OPERATIONAL EXPERIENCE OF CW SRF INJECTOR AND MAIN LINAC CRYOMODULES AT THE COMPACT ERL (cERL)

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19+1 pages

cERL Injector Cryomodule

cERL Main linac cryomodule

ERL2015 , Stony Brook, NY, USA, June 7-12, 2015

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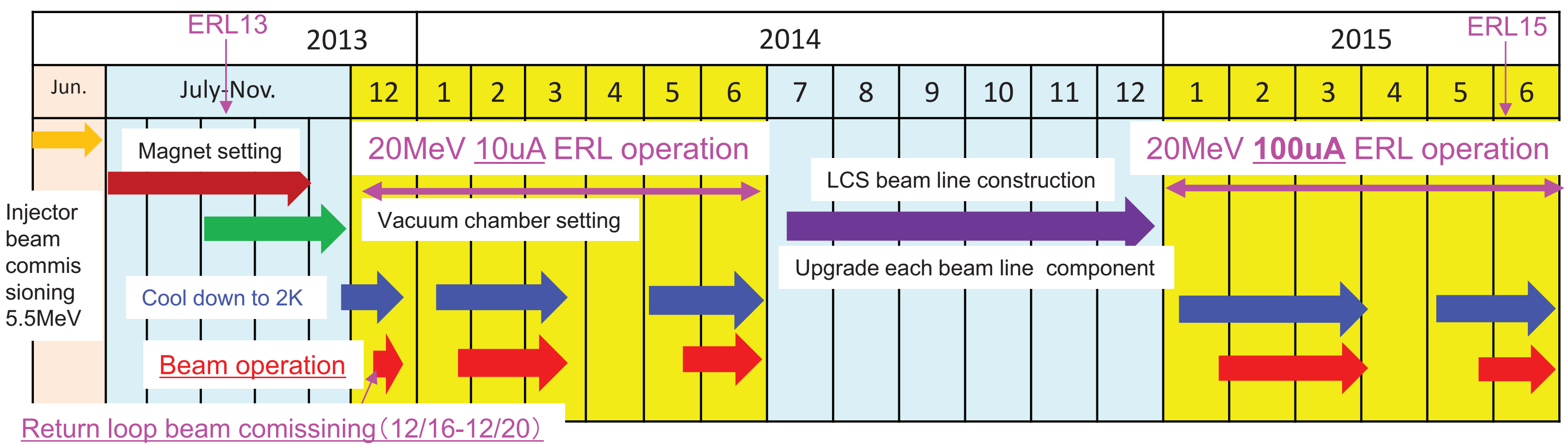
  - Measure the performance of two cryomodules during long term CW beam operation.



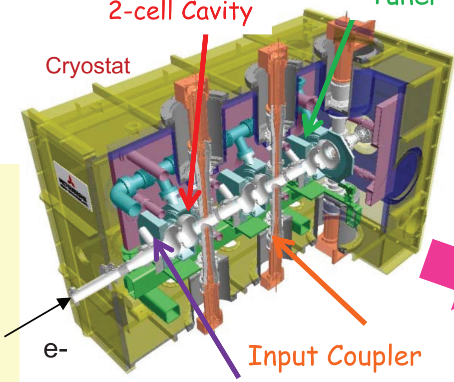
A) Apparatus of cERL injector & main linac cryomodule

T.Furuya & E.Kako et.al

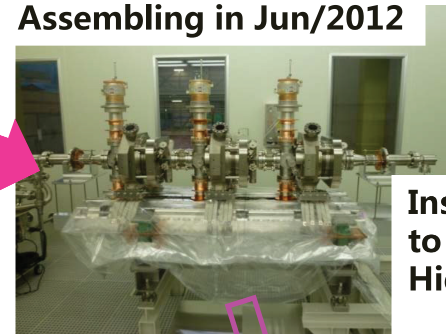
Injector module

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



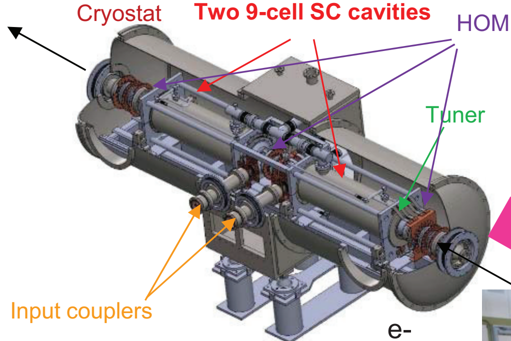
Assembling in Jun/2012



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

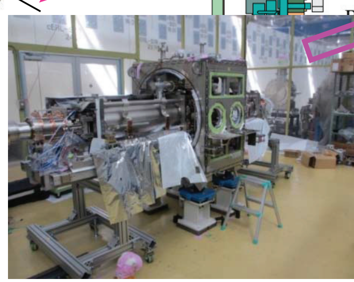
Main linac module

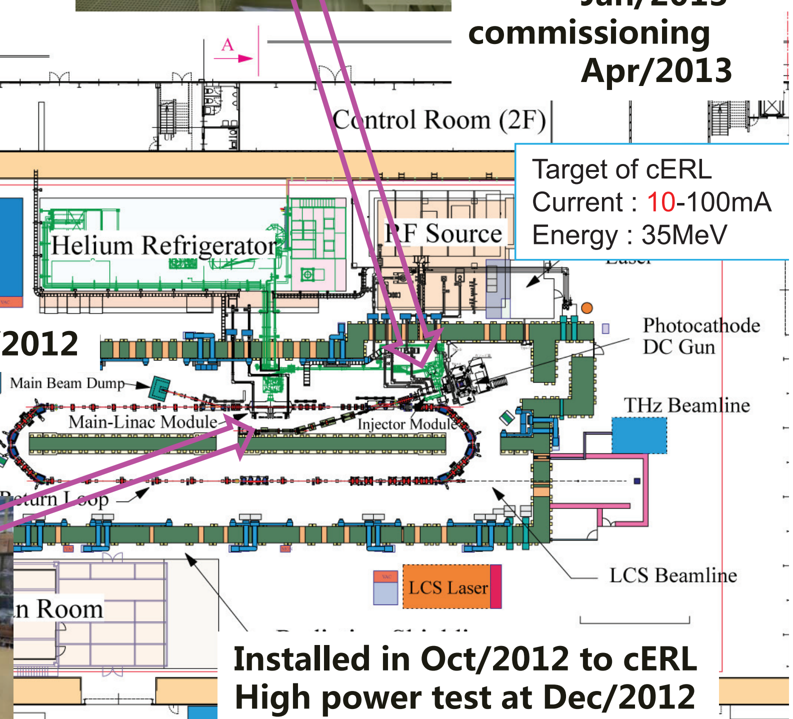
HOM damped (for 100mA BBU suppression)
9-cell cavity (named as ERL-model2) × 2



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





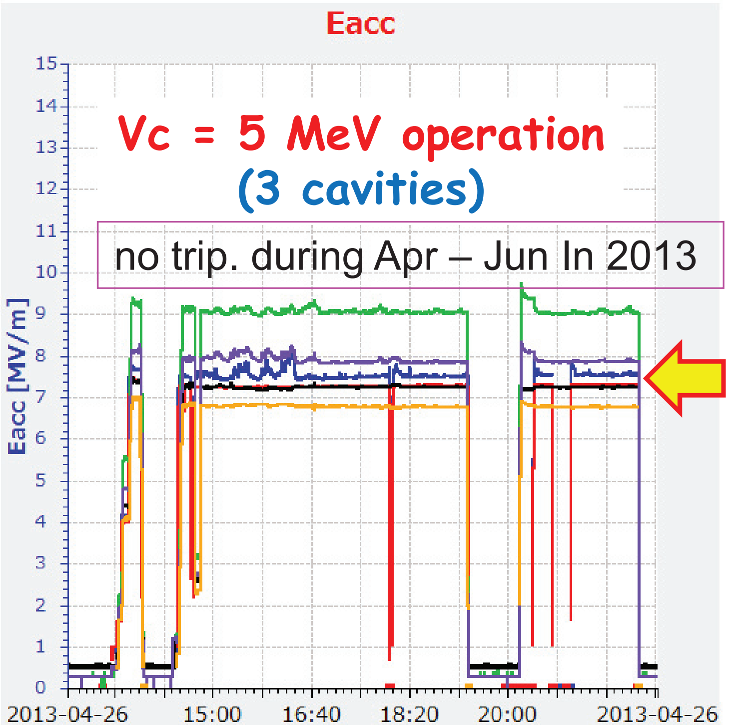
Target of cERL
Current : 10-100mA
Energy : 35MeV

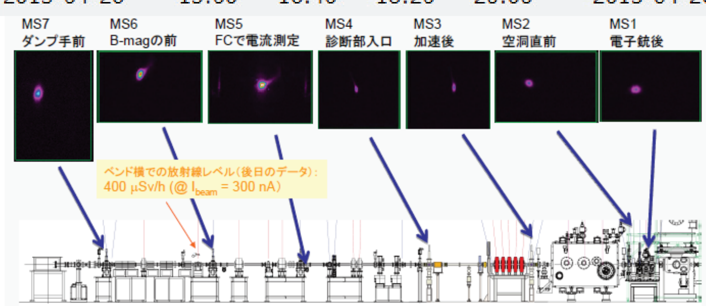
Installed in Oct/2012 to cERL
High power test at Dec/2012
Commissioning Dec/2013

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

5.5MeV beam was accelerate by Injector cryomodule

By E. Kako et al.

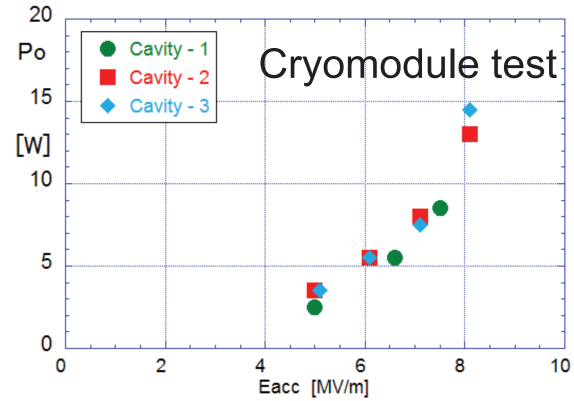


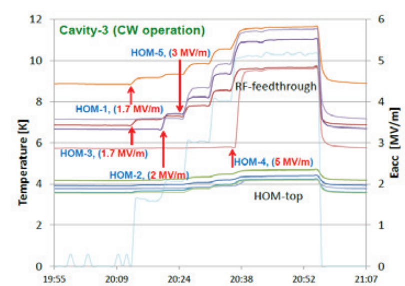


HOM coupler heating was unexpected more than 2MV/m field in cryomodule operation. (It was not shown in V.T) But 5.5 MeV injector operation was achieved within our cryogenic capacity. Input coupler was tested up to CW 30kW in test bench and operated within 10kW at present.

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

Total 5MV acceleration
No coupler kick was observed.





