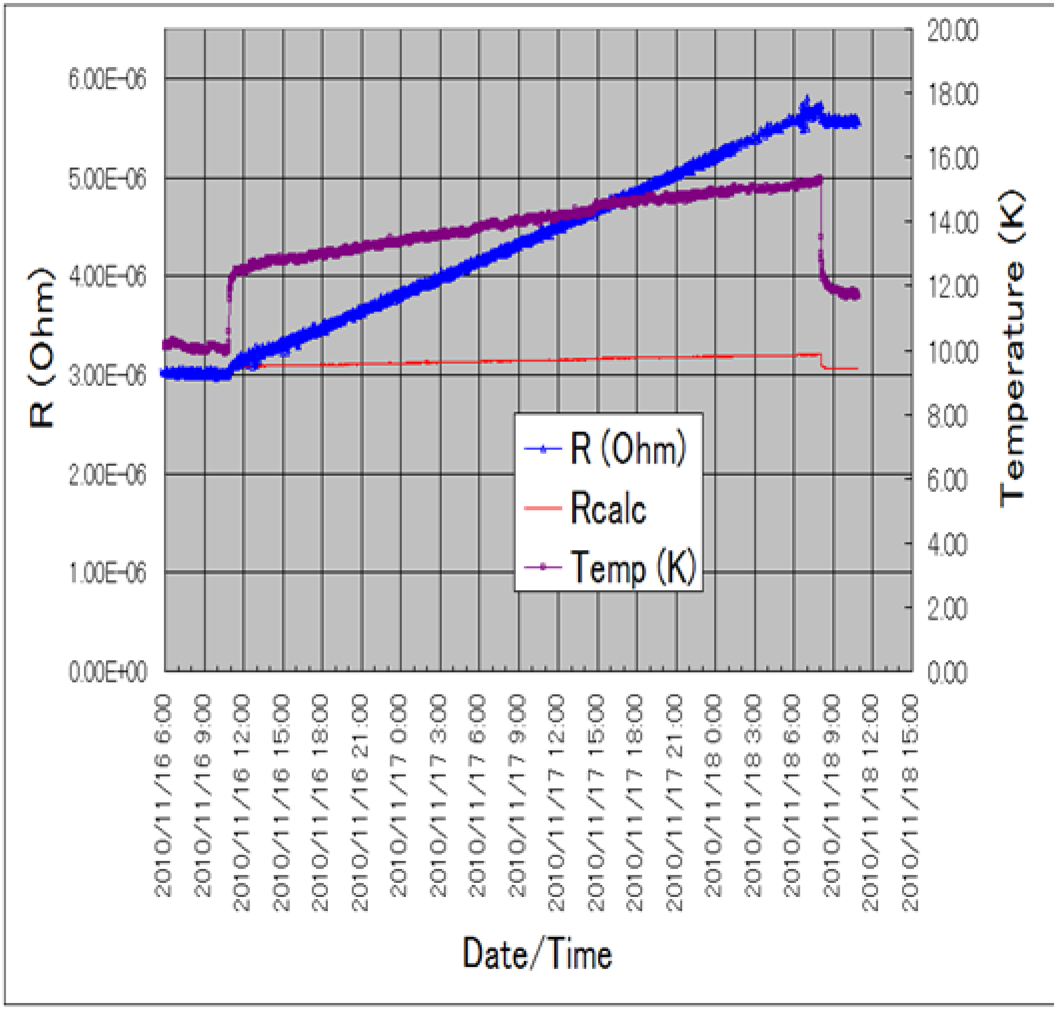


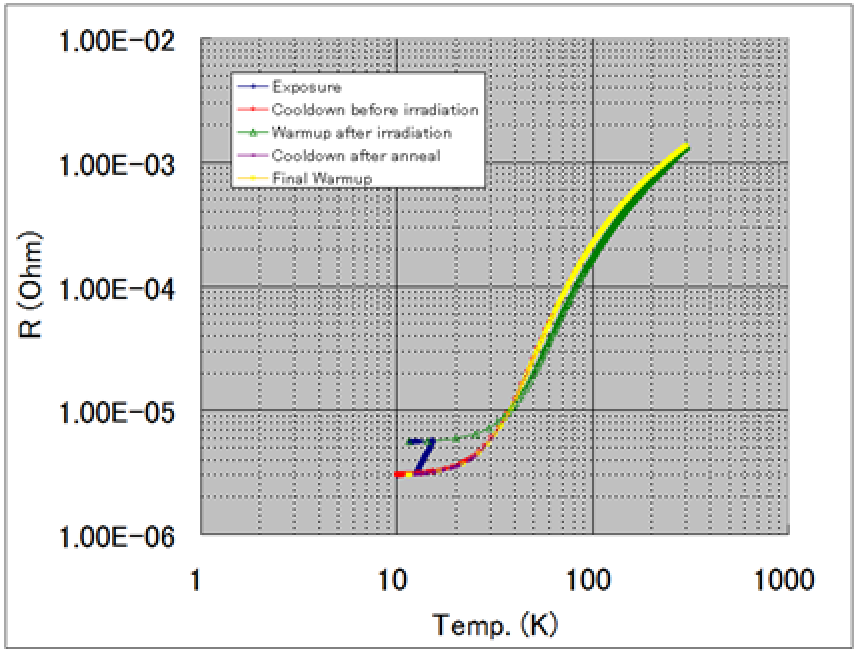


Operation history



Preliminary results on irradiation induced resistivity and recovery





Summary

- Solenoid capture scheme has been successfully launched in MuSIC
  - Capture pions in 3.5 T field
  - 10^8 - 10^9 $\mu+$, $\mu-$ /sec (0.4kW proton beam)
  - LHe free refrigeration by GM cryocoolers
- Commissioning with low intensity proton beam (1nA) has been successfully done at the end of July 2010

- COMET aims at producing much more muons beam using 56kW J-PARC proton beam
  - Capture in 5T
- Larger bore ~1300mm
  - Ongoing design studies on structure against high stress on the coils
- Severe radiation environment ~10^{21} n/m^2
  - Quench protection, cooling

- Check irradiation damage and recovery with realistic Al alloy
- Preliminary results from 2 day irradiation at KUR
- irradiation induced resistance reaches comparable to original residual resistance of high strength aluminum stabilizer
  - The integrated neutron flux is around 10^{20} n/m2
  - we will fix by measuring Ni foil activation later.
- We confirm recovery by thermal cycle to room temp.
- Continue to collect data in the next year
- Will feed back to solenoid design