27th International Conference on Magnet Technology (MT27)
Fukuoka, Japan / 2021

SESSION ID: THU-PO3-LN2-06

OPTIMIZED DESIGN OF CRYOGEN-FREE MAGNET CONSIDERING THERMAL INSULATED STRUCTURES FOR 170-GHZ GYROTRON

Seokho Nam[a], Seungje Lee[b], and Jae Young Jang[c*]

[a]**Korea Institute of Fusion Energy in Korea**, [b]JH Engineering Co., Ltd., in Korea and [c*]Korea University of Technology & Education (KOREATECH) in Korea

ABSTRACT

A electron cyclotron is to heat a plasma by driving current in a fusion system. This system requires strength and accurate magnetic field distribution for the interaction of the electron beam and radio frequency wave energy. The magnet of the system consists of a conduction-cooled superconducting magnet for 7 T and structures connected with a 2nd stage GM cryocooler of 1.5 W at 4 K for cooling of the magnet. This paper deals with the design of magnet and conduction-cooling structures considering electrical and thermal stabilities. The design and quench analysis are carried out to develop the 7 T class superconducting magnet for electron cyclotron. The magnet is wound with the NbTi conductor. The inner bore of the superconducting coil is 200 mm to obtain the resonance region. The optimal magnet design considering the normal stresses generated by the electromagnetic force, magnet critical current margin, axial field profile, field uniformity and losses under the AC operation (charging/discharging) is implemented before fabrication. Quench analysis is also carried out to ensure safe operation of the gyrotron magnet. And then, the frameworks were designed considering heat transfer and cooling watt of the GM cryocooler. The 170-GHz gyrotron magnet will be fabricated with an auto-mated winding machine based on to the design results.

1. GYROTRON MAGNET DESIGN

- To design the 170 GHz gyrotron magnet with specific conditions, we adopt an optimization method employing genetic algorithm.
- Table I and Fig. 1 show the deign variables and algorithm.

TABLE I
DESIGN SPECIFICATIONS OF THE 170 GHZ GYROTRON MAGNET

Parameters	Constraints
Center field	> 7.2 T (with NbTi wire)
Winding bore	> 200 mm
Field uniformity	< 0.1 % @10 mm DSV*
Field(axial) tolerance	< 0.1 % (z<15mm) / < 3 % (z≥15mm)
Operating current	150 A
Max. hoop stress	< 130 MPa
Radial stress	Negative (Compressive)
Critical current margin	> 30%
Height	< 270 mm
Max. temperature	< 150 K
Max. voltage	< 1.8 kV

