High power CW tests of cERL main-linac cryomodule

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- cool down to 2K and performence test at 2K
- Results of High power test
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SRF2013 @Paris. (2013.Sep.23-Sep.28)

Compact ERL(cERL) at KEK

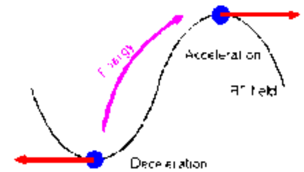
Current : 10-100mA
Emittance : 0.1-1 mm mrad
Bunch length :0.1-3ps

cERL parameters Red: initial case

Requirements of cERL main linac

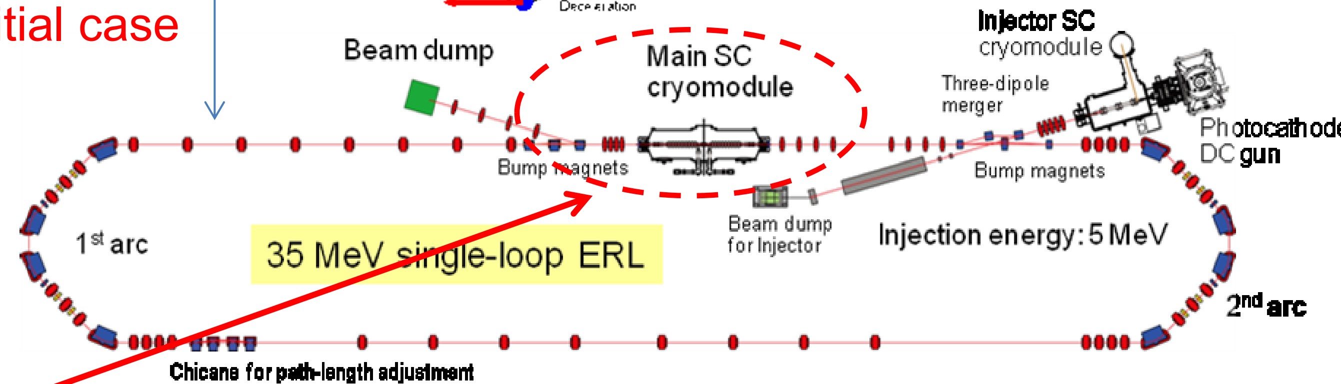
Frequency : 1.3 GHz
Gradient: 15MV/m
Q0: >1*10^10
Beam current : max 100mA
(100mA (in)+ 100mA(out))

Apparatus of cERL



$$P_{loss} = \frac{V_c^2}{(R/Q)Q_0}$$

Ploss = 25W/m (15MV/m)

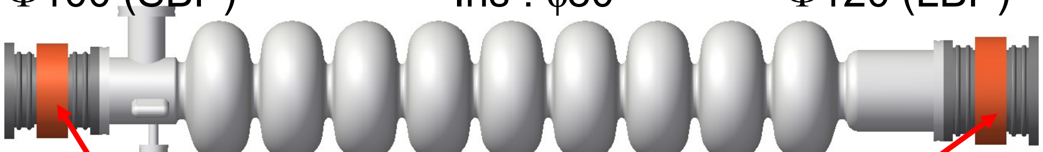


ERL-model-2 cavity: 600mA can be circulated in design

H.Sakai et al., Proc. of ERL07 (2007). All HOMs damped to both end

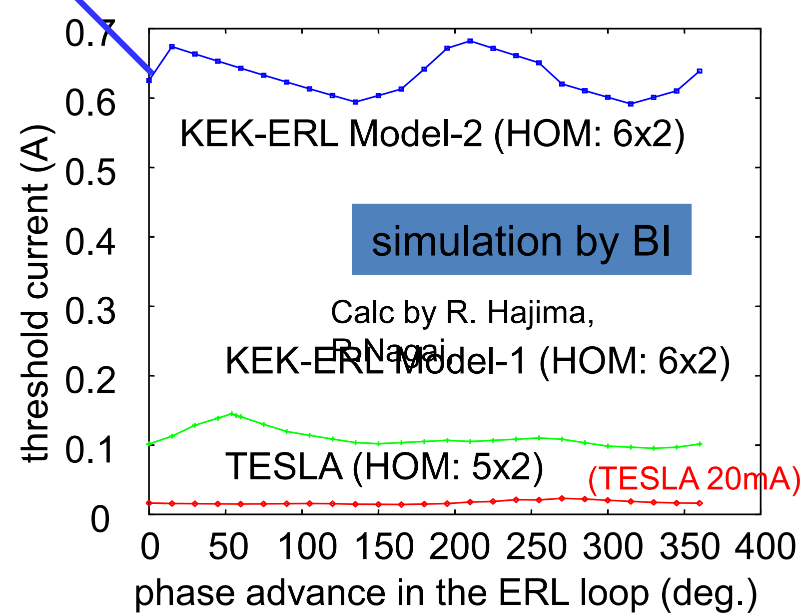
HOM-BBU calculation
(w/o HOM randamization)

Φ100 (SBP) Iris : ϕ80 Φ120 (LBP)



HOM absorber

HOM absorber



Parameters of cERL main linac

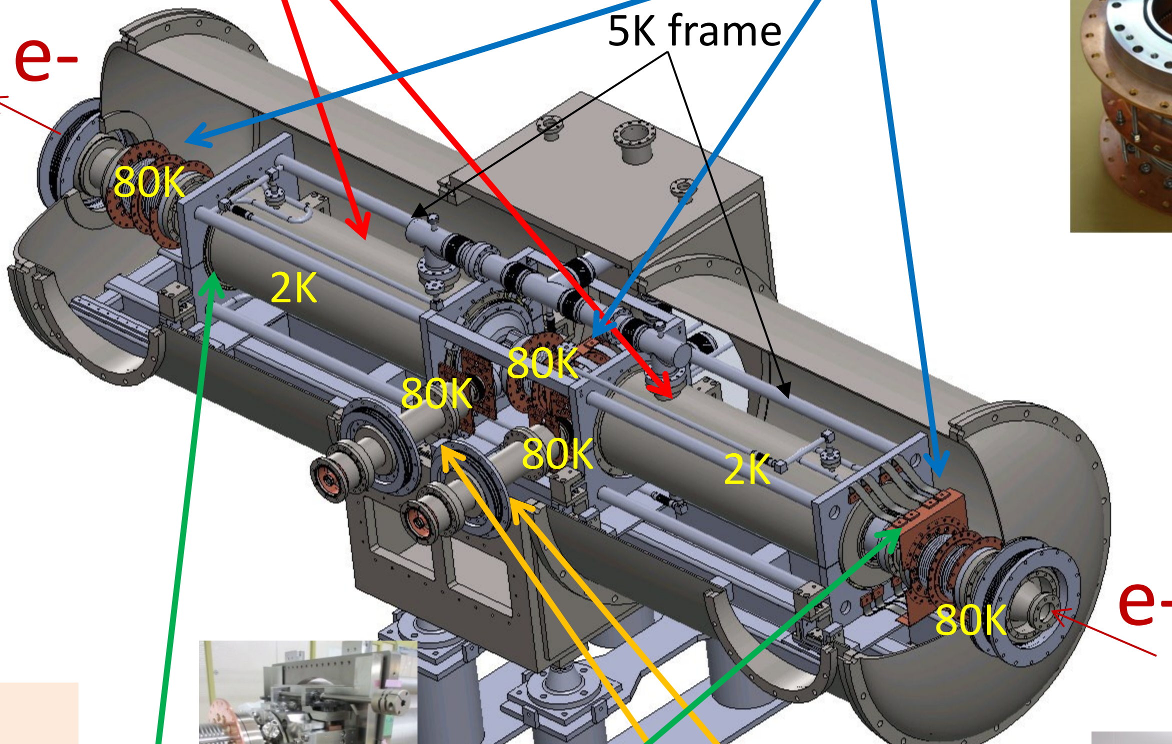
():TESLA cavity

Frequency	1300 MHz	Eacc	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)

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



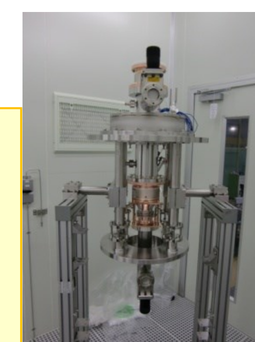
(Compact) ERL target

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)

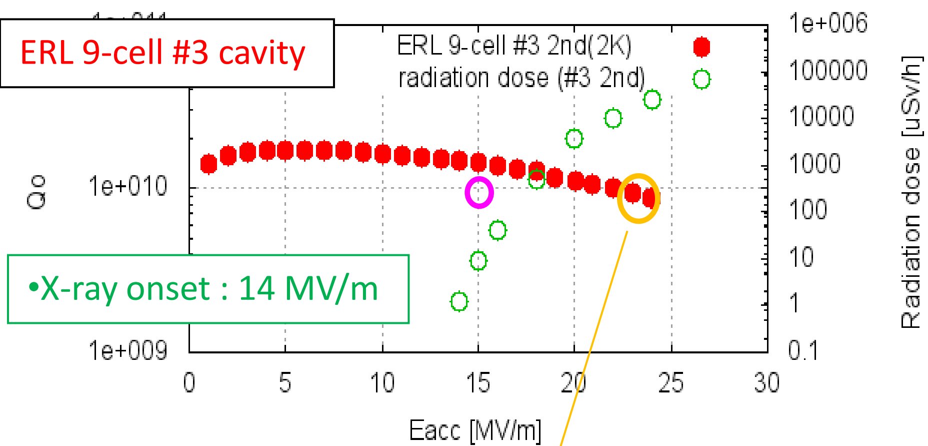


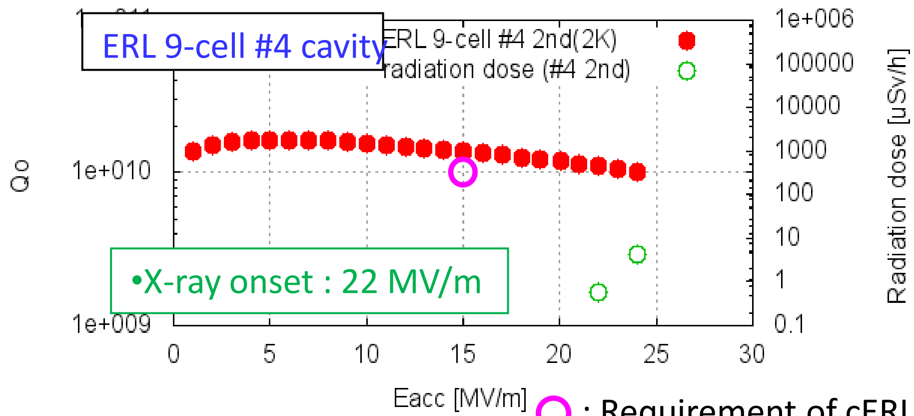
Results of vertical test of cERL Main linac two cavities

