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

7th IHEP-KEK SCRF Collaboration meeting

2017/July/15

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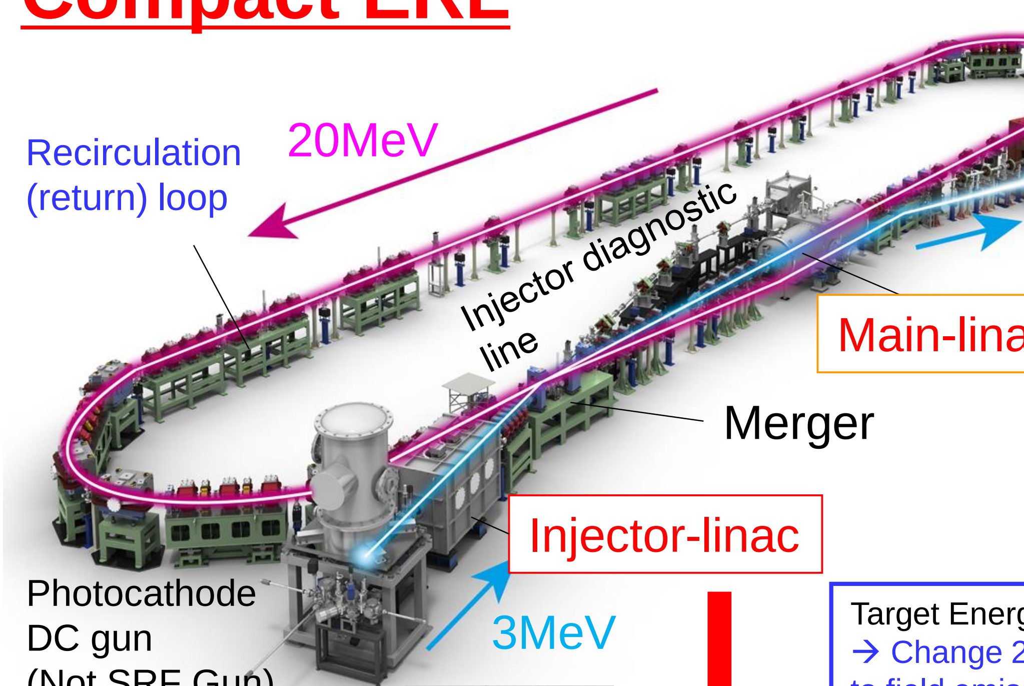
Contents

Compact ERL



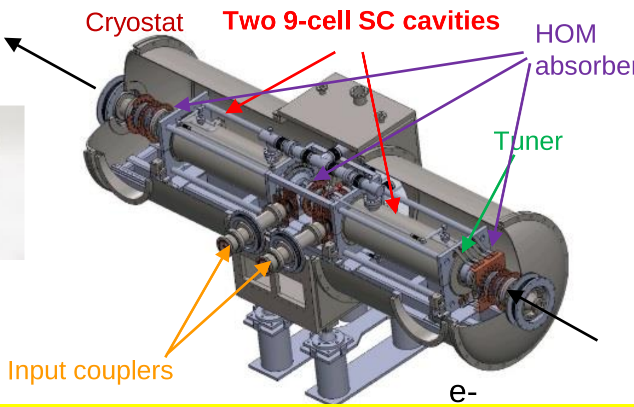
Target Energy : 35MeV
→ Change 20MeV due to field emission

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

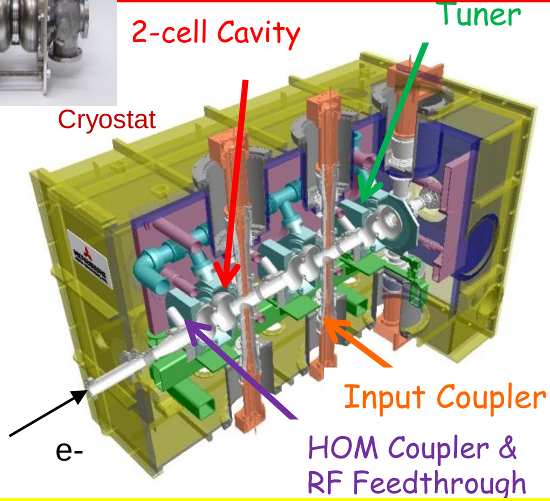


Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

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



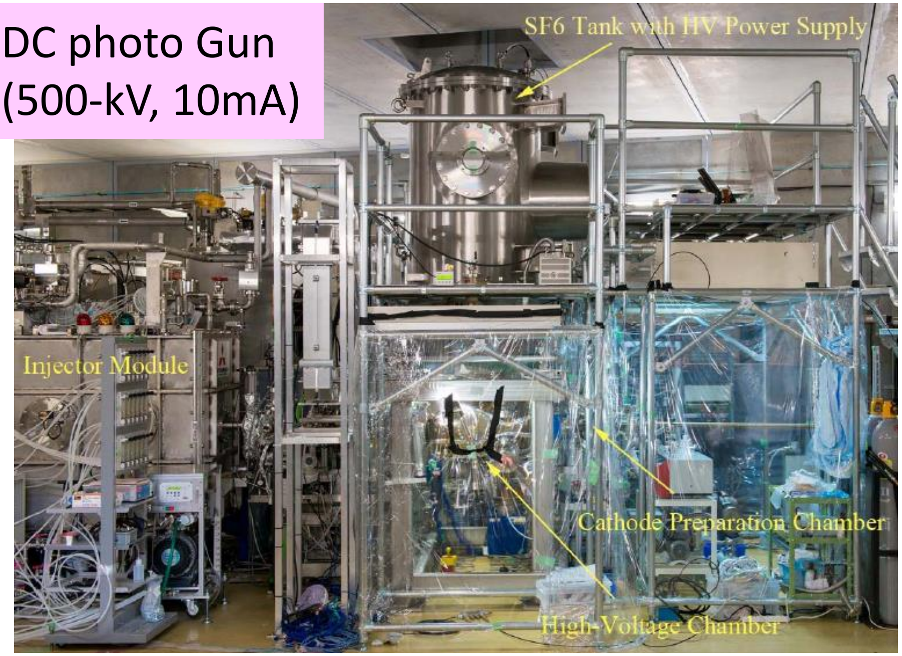
Requirement was satisfied at V.T and for initial 10mA requirement .

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)

Major Components for the cERL

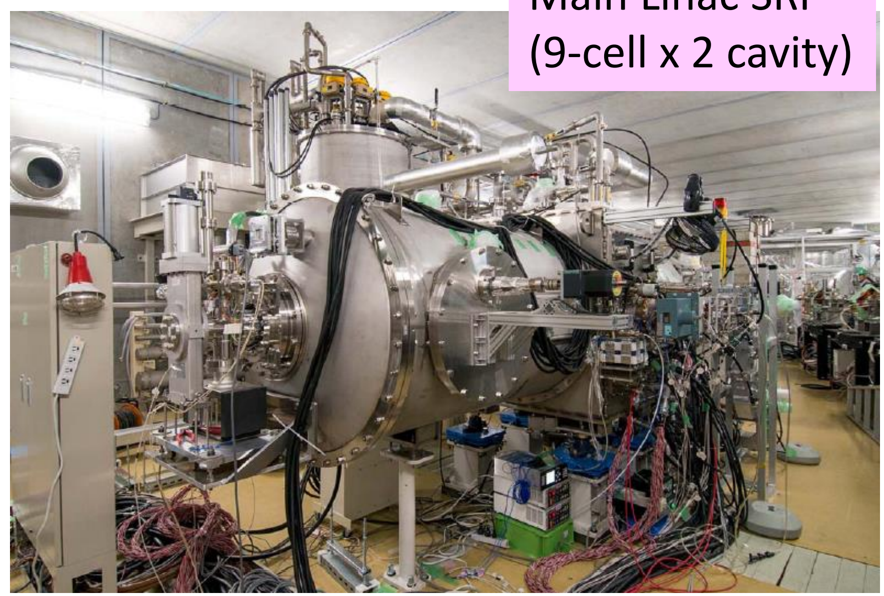
DC photo Gun
(500-kV, 10mA)

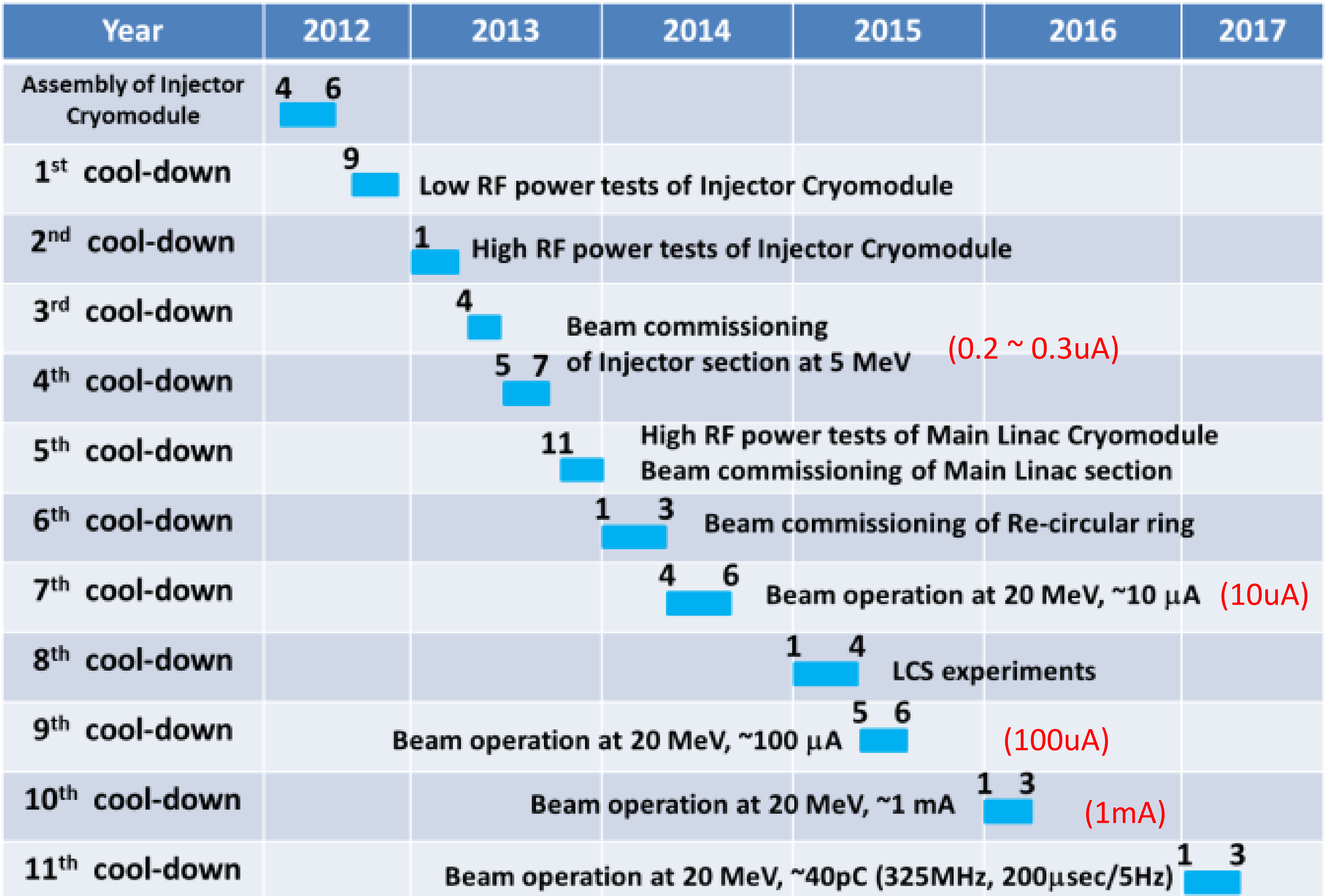


Injector SRF
(2-cell x 3 cavity)

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

Main Linac SRF
(9-cell x 2 cavity)





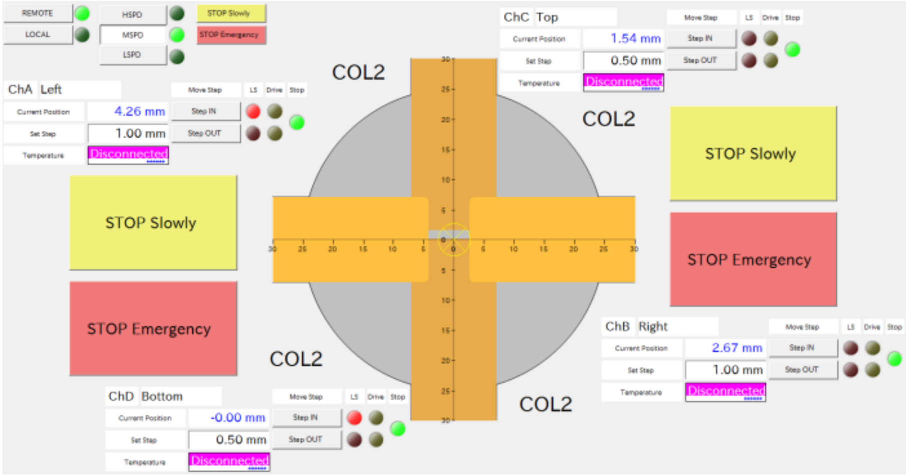
Year
2012
2013
2014
2015
2016
2017
Assembly of Injector Cryomodule
4 6
1st cool-down
9
Low RF power tests of Injector Cryomodule
2nd cool-down
1
High RF power tests of Injector Cryomodule
3rd cool-down
4
Beam commissioning of Injector section at 5 MeV
(0.2 ~ 0.3uA)
4th cool-down
5 7
5th cool-down
11
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 (325MHz, 200μsec/5Hz)

