DEVELOPMENT OF SC-QWR AND ITS CRYOMODULE FOR LOW-BETA ION ACCELERATORS AT RIKEN RIBF

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RIKEN Nishina Center

SRF 19 DRESDEN

June 30th – July 5th, 2019

V3

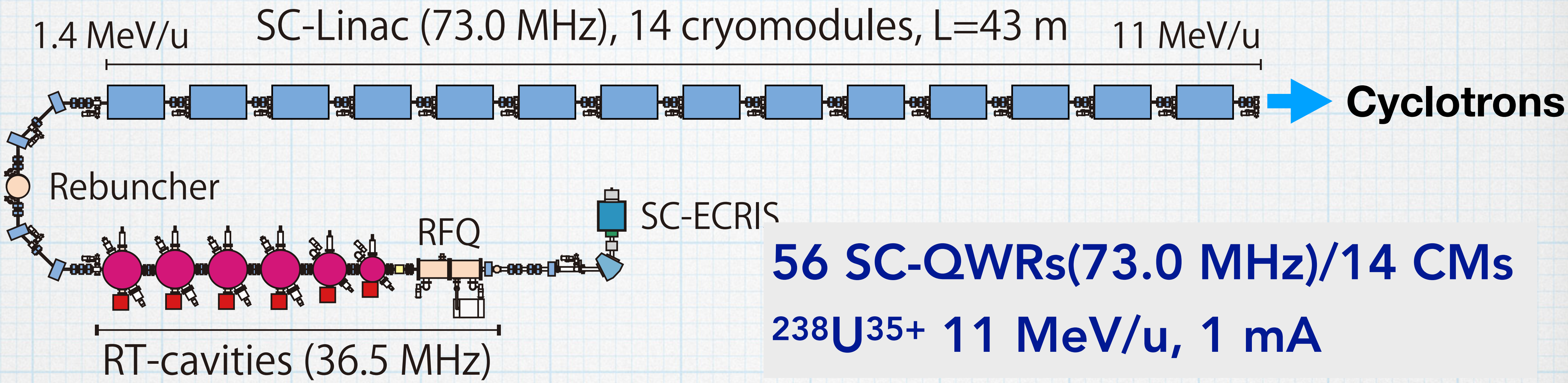
Outline

1. Introduction
2. Development of SC-QWR
3. Development of Prototype Cryomodule
4. RIKEN Linac Upgrade (SRILAC)

Summary

SC-LINAC PROJECTS AT RIBF

(1)New Injector SC-Linac for RIBF (K. Yamada, SRF2013) 2013-



56 SC-QWRs(73.0 MHz)/14 CMs

$^{238}U^{35+}$ 11 MeV/u, 1 mA

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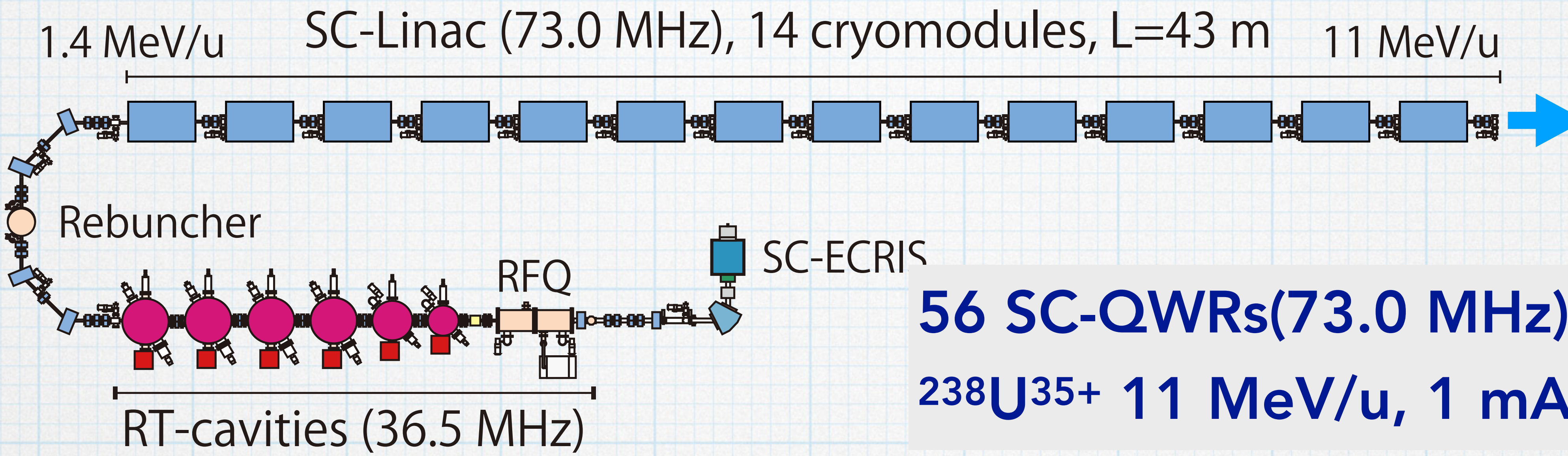

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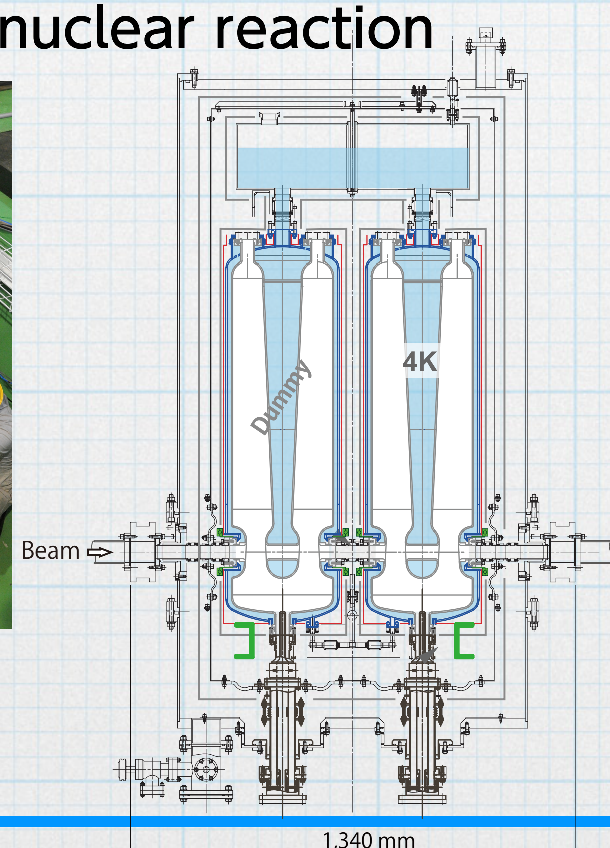
(2)ImPACT Program (N.S., SRF2015,2017)

2014-2019

Nuclear transmutation via nuclear reaction



Prototype CM
SC-QWR(75.5 MHz)

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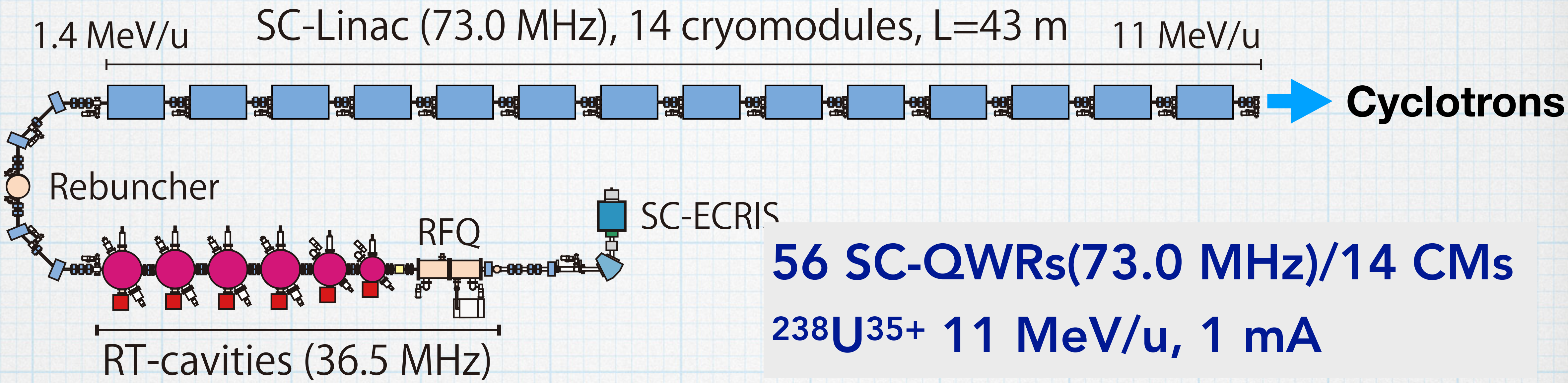

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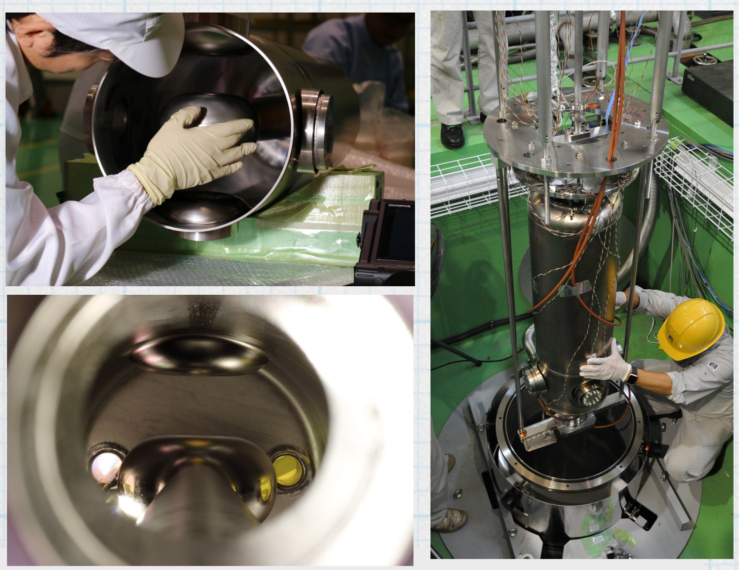
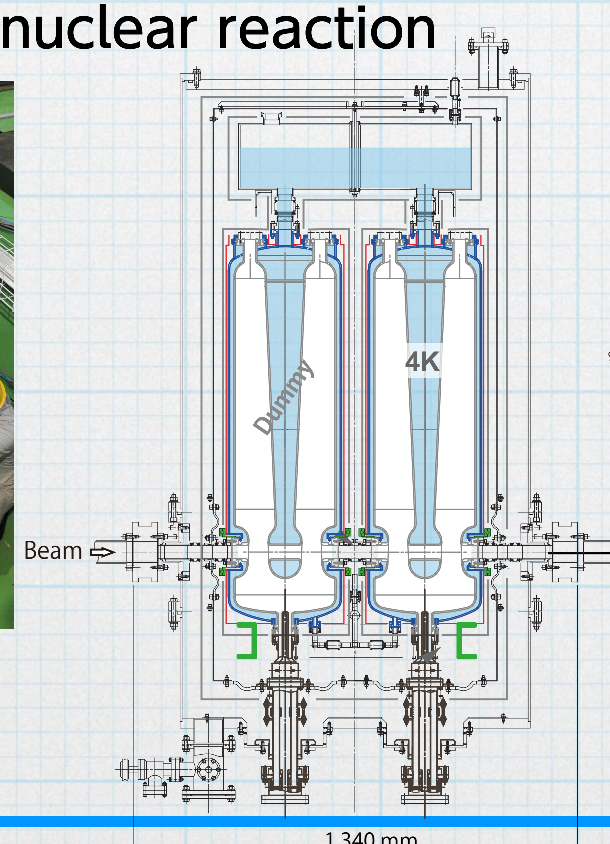




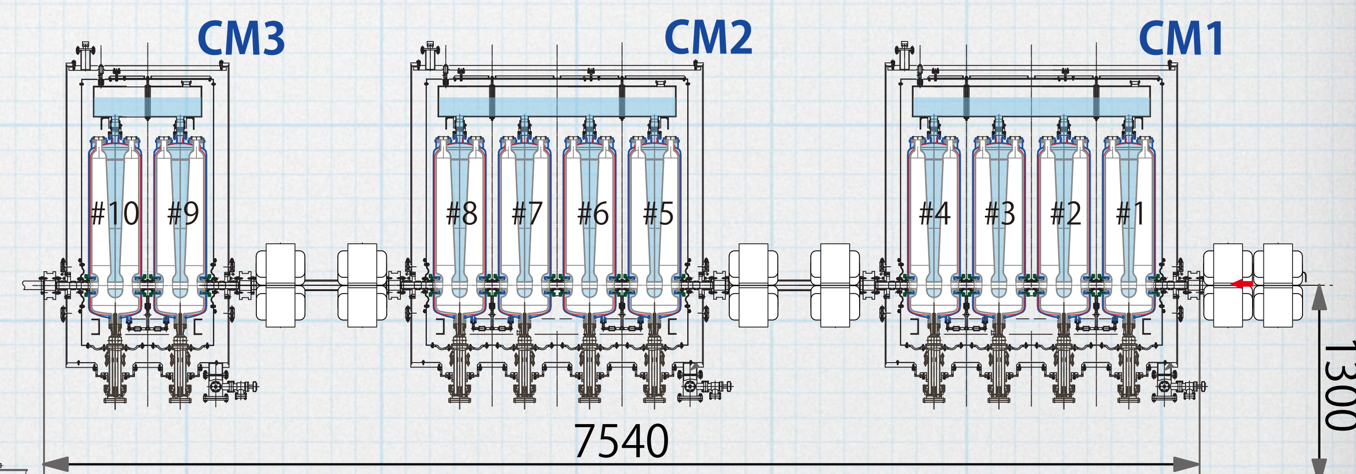
Prototype CM

SC-QWR(75.5 MHz)

(3)SRILAC (N.S., LINAC2018)

2016-

Super Heavy Element synthesis(Z>118)



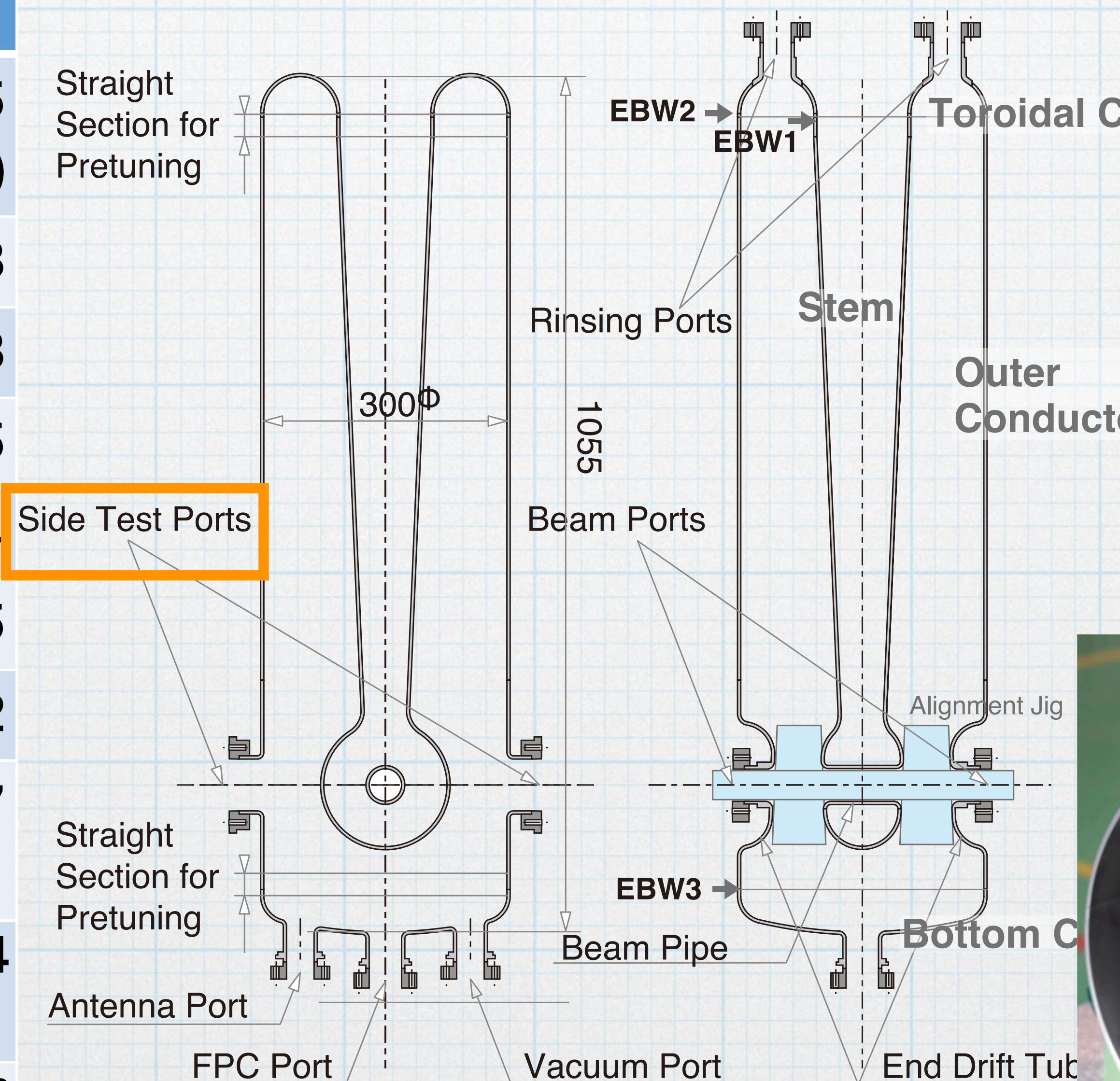
10 SC-QWRs(73.0 MHz)/3 CMs

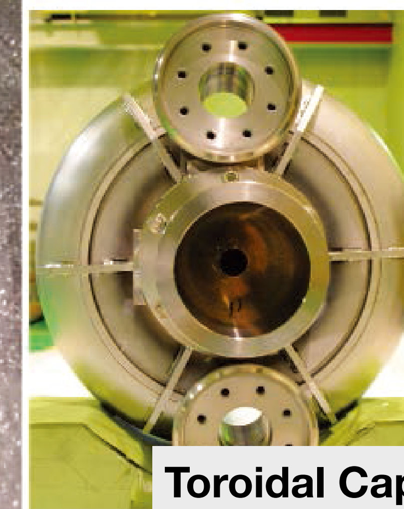
A/q=6 6.5 MeV/u, 10 pμA

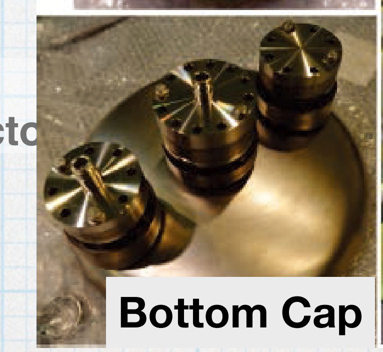
Prototype SC-QWR(75.5 MHz)

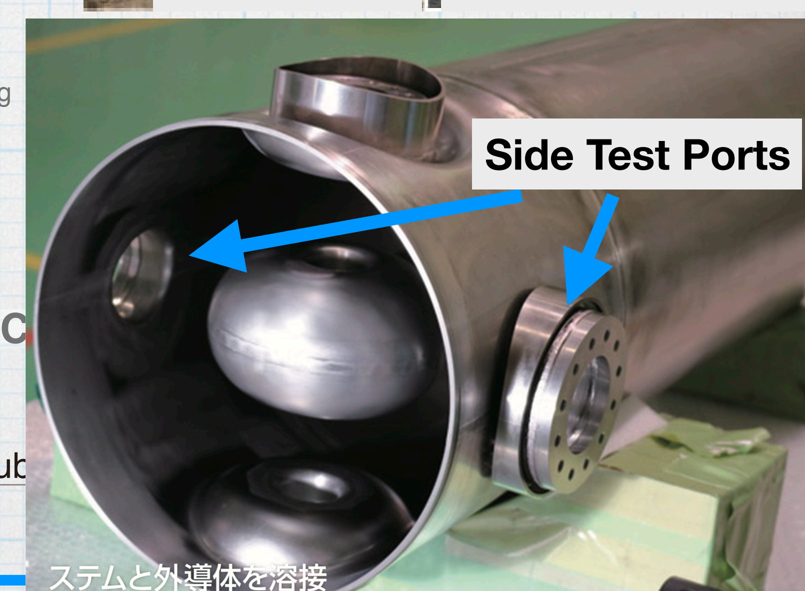
- Quarter-Wave resonator with an optimum β 0.08
- Slow tuner compressing the acceleration gaps
- Side test ports for block tuner
- BCP for surface processing (RRR 250 TD):Q_0 9.4x10^8

Parameters	
Frequency (MHz)	75.5 (CW)
Optimum β	0.08
R_{sh}/Q_0 (Ω)	578
G (Ω)	23.5
V_{acc}(MV)	1.44
E_{acc} (MV/m)	4.5
E_{peak}/E_{acc}	6.2
B_{peak}/E_{acc}(mT/(MV/m))	9.7
Operating Temerature(K)	4
Target Q_0(R_S=25 nΩ)	9.4×10^8









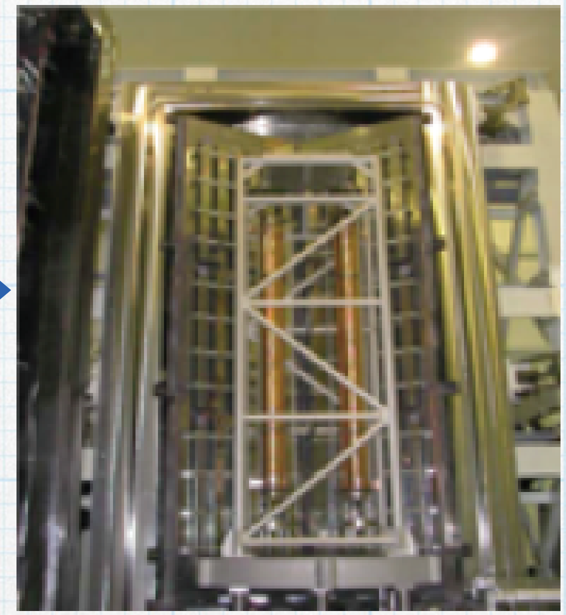
Surface Processing

- BCP(100 μm)→Annealing(750°C, 3hr)→BCP(20 μm)→Baking(120°C, 48hr)

