2020 EMuS & MOMENT General Meeting

EMuS Capture Solenoids

Thermal Analysis & Quench Protection

Accelerator Division, IHEP
Superconducting Magnet Group

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2020.12.11- CSNS

Contents

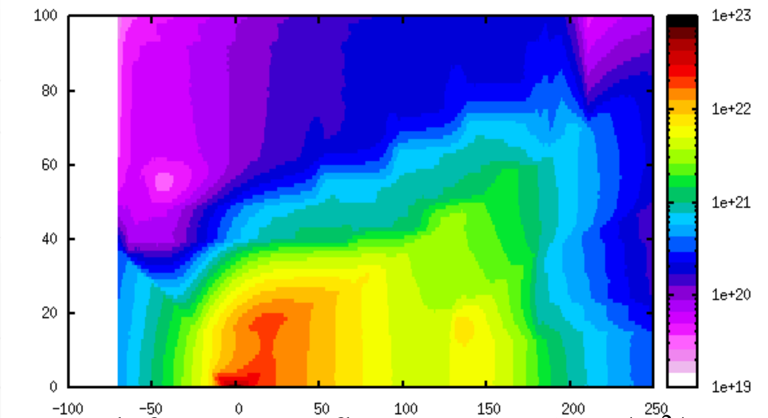
1. Magnet Characteristics

- Radiation Environment
- Degradation of Magnet Materials
- Magnet Structure

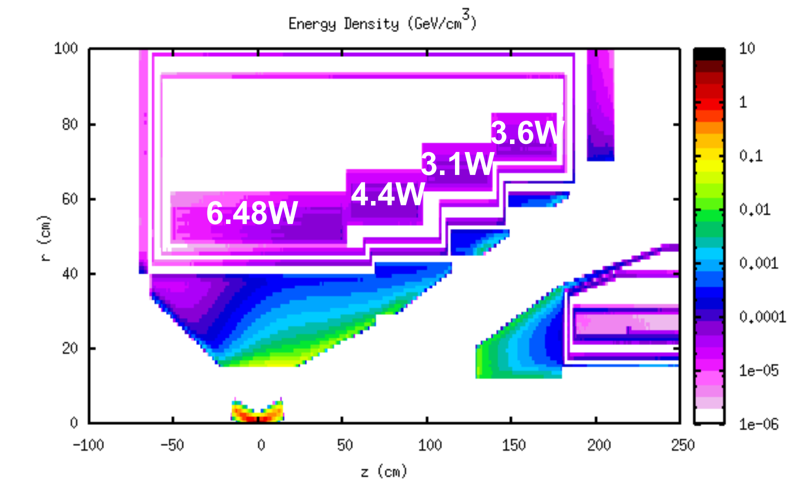
Radiation Environment

Continuous Irradiation → Magnet Structural Materials → Energy Deposition → Non-uniform Internal Heat Generation on Coil (over 6W for CS1)

Neutron Flux → Aluminum & Copper → Degradation of RRR → a). Thermal conductivity↓ b). Resistivity↑



Peak fast neutron fluence ~ 4.5E20 N/m^2/y

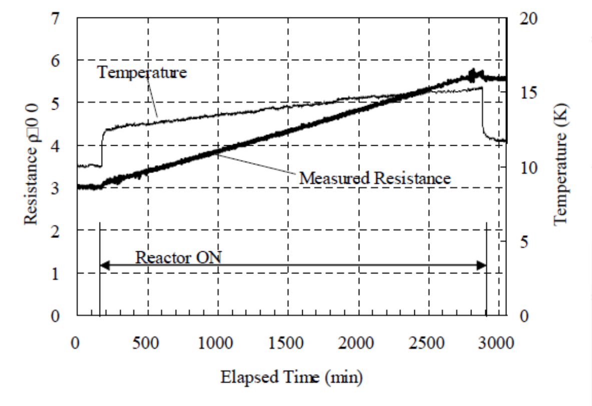


- Energy Deposition over 6W （CS1 for example）
- Degradation of RRR （Remaining 40% for 150days）

Degradation of Magnet Materials

COMET Research:

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



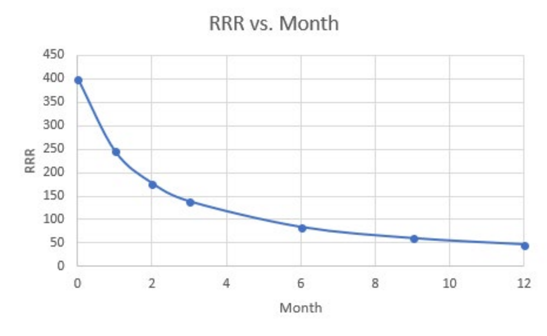
Degradation of:

- Thermal Conductivity↓
- Electrical Conductivity↓

$$RRR = \frac{\rho_{RT}}{\rho_0 + r \times \Phi_n \times t_{op}}$$

Assume neutron induced resistance: $r = 0.03\ n\Omega \cdot m$ for 10^{20} n/m^2 [1]

Operation time(days)	0	30	60	90	120	150	200
Neutron Fluence(N/m^2)	0	6.75E19	1.35E20	2.03E00	2.70E20	3.38E20	4.50E20
RRR	400	308	250	211	182	160	133
RRR Residual Coeff(%)	100%	77%	62.5%	52.75%	45.5%	40%	33.25%

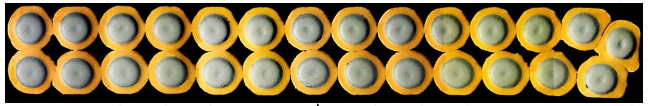


Wiedemann-Franz Law:

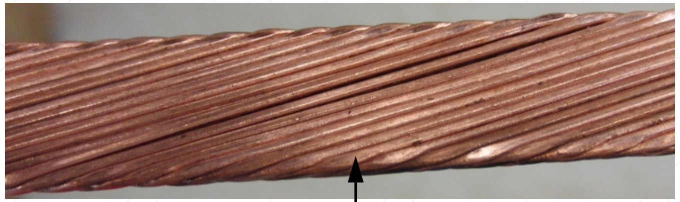
$$\lambda \cdot \rho = L \cdot T$$

References: M. Yoshida et al., "Low-temperature neutron irradiation tests of superconducting magnet materials using reactor neutrons at KUR," in Proc. AIP Conf., 2011, vol. 1435, pp. 167–173.

