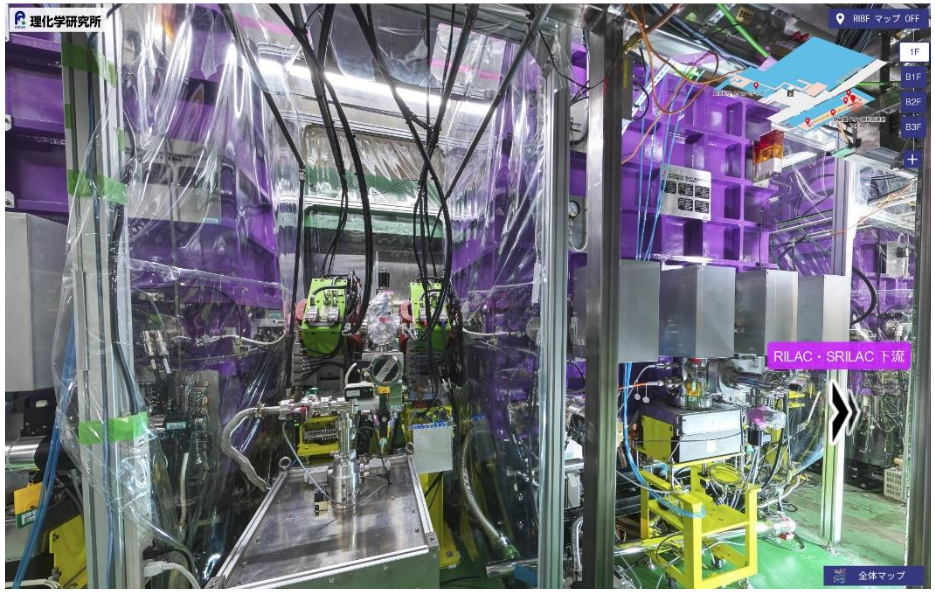
Operational Experience for RIKEN Superconducting Linear Accelerator



<u>Kazunari Yamada</u>

M. Fujimaki, H. Imao, O. Kamigaito, M. Komiyama, K. Kumagai, T. Nagatomo, T. Nishi, H. Okuno, K. Ozeki, N. Sakamoto, K. Suda, A. Uchiyama, T. Watanabe, Y. Watanabe

\- **RIKEN Nishina Center, Wako, Saitama, Japan**

MOIXA04, SRF2023 June 26, 2023

Contents

1. Overview of RIKEN Heavy-ion SC-Linac (SRILAC)

2. Operational experience in four years

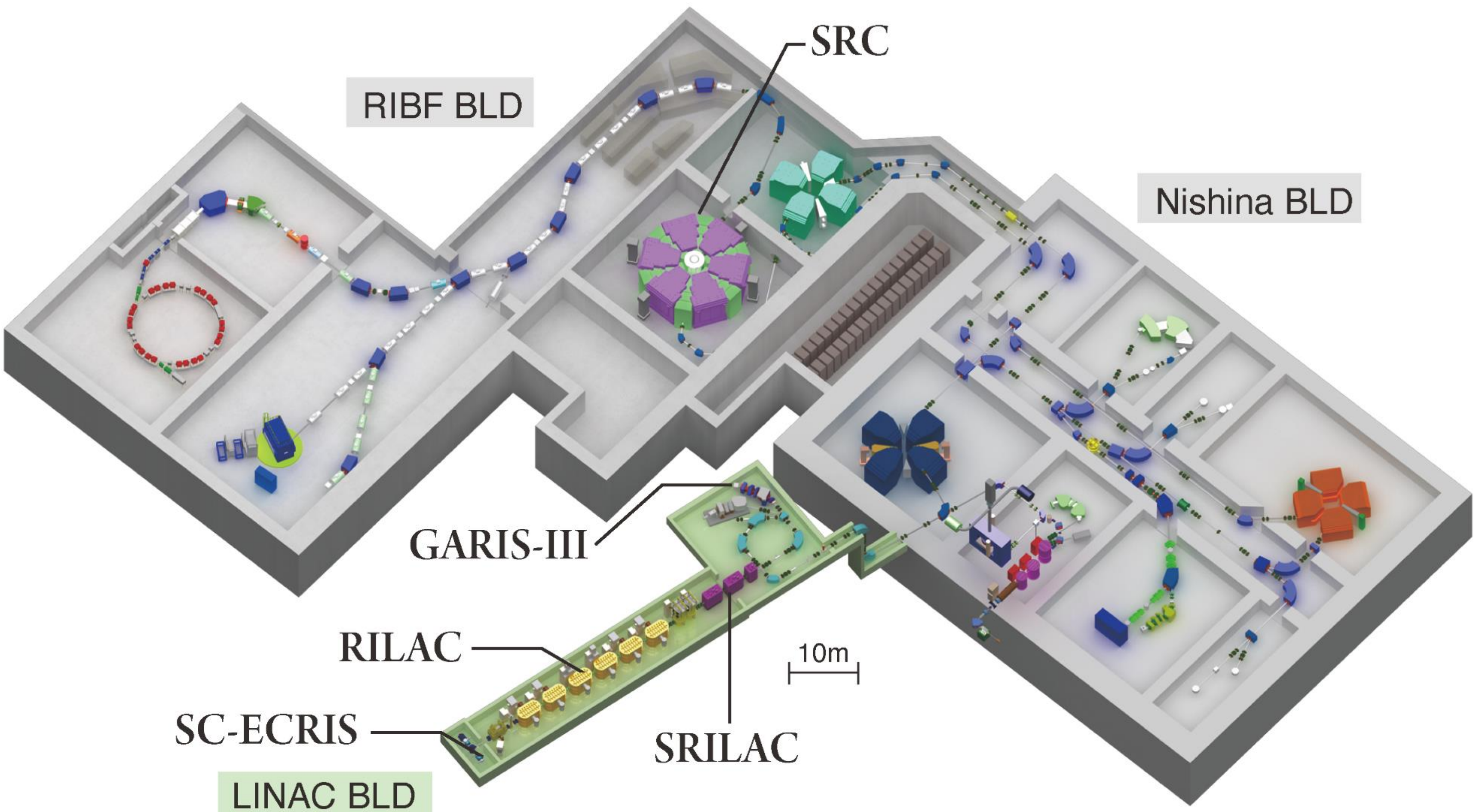
- Downtime & availability
- Beam tuning & phase ellipse measurement using BEPMs
- He pressure fluctuation & tuner control
- Field emission & pulse conditioning
- Coupler problem & ongoing measures

3. Summary

RIKEN RI Beam Factory (RIBF)

Scientific goals of RIBF:
- Establish ultimate nuclear model
- Elucidate elements synthesis
- Promote application of ion beams

- Acceleration of **all** ions up to 345 MeV/u (70% of *c*) in **CW** mode
- Production of RI beams in the **whole** mass region



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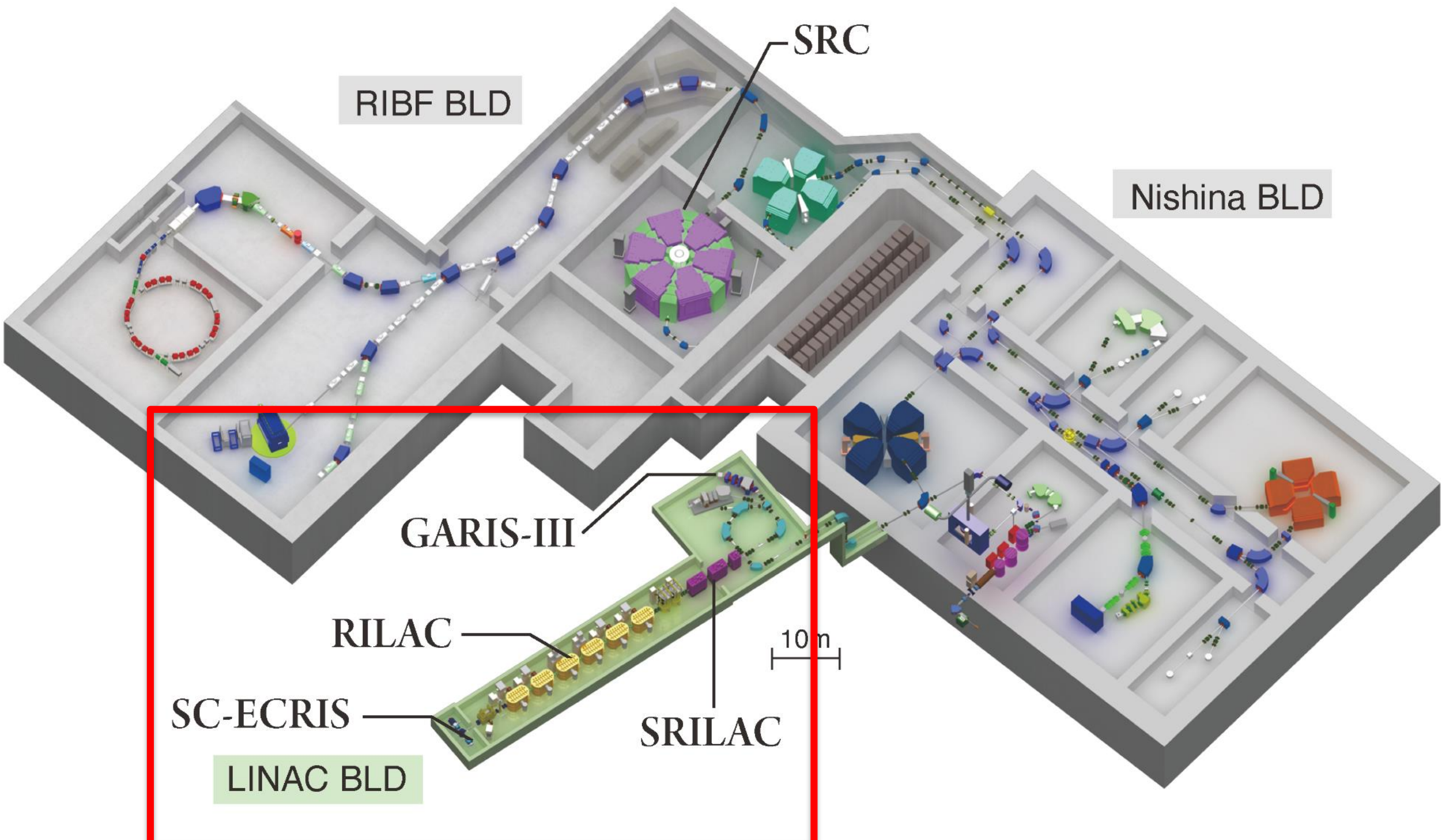