HF:
HNO_3:
H_3PO_4
=1:1:2

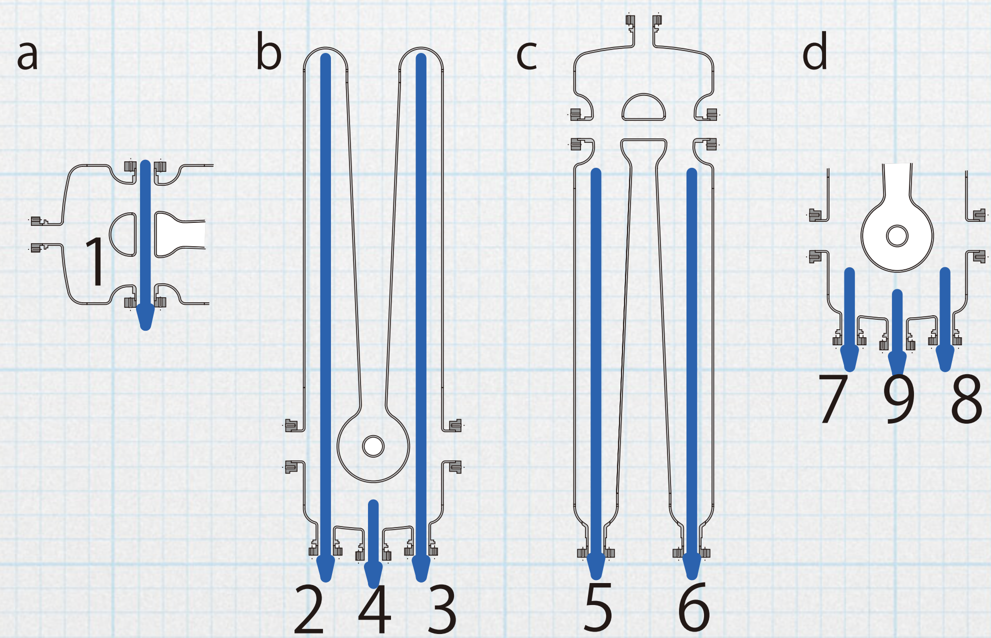
BCP1

Annealing

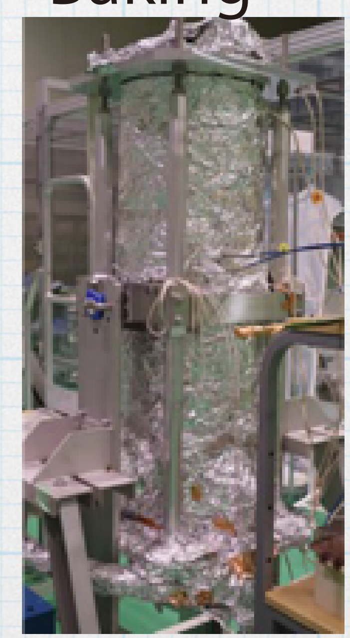


BCP2

HPR



Baking

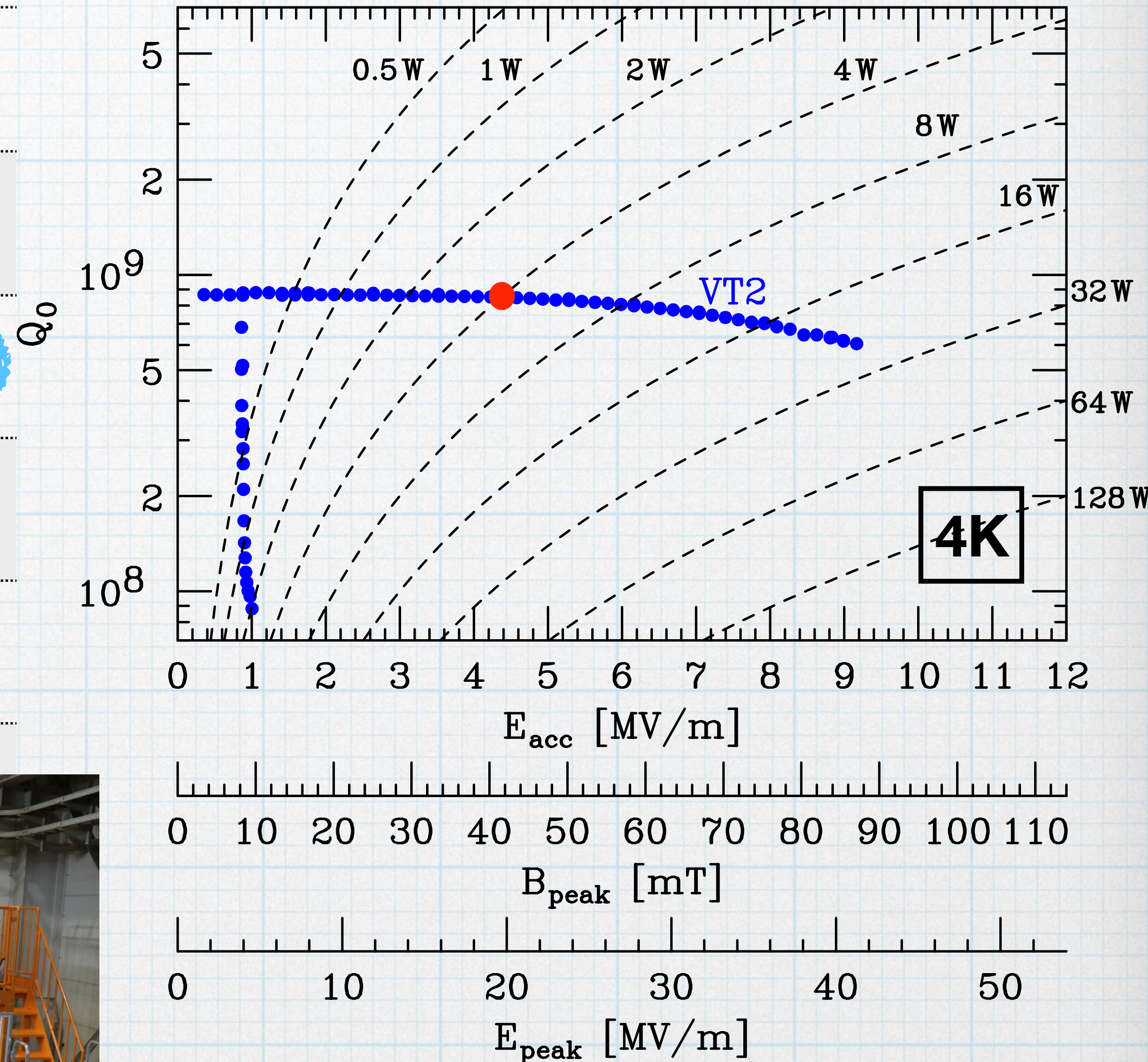


Surface processing (BCP, Annealing, HPR) facility has been developed by MHI-MS.

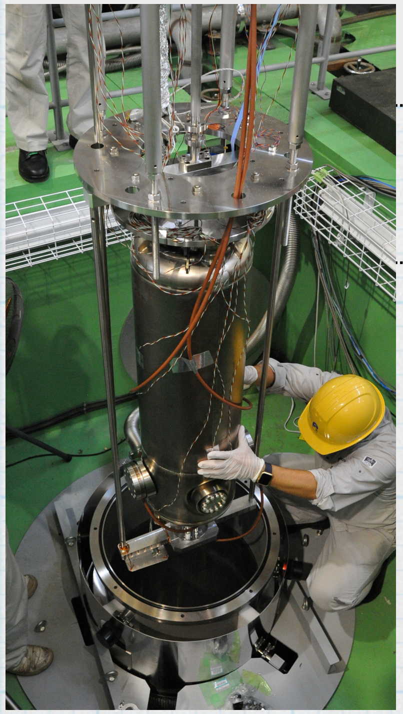
Performance of Cavity

- BCP(100 μm)→Annealing(750°C, 3hr)→BCP(20 μm)→Baking(120°C, 48hr)

Proc.	BCP1 (μm)	Anne-aling	BCP2 (μm)	HPR	Baking	Q_0 @4.5 MV/m
VT1	-	-	19.5	yes	120°C, 48hr	N/A
VT2	97.7	750°C 3hr	23.0	yes	120°C, 48hr	8.7×10^8



Measurement was performed at KEK.



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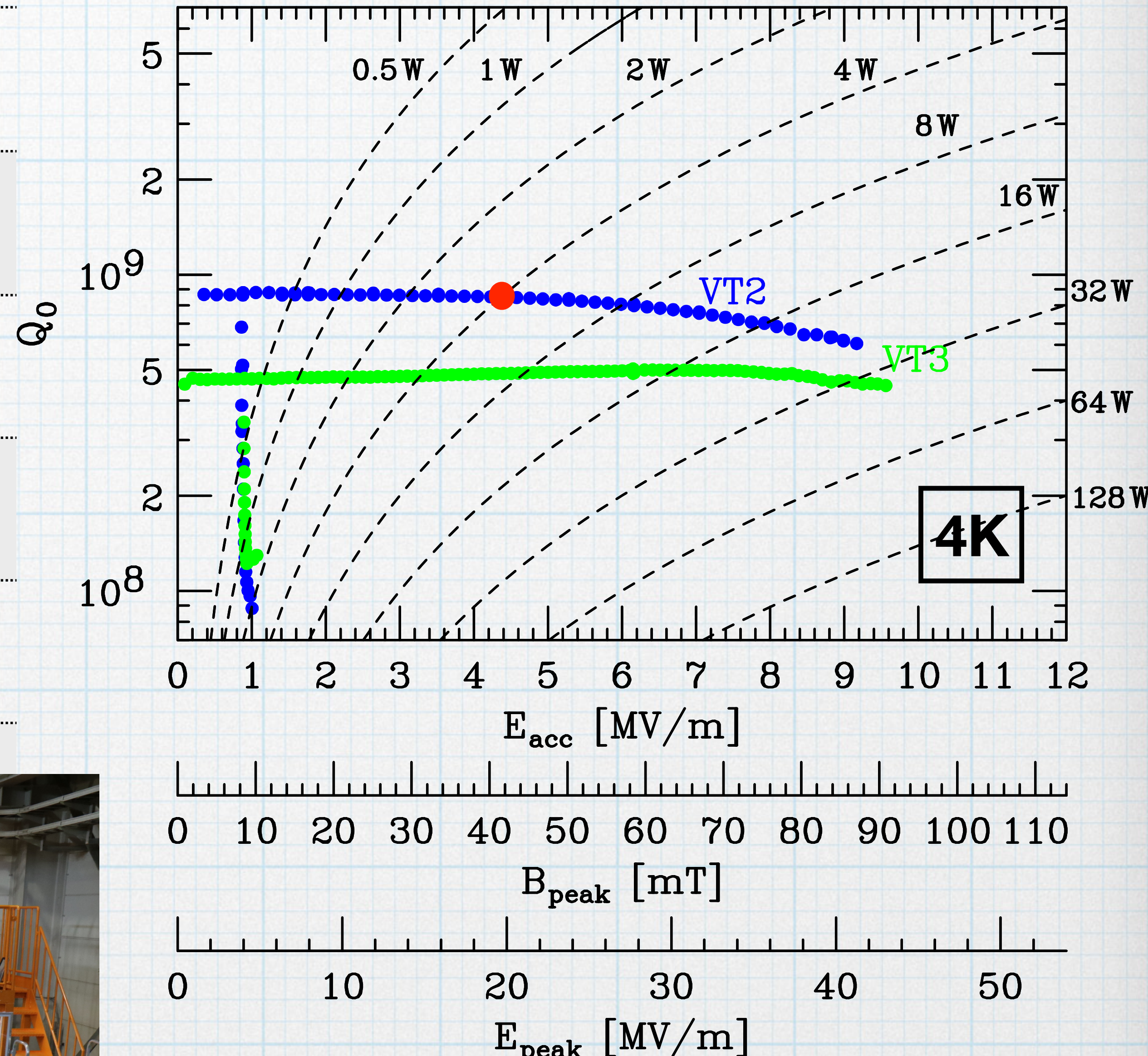

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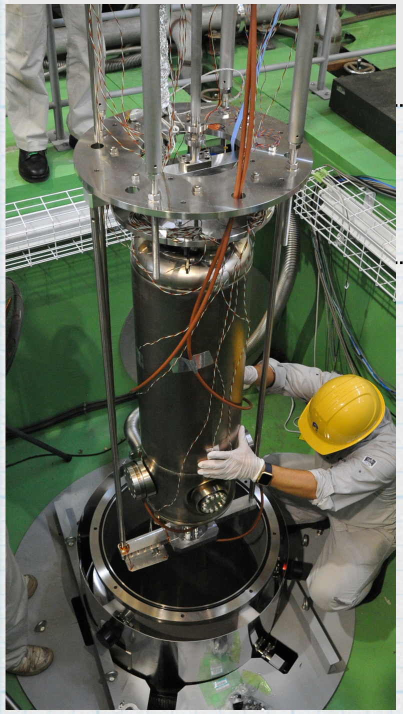

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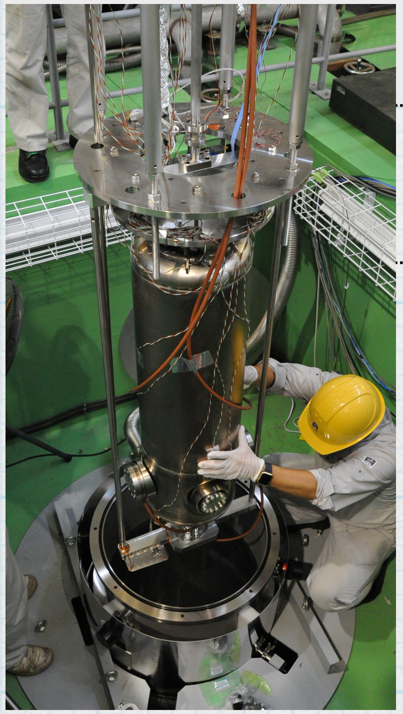

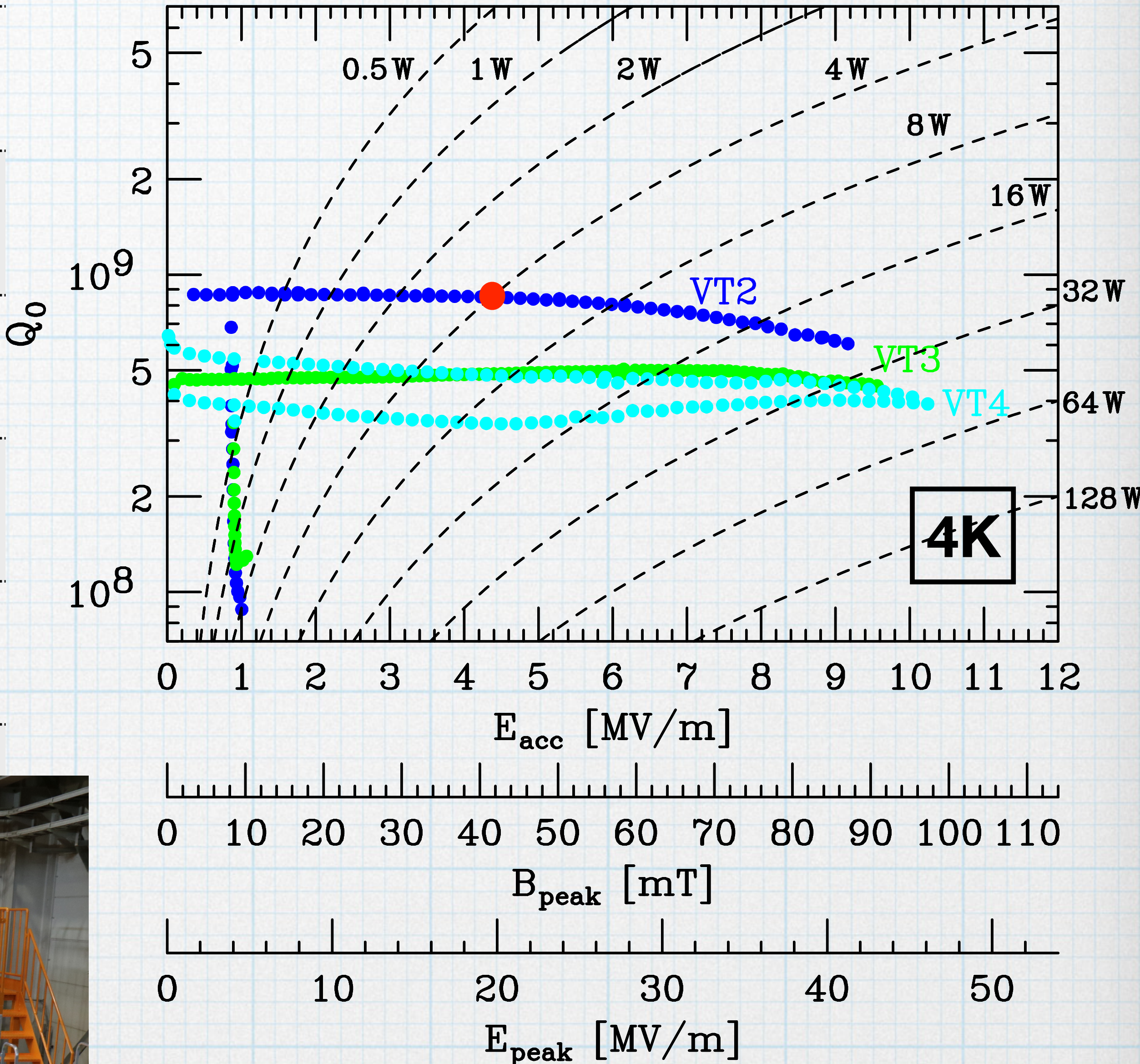

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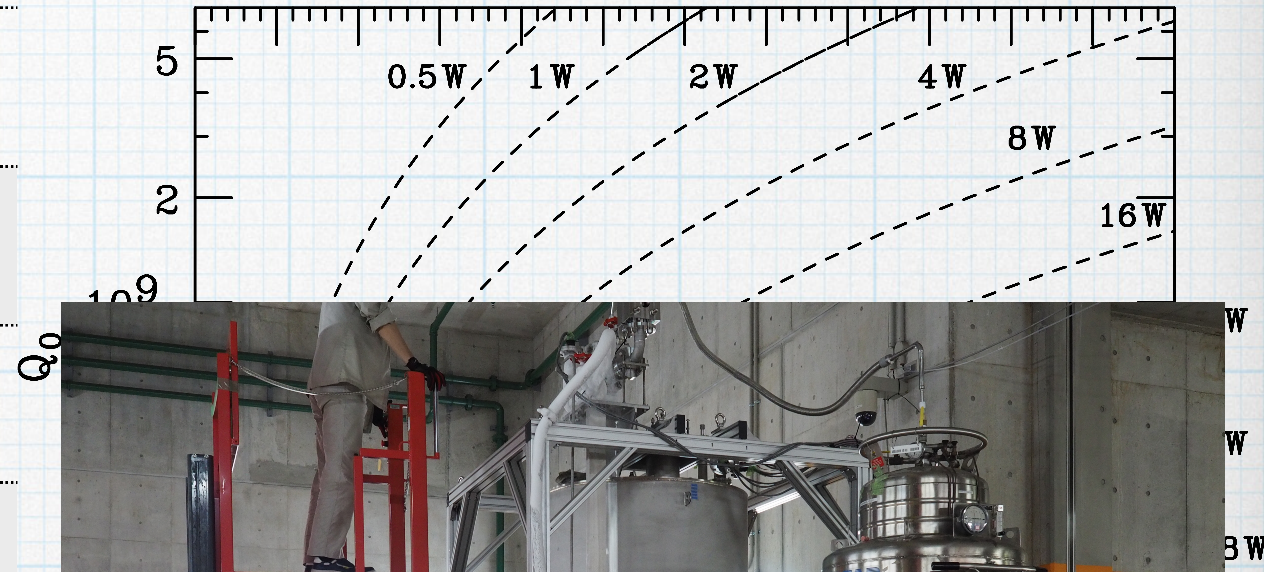

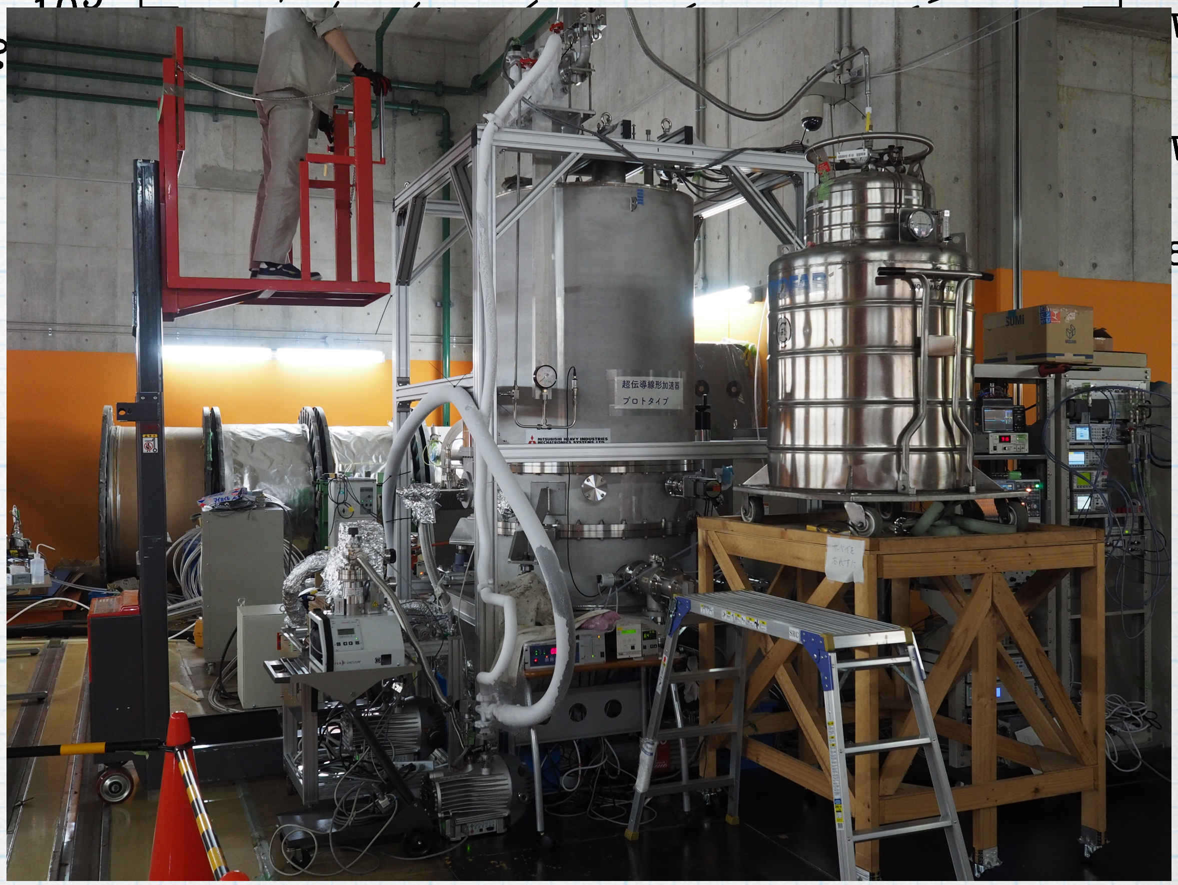

→Cavity was assemble to the test cryomodule.

- Cool-down test
- RF Test (Reported in SRF'17)

Study of cavity performance was continued.

→Cavity was disassembled from the test cryomodule.

→Design modification was made to the SRILAC cavities.

