Radiation study of the target station

Guang Zhao (zhaog@ihep.ac.cn),

Zongtai Xie, Zhilong Hou, Nikos Vassilopoulos, Ye Yuan, Mu Qili, Jing Hantao

EMuS Review Meeting

Dongguan, Guangdong

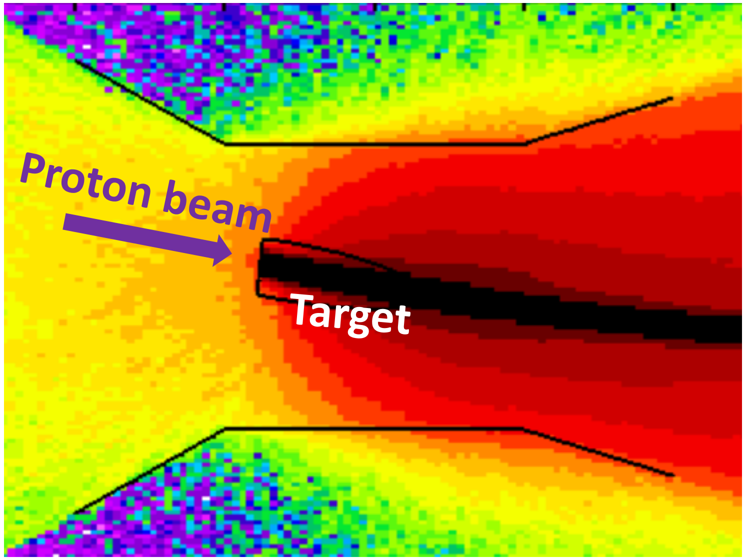
Nov. 20th, 2018

Outline

- ☐ **Introduction**
- ☐ **Radiation calculation for the baseline scheme**
- ☐ **Radiation calculation for the baby scheme**
- ☐ **Conclusion**

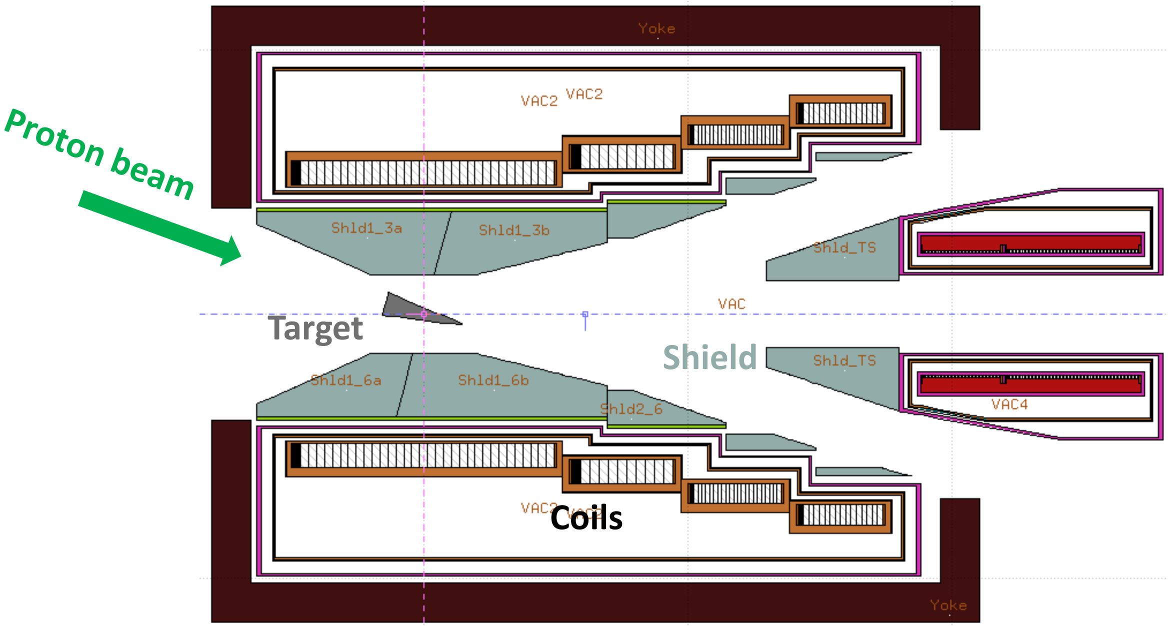
Introduction

- ❑ **The interaction between the proton beam and the target produces high radiation.**
- ❑ **The performance of the superconducting magnets in such high irradiation environment can be degraded**
- ❑ **Simulation need to be done in order to understand the radiation and guide the design of the target station**

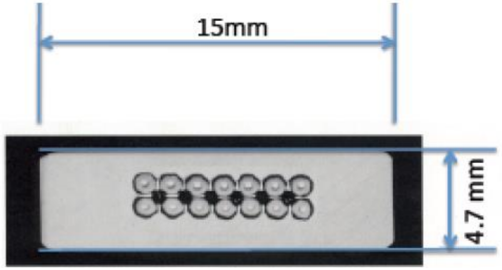


Radiation calculation for the baseline scheme

- **The baseline scheme design**
    - 1.6 GeV, 5 kW proton beam
    - Conical carbon target (better for surface muon production and radiation)
    - 4-coil/3-step superconducting adiabatic solenoid (high particle collection efficiency)
    - Tungsten shields to protect the coils from radiation

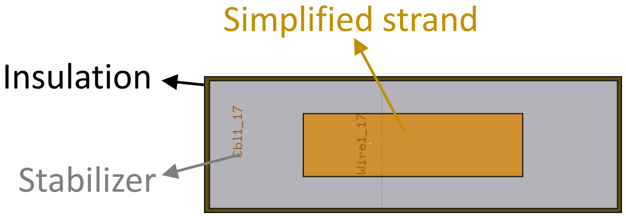


Geometry description in simulation

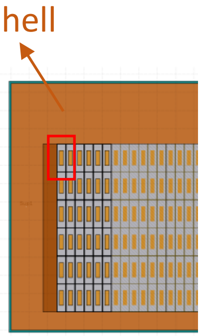


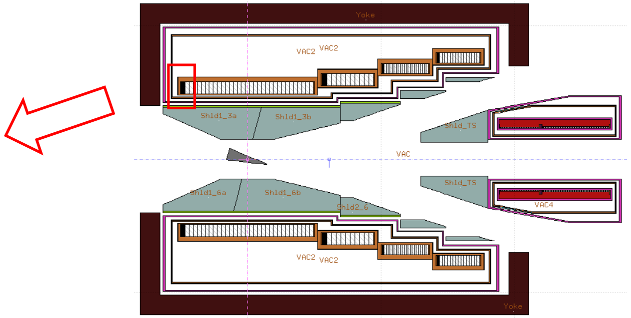
Al stabilized Rutherford cable

Item	Value
Cable Dimension	w/o insulation: $15 \times 4.7\ mm^2$
	w/ insulation: $15.3 \times 5.0\ mm^2$
Strand	Diameter: 1.15 mm
	Number: 8×2
Stabilizer	Aluminum
Insulation	Polyimide
Support shell	Al5083
Initial RRR	400 (stabilizer)



Cable model in simulation





Radiation limit: peak dose in epoxy < 7 MGy for lifetime

- The most restricted radiation limit is the maximum local radiation dose to the superconductor insulation and epoxy over the lifetime of the experiment.
- In particular, the epoxy used to bond the insulation to the superconducting cable can tolerate a ***maximum of 7 MGy (0.7 MGy/y for 10 years operation)*** before it experiences a 10% degradation in its shear modulus.
- The tungsten shields are designed to protect the SC cables from radiation and their layout need to be optimized.

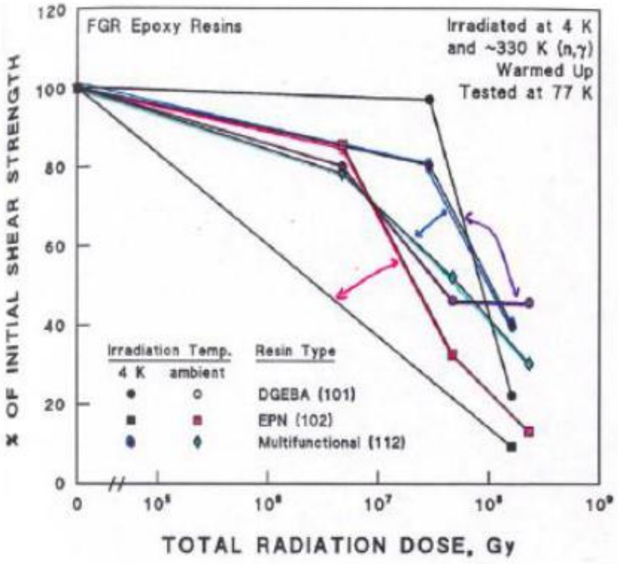
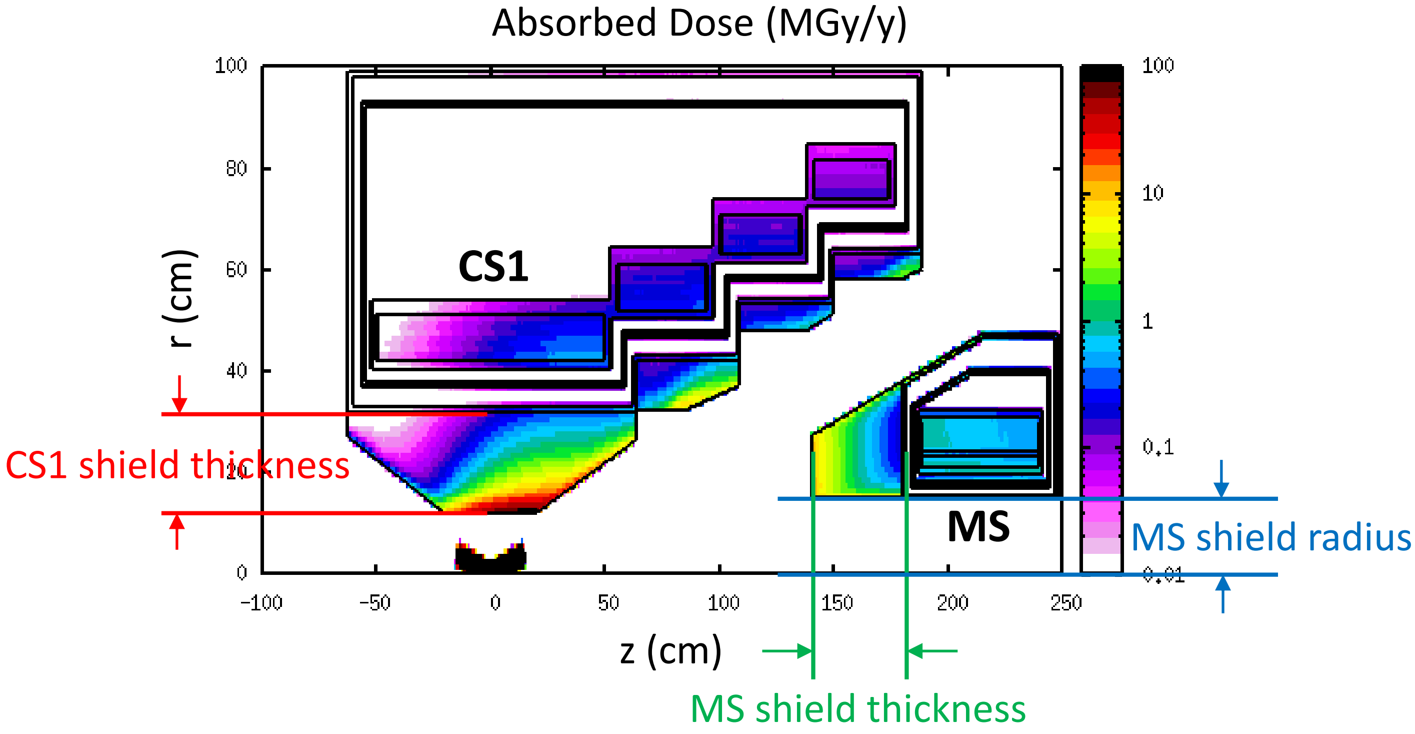


Figure 1.25. A comparison of the shear strengths of three types of reinforced epoxy resins that were reactor-irradiated at both 4 K and at ambient temperature. See text for differences in the fast neutron spectrum in the two reactors. Data from Munshi [1991]. (Supplementary Tables A. 3-3 and A. 8-4.)

