Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Long-term reliable and stable SRF operation in cERL

Hiroshi Sakai (KEK)
on behalf of Compact ERL Development Team

- Introduction
- Operational issues and recovery of SRF
- summary

cERL Injector Cryomodule

cERL Main linac cryomodule

20 pages

Introduction

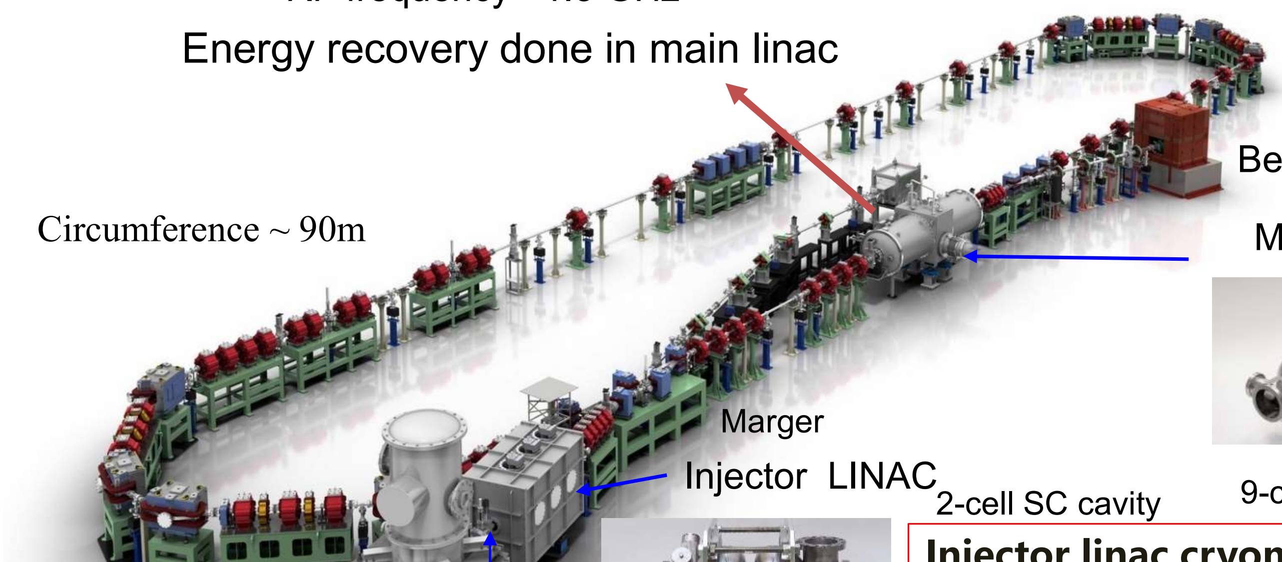
Compact ERL (cERL) in KEK

Injector & Main linac made by MHI.

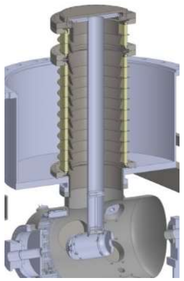
RF frequency= 1.3 GHz

Energy recovery done in main linac

Circumference ~ 90m



Photocathode DC gun
(Not SRF gun)



9-cell SC cavity

2-cell SC cavity

Main linac cryomodule
9-cell cavity (named as ERL-model2)× 2
HOM damped (for 100mA BBU suppression)

(main linac design)

Input power : 20kW CW

E_{acc}: 15 MV/m

Unloaded-Q: $Q_0 > 1\times10^{10}$

H. Sakai, E. Cenni, K. Enami, T. Furuya, M. Sawamura, K. Shinoe and K. Umemori, Phys. Rev. Accel. and Beams 22 022002-1 – 022002-22 (2019)

Injector linac cryomodule
2-cell cavity × 3
Double input coupler

(Injector design)

Input power :

180kW/coupler (10mA, max 10MeV)
→ now 10kW/coupler

E_{acc}: 15 MV/m (max 10MeV)

Unloaded-Q: $Q_0 > 1\times10^{10}$

K. Watanabe, S. Noguchi, E. Kako, K. Umemori, and T. Shishido, Nucl. Instrum. Methods Phys. Res. A **714**, 67 (2013)

Pink is present operation value

Design parameters of the cERL

Nominal beam energy	35 MeV → 17.5-19.5 MeV
Nominal Injector energy	5 MeV →2.9-5 MeV
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)

Current status of high power RF sources

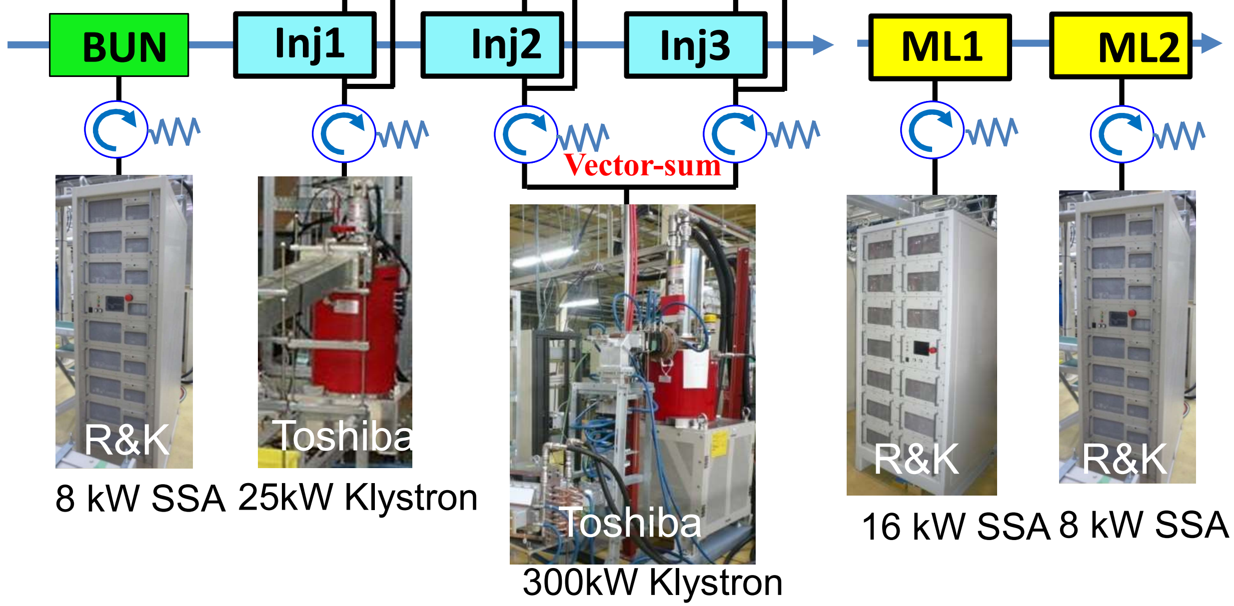
	Buncher	Inj-1	Inj-2	Inj-3	ML-1	ML-2
Cavity	NC	2cell-SC	2cell-SC	2cell-SC	9cell-SC	9cell-SC
Cavity Voltage	114 kV	0.7 MV	0.7 MV	0.7 MV	8.6 MV	8.6 MV
Field Gradient (Desgin)		3 MV/m (7.5MV/m) 7MV/m (5M Voperation)	3MV/m (7.5MV/m) 7MV/m (5M Voperation)	3MV/m (7.5 MV/m) 7MV/m (5M Voperation)	8.6 MV/m (15MV/m) (→ 6MV/m from 2017)	8.6 MV/m (15MV/m)
Q_L	1.1×10^5	1.2×10^6	5.8×10^5	4.8×10^5	1.3×10^7	1.0×10^7
Cavity Length	0.068 m	0.23 m	0.23 m	0.23 m	1.036 m	1.036 m
RF Power @Low beam current	3 kW	0.53 kW	2.6 kW		1.6 kW	2 kW

Total energy

Injector 3MeV
Total : 20MeV
(from 2017
17.5 MeV)

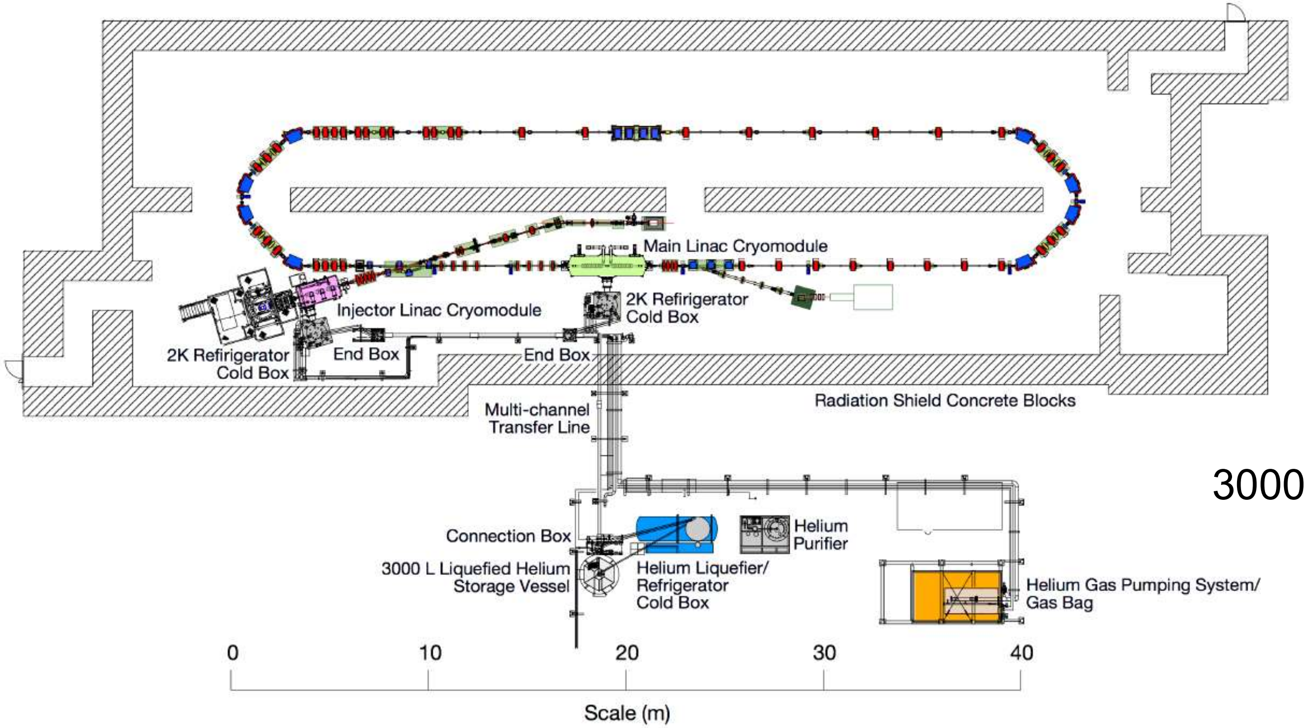
<Design>
100mA beam &
Vc= 2MV at Inj.Cav

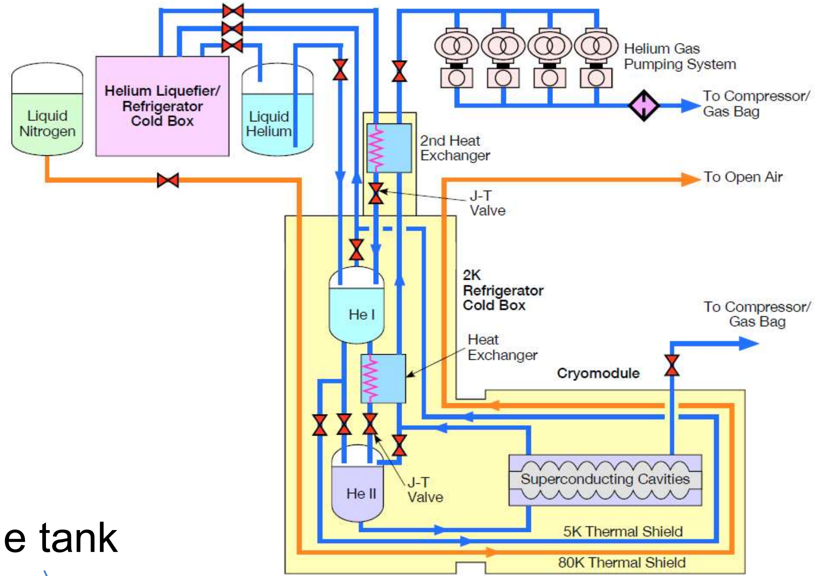
200kW RF power is necessary for each inj. cavity.



cERL Cryogenics

H.Nakai et al.