Carried out V.T of 2 ERL-model-2 cavities for cERL in 2011.
Achieve 25MV/m (administrative limit) :
Satisfy cERL requirement : Q0>1*10^10@15MV/m

K.Umemori et al., Proc. of IPAC12, p2227

For module assembly





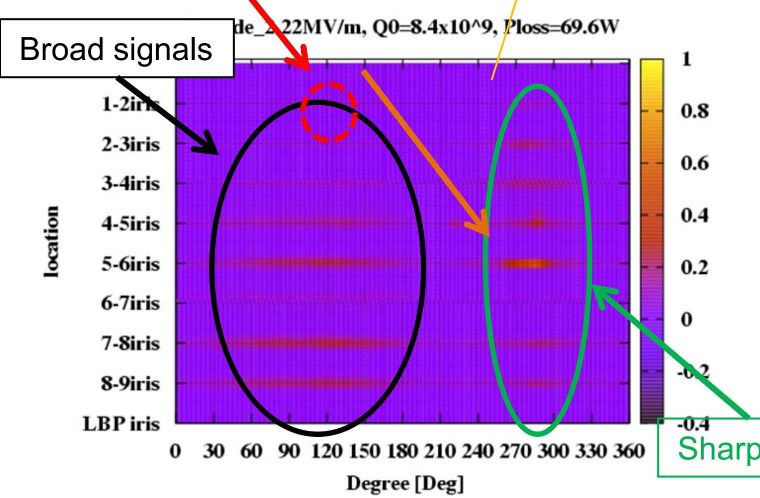
: Requirement of cERL

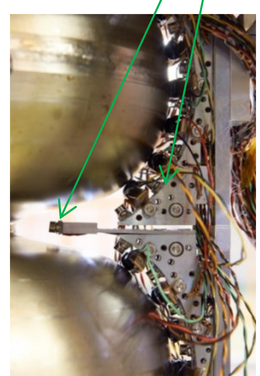
Field emission profile by rotating X-ray mapping

Candidate of source

(#3 cav., 2nd VT, Eacc=22MV/m)

PIN diode





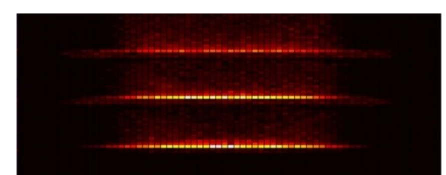
Sharp traces on cell

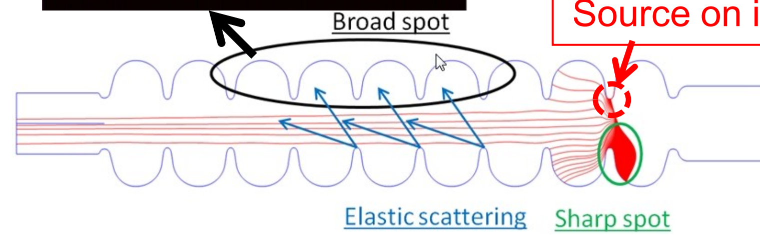
H.Sakai et al., Proc. of IPAC 2010 ,p2950

Simulation (with Fowler Nordheim eq.)

Field emission Profile on Nb surface simulated with including EGS5 (radiation with materical interaction)

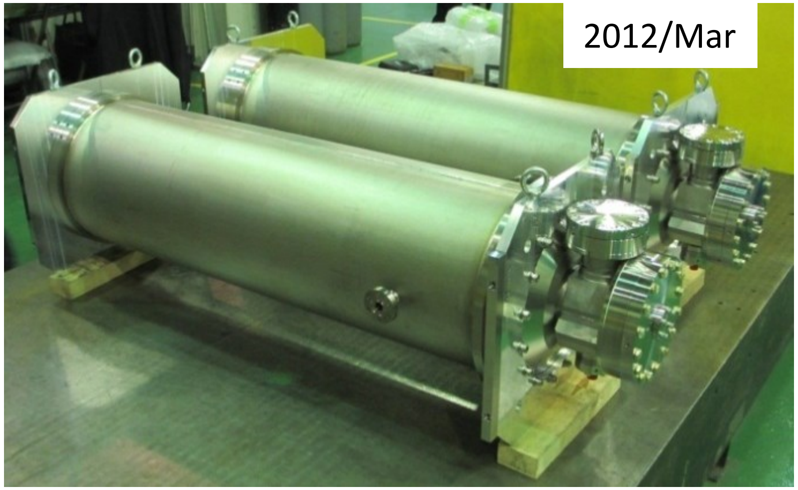
See detail
Enrico Cenni IPAC12, p295, and Doctor thesis





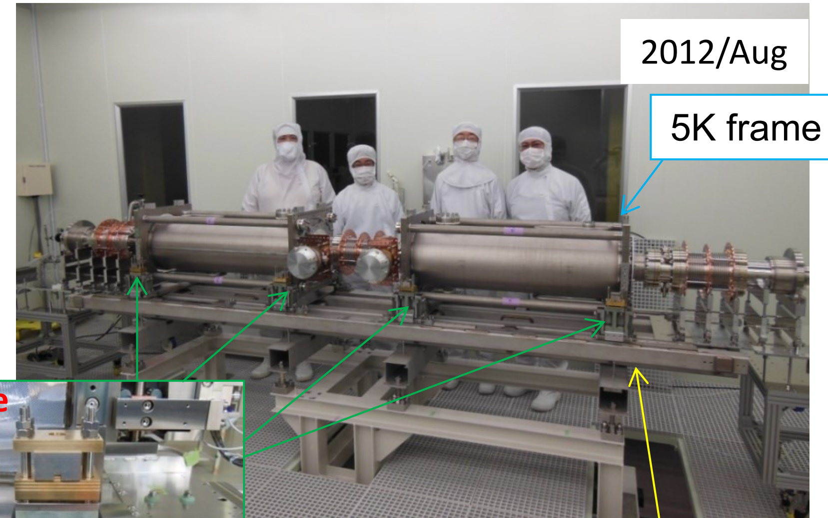
Measured profile were clearly explained by simulation .
We can know the localized source of field emission in V.T

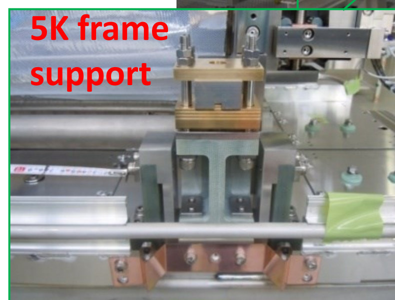
Module Assembly after V.T



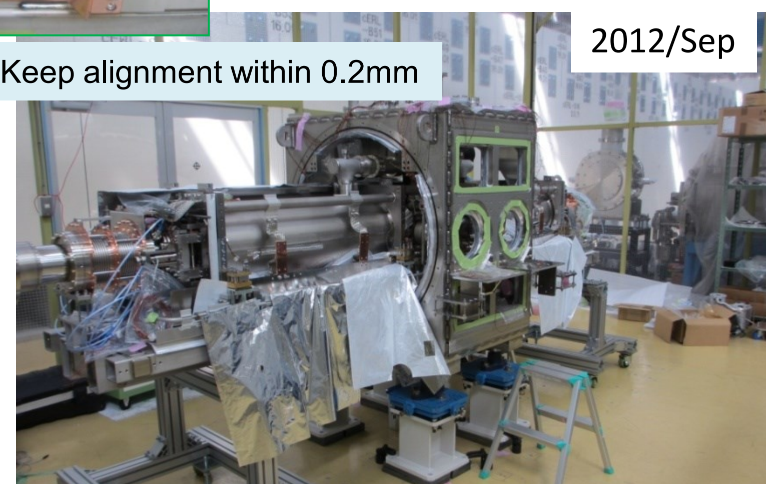
After Ar gas purging into cavities,He jacket, were welded on cavities. Diameter of jacket is 300 mm to make He level inside the jacket to fulfill CW operation ,

Cavities, HOM absorbers and cold window of input couplers were assembled in class 4 clean room supported by backbone through 5K frame support