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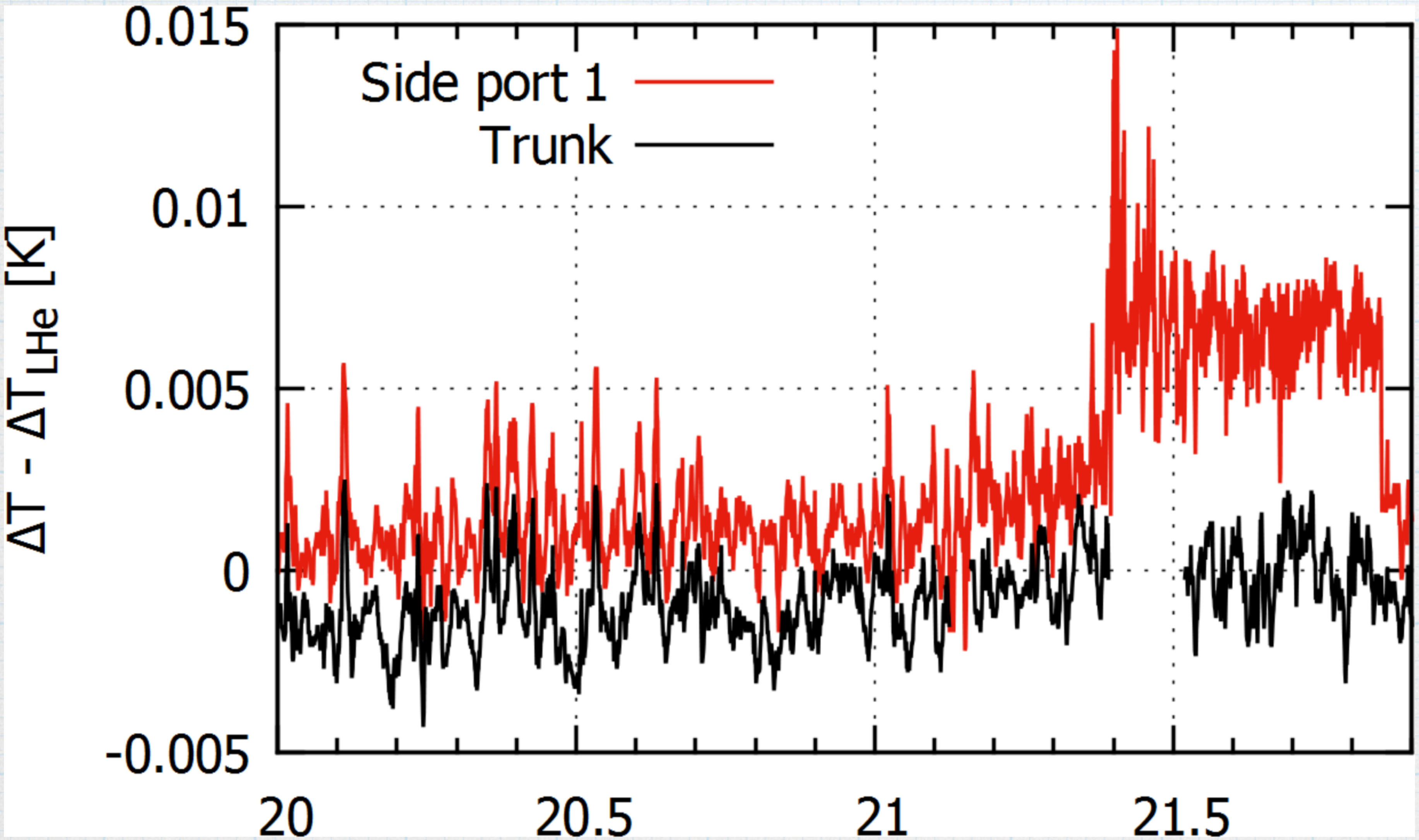
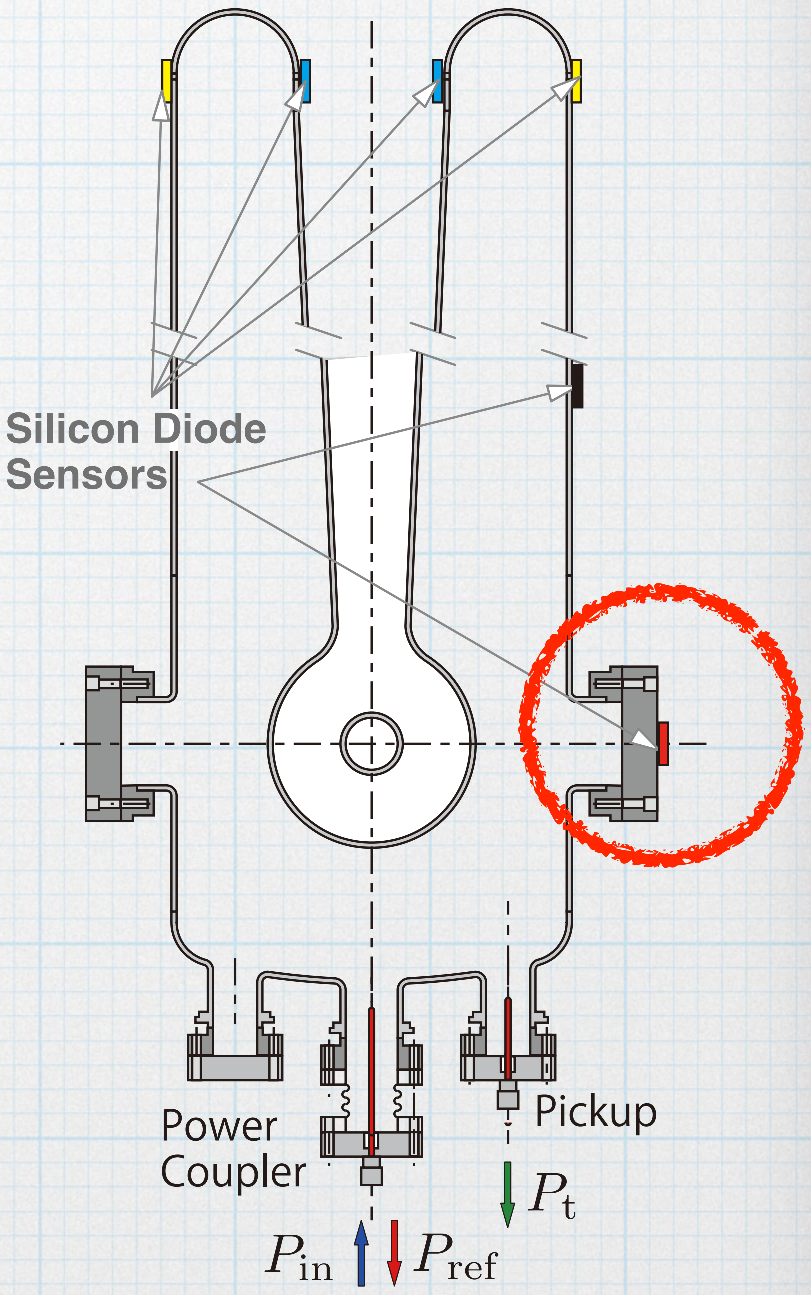
Summary

Why the cavity got degraded?

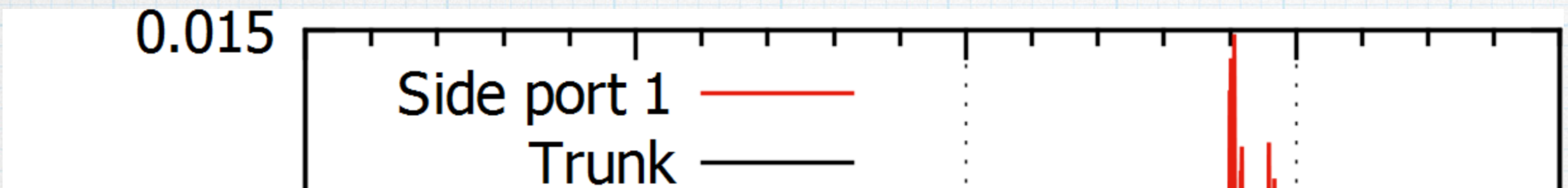
- During conditioning of multipacting temperature rise of the blank flange of the test port was observed.

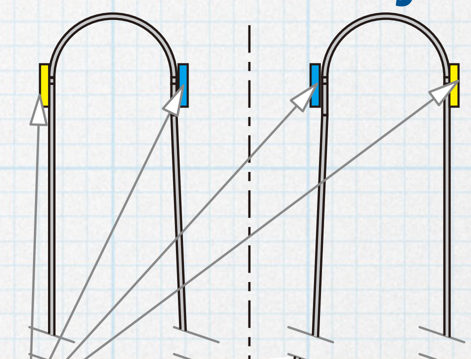


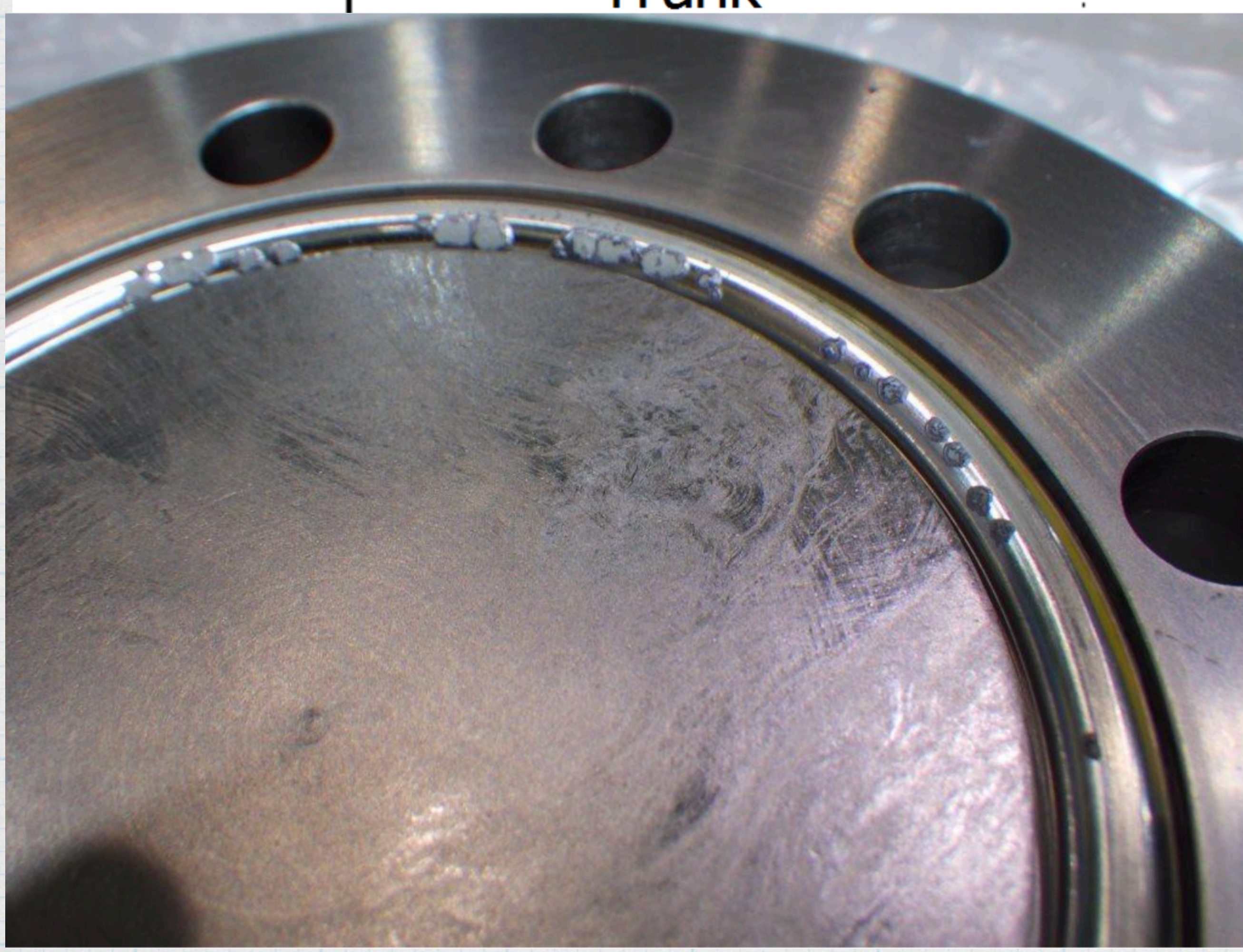


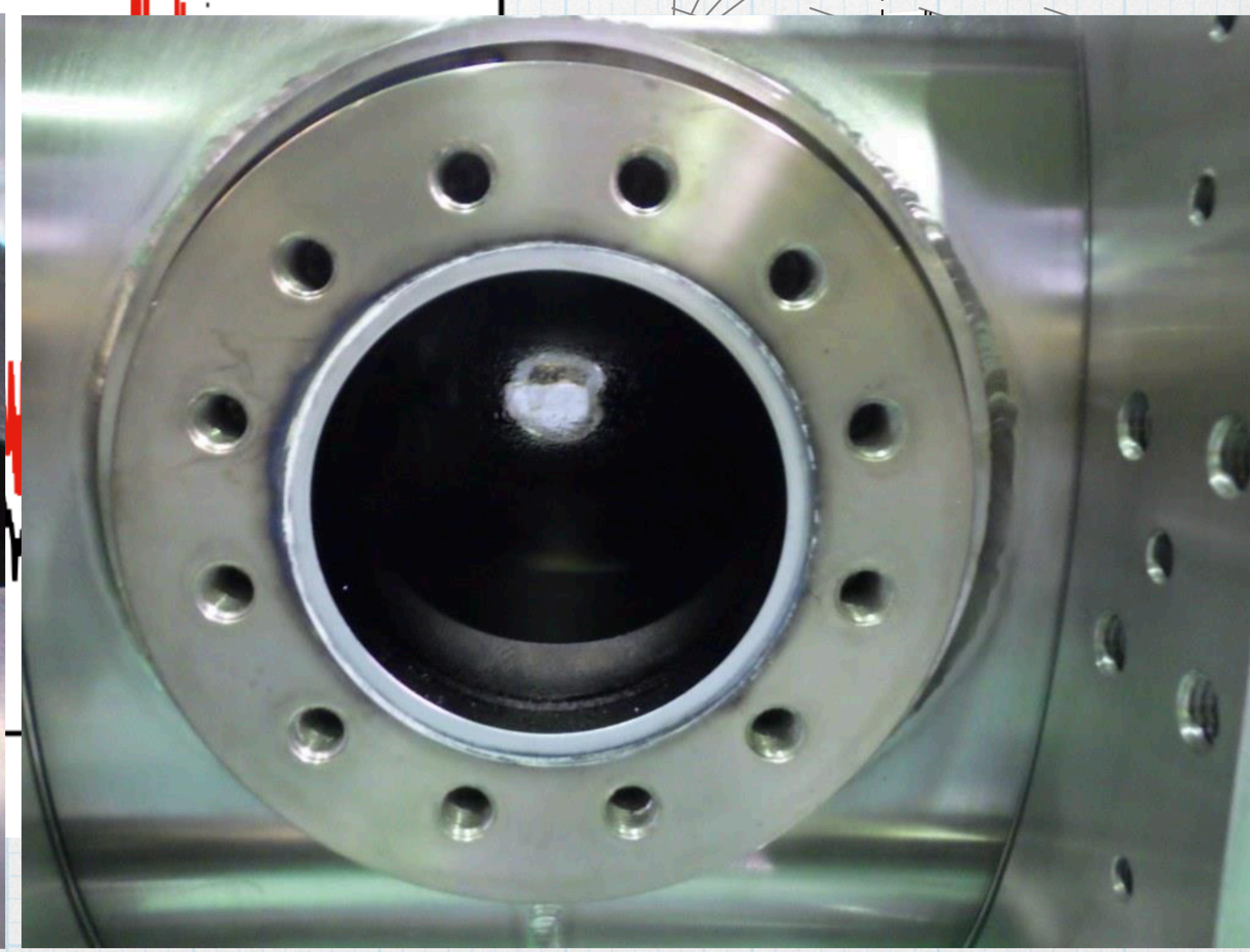
Why the cavity got degraded?

- During conditioning of multipacting temperature rise of the blank flange of the test port was observed.
- Vacuum seal of the side test port(U-TIGHTSEAL) was found seriously damaged after VT4.









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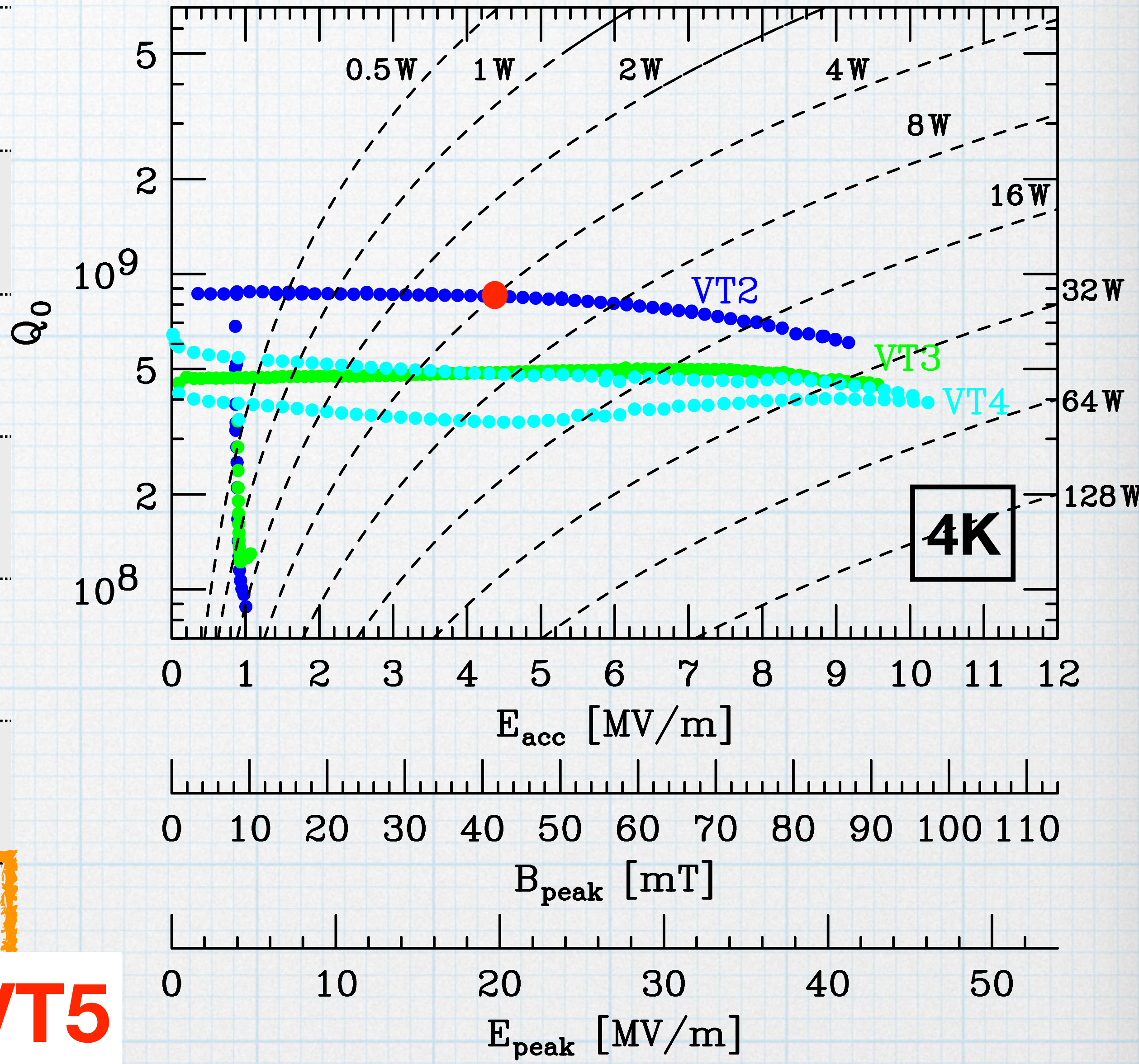
VT3	-	-	21.9	yes	120°C, 48hr	4.7x10⁸
VT4	-	-	-	yes	120°C, 48hr	4.7x10⁸
VT5	-	-	D26.5 +21.5	yes	120°C, 48hr	

- Clean up the flange surfaces
- Exchange U-TIGHTSEAL
- Differential Etching + BCP2+HPR+Baking

→ VT5



Measurements were performed at KEK.

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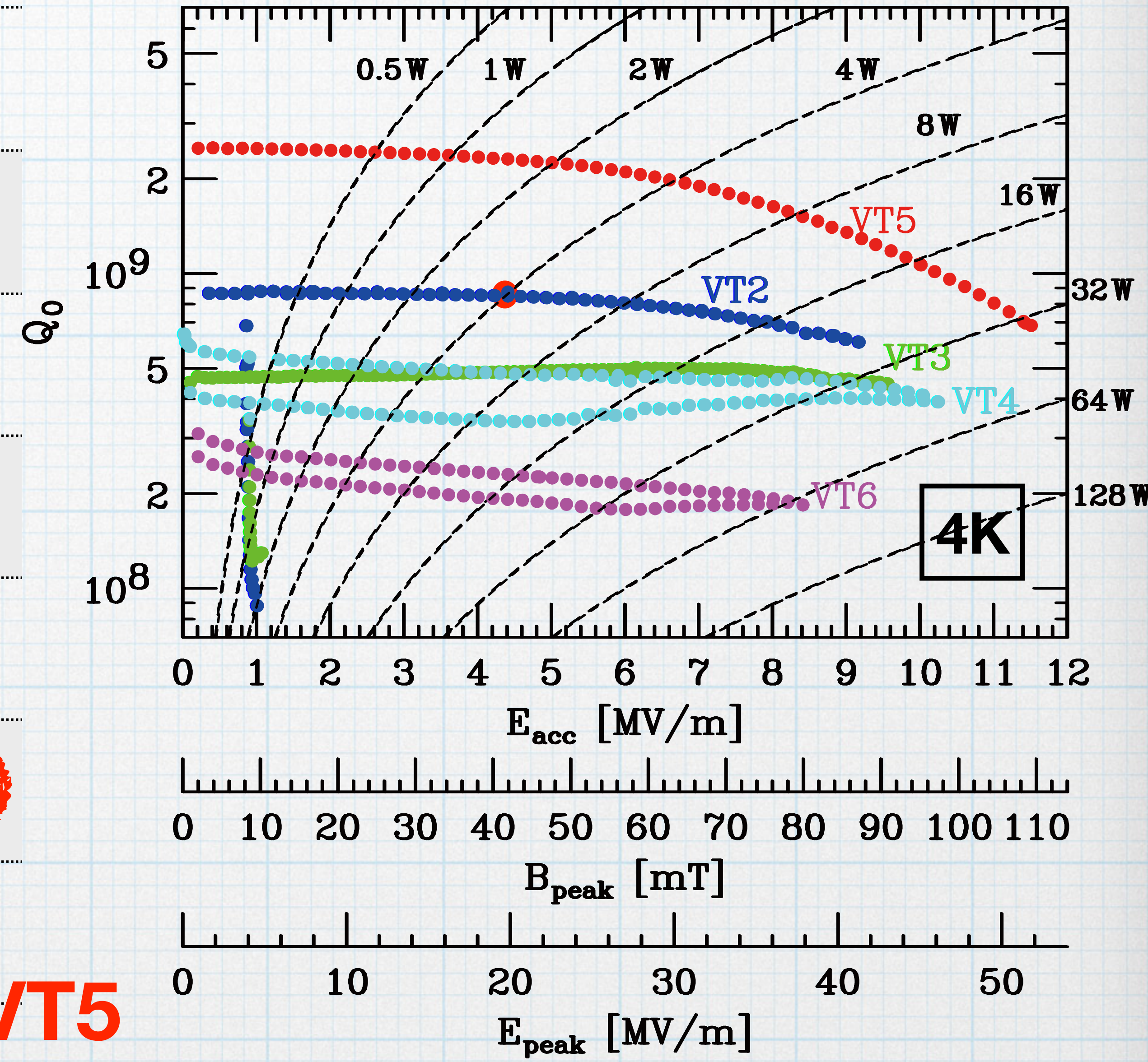
VT4	-	-	-	yes	120°C, 48hr	4.7x10⁸
VT5	-	-	D26.5 +21.5	yes	120°C, 48hr	2.3x10⁹

- Clean up the flange surfaces
- Exchange U-TIGHTSEAL → **VT5**
- Differential Etching + BCP2+HPR+Baking



Measurements were performed at KEK.

