Design of a Conduction-Cooled 2.856 GHz Nb_3Sn SRF Cavity and Compact Cryomodule for Electron Accelerator

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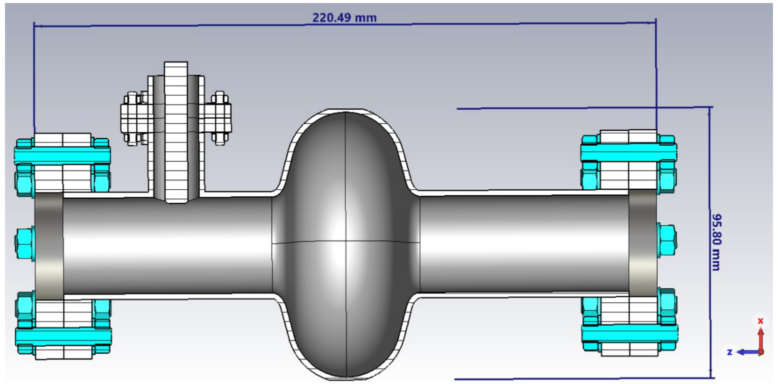
Goals

Nb_3Sn cavities have shown higher efficiency at 4K compared to pure niobium cavities when cooled using a conduction cooling system. This increased efficiency makes them suitable for more compact and cost-effective accelerator. Conduction-cooled SRF cavities, operating at 4K, do not require large-scale helium refrigerator systems, enhancing the compactness and efficiency of accelerator. Currently, a conduction cooling cryomodule is under optimization process.

- Conduction cooled 2.856 GHz cavity to be integrated to an existing linac at Tohoko University.
- Cavity RF parameters for 10 MV/m accelerating electric field to provide approximately 0.5MeV of energy gain to the electron beam.
- Compact cryocooled cryomodule to fit in limited space of one meter.

2.856 GHz cavity electromagnetic design

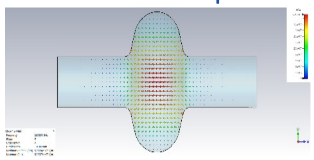
- The 2.856 GHz cavity design was scaled from 1.3 GHz Tesla shape design.
- CST Studio[1] was used for the simulation calculations.



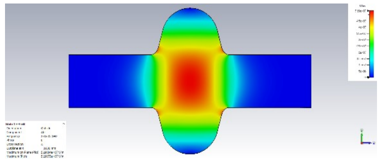
Cavity RF parameters for E_{acc} =10 MV/m is summarized in table below

Parameter	Unit	Value
Frequency	[GHz]	2.856
Voltage	[MV]	0.525
E_{acc}	[MV/m]	10.000
R_{shunt}	[MΩ]	0.806
R/Q	[Ω]	109.600
E_{pk}	[MV/m]	17.894
B_{pk}	[mT]	42.227
E_{pk}/E_{acc}		1.789
B_{pk}/E_{acc}	[mT/MV/m]	4.223

