Conduction cooling research in KEK/Japan towards liquid helium free SRF accelerator

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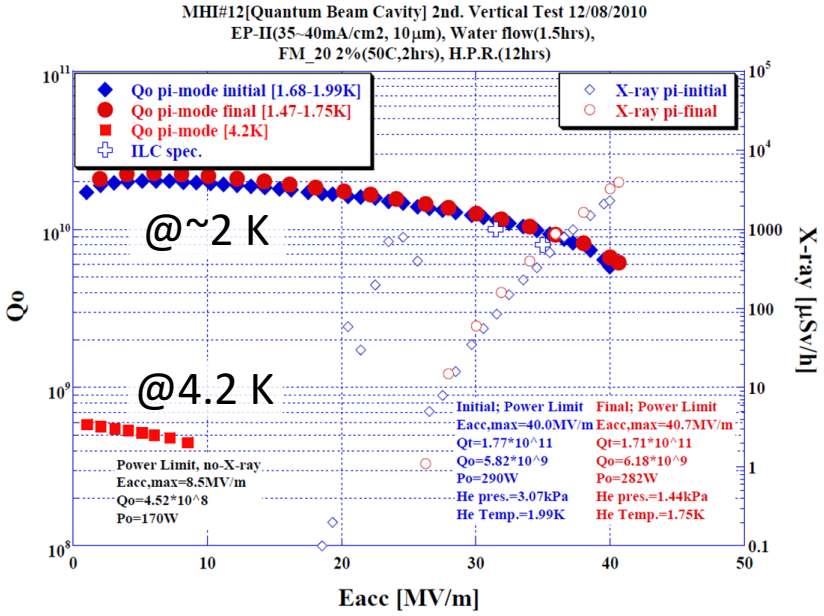
Conventional SRF cavity

- SRF cavity: Ultra low RF resistance, hence, high current CW operation possible

Niobium (Tc at 9.2K)

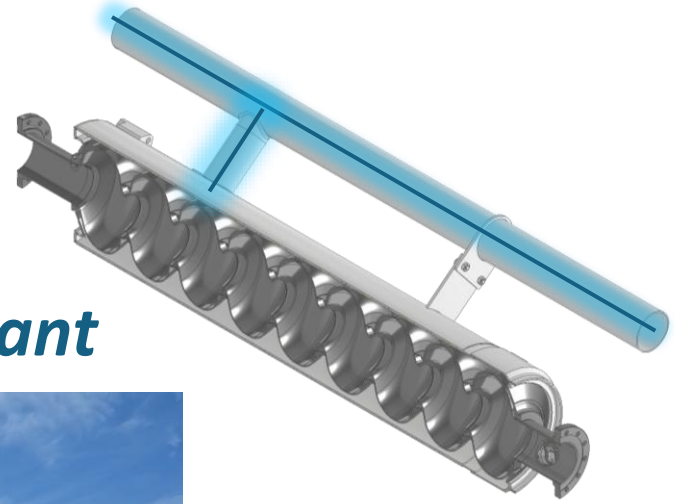
1.3 GHz - 9 cell

- 1.3 GHz Cavity performance



Liquid helium immersion cooling

Since all cavity surfaces face liquid helium, this is one of the best cooling methods.



Helium liquefaction plant

This system perfectly fits large accelerators using many Nb cavities.

But how about for small accelerators?

Towards small SRF accelerator

- Demands for the cooling system must be **easy operation** and **small footprint**, etc…
- Also, **high pressure gas safety** associated with the **use of liquid helium** is another obstacle.

◆Now, Nb_3Sn cavities are attracting worldwide attention.

➢The high Tc of the Nb_3Sn cavity allows high Q-values at 4.2 K resulting low RF heating.

Nb	Tc 9.2 K
Nb_3Sn	Tc 18.3 K

➢With 1 cell 1.3 GHz cavity, Q_0 10^{10} at Eacc 10 MV/m → **1W at 4.2 K**

◆A commercial 4K cryocooler has a few watts of cooling capacity at 4.2 K.

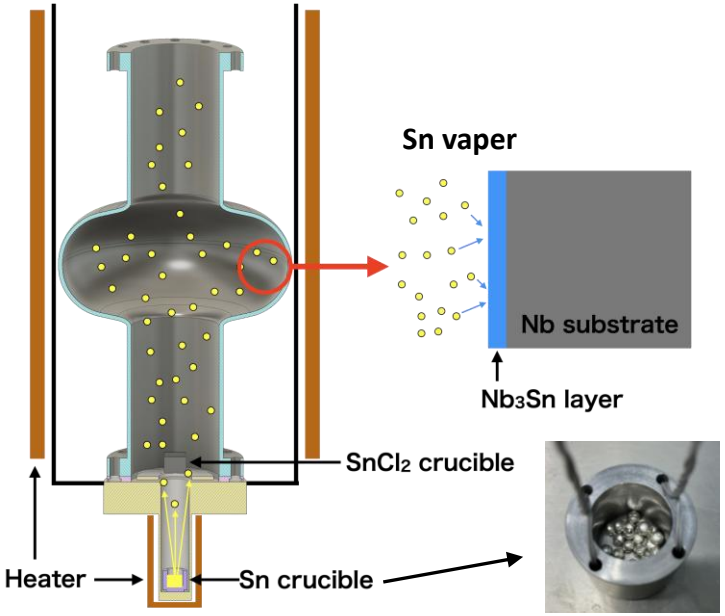
Nb_3Sn cavity + 4K cryocooler = *Game changer*

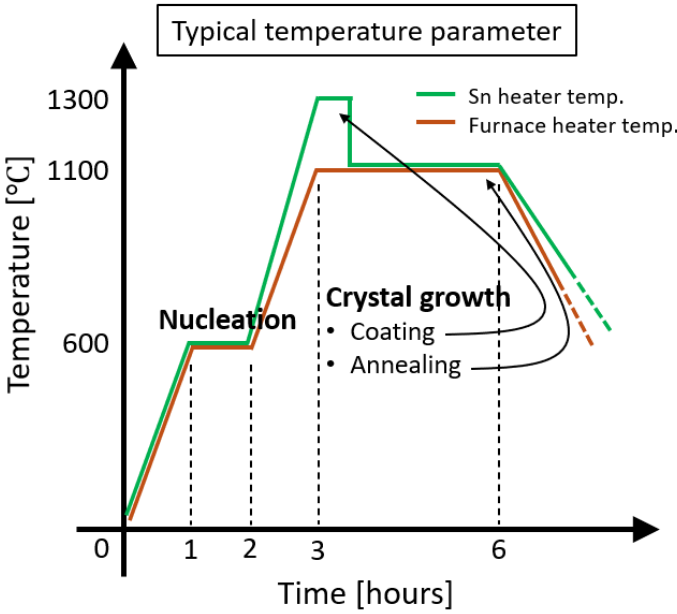
Main two challenges are
- ✓ Nb_3Sn cavity fabrication (coating),
- ✓ ***thermal conduction cooling technique***.