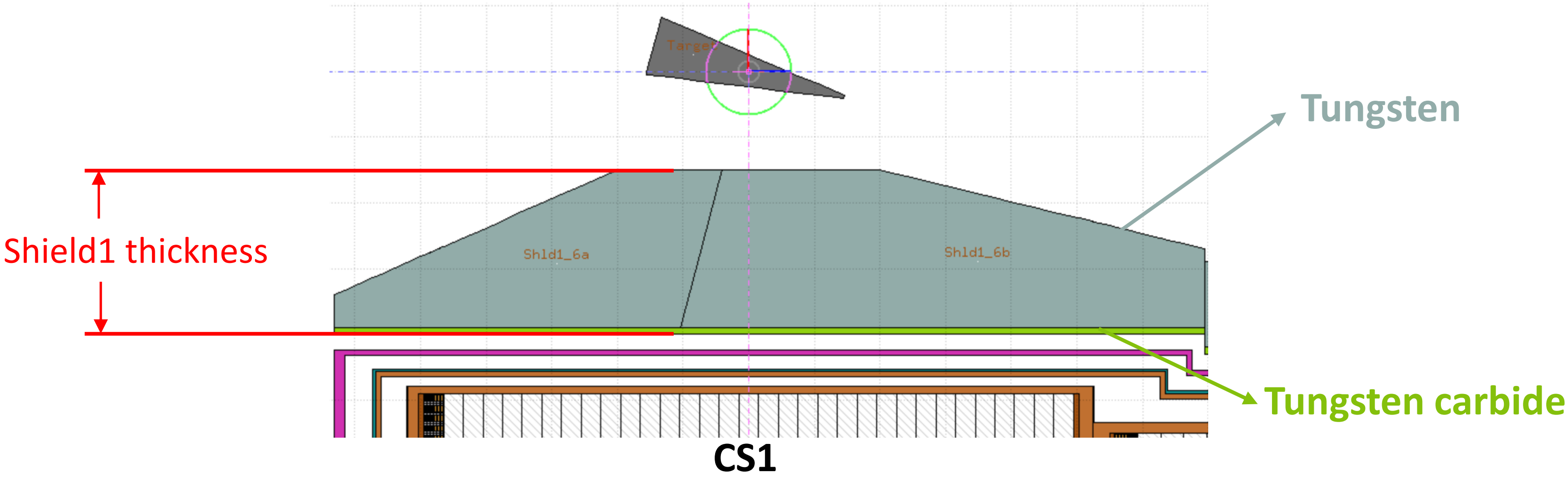
Radiation Hard Coils, A. Zeller et al, 2003

Shield optimization

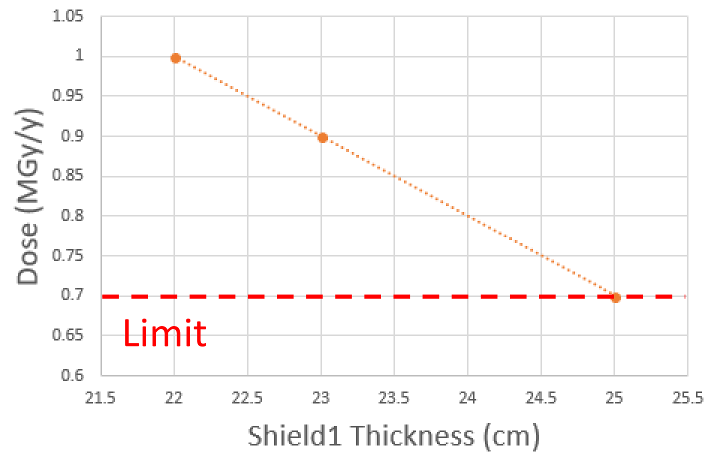
- From simulation results, the first capture solenoid (CS1) and the matching solenoid (MS) experience the largest dose. Their shield layouts should be optimized.



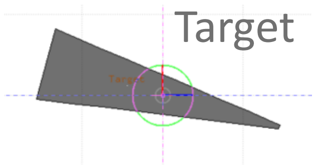
CS1 shield optimization

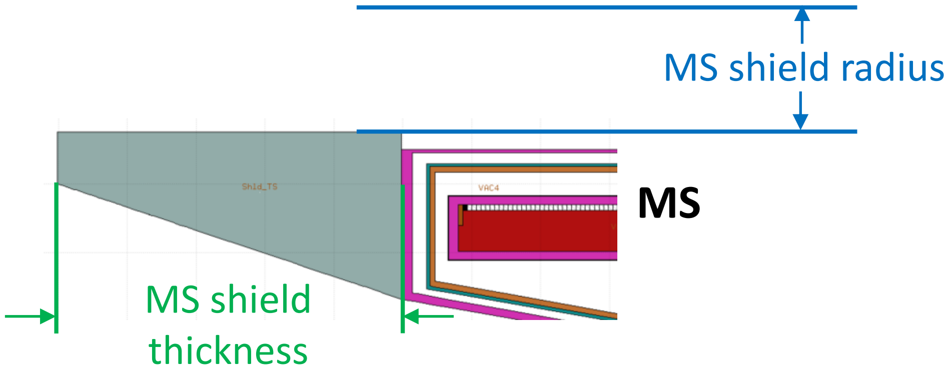


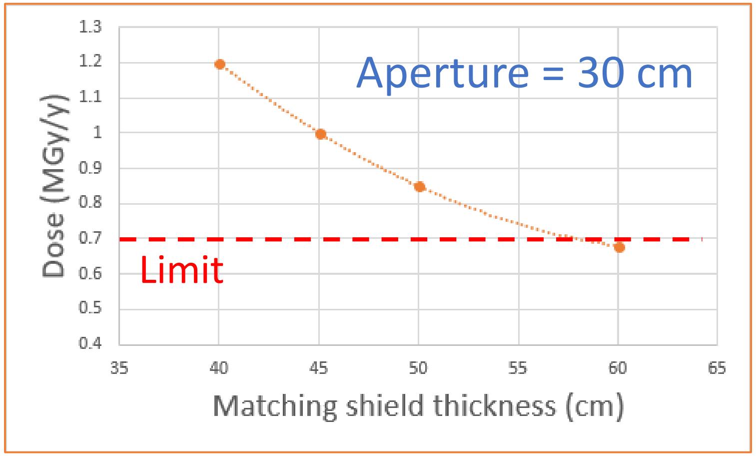
- ✓ From simulation results, tungsten carbide can effectively stop soft neutrons, which lead to *15%~20% less dose* for the first coil.
- ✓ Put 1cm-thick tungsten carbide at the inner most part of the first shield.
- ✓ The thickness of the first shield should be *no less than 25 cm*.

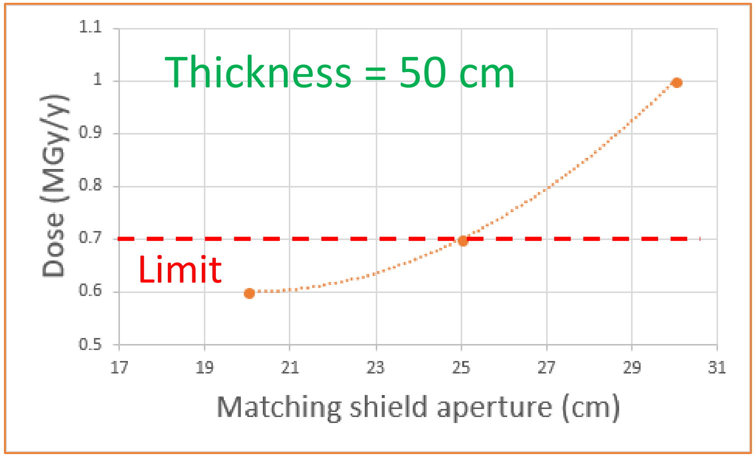


MS shield optimization







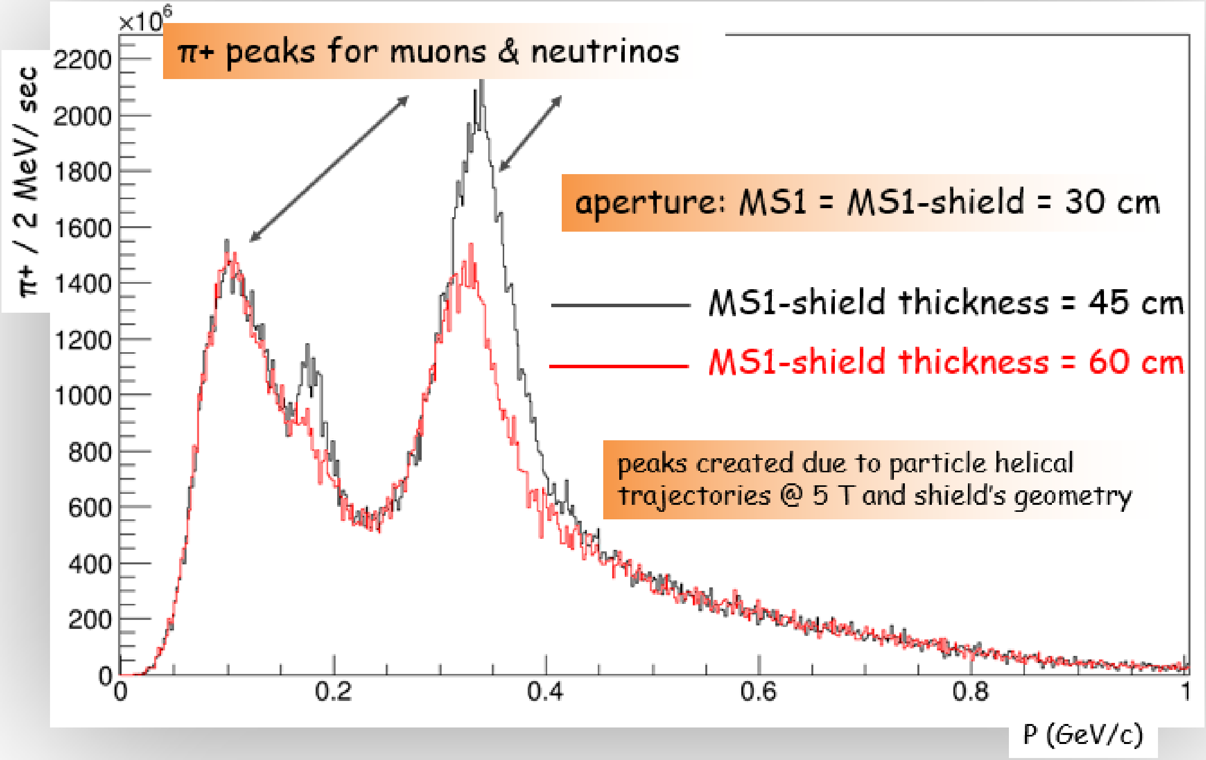


Two possible options:

a) Aperture = 30 cm; thickness = 60 cm
b) Aperture = 25 cm; thickness = 50 cm

MS shield optimization (cont.)

