“Design & Analysis of Superconducting Magnet System for Low energy Nuclear Reactions”

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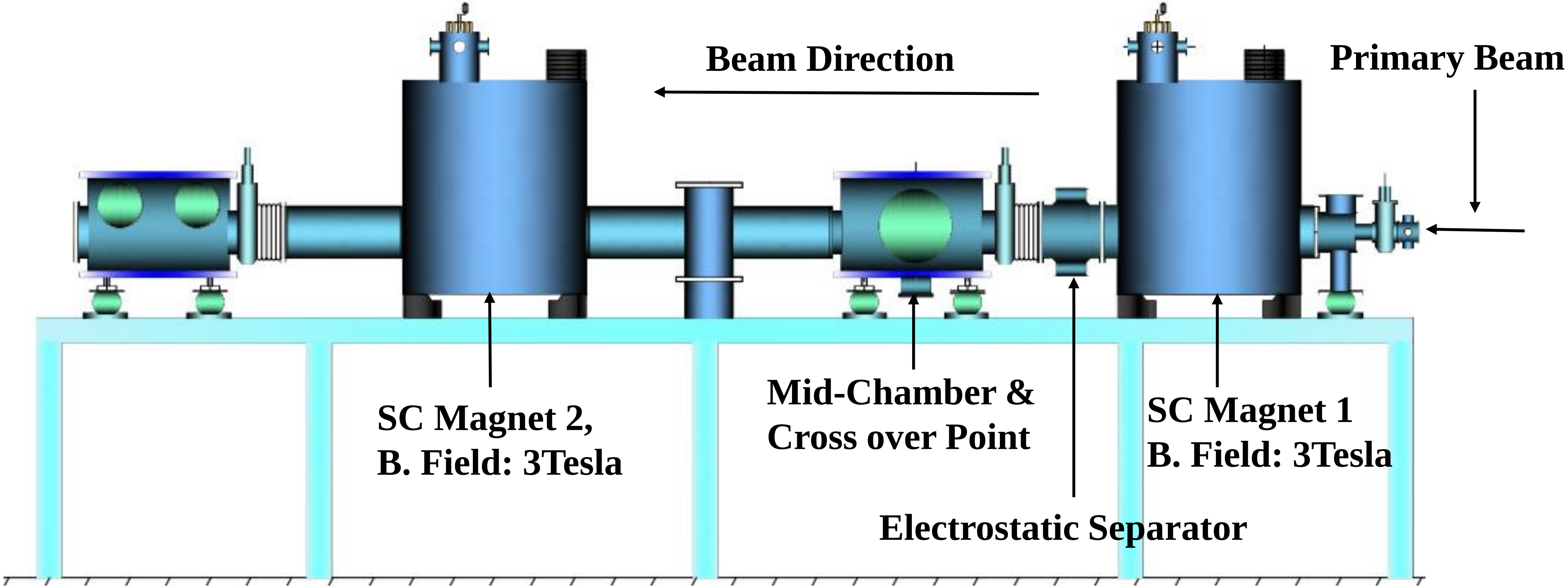
Outline

- ✓ Overall System Layout
- ✓ Superconducting Magnet System Design Consideration
- ✓ Engineering design and components of SC Magnet
- ✓ Heat Flow Path
- ✓ Available Cooling Capacity
- ✓ Different Types of Superconducting wire & Critical Surface for NbTi
- ✓ SC Solenoid Design for 3Tesla
- ✓ Static Structural Analysis for SC Solenoid
- ✓ Quench Analysis: Intentionally Heat Triggered Normal Zone Propagation Study
- ✓ Current status of development of SC Magnet for low energy nuclear reaction
- ✓ Summary and Conclusion
- ✓ Future Work

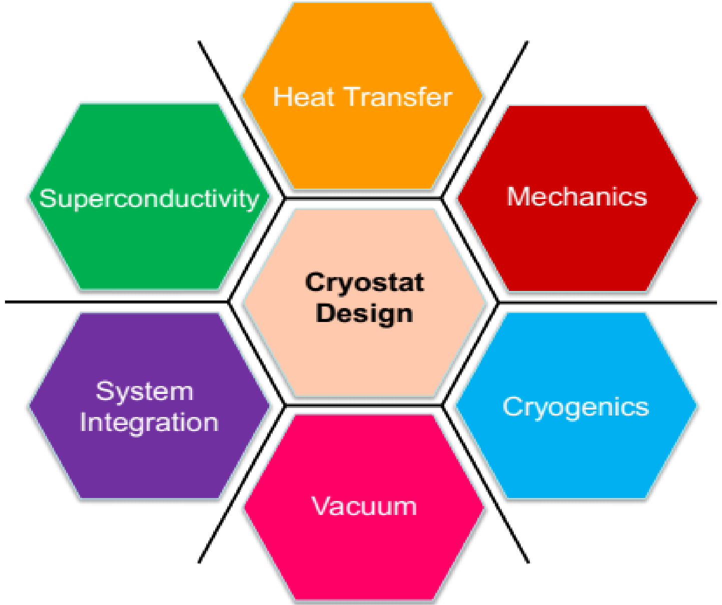
Overall System Layout



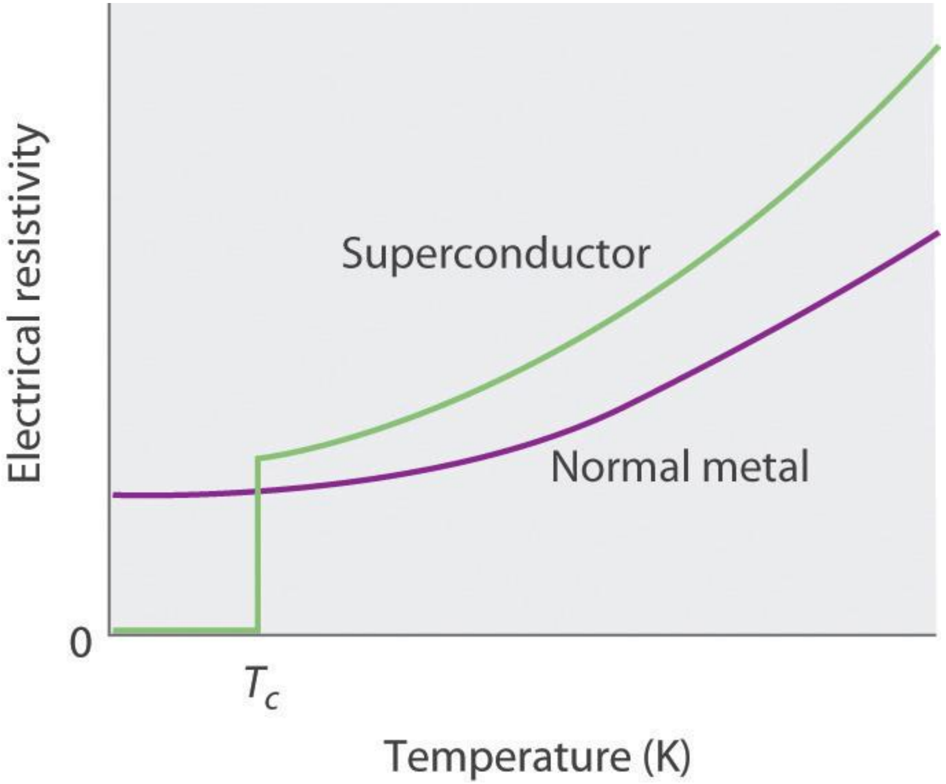
Conceptualized Beam Layout for Low energy Reactions

Superconducting Magnet System Design Consideration

- Integrated Electromagnetic, Thermal and Structural Design
- Heat Flow Path & Thermal Load estimation and Available budget
- Cooling + Right material usage
- Cryogenic Instrumentation
- Quench Detection & Protection system
- Winding of SC coils with cryogenics class epoxy