3000l He tank

- Injector and main linac cooled by one cryogenic system
- 3000l Liquid He storage
- 500W He refrigerator @ 4.4K
- Pumping at warm (2K) 80 W (3kPa) (80 m^3/h)

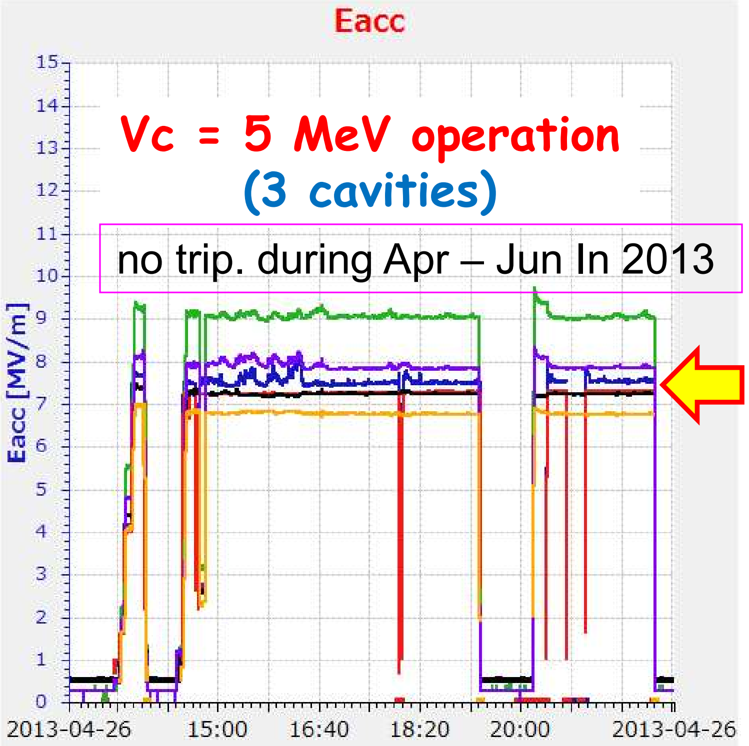
purifier

Performance of Injector cryomodule (2013.Apr.-June)

5.5MeV beam was accelerate by Injector cryomodule

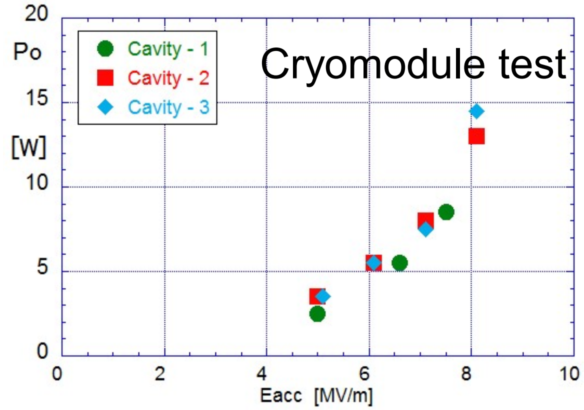
By E. Kako et al.

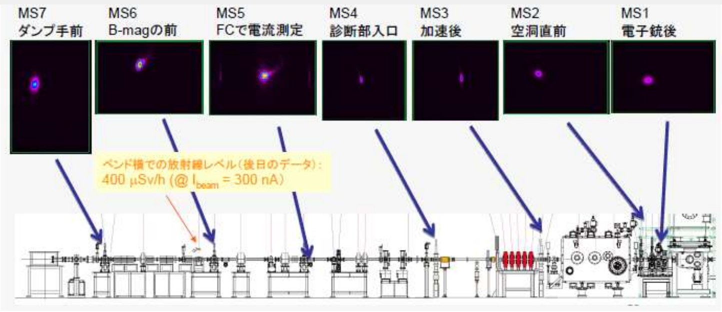
HOM coupler heating was unexpected more than 2MV/m field in cryomodule operation. (It was not shown in V.T) But 5.5 MeV injector operation was achieved within our cryogenic capacity. Input coupler was tested up to CW 30kW in test bench and operated within 10kW at present.

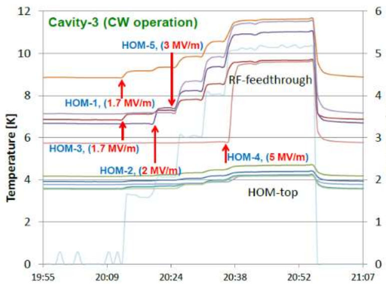


Cav1 : 7.11MV/m
Cav2 : 7.25MV/m
Cav3 : 6.82MV/m

Total 5MV acceleration
No coupler kick was observed.







HOM heating

HOM feedthrough

For high field of more than CW 5 MV/m, HOM heating is issue.

Performance of main linac cryomodule before beam operation (2012.Dec)

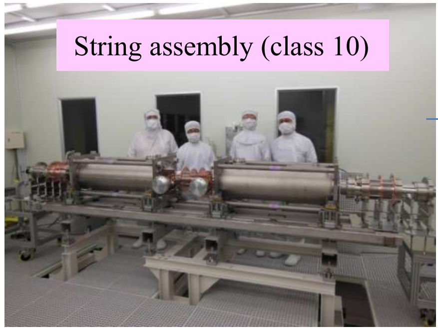
Summary of performance of cryomodule test in 2012

Vc=16 MV was achieved. Vc=13.5-14 MV could be kept for more than 1 hour.

Onset of radiation due to field emission: 8-10 MV/cavity

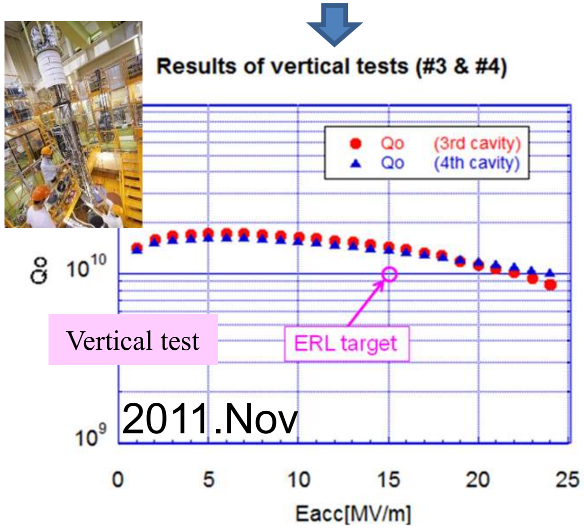
Deside →
8.5MV/cav in operation
not to get field emission

ERL model-2 9cell cavities for cERL

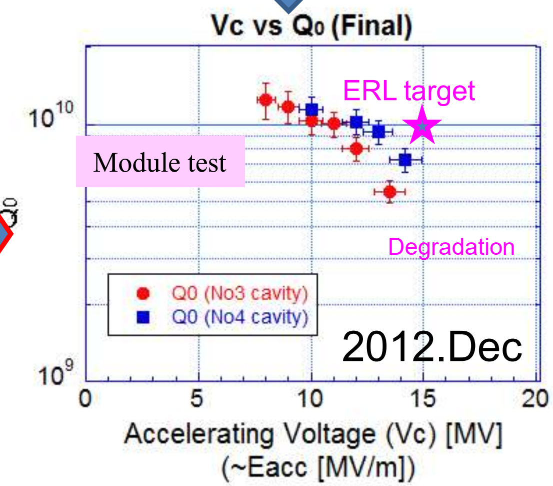


Main linac cryomodule set in cERL

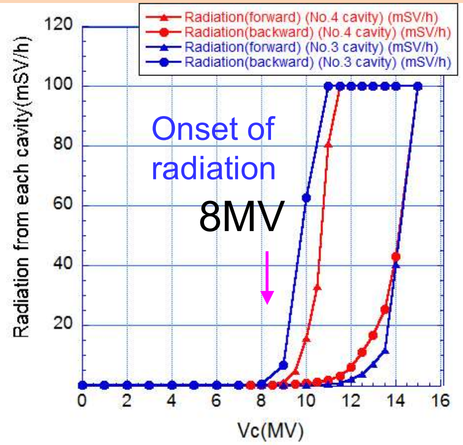
Some dusts would be contaminated during string assembly → problem



Results of VT of two ERL 9cell cavities.
(No radiation below 14MV/m)



Degradation was observed in cryomodule high powe test ($V_c = 1.038 \times E_{acc}$)



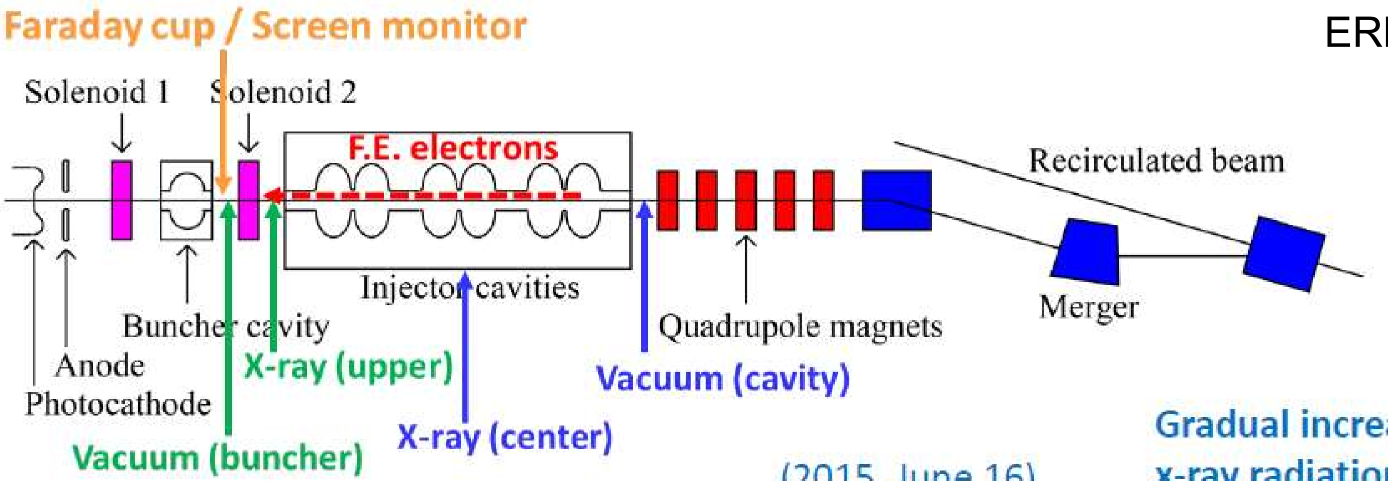
radiation monitors were set on both sides

For high field of more than 10MV, field emission is issue for main linac.

