Long-term Stable Operation of cERL Cryomodules

ERL2024@KEK

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(on behalf of cERL-SRF team)

Outline

- cERL SRF cryomodule
- Operation status of cERL SRF cryomodules
  - Typical operation status
  - Degradation and recovery of cavity performance
- Toward future higher performance cryomodule
  - New cavity design
  - New HOM absorber design
  - Clean assembly technique
- Summary

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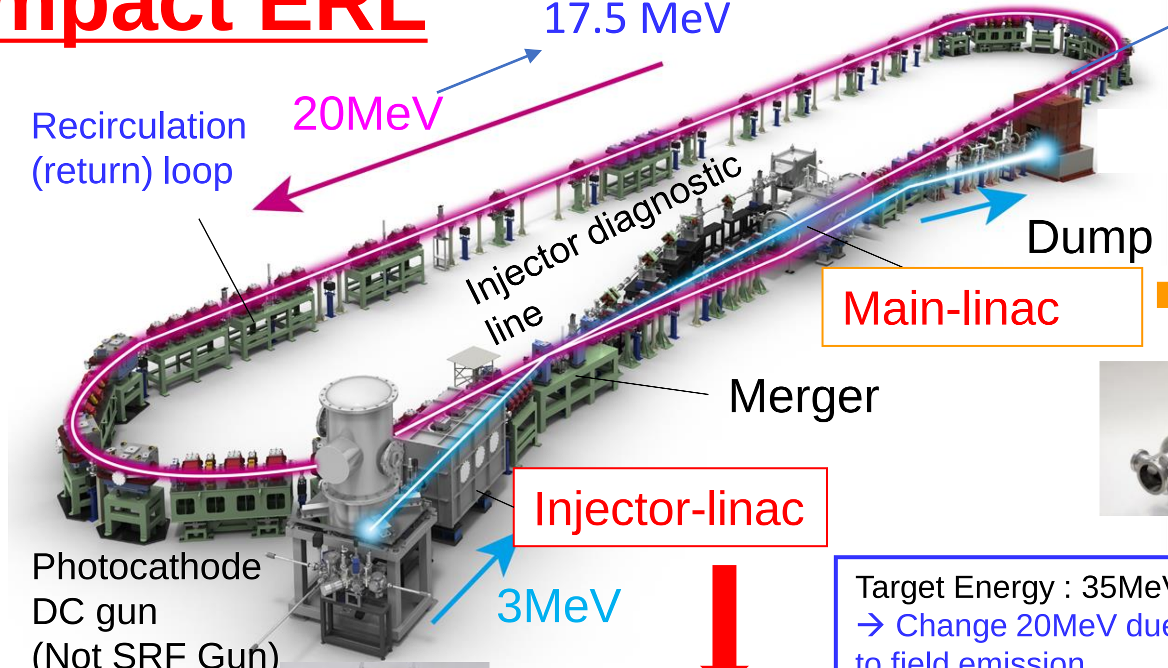
Compact ERL



Target Energy : 35MeV
→ Change 20MeV due to field emission

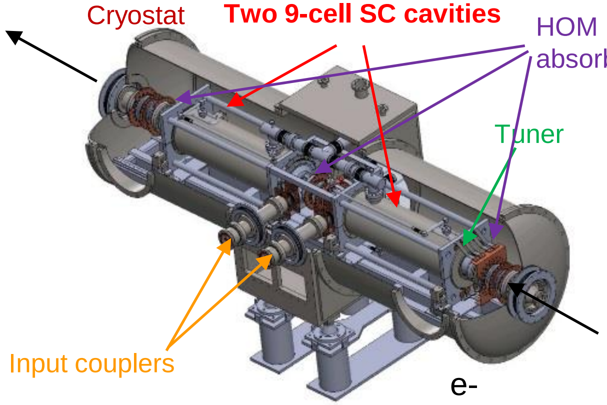
Main linac module

HOM damped (for 100mA circulation to suppress HOM-BBU in design)

9-cell cavity (ERL-model2) × 2

RF frequency: 1.3 GHz
Input power : 20kW CW (SW)
E_{acc}: 15 MV/m (design)
Unloaded-Q: $Q_0 > 1\times10^{10}$

H.Sakai et al. "Field emission studies in vertical test and during cryomodule operation using precise x-ray mapping system". Phys. Rev. Accel. Beams 22, 022002 (2019)



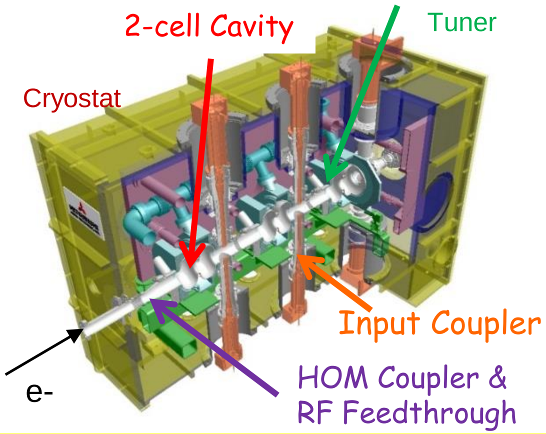
Requirement was satisfied at V.T. **Issue:** Heavy F.E was met @9-10MV/m after string assembly. & met quench shown later In detail

Injector module

K. Watanabe, et al. "Development of the superconducting rf 2-cell cavity for cERL injector at KEK" Nucl. Instru. Meth. A Vol. 714, p67-82 (2013)

2-cell cavity × 3
Double coupler

RF frequency: 1.3 GHz
Input power :
10kW/coupler (10mA, 5MeV)
180kW/coupler (100mA, 10MeV)
E_{acc}: 7.6MV/m (5MeV)
15MV/m (10MeV)
Unloaded-Q: $Q_0 > 1\times10^{10}$



Issue: We met the HOM coupler heating if field increased more than 7MV/m. It is the reason for heating not perfectly to be filtered in HOM coupler and results in lower Q0 than 1×10^{10}.

