Long-term operation experience with beams in Compact-ERL cryomodules

SRF2017@Lanzhou

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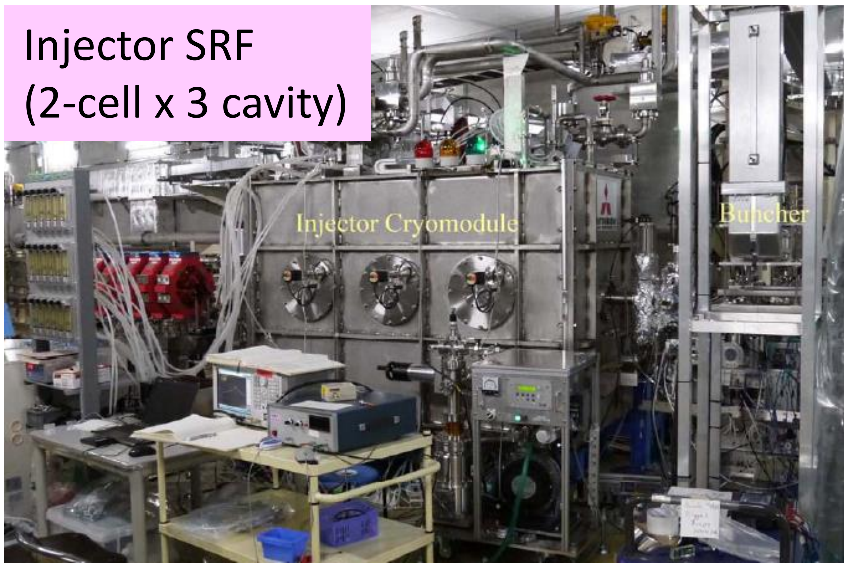
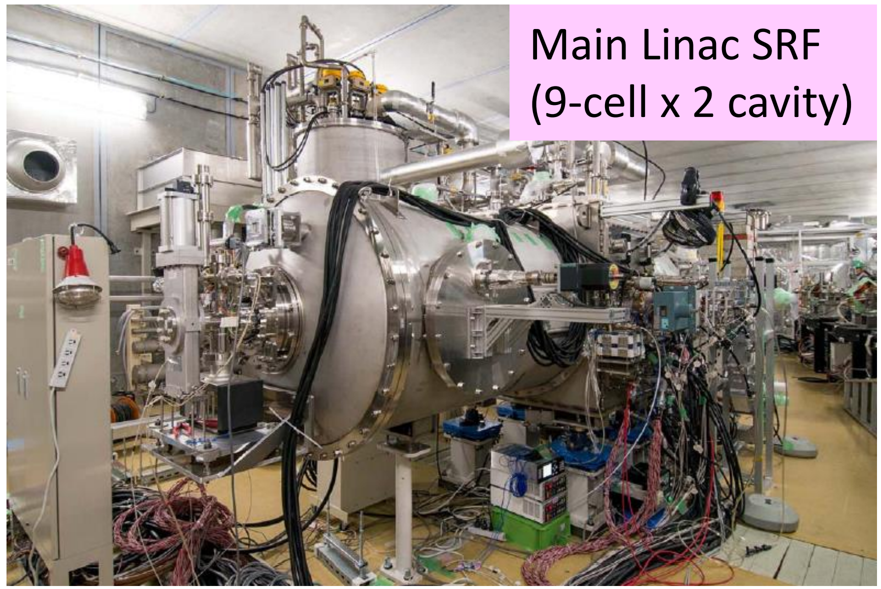
Outline

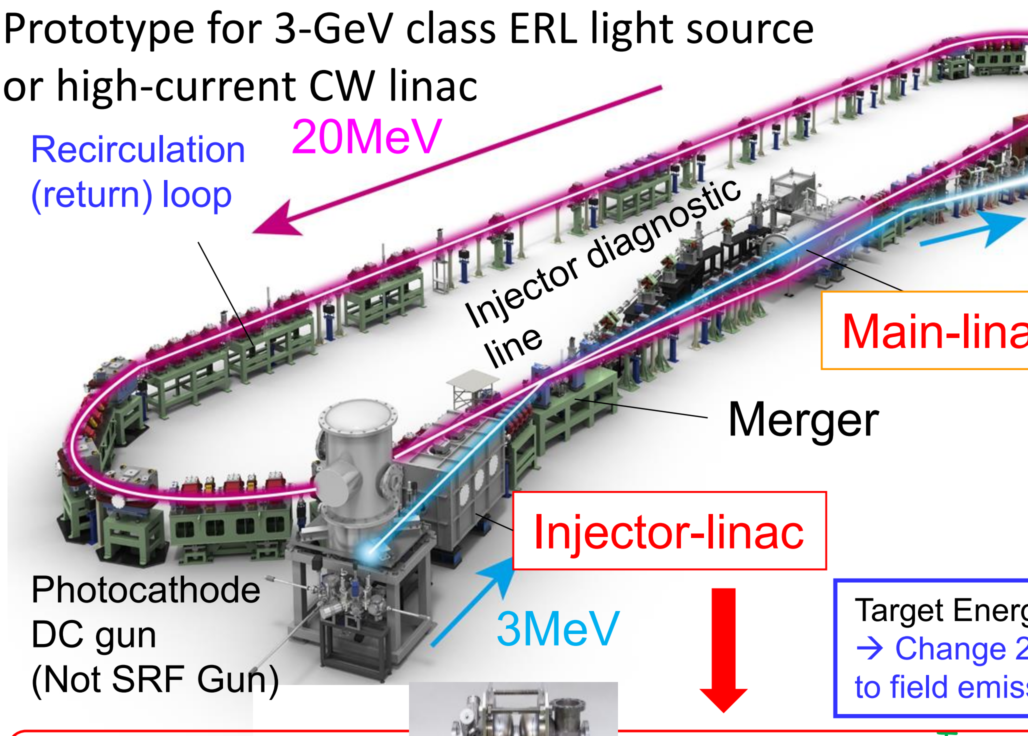
- Introduction of Compact ERL
- Beam commissioning of cERL
- Typical SRF performance
- Long term operation of SRF cryomodule
  - ➢Injector linac
  - ➢Main linac
- Summary





Compact ERL

Prototype for 3-GeV class ERL light source or high-current CW linac



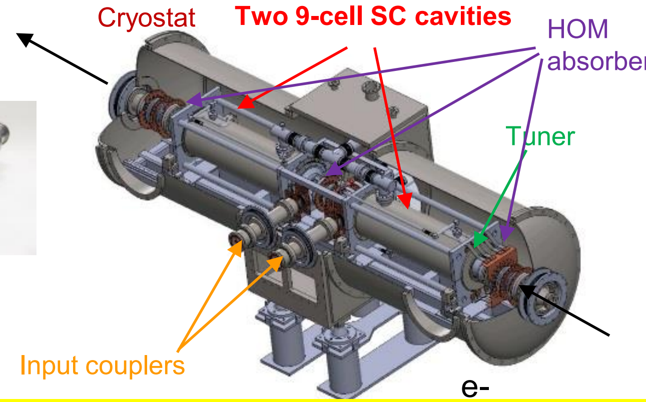
Target Energy : 35MeV → Change 20MeV due to field emission

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

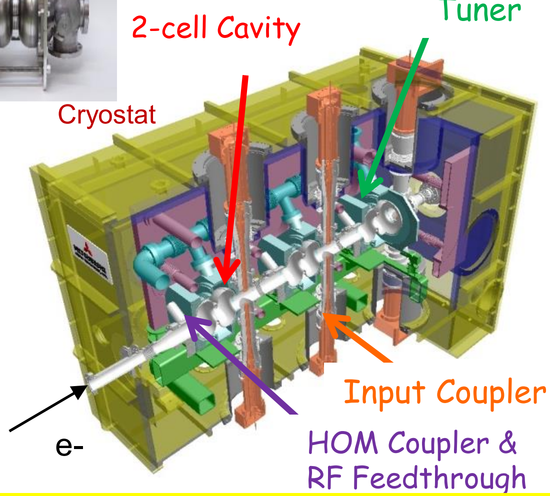


Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

Injector module

2-cell cavity × 3
Double coupler

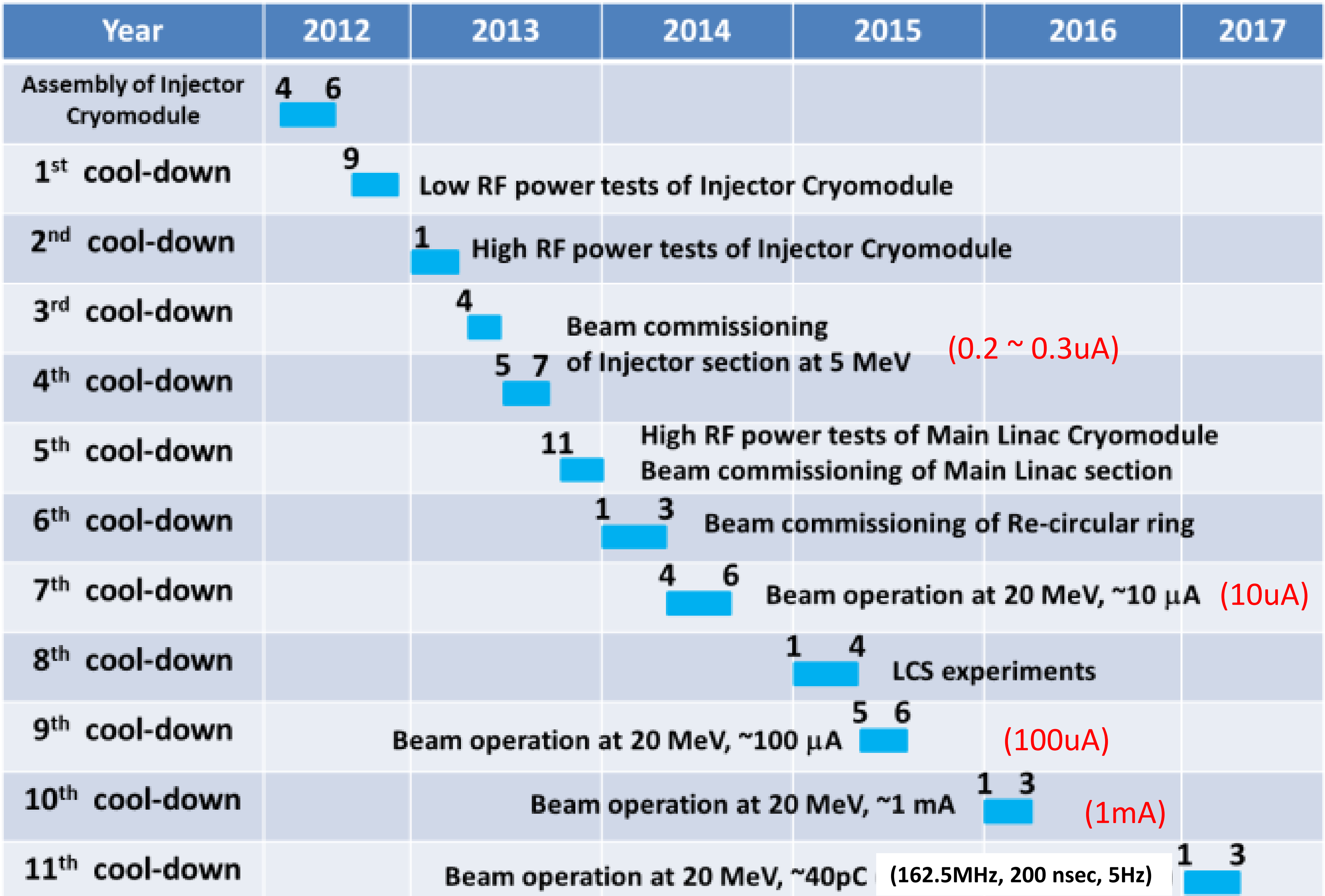
RF frequency: 1.3 GHz
Input power :
10kW/coupler (10mA, 5MeV)
180kW/coupler (100mA, 10MeV)
E_{acc}: 7.6MV/m (5MeV)
15MV/m (10MeV)
Unloaded-Q: $Q_0 > 1\times10^{10}$



Requirement was satisfied at V.T and for initial 10mA requirement .