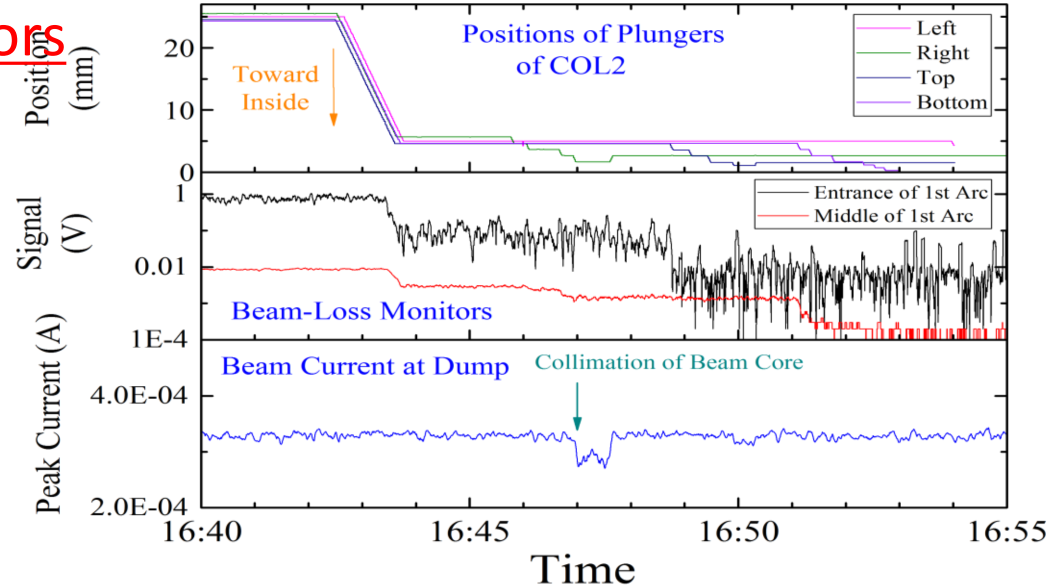
Strategy for beam commissioning

- 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 conditioning by using collimators



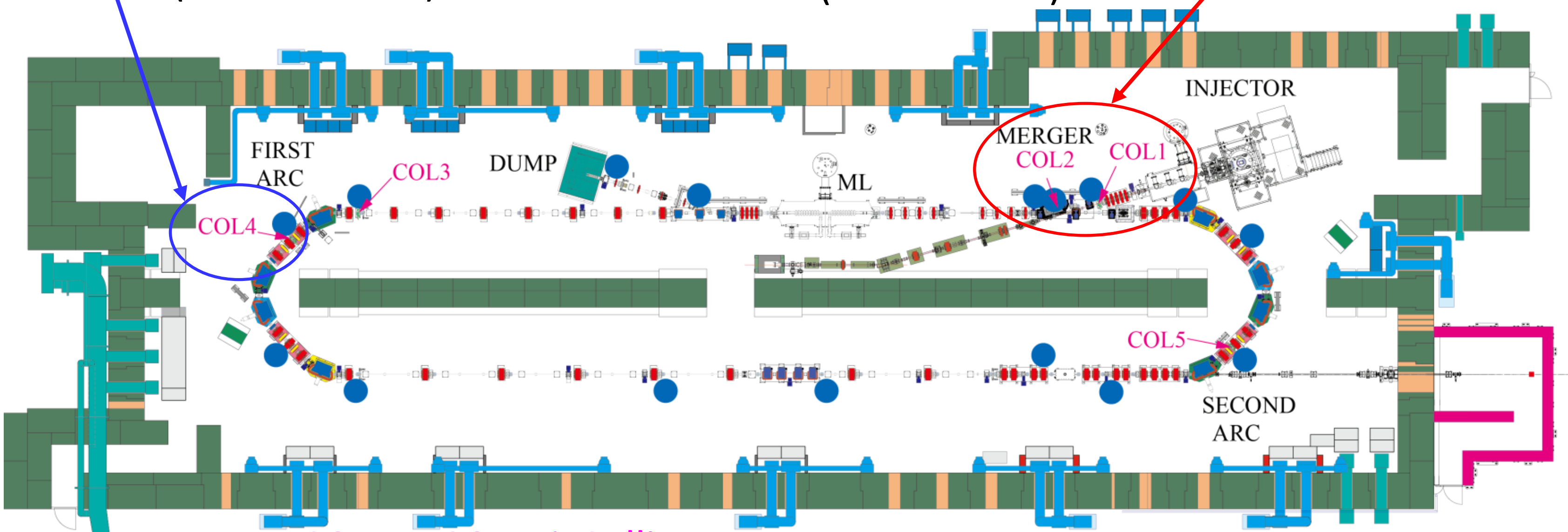


Collimator at first arc section(COL4) is also used.

(E = 19.9 MeV)

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

(E = 2.9 MeV)

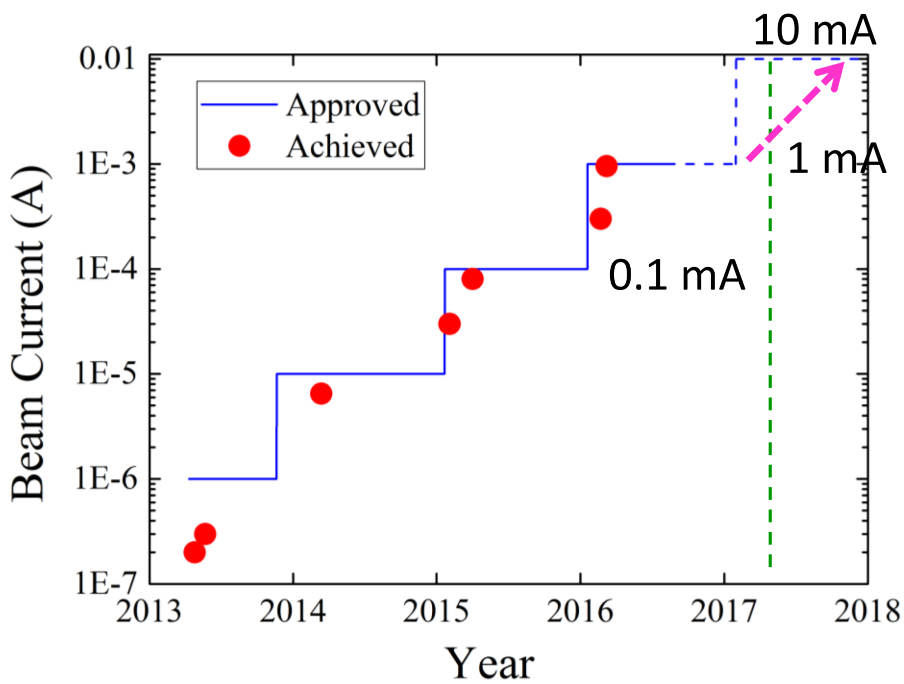


COL1〜COL5：Collimator

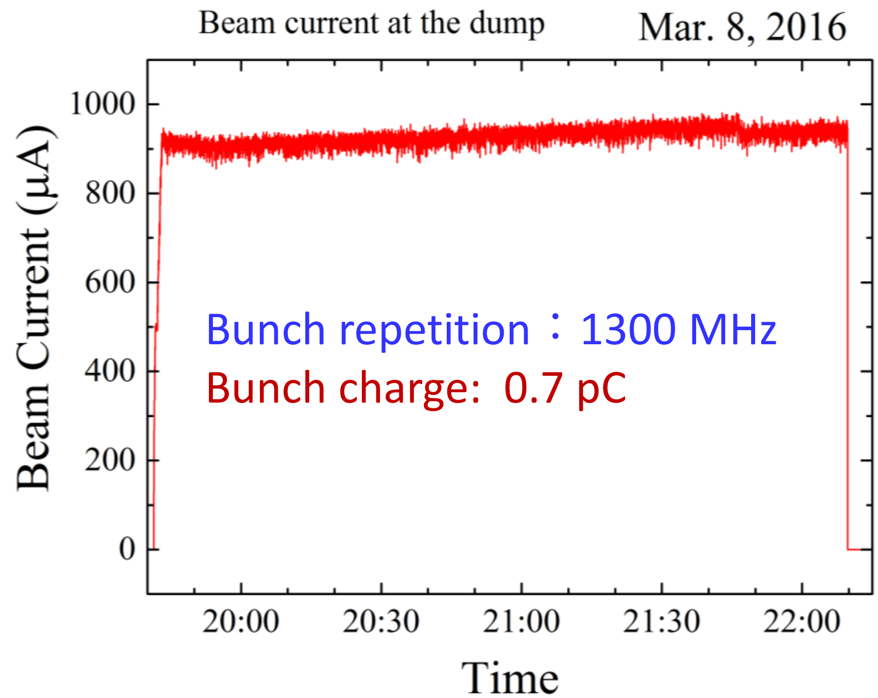
● FAST LOSS MONITOR

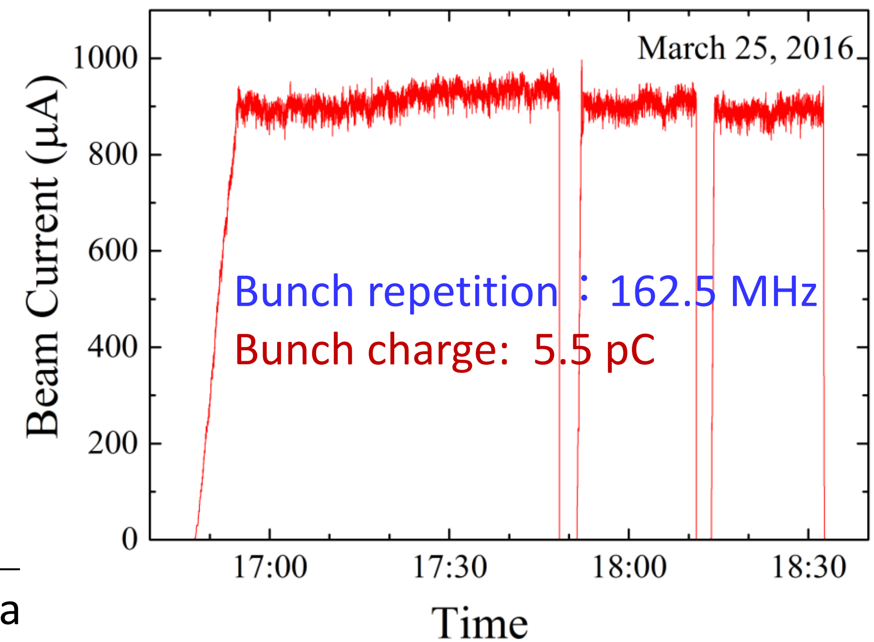
2016 Japan Accelerator Society Meeting, Shogo Sakanaka

Beam current upgrade



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



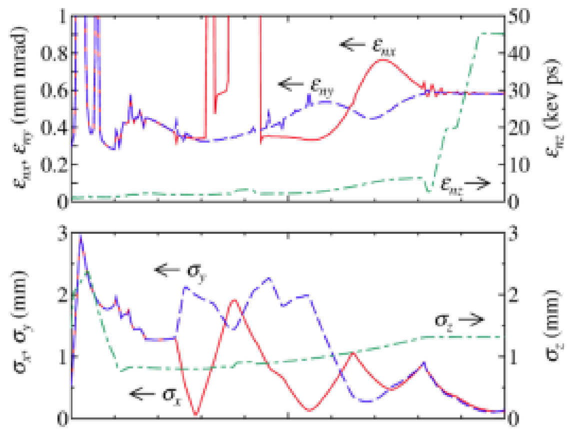


2016 Japan Accelerator Society Meeting, Shogo Sakanaka

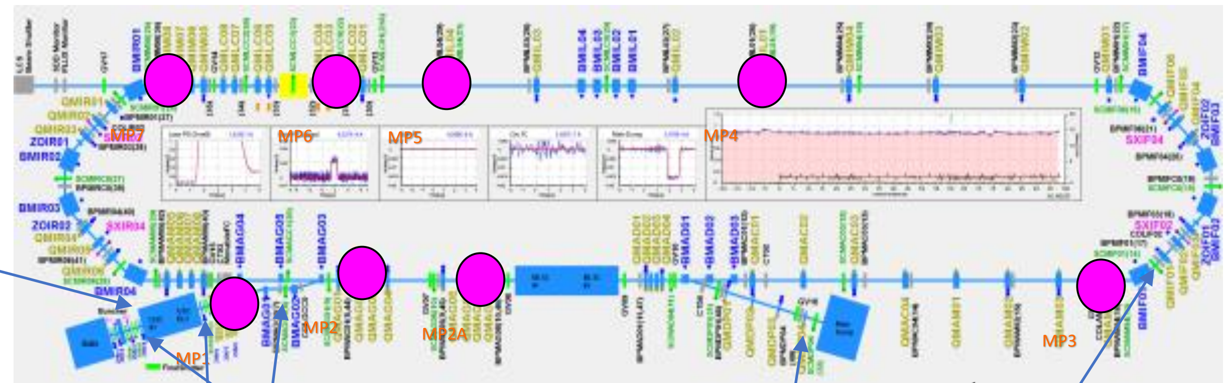
Matching of beam profile and measured emittance with high charge