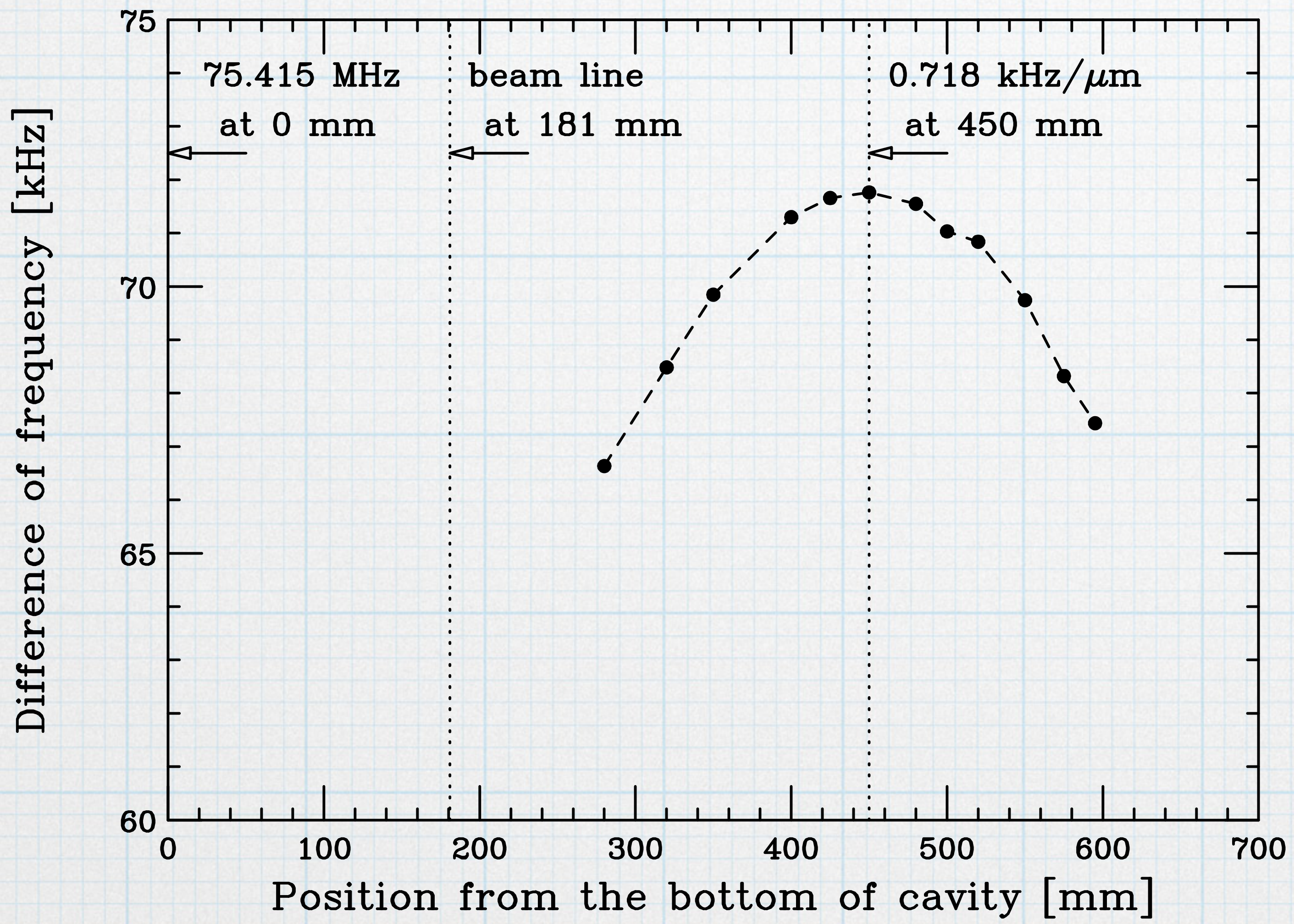
The cavity yielded Q_0 4.5 times of that of VT2

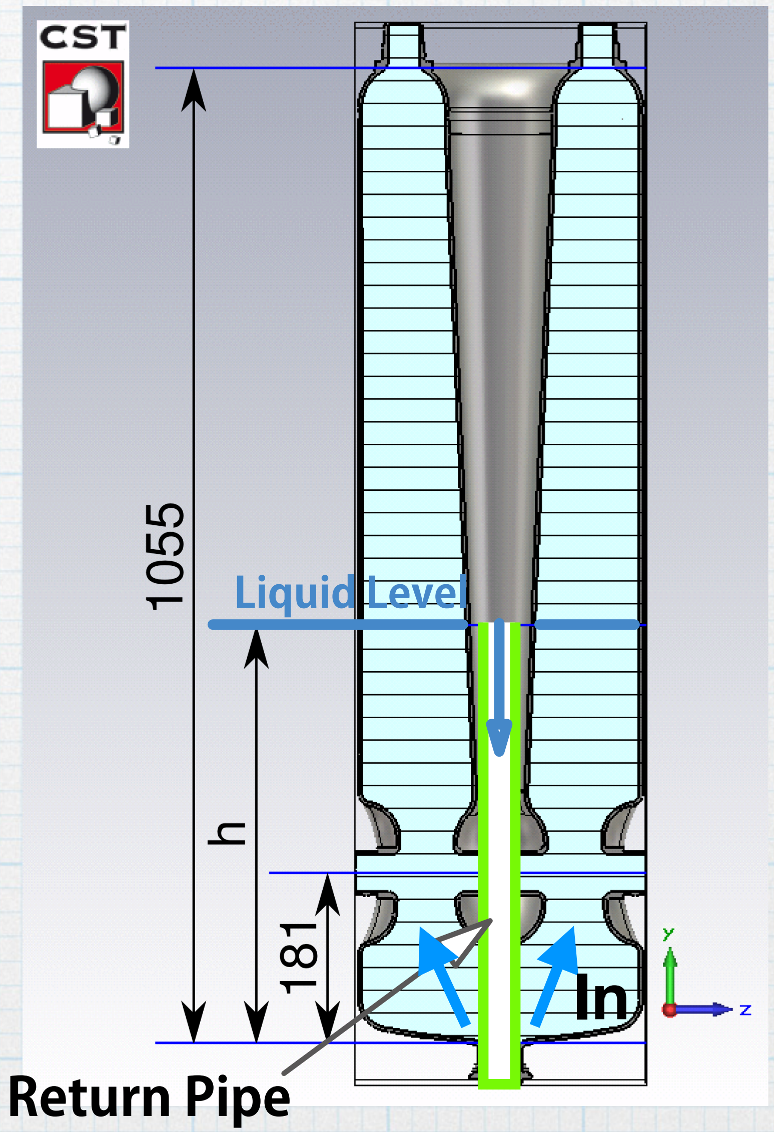
Differential Etching

- Frequency tuning during fabrication is time-consuming.
- One effective way of frequency tuning is differential etching.

L. Popielarske et al., Linac'12, MOPB071

- The frequency shift was estimated by MWS simulations.





- Differential etching of 26 μm increased the frequency by 12.6 kHz at 4K.

Side Test Ports for Frequency Tuning

- Frequency tuning during fabrication requires a lot of attention.
- Cold tuner adjust the frequency at 4.5 K with an order of 0 to -10 kHz squeezing beam ports with 5,000N.
- During operation cold tuner trims frequency detuning due to variation of He pressure, microphonics, Lorentz force detuning , beam loading, and etc. within a band width of ±60 Hz.

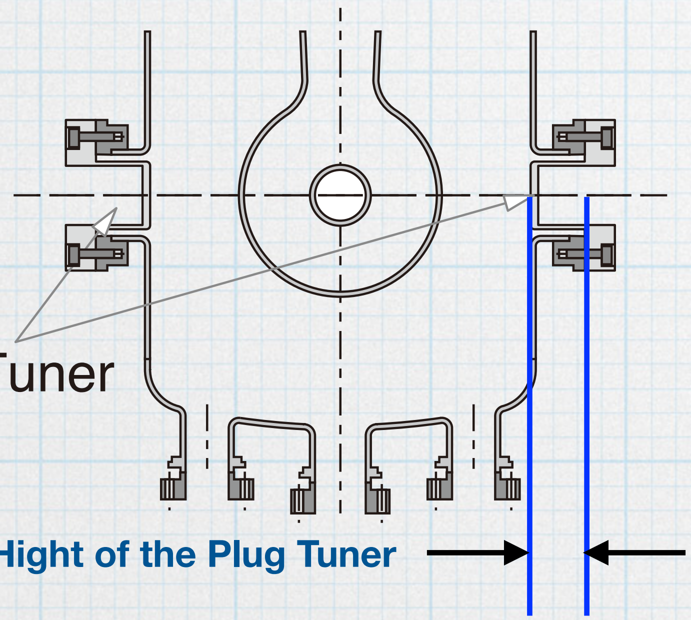
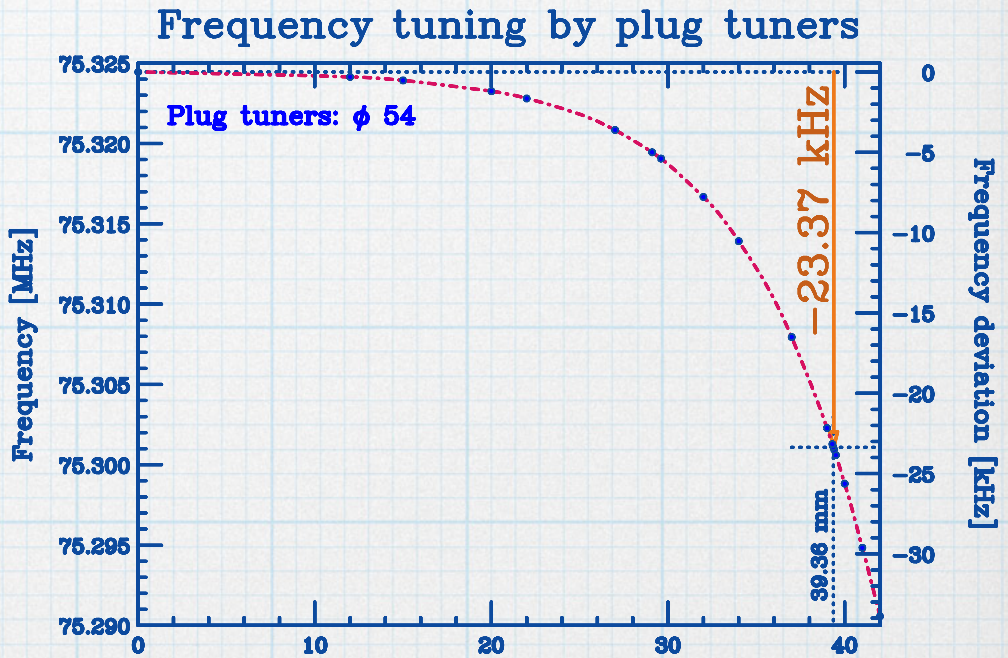


Photo of a plug made of pure Nb



Hight of the Plug Tuner

- A pair of plug lowers the frequency with an order of a few 10 kHz.
- Plugs machined with a high precision can adjust the frequency within 1 kHz.
- Possibility as a dynamic tuner: Δf/Δt = a few kHz/mm.

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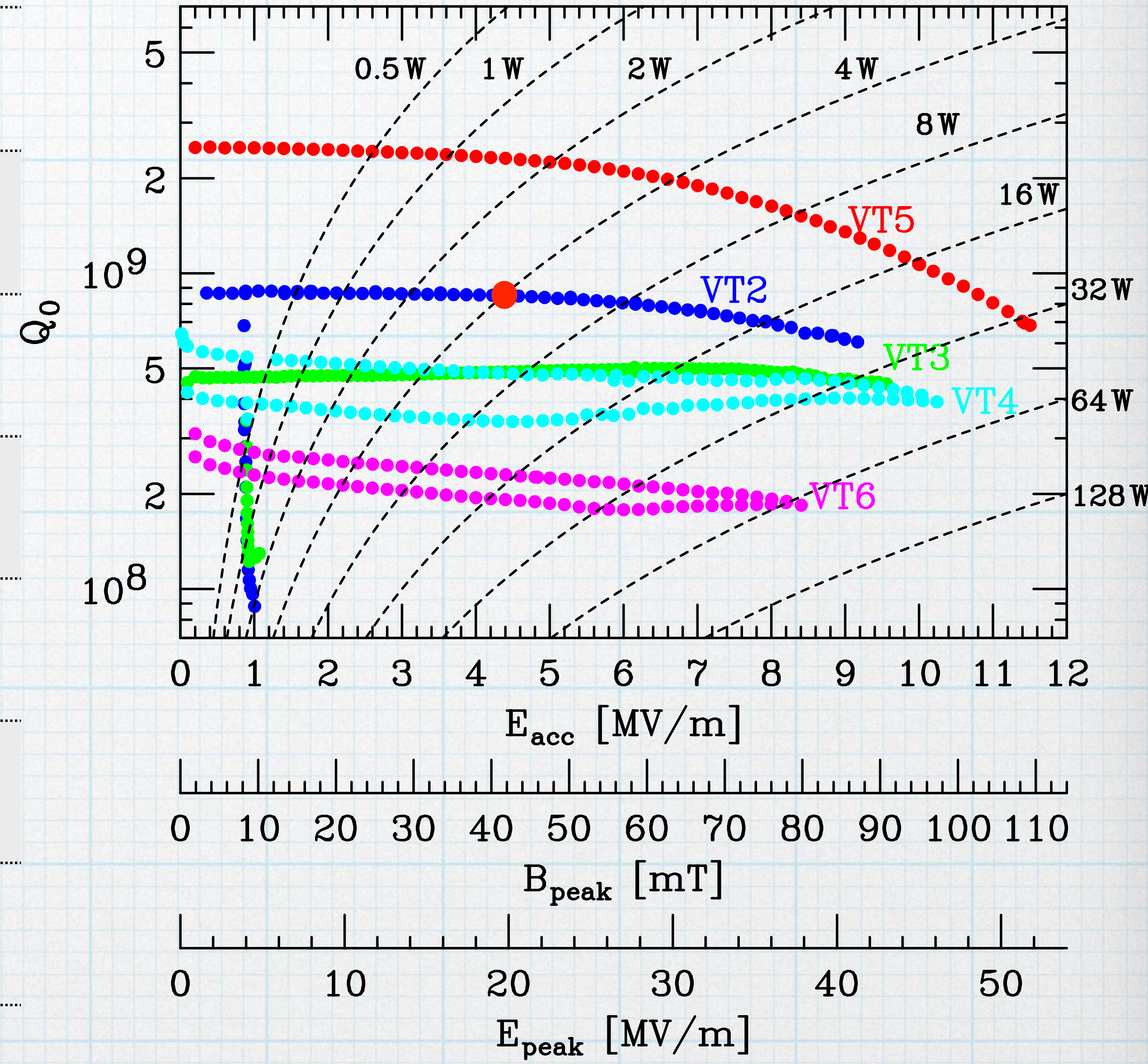
VT5	-	-	D26.5 +21.5	yes	120°C, 48hr	2.3×10^9
VT6	-	-	-	-	-	1.9×10^8



Measurements were performed at KEK.

Plug tuner degrades Q_0 to 1/10 of that of VT5

Observed frequency shift 27.2 kHz while the estimation was 23.4 kHz.

Modification of the cavity design

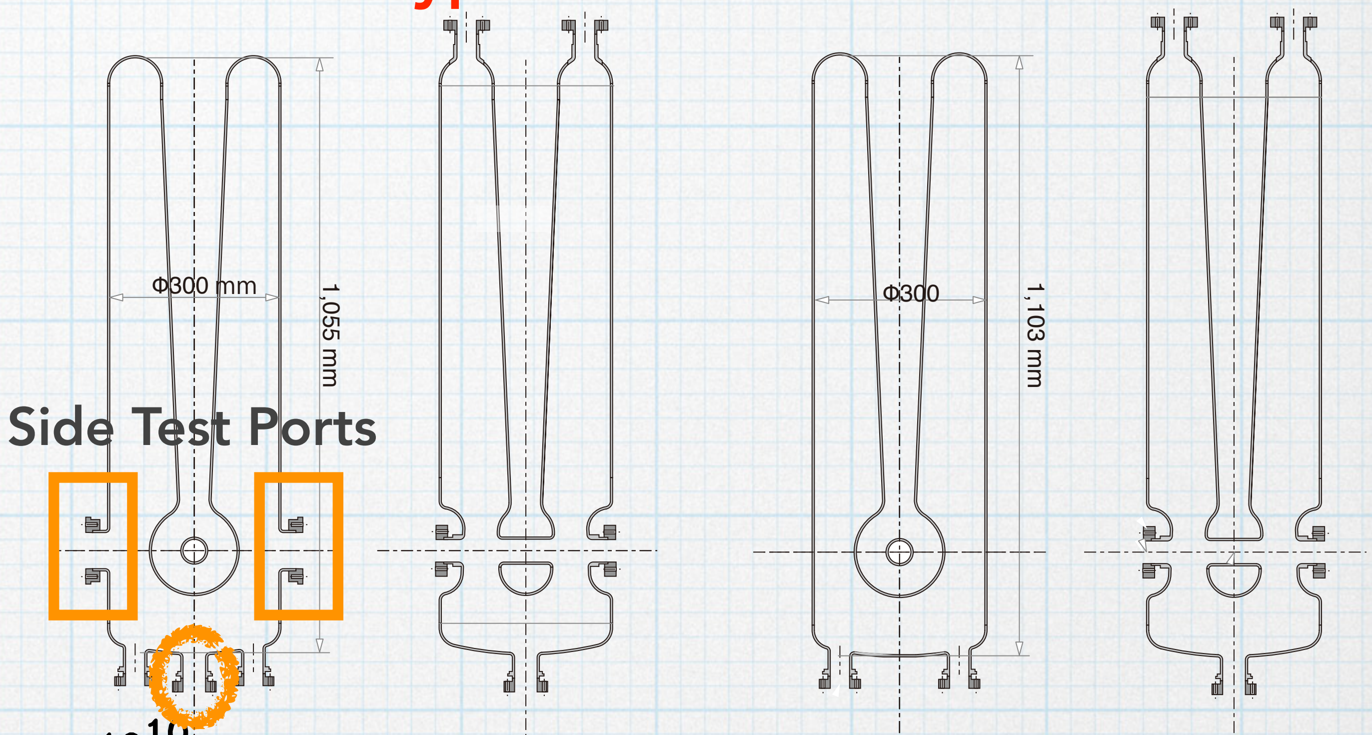
■ Design modification of the cavity for the SRILAC.