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV →17.5MeV
Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

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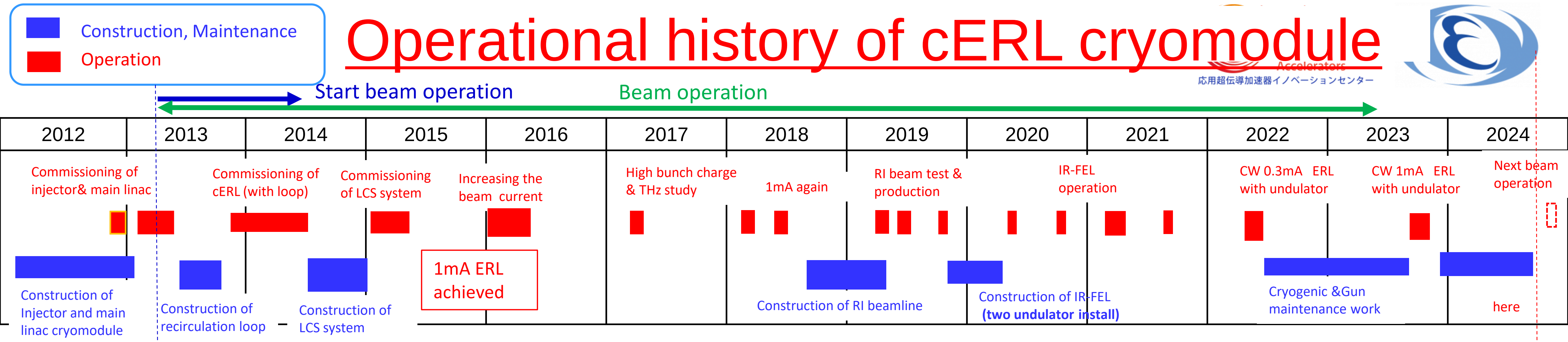
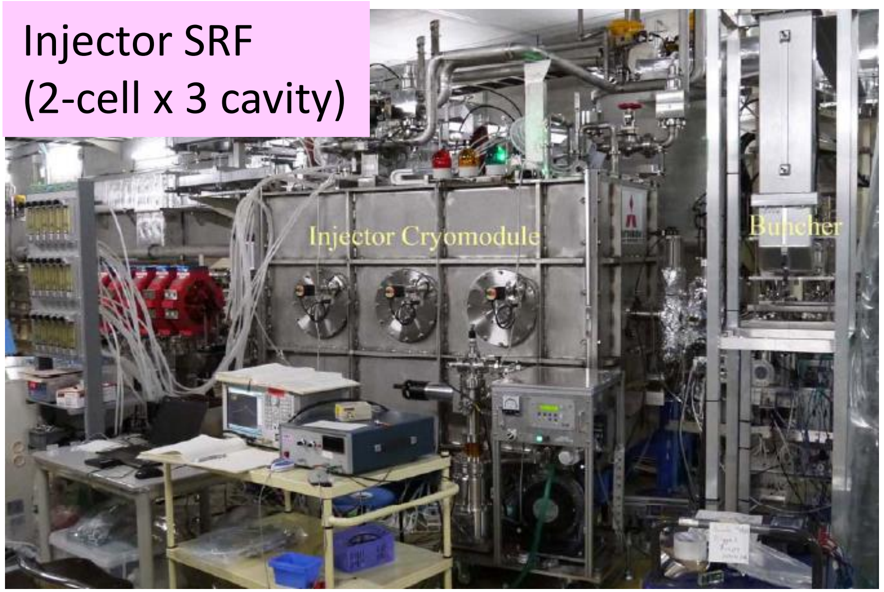
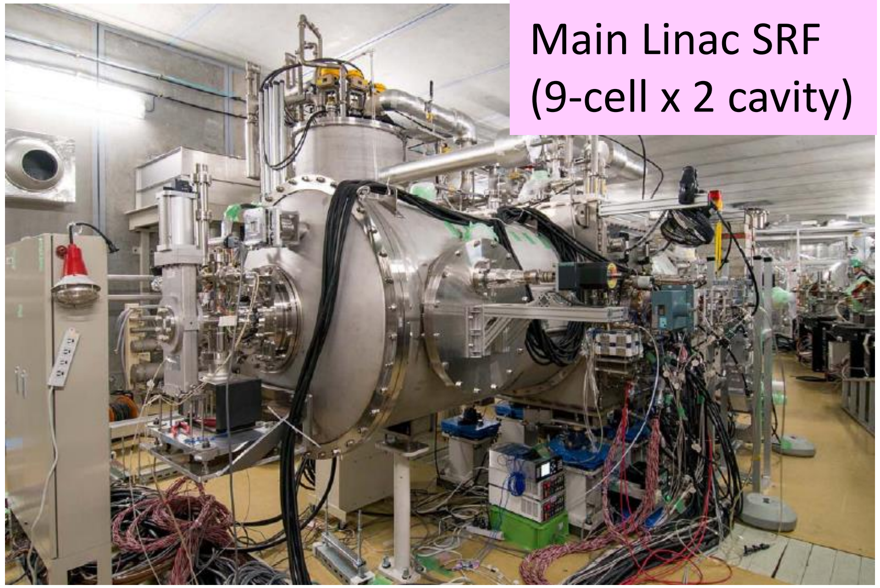
Operational history of cERL cryomodule







cERL beam operation from Oct. 2019 to Mar. 2023

Period(beam operation time)	Energy[MeV] (Comment)	Current
2019.Oct. (3 weeks)	17.5 (loop)	60 pC/ bunch
	19.0 (IR)	~1 uA (CW)
2020.Jun. (4 weeks)	17.5 (loop)	60 pC/ bunch
2020.Jun. (3 weeks)	17.5 (loop)	60 pC/ bunch
2021.Feb-Mar. (6 weeks)	17.5 (loop)	60 pC/ bunch
	23.0 (IR)	1pC/bunch (pulse)
2021.Oct. (3 weeks)	17.5 (loop)	40 pC/ bunch
	10.0 (IR)	~1uA (CW)
2022.Feb-Mar. (3 weeks)	17.5 (loop)	300uA (CW)
	10.0 (IR)	~1uA (CW)
2023.Nov. (5 weeks)	17.5 (loop)	60 pC/ bunch 1mA (CW)

Operation status of cERL SRF cryomodule

[Injector]

- Field emission need to be processed to keep operation condition
- Large heat load at HOM coupler
- Eacc ~ 7 MV/m

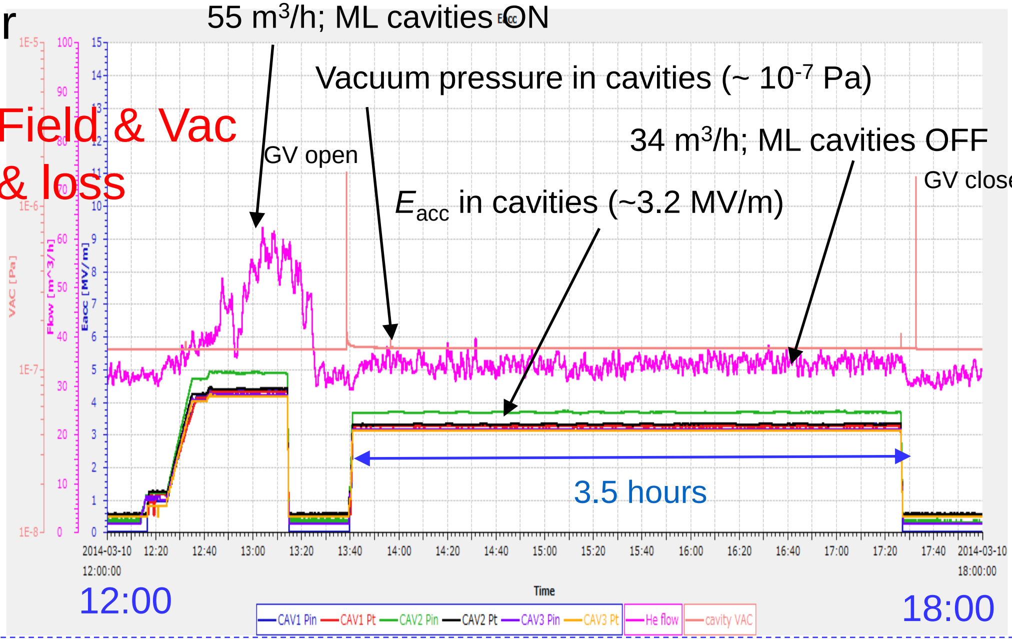
[Main linac]

