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Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Development of CW 100-kW class high-power coupler for conduction cooled L-band Nb_3Sn accelerator

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Co-supervisor: **Dr. Ashish Kumar**

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- Introduction
- High power test of cERL injector coupler
- RF design
- Thermal design
- Structural Analysis
- Final design of the coupler
- Current status & Future
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Introduction

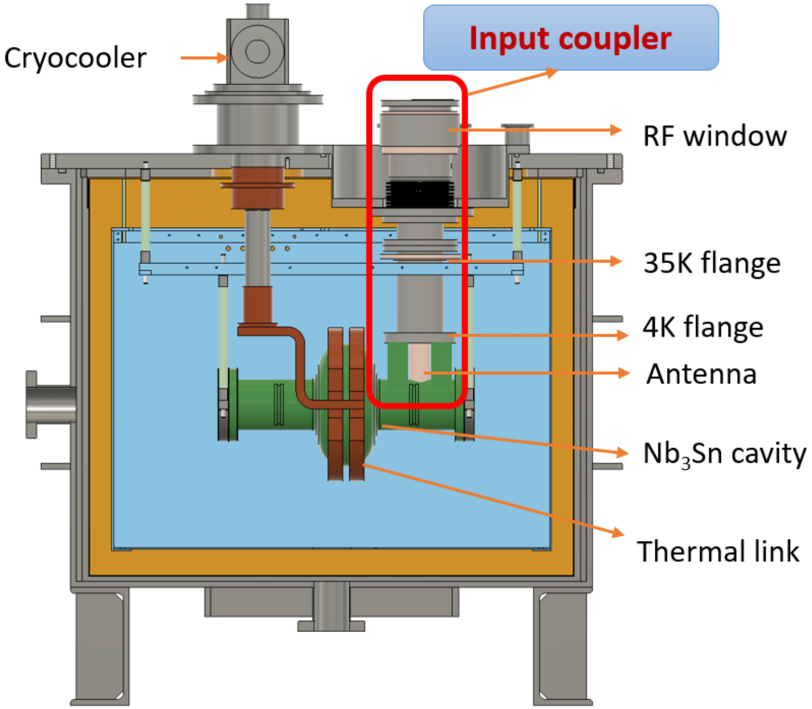
Goal: *Development of CW 100 kW class high power input coupler for conduction cooled L-band Nb_3Sn accelerator*

Motivation:

- To generate high current electron beam
- To realize compact, cheaper and reliable accelerator system
- Overall system could be entirely cooled by commercially available cryocoolers

Possible Applications:

1. For future ERL machines, to generate 10-100 mA beam current operation in CW mode
2. For industrial use, such as wastewater treatment, radioisotope production etc.



Conceptual design of Nb_3Sn cryomodule

Courtesy: Yamada san (Cryomodule for Nb_3Sn cavity)

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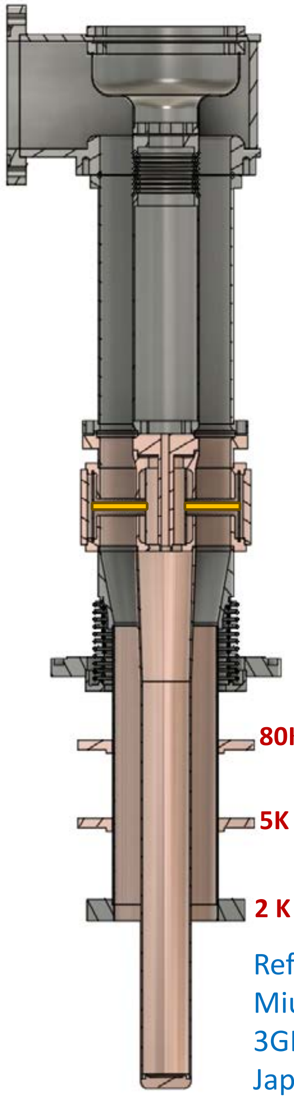
History & experience of high-power transmission in cERL injector coupler

cERL injector coupler



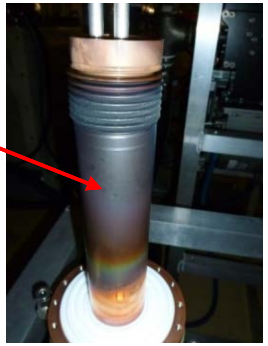
Parameter	Value
Frequency	1.3 GHz
Power (Test bench)	30-40 kW in CW mode
RF window	Single, disk type

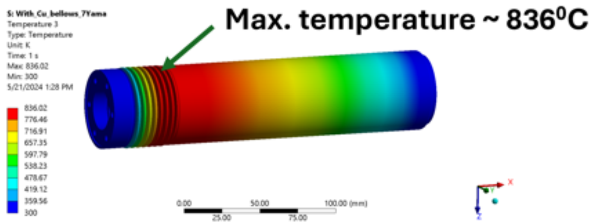
- Originally, designed to transfer 100 kW RF power in CW mode for L band niobium SRF cavities
- Power transfer was limited to 30-40 kW in CW
- Limited by excessive heat load at warm section

Reference: Nama, P., Kumar, A., Arakawa, D., Umemori, K., Kako, E., Sakai, H., & Miura, T. (2023). Experimental result of high-power transmission through 1 . 3GHz cERL injector prototype coupler PASJ2023 - Particle Accelerator Society of Japan 2023, 804–807.

