Cryogen Recondensed Cooling System for Electron Beam Ion Source Employing 7 T Superconducting Solenoid Magnet

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Background

Electron beam and proton accelerators have been used by many users in a wide range of fields. Development of an Electron Beam Ion Source (EBIS) capable of short pulse operation of less than 1 μs is needed to improve the utilization efficiency of users and to widen application field. In this cooling mechanism, the liquid helium recondensation system was adopted because the approach is not easy by the strong x-ray generated during the operation of the EBIS system. Therefore, the cryogen recondensed cooling system was designed for an EBIS employing 7 T superconducting solenoid magnet. The proposed cooling system was implemented in a large and horizontal direction based on the unique shape of the superconducting magnet.

Objectives

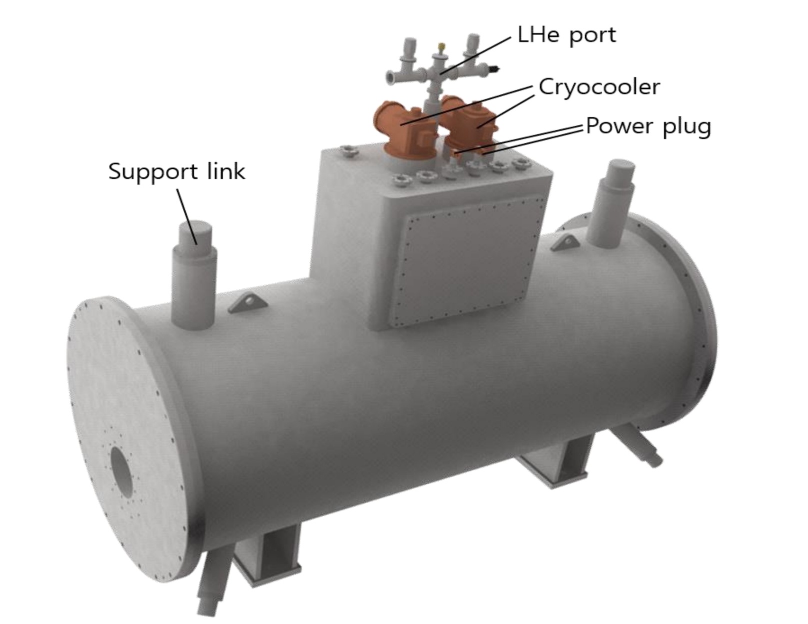
- The thermal stability should be evaluated by calculating whether the generated heat load in each stage is below the cryocooler capacities.
- The stress and deformation by temperature gradient should be confirmed to secure the structural stability.

Conclusion

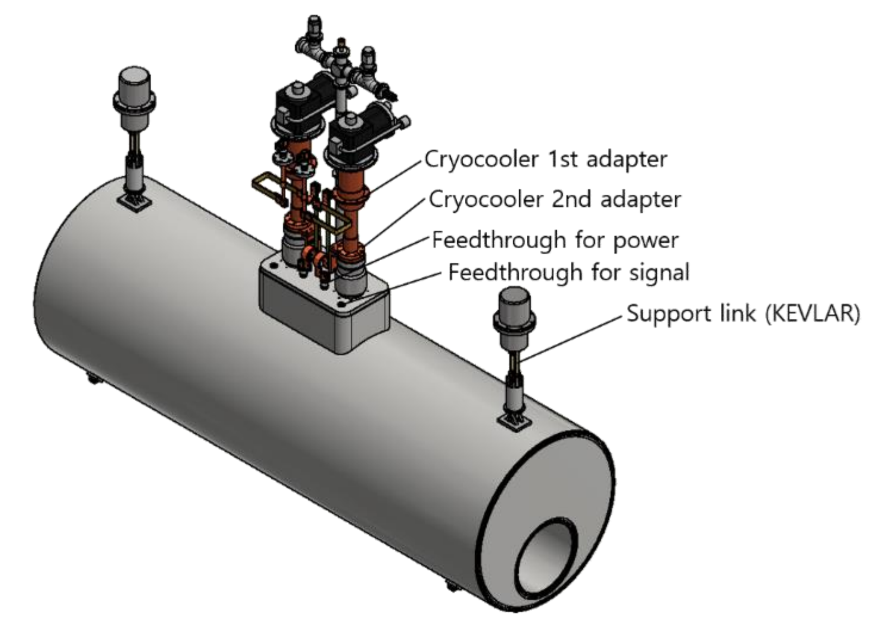
- The cryostat of superconducting magnet for EBIS was successfully designed with relatively large and horizontal structure.
- The designed model was calculated by thermal and structural analyses by using the finite element analysis.
- When current was not applied, both thermal shield and helium vessel had cooling margin of ~60 %.
- The maximum thermal stress for the temperature gradient was much lower than the yield strength of the medium.
- The deformation due to the thermal stress was estimated to be ~0.33 %.
- the designed cryostat was thermally and structurally stable and is expected to be well applied to the EBIS system.