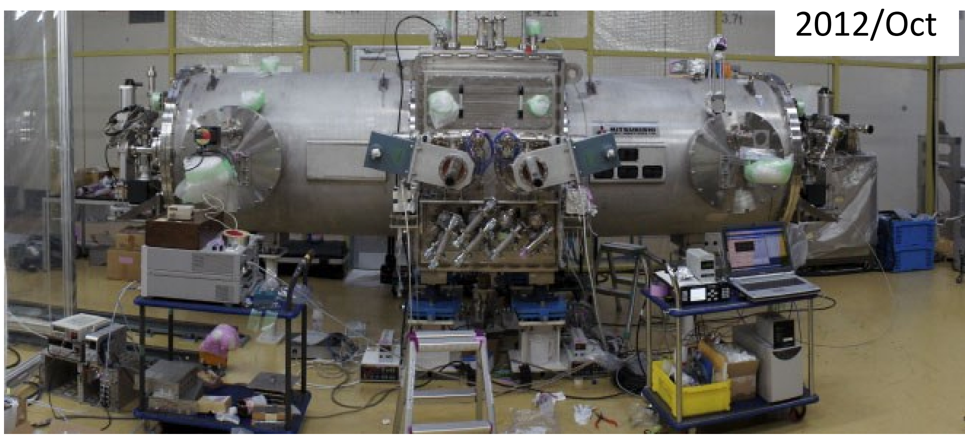


Backbone set at 300K



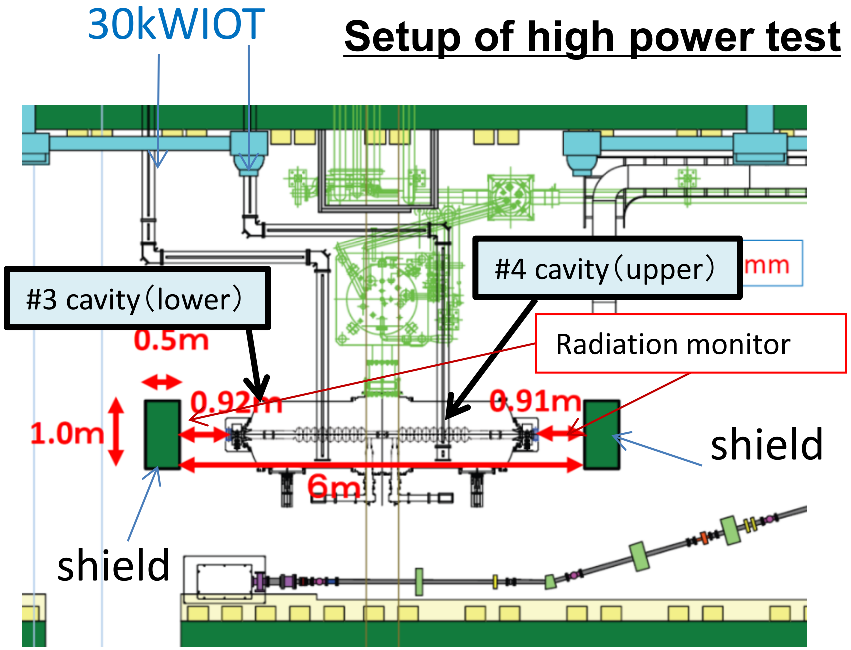
Keep alignment within 0.2mm

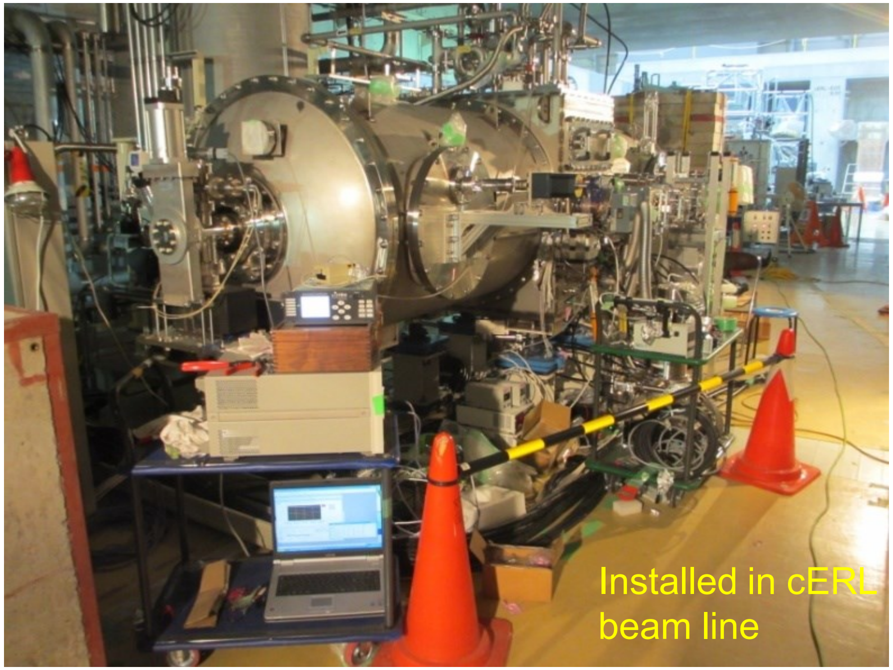
Assemble He line, magnetic shield, thermal Insulator, sensor and so on



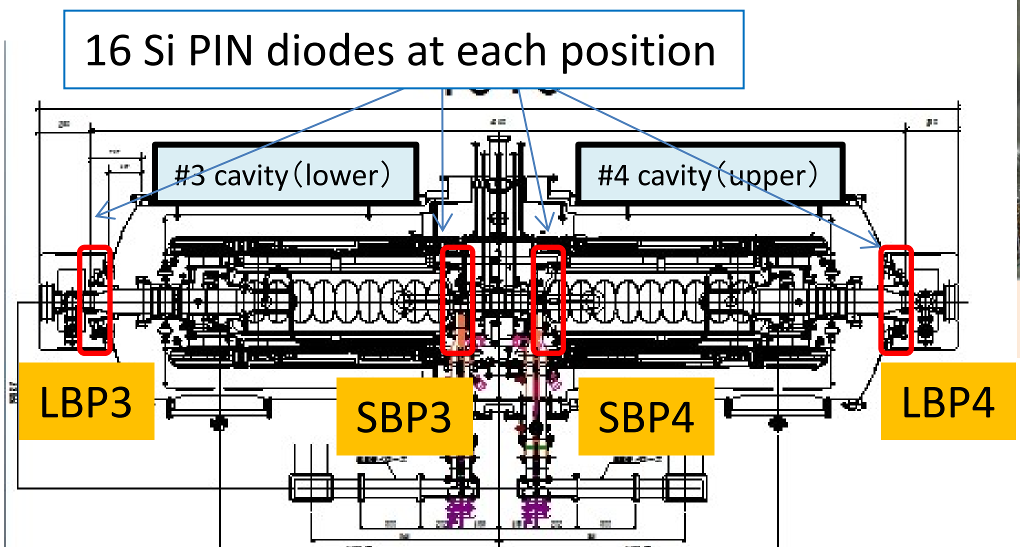
After fixing alignment, warm window were set and vacuum vessel were mounted. Gate valves were set on both sides

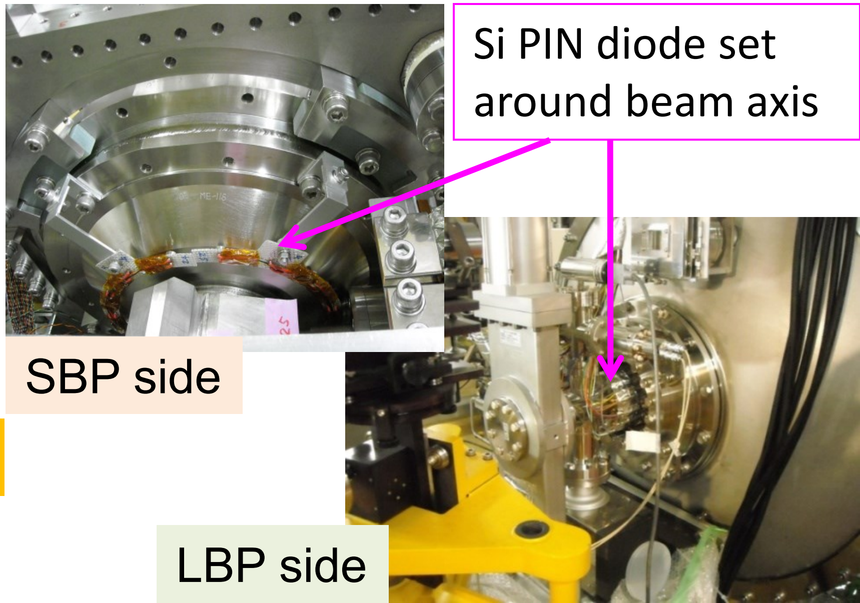
Setup of high power test at cERL beam line



