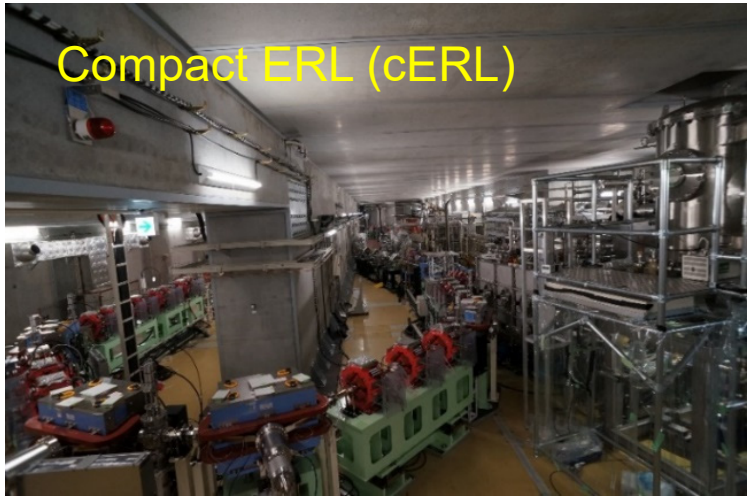
KEK ERL SRF operational experience

Hiroshi Sakai (KEK) (on behalf of cERL SRF development team)

- Introduction of cryomodule
- Cryomodule performance of cERL (ML)
- Operational experience of cERL cryomodule
- Summary



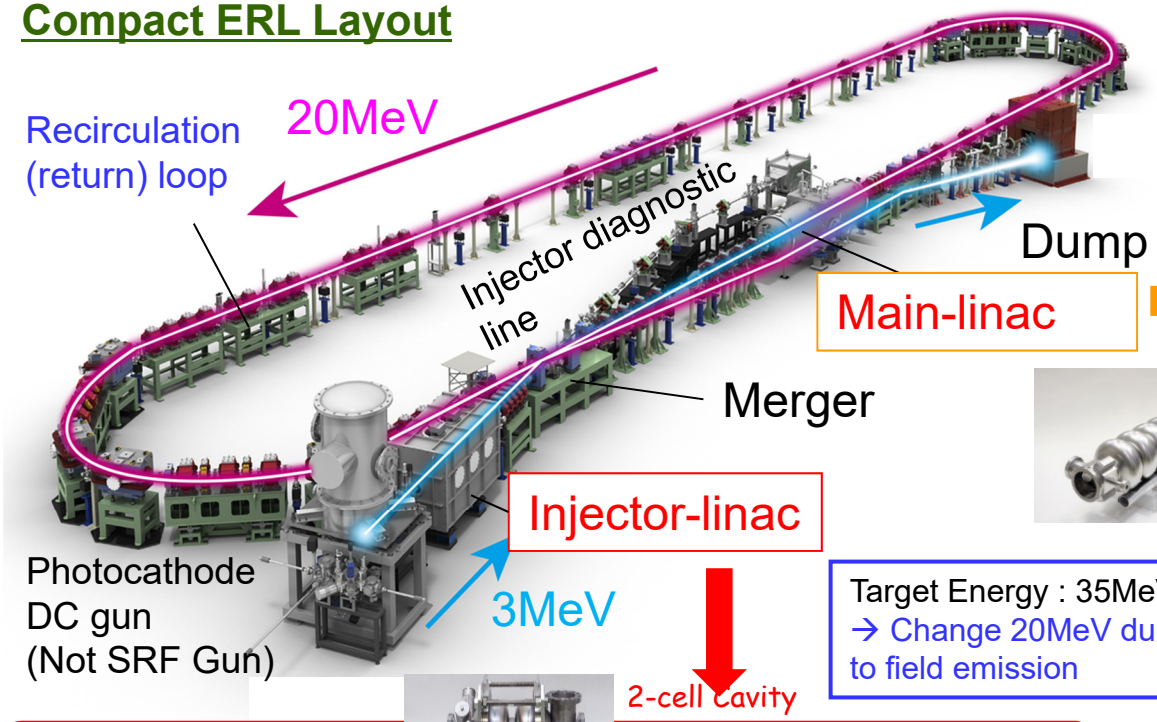
Compact ERL (**cERL**) has been constructed in 2013 at KEK to demonstrate energy recovery with low-emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL & CW-FEL.
→ In addition, Industrial application start in 2017

20min. + 5min.

21 pages

Comact ERL (cERL) in KEK & cERL cryomodules

Compact ERL Layout



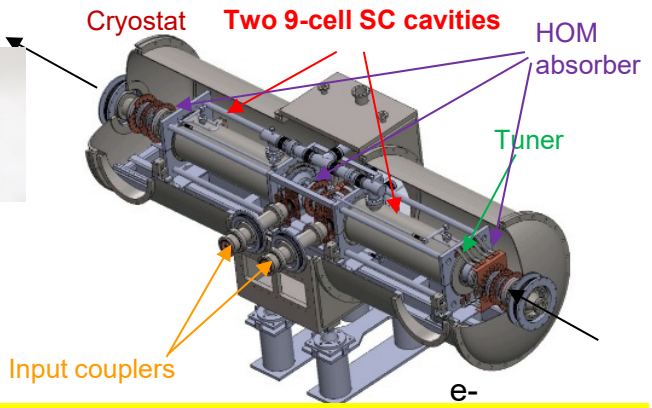
Target Energy : 35MeV
→ Change 20MeV due to field emission

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: $Q_0 > 1\times10^{10}$



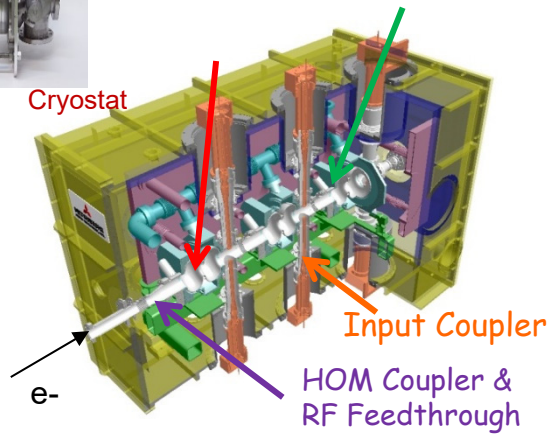
Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

Injector module

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: $Q_0 > 1\times10^{10}$



Recent Injector performance is shown in E. Kako, "Degradation and Recovery of Cavity performance in Compact-ERL injector cryomodule at KEK" (Thu)

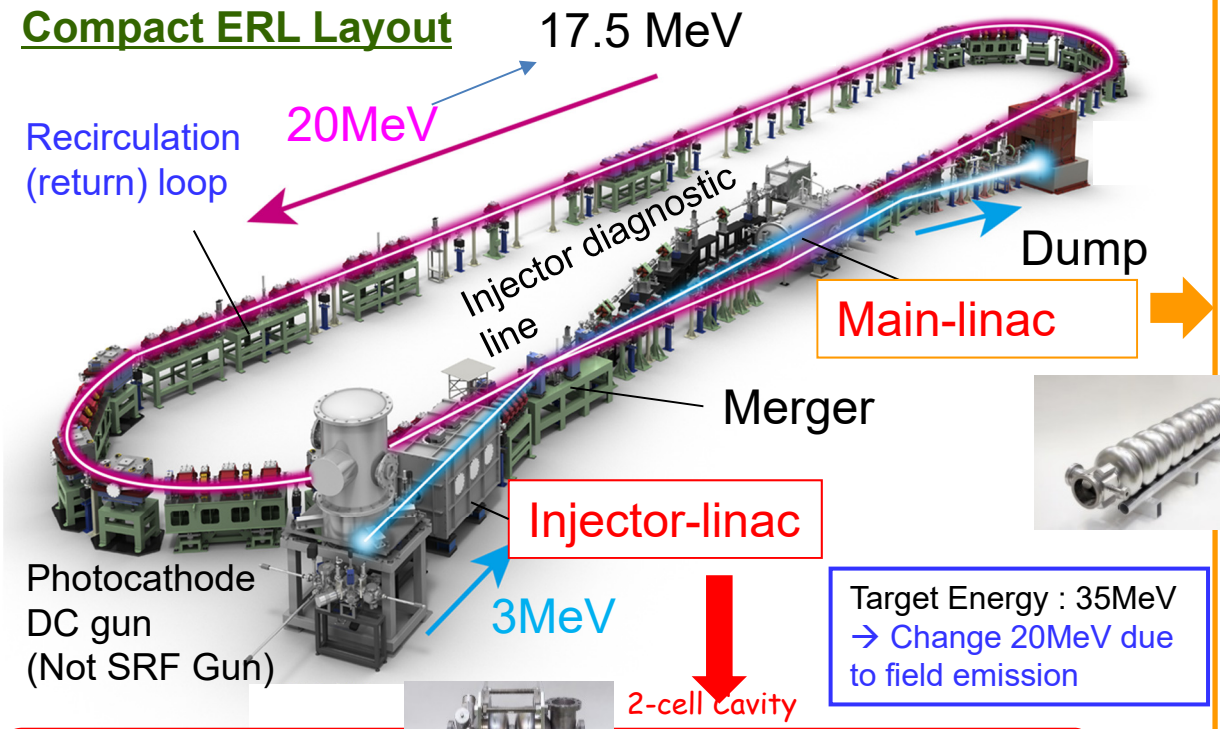
We mainly talk about Main linac performance today.

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV
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)

Comact ERL (cERL) in KEK & cERL cryomodules

Compact ERL Layout



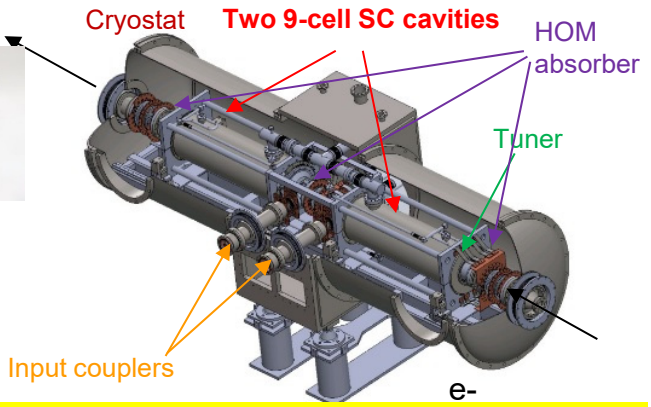
Target Energy : 35MeV
→ Change 20MeV due to field emission

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: $Q_0 > 1\times10^{10}$



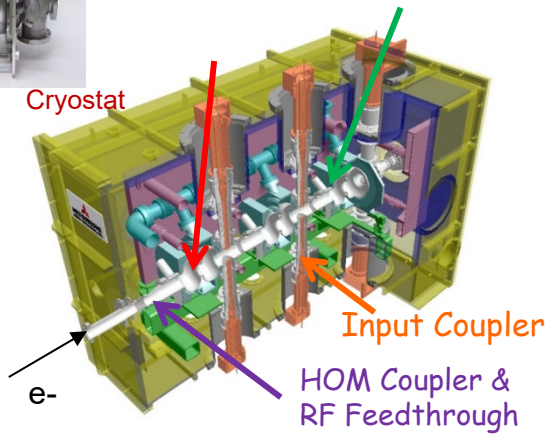
Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

Injector module

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: $Q_0 > 1\times10^{10}$



Recent Injector performance is shown in E. Kako, "Degradation and Recovery of Cavity performance in Compact-ERL injector cryomodule at KEK" (Thu)

We mainly talk about Main linac performance today.

Design parameters of the cERL

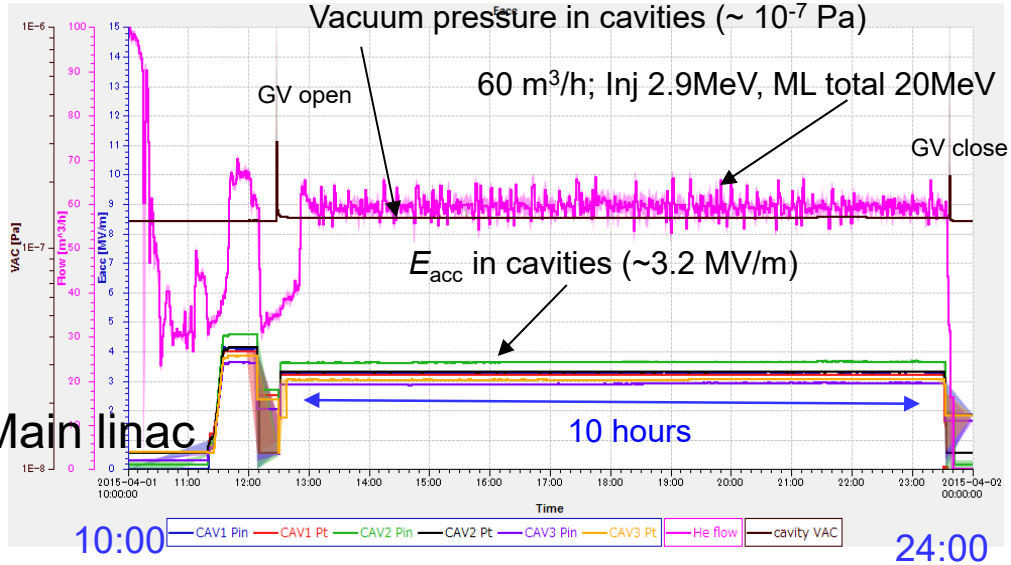
Nominal beam energy	35 MeV → 20MeV
Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

One day profiles of both injector & main linac cryomodule operation (2015.Apr.1)

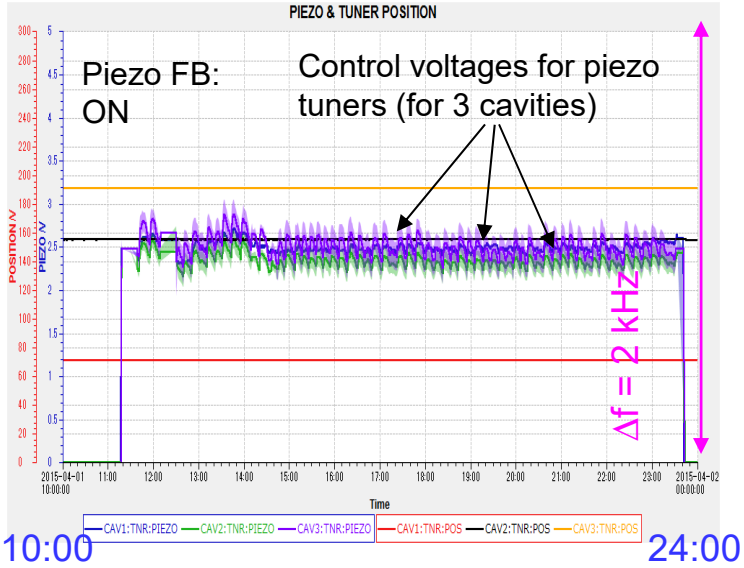
Injector

Basically, Injector & main linac was stably operated by using low level control with piezo tuner