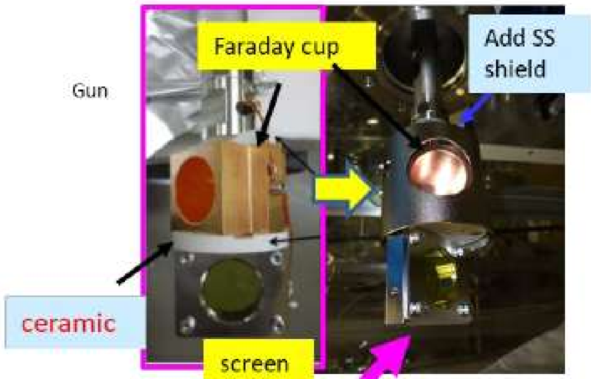
Operational issue and recovery of SRF

Injector FE recovery from unexpected events

ERL2019 E. Kako et al



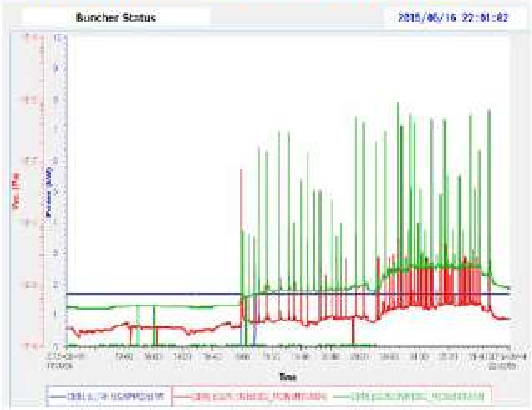
Screen monitor in front of Gun



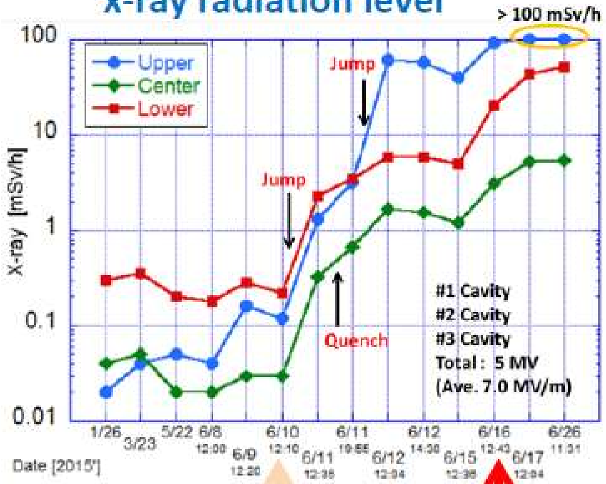
Make shield not to hit FE to faraday cup & ceramic

(2015, June 16)

Many bursts of vacuum pressure



Gradual increase of x-ray radiation level



1 week

(2015, June 16)

Vacuum discharge caused by charging-up of Faraday-cup due to field emitted electrons come from injector cavities.

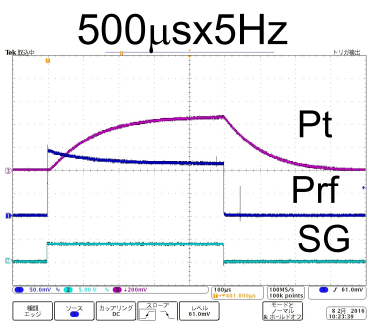
Recovery by Pulse processing at injector cryomodule

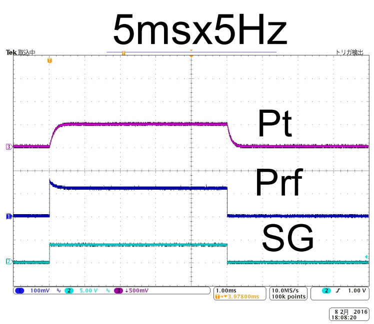
See detail on IPAC16 WEPMB013
& TTC meeting WG1 presented by E.Kako.

We carefully carried out the pulse processing by changing the pulse length from 0.5ms to 5ms and finally CW not to make the fatal damage to the cavity

RF conditions of pulse processing

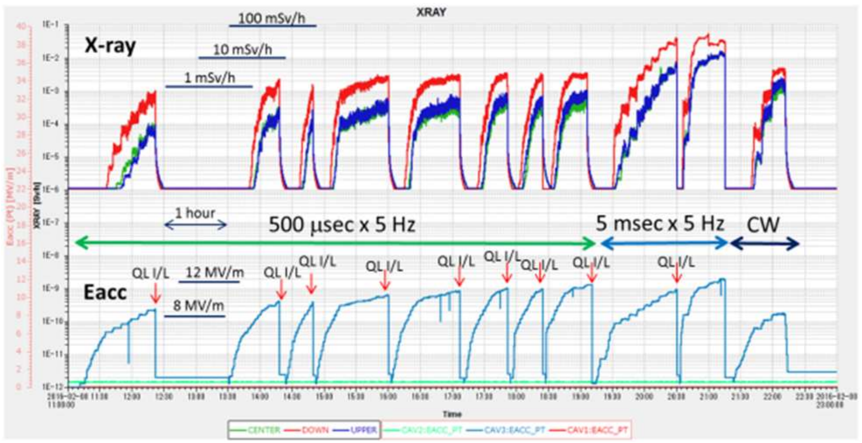
	No.1 Cavity	No.2 Cavity	No.3 Cavity
Q_L	1.2×10^6	5.3×10^5	5.4×10^5
filling time τ	0.15 msec	0.07 msec	0.07 msec
Required RF power at 15 MV/m	12 kW	27 kW	27 kW
Required RF power at 20 MV/m	21 kW	47 kW	47 kW

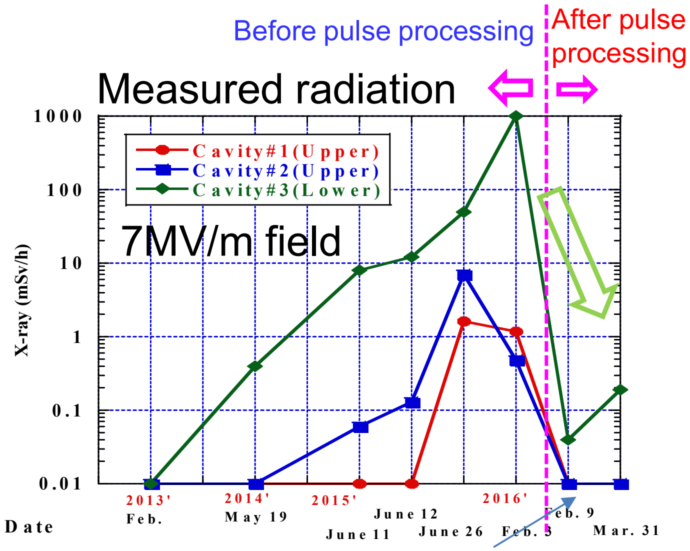




Pulse shape (ex.: No.3 Cavity)

History of pulse processing of No.3 injector Cavity(11 hours)





No field emission

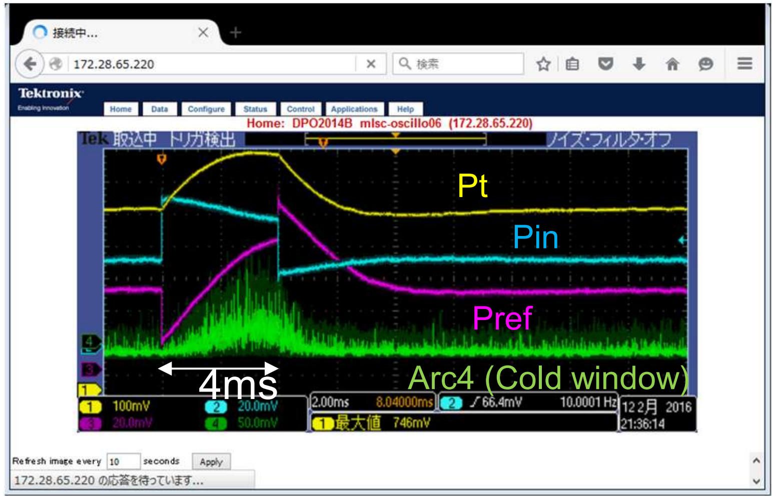
Quench protected by QL decay curve by LLRF

By appropriate pulse processing, we drastically recover the cavity performance and do the 5MV operation in 2016.

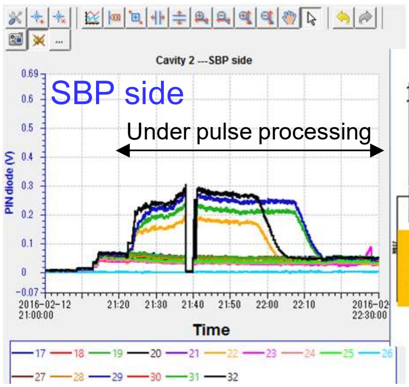
Even though sudden FE increased, high peak pulse processing worked well for injector cryomodule. → keep stable operation

Example of pulse processing for Main linac (ML2)

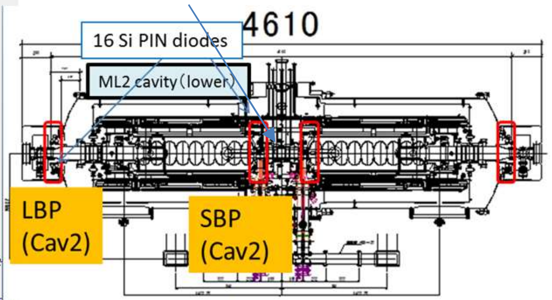
ML2 Pulse Aging (10Hz)
Vc=8.57MV(CW)+2.3MV(10Hz x 4ms)=10.9 MV
:40min pulse aging was done.



History of pulse processing: In ML, we were processing by monitoring side 32 PIN diodes