Burnt Inner conductor due to 100 kW power transmission for one minute

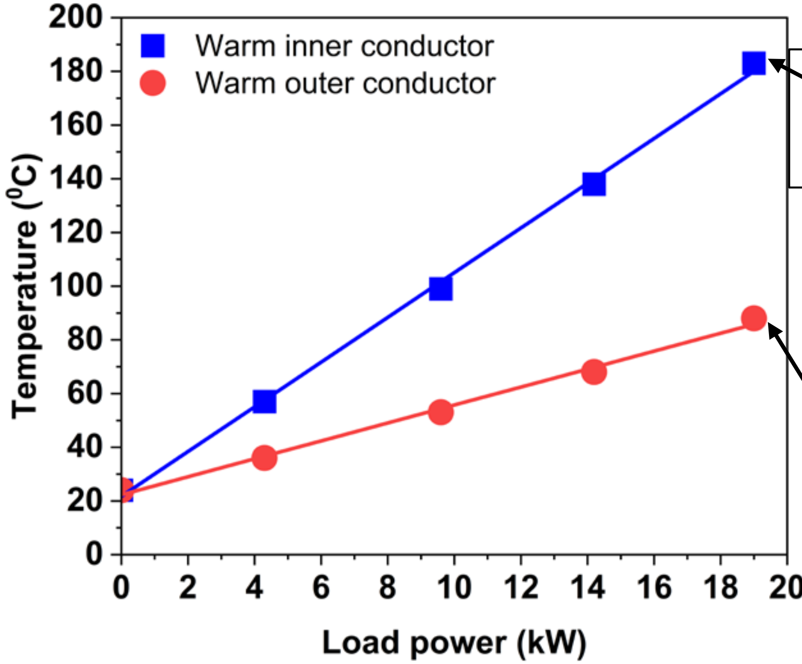
Cu coated SUS





Thermal simulation with 100 kW RF load

Temperature versus power for warm inner and outer conductor



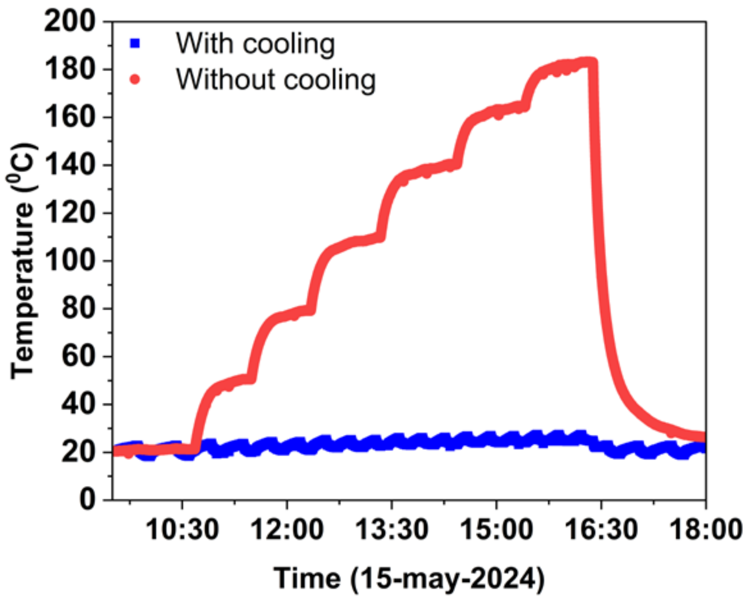
~180^{0}C at 20 kW
~ 850^{0}C at 100 kW

~90^{0}C at 20 kW
~350^{0}C at 100 kW

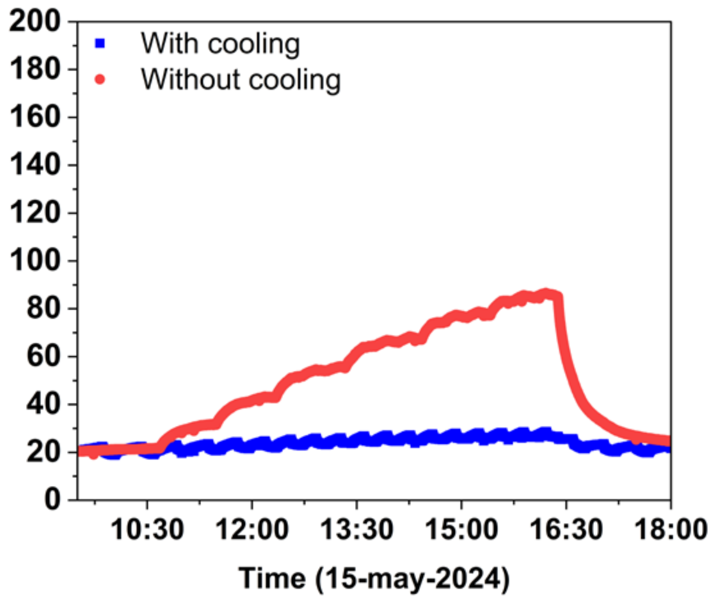
Modification in cERL injector coupler

- Warm inner and outer conductor was modified
- Modifications include introduction of water-cooling channels
- High Power test was performed up to 27 kW in CW mode

Temperature profile of warm inner conductor

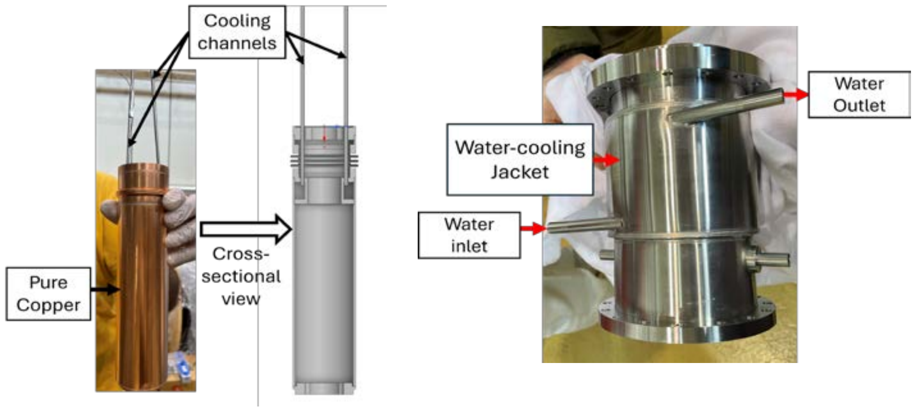


Temperature profile of warm outer conductor



Modified warm inner conductor

Modified warm outer conductor



Material: Pure copper

Material: Cu coated SUS

- With water cooling to the inner and outer conductor, the temperature rise was effectively suppressed for input power up to 27 kW in CW mode.
- Extrapolating up to 100 kW, the temperature is limited up to 50^{0}C.
- **With water cooling, it would be possible to transmit power up to 100 kW in CW mode.**

Reference: P. Nama et al., "Effective thermal load mitigation in cERL injector coupler through warm section modification", in Proc. LINAC2024, Chicago, IL, USA, Aug. 2024, pp. 704-707. doi:10.18429/JACoW-LINAC2024-THPB073

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Design Consideration

1. **Thermal design for cold section:** To accommodate the conduction cooling scheme by cryocooler and to remove all the liquid cryogens
2. **RF window design:** To accommodate the newly available ceramic material [Alumina (Epsilon = 9.7, Loss tangent= 4e-5)] from company
3. **Warm section design:** Better heat load management, more space for cooling and easier assembly procedure