π+ momentum distribution at MS1
MS1-shield thickness 60 vs 45 cm



π+ peaks for muons & neutrinos

aperture: MS1 = MS1-shield = 30 cm

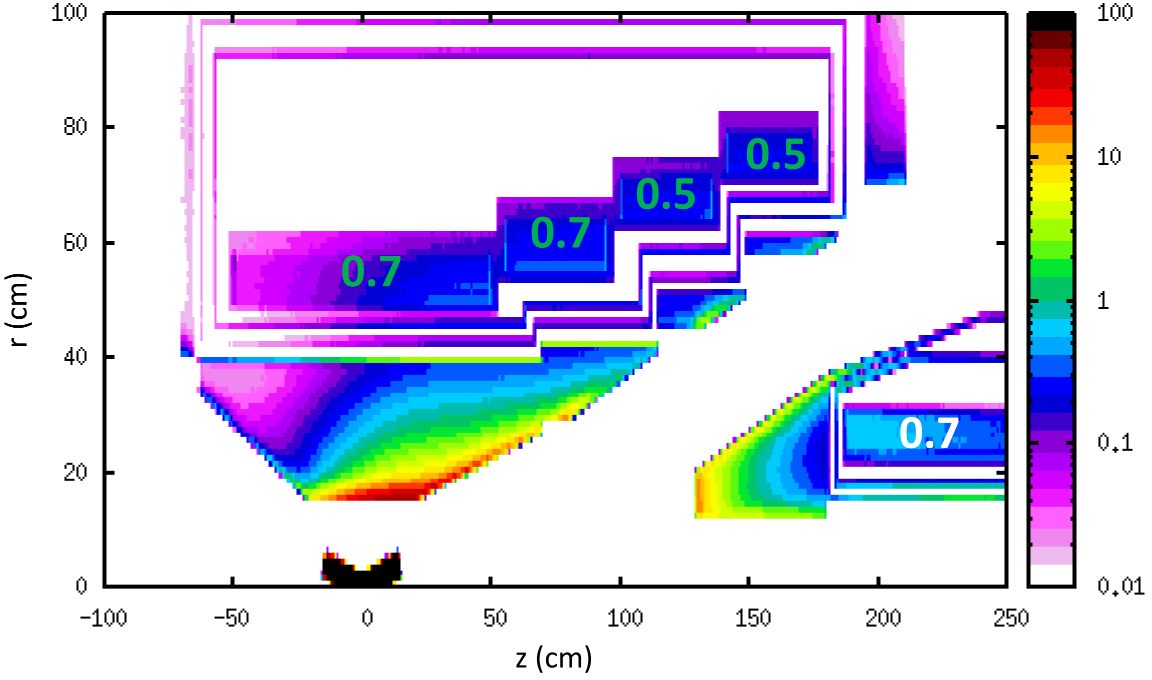
peaks created due to particle helical trajectories @ 5 T and shield's geometry

Shorter MS1-shield thickness is better for the neutrino beam

Peak dose for 1 year operation (MGy)

The optimal shield configuration:

- CS1 shield thickness: 25 cm
- MS shield thickness: 50 cm
- MS shield aperture: 25 cm



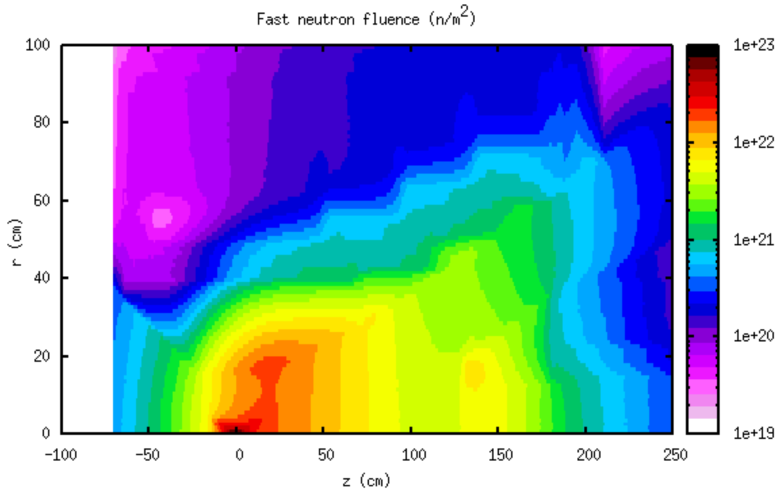
Peak doses are below the 0.7 MGy/y limit for all solenoid coils

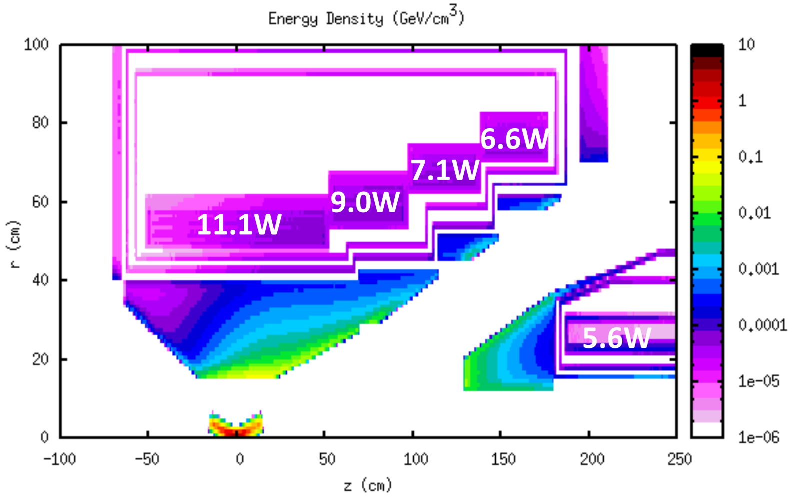
Radiation limits for the conductors

- ❑ **RRR limit**
  - ❑ RRR is defined as the ratio of the electrical resistance at room temperature of a conductor to that at 4.5 K.
  - ❑ RRR is an important parameter for the superconducting magnet design that affects the magnet performance during operation in superconducting mode and irreversible transition to the normal state (quench).
  - ❑ For a given sample exposed to various neutron spectra, the RRR will decrease. For the Al stabilizer, *we require RRR is not larger than 100.*
- ❑ **Temperature limit**
  - ❑ The operation temperature of the superconducting coils should below the critical value with a sufficient margin. *The values are 5.9K and 5.5K for low and high magnetic field modes.*

Neutron fluence and energy density

Peak fast neutron fluence in coils ~ 1.7E21 n/m^2/y





Neutron irradiation tests at Kyoto Univ. Research Reactor Institute

Al stabilizer sample

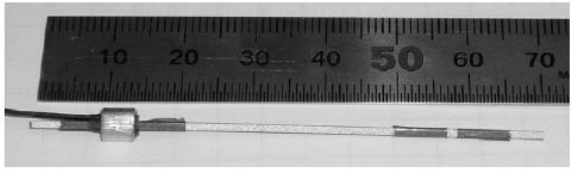


FIGURE 2. The aluminum sample cut from the aluminum stabilized superconductor attached with a voltage sense wire.

Al's electrical resistance in neutron irradiation environment

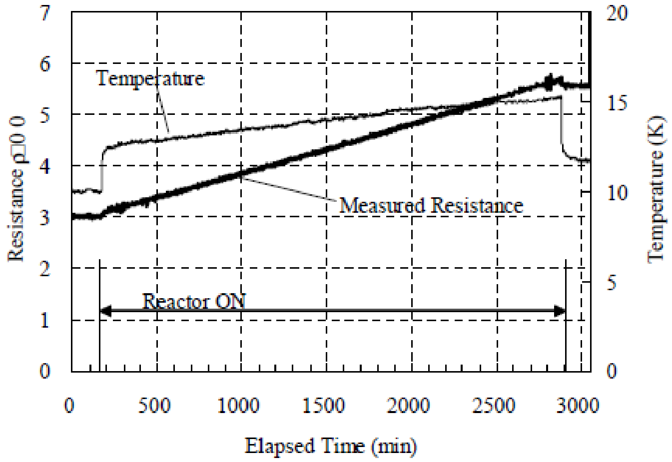
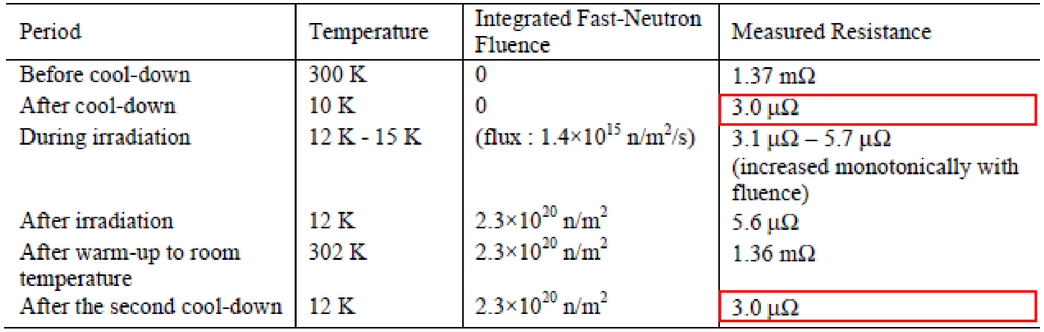


TABLE 2. Summary of the Resistance Changes Observed in the Experiment

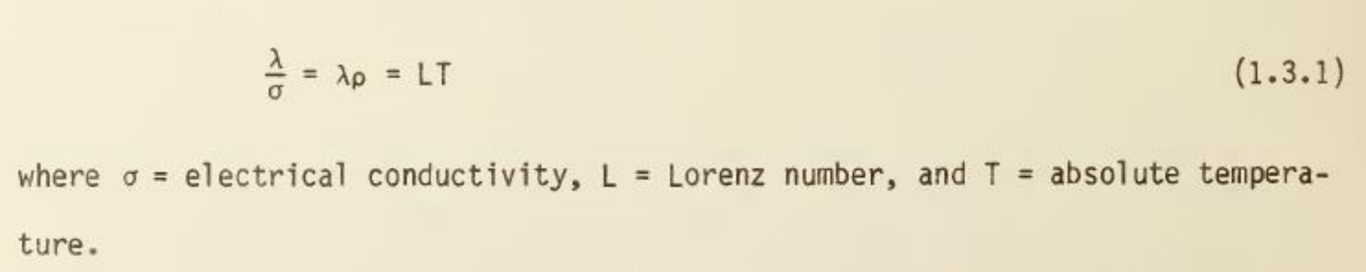


Period	Temperature	Integrated Fast-Neutron Fluence	Measured Resistance
Before cool-down	300 K	0	1.37 mΩ
After cool-down	10 K	0	3.0 μΩ
During irradiation	12 K - 15 K	(flux : 1.4×10^{15} n/m²/s)	3.1 μΩ – 5.7 μΩ (increased monotonically with fluence)
After irradiation	12 K	2.3×10^{20} n/m²	5.6 μΩ
After warm-up to room temperature	302 K	2.3×10^{20} n/m²	1.36 mΩ
After the second cool-down	12 K	2.3×10^{20} n/m²	3.0 μΩ

- ✓ Neutron induced resistance rate is $0.03\ n\Omega\cdot m$ for 10^{20} n/m²
- ✓ The resistance can be recovered by warming up to room temperature

M. Yoshida *et al.*, *Proc. AIP Conf.*, 2011, vol. 1435, pp. 167–173.

Wiedemann-Franz-Lorenz (WFL) law



$$\frac{\lambda}{\sigma} = \lambda\rho = LT \qquad (1.3.1)$$

where σ = electrical conductivity, L = Lorenz number, and T = absolute temperature.