- Suffered from field emission
- Need pulse processing to keep operation condition
- Abnormal heat load exists for ML-1
- Eacc = 7~10 MV/m

Typical one day operation of cERL SRF (Year2014)

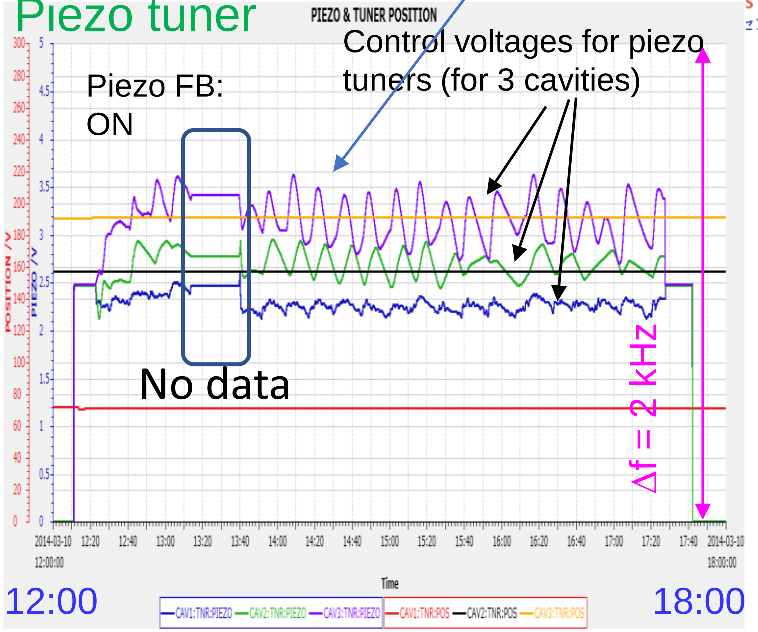
Synchronized with 80K line temperature

Injector

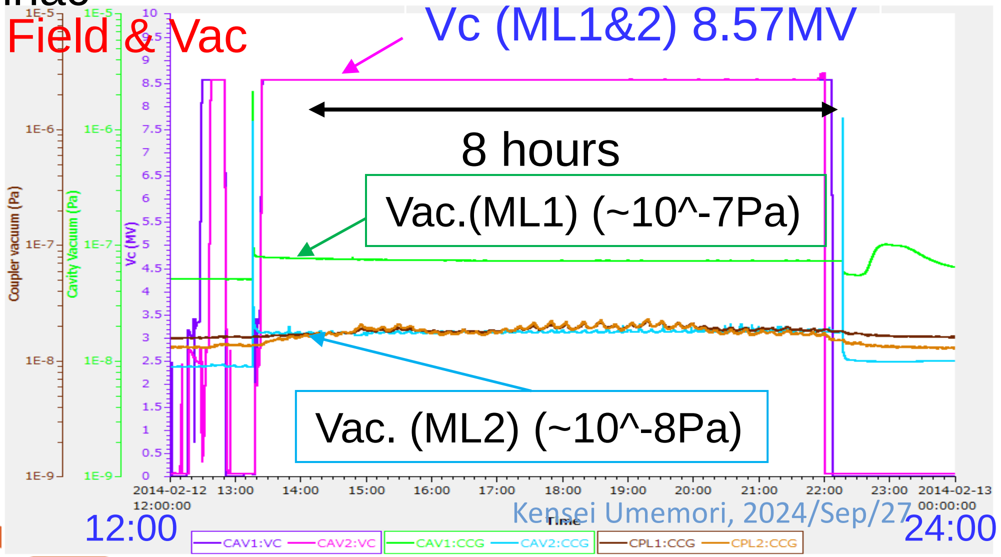


Piezo tuner

INJ

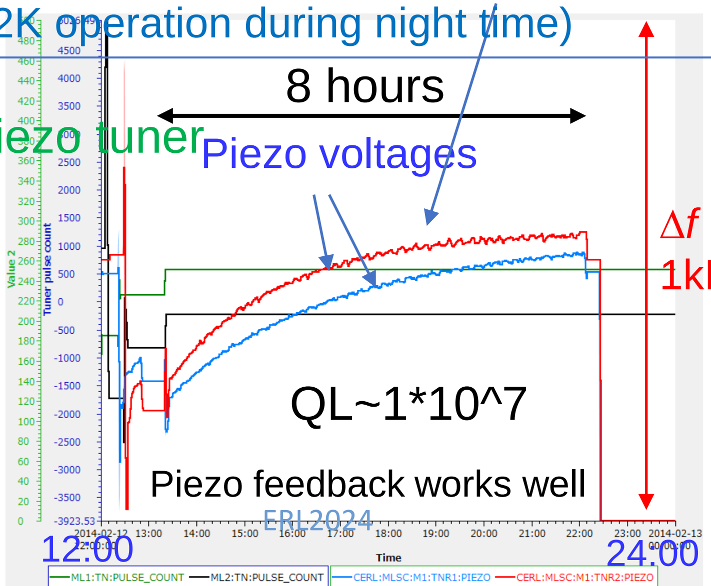


Main linac



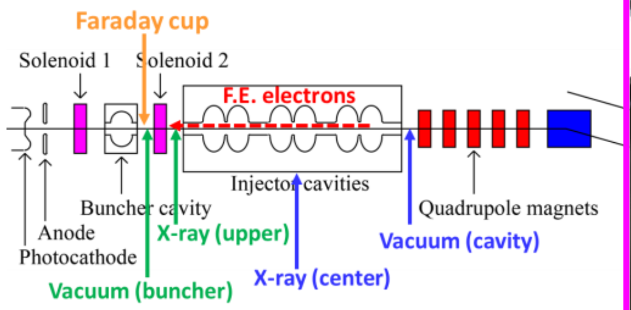
Drift due to temperature change of tuner system (Stop 2K operation during night time)