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)


Year
2012
2013
2014
2015
2016
2017
Assembly of Injector Cryomodule
4 6
1st cool-down
9
Low RF power tests of Injector Cryomodule
2nd cool-down
1
High RF power tests of Injector Cryomodule
3rd cool-down
4
Beam commissioning
of Injector section at 5 MeV
(0.2 ~ 0.3uA)
4th cool-down
5 7
5th cool-down
11
High RF power tests of Main Linac Cryomodule
Beam commissioning of Main Linac section
6th cool-down
1 3
Beam commissioning of Re-circular ring
7th cool-down
4 6
Beam operation at 20 MeV, ~10 μA
(10uA)
8th cool-down
1 4
LCS experiments
9th cool-down
5 6
Beam operation at 20 MeV, ~100 μA
(100uA)
10th cool-down
1 3
Beam operation at 20 MeV, ~1 mA
(1mA)
11th cool-down
1 3
Beam operation at 20 MeV, ~40pC
(162.5MHz, 200 nsec, 5Hz)

Strategy for beam commissioning

- In each step, beam current is limited by radiation safety.
- Important point is "to control loss of beam", even in the case of high-current operation.

↓

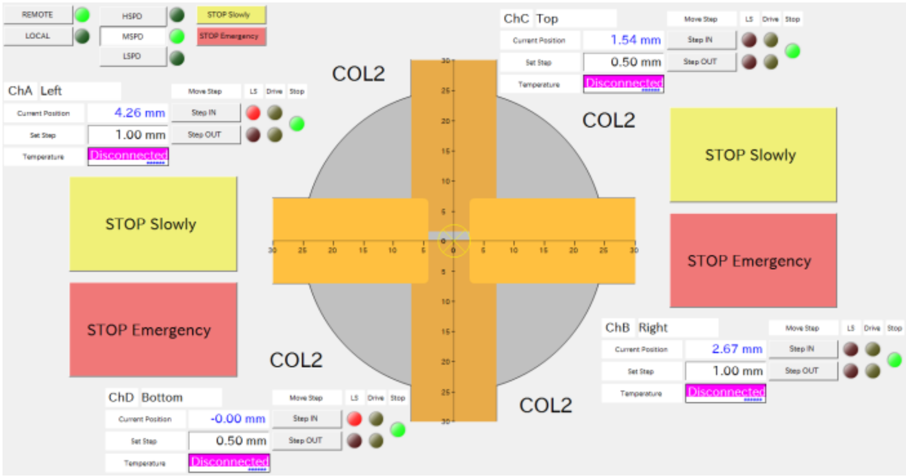
1. Beam commissioning start from pulse mode(~1us). After adjustment (control of beam loss), move to CW mode.
2. Sophisticated beam tuning(optics matching) based on beam based alignment is carried out.
3. Collimators have important role to realize "controlled beam loss".
4. Interlock system, such as loss monitor and radiation monitor, is essential to minimize accidental beam loss.

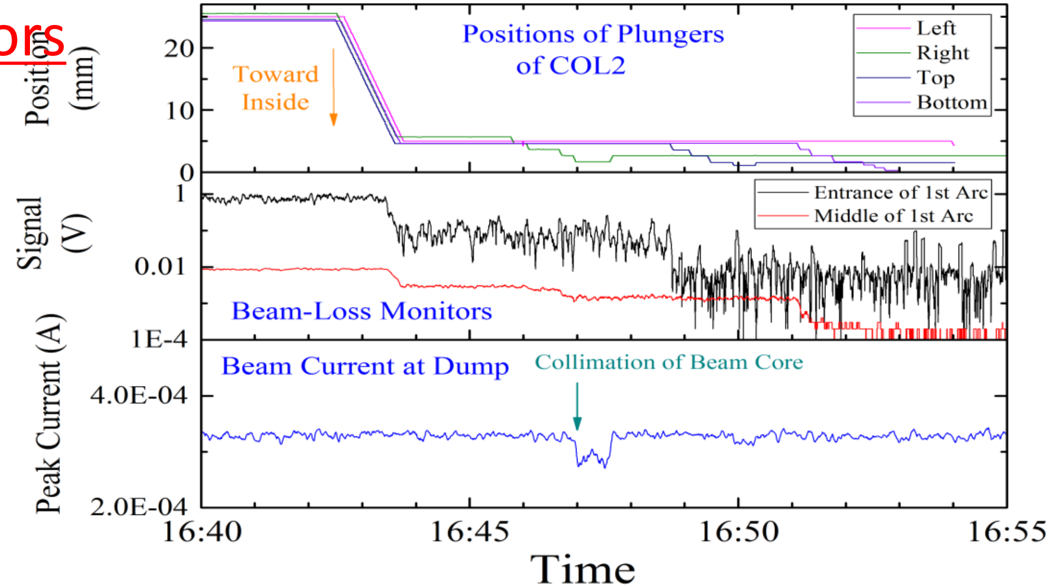
Beam loss may cause unexpected vacuum burst or discharge

→ This may cause degradation of SRF cavity

※ Control of beam loss is important to avoid unwanted degradation

Beam conditioning by using collimators



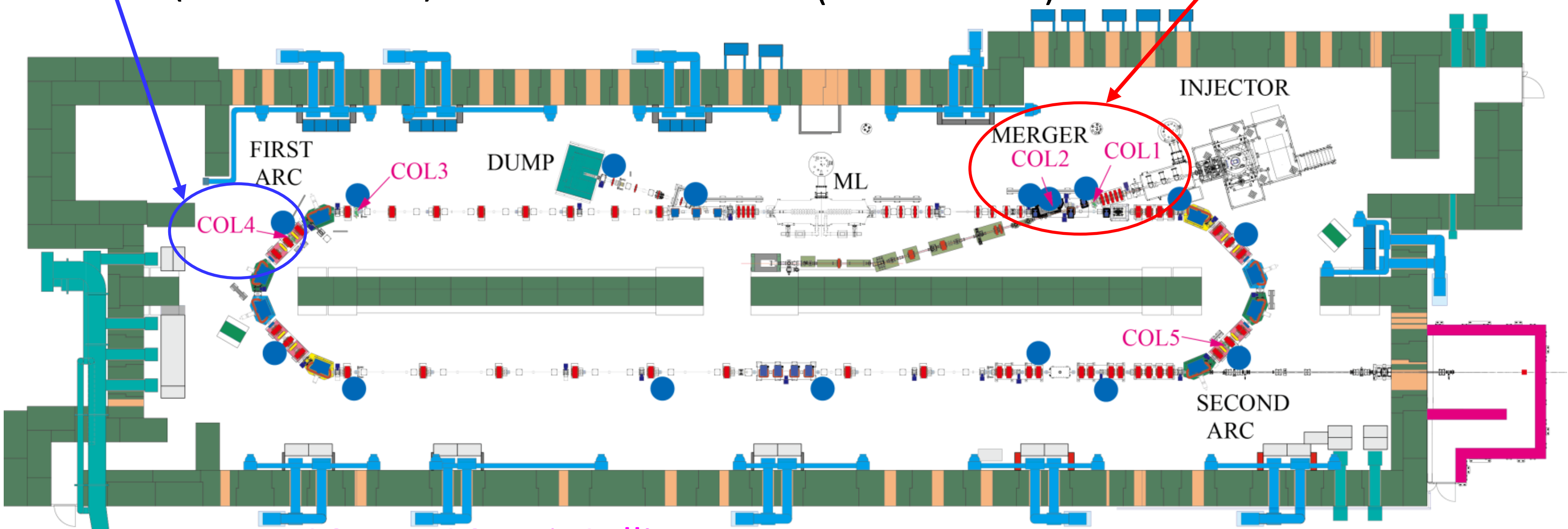


Collimator at first arc section(COL4) is also used.