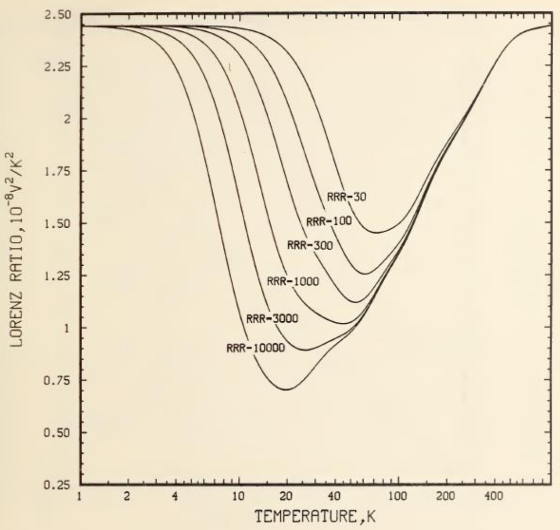


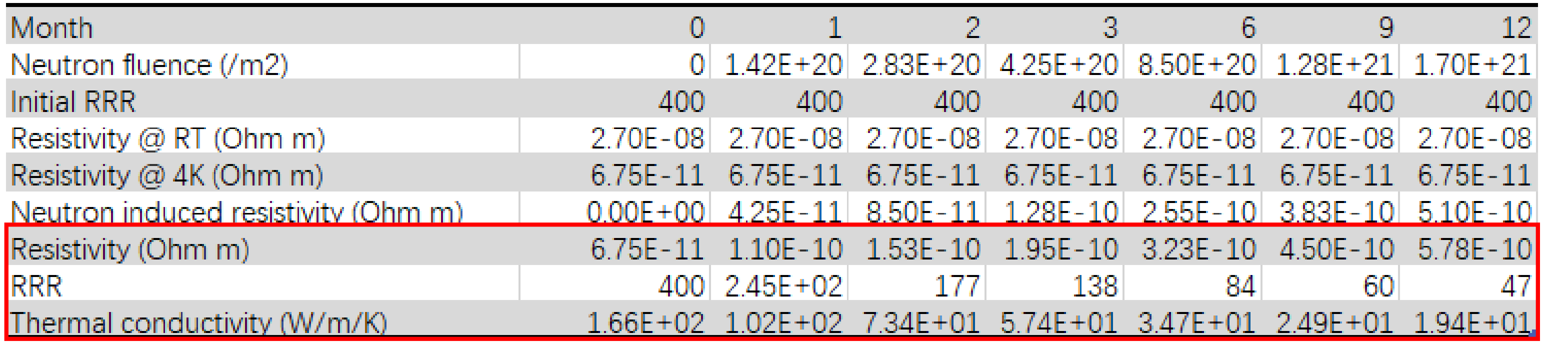
Figure 3.3.8 Lorenz ratio for aluminum as a function of temperature calculated from eq.(1.2.3) and eq.(1.1.3) at selected values of RRR.

- For RRR = 1000
  - $LT \approx 11 \times 10^{-9}\ V^2/K^2$ @ $4.5\ K$
- For RRR = 400
  - $LT \approx 11.2 \times 10^{-9}\ V^2/K^2$ @ $4.5\ K$

J. Hust and A. Lankford, National Bureau of Standards, Boulder, CO, USA, DOE-HDBK 1017/2-93, 1984.

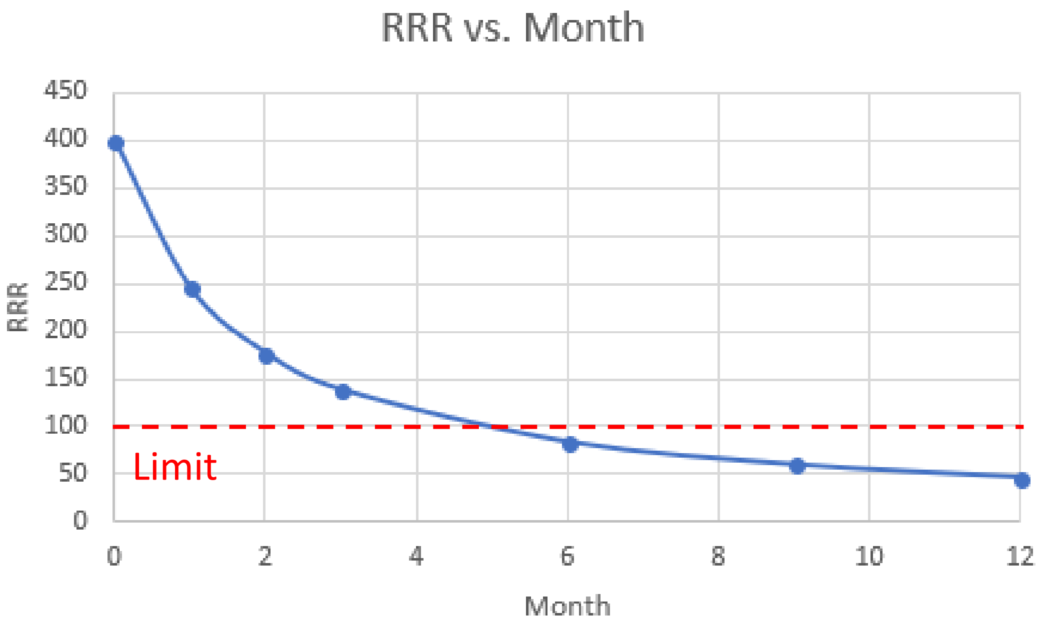
Radiation estimation for Al stabilizer

- **Effective RRR is calculated as** $RRR = \frac{\rho_{RT}}{\rho(t)} = \frac{\rho_{RT}}{\rho_0 + r\times\Phi(t)}$
- **Assume**
  - Neutron induced resistance
    - $r = 0.03\ n\Omega\cdot m$ for 10^{20} n/m^2 (page 14)
  - According to WFL law, resistivity $\rho(t)$ and thermal conductivity $\lambda(t)$ obey
    - $\rho(t)\cdot\lambda(t) = LT$ (page 15)



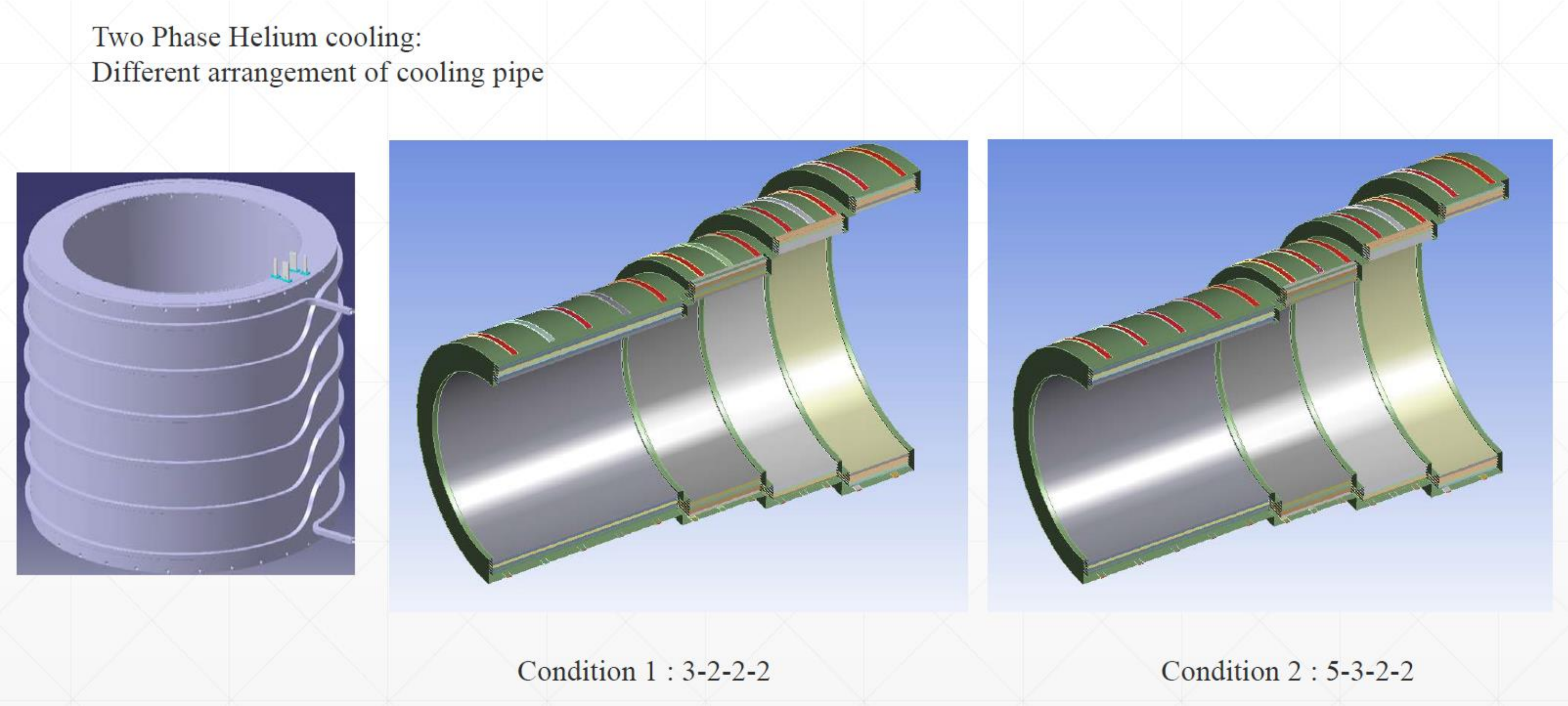
Month	0	1	2	3	6	9	12
Neutron fluence (/m2)	0	1.42E+20	2.83E+20	4.25E+20	8.50E+20	1.28E+21	1.70E+21
Initial RRR	400	400	400	400	400	400	400
Resistivity @ RT (Ohm m)	2.70E-08	2.70E-08	2.70E-08	2.70E-08	2.70E-08	2.70E-08	2.70E-08
Resistivity @ 4K (Ohm m)	6.75E-11	6.75E-11	6.75E-11	6.75E-11	6.75E-11	6.75E-11	6.75E-11
Neutron induced resistivity (Ohm m)	0.00E+00	4.25E-11	8.50E-11	1.28E-10	2.55E-10	3.83E-10	5.10E-10
Resistivity (Ohm m)	6.75E-11	1.10E-10	1.53E-10	1.95E-10	3.23E-10	4.50E-10	5.78E-10
RRR	400	2.45E+02	177	138	84	60	47
Thermal conductivity (W/m/K)	1.66E+02	1.02E+02	7.34E+01	5.74E+01	3.47E+01	2.49E+01	1.94E+01

Degradation of the Al stabilizer



__The RRR of the Al stabilizer downgrade to 100 after 5-month continuous operation.__ Then it can be 100% covered by warming up the superconducting solenoids to room temperature.