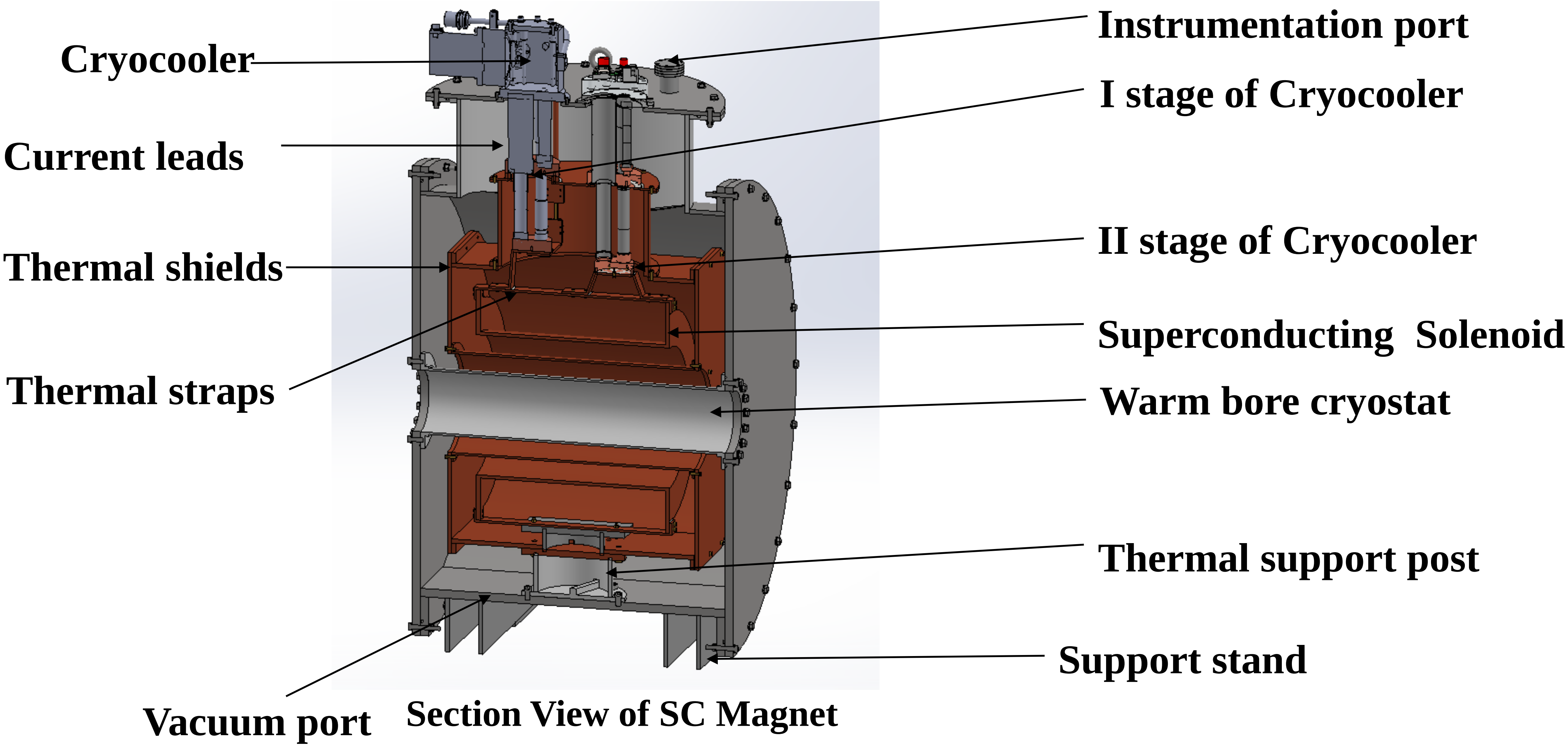


Engg. Discipline involved in SC Magnet System Design



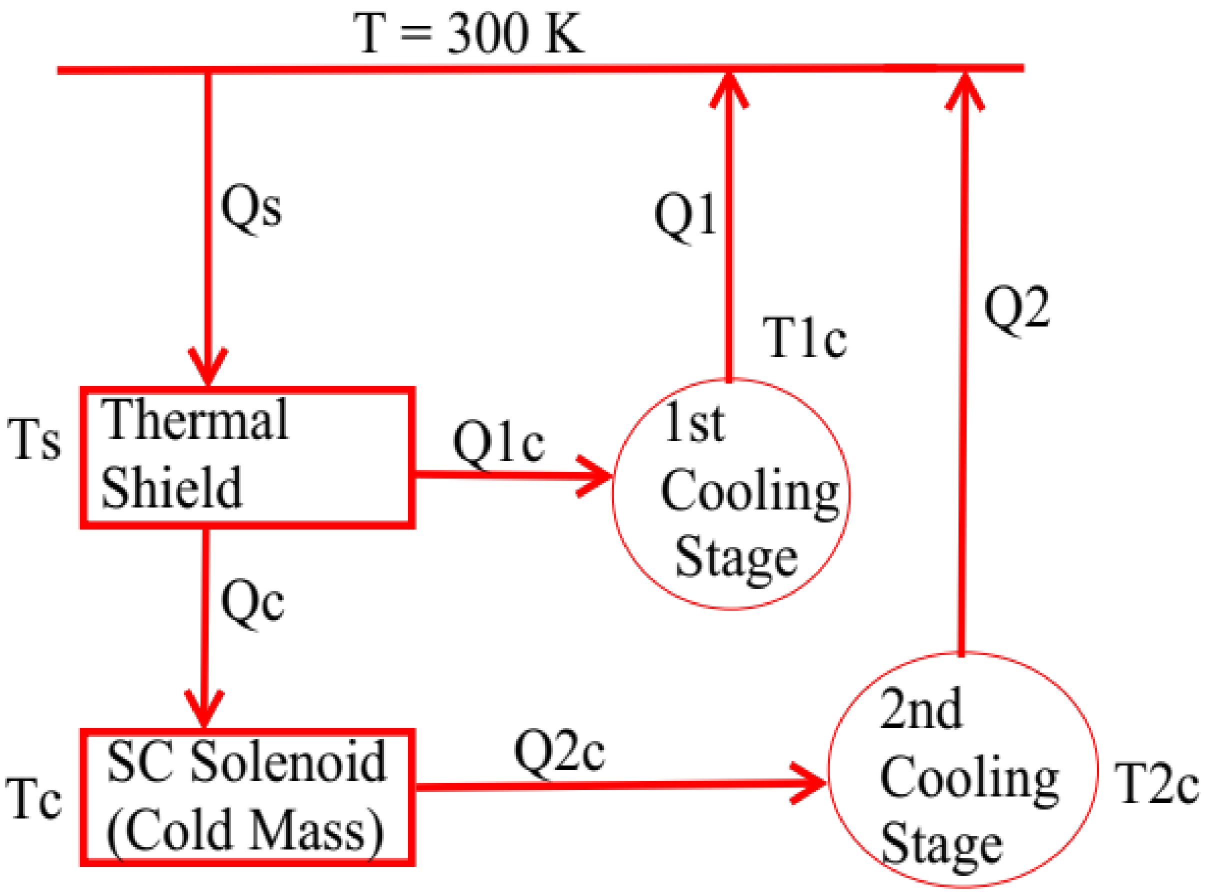
Unique Behaviour of SC Material

Engineering design and components of SC Magnet



Section View of SC Magnet

Heat Flow Path



Temperature of Thermal Shield to be maintained ≤ 45 K

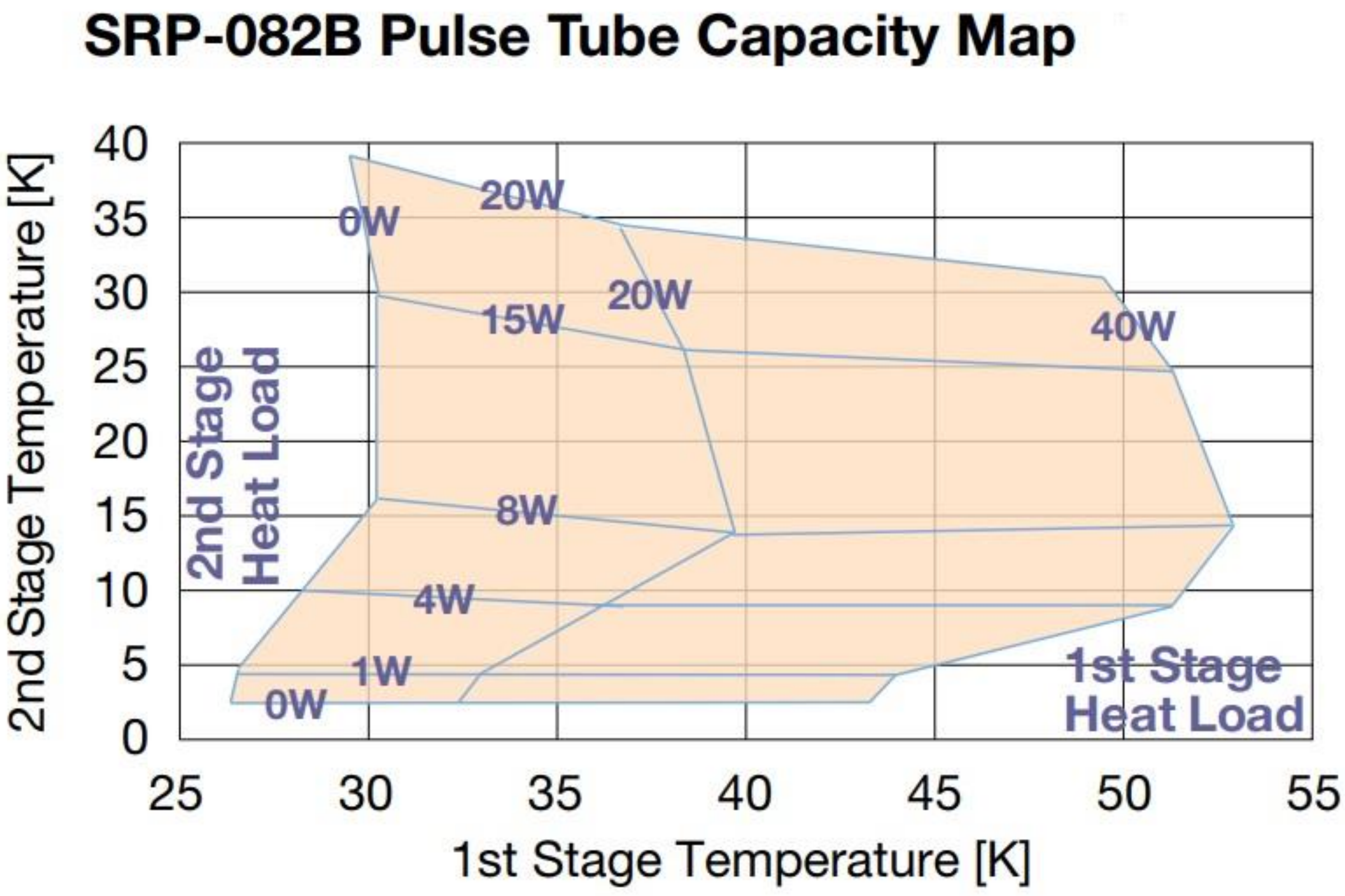
- First stage capacity is 40 W @ 45 K
- Design Criteria is to minimise the Heat Load at 1st Stage of Cryocooler below 40 W

Temperature of Cold Mass to be maintained ≤ 4.2 K

- Second stage capacity is 1 to 1.5W @ 4.2 K
- Design Criteria is to minimise the Heat Load at 2nd Stage of Cryocooler below 1 W

Heat Load Estimations at Thermal Shield after wrapping 30 Layers of MLI: 45 Watt
At Cold mass, it is 0.5 Watt