(E = 19.9 MeV)

Collimator at low energy region (COL1, 2) are mainly used

(E = 2.9 MeV)

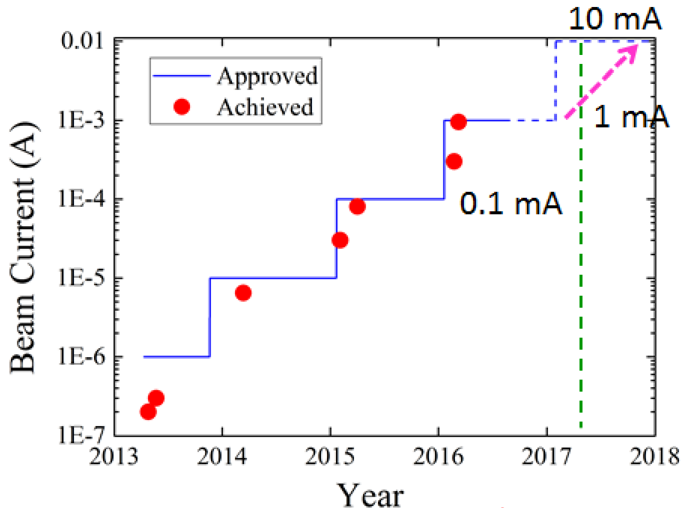


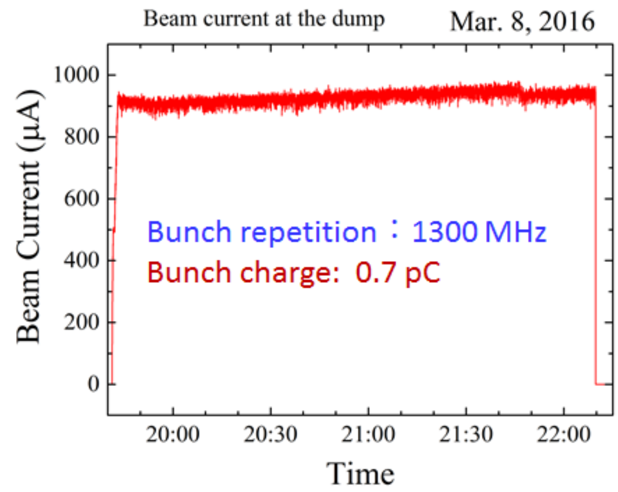
COL1～COL5 : Collimator

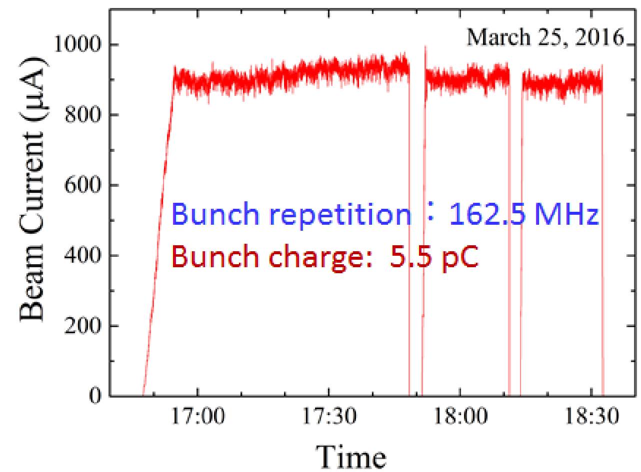
● FAST LOSS MONITOR

Beam current upgrade

2016 Japan Accelerator Society Meeting, Shogo Sakanaka



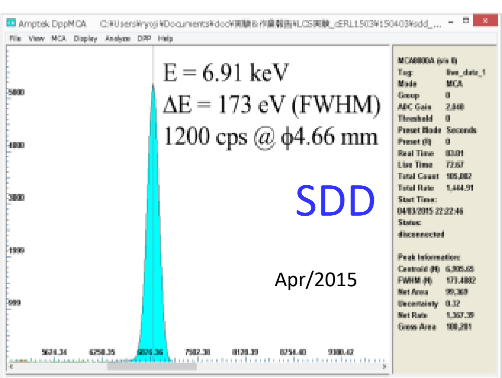


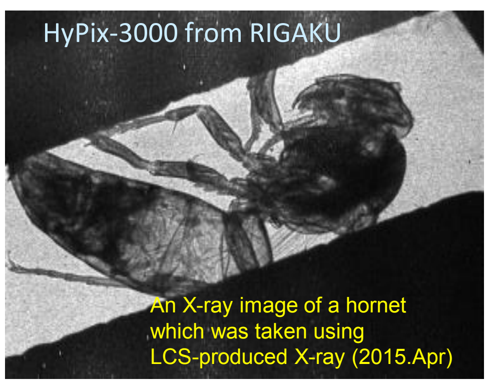


- Beam current increased step by step.
- Now 1mA(CW) electron beam is operated with energy recovery mode.

Experiment① Laser Compton scattering

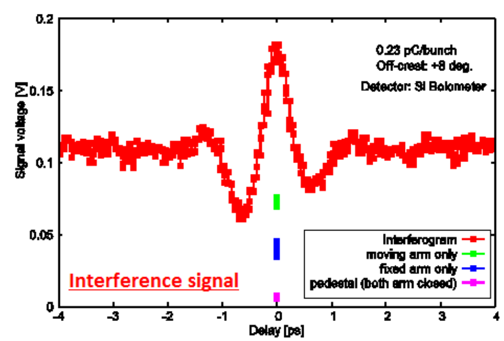
Bright X-ray LCS beam can be generated by using 0.9 mA with low emittance beam. Imaging was successfully taken.

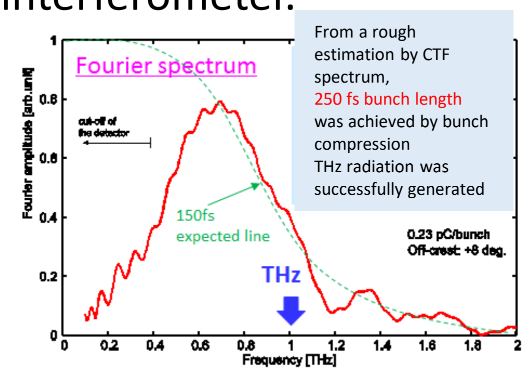




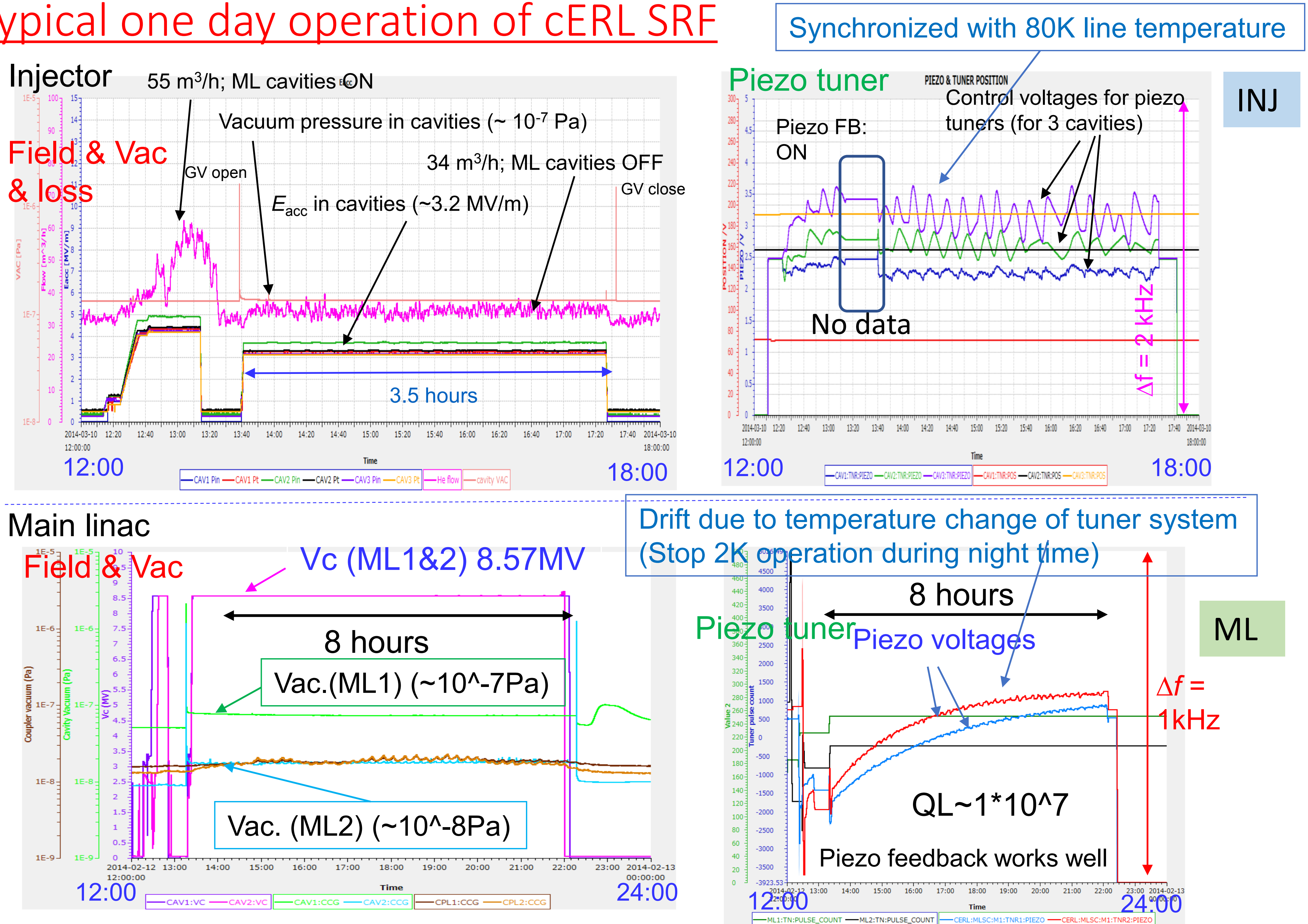
Experiment② THz generation

Electron bunch was compressed to ~250fs using sextupole magnet. THz component generated by a coherent transition radiation (CTR) monitor is analyzed by a Michelson interferometer.