Thermal analysis: cooling



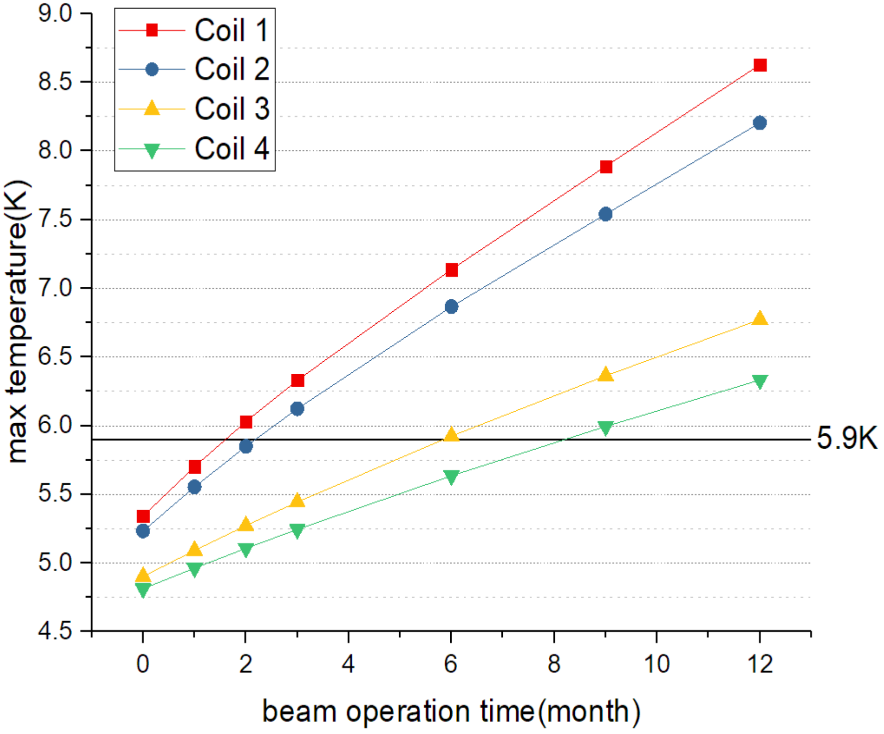
Two Phase Helium cooling:
Different arrangement of cooling pipe

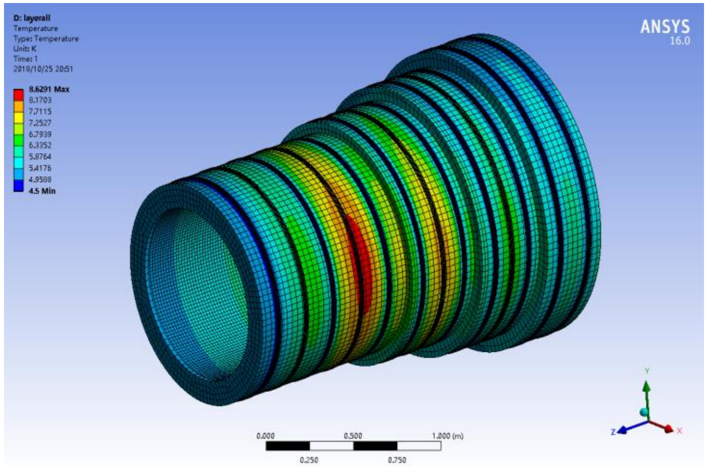
Condition 1 : 3-2-2-2

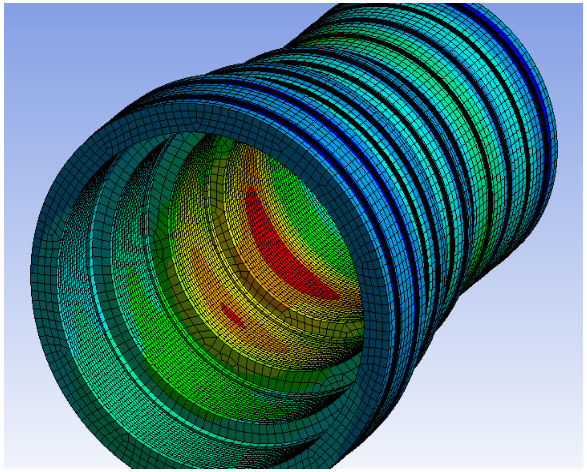
Condition 2 : 5-3-2-2

Taking electrical resistivity and thermal conductivity during operation into account, we calculate the temperature of coils using ANSYS

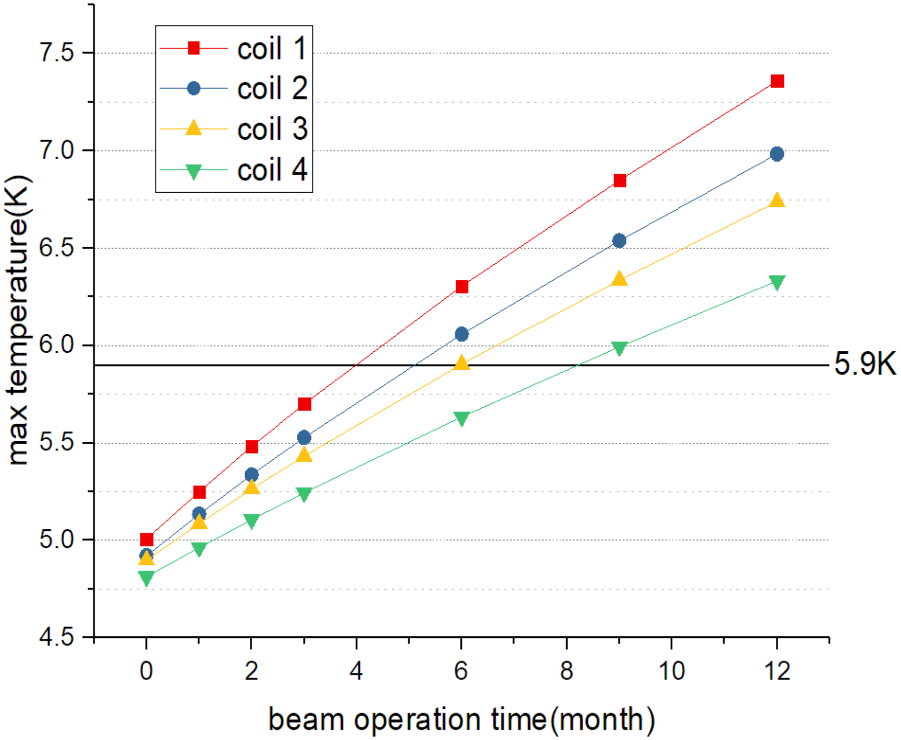
Max temperatures on coils (condition 1)

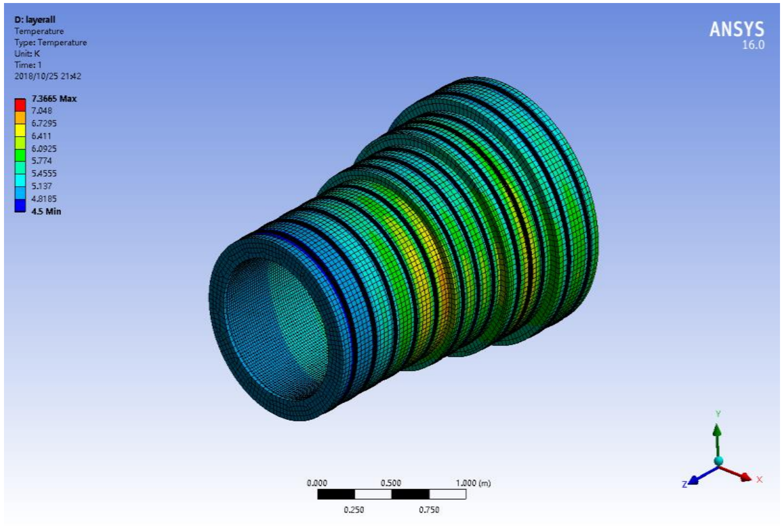


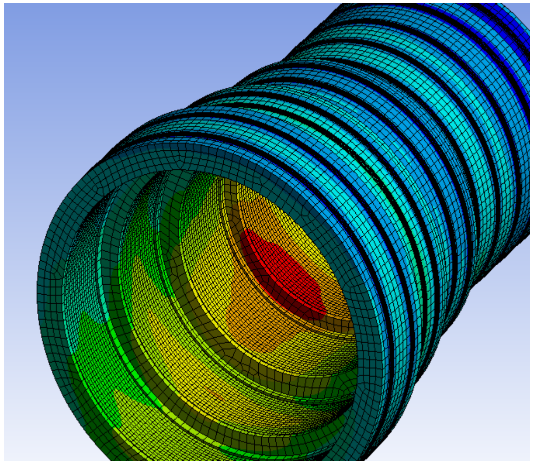




Max temperatures on coils (condition 2)



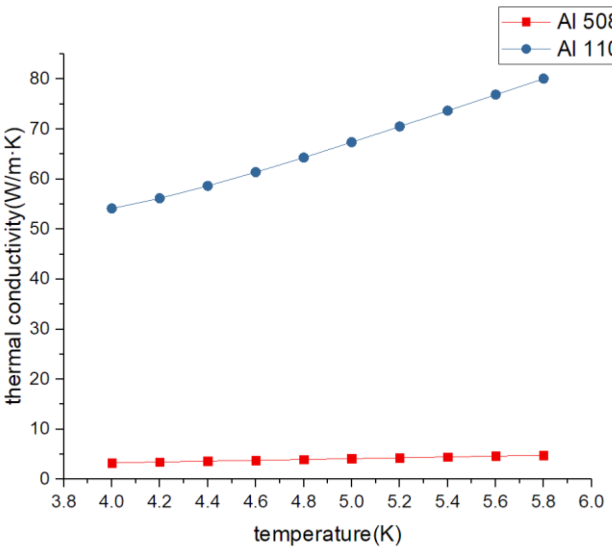




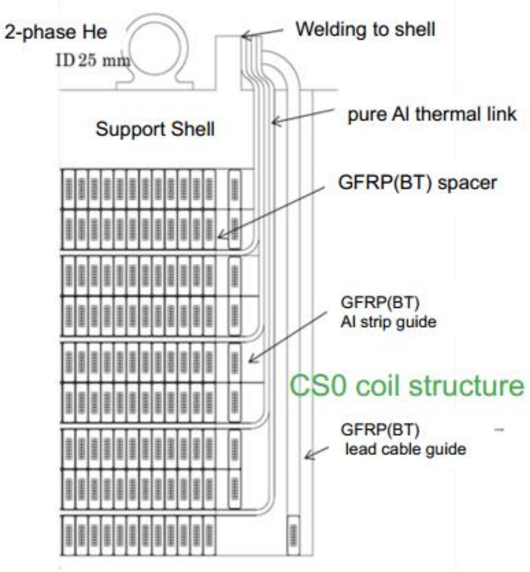
For coil1 & coil2, 15~20% lower temperature