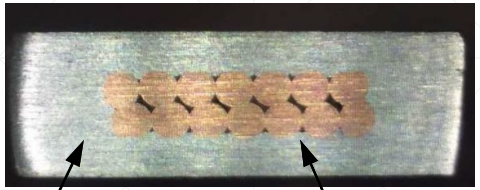
Magnet Structure



Cross section of Rutherford cable

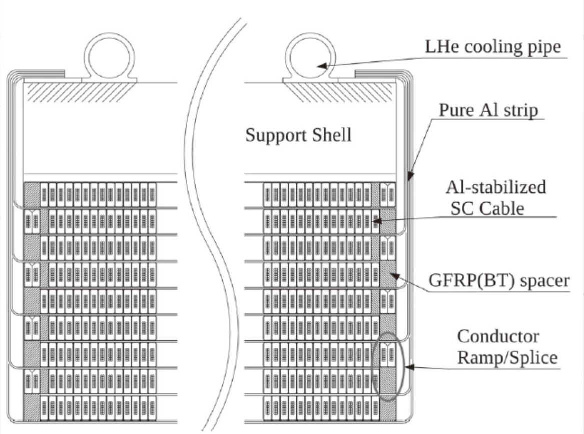


Rutherford cable

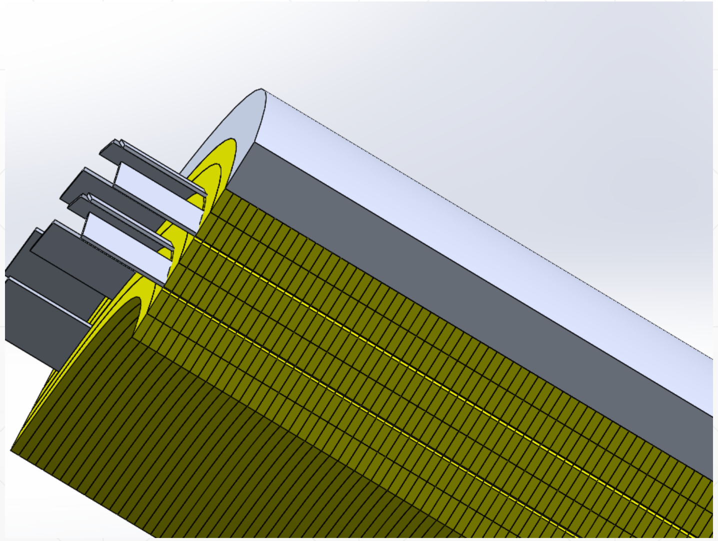


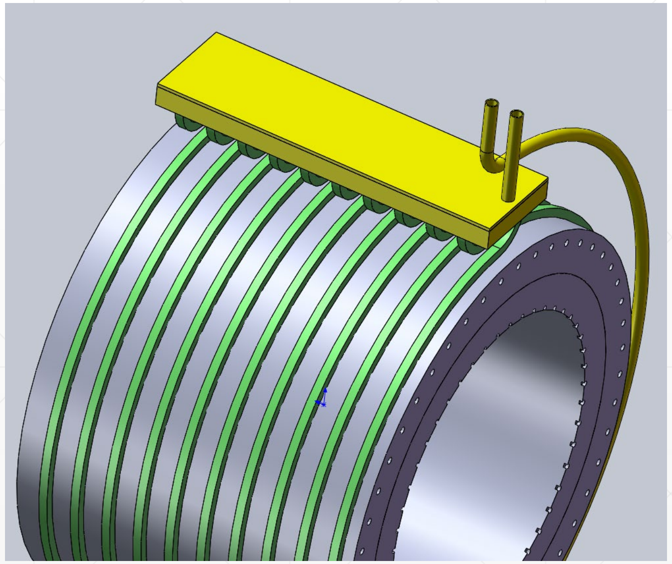
Aluminum Stabilizer

Rutherford cable



Pure Aluminum strip





Thermosiphon Cooling Piping

2. Thermal Analysis

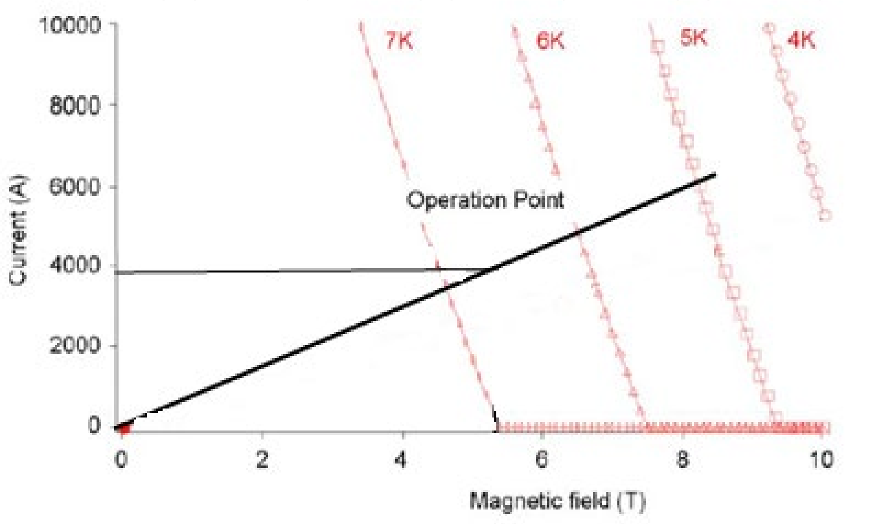
- Beam Operation Time
- LHe Piping & Insulation
- Pure Aluminum Strip

Beam Operation Time

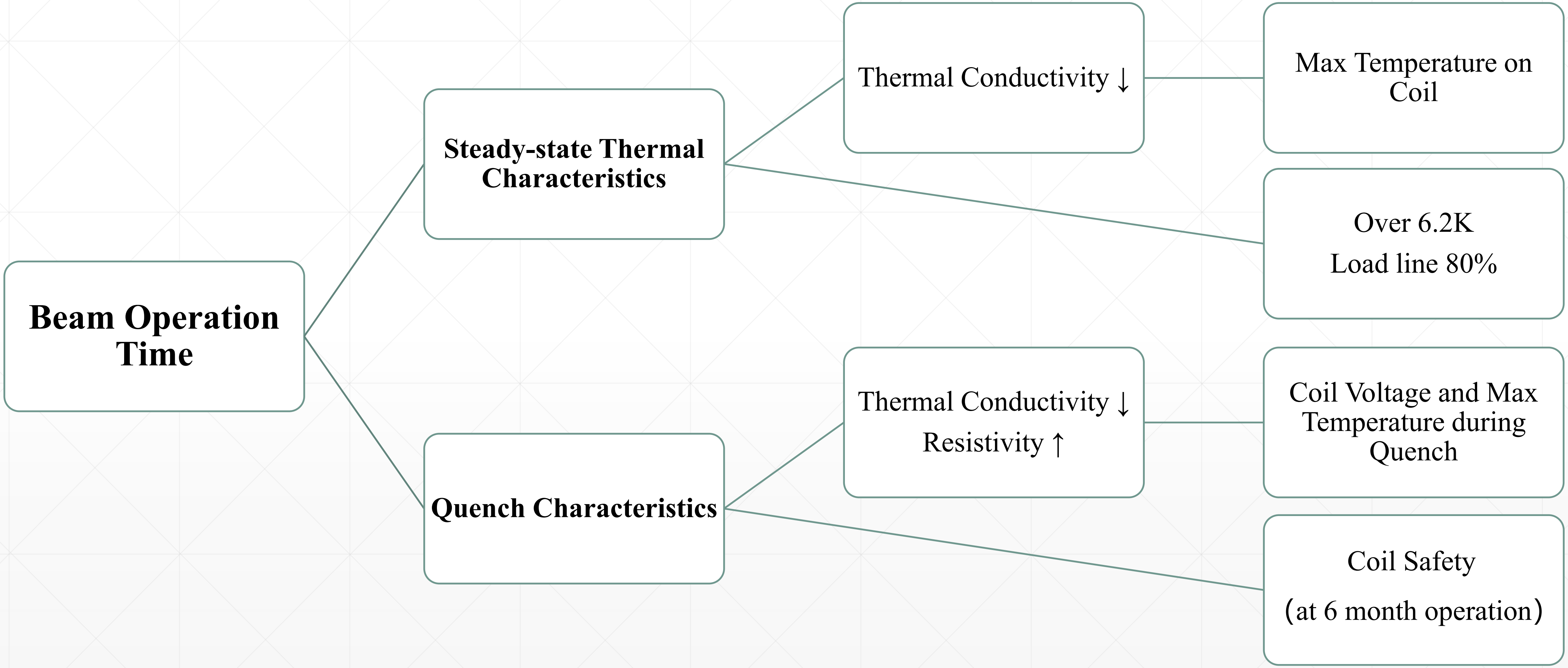
- **Current capacity of Magnet Cable**
  - Ic of strand@5.5 K ,5.5 T = 570 A
  - Ic of cable @5.5 K ,5.5 T = 570 *16* 85% = 7752 A （16 strand）
  - Iop = Jcoil*2l*（a2-a1）/N = 3255A （l：half height of coil，a1、a2：radius of coil）
  - Iop/Ic = 3255 A/ 7752 = 41.9%（16 strand）