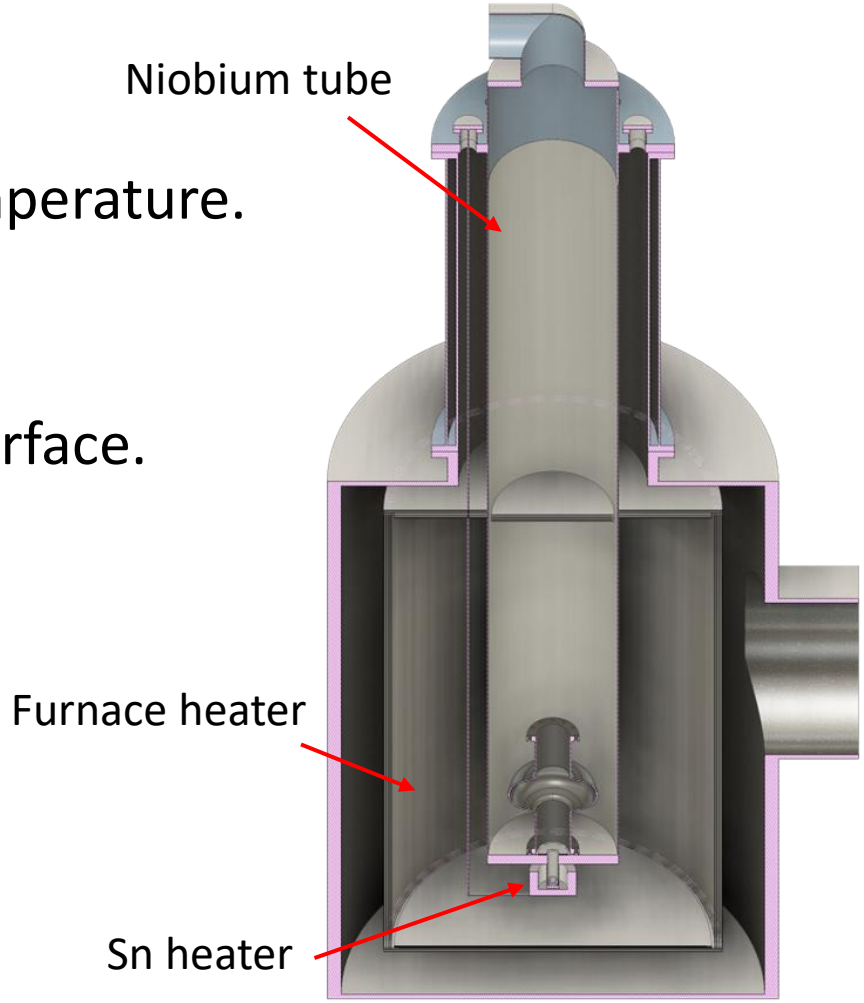
Nb_3Sn coating

Vaper diffusion method

- Nucleation
  $SnCl_2$ diffuses to cavity inner surface at intermediate temperature.
  They works as nucleation agent for coming Sn.
- Crystal growth
  Nb_3Sn layer grows around nucleation agent on the Nb surface.