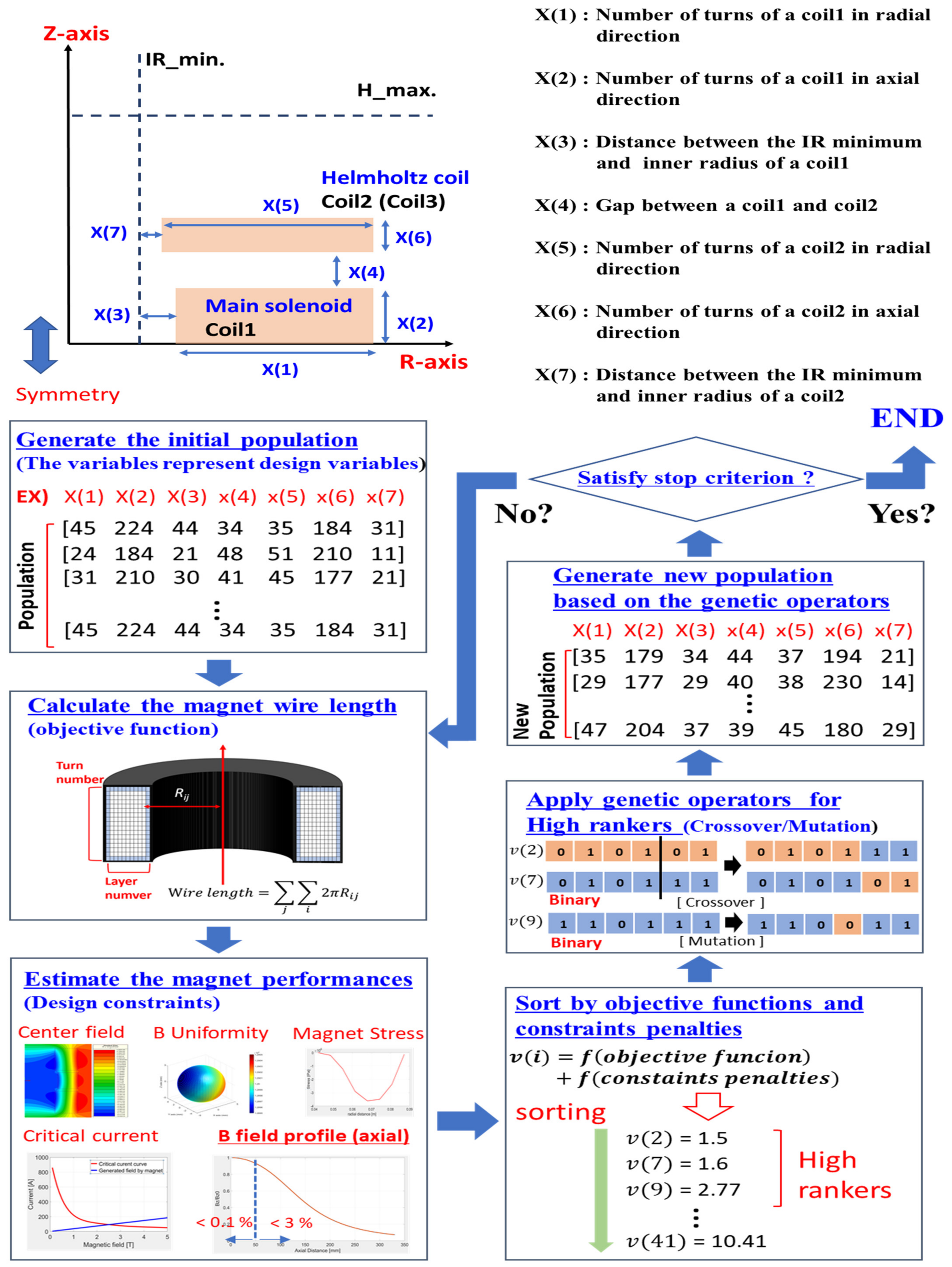


Fig. 1. Quench Simulation Results

- To design, a NbTi wire was selected considering current, field, Cu/non-Cu ratio, filament #, and twisted pitch length.
- The design results from the optimization code are shown in Table II and Fig. 2.
- After magnet design, the structures were designed considering cooling watt and heat transfer.
  - bobbin, thermal shields, vacuum vessel, thermal insulation supports, and thermal link were designed.
- The induced heat transfer was calculated, and the results show in Table III.