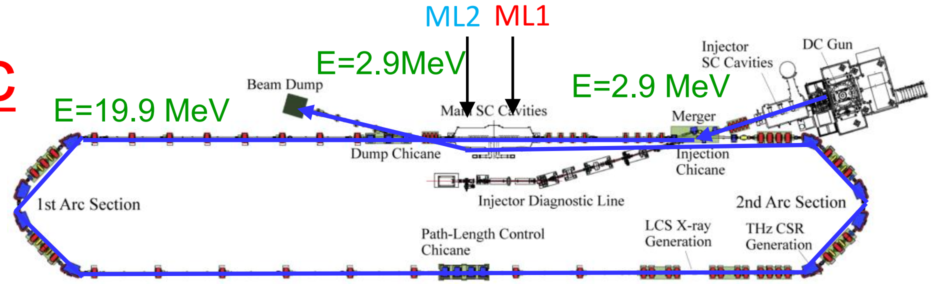
Typical one day operation of cERL SRF



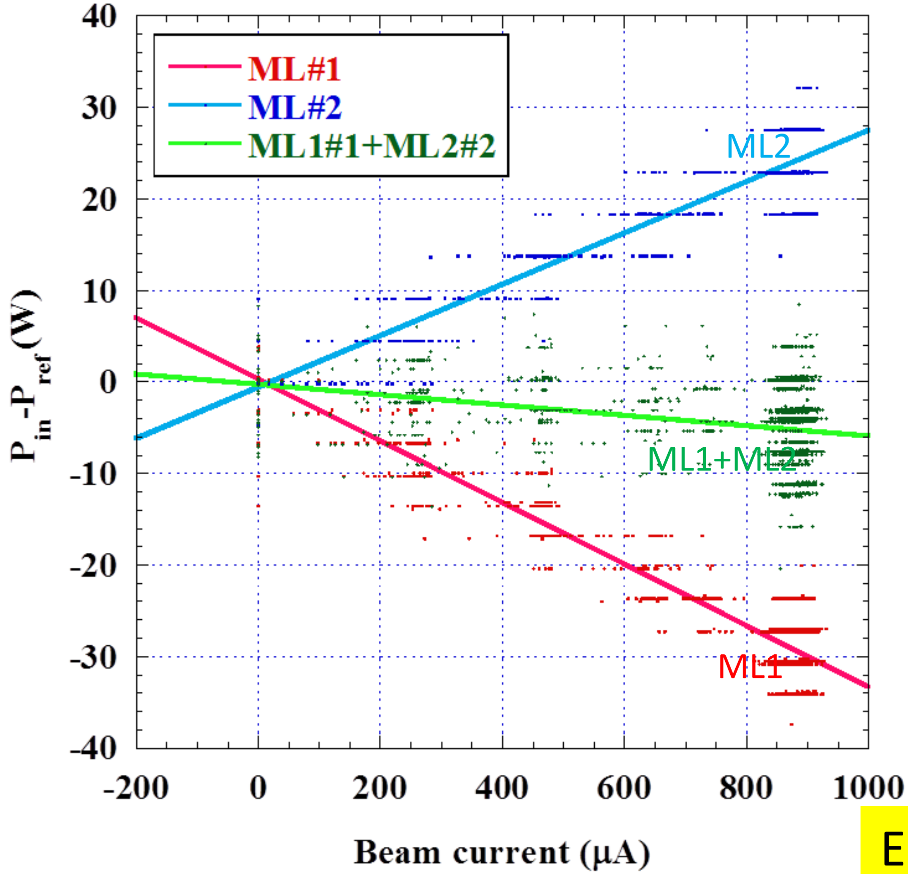
Energy recovery at main linac

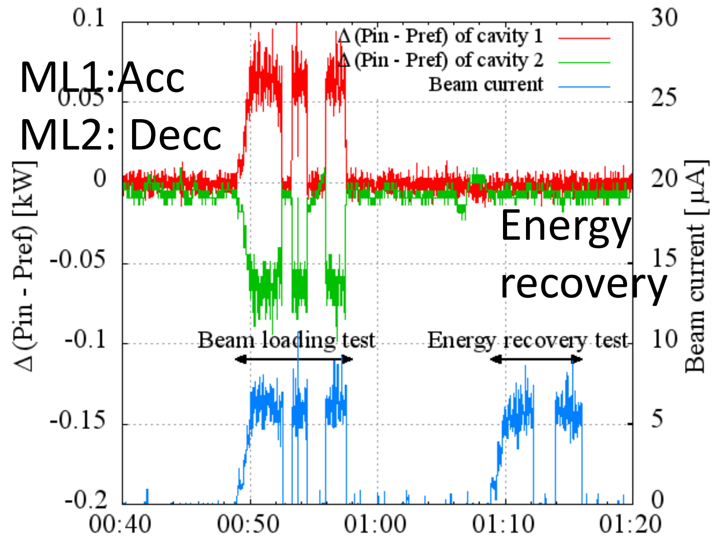
Pin – Pref ～ Ploss + Pbeam

Δ(Pin – Pref) ～ Pbeam ← Beam loading



ML





Energy loss measured from the graph = 4 W. (+-4W)

Required power without recovery is :

17.14 MV x 900 uA = 15.4 kW

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

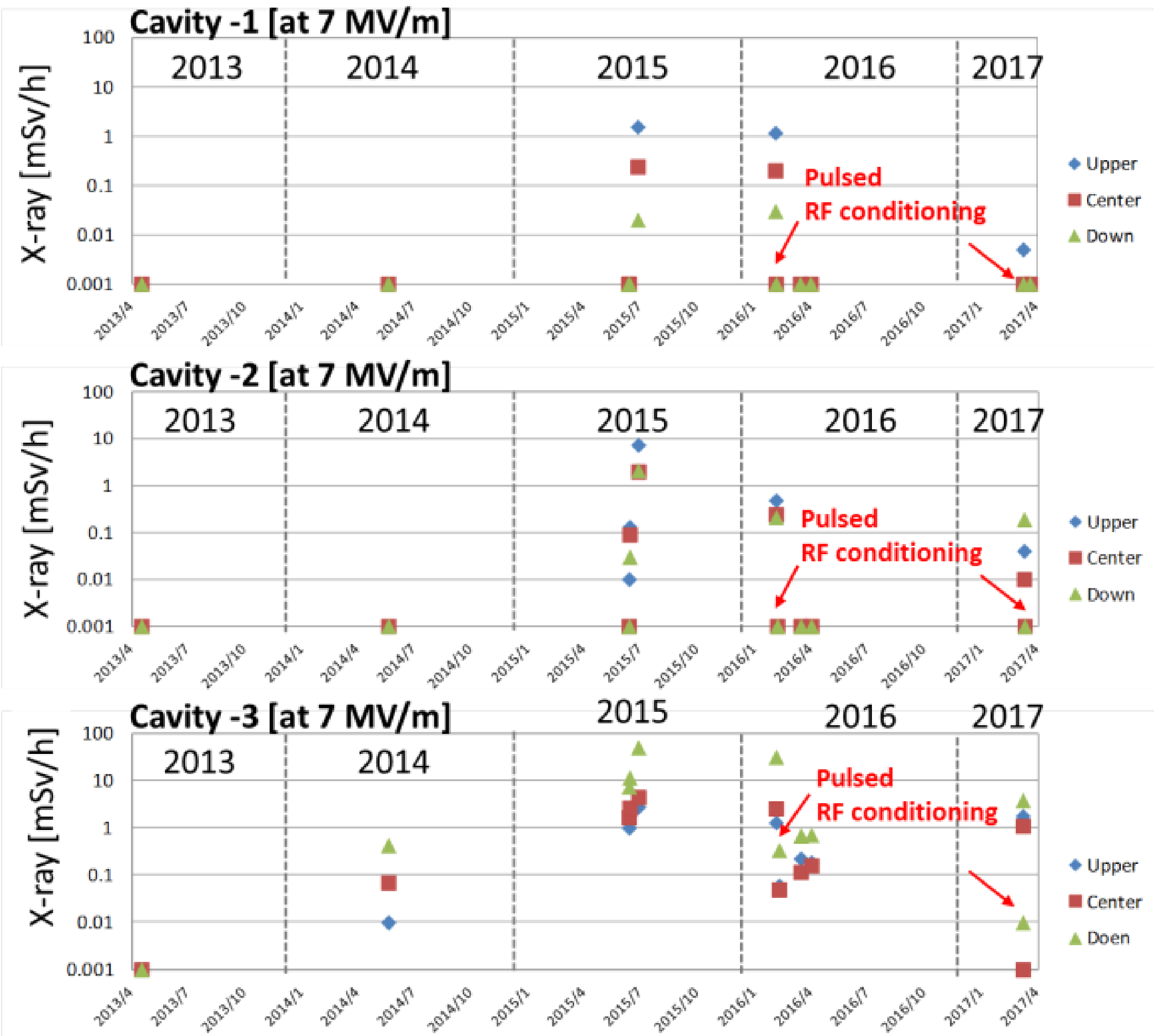
Cavity voltage：

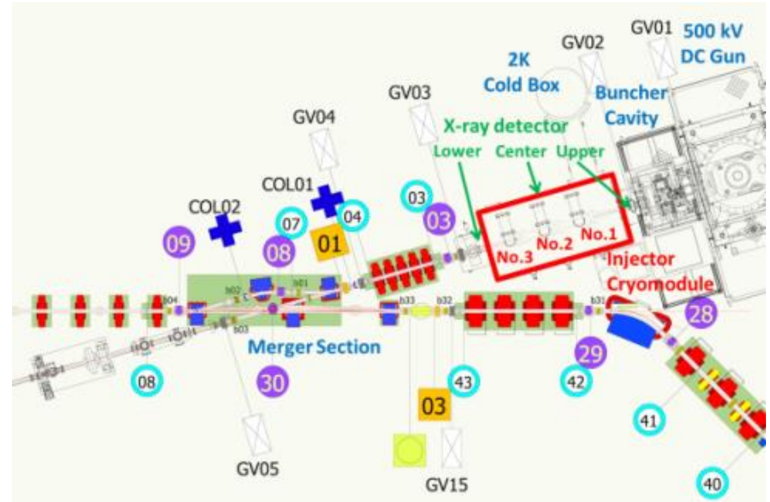
8.56 MV (ML1), 8.57 MV (ML2)

Current: 0 ～ 900uA

※ different slop of ML1/ML2 come from energy difference of (acceleration – deceleration) beam

Long term operation of cERL injector cryomodule





Sometimes performance degraded by field emission. Especially, sudden jump at 2015.

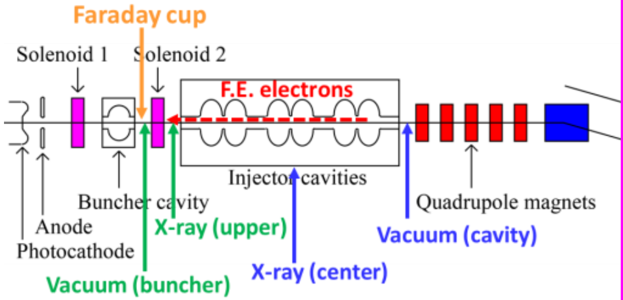
Try to suppress it by applying high power pulsed processing.

See detail on MOPB097
E.Kako et. al.