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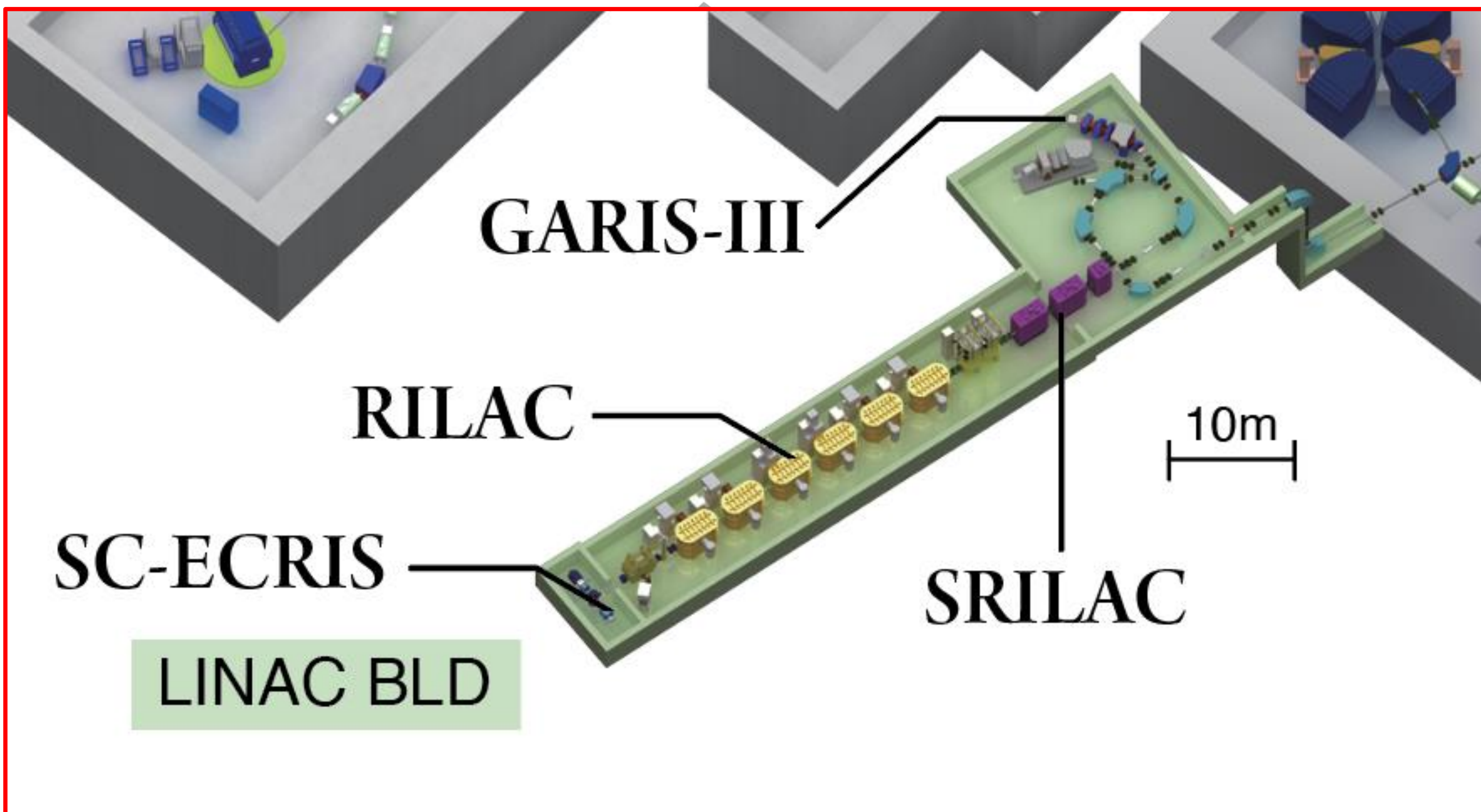
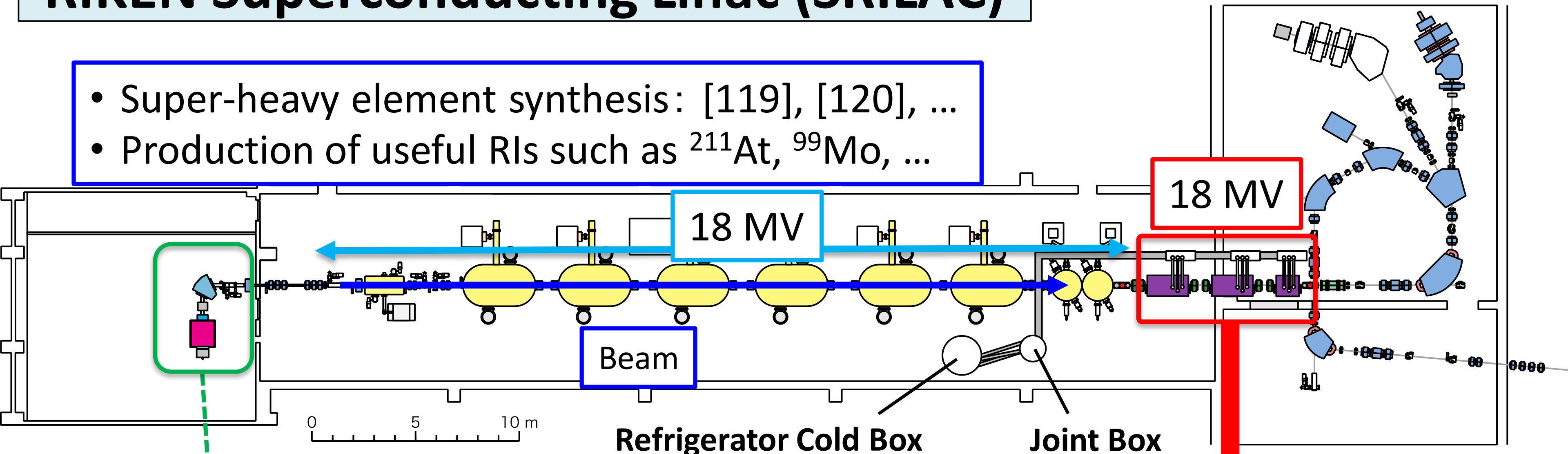
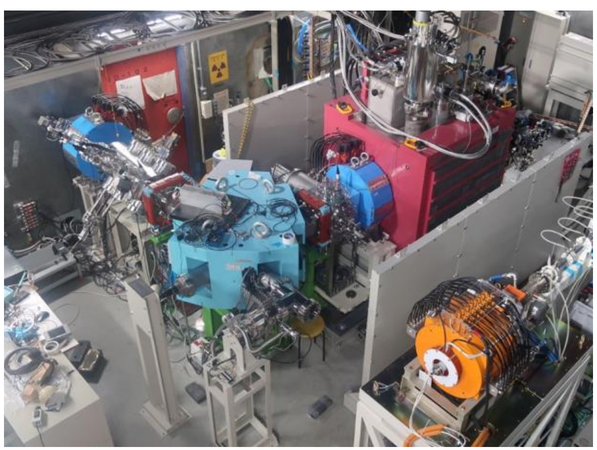


RIKEN Superconducting Linac (SRILAC)

- Super-heavy element synthesis: [119], [120], …
- Production of useful RIs such as ^{211}At, ^{99}Mo, …



28-GHz SC-ECRIS



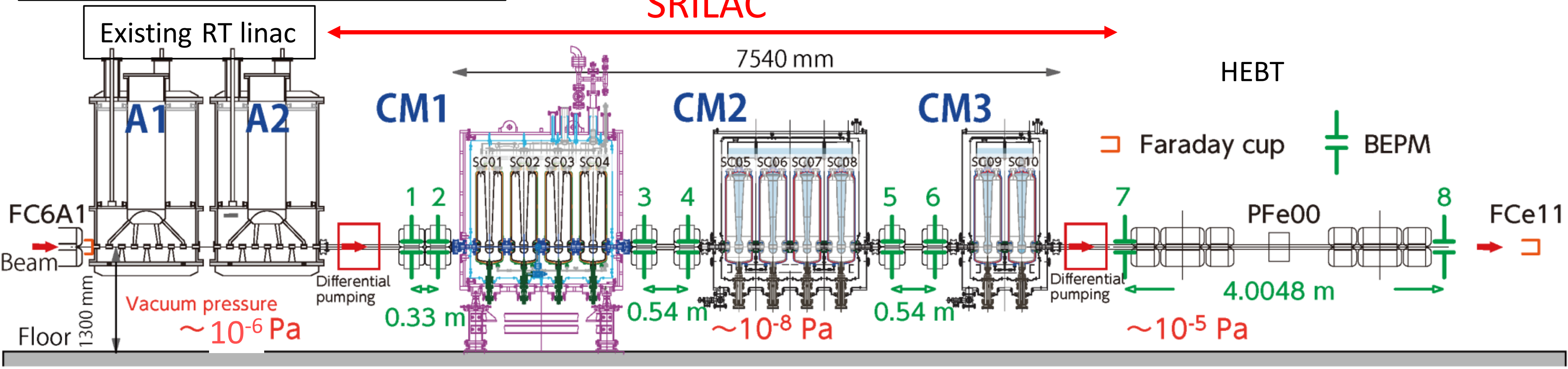
Higher Intensity

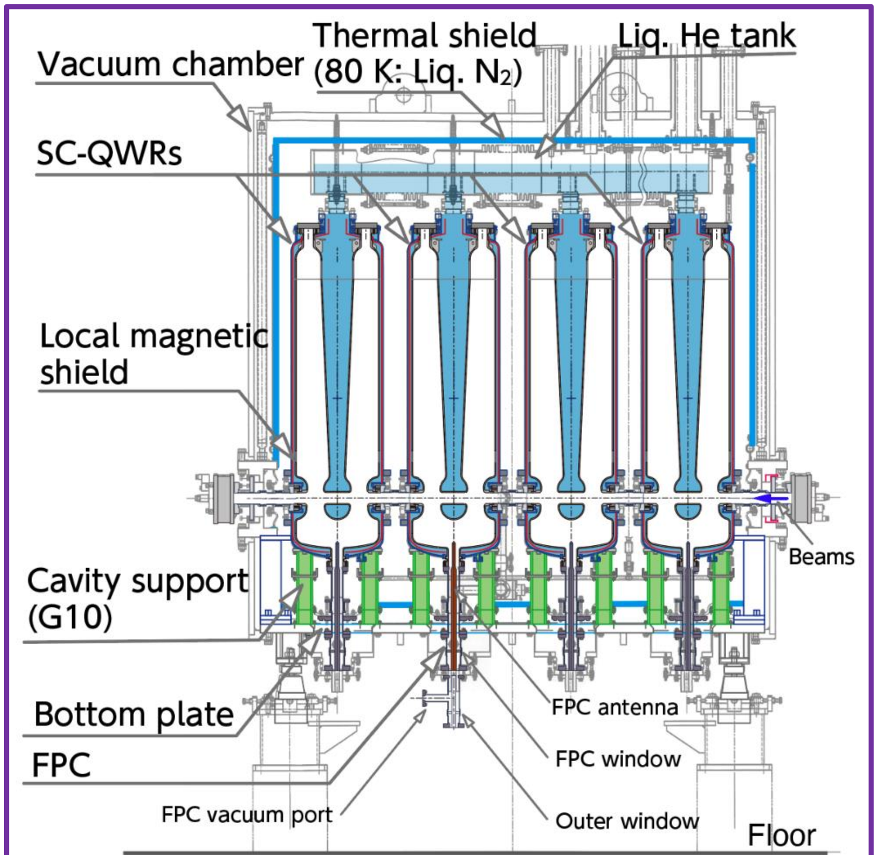
Superconducting Booster Linac "SRILAC"