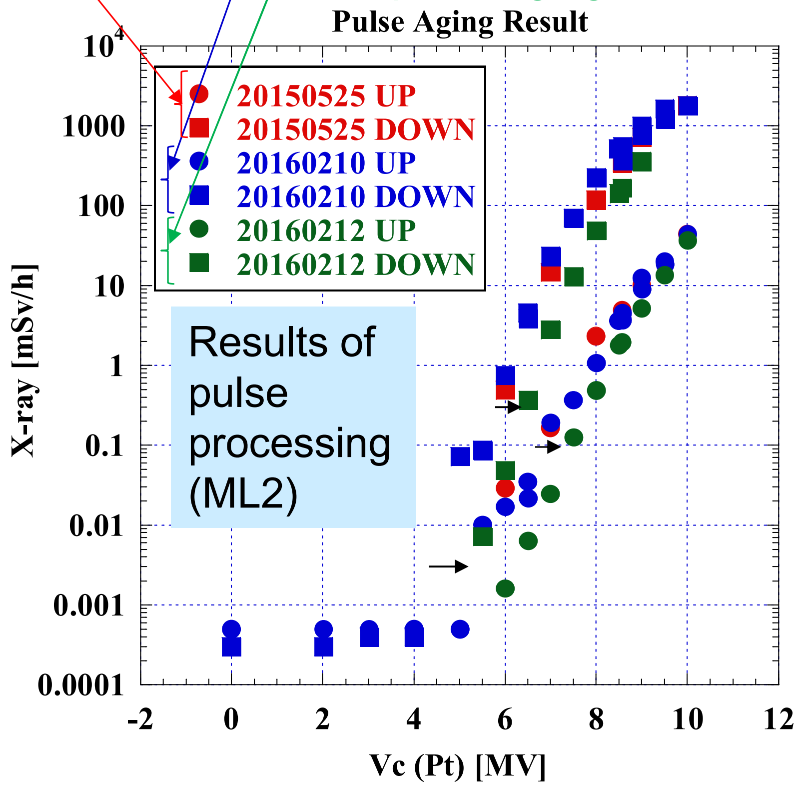
Arc sensor



2015/5/25

Before pulse processing

After pulse aging



ML2 Vc vs ALOKA monitor

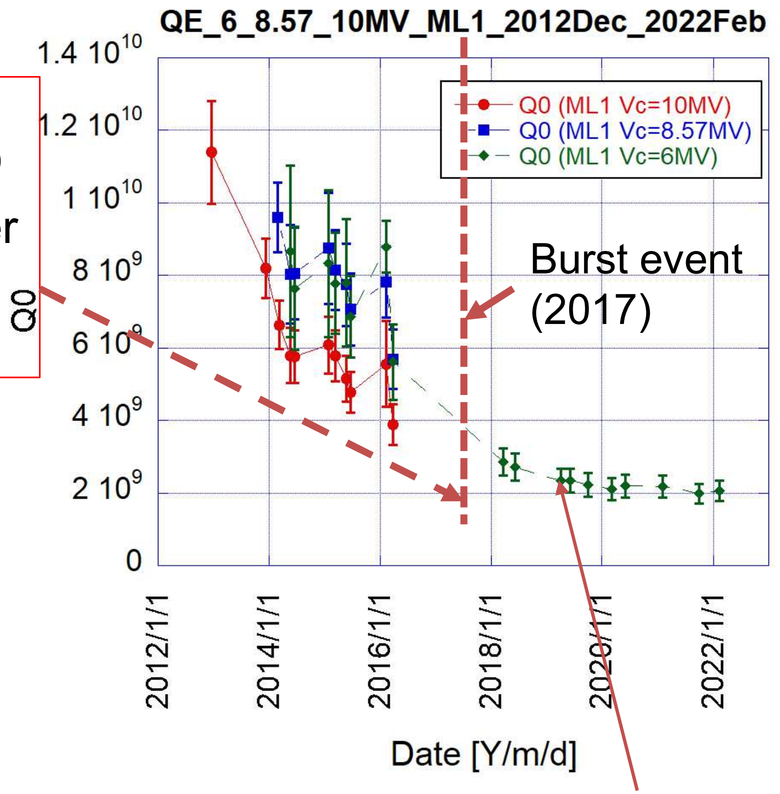
- Onset moved up 0.5 MV.
- Radiation reduced half on same acc. field.

→Pulse processing works well.

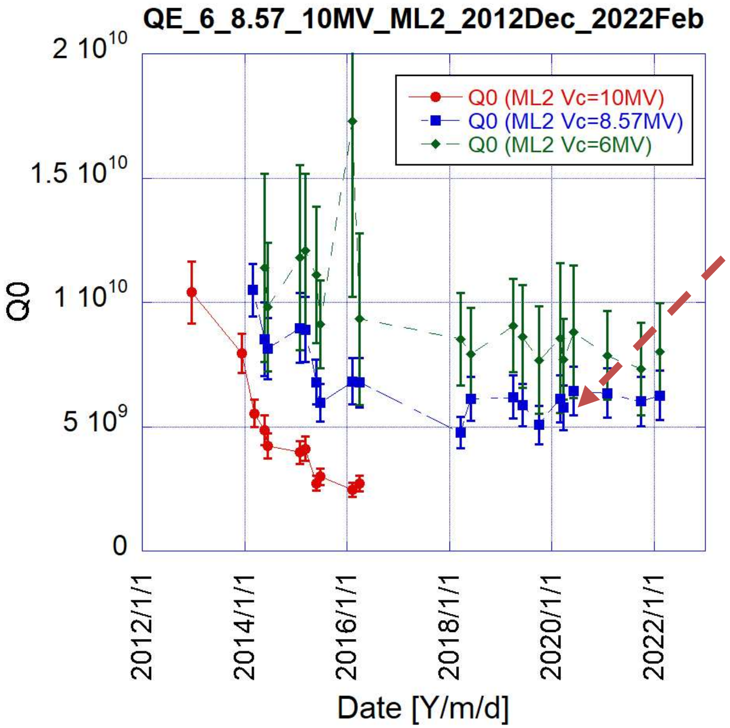
Main linac Q-value history (2012.Dec. ~ 2022.Mar.)

Cavity kept Q0 ~2 x 10^9 on ML1 after unknown burst event

No.1 cavity



No.2 cavity

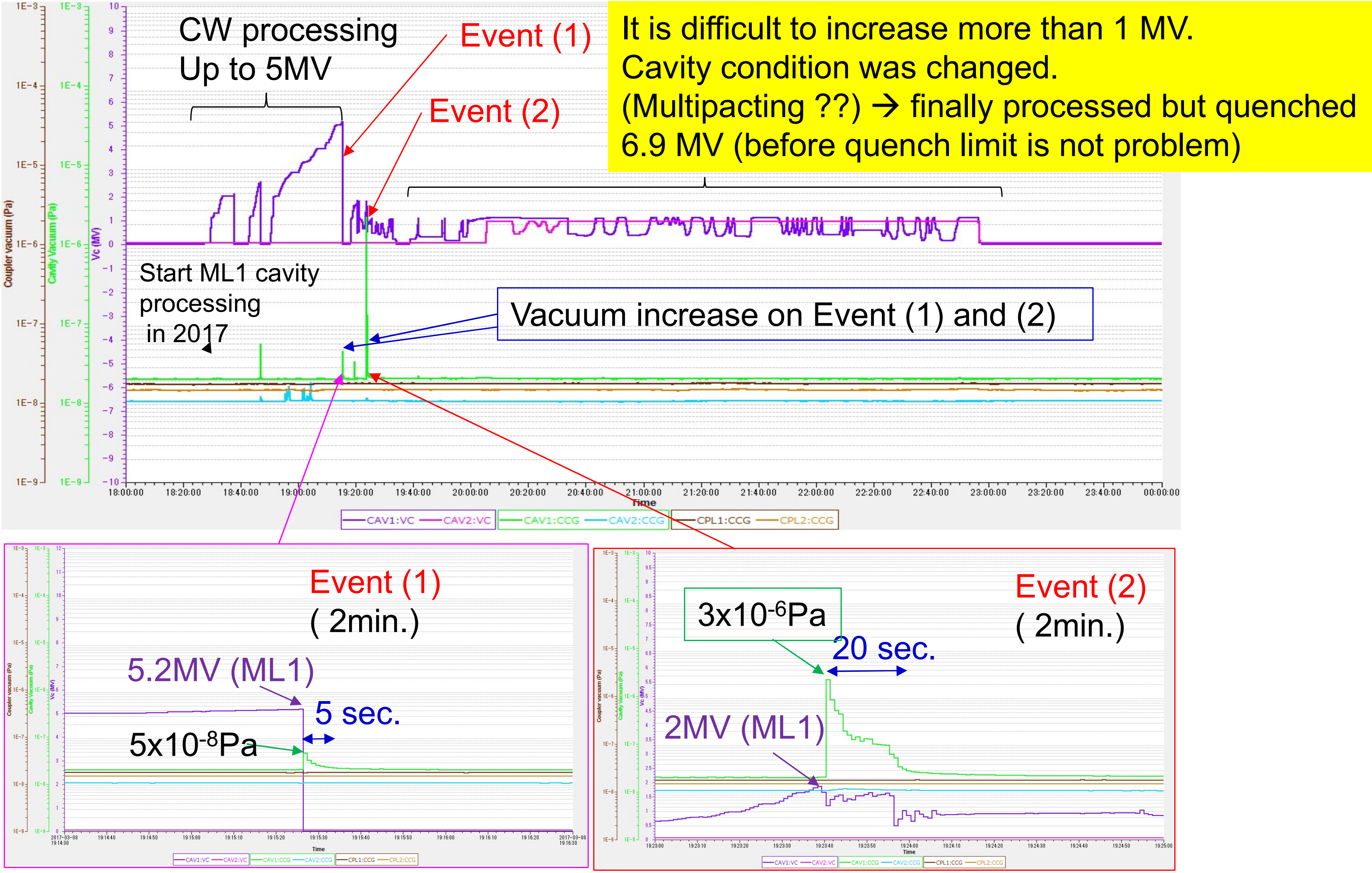


Cavity kept Q0 ~6 x 10^9 on ML2 at 8.6 MV from 2015 to 2022

This Q-value is not determined by R_{BCS} but by R_{res}.

Due to the low Q-value of ML1, first we need to reduce the field down to 17.5 MeV in 2018.

ML1 under cavity processing on March 2017



Some explosion occurred ??

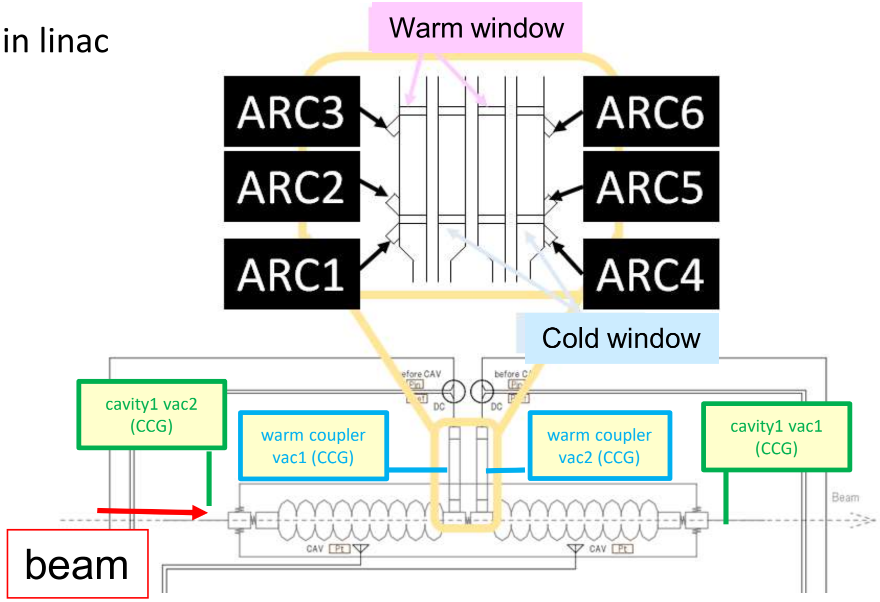
It is difficult to overcome the quench field

ITL lists and what happen during arc events in main linac

ITL lists

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

Quench is protected Pt decay

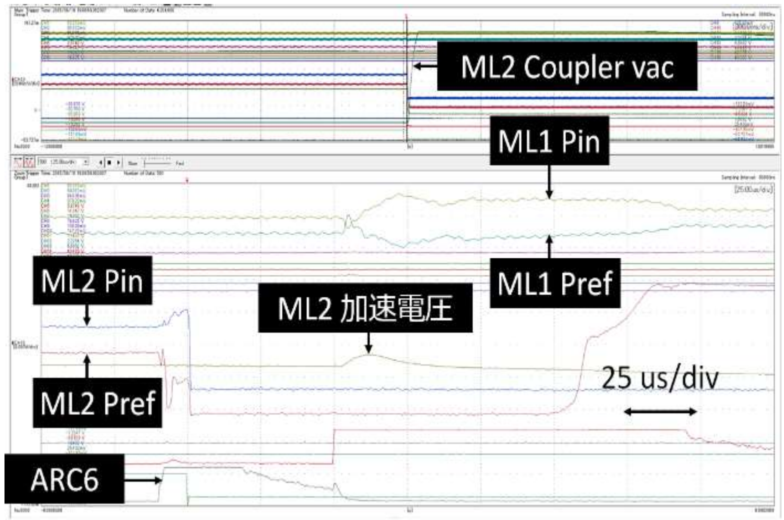


Warm window 2 arc events :

Discharge 9us keep → RF off ITL

On the other hand vacuum of warm window became worse after 100ms. → vacuum event is very slow.

