Field emission at KEK-cERL

TTC meeting 2025@IBS

2025/04/10

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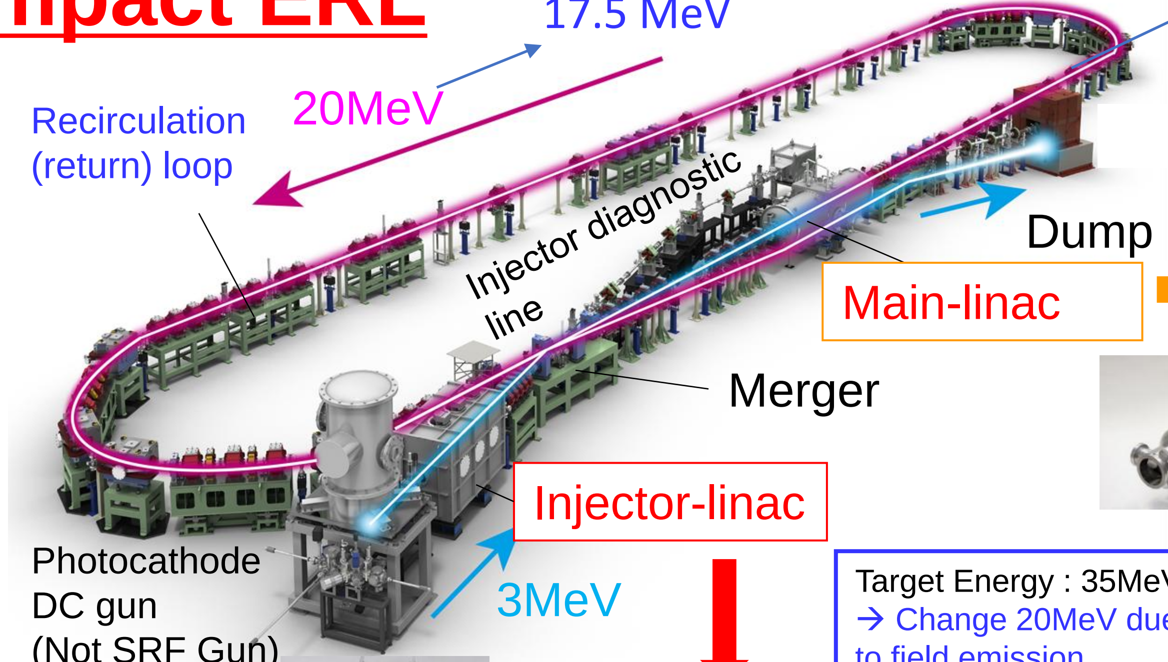
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

General facts about the accelerator

Question	Answer
Year built/commissioned	2012
Cryomodule string layout (continuously cold, warm sections,…)	Single cryomodule both for injector and main linac. Both side is warm section.
Particle free installation practices/protocols applied	Main linc: Tried to do particle free assembly. But lack of experience, we made some mistake. - Not clean enough circumference, especially for gate valve assembly - HOM damper difficult to clean. Issue of clack on absorber - High Esp design of cavity (Esp/Eacc ~3.0)
Peak surface field at nominal operation gradient	Injector: Esp 7~14 MV/m Main linac: Eap~ 24 MV/m
Administrative/operational radiation limits (How were limits decided?)	No administrative limit. - Measured radiation dose > 1 Sv/h Cooling capacity of cryogenic system is limitation. (Total ~80W at 2K for injector and main linac.)
Pulsed or CW operation?	CW

Compact ERL



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

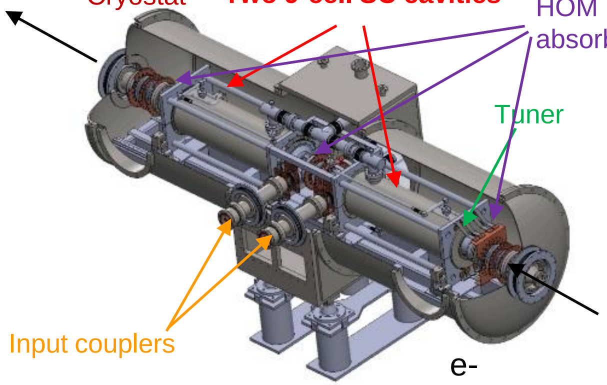
Main linac module

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 > 1×10^{10}

H.Sakai et al. "Field emission studies in vertical test and during cryomodule operation using precise x-ray mapping system". Phys. Rev. Accel. Beams 22, 022002 (2019)



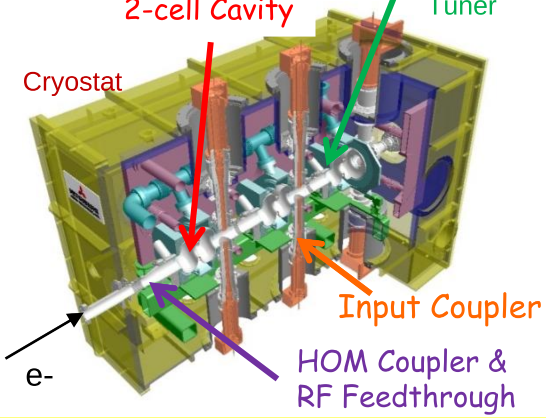
Requirement was satisfied at V.T. **Issue:** Heavy F.E was met @9-10MV/m after string assembly. & met quench shown later In detail

Injector module

K. Watanabe, et al. "Development of the superconducting rf 2-cell cavity for cERL injector at KEK" Nucl. Instru. Meth. A Vol. 714, p67-82 (2013)

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 > 1×10^{10}



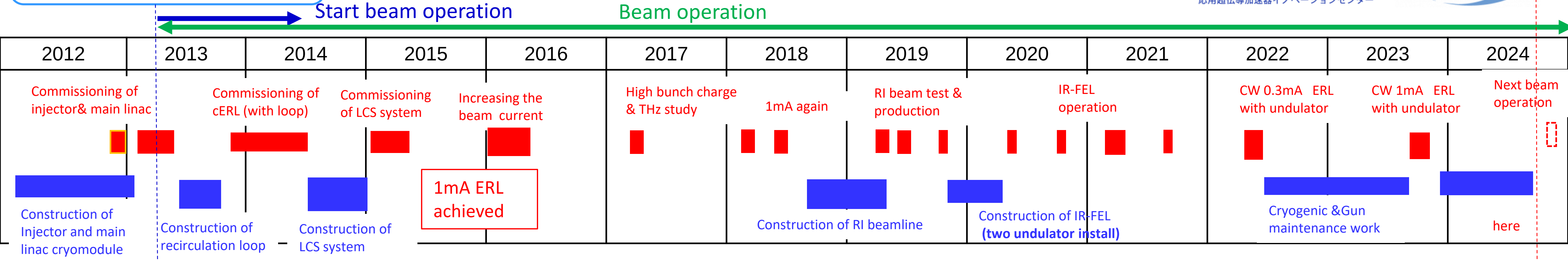
Issue: We met the HOM coupler heating if field increased more than 7MV/m. It is the reason for heating not perfectly to be filtered in HOM coupler and results in lower Q0 than 1x10^{10}.