Available Cooling Capacity



Cryocooler

Heat Load Estimations are well within the limit allowed by Cryocooler

Different Types of Superconducting wire & Critical Surface for NbTi

LTC superconducting wire

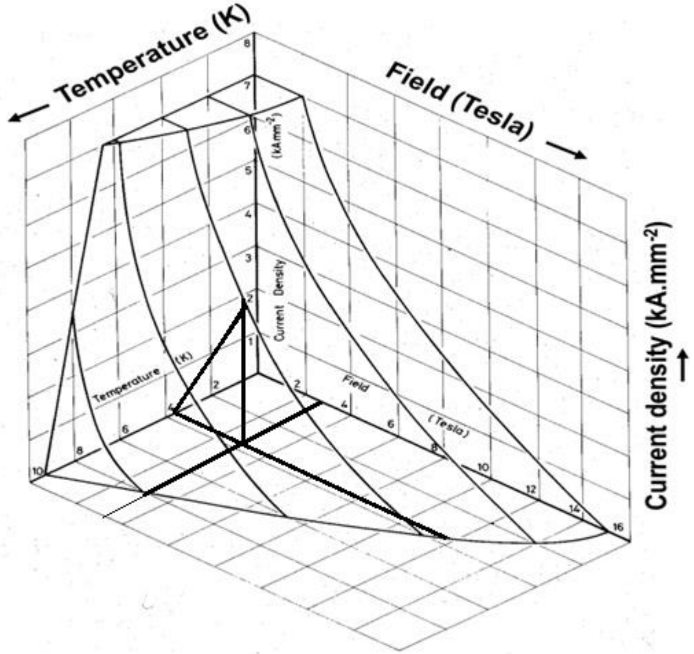
- **NbTi**
- Nb3Sn, Nb3Al

MTC superconducting wire

- MgB2

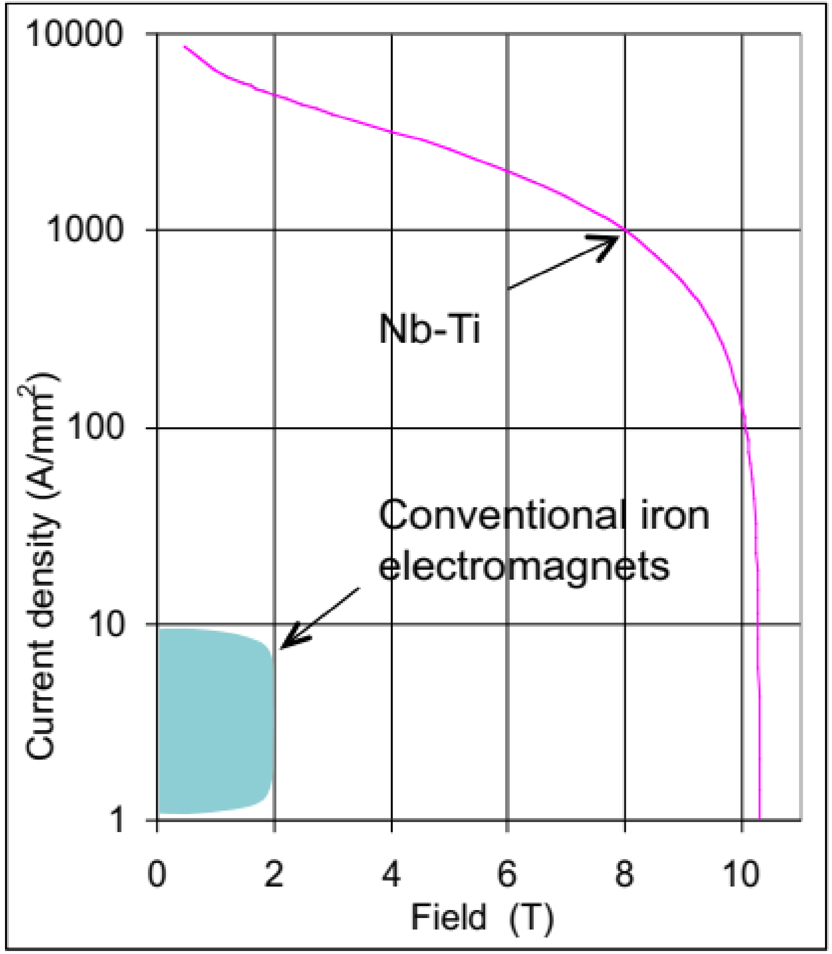
HTC superconducting wire

- Bismuth tape
- YBC



Critical Surface of NbTi

Critical values $NbTi$			
T_{c0}	J_{c0}	H_c1	H_c2
$9.2\ K$	$\sim 10^6\ A/mm^2$	$0.1\ T$	$10\ T$



Motivation for SC Magnet

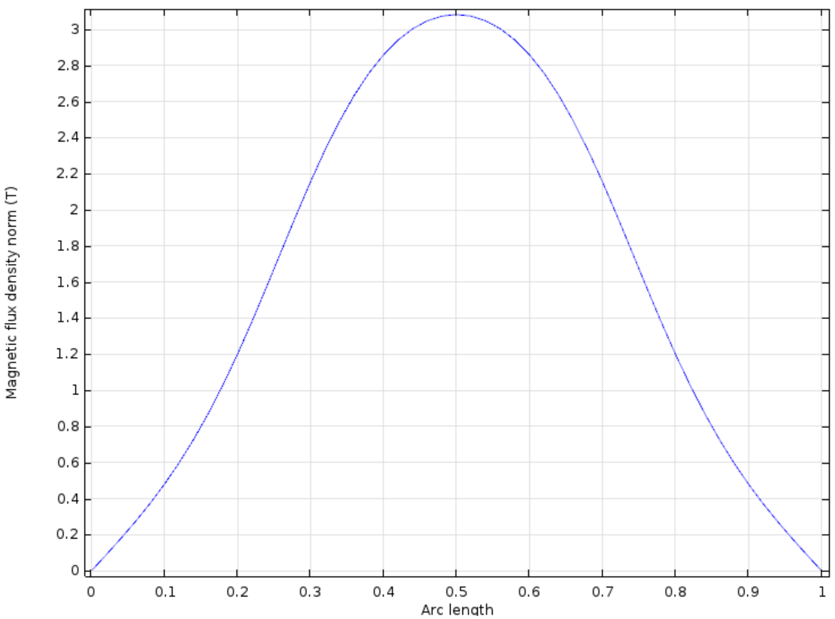
Engineering current density

(J_{eng}) = $J_{commercial}$ * λ_{metal} (fill factor)* $\lambda_{winding}$ (space occupied by insulation etc)

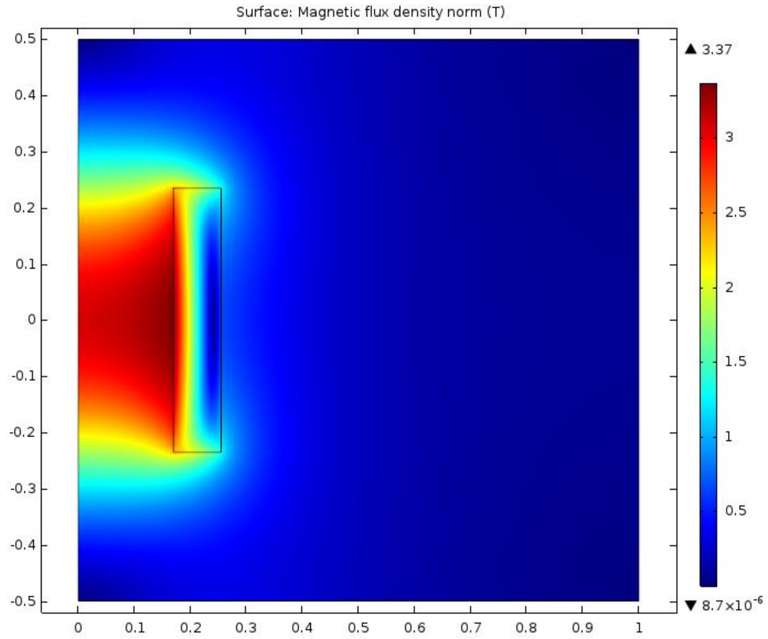
So typically Jeng is only 15% to 30% of Jc (commercial available)

Superconducting Solenoid Design for 3T

S N	Parameter	Value	Unit
1.	Length	450	mm
2.	ID	340	mm
3.	OD	510	mm
4.	Peak B field	3	T
5.	MMF	15,00,000	At
6.	Current	200	A
7.	Turns	8500	-
8.	Magnetic energy	52	kJ
9.	Conductor	NbTi	-
10	Cu-SC ratio	4	-