HOM heating

HOM feedthrough

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

Summary of performance of cryomodule test in 2012

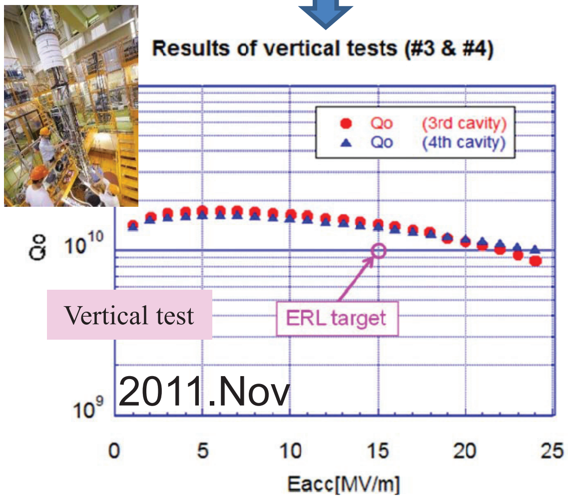
Vc=16 MV was achieved. Vc=13.5-14 MV could be kept for more than 1 hour.
Onset of radiation due to field emission: 8-10 MV/cavity

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

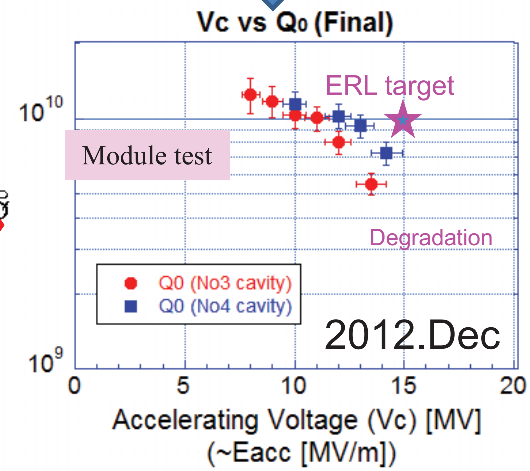
ERL model-2 9cell cavities for cERL

Main linac cryomodule set in cERL

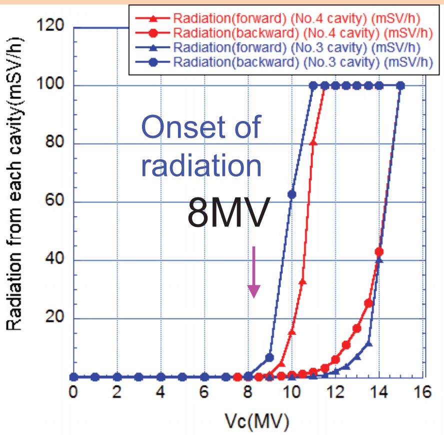
Some dusts would be contaminated during string assembly → problem



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



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

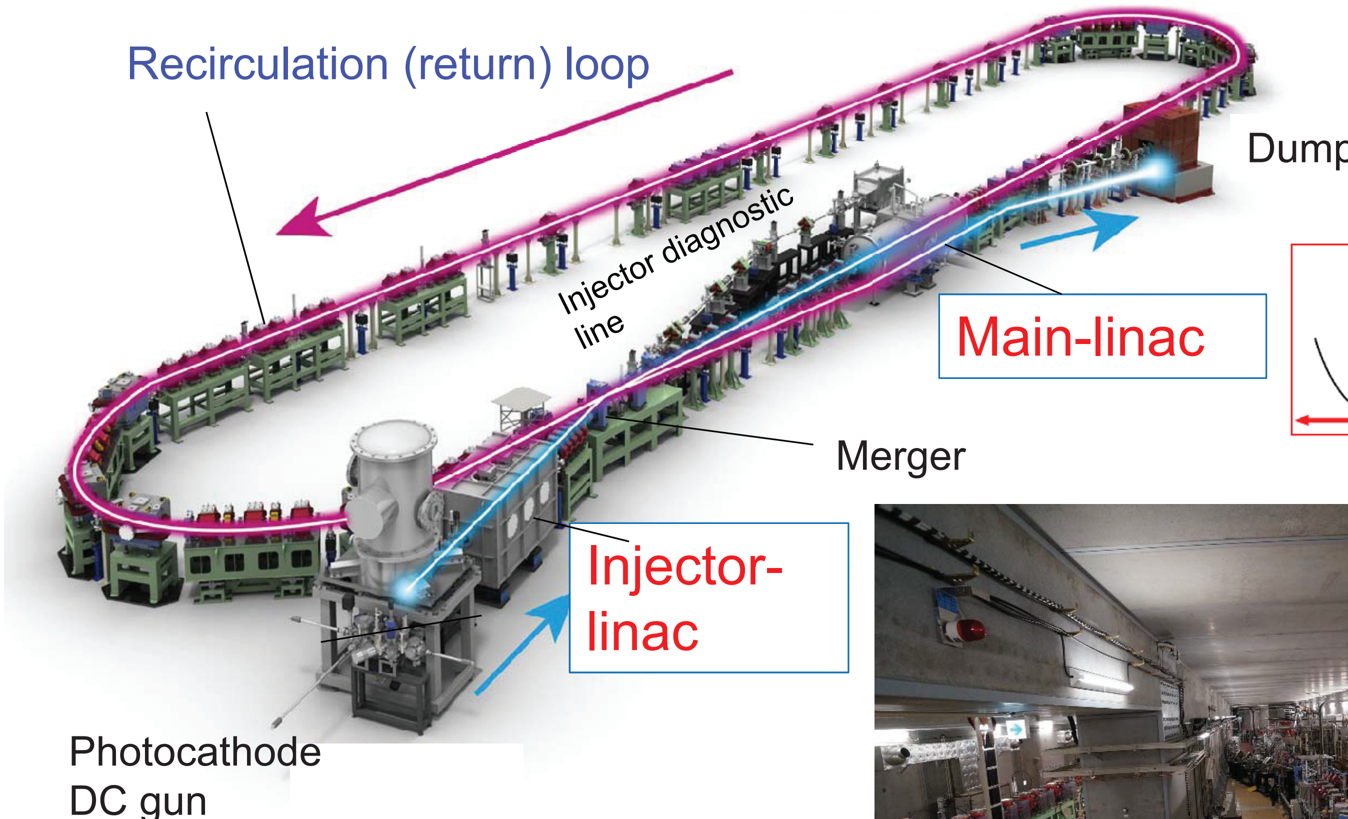


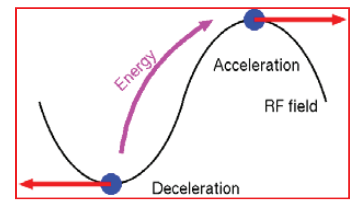
radiation monitors were set on both sides (See detail in page 12)

B) Progress from ERL2013

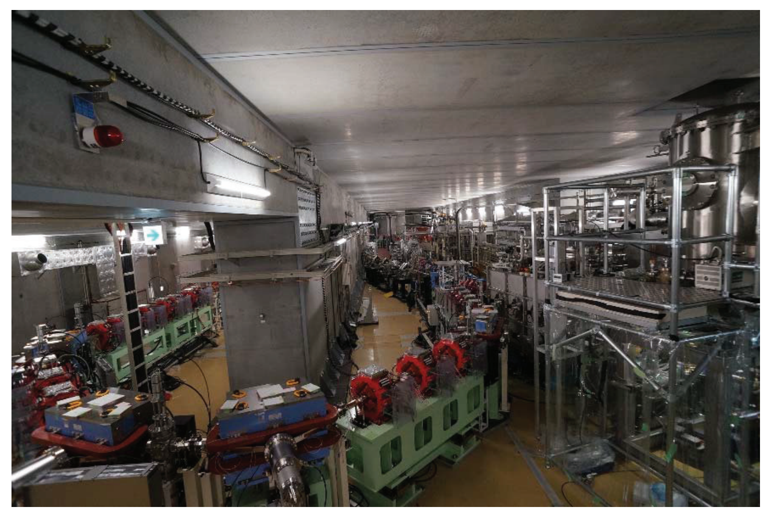
Compact ERL Layout

Start beam operation with return loop





- Completed in Dec. 2013.
- Commissioned during Dec. 2013 - .



Beam operation was started with return loop by using injector and main linac cryomodule

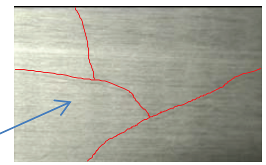
- **Due to the large field emission, we set the total beam energy to 20MeV**
  - Energy : 20MeV (ML:17.14MeV(8.57MV+8.57MV)+Inj 2.9MeV)
  - Beam current : 1.3GHz 10uA current (CW) with Energy recovoery

Initial target of cERL (2014)

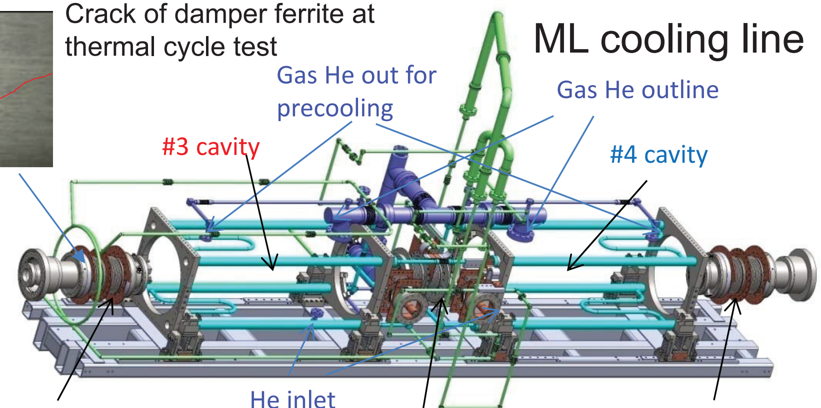
Strategy of cooling

・HOM damper should be cooled down slowly, to avoid cracking of ferrite.3K/h was required for 80K line, which cool the HOM dampers.

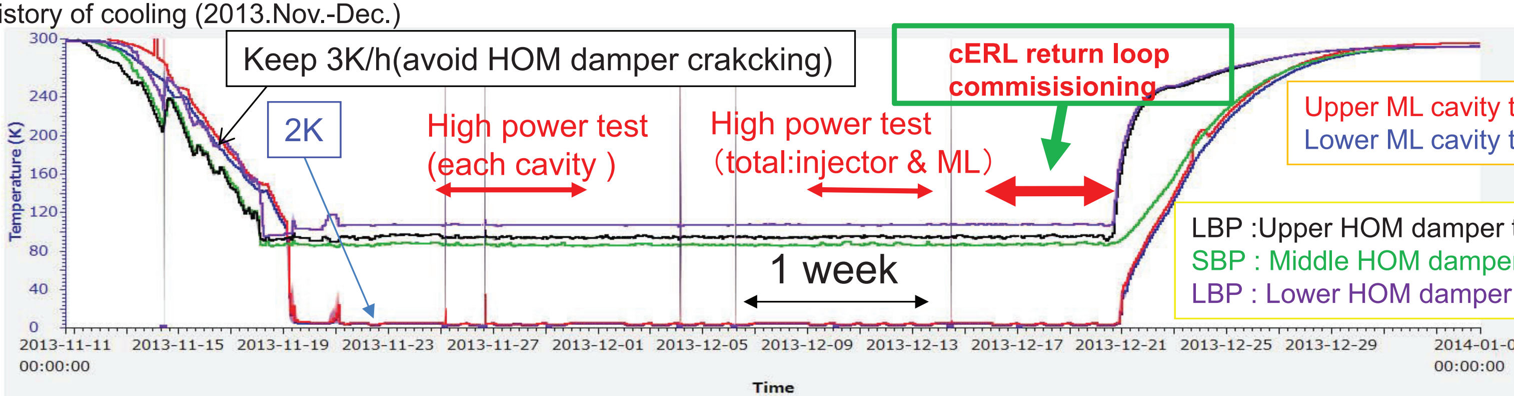
・Relatively large temperature difference was avoided within each 2K, 5K(He) and 80K(N_2) lines.



Crack of damper ferrite at thermal cycle test



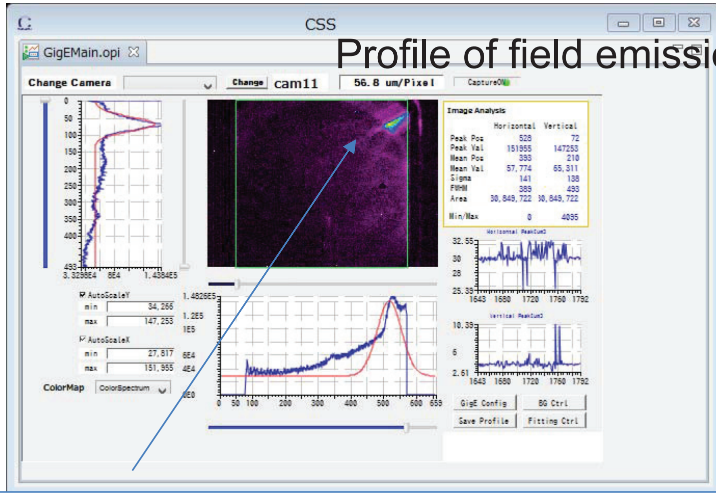
History of cooling (2013.Nov.-Dec.)