	ε	tanδ	Comment
Old ceramic	9.2	4e-4	Discontinued
New ceramic	9.7	4e-5	Available

In current design, it's difficult to tighten screws with very less space

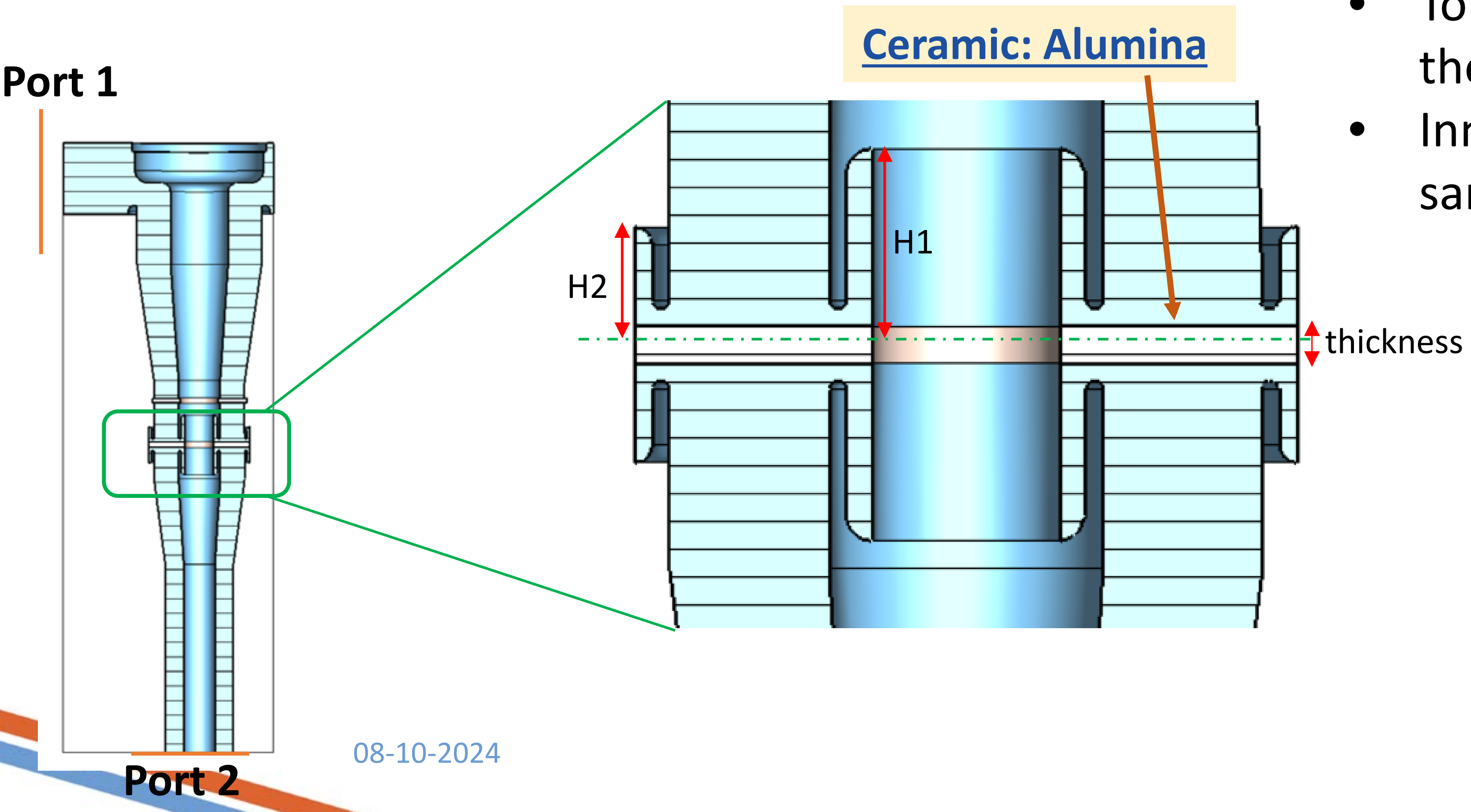
RF Window and choke structure

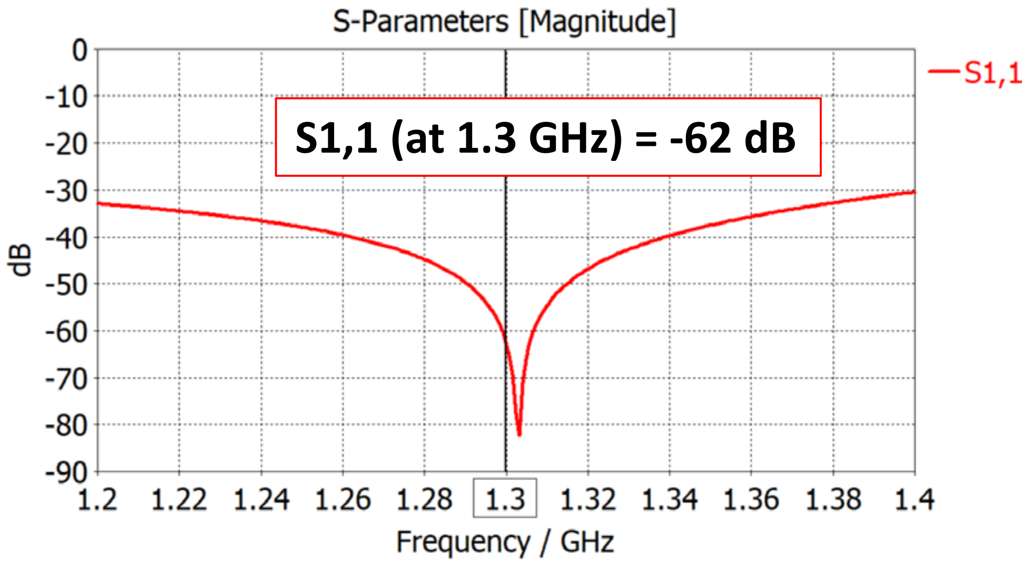
- Role of RF window: To protect cavity vacuum while passing the RF with low loss
- Material: Alumina 99%
  (Epsilon = 9.7, Loss tangent= 4e-5)

tan δ	Power loss (W)	Comment
4e-4	20.2	cERL
4e-5	2	New coupler

10 times less power loss in the new ceramic material

- To optimize the choke geometry, the thickness of the ceramic and height H1 and H2 was varied.
- Inner and outer diameter of ceramic was kept same as cERL injector coupler

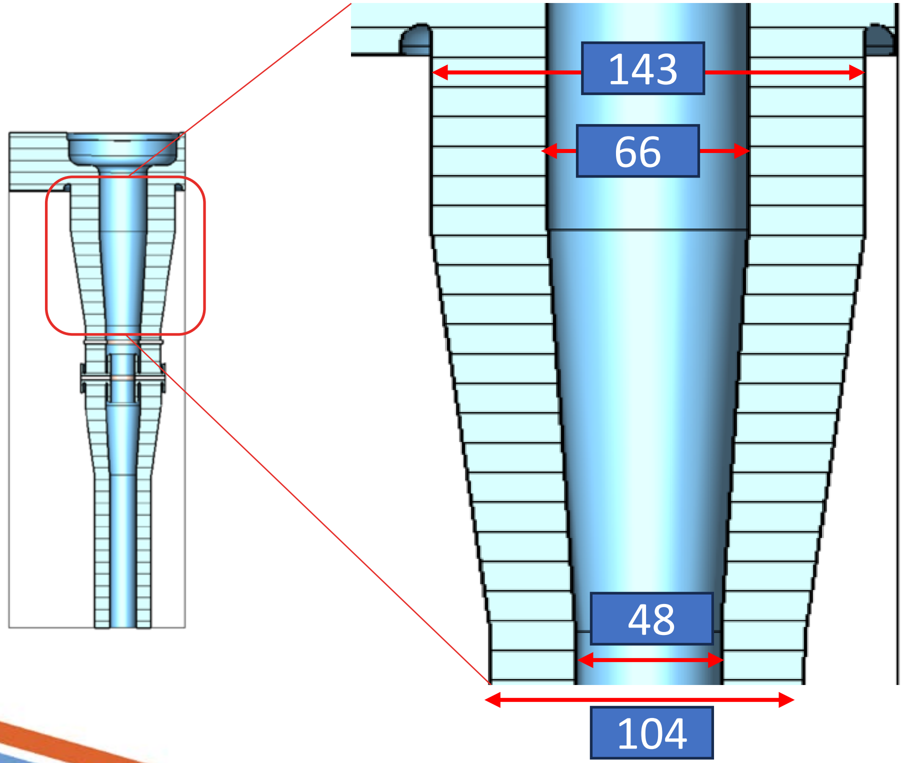




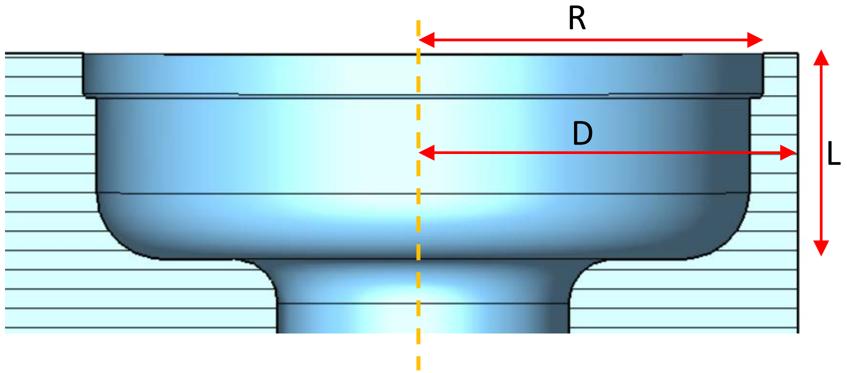
Warm Section and doorknob Design

Serves three purposes:
1. Larger area would be helpful in reduction of power loss
2. More space to accommodate cooling channels
3. Easier to assemble with RF window and cold part

Length of the straight and tapered section was optimized while keeping the impedance same



Size of the doorknob is optimized by changing:
1. Length of the doorknob (L)
2. Radius of the doorknob (R)
3. Location of the short plate (D)