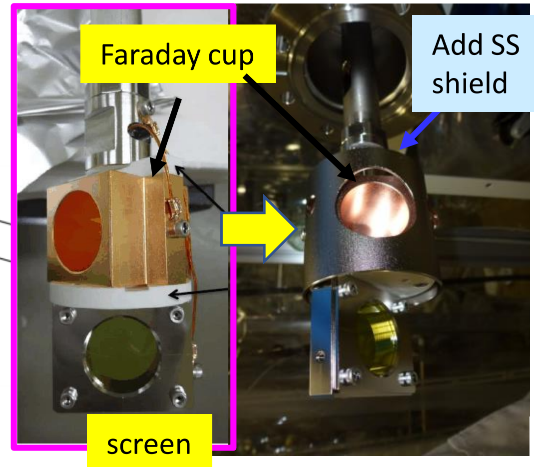
INJ

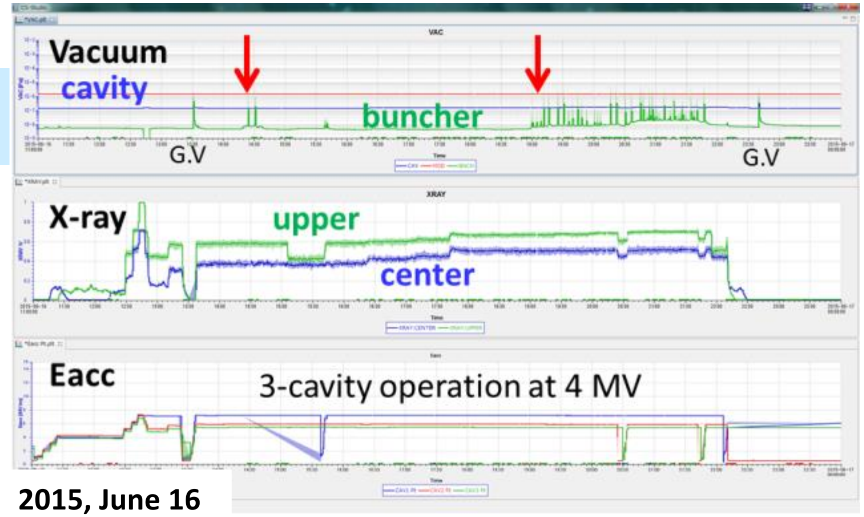
Unexpected discharge(1)

INJ



Screen monitor in front of Gun

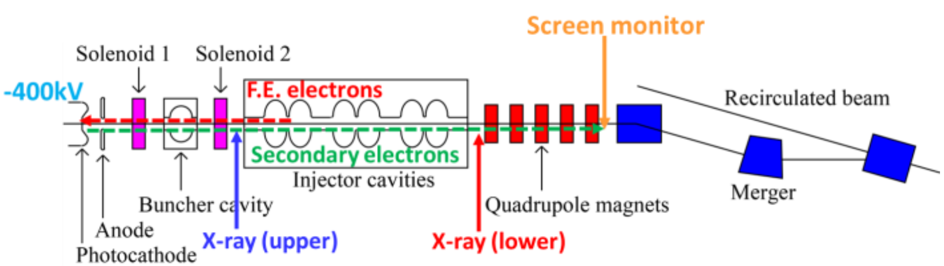


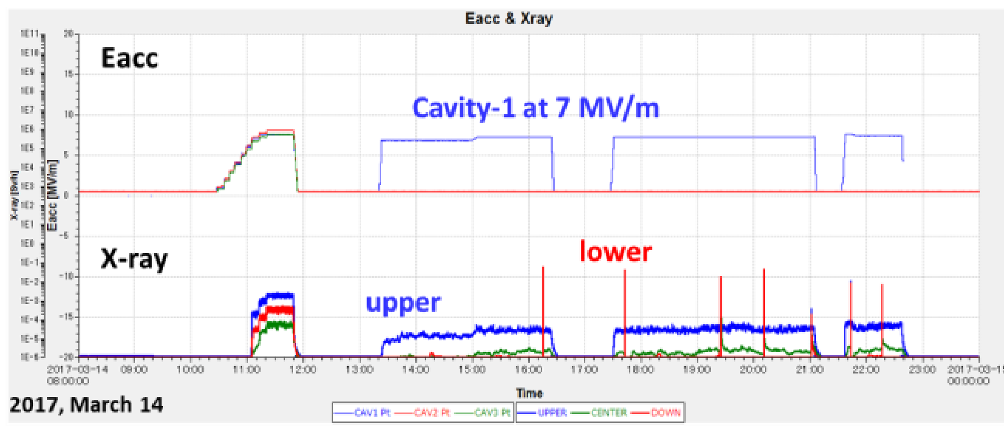


Field emitted electron induce a charge up of Faraday cup.
⇒Discharge lead to vacuum deterioration and increase of radiation.
Improvement on Faraday cup solved problem.

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

Unexpected discharge(2)





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.

See detail on MOPB097 E.Kako et. al.

Recovery by Pulse processing at injector cryomodule

INJ

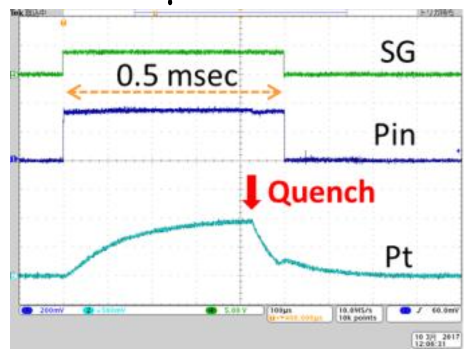
Sometimes the pulse processing is applied for injector cavities.
Pulse length start from 0.5ms, then 5ms and finally CW

See detail on MOPB097
E.Kako et. al.

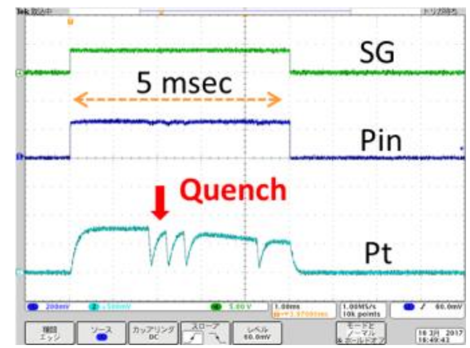
RF conditions of pulse processing

	No.1 Cavity	No.2 Cavity	No.3 Cavity
Q_L	1.2 x 10^6	5.3 x 10^5	5.4 x 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

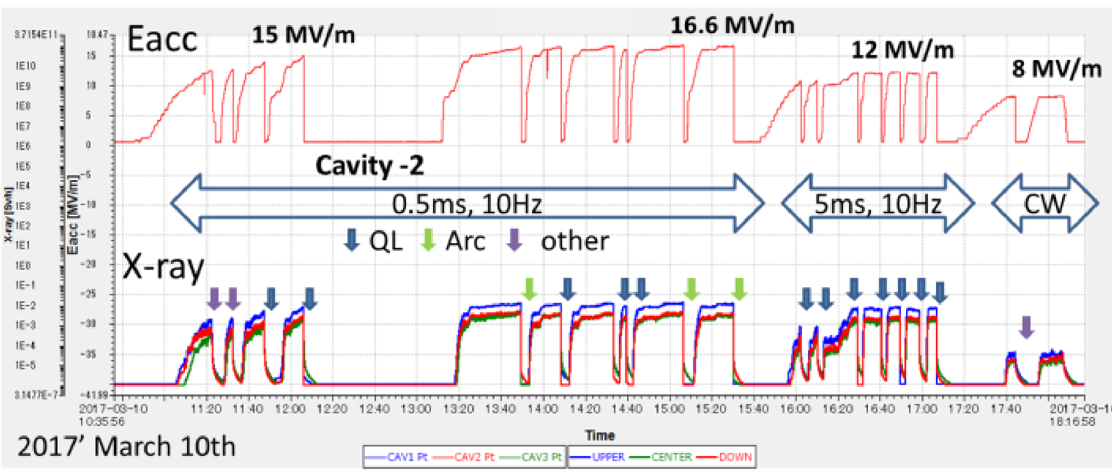
500µsx5Hz

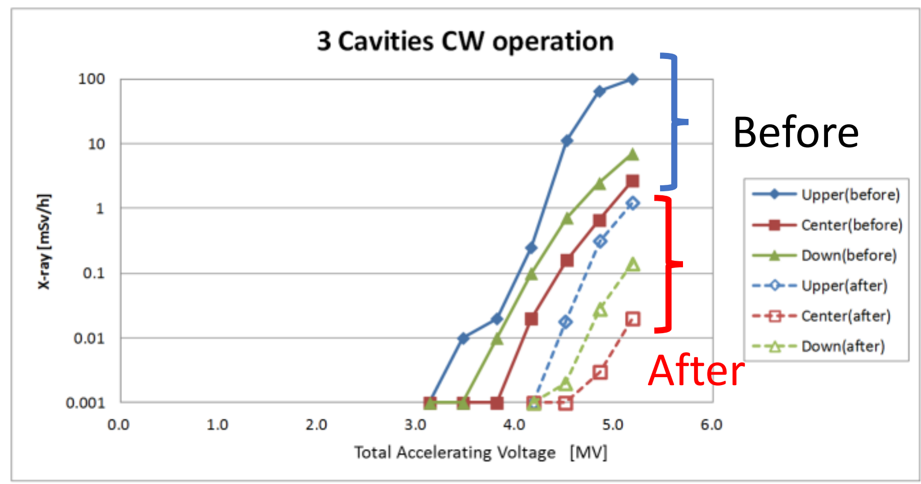


5msx5Hz



History of pulse processing of No.3 injector Cavity(8 hours)