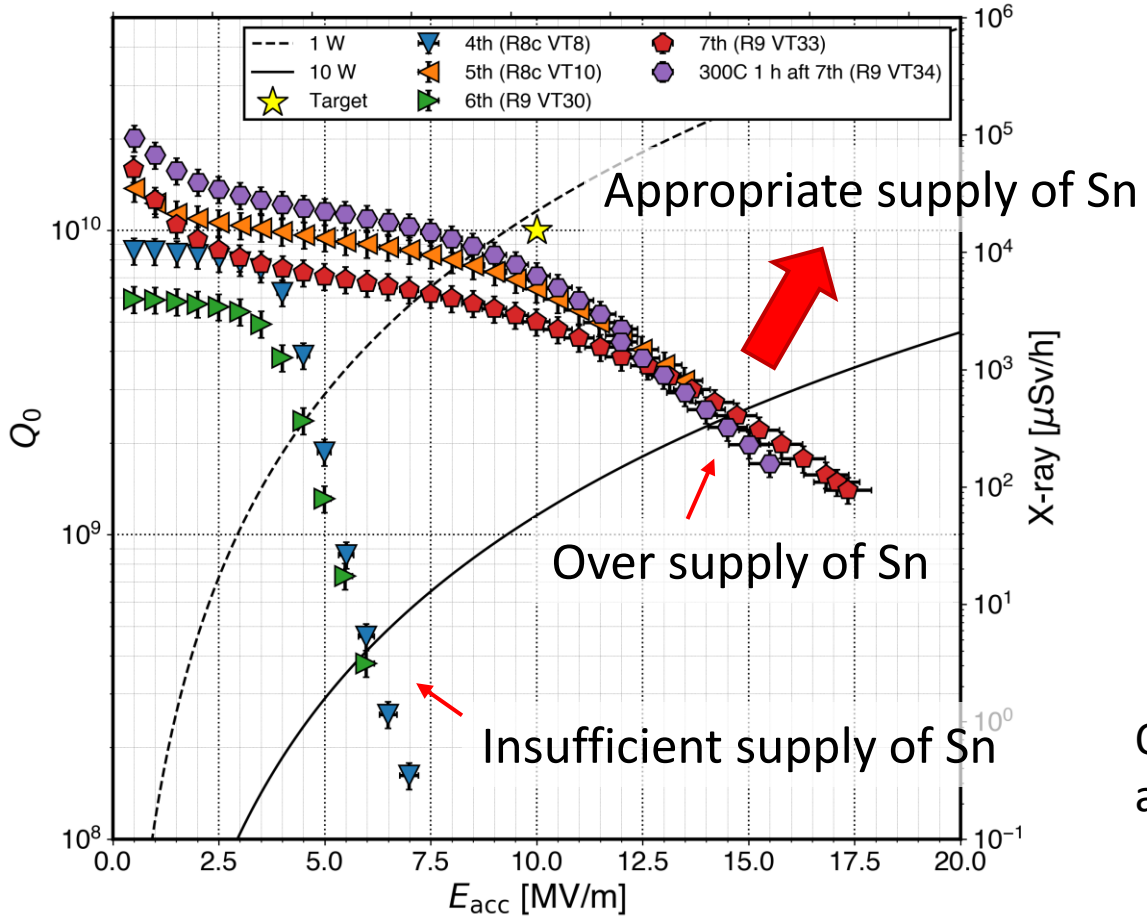


Coating furnace

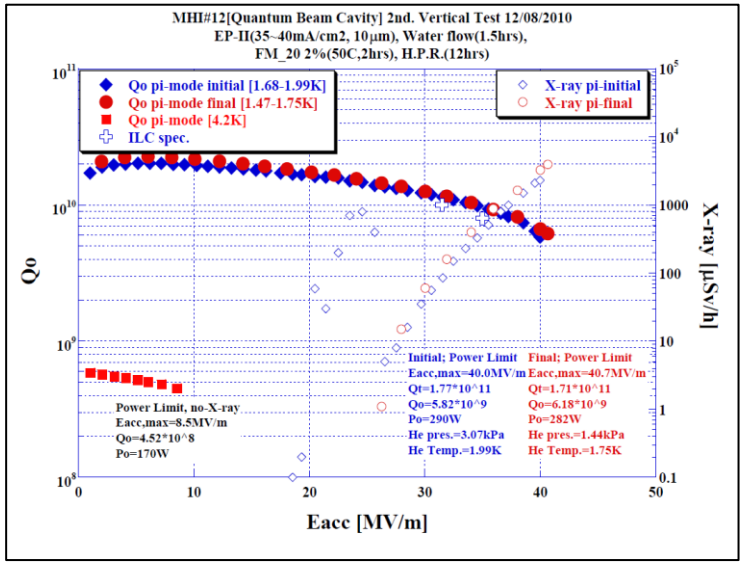
KEK Nb_3Sn: VT with liquid helium

- Q values exceeded 10^{10} and Eacc reached more than 17 MV/m.

Nb_3Sn cavity at 4.2K liquid helium



Cf: Nb cavity at 2.0K



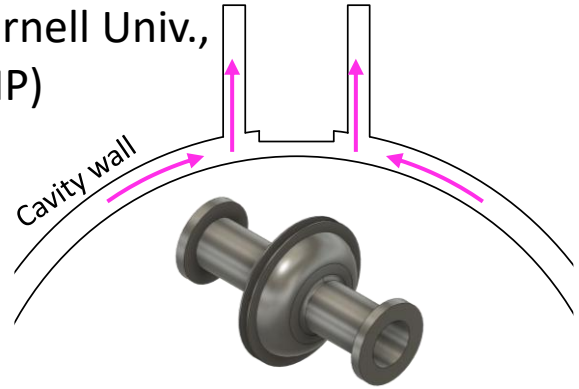
Optimizations for amount of Sn and $SnCl_2$, coating jigs and heating temperature parameters are underway.

Thermal conduction cooling

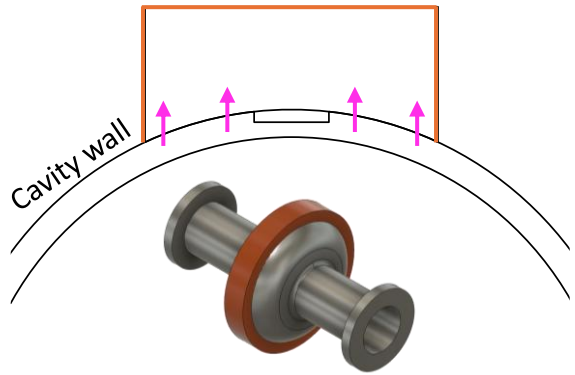
- RF heating caused by magnetic field is concentrated in the **cavity equator** region.
- Possible cooling schemes

: Heat flow

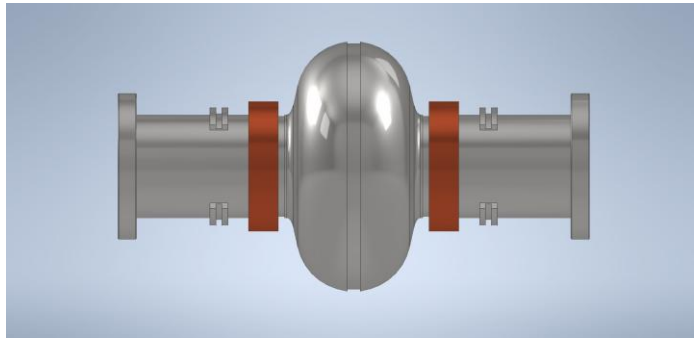
Welding Nb rings (FNAL, JLab, Cornell Univ., IMP)