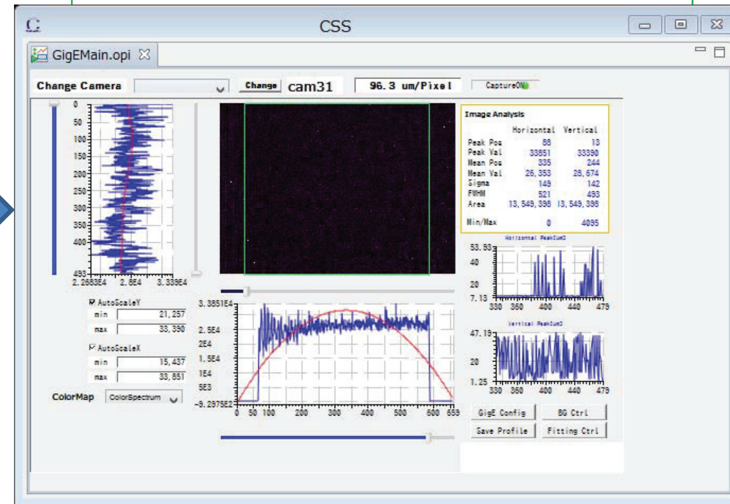
Normal operation of beam and/or high power test

start cooling (9:00～12:00) to 2K。13:00～22:00(or24:00) ,2Kkeep＆study, midnight & weekend 4K keep

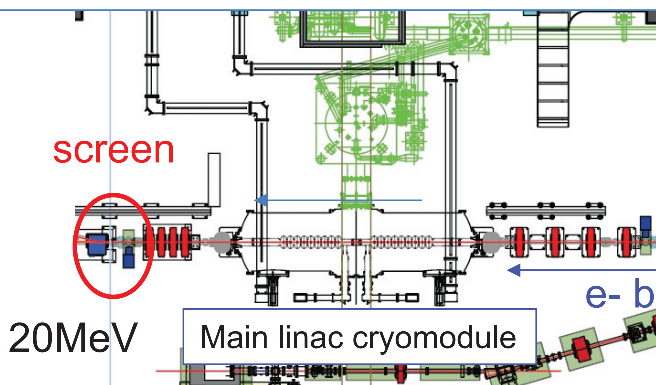
First beam operation in 2013 Dec.
(Screen shot of field emission and this effect)

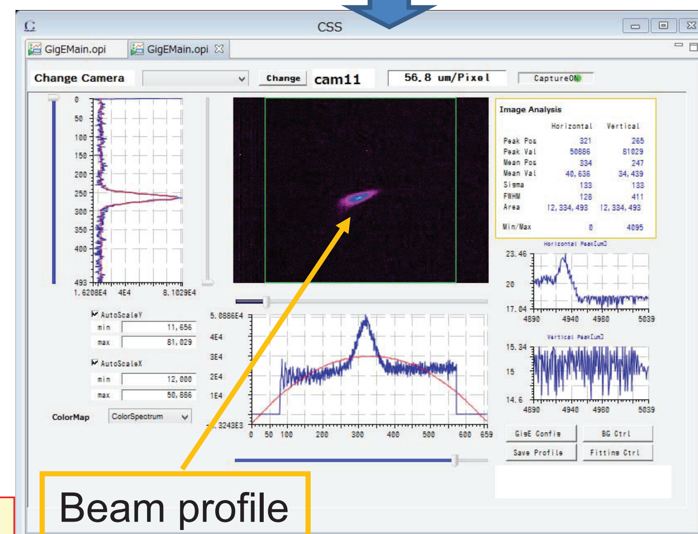


When we shorten the gate width to 10us, we could not see the field emission.



Screen shot of field emission of 8.3MV of ML1 & 8.3MV of ML2 8.3MV with gate width of 100ms of CCD camera. We could see the profile of field emission.



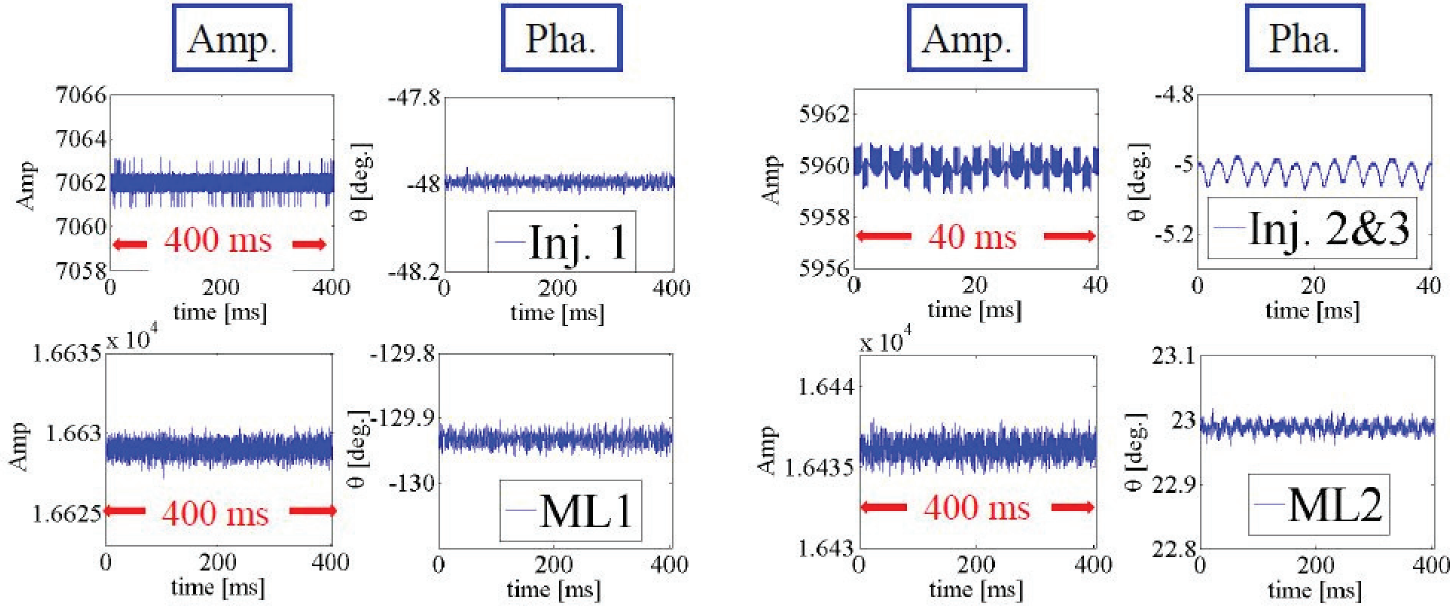


We could acceralate the beam without HOM damper effect and/or coupler kick.
No field emission effect was observed during beam operaion.

After that, we could see the beam profile without field emission effect with 10us gate width of CCD.

Power & LLRF stability in beam operation

F.Qiu & T.Miura et al



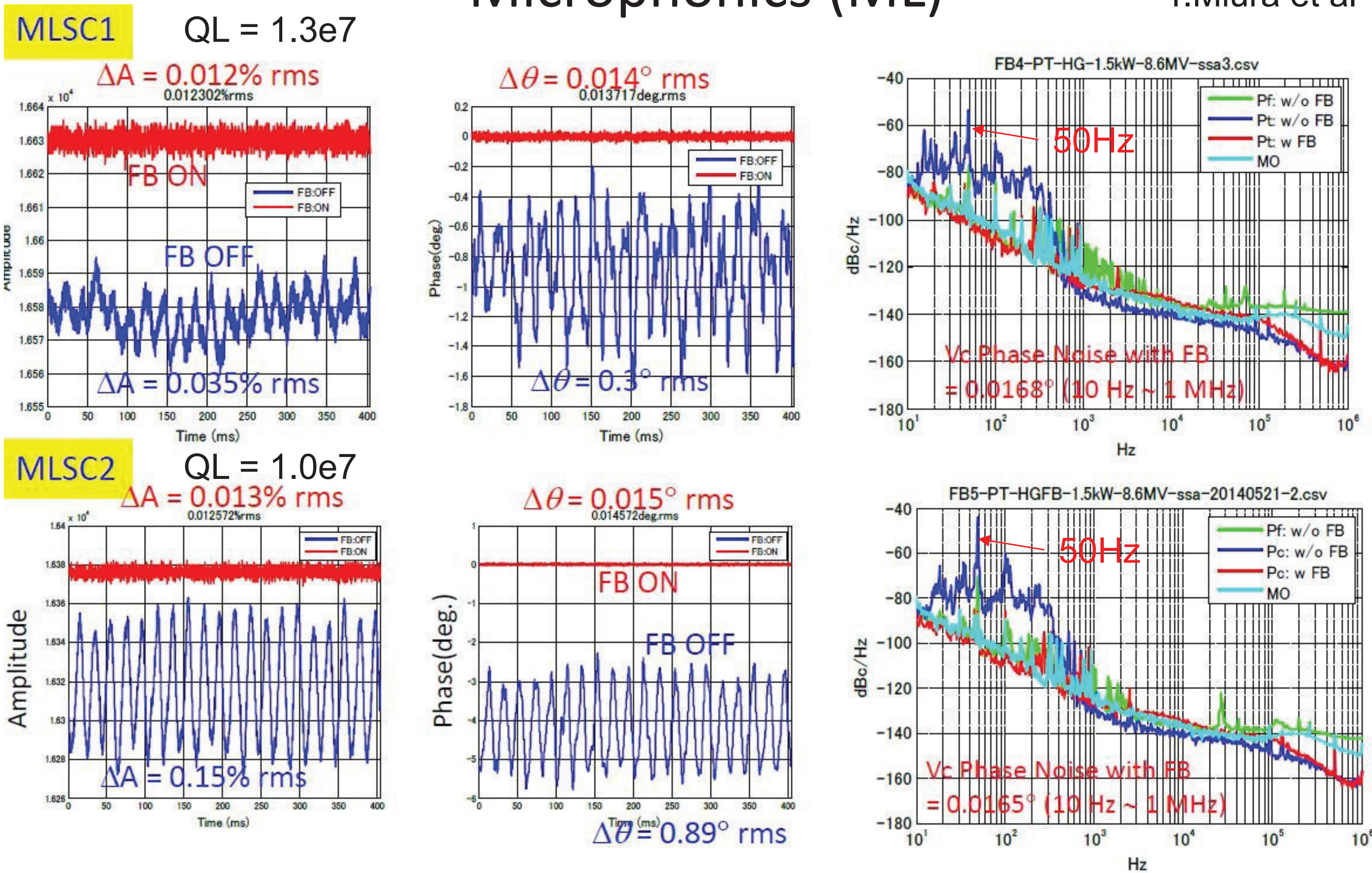
SC Cavity	Inj1(2cell)	Inj2(2cell)	Inj3(2cell)	ML1(9cell)	ML2(9cell)
Acc. Field	3.2MV/m	3.3MV/m	3.0MV/m	8.3MV/m	8.3MV/m
power	0.53kW	1.4kW	1.0kW	1.6kW	2kW
QL	1.2e6	5.8e5	4.8e5	1.3e7	1.0e7
ΔA/A(% rms)	0.006%	0.007%		0.003%	0.003%
Δθ(deg rms)	0.009deg	0.025deg		0.010deg	0.007deg

Satisfy our requirements of ΔA/A < 0.1% , Δθ < 0.1 deg for cERL operation

See detail in Qiu's talk of "Performance of the Digital LLRF System for cERL at KEK" on Wednesday.

Microphonics (ML)

T.Miura et al



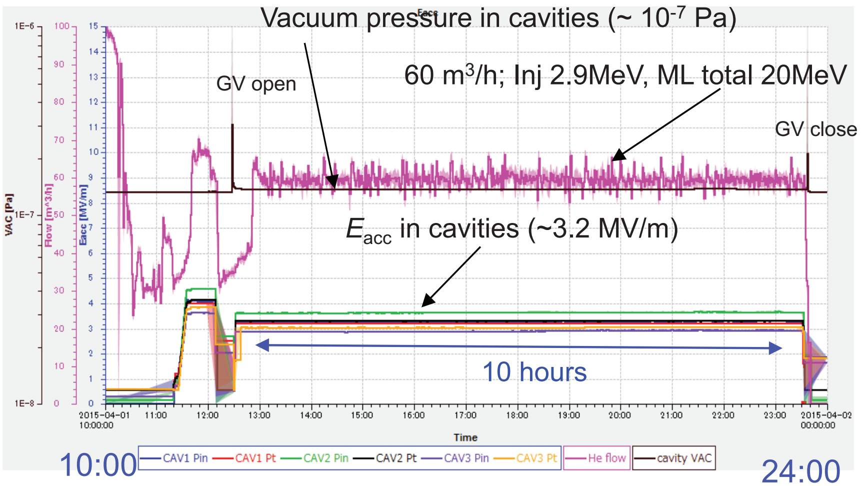
Acc. field with Higher QL of ML tend to be disturbed by microphinics. We measure the microphonics.
50Hz Microphonics which come from rotary pump for cryomodule was main component. However this was suppressed by LLRF optimization. Field was stabilized for stable beam operation.

