Shielding design and radiation damage for the target station

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Outline

- **Introduction**

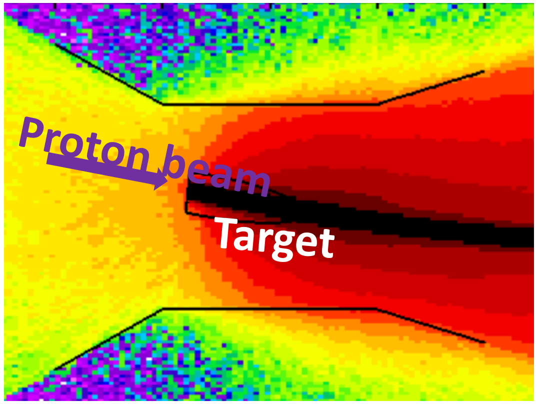
- **Shielding design**
  - Proton extraction
  - Optimization based on dose calculation

- **Radiation damage**
  - Conductor stability based on neutron fluence
  - Thermal analysis based on energy deposition

- **Summary**

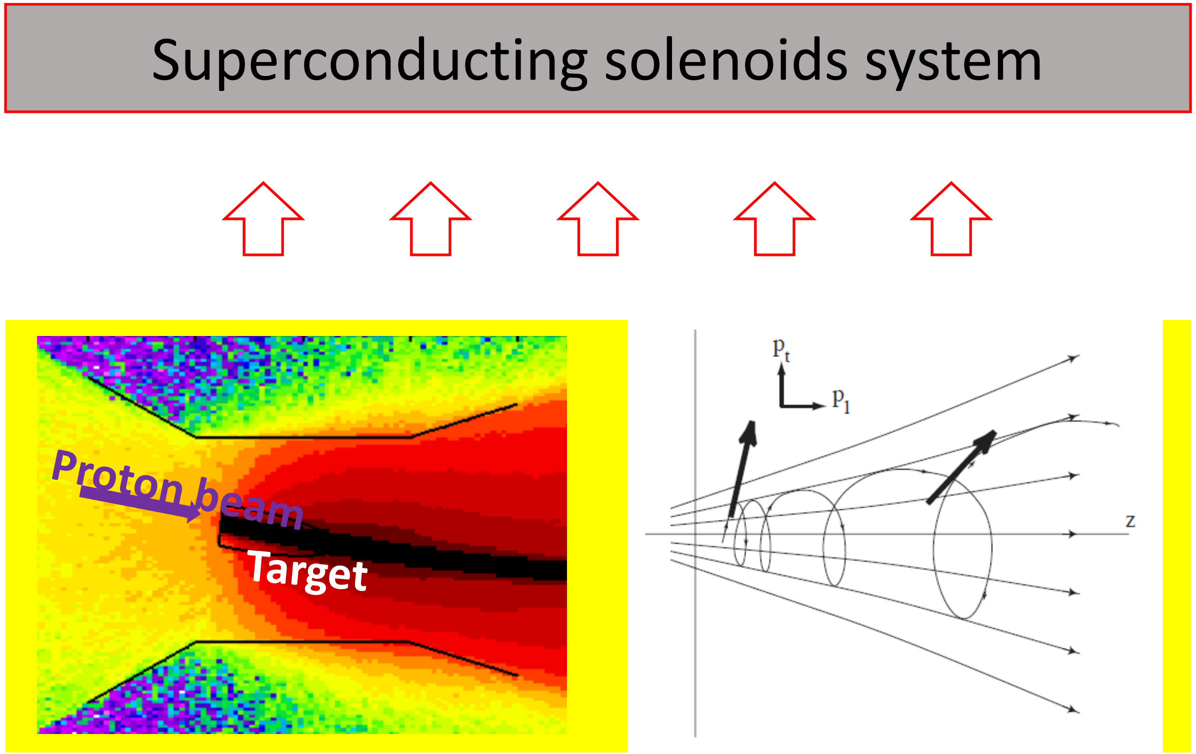
Introduction

Superconducting solenoids system



Huge number of secondary particles produced in the target

Introduction



Superconducting solenoids system

High radiation damage

High collection efficiency

Forward collection in high magnetic field

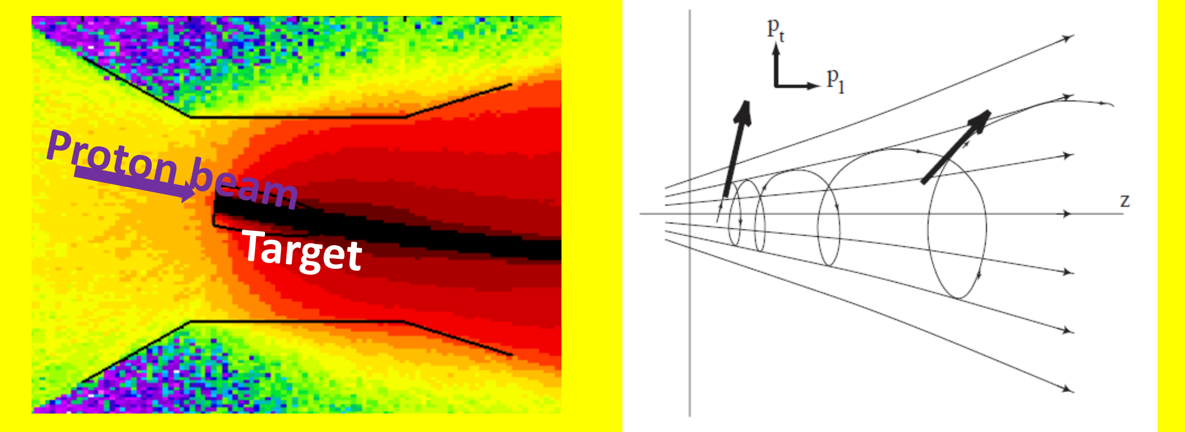
Introduction

Superconducting solenoids system

High radiation damage

Shielding system

Important and challenging!