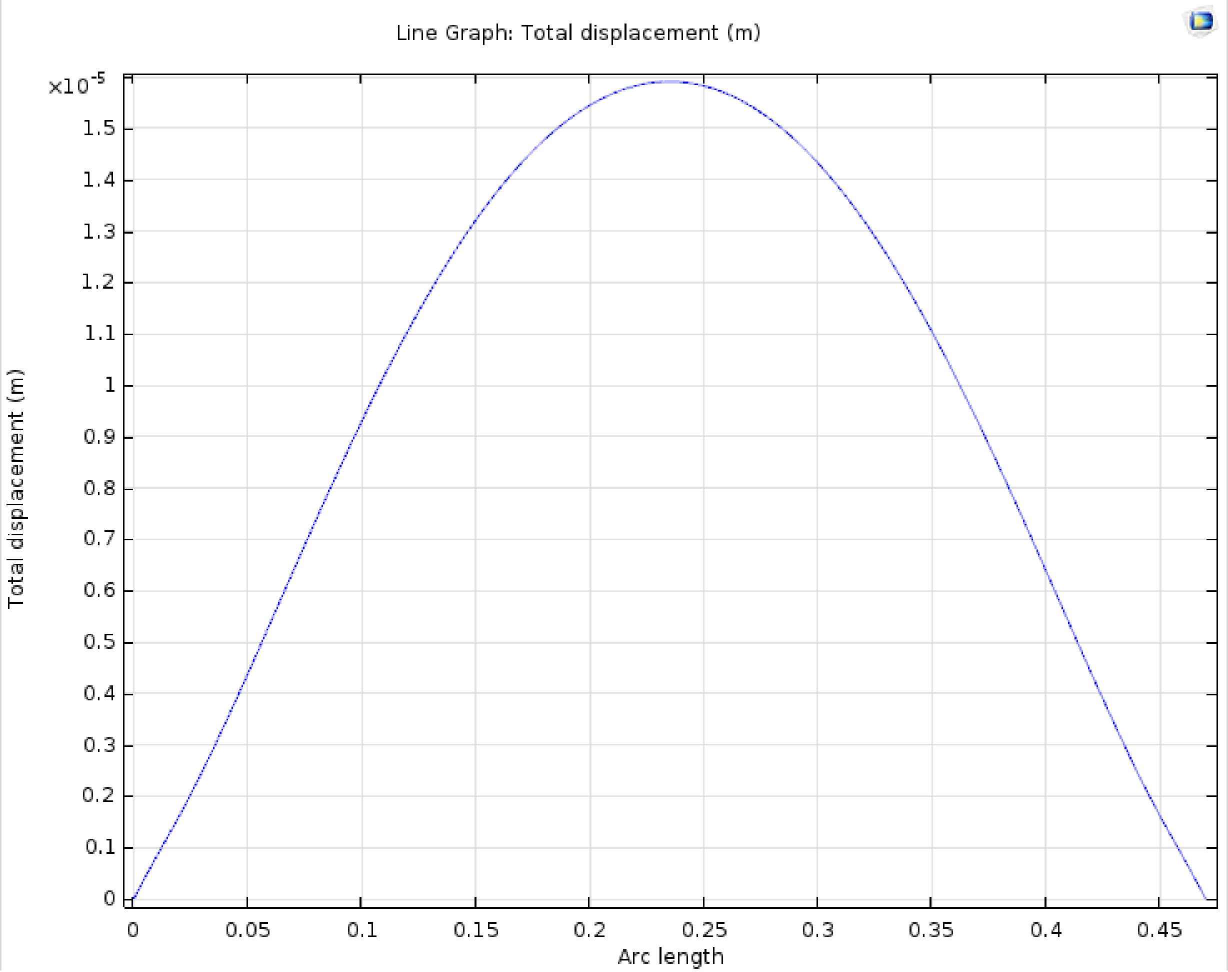


Longitudinal B-Field of SC Solenoid

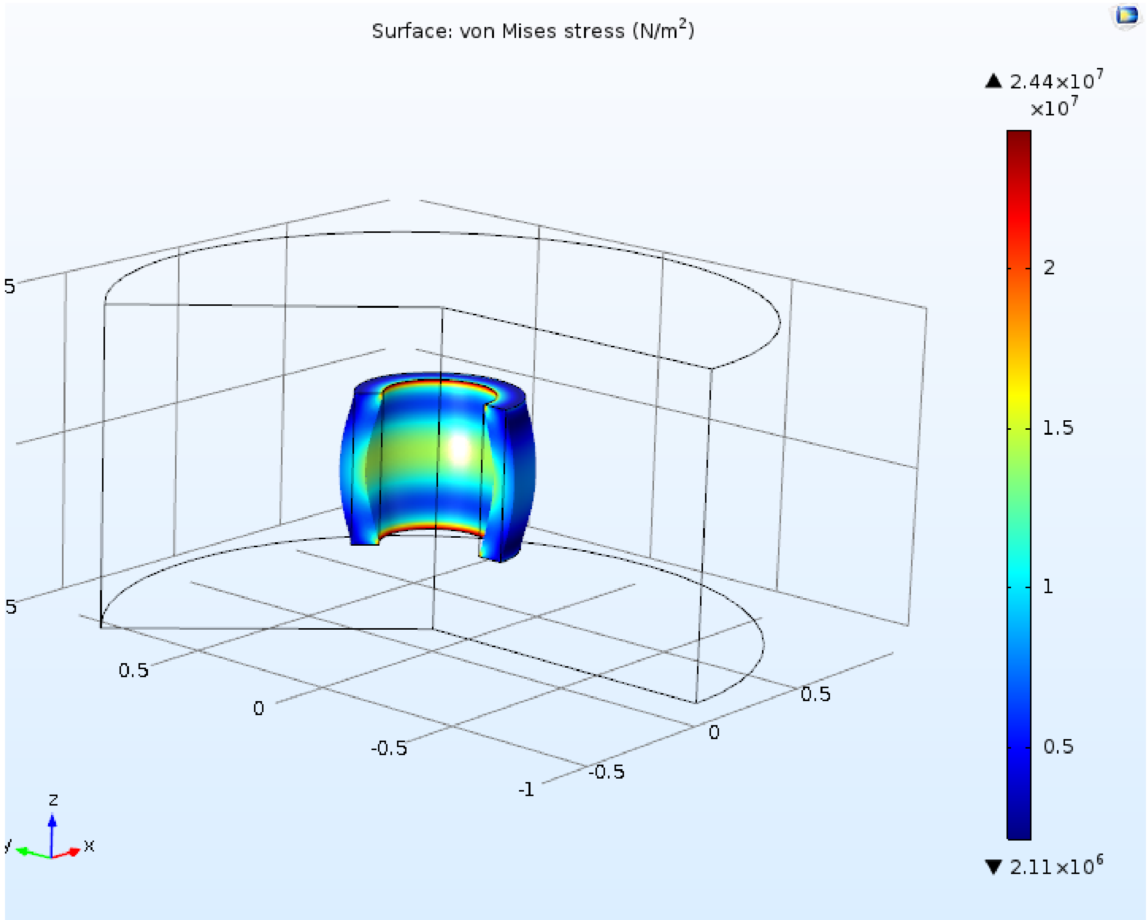


Magnetic Flux Density

Static Structural Analysis of Superconducting Solenoid Magnet



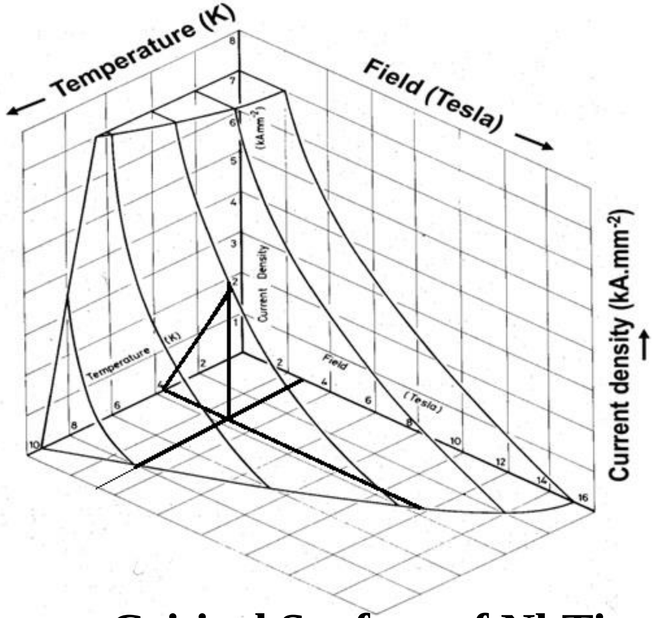
Maximum Deflection: 15 microns



Max. Von-Mises Stress: 24 MPa

Quench Simulation using COMSOL Software

Quench: Transition of a conductor from the superconducting to the normal conducting state.



Critical Surface of NbTi

<u>External Disturbances Causes Quench</u>

Mechanical events

- Wire motion under Lorentz force
- Winding deformations and failures

Electromagnetic events

- Flux-jumping, AC loss (most magnet types)

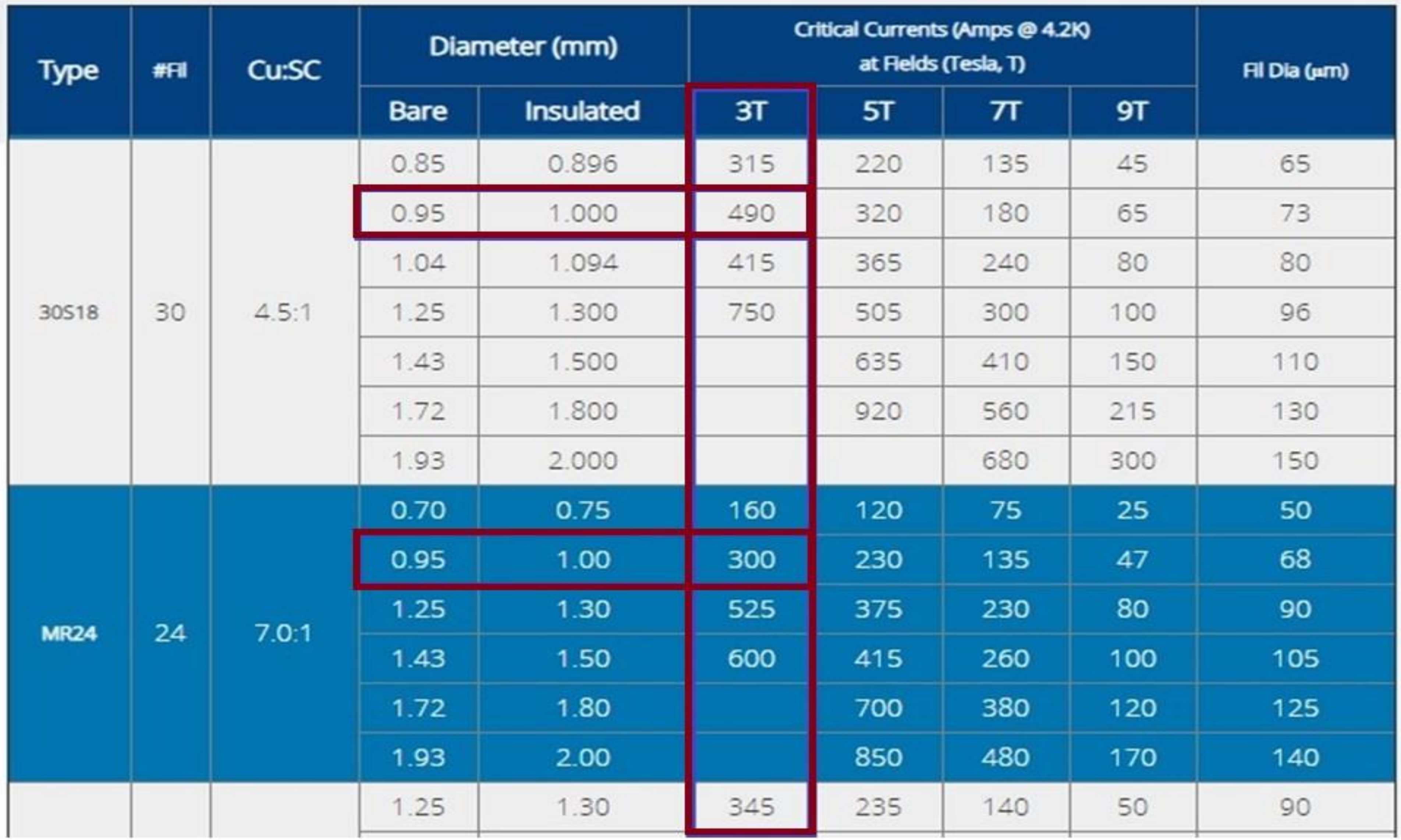
Thermal events

- Current leads, instrumentation wires heat leaks through thermal insulation, degraded cooling.

Quench Problem is categorised into:

1. Electrical problem: V-I characteristics, dependency of the conductor resistivity on B-field, Temperature
2. Magnetic problem: inductance and eddy-current effects inside the coil and in other structural elements.
3. Heat transfer from solid to helium: Not applicable in this case as it is cryogen free
4. ***Thermal problem in solids: Joule losses in conductor***
5. Thermal and fluid-dynamic problem of helium: Not applicable in this case as it is cryogen free

NbTi Superconducting Wires / Critical Currents



Type	#Fil	Cu:SC	Diameter (mm)		Critical Currents (Amps @ 4.2K) at Fields (Tesla, T)				Fil Dia (μm)
			Bare	Insulated	3T	5T	7T	9T	
30S18	30	4.5:1	0.85	0.896	315	220	135	45	65
			0.95	1.000	490	320	180	65	73
			1.04	1.094	415	365	240	80	80
			1.25	1.300	750	505	300	100	96
			1.43	1.500		635	410	150	110
			1.72	1.800		920	560	215	130
			1.93	2.000			680	300	150
MR24	24	7.0:1	0.70	0.75	160	120	75	25	50
			0.95	1.00	300	230	135	47	68
			1.25	1.30	525	375	230	80	90
			1.43	1.50	600	415	260	100	105
			1.72	1.80		700	380	120	125
			1.93	2.00		850	480	170	140
			1.25	1.30	345	235	140	50	90

NbTi Superconductor Characteristics & Critical Temp at 3Tesla

Base line for the NbTi with reasonable accuracy is

$B_{c2}(T) = B_{c2}(0)\,[1 - \{T / T_c(0)\}^{1.7}]$ when $0 < B < 10$ Tesla

$T_c(B) = T_c(0)\,[1 - \{B / B_{c2}(0)\}]^{0.59}$

Where $T_c(0) = 9.2$ K, $B_{c2}(0) = 14.5$ T, **$B_{c2}(4.2) = 10.4$ T**

$T_c(B{=}3T) = 8.02$ K

The value Jc is dependent over the Tc for the particular B.