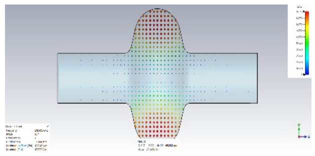
- Electric field profile



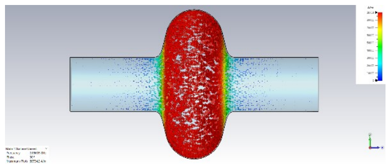
- Absolute Electric field

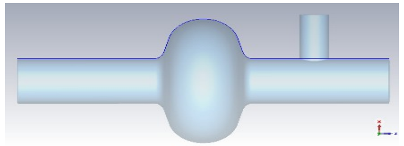


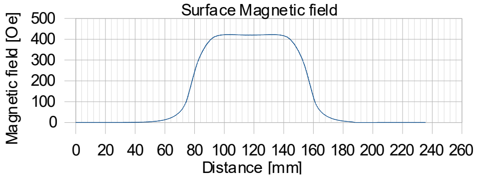
- Magnetic field profile

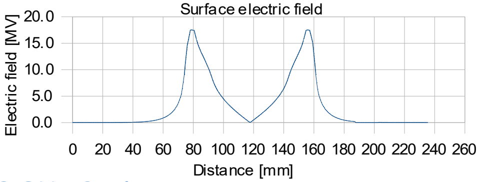


- Surface current



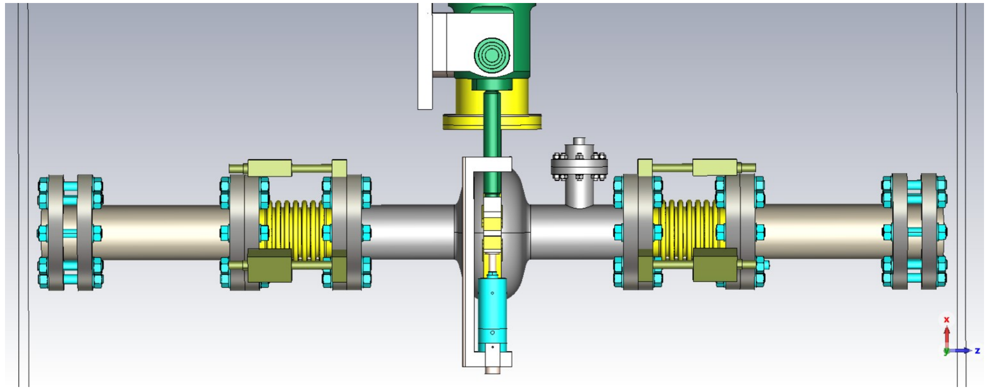


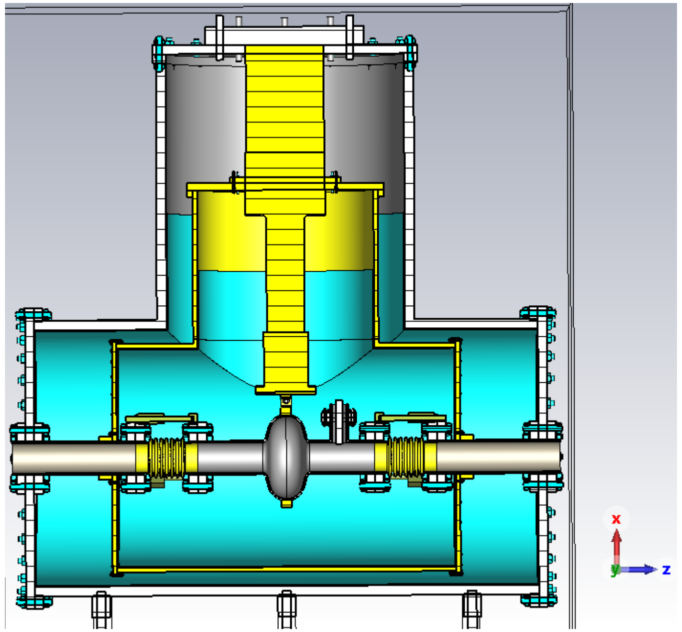


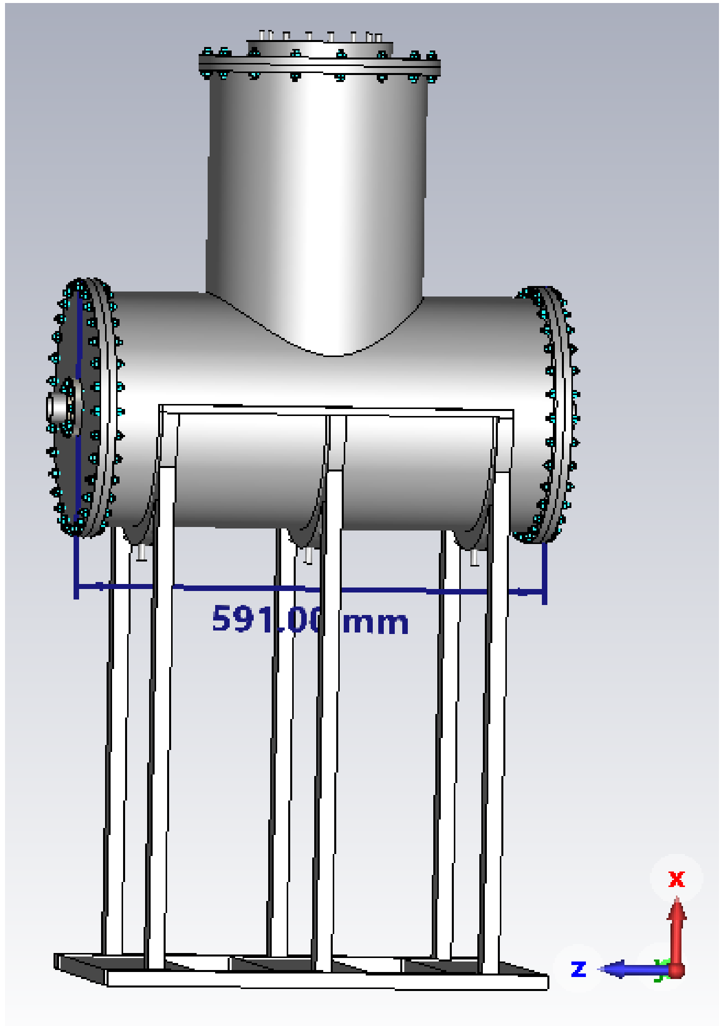


2.856 GHz cryomodule design

- **Cryomodule consists of:**
- 2.856 GHz cavity.
- Ring serves the purpose of dual function; conduction cooling system and Tuner.
- Cryocooler with a cooling capacity of around 1.8 W at 4.2 K.
- Magnetic shield to reduce the external magnetic field to less than 0.5 mG.
- Thermal shield connected to stage 1 of the cryocooler.
- Vacuum vessel.