T. Miyajima, Proc IPAC'15

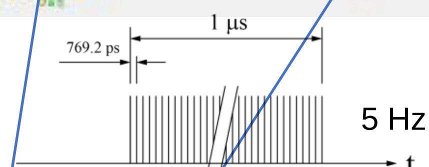
Calc. of injector parts :
390 keV Gun, 7.7 pC/bunch, laser 3 ps/8 pulse stack



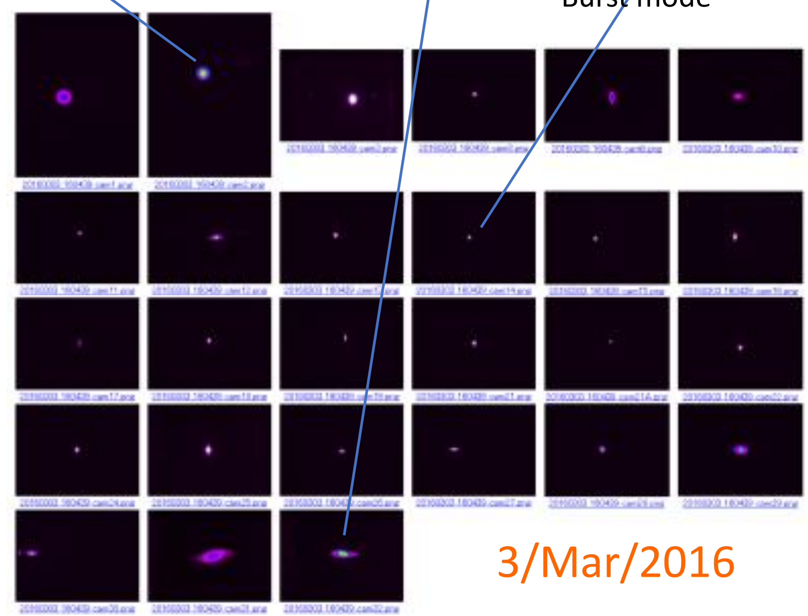
Add new matching point not to make beam loss by using burst mode



collimator



Matching Example
(0.5 pC/bunch)



3/Mar/2016

Small beam profile was achieved by matching and collimator

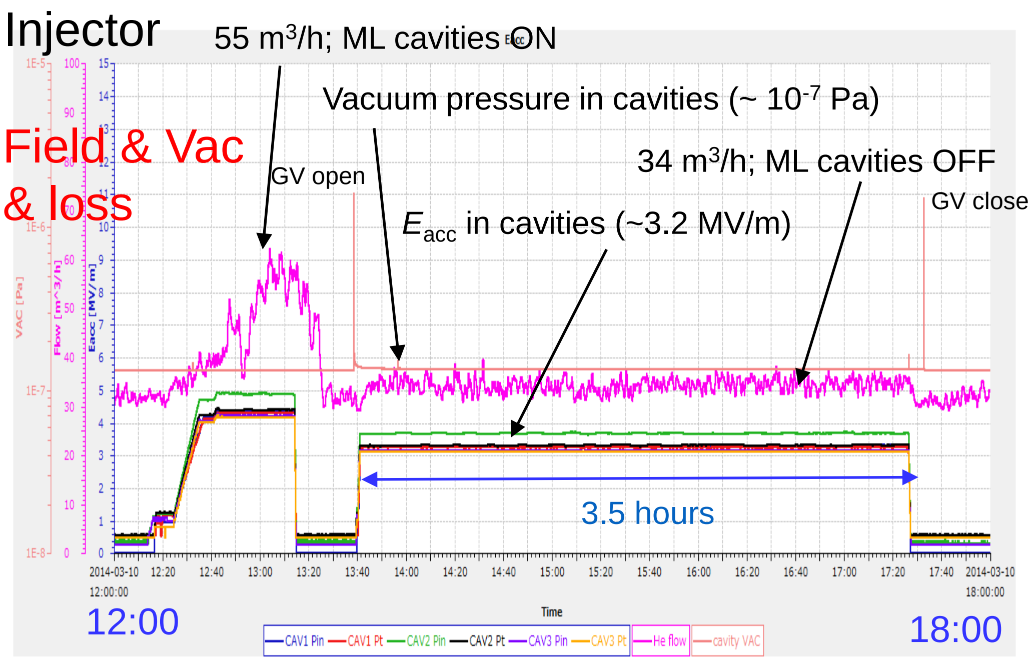
Measured emittance

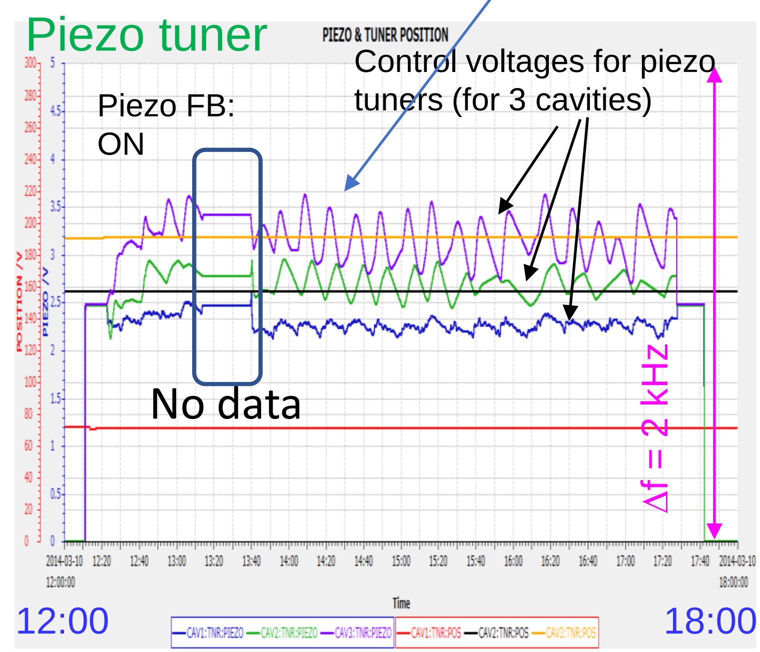
Bunch Charge	Normlized Emittance at arc Horiz/Vert [mm.mrad]
0.02 pC	0.14 / 0.14
0.5 pC	0.27 / 0.17
7.7 pC	1.5 / 1.1 (Tentative)

After sophisticated matching, beam profile became good and measured emittance was almost reached our requirements of 1 mm mrad normalized emittance at 7.7pC (equal = 10mA@1.3GHz)
(previous 5mm mrad@7.7pC before 2015)