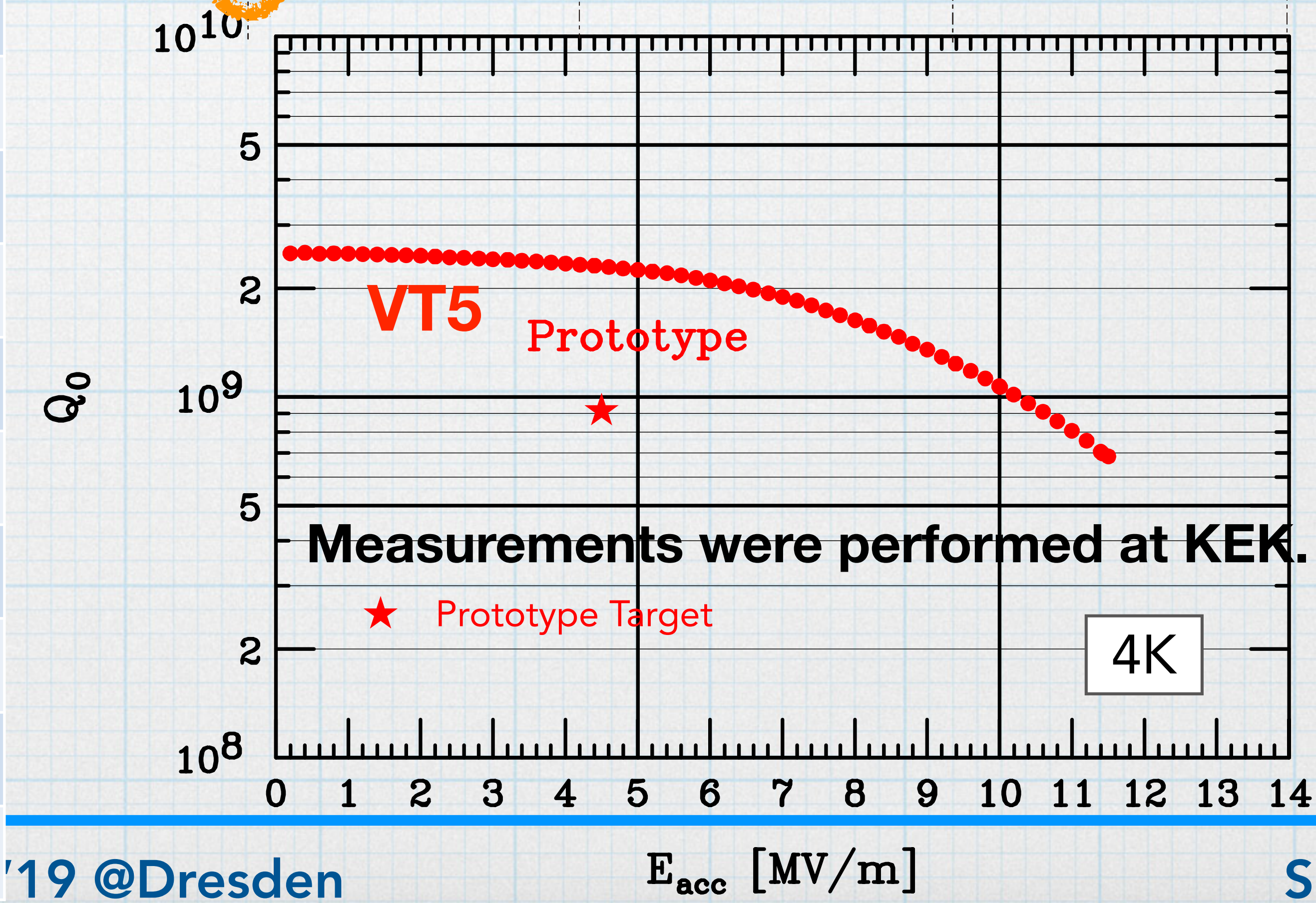
Frequency 75.5 MHz → 73.0 MHz

Removal of the side test ports

Parameters	Prototype	SRILAC
Frequency (MHz)	75.5 (CW)	73.0 (CW)
Temperature (K)	4	4
Height [mm]	1055	1103
Optimum β	0.08	0.08
L_{cav} (mm)	318	320
E_{peak}/E_{acc}	6.0	6.2
B_{peak}/E_{acc}(mT/(MV/m))	9.5	9.79.6
R_{sh}/Q_0 (Ω)	578	579
G (Ω)	23.5	22.4
V_{acc}(MV)	1.44	2.16
E_{acc} (MV/m)	4.5	6.8
Q_0@E_{acc}	2.3x10⁹	
P_0@E_{acc} (W)	1.5	
Q_{pickup}	2.8×10¹¹	

Prototype SRILAC





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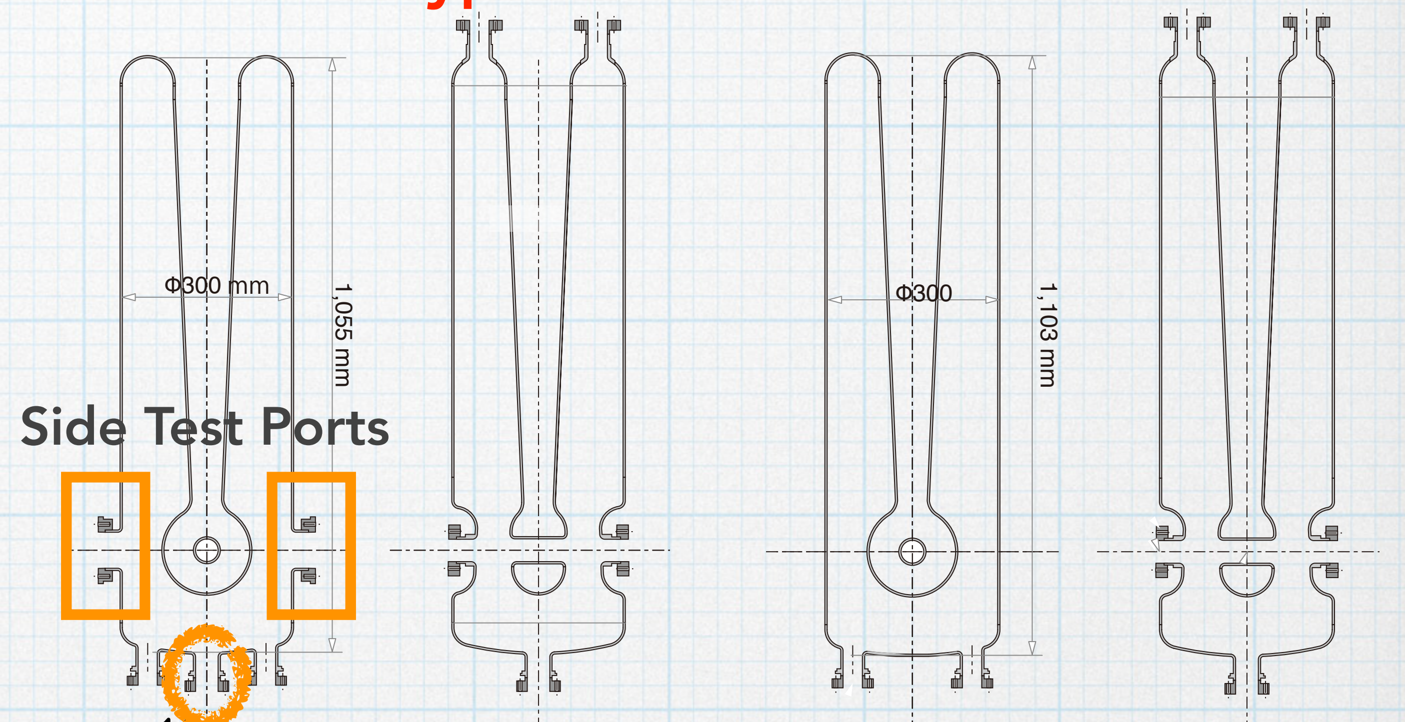
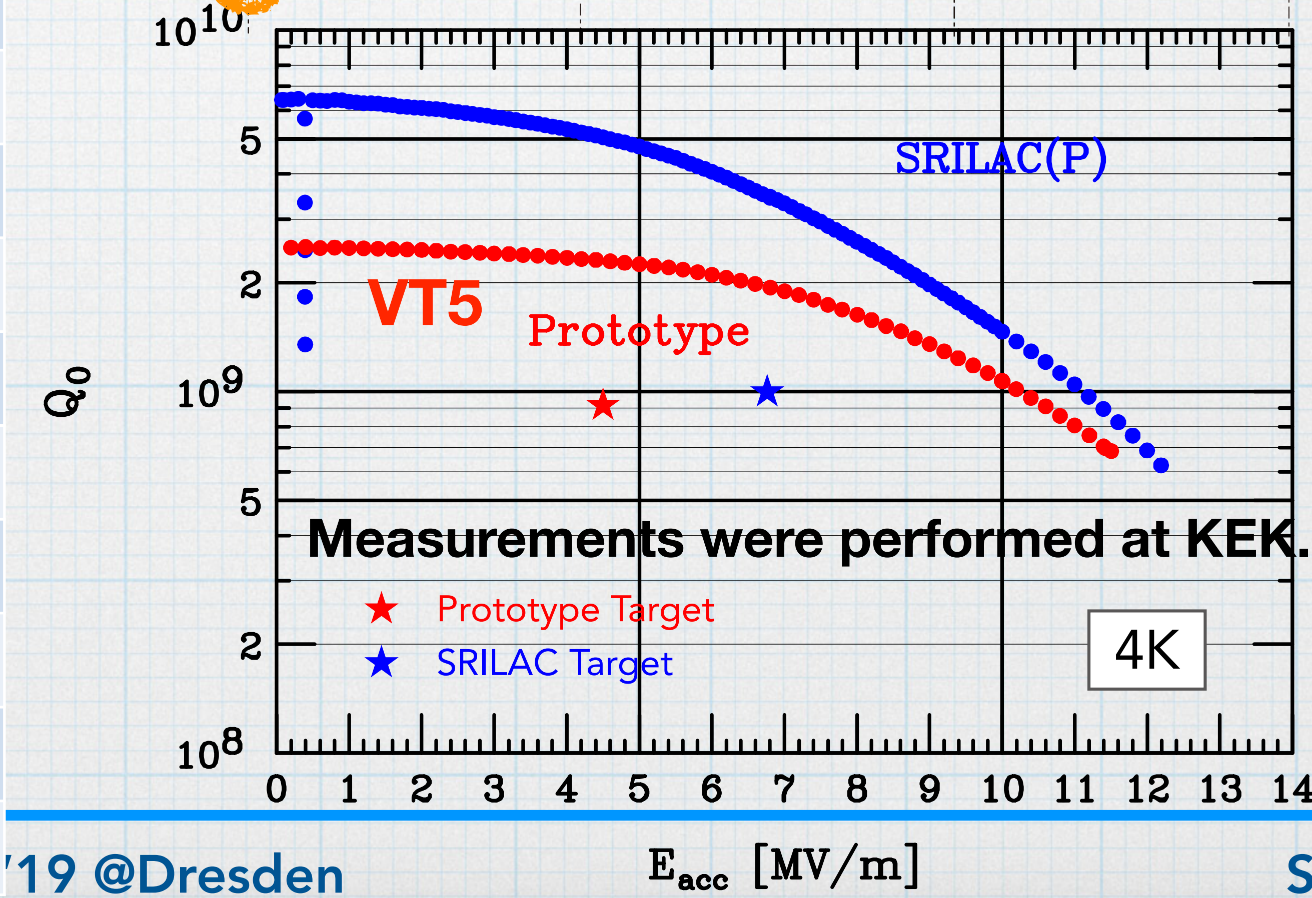
B_{peak}/E_{acc}(mT/(MV/m))	9.5	9.79.6
R_{sh}/Q_0 (Ω)	578	579
G (Ω)	23.5	22.4
V_{acc}(MV)	1.44	2.16
E_{acc} (MV/m)	4.5	6.8
Q_0@E_{acc}	2.3×10^9	3.4×10^9
P_0@E_{acc} (W)	1.5	2.4
Q_{pickup}	2.8×10^{11}	1.0×10^{11}

Prototype

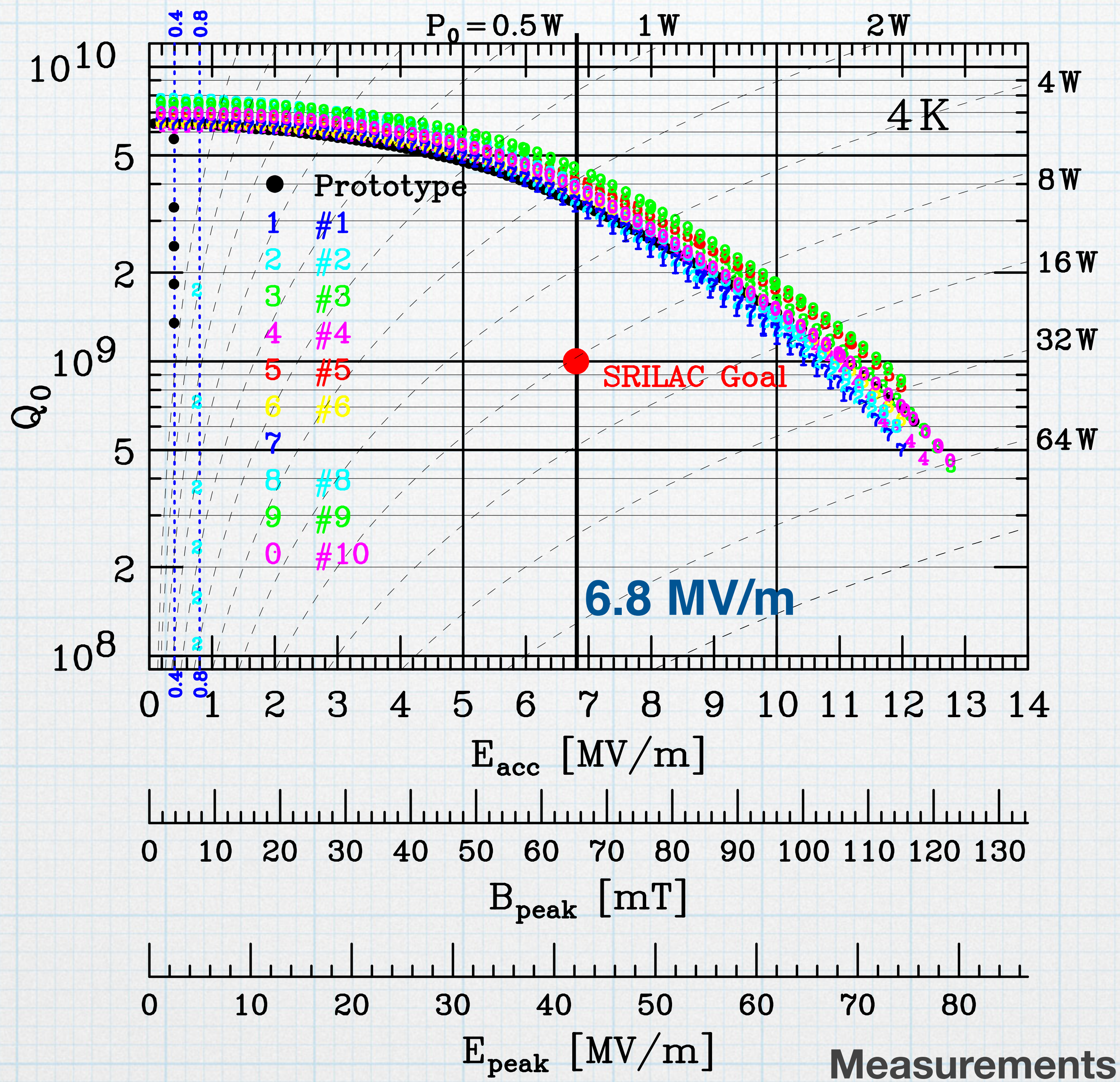
SRILAC



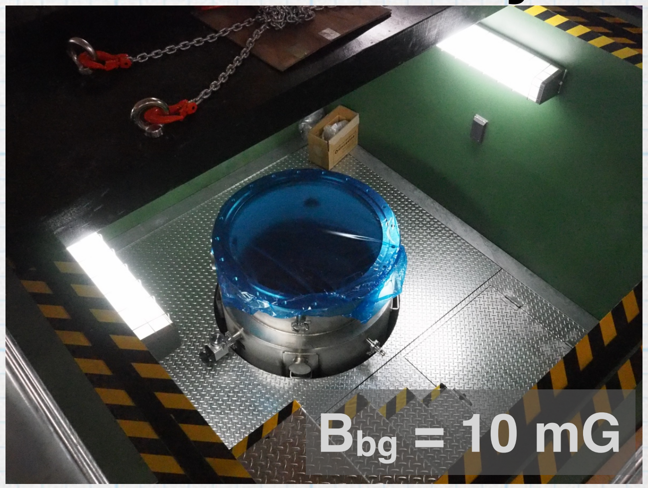


Performance of the Cavities for the SRILAC

TUP037: K. Yamada et al.



RIKEN VT Facility

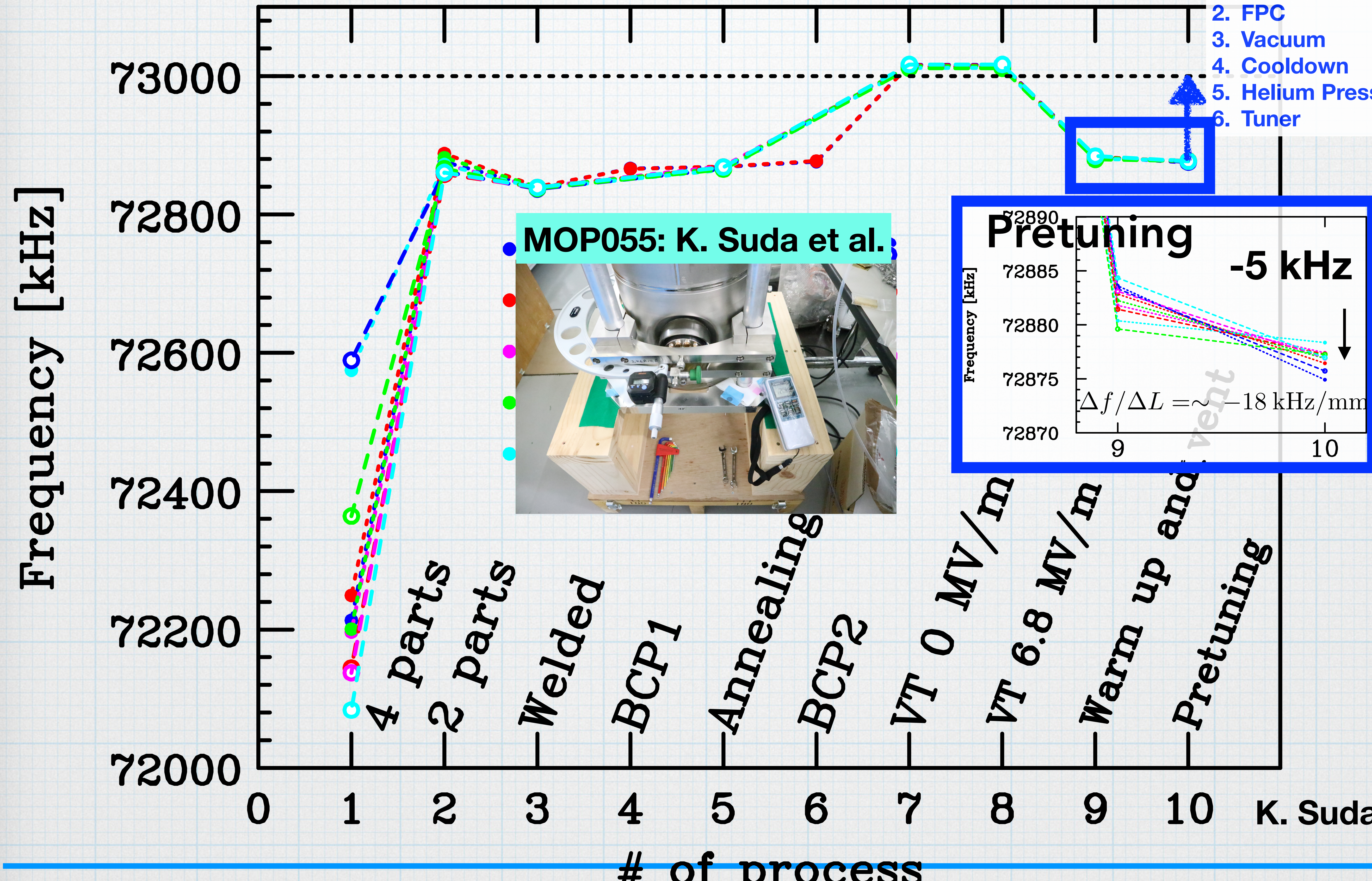


Measurements were performed at RIKEN.

All the ten SC-QWRs showed almost comparable performances in terms of the prototype cavity for the SRILAC.

History of Frequency Tuning

1. Jacketing
2. FPC
3. Vacuum
4. Cooldown
5. Helium Pressure
6. Tuner



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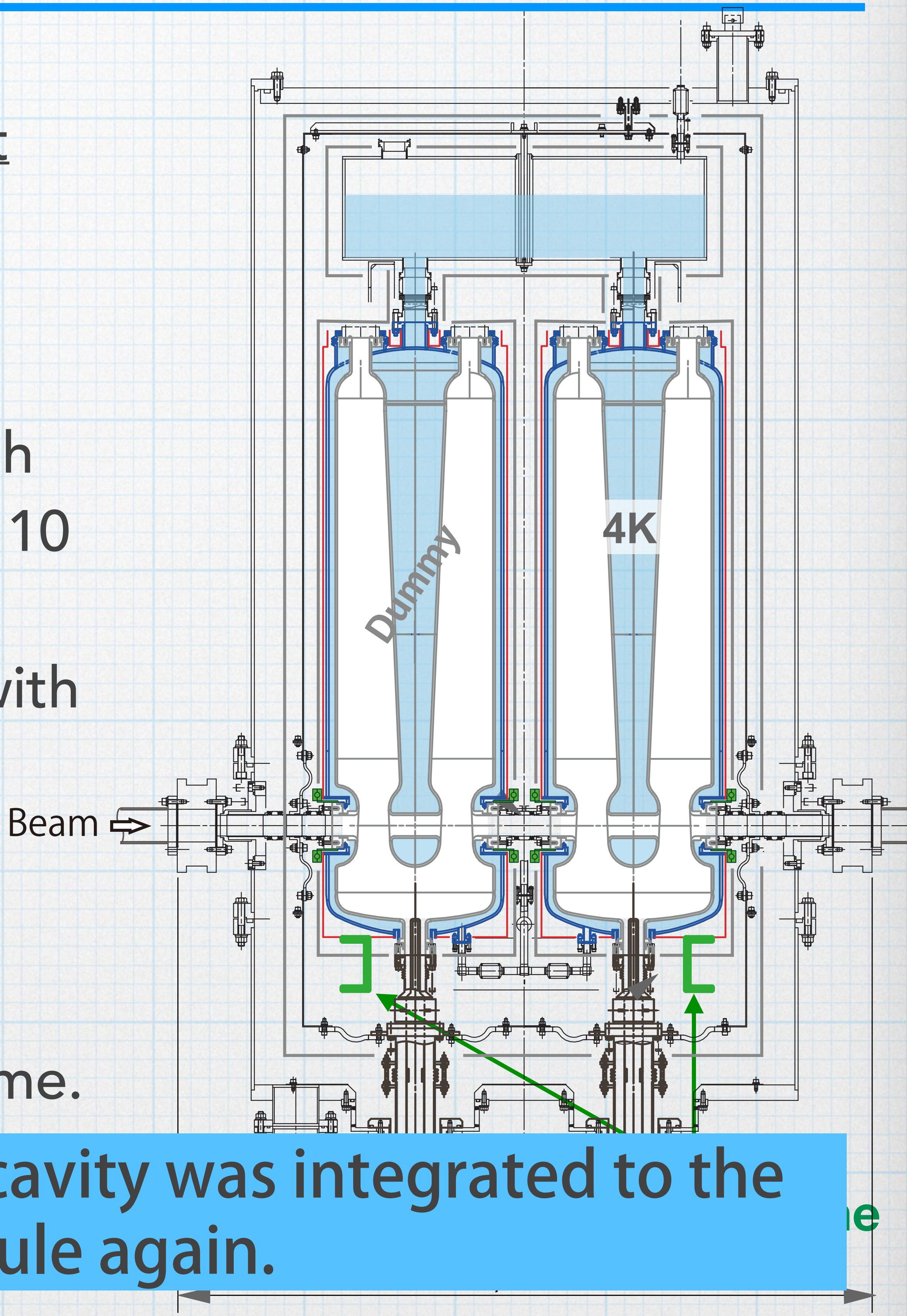
Summary

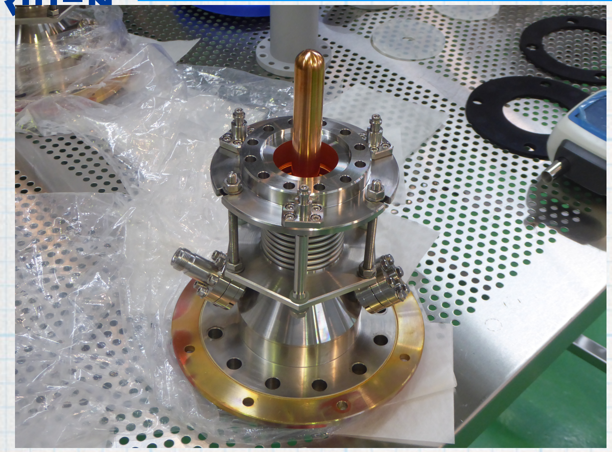
Prototype Cryomodule

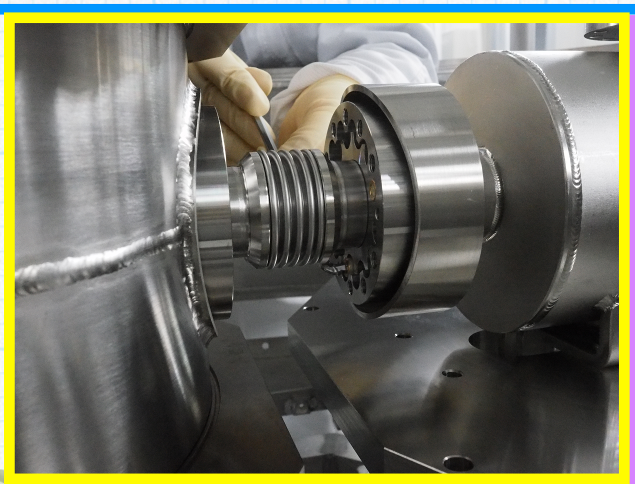
- The operating temperature is 4K.
- The cavity is enfolded in the helium jacket made of titanium.
- Local magnetic shield is attached on the helium jacket.
- A pair of fundamental power couplers with double window was developed to accept 10 kW rf power.
- The cryostat vacuum vessel is equipped with a thermal shield cooled by CH-110 77K Cryocooler instead of utilizing liquid nitrogen.
- Propping up structure:
  Cavities are mounted on the common frame.