0day	150days	Over 200days
RRR: No degradation	RRR: remaining 40%	RRR: remaining 20%
5.0T mode (decay muon)	1.0T mode (surface muon)	Recovery

- With continuous operation, the **Temperature** of the magnet will **Gradually Increase** due to the decrease of the thermal conductivity of the material.

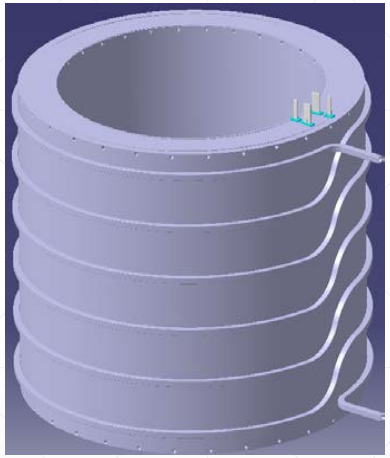


Beam Operation Time

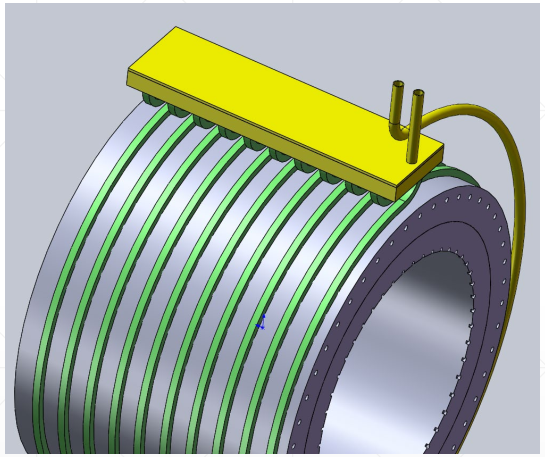


LHe Piping & Insulation

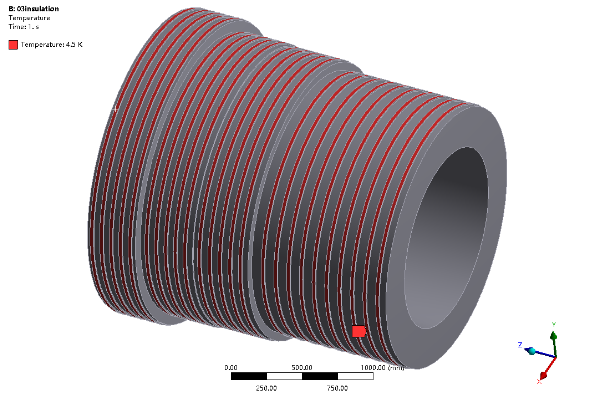
Two-phase Helium Flow



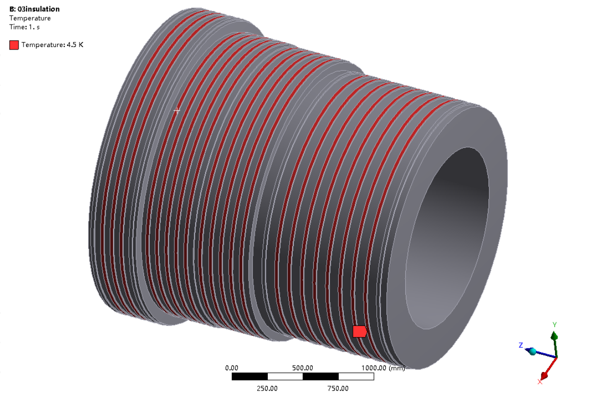
~~Forced-flow Piping~~



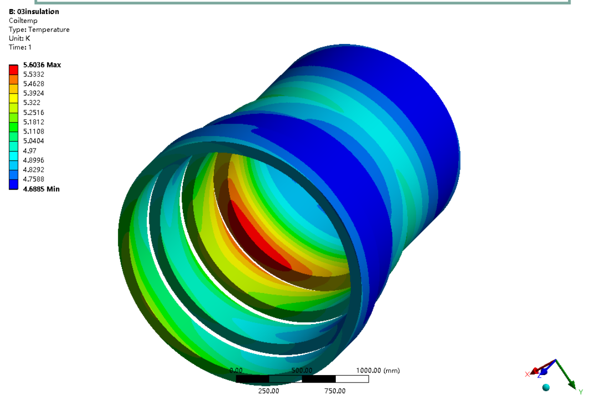
Thermosiphon Piping



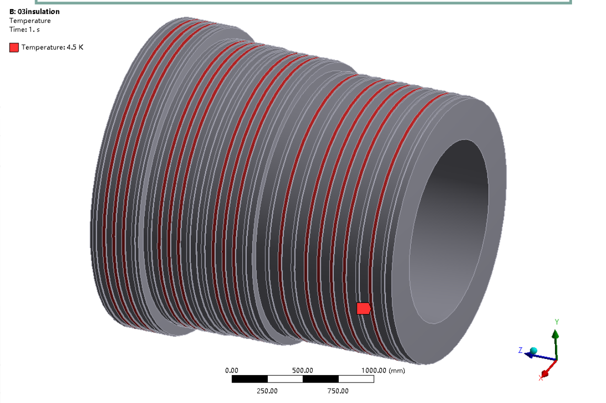
10-5-5-5 Piping



8-5-5-3 Piping



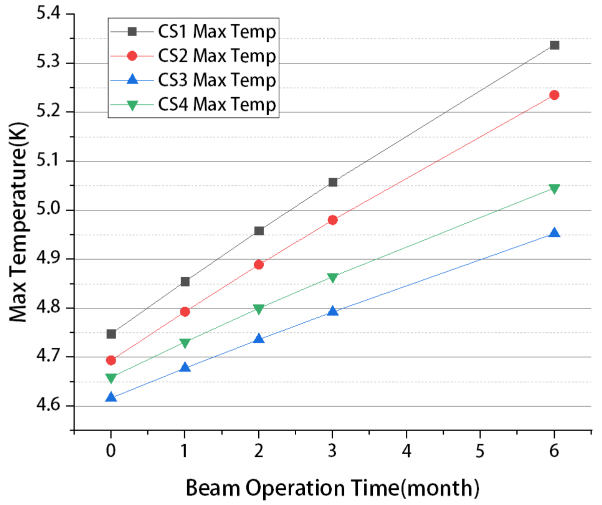
FEM Coil Temperature

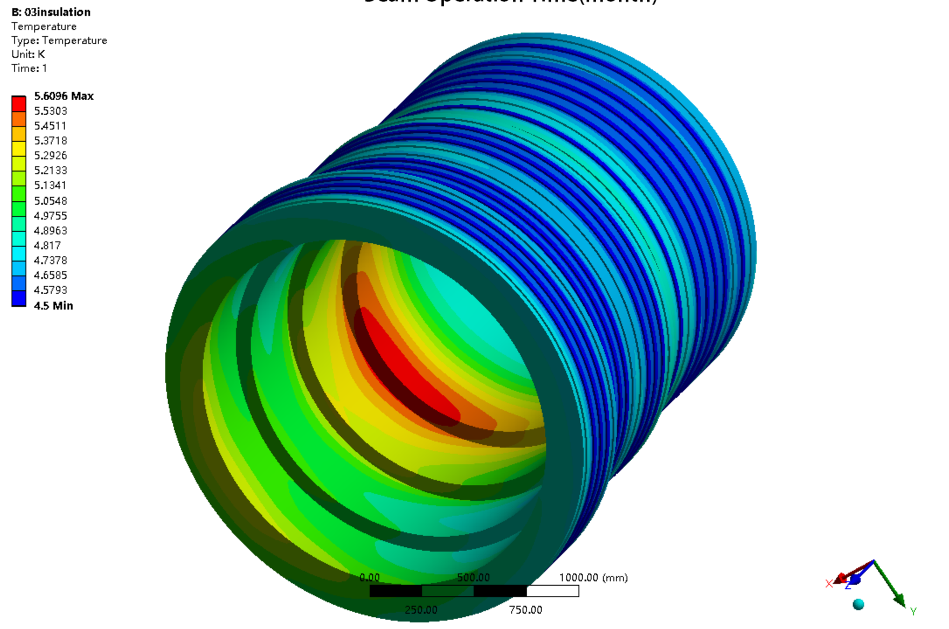