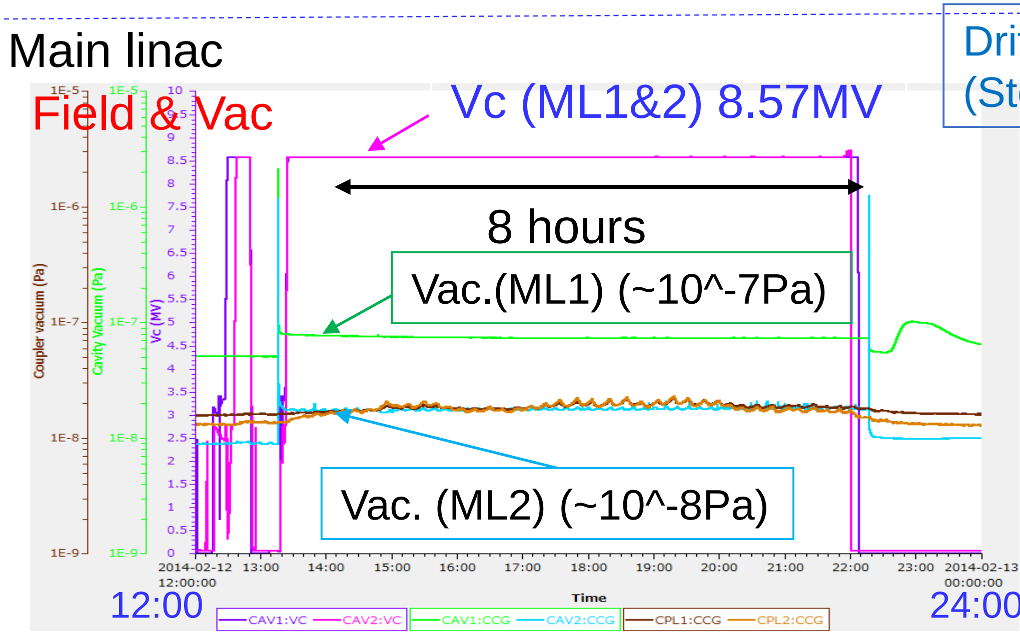
Typical one day operation of cERL SRF

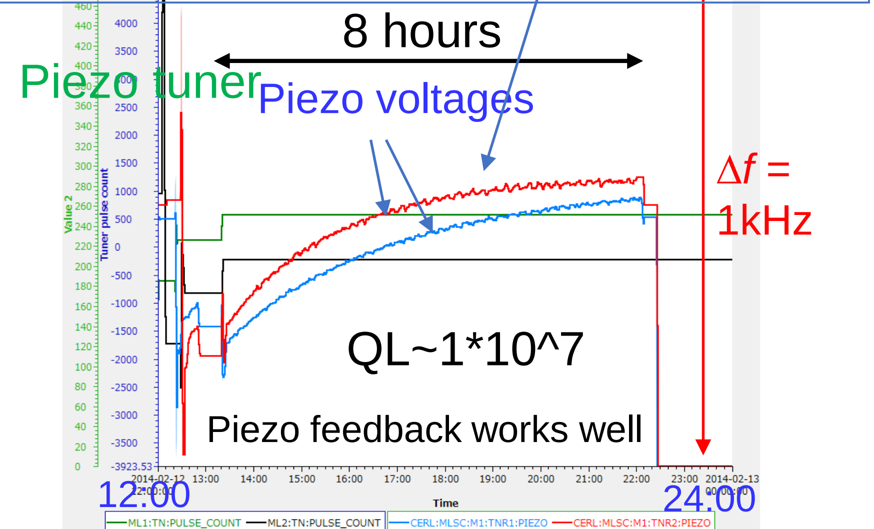
Synchronized with 80K line temperature





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

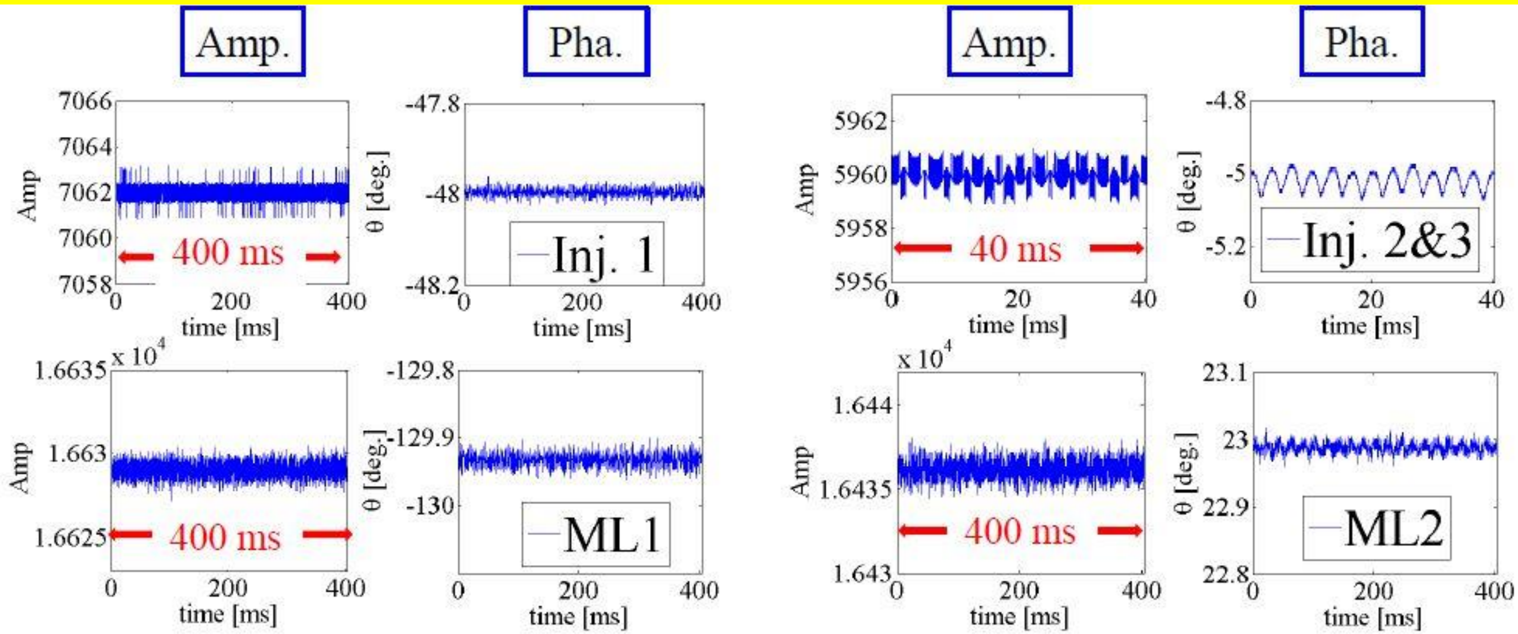




Power & LLRF stability in beam operation

F.Qiu & T.Miura et al

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

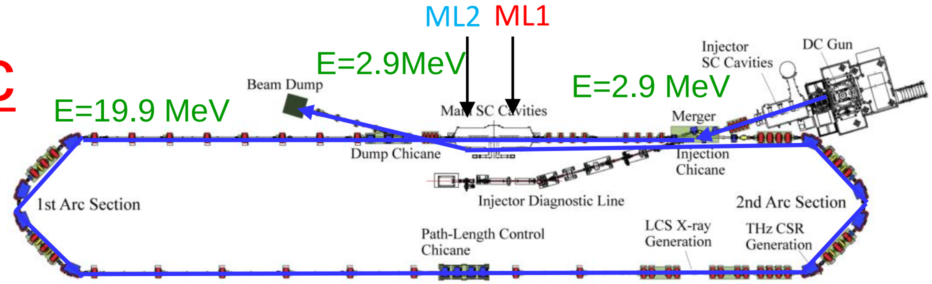


FPGA
Virtex5-FX

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

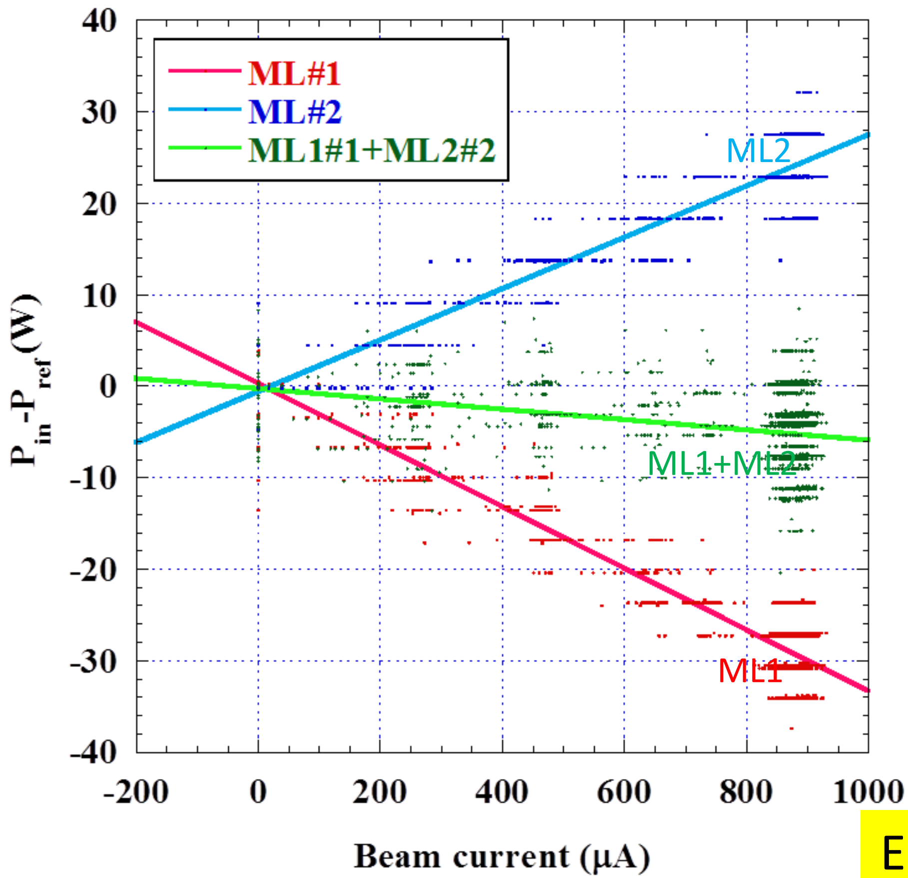
SC Cavity	Inj1(2cell)	Inj2(2cell)	Inj3(2cell)	ML1(9cell)	ML2(9cell)
Acc. Field	3.2MV/m	3.3MV/m	3.0MV/m	8.3MV/m	8.3MV/m
power	0.53kW	1.4kW	1.0kW	1.6kW	2kW
Power source	25 kW klystron	300kW klystron (Vector sum)		16 kW solid state Amp	8kW solid state Amp
QL	1.2e6	5.8e5	4.8e5	1.3e7	1.0e7
ΔA/A(% rms)	0.006%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

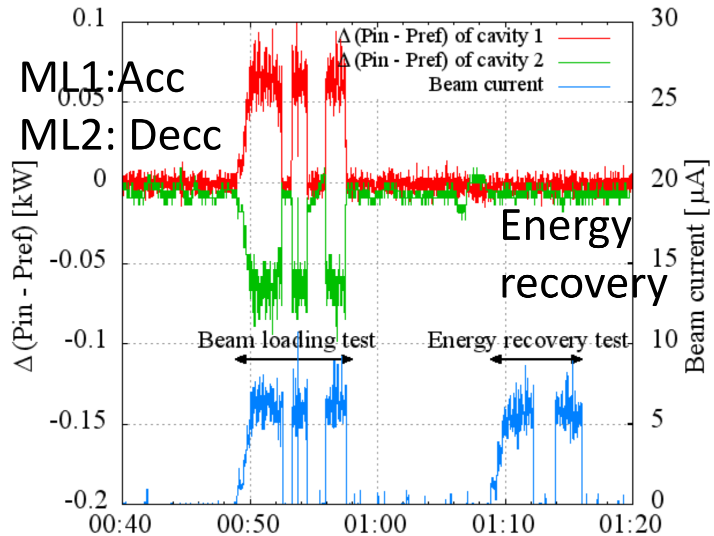
Energy recovery at main linac



Pin – Pref ～ Ploss + Pbeam

Δ(Pin – Pref) ～ Pbeam ← Beam loading





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

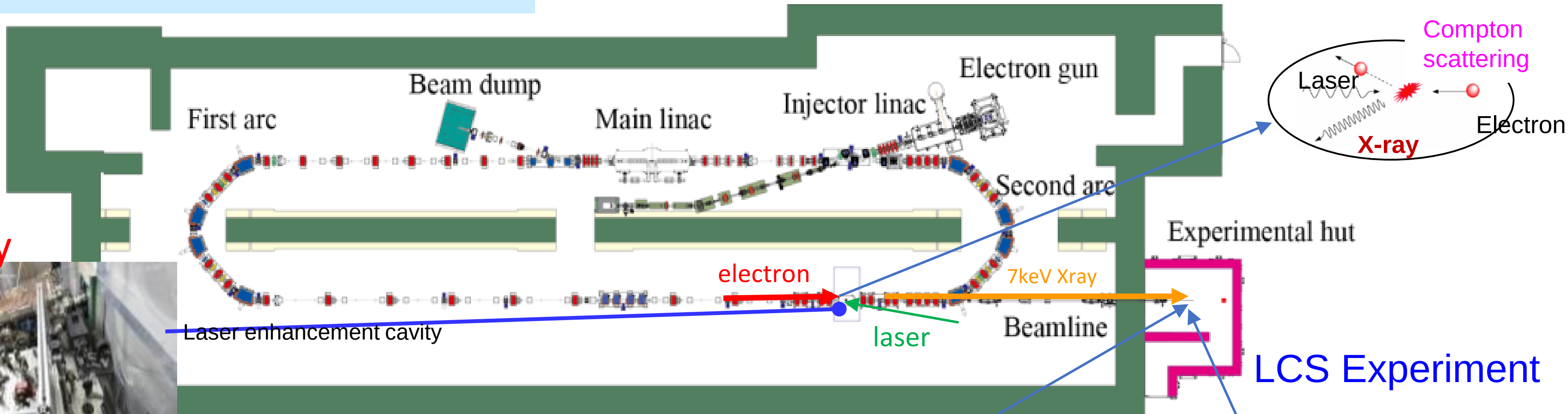
Example of cERL beam usage

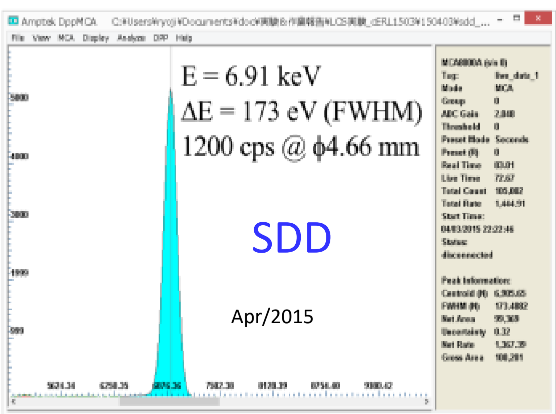
Production of high intensity X-ray From Laser Compton Scattering (LCS)

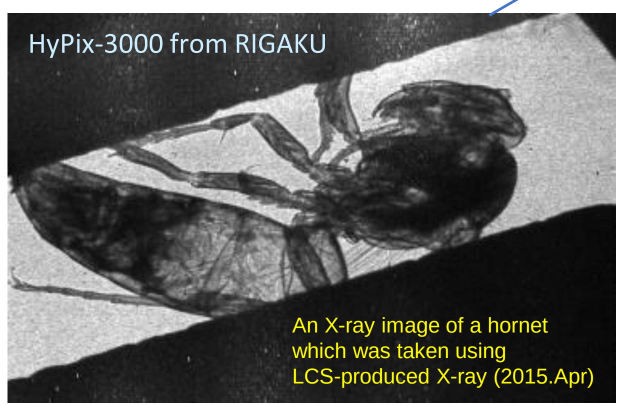
Parameters in Mar/2016:
Beam : 5.5 pC/bunch, 162.5 MHz CW
Laser : 1064 nm, 39.4 μJ/pulse
Energy resolution :210 eV@6.87 keV

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

Laser with optical cavity







Example of cERL beam usage

THz generation by compressed ~ 100 fs bunch

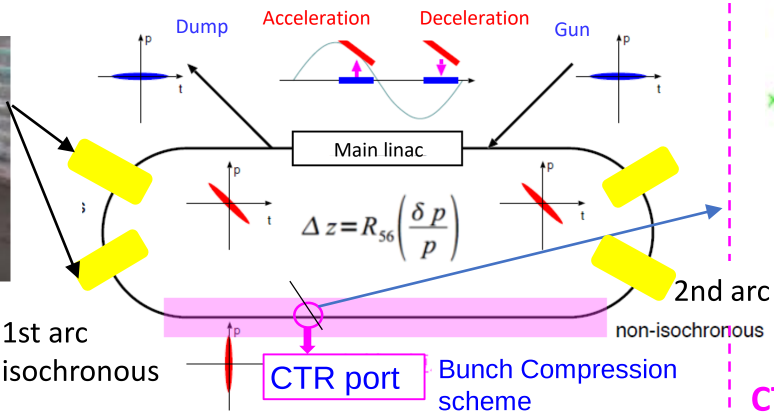
Electron bunch was compressed to ~100fs using sextupole magnet. THz component generated by a coherent transition radiation (CTR) monitor is analyzed by a Michelson interferometer.

Bunch density length: $\rho(t) \propto e^{-\frac{t^2}{2\sigma^2}}$

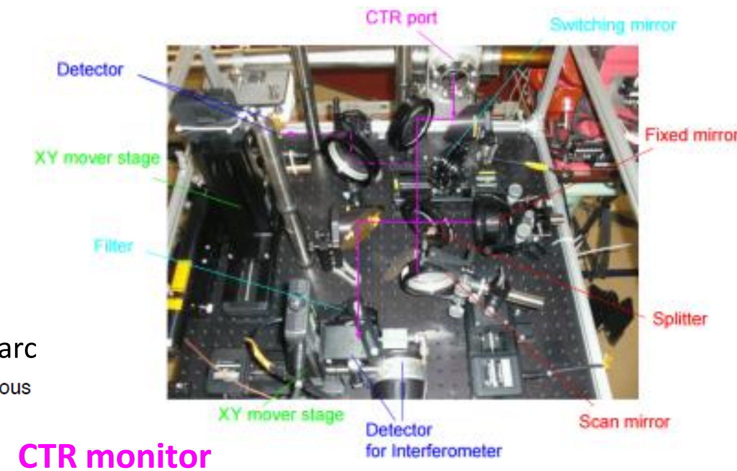
Interference signal: $f(\tau) \propto e^{-\frac{\tau^2}{4\sigma^2}}$

Fourier transformation: $\hat{f}(\nu) \propto e^{-(2\pi\nu)^2\sigma^2}$

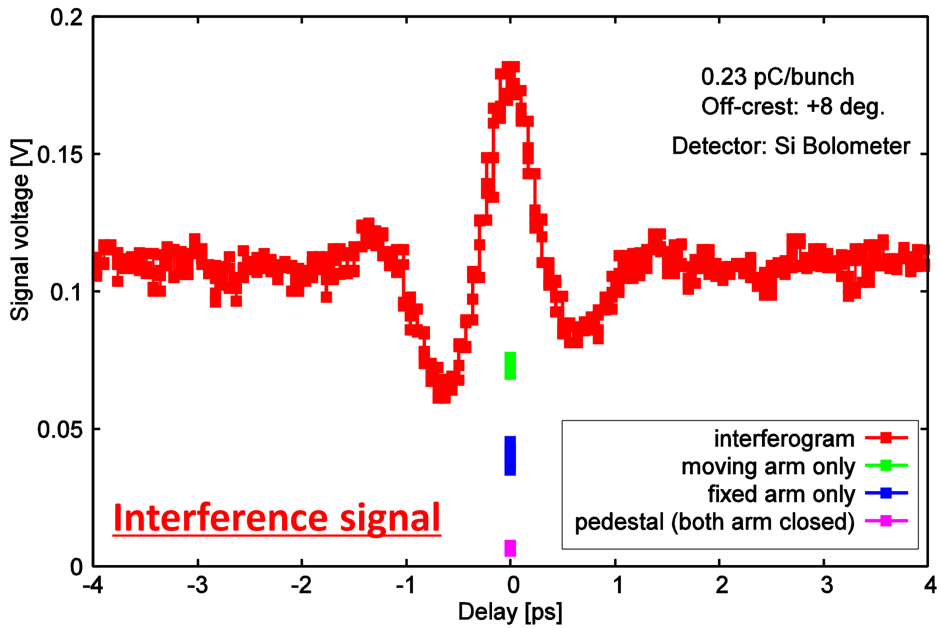
Newly installed sextupole magnets.