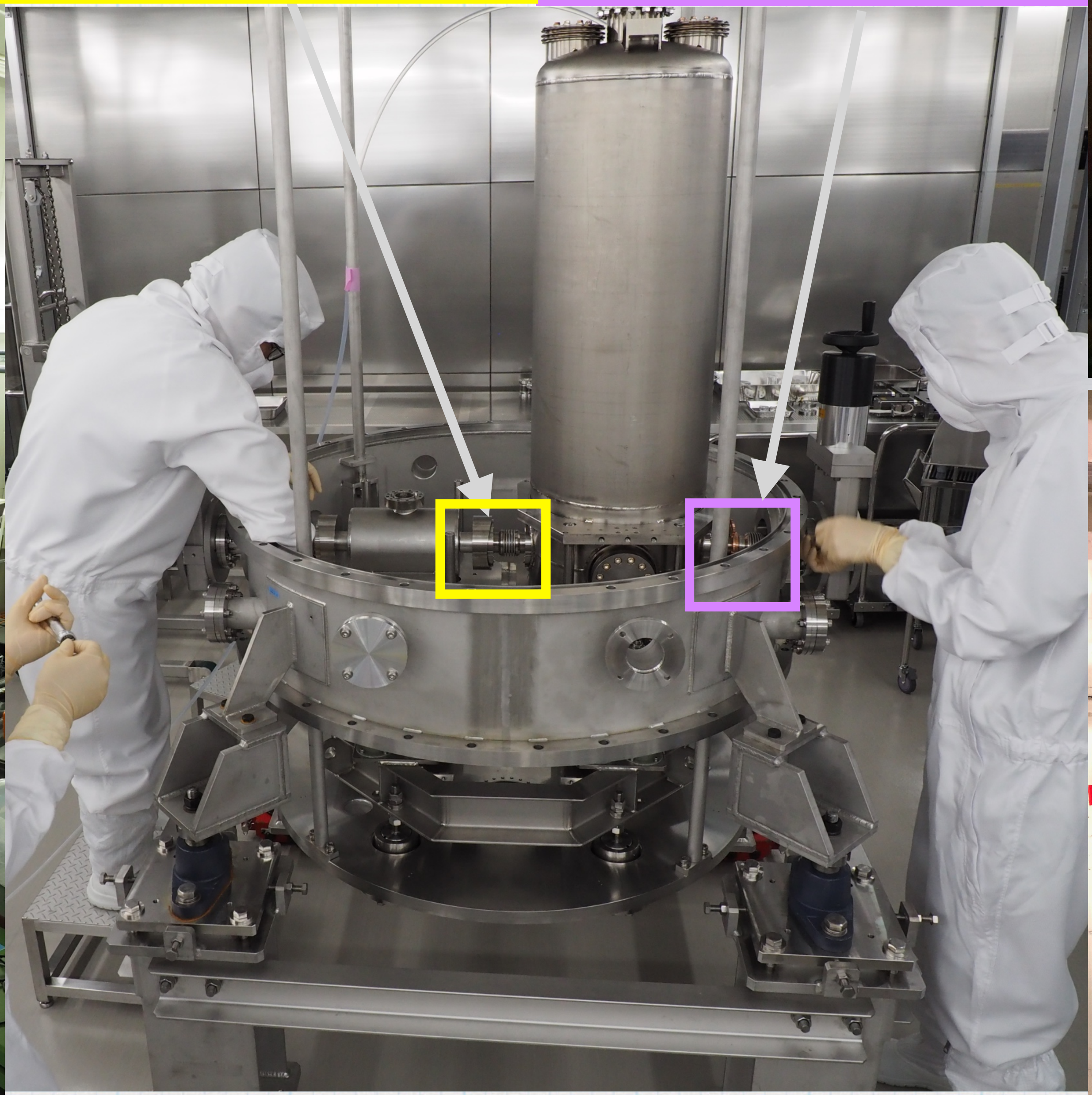


After the series study, the prototype cavity was integrated to the prototype cryomodule again.

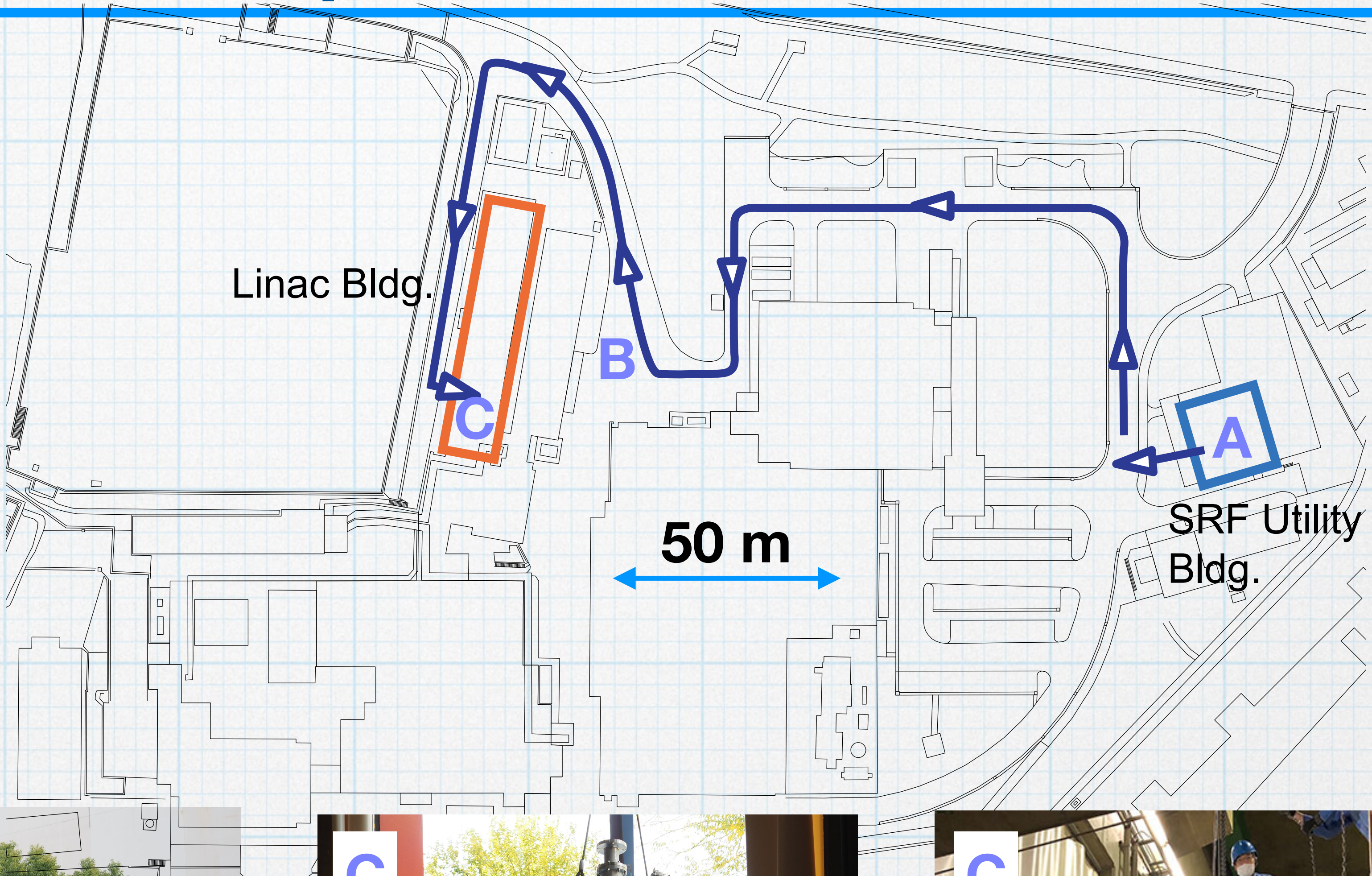
Cryomodule Assembly (ISO Class 1)





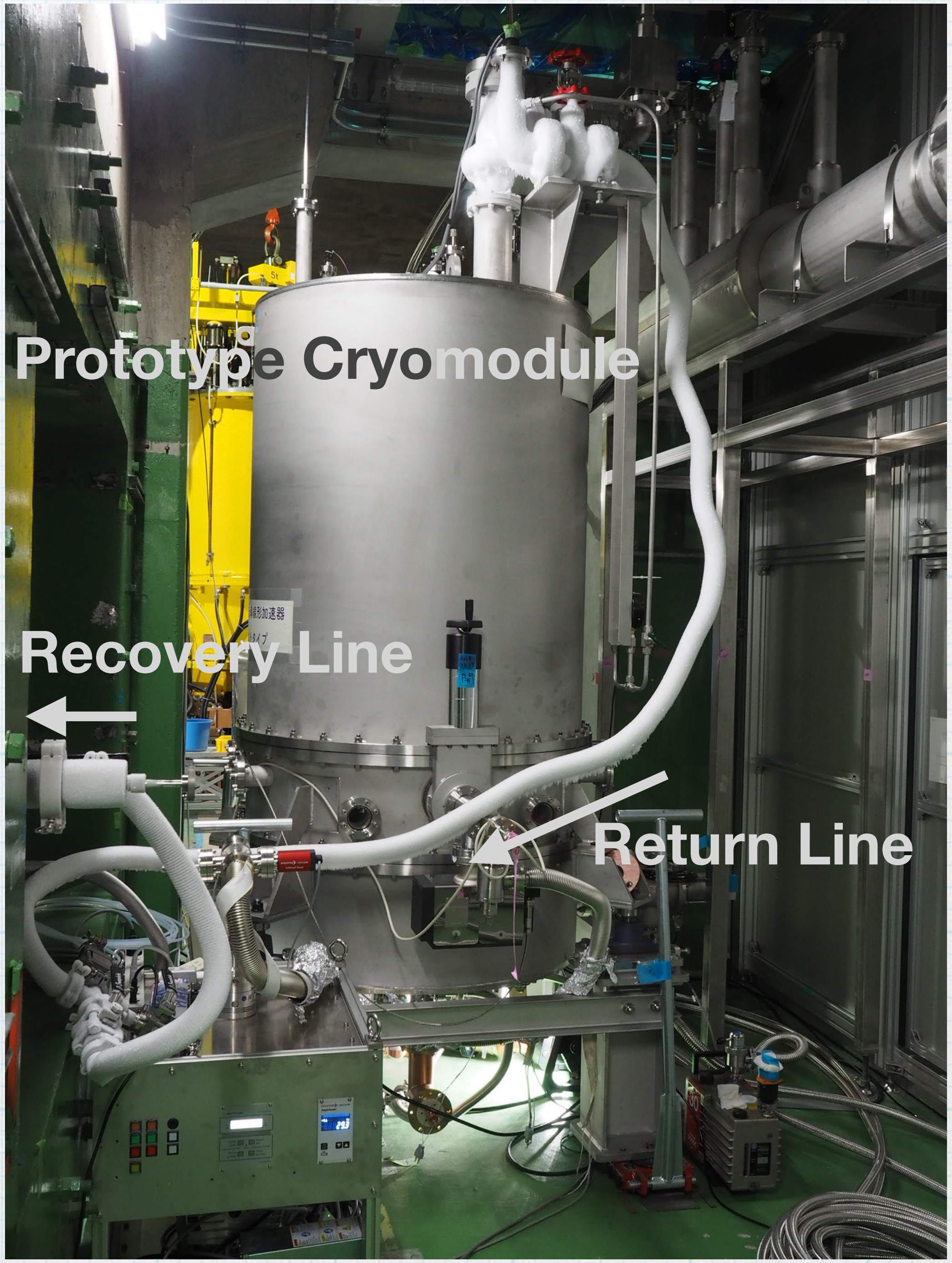


Transportation



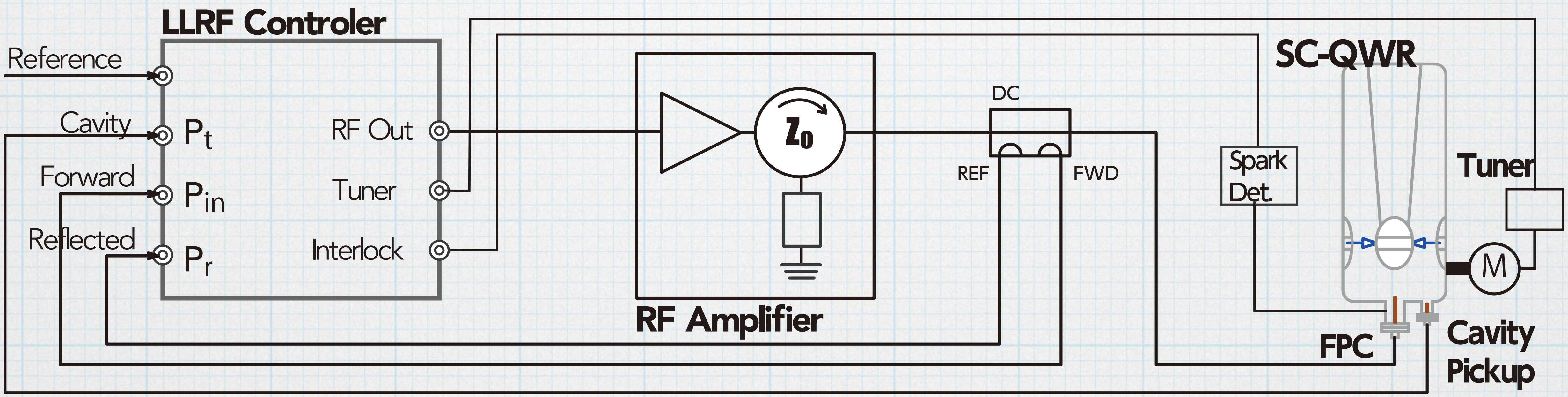
Cool-down and RF Test

- Cryomodule was cooled with liquid helium supplied from helium dewars.
- Long-term operation was attempted at the cave of the linac bldg.



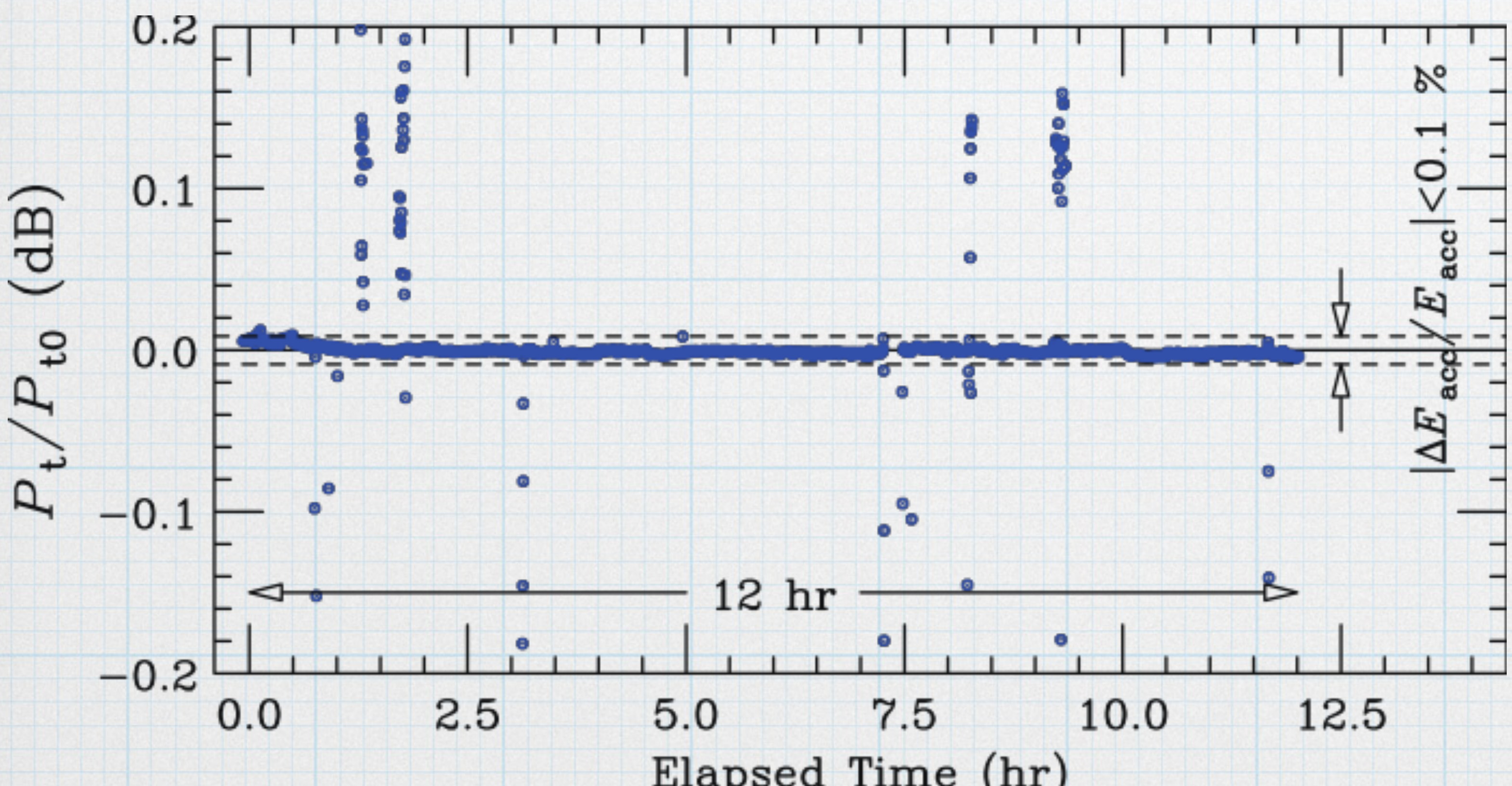
Long-Term RF Test

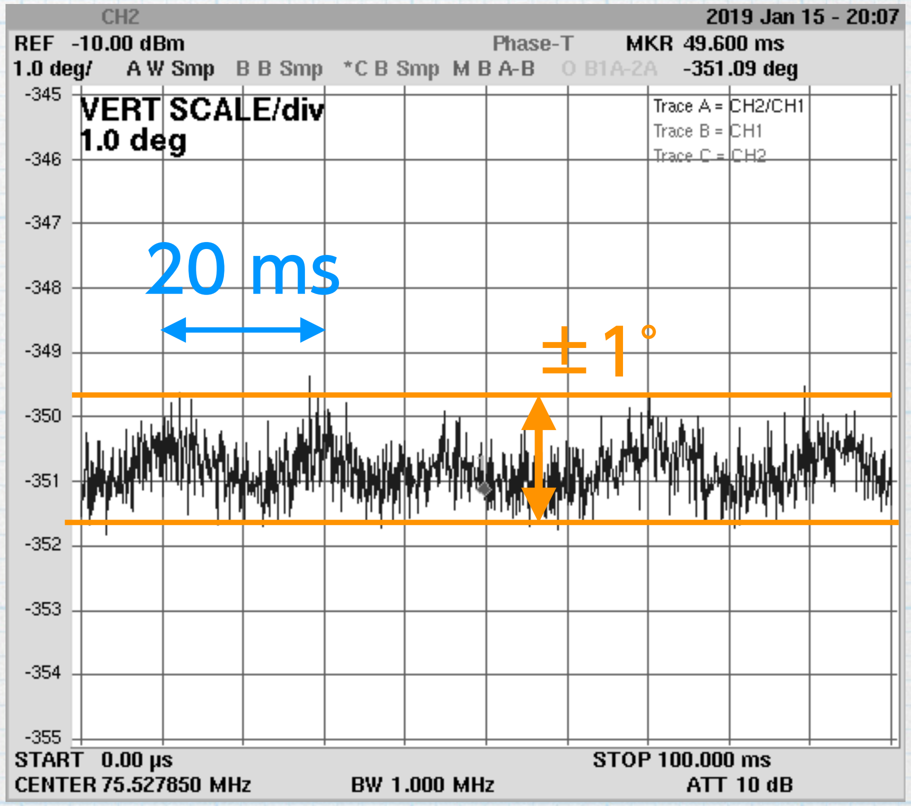
- 12 hr operation at 4.75 MV/m
- Liquid helium was supplied from 1000 l dewar.
- Frequency of the signal generator was manually tuned.
- Newly developed LLRF based on FPGA
- Solid state amplifier (4.5 kW)



Long-Term RF Test

- 12 hr operation at 4.75 MV/m
- Liquid helium was supplied from 1000 l dewar.
- Frequency of the signal generator was manually tuned.
- Newly developed LLRF based on FPGA
- Solid state amplifier (4.5 kW)
- **Long term stability of pickup level (Pt) was within ±0.1%**
- **Phase error observed was within ±1 deg.**
- **X-ray level was about 0.8 μSv/h**





***Cryo-cooler was turned off!**

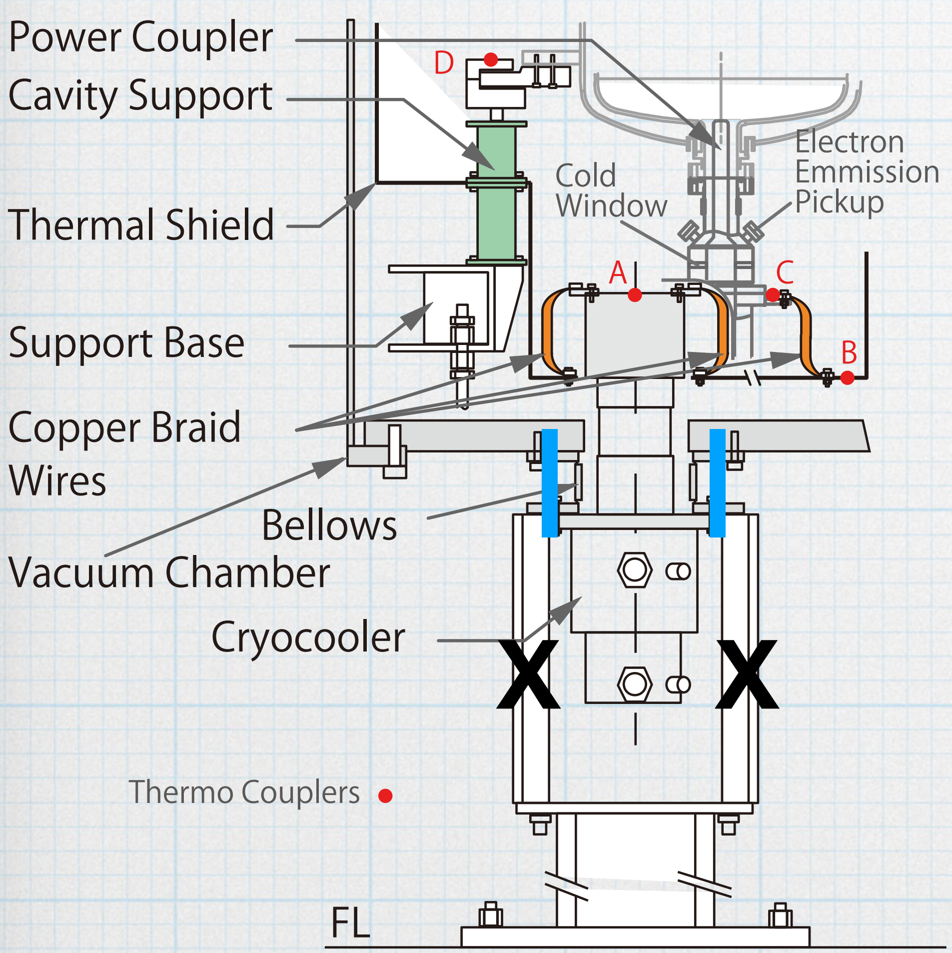
Reliability with a criteria $\Delta E_{acc}/E_{acc}$ ≦±0.1% was 95%