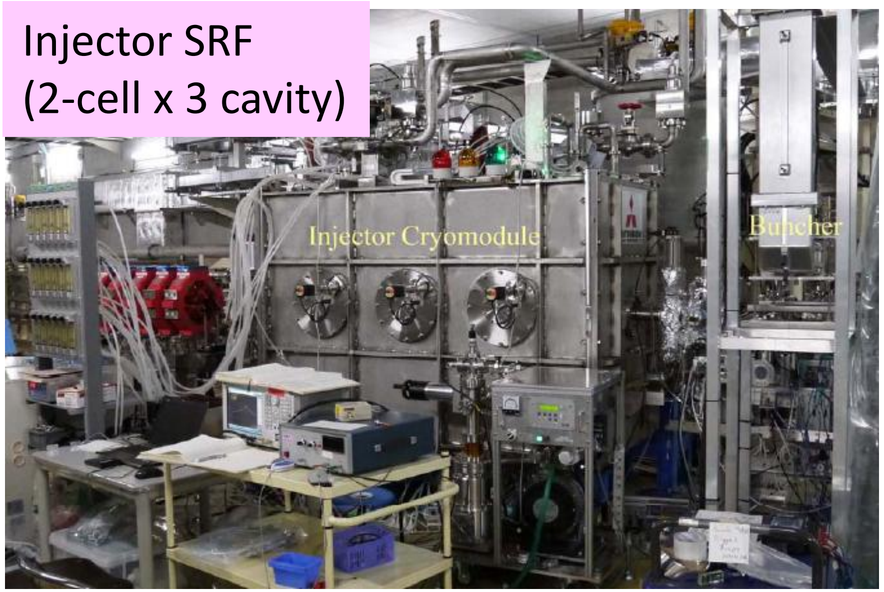
Design parameters of the cERL

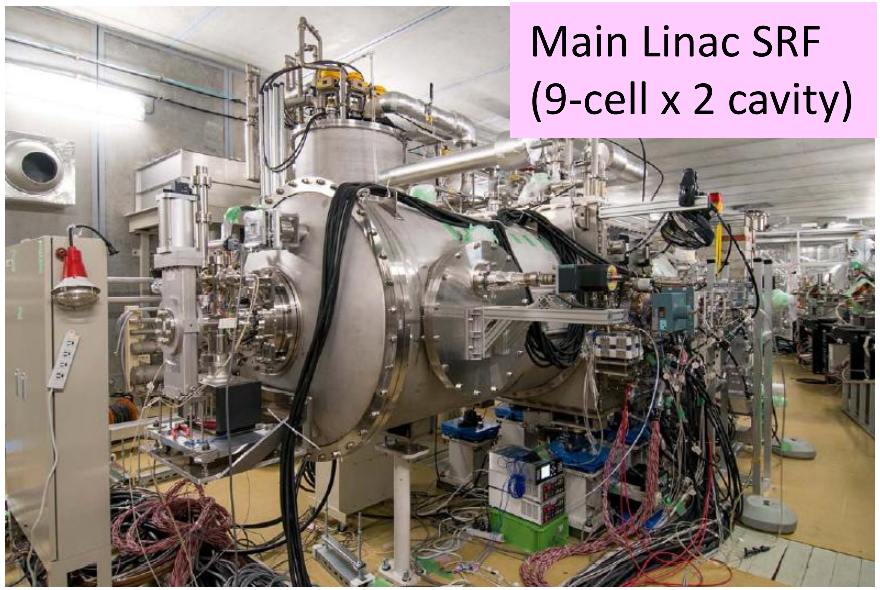
Nominal beam energy	35 MeV → 20MeV →17.5MeV
Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

Operational history of cERL cryomodule

Construction, Maintenance
Operation







cERL beam operation from Oct. 2019 to Mar. 2023

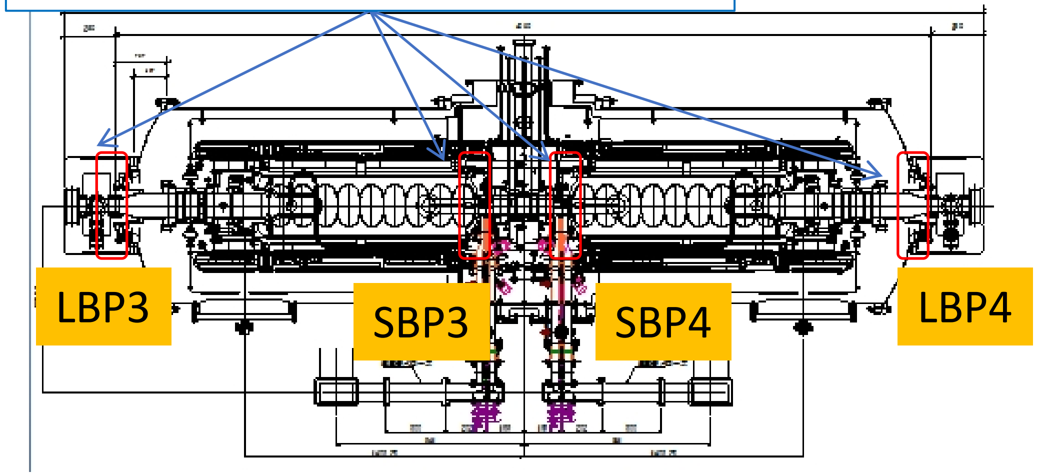
Period(beam operation time)	Energy[MeV] (Comment)	Current
2019.Oct. (3 weeks)	17.5 (loop)	60 pC/ bunch
	19.0 (IR)	~1 uA (CW)
2020.Jun. (4 weeks)	17.5 (loop)	60 pC/ bunch
2020.Jun. (3 weeks)	17.5 (loop)	60 pC/ bunch
2021.Feb-Mar. (6 weeks)	17.5 (loop)	60 pC/ bunch
	23.0 (IR)	1pC/bunch (pulse)
2021.Oct. (3 weeks)	17.5 (loop)	40 pC/ bunch
	10.0 (IR)	~1uA (CW)
2022.Feb-Mar. (3 weeks)	17.5 (loop)	300uA (CW)
	10.0 (IR)	~1uA (CW)
2023.Nov. (5 weeks)	17.5 (loop)	60 pC/ bunch 1mA (CW)

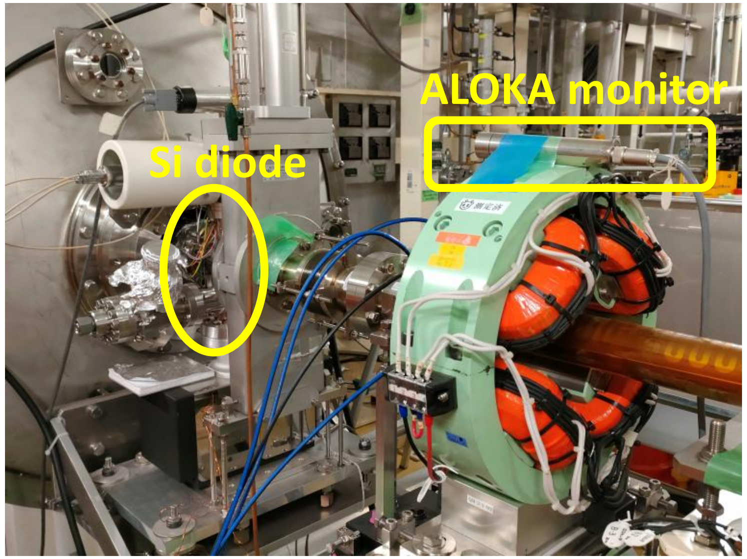
Instrumentation to measure/monitor radiation