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

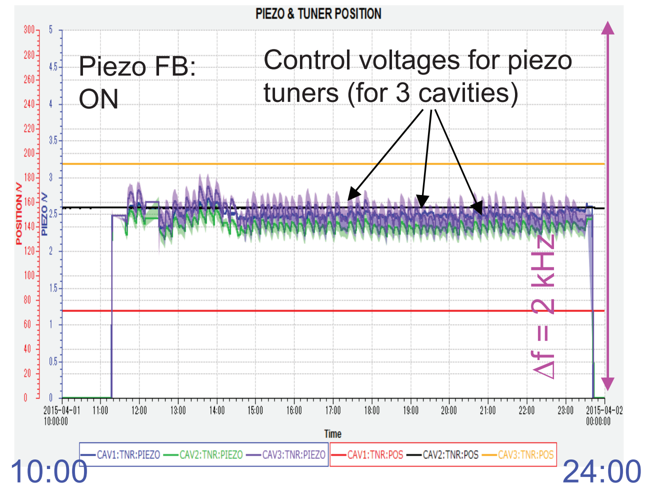
Injector

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

Field & Vac & loss



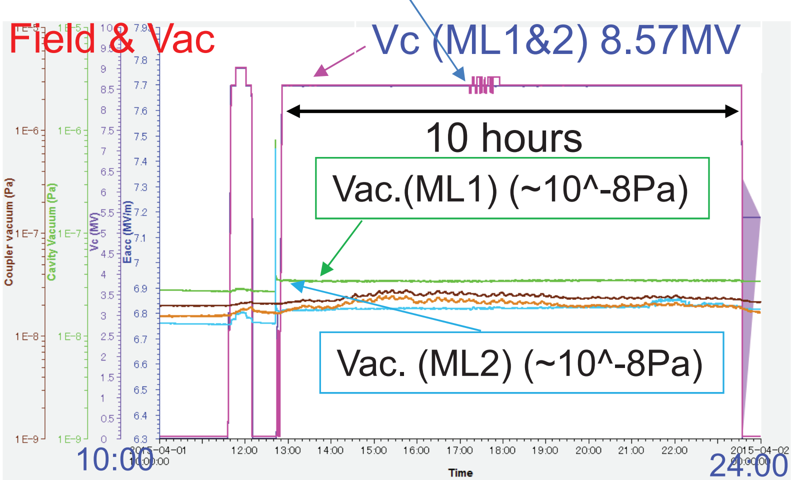
Piezo tuner



Main linac

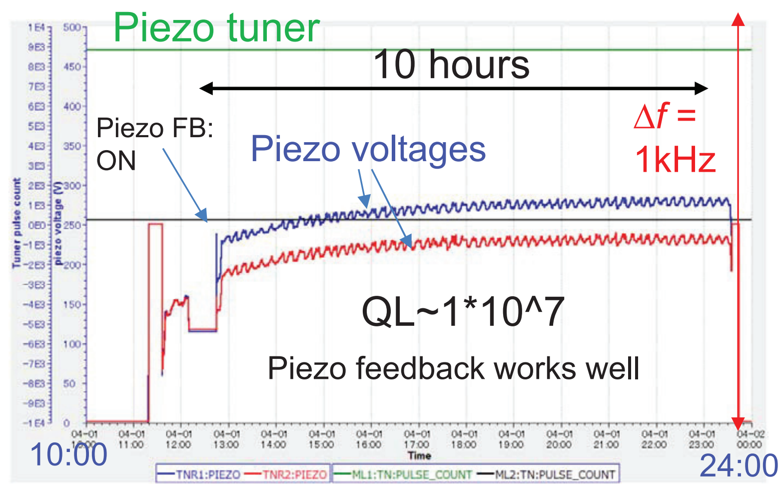
This fluctuation come from dispersion measurement

Field & Vac

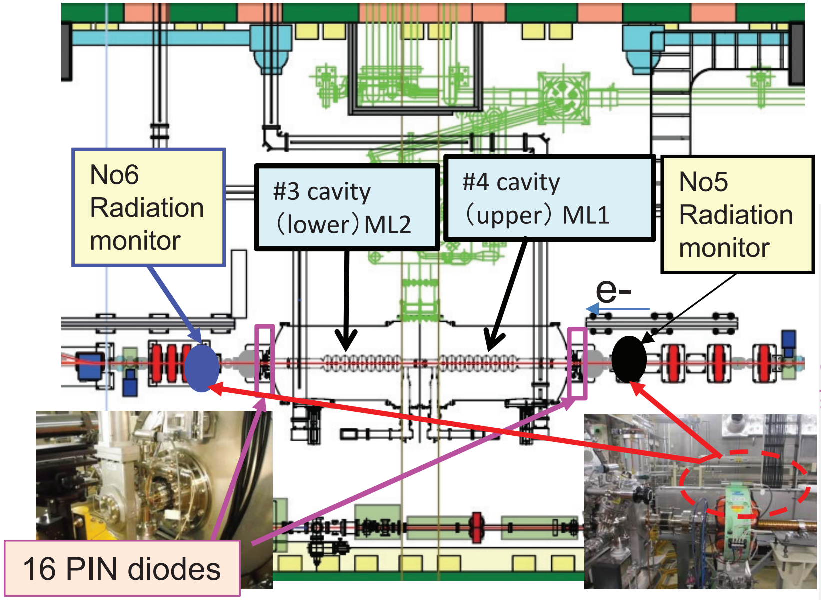


Piezo drift caused from 4K to 2K cooling at morning.

Piezo tuner

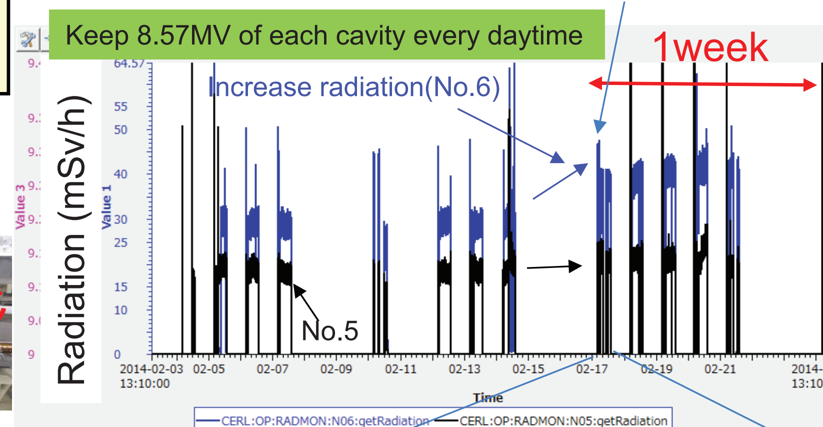


What happened during long term beam operation to ML cavities (radiation & cavity performance)



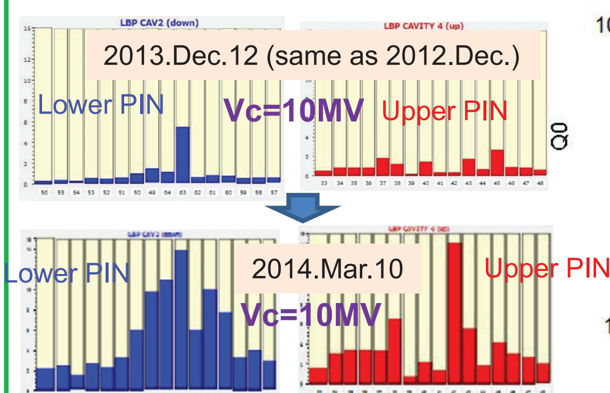
We set two types of radiation monitor. (radiation monitor (ALOKA), PIN profile monitor) near the beam axis.

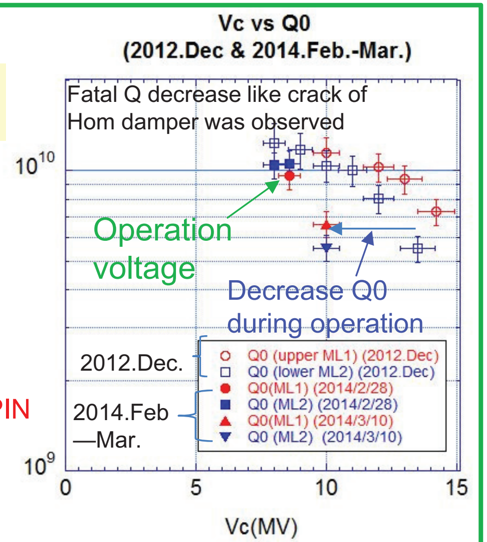
Radiation measurement during beam operation with 20MeV for 3 weeks. We found sudden jump after 2weeks operation.

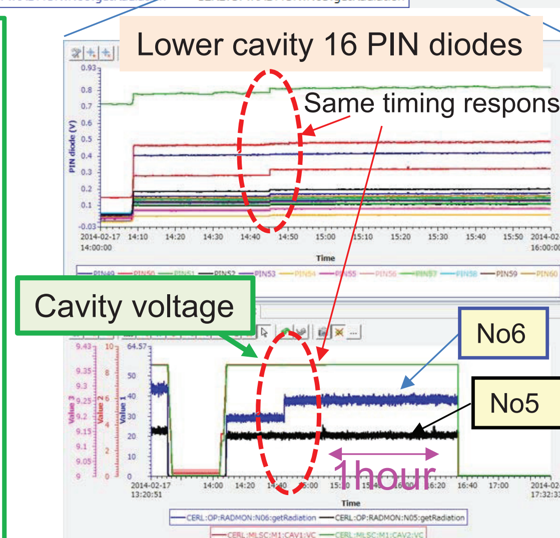


Q degradation & change of PIN diodes

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



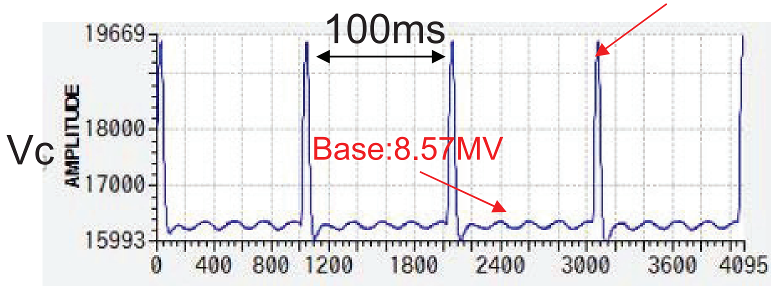




Apply pulse processing

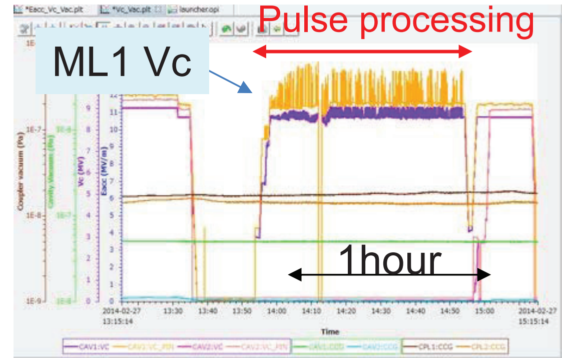
During beam operation, we apply pulse processing in order to eliminate the field emission source by applying high field.

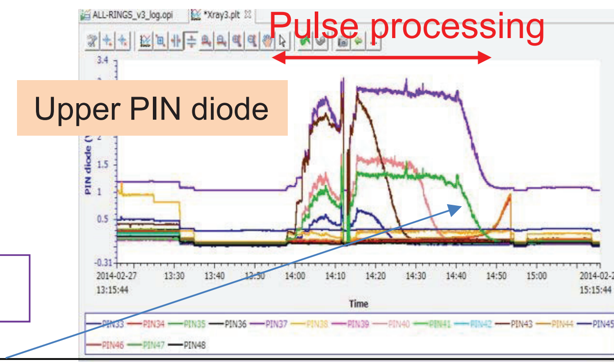
Measured voltage(digital)(Vc)



Duty 10Hz 4ms [peak:11MV] (pulse)

QL ~ 1*10^7 → τ ½ = 1ms , 4ms is larger τ ½





When we applied pulse processing, we could see the decreasing of PIN signal individually. → pulse processing works well

Pulse processing applied (10Hz 4ms) 8.5MV+2.5MV(pulse)

ML1:15min + 1hour

ML2:15min + 1hour

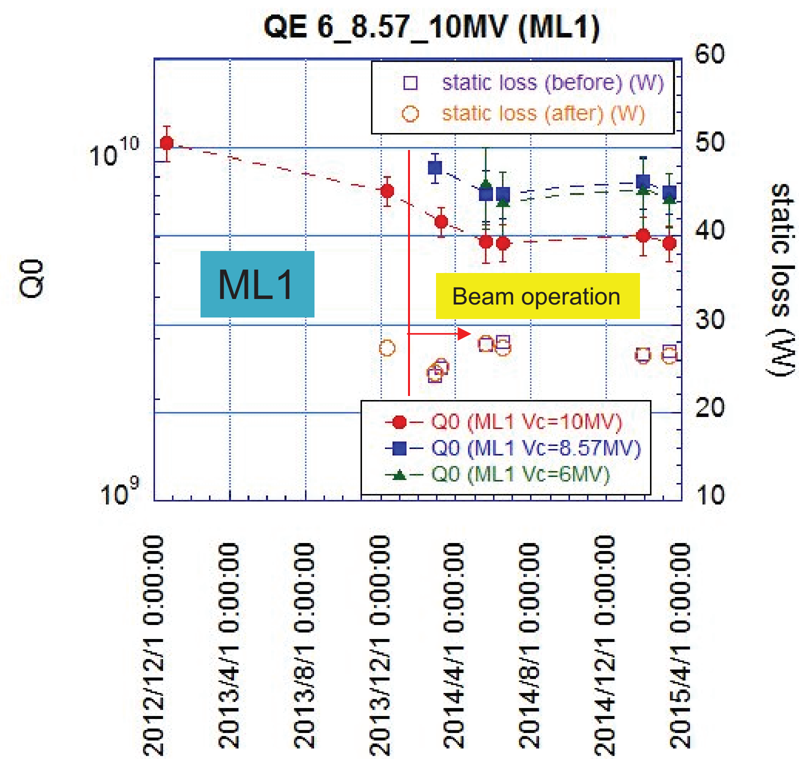
Pulse processing was effective for both cavities. (ML1: 8.57MV & ML2:8.57MV)