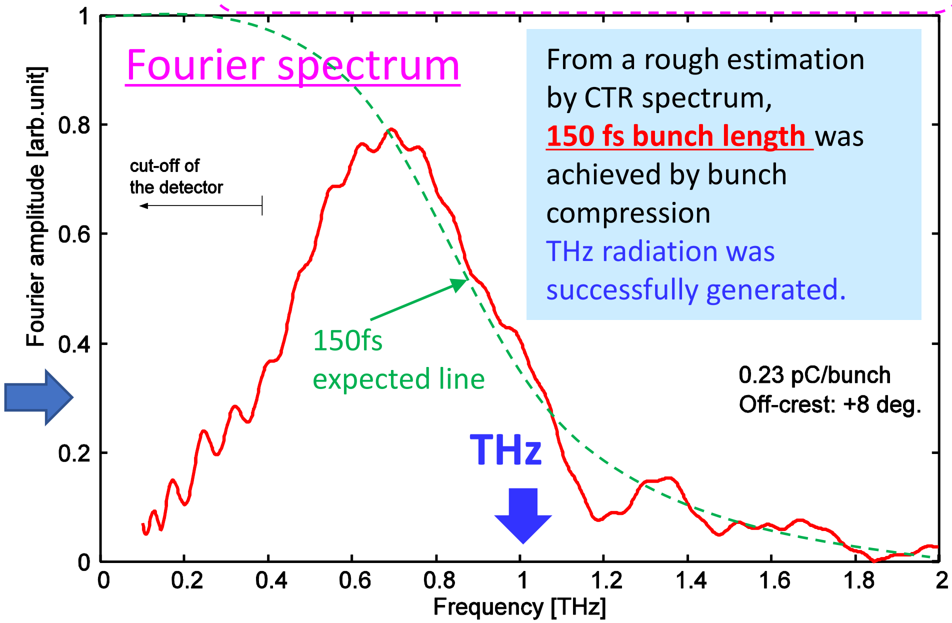


Bunch Compression scheme



CTR monitor



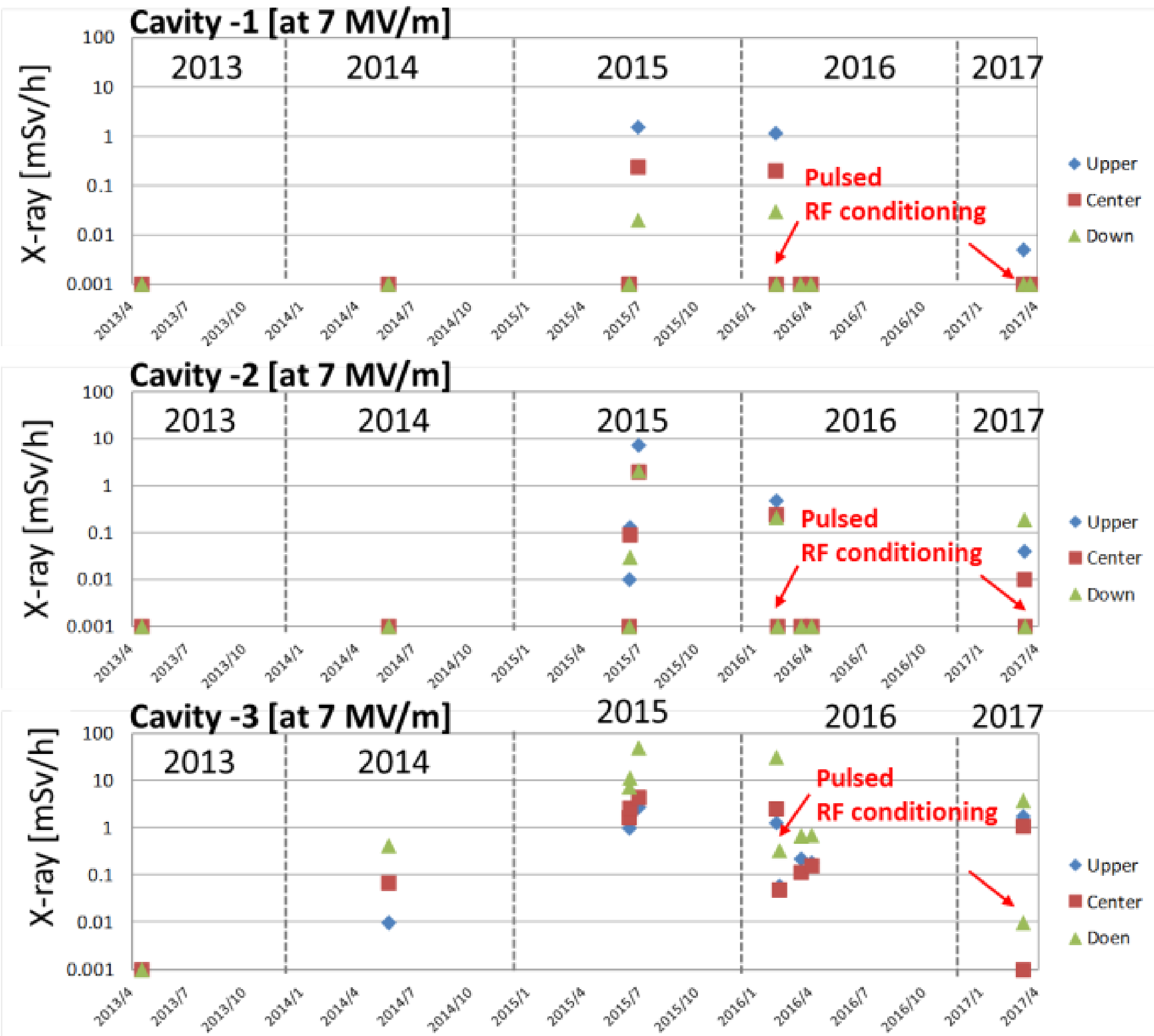


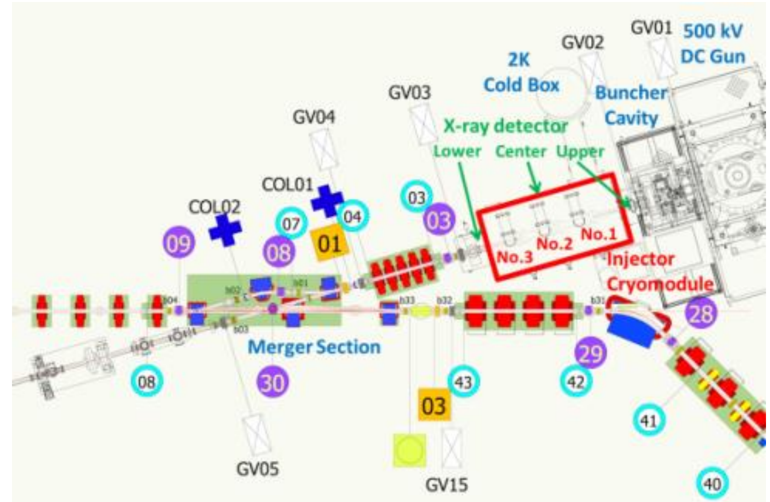
From a rough estimation by CTR spectrum, **150 fs bunch length** was achieved by bunch compression

THz radiation was successfully generated.

Interferogram and its Fourier spectrum measured by liquid-helium cooled Si bolometer.

Long term operation of cERL injector cryomodule



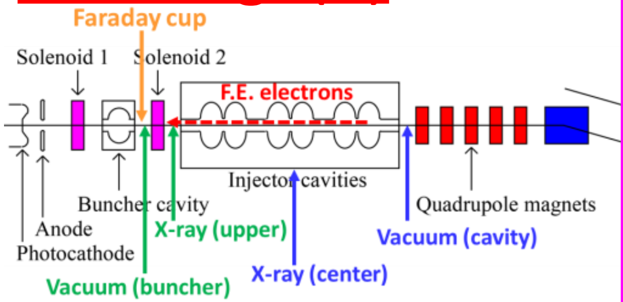


Sometimes performance degraded by field emission. Especially, sudden jump at 2015.

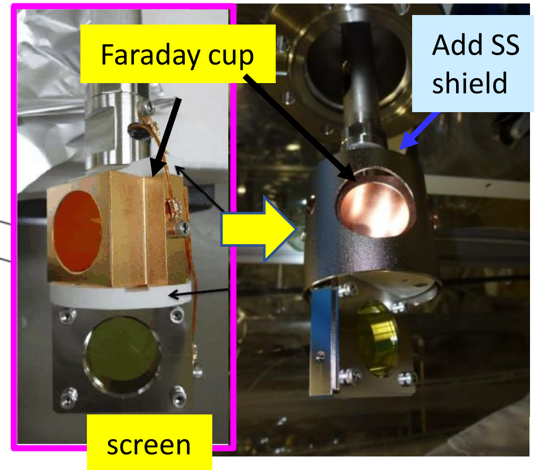
Try to suppress it by applying high power pulsed processing.

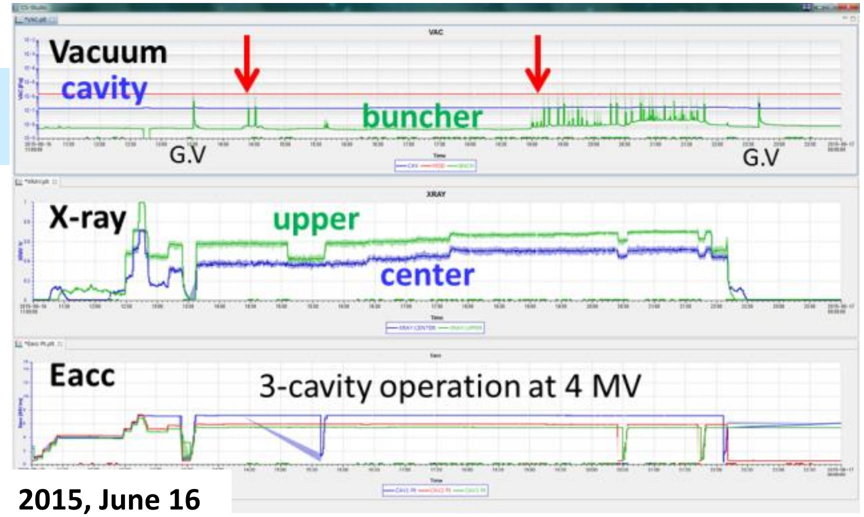
See detail on MOPB097
E.Kako et. al.

Unexpected discharge(1)



Screen monitor in front of Gun

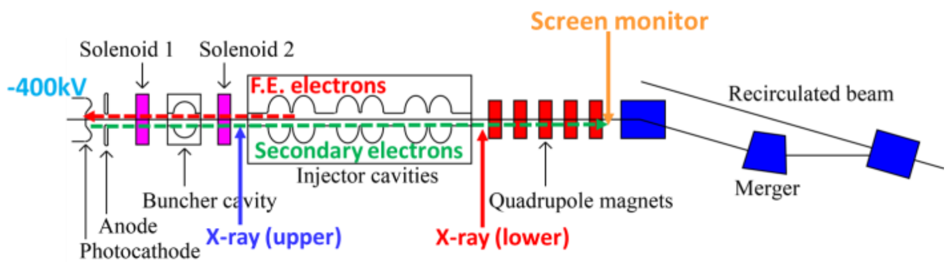


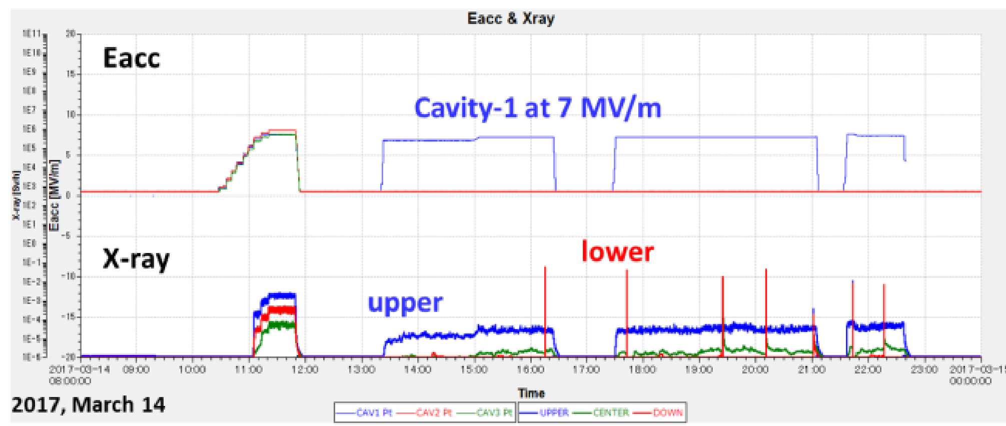


Field emitted electron induce a charge up of Faraday cup.
⇒Discharge lead to vacuum deterioration and increase of radiation.
Improvement on Faraday cup solved problem.