Field & Vac & loss

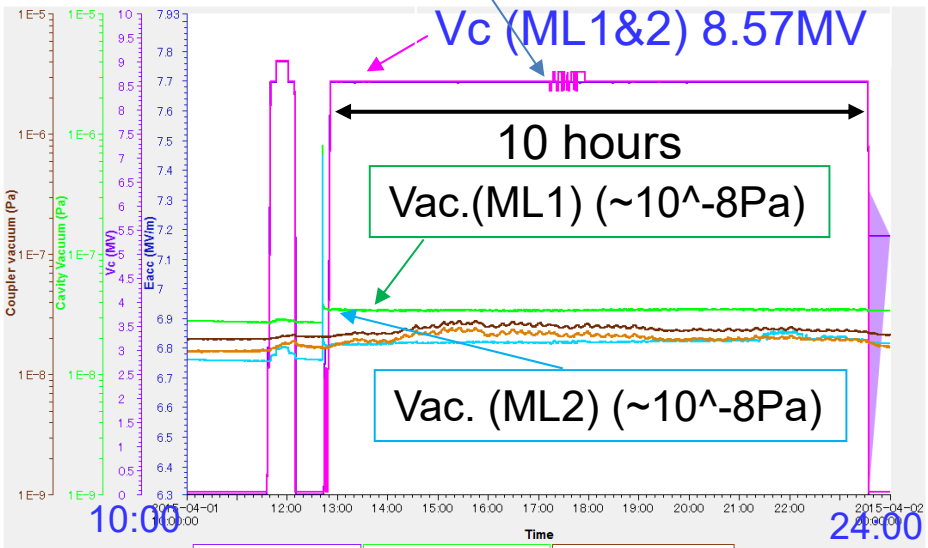


Piezo tuner



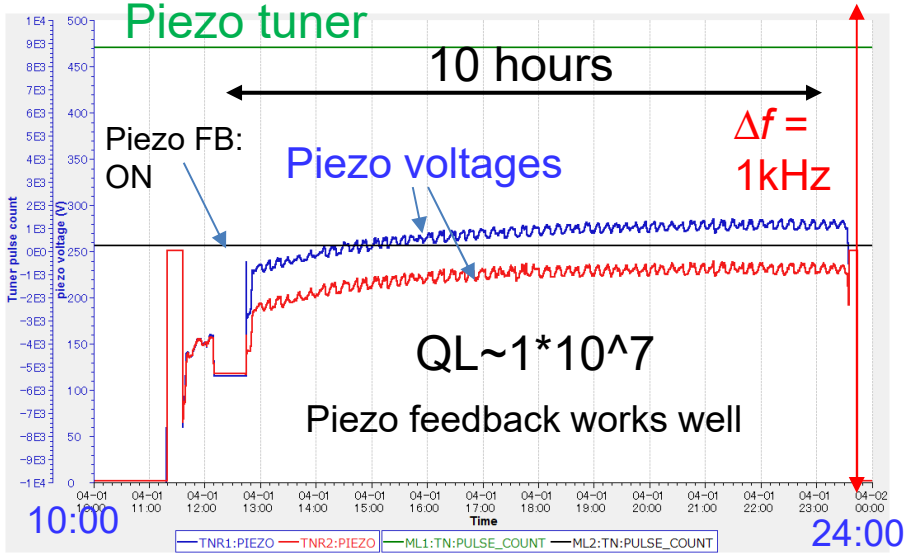
This fluctuation come from dispersion measurement

Field & Vac



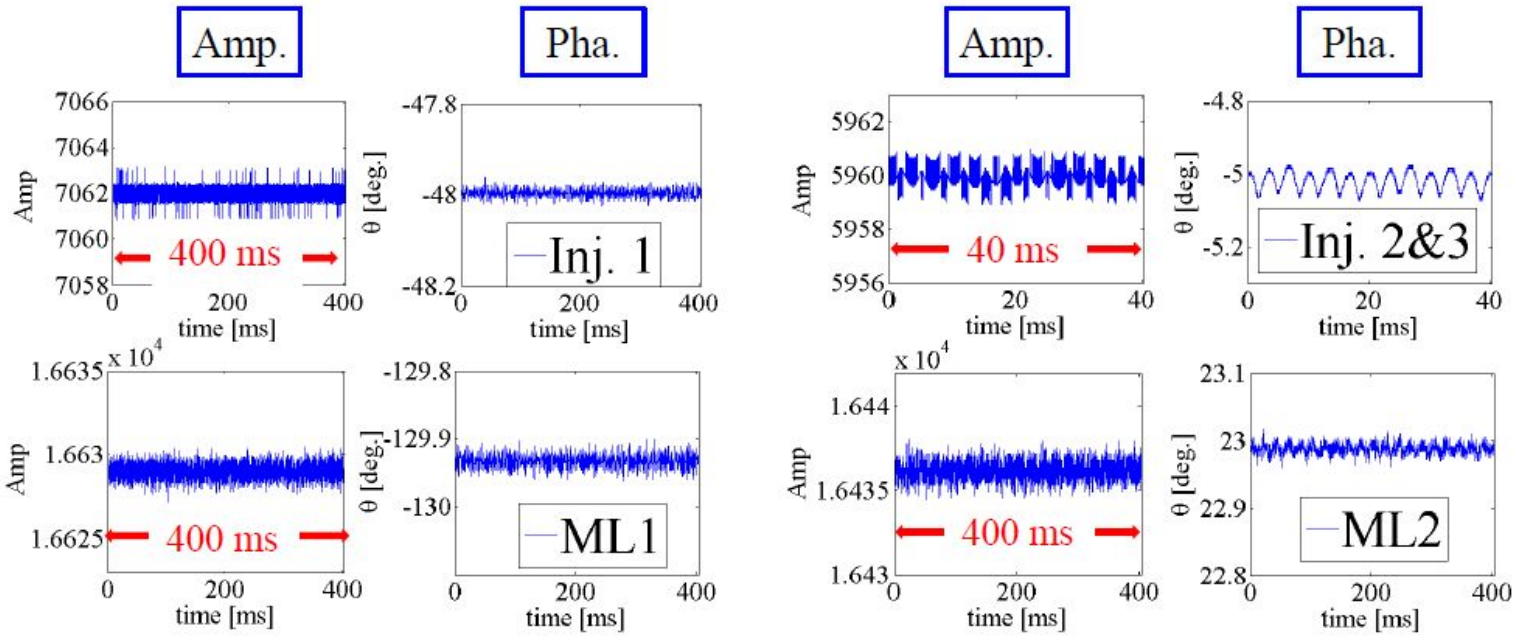
Piezo drift caused from 4K to 2K cooling at morning.

Piezo tuner



Power & LLRF stability in cERL beam operation

Satisfy our requirements of ΔA/A < 0.01% , Δθ ~ 0.01 deg for cERL operation. Suppress michrophonics.



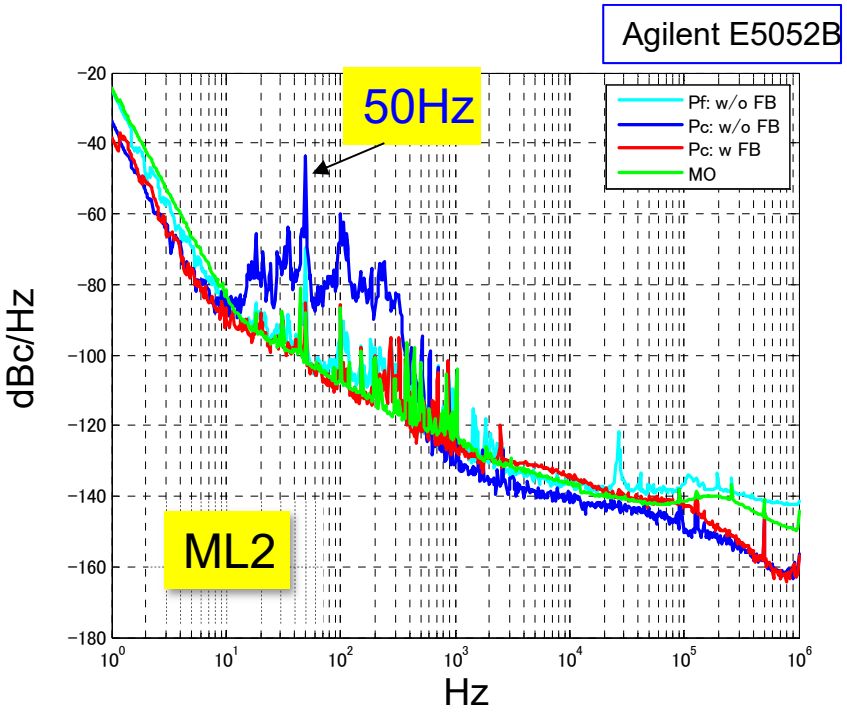
FPGA
Virtex5-FX

Beam stability was also achieved within 0.01% by measuring momentum jitter at screen monitor on arc section thanks to LLRF optimization

SC Cavity	Inj1(2cell)	Inj2(2cell)	Inj3(2cell)	ML1(9cell)	ML2(9cell)
Acc. Field	3.2MV/m	3.3MV/m	3.0MV/m	8.3MV/m	8.3MV/m
power	0.53kW	1.4kW	1.0kW	1.6kW	2kW
Power source	25 kW klystron	300kW klystron (Vector sum)		16 kW solid state Amp	8kW solid state Amp
QL	1.2e6	5.8e5	4.8e5	1.3e7	1.0e7
ΔA/A(% rms)	0.006%	0.007%		0.003%	0.003%
Δθ(deg rms)	0.009deg	0.025deg		0.010deg	0.007deg

Microphonics suppression in ML (Phase noise jitter measurement using Signal Source Analyzer)

T. Miura, IPAC2014 @Dresden



Vc Phase Noise with RF FB (10Hz-1MHz)=0.017deg

Vc Phase Noise w/o RF FB (10Hz- 1MHz)=0.73 deg

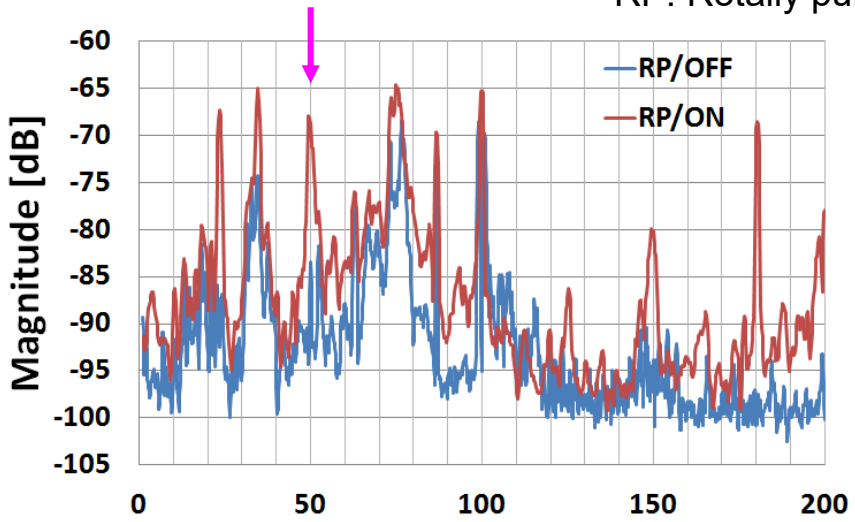
Microphonics is observed at 10 Hz - 400Hz.

Phase noise by Microphonics was suppressed well by RF FB.
Phase noise of Vc with FB was almost the same as that of Master Oscillator.

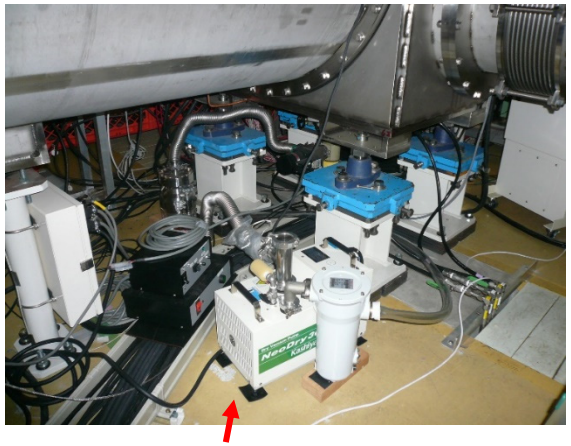
F. Qiu, "Characterization of Michrophinics in the cERL main linac superconducting cavities" (Tue)

Vibrational state of "floor" around Main Linac

RP: Rotally pump



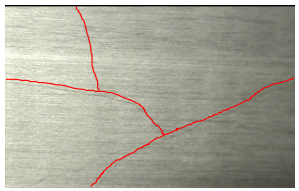
M.Egi, IPAC2014



The rubber sheet was inserted under the scroll pump.
The 50 Hz vibration is suppressed.