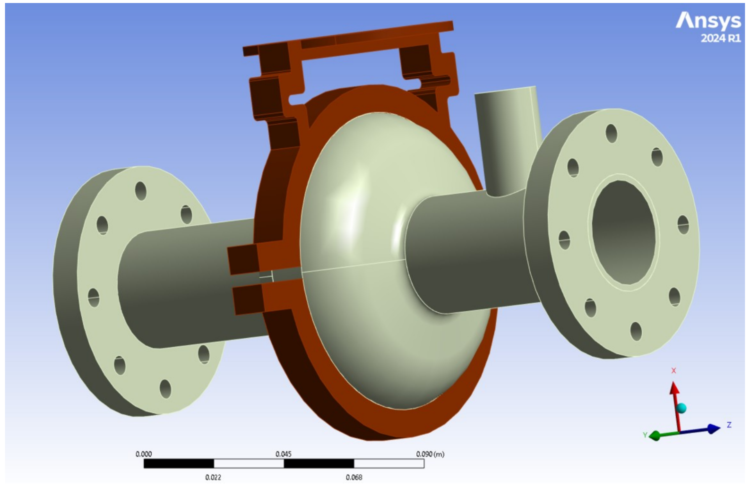


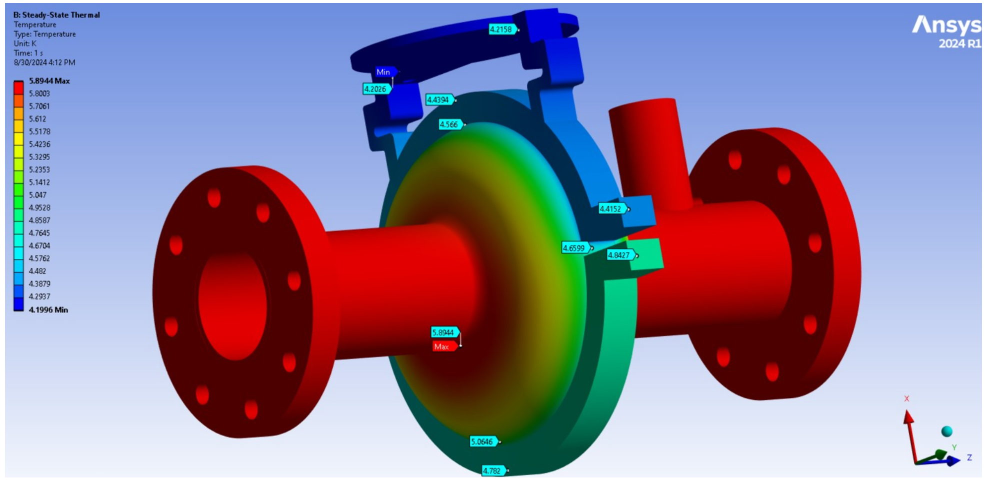




Thermal study for the conduction cooling system of the cavity

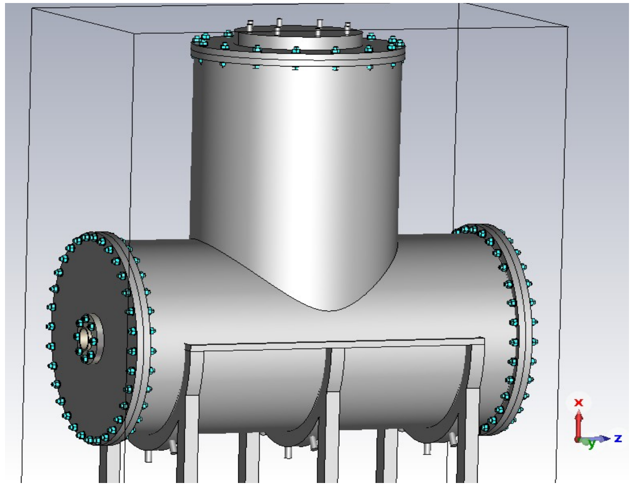
- Conduction cooling system consists of ring surrounding the cavity equator connected to stage 2 of cryocooler head.
- Copper material with RRR= 300 was utilized for Ansys thermal simulation study[2].
- Heat load of 1.5 W was applied at cavity equator, it showed a temperature rise of ΔT = 1.6 K.