In current design, it's difficult to tighten these screws with very less space

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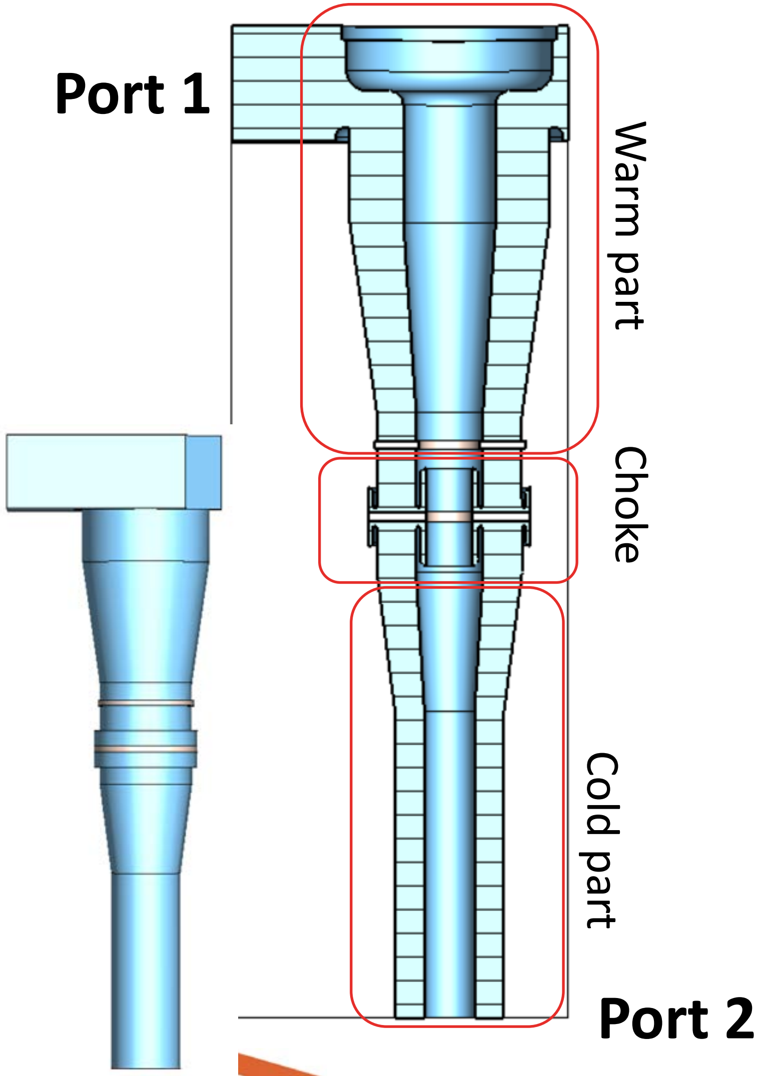
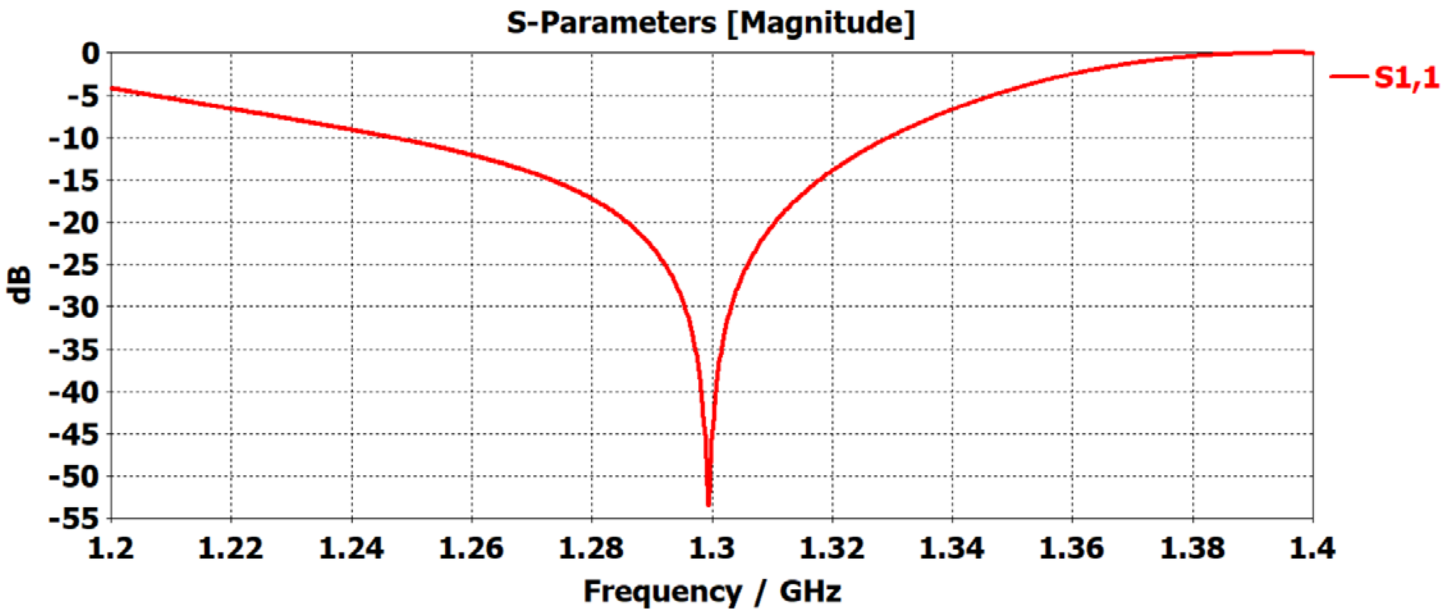
RF design optimization

CST model for RF calculations





S1,1 (at 1.3 GHz) = -44.2 dB
Bandwidth (at -20 dB) = 24.6 MHz

- **RF design is finalized, and then thermal design optimization was performed**

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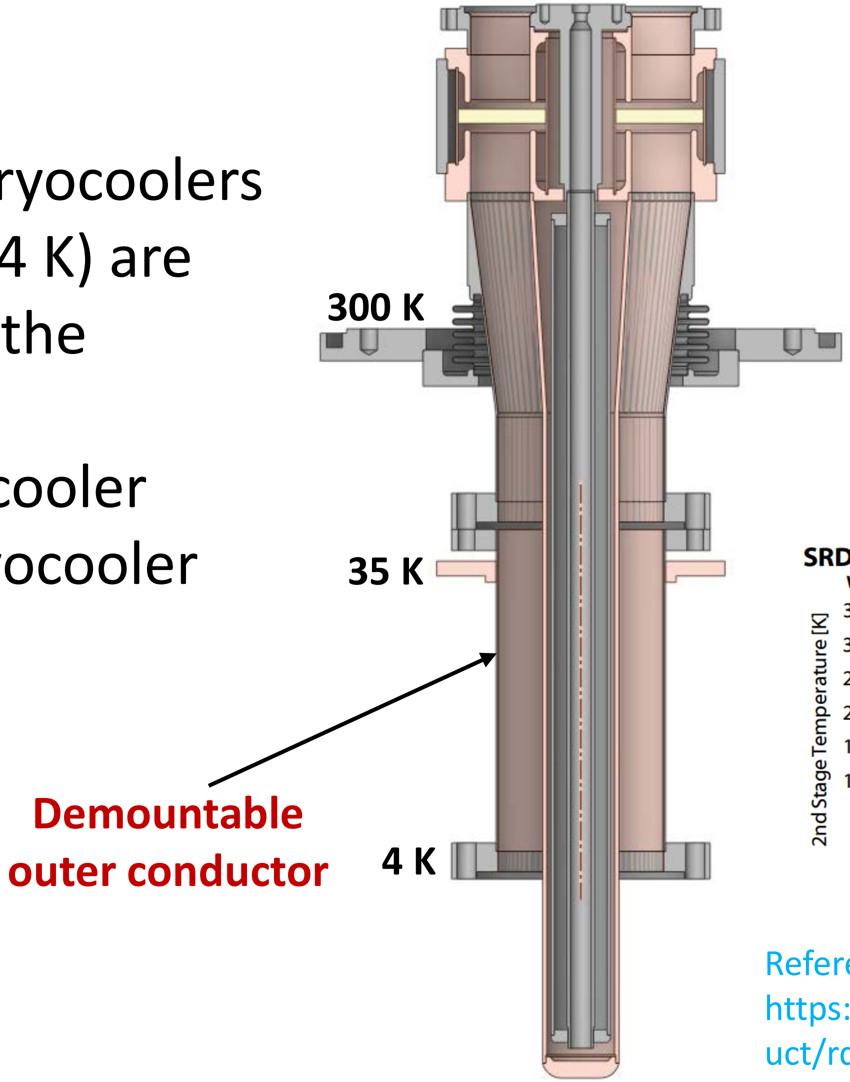
Thermal Design Consideration

- Coupler will be conduction cooled by cryocoolers
- Thermal intercepts (at 300 K, 35 K and 4 K) are introduced based on the availability of the cryocoolers
- 35 K temperature by first stage of cryocooler
- 4 K temperature by second stage of cryocooler

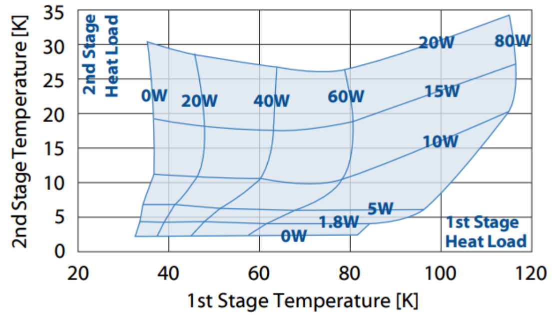
Cooling capacity of cryocooler

- At 4 K = 1.8 W
- At 35 K = 10-15 W



RDE-418D4 4K Cryocooler Series

SRDE-418D4 Cold Head Capacity Map (50 Hz)
With F-50 Compressor and 20 m (66 ft.) Helium Gas Lines