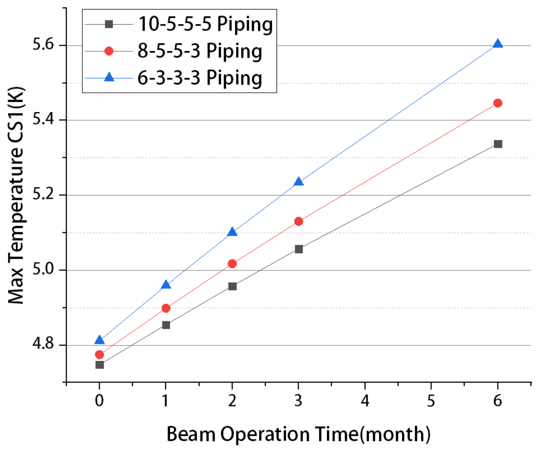
5-3-3-3 Piping

LHe Piping & Insulation

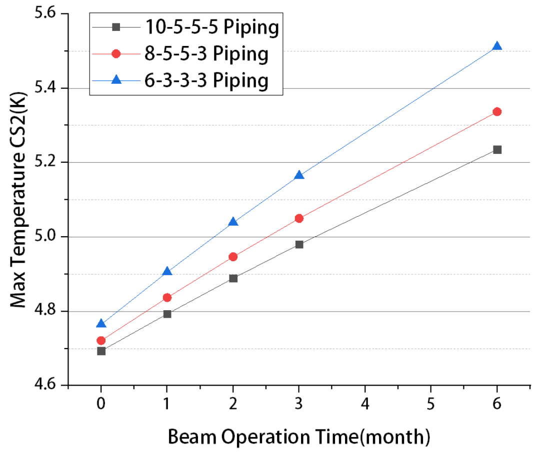
FEM Coil Temperature



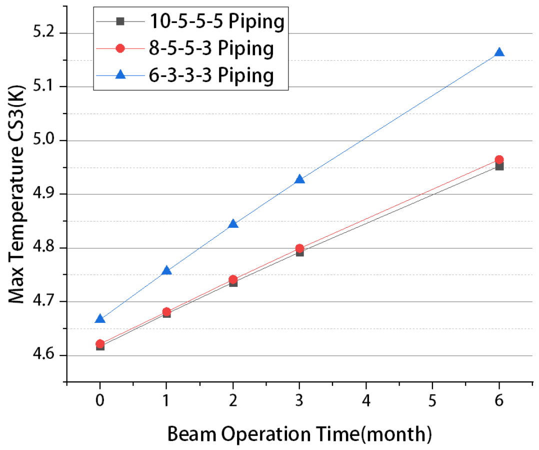




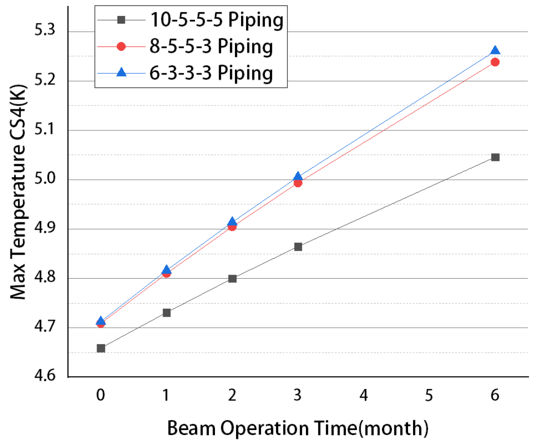
CS1



CS2



CS3

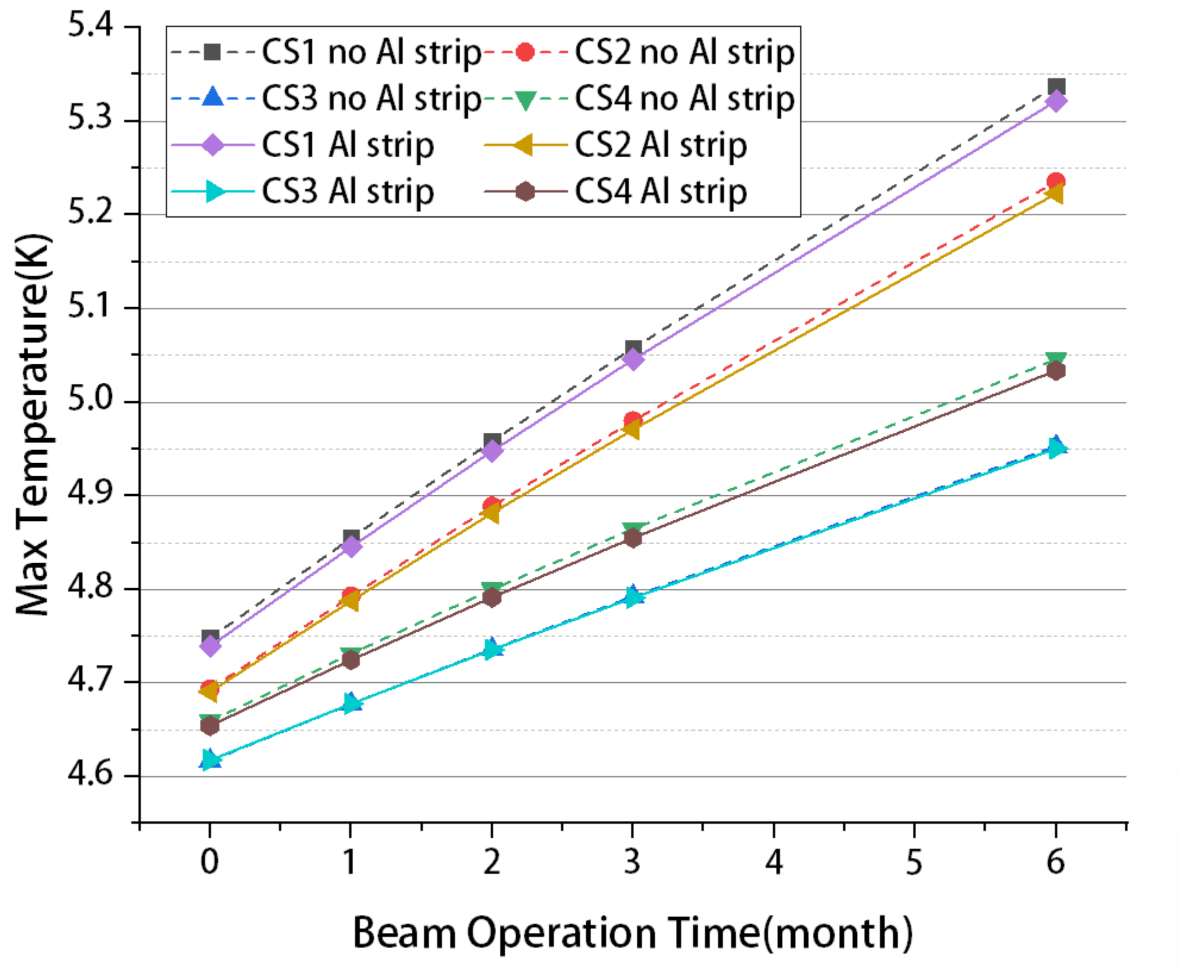


CS4

Pure Aluminum Strip (Also called: Quench Propagator)

Steady-state Thermal：

- Increase temperature margin



Quench Characteristics：

- Increase quench propagation speed
- Shorten the overall quench time

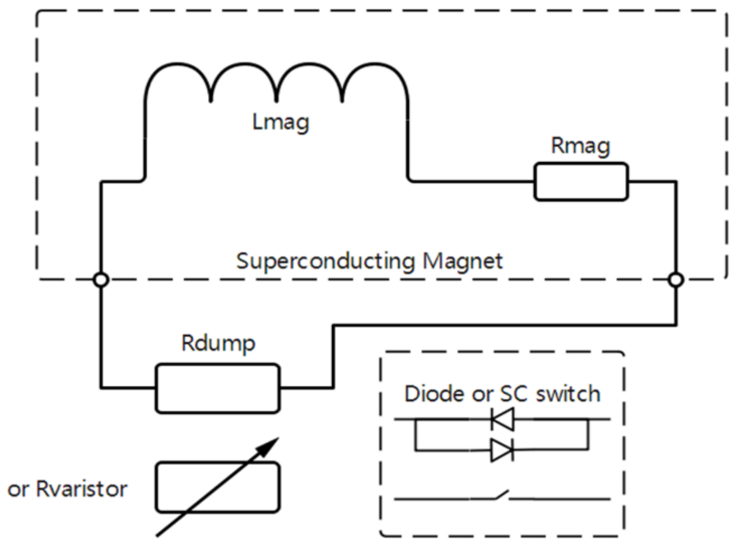
days	v_{cable}	τ_{cable}	v_{axial}	τ_{axial}	v_{thick}	τ_{thick}
0	1.547m/s	1481ms	0.209m/s	2259ms	0.359m/s	334ms
60	1.547m/s	1481ms	0.263m/s	1796ms	0.447m/s	268ms
120	1.547m/s	1481ms	0.307m/s	1539ms	0.516m/s	233ms
150	1.547m/s	1481ms	0.326m/s	1448ms	0.546m/s	219ms

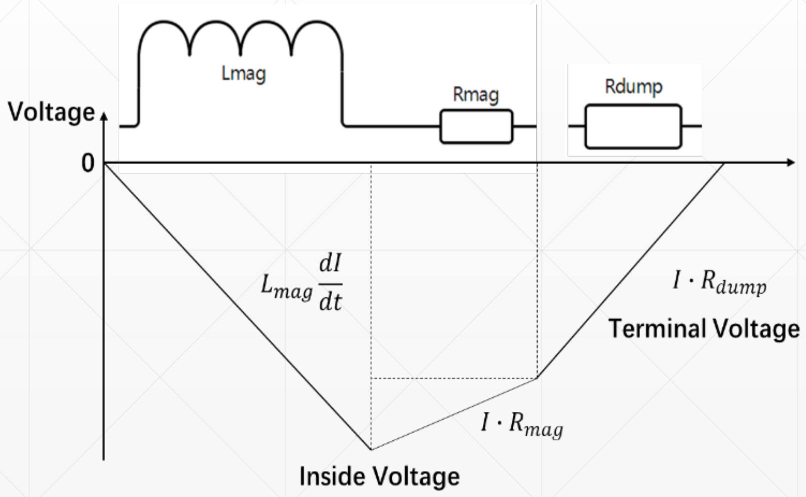