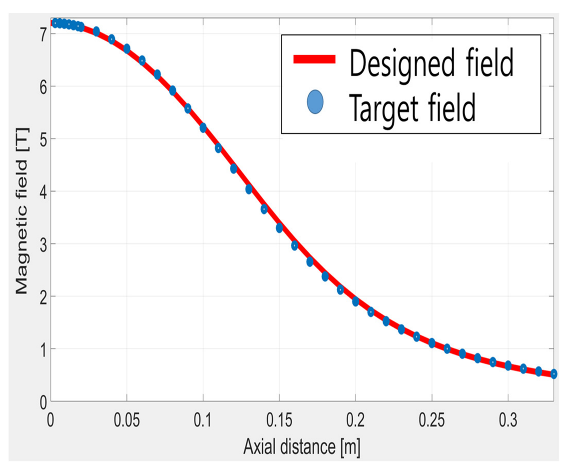


Fig. 2. Calculated field profile of the designed magnet

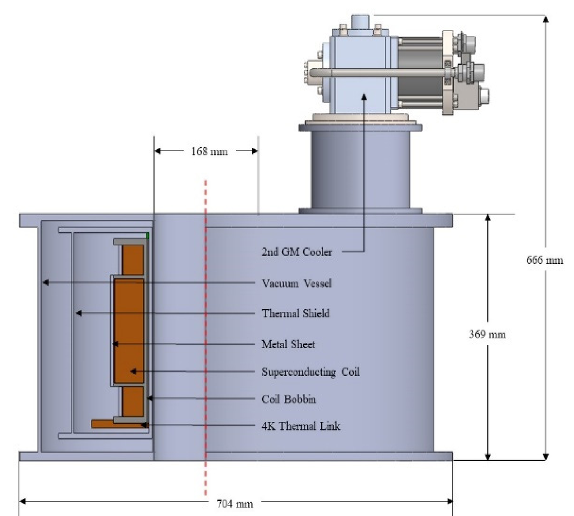


Fig. 3. Conceptual design of 170 GHz gyrotron magnet

TABLE II
DESIGN SPECIFICATIONS OF THE 170 GHZ GYROTRON MAGNET

Parameters	Dimensions
Coil 1 inner radius	100 mm
Coil 1 outer radius	147.7 mm
Coil 1 turn number	53 (radial) /174 (axial)
Coil 2(3) inner radius	100.7 mm
Coil 2(3) outer radius	133.3 mm
Coil 2(3) turn number	37 (radial) /50 (axial)
Gap between coil1-coil2(3)	5.3 mm
Height	257.2 mm
Total length	9.89 Km

Parameters	Performance
Center field	7.2 T
Total Inductance	23.8 H
Field uniformity	0.07 % @ 10 mm DSV
Field (axial) deviation	< 0.08 % (z<15mm) / < 2.96 % (z≥15mm)
Magnetic hoop stress	89.8 MPa (radial stress < 0)
Critical current margin	> 40 % @ 4.2 K

TABLE II
HEAT TRANSFER OF DESIGNED 170 GHZ GYROTRON MAGNET

Parameters	1st Stage [W]	2nd Stage [W]
Cooling Watt	45	1.5
Conductive Heat	0.26	0.009
Radiative Heat	4.77	0.006
HTS Current Lead	10.96	0.19
Cooling Margin	29.01	1.295

2. QUENCH ANALYSIS

- Quench analysis was carried out by using the simulation program (made by MATLAB/SIMULINK) for safe operations of the designed NbTi magnet.
  - Analyzed normal zone propagation,
  - Calculated hot spot temperature,
  - Calculated peak voltage.
- To avoid high voltage generation, sub-division method was adopted in the magnet.
- Fig. 5 shows the quench protection circuit (a) and simulation results of normal zone propagation (b).
- Maximum temperature and voltage are under 85 K and 1.7 kV, respectively.
- The magnet is expected to meet design conditions.