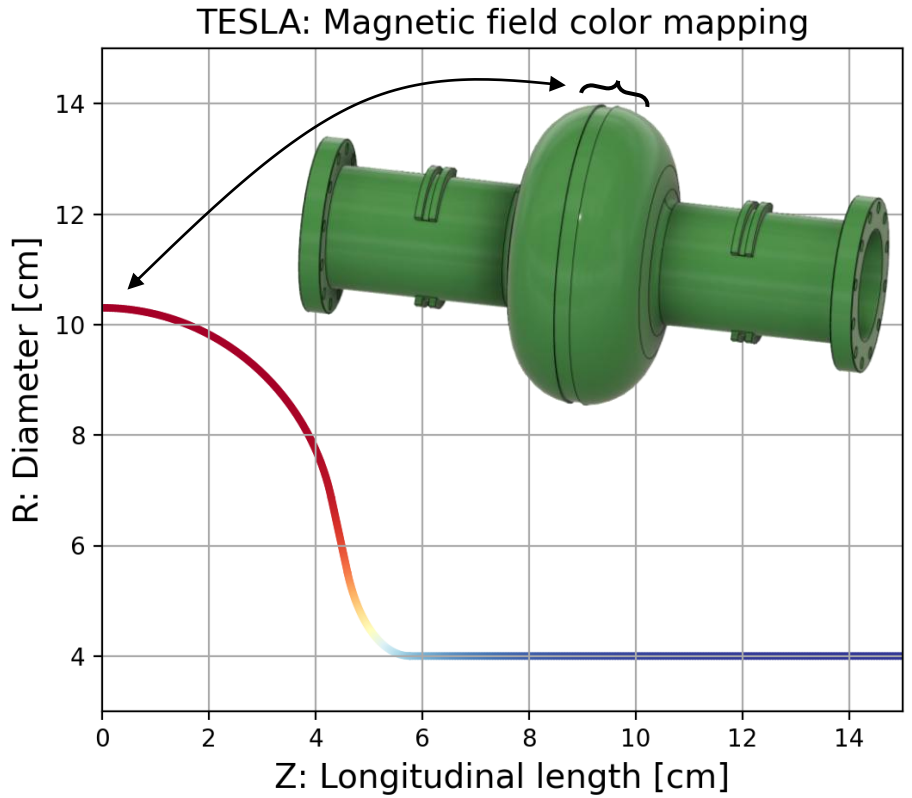


Covering equator region (KEK)



Clamping beam tube (Cornell Univ., Tohoku Univ.)

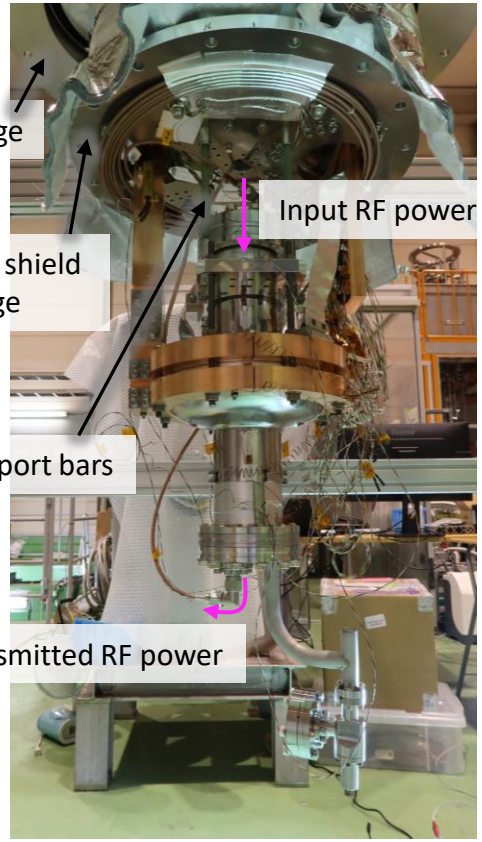


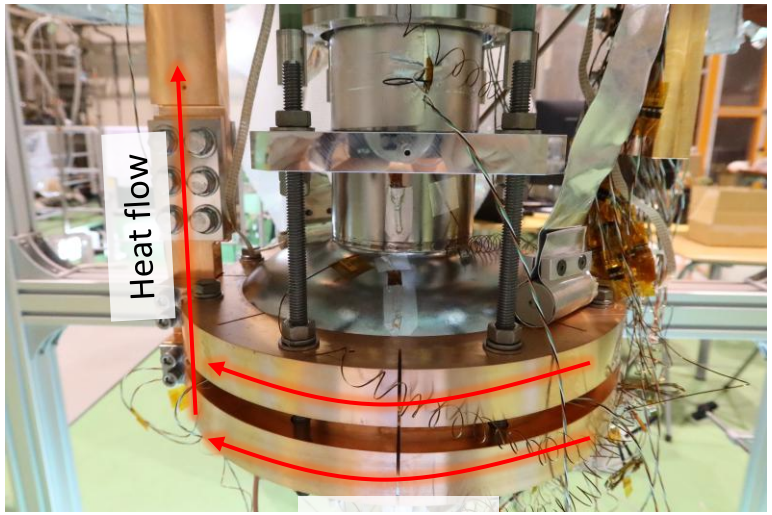


Each institutes develop their own ways.

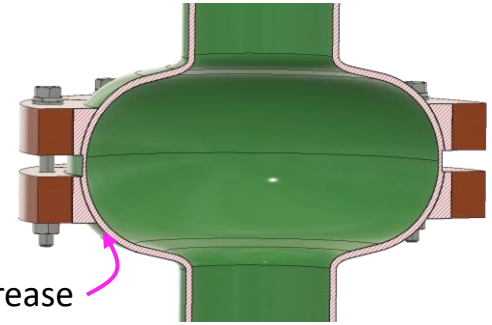
KEK's trial

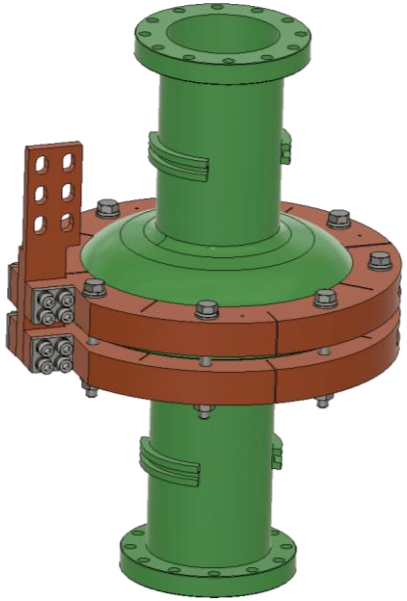
- So far, I have tried to "cover equator region" by copper rings because:
  - ➢ thermal conductivity of Niobium is very bad at low temperature compared to copper,
  - ➢ short time implementation.