days	v_{cable}	τ_{cable}	v_{axial}	τ_{axial}	v_{thick}	τ_{thick}
0	1.547m/s	1481ms	0.289m/s	1629ms	0.359m/s	334ms
60	1.547m/s	1481ms	0.366m/s	1292ms	0.447m/s	268ms
120	1.547m/s	1481ms	0.427m/s	1105ms	0.516m/s	233ms
150	1.547m/s	1481ms	0.455m/s	1037ms	0.546m/s	219ms

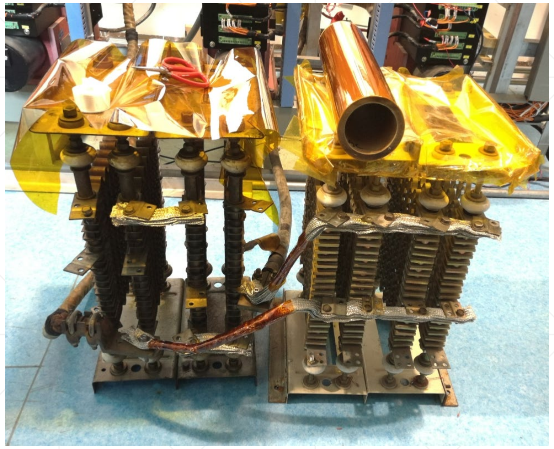
3. Quench Protection

- Dump Resistor & Varistor
- Analysis of Parameters
- Safety at 150days Operation

Dump Resistor & Varistor







Dump Resistor

R_{dump}

- Liner U-I
- Stainless-steel (Air or Water cooling)
- High reliability

Varistor

$R_{var} = KI_{t1}^{\beta-1}$

- Nonlinear U-I
- SiC or ZnO Assembly
- Fast current decay
- Lower temperature rise & MIITs

Dump Resistor & Varistor

25kW Baseline Design

Parameter	Value	Unit
Inductance	4.8	H
Current	3255	A
Storage Energy	25	MJ
Design Voltage	500	V