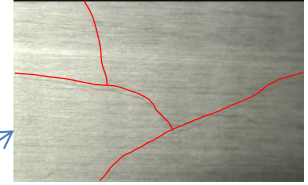


PIN radiation profile monitor set around beam axis





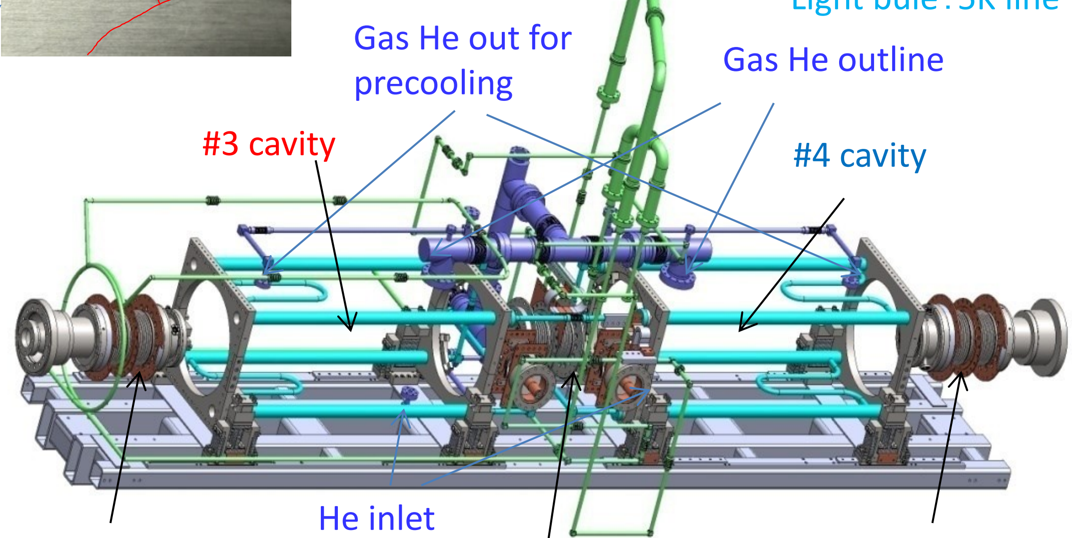
Cryomodule Cooling to 2K



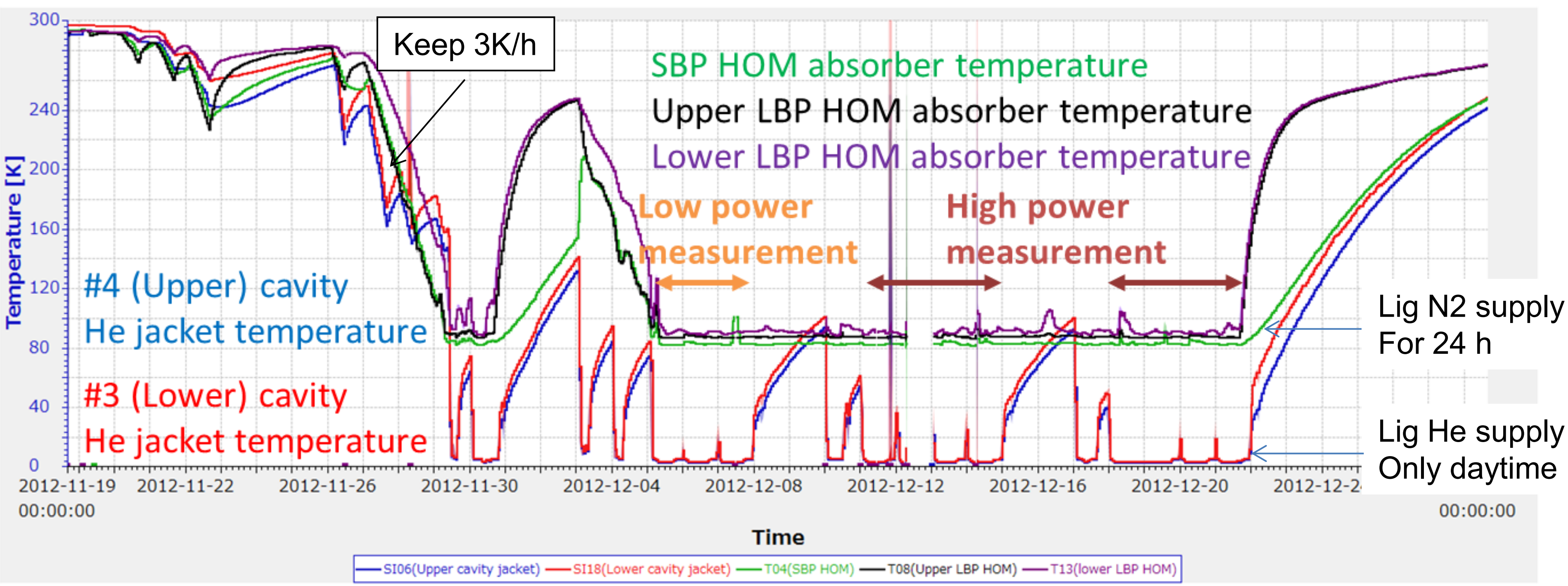
Strategy of cooling

・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.

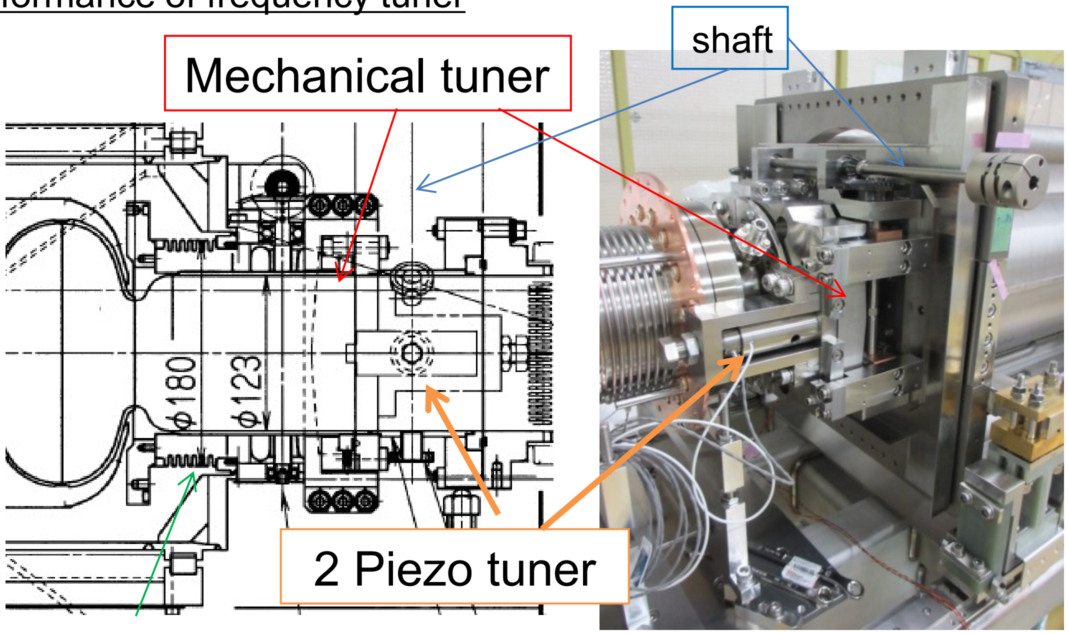


History of 2k cooling



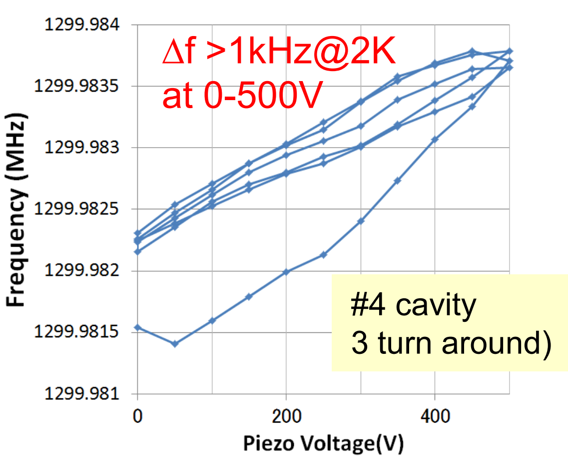
Performance test of cERL cryomodule

Performance of frequency tuner

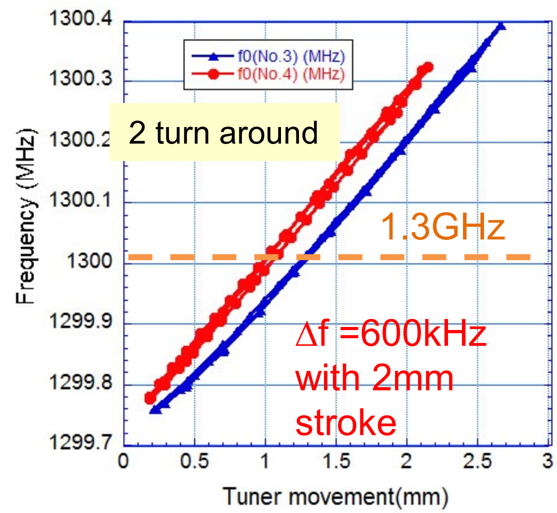


Cancel pressure variation

Piezo performance @ 2K

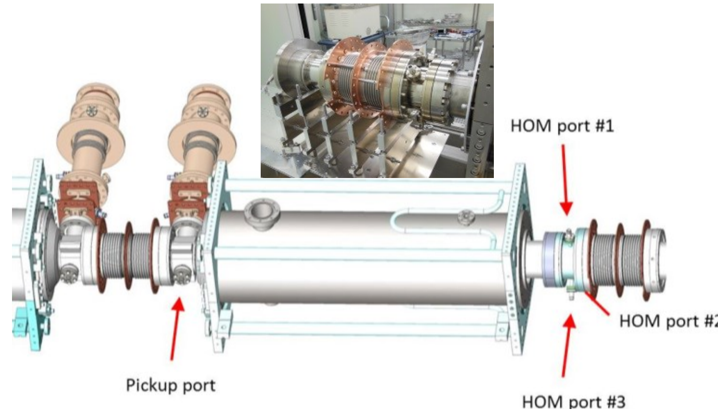


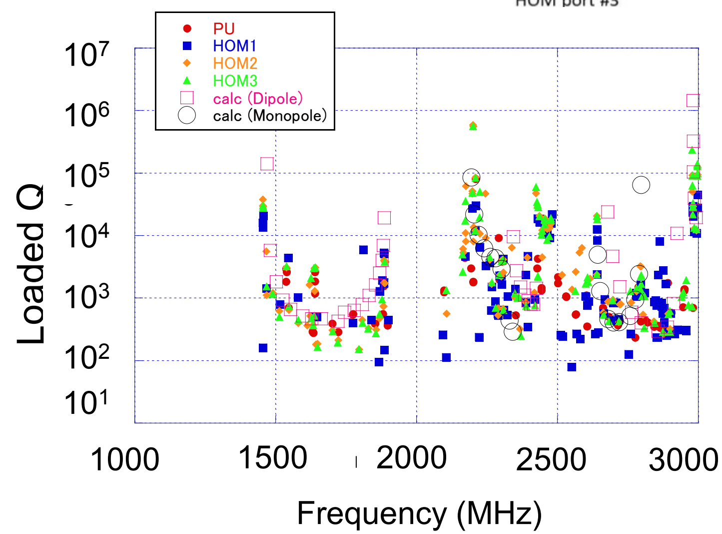
Coarse mechanical tuner stroke @ 2K



Course and fine piezo tuners also worked smoothly and had enough stroke under 2K cooling.

HOM properties under 2K condition





- Using fundamental pickup port (PU) and HOM ports (HOM1, 2, 3), HOM characteristics were measured.
- Their behavior, frequency and loaded Q-values, were generally agreed with calculation results.

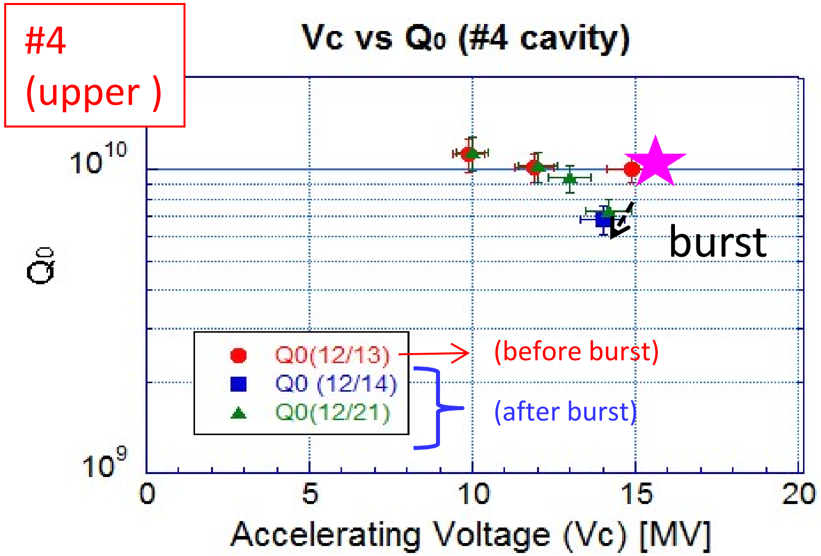
Upper QL : 1.54*10^7
Lower QL : 1.15*10^7