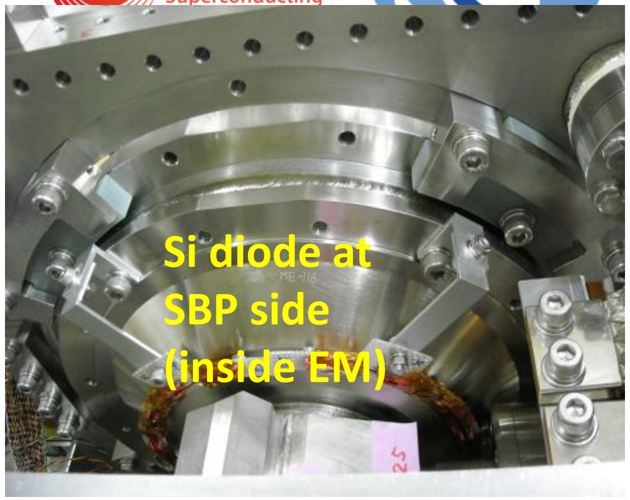
Question	Answer
Type of sensors ・Integration time of sensor ・Energy spectrum recorded?	- No energy spectrum measured. - ALOKA γ-ray monitor has been located around beamline. - Si diodes have been mounded around cavity beamtube to measure radiation signal and angular distribution.
Locations and coverage of the machine	- ALOKA is located both outside of cryomodule on beamline. - Si diode is located both end of cavities around the beamtube. (One side is exactly same geometry with VT.)
Continuous monitoring or interval of measurements?	Continuous monitoring by EPICS
Alternative ways to detect field emission?	No

Reference for p6, 8, 11, “Field emission studies in vertical test and during cryomodule operation using precise x-ray mapping system”. H. Sakai, et. al., Phys. Rev. Accel. Beams 22, 022002 (2019)