- 10 SC-QWRs in 3 cryomodules
- E_{max}: 6.5 MeV/u for M/q = 6 ions
- Budget approved in FY2016
- Construction: 2016 – 2019

Higher Energy

Layout of SRILAC

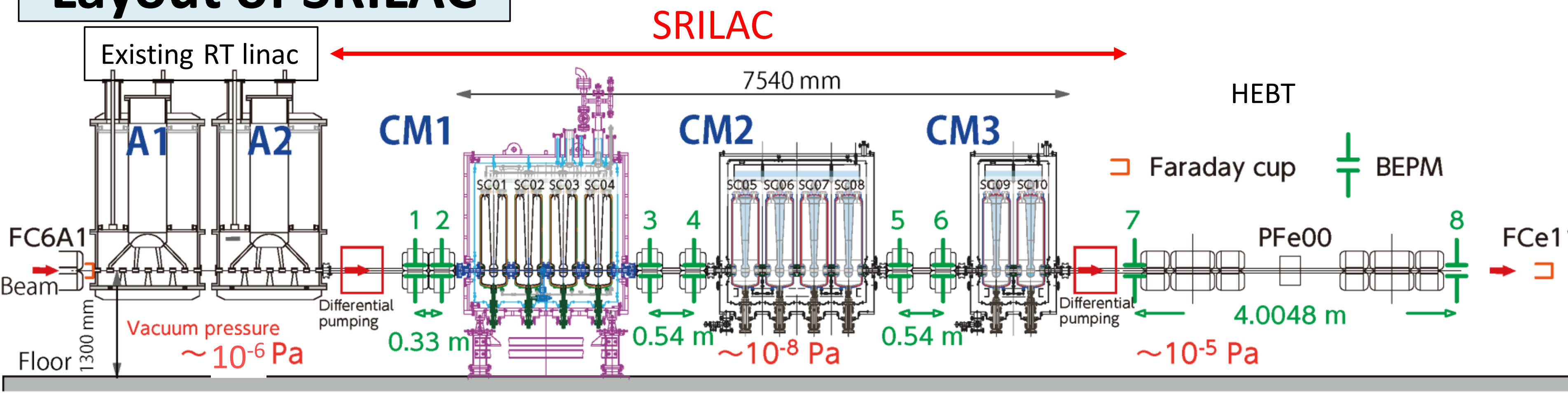


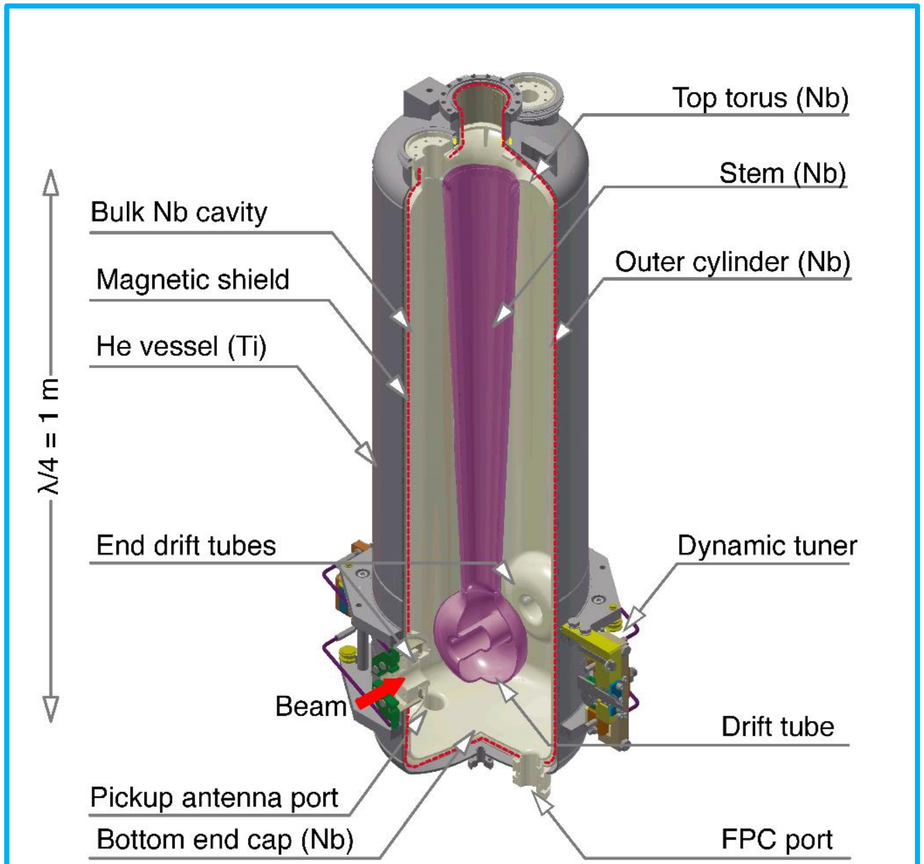


Design parameters

Number of cryomodules	3
Number of cavities	10
Frequency	73.0 MHz (CW)
Operating temperature	4.5 K
E_{inj}	3.6 MeV/u
E_{ext}	6.5 MeV/u for M/q=6 (tunable)
Total voltage	18 MV (goal)

Layout of SRILAC





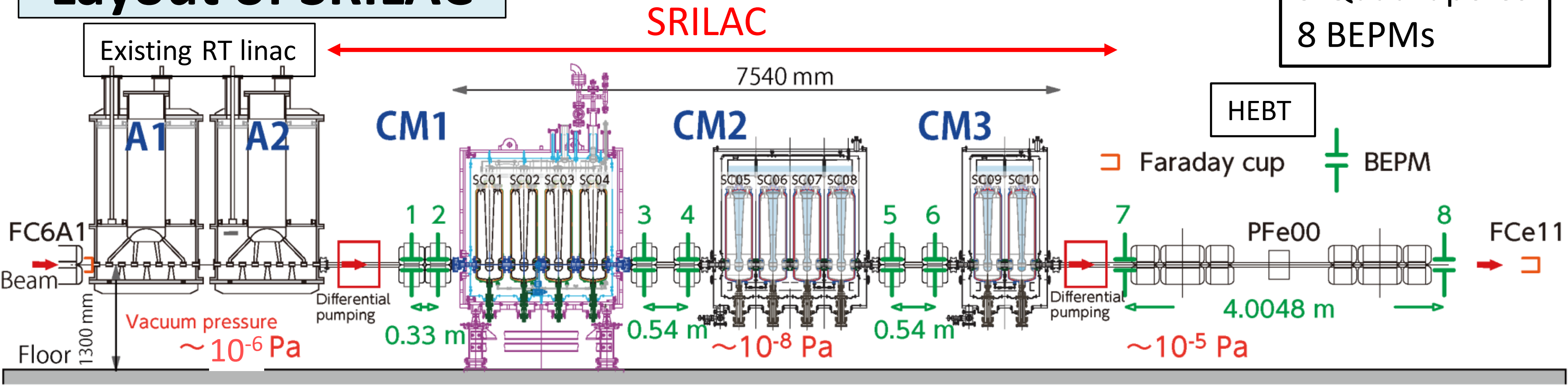
- Pure Nb QWR (RRR 250, Tokyo Denkai) with BCP based surface processing
- BCP(100 mm) → Annealing 700 ℃, 3 hrs → BCP(20 mm) → HPR → Baking(120 ℃, 48 hrs)
- Compliant with the High Pressure Gas Safety Act in Japan

Design parameters

Frequency [MHz]	73.0
Duty [%]	100
β_{opt}	0.078
Aperture [mm]	$\phi 40$
G [Ω]	22.4
R_{sh}/Q_0 [Ω]	579
Q_0	1.0×10^9
P_0 [W]	8
V_{acc} [MV] at $E_{acc} = 6.75$ MV/m, $\beta = 0.078$	2.16
E_{acc} [MV/m]	6.75
E_{peak}/E_{acc}	6.2
B_{peak}/E_{acc} [mT/(MV/m)]	9.6