$J_c(B, T) = J_c(B, 4.2)\,[(T_c(B) - T) / (T_c(B) - 4.2)]$ Lubell’s Approximation

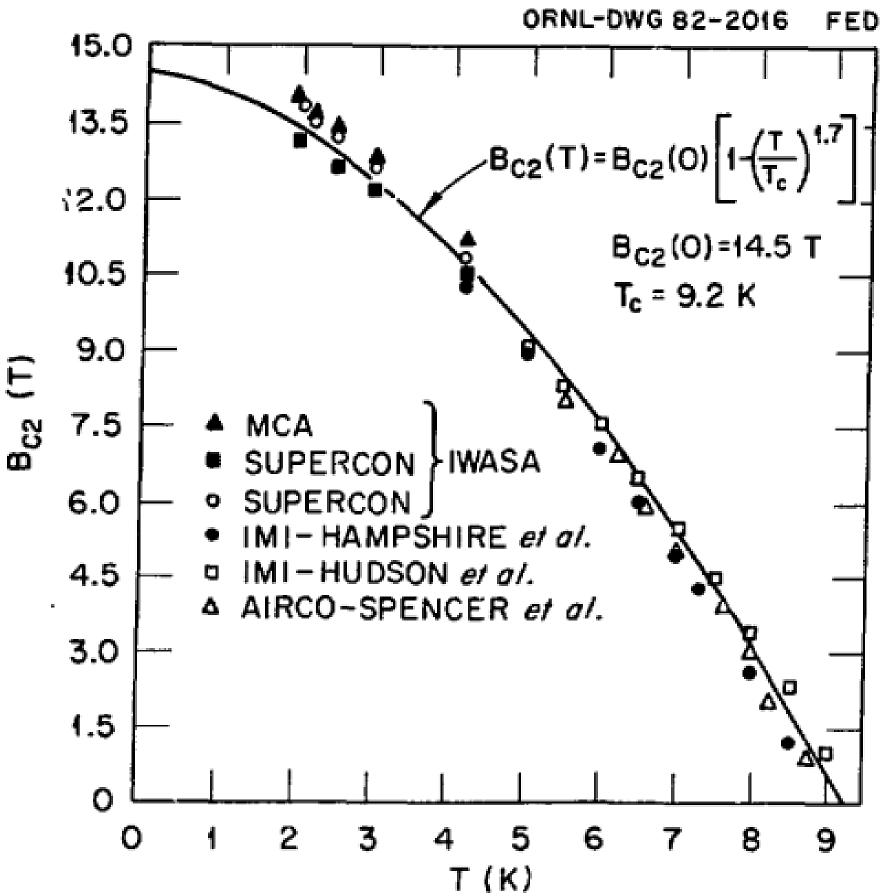
If operating temperature is 4.2 K

$J_c(B, T) = J_c(B, 4.2) = 4500$ A / mm2

Je = 0.2 * 4500 = 900 A / mm2

Ie / A = 900 * 0.64 = 576 A

Courtesy: *Empirical scaling formulas for critical current and critical field* ***for commercial NbTi: M S Lubell***

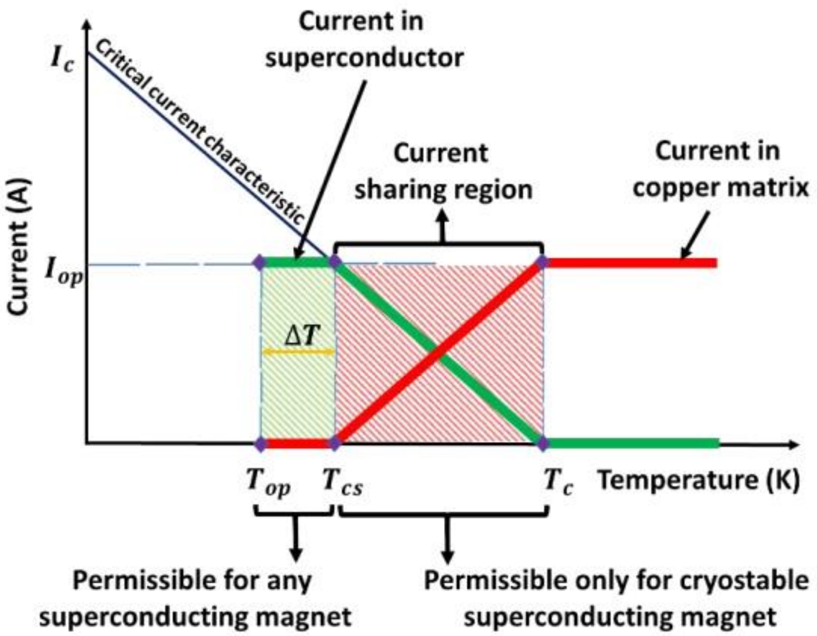


Upper critical field vs temperature *for NbTi commercial conductor of nominal composition 44 wt % Ti to 48 wt % Ti.*

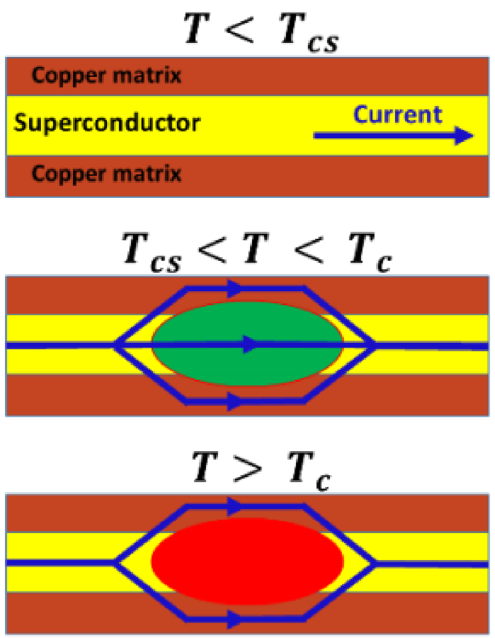
To achieve moderate thermal margin, the operating current has been chosen 60 %

For 30S18 (~ 294A) of the critical current (490 A, for wire diameter 0.9mm **) at the peak field (3T) , For MR24 (~ 180A) of the critical current (300 A) at the peak field (3T)**

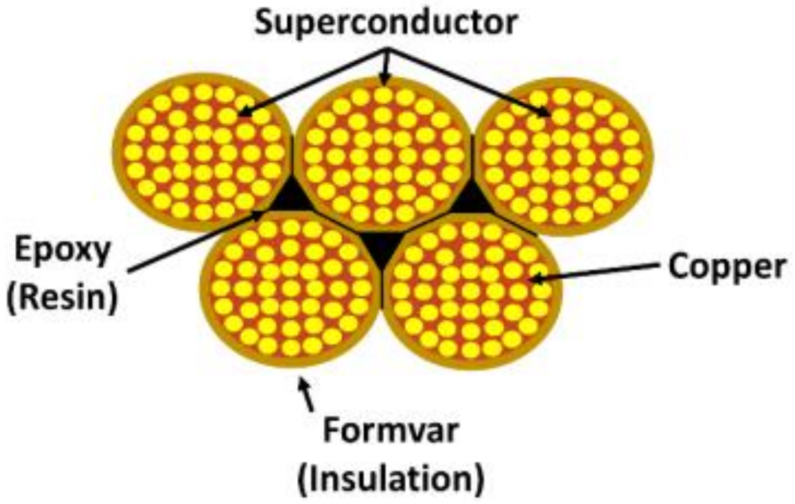
Current sharing Temperature and Temperature margin



Current sharing model for composite superconductor wires



Current distribution in composite superconductor at different temp regimes



Filaments of superconductor are embedded in matrix of copper

$T_{cs}\,(B, J) = T_{OP} + \{(T_c\,(B) - T_{OP})\,(1 - (J_{op} / J_c))\}$

$= 4.2 + \{\,(8.02 - 4.2) * 0.4\,\} = 6.11$ K

Where $J_{op} / Jc = 0.5$

Therefore, Margin = $T_{cs}\,(B, J) - T_{OP} = 1.91$ K

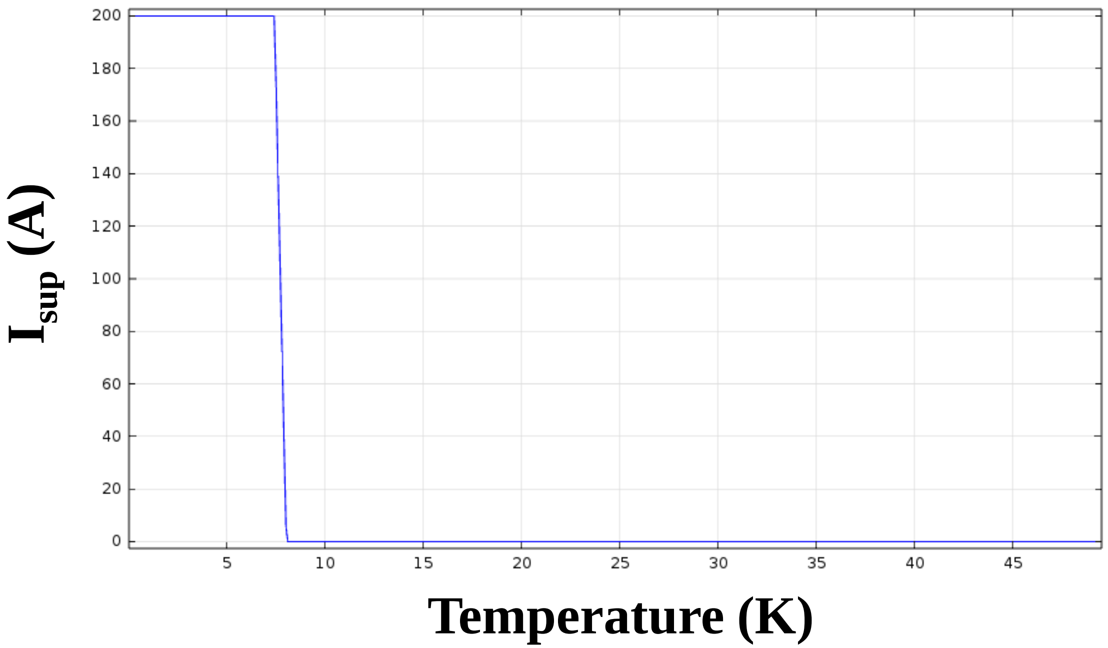
$I_{OP} = 0.5$ to $0.7 * I_{quench}$

1 D Quench Analysis of Superconducting NbTi Strand

S.N	Parameters	Values
1.	Length of the wire (L)	1000 mm
2.	Diameter of the wire (dwire)	1 mm
3.	Copper to Superconductor ratio (*f*)	4.5
4.	Operating Magnetic Field (B)	3 T
5.	Diameter of Copper ($d_{cu} = \sqrt{\frac{f}{1+f}}\, d_{wire}$)	0.894 mm
6.	Critical Temperature (T_c)	8.02 K
7.	Current Sharing Temperature (T_{cs})	6.11 K
8.	Operating Temperature (T_{op})	4.2 K
9.	Temperature Margin	1.91 K
10.	Maximum Current	200 A

