Preliminary design and analysis of 20 K helium cooled MgB_2 based superconducting current feeder system for Tokamak application

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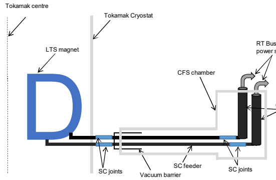
27th International Conference on Magnet Technology (MT-27)

Fukuoka, Japan / 2021

Primary Abstract ID: 962 [THU-PO3-614-03]

Introduction

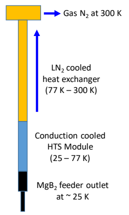
- Magnesium diboride (MgB_2) with a T_c of 39 K, could be a potential alternative owing to its lower manufacturing cost, ductile nature and ease of availability compared to other HTS specially in moderate magnetic field (up to 5 T) application like in MRI magnets. To assess its suitability, 1-D thermo-hydraulic study of 10 kA rated MgB_2 current feeders system (CFS) cooled with 20 K helium for SST-1 tokamak is reported as a case study. It yields a temperature margin of 6 – 16 K across the entire length of feeder depending up on mass flow rate of helium. There is also a possibility of cooling a binary current lead (HTS + MgB_2) from cold helium coming out from the feeder. There are also benefits of lower mass flow requirement, higher temperature margin, reduced pressure drop, lesser frictional pressure loss and lesser pumping power for cold circulator pump needed for forced flow cooling.



Schematic of the TF feeder layout from SST-1 cryostat to CFS chamber

Objective and Motivation

- Low temperature superconductors (LTS) like NbTi/Nb_3Sn based magnets and their feeders are normally cooled using liquid helium and have lower temperature margin of (0.5 K - 2 K). While MgB_2 based feeders cooled using cold helium gas at 10 – 25 K can save cryogenic cost significantly and provide better cryo-stability as well as higher temperature margin than LTS.
- Existing NbTi/Cu based CFS in SST-1 consume 1.2 g/s helium per pair at 4.5 K, 4 bar (a). So for 10 pairs, we have 12.0 g/s helium requirement. While our proposed MgB_2 feeders cooled using 20 K helium, would only require 6 g/s (0.6 g/s X 10 pairs).
- A binary current lead (HTS + MgB_2) is envisaged to be cooled with 25 K helium coming out from the feeder, which could save additionally 7 g/s liquid helium from cryoplant (~ 55% of total cryogenic plant capacity 1.3 kW at 4.5 K) required for vapor cooled CLs of SST-1 Tokamak.
- There is significant cryo capacity saving by a factor of 3 using this concept which motivated us to pursue present work. Such an MgB_2 SC current feeder system also has the advantage of higher Carnot efficiency. Additionally the coefficient of performance (COP) for cryogenic plant reduces at higher operating temperatures resulting in reduced cryogenic operational cost & power requirement. It could provide an economical, safe & reliable choice for next generation SC feeders.



Binary current lead (HTS + MgB_2)

Thermo-hydraulic analysis of MgB_2 feeder

- For SC, critical current density (J_c) is defined over the area of MgB_2 in the wire since this is a clearly defined quantity. We have used Kramer model scaling law of the critical current $I_c(B,T)$ is defined by the following expression:

$$I_c(B,T) = \frac{C(T)}{B}\left(\frac{B}{B^*(T)}\right)^p\left(1-\frac{B}{B^*(T)}\right)^q \quad (1)$$

where,

$$B^*(T) = B^*(0)\left(1-\left(\frac{T}{T_c}\right)^\alpha\right) \quad (2)$$

$$C(T) = C_0\left(1-\left(\frac{T}{T_c}\right)^\beta\right)^\gamma \quad (3)$$

where, T_c is the superconducting transition temperature, $B^*(T)$ is irreversibility field. For design purpose, following values of scaling parameters are used for MgB_2 wires [4], C_0 = 2.89 × 10⁴ AT, $B^*(0)$ = 13.5 T, operating temperature T_{op} = 4.5 K, critical temperature T_c = 39 K, α = 1.2, p = 0.5, q = 5, γ = 1.89 and β = 1.55.