Layout of SRILAC

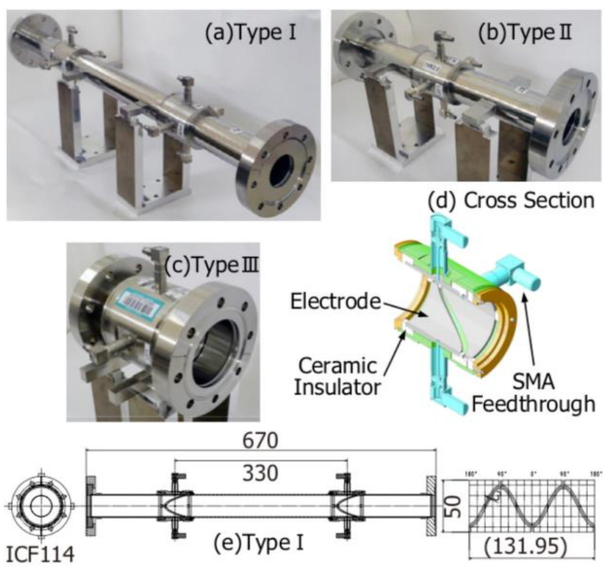
9 Quadrupoles
8 BEPMs



BEPMs

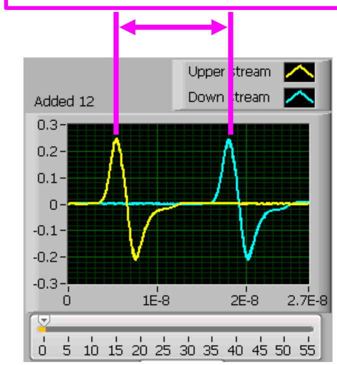
Energy and beam position measurement

RT quadrupoles

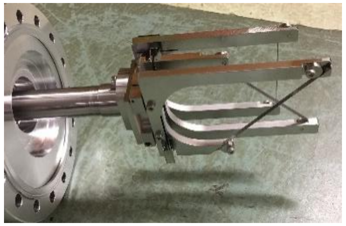


T. Watanabe et al., IBIC2020 FRAO04

TOF → Energy

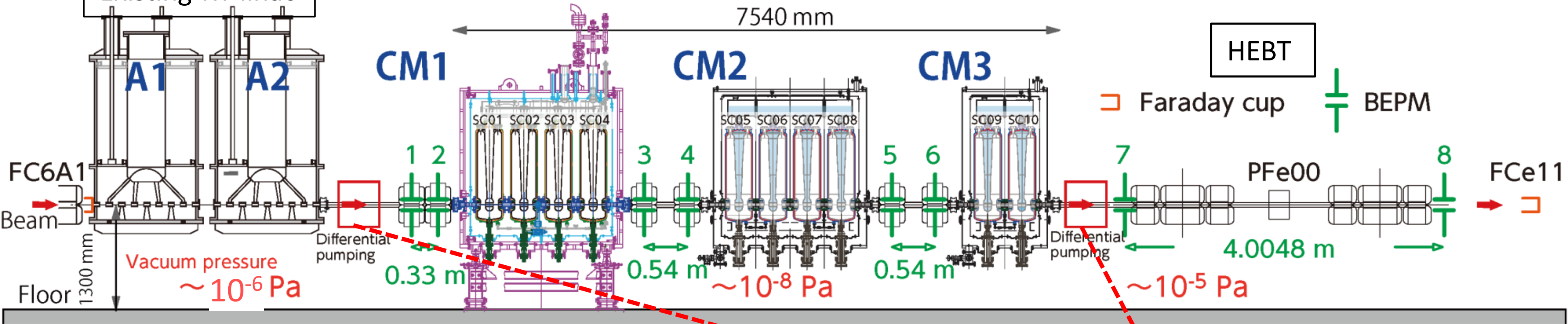


Wire Scanner

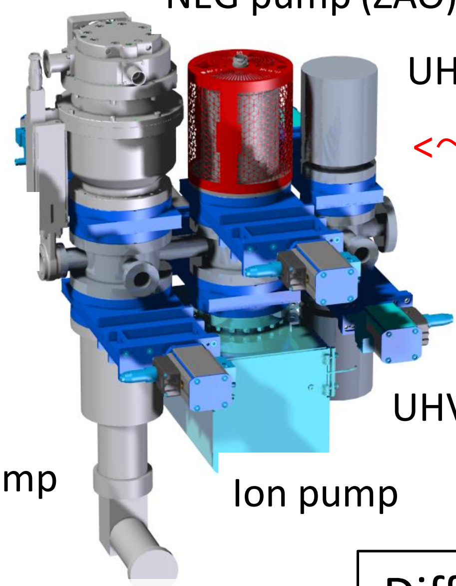


Faraday cup

Layout of SRILAC



Prevent gas flow from the RT section



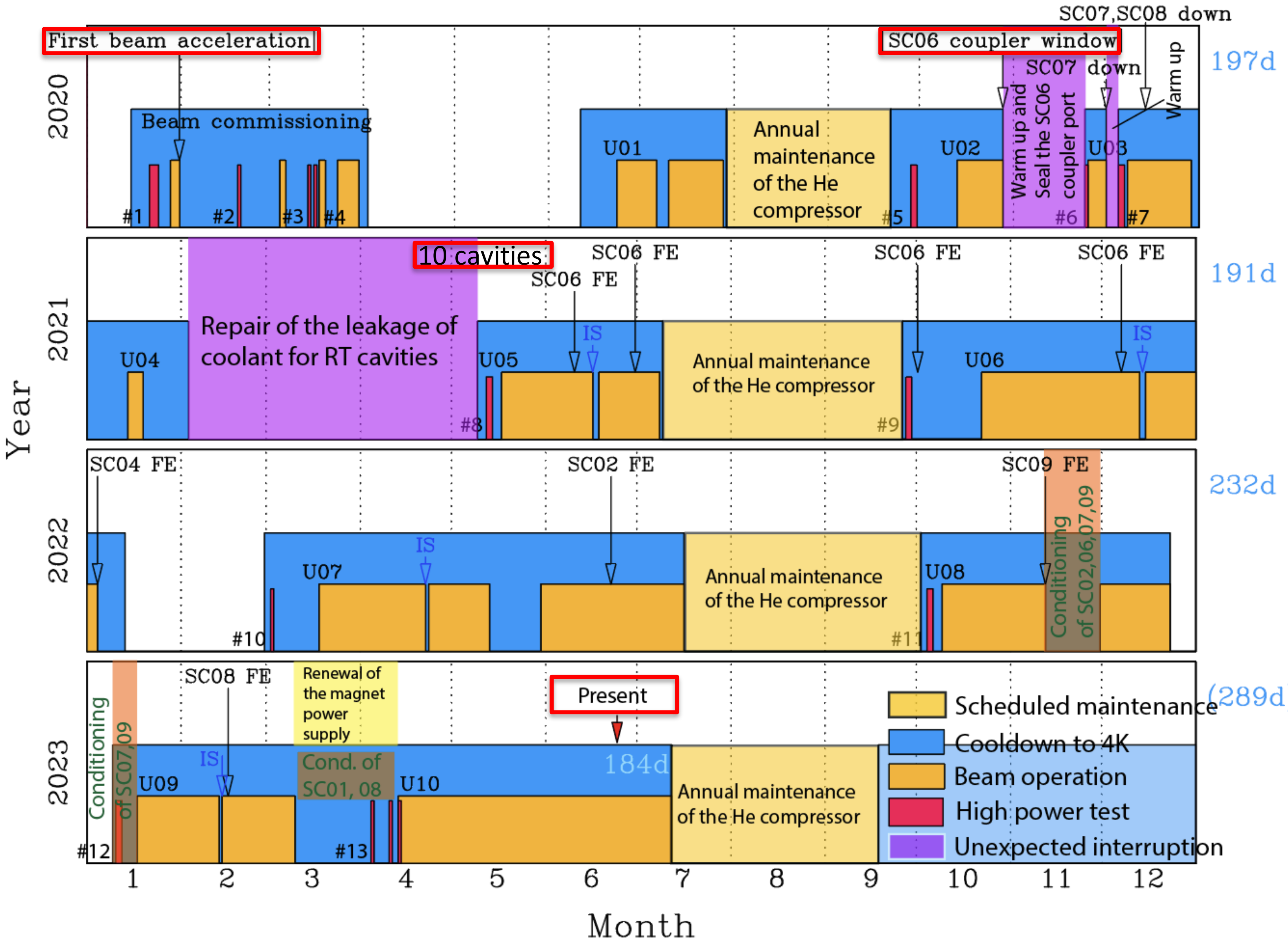
H. Imao et al., SRF2019 TUP013

Differential Pumping

Operational History of SRILAC

1st beam: Jan. 2020, Vacuum leakage: Oct. 2020, Operation of all 10 SC-QWRs: May 2021

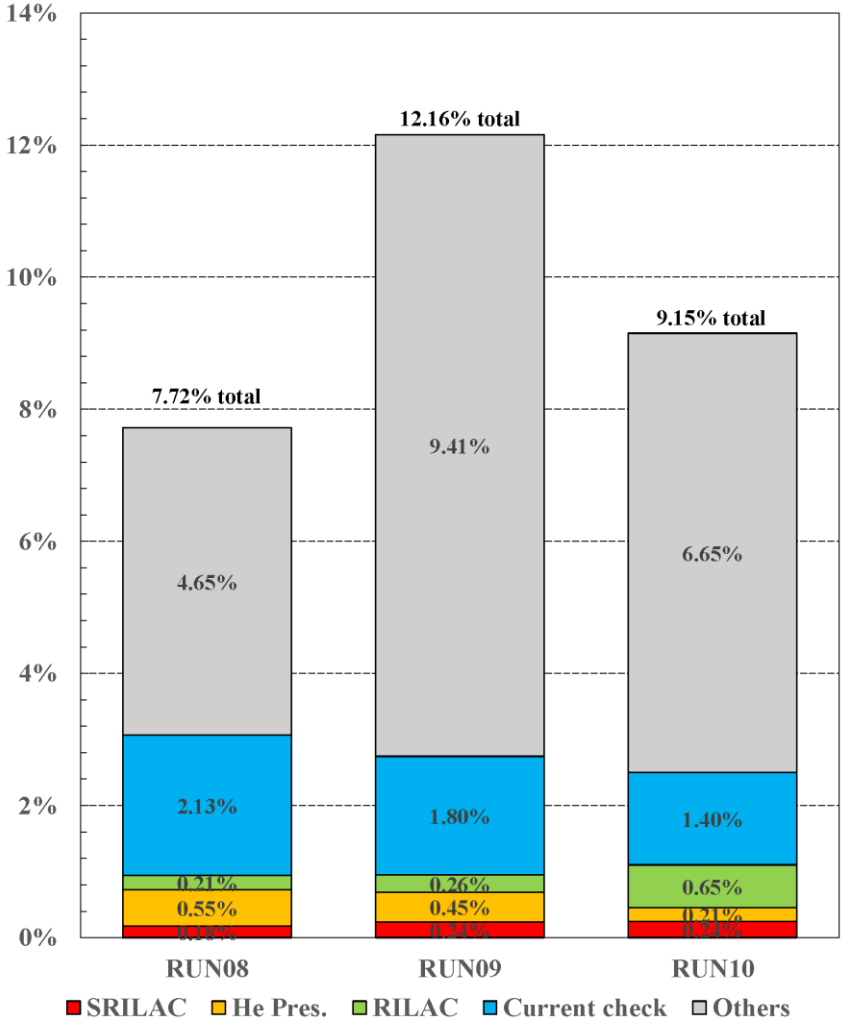
4 years operation for 10 user runs



Down Time and Availability

Availability = actual BT / scheduled BT

Average daily downtime for the last 3 runs



Oct. 11 – Dec. 22, 2022 | Jan. 18 – Mar. 9, 2023 | Apr. 16 – Jun. 15, 2023

Others include the beam stop time due to ion source restart.