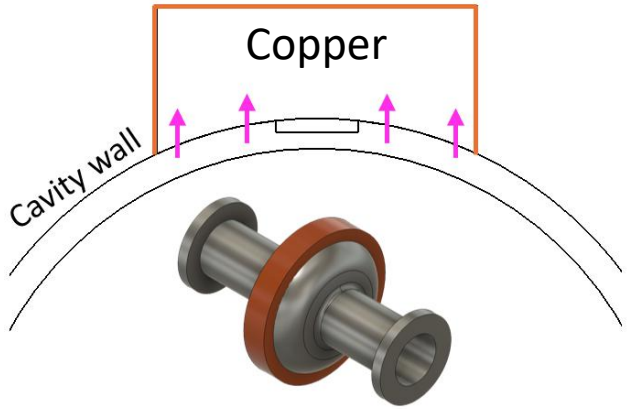


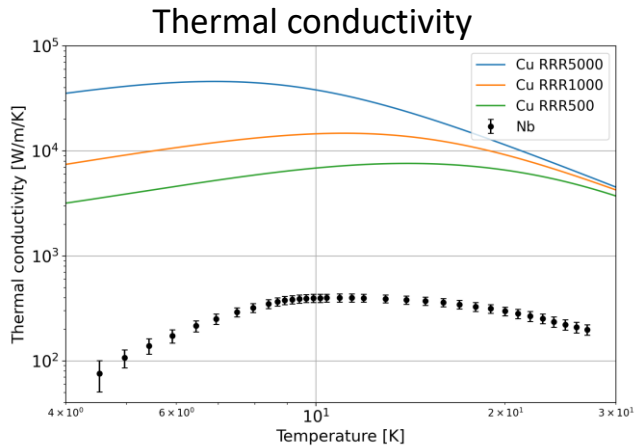


RF heating









New attempt at KEK

- Cryocoolers typically have a few watts of cooling capacity.
- SHI has developed a high cooling capacity GM-JT cryocooler with 9 W at 4.2K.

Comparison of cryocoolers			
Manufacturer	Model	Cooling power	COP*
Sumitomo Heavy Industries	GM-JT	9W@4.2K	0.063%
	GM: RDE-418D4	2.0W@4.2K	0.027%
	PT: RP-182B2S	1.5W@4.2K	0.010%
Cryomech	PT: PT425	2.7W@4.2K	0.021%

* Coefficient of Power
= Cooling power@4.2K / power consumption × 100

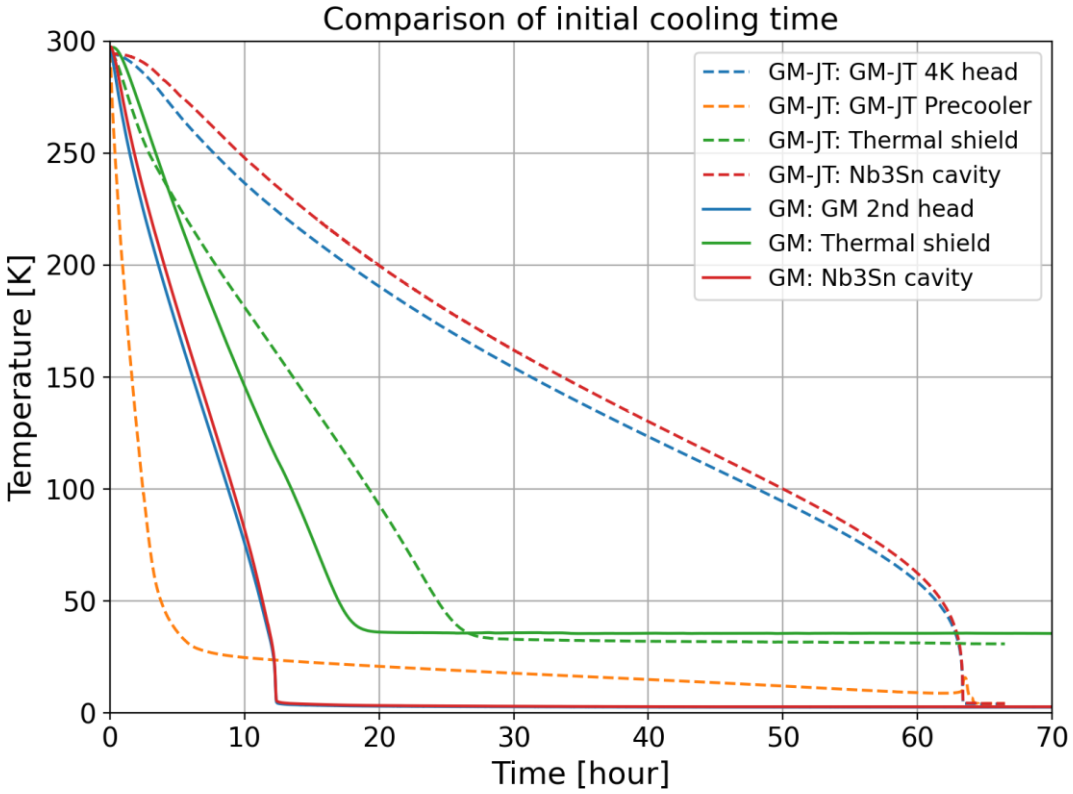
RJT-100
https://shicryogenics.com/product/rjt-100-4k-gm-jt-cryocooler-series/

- KEK got an opportunity to borrow this GM-JT cryocooler for half year and applied to Nb_3Sn cavity conduction cooling.

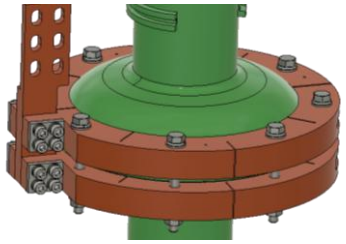
Cooling

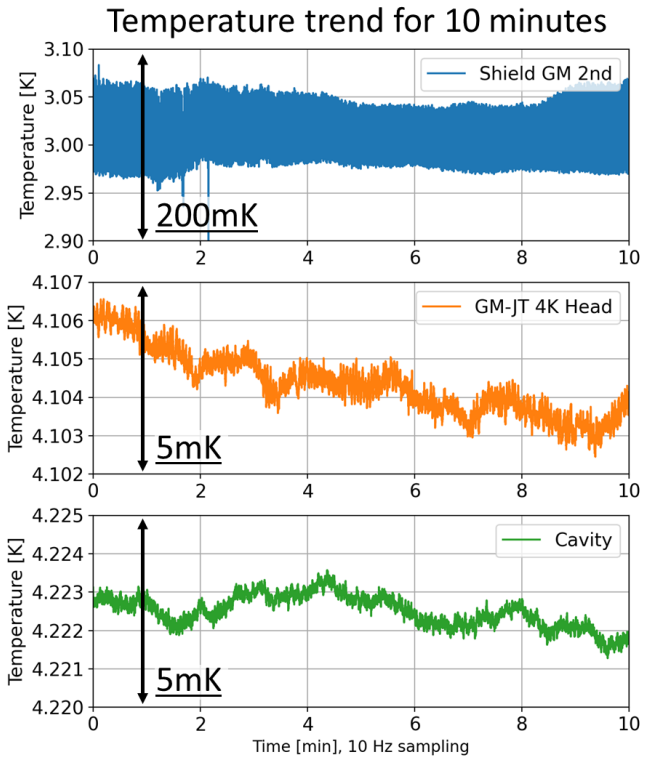
- Two cooling results with a GM-JT and a GM are compared in this slide.