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

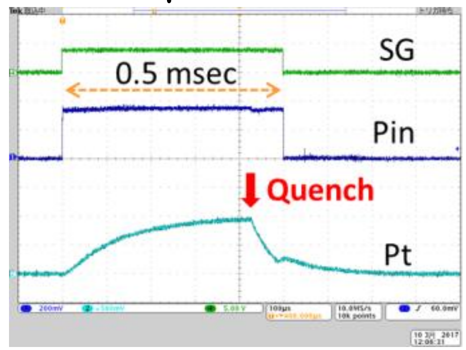
Sometimes the pulse processing is applied for injector cavities.
Pulse length start from 0.5ms, then 5ms and finally CW

See detail on MOPB097
E.Kako et. al.

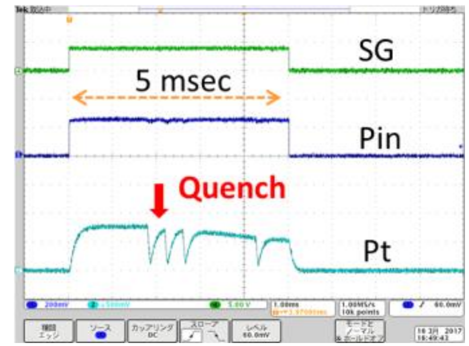
RF conditions of pulse processing

	No.1 Cavity	No.2 Cavity	No.3 Cavity
Q_L	1.2×10^6	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

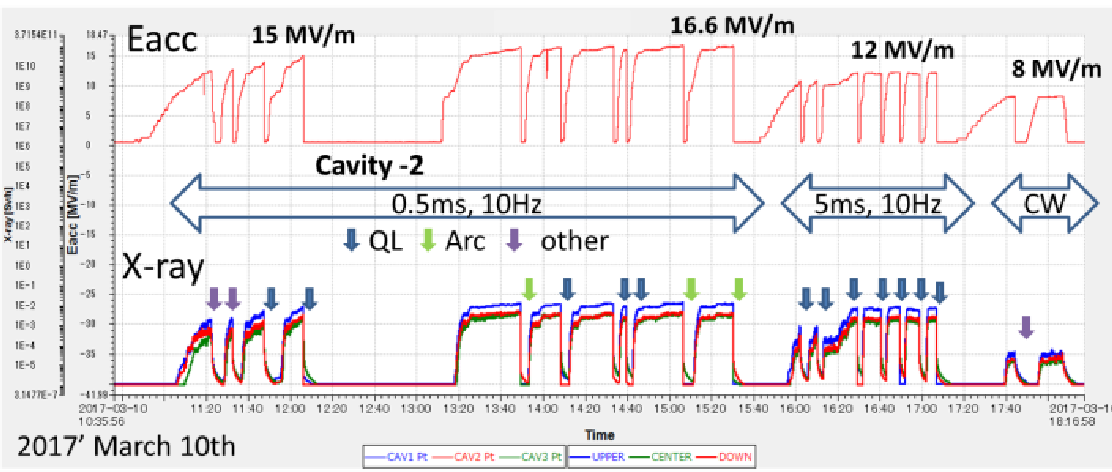
500μsx5Hz

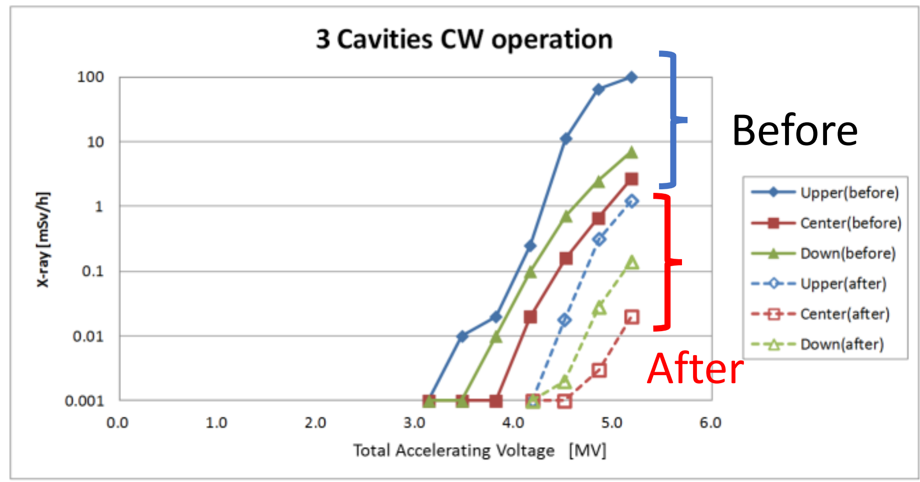


5msx5Hz



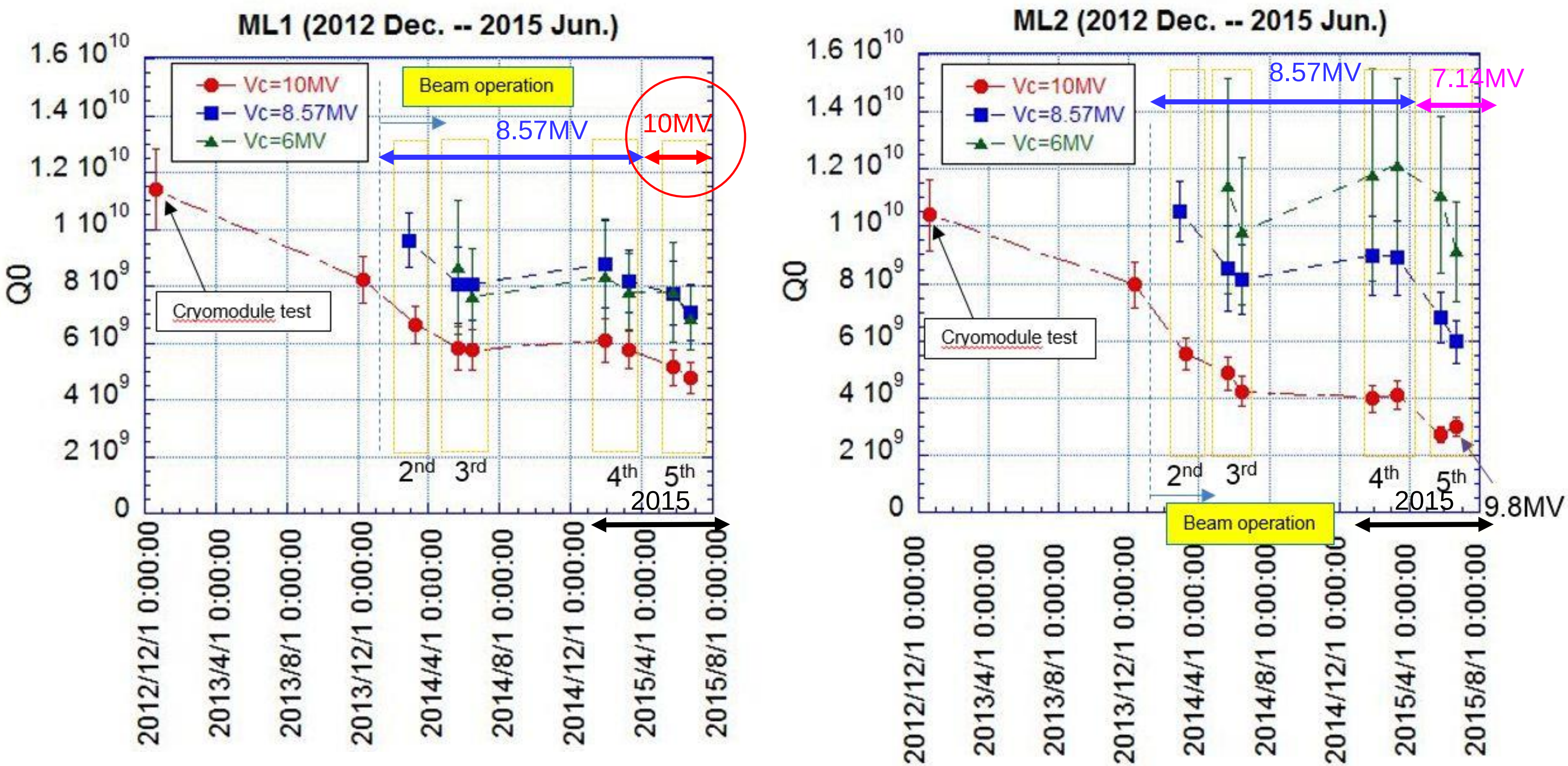
History of pulse processing of No.3 injector Cavity(8 hours)





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)

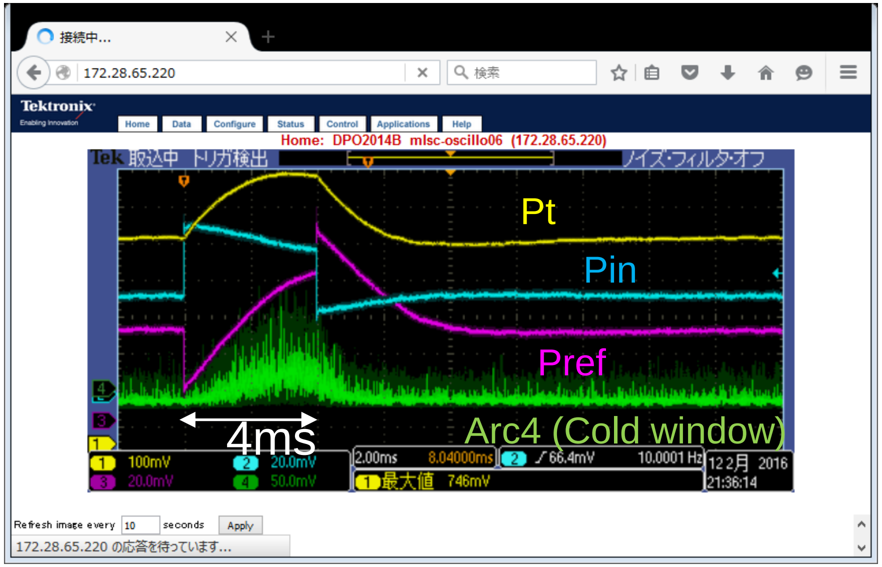


We met Q degradation during beam operation. But we kept same performance within error bars after degradation from May 2014 to March 2015 and no trip was observed for 1.5 months, even if no pulse processing was applied in 2015. So in 5th phase in May – June 2015, one cavity of ML1 increase the field from 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.

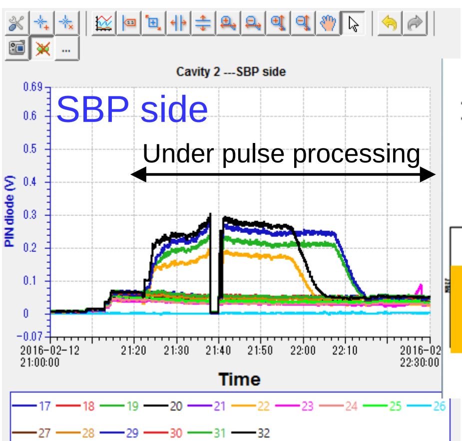
- In 2016, we continued 10MV operation to keep this field during 1mA operation.
- And we tried pulse processing to improve cavities performances more.

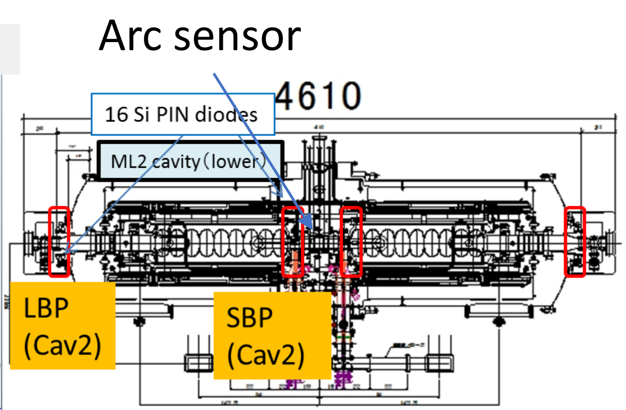
Example of pulse processing（ML2)

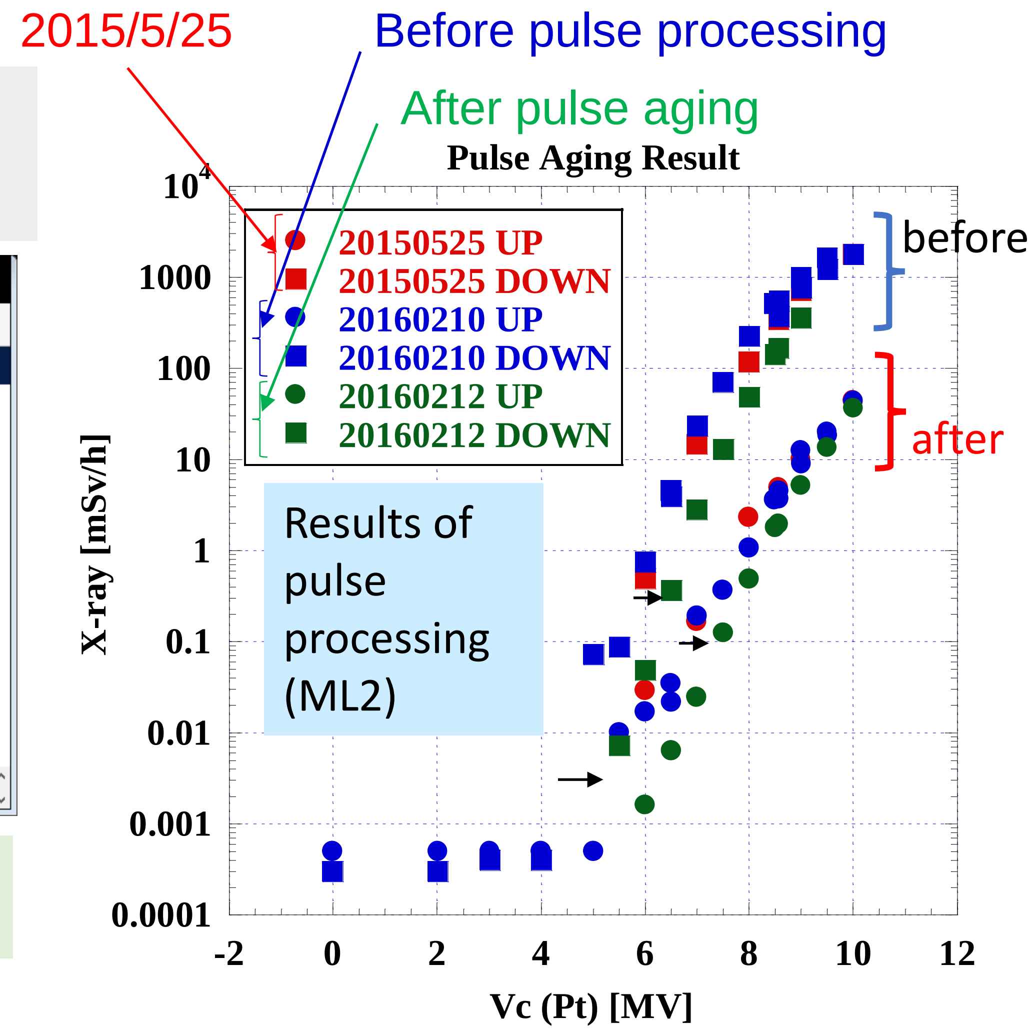
ML2 Pulse Aging (10Hz)
Vc=8.57MV(CW)+2.3MV(10Hz x 4ms)=10.9 MV
:40min pulse aging was done.