Overall availability of linac is around **90%**

SRILAC + He Pres. = Downtime of SRILAC

SRILAC: Unlock of voltage/phase regulation
He Pres.: Unwanted He pressure fluctuations

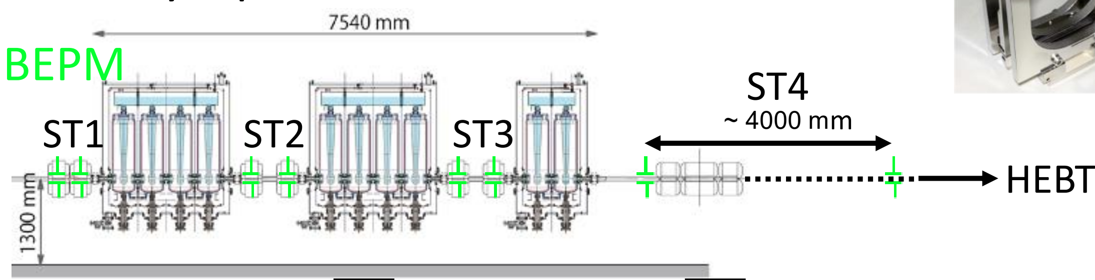
<u>Availability of SRILAC for the last 3 runs</u>

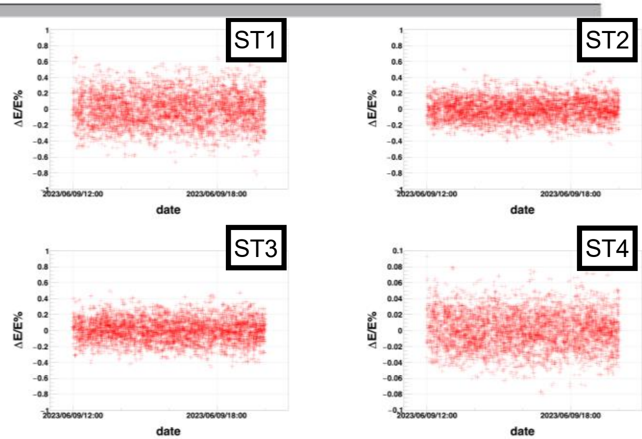
RUN08: 99.3%
RUN09: 99.3%
RUN10: 99.5%

Expected to improve with the current modification of the digital LLRF circuit for SRILAC

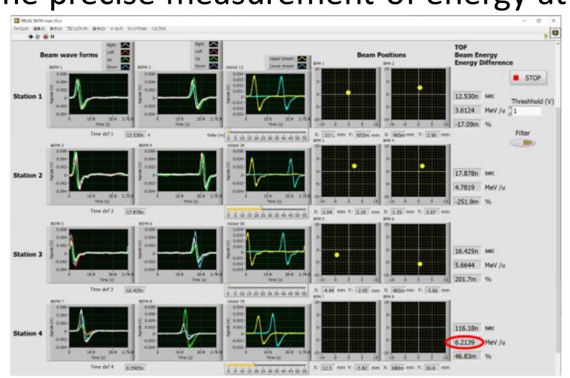
Beam Tuning of SRILAC

- Energy and position measurement by BEPMs
- Response of vacuum level
- Faraday cup and wire scanner in HEBT





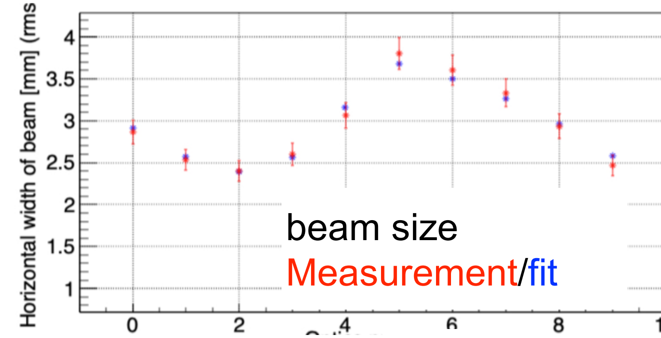
Real-time precise measurement of energy at each station



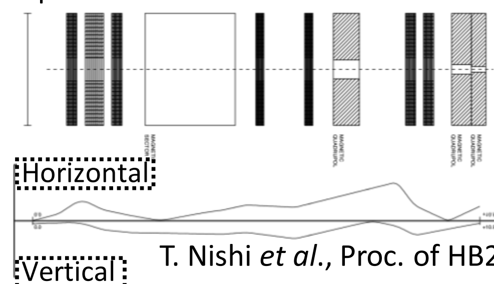
Energy and position monitoring

Wire Scanner

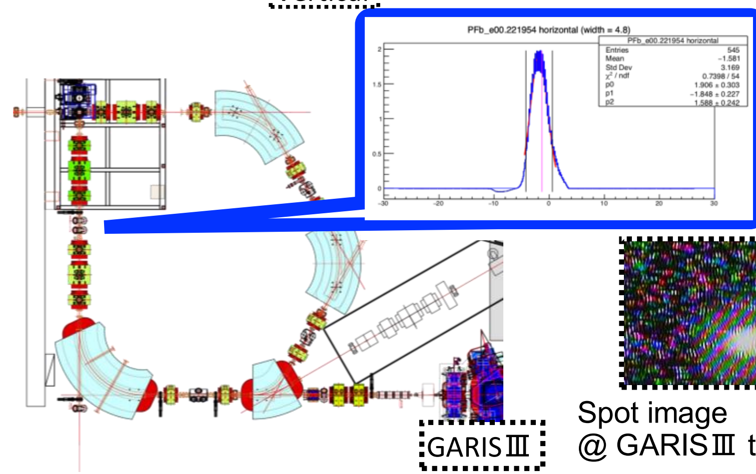
Q-scan measurement
10 measurements / ~ 10 minutes

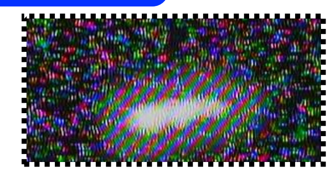


Optics calculation



T. Nishi *et al.*, Proc. of HB2021, THBC1





Spot image
@ GARISⅢ target (Viewer)

Total tuning time (all after ion source)
Cold start: ～48 h
Re-start: ～12 h

Phase Ellipse Measurement by BEPMs

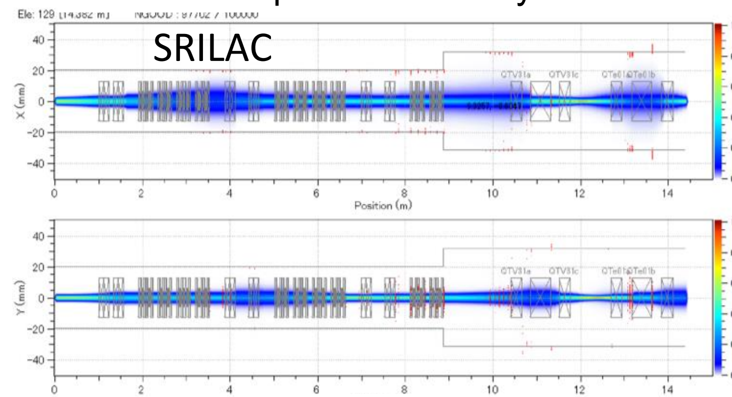
BEPM signals also can be utilized to estimate phase ellipse.
→ Non-destructive phase ellipse monitor

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_8 \end{pmatrix} = \begin{pmatrix} M_x(1|0)_{11}^2, -2M_x(1|0)_{11}M_x(1|0)_{12}, M_x(1|0)_{12}^2, -M_y(1|0)_{11}^2, 2M_y(1|0)_{11}M_y(1|0)_{12}, -M_y(1|0)_{12}^2 \\ M_x(2|0)_{11}^2, -2M_x(2|0)_{11}M_x(2|0)_{12}, M_x(2|0)_{12}^2, -M_y(2|0)_{11}^2, 2M_y(2|0)_{11}M_y(2|0)_{12}, -M_y(2|0)_{12}^2 \\ \vdots \\ M_x(8|0)_{11}^2, -2M_x(8|0)_{11}M_x(8|0)_{12}, M_x(8|0)_{12}^2, -M_y(8|0)_{11}^2, 2M_y(8|0)_{11}M_y(8|0)_{12}, -M_y(8|0)_{12}^2 \end{pmatrix} \begin{pmatrix} \epsilon_x\beta(0)_x \\ \epsilon_x\alpha(0)_x \\ \epsilon_x\gamma(0)_x \\ \epsilon_y\beta(0)_y \\ \epsilon_y\alpha(0)_y \\ \epsilon_y\gamma(0)_y \end{pmatrix}$$

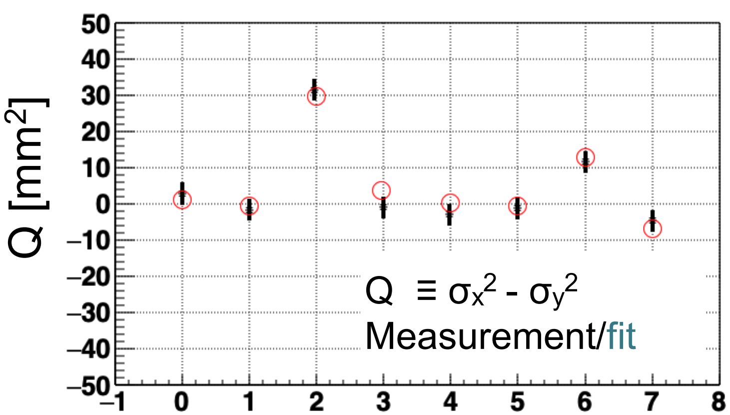
$Q \equiv \sigma_x^2 - \sigma_y^2 = k_q*(V_L + V_R - V_U - V_D)/\Sigma_V - \langle x\rangle^2 - \langle y\rangle^2$
(quadrupole moments)
k_q: constant
M: transfer matrix (calculated by TraceWin)

R. H. Miller *et al.*, in Proc. of HEAC'83, Fermilab, IL, USA, 1983, pp. 603—605.

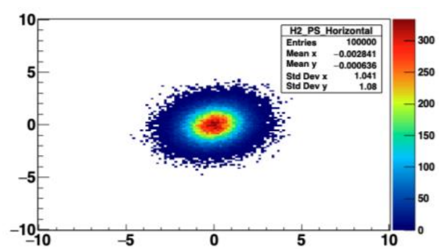
Beam envelope calculated by TraceWin



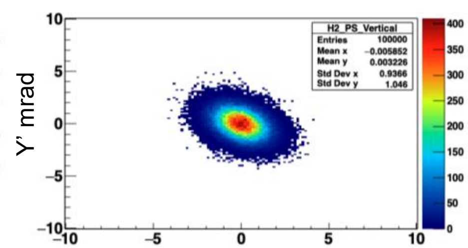
Position



Estimated Phase Ellipse (horizontal)



Estimated Phase Ellipse (vertical)



<u>Developing this method to reproduce the beam envelope in SRILAC</u>

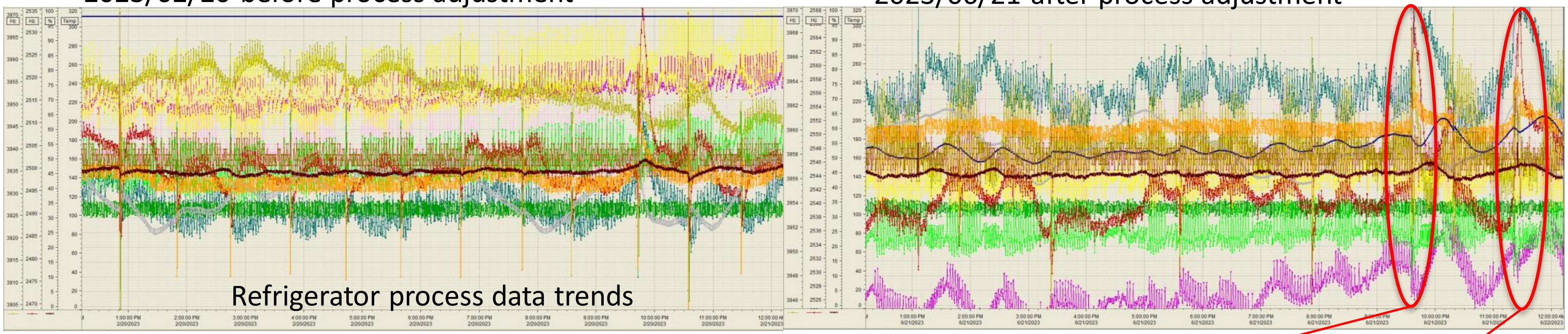
For details: T. Nishi, MOPMB086

Stability of He Pressure

- Absolute pressure of He is well stabilized within ±0.2 kPa in CMs by controlling each gas-return valve.
- Periodic pressure fluctuations are observed in the refrigerator.
- Process adjustments have reduced the frequency of pressure fluctuations.
- There still remains the problem of occasional large fluctuations.
  → CMs are affected and RF regulation is unlocked for several tens of seconds (depends on which cavity).