Max input power (Pin) is 5kW during high power test

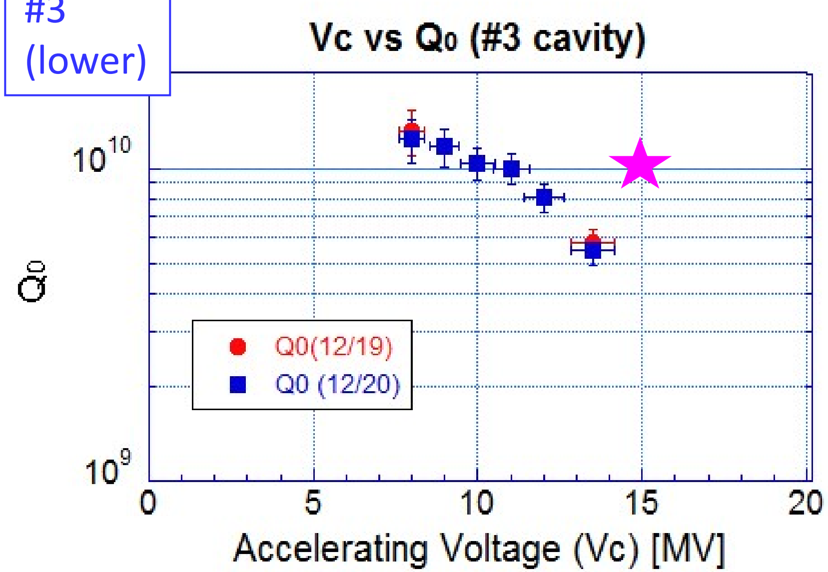
Results of high power test (Vc vs Q0)

- High power test was done one by one cavity.
- Input coupler was processed up to 25kW before high power test.
- Both cavities reached to Vc = 16MV.
- Q_0 of #4 cavity decreased during processing.
- Field emission on-set was 8-9 MV for both cavities.
- Low field (<10MV/m) reached Q0>1*10^10. (no effect of HOM damper and magnetic shield works well. (→ **Mika Masuzawa , WEIOD02**)

#4 (upper)

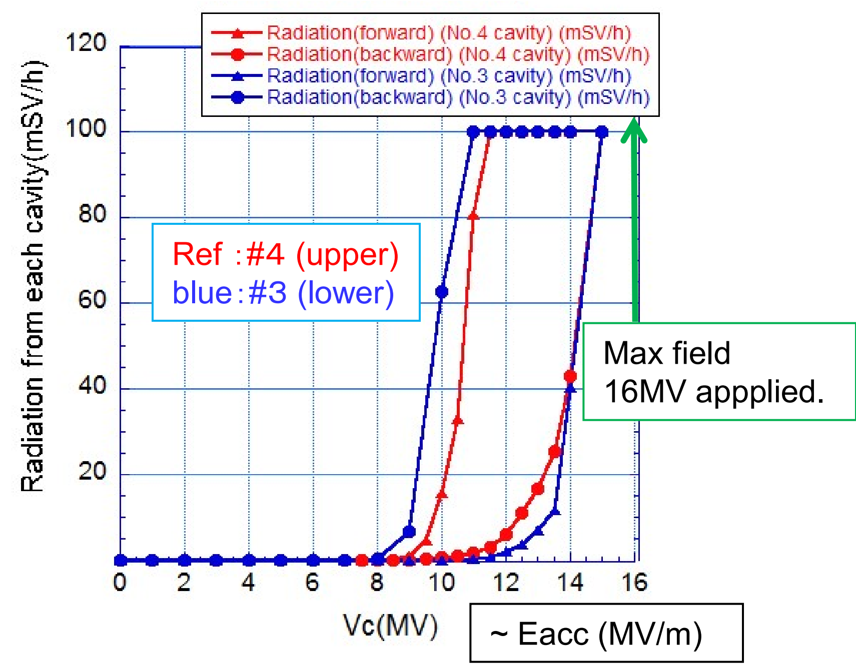


#3 (lower)



★ : Requirement of cERL

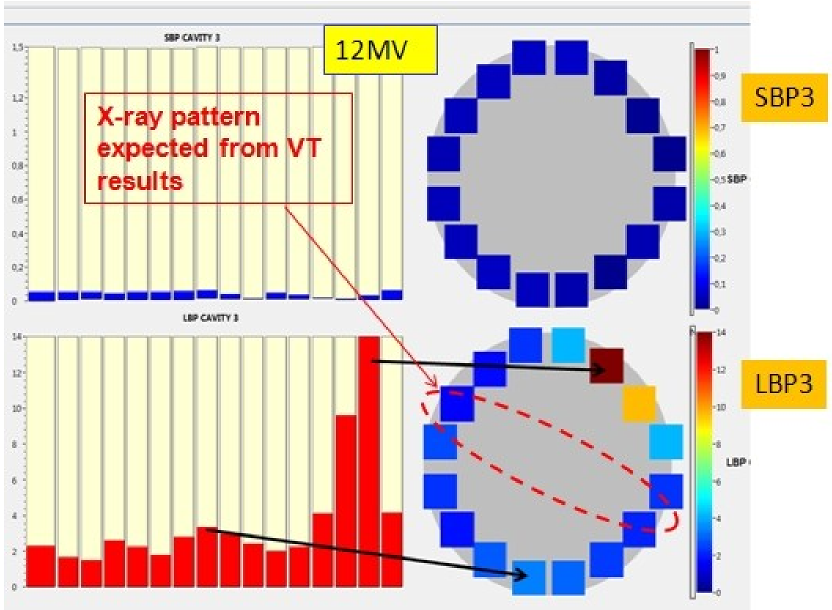
Measured radiation of each cavities at final state

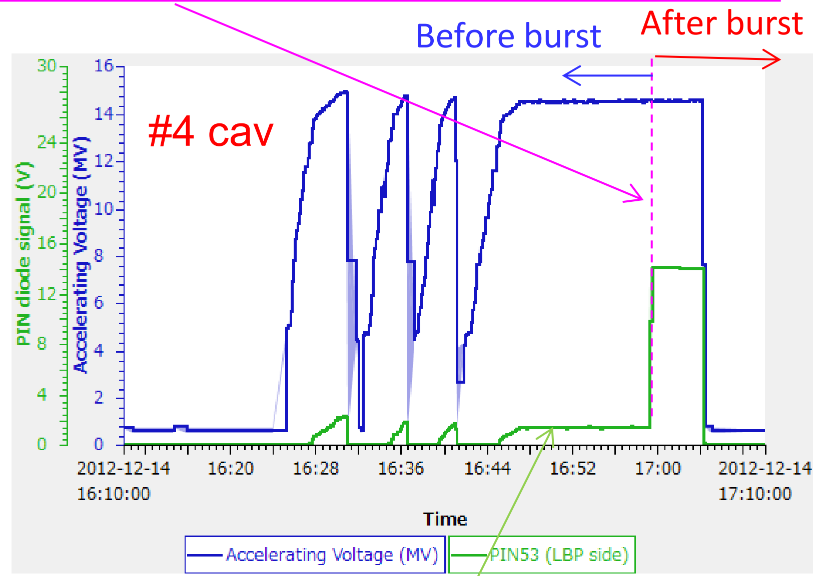


Detail radiation profile measurement

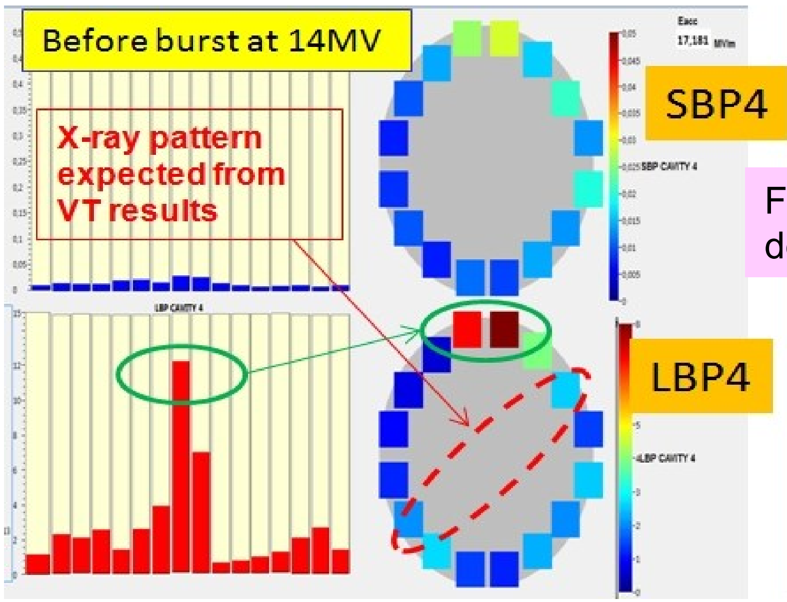
Sudden burst event was observed under keeping field of 14.5MV

#3 (lower)

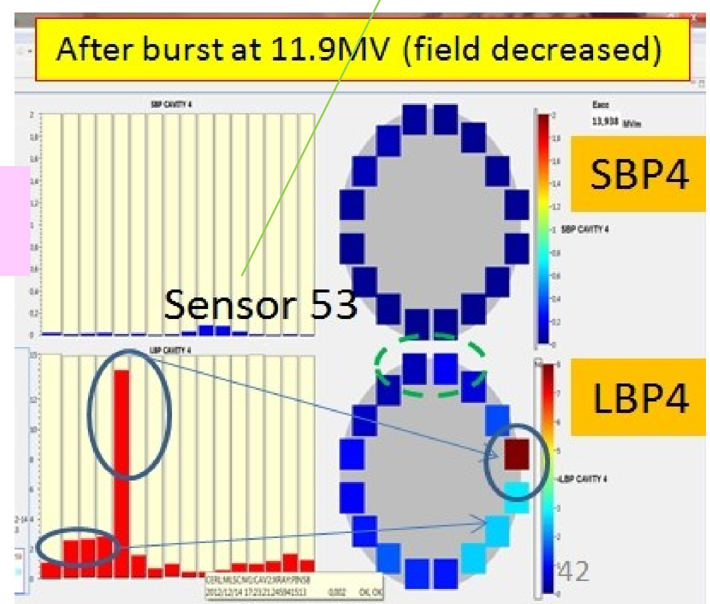




#4 (upper)