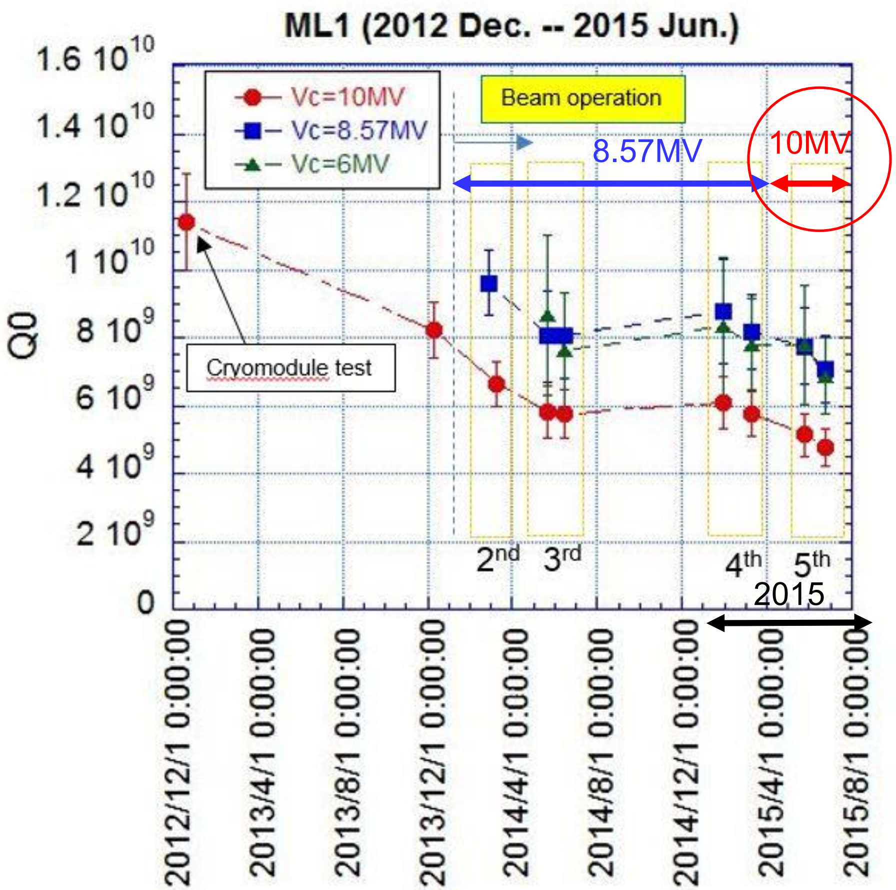


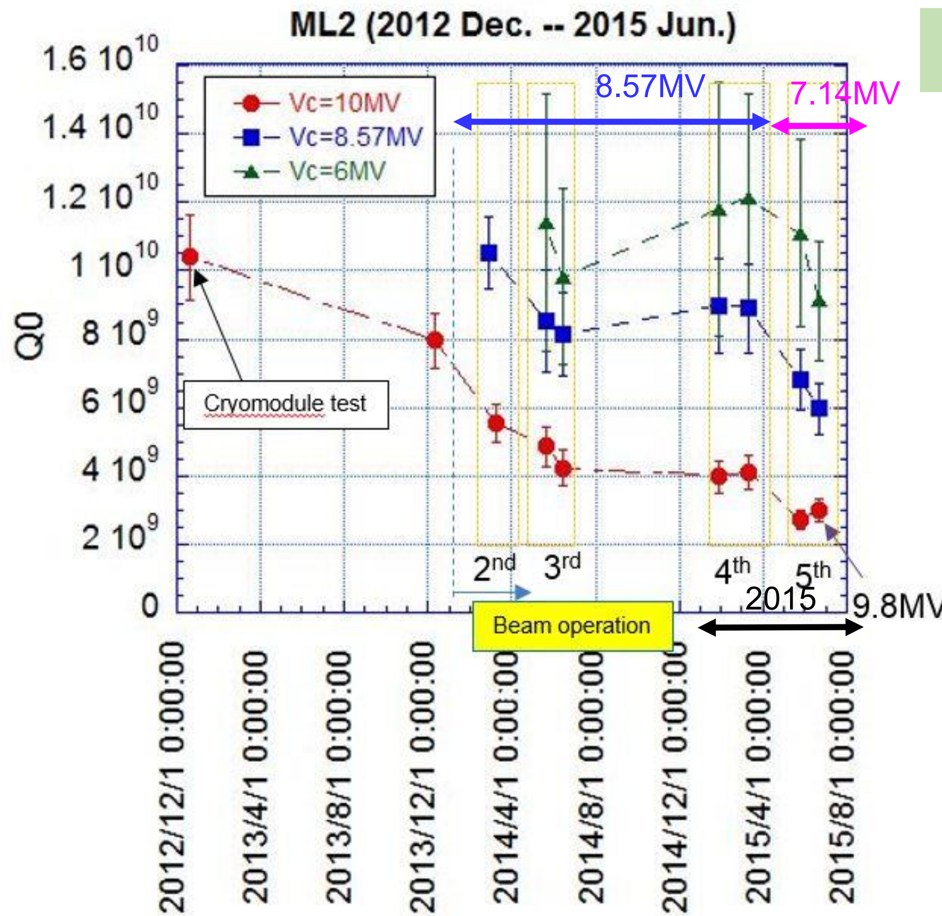


Above are example of pulse processing applied at 2017/March.
Radiation level of each cavities decrease around two orders.

Long term cavity performance of Main linac cavities before 1mA operation (3 years)

ML



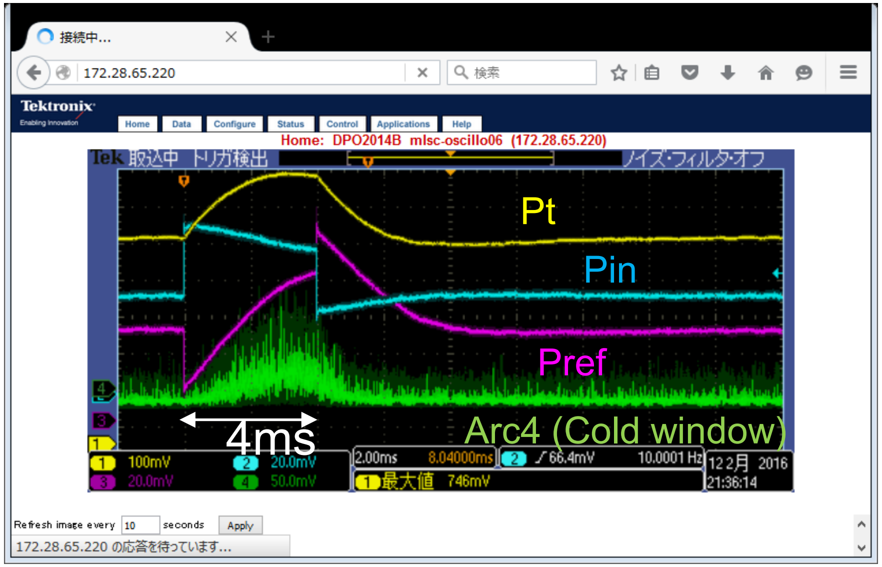


We met Q degradation during beam operation. But we kept same performance within error bars after degradation from May 2014 to March 2015 and no trip was observed for 1.5 months, even if no pulse processing was applied in 2015. So in 5th phase in May – June 2015, one cavity of ML1 increase the field from 8.57 MV to 10MV operation to survey how much field could be operated for a long time. Finally, in 5th phase, we successfully operate 10MV field in ML1 cavity.

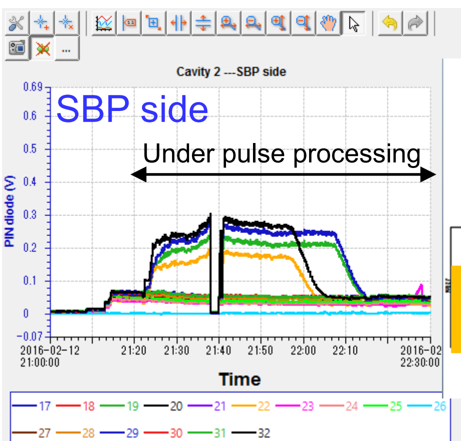
- In 2016, we continued 10MV operation to keep this field during 1mA operation.
- And we tried pulse processing to improve cavities performances more.

Example of pulse processing (ML2)

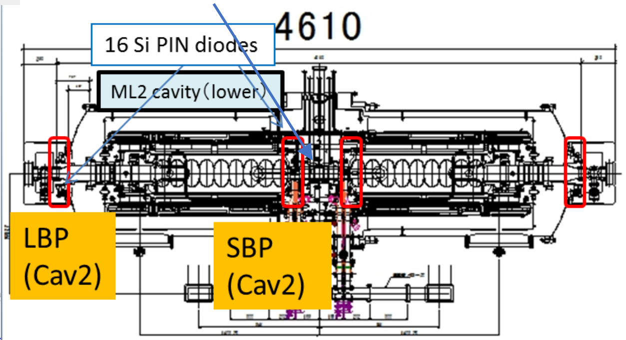
ML2 Pulse Aging (10Hz)
Vc=8.57MV(CW)+2.3MV(10Hz x 4ms)=10.9 MV
:40min pulse aging was done.