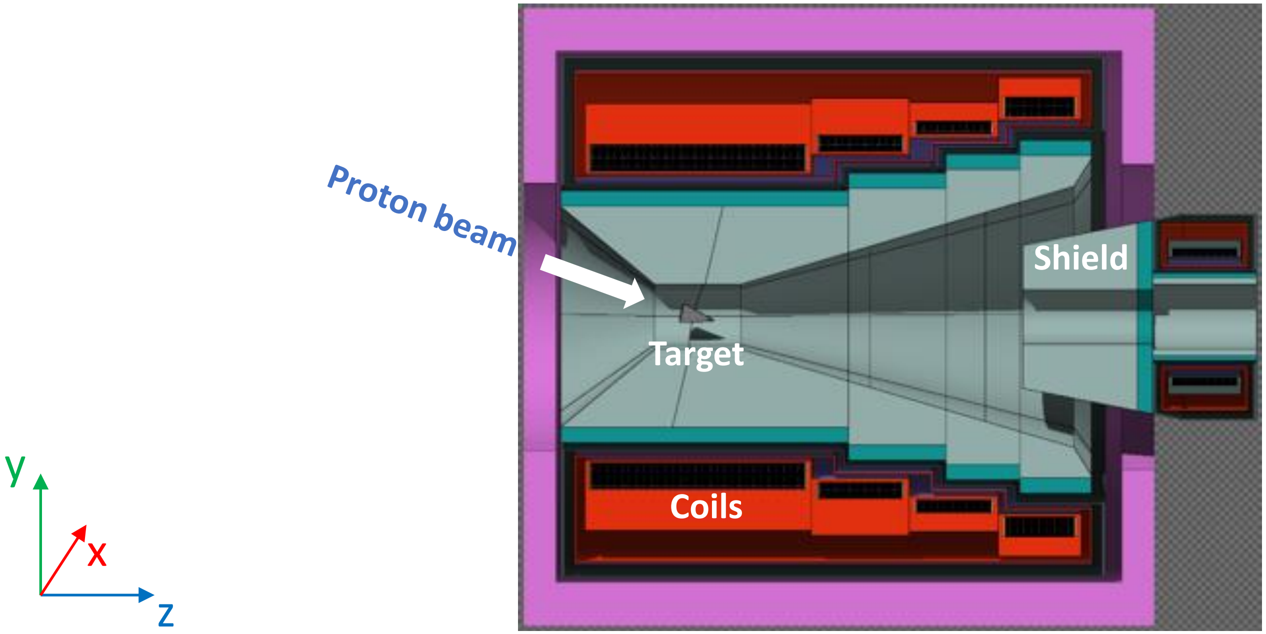


High collection efficiency

Need shields to protect the superconducting solenoids

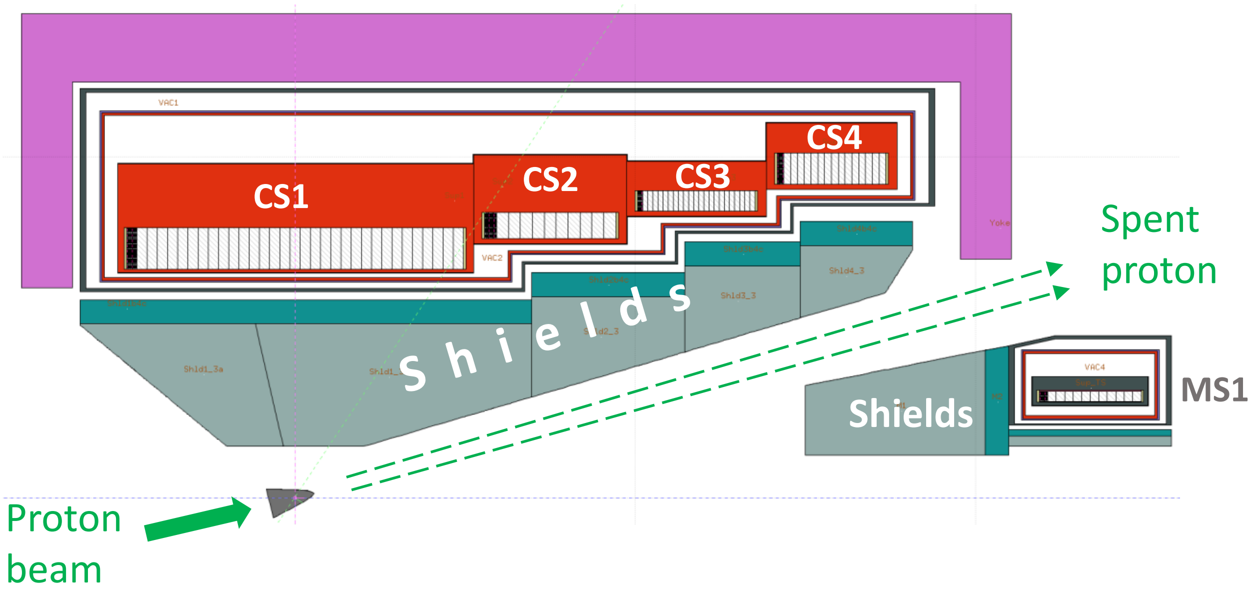
The target station

- 1.6 GeV, 25 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 irradiation



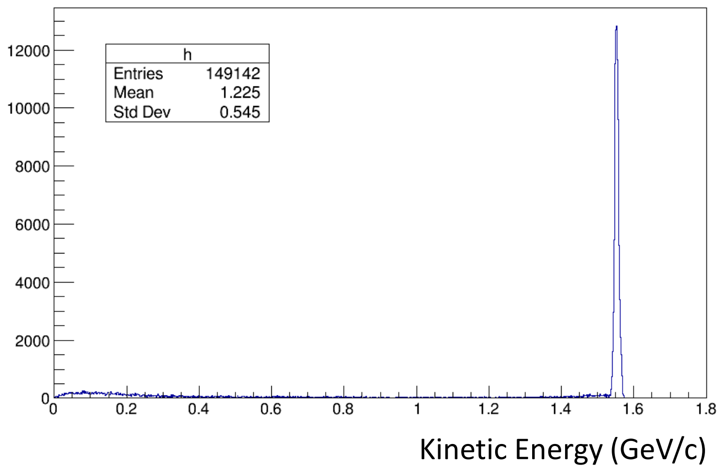
Shield design

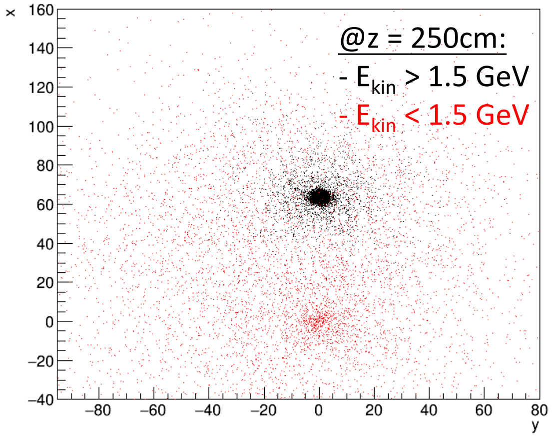
- **Shields are placed in between the beam and the solenoids in order to protect the cables from irradiation**
- **The design of the shields should consider**
  - Proton extraction
  - Radiation limit on the super conducting solenoids