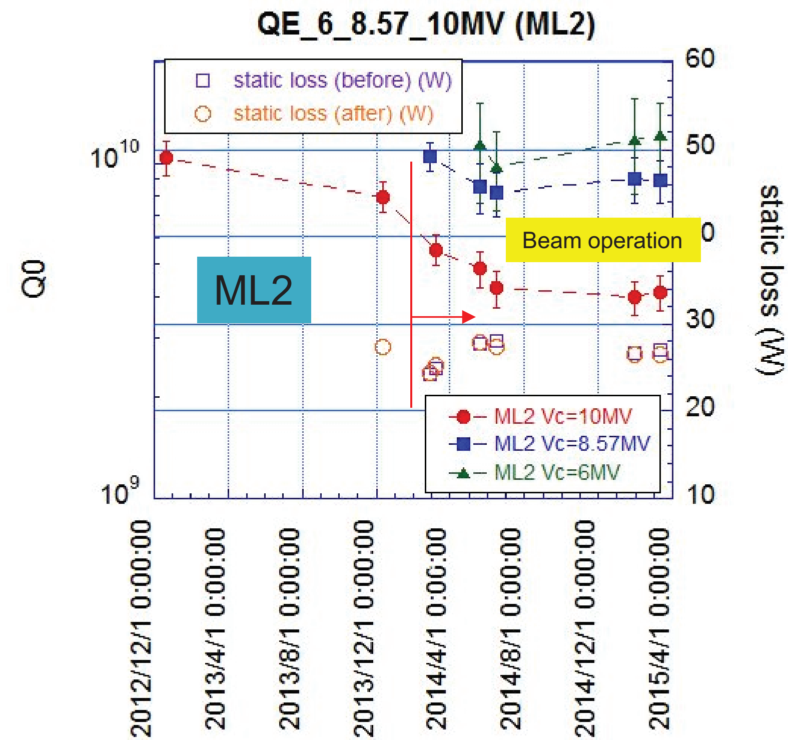
Upper radiation(No.5) 38.7mSv/h (2/25 21:00) → 20.48mSv/h (2/26 21:47)

Lower radaition(No.6) 133mSv/h (2/25 21:00) → 77.9mSv/h (2/26 21:47)

Radiation reduced to half by pulse processing. Now pulse aging works for reducing field emission during beam operation. We plan to try He processing (after trying at V.T in detail.)

Q-value history (from Dec.2012 to Mar. 2015)



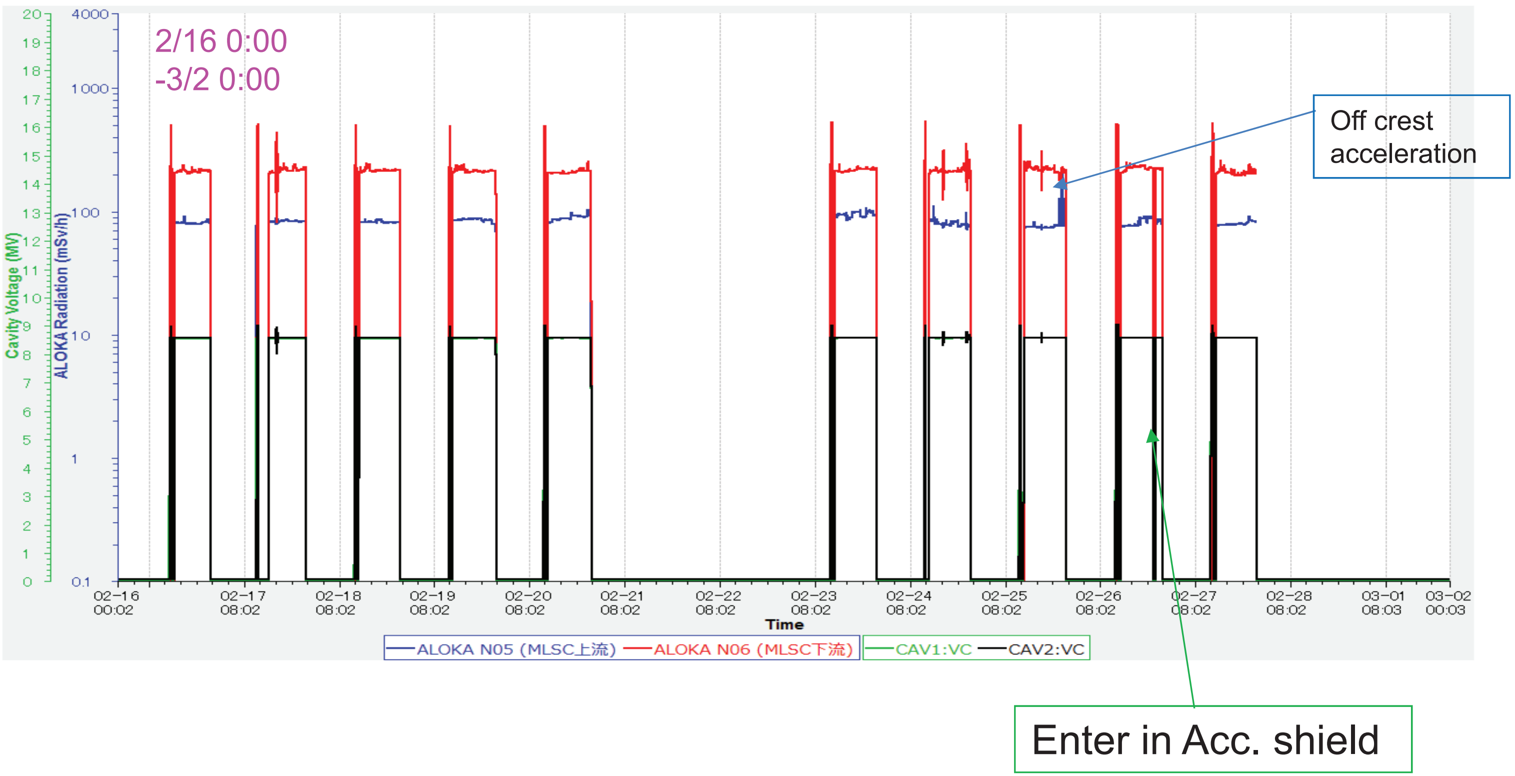


Q0 values were measured by He gas flow ratio by keeping CW field. We met Q degradation during beam operation. But we kept same performance within error bars after degradation from May 2014 to March 2015. 3 times we tried pulse processing in 2014. In 2015 no pulse processing was applied. Static loss was kept to almost 27W
→ We continue to see the cavity performance on next beam operation.

Long term operation of ML cavities with radiation

(ML1) (ALOKA No5) : 200-220mSv/h
(ML2) (ALOKA No6) : 80mSv/h

→ During the beam operation in 2015, radiation level was kept in stable.



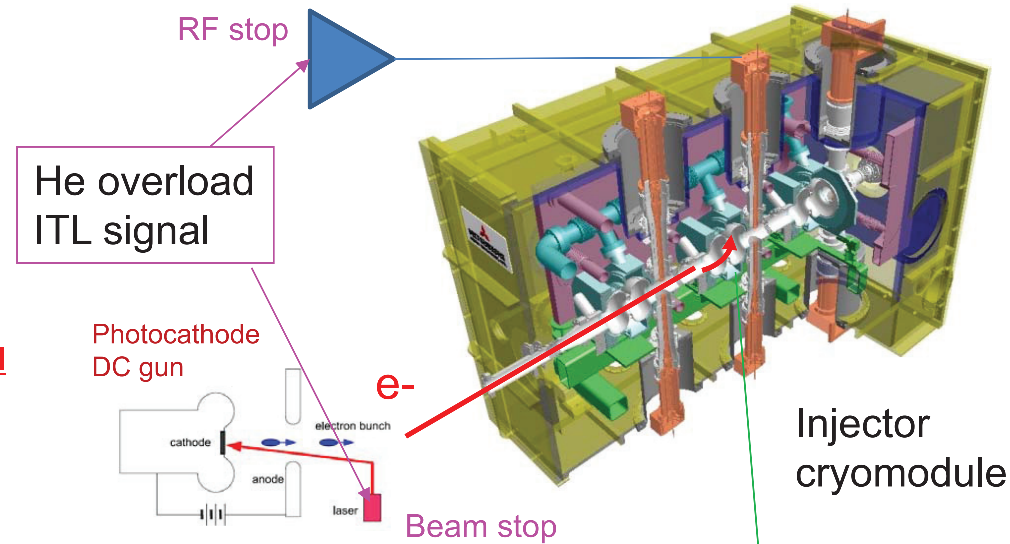
<u>In 2015 run, No trip of cERL Main linac was observed in 1.5 month beam operation.</u>
<u>No radiation increase was observed after long beam operation from May 2014 to Mar. 2015</u>

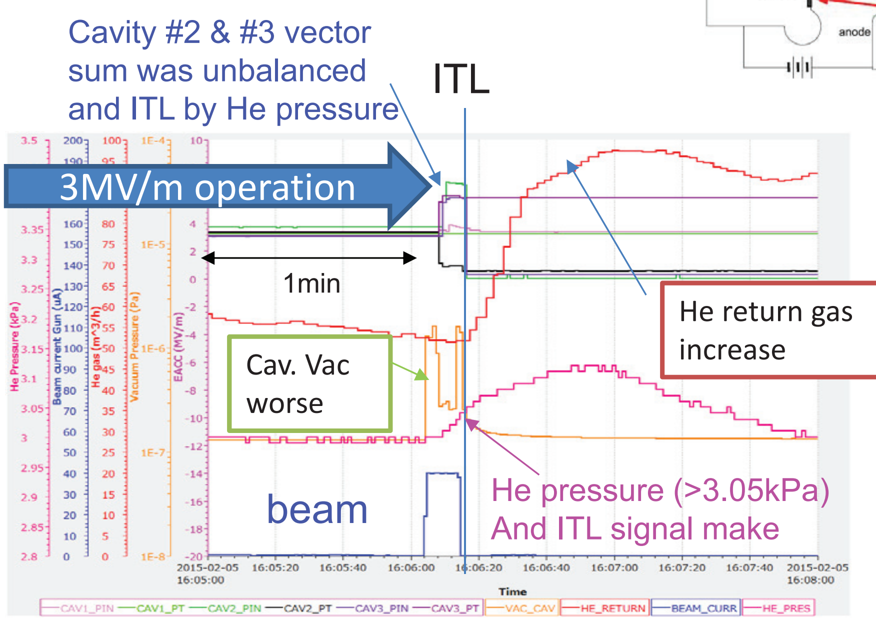
Quenched by unwanted CW beam (injector) (for safety operation)

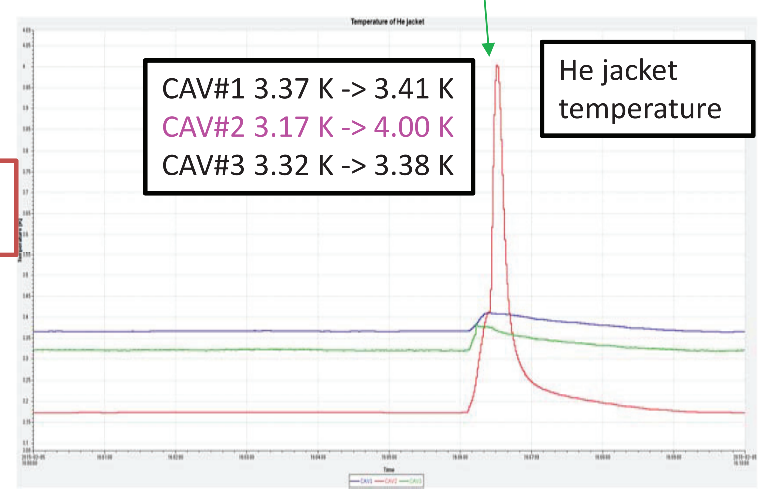
By setting miss of laser parameter of gun, more than 50uA beam suddenly come and hit the #2 inj cavity.

Sudden heating of cav was observed. In this case He overload ITL make the beam and RF stopped.

For miss operation, many beam and RF ITL need to be considered.







Statistics of trip ratio (ITL)

- 2014.May.22 ~ Jun.20 : 4.5 weeks（cavity operation time：10:00～22:00 or 23:00）
  - Injector ITL :   0 times
  - Main linac ITL :   19 times
    - Main reason is LLRF gain is too high (severe from the fluctuation and beam loading on pulse operation)

Change LLRF gain to optimize to ML1,2

- 2015.Jan.29 ~ Apr.3 : 9.5 weeks（cavity operation time：10:00～22:00 or 23:00）
  - Injector ITL :   18 times
    - INJ #1 : 10 times
    - INJ # 2- #3 8 times

    after quench by beam shown in previous page RF threshold was changed to lower. That would affect the ITL increase (tend to hit Klystron noise). We need to optimize.
  - Main linac ITL :   8 times
    - ML #1 : 7 times
    - ML #2 : 8 times

    Both 7 times

    By changing the LLRF gain, number of ITL drastically reduced. Main reason is earthquake & vacuum ITL from outside of cavity & warm window arc ITL.