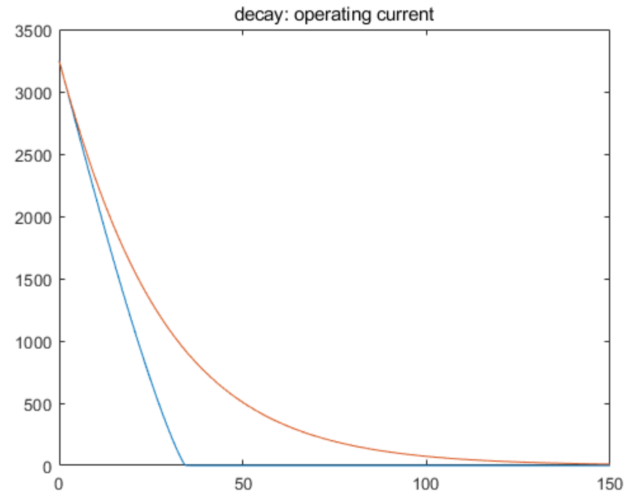
Dump resistor

Parameter	Value
Rdump	150mΩ
tdelay	100ms

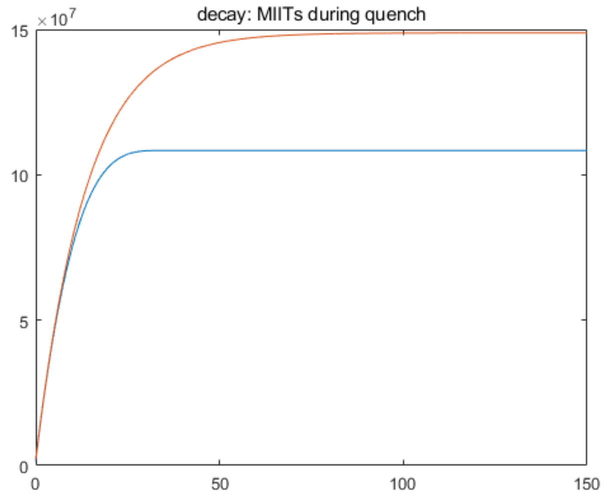
Varistor

Parameter	Value
K	160
β	0.14
tdelay	100ms

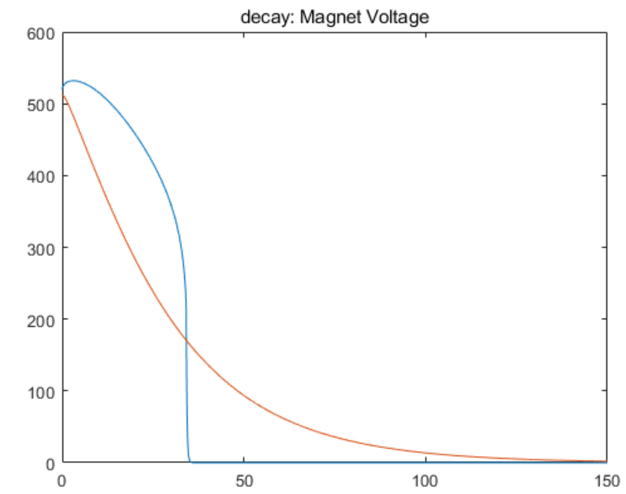
Red: Dump resistor & Blue: Varistor



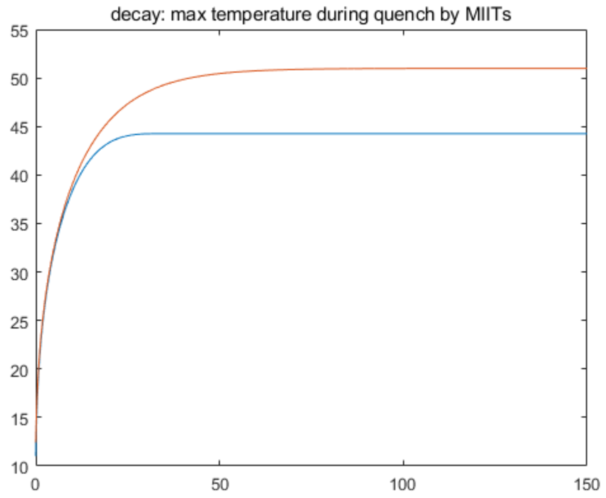
Current decay time



MIITs



Magnet Voltage



Temperature

Analysis of Parameters

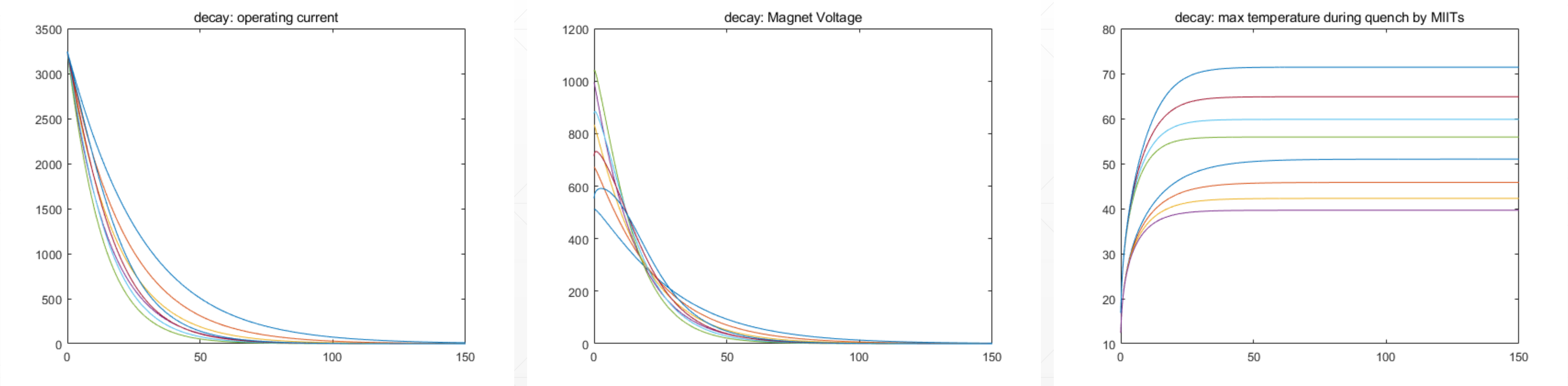
RRR Degradation

Rdump

tdelay=100ms

Dump resistor

Rdump(mΩ)	tdelay(ms)	Current decay time（s, 1% Iop）	Magnet Voltage（V）	Max Temperature rise（K）	Storage Energy Dumpling rate（%）
Beam Operation Time: 0day					
150mΩ	100ms	121.3s	511.51V	50.98K	87.15%
200mΩ		97.5s	672.17V	45.81K	91.18%
250mΩ		80.9s	833.32V	42.26K	93.42%
300mΩ		68.9s	994.14V	39.64K	94.81%
Beam Operation Time: 150days					
150mΩ	100ms	70.8s	591.14V	71.41K	62.59%
200mΩ		67.0s	731.94V	64.85K	72.09%
250mΩ		61.5s	884.64V	59.81K	78.40%
300mΩ		55.9s	1040.85V	55.89K	82.71%