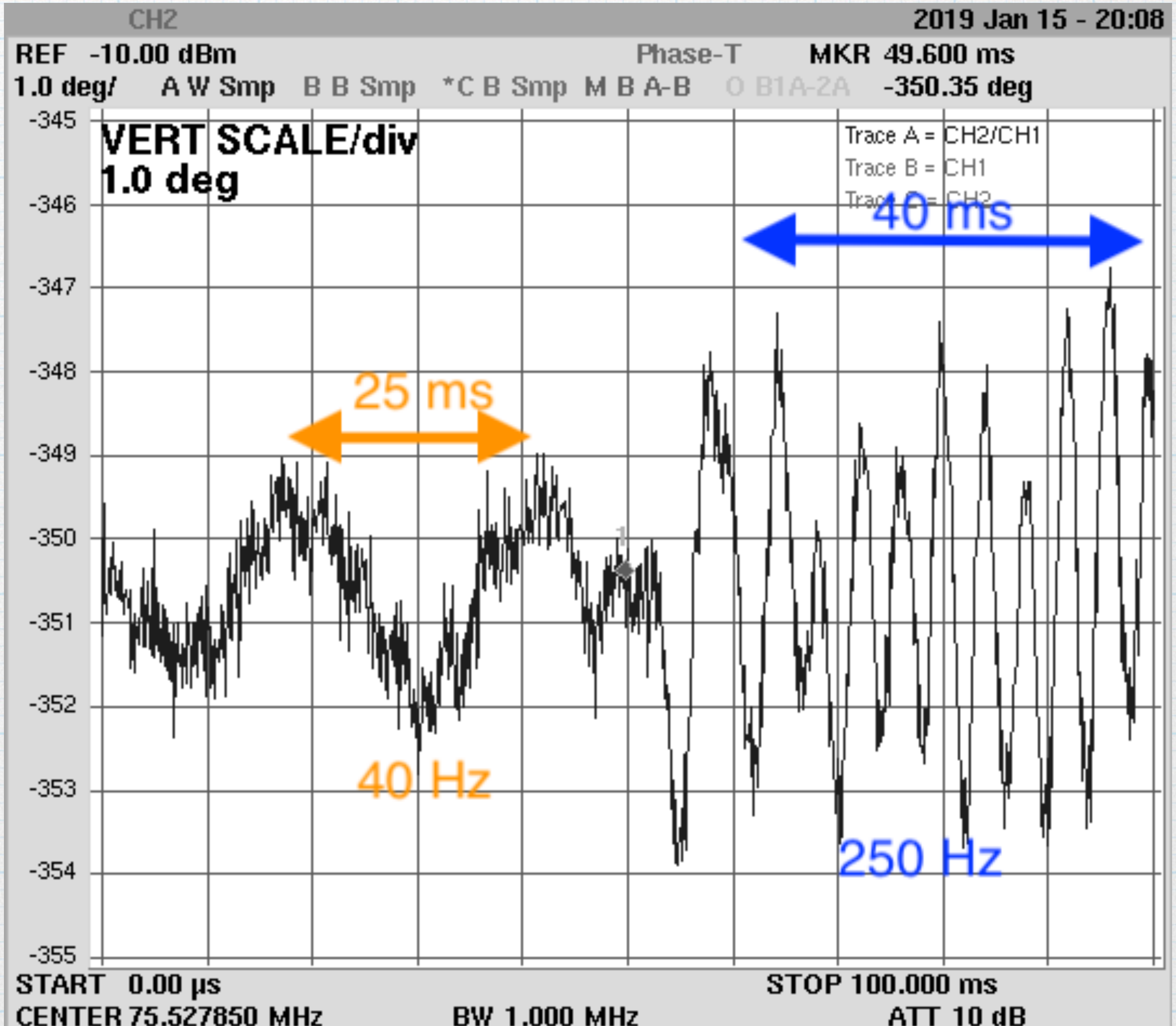
Observation of Microphonics

- Vibration of the cryo-cooler excited the mechanical vibration.
- Microphonics are clearly observed as phase oscillation.

40 Hz : Predicted

250 Hz: Other part?

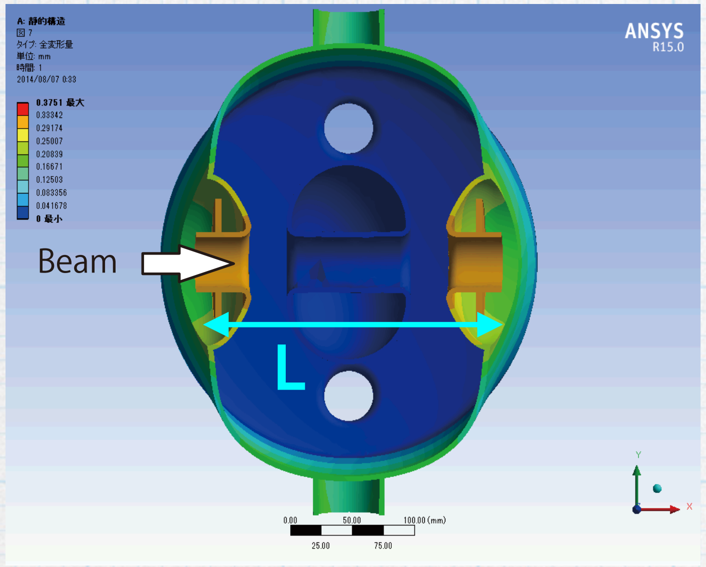


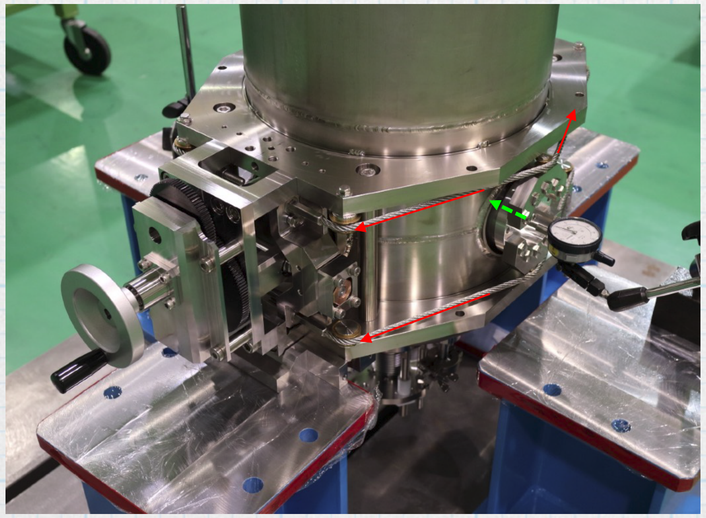


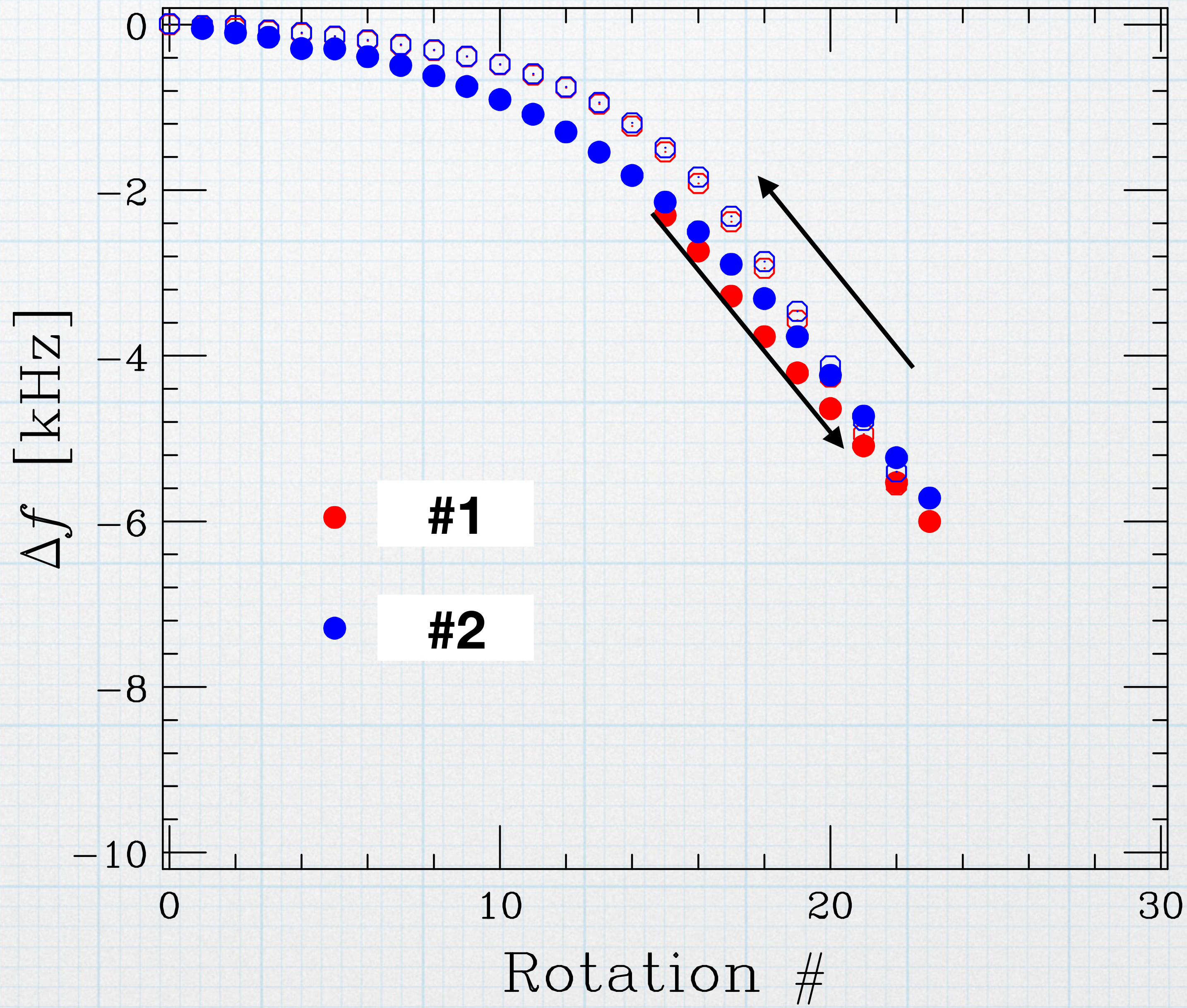
TUP042: O. Kamigaito et al.

Slow Tuner

- Frequency is lowered by squeezing accelerating gaps.
- $\Delta f/\Delta L$ = 20 kHz/mm
- Frequency shift vs. rotation number of the handle was measured **at 4K**.





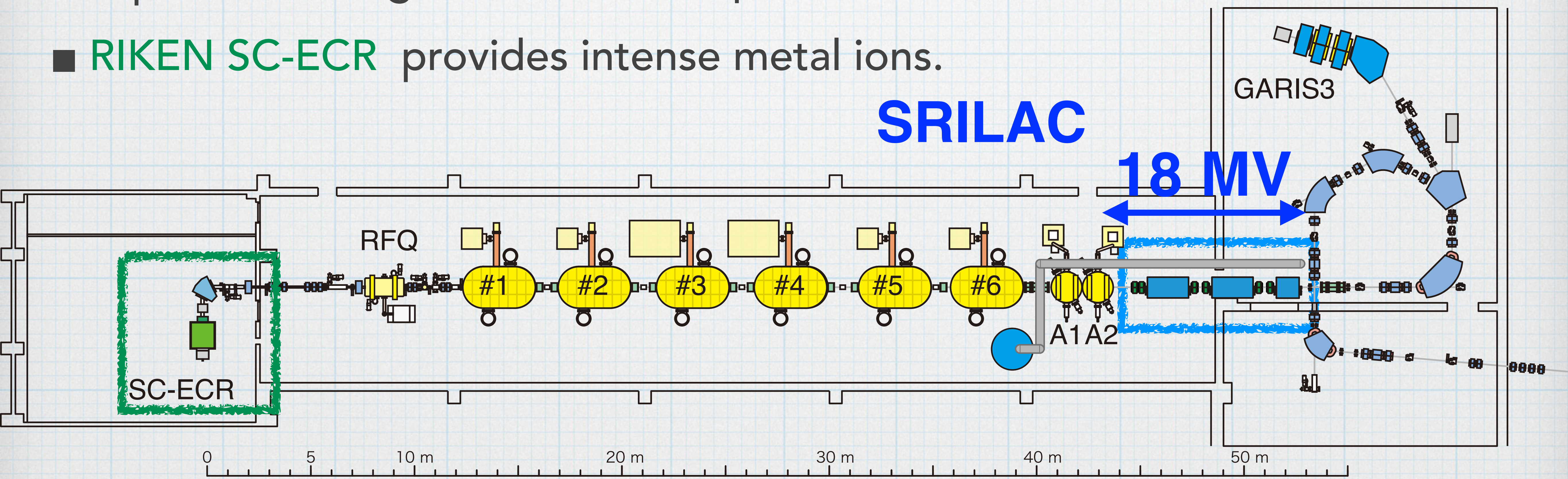


Mechanical loss was rather large → New design for SRILAC cavities

Outline

Upgrade of RIKEN Linac

- For 113 experiment $^{70}Zn^{14+}$ (A/q = 5) was accelerated to 5 MeV/u.
- The RILAC is going to have upgrade aiming to continue super heavy element (SHE) search experiment challenging the 8th row of the periodic table of elements (A>119).
- Upgrade goal: Ions A/q = 6 will be accelerated up to 6.5 MeV/u.
- The last four RT-DTL tanks were replaced by high-performance superconducting linac based on quarter wave resonator.
- RIKEN SC-ECR provides intense metal ions.



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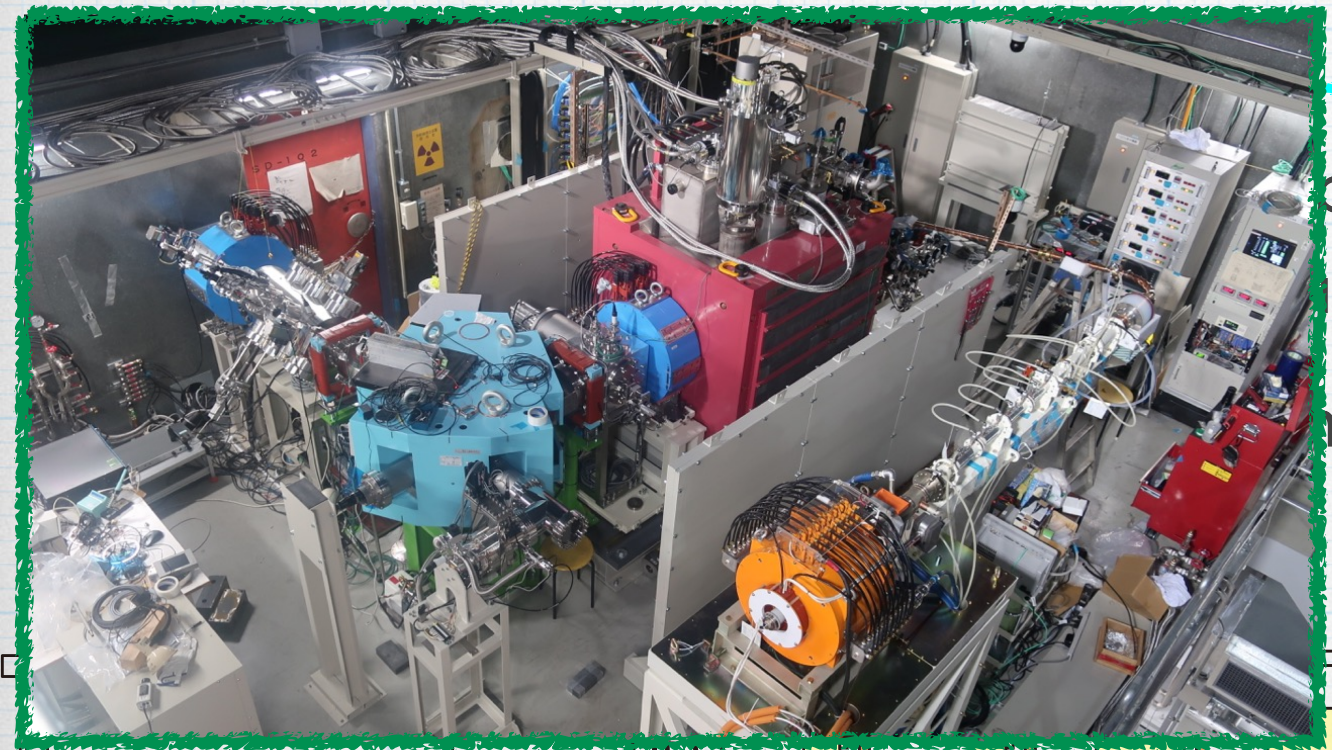
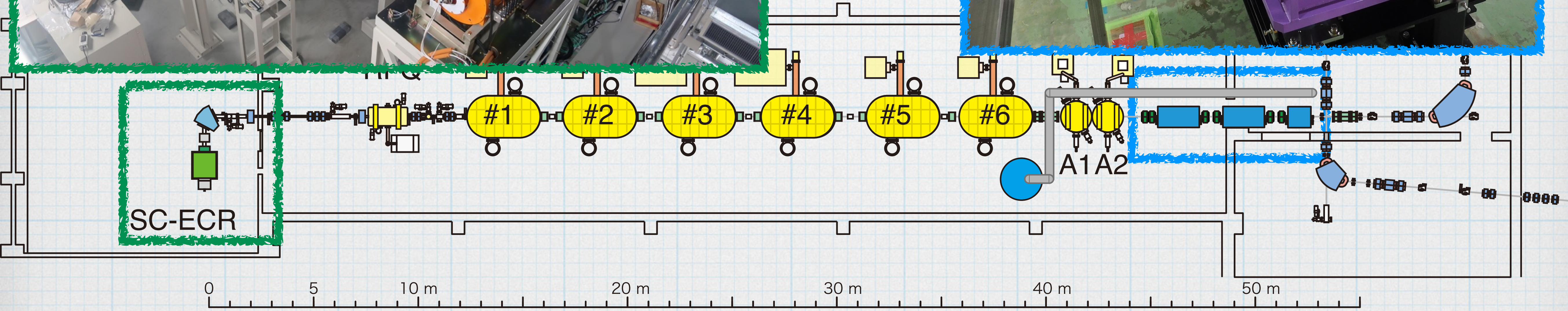




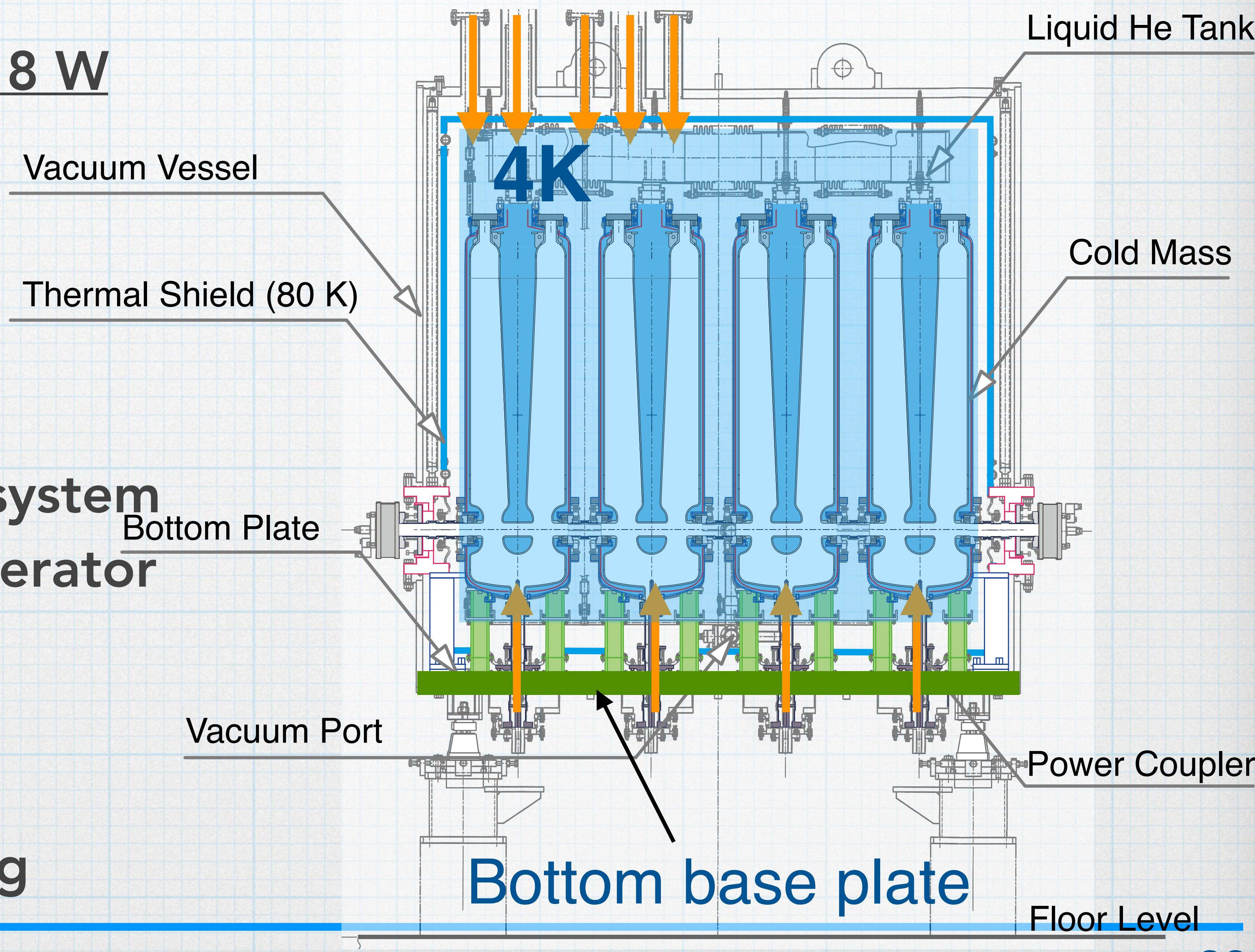
Design Modification of Cryomodule

ITEMS	Prototype	SRILAC
Frequency (MHz)	75.5 (c.w.)	73.0 (c.w.)
Operating Temp.(K)	4	4
#of cavities	2	4
Length(mm)	1337	2200
Cold Focusing Element	No	No
Shape	Cylinder	Rectangler
Material	Stainless Steel	Carbon Steel
Thermal Shield(K)	40	80
Local Magnetic Shield	On the helium jacket	Inside the jacket
Thermal Shield Cryo-cooler	Yes	Yes
Liquid N2	No	Yes
Cavity Intervals	420	430
Static Heat Load(W)	3.6	18
Cavity Support	Propping up	Propping up
Platform	Common frame	Bottom plate

Cryomodule for the SRILAC

- Operation temperature is 4K.
- Cryostat chamber maintain the cold mass which consists of cavities, helium vessel, FPCs, magnetic shields, dynamic tuner 4K with 80 K shield.
- Cavities are supported by four pillars on the rigid bottom base plate.