Reference: https://www.shicryogenics.com/product/rde-418d4-4k-cryocooler-series/

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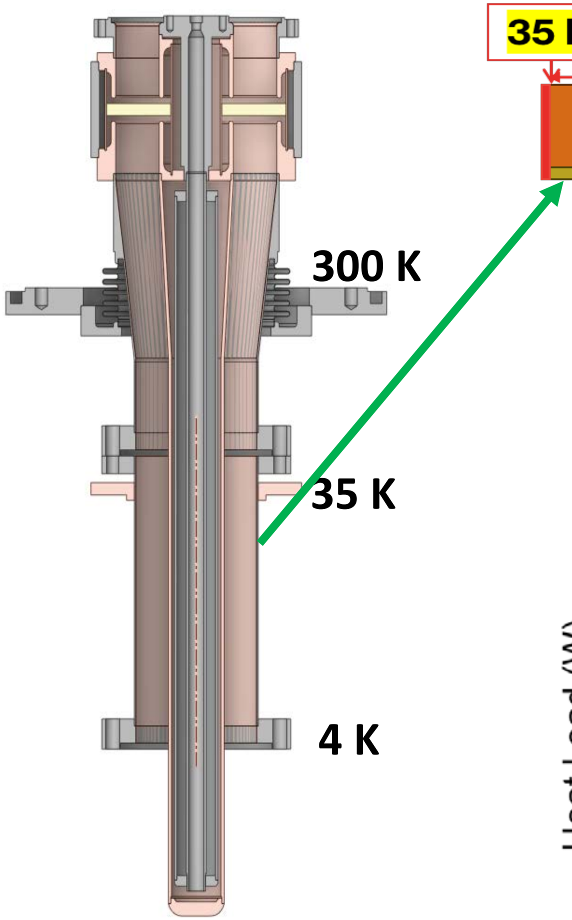
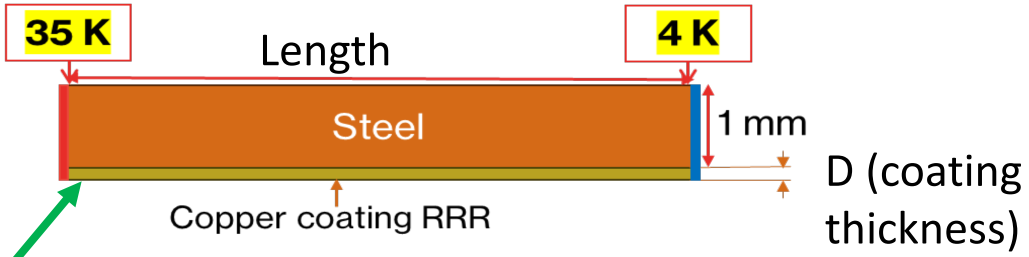
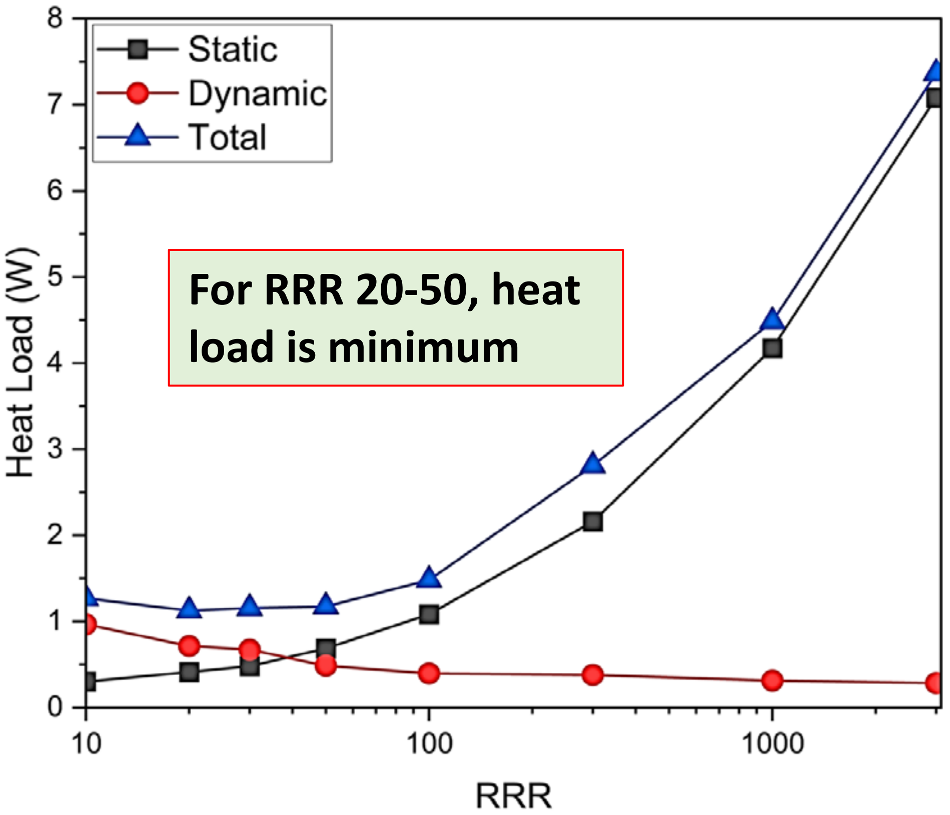
Thermal Design Optimization: Effect of RRR

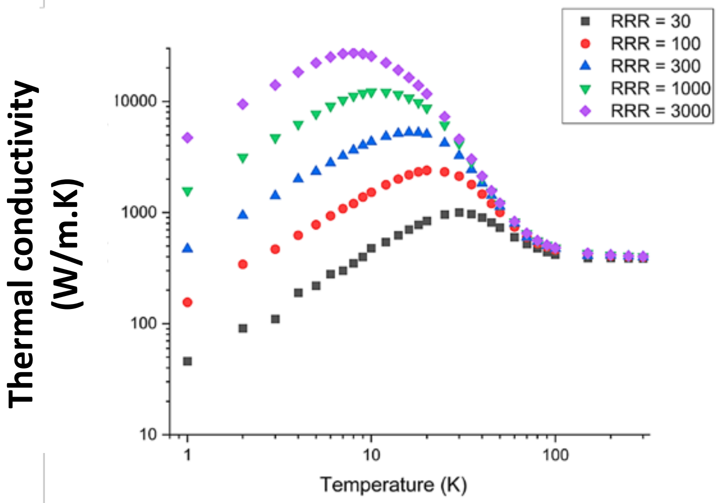




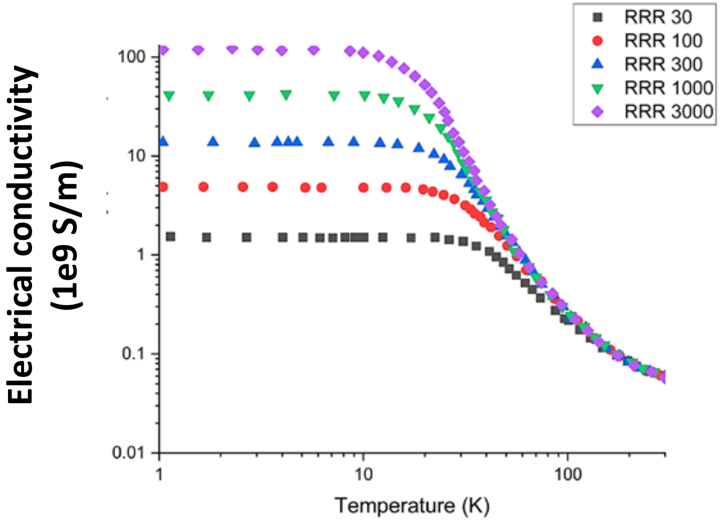
Effect of Cu RRR on heat load at 4 K region