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





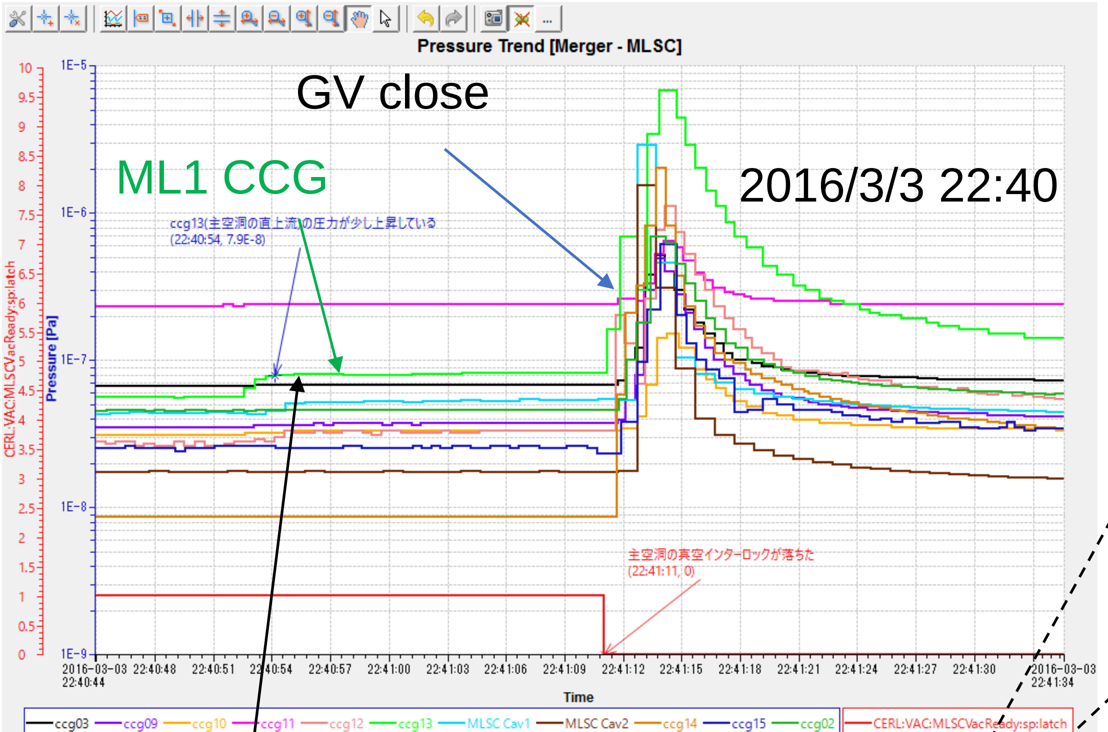


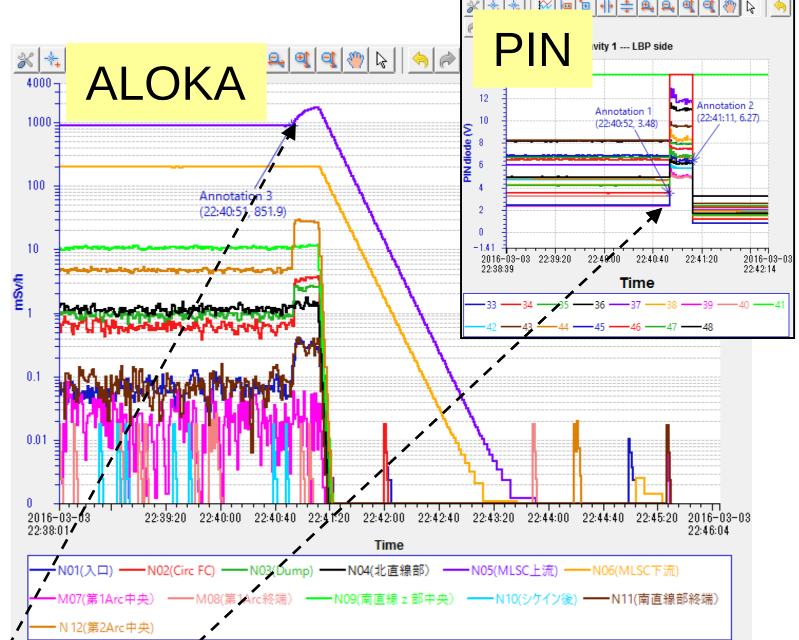
ML2 Vc vs ALOKA monitor

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

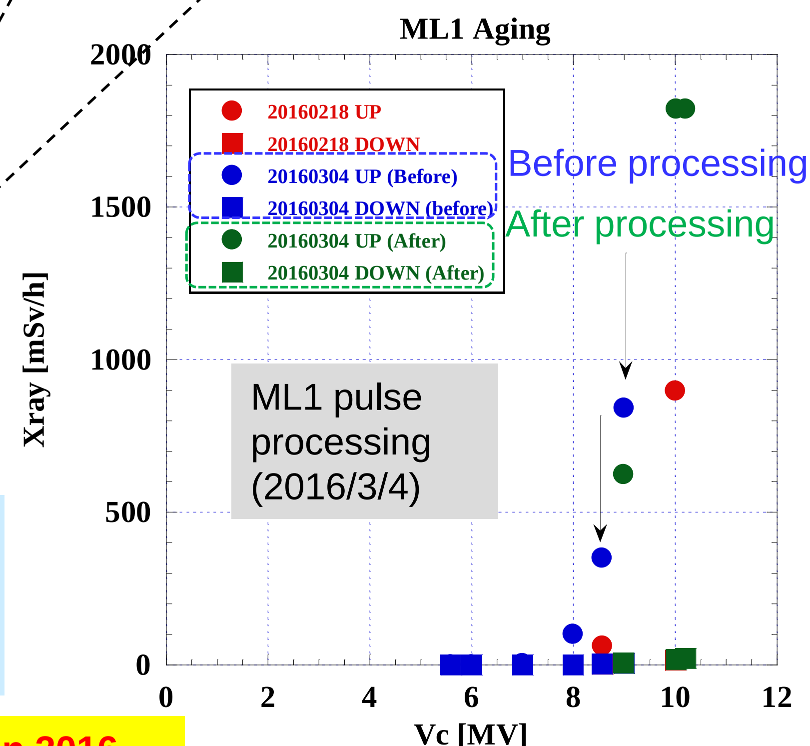
→Pulse processing works well.

vacuum event of ML1 and pulse processing





ML1 CCG vacuum become worse before 17 sec of ITL. At the same time, we met radiation increase. After this ITL, we could not keep 10MV field. Then we tried pulse processing for ML1 and reduced the radiation. But the cavity performance become worse due to field emission compared to that before ITL.



Pulse processing works well for both cavities. Especially, the cavity performance of ML2 cavity become better. Unfortunately, we met big vacuum event. The cavity performance become worse even if pulse processing was applied.

We could not keep 10 MV of ML1 due to this vacuum event in 2016.

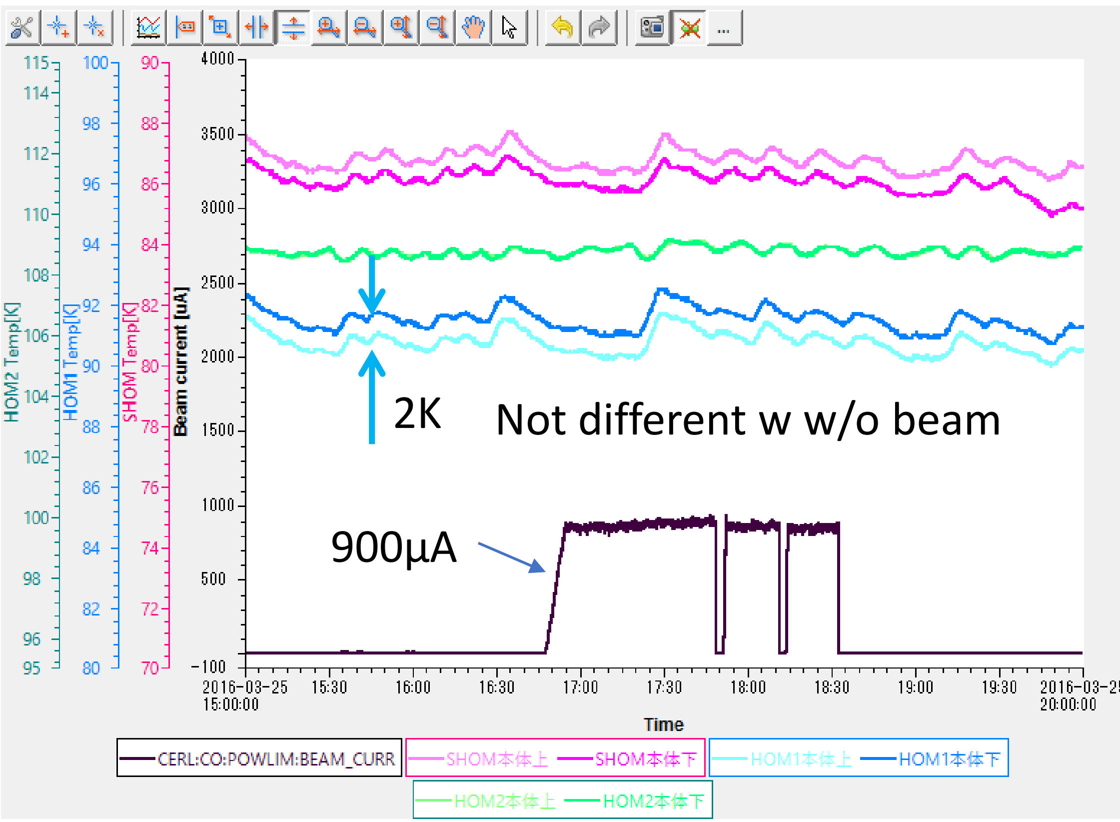
Heat load on HOM absorber

Temperature rise at 162.5MHz x 0.9mA

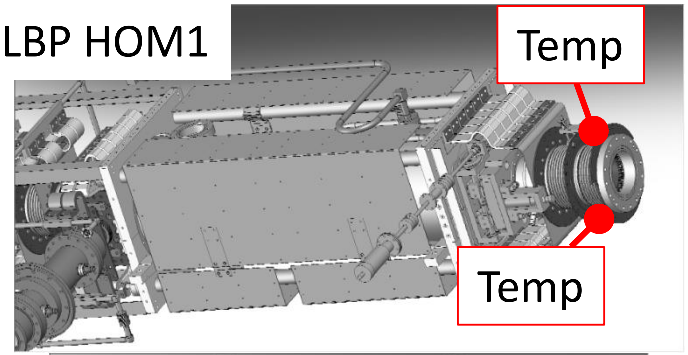
Expected heat load of ML : Loss Factror 10[V/pC]@3ps
Cavity Loss Power=7.7pC x 900μA x10V/pC x 2= 140 mW