ML

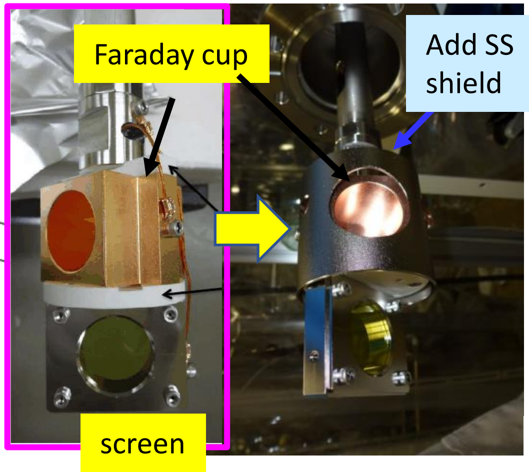


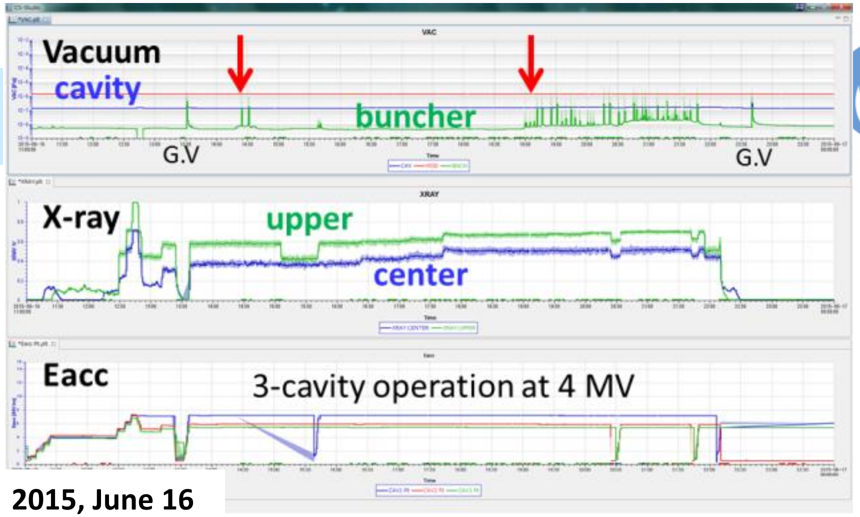
Unexpected discharge(1)

INJ



Screen monitor in front of Gun



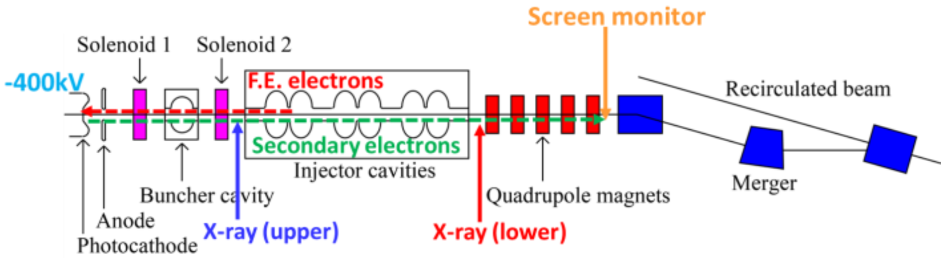


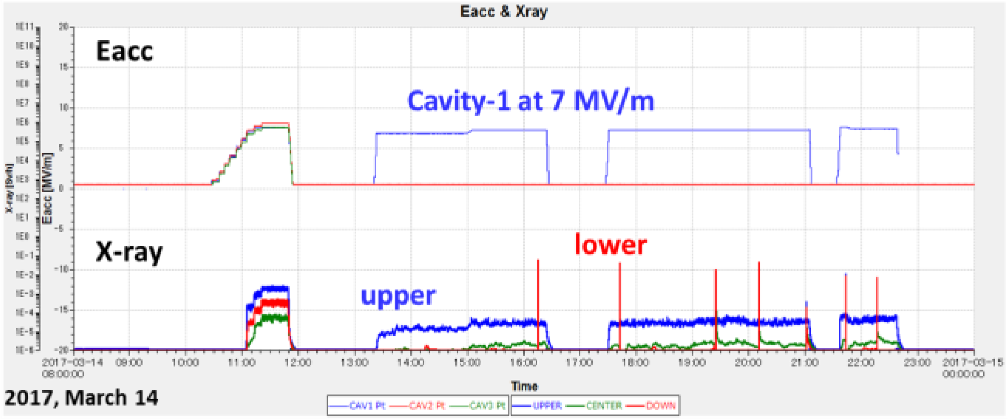
2015, June 16

Field emitted electron induce a charge up of Faraday cup.
⇒Discharge lead to vacuum deterioration and increase of radiation.
Improvement on Faraday cup solved problem.

Both case, interaction of F.E. and surrounding components.

Unexpected discharge(2)



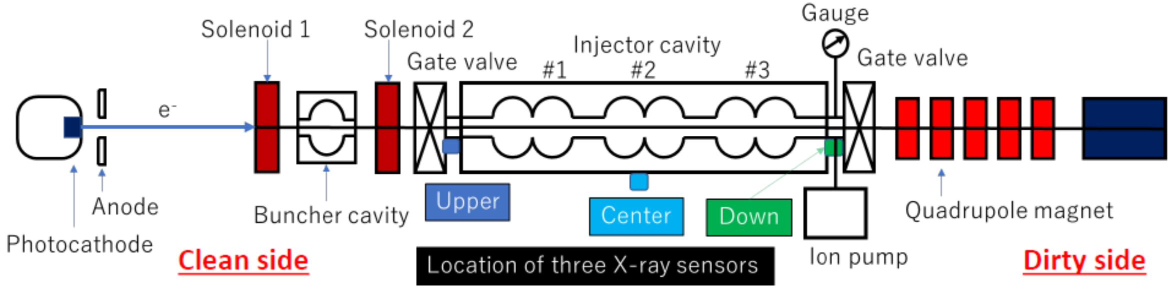


2017, March 14

Field emitted electron hit photocathode → Secondary electron extracted by DC voltage and accelerated by injector cavities. Finally collide with the screen monitor.
⇒ Lead to vacuum spike and increase of radiation.