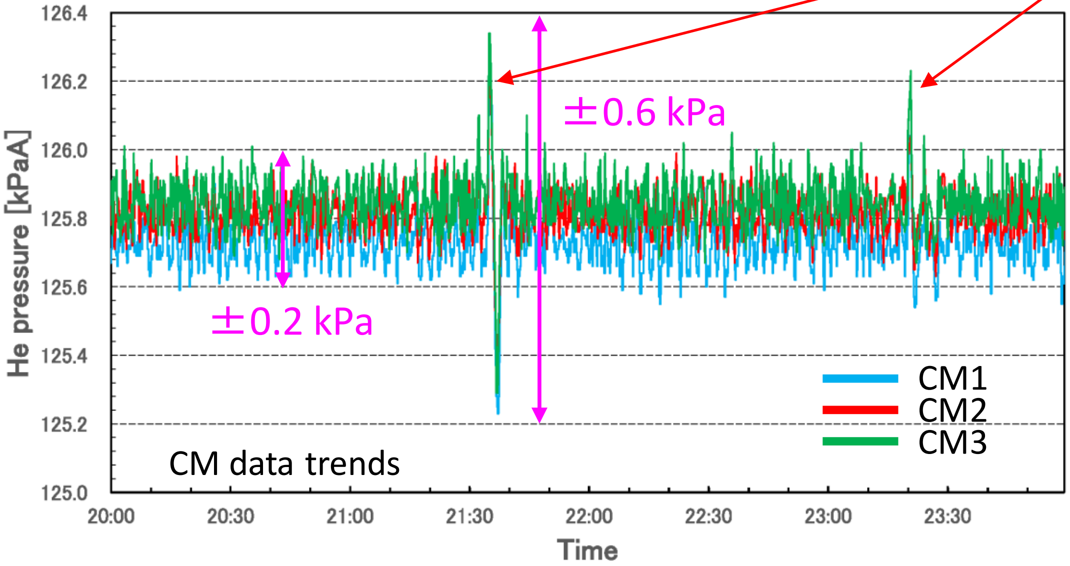
2023/02/20 before process adjustment

2023/06/21 after process adjustment



He refrigerator

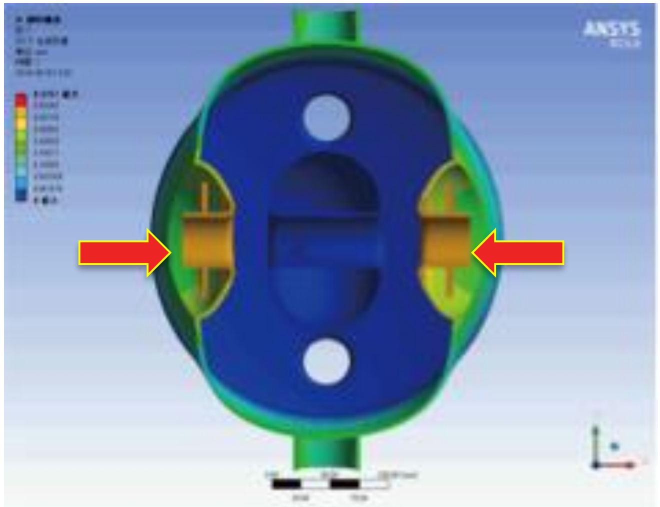
Air Liquide HELIAL MF
Cooling capacity: >600 W @4.5 K

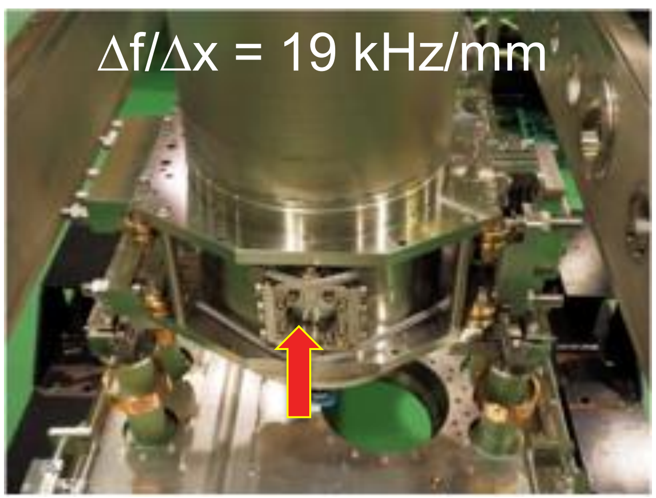


Frequency Tuner Control

Frequency is lowered by squeezing accelerating gaps by a stepping motor.

Max. : -14 kHz

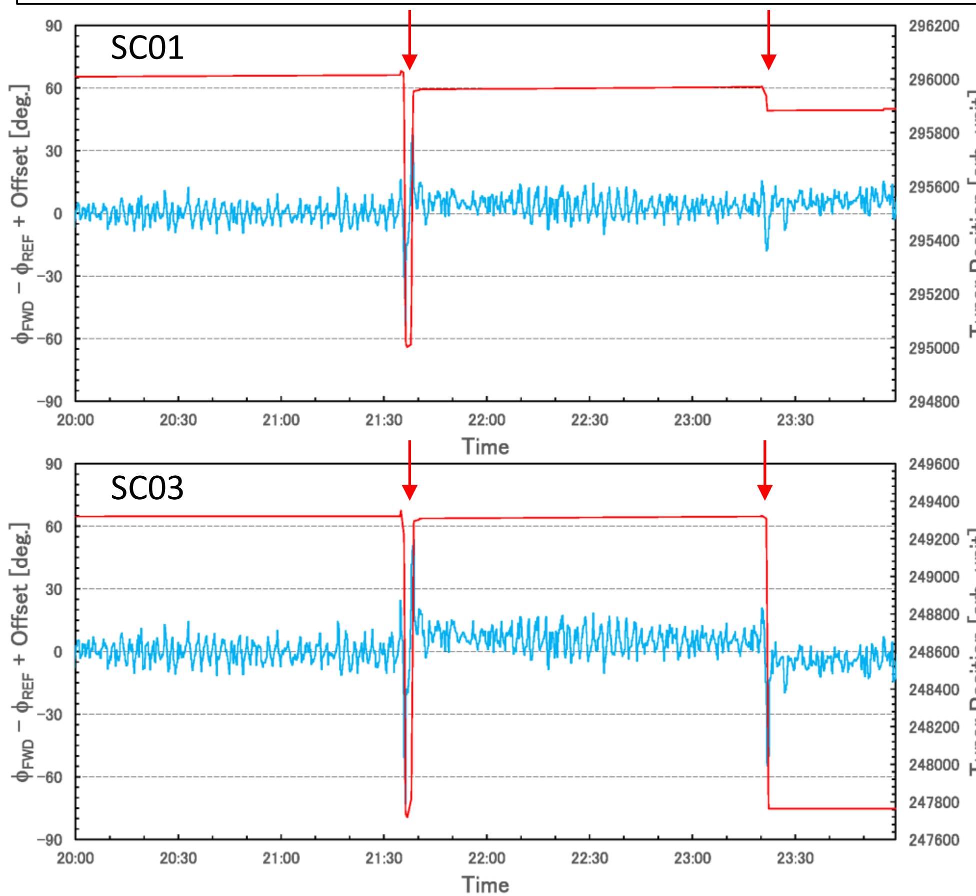




K. Suda et al., SRF2019 MOP055

- Frequency variation is compensated by proportional control of tuner.
- Tuner is driven by phase difference $\Delta\phi = \phi_{FWD} - \phi_{REF}$.

Stable except during large pressure fluctuations

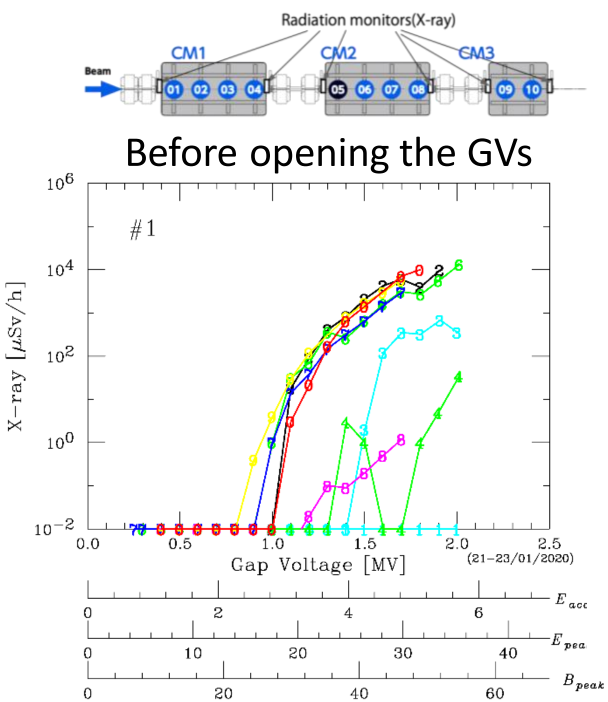


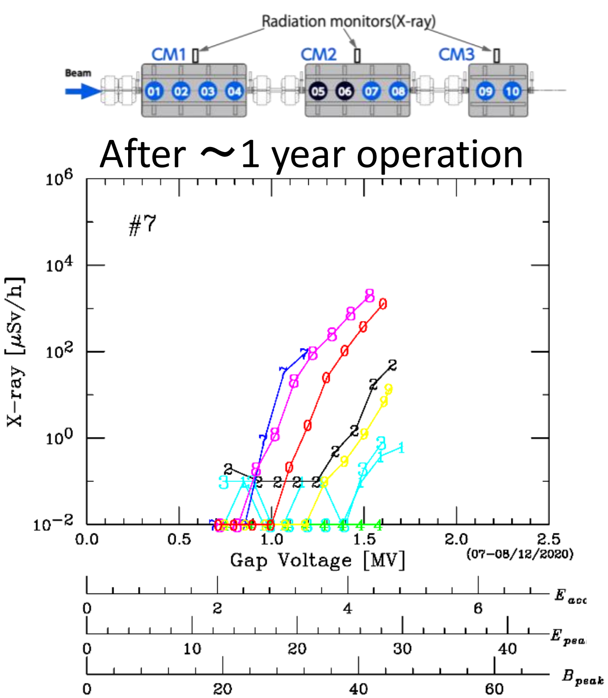
$\Delta f/\Delta P_{He}$ = -2 Hz/hPa ⇨ | Δ f | < 8 Hz < BW/2 (25 Hz)