Analysis of Parameters

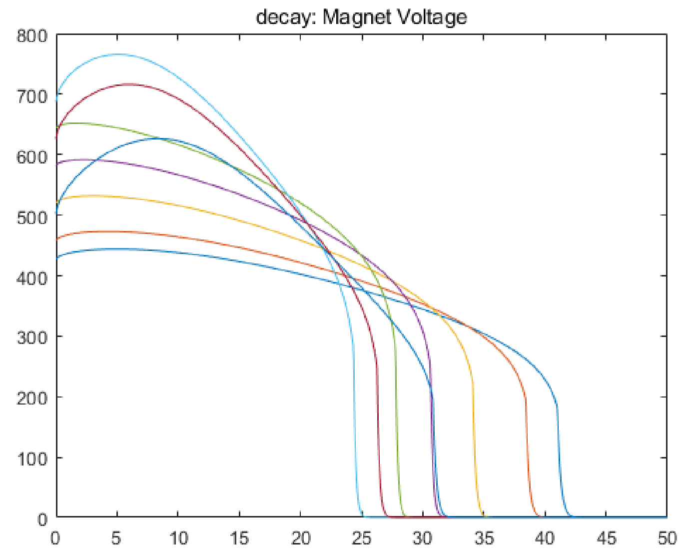
Varistor

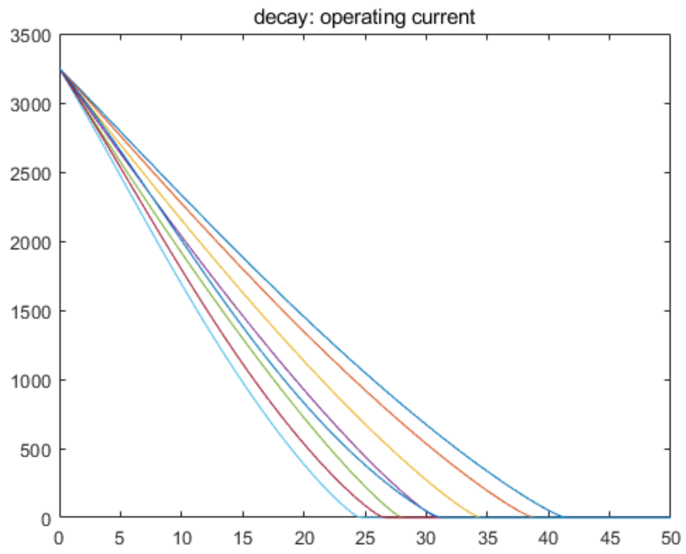
RRR Degradation

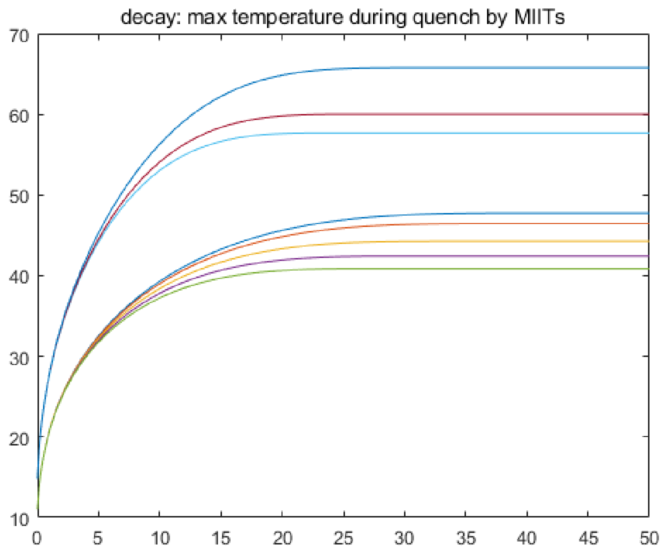
K, β

tdelay=100ms

K	β	Current decay time (s, 1% Iop)	Magnet Voltage (V)	Max Temperature rise (K)	Storage Energy Dumpling rate (%)
Beam Operation Time: 0day					
140	0.14	38.1s	473.01V	46.47K	90.86%
160		33.8s	532.03V	44.25K	92.39%
180		30.4s	591.77V	42.42K	93.54%
200		27.6s	652.01V	40.86K	94.44%
Beam Operation Time: 150days					
140	0.14	30.5s	626.44V	65.77K	70.79%
160		28.1s	669.32V	62.68K	74.92%
180		26.0s	716.15V	60.01K	78.22%
200		24.2s	765.91V	57.69K	80.90%