- Static Heat Load to 4K: 18 W
  - FPC: 6 W
  - Helium pipes: 4.5 W
  - Tuner: 2.5 W
  - Cavity support: 2 W
- Liquid helium cryogenic system using a HELIAL MF refrigerator (Air Liquide) with 600 W cooling power.
- Carbon steel vessel
  →Magnetic field shielding



Cryomodule for the SRILAC

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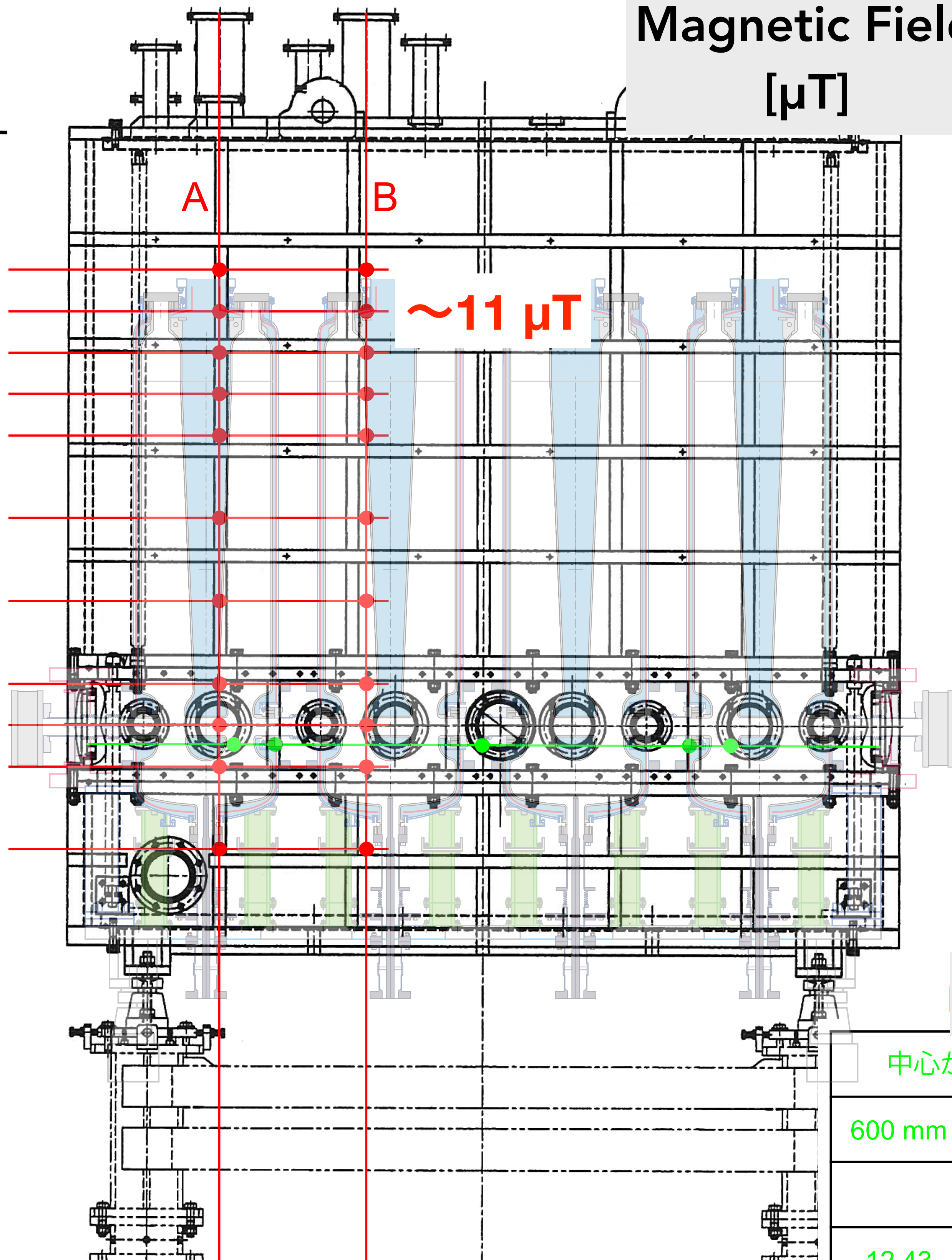


Magnetic Field [μT]

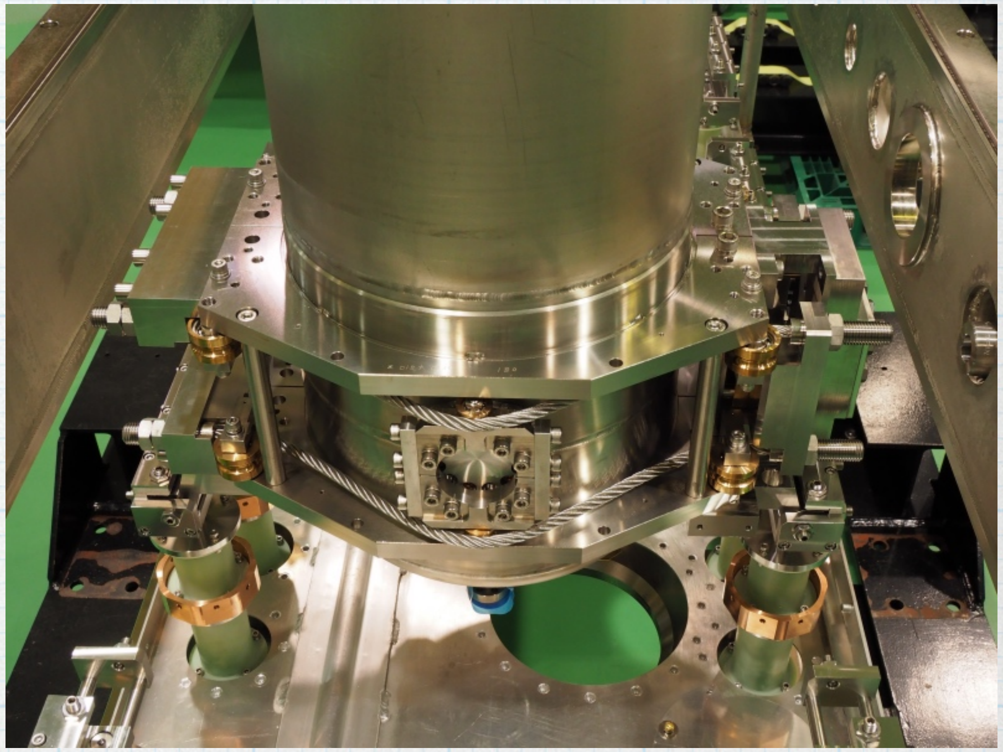
	A	B
2.4	11.53 (39.85)	10.49
2.3	11.23 (39.95)	10.38
2.2	11.33 (39.72)	10.46
2.1	11.56 (40.34)	10.75
2.0	11.83 (39.51)	11.25
1.8	12.06 (40.49)	12.00
1.6	11.99 (40.40)	12.36 (39.40)
1.4	12.03 (40.00)	12.74
1.3	12.32 (41.21)	12.69
1.2	12.88 (41.70)	12.47
1.0	13.56 (41.08)	10.34 (40.94)

@Beam Line Level 端

中心から北へ		中心	中心から南へ	
600 mm	500 mm		500 mm	600 mm
		12.98	12.49	12.52
12.43	12.45	12.46		

Local Magnetic Shield

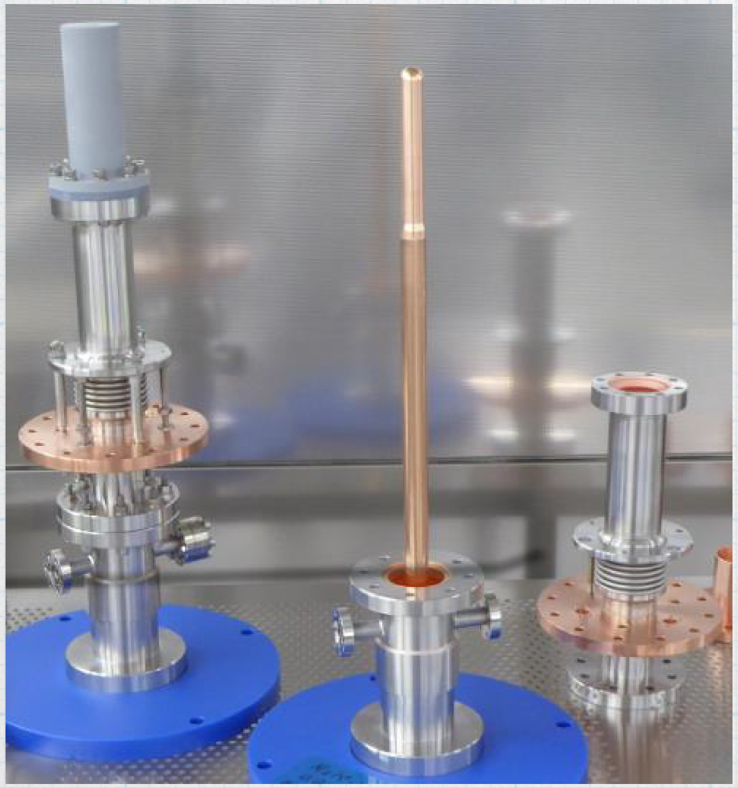
- After pre-tuning Ti jacket and μ-metal magnetic shield was installed.
- Local magnetic shield is placed inside the helium jacket
  - Simple structure with a good shielding
  - Easy handling



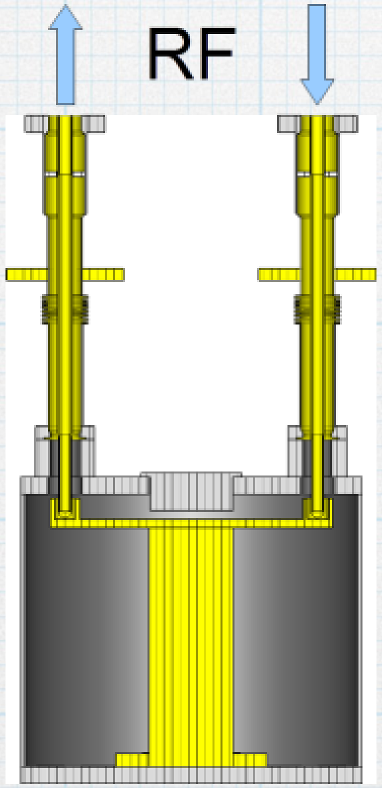
Frequency Tuner

Fundamental Power Couplers

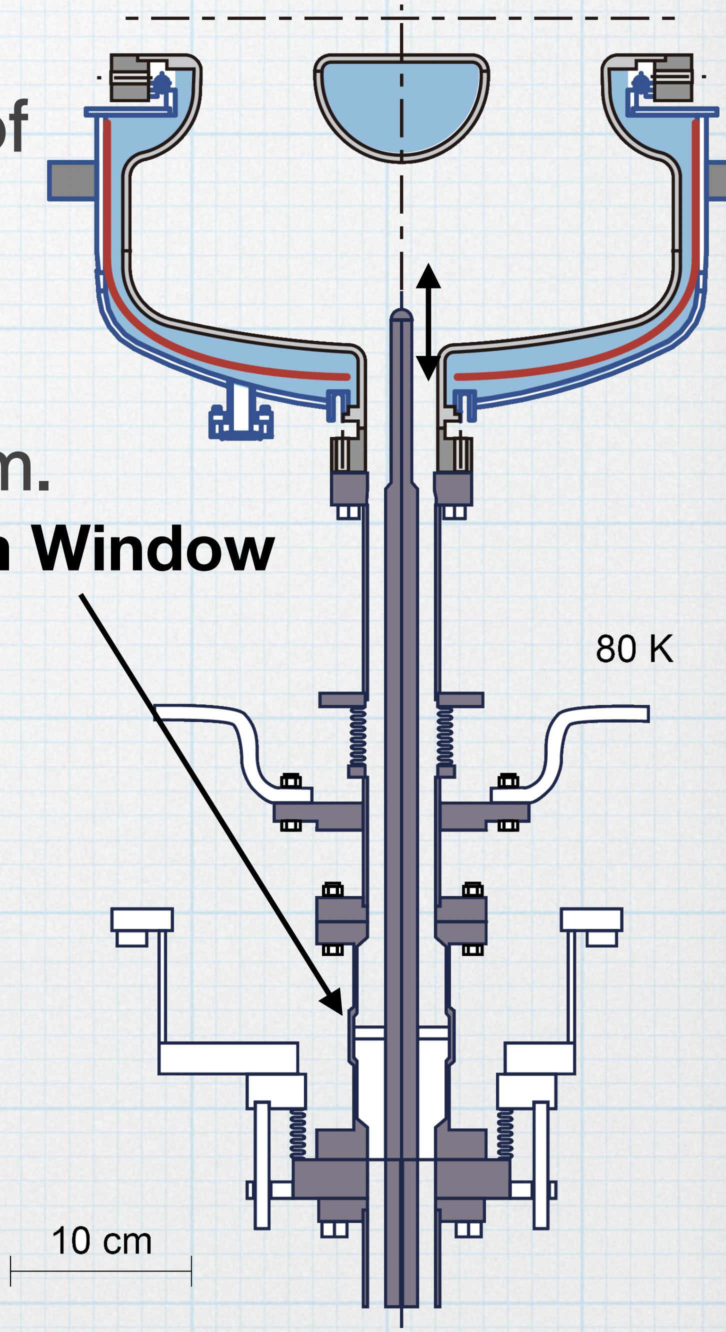
- Single-RT-window
- Coupling tunable : Q_{ext} : from $1x10^6$ to $4.5x10^6$
- A pair of FPCs were conditioned with 5 kW RF power of CW and traveling wave mode.
- Cleaning of the coupler and assembling to the test resonator were performed in the ISO class 1 clean room.



Photos of FPC

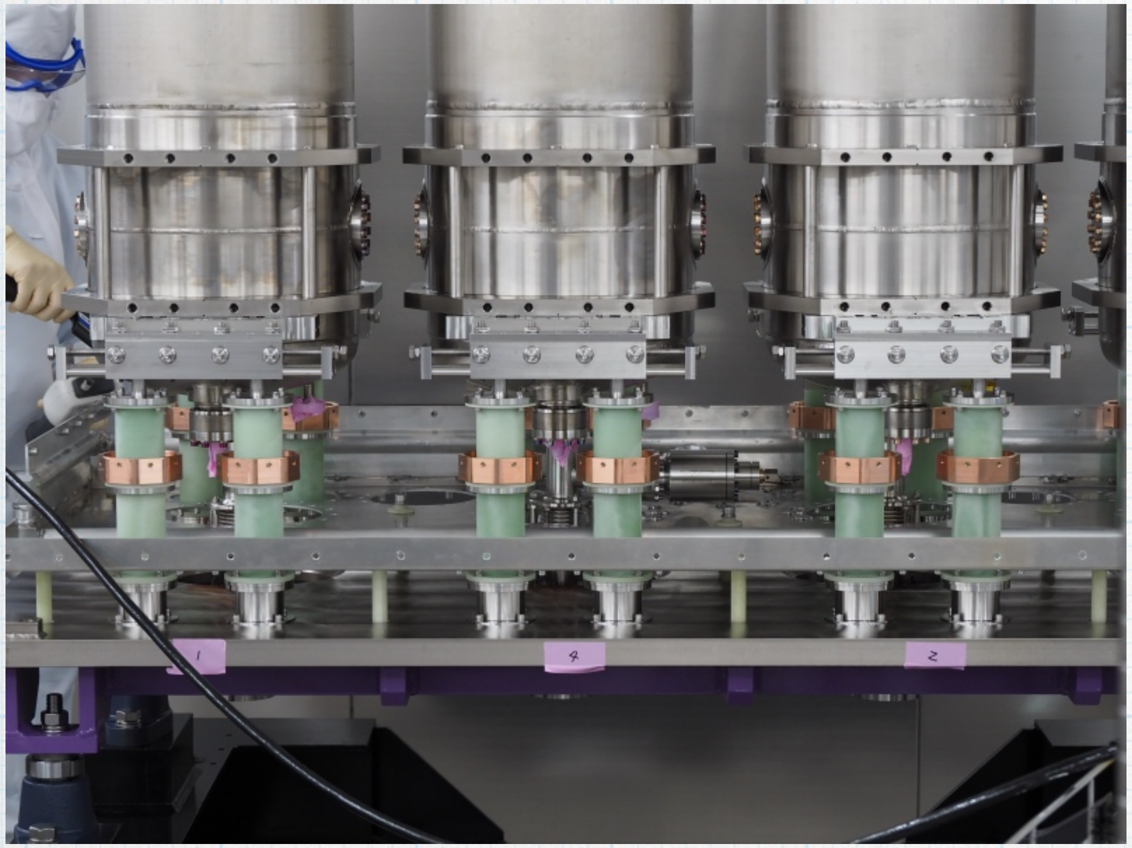


Conditioning Resonator



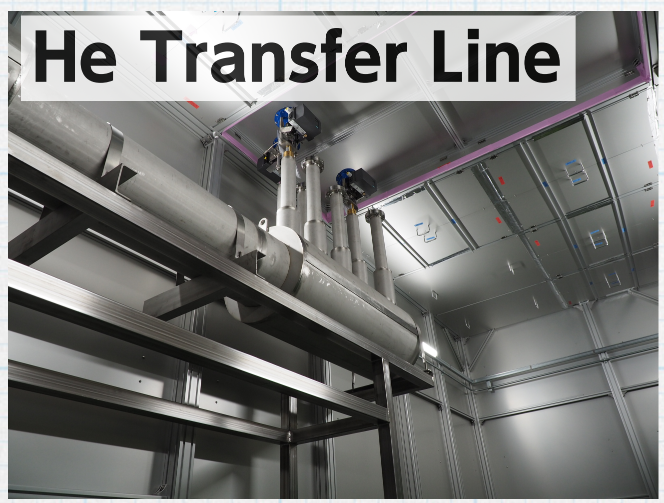
Schematic of FPC

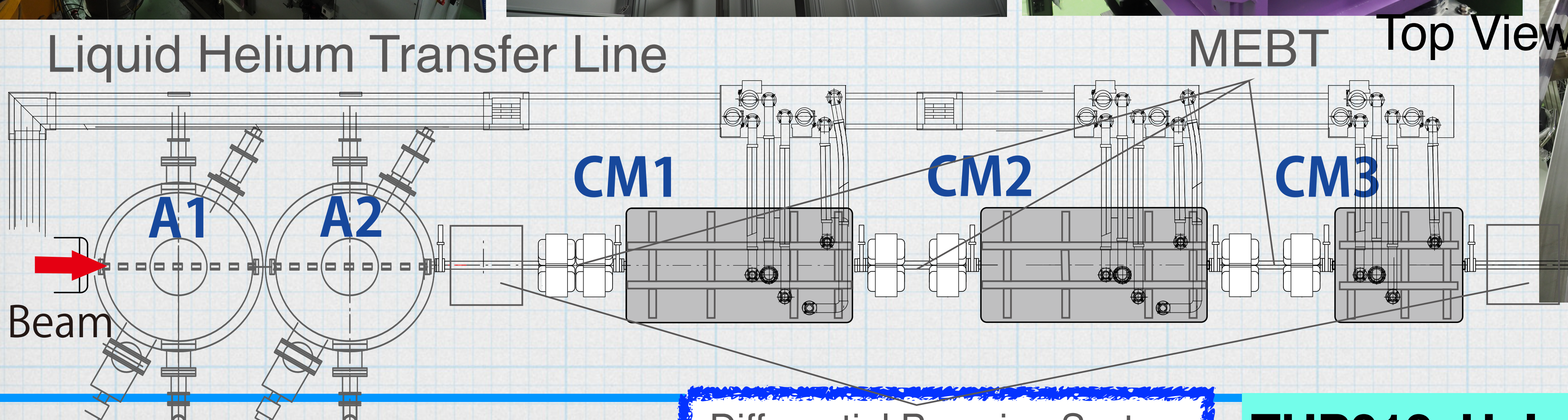
Cryomodule Assembly at ISO Class 1



Construction Status

- ✓ Installation and alignment of cryomodules
- ✓ Installation of helium refrigerator and transfer line
- ✓ Inspection by Saitama prefecture
- ○ Installation of the control system is underway.
- ○ First cooling down will be started in August.
- ○ Beam pipes and a pair of differential pumping system will be installed in this September.





Summary and Perspective

Prototype Superconducting Linac

- R&D of Superconducting Cavity started since 2013 at RIKEN
- First prototype cavity achieved Q0 2×10^9 successfully.
- Newly developed RF system worked well.

RIKEN Linac upgrade

- RIKEN heavy ion linac will have acceleration voltage and intensity
- Upgrade by introducing a superconducting linac based on high performance SC-QWRs and SC ECR ion-source.
- Ten SC-QWRs were fabricated and processed.All the cavities have a good performance.
- Three cryomodules were assembled and installed to the linac bldg.
- Construction of the control system is underway.
- Cooling test will be made in August.
- SC-ECR will be ready by the end of October.

Beam commissioning is scheduled in the third quarter of FY2019

Related Papers

Cavity Fabrication-MOP055: K. Suda *et al.*, *RIKEN Nishina Center,* "Fabrication and Performance of Superconducting Quarter-Wavelength Resonators for SRILAC"

Cavity Protection-TUP013: H. Imao *et al.*, *RIKEN Nishina Center,* "Non-evaporable Getter-based Differential Pumping System for SRILAC at RIBF"

Construction Status-TUP037: K. Yamada *et al.*, *RIKEN Nishina Center,* "Construction of Superconducting Linac Booster for Heavy0Ion Linac at RIKEN Nishina Center"

Microphonics-TUP042: O. Kamigaito *et al.*, *RIKEN Nishina Center,* "Measurement of mechanical vibration of SRILAC cavities"

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Thank you for your attention.