Injector performance from Oct. 2019 to Feb. 2022

- We once met the **sudden severe X-ray increase** during beam operation in Jun. 2020.
- F.E onset reduced from 8 MV/m to 5 MV/m in Inj #2 cavity. We do not know the reason.
- After pulse processing, F.E onset recovered at normal level. → **kept 7 MV/m operation**

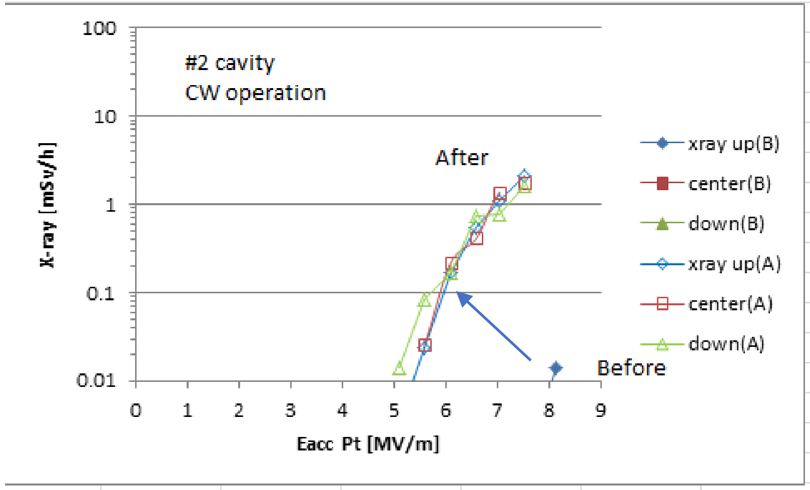


(Before pulse processing)
CW = 8MV/m (onset 5MV/m)

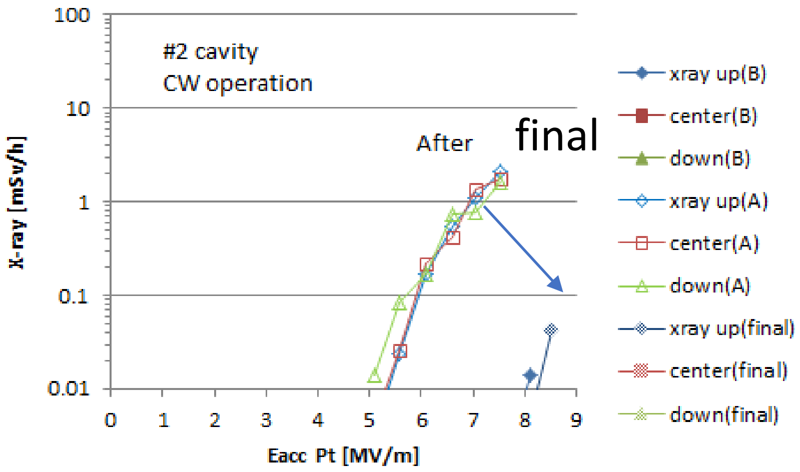
Pulse duty (0.5ms 10Hz)
18 MV/m (~2 hours)

Pulse duty (5ms 10Hz)
12 MV/m (~1 hours)

(After Pulse processing)
CW = 8MV/m (onset 8MV/m)

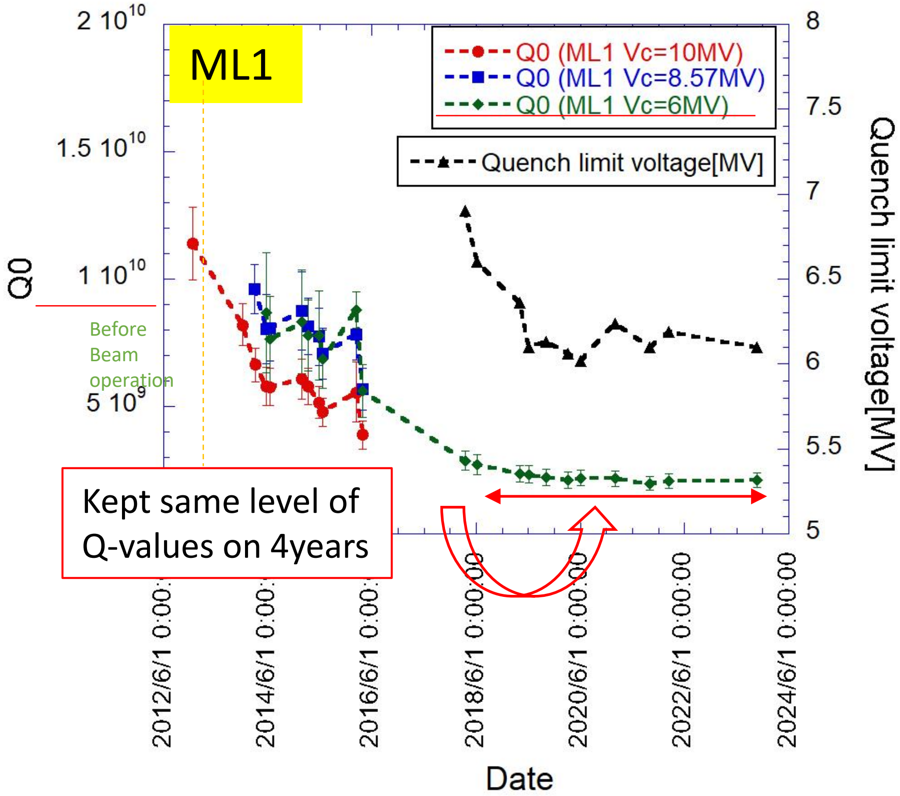


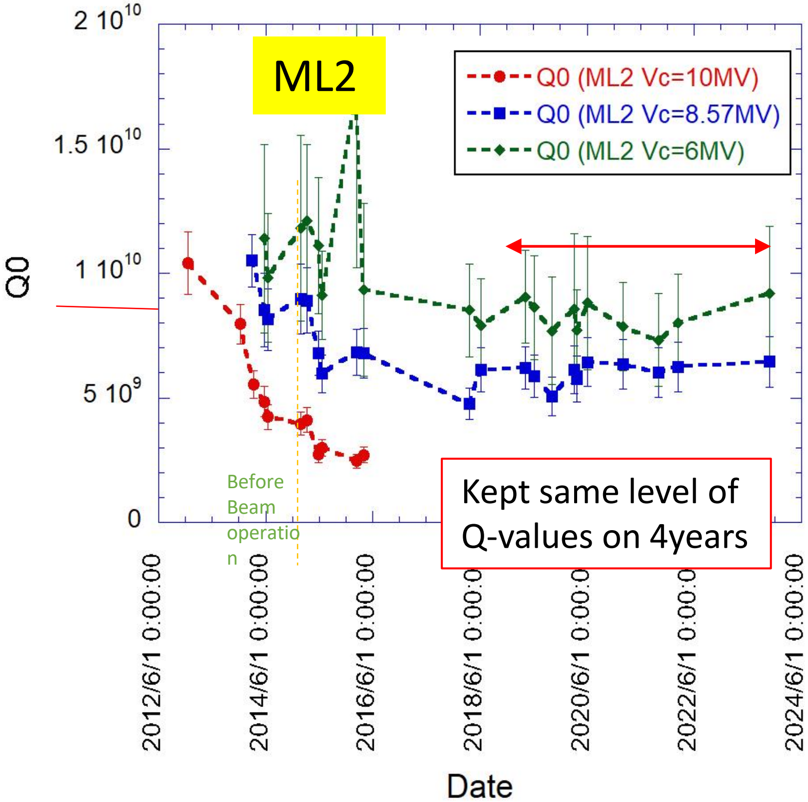
2020.Jun.18
Suddenly x-ray onset reduced