Safety at 150days Operation: Dump resistor Baseline

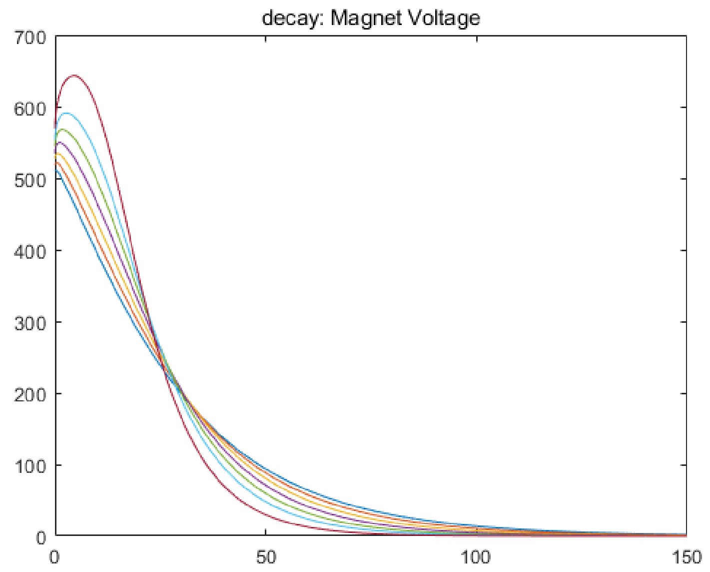
RRR Degradation

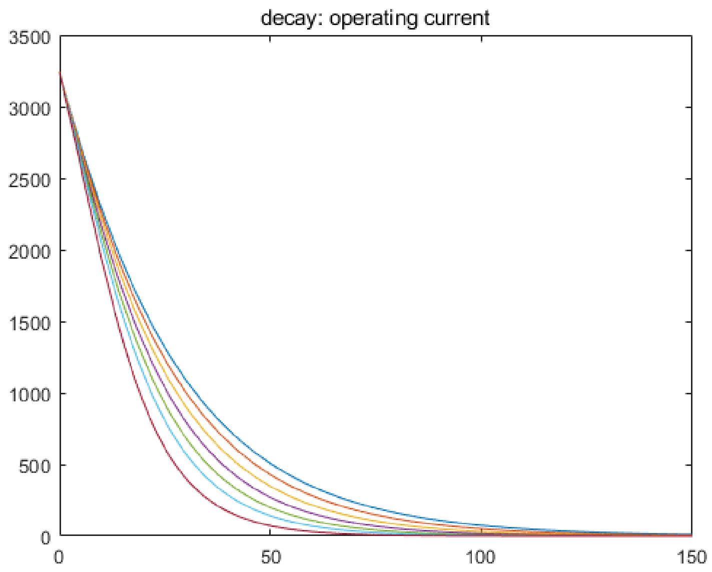
Rdump=150mΩ

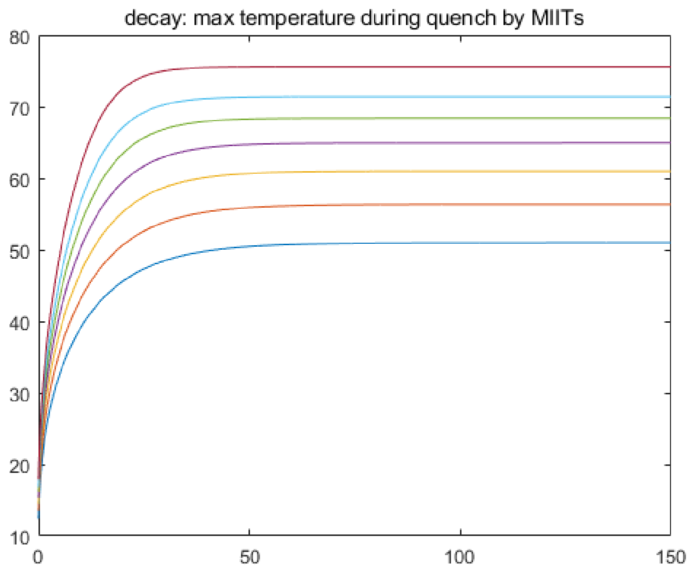
tdelay=100ms

Dump resistor

f_{RRR}	Beam Operation Time（day）	Current decay time（s, 1% Iop）	Magnet Voltage（V）	Max Temperature rise（K）	Storage Energy Dumpling rate（%）
1	0	121.3s	511.51V	50.98K	87.15%
0.77	30	110.2s	522.07V	56.36K	82.04%
0.625	60	99.1s	534.77V	61.00K	76.82%
0.5275	90	89.0s	549.67V	64.94K	71.84%
0.455	120	79.2s	568.16V	68.41K	67.04%
0.4	150	70.8s	591.14V	71.41K	62.59%
0.3325	200	59.2s	643.33V	75.59K	55.97%







Safety at 150days Operation: Varistor Baseline

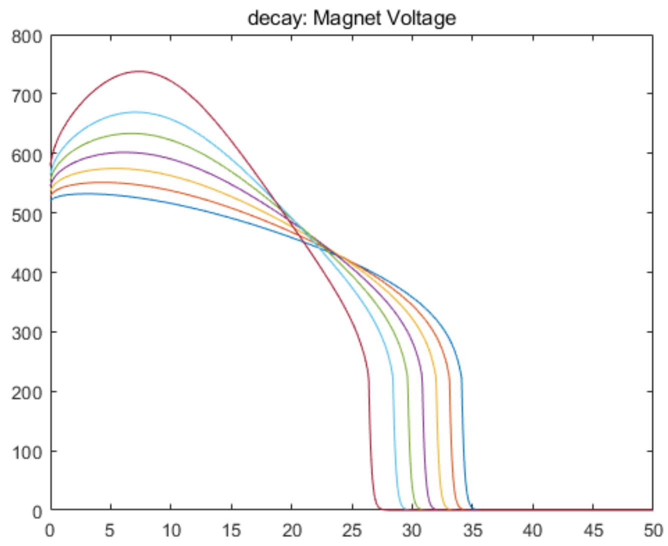
RRR Degradation

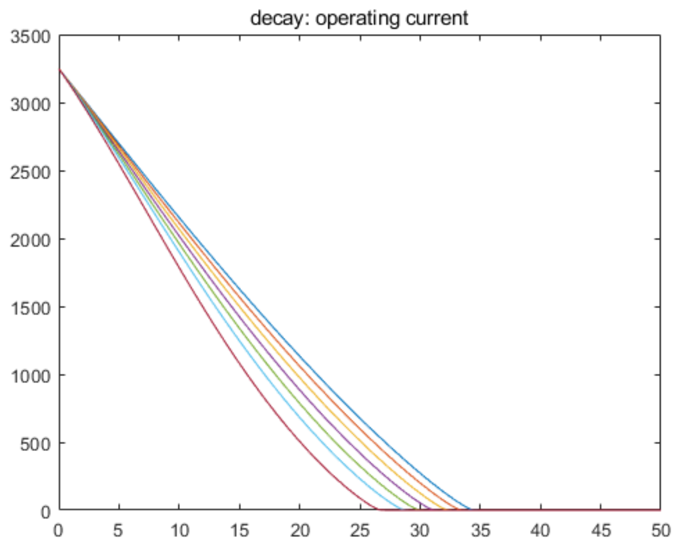
K=160, β=0.14

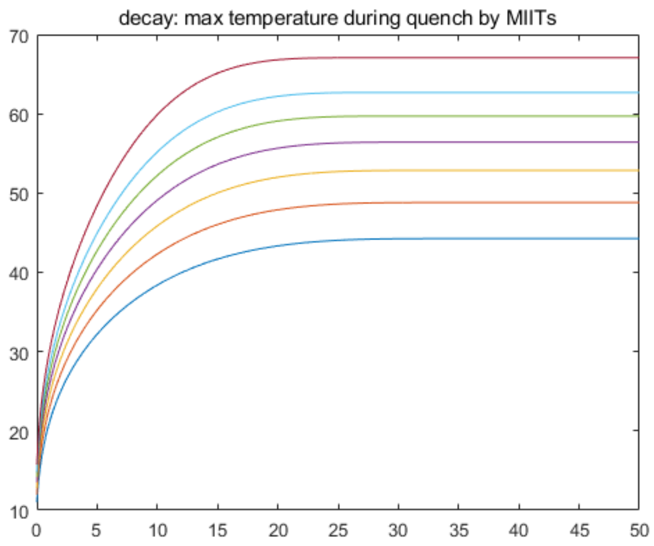
tdelay=100ms

Varistor

f_{RRR}	Beam Operation Time (day)	Current decay time (s, 1% Iop)	Magnet Voltage (V)	Max Temperature rise (K)	Storage Energy Dumpling rate (%)
1	0	33.8s	532.03V	44.25K	92.39%
0.77	30	32.8s	551.15V	48.80K	89.16%
0.625	60	31.7s	574.64V	52.85K	85.69%
0.5275	90	30.6s	601.78V	56.42K	82.16%
0.455	120	29.4s	633.56V	59.70K	78.52%
0.4	150	28.1s	669.32V	62.68K	74.92%
0.3325	200	26.1s	737.74V	67.06K	69.07%







A Brief Summary

中科院高能所超导磁体组
Superconducting Magnet Group, IHEP

Steady-state Thermal Characteristics:

- Under 6.2K
- Max Temperature: CS1

Quench Characteristics:

- Main Danger: Magnet Voltage
- Safe: Max Temperature
- Protection Design : Acceptable at any time

Magnet Design:

- Thermosiphon LHe Piping
- Pure Aluminum Strip
- Possibility of Applying Varistor

Ensure Coil Safety in 200days Operation
(at least 150days 5T)

Next Focus

- **Aluminum Stabilizer**
- **Insulation**
- **Multi-layer Coil Winding Methods**

- **Updates of Calculation**

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2020.12.11- CSNS

Q&A

Main References:

1. *M. Yoshida et al., "Low-temperature neutron irradiation tests of superconducting magnet materials using reactor neutrons at KUR," in Proc. AIP Conf., 2011, vol. 1435, pp. 167–173.*
2. *Y. Yang et al., "Study of Irradiation Effects on Thermal Characteristics for COMET Pion Capture Solenoid," in IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, pp. 1-5*
3. *X. Tong, et al."铝稳定体卢瑟福缆剩余电阻率的测量." 低温工程 .05(2018):39-44. doi:.*
4. *Z. Hou et al., "Conceptual Design of the Capture Superconducting Solenoid for Experimental Muon Source," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 5, pp. 1-7*

EMuS Capture Solenoids

——Thermal Analysis & Quench Protection

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