Arc sensor is very important to quickly prevent the break of ceramic window from the discharge event.

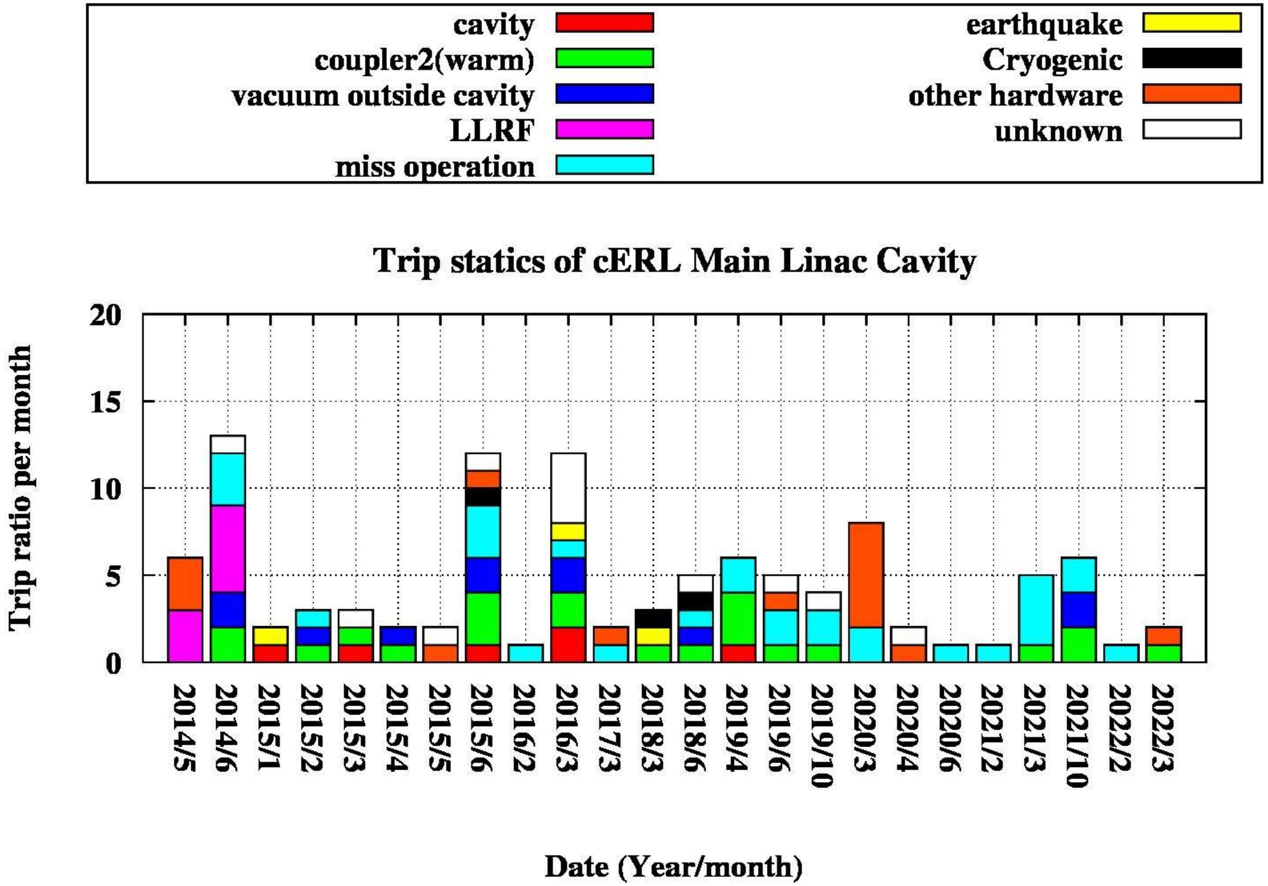


2015.Jun.18 19:00 event of arc6 and vac warm window.

For CW operation like ERL, it is important to make fast ITL.

Trip statics of main linac (2014.May~2022.Mar.)

Mainly trips were occurred by mis operation and warm coupler window arc event.
This warm coupler arc event were occurred per month. → it is very important for arc sensor

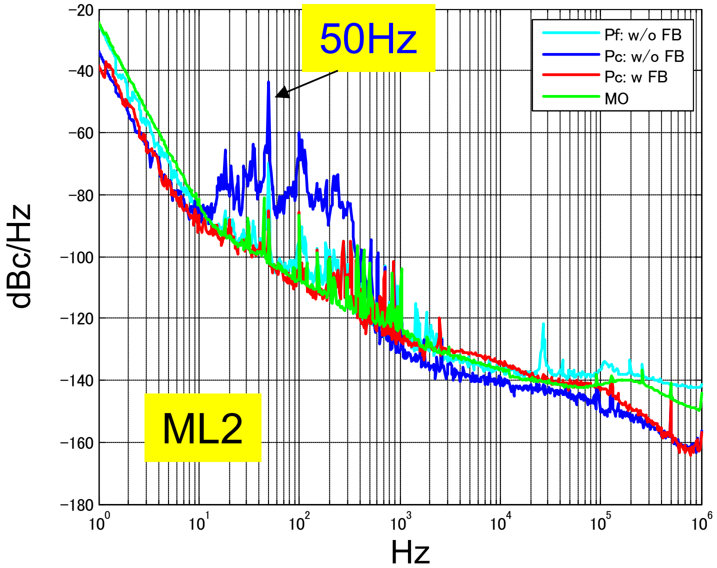


There were a few trip per month concerning about cavity due to optimum operating field and processing.

Phase noise jitter measurement using Signal Source Analyzer (Microphonics)

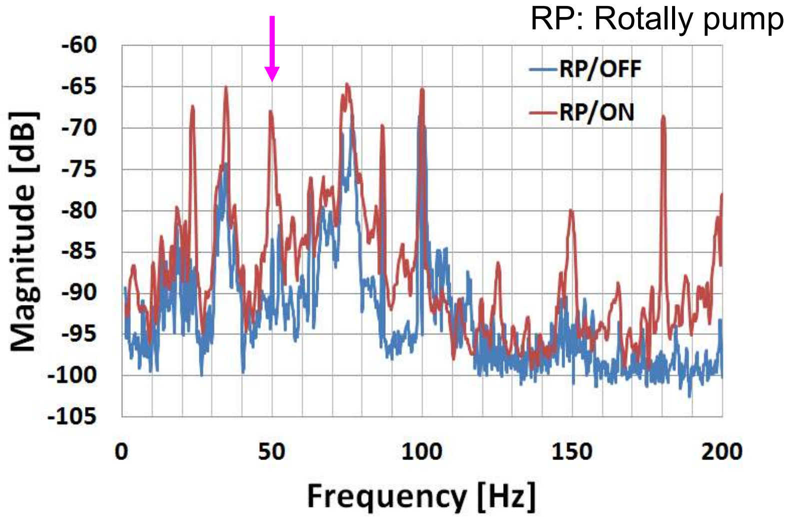
T. Miura, IPAC2014 @Dresden

Agilent E5052B



M.Egi, PASJ2016 (MOP025)

Vibrational state of "floor" around Main Linac

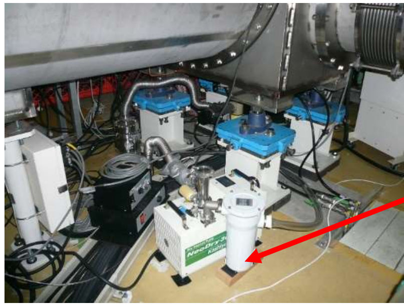


Vc Phase Noise with RF FB (10Hz-1MHz)=0.017deg

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.

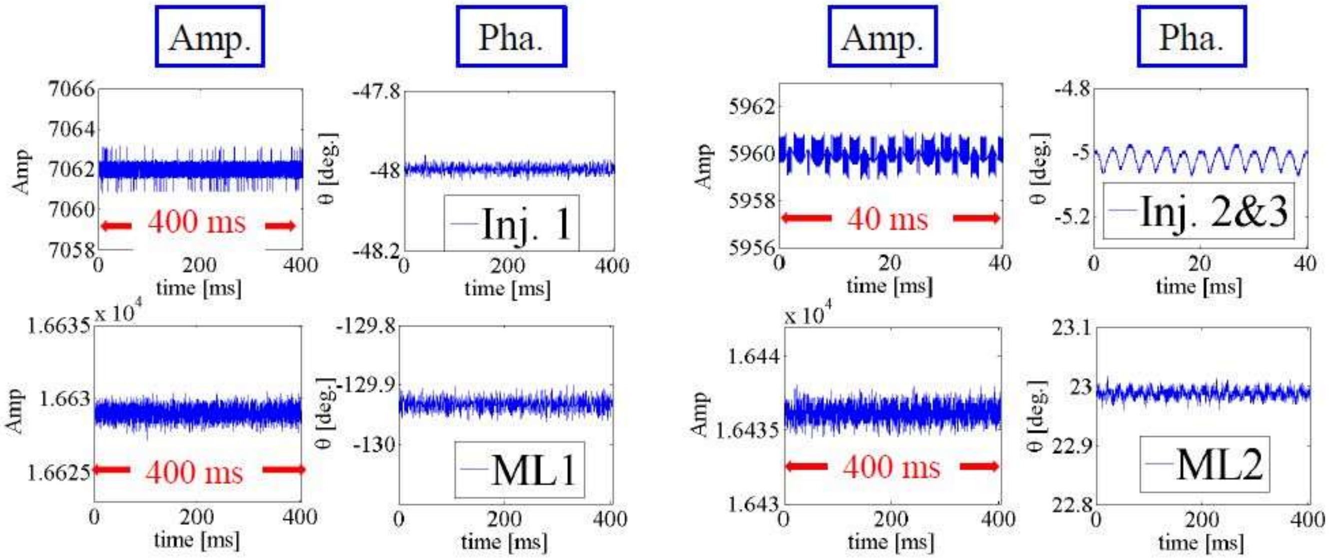


The rubber sheet was inserted under the scroll pump. The 50 Hz vibration is suppressed.