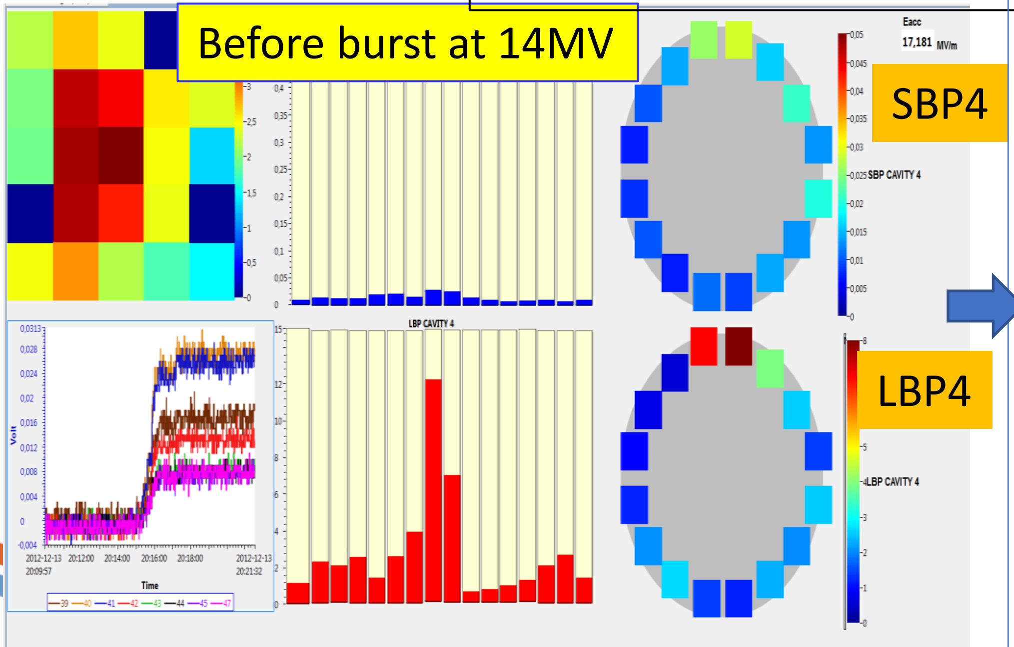
16 Si PIN diode at each position

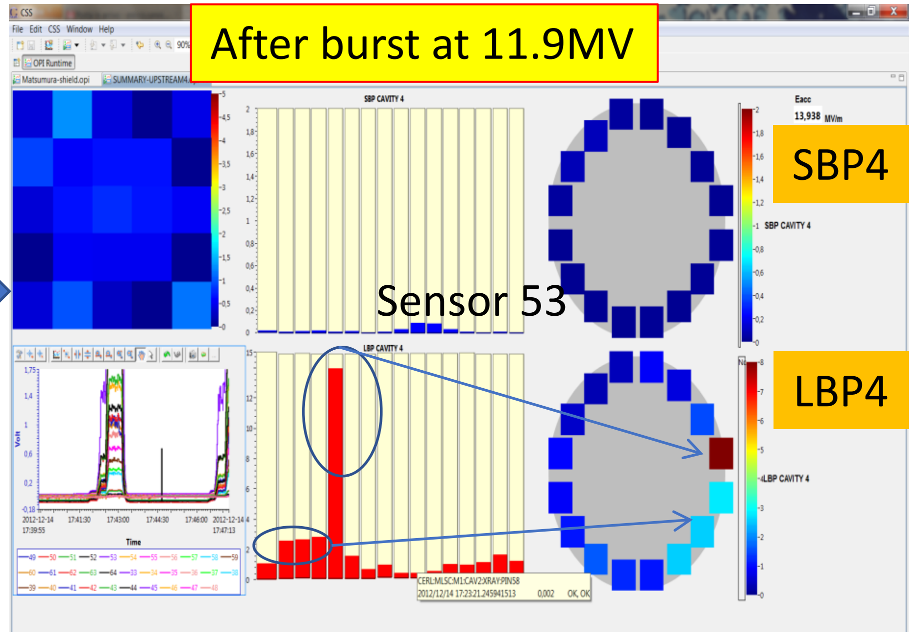


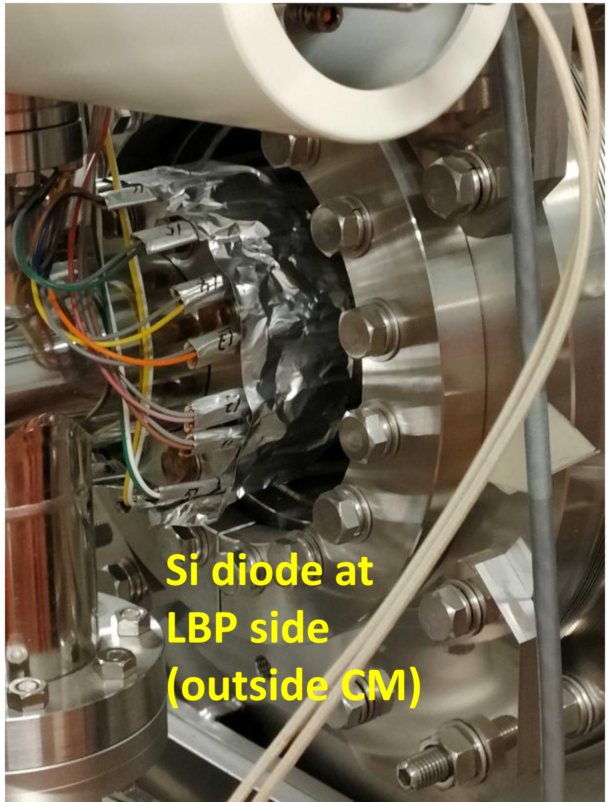




Radiation pattern changed after X-ray burst

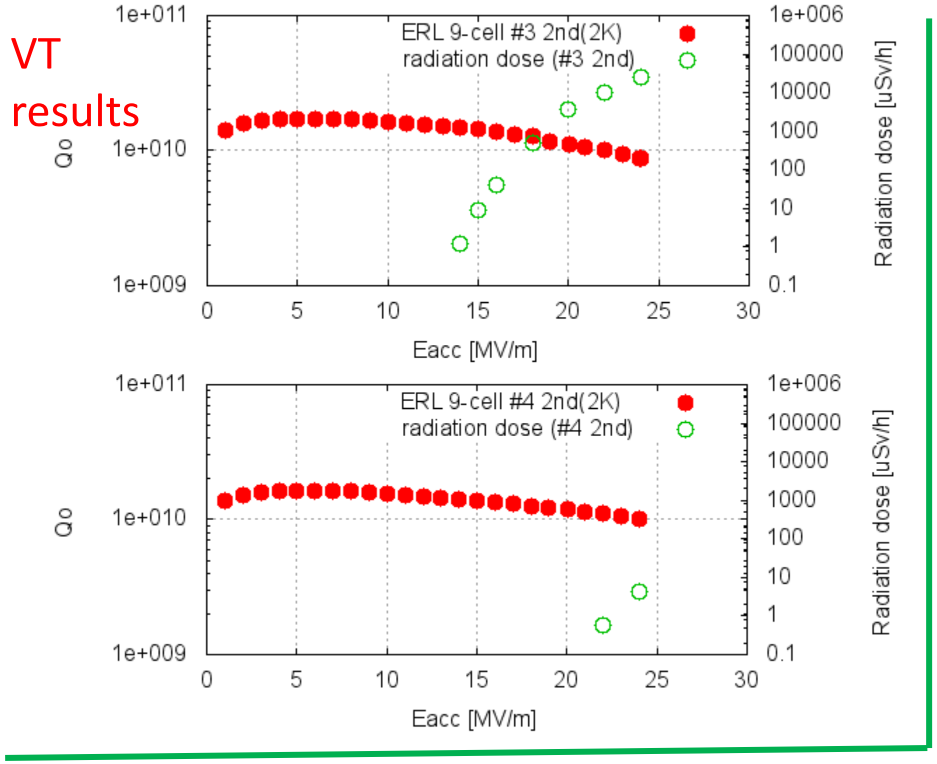


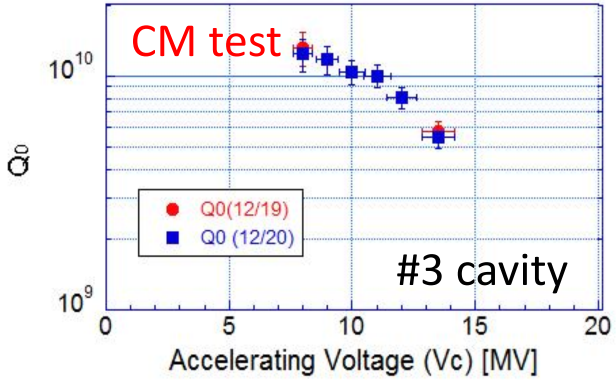


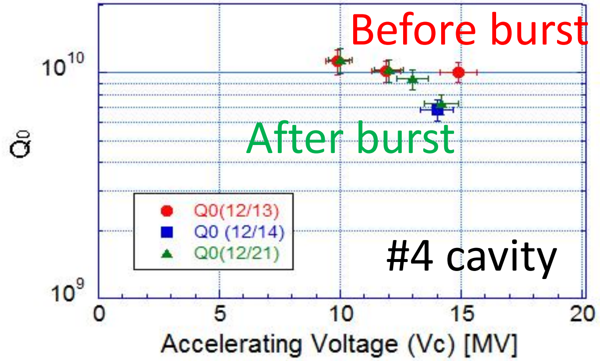


Field emission situation during commissioning

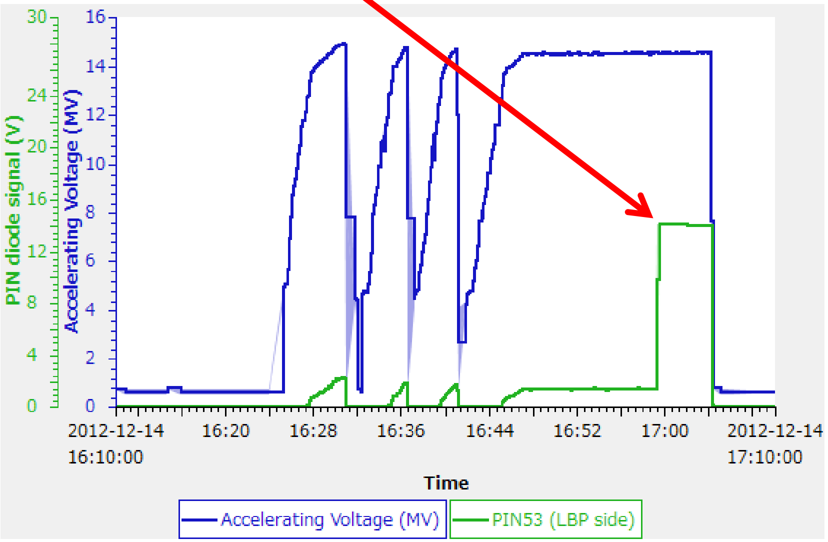
Question	Answer
Comparison to cavity performance before installation / during acceptance testing	- Si diodes of SBP side were mounted at same position, around beamtube, both for VT and cryomodule for direct comparison.
Field emission situation as measured during commissioning	Main linac: - During commissioning a burst event happened and F.E. onset completely decreased. - Si diodes showed completely different angular distribution.
Any known causes for the field emission (e.g. vacuum/gas sources, particulate sources,…)?	Main linac: Cause of burst event during main linac during commissioning is most probably came from assembly procedure.