Proton extraction

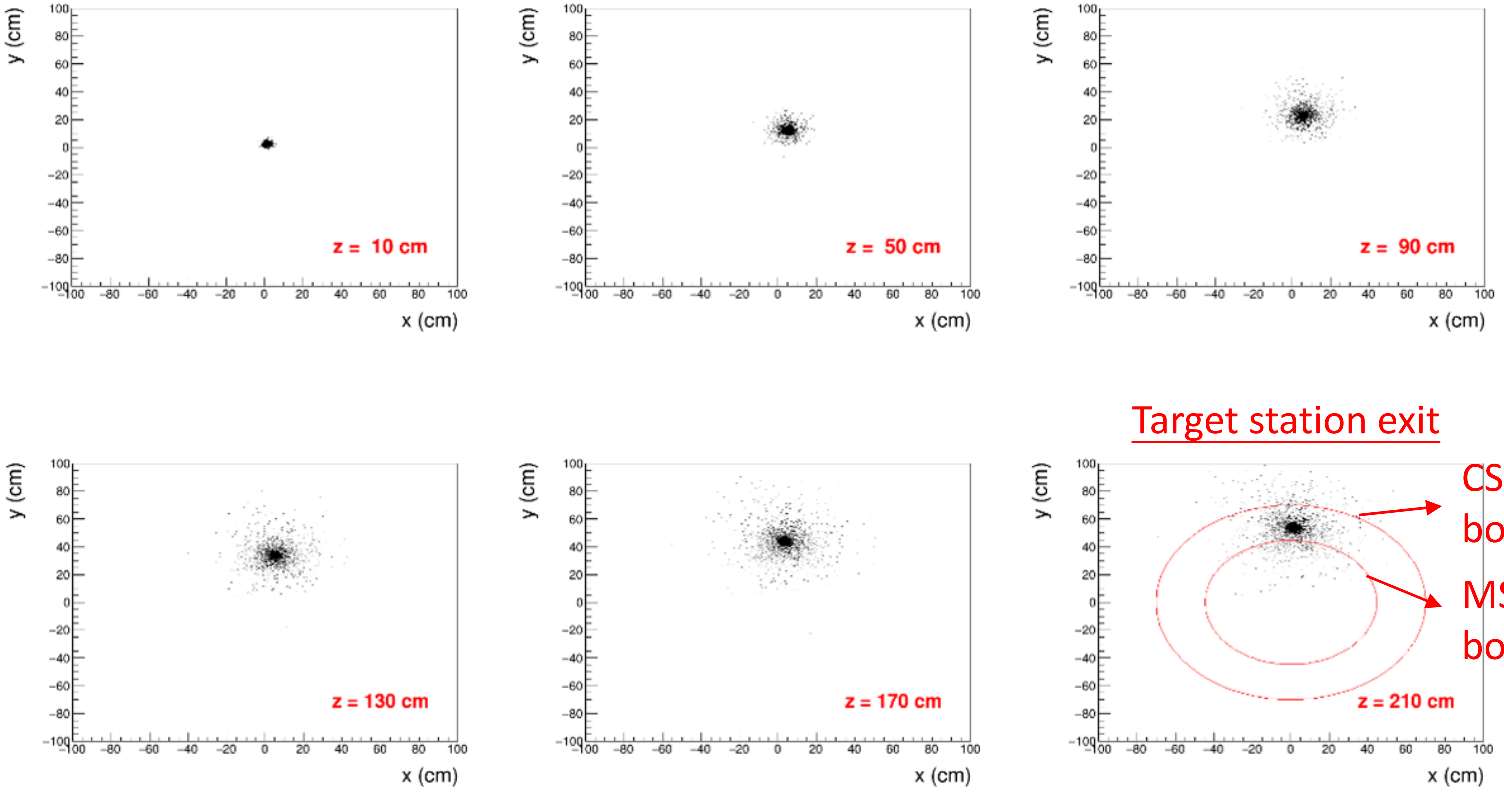
- **High momentum protons must be extracted out of the target station**
- **The high momentum proton trajectories constrain the overall layout**
- **Study the proton beam trajectories in strong magnetic field (5T/1T)**





Some low momentum protons are focused. As the high momentum protons deposit most, we only take them into account

Proton beam in (x, y) (5T field)