Power & LLRF stability in beam operation

F.Qiu & T.Miura et al

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

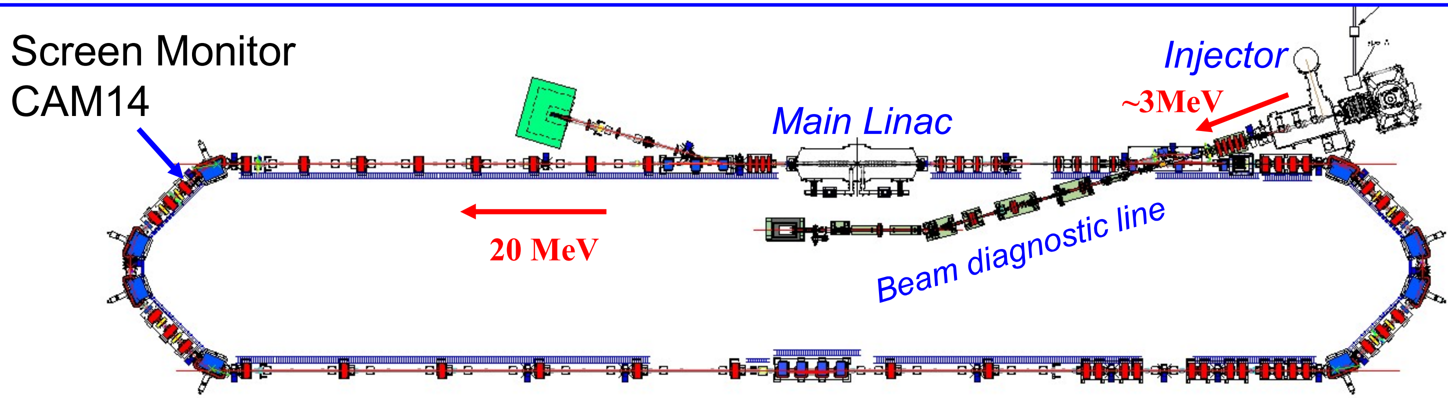


FPGA
Virtex5-FX

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

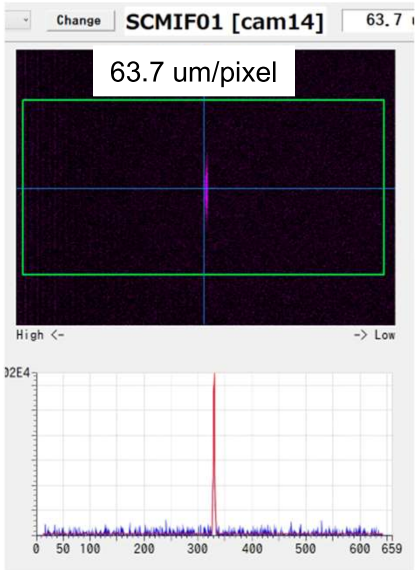
SC Cavity	Inj1(2cell)	Inj2(2cell)	Inj3(2cell)	ML1(9cell)	ML2(9cell)
Acc. Field	3.2MV/m	3.3MV/m	3.0MV/m	8.3MV/m	8.3MV/m
power	0.53kW	1.4kW	1.0kW	1.6kW	2kW
Power source	25 kW klystron	300kW klystron (Vector sum)		16 kW solid state Amp	8kW solid state Amp
QL	1.2e6	5.8e5	4.8e5	1.3e7	1.0e7
ΔA/A(% rms)	0.006%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

Stability of Beam Momentum

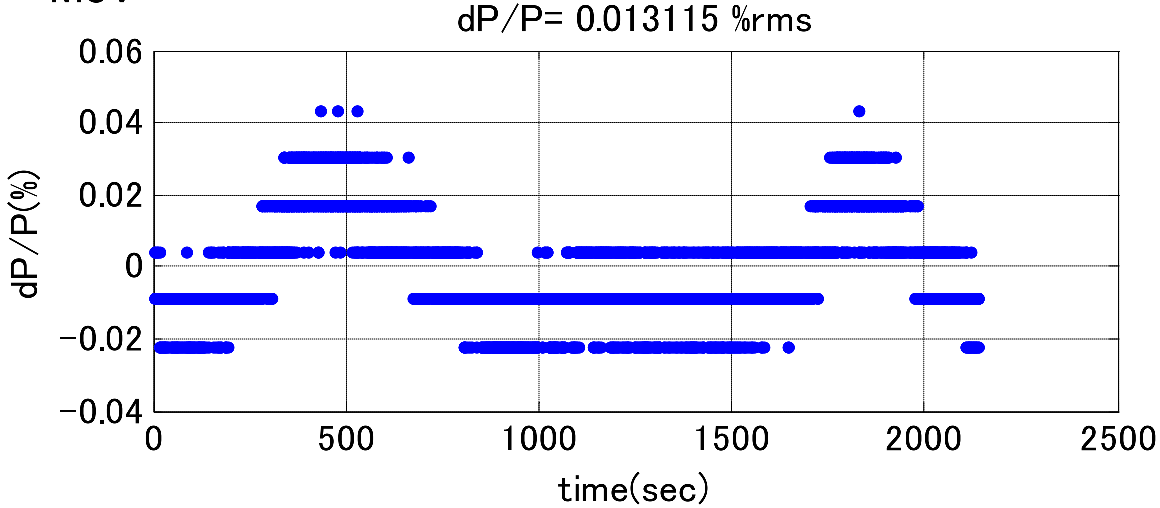


Takako Miura

Screen Monitor



Dispersion : η_X= 0.487m
Beam: 5Hz, 3ps rms, 23 fC, total Energy=19.9 MeV

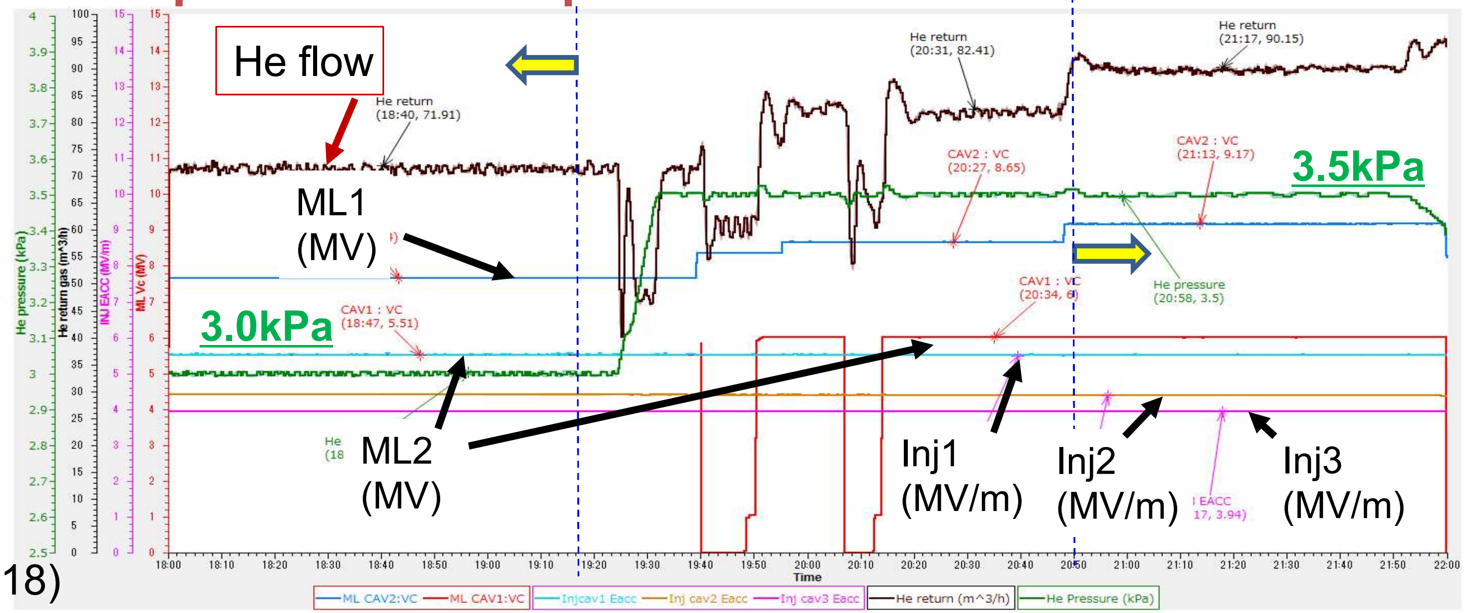


Momentum drift in the period of ~15 minutes was observed.

Thanks to this stability, we could FEL operation.

Total performance after changing He pressure

(17.5MeV operation) (19.5MeV operation)



(2019/6/18)

3.0 kPa : 1.99 K
3.5 kPa : 2.04 K
If Rs is dominated by Rres, we have little difference of Rs between 3.0 kPa and 3.5 kPa.

On the other hand, actual cryo capacity is linear to the pressure of the He pressure tank. In our case
3.0 kPa : 85 m^3/h
3.5 kPa: 99 m^3h

We tried to change the He pressure from 3.0 kPa to 3.5 kPa and tried higher energy operation.

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

Injector 4 MeV operation

19.5MeV operation, we could keep more than 1 hour by changing He pressure.

From this test, we will operate under 3.5 kPa and can increase the beam energy 19.5 MeV again.
→ obtain more margin for stable beam operation.

Summary

- Injecto cryomodule is limited by HOM heating and main linac was limited by FE.
- By appropriate pulse processing, injector cavity performance were drastically improved in 2016 and we successfully carried out stable beam operation.
- The performance of ML SC cavities were gradually degraded by field emission from 2013. But by appropriate pulse processing, cavity performance were kept and we successfully carried out stable beam operation even though we met the unexpected burst event in 2017.
- Fast arc interlock is very important to keep long term beam operation.
- RF stability of 0.01% of dA/A and 0.01 deg were performed under 1*10^7 QL. And beam was very stable. Microphinics was suppressed.

  → lead SASE-FEL operation
- 3.5 kPa cryogenic control enlarge the cryogenic performance keep stable beam operation.

Next plan

- We also plan to make the new cryomodule with new 9cell cavities to overcome field emission problem with higher gradient for EUV-FEL and/or CW-XFEL.

cERL Team (2019-2022)

High Energy Accelerator Research Organization (KEK)
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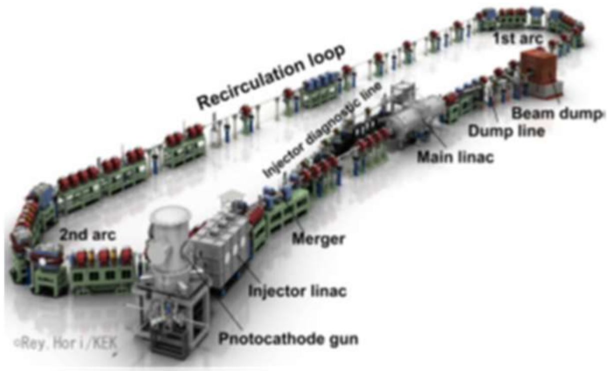


backup

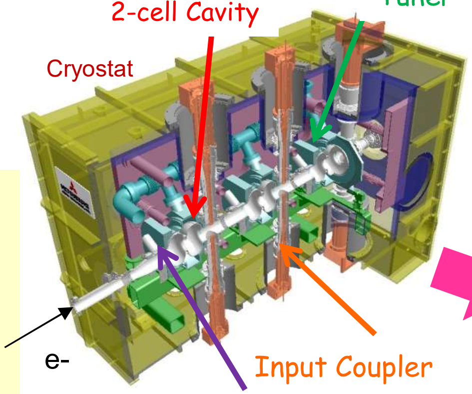
A) Apparatus of cERL injector & main linac cryomodule