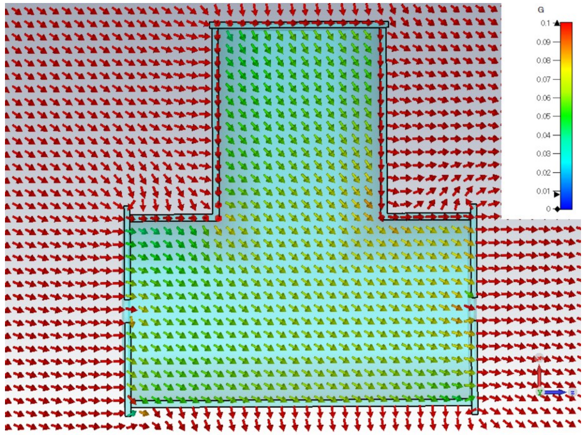


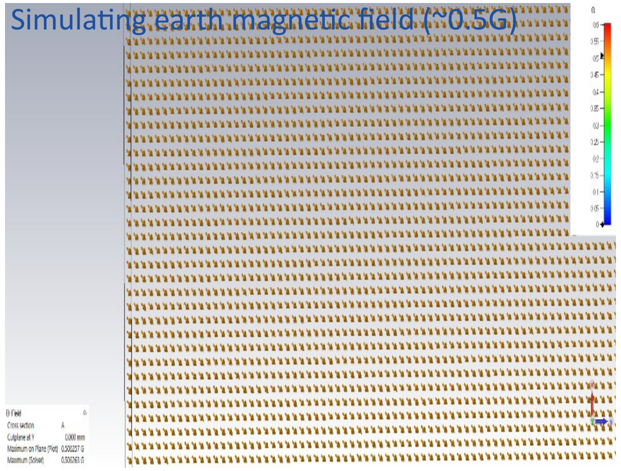


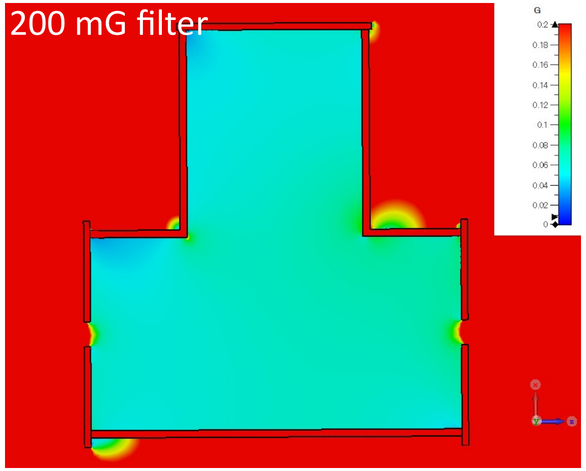
Vacuum vessel for 2.856 GHz cavity

- SS400 vacuum vessel with a thickness of 11 mm can reduce the external magnetic field (earth magnetic field roughly equal to 0.5 G) to less than 65 mG.
- After the vessel fabrication, demagnetization process maybe needed to minimize residual fields in vessel.
- The simulated earth magnetic field is assumed that its strength is 0.5 G, pointing from north west to south east.