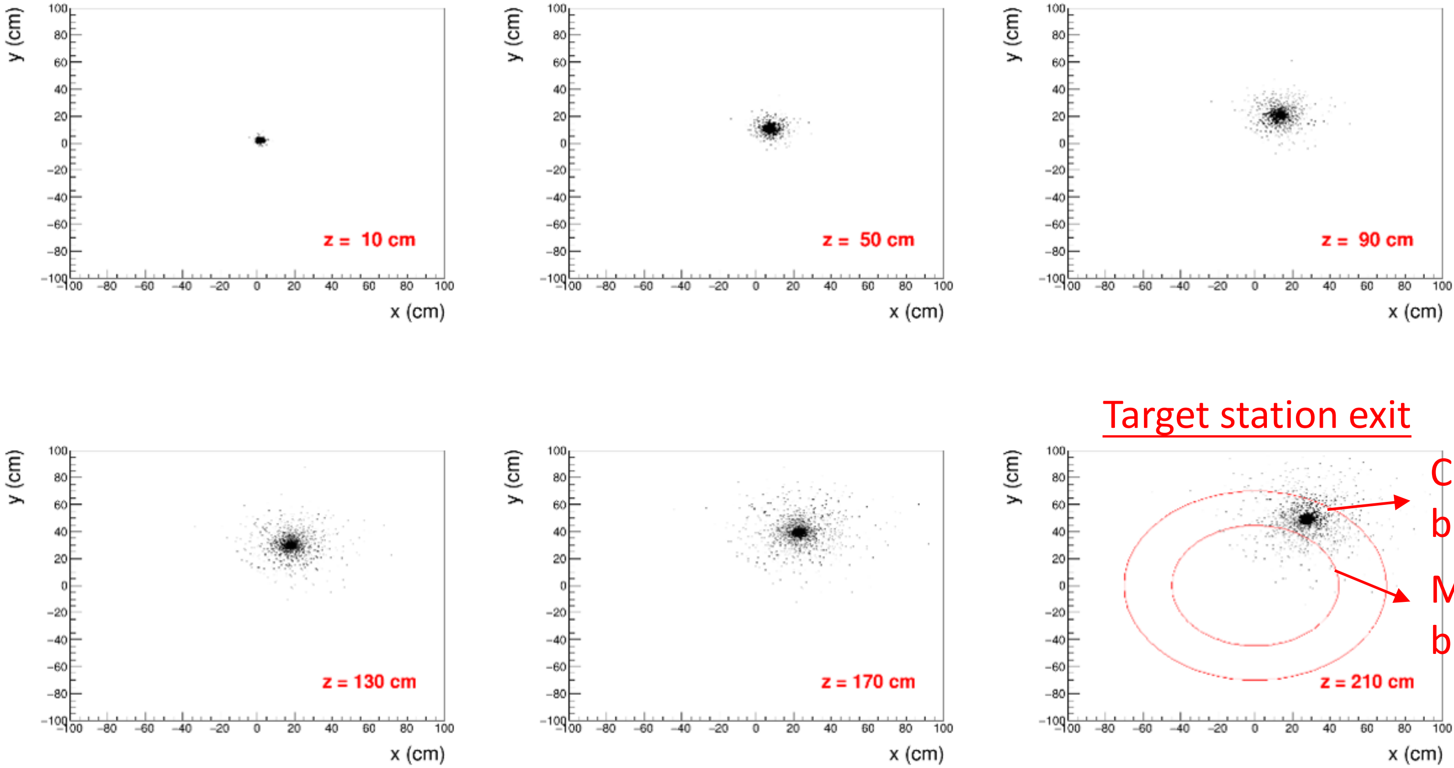


Target station exit

CS4 Shielding boundary

MS1 Shielding boundary

Proton beam in (x, y) (1T field)



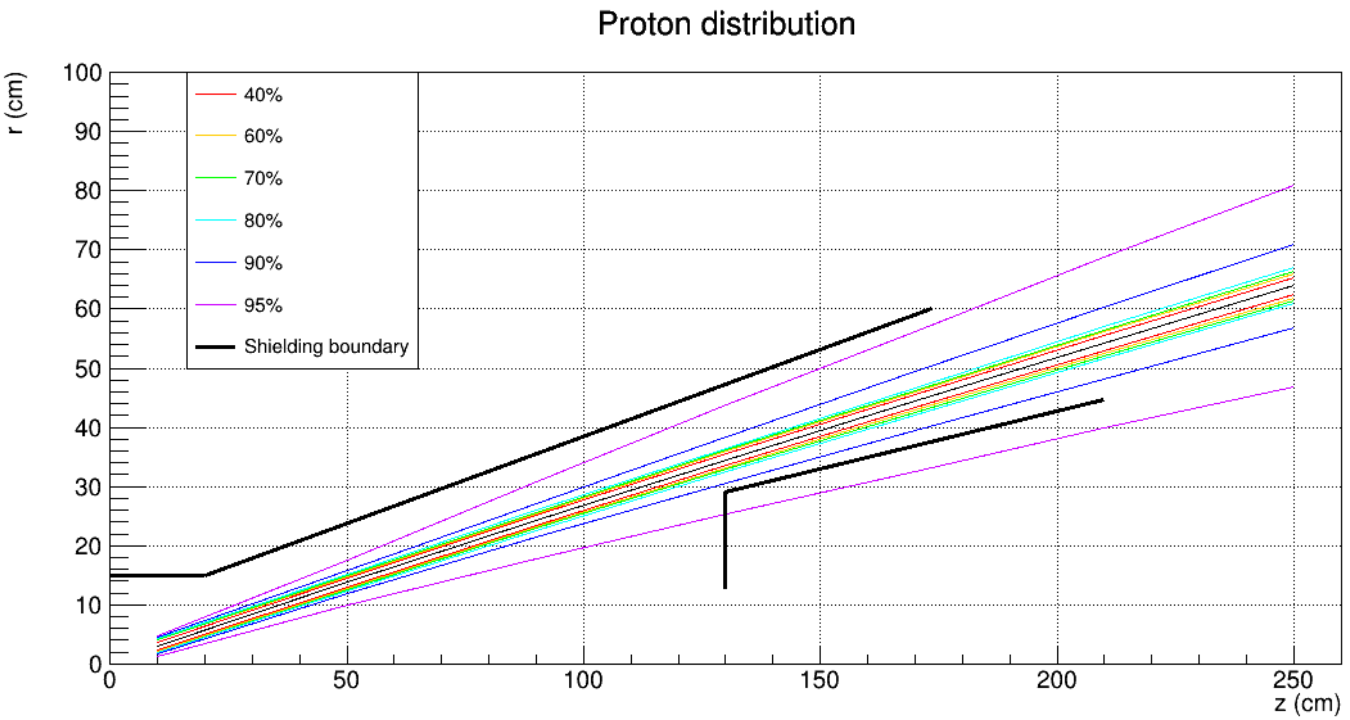
Target station exit

CS4 Shielding boundary

MS1 Shielding boundary

The exit positions of the beam for different fields locate in a "circle", which means the beam can be extracted by a ring-like gap

Proton distribution in (r, z)



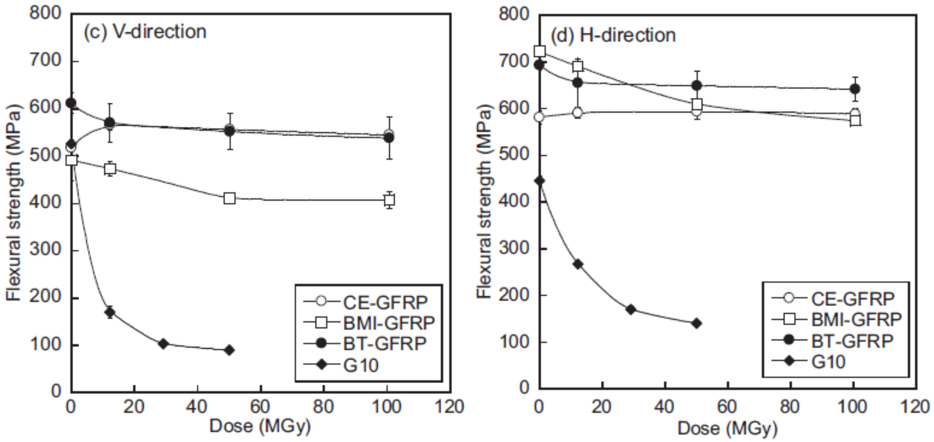
The proton beam’s radius almost increases linearly, so the inner shielding should be in cone-shape (current shields can extract > 90% of the beam)