T.Furuya &
E.Kako et.al

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

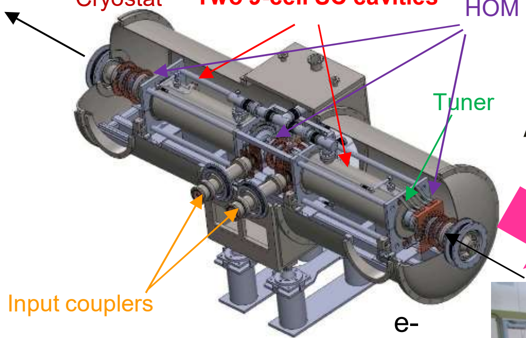


Assembling in Jun/2012

Install in Jul/2012 to cERL
High power test Jan/2013
commissioning Apr/2013

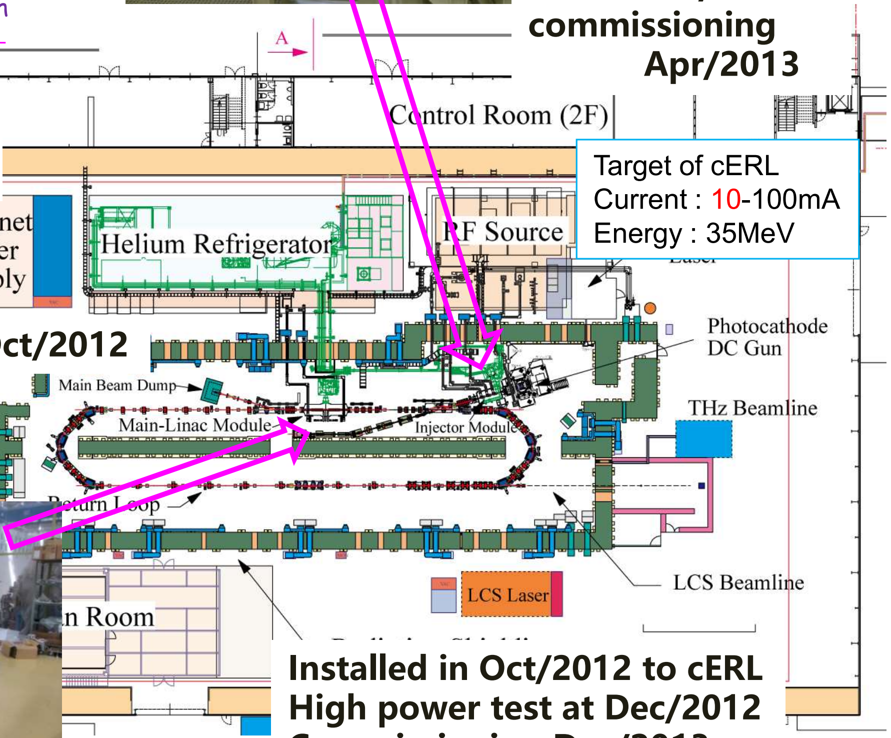
Main linac module

HOM damped (for 100mA BBU suppression)
9-cell cavity (named as ERL-model2) × 2



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

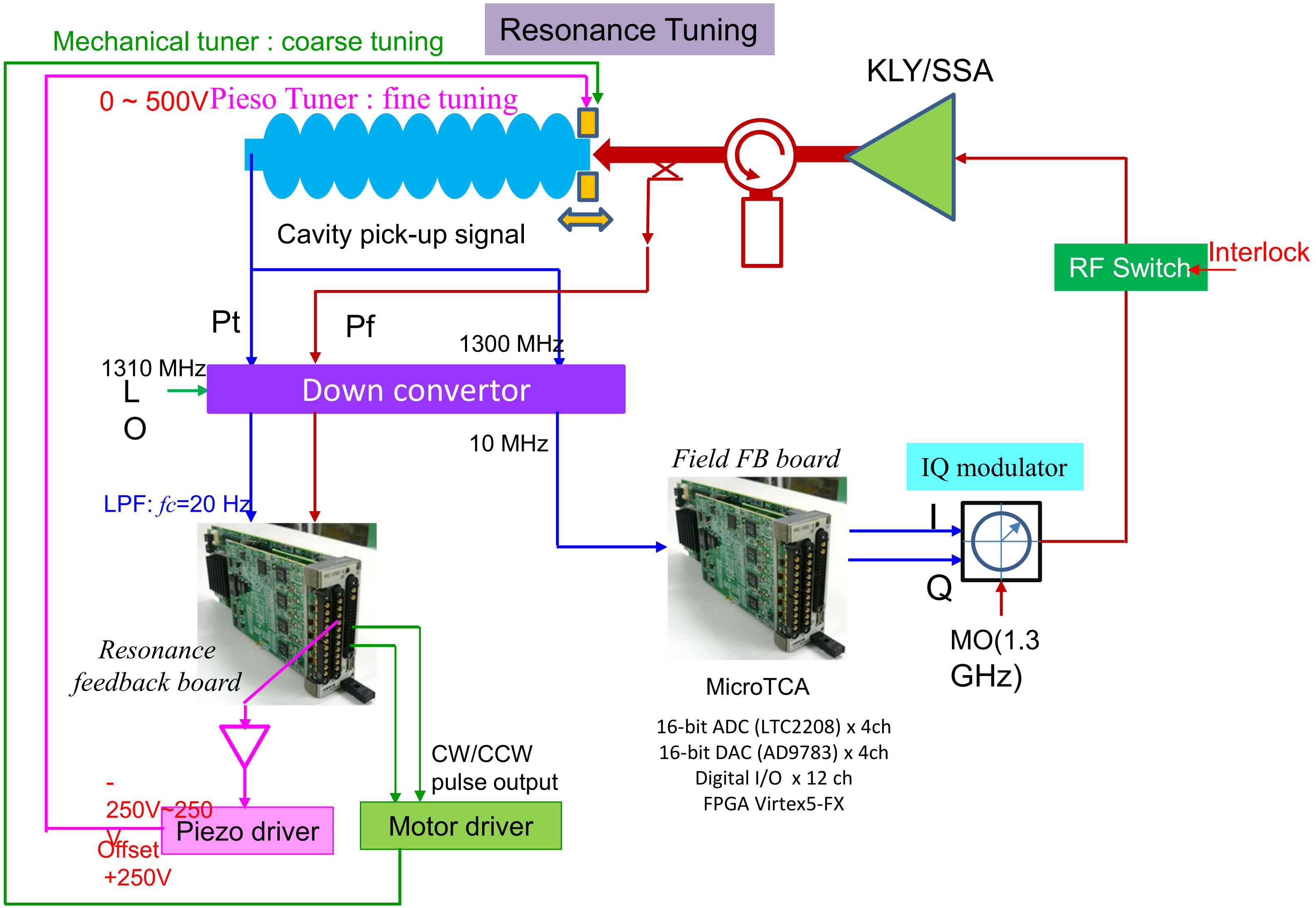
Assembling in Oct/2012



Target of cERL
Current : 10-100mA
Energy : 35MeV

Installed in Oct/2012 to cERL
High power test at Dec/2012
Commissioning Dec/2013

Digital LLRF System at cERL



Waveform of ML Cavities

T. Miura, IPAC2014 @Dresden

ML1

ΔA = 0.012% rms
Δθ = 0.014° rms

ΔA = 0.035% rms
Δθ = 0.3° rms

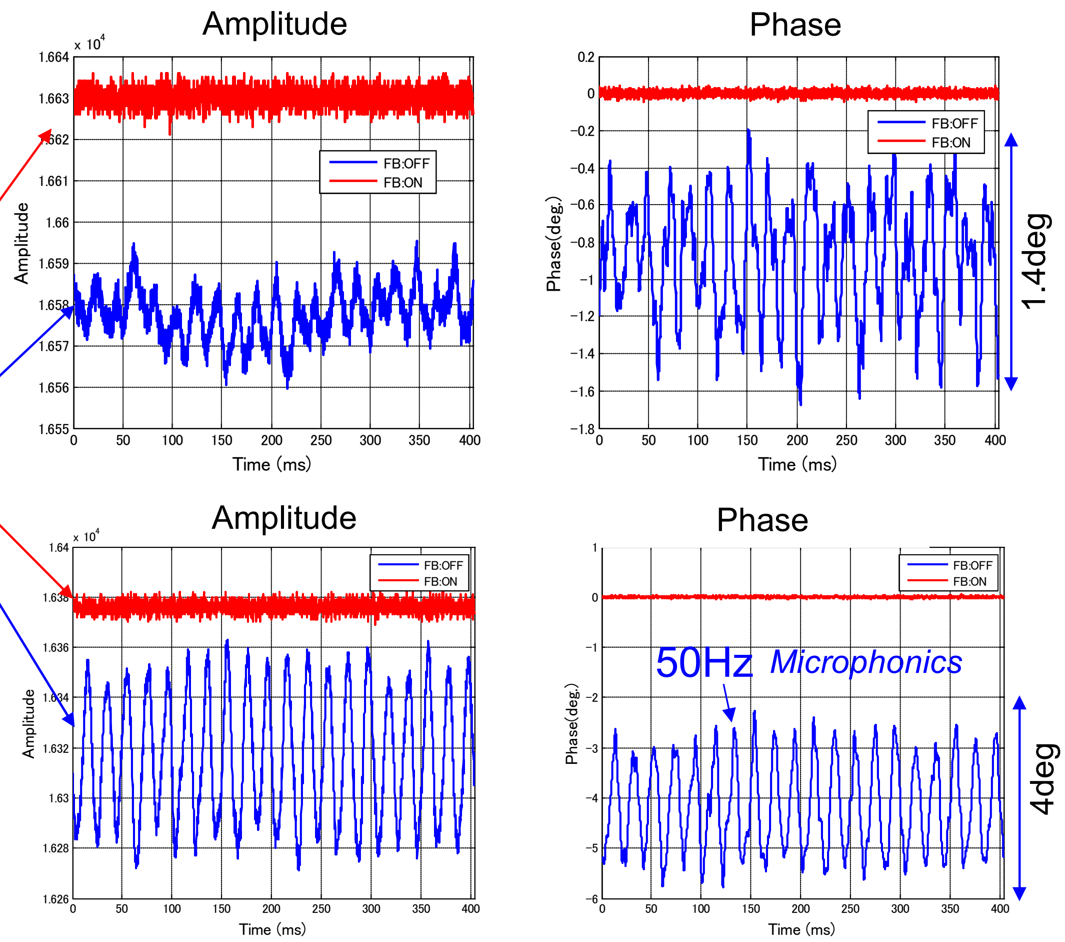
Vc: w field Feedback

Vc: w/o field Feedback

ML2

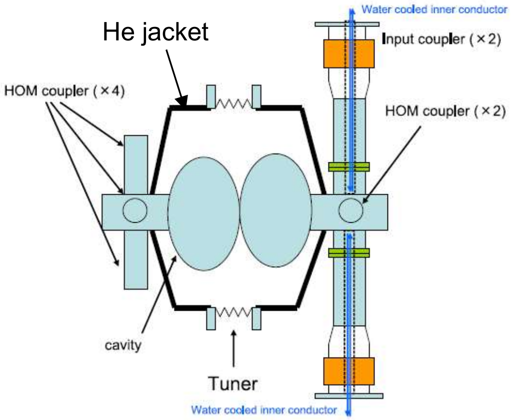
ΔA = 0.013% rms
Δθ = 0.015° rms

ΔA = 0.15% rms
Δθ = 0.6° rms

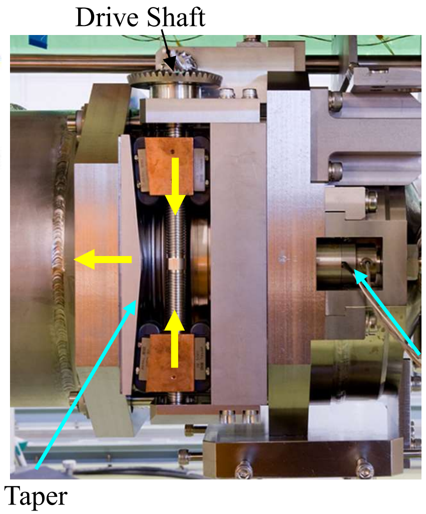


Field fluctuation by Michrophonics is stabilized by RF Feedback

Tuner system of Injector Linac



Slide-Jack tuner

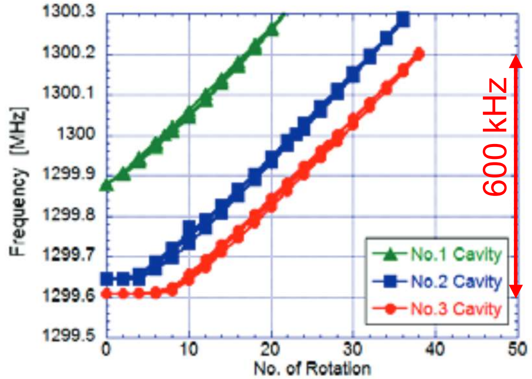


Piezo tuner
0-500V
stroke= 4 μm@2K

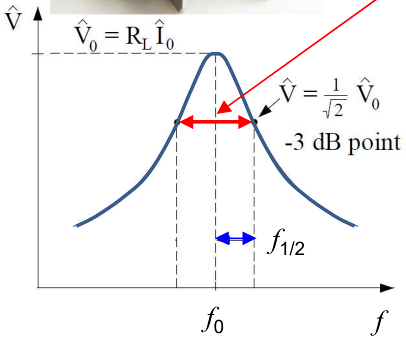
The same as KEK-STF tuner system

E. Kako, IPAC2013

20 kHz/rotation



performance of slide-jack tuner



$2\Delta f_{1/2} = f_0 / Q_L$

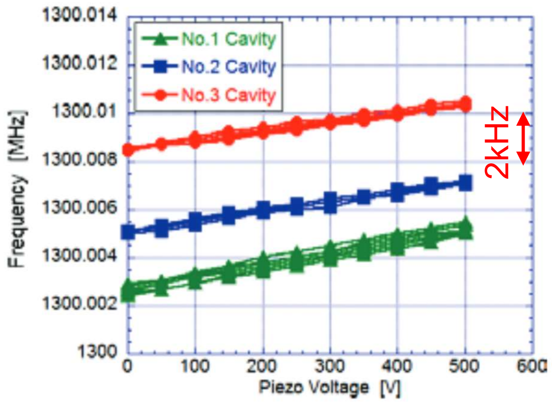
Inj1: Q_L = **1.2 ×10⁶, 2Δ$f_{1/2}$ =1.1 kHz**