Designed System

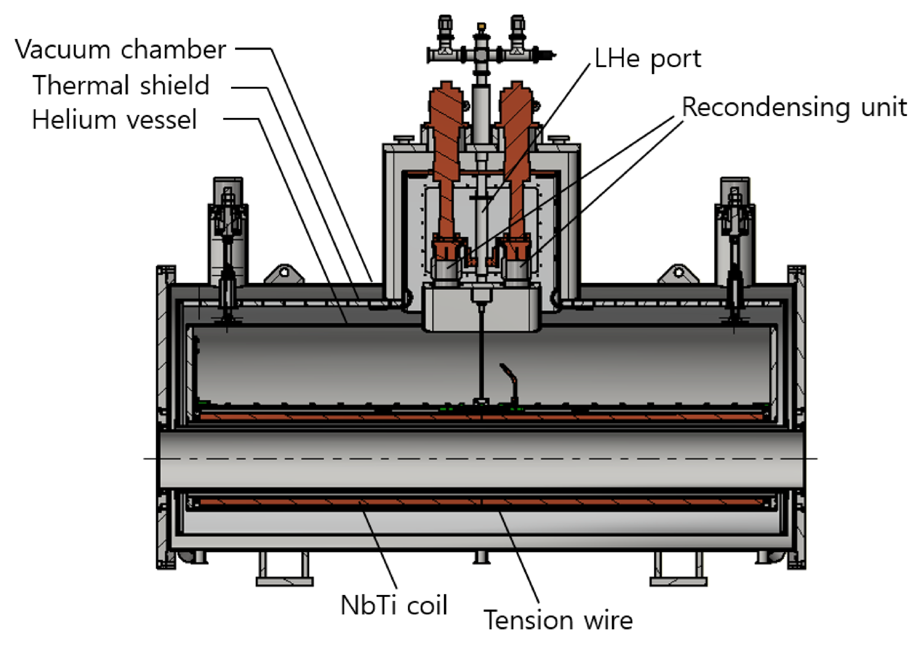
Cryogen Recondensed Cooling System



The overall structure of the cryogen recondensed cooling system.



The structure of the helium vessel and componets connections.



Cross section of the cryogen recondensed cooling system.

Design Parameters

Parameters	Values
Outer diameter of vacuum chamber	950 mm
Inner diameter of vacuum chamber	204 mm
Outer diameter of thermal shield	840 mm
Inner diameter of thermal shield	230 mm
Outer diameter of helium vessel	662 mm
Inner diameter of helium vessel	260 mm
Horizontal length of cryostat	2300 mm
Capacity of helium vessel	400 L
Internal pressure of helium vessel	3×10^5 Pa
Leak rate of vacuum for cryostat	1×10^{-9} Pa•m³/s

Heat Load Calculation

- Conduction

$$Q_{con} = \frac{A}{l}\int_{T_L}^{T_H} k(T)\,dT$$

- Radiation

$$Q_{rad} = \sigma \cdot A \cdot \frac{\varepsilon}{N+1} \cdot (T_H^{\,4} - T_L^{\,4})$$