Dose limit

- **The most restricted radiation limit is the maximum local radiation dose to the superconductor insulator over the lifetime of the experiment.**

- **According to ref[1], after 100 MGy irradiation, glass fiber reinforced plastics (GFRPs) retains more than 88% of its flexural strength.**

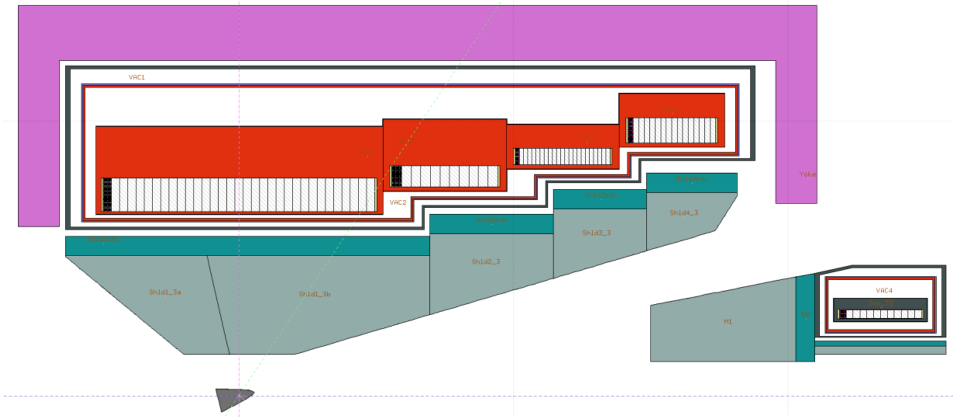
- **In our study, we conservatively use 30 MGy as the radiation limit for the insulator**



[1] Fusion Engineering and Design 112 (2016) 418–424

Shields optimization

- **The thickness and the position are optimized according to the peak dose on the superconducting solenoids**
- **Various of shielding materials are considered**
- **Final design:**



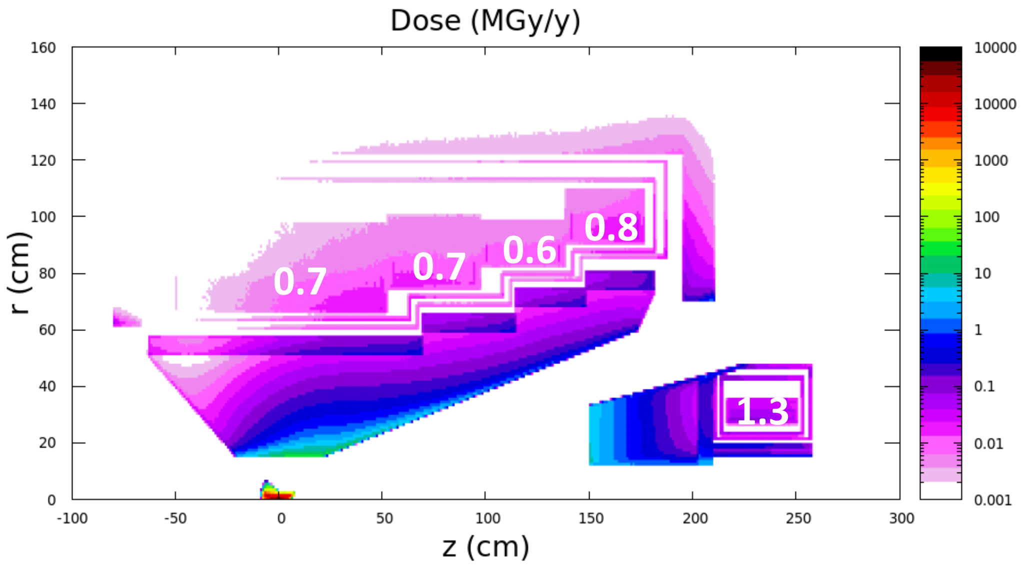
Capture Solenoid Coils	Length cm	Start Position cm	Max. Field T	Inner Radius cm	Inner W Shielding radius (min, max) cm	W shielding thickness (min, max) cm
CS1	100.35	-49.5	5	67	15	43
CS2	36.5	55.75	-	76	29.5, 42.7	36.5, 23.3
CS3	34.5	100.75	-	84	42.7, 52.7	32.3, 22.3
CS4	31.9	141.7	-	92	52.7, 60	28.3, 21
MS1	30.0	218.7	-	28	15	60

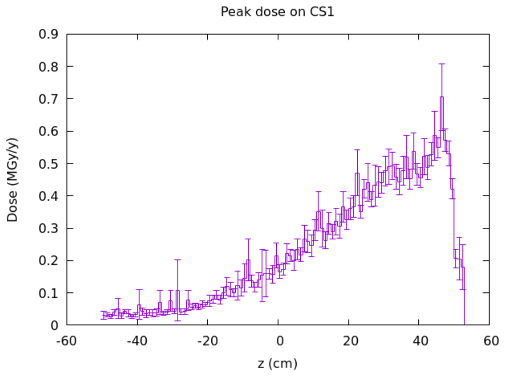
Key parameters:

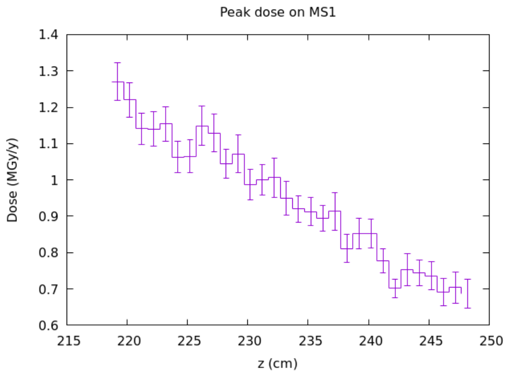
- ✓ CS1 shield thickness: 43 cm
- ✓ MS1 shield thickness: 60 cm
- ✓ MS1 shield position: 218.7 cm
- ✓ Material: W + B_4C (thickness: 7 cm (2 cm for inner MS))

See Nitin's report for optimization details

Dose distribution


Dose (MGy/y)