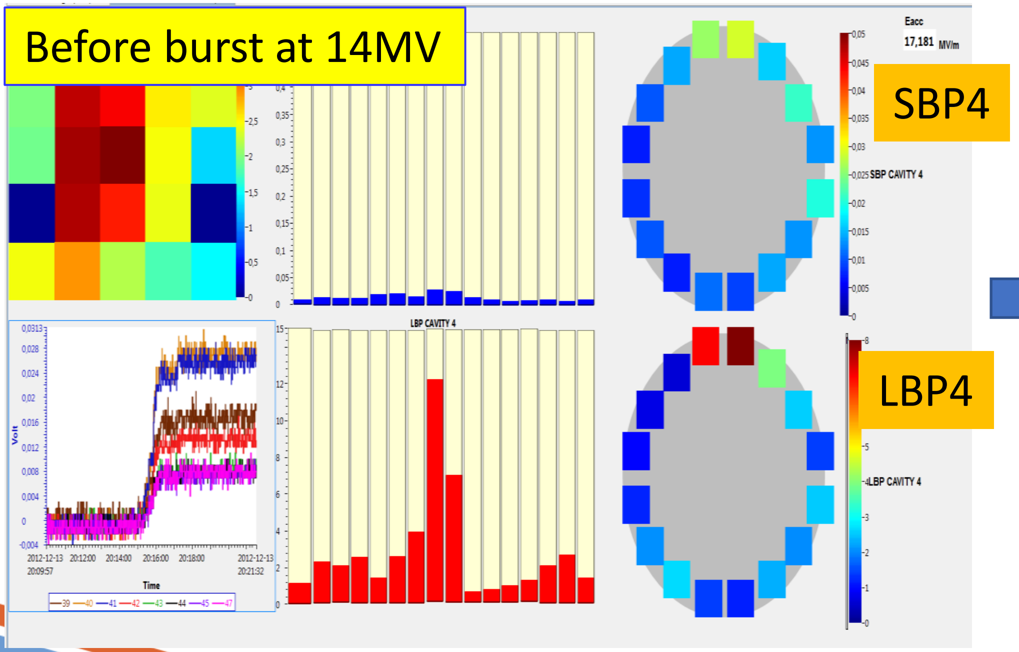


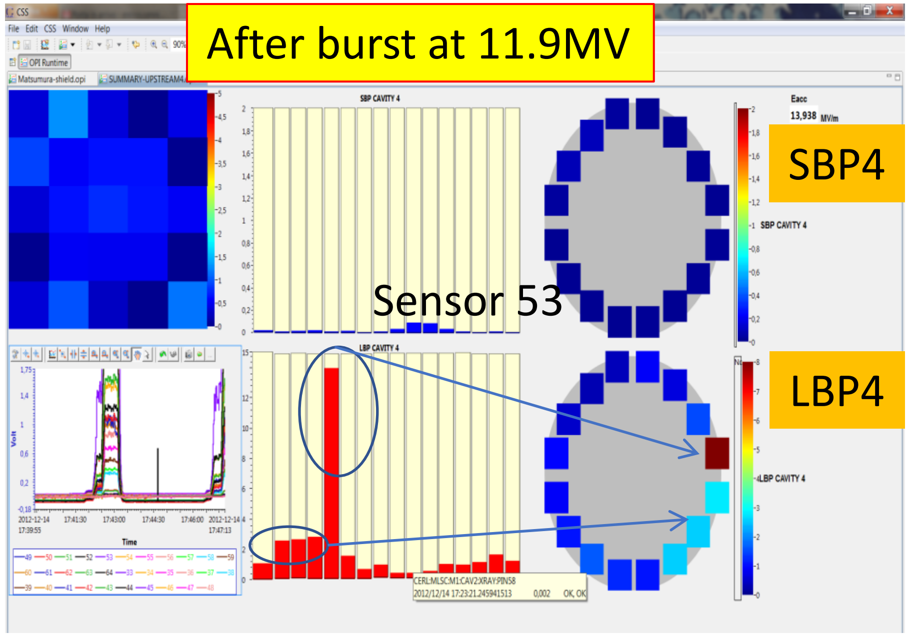




X-ray burst happened, and sensor 53 suddenly increased while keeping field.





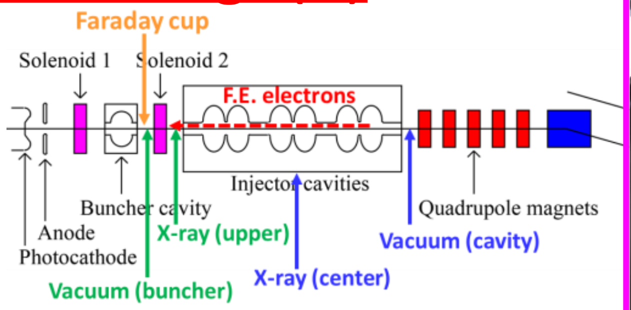


Evolution of field emission over lifetime of machine

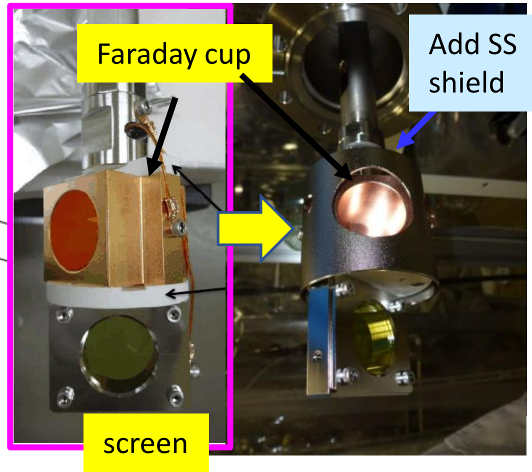
Question	Answer
How has field emission in the machine changed over time (location and magnitude)?	We often observe jump of radiation magnitude by ALOKA. Si diodes show change of angular distribution, i.e. location of emitter.
Are there any spatial patterns observed?	Angular distributions around beamtube have been observed.
Are there known reasons or events this can be correlated with?	Injector: - Field emission induced charge up on Faraday cup. Then discharge with vacuum spike caused increase of radiation level. - Field emitted electron hit photocathode → Secondary electron extracted by DC voltage and accelerated by injector cavities. Finally collide with the screen monitor. Then lead to vacuum spike and increase of radiation.
How much performance has been lost due to the increase in field emission?	Cryogenic loss increased and operation gradient was decreased. However, after pulse processing, it could be recovered.

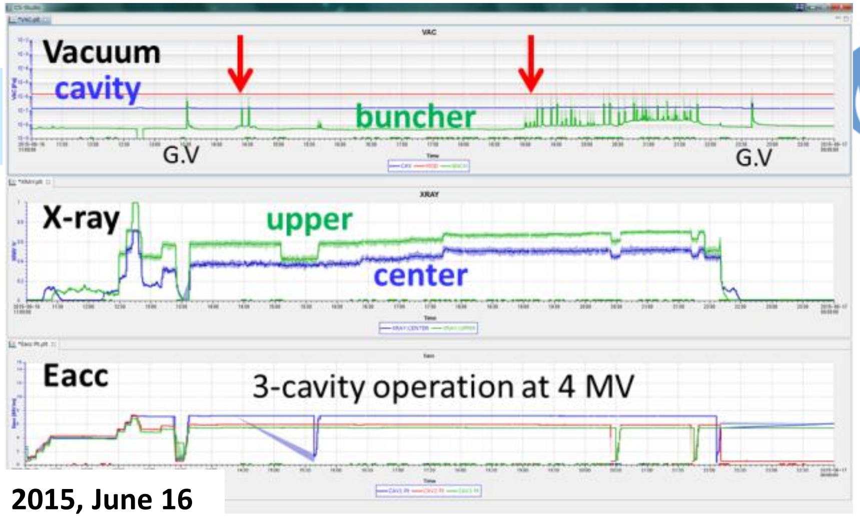
Unexpected discharge(1)

INJ



Screen monitor in front of Gun





2015, June 16

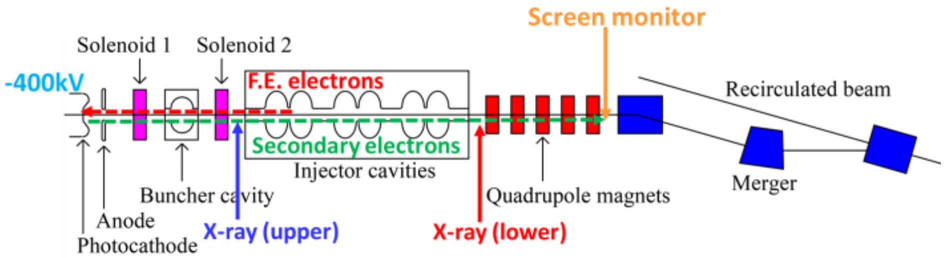
Field emitted electron induce a charge up of Faraday cup.

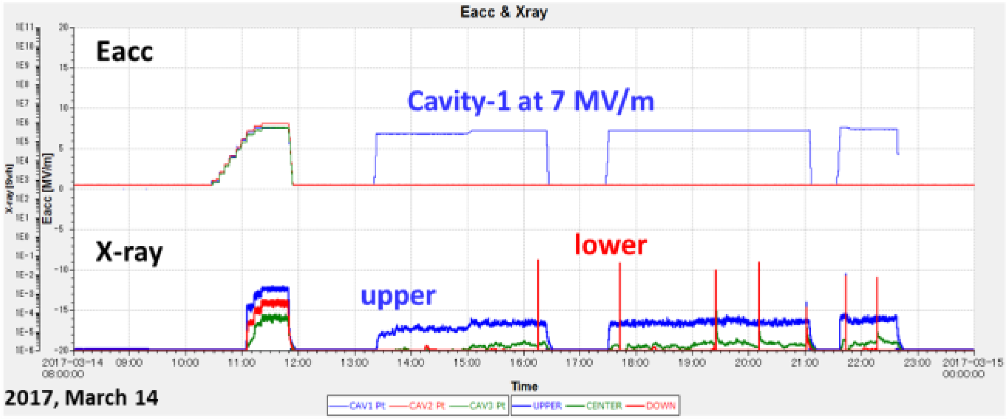
⇒Discharge lead to vacuum deterioration and increase of radiation.

Improvement on Faraday cup solved problem.