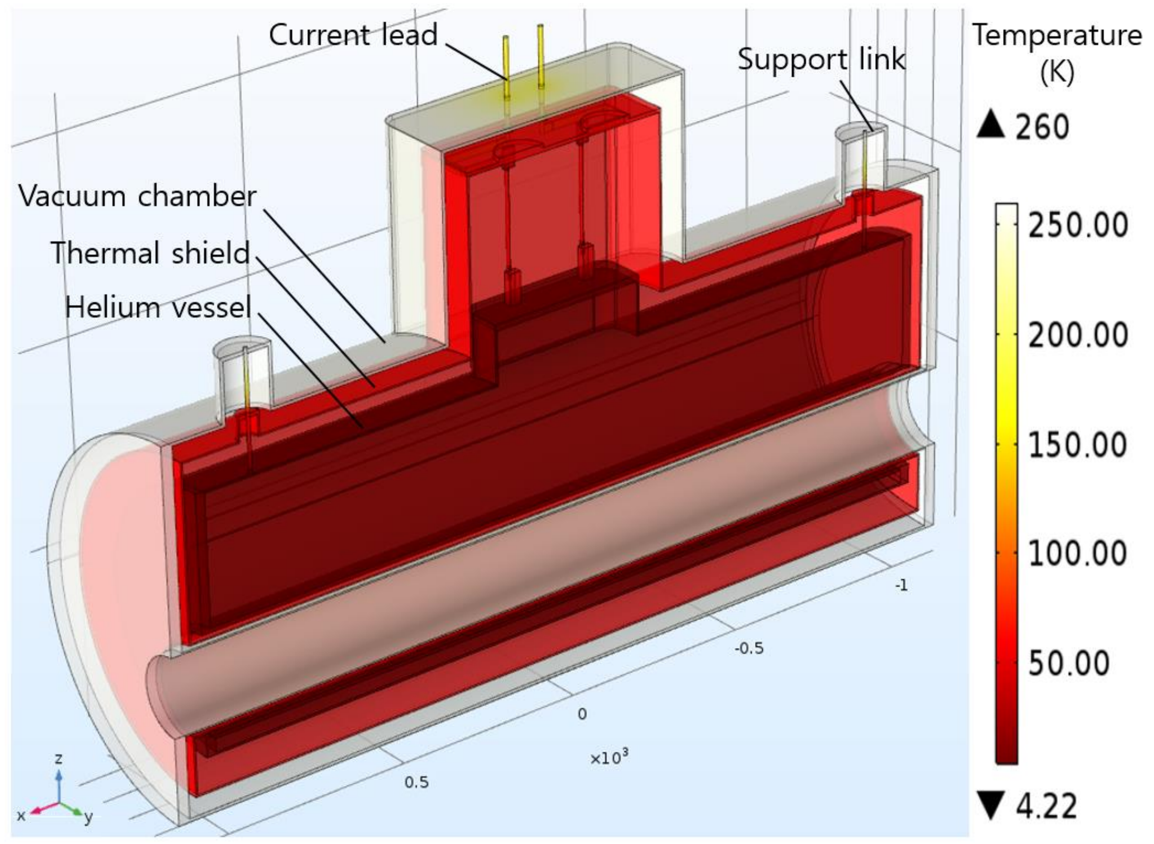
- Residual gas conduction

$$Q_{rgc} = \left(\frac{a}{4} \cdot \frac{\gamma+1}{\gamma-1} \cdot \sqrt{\frac{2 \cdot R}{\pi \cdot M}}\right) \cdot P \cdot \frac{T_H - T_L}{\sqrt{T_{ave}}}$$

k(T) – thermal conductivity with Temp.
σ – Stephen-Boltzmann constant
ε – emissivity
N – turn number of MLI
a – accommodation coefficient
γ – specific heat ratio of the gas
R – gas constant
M – molecular weight of gas
P – gas pressure

Analysis Results

Thermal Analysis



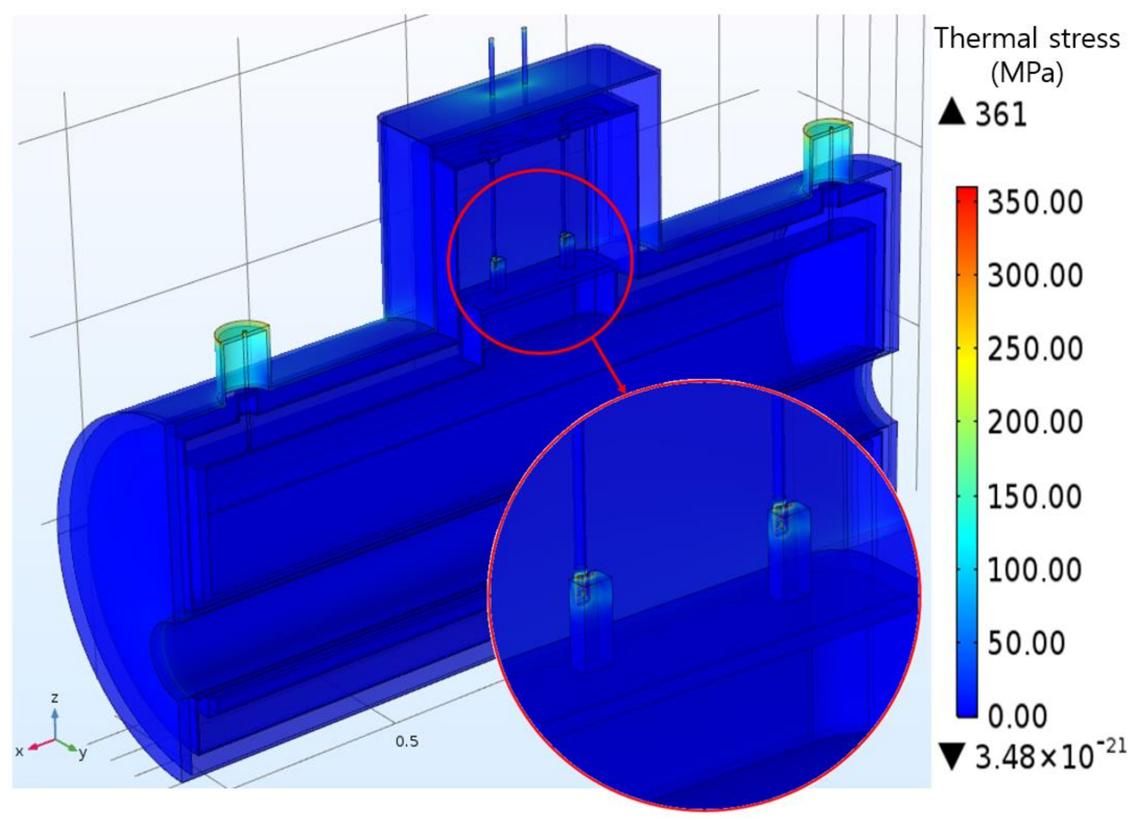
Temperature distribution of cryostat with current leads and support links.