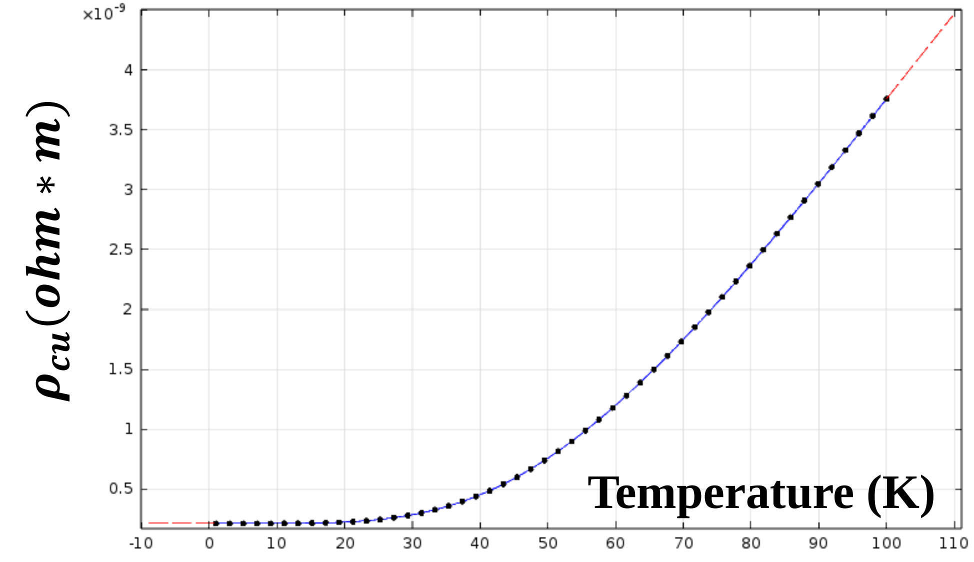
Current I_{cu} is modelled as a piecewise function:

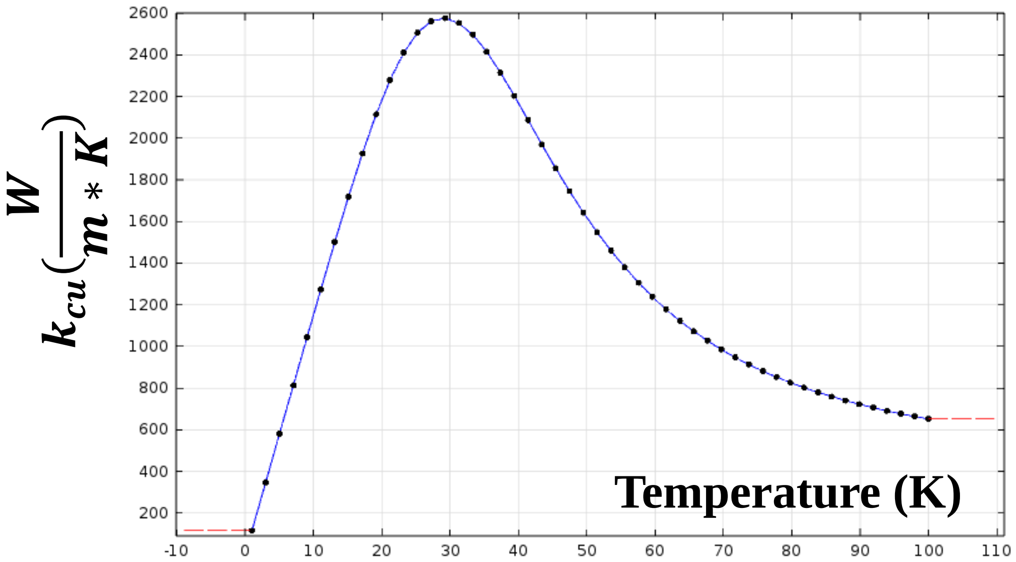
$$\boldsymbol{I_{sup}} = \begin{cases} \boldsymbol{I_{op}} & \boldsymbol{T_{op} < T < T_{cs}} \\ \boldsymbol{I_{op}\left(1 - \left(\frac{T - T_{cs}}{T_c - T_{cs}}\right)\right)} & \boldsymbol{T_{cs} \leq T < T_c} \\ \boldsymbol{0} & \boldsymbol{T_c \leq T} \end{cases}$$

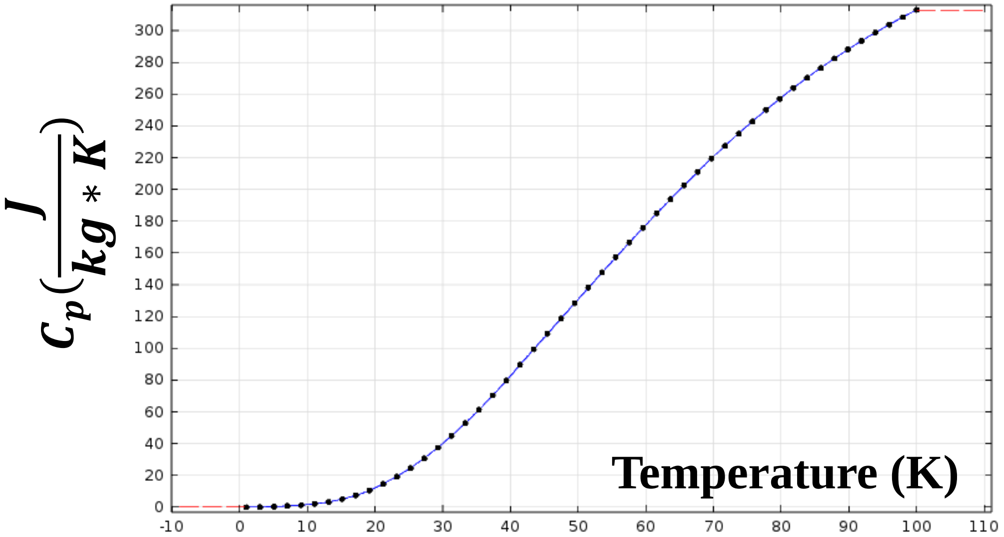


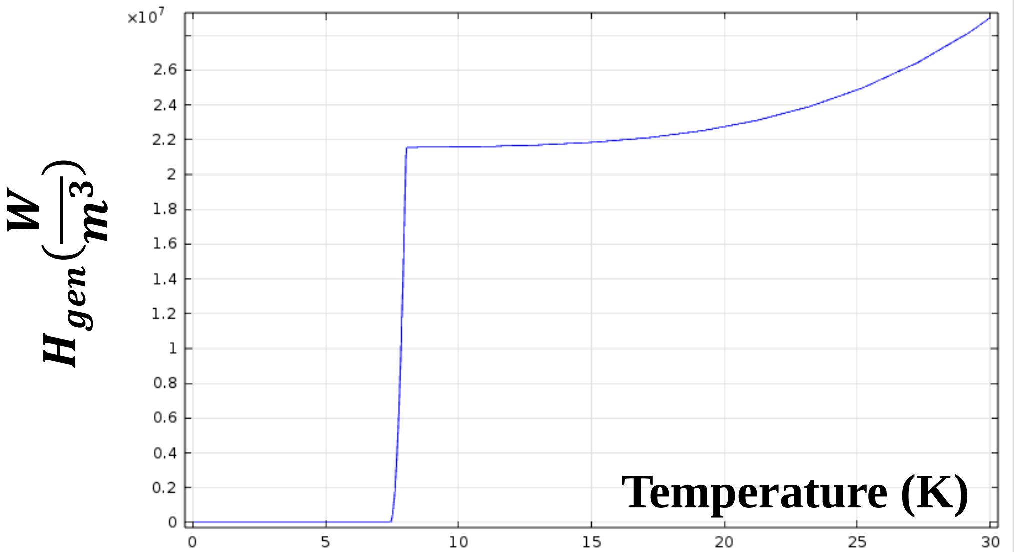
1 D Quench Analysis of Superconducting NbTi Strand (Cont…)

(Temperature dependent Material Properties)