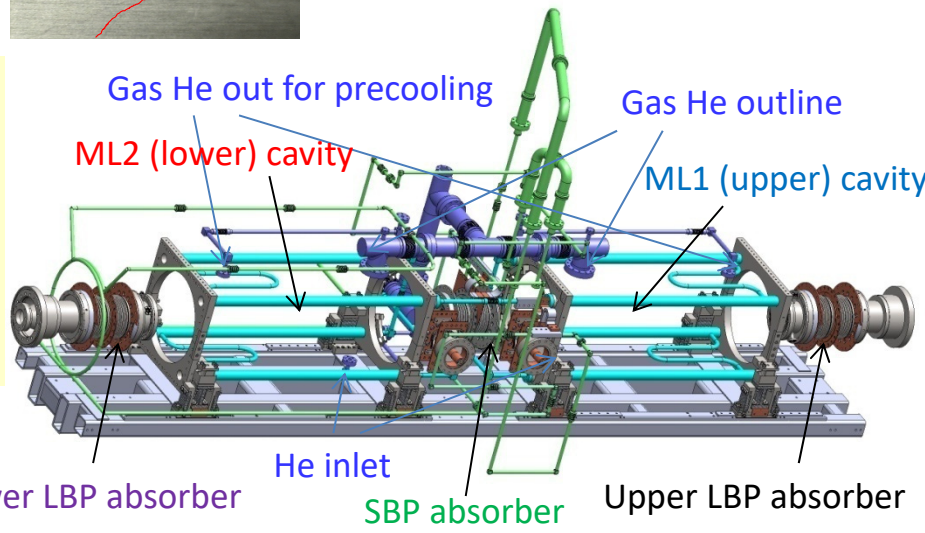
Cooling procedure to 2K

We saw some crack at HOM damper when cooling speed is fast



Cooling pipe configuration

Green : 80K line
Blue : 2K line
Light bule : 5K line



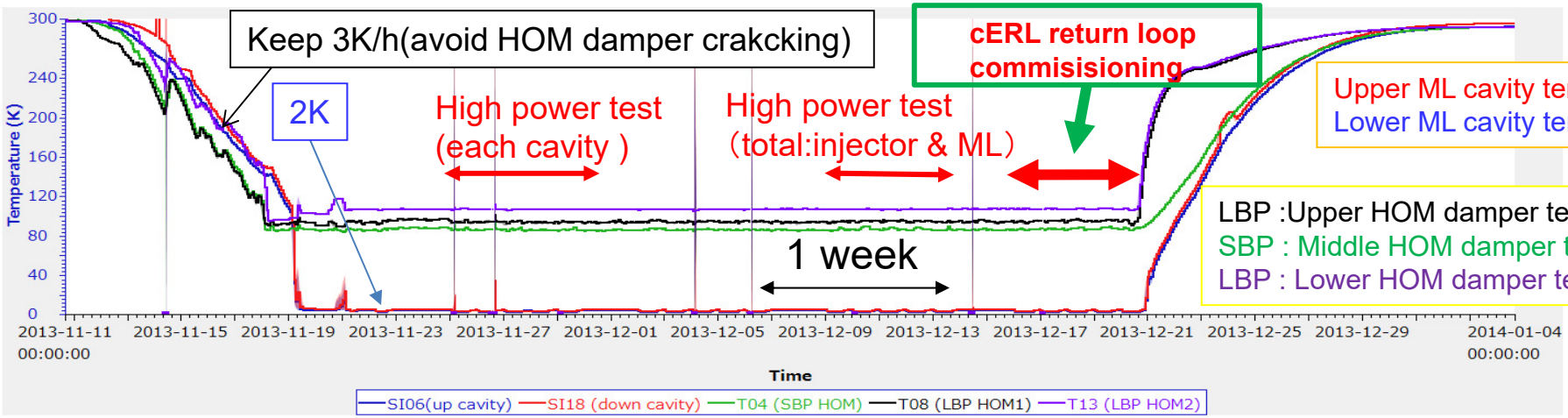
Strategy of cooling (mainly Main linac)

- Keep 3K/h at 80 K not to break HOM damper
- 2K, 5K(He) and 80K(N_2) line need to keep ΔT < 50K condition to
- fast cooling down from 150 K to 2 K to avoid Q-disease.

Injector was cooled at same time.

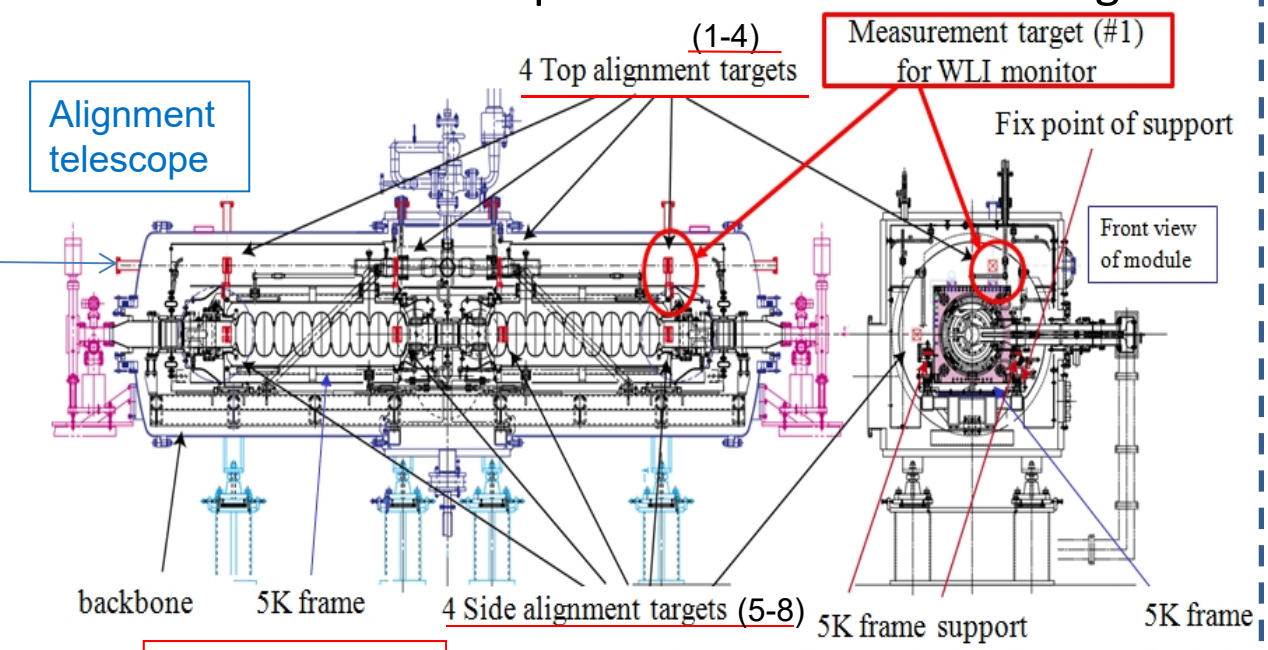
History of 2K cooling

History of cooling (2013.Nov.-Dec.)



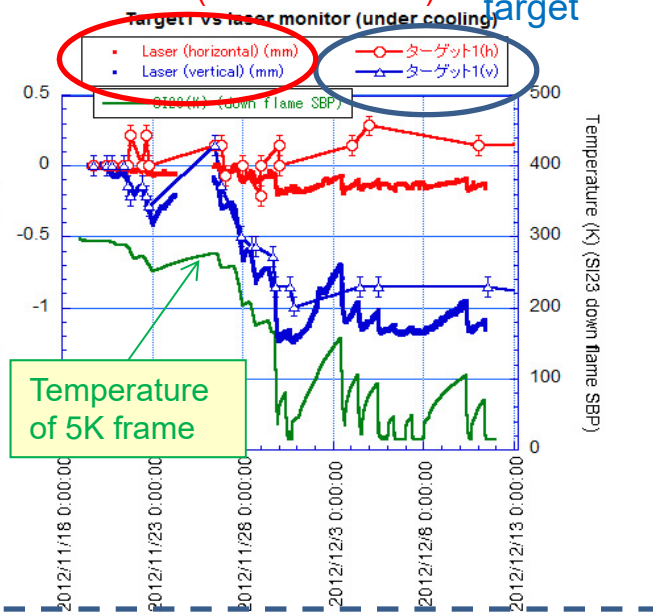
3 weeks keep 2K cooling (1 weeks for Low level measurement and 2 weeks for High power test)

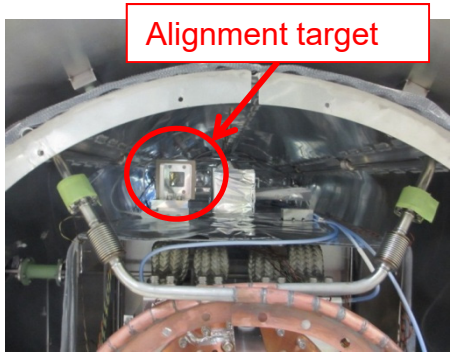
Measurement of displacement unde 2K cooling



H.Sakai et al., MOP069 in SRF2013

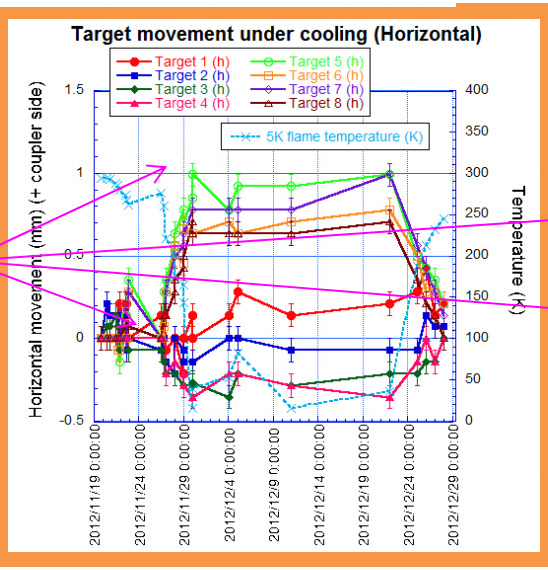
WLI monitor (10um reslution)

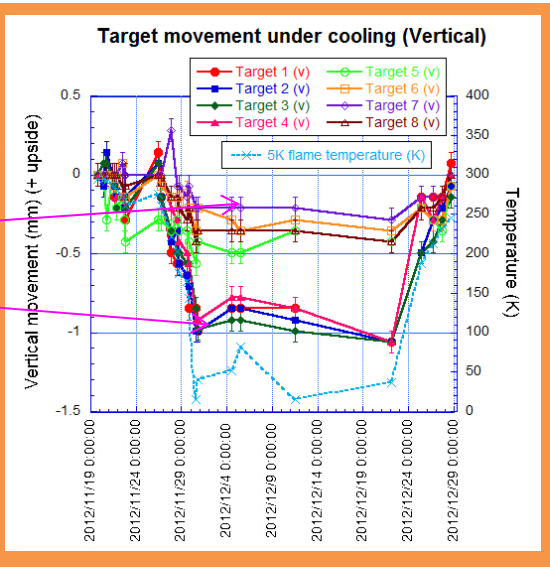




Measured displacements of targets

Move same way with targets at same transverse position

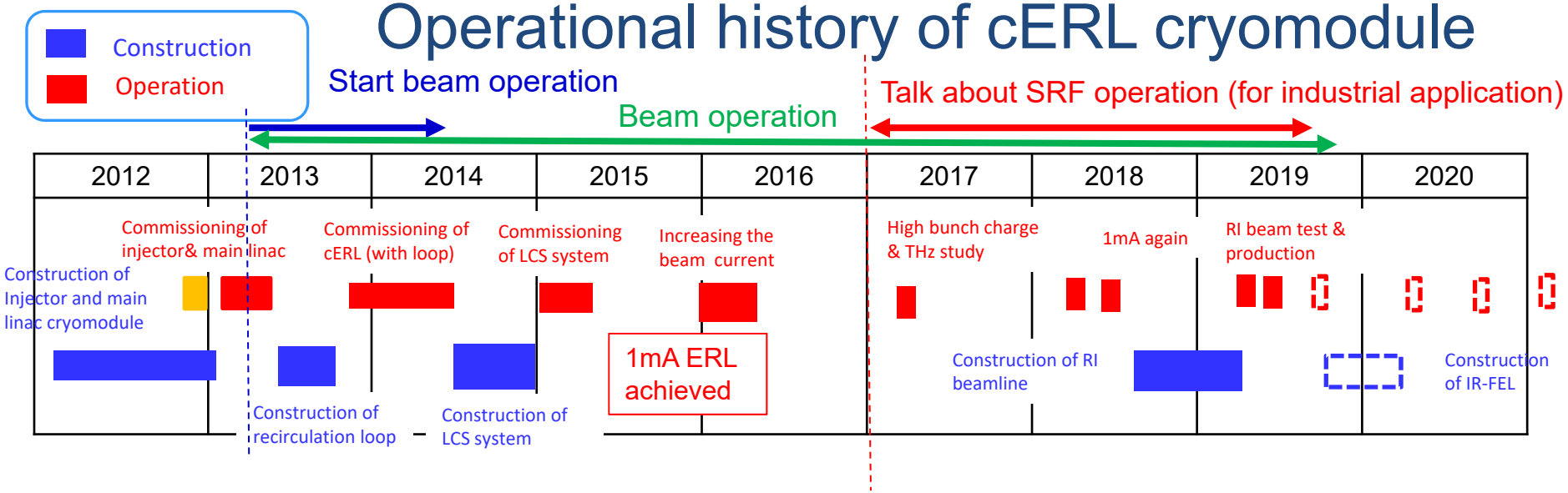




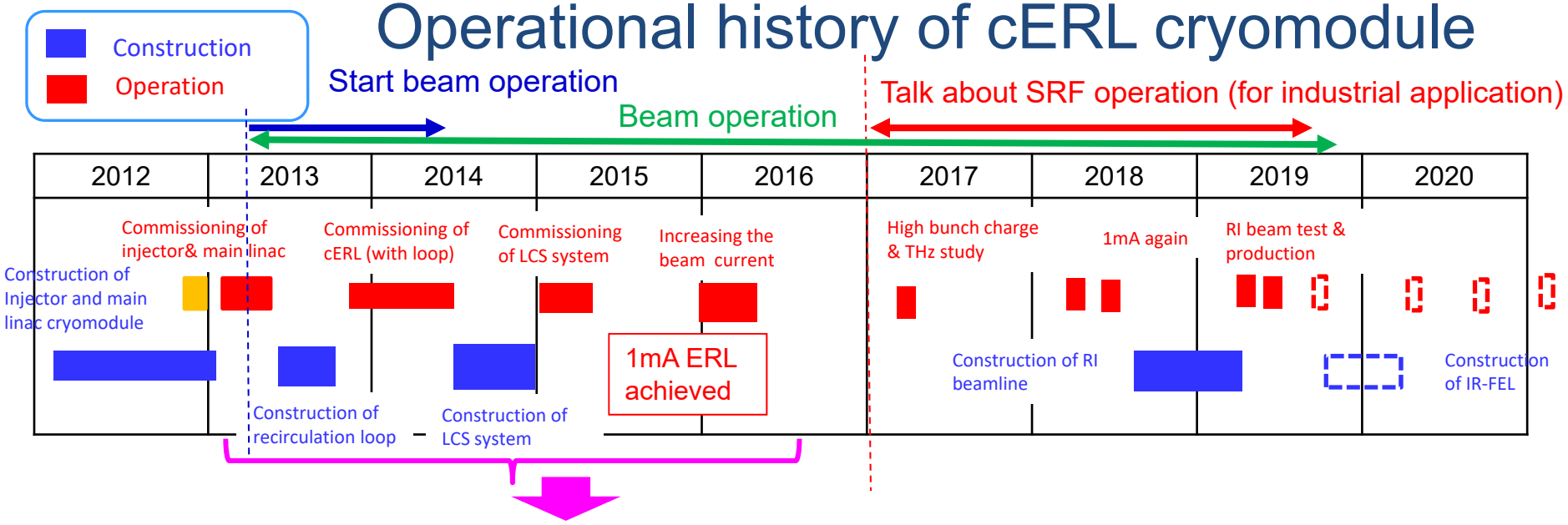
Summary of displacements of targets and cavities between RT to 2K	Horizontal (mm)	Vertical (mm)
Target 1-4 (Average)	-0.2	-0.9
Target 5-8 (Average)	1.0	-0.3
Average movement of cavity center (from target 5-8)	0.4	-0.3