Field decreased

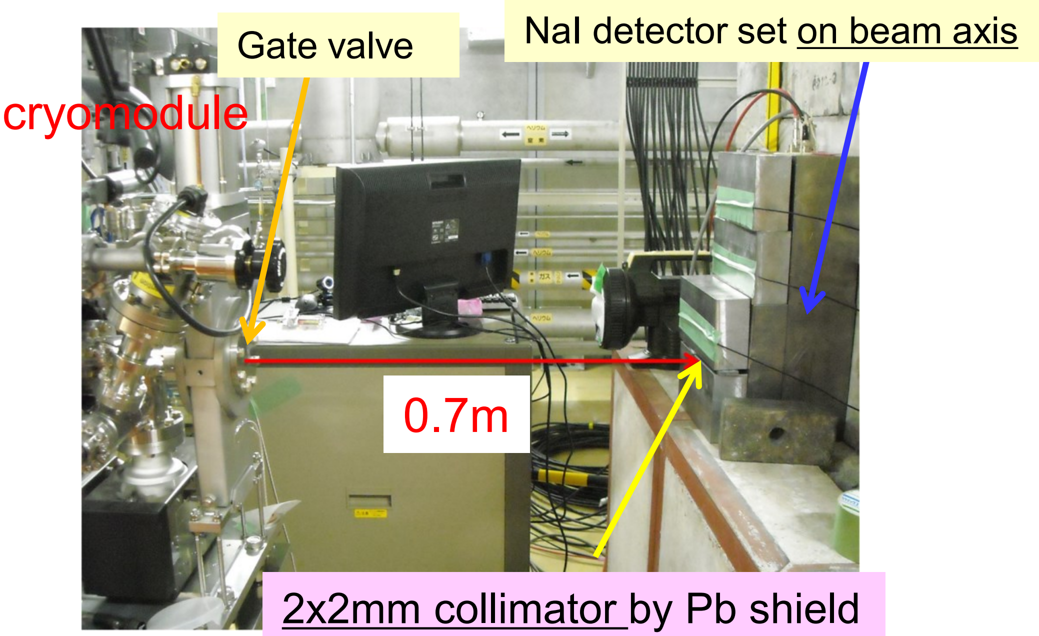


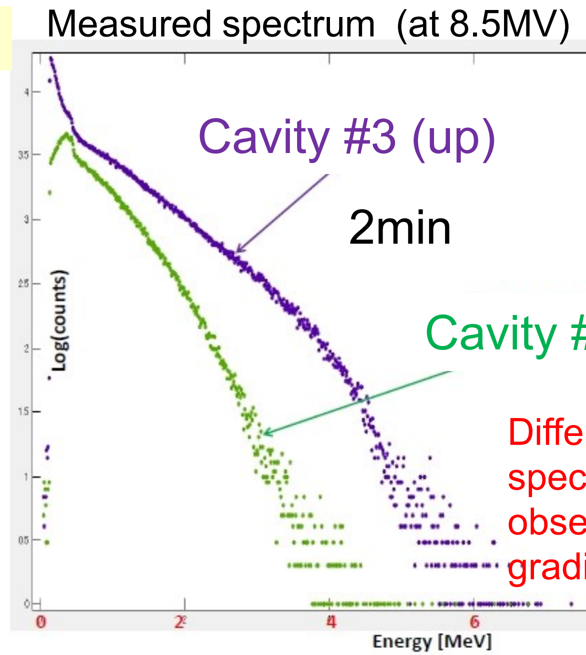
- Radiation pattern was changed from V.T
- Radiation pattern also changed after X-ray burst

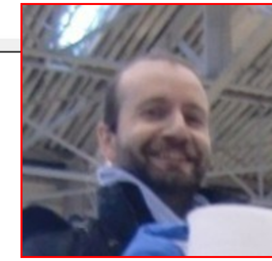
- Another new radiation sources were produced during assembly work and high power test.

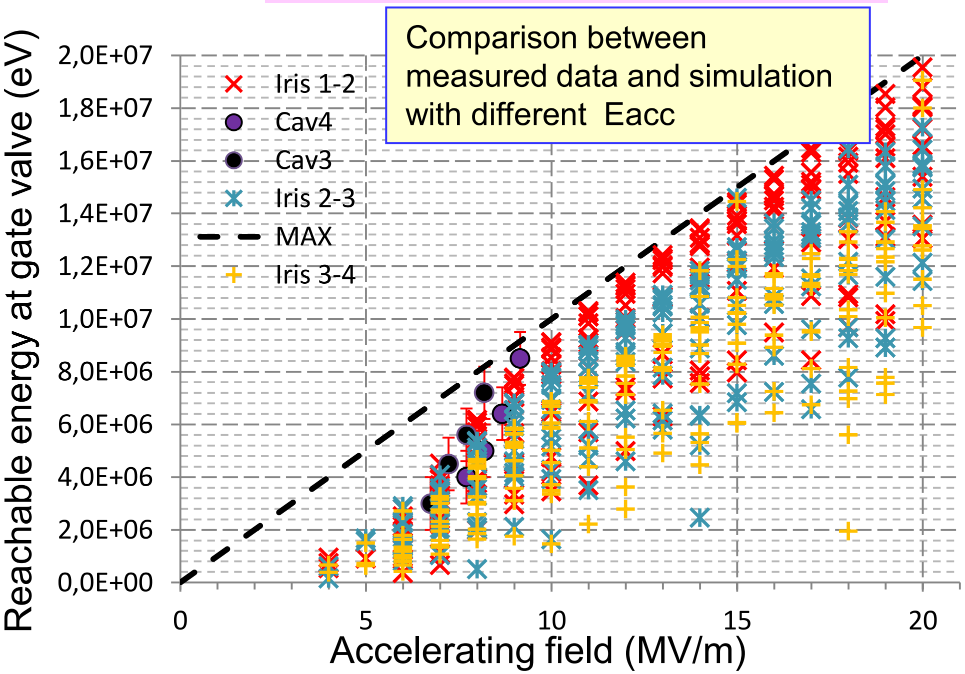
Survey location of field emission source by NaI