No cavity activation come from field emission was observed during beam operation
Now we try more higher field (10MV) operation to take the trip statics on high field.

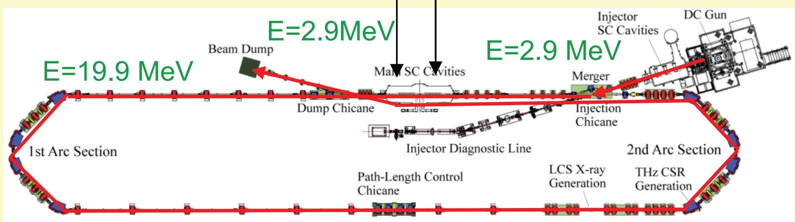
Confirmation of Energy Recovery (I_0 = 30 μA)

H.Sakai et al

Almost 100% Energy recovery was confirmed with CW 30uA.

ERL operation

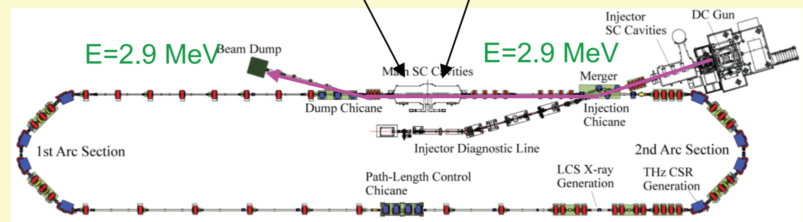
Cavities 1 and 2: acceleration (1st pass) and deceleration (2st pass)



Non-ERL operation

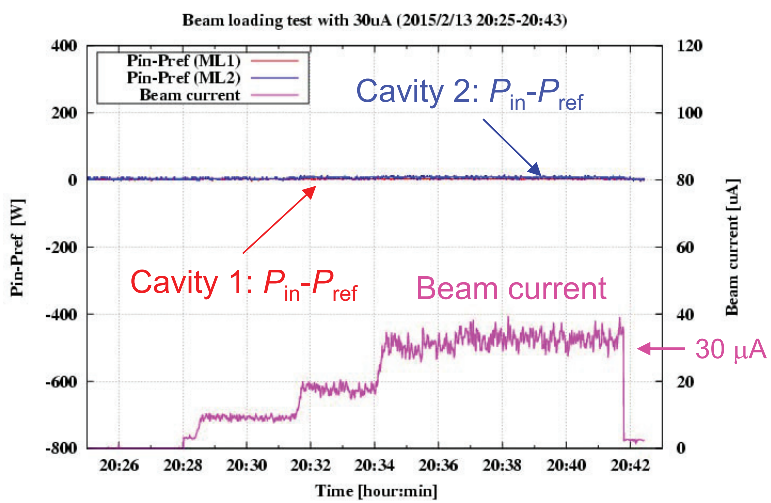
Cavity 2: deceleration (Vc=8.57 MV/cavity)

Cavity 1: acceleration (Vc=8.57 MV/cavity)

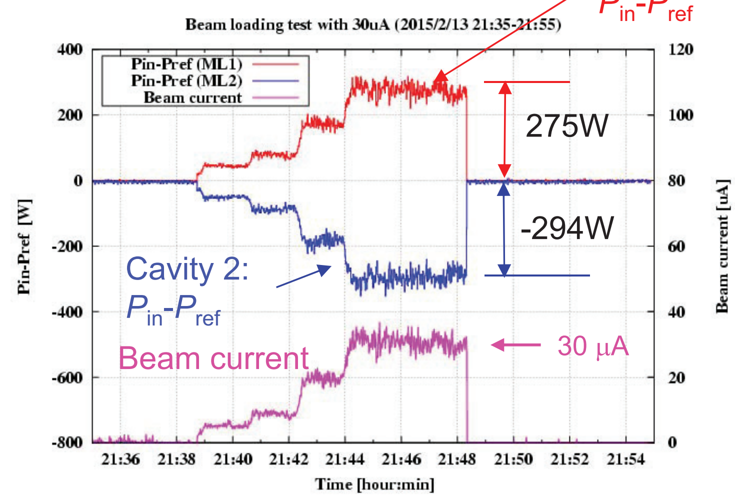


No beam loading

Energy recovery: 100-98.6%
(within accuracy of the measurement)



Beam loading (+ and -)



(Power lost in cavity) = (P_{in} : input power to cavity) - (P_{ref} : reflected power from cavity)

Summary

- From ERL2013, we construct the return loop and start the beam operation with ERL.
- Due to the heavy field emission, circulated beam energy reduced to 20MeV. However, Energy recovery with CW 80uA beam was done at present.
- In beam operation, we kept stable operation by using digital feedback system and suppressed the microphonics.
- Several trips were observed on a year. No crucial hardware trouble ,for example, come from miss operation of CW beam & or quench was met by fast & sophisticated ITL system to beam and RF.
- We met the Q degradation & radiation increase during beam operation on ML. We can apply pulse processing pragmatically. Now we keep stopping the cavity degradation.

Next plan

- We continue to see the cavity performance during the CW beam operation with higher current up to more than 10mA. (check the HOM damper performance)
- We also plan to make the new cryomodule with four 9cell cavities to overcome field emission problem with higher gradient and prepare the mass production.

Discussion items (My interest)

- What parameters are to be cared in designing cavity and cryomodule for stable beam operation ? (What is the present status for high current ERL ?)
  - HOM suppression is essential for high current beam. How much current can be circulated in design ? HOM damper/couple limit at present ?
  - Epk/Eacc is to be lower for field emission suppression.
  - QL vs michrophonics → discuss in LLRF session ?
  - How much high power can feed to the beam of high current especially injector cryomodule power coupler. (Cornell works on 75mA, 50kW/coupler)
- What is the optimum CW operation field with High-Q for a long time ?
  - At present, 15-20MV/m and Q0=(1-3)*10^10 desired

    (LCLS-II : 1.3GHz, 9cell, 16MV/m, Q0=2.7*10^10 (N2-dop), 300uA)

    (CEBAF : 1.497GHz, 7cell, 19.2MV/m, Q0=8*10^9. more than 10 uA)
  - How long high-Q was kept and how much degradation ratio?
  - Q0 degradation was stopped or not during beam operation ?
  - What is the real performance of cryomodule not the V.T especially including the mass production phase ?

    (Comparison between V.T and cryomodule performance) backup

Design strategy of ERL main linac cavity for HOM damping

(Please see K.Umemori of APAC06 in details)

():TESLA cavity

Frequency	1300 MHz	Gradient	15-20MV/m
Q0	1e+10	Coupling	3.8 % (1.9%)
R_{sh}/Q	897 Ω (1007Ω)	$Q_o \times R_s$	289 Ω
E_p/E_{acc}	3.0 (2.0)	H_p/E_{acc}	42.5 Oe/(MV/m)

Design based on TESLA cavity

TESLA cavity

Model 1

Enlarged beam pipe

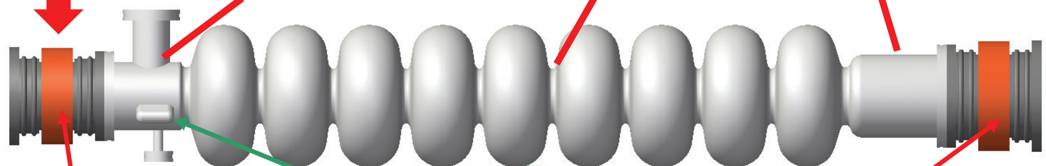
KEK-ERL Model-2

Change cell shapes

SBP dia.: ϕ100
TE11: 1.757 GHz
TM01:2.295 GHz

Iris dia.: ϕ80
TE11: 2.196 GHz
TM01: 2.869 GHz

LBP dia.: ϕ120
TE11: 1.464 GHz
TM01:1.913 GHz



HOM absorber

Eccentric Fluted Beampipe(EFB)

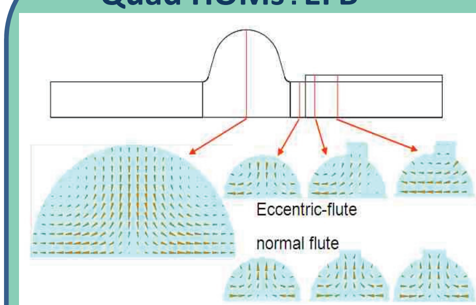
HOM absorber

Points

1) Large beampipe + HOM absorbers
2) Optimize cell shape for ERL operation
3) Eccentric Fluted Beampipe (EFB) for Quad HOMs

No monopole modes around multiples of 2.6GHz within +/- 40MHz

Quad HOMs : EFB



Extract Quad HOMs by changing dipole mode thanks to EFB.

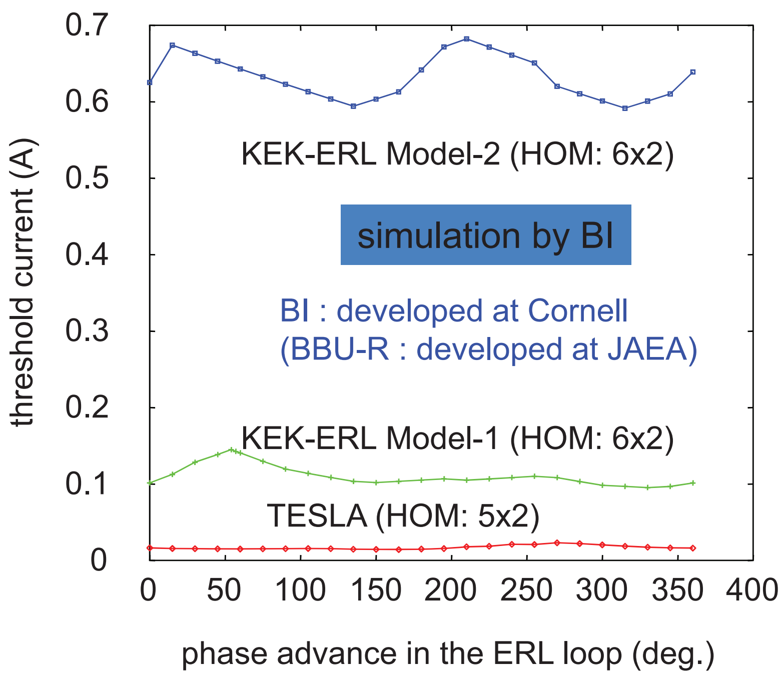
M. Sawamura et al., Phys. Rev. ST Accel. Beams 13, 022003(2010).

Results of design:
・Figure of merit:
Improve HOM-BBU threshold up to 600mA of KEK-ERL model-2 (next)
・Demerit
Epak/Eacc is 1.5 times higher than TESLA cavity.
Field emission will occur at lower acc. Field.
→ Need to verify by V.T

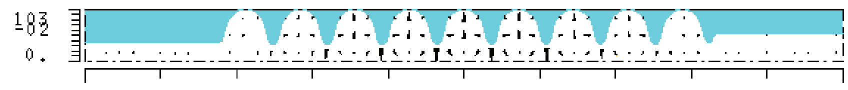
HOM-BBU threshold current(dipole)

(Calculation performed by
R. Hajima, R.Nagai, JAEA)

E_{inj} = 10 MeV, E_{loop} = 5 GeV, E_{acc} = 20 MV/m

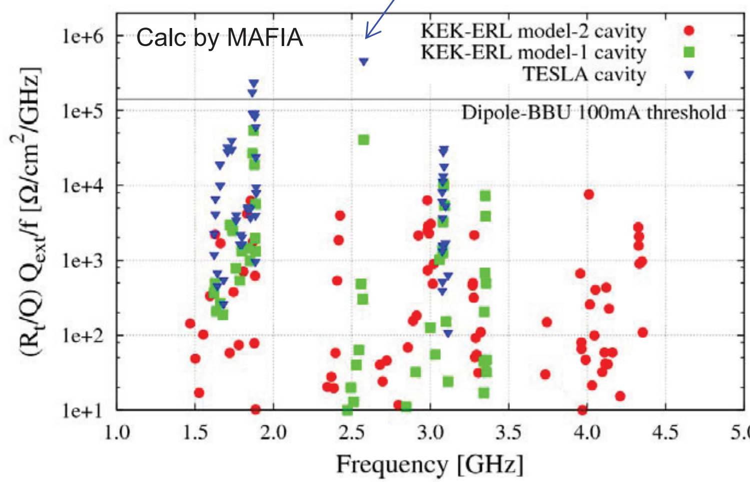


TE-iris



TESLA cavity has TE-iris mode with high R/Q at 2575MHz.