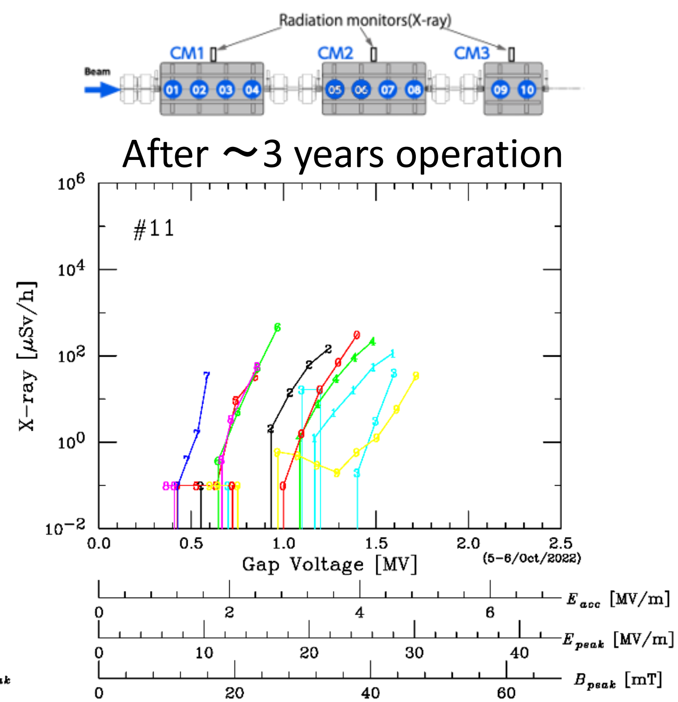
Stable operation for more than 3 years

Degradation of SC-QWR performance

- After an impact of SC06 coupler-window-break emission levels of SC07, SC08 became higher than those of the measurement #1.
- The deterioration of SC05, 06, 07, and 08 (CM2) is significant.
- X-ray emissions were gradually increasing in the CM1 and CM3 after 3 years.
- Increase in the emissions occurs suddenly during beam delivery.
- No events such as increased beam loss or gate valve opening/closing at this time.



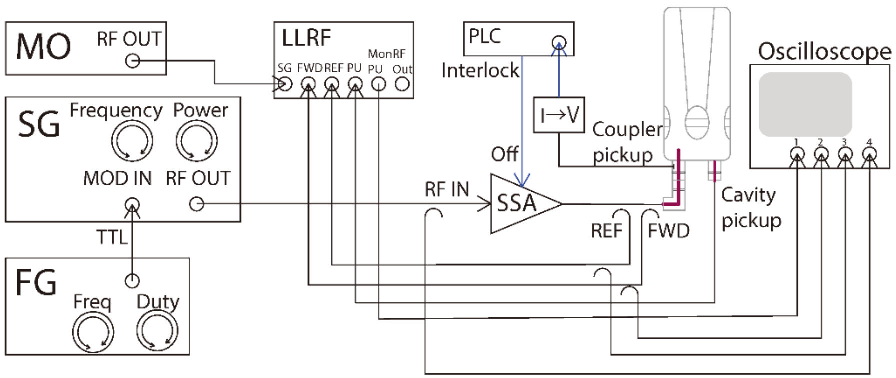


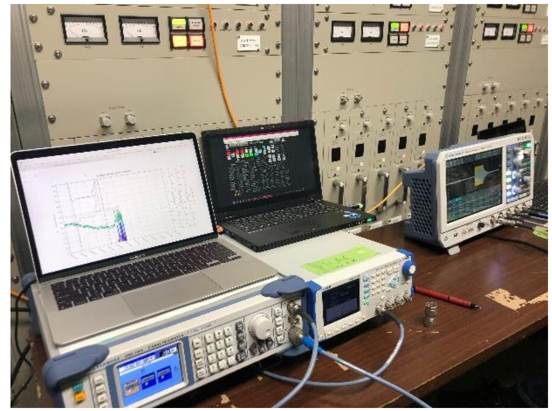


Pulse Conditioning

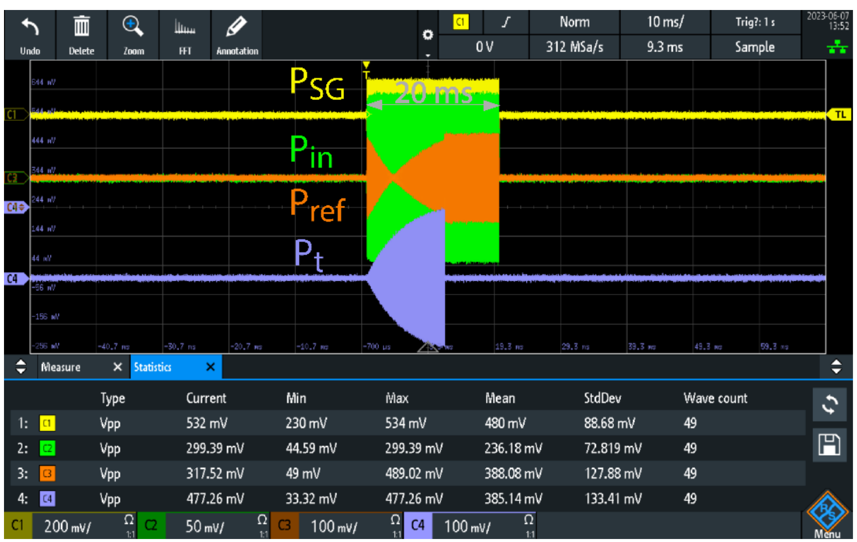
We introduced pulse conditioning using a temporary setup.

- Temporary setup using a signal and function generator
- Interlock remains active

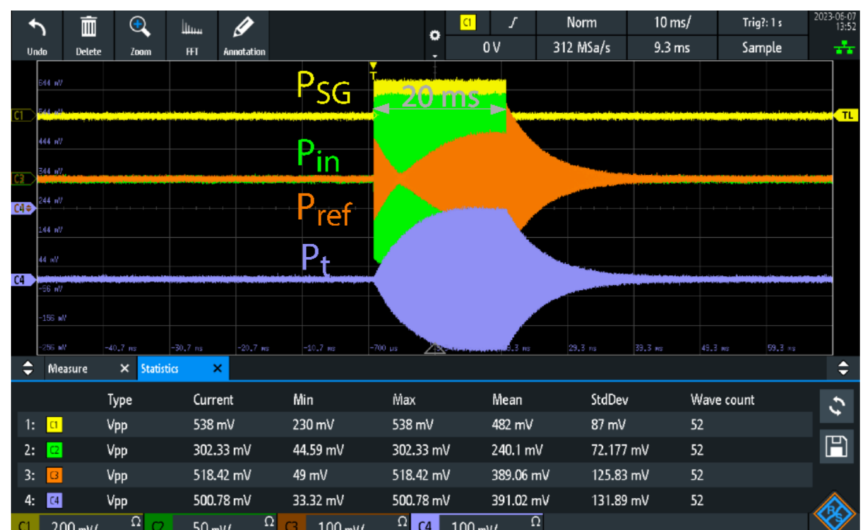




Freq: 0.5 Hz, Duty: 1%, Pulse width: 20 ms, ～2.5 MV max.