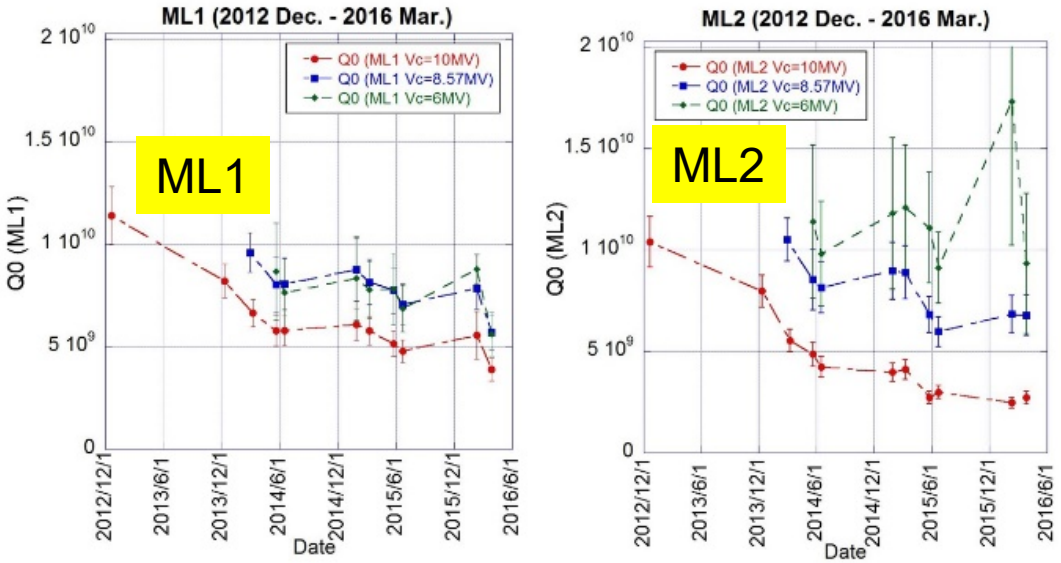
- About 0.4mm of cavity center movement was evaluated horizontally and vertically , which agreed with expected values of thermal shrink of 5K supports.
- These vales were within alignment error from beam requirement of 1mm.

Operational history of cERL cryomodule



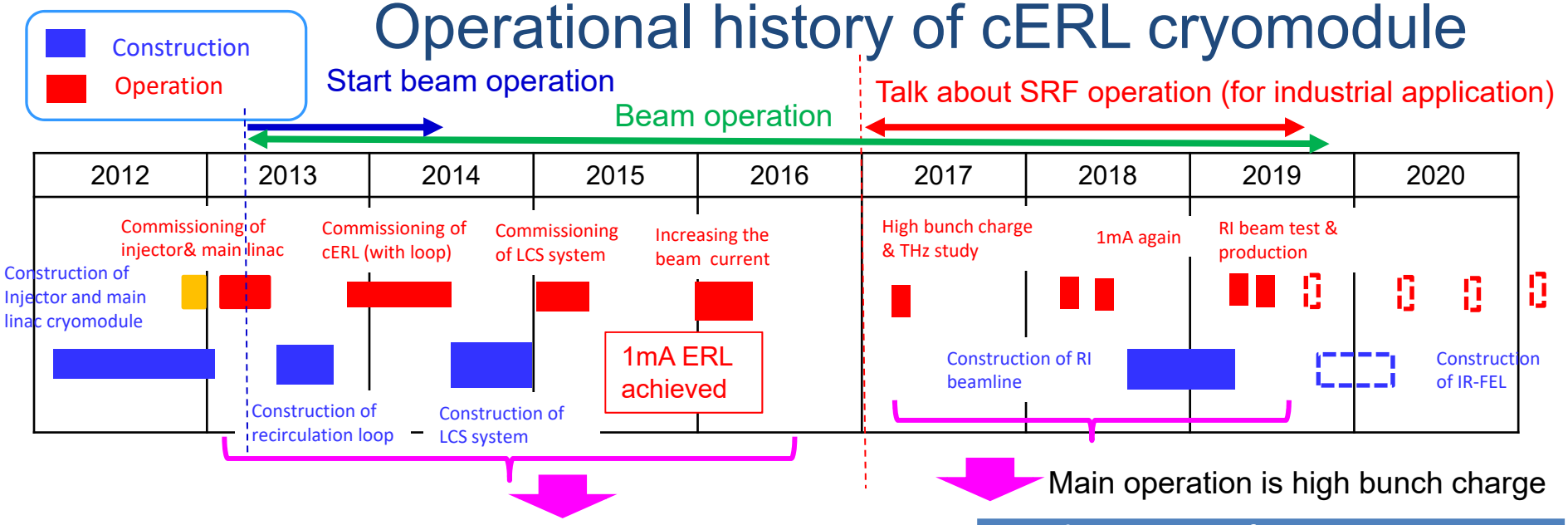
Operational history of cERL cryomodule

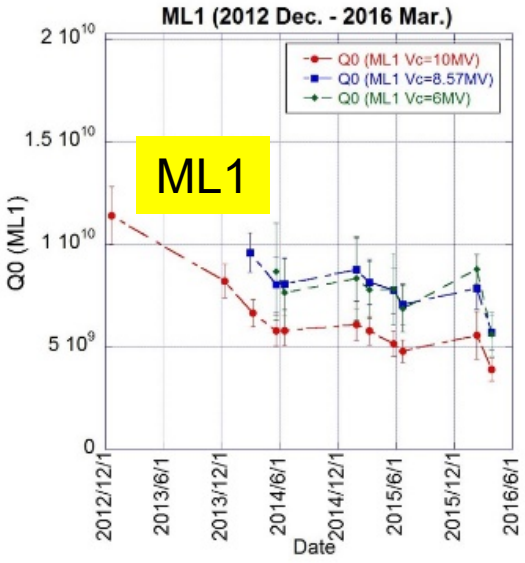


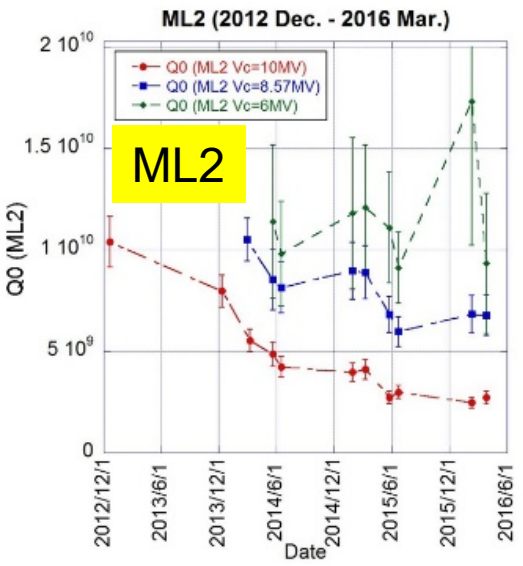


We met Q degradation during beam operation.
Main reason is field emission from 2012 to 2016.

Operational history of cERL cryomodule





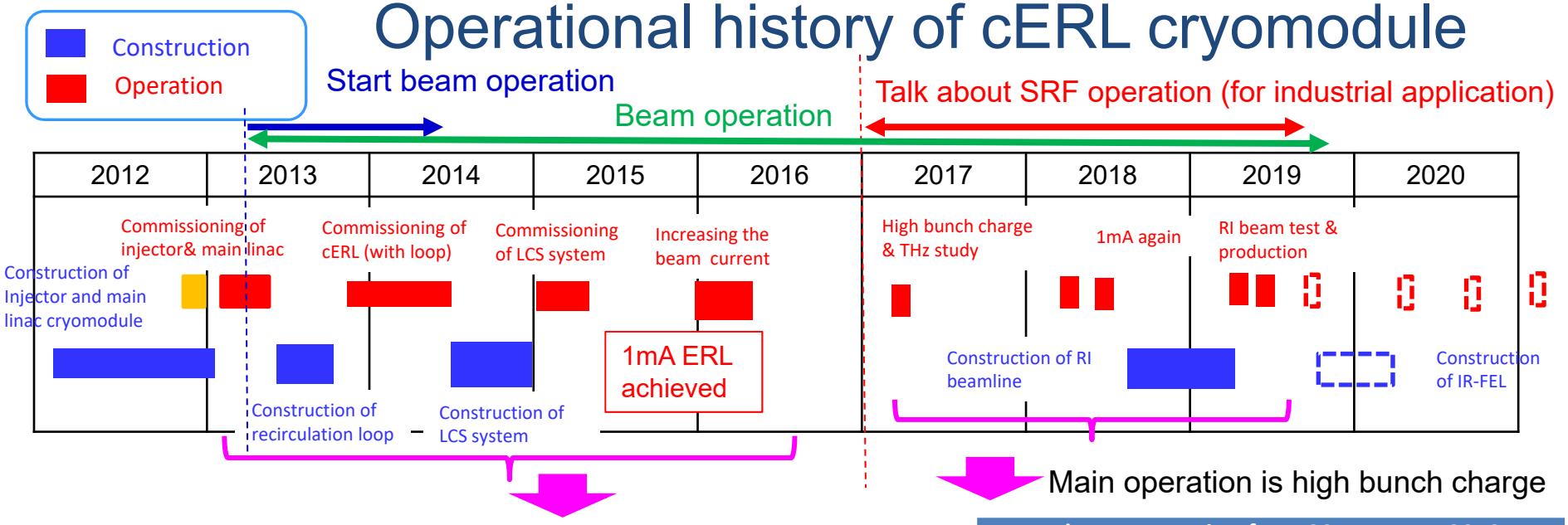


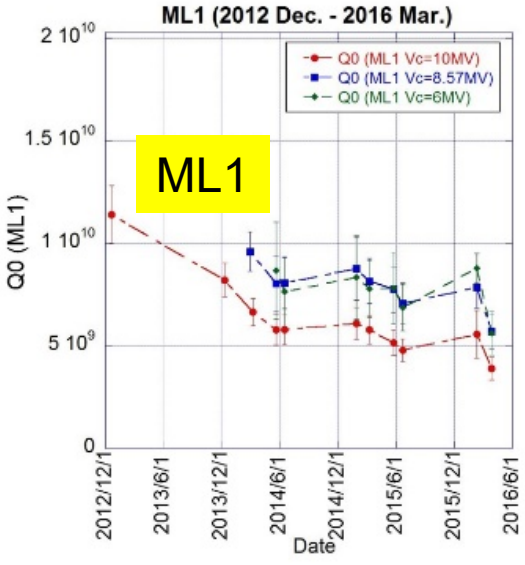
cERL beam operation from 2017 to Jun. 2019		
Period (operation time)	Energy [MeV] Comment)	Current [mA]
2017.Mar. (3 weeks)	(20→) 17.5 (degradation)	60 pC/ bunch
2018.Mar. (2 weeks)	17.5	60 pC/ bunch
2018.Jun. (4 weeks)	17.5	60 pC/ bunch & 1 mA (CW)
2019.Apr. (4 weeks)	17.5	60 pC/ bunch
2019.Jun. (4 weeks)	17.5→19.5 (3.5 kPa operation)	60 pC/ bunch & CW beam (<10μA)

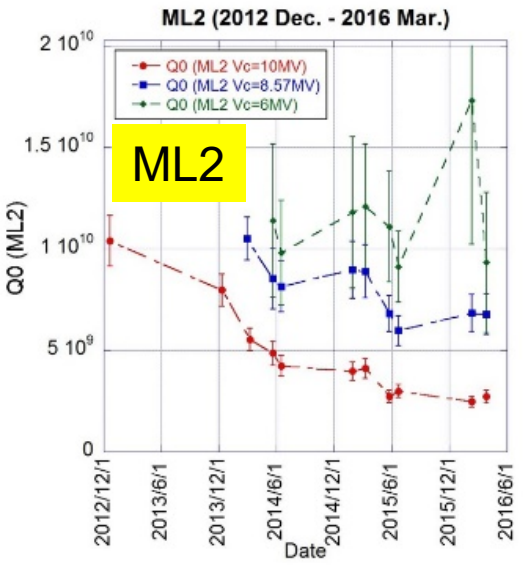
We met Q degradation during beam operation.
Main reason is field emission from 2012 to 2016.

But from 2017 ML1 did not reach more than 7MV after unknown burst event.

Operational history of cERL cryomodule







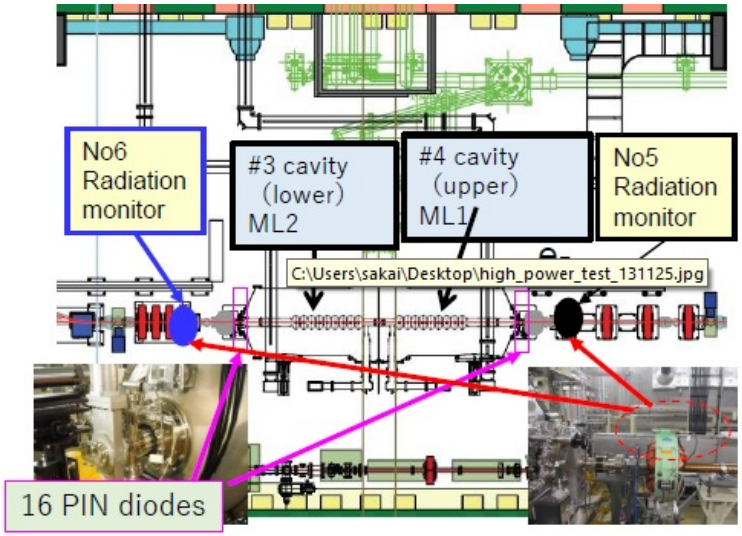
cERL beam operation from 2017 to Jun. 2019		
Period (operation time)	Energy [MeV] Comment)	Current [mA]
2017.Mar. (3 weeks)	(20→) 17.5 (degradation)	60 pC/ bunch
2018.Mar. (2 weeks)	17.5	60 pC/ bunch
2018.Jun. (4 weeks)	17.5	60 pC/ bunch & 1 mA (CW)
2019.Apr. (4 weeks)	17.5	60 pC/ bunch
2019.Jun. (4 weeks)	17.5→19.5 (3.5 kPa operation)	60 pC/ bunch & CW beam (<10μA)

We met Q degradation during beam operation.
Main reason is field emission from 2012 to 2016.