	GM-JT (RJT-100)	GM (RDE-418D4)
Cooling time	63 hours	12 hours
Cavity min. temp.	4.1 K	2.7 K



- Temperature stability of GM-JT was excellent with around a few mK fluctuation.
- The circumferential temperature distribution was very small, less than 50 mK.

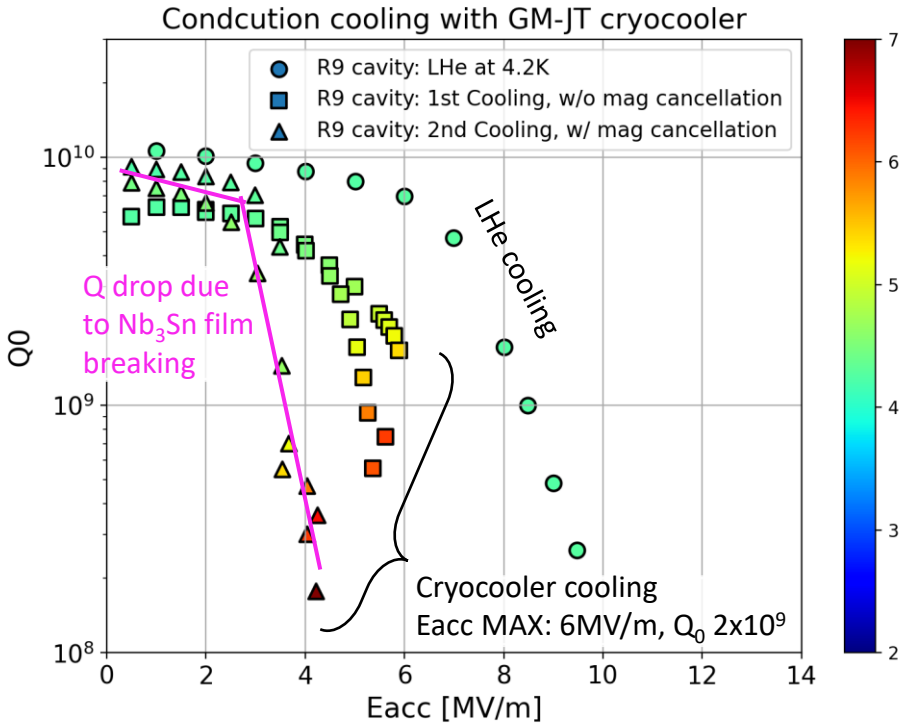


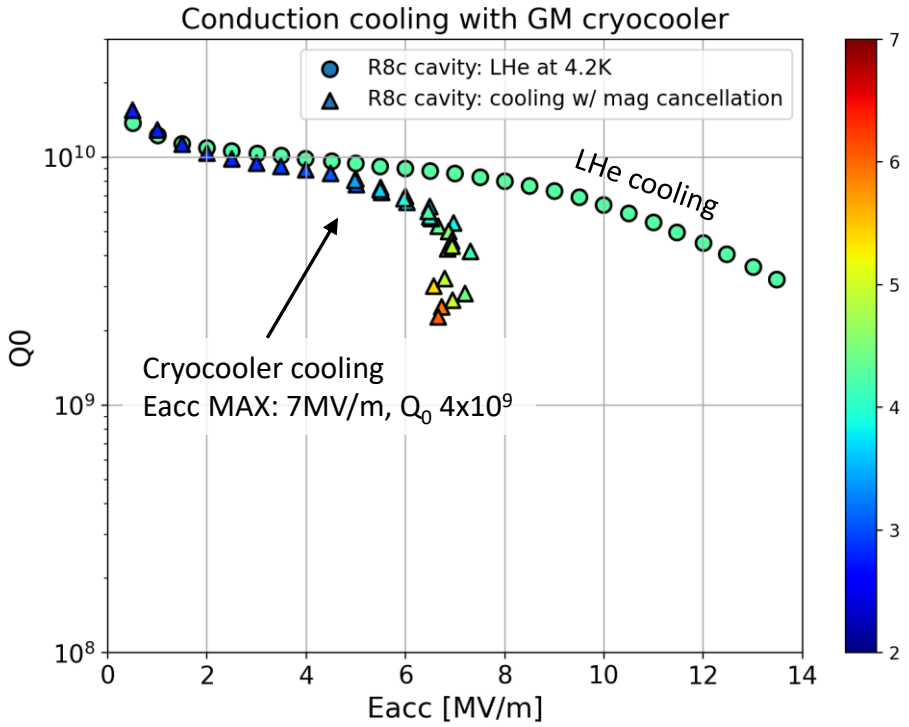


Conduction-cooled RF test

Once cooling was completed, the cavity was warmed up above 20 K and cooled down with cooling speed of 3K/h to eliminate magnetic flux trapping caused by thermoelectromotive force.