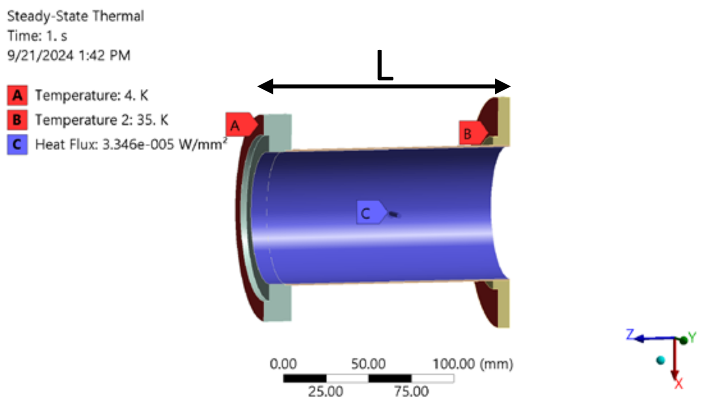
Thermal conductivity v/s temperature



Electrical conductivity v/s temperature

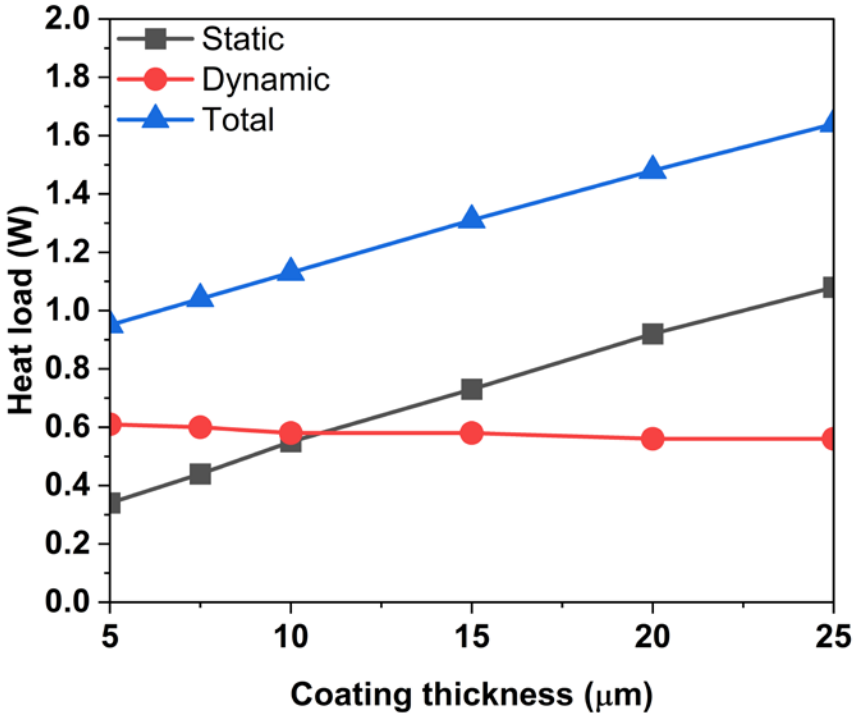


Thermal design optimization



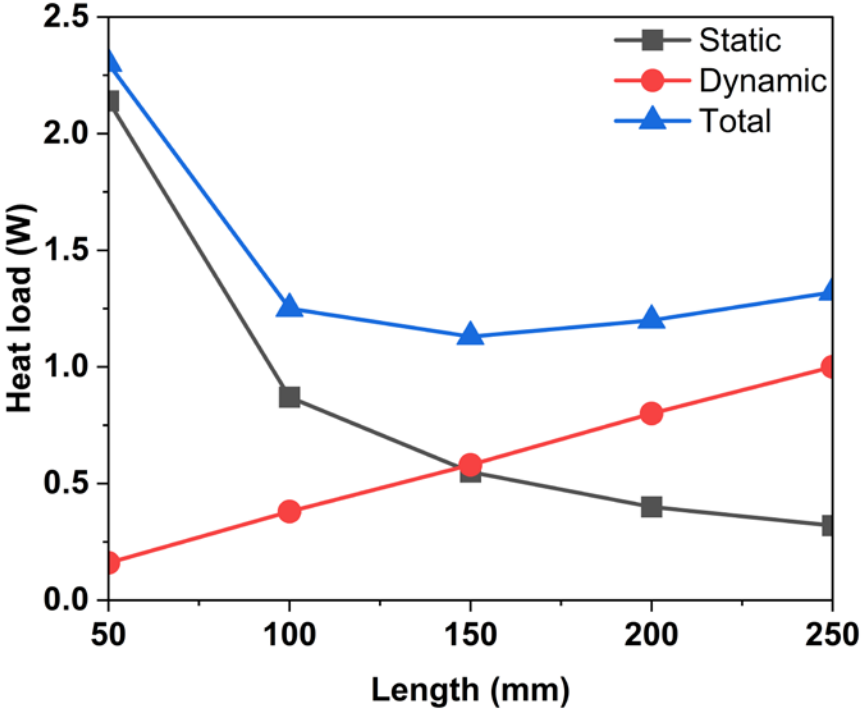
1. Copper coating thickness
2. Distance b/w thermal intercepts (L)

Effect of copper coating thickness



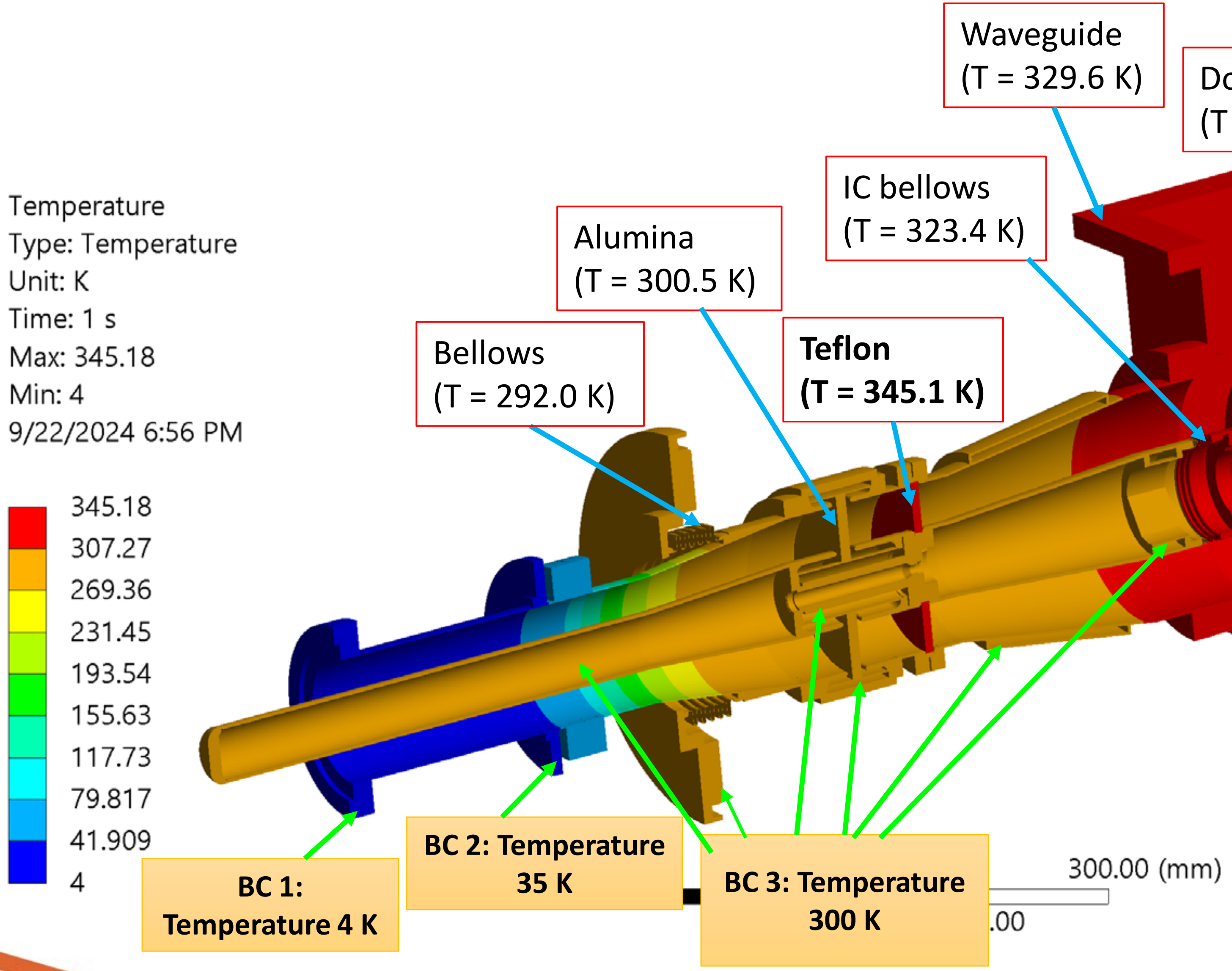
- Coating thickness below 10 μm is not suitable for good RF transmission.
- At 10 μm, total heat load was 1.13 W.

Distance between 4 K and 35 K intercepts



- Trade off in static and dynamic heat load with the position of the thermal anchor
- At 150 mm, total heat load was minimum.