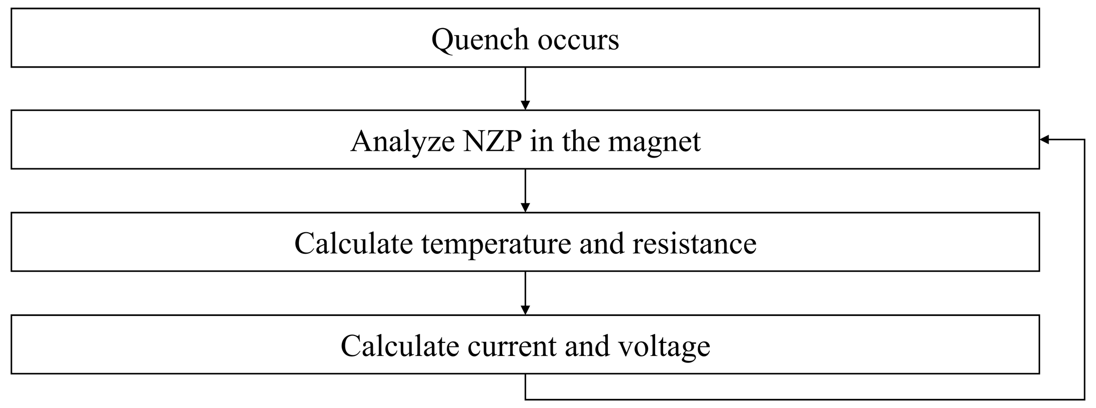
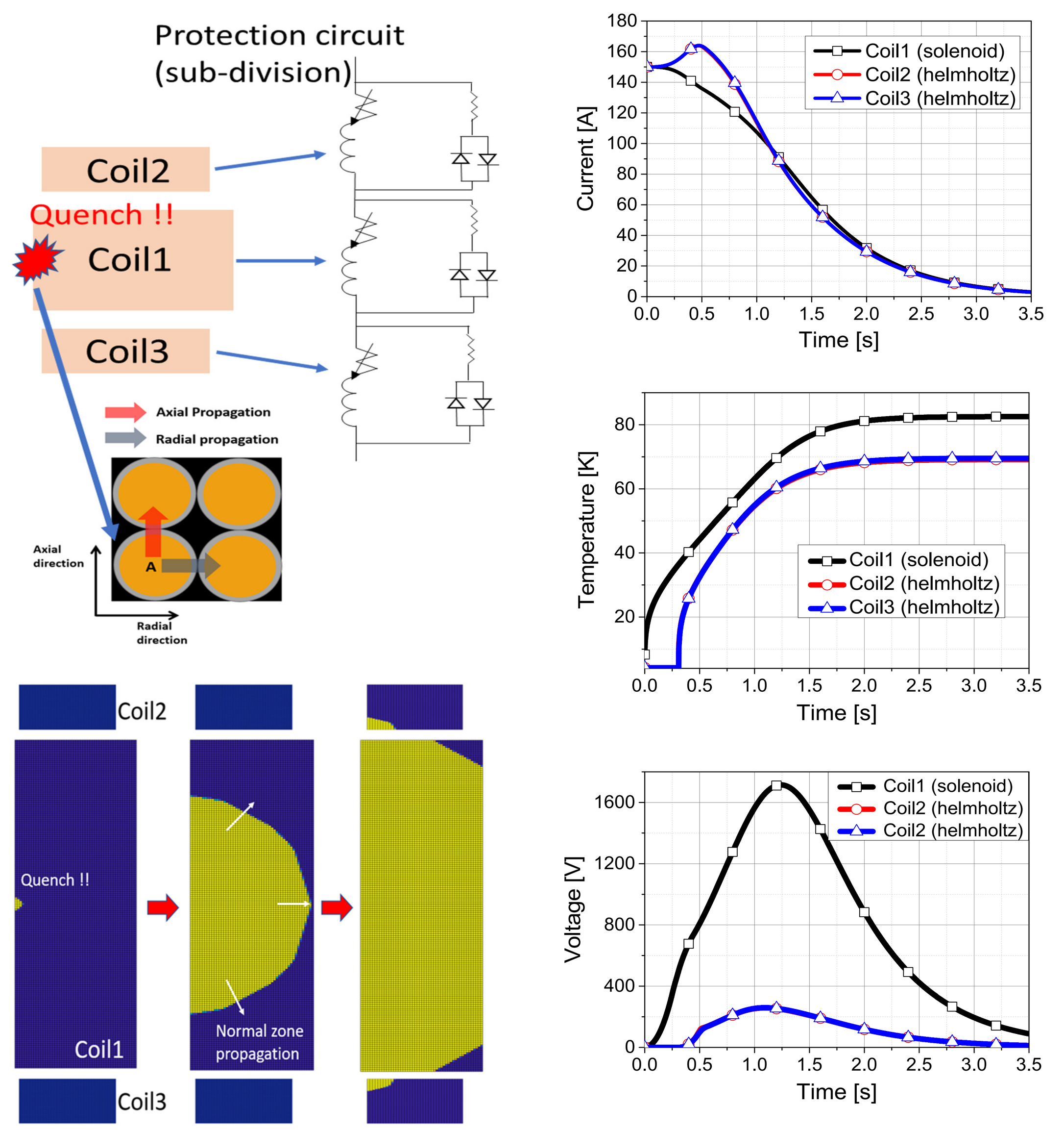