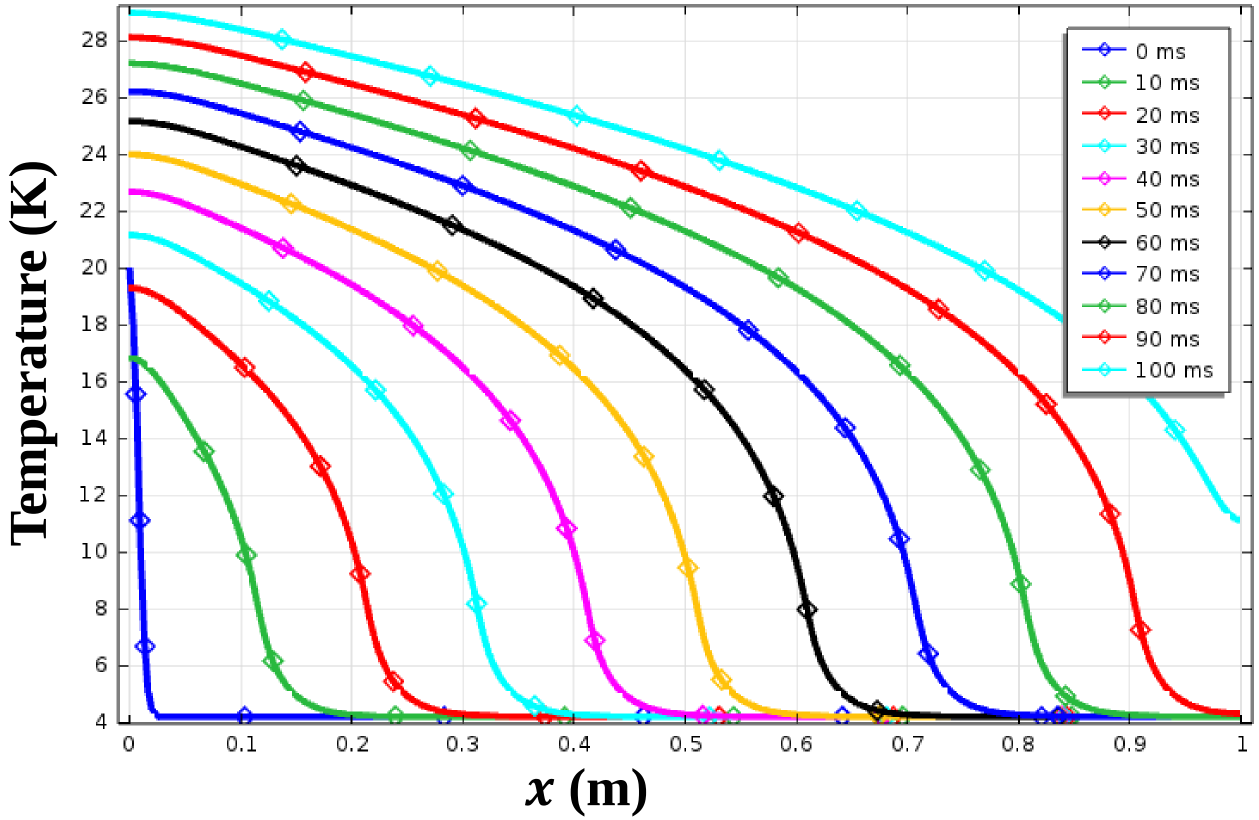


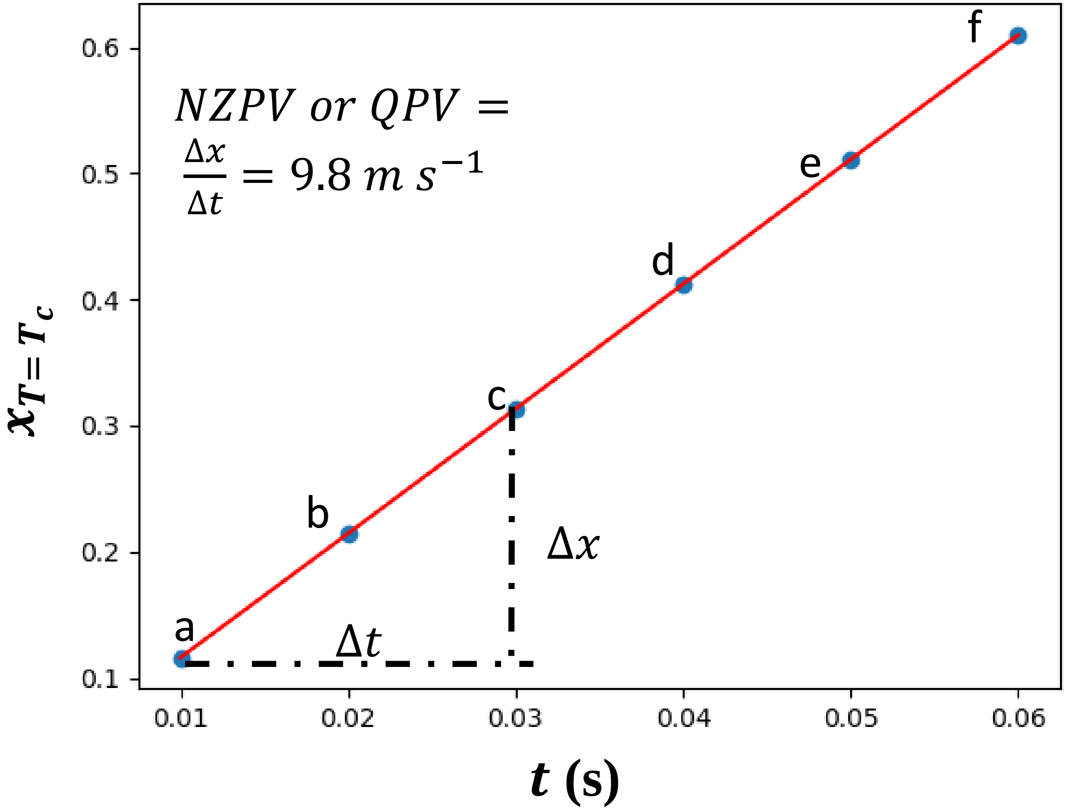




Heat generation per volume: $H_{gen} = \rho_{cu} * \left(\frac{I_{op}-I_{sup}}{a_{cu}}\right)^2 \ (\frac{W}{m^3})$

Normal Zone Propagation (Or Quench Propagation)

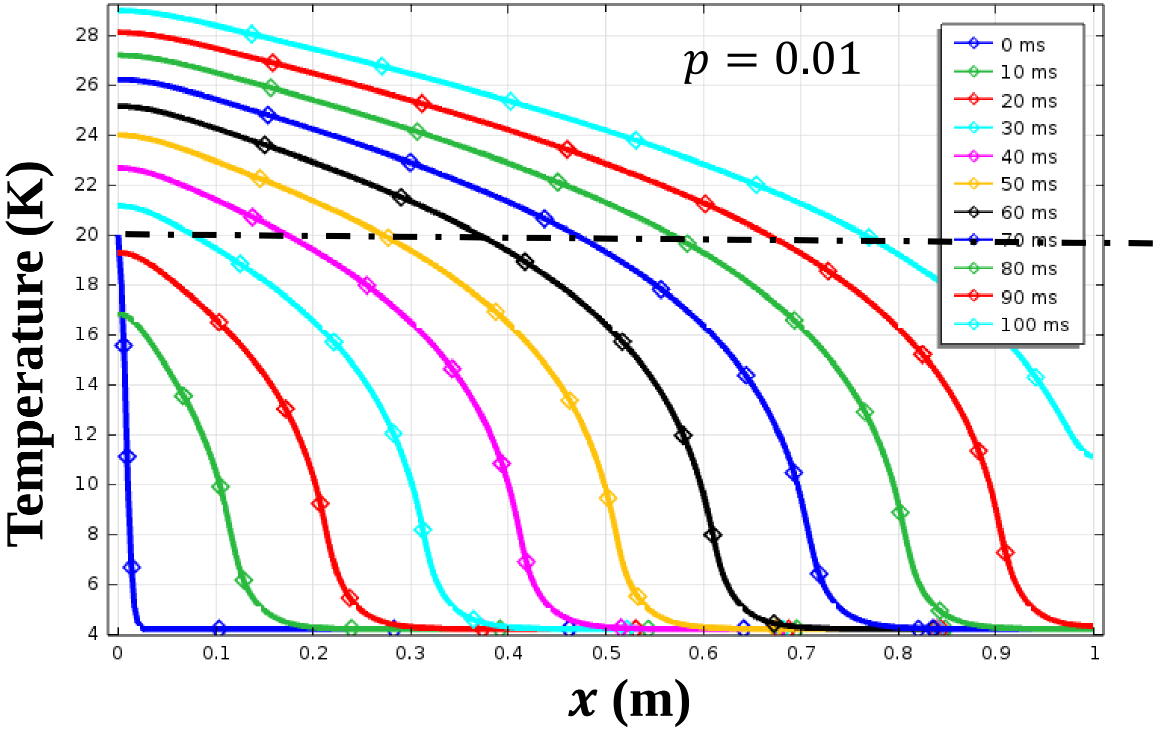




Heat transfer during the process: $\boldsymbol{\rho C_p \frac{dT}{dt} = \nabla\left(k * (\nabla T)\right) + H_{gen}}$

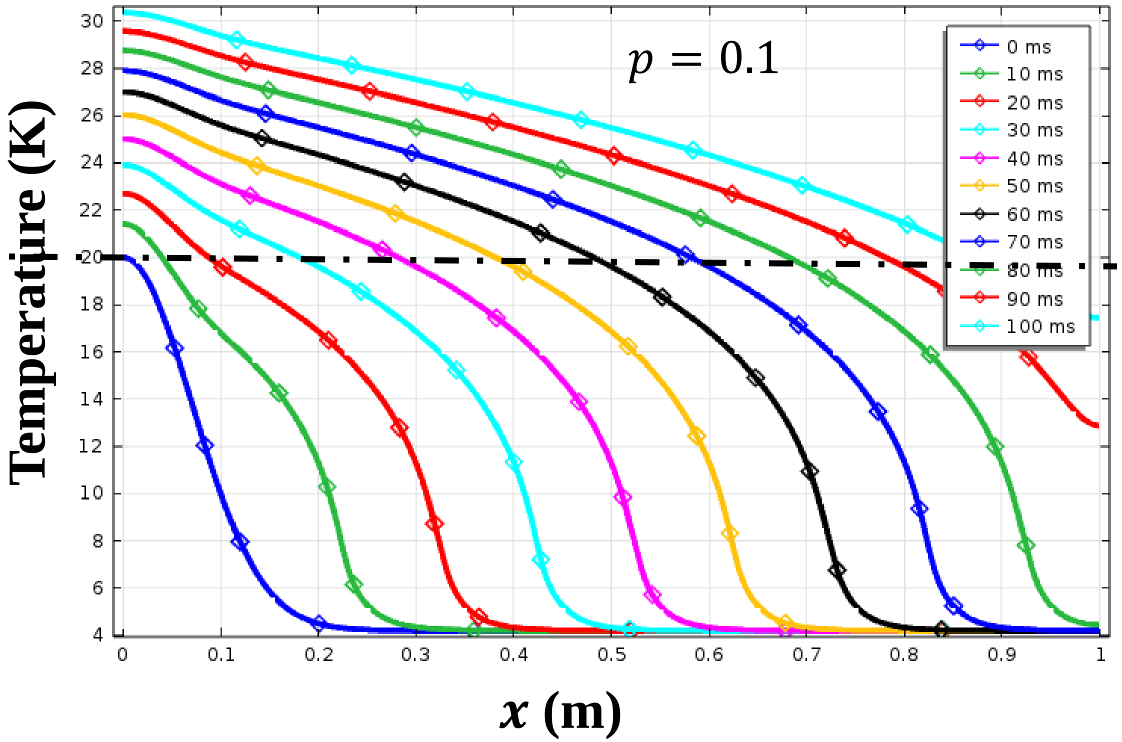
Intentional Disturbance as a Gaussian pulse of temperature as initial value: $\boldsymbol{T(x) = T_{dist,max} + (T_{dist,max} - T_{op})e^{\left(-\left(\frac{x}{p}\right)^2\right)}}$