Peak dose on CS1


Peak dose on MS1

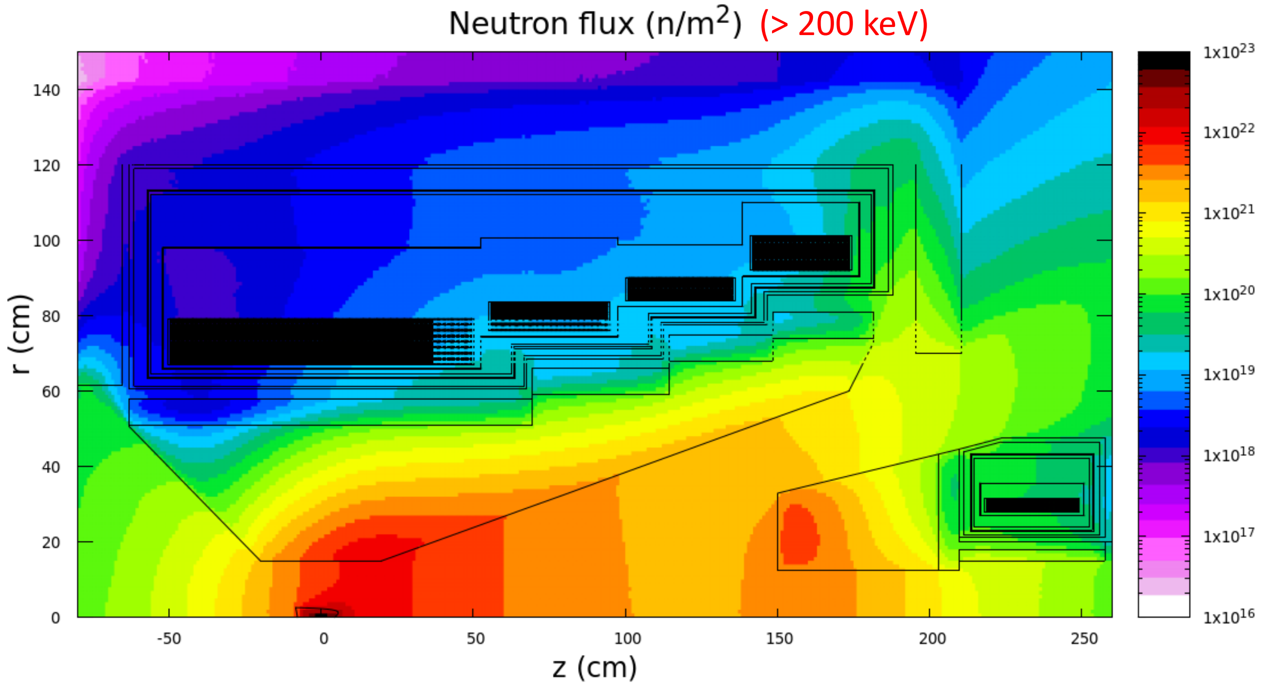
For 30 MGy limit,

- ✓ CS's can stand for more than 30 years
- ✓ MS can stand for about 23 years

Radiation damage calculation

- **RRR limit (conductor)**
  - 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 (solenoid)**
  - The operation temperature of the superconducting coils should below the critical value with a sufficient margin. *The limit is 6.2K for 5T magnetic field.*

Fast neutron flux distribution



- Peak fast neutron flux on solenoids is 4.5E20 n/m^2
- RRR of the solenoid conductor can be decreased by exploding in neutron irradiation

Neutron irradiation tests at Kyoto Univ. Research Reactor Institute

Al stabilizer sample

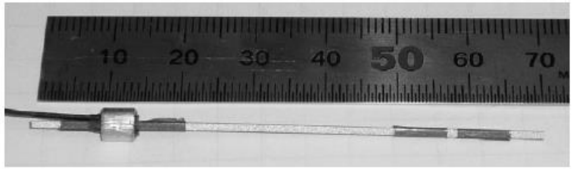
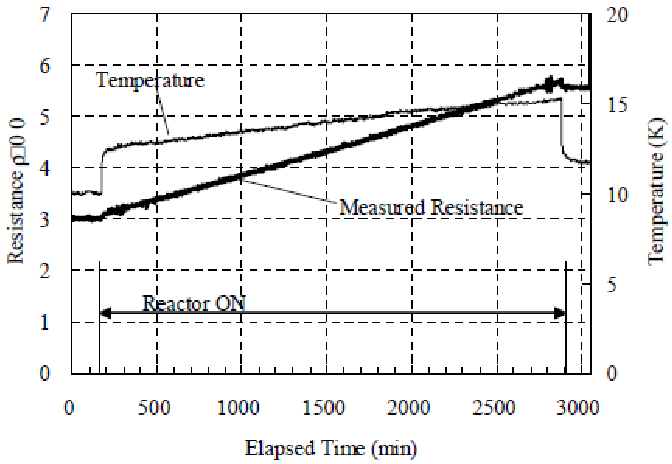


FIGURE 2. The aluminum sample cut from the aluminum stabilized superconductor attached with a voltage sense wire.