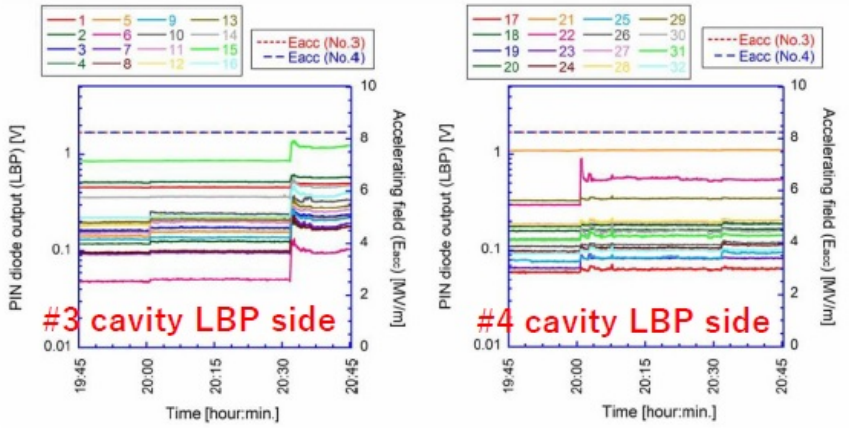
But from 2017 ML1 did not reach more than 7MV after unknown burst event.

What happened in long term beam operation ? And how to keep cavity performance ?

Radiation profiles by field emission during beam operation



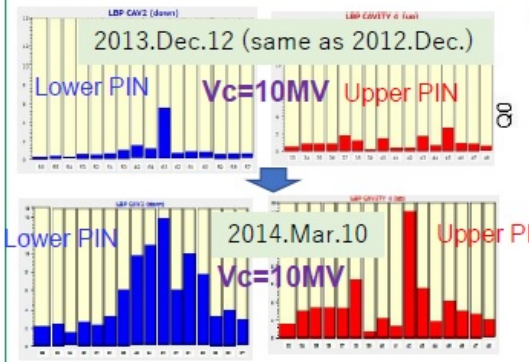
Example of sudden jump of radiation signals detected by PIN diodes, during beam operation (No correlation with beam)

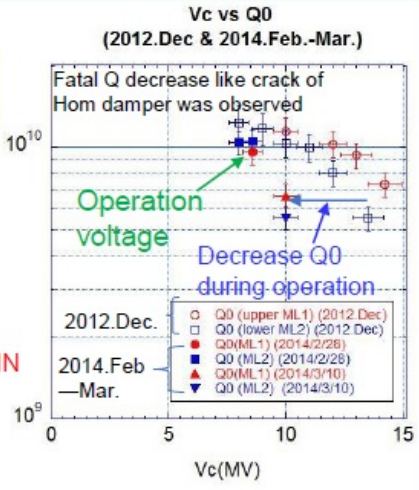


Fixed PIN diodes can observe change of radiation distribution.
We could find some hint from the distribution,
- -- New emitter coming?
- -- Existing emitter become worth?
- -- How's status of processing?
- -- Can do correlation study with beam etc.

Q degradation & change of PIN diodes

We met Q degradation during beam operation.
PIN profile were also increased totally.

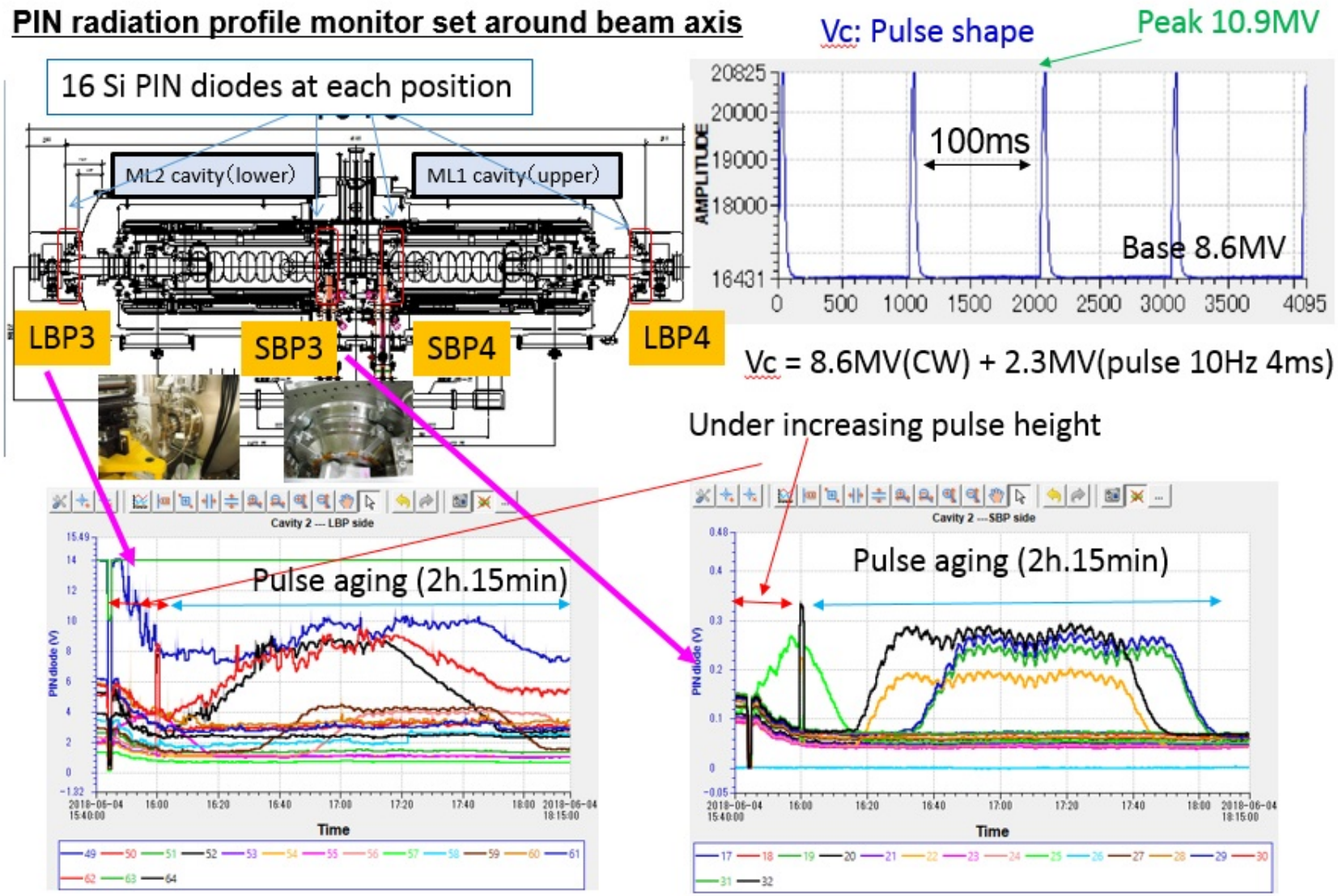




Field emission increased during long-term beam operation
Some particulates come into the cavity from outside during beam operation ??
We applied pulse processing to keep cavity performance.

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)

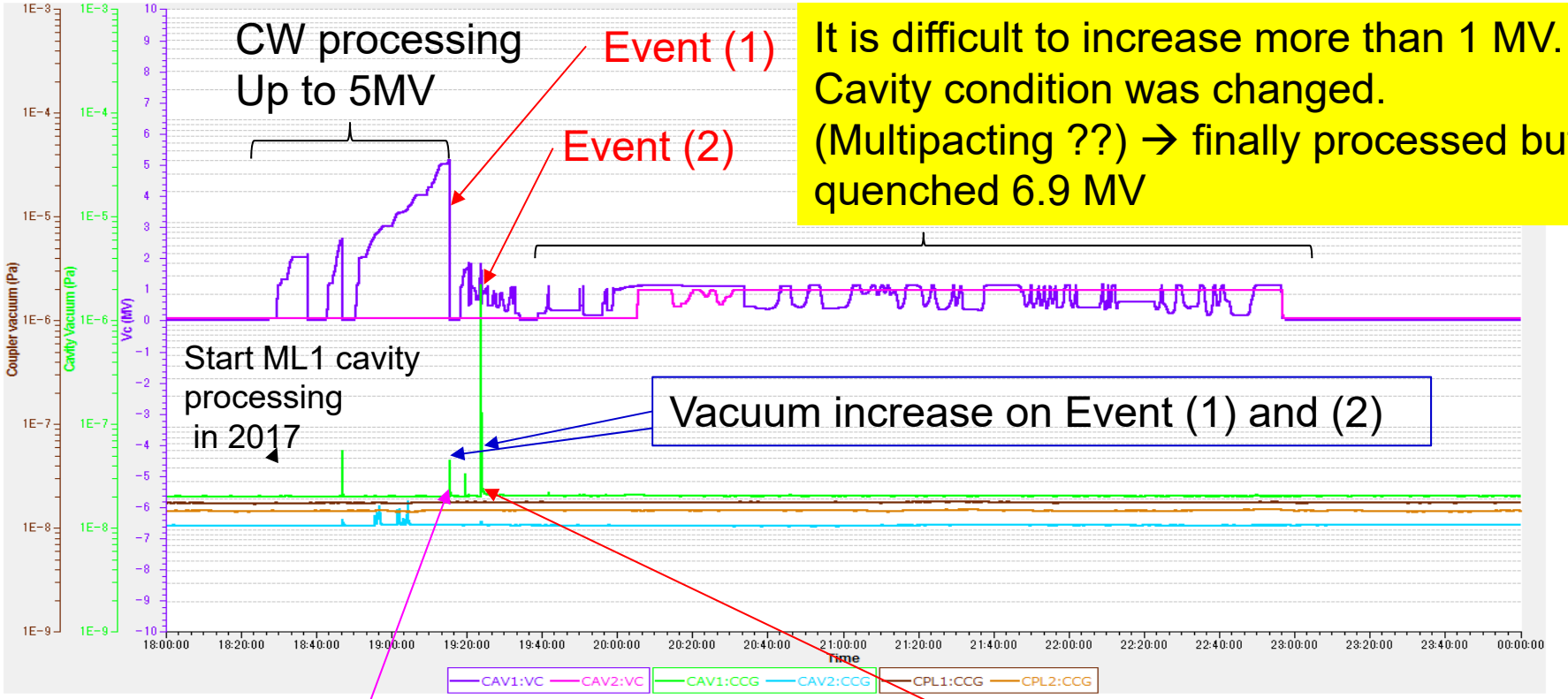
Pulse processing of ML2 cavity in 2018.Jun. (Normal processing)

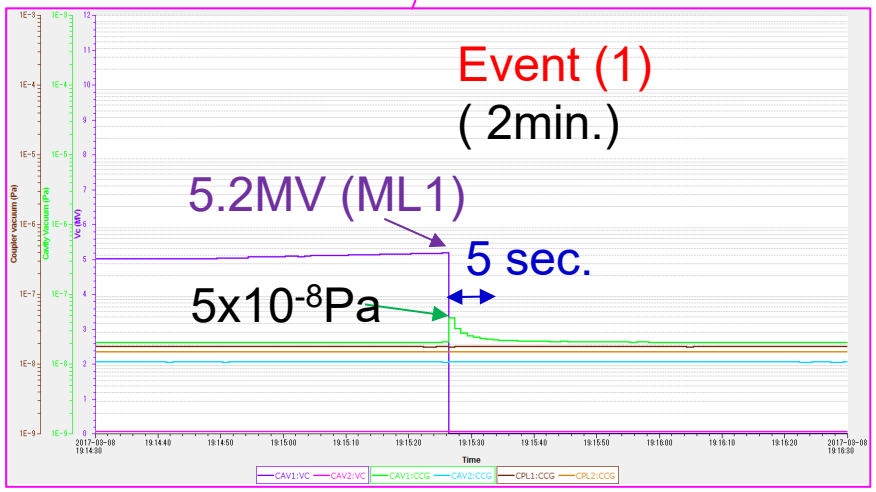


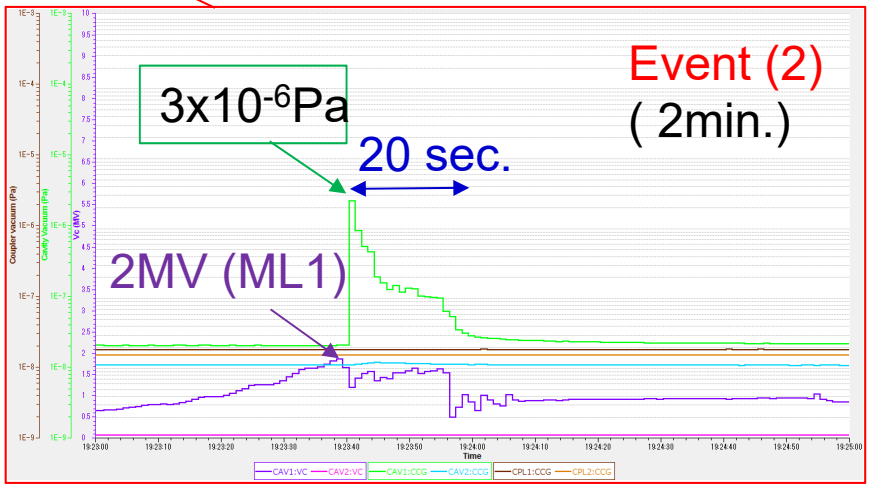
Pulse processing for ML2 cavity at 9th phase to recover Q decreasing during beam operation. Lower figures shows the trend of the PIN diode signals set on the both ends of ML2 cavity under the pulse processing . Radiation was decreased and Q-value recovered.