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

Unexpected discharge(2)





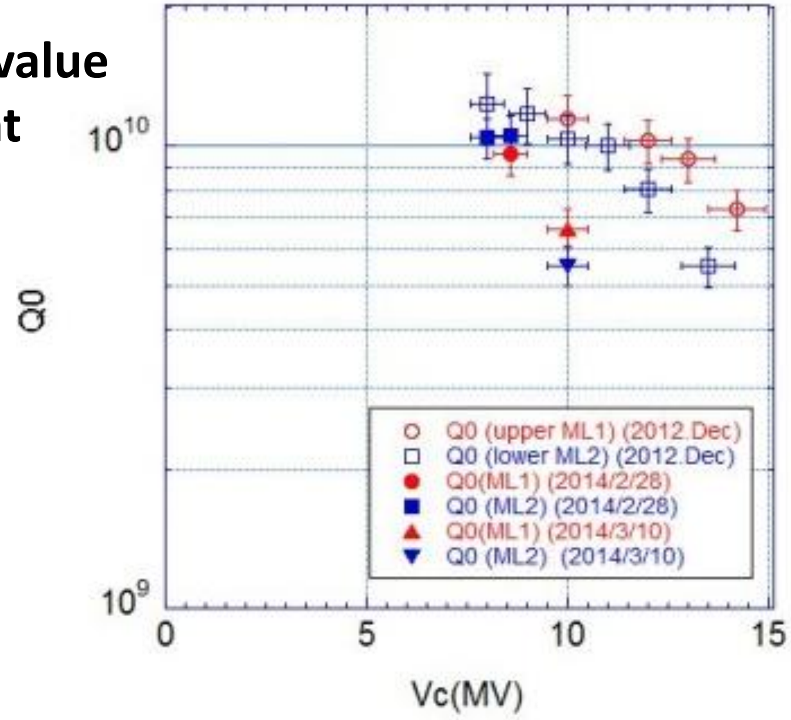
2017, March 14

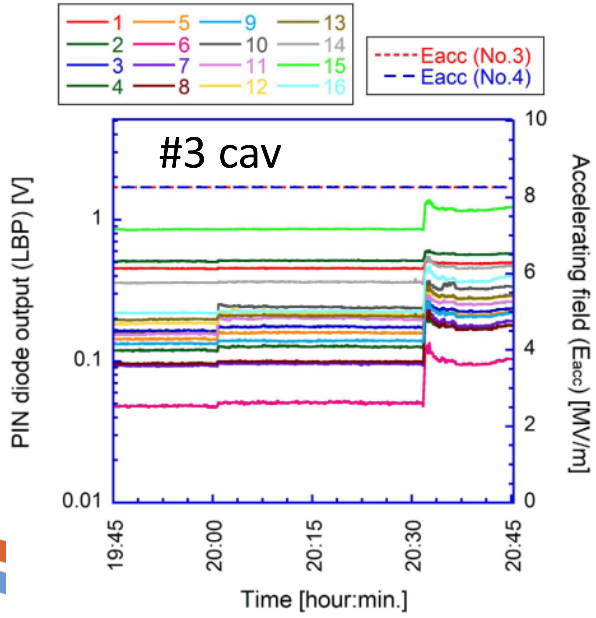
Field emitted electron hit photocathode → Secondary electron extracted by DC voltage and accelerated by injector cavities. Finally collide with the screen monitor.

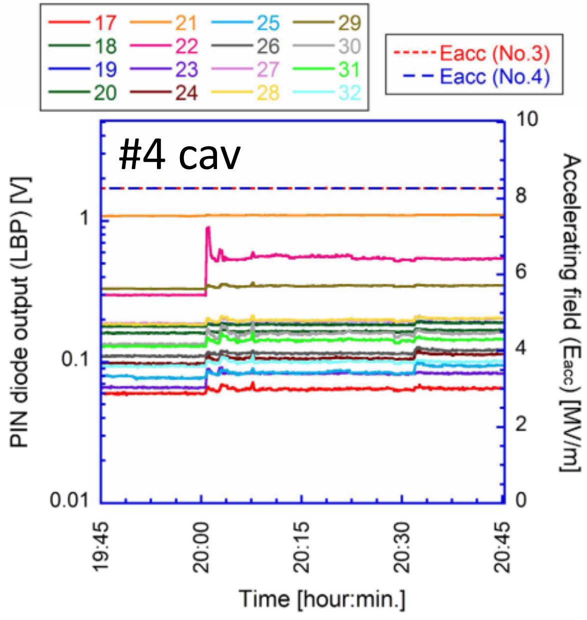
⇒ Lead to vacuum spike and increase of radiation.

See detail on MOPB097 E.Kako et. al.

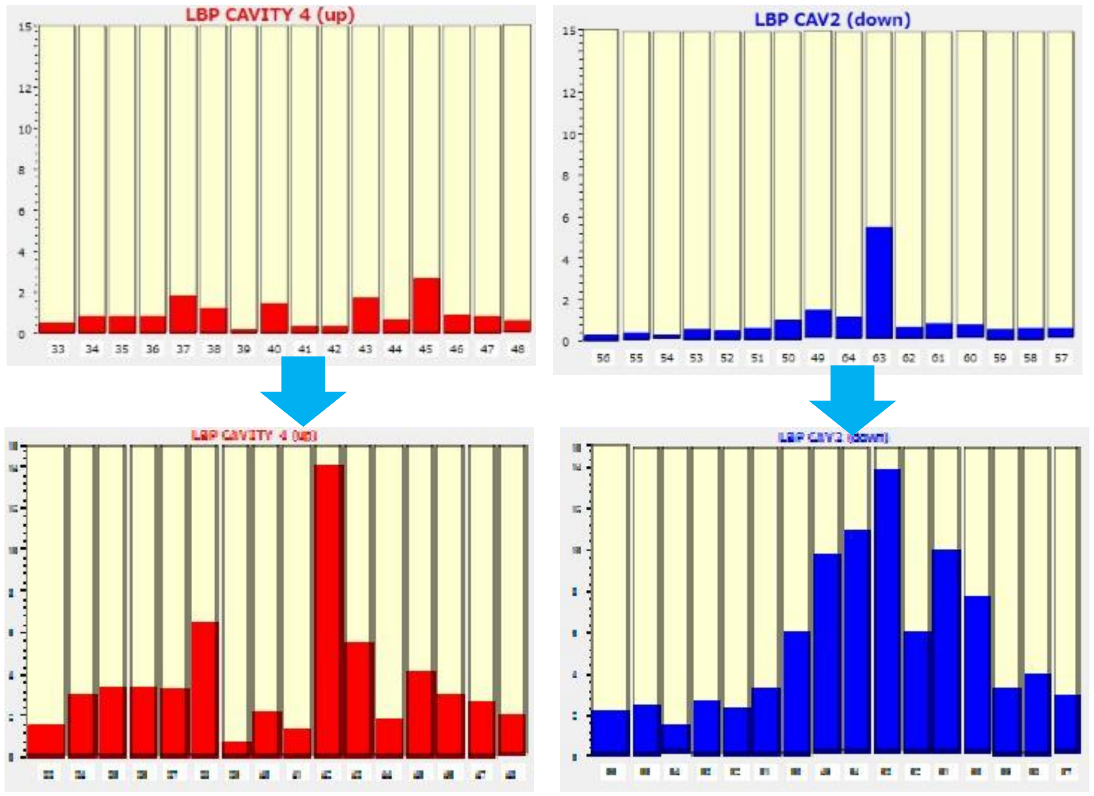
History of Q value measurement







Increase of radiation signal around beampipe



- Degradation of cavity performance was observed.
- Also it was observed that field emission signal becomes stronger than before.