Fig. 4. Flow Chart for quench propagation analysis



(a) System scheme and propagation (b) Quench analysis

Fig. 5. Quench Simulation Results

3. MANUFACTURING RESEARCH

- To minimize manufacturing errors of superconducting coil, the automatic winding skills are required for manufacturing coils.
- For this reason, JHENG is developing the automatic winding methods.
- To apply the automatic winding method in superconducting coils, two systems must be researched.
  - Automatic winding machine and winding skills.
  - Development of vacuum impregnation system and recipes for impregnation
- The developed automatic winding and vacuum impregnation systems are shown in Fig. 6-(a) and 6-(b), respectively.
- These systems and skills will be used to manufacturing the gyrotron magnet.

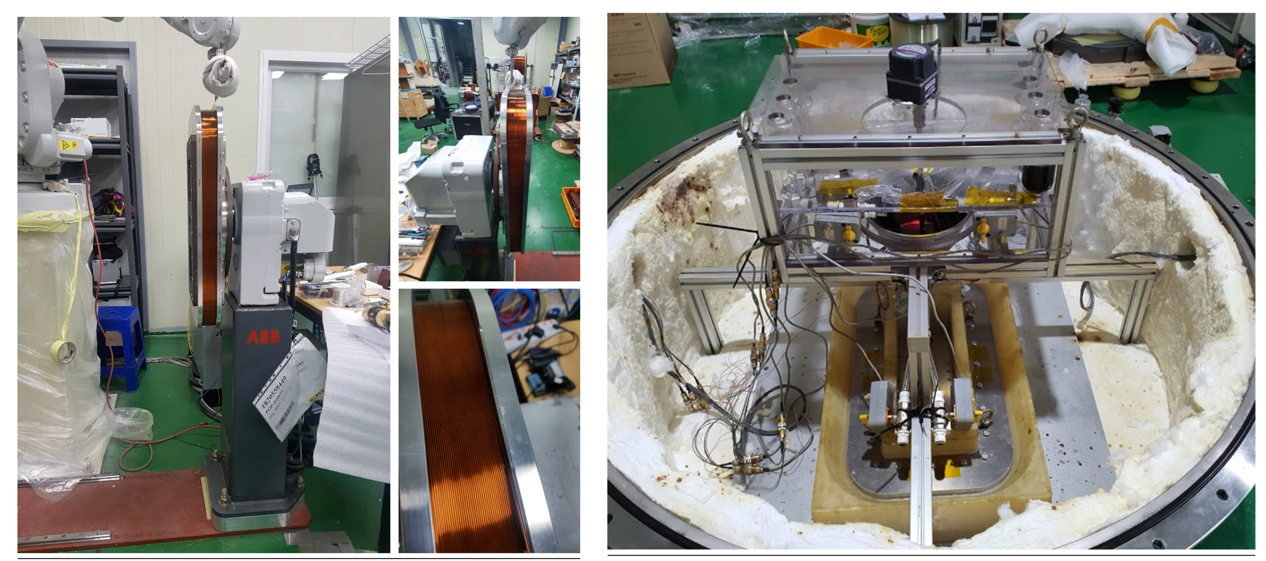

(a) Automatic winding machine (b) Vacuum impregnation machine

Fig. 6. Manufacturing System for Superconducting Magnet

4. CONCLUSION

- The superconducting coils were designed using an optimization method employing genetic algorithm.
- The design constraints are center field, field uniformity, magnetic stress, critical current, and field tolerance.
- Structures for the magnet are designed considering thermal properties and cooling watt of the GM cryocooler.
- After design, quench simulation was carried out for safe operations of the magnet during a quench.
- As a results, the designed magnet is expected to satisfy the design conditions and operate stably.
- The magnet will be fabricated based on the design results.

This paper was supported by Education and Research promotion program of KOREATECH in 2021 (Corresponding author: J. Y. Jang).
This work was supported by the Korean Ministry of Science and ICT.

KOREA INSTITUTE OF FUSION ENERGY