Al's electrical resistance in neutron irradiation environment



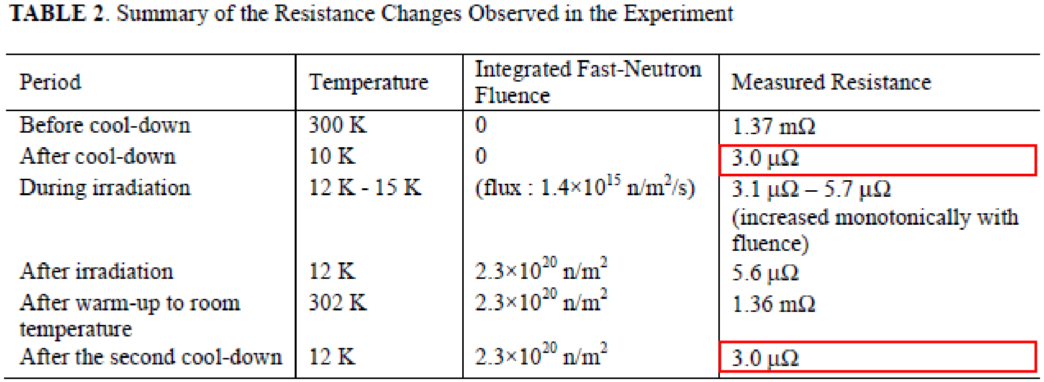


TABLE 2. Summary of the Resistance Changes Observed in the Experiment

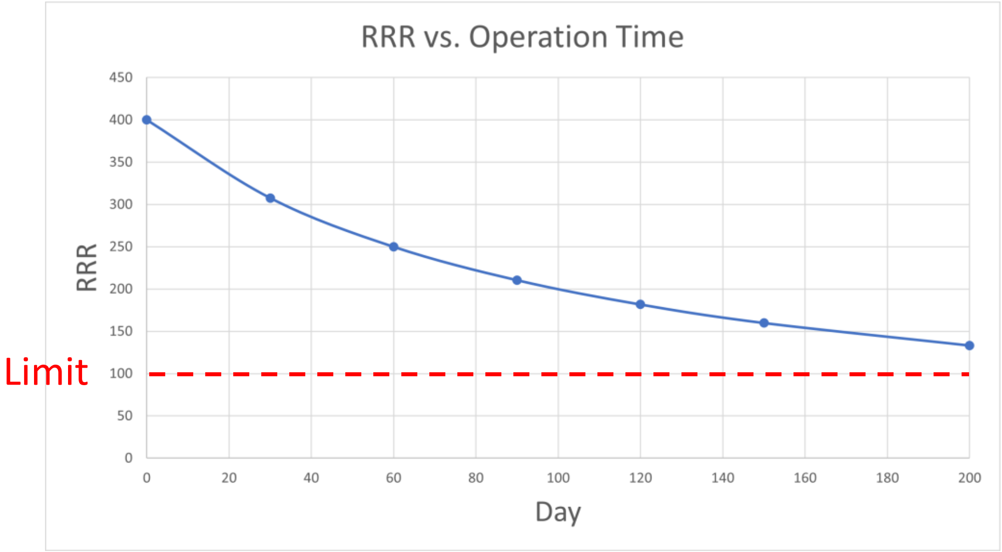
Period	Temperature	Integrated Fast-Neutron Fluence	Measured Resistance
Before cool-down	300 K	0	1.37 mΩ
After cool-down	10 K	0	3.0 μΩ
During irradiation	12 K - 15 K	(flux : 1.4×10^{15} n/m^2/s)	3.1 μΩ – 5.7 μΩ (increased monotonically with fluence)
After irradiation	12 K	2.3×10^{20} n/m^2	5.6 μΩ
After warm-up to room temperature	302 K	2.3×10^{20} n/m^2	1.36 mΩ
After the second cool-down	12 K	2.3×10^{20} n/m^2	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

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

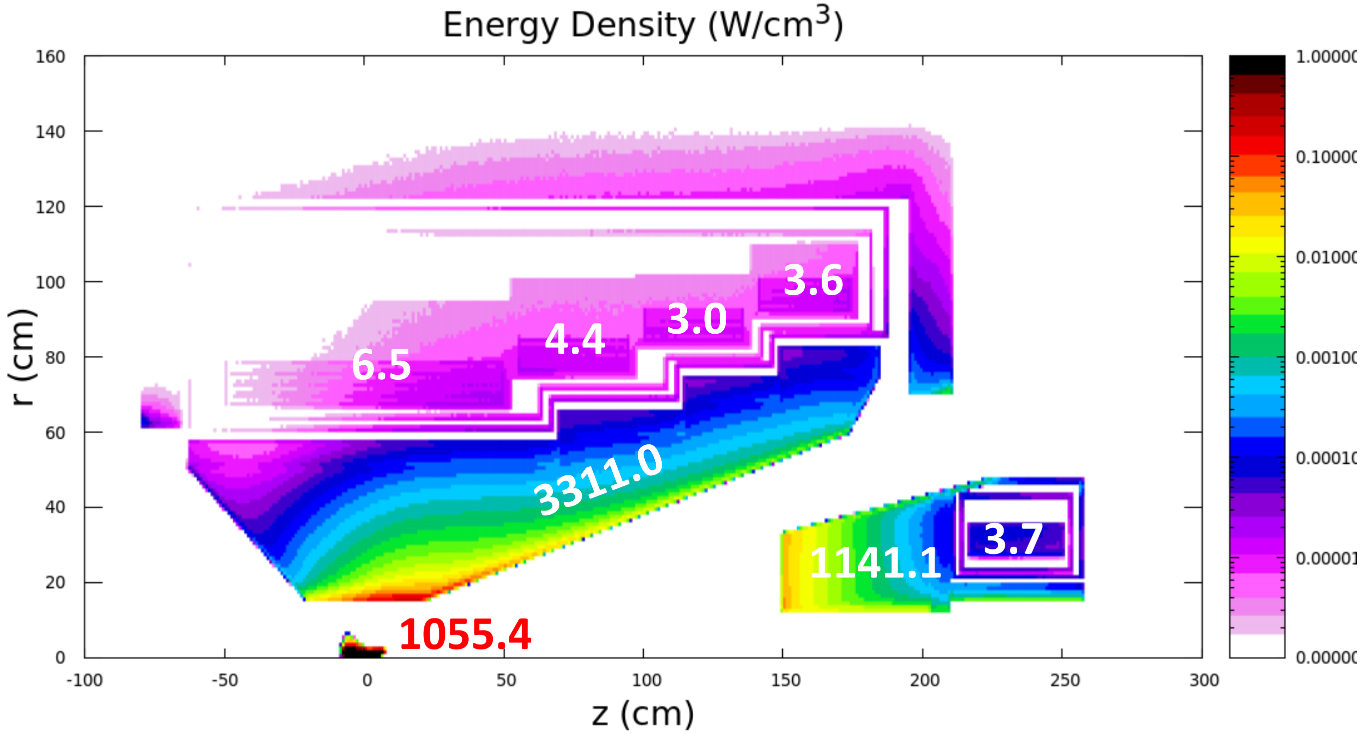
RRR estimation for Al stabilizer

- **Effective RRR is calculated by** $RRR = \frac{\rho_{RT}}{\rho(t)} = \frac{\rho_{RT}}{\rho_0 + r \times \Phi(t)}$
- **Input the following parameters to the formula**
  - Neutron induced resistance: $r = 0.03\ n\Omega \cdot m$ for 10^{20} n/m^2 (last page)
  - Initial RRR: 400 ($\rho_{RT} = 2.7 \times 10^{-8} \Omega, \rho_0 = 6.75 \times 10^{-11} \Omega$)