Thermal analysis: thermal bridge

- Inserting Al 1100 strips between the coil layers can lead to better thermal transfer.
- The Al 1100 has much better thermal conductivity compared to Al 5083
- COMET magnetic coil design show promising results



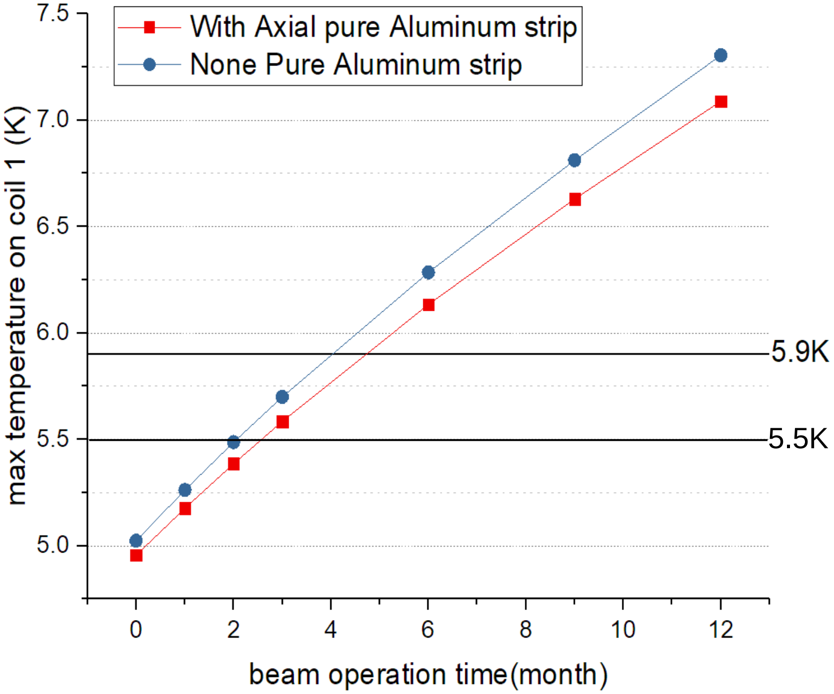
Al's thermal conductivity



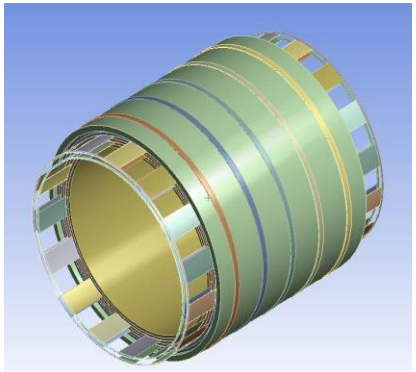
COMET's CS0 coil

Max temperatures on coils

w/ condition2 cooling

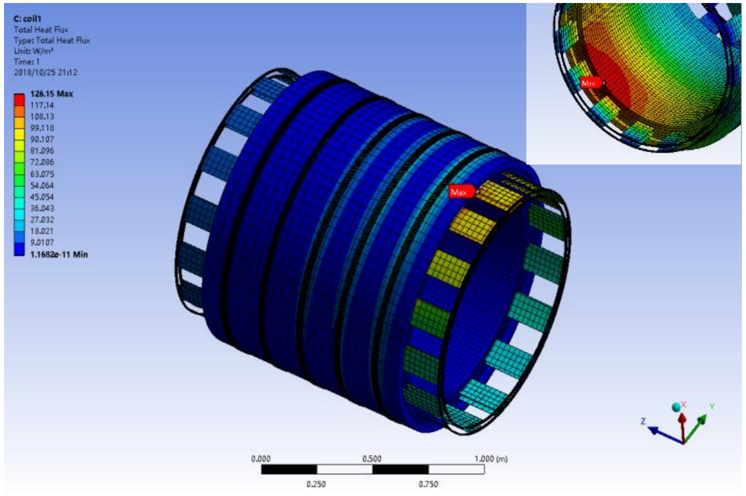


~4% lower temperature
the coils can continuously run for 5 months in total
(high field mode + low field mode)



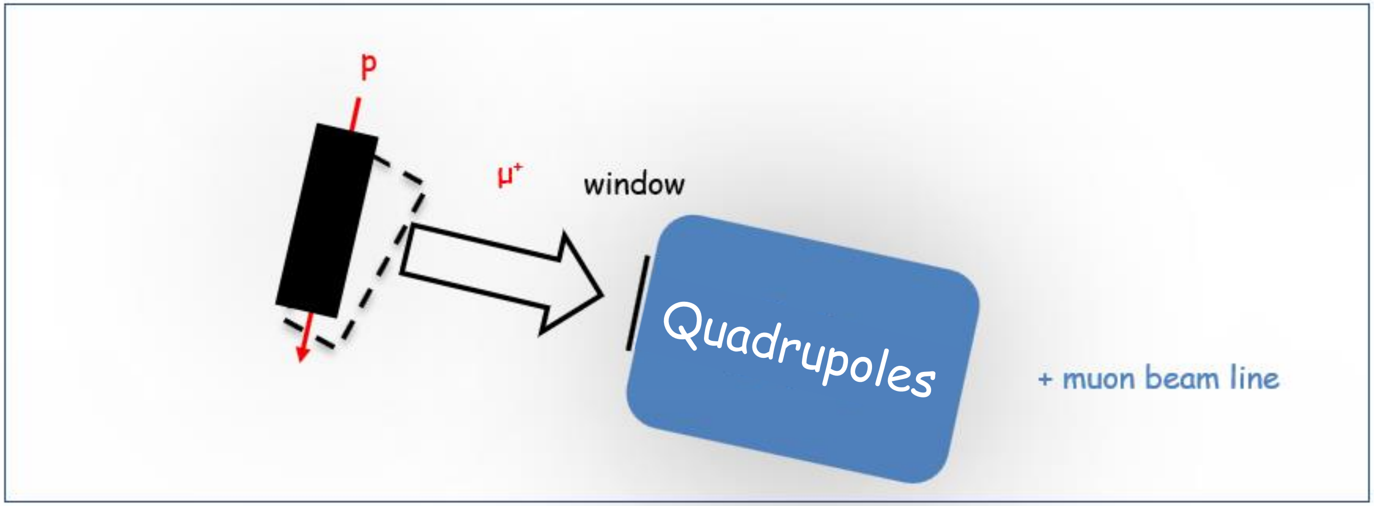
Axial pure Al strips:

- 12 pieces in azimuthal
- 2 layers
- Thickness: 0.9 mm

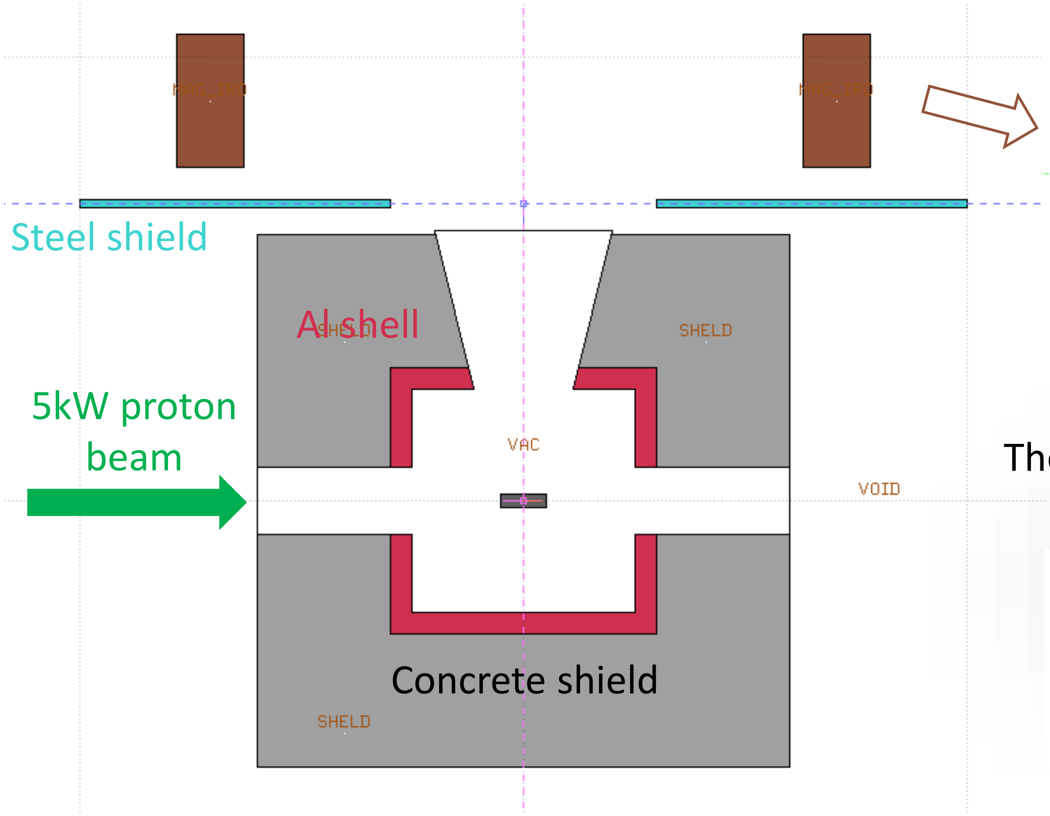


Radiation calculation for the baby scheme

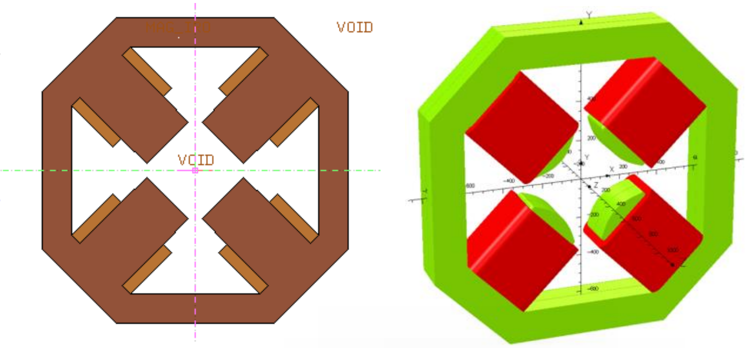
- **The baby scheme design**
  - Thin targets for proton beam recirculation
  - Quadrupoles (lower acceptance, focusing) place at 90 deg or higher angle
  - High polarization, less contamination from decay muons
  - ISIS target and beam window geometries show promising results