Pulse processing was effective for ML2.

Details of unknown event of ML1 under cavity processing on March 2017



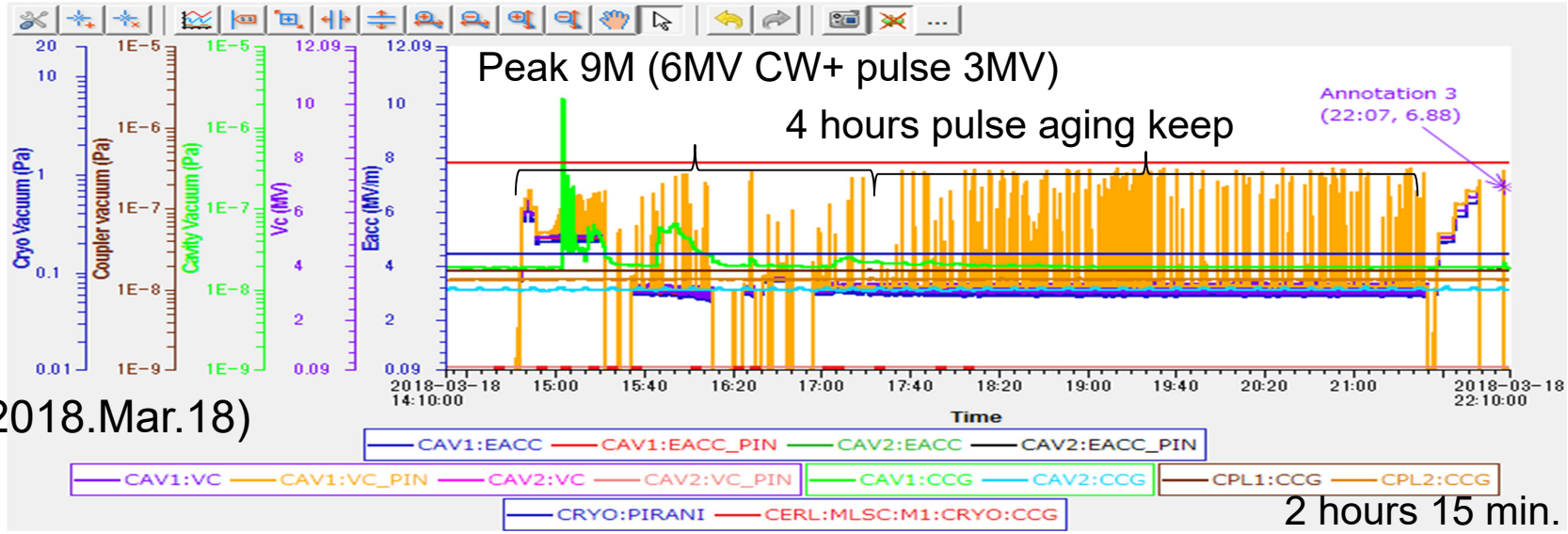




Some explosion occurred ??

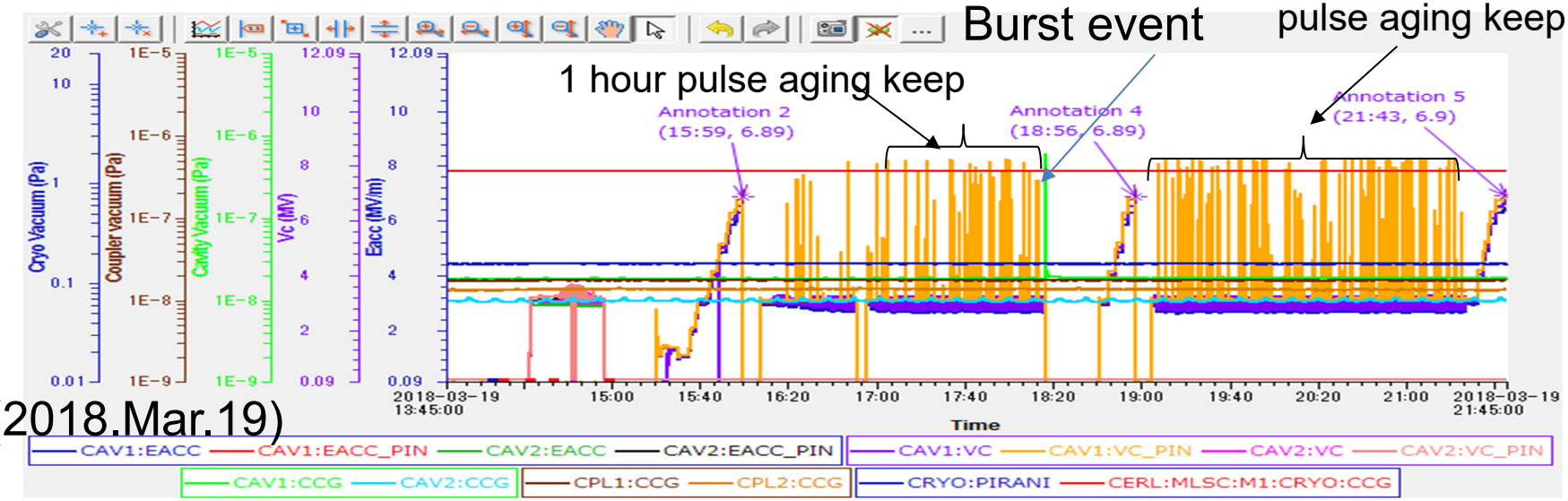
Pulse processing of ML1 cavity after unexpected events

we tried pulse processing for totally10 hours.



(2018.Mar.18)

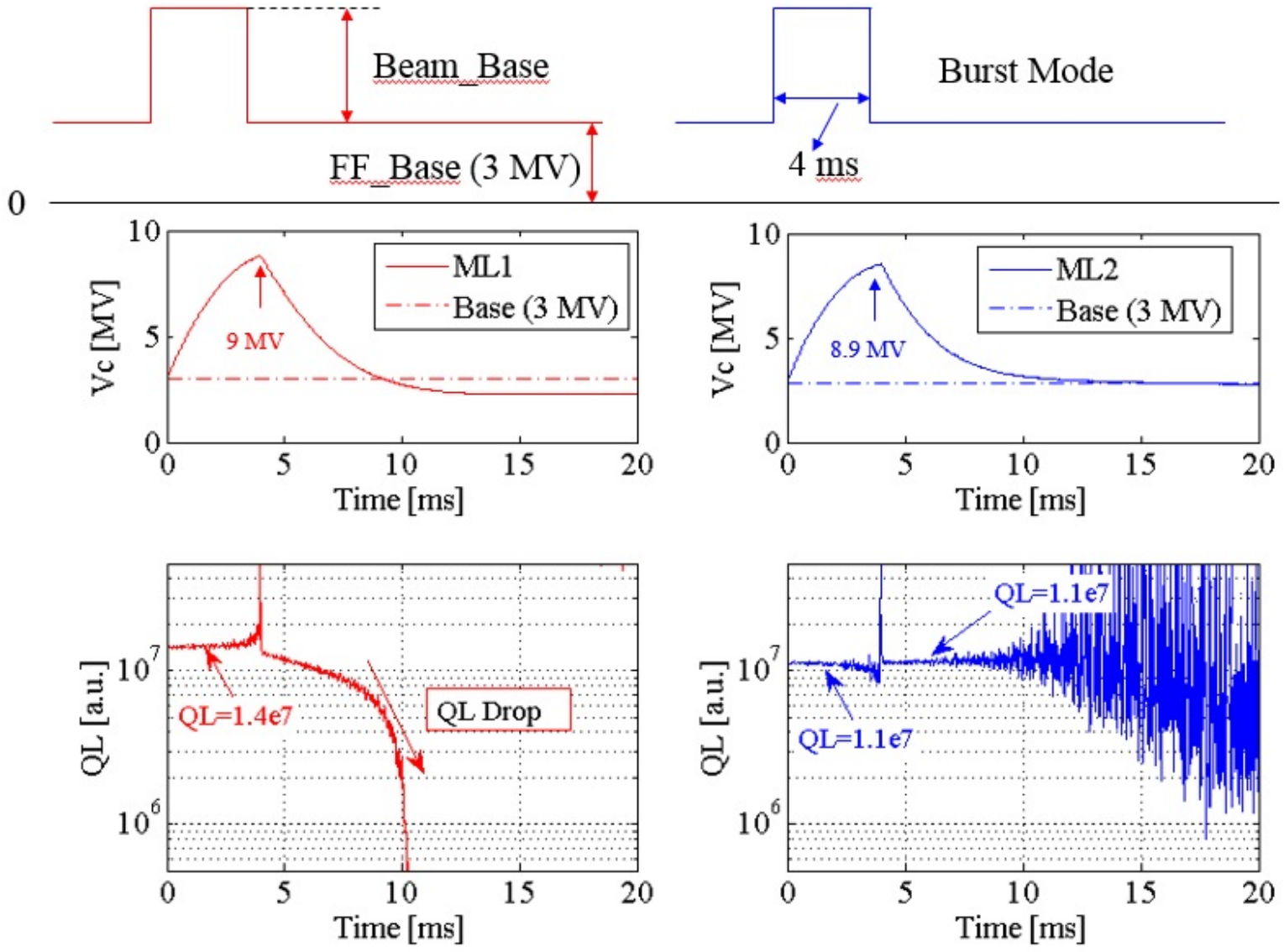
2 hours 15 min. pulse aging keep



(2018.Mar.19)

Pulse processing was not effective for the ML1 cavity after these unexpected events. → what happened.

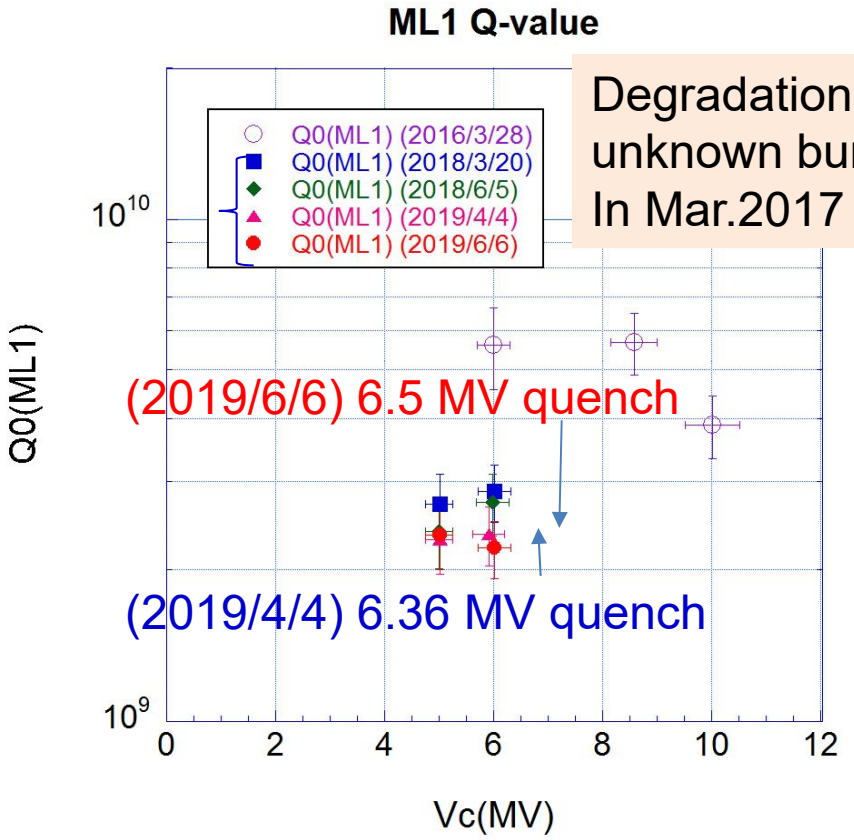
QL measurements during pulse processing after unexpected event



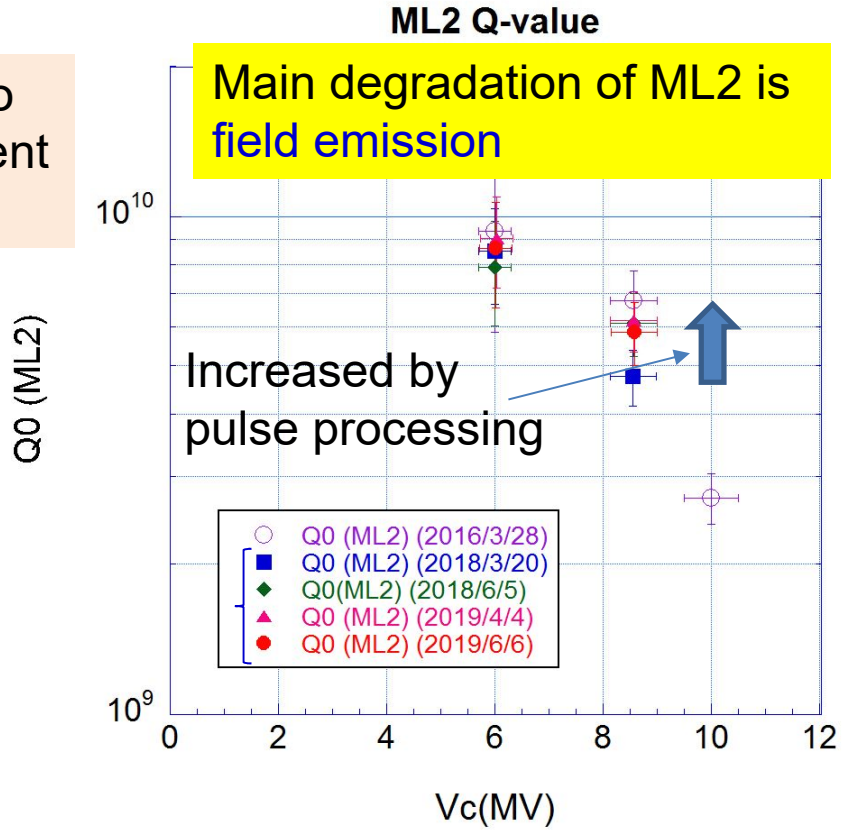
For ML1, we found thermal breakdown at the higher than 7 MV field. Limitation of ML1 is not field emission but thermal breakdown after event.