Enrico Cenni et al., TUP091 in SRF2013



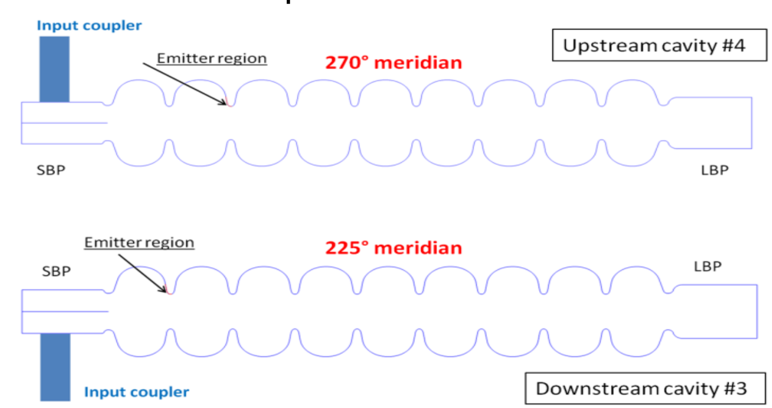






Measured error is assumed end point of bremsstrulung effect

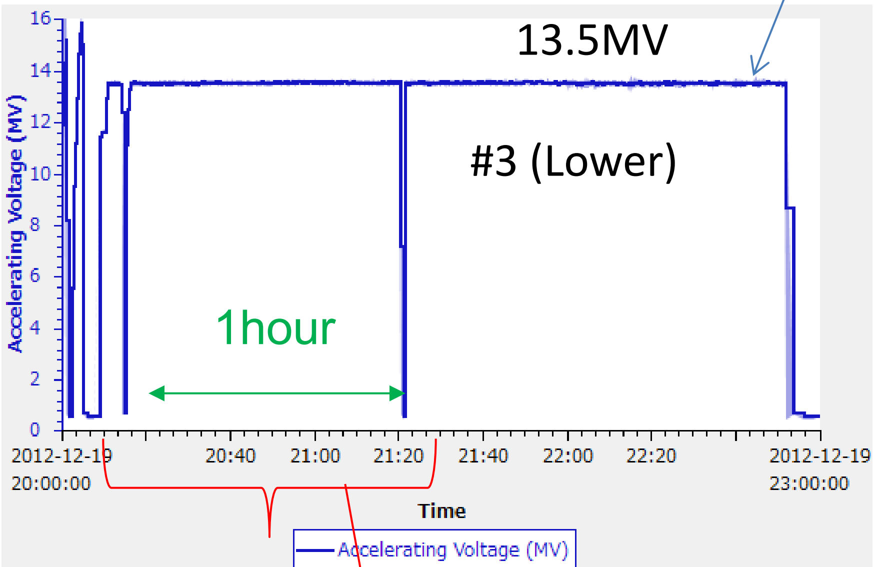
Estimated source position

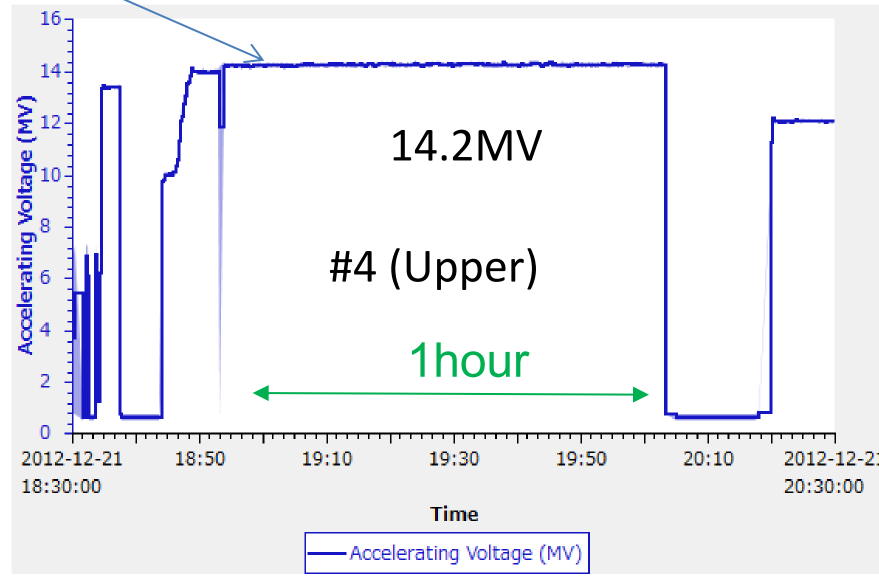


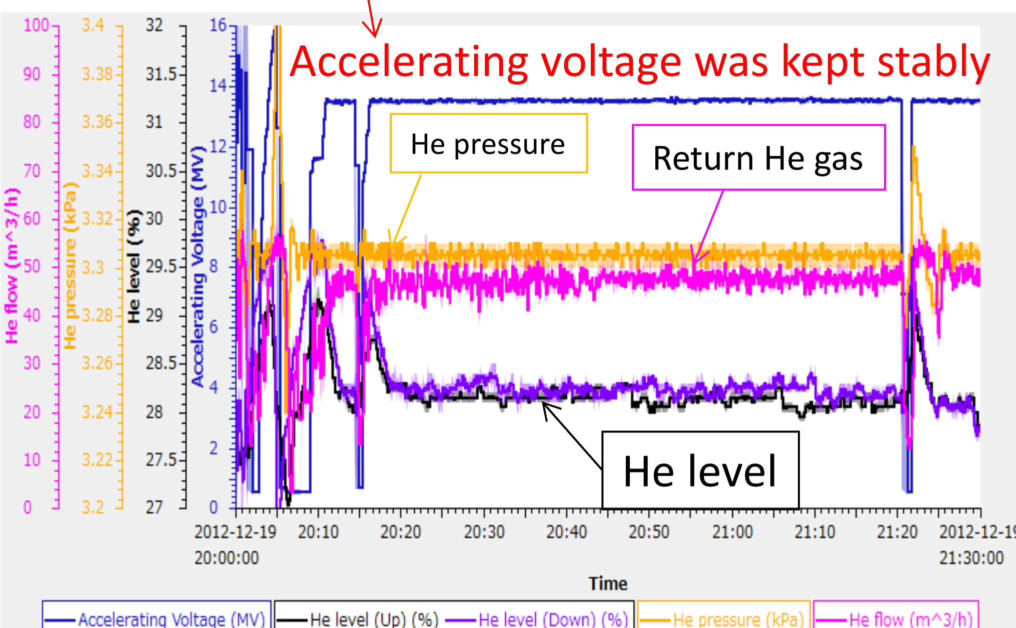
Position near SBP and input port is estimated as a radiation source. String assembly work was poor near SBP side ?? Coupler also caused the burst ??

Vc keep test

Accelerating Voltage



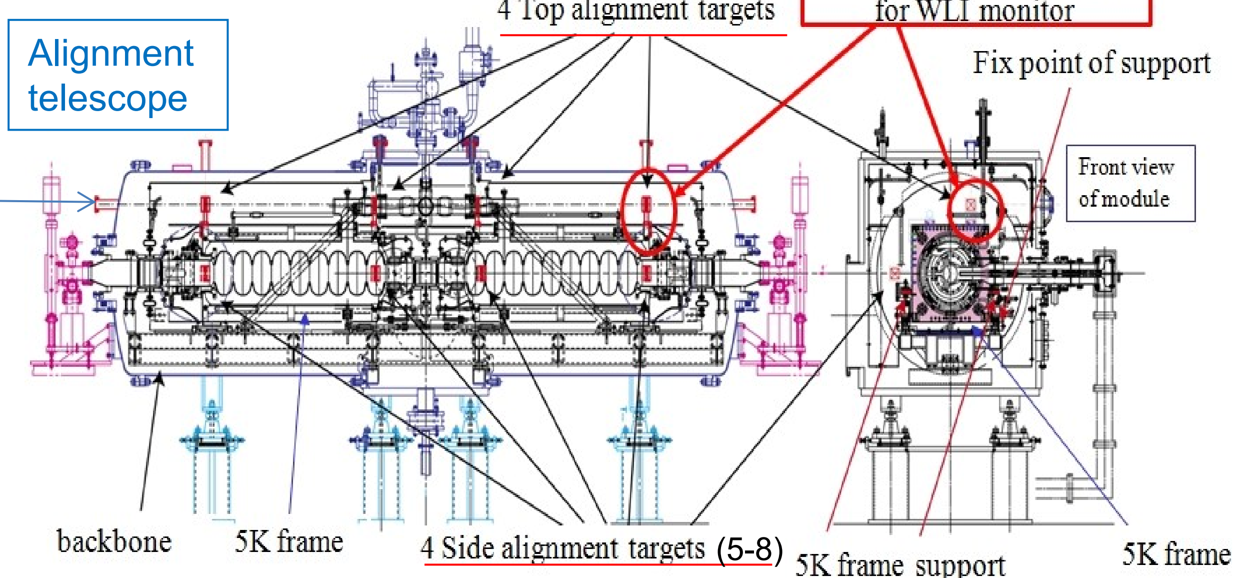




- We can keep the following voltages of
  Upper cavity : 14.2MV
  Lower cavity : 13.5MV
  for more than 1 hour. (40-45W heat @2K)
- We cannot keep more than 14.5MV field because of the lack of the cryogenic power (>50m^3/h ～50W)

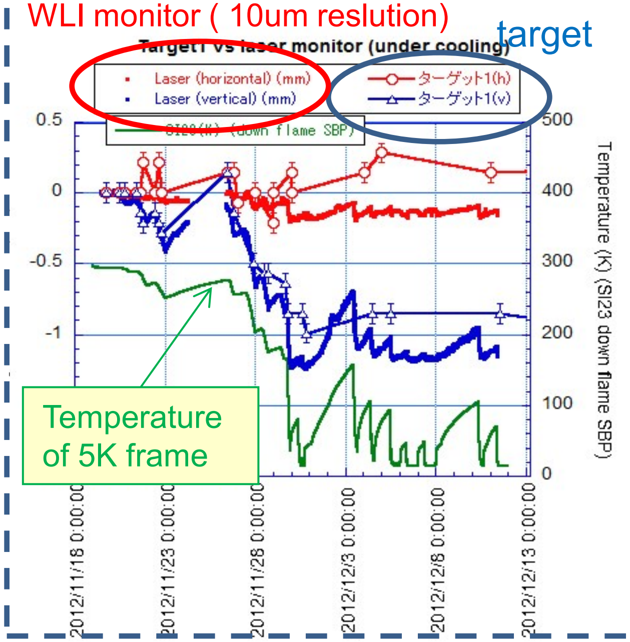
We note that He gas return, He level and He pressure were also stable. Especially He pressure was kept stable within 10Pa (measured)

Measurement of displace ment unde 2K cooling

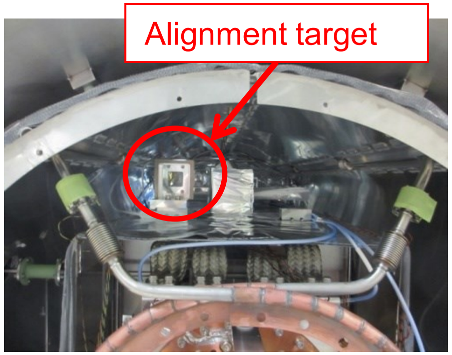


H.Sakai et al., MOP069 in SRF2013

WLI monitor (10um reslution)