Field emission remediation

Question	Answer
Have there been attempts to decrease field emission in situ?	Pulse processing has been often applied. For example, Injector: 18 MV/m (0.5ms, 10Hz), 12 MV/m (5ms, 10Hz) Main linac: 8.9 MV (CW) + 2.9 MV (4ms pulse, 10 Hz)
If yes, what and to what level of success?	Injector: - F.E. onset improve > 8MV/m (No F.E. for operation voltage) Main linac: - Degradation during operation can be recovered. - Radiation level decrease more than 1/10.
If cryomodules have been removed due to field emission, has the issue resurfaced in the replacement?	No experience.

Recovery by Pulse processing at injector cryomodule

INJ

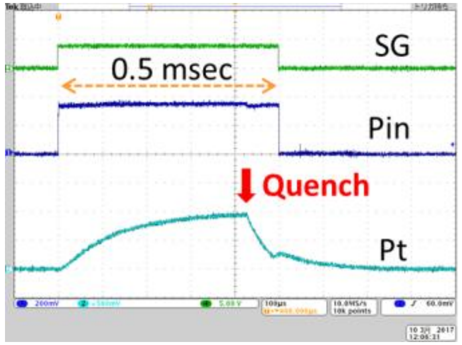
Sometimes the pulse processing is applied for injector cavities.
Pulse length start from 0.5ms, then 5ms and finally CW

See detail on MOPB097
E.Kako et. al.

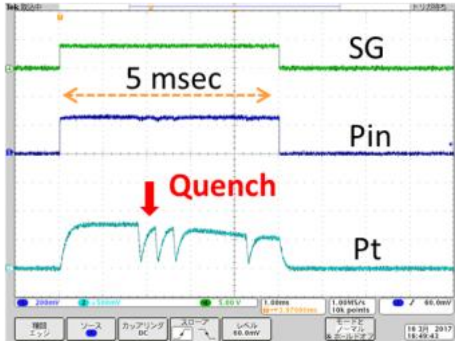
RF conditions of pulse processing

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

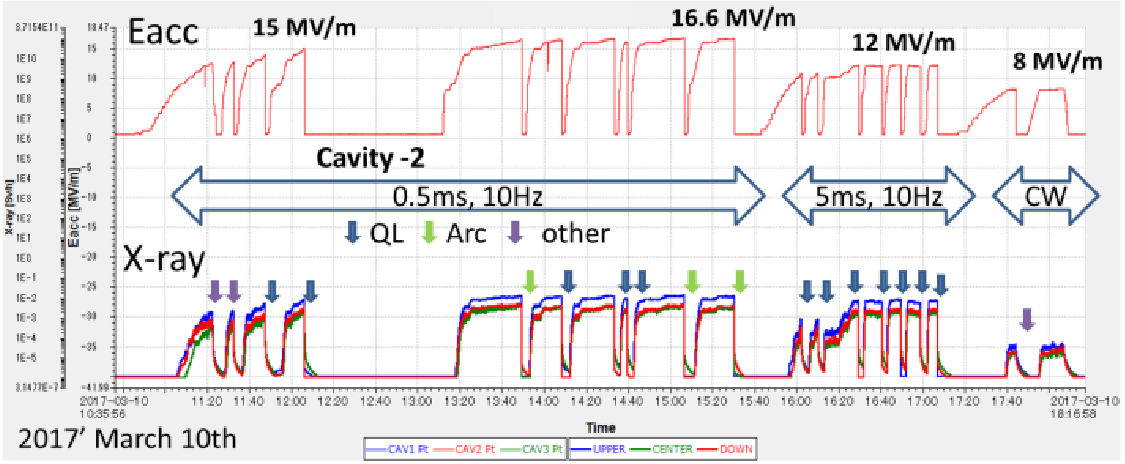
500μsx5Hz

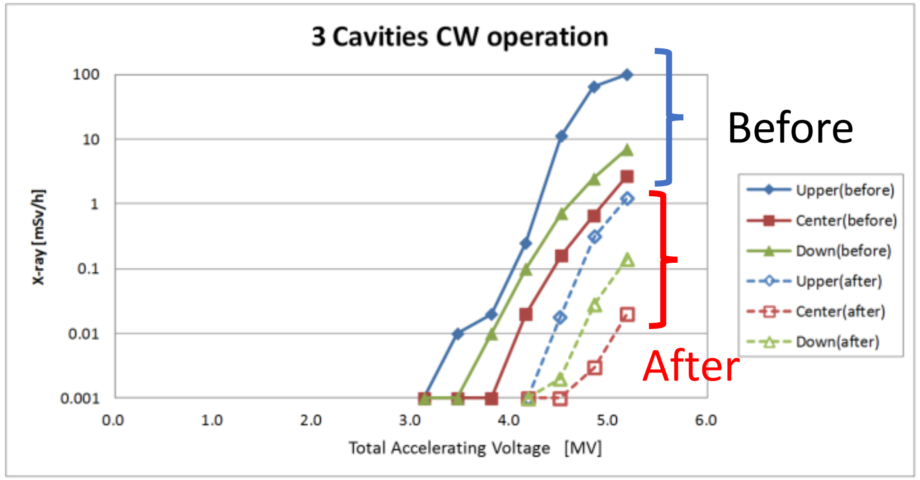


5msx5Hz



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

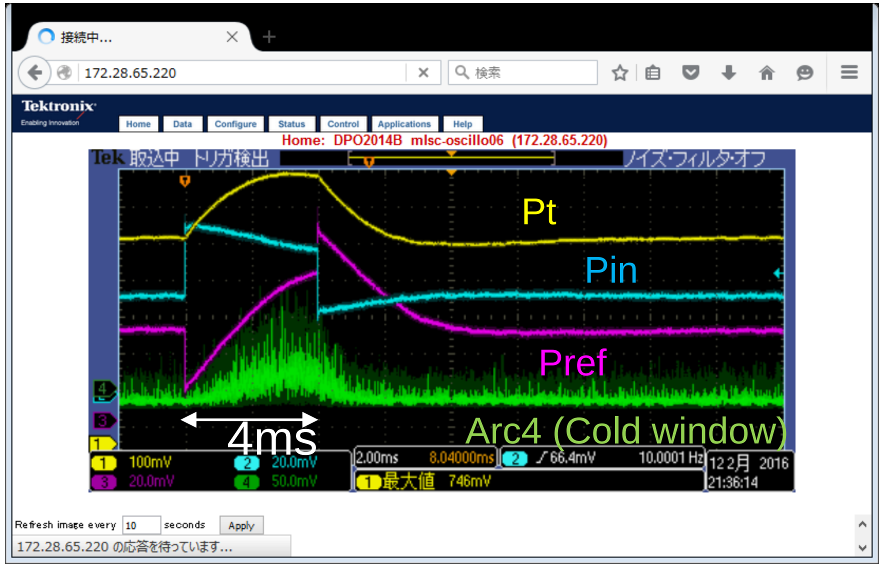




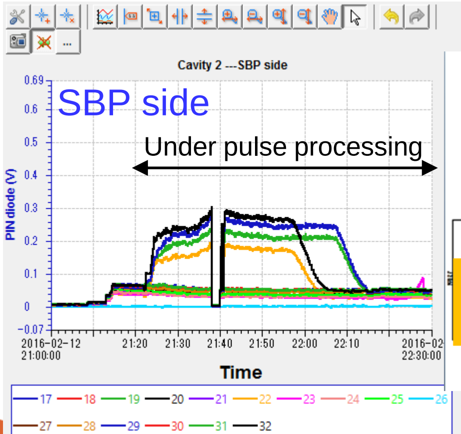
Above are example of pulse processing applied at 2017/March.
Radiation level of each cavities decrease around two orders.