Sudden decline during a pulse

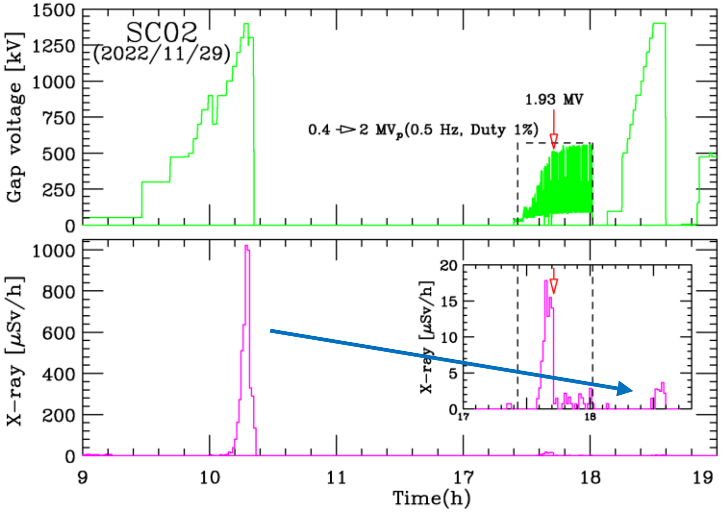


Normal pulse

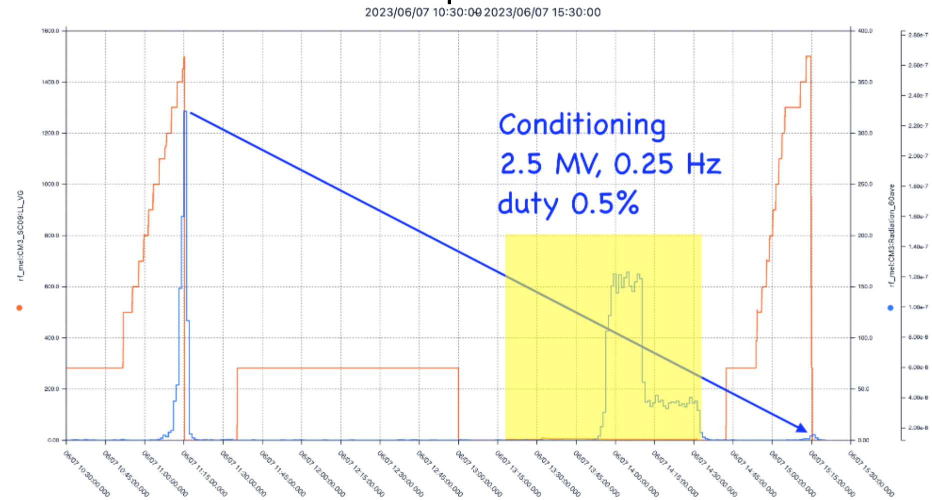
Effects of Pulse Conditioning

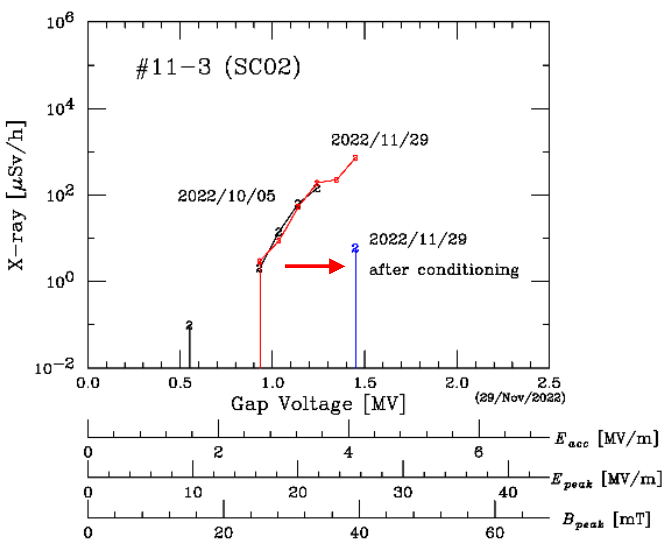
Pulse conditioning is very effective in the SRILAC for performance recovery.

Example for SC02



Example for SC09





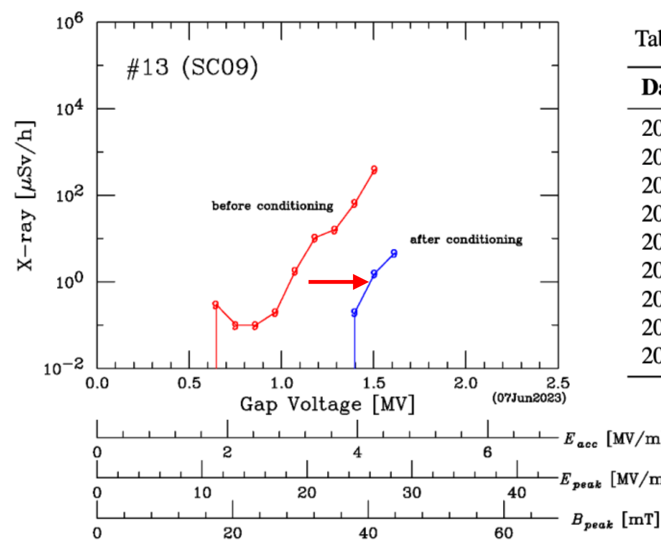


Table 3: History of pulsed power conditioning

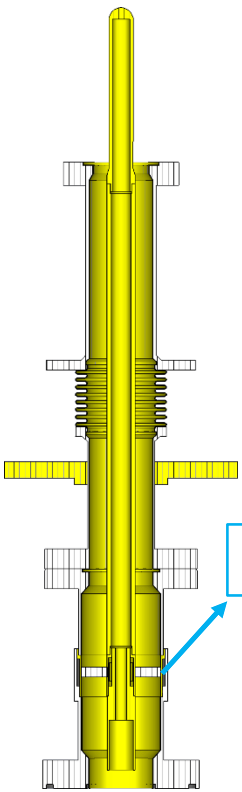
Date	**Cavity**	**Time**	V_p^{max} **[MV]**
2022/11/22	SC07	7:37	1.34
2022/11/24	SC06	4:05	1.52
2022/11/28	SC09	1:14	1.57
2022/11/29	SC02	0:37	1.98
2023/1/12	SC07	0:54	1.55
2023/1/13	SC09	1:44	1.99
2023/3/29	SC08	2:35	1.80
2023/4/13	SC01	0:40	2.23
2023/6/7	SC09	1:13	2.54

For details: N. Sakamoto, WEPWB085

Problem on FPCs and Temporary Measures

- Vacuum leak at SC05 (Nov. 17, 2019)
  during warm-up process after 4th cooling down test before high power RF test
- Vacuum leak at SC06 (Oct. 27, 2020)
  during beam delivery

⇨ Inside of all couplers were rusted due to condensation.



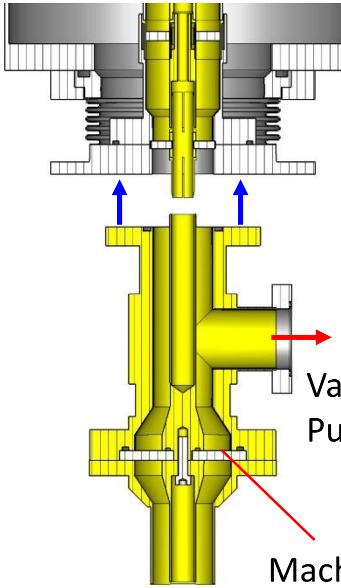
Single RT window

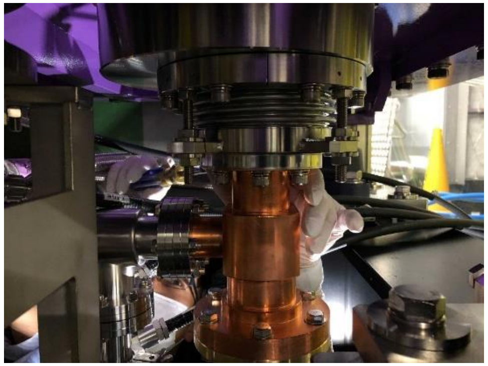
SRILAC FPC

Original coupler of SRILAC

Rust inside SC01 coupler

Temporary measures:
Outer window were attached on <u>all 10 couplers.</u>

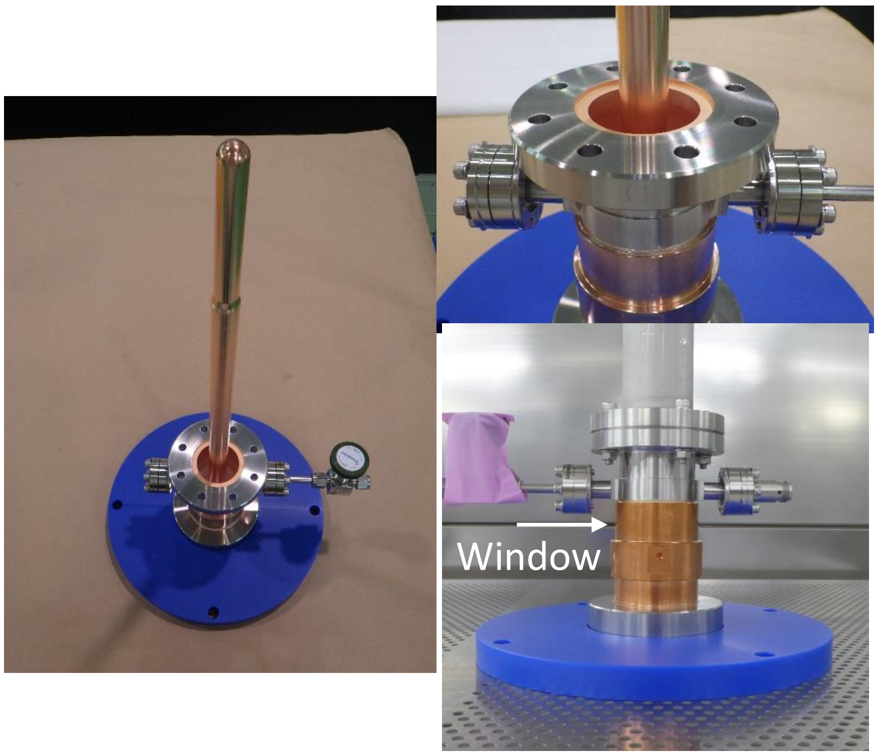




In use for almost 2 years without any problems

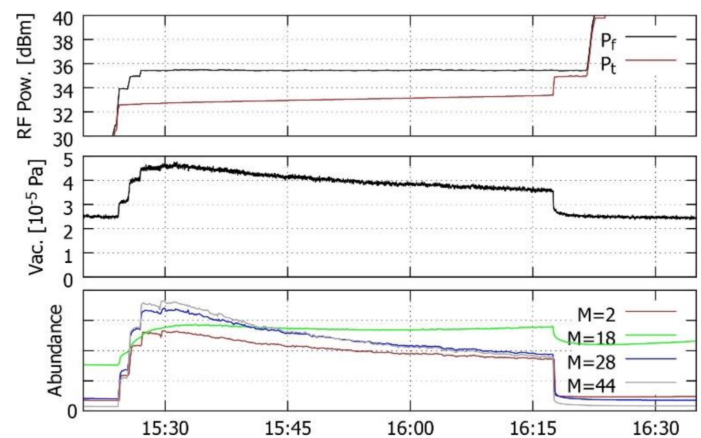
Fabrication of New FPCs

- 10 new couplers were fabricated with countermeasures not to cool the vacuum window.
- Outer conductors were to remain original.
- Currently pre-processing in order
- Trying to make a bias-applying system for prevention of MP



New coupler with a vacuum window

RF processing with RGA



For details: K. Ozeki, WEPWB101

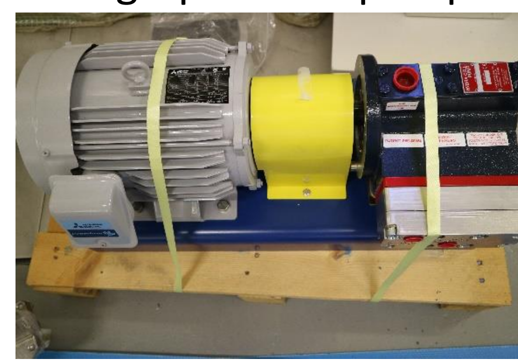
Fabrication of Spare Cavity

- 2 spare SC-QWRs are being fabricated.
- Frequency pre-tuning and EBW completed on 2 bulk Nb cavities.
- Surface treatment and jacket welding will be performed in the future.
- We are also beginning to prepare a HPR system as simple as possible.

Frequency pre-tuning of SC-QWR

In storage

High-pressure pump



Summary

- SRILAC has been in actual operation for 4 years.
- Availability of the SRILAC part is over 99%.
- Beam tuning time is getting shorter.
- Pulse conditioning recovered the performance degradation caused by field emissions.
- The problem of helium pressure fluctuations still remains.
- New couplers and cavities are being prepared.

See you at the SRF2025 in Tokyo!