The latest cavity performance (summary of cavity performance)

Measurement of Q-values of both cavities (ML1,2) in 2018 & 2019 with 2016



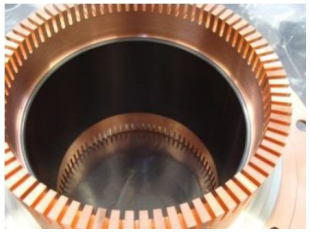
Degradation due to unknown burst event In Mar.2017

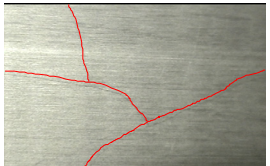


Main degradation of ML2 is field emission

Main degradation of ML is thermal breakdown

cERL HOM absorber





- We could not obtain the higher Q-values in 2019 than that in 2016.
- We could recover the ML2 cavity performance.

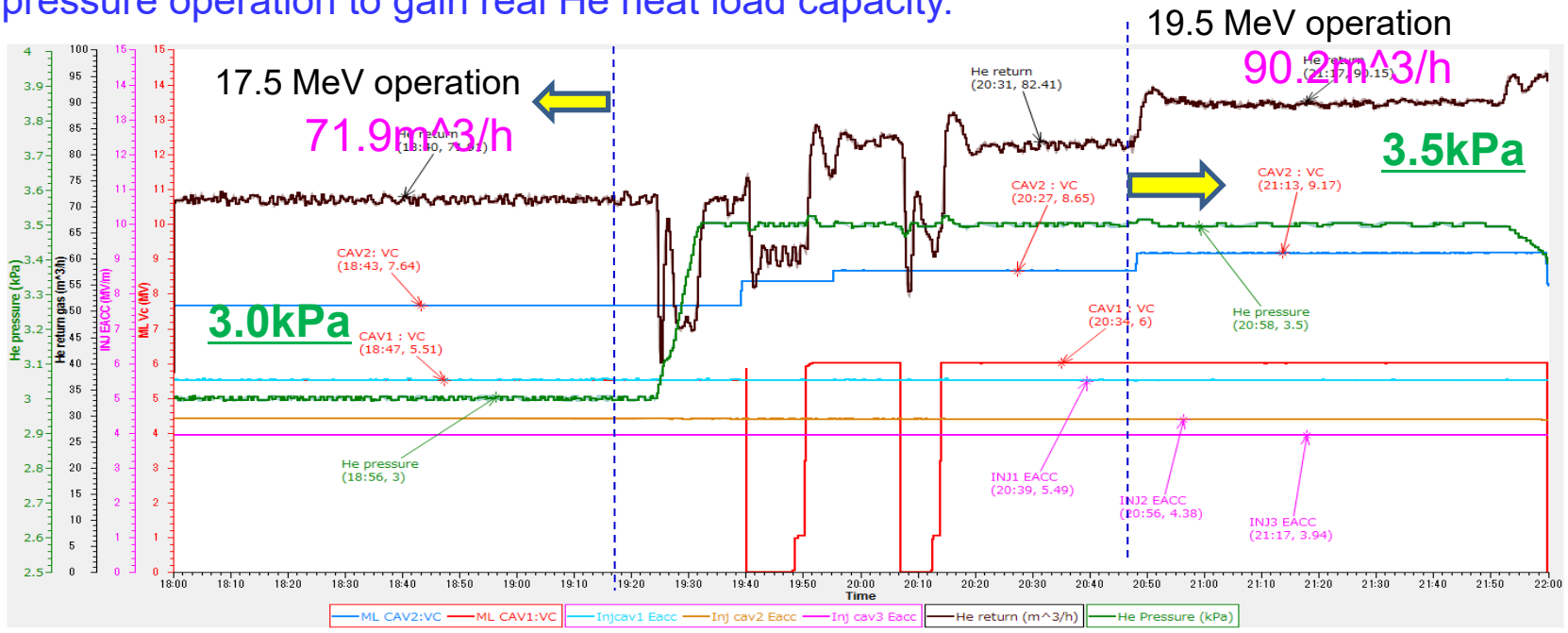
During the burst event, we observed the long vacuum increasing event. At this event, discharge would occur and some components like HOM absorber, ceramic of the input coupler and/or the other vacuum components near ML1 cavity would break and make some particulate in the ML1 cavity.

3.5kPa operation & results (2019.Jun)

change

He pressure	Heat capacity	He temperature
3.0 kPa	85 m^3/h	1.986 K
3.5 kPa	99 m^3/h	2.039 K
4.0 kPa	113 m^3/h	2.087 K

In our case, Q-value is determined by residual resistance not BCS resistance. → did not mainly depend on He pressure (3.0kPa). On the other hand, cryogenic heat capacity is linear to the He pressure.→ We tried the higher He pressure operation to gain real He heat load capacity.



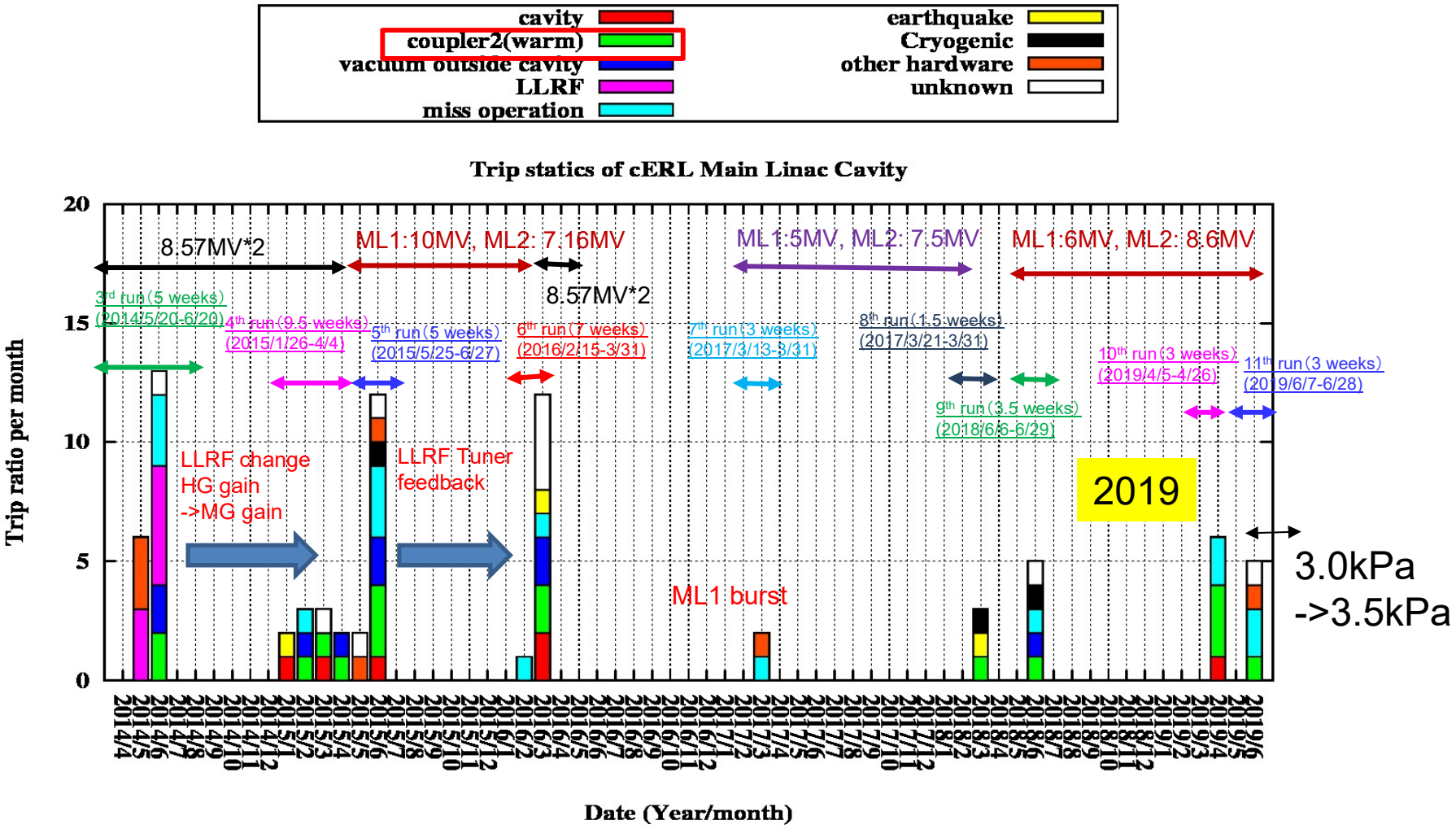
Total energy	INj1(MV/m)	INj2(MV/m)	INJ3(MV/m)	ML1(MV)	ML2(MV)	He pressure	He flow
17.5MeV	5.49	4.38	3.49	5.5	7.65	3.0kPa	71.9m^3/h
19.5MeV	5.49	4.38	3.49	6	9.15	3.5kPa	90.2m^3/h

Keep injector 4 MeV

19.5MeV : 1hour keep

Finally (6/25 – 6/28) 3.5kPa operation could keep 19.5 MeV energy for RI irradiation.

ML Trip ratio (longterm) (2014.Apr. ~ 2019.Jun.)

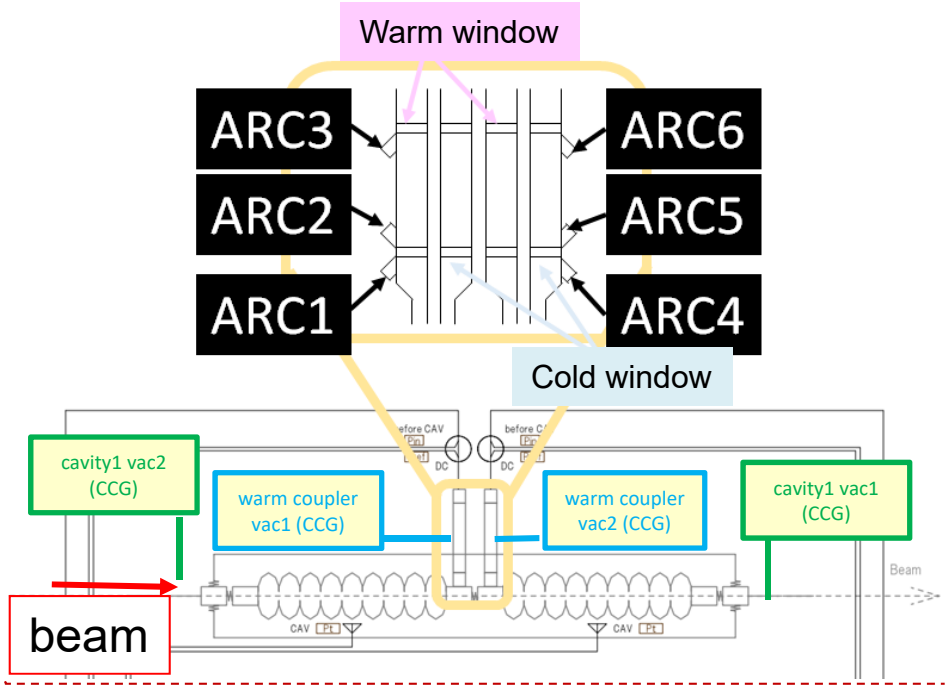


After optimization of LLRF gain in 2014, we kept small trip ratio in 2015. If cavity field increased higher in 2015. trip ration increased. Main reasons of trip come from the warm coupler (ML2) discharge event (light green). We did not know why these discharged events would occur. However, we could safely turn off RF within 10us by using ITL of arc sensor of input coupler.

Essential interlocks for cavity

ITL about cavity

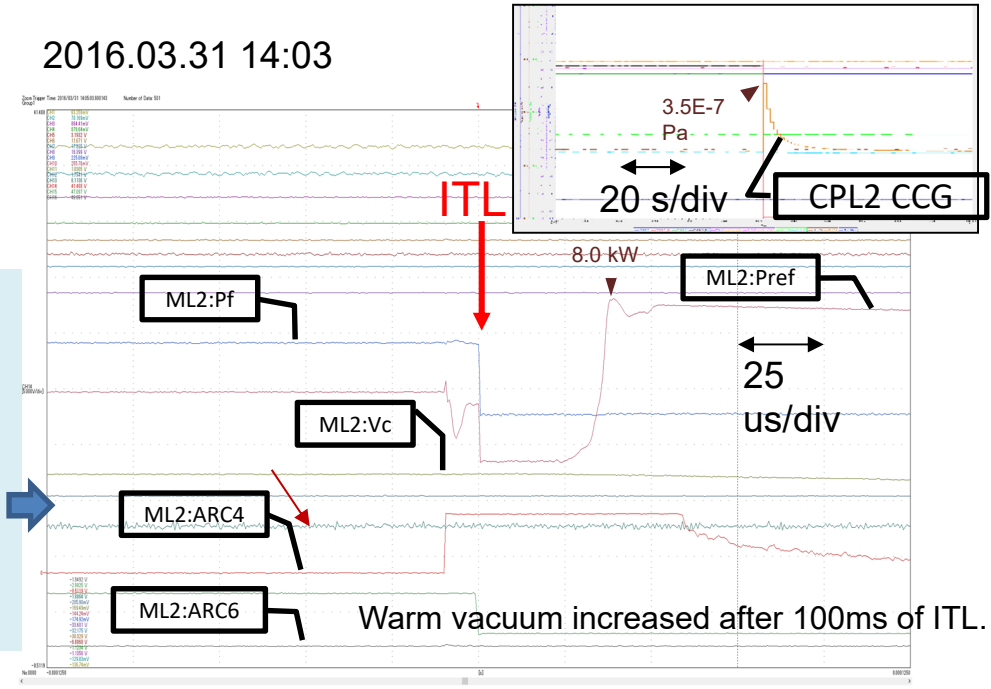
Sensor	ITL level	ITL response	ITL use
RF input(Pin)/refrection(Pref)	5 kW	1-10 μs	RF OFF ITL
加速電圧(P	9.2 MV(8.6 MV運転時)	1-10 μs	RF OFF ITL
ARC sensor	Sensitive	1-10 μs	RF OFF ITL
Vacuum	1.0E-5Pa(Cavity＆Coupler)	100 -500 ms	RF OFF ITL/GV CLOSE
He	3.05 kPa	100 -500 ms	RF OFF ITL
Potentio meter	-		Only for measuring
Load cell	-		Only for measuring
Temperature	-		Only for measuring