The current sharing temperature (T_{cs}) & temperature margin are expressed as:

$$T_{cs} = T_{op} + (T_c - T_{op})\left(1-\frac{I_{op}}{I_{cop}}\right)$$

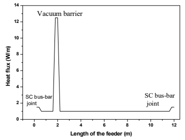
Where, I_{cop} is critical current at operating temperature.

$$T_{margin} = T_{cs} - T_{op}$$

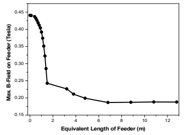
20 K Helium cooled MgB_2 current feeder system

Thermo hydraulic study for MgB_2 feeder is performed using 1-D steady-state hydraulic analysis. For this analysis, following are the basic assumptions:

- Cooling media is forced flow helium at 20 K, 0.4 MPa
- Coolant entry from the magnet end is considered which is a high magnetic field side where the temperature margin is relatively lower compared to that of the current leads (CL) side.
- The void fraction in the cable is ~ 45%
- The joint resistance of 2.0 nΩ is considered for each SC joint at the magnet terminal and at CL bottom terminal.
- Modified Katheder type friction factor for CICC is used in the analysis
- The scaling parameters used for MgB_2 wires are used as per [4]
- The minimum temperature margin requirement is ~ 1.5 K



Heat flux profile along MgB_2 feeder

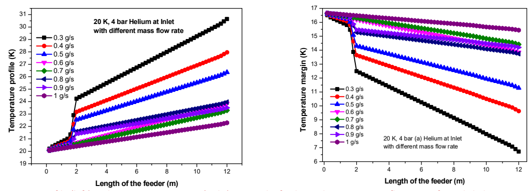


Estimated magnetic field profile along the length of feeder in SST-1 Tokamak

Design parameters & thermo-hydraulics of MgB_2 feeder

Conductor type	MgB_2 wires (1 mm diameter with 20 % MgB_2 fraction) Matrix materials: Monel, Nb barrier
Jc @ 20 K & 0.5 T	~ 4000 A/mm²
Operating Current	10 kA
Design Current	36 kA
Cable parameters	24 MgB_2 wires (twisted wires pattern); 72 Cu wires as stabilizer (1 mm diameter with RRR = 100)
Coolant	Gaseous helium at 20 K, 4 bar (a)
CICC Diameter	OD: 14.8×14.8 (mm²), ID: 11.8×11.8 (mm²)
Conduit material thickness	1.5 mm thick SS304L
Void fraction	~ 45 % (+/- 2 %)
Helium flow area	63.77 mm²
Cu cross sectional area	56.57 mm²
MgB_2 cross sectional area	18.86 mm²
Wetted perimeter	0.267 m
Hydraulic diameter	0.833 mm

Design parameters of proposed MgB_2 feeder



Temperature profile (left) and temperature margin (right) across the feeder with varying mass flow rate of supply helium at 20 K, 4 bar (a)

Pressure drop across MgB_2 feeder

- For a steady flow of an incompressible fluid in a pipe, pressure drop can be found using the following relation:

$$\Delta P = \frac{f L \rho v^2}{D_h}$$

where ΔP is the pressure drop, f is friction factor, L is the length of the cable, D_h is the hydraulic diameter of CICC, ρ and v are the density and velocity of coolant (helium).

- For calculating ΔP inside CICC, modified Katheder type friction factor is used given as:

$$f = \frac{1}{\varphi^{0.72}}\left[\frac{19.5}{Re^{0.88}} + 0.051\right]$$

where φ is the void fraction of CICC,

- Re is the Reynolds number given as:

$$Re = \frac{\rho v D_h}{\eta}$$

where η is dynamic viscosity of He.

- Velocity of fluid can be found using relation:

$$v = \frac{\dot{m}}{A_f\,\rho}$$

where, $\dot{m}$ is the mass flow rate and A_f is the flow cross-sectional area of helium.

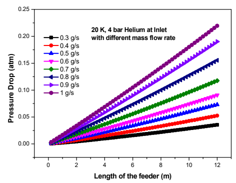
- Wetted perimeter (p_w) is given as:

$$p_w = 0.73\, N_s \pi a + 4\, ID$$

where N_s is the number of wires, a is the diameter of SC wire and ID is the inner diameter of CICC.