9 W@4.2 K



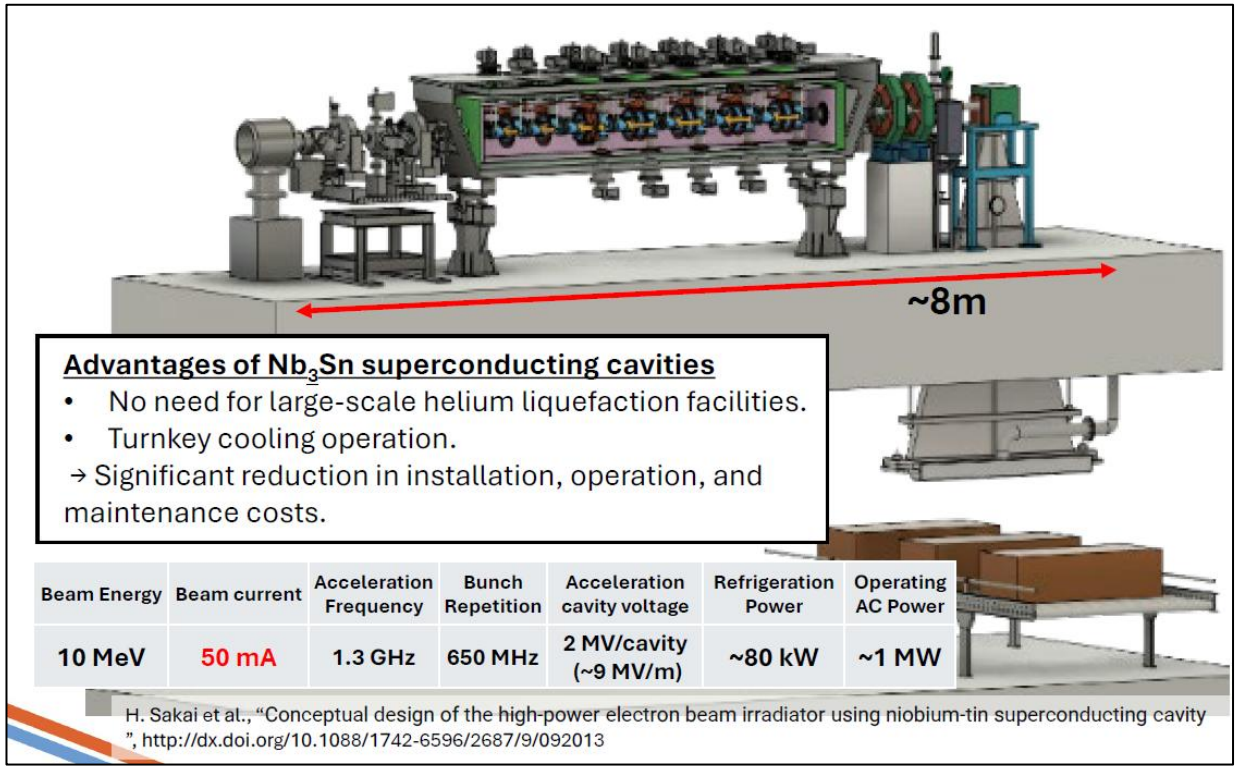


1.8 W@4.2 K

- The improvement of Nb_3Sn cavity quality enabled high Eacc even with a small cooling capacity cryocooler.
- Nb_3Sn film seemed to be broken due to strong clamping force by copper rings.

Future plan in KEK

- Our goal for the Nb_3Sn cavity is not just RF testing but **beam acceleration**.
- We are looking for possibility to install a single cell Nb_3Sn cryomodule into cERL accelerator in KEK.



Beam Energy	Beam current	Acceleration Frequency	Bunch Repetition	Acceleration cavity voltage	Refrigeration Power	Operating AC Power
10 MeV	50 mA	1.3 GHz	650 MHz	2 MV/cavity (~9 MV/m)	~80 kW	~1 MW

H. Sakai et al., "Conceptual design of the high-power electron beam irradiator using niobium-tin superconducting cavity ", http://dx.doi.org/10.1088/1742-6596/2687/9/092013

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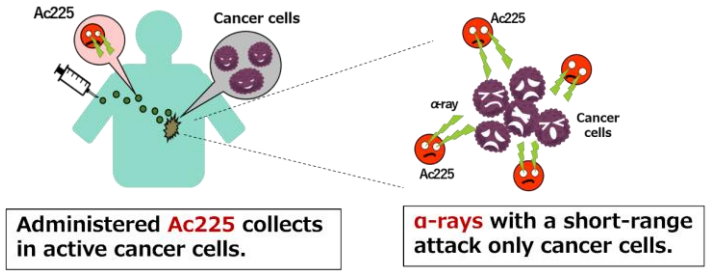
Also, as one of future application, we have designed 10MeV-50mA electron beam irradiator based on conduction cooled Nb_3Sn cavities.

Conduction cooling research in Tohoku Univ.

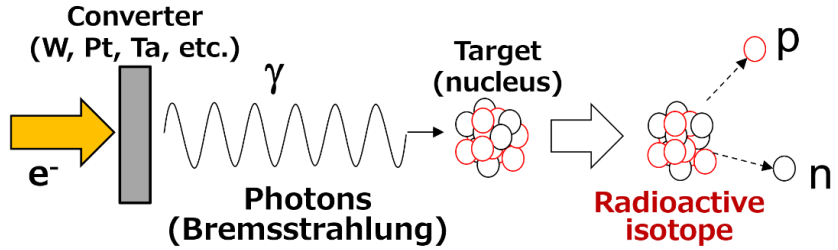
Medical isotope production

Courtesy: S. Kashiwagi

- Tohoku Univ. is the world leading institute for medical isotope production by electron accelerator.
  1) Production of $^{99}Mo/^{99m}Tc$ for SPECT.
  2) Production of ^{225}Ac for Targeted Alpha Therapy (TAT)



- Photonuclear reaction

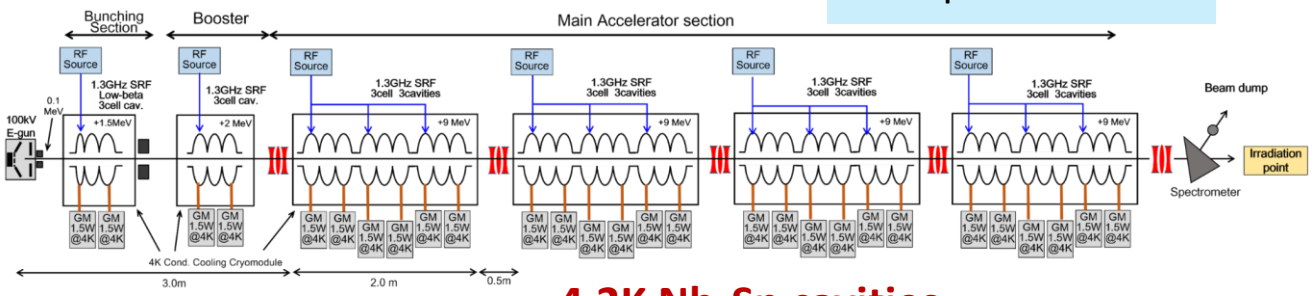


Target	Reaction	RI
Ra-226	226Ra(γ, n)225Ra 225Ra→225Ac + e	Ac-225

- Fundamental research for accelerator upgrade concept

Beam energy: 10~60 MeV
Repetition: 300 pps
Ave. beam curr.: ~230 uA
→ **Beam power ~10kW**