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



Arc sensor

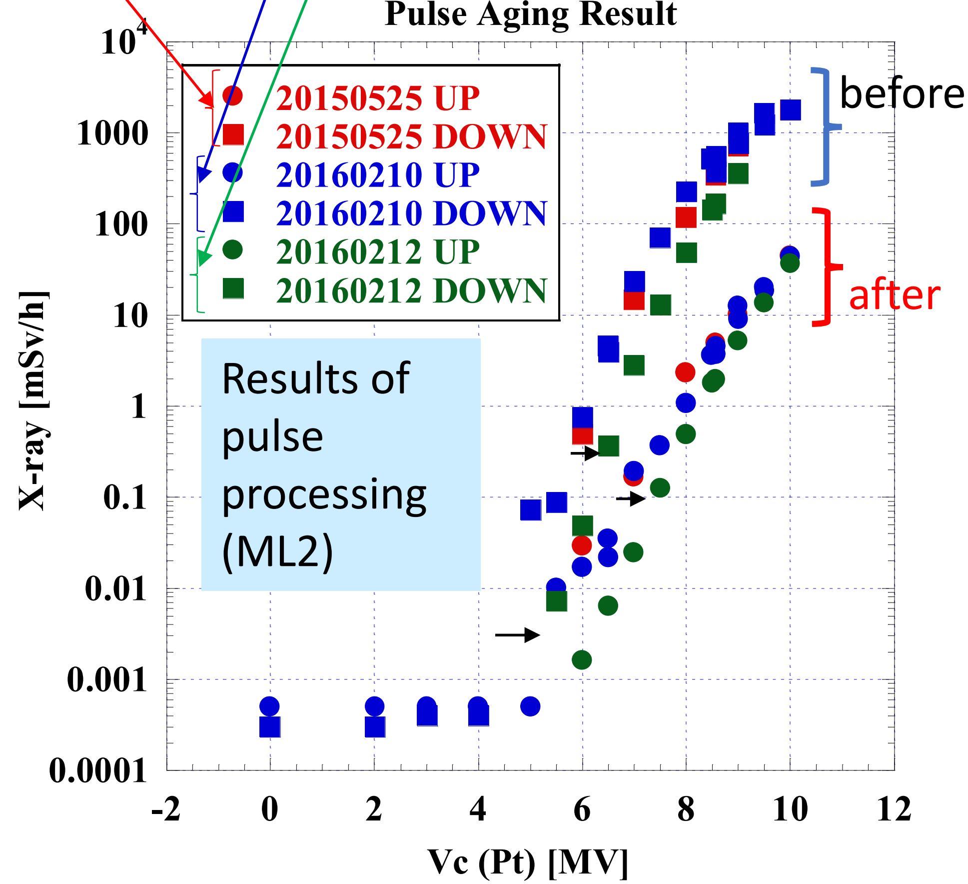


2015/5/25

Before pulse processing

After pulse aging

ML



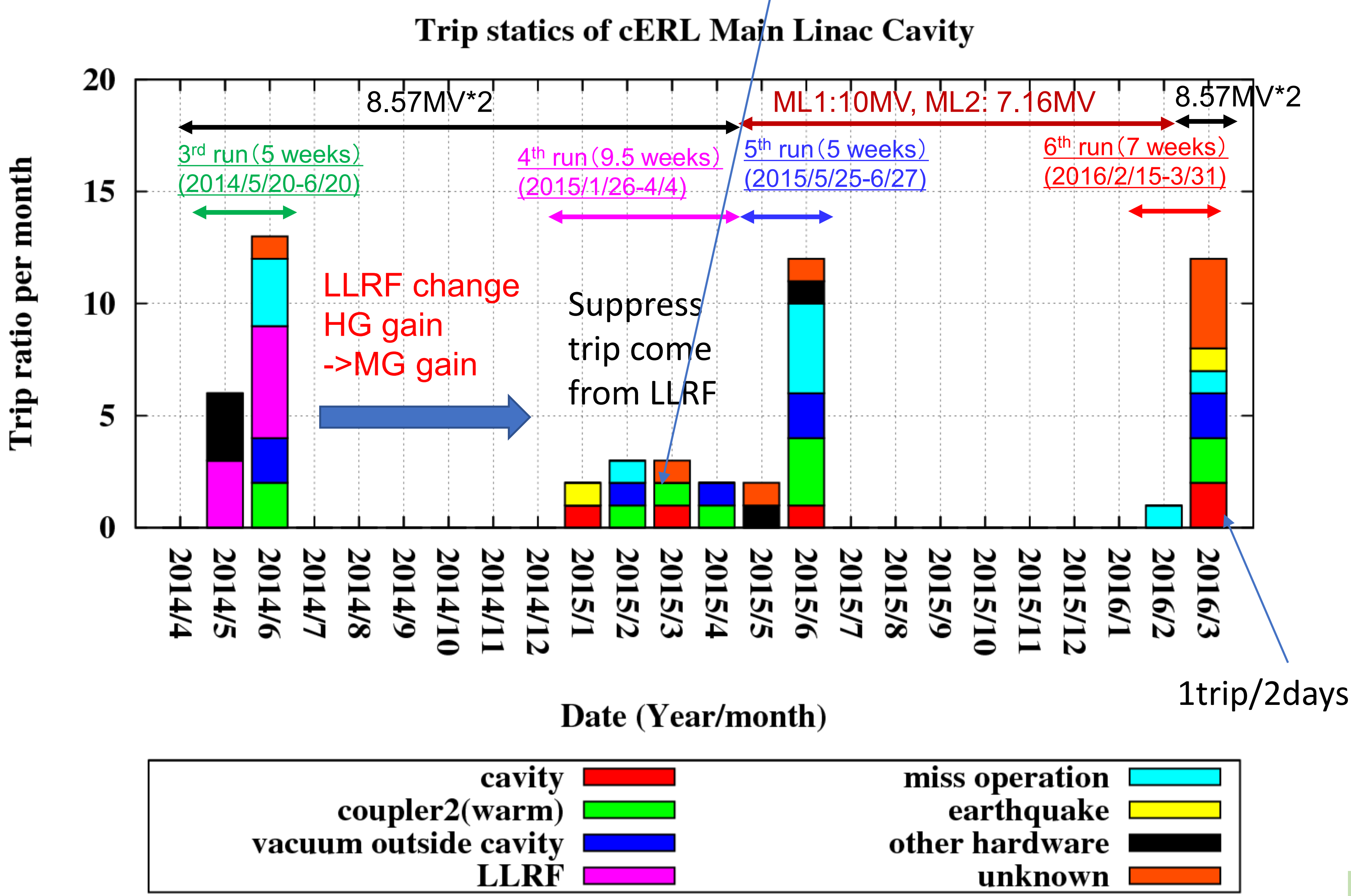
ML2 Vc vs ALOKA monitor

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

→Pulse processing works well.

Trip Statistics of cERL Main Linac cavities for 2 years

4th & 5th phase we did not apply pulse processing. But we had no trip for 1.5 month in 4th phase.



Stable beam operation was done by using this cryomodule for 3 years.
Main issues of trip is warm coupler of ML2 now.

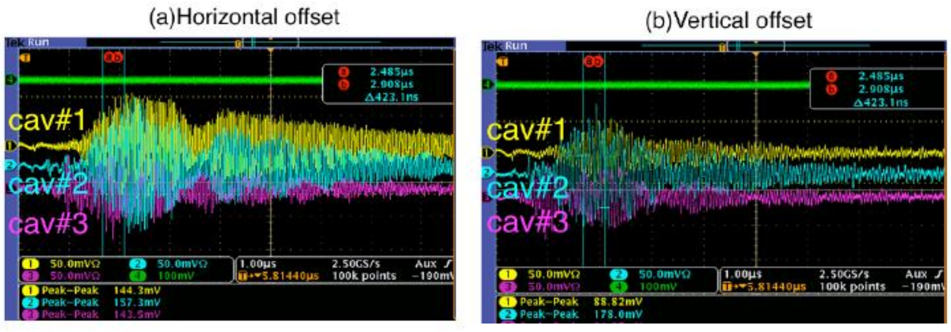
ML

Studies using HOM signal of injector cavity

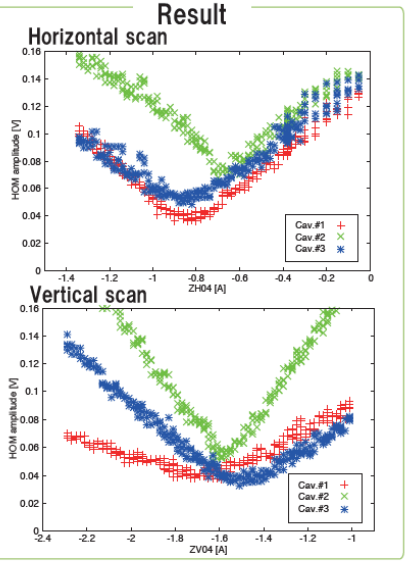
INJ

1) estimation of alignment error from dipole HOM

Dipole HOM (~1800MHz) signal of each cavities were used to estimate alignment error.



Result

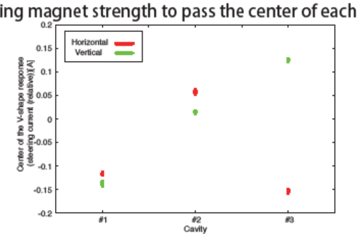


Estimation of misalignment

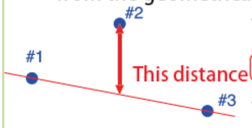
Analysis

Fitting the V-shape curve by a hyperbolic curve, the minimum point was obtained.

Steering magnet strength to pass the center of each cavity



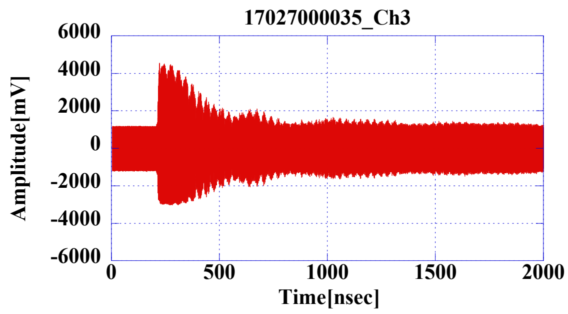
Calculate the relative distance from the geometrical layout.

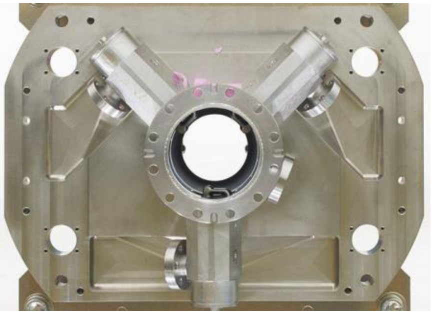


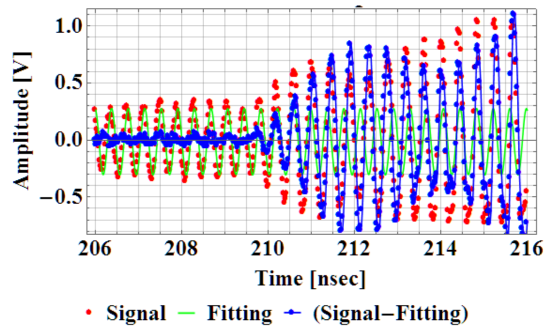
Plane	Relative misalignment
Horizontal	2.51 ± 0.05 mm
Vertical	0.27 ± 0.04 mm

See detail on MOPB096 Y. Honda et. al.

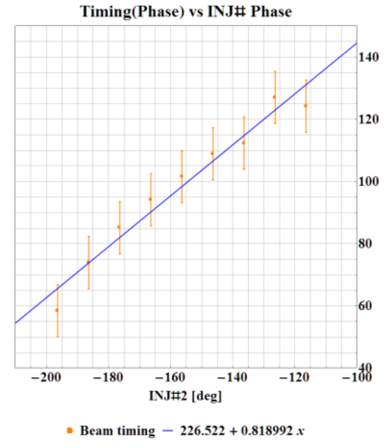
2) Estimation of beam timing from monopole HOM







- TM011 (2800 MHz) signal is used.
- Applying adequate RF filters
- Beam timing seems to be monitored.
- Study was just started. More detailed study will continue.

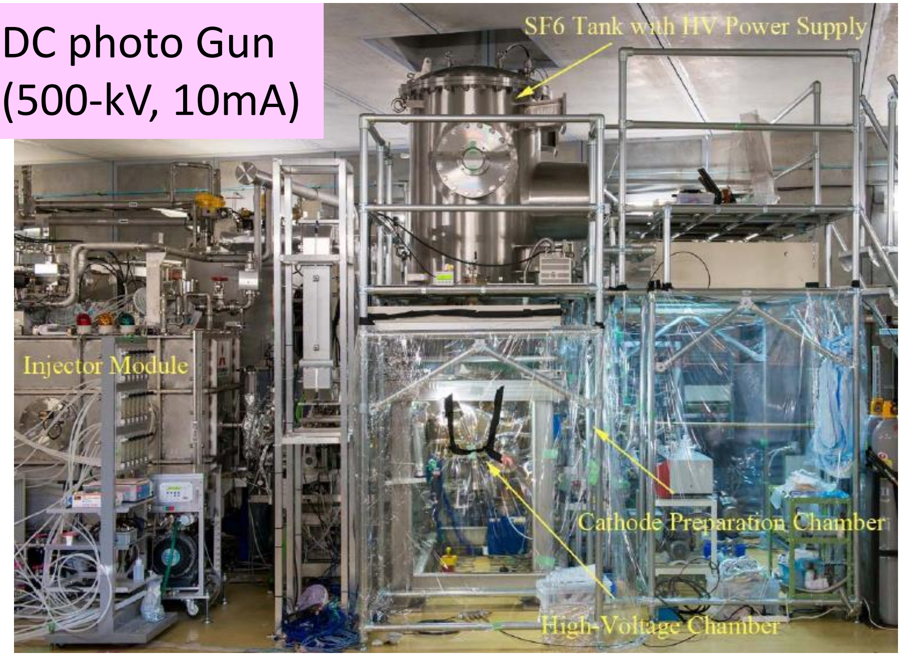


Summary

- Beam commissioning of cERL started at 2013. Since then, we experienced four years of beam operation.
- Beam current of cERL was increased step by step and reached to 1mA CW.
- Amount of beam loss is controlled during beam commissioning.
- Both of injector linac and main linac suffer from degradation by field emission.
- Pulse processing is helpful to keep cavity performance.
- Sometimes combination of field emission and surrounding components made discharge and led to degradation.