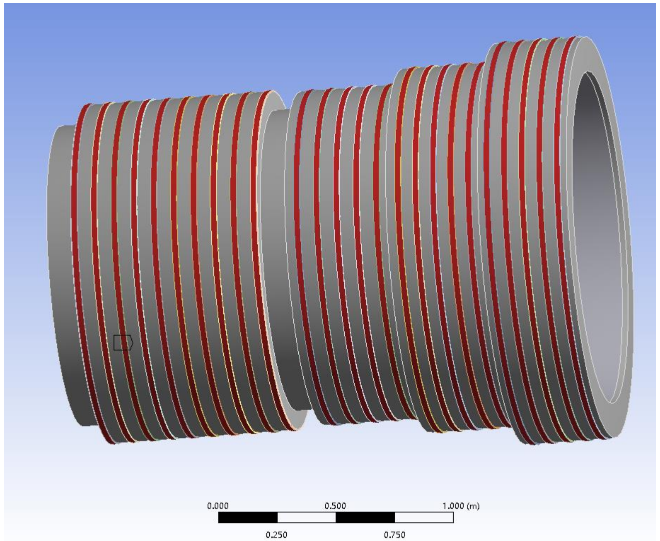
- ✓ The solenoid-system can run for a whole accelerator year.
- ✓ The RRR can be 100% recovered by warming up the system to room temperature.

Energy deposition distribution



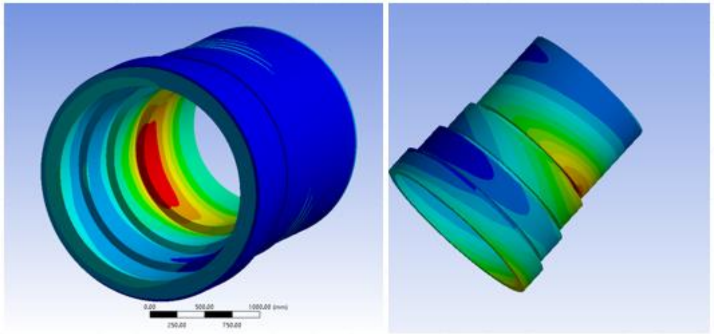
Total power deposition: 5.6 kW out of 25 kW

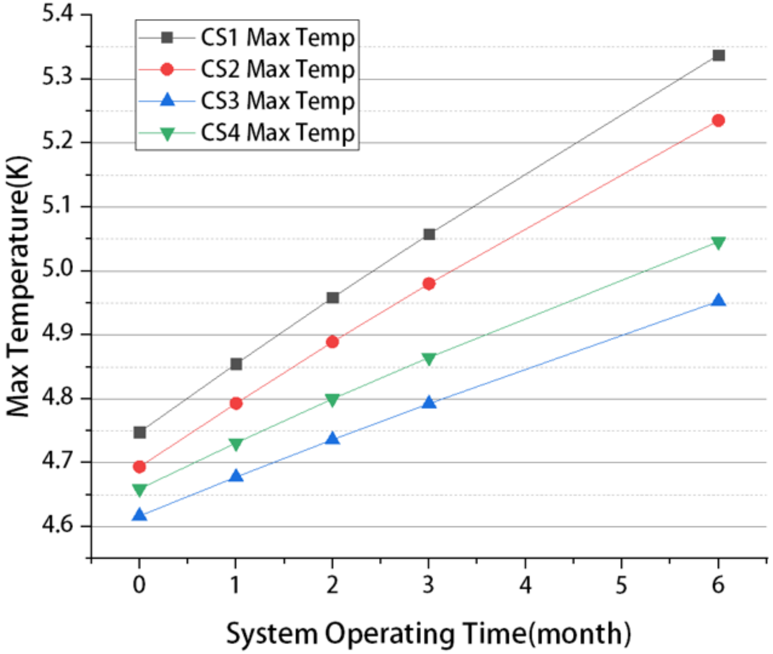
Thermal analysis



Cooling pipe number: 10-5-5-5
No Al thermal bridge

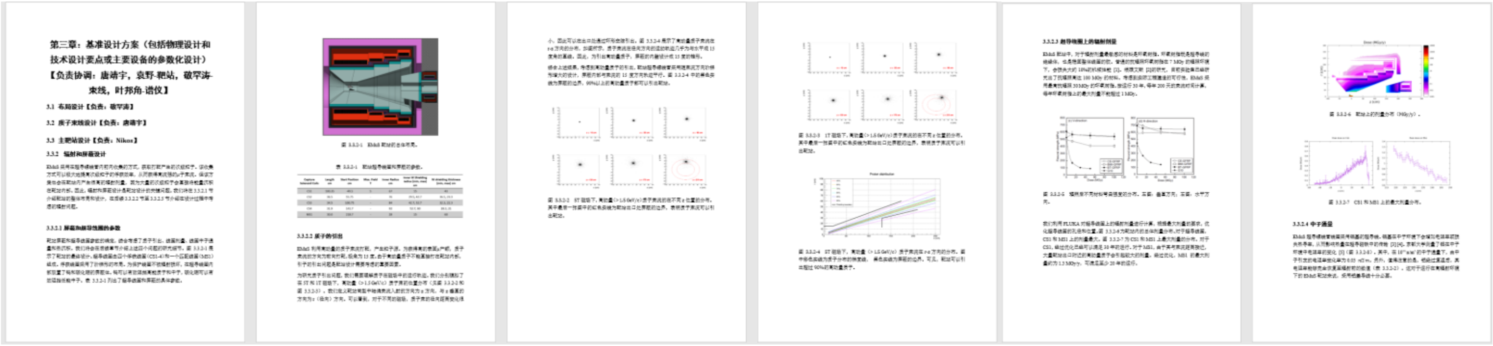
The temperatures are all below the 6.2 K limit after 6-month operation. (See Zongtai's report for details, and also for the quench analysis)





Summary

- **A detail radiation study has been carried out**
    - W+ B_4C shields are designed for the superconducting solenoid protection considering:
        - Proton extraction: can extract in both 5T/1T fields
        - Dose on coils: 30-year for CS, 23-year for MS
    - Radiation damage is estimated
        - RRR of conductor: can run for a whole accelerator year
        - Temperature: can run for at least 6 months
- **TDR is almost ready**



第三章：基准设计方案（包括物理设计和技术设计要点或主要设备的参数化设计）【负责协调：唐靖宇，袁野-靶站，敬罕涛-束线，叶邦角-谱仪】

3.1 布局设计【负责：敬罕涛】

3.2 质子束线设计【负责：唐靖宇】

3.3 主靶站设计【负责：Nikos】

3.3.2 辐射和屏蔽设计

3.3.2.1 屏蔽和超导线圈的参数