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

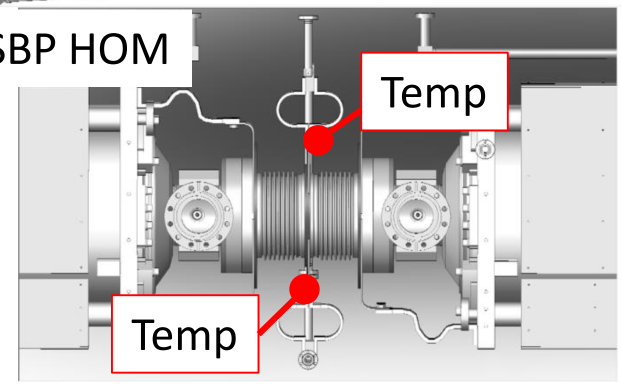
No temperature rise of HOM damper



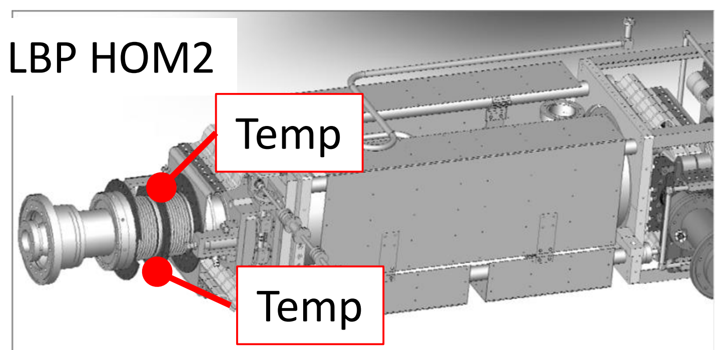
LBP HOM1



SBP HOM

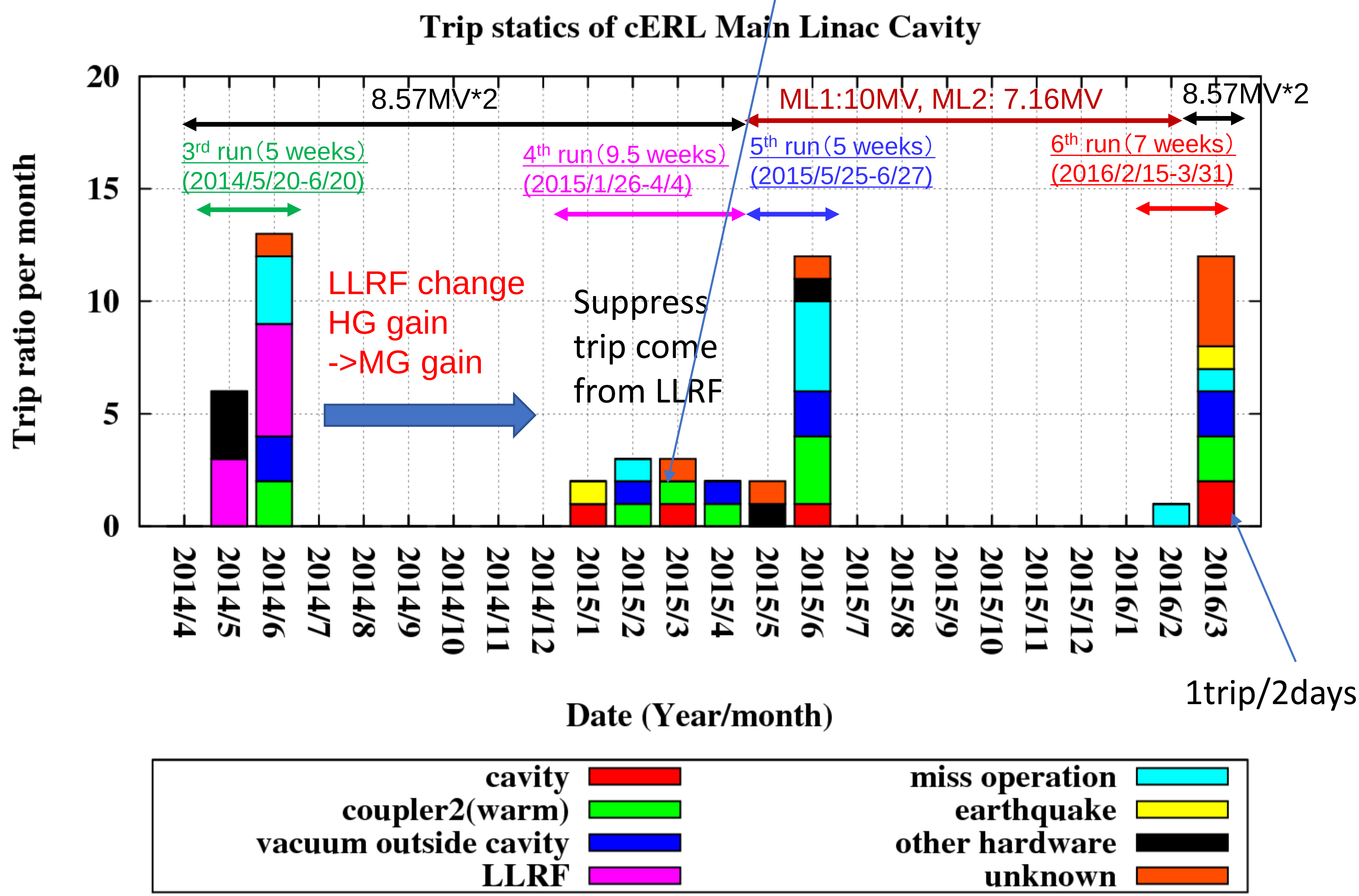


LBP HOM2



Trip Statistics of cERL Main Linac cavities for 2 years

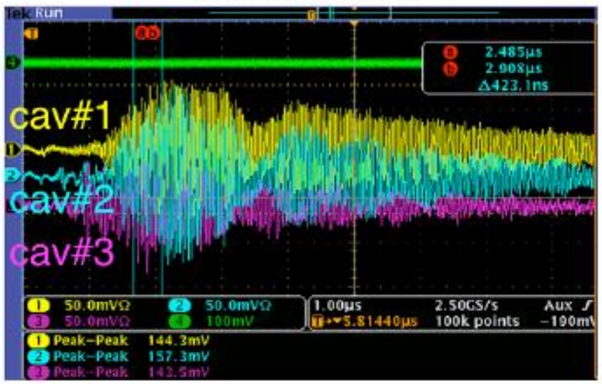
4th & 5th phase we did not apply pulse processing. But we had no trip for 1.5 month in 4th phase.



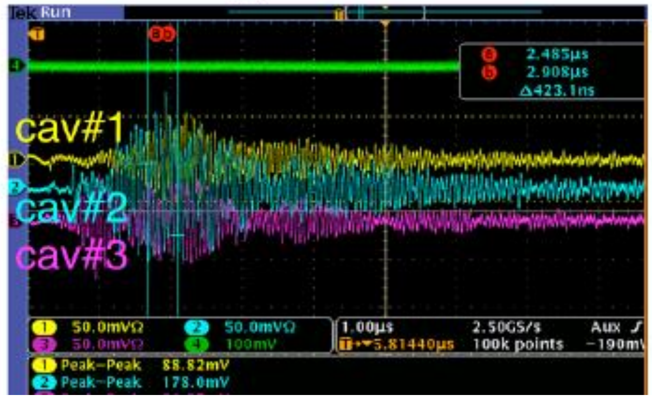
Stable beam operation was done by using this cryomodule for 3 years.
Main issues of trip is warm coupler of ML2 now.

Estimation of alignment error from HOM signal of injector cavities

(a)Horizontal offset



(b)Vertical offset



See detail on MOPB096
Y. Honda et. al.

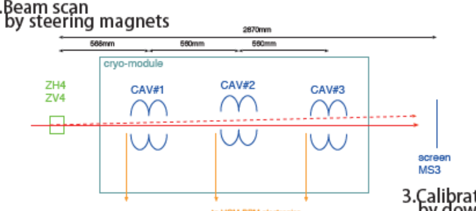
Dipole HOM (~1800MHz) signal of each cavities were used to estimate alignment error.

Measurement and Result

Procedure

Believing the beam trajectory to be straight,
HOM amplitudes of the three cavities were mesured while scanning the beam to detect cavity centers.

1.Beam scan
by steering magnets



3.Calibration
by downstream screen

2.Measure HOM amplitude

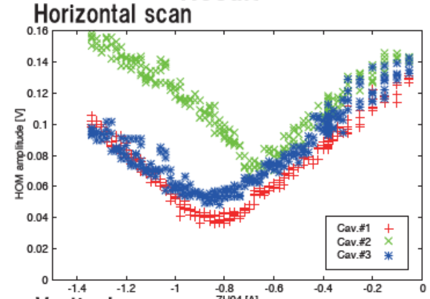
Beam parameter

Parameter	Value	Comment
Bunch charge	6 pC/bunch	
Bunch repetition	162.5 MHz	
Macro-pulse width	1 μs	
Kinetic energy	390 keV	Inj. cavity turned off
Buncher status	off	reducing beam divergence

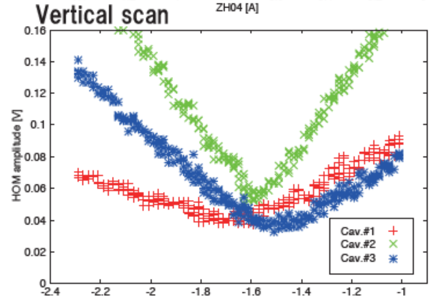
RF power was turned off for avoiding kick due to the acc field.

Result

Horizontal scan



Vertical scan

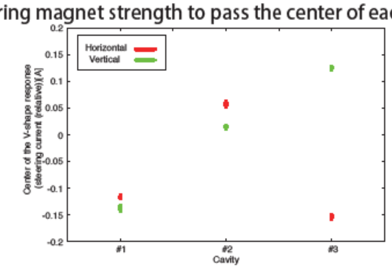


Estimation of misalignment

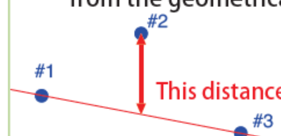
Analysis

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.

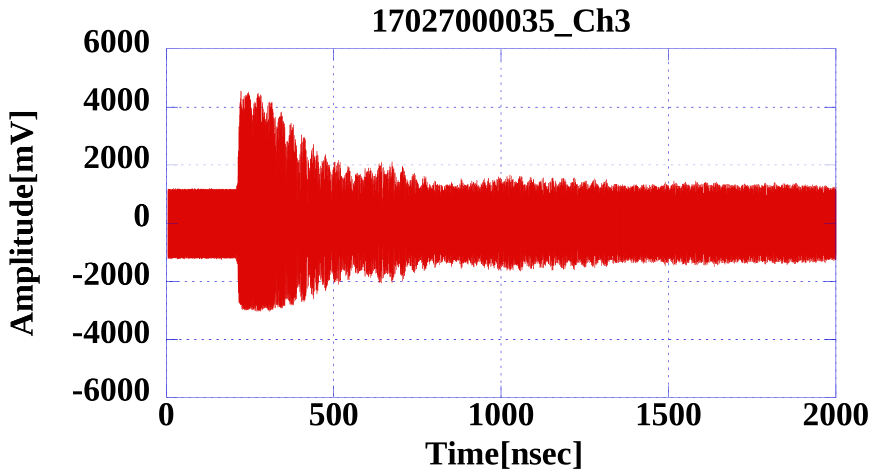


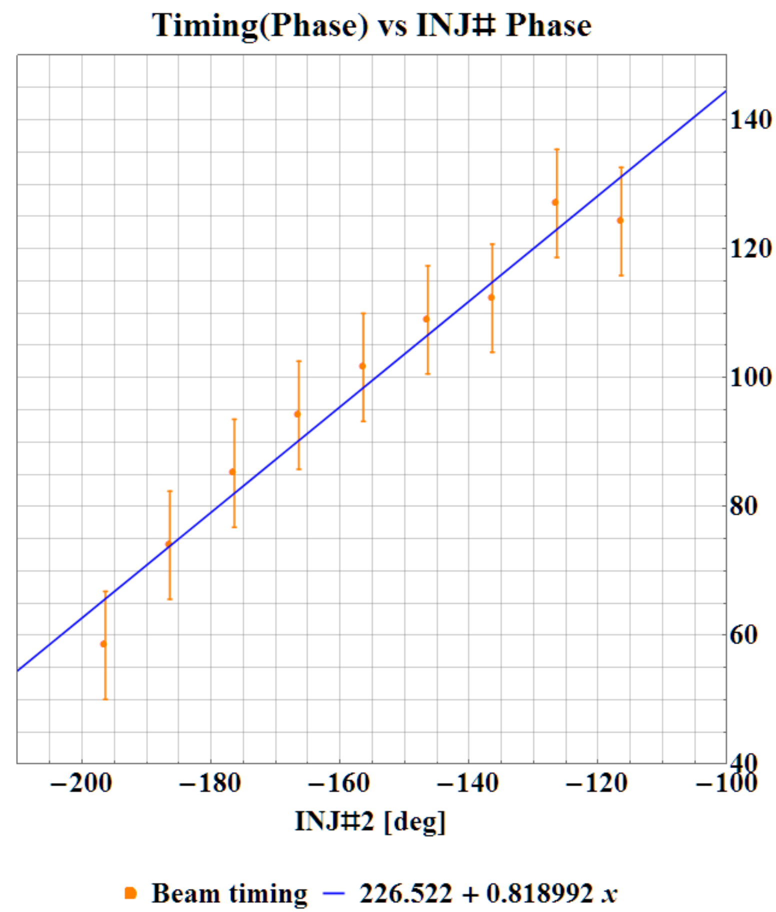
Plane	Relative misalignment
Horizontal	2.51 ± 0.05 mm
Vertical	0.27 ± 0.04 mm

Estimation of beam timing(phase) using HOM signal on injector cavities

- Study was just started.
- Try to realized beam timing by observing HOM signal of TM011 (2800 MHz)

- Tried to increase S/N of HOM signal by applying adequate RF filters ⇒ Rise up of signal can be seen.
- Beam timing seems to be monitored.
- 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.