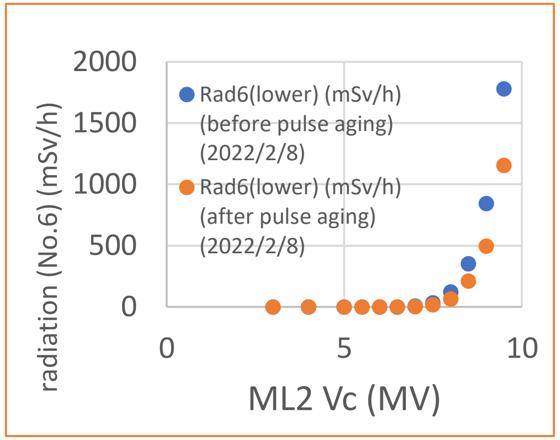
2020.Jun.19
X-ray onset before and after pulse processing、

Main linac performance (long-time Q-value history (2012.Dec – 2023.Dec))





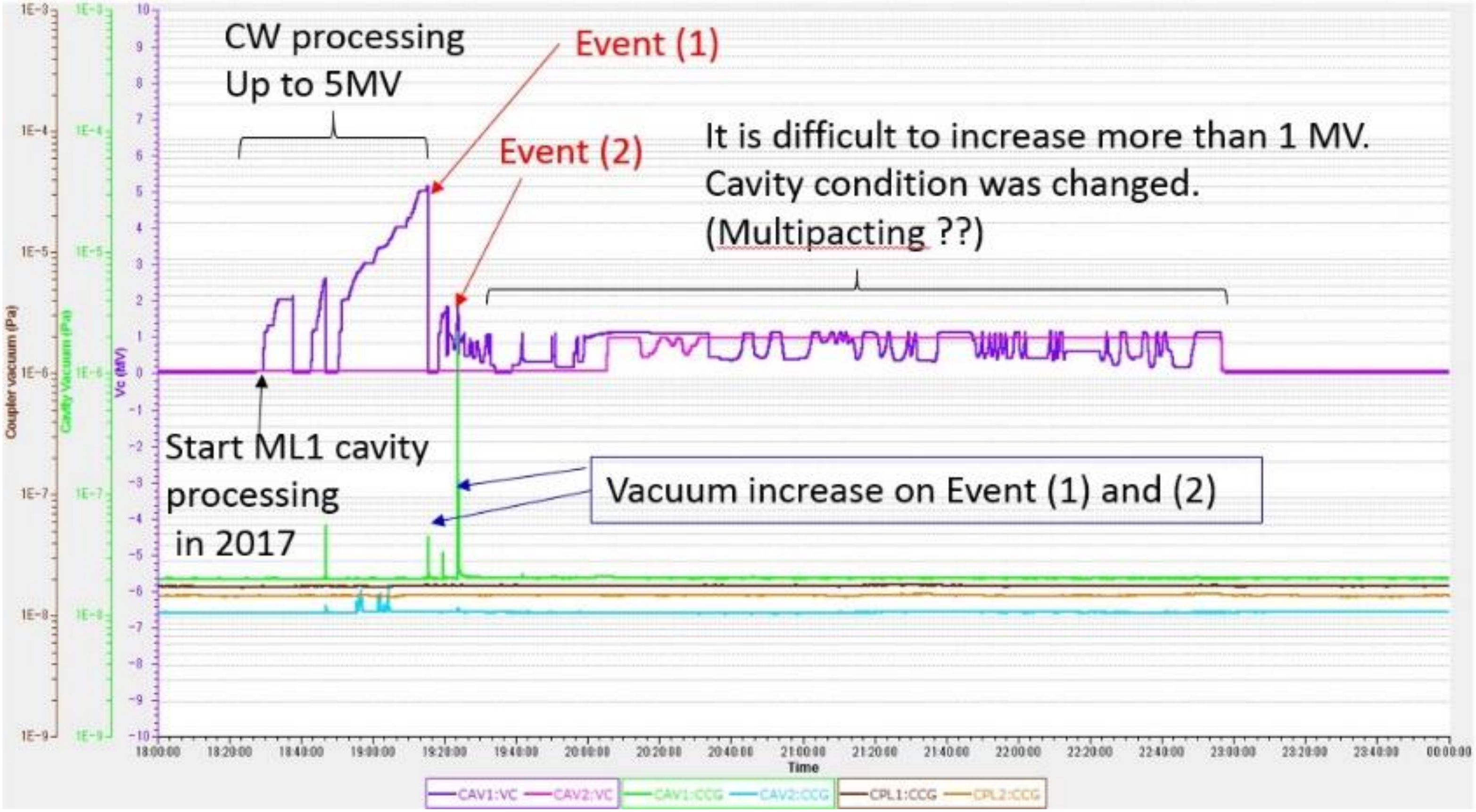
ML Pulse processing (peak 11.7MV)
Vc = 8.8MV(CW) + 2.9MV(pulse 10Hz 4ms) (3 hours apply)



After pulse processing, **0.5 MV onset of x-ray was increased**. X-ray monitor was set at the downstream of cryomodule.

- Before the beam operation, we could keep 1×10^{10} at 10MV on both cavities in 2012.
- Main degradation of ML1 is thermal breakdown from 2017.
- After that, quench limit and Q-values gradually reduced.
- Cavity performance is suffered from field emission. In the latest four years, we kept the same Q-values in both cavities by applying the pulse processing on every cERL operational phase.

Performance degradation on ML1 cavity



- During the conditioning of ML1 cavity before 2017 beam operation, something bad happened.
- After this event, ML1 cavity can not reach more than 7 MV/m.
- If keeping field at some level, Eacc starts to decrease.

→ Thermal quench occur

What is the reason??

-- Seems that lossy material inside cavity

-- A piece of HOM absorber? Discharge at coupler?