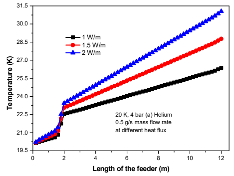
- Hydraulic diameter is calculated using:

$$D_h = \frac{A_f}{p_w}$$

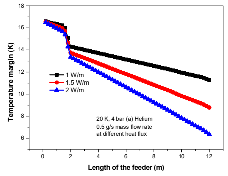


Pressure drop across the feeder with varying mass flow rate of supply helium at 20 K, 4 bar (a)

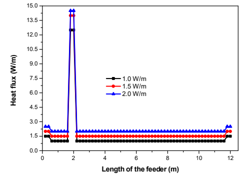
Effect of varying heat flux on feeder



Temperature profile along the feeder



Temperature margin across the feeder



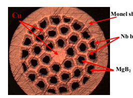
Varying heat flux across the feeder

- Under abnormal events like vacuum degradation in cryostat, additional heat loads falls on feeder. It leads to increase in temperature of the feeder and thus reducing temperature margin of the superconductor and may lead to quench.
- For heat flux ranging from 1.0 W/m to 2.0 W/m, temperature profile and temperature margin across the feeder are calculated for optimum mass flow rate of helium at 0.5 g/s.
- With increasing heat flux, temperature margin across feeder reduces as the temperature rises due to increased heat loads.
- For heat flux of 2 W/m, temperature margin of minimum 1.5 K is achieved with 0.5 g/s helium flow.

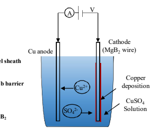
Summary and Conclusion

- Preliminary design and thermohydraulic study of 20 K helium cooled MgB_2 based superconducting current feeder system is performed.
- Temperature margin and corresponding pressure drop along this feeder are calculated for mass flow rates ranging from 0.3 g/s to 1.0 g/s helium at 20 K, 4 bar (a) with a cooling inlet from the magnet side.
- From our study, MgB_2 SC feeder yields a temperature margin of more than 6 K across the entire length of feeder for optimum mass flow rate of 0.3 g/s at 20 K, 4 bar (a). Effect of varying heat flux is also carried out on performance of this feeder.
- A binary current lead (HTS + MgB_2) is envisaged to be cooled with helium coming out from the feeder. There is significant cryo capacity saving using this concept. It provides benefits of lower mass flow requirement, higher temperature margin and reduced pressure drop than existing NbTi based feeder.
- Development of a prototype MgB_2 short cable and its SC joint fabrication procedure using Cu electroplating technique is now underway. Such a MgB_2 based current feeder is planned which could provide an economical, safe and reliable choice for next generation SC feeders in future.

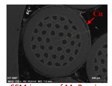
Prototyping and Test Plan



Micrograph of cross-section of commercial MgB_2 wire

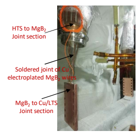


Cu electroplating set-up for fabrication of MgB_2 SC joints

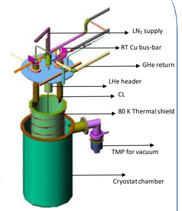


SEM image of MgB_2 wire with electroplated Cu

Heat treatment of MgB_2 short cable (twist & react)



HTS module to MgB_2 joints



Schematic of CL Test Set-up

Acknowledgements:

The authors would like to thank Mr. U. Prasad (Magnet System Division) for fruitful technical discussions and suggestions related to this work; Mr. D. Sonara, Mr. H. Nimavat, Mr. A. Garg and all members of SST-1 Cryogenic Division for helping in preparations for HTS+MgB_2 current leads test set-up; Dr. K. P. Singh, Mr. P. Mokaria, Mr. S. Belsare, Ms. P. Patel (members of the High Temperature Technology Division) for extending help with optical measurement and heat treatment of MgB_2 wires; Ms. P. Kikani and Ms. N. Chandwani (members of Atmospheric Plasma Division) for SEM and EDX analysis of MgB_2 wires.

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