Dipole mode distribution



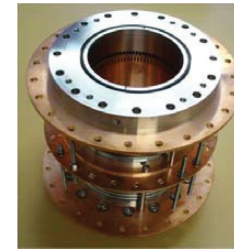
BBU threshold are significantly improved
More than 600mA is possible for KEK-ERL model-2 cavity.

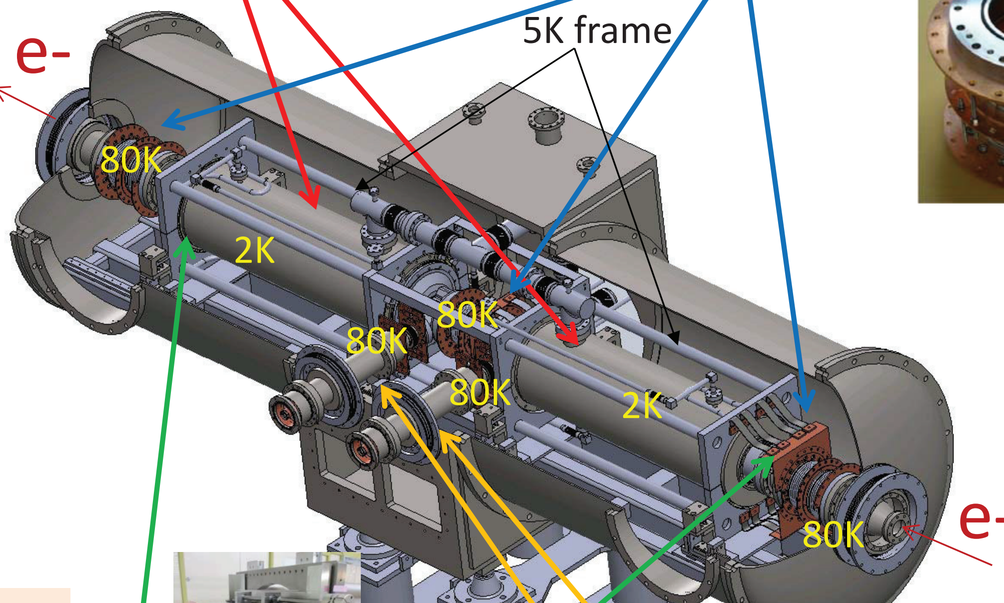
name	Cavity shape and beam pipe	Ith (max threhold)
KEK-ERL model-2 cavity	New cavity shape + Large beampipe absorber	<600mA ○
KEK-ERL model-1 cavity	TESLA cavity shape + Large beampipe absorber	<100mA △
TESLA cavity	TESLA cavity shape + Loop-type HOM coupler	<20mA ×

Compact ERL main linac cryomodule configuration

9cell superconducting cavity
Q0 > 1*10^10 @15MV/m

HOM absorber
- HIP ferrite on Copper beampipe
- Operation at 80K. (expected 150W HOM power)
- Check enough absorption ability of ferrite at 80K





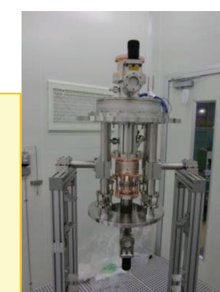
(Compact) ERL target

Frequency : **1.3 GHz**
Input power : **20kW CW (SW)**
Gradient: **15MV/m**
Q0: **>1*10^10**
Beam current : **max 100mA**
(against HOM-BBU instability)

2-cavity cryomodule was developed for compact ERL main linac to demonstrate the high current ERL operation at cERL. We have done the high power test by using this cryomodule.

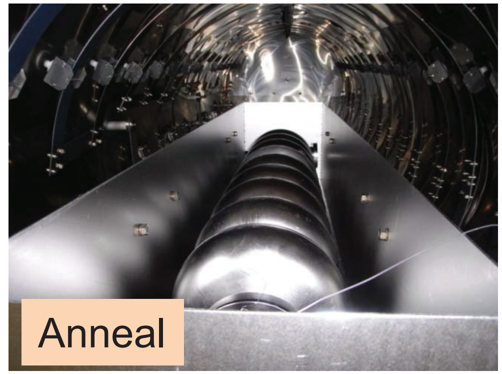
Frequency Tuner
Slide jack tuner (mechanical)
piezo tuner(fine tuning)

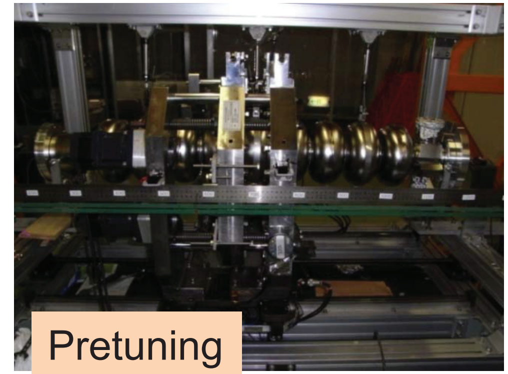
Input coupler
- 20kW CW (standing wave)
- Cold and warm window
- HA997 ceramic is used
- QL=(1-4)*10^7(variable)



Preparation for Vertical test

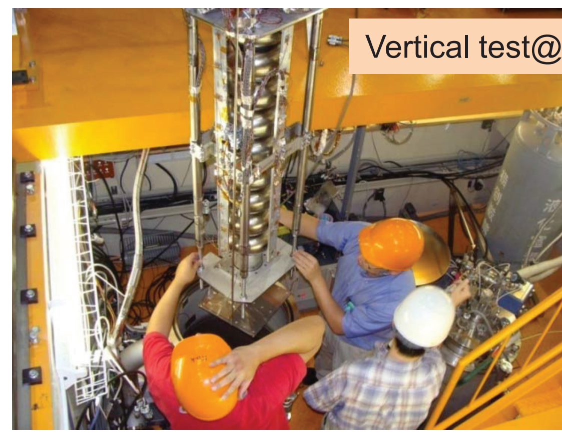

EP


Anneal


Pretuning

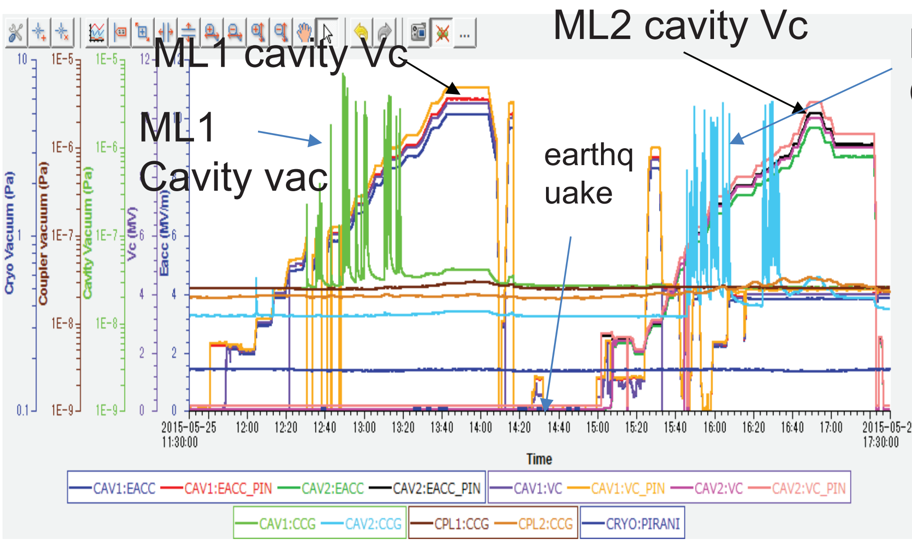

High pressure rinse(HPR)


Assembly@class 10


Vertical test@STF

fabrication(EBW) → Electro Polish(EP) (100um)→ Anneal (750deg,3h)→ pretuning→ final EP(20um)
→ Ultra Sonic(50deg,1h)→ HPR(8MPa,7h)→ Aseembly → Baking(150deg,48h) → Vertical test

ML Cavity aging (2015.May.25)



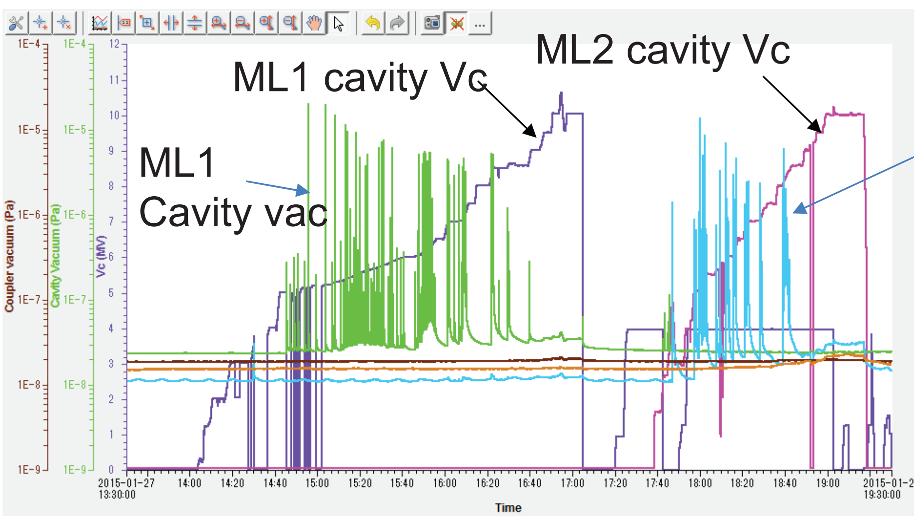
ML2
Cavity vac

We can see the vacuum activation during 5MV-9MV

ML1 max 10.5MV : cavity aging。
ML2 max 10.0MV : cavity aging。

2015.May.25

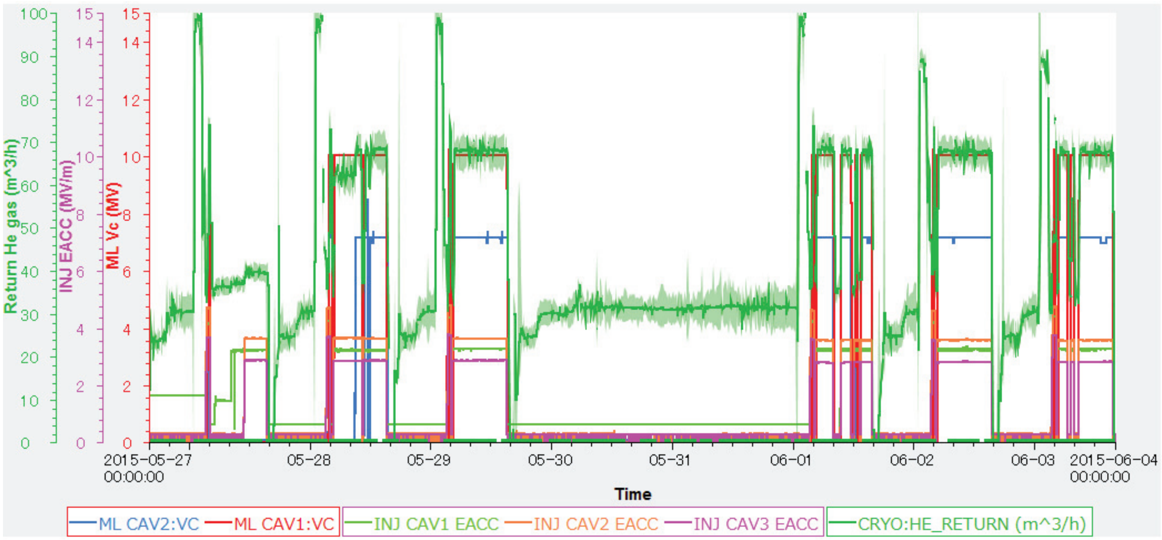
2015.Jan.27(previous case)