H.Sakai et al. "LONG-TERM OPERATION WITH BEAM AND CAVITY PERFORMANCE DEGRADATION IN COMPACT-ERL MAIN LINAC IN KEK" Proc. of LIINAC2018

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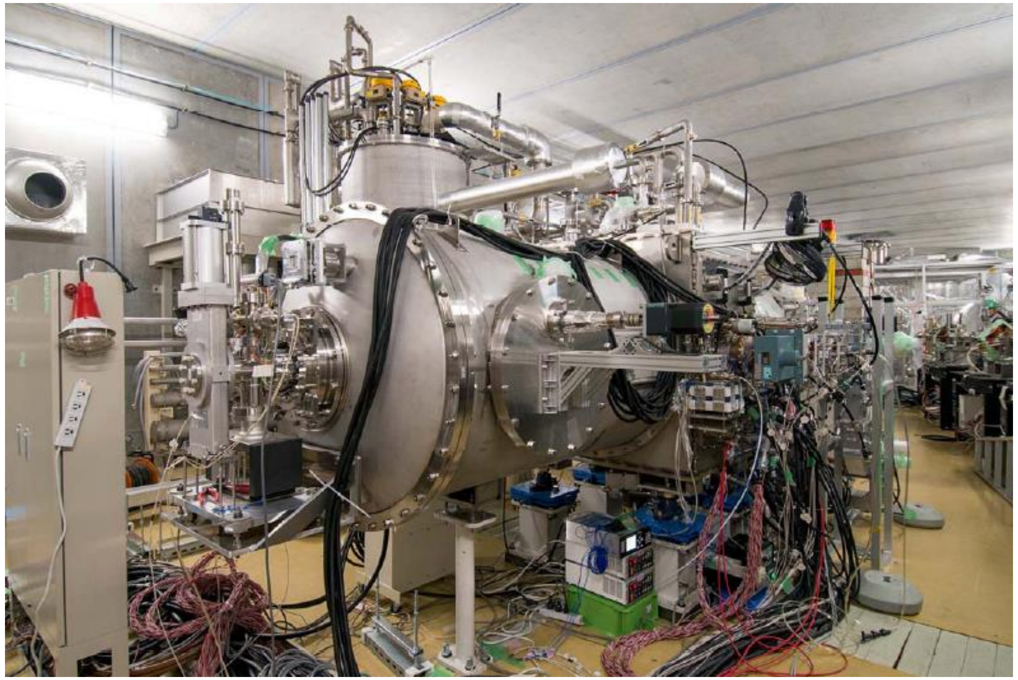
What we learned from current ML cryomodule



- Current Cavity design is too attractive
  - Epeak / Eacc = 3.0 (for strong HOM damping)
  - Risk for field emission
- Current HOM absorber is somewhat risky
  - Crack occur during cooldown
  - Difficult to cleaning before assembly
- Clean assembly procedure was not well enough
  - Our (ML team) first cryomodule assembly and lack of knowledge.
  - Not all dirty components are covered
  - Gate valves exist outside the cryomodule

New cavity design

We want to use this cavity for EUV-FEL!

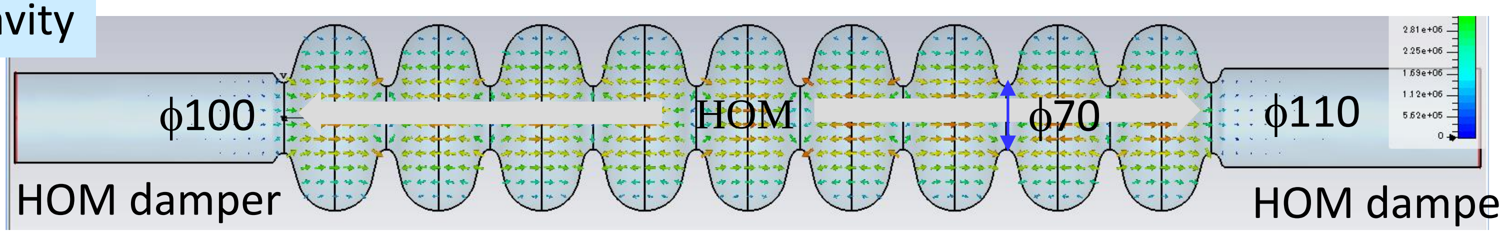
CW operation

How to overcome field emission

TESLA-type 9-cell cavity + Large beam pipes(100ϕ & 110ϕ)

Only end cell was modified to match the impedance to beam pipe.

EUV cavity



Details are published in *"Damped superconducting structure for EUV light source based on energy recovery linac "* *Taro Konomi at al.* *Physical Review Accelerators and Beams 26(12) 1-14 (2023)*

HOM damped type (for 10 mA ERL operation)

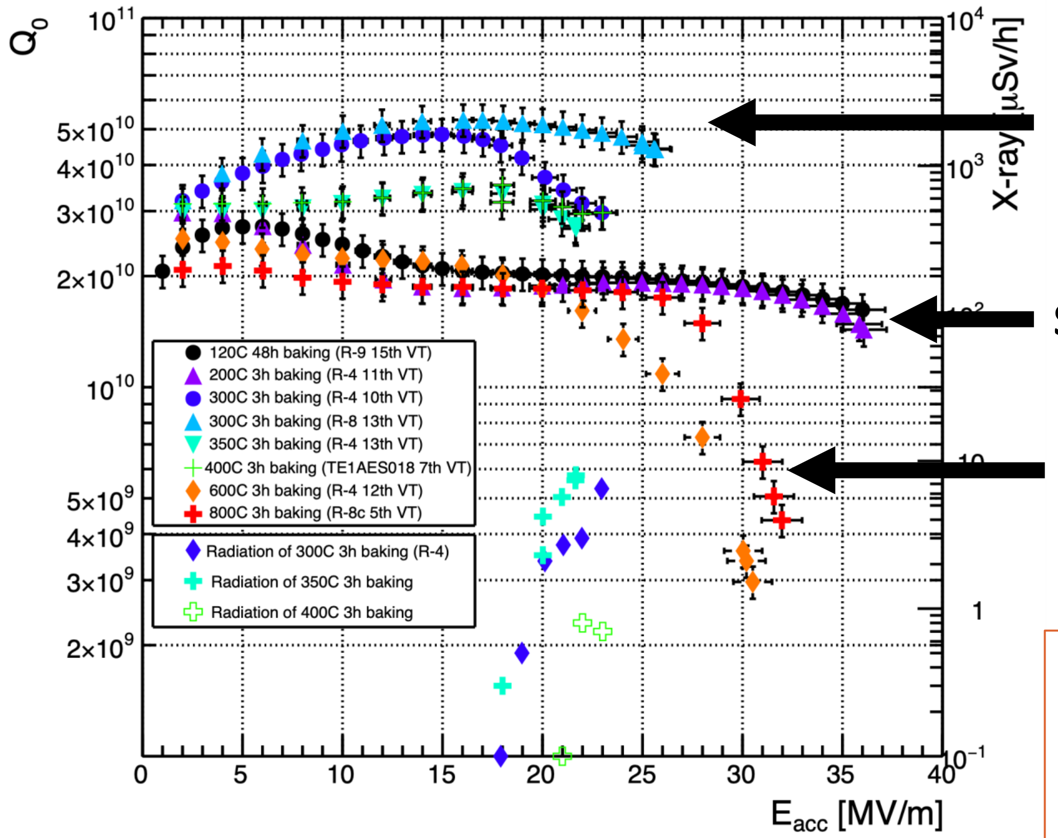
Parameters for acceleration mode

	cERL	EUV		cERL	EUV
Frequency	1300 MHz	**1300 MHz**	Iris diameter	80 mm	70 mm
R_{sh}/Q	897 Ω	**~1000 Ω**	$Q_o \times R_s$	289 Ω	∼270 Ω
E_p/E_{acc}	3.0	**~ 2.0**	H_p/E_{acc}	42.5 Oe/(MV/m)	∼42.0 Oe/(MV/m)