Beam power : 400 kW
Beam energy= 40 MeV
Average current ~10 mA
Bunch charge ~8 pC
Rep. =1300 MHz

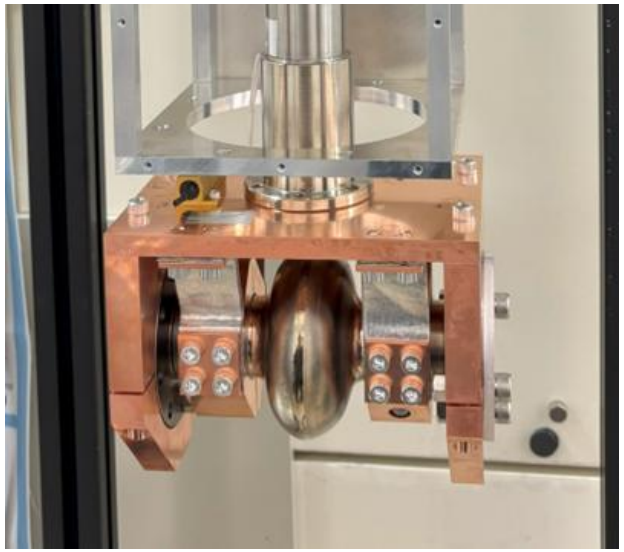


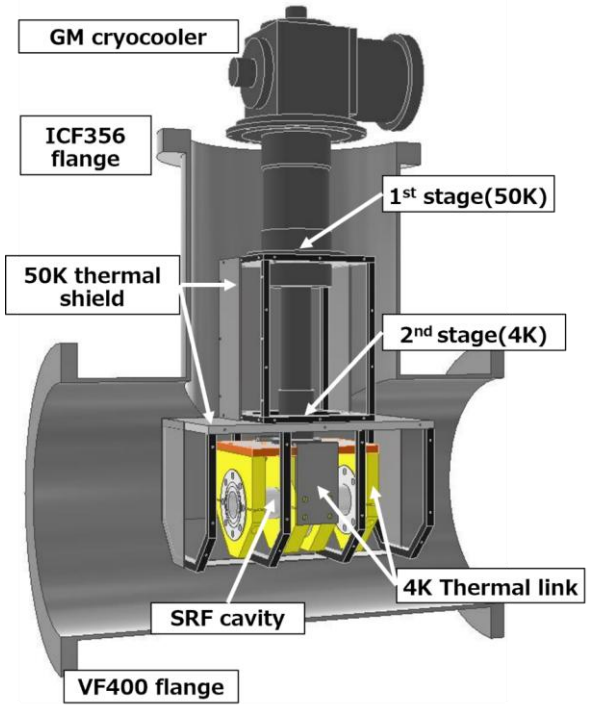
4.2K Nb_3Sn cavities

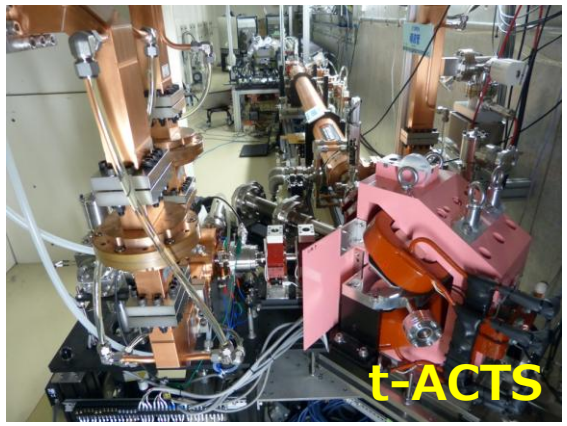
Conduction cooling in Tohoku Univ.

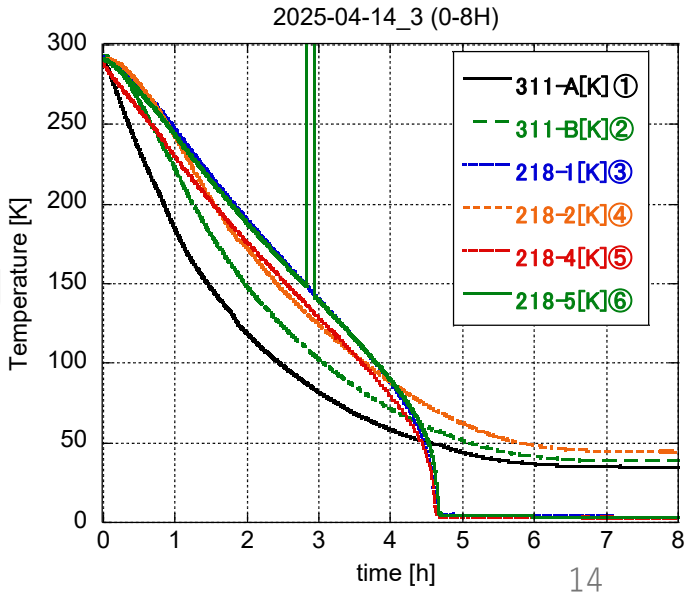
Courtesy: S. Kashiwagi

- Tohoku Univ. has plan to install **the S-band Nb_3Sn cavity** (single cell) into the t-ACTS accelerator to demonstrate beam acceleration.
- Conduction cooling test with pure Nb cavity is underway. Beam tube was clamped by copper block. It was successfully cooled down to below 4 K.









Summary

- Conduction cooling research in KEK was started in 2022. We have ever used the GM-JT and the GM cryocoolers to cool down cavities.
- RF performance with conduction cooling condition has been gradually improving with Nb_3Sn cavity performance increase.
- We are aiming Q_0 10^{10} at 10 MV/m to demonstrate beam acceleration in cERL at KEK.

- Tohoku Univ. has also started conduction cooling research for RI production.
- They succeeded to cool down the cavity below 4 K.

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