Example of pulse processing (ML2)

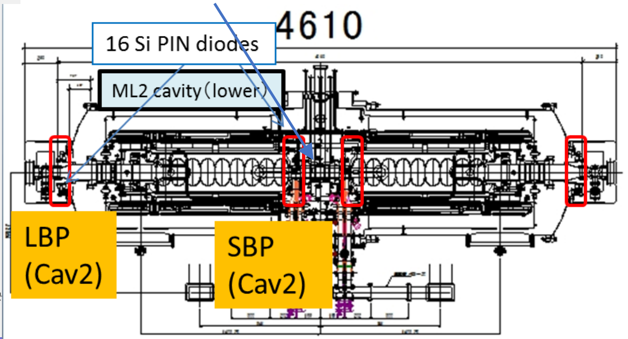
ML2 Pulse Aging (10Hz)
Vc=8.57MV(CW)+2.3MV(10Hz x 4ms)=10.9 MV
:40min pulse aging was done.



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



Arc sensor

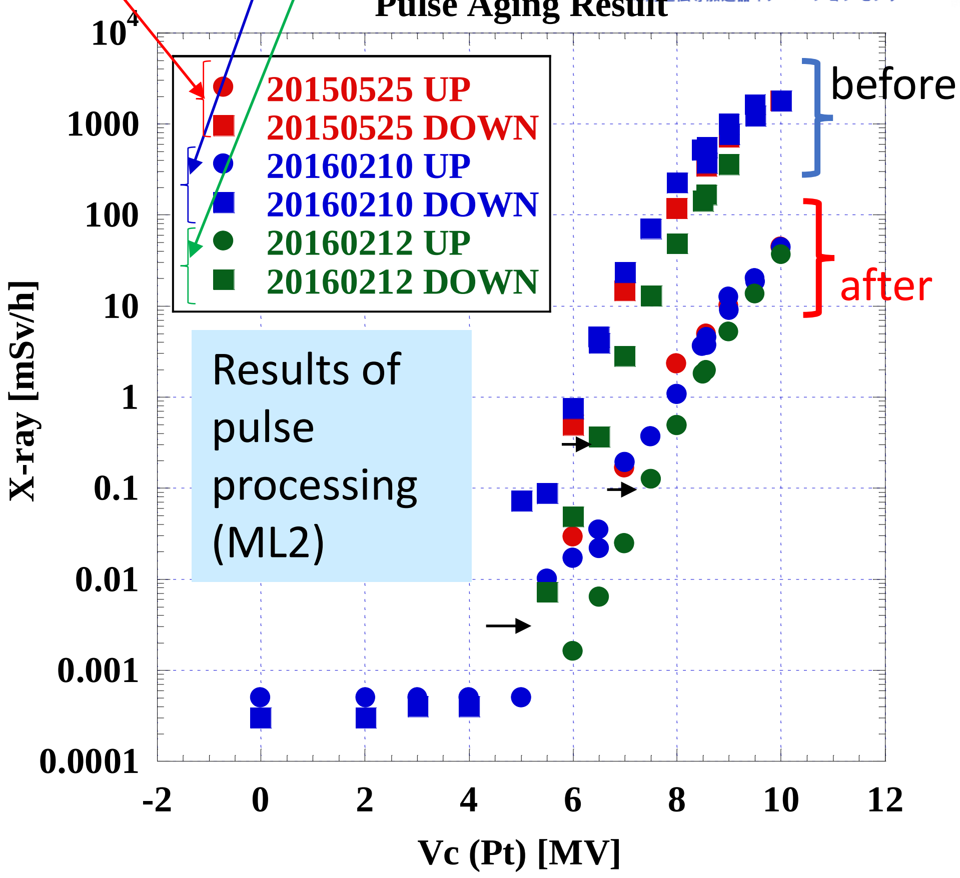


2015/5/25

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.

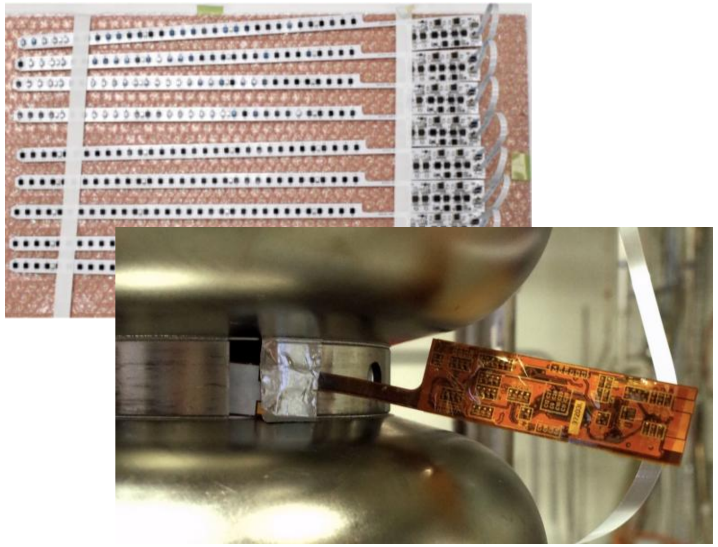
→Pulse processing works well.

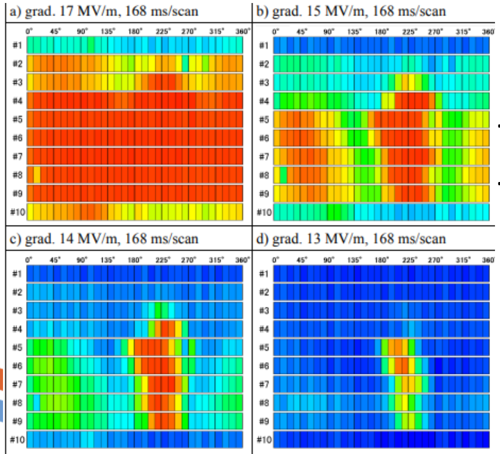
Unique suggestion

- Any device or technique to deal with Field Emission that others might not be aware of or using

SX-sensor

JINST 19(2024)12, A12001, Kuriyama et. al.,
Journal of physics 2687(2024)072025, Kuriyama et. al.,
IPAC2017, MOPVA075, H.Tongu et. al.,



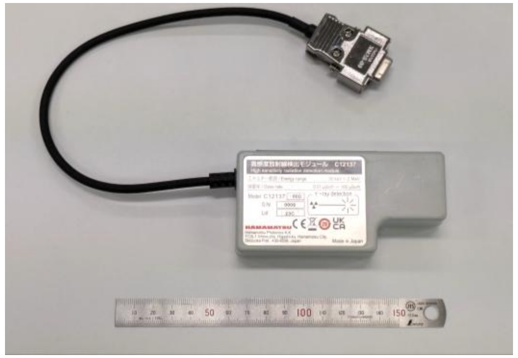


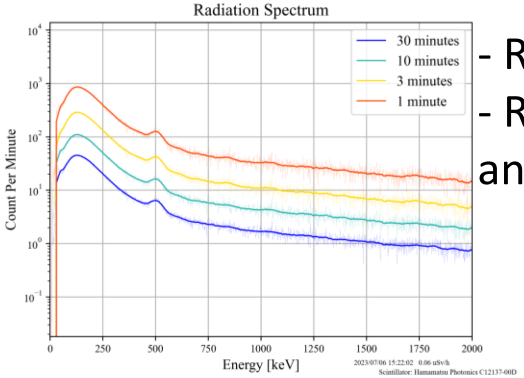
-Very compact
-No effect of hole at stiffener.

Compact radiation monitor

Hamamatsu Photonics C12137

- CsI (Tl) Scintillator
- 30 – 2,000 keV
- 0.01 – 100 uSv/h
- USB or RS-232C (Serial)





- Relatively cheap
- Radiation dose and spectrum

Vacuum particle monitor

TTC2020@CERN, H. Sakai
PASJ2021, WEPI002, H. Sakai