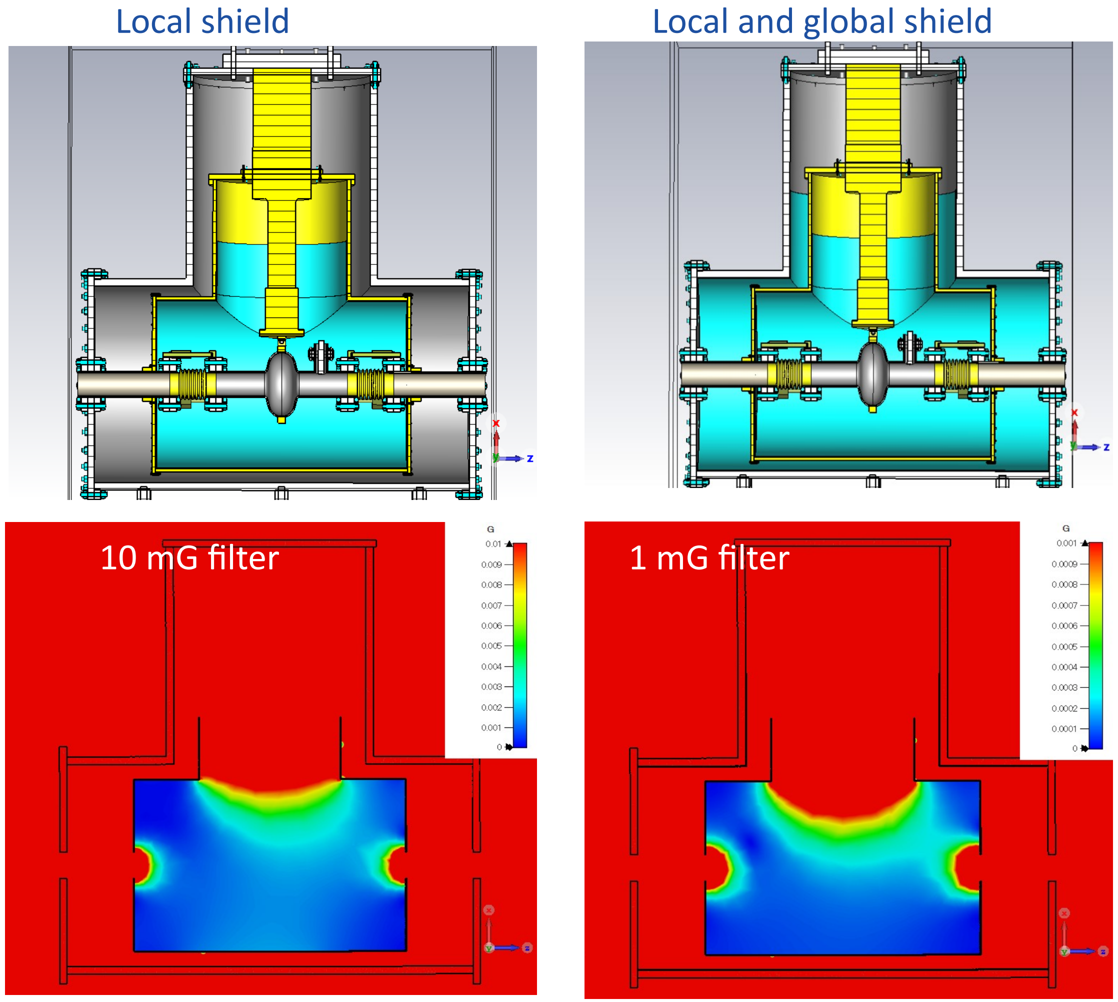






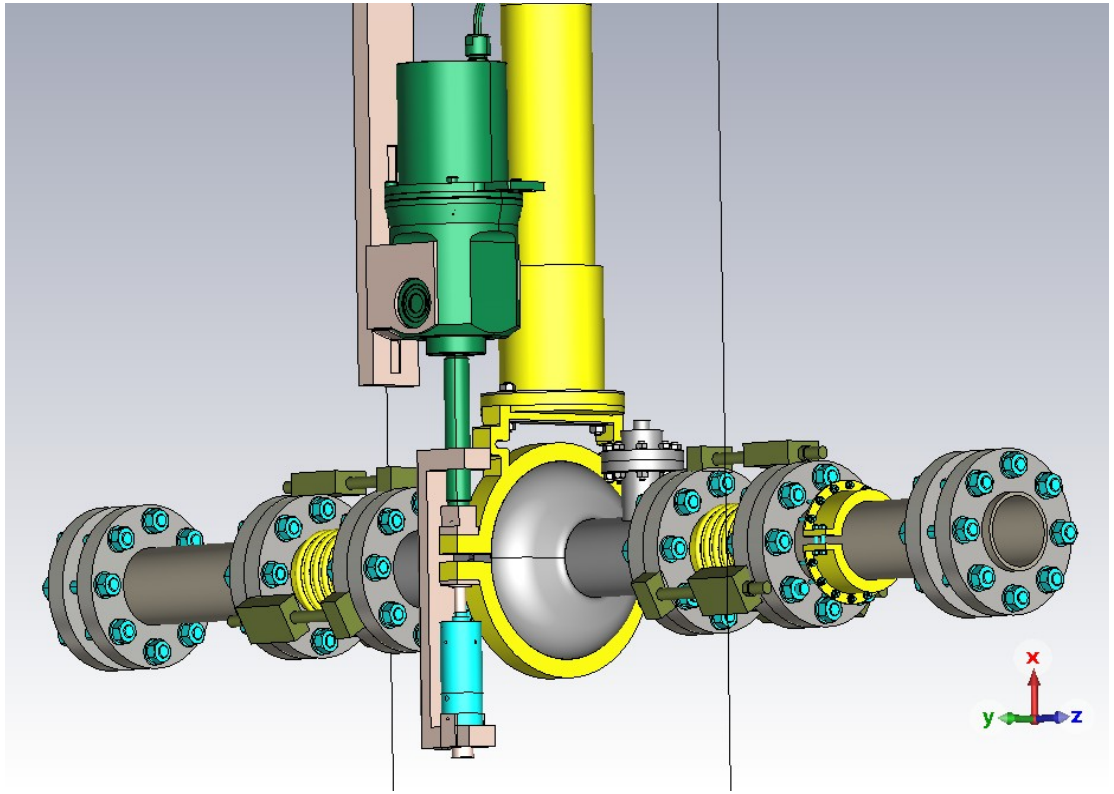
Magnetic shielding for 2.856 GHz cryomodule

- Double magnetic shield to reduce the external magnetic field (Roughly equal to 65 mG) to less than 0.6 mG.
- Local magnetic shielding would be covering the thermal shield from inside with multi-layer shield of thickness =1mm. It can reduce the external field from 65mG to 3 mG.
- Global magnetic shielding involves covering the interior of the vacuum vessel with a similar 1 mm multi-layer shield to further reduce magnetic field at cavity region from 3 mG to less than 0.6 mG
- Magnetic shield material used in the simulation is Permalloy with maximum relative permeability of 90000.