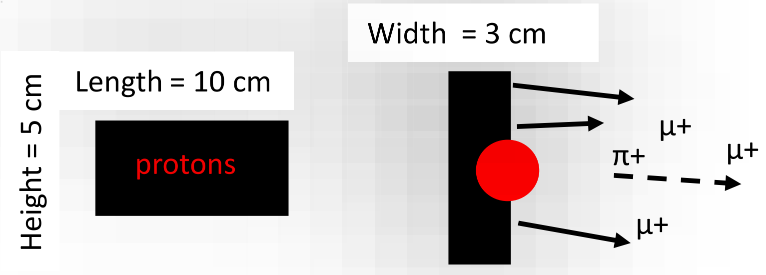
Geometry description in simulation



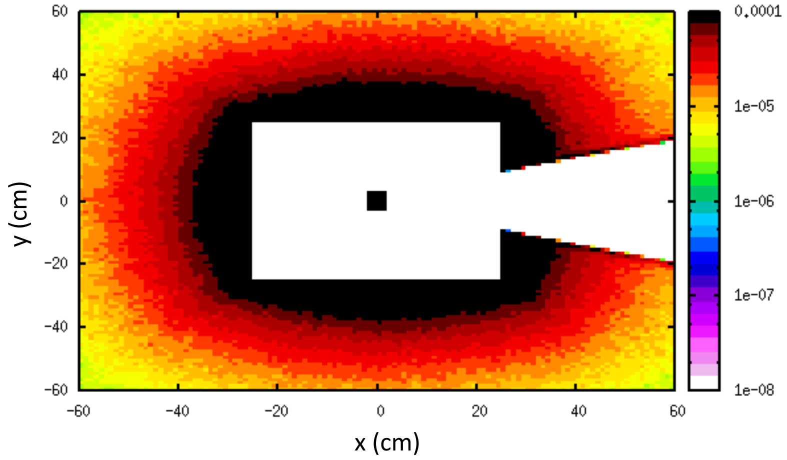
The 1st quadrupole magnet

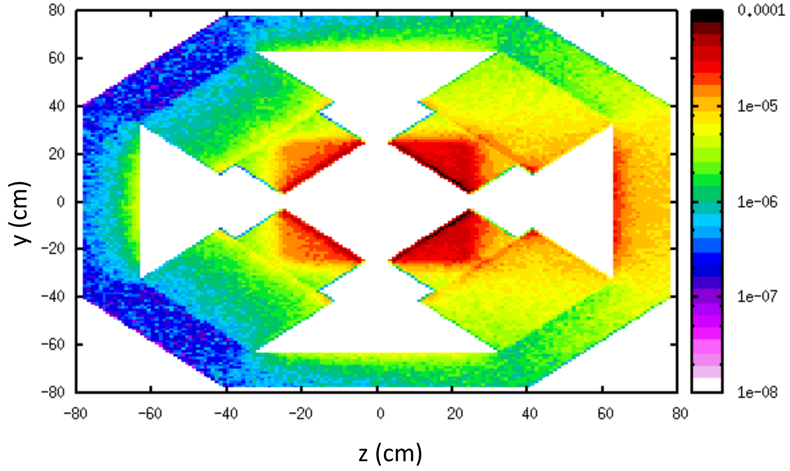


The thin target (semi-interact with the beam)



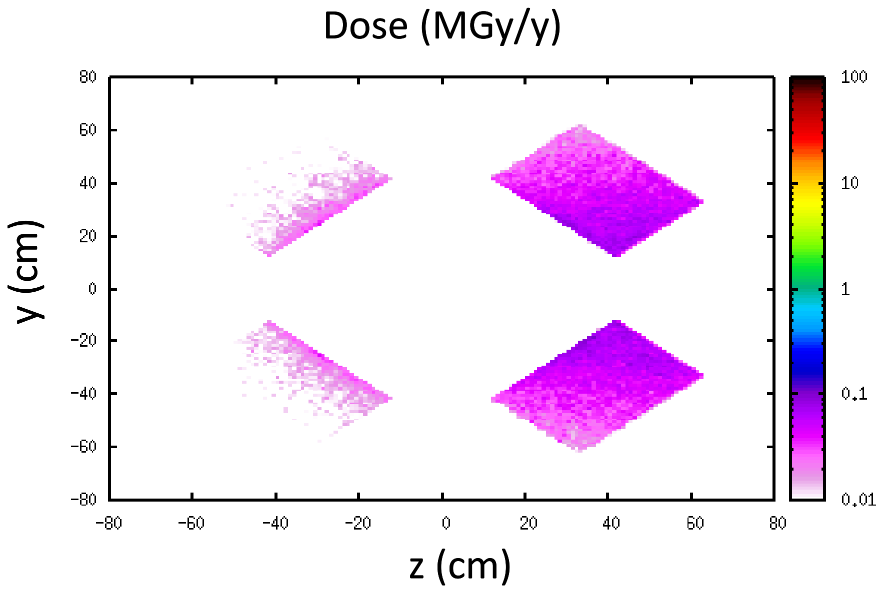
Power density (W/cm^3)

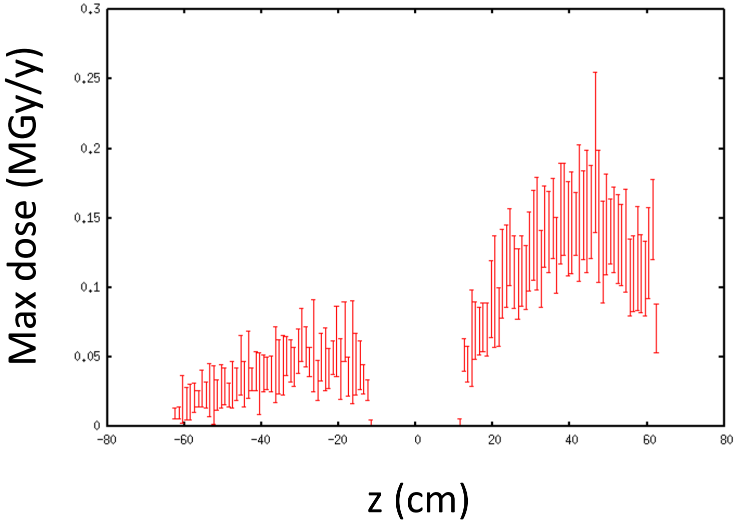




	Power deposition (W)
Target	75.1
Container	37.1
Concrete shield	135.3
Coil1	0.24
Coil2	0.06
Coil3	0.06
Coil4	0.24
Magnet Iron	2.7
Steel shield	1.7

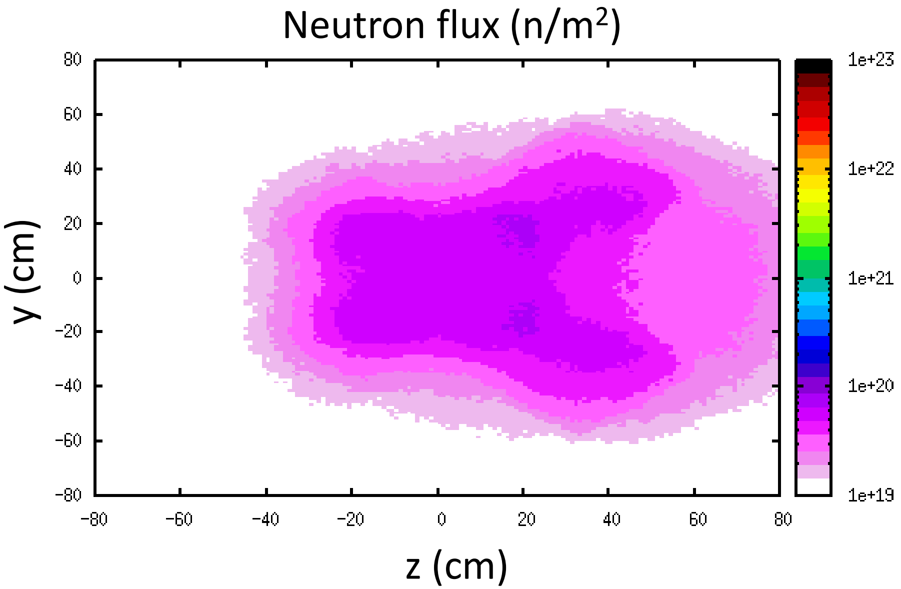
Dose on the coils (MGy/y)

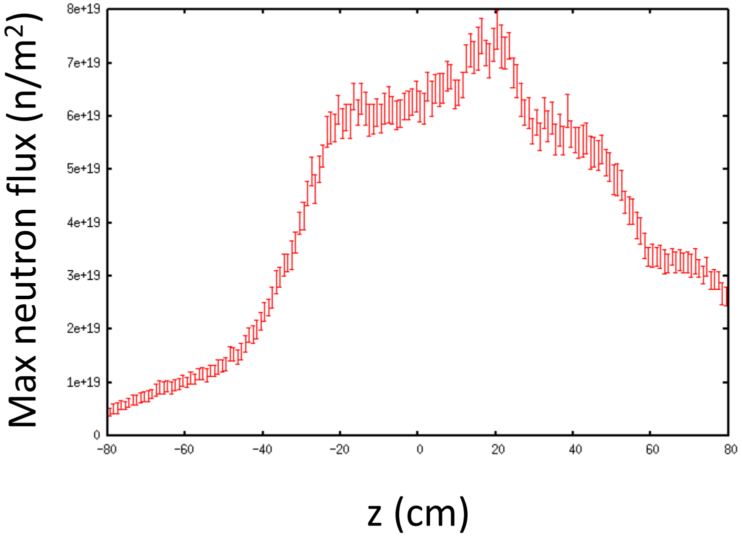




Much less dose (0.2 MGy) than the baseline scheme (0.7 MGy)

Neutron flux on the coils





Over 1 order of magnitude (8E19 n/m^2) lower than the baseline scheme (1.7E21 n/m^2)

Summary

- **The radiation simulation for the target station has been presented.**
- **For the baseline scheme**
  - The shield layout is optimized by the peak dose in the epoxy. The optimal parameters are:
    - CS1 shield thickness: 25 cm
    - MS shield thickness: 50 cm
    - MS shield aperture: 25 cm
  - The degradation of the stabilizer is estimated
    - The RRR of the Al stabilizer degrades to 100 for 5-month operation
  - Thermal analysis is carried out by considering the cooling and thermal bridge (refer Donghui’s report for shielding cooling)
    - The maximum temperature in the 1st coil arises above 5.9K after 5-month high field + low field operation

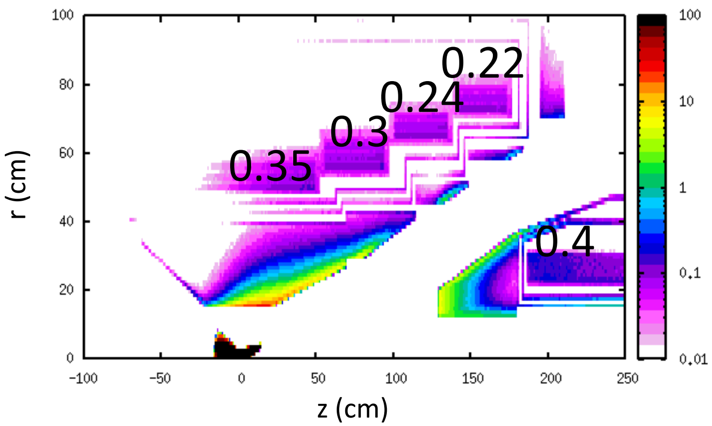
Summary (cont.)