If Qo is 1x10^10
22 W per cavity will be produced under 15MV/m
→ If Q0 is 3x10^10
→ 7 W/cavity unde 15MV/m
High-Q is very important

High-Q technology (Mid-T baking, mag. shield)

Mid-T furnace baking



T. Ito et al, "Influence of furnace baking on Q–E behavior of superconducting accelerating cavities"
https://doi.org/10.1093/ptep/ptab056

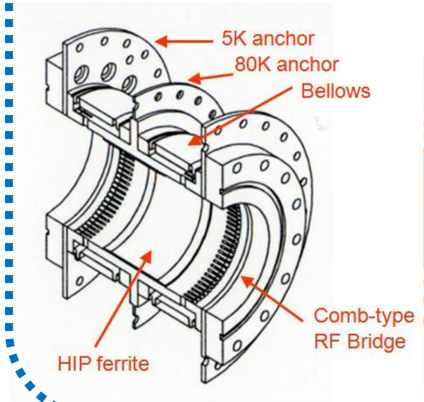
Apply mid-T baking to achieve high-Q operation

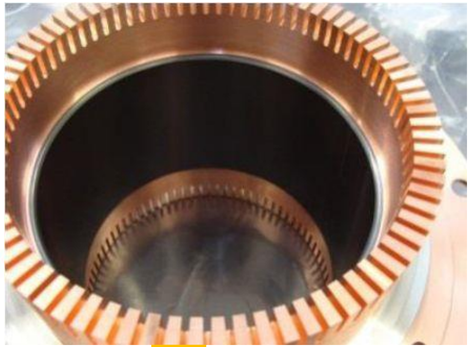
High-Q operation of SRF cavities

- Mid-T baking for cryomodule operation
- Qo ~ 3e10 @ 15 MV/m
- Not only surface treatment but also design of magnetic shield are very important.

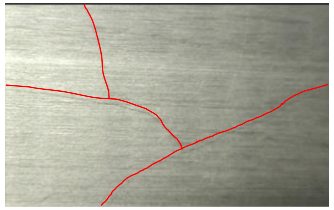
HOM absorber based on AlN

Current cERL HOM damper





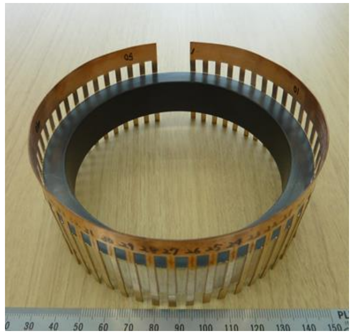
Ferrite with HIP bonding



Fragile under thermal cyle

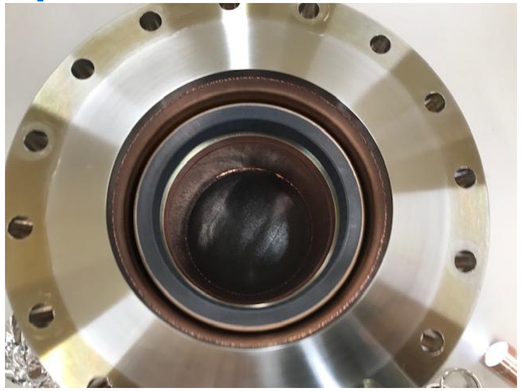
New HOM absorber with AlN development

AlN cylinder Brazing test

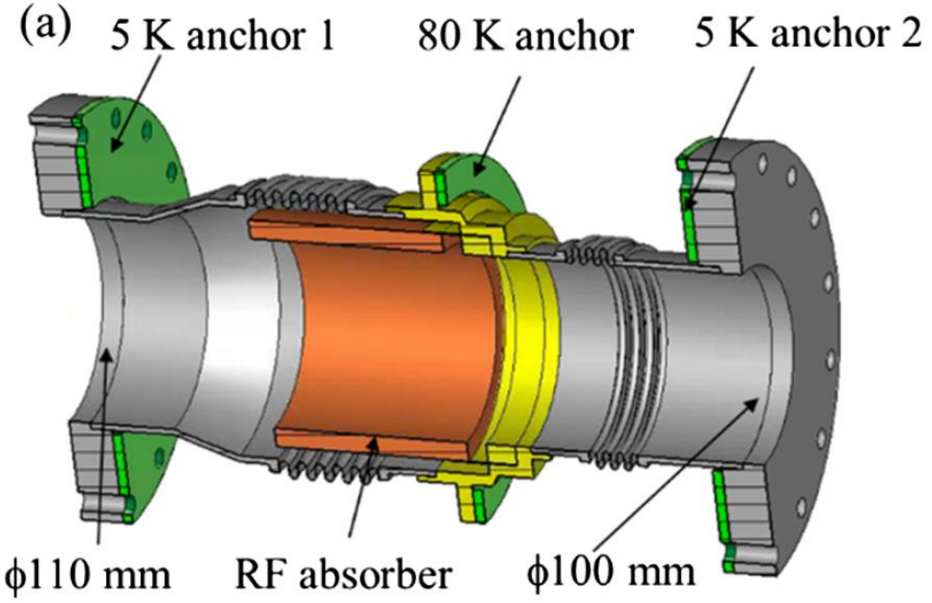


T. Ota, et. al. SRF workshop 2019

Welding test with AlN cylinder



- AlN has good absorption of higher component
  with liq.N2 condition
- Low outgassing in vacuum
- Brazing of AlN with copper is OK for liq. N



Clean assembly technique

- Apply all clean assembly technique, which we have learned after the ML cryomodule assembly.
- Slow pump and purge system
- Clean gate valve and position of gate valve
- Robotics/automation(?)

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- cERL injector and main linac SRF cryomodule have operated more than 10 years.
- Both cryomodules have been suffered from field emission.
- Pulse processing have been applied to suppress field emission.
- Abnormal heat load is also observed at main linac cavity. Some lossy material is suspected.
- We have designed new cavity and HOM absorbers. If there is a chance, we would like to renew the main linac cryomodule.