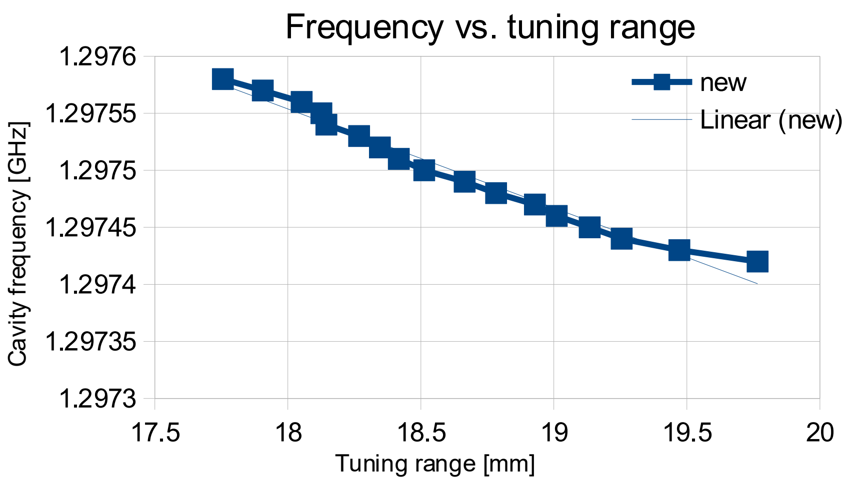
Tuning system for 2.856GHz cavity

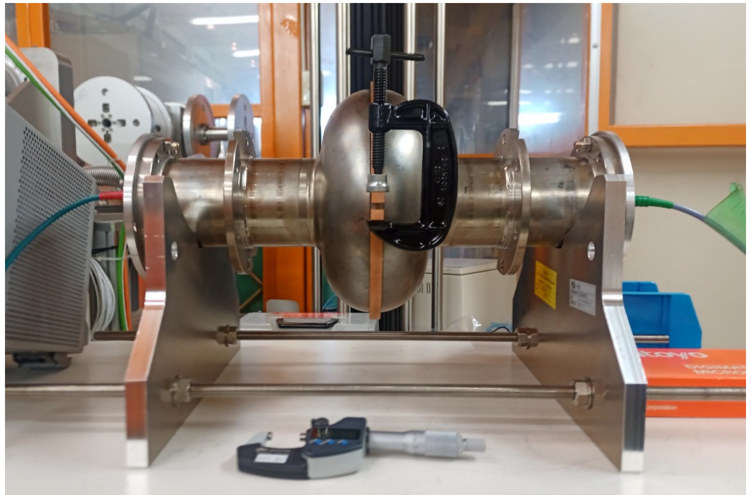
- Tuning system consists of:
- Stepper motor for slow tuning.
- Piezoelectric for fast tuning.
- Titanium C-shape clamp to hold the motor and piezo.
- Titanium slider frame to allow motor move vertically.
- Tuning principle is compressing the cavity equator by the conduction cooling ring.