Thermal analysis under cryogenic temperature



Other boundary conditions:

- Heat flux on all RF surface
- Internal heat generation from ceramic and Teflon plate
- Natural air convection

Temperature	Static (W)	Dynamic (W)	Total (W)
4 K	0.54	0.57	1.11
35 K	8.54	3.06	11.6

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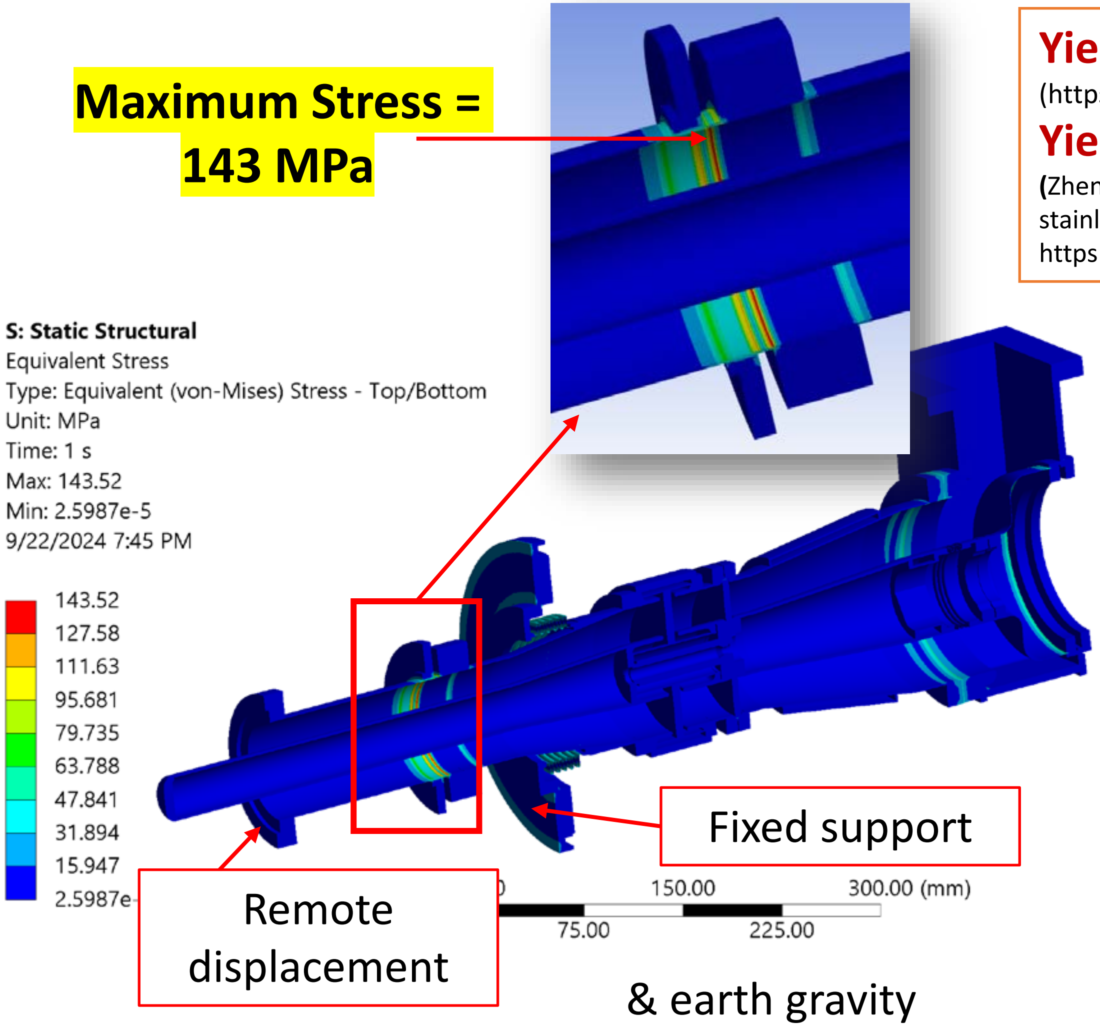
Structural analysis: Stress & deformation

Yield strength of steel 304 (at room temperature) = 215 MPa

(https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mq304a)

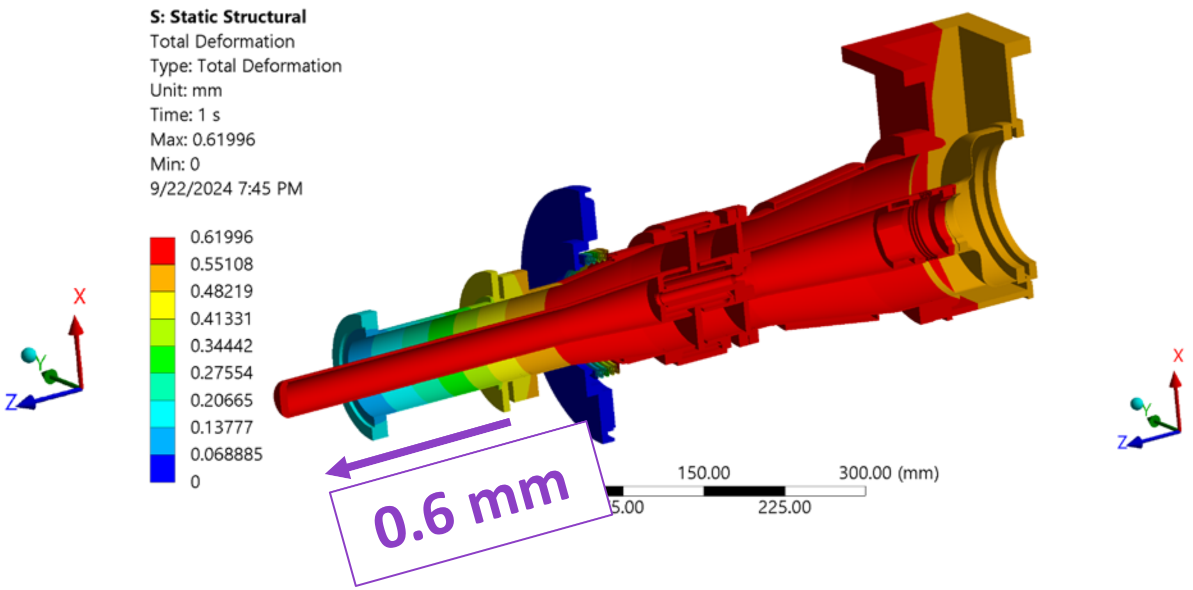
Yield strength of AISI steel 304 at 77 K is 420 MPa

(Zheng, C., & Yu, W. (2018). Effect of low-temperature on mechanical behavior for an AISI 304 austenitic stainless steel. *Materials Science and Engineering: A*, *710*(September 2017), 359–365. https://doi.org/10.1016/j.msea.2017.11.003)