Results of the heat loads in the designed cooling system.

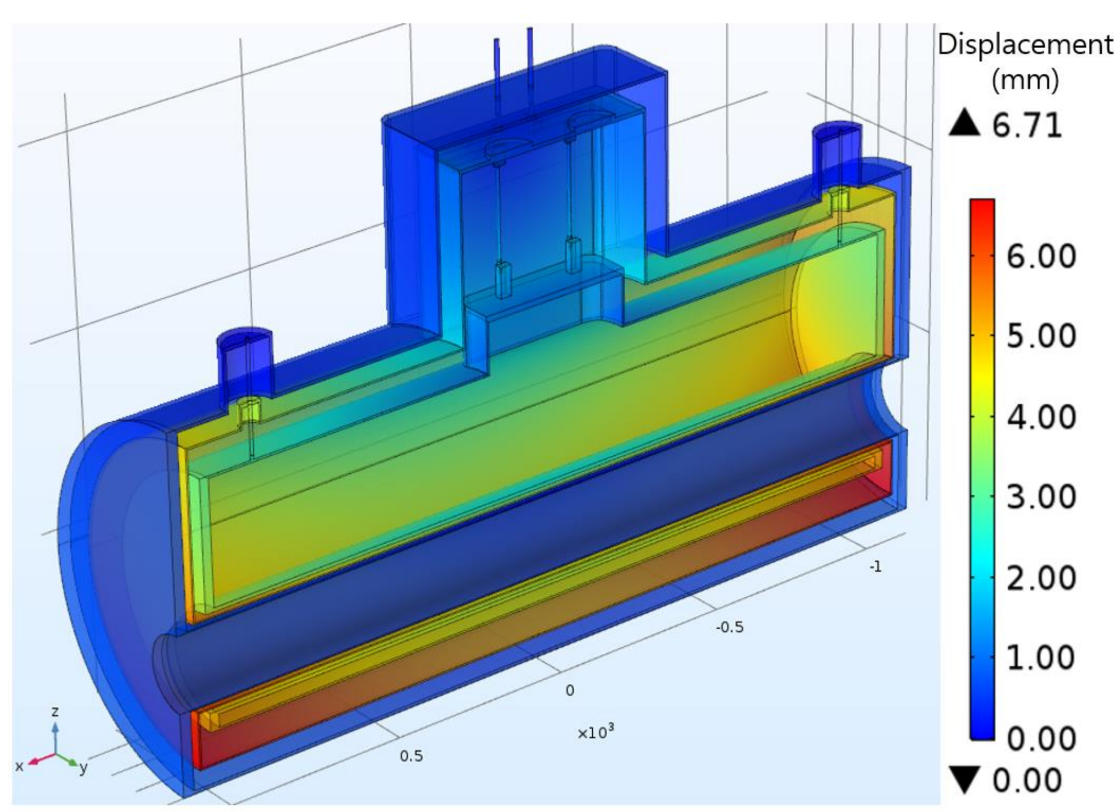
Heat loads	Thermal shield (W)	Helium vessel (W)
Conduction	11.104	0.363
Joule heating	33.05	0.076
Radiation	1.85	0.175
Total without current	12.954	0.538
Total with 200 A current	46	0.614

- The cooling capacity of the cryostat is 50 W at the 1st stage and 1.5 W at the 2nd stage.
- When a current is applied, there is a cooling margin of ~8 % (~4 W) and ~59 % (~0.88 W) in shield and helium vessel, respectively.
- When the current is not applied, both the 1st and 2nd stages have a margin of ~60 %.

Structural Analysis



Thermal stress results of structural analysis for ½ cryostat model.



Total displacement results of structural analysis for ½ cryostat model.

- The maximum thermal stress distributions in the thermal shield and helium vessel were calculated to be 0.1 MPa and 0.23 MPa, respectively.
- The maximum thermal stress, 361 MPa, was calculated at the support link of the vacuum chamber.
- The total displacements were calculated to be 6.7 mm and 5.24 mm in the thermal shield and helium vessel, respectively.
- The calculated maximum displacement of 6.7 mm is 0.33 % strain relative to the length of cryostat.

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