Monitoring arc event when ITL works

(Normal RF fall down)
RF power decrease 1ms,

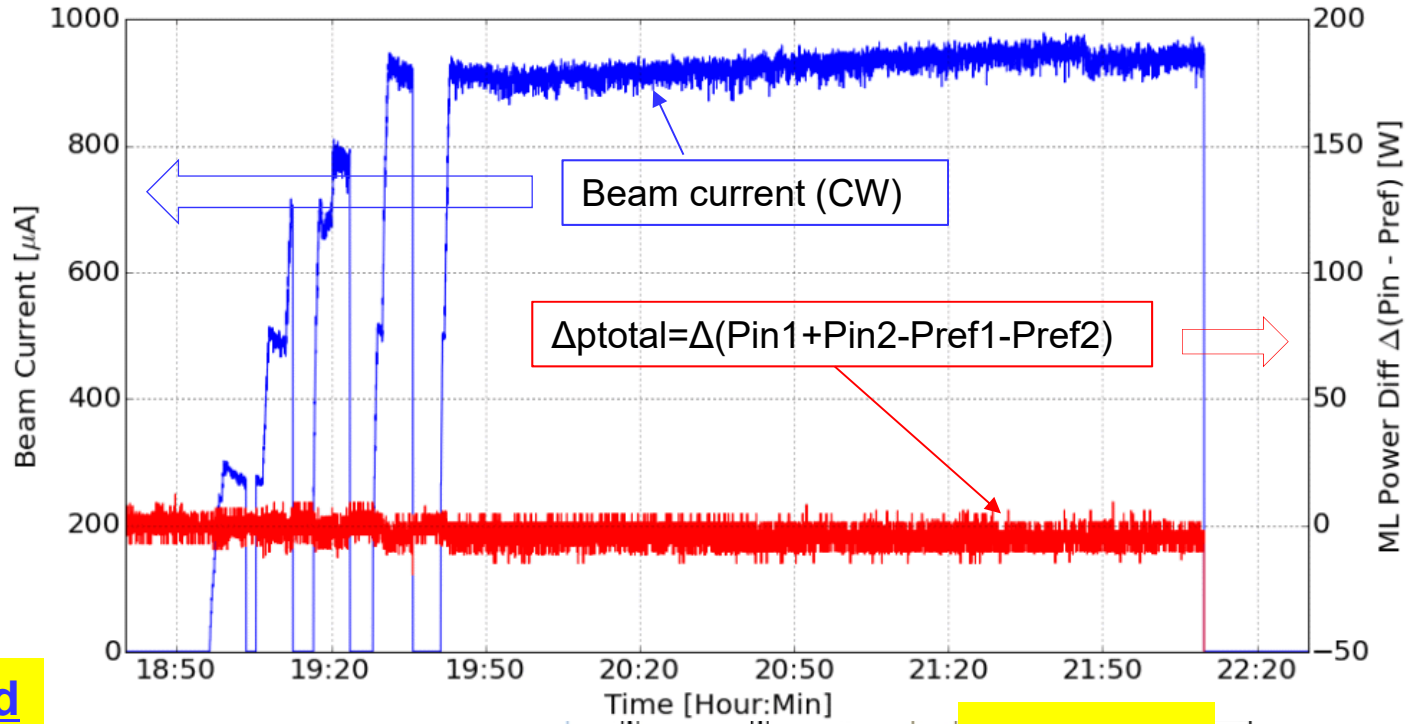
2016.3.31 14:03 (warm coupler ITL)
CPL2(Warm-side) discharged between cold and warm window (arc4,6 works in left figure). ITL works within 10us after arc sensor works. Discharged electron/ions (plasma) in CPL2 (warm-side) suddenly cut the RF transmission (short)。Power did not reflected from cavity by these plasma. CPL2 vacuum increased later 。Beam and ITL were not related.



Fast ITL of arc sensor helps cavity not to lead fatal problem like window break. (vacuum ITL is too late)

Successful ~ 1mA CW beam operation with energy recovery

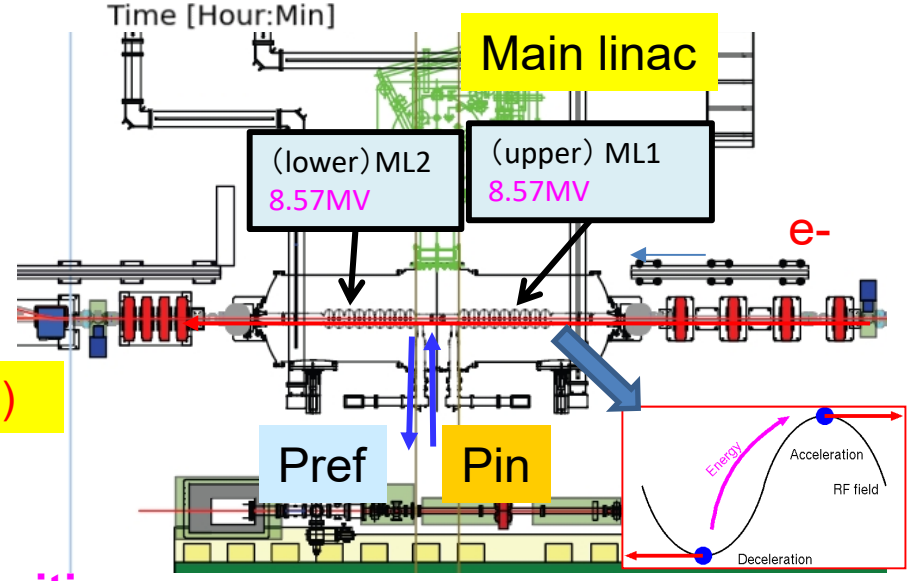
Change CW mode and increase the beam current : Reach 0.9 mA after the 1mA approval from the government at 8th/Mar/2016.



No HOM-BBU was observed.

No HOM heat load

red : Difference between an input (Pin) and a reflected (Pref) power of the ML. Energy loss measured from the graph = 4 W. (error +-4W)
Required power without recovery is :
17.14 MV x 900 uA = 15.4 kW



Energy Recovery is almost 100.0% (error +-0.03%)

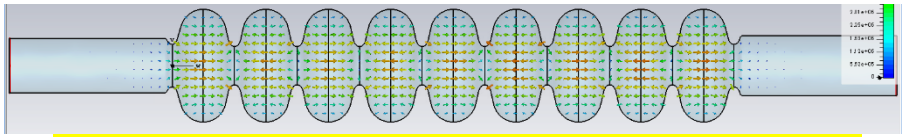
This measurement agree well with beam loss measurement of less than 0.01%

Toward 10 mA CW operation with these cavities

Toward reliable operation for SRF cryomdule for high current beam on cERL

Field emission is main issue for reliable operation. → How to overcome field emission

EUV cavity design Done by T.Konomi



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

	ERL Model 2	EUV
R_{sh}/Q	897 Ω	~1000 Ω
E_p/E_{acc}	3.0	~ 2.0
Iris diameter	80 mm	70 mm
H_p/E_{acc}	42.5 Oe/(MV/m)	~42.0 Oe/(MV/m)

Satisfy the HOM-BBU threshold of more than 100mA by EUV cavity.

Stable operation at 12.5 MV/m seems achievable due to reduced E_p/E_{acc}.

H. Sakai, et., al. "SUPERCONDUCTING ACCELERATOR FOR ERL BASED FEL EUV LIGHT SOURCE AT KEK " Porc, of SRF2017, Lanzhou, China, MOXA04, p13 (2017)

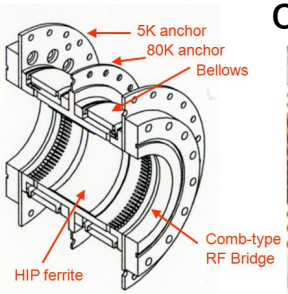
How to reduce the unwanted particulate into the cavity ? → clean components

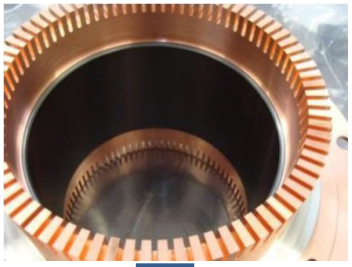
R&D for Clean assembly work

Open clean bench KOACH (ISO class 1) for local clean bench

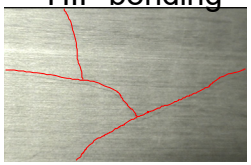
Slow pumping/venting system with vacuum particle sensor.
Both were already applied for STF cryomodule assembly work.

cERL HOM damper





Ferrite with HIP bonding

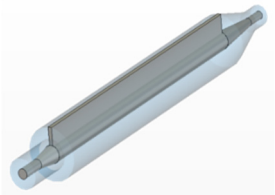


Fragile under thermal cyle

T. Ota, et. al. SRF workshop 2019

AlN cylinder

M.Sawamura, "Development of HOM coupler with C-shaped waveguidefor ERL operation" (Thu)



C-shaped waveguide

Nitrogen doping for High-Q approach in KEK

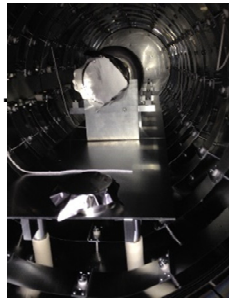
Courtesy of K.Umemori

This work is under US-Japan collaboration

$$Q_0 = \frac{\Gamma}{R_s}$$

← *Determined by cavity shape*

Recently (2013) by applying the nitrogen doping during annealing (N-doping), it is found that R_S is reduced at FNAL. KEK also carried out the N-doping/N-infusion technique in the J-parc furnace in 2017 and successfully carried out this improvements by improving the VT condition.



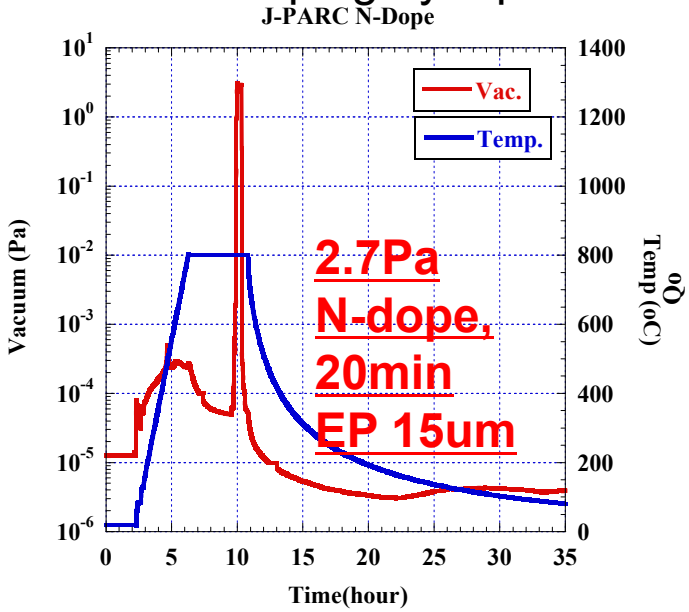
$$R_S = R_{BCS}(T) + R_{residual}$$

Minimizing Rs is the Key for High-Q applications.

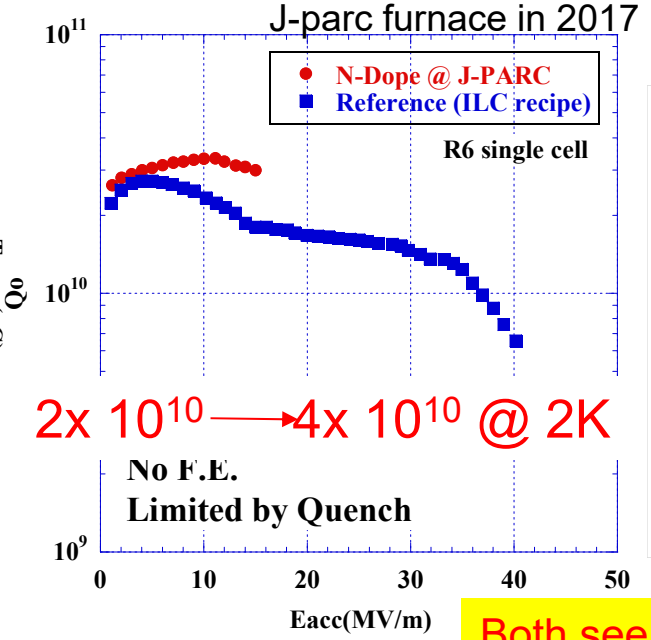
A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication) – selected for highlights of 2013

Both used cryopump

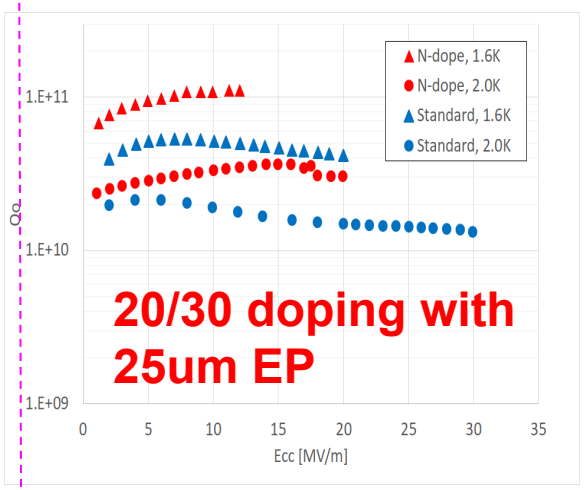
N-doping by J-parc furnace



J-parc furnace in 2017



KEK new furnace in 2018



T. Okada, et. al. "Improvement of cavity performance by nitrogen doping at KEK" ,Proc. of LINAC18, TUPO065, Beijing, China (2018)

Both see the anti-Q slope with high-Q. N-dope successfully has done in KEK.

Summary

- KEK cERL cryomodule are opartating from 2012 until now. We apply the optimum cryomodule desing and cooling down procedure. We did not meet fatal cavity accident and keep the stable beam operation under LLRF optimization.
- Unfortunately, we met the cavity degradation under beam operation. Main issues is field emission.
- Monitoring is essential to keep cavity performance. For example, pulse processing is effective to reduce the field emission by monitoring PIN profile monitors. And critical ITLs like arc sensors of input coupler. are important to avoid fatal cavity accident.
- In 2017 & 2018, we met severe cavity degradation, for ML1 we did not recover the cavity performance by pulse processing. On the other hand, we could recover the cavity performance of ML2. Injector cavity kept cavity performance by pulse processing. We would like to open the ML cryomodule to investigate the source. And we want to increase beam current more than 10 mA.
- Higher-Q R&D also tried to reduce CW heat load.
- SRF Gun is under developing for CW high current beam generation in KEK.

T.Konomi, “vertical test results and preparation for horizontal test of the KEK SRF gun #2” (Wed)