Equivalent Stress

Maximum deformation = 0.6 mm

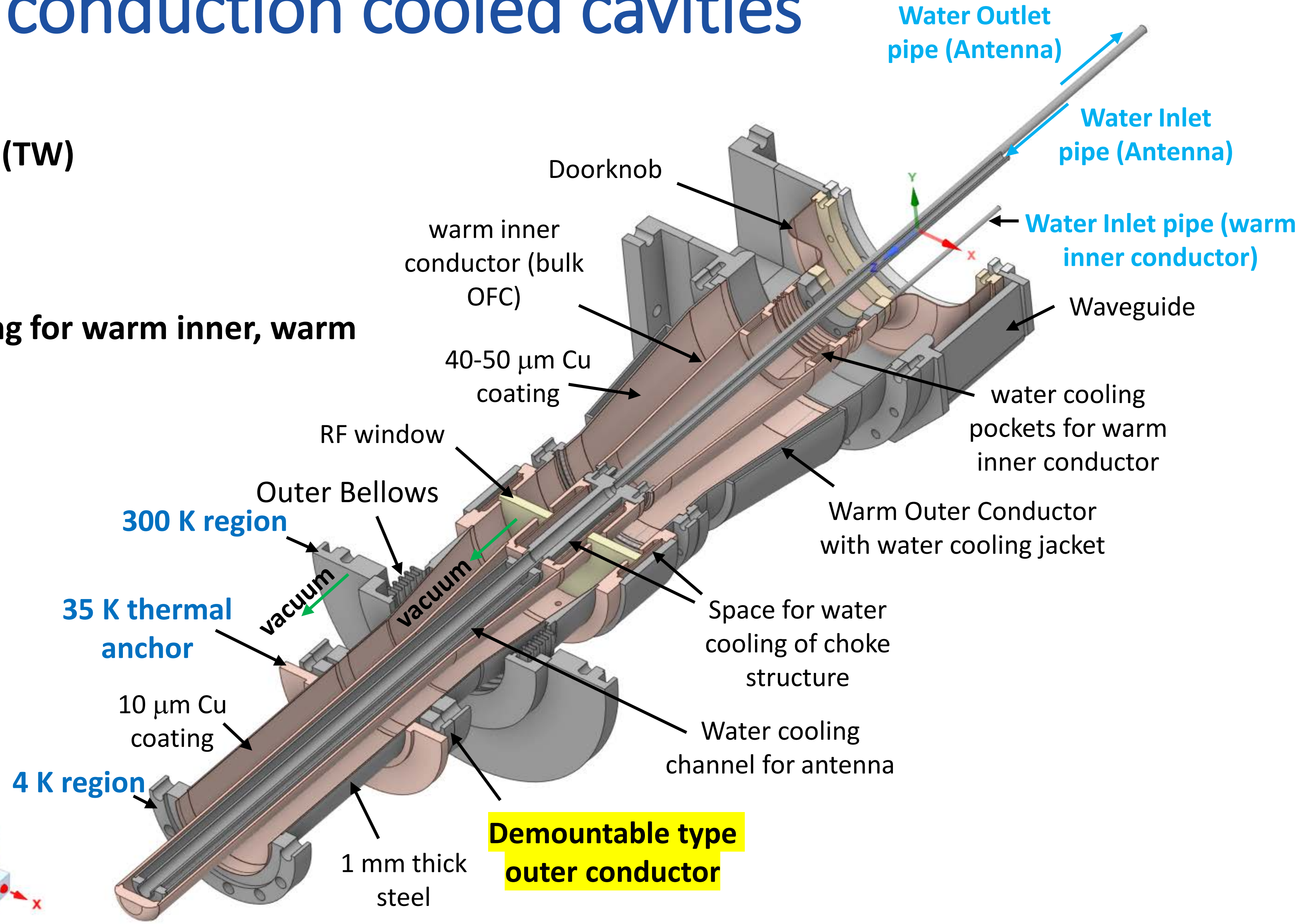


Total deformation

Contents

Design of the coupler for 100 kW transmission for conduction cooled cavities

- Frequency: 1.3 GHz
- Power = 100 kW in CW mode (TW)
- RF window: Single, disk type
- Impedance = 46.4 Ohm
- Material: Alumina 99%
- Cooling Scheme: Water cooling for warm inner, warm outer conductor and antenna



Note

- Water outlet pipe for warm inner conductor is hidden in this diagram
- Inlet and outlet for warm outer conductor and outer choke is not shown in this diagram

Contents

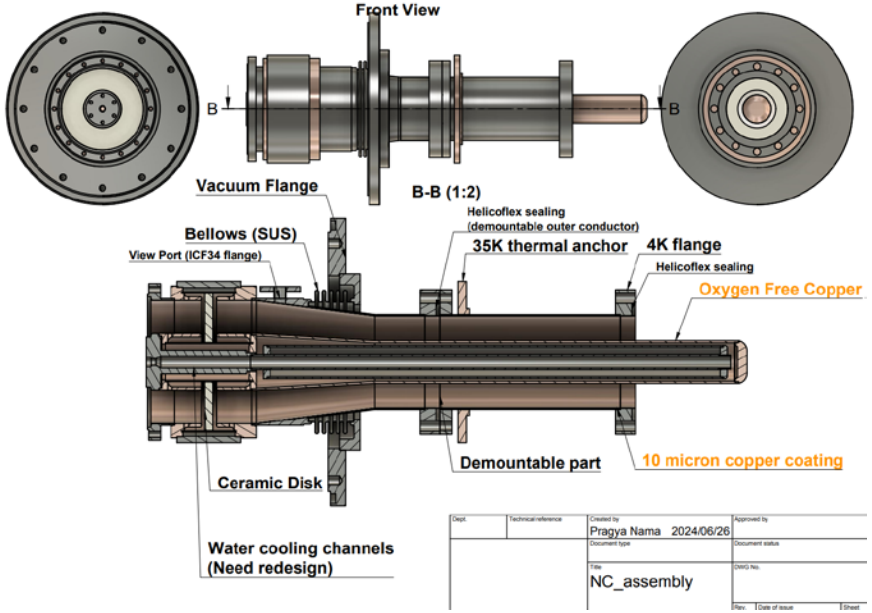
Current Status of coupler development

- **Simulation:** Coupler design is finalized (Multipacting analysis is ongoing)

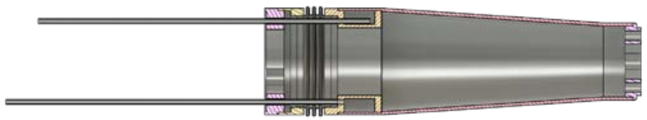
- **Fabrication: Will be completed early 2025**
  - Disk type ceramic was purchased, and TiN coating was done.
  - <u>Fabrication started for:</u>
1. RF window with cold part and antenna
2. Tapered type warm outer conductor with water cooling jacket
3. Inner conductor with water cooling and
4. Doorknob

- **High power test: Spring 2025**

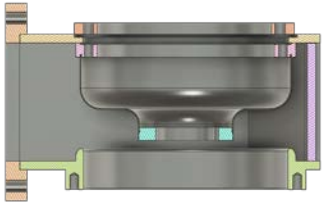
RF window and choke structure



Warm Inner conductor



Doorknob



Warm Outer conductor

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Alternative to copper coating

Coating of superconducting material: MgB_2 (T_c = 39 K)

- Coating with MgB_2 on stainless steel
- MgB_2 is a superconductor with T_c = 39 K
- Thermal anchor is at 35 K so, the MgB_2 will have zero dynamic heat load below this.

- For example, 20 μm MgB_2 coated on SUS:

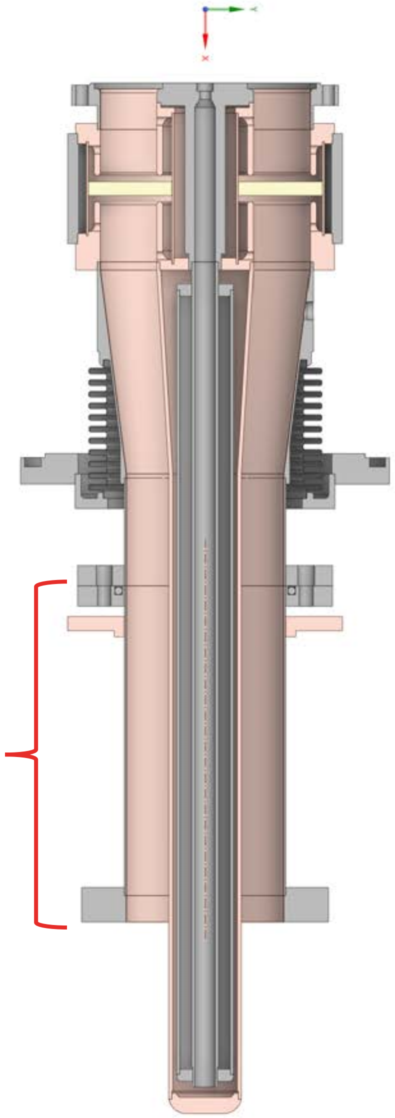
Static heat load: 0.07 W

Dynamic heat load: Zero

(thanks to superconductivity!)

Demountable type outer conductor

(In future, will be replaced by MgB_2 coated section)



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Summary of coupler R&D

- Design of the CW 100-kW class high power coupler for conduction cooled accelerator is finalized.
- RF design was optimized and **S1,1 at 1.3 GHz is -44 dB** with bandwidth 25 MHz.
- Thermal design optimization was performed and **total heat load at 4 K is 1.11 W**.
- **With MgB_2 coating on SUS, total heat load would be 0.07 W.**
- Structural analysis was performed under cryogenic temperature with heat load for the coupler. **Maximum stress was 143 MPa and maximum deformation was 0.6 mm.**
- Fabrication of the new coupler has started and expected to be complete in January 2025.
- RF power test is planned to be done spring 2025.

Acknowledgement

I would like to acknowledge help and support of my mentors **Prof. Eiji Kako and Prof. Hiroshi Sakai**.

I would like to thank **Miura san, Arakawa san and RF group** for the help & support.

Thank you for your attention!