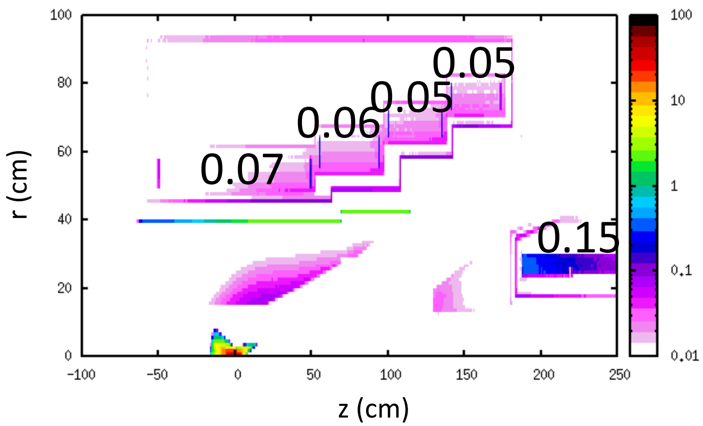
- **For the baby scheme**
  - As the thin target interact with the beam less probably, the radiation is much less than the baseline scheme
- **Next to do**
  - Further optimize the baby scheme design
  - Further optimize thermal bridge design
  - Perform the quench analysis

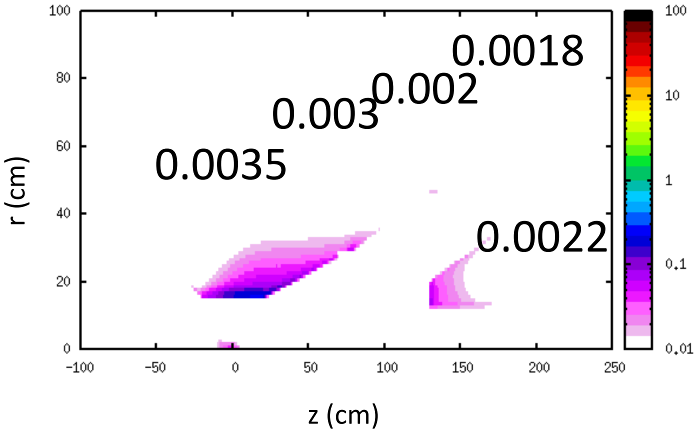
Thank you

Backups

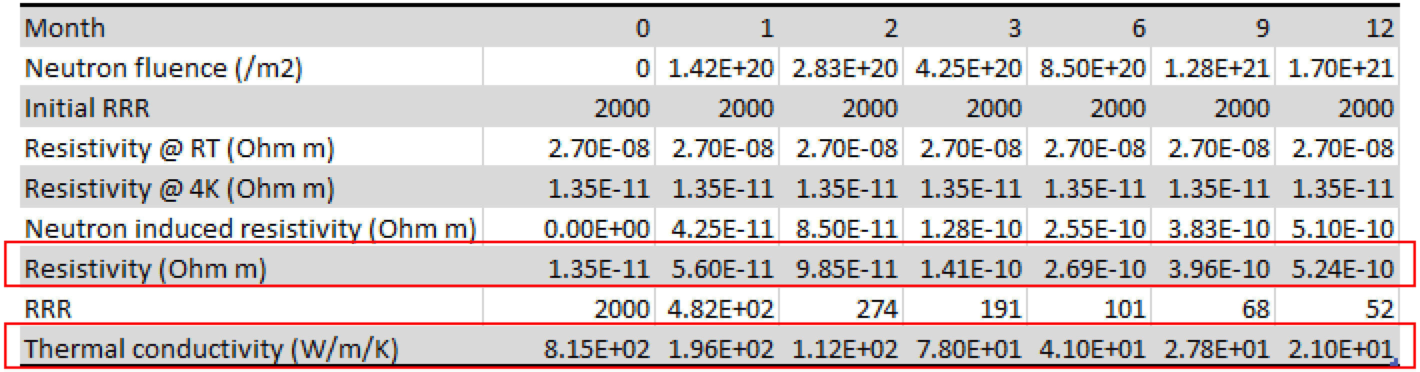
Dose for different particles (MGy/y)


Proton


Neutron

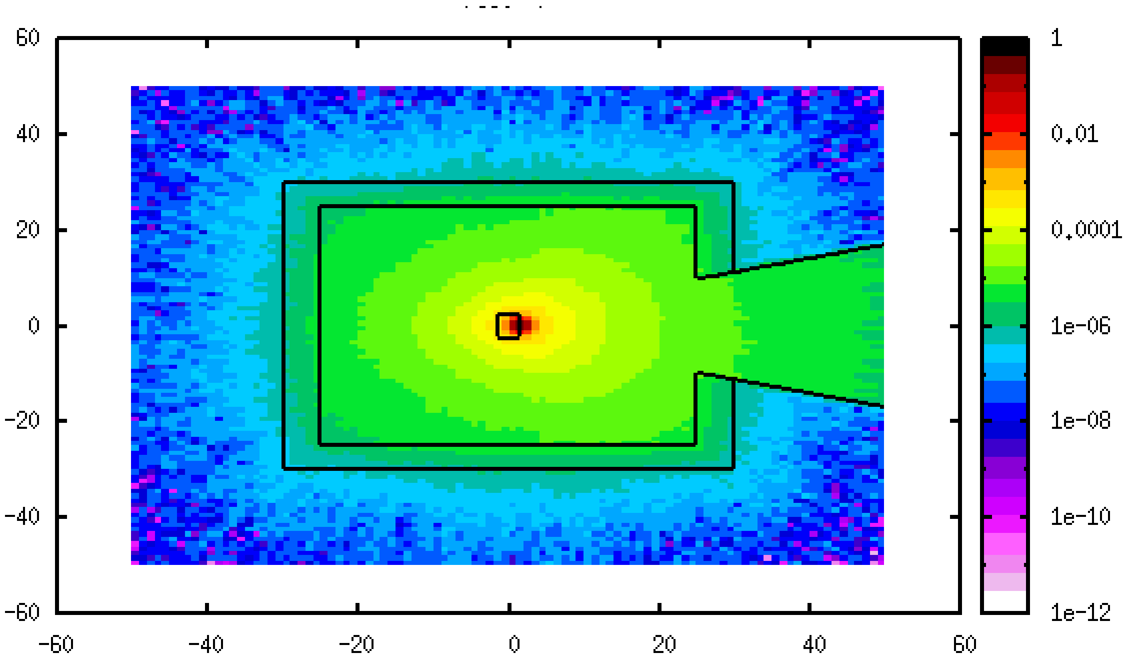

Photon

Degradation of Al strip

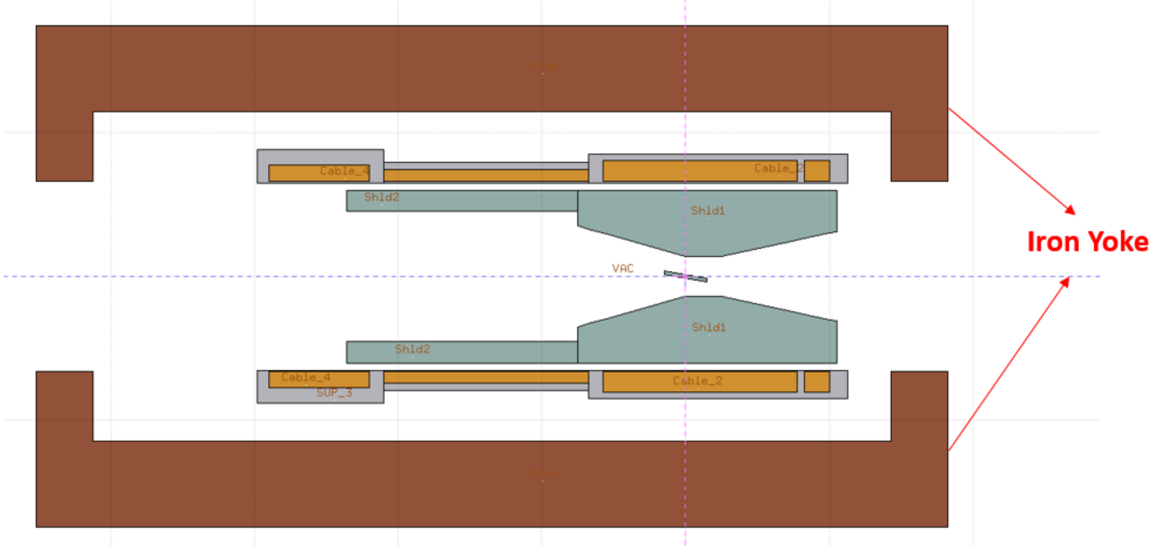


Month	0	1	2	3	6	9	12
Neutron fluence (/m2)	0	1.42E+20	2.83E+20	4.25E+20	8.50E+20	1.28E+21	1.70E+21
Initial RRR	2000	2000	2000	2000	2000	2000	2000
Resistivity @ RT (Ohm m)	2.70E-08	2.70E-08	2.70E-08	2.70E-08	2.70E-08	2.70E-08	2.70E-08
Resistivity @ 4K (Ohm m)	1.35E-11	1.35E-11	1.35E-11	1.35E-11	1.35E-11	1.35E-11	1.35E-11
Neutron induced resistivity (Ohm m)	0.00E+00	4.25E-11	8.50E-11	1.28E-10	2.55E-10	3.83E-10	5.10E-10
Resistivity (Ohm m)	1.35E-11	5.60E-11	9.85E-11	1.41E-10	2.69E-10	3.96E-10	5.24E-10
RRR	2000	4.82E+02	274	191	101	68	52
Thermal conductivity (W/m/K)	8.15E+02	1.96E+02	1.12E+02	7.80E+01	4.10E+01	2.78E+01	2.10E+01

Proton flux around the baby target

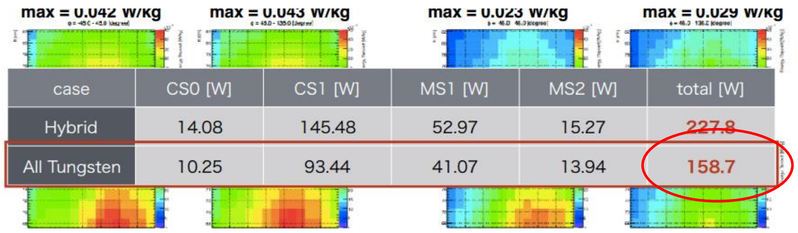


Cross check with a simplified COMET geometry



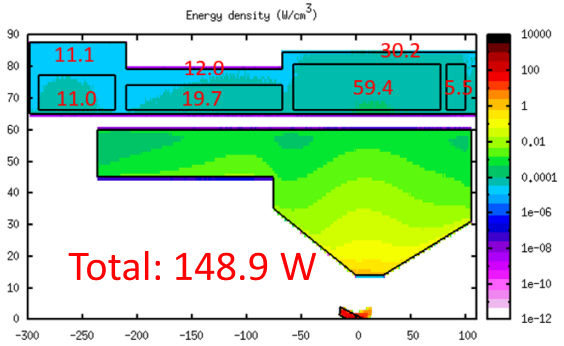
Iron Yoke

COMET's results



case	CS0 [W]	CS1 [W]	MS1 [W]	MS2 [W]	total [W]
Hybrid	14.08	145.48	52.97	15.27	227.8
All Tungsten	10.25	93.44	41.07	13.94	158.7

Our results



Total: 148.9 W