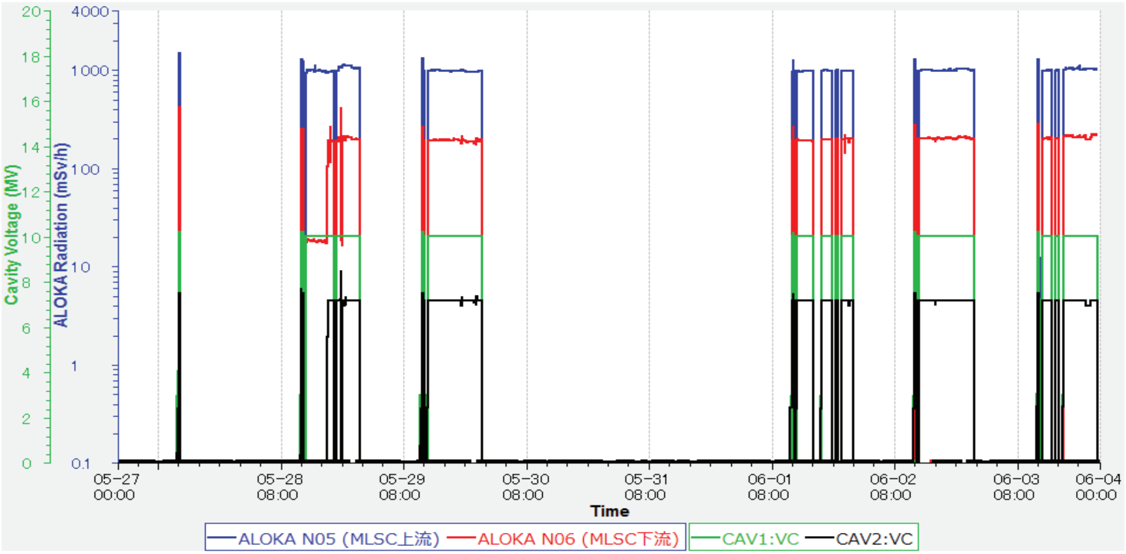
ML2
Cavity vac

We also see the same case in the previous aging after 2K cooling

Recent status of 10MV operation of ML1



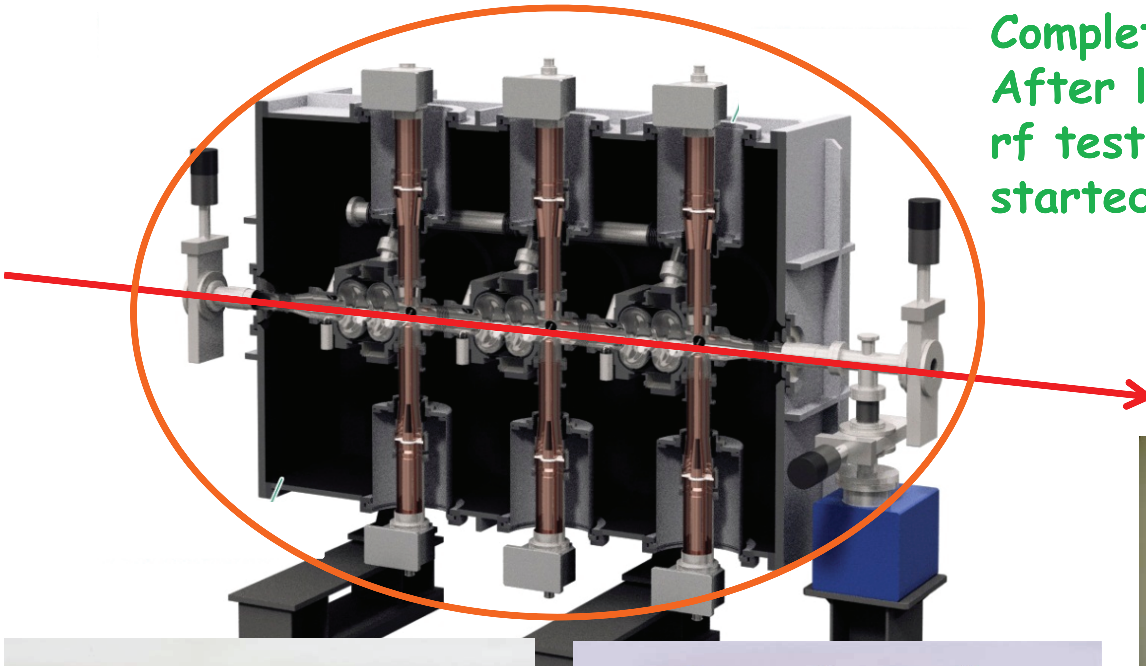
Inj total 2.9MV
ML1 10MV
ML2 7.14MV
He return ave 68m^3/h
(65-70m^3/h)



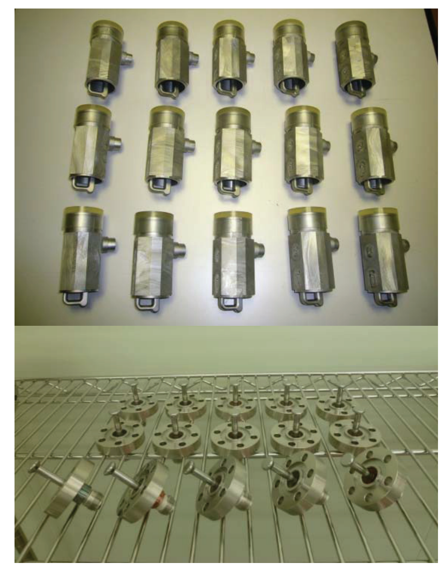
MLSC ALOKA
No5 980-1000mSv/h
No6 190-200mSv/h
stable

cERL Injector Cryomdule

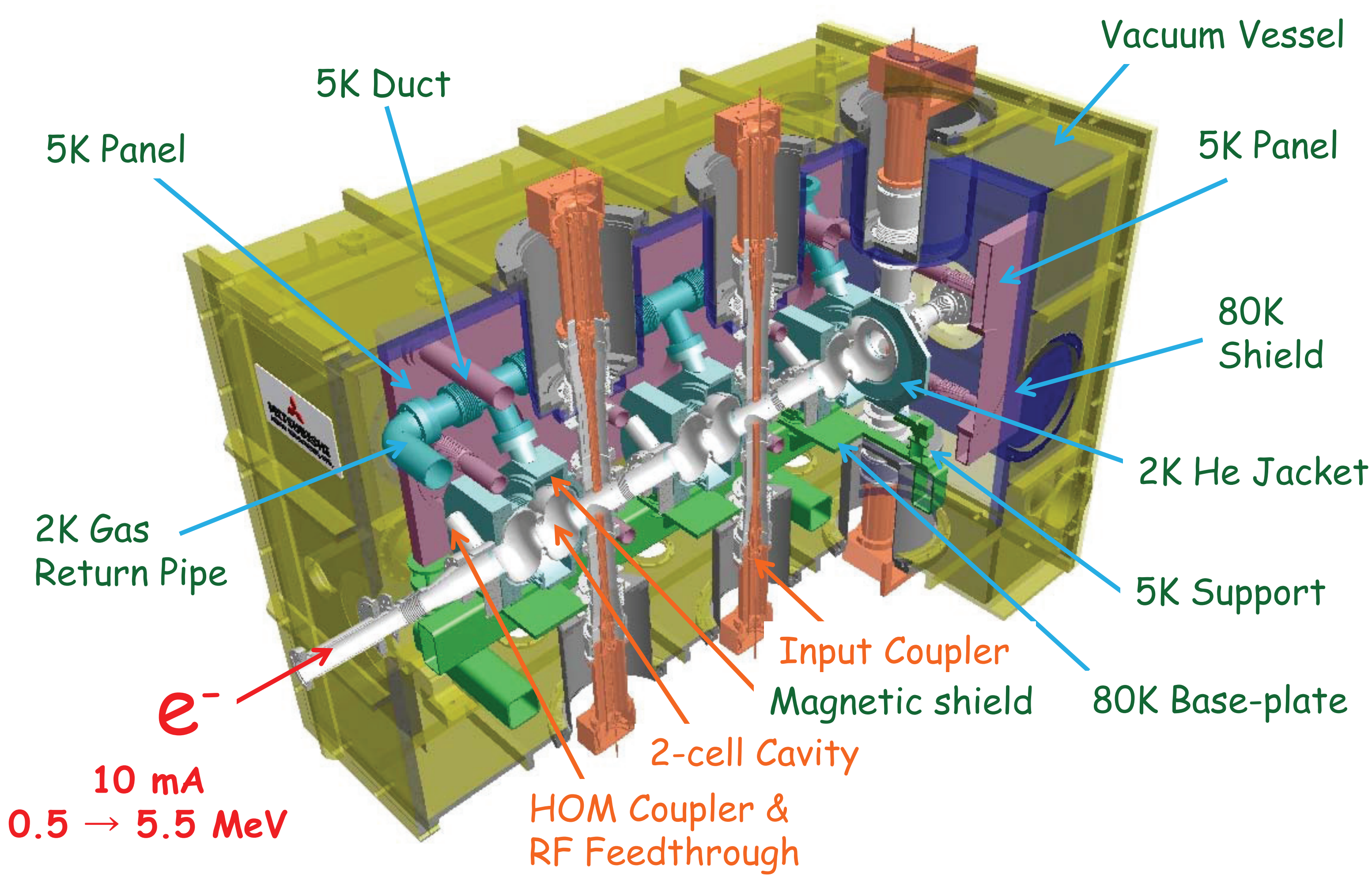
Completed in 2012, June. After low and high power rf tests, beam operation started in 2013, April.



e^- beam
0.5 → 5.5 MeV
10 mA



cERL Injector Cryomdule (2)



Main Specification for Injector Cryomodule

(cERL injector ; I_{beam} = 10 mA, E_{beam} = 5 MeV)

	Cavity - 1	Cavity - 2	Cavity - 3
Vc	1.5 MV	1.75 MV	1.75 MV
Eacc	6.5 MV/m	7.6 MV/m	7.6 MV/m
Q_L (10mA)	7.2×10^5	8.4×10^5	8.4×10^5
P_{RF} (10mA)	15 kW /2	17.5 kW /2	17.5 kW /2
RF Source	Klystron - 1 30kW, CW	Klystron 300kW,	- 2 CW

I_{beam} = 100 mA, E_{beam} = 10 MeV for future 3GeV-ERL

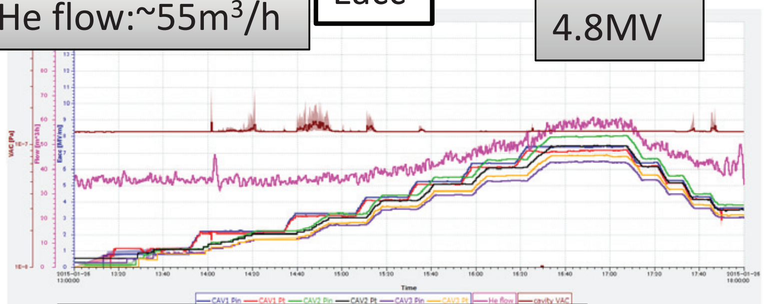
Final target of required RF power = CW 100 kW, (5 cavities)

First aging of injector cryomodule

He flow:~55m^3/h

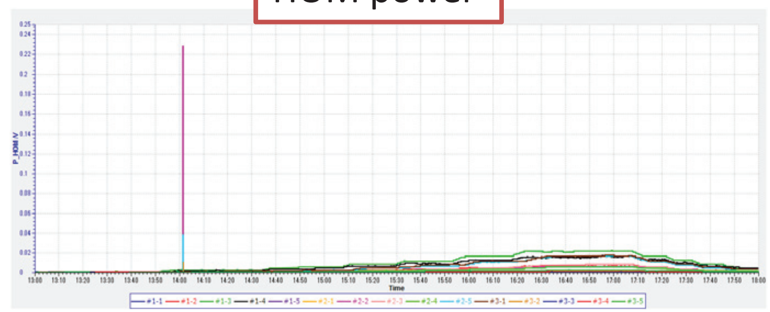
Eacc

7MV/m
4.8MV



Sometimes vacuum works.

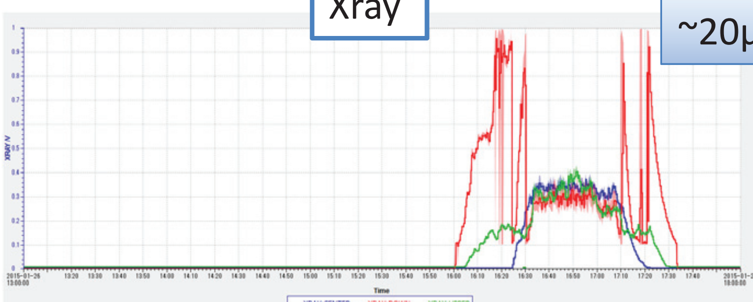
HOM power



Quench at HOM coupler

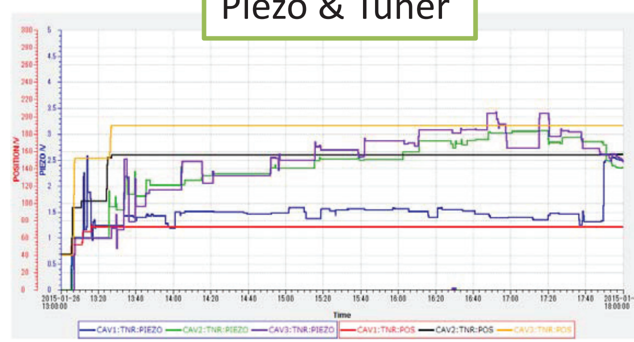
Xray

~20μSv/h



Xray was appeared up to 5MV/m

Piezo & Tuner



Manually operated of piezo feedback during aging

System for He processing