Effect of the Gaussian parameter *p* on Temperature profiles



For small p After initial fall the quench propagates on

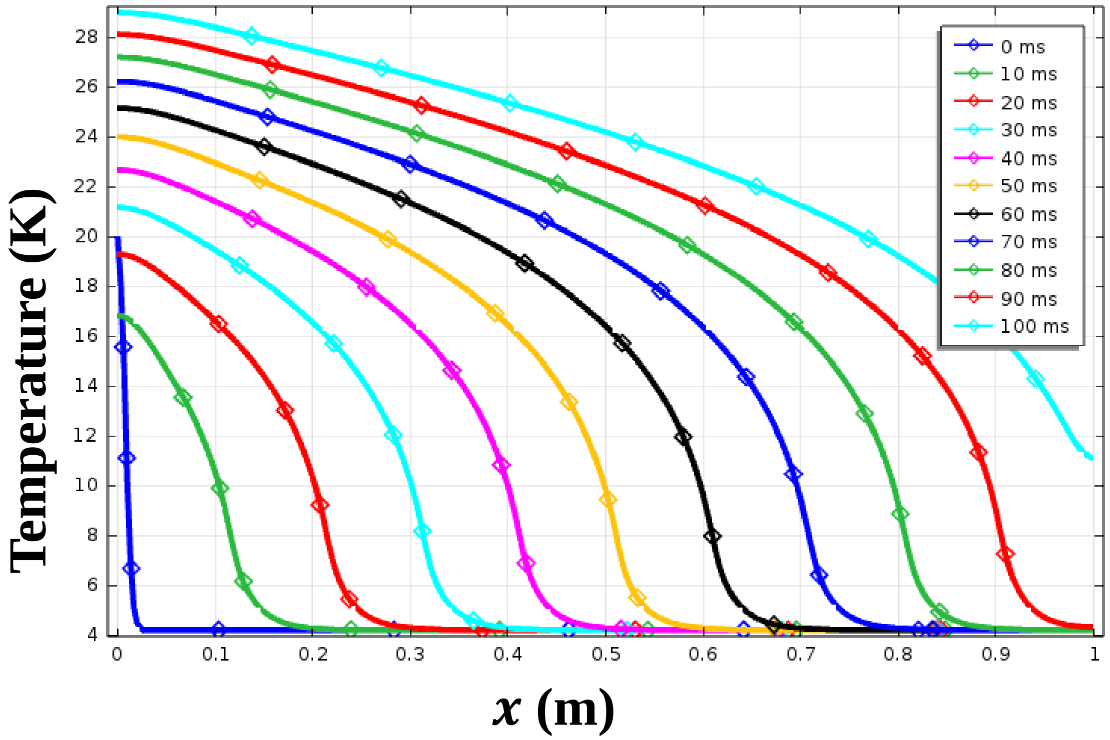
$T_{dist,max} = 20\ K$



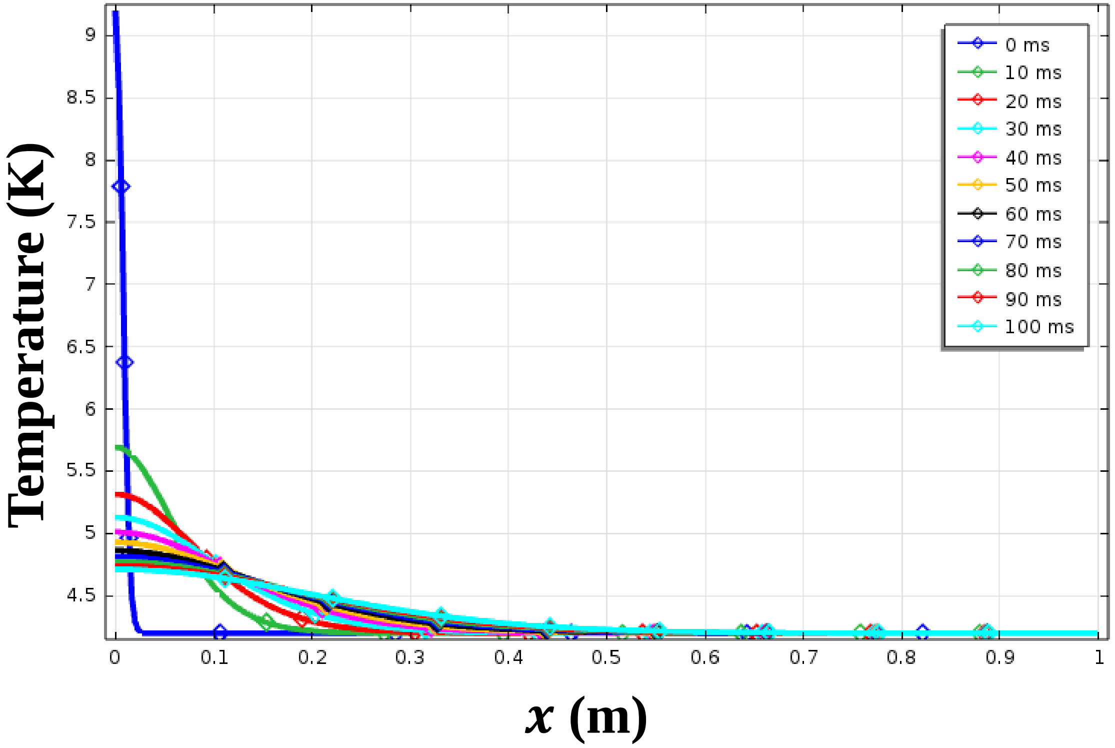
For large p temp. continuously rises, without falling

The maximum temp. of the disturbance is at the origin of the wire and that’s where the process starts. The shape of temp. profile at 0 ms is the initial value as the disturbance mimicking the quench process.

Recovery of the superconducting State



For $T_{dist,max}$ = 20 K, disturbance is self sustain and propagates endlessly



For $T_{dist,max}$ = 9.2 K, disturbance falls to lower temperatures and continues to fall, the quench in this case dies out soon and the system remains in the superconducting zone, which indeed disturbed but is not lost.

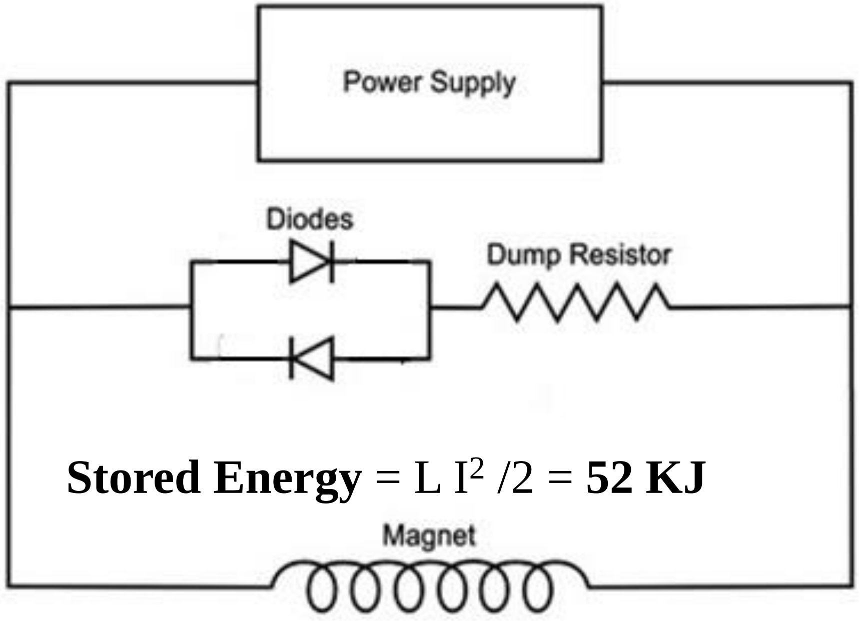
Diode-Resistance Quench Protection System

- A set of special diodes is connected in series with shunt resistance
- Diodes prevents flow of current through the resistor during ramping up and ramping down – two sets of back to back diodes used
- Arrangement allows current in either direction during a quench
- At the initiation of quench > voltage starts rising until the diode ‘switches on’ and current starts flowing through the resistor – peak voltage reaches in resistor.

Limitation: continuous dissipation of heat on the dump resistor during magnet charging and discharging because of charging/discharging voltage (- L di/dt).

To reduce this heat dissipation, **back to back diodes are placed in series with the dump resistor**. The forward voltage of the diode restricts the unwanted heat dissipation during charging or discharging of the magnet.

In back-to-back diode scheme, current will start flowing through bypass resistor only when the voltage across resistor crosses threshold level of voltage determined by forward voltage of diode.



Stored Energy = L I^2 /2 = **52 KJ**

Quench Protection Circuit

Current status of Development of SC Magnet

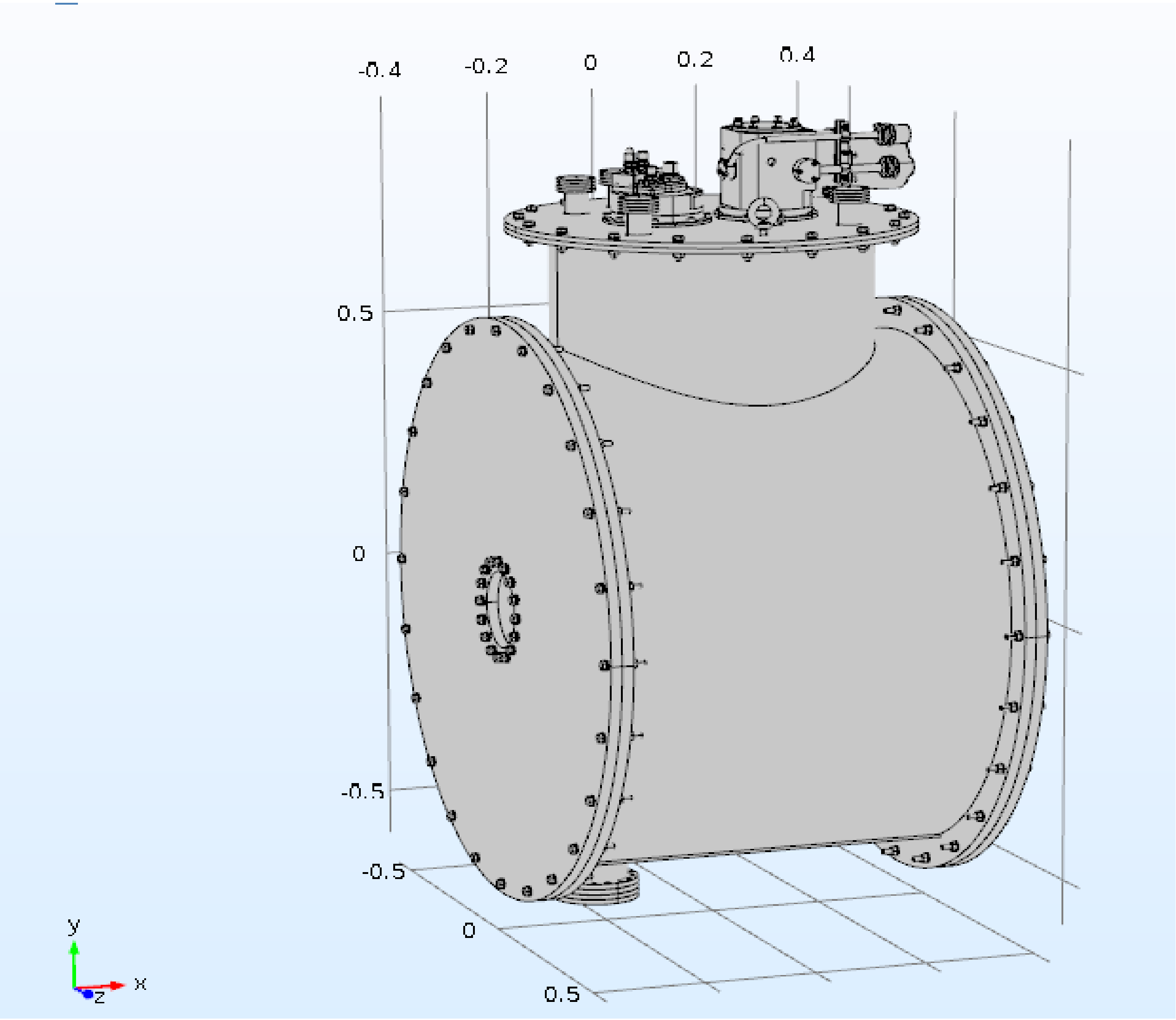
(For low energy nuclear reaction)

1. Cryostat Design completed
    - Heat load estimation
    - Resistive region of Current lead optimization
    - MLI
    - Support Post
    - Vacuum vessel
    - Thermal strapping

2. SC Solenoid design completed

3. Fabrication of Cryostat is in advance stage

4. Quench Protection system is in advance technical discussion stage.



Summary & Conclusion

1. Conceptualized Beam Layout for Low energy Reactions
2. Involvement of different engineering disciplines
3. Temperature dependent behaviour of Superconducting materials
4. Engineering design and components of SC Magnet
5. Heat Flow Path
6. Available Cooling Capacity
7. Different Types of Superconducting wire & Critical Surface for NbTi
8. Solenoid design for 3T
9. Static structural for evaluating Maximum Von-Mises Stress
10. Normal zone propagation and its velocity
11. Recovery the superconducting State
12. Diode-Resistance Quench Protection System
13. Current status

Future Work

1. 3D Quench Analysis (Transient Heat Transfer) to be carried out
2. V-I characteristics, dependency of the conductor resistivity on B-field, Temperature
3. Inductance and eddy-current effects inside the coil and in other structural elements
4. Quench Protection system

Thank You For Your Kind Attention