Major Components for the cERL

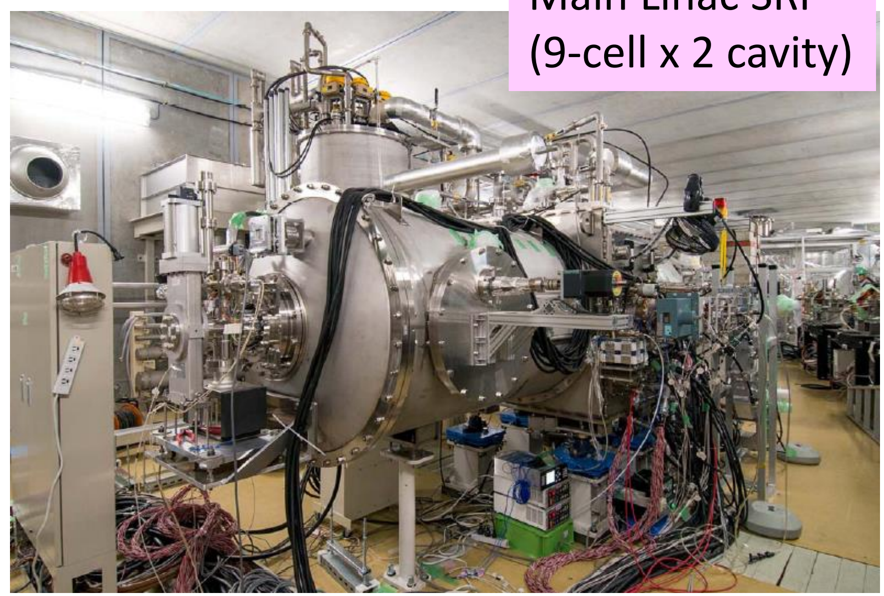
DC photo Gun
(500-kV, 10mA)



Injector SRF
(2-cell x 3 cavity)

Liq. He plant
(600W@4K, 80W@2K)

Main Linac SRF
(9-cell x 2 cavity)



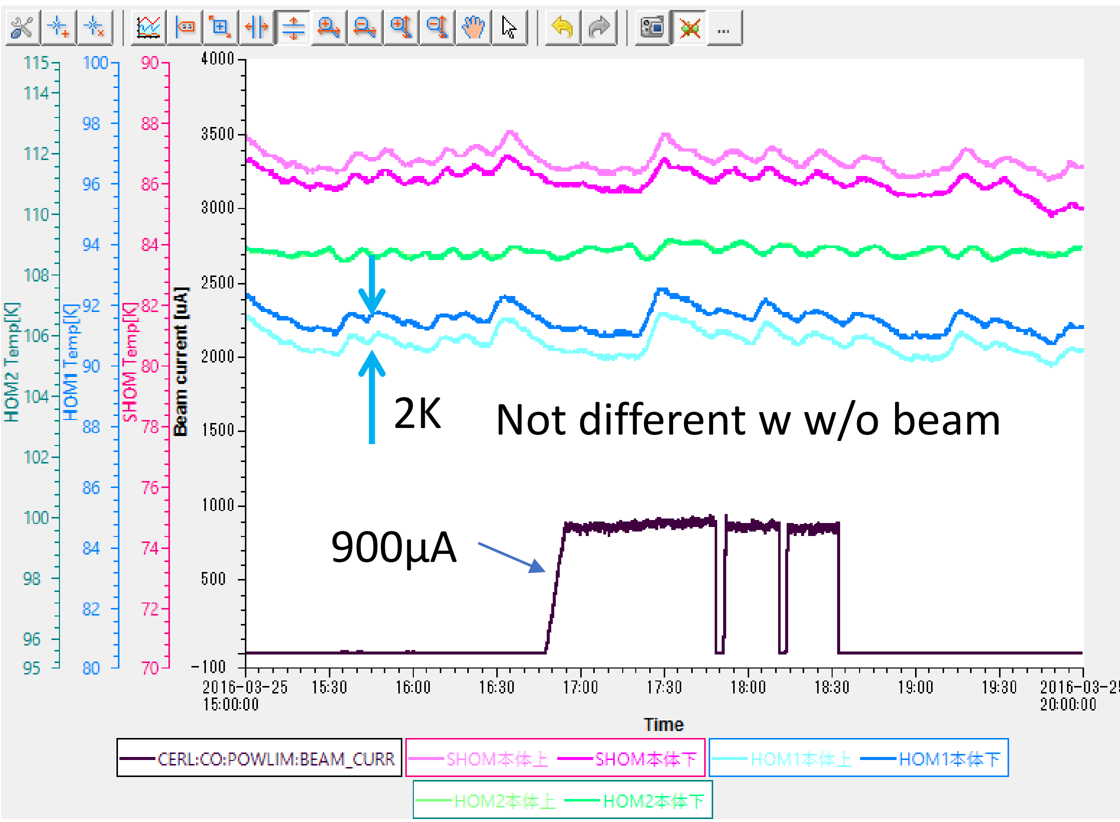
Heat load on HOM absorber

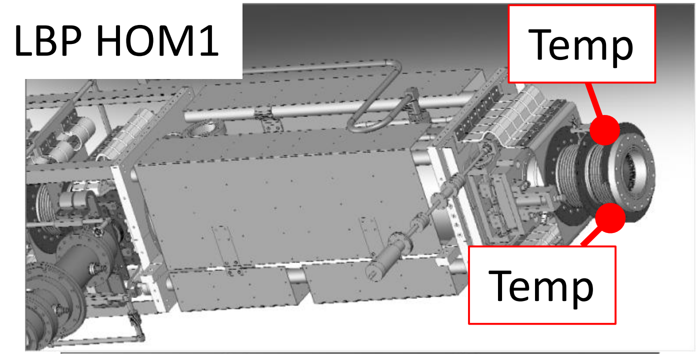
Temperature rise at 162.5MHz x 0.9mA

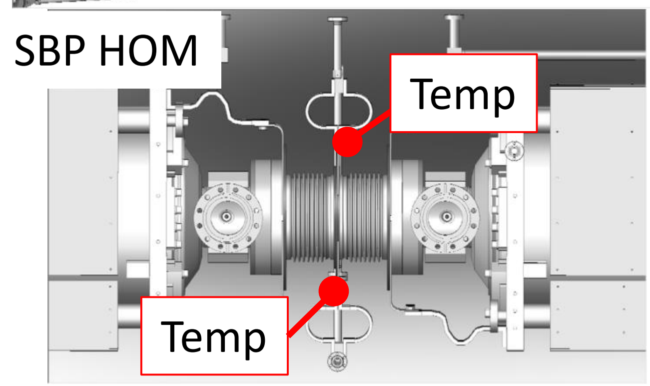
Expected heat load of ML : Loss Factror 10[V/pC]@3ps
Cavity Loss Power=7.7pC x 900μA x10V/pC x 2= 140 mW

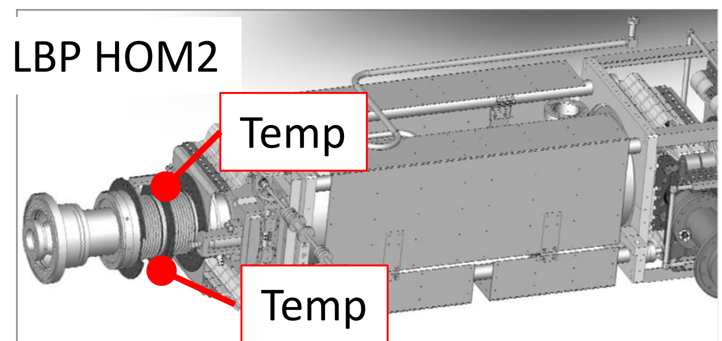
Parameter	Value
Current	900 μA
Repetition	162.5 MHz
Bunch length	3ps

No temperature rise of HOM damper





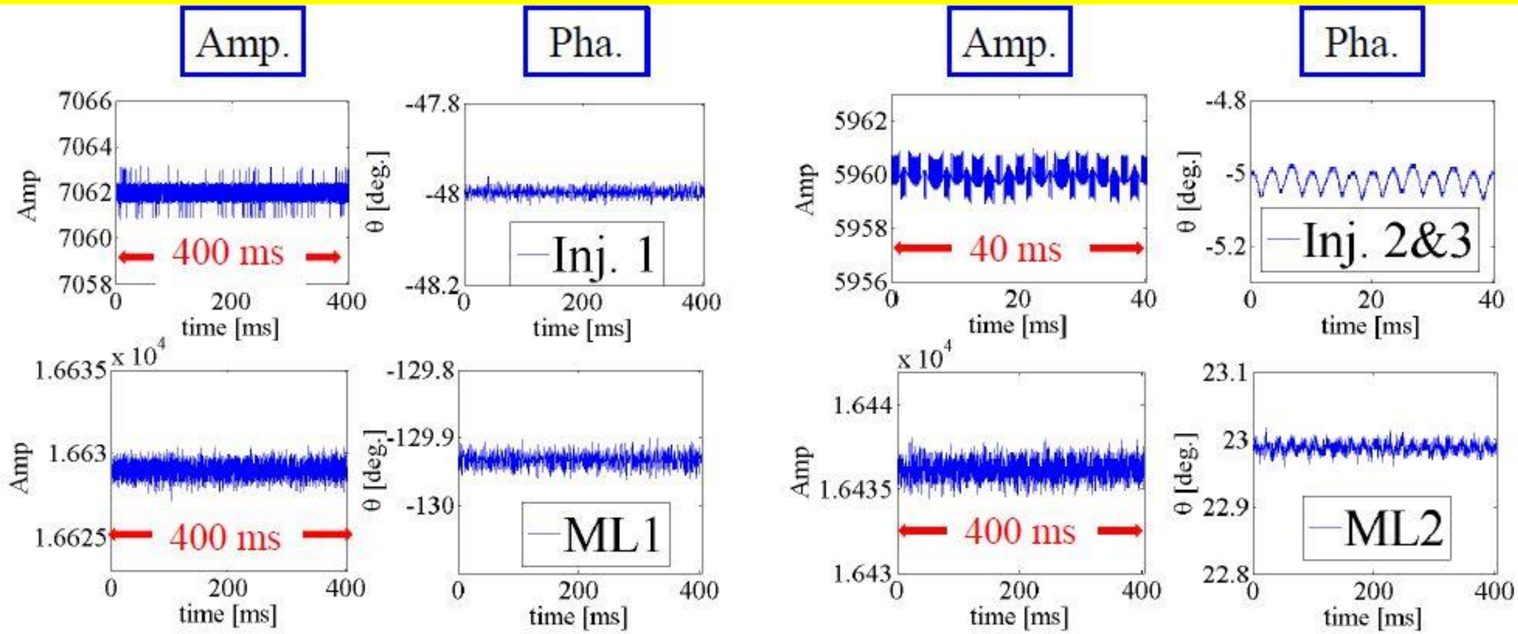




Power & LLRF stability in beam operation

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