Inj2: Q_L = **5.8 ×10⁵, 2Δ$f_{1/2}$ =2.2 kHz**

Inj3: Q_L = **4.8 ×10⁵, 2Δ$f_{1/2}$ =2.7 kHz**

Piezo tuner can cover the band width.

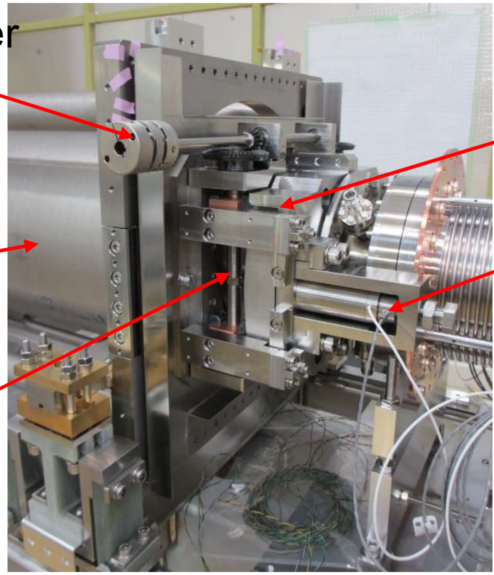
Piezo: 0-500V => 2 kHz



performance of piezo tuner

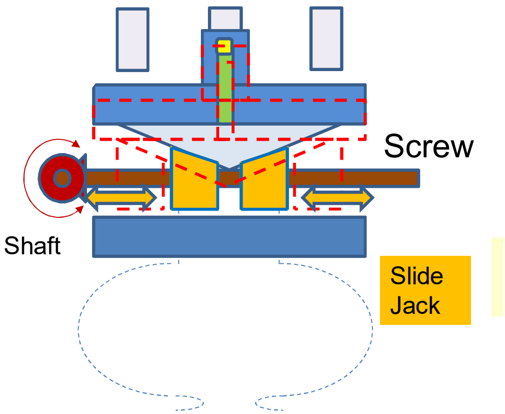
Tuner system of Main Linac

H. Sakai, SRF2013 @Paris

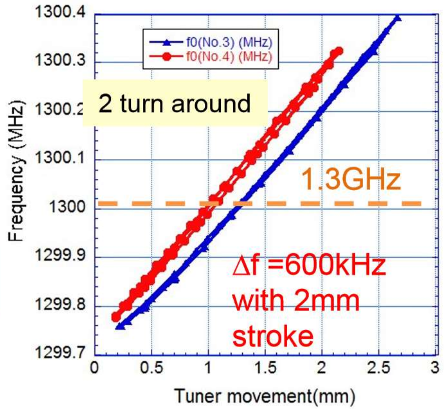


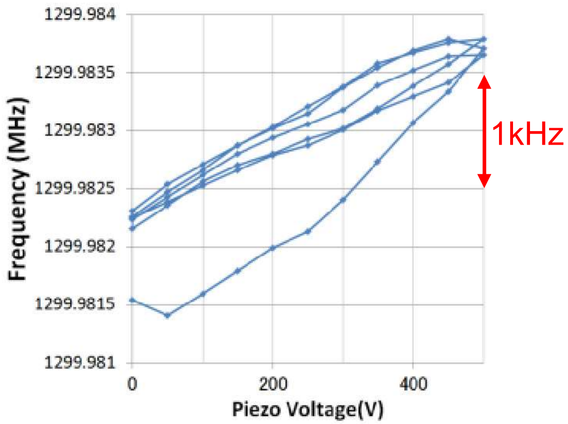
Piezo tuner
0V - 500V (offset=250V)
Stroke= 4 μm @ 2K
40 μm @ 300K
(1 μm: 300Hz)

$Q_L = 1 \times 10^7$
$2\Delta f_{1/2} = f_0 / Q_L = 130$ Hz



Coarse mechanical tuner stroke @ 2K





Recovery by pulse processing of injector cavity under sudden FE increase

Courtesy of
E.Kako

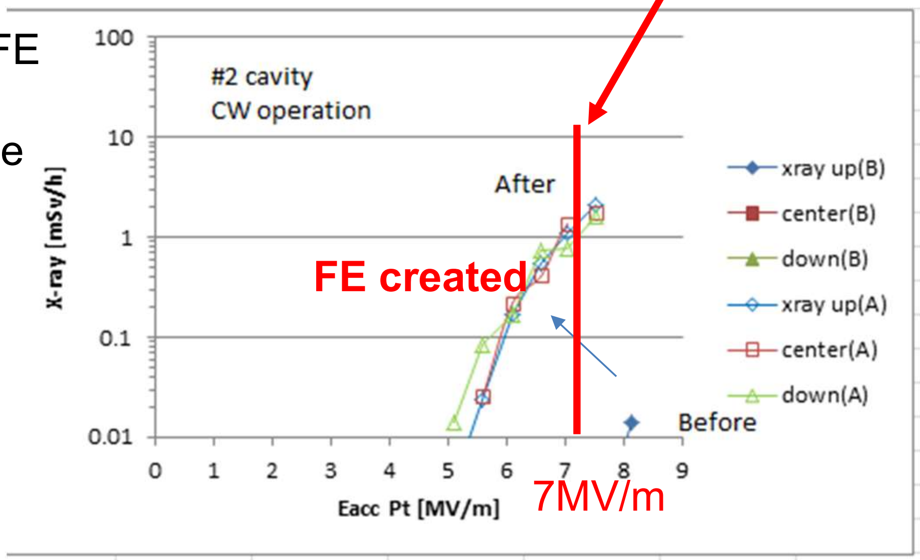
Pulse processing condition
0.5ms & 5ms with 10Hz
>15 MV/m field

During 3 years operation, once we met sudden FE increase on 2020.June.18.
-> It is difficult to operate when FE onset was decreased below 7 MV/m.

Before pulse processing

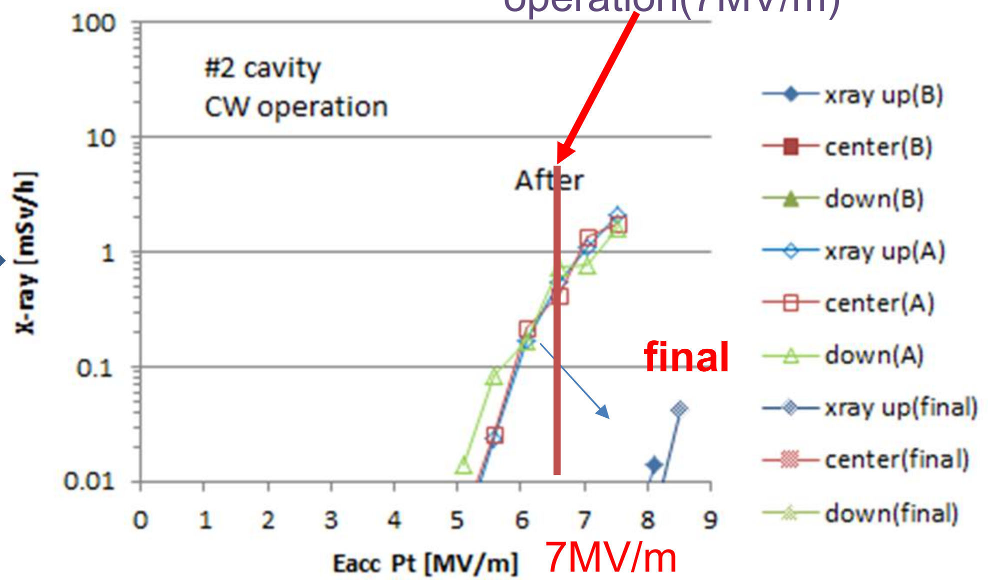
Nominal field of 5MeV operation(7MV/m)

Once FE onset became worse



After pulse processing

Nominal field of 5MeV operation(7MV/m)



After pulse processing, field emission onset recovered to more than 8MV/m , higher than nominal value.

Even though sudden FE increased, high peak pulse processing worked well for injector cryon
→ keep stable operation

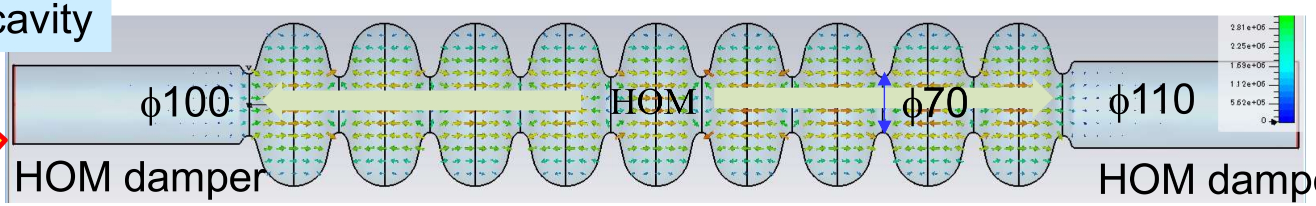
Design of Main Linac Cavity for EUV-FEL

How to overcome field emission

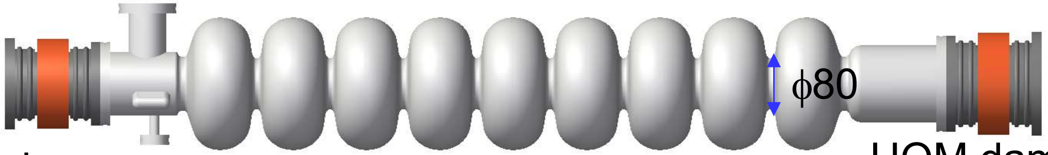
EUV cavity – TESLA-type 9-cell cavity + Large beam pipes(100ϕ & 110ϕ)

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

EUV cavity



cERL cavity (Model 2) – HOM damped cavity for 100mA operation



Parameters for acceleration mode

	ERL Model 2	EUV		ERL Model 2	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)

From cERL stable beam operation of 8.3 MV/m in 3 years with less trip ratio.
Stable operation at 12.5 MV/m seems achievable due to reduced E_p/E_{acc}.