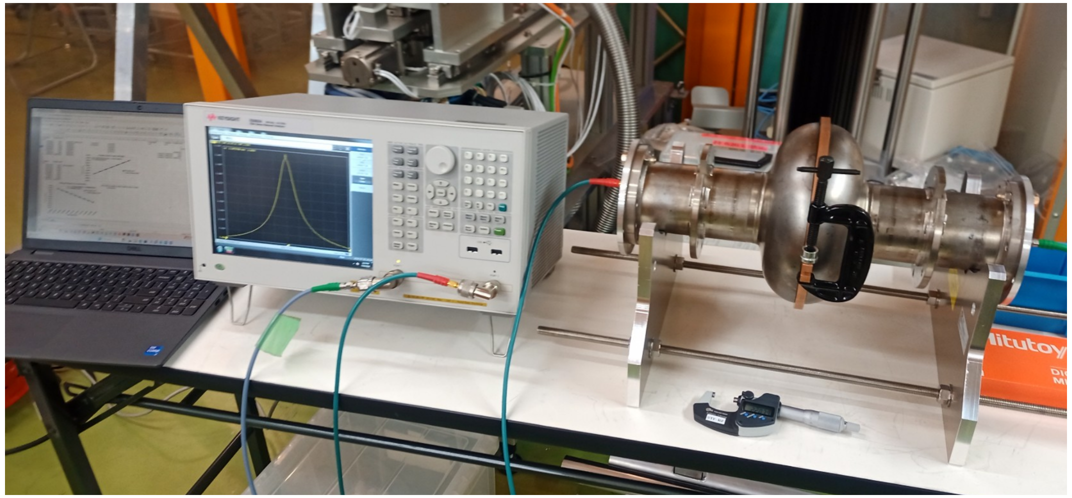


Preliminary measurement result of tuning system

- Since 2.856 GHz cavity hasn't been fabricated yet, 1.3 GHz. cavity was used to investigate the tuning method performance.
- Preliminary results showed that reducing cavity circumference by 1mm increases cavity frequency by 100 kHz.
- The relation between tuning range and frequency is almost linear.







Summary

- 2.856 GHz cavity design has been finalized and fabrication process is ongoing.
- Cryomodule design has been completed.
- Conduction cooling system is capable of cooling down cavity to 4.2 K.
- Combination of local and global magnetic shielding scheme shows that it's very promising to minimize external magnetic field to lower than 0.5 mG.
- Tuner system will be tested to validate the performance reliability and robustness.
- Cryocooler vibration is a concern in regard to cavity performance. The microphones will be evaluated and mitigated if needed.

Thank you very much for your attention! Questions?

Backup slide

Thermal contraction of cavity equator calculations

Coefficients of Thermal Expansion (CTE)

Using the average CTE values from room temperature to 4 K:

- Niobium (Nb): $\alpha_{\mathrm{Nb}} \approx 7.3 \times 10^{-6}\,\mathrm{K}^{-1}$
- Nb_3Sn: $\alpha_{\mathrm{Nb_3Sn}} \approx 6.5 \times 10^{-6}\,\mathrm{K}^{-1}$
- Copper (Cu): $\alpha_{\mathrm{Cu}} \approx 16.5 \times 10^{-6}\,\mathrm{K}^{-1}$

Calculation for Thermal Contraction

The change in radius Δr can be calculated as:

$$\Delta r = r_0 \times \alpha \times (T_1 - T_2)$$

where:

- $r_0 = 46.845\,\mathrm{mm}$ (initial radius at room temperature),
- α is the CTE for each material,
- $T_1 = 293\,\mathrm{K}$ and $T_2 = 4\,\mathrm{K}$, so $T_1 - T_2 = 289\,\mathrm{K}$.

1. Niobium (Nb)

$$\Delta r_{\mathrm{Nb}} = 46.845\,\mathrm{mm} \times 7.3 \times 10^{-6} \times 289 = 0.0987\,\mathrm{mm} \approx 98.7\,\mu\mathrm{m}$$

2. Nb_3Sn

$$\Delta r_{\mathrm{Nb_3Sn}} = 46.845\,\mathrm{mm} \times 6.5 \times 10^{-6} \times 289 = 0.0878\,\mathrm{mm} \approx 87.8\,\mu\mathrm{m}$$

3. Copper (Cu)

$$\Delta r_{\mathrm{Cu}} = 46.845\,\mathrm{mm} \times 16.5 \times 10^{-6} \times 289 = 0.2233\,\mathrm{mm} \approx 223.3\,\mu\mathrm{m}$$

Summary of Thermal Contraction from 293 K to 4 K

For a hollow cylinder with an initial radius of 46.845 mm:

- Niobium (Nb): Contracts by approximately 98.7 µm.
- Nb_3Sn: Contracts by approximately 87.8 µm.
- Copper (Cu): Contracts by approximately 223.3 µm.

These values represent the decrease in radius due to thermal contraction when cooling from room temperature to 4 K.