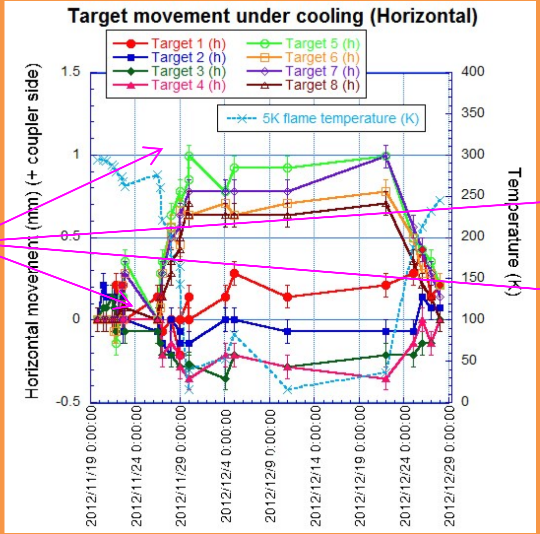


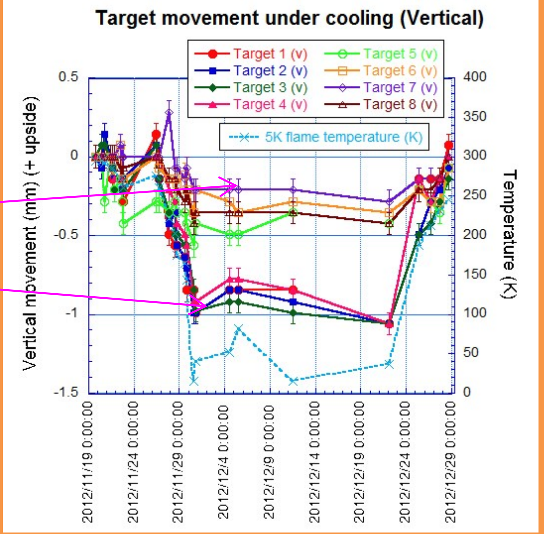
Alignment target



Measured displacements of targets

Move same way with targets at same transverse position





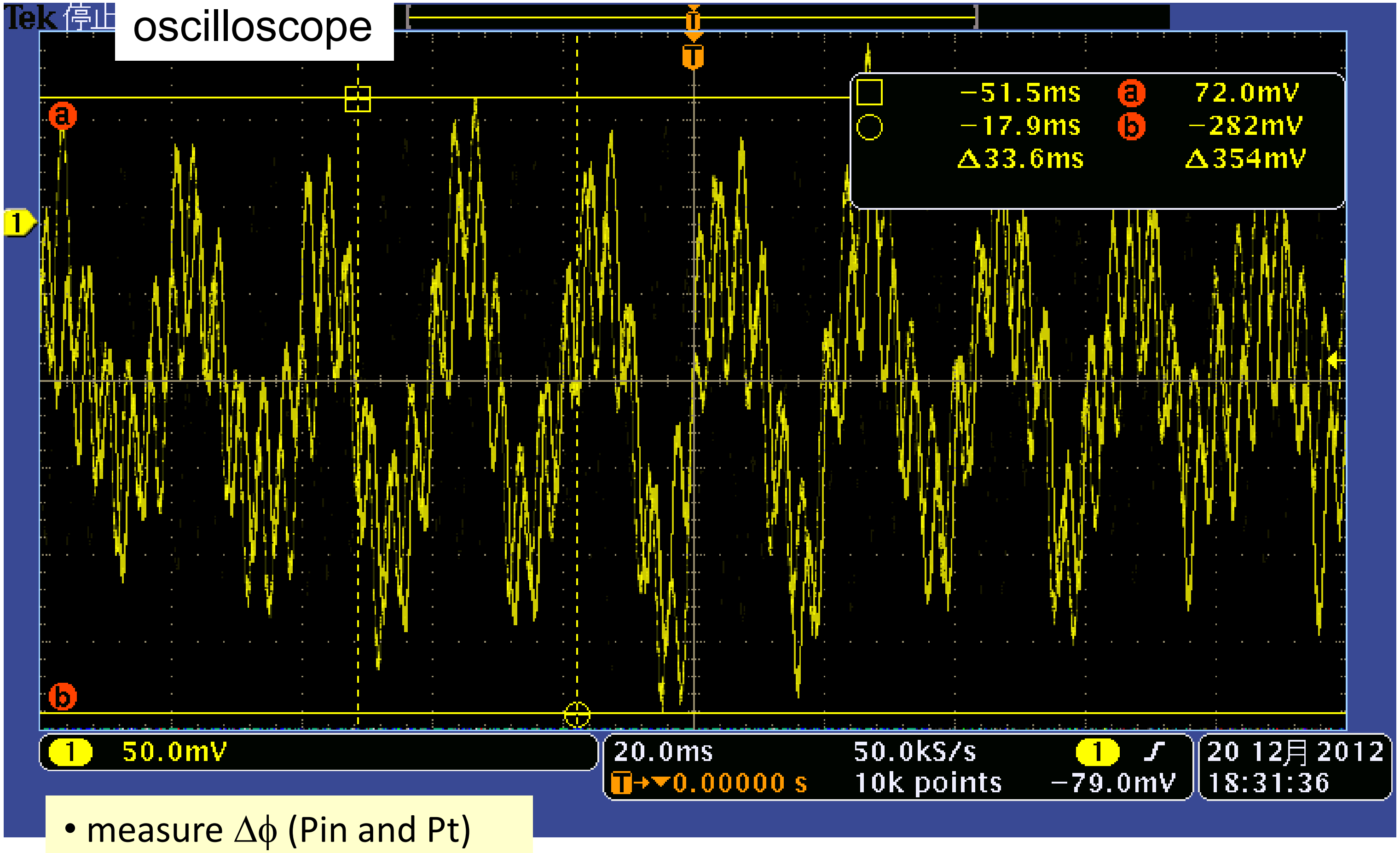
Summary of displacements of targets and cavities between RT to 2K	Horizontal (mm)	Vertical (mm)
Target 1-4 (Average)	-0.11	-1.06
Target 5-8 (Average)	0.87	-0.37
Average movement of cavity center (from target 5-8)	0.39	-0.37

- About 0.4mm of cavity center movement was evaluated horizontally and vertically , which agreed with expected values of thermal shrink of 5K supports.
- These vales were within alignment error from beam requirement of 1mm.

2K microphonics measurements

•Example of#3 cavity, QL = 1.15*10^7

Pk-pk =7Hz



- measure Δϕ (Pin and Pt)
- LLRF Feedback loop off
- Field set to 2.5MV/m

・Pk-pk = 7Hz by oscilloscope. It allow us to increase the QL higher than several *10^7 → lower power

・Main peak was observed at 49.5Hz (not 50Hz of electrical noise) by FFT analyzer ,which was not come from cavity resonance frequency.

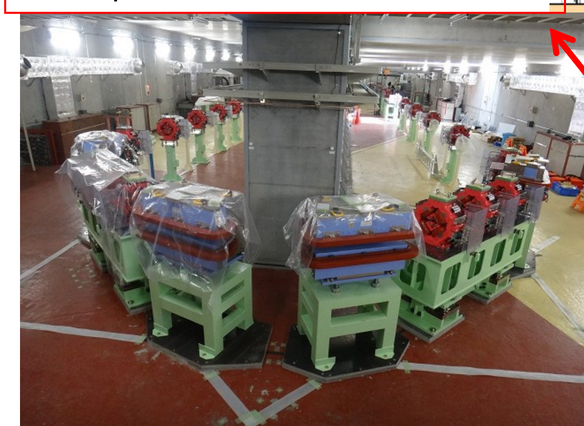
We need to continue measuring michrophinics on next cERL operation

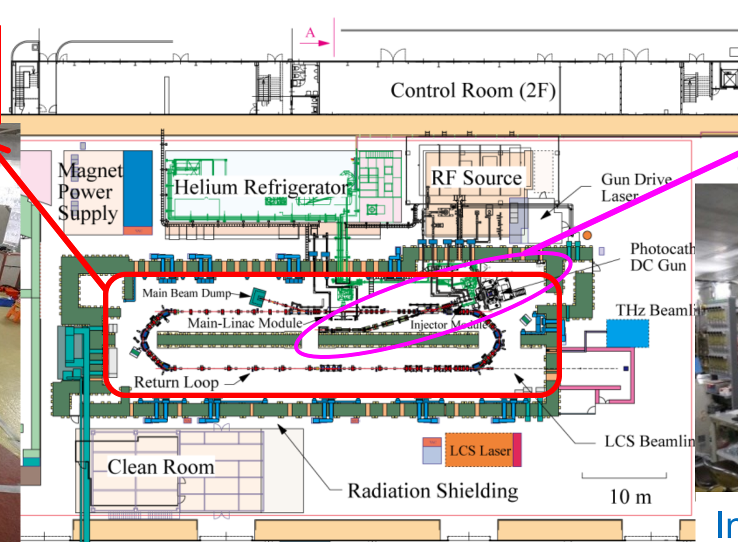
Summary

- After V.T, we prepared the main linac cryomodule with two 9cell ERL cavities and installed it into cERL beam line on 2012/Oct.
- Main linac cryomodule was able to cooled down to 2K by controlling the cooling condition including 3K/h speed at HOM absorber.
- Both cavities reached 16MV by feeding CW power. But we met the <u>severe field emission</u> by newly produced emitter which came from the cryomodule assembly work and during high power test.
- We can keep <u>13.5-14MV</u> of accelerating voltage for more than 1 hour.
- Cavity movement was 0.4mm under 2K cooling
- Michrophinics was measured to 7Hz of Pk-Pk. We need to measure more.

• In 2013, beam operation of injector was started. During summer shutdown we will install round loop of cERL. After that we will start the beam operation with energy recovery on cERL.
• <u>Main linac stable operation of cERL is next issues for our module by Digital LLRF for beam operation.</u>
•To improve the gradient , we also try the He processing to our cryomodule.

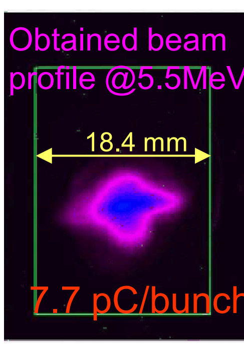
Now we construct the return loop for ERL operation at Dec. in 2013





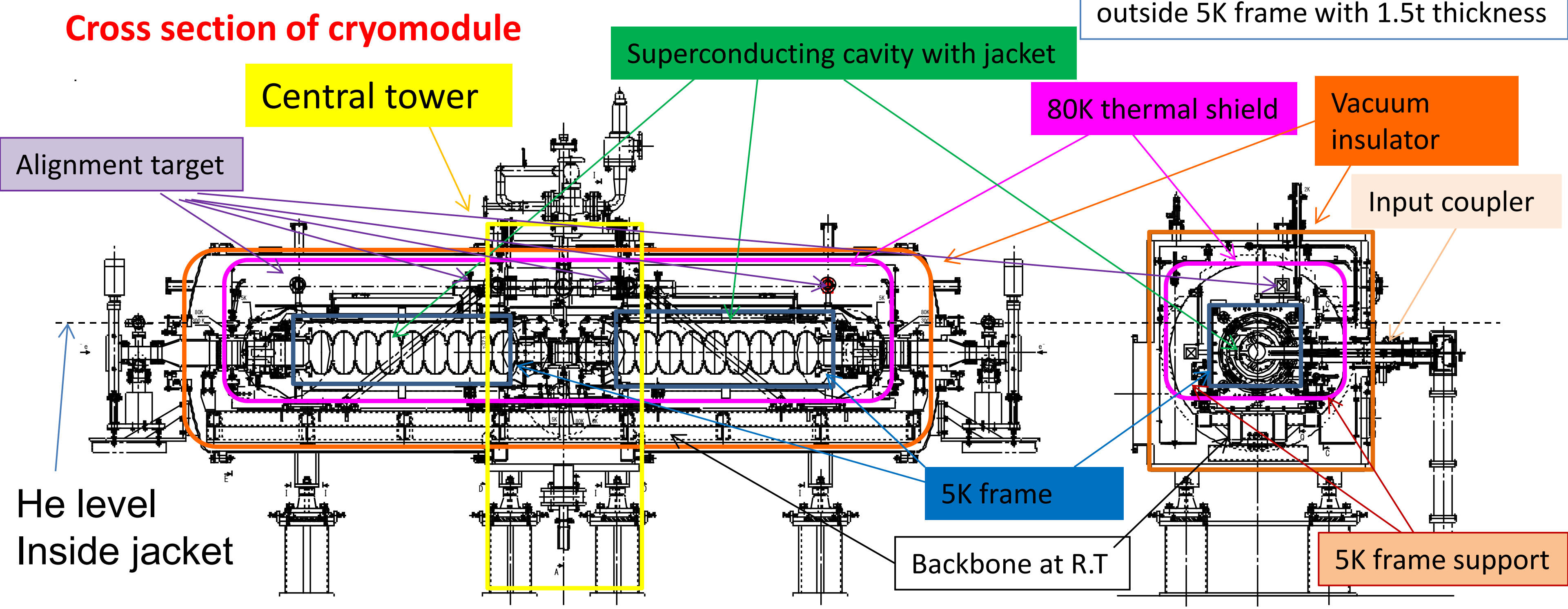
cERL Injector commissioinig was done at April-June in 2013.

Injector cryomodule



Backup

Detailed design of Cryomodule of cERL main linac



Requirements

Dynamic loss (**need margin 80W @ 2K of cooling ability**)

Cavity : 25 W (for 2K) / cavity(@15MV/m)

Input coupler : 1.5 W (for 5K) / coupler

HOM absorber : 150W (for 80K)/ cavity (100mA)

Alignment

±1 mm from beam line

Support

Cavity(2K) – 5K frame– backbone(300K) – Central tower(300K) （supported from bottom side）

Method

Against CW operation

・Enlarge ϕ300mm diameter of jacket and make enough surface of He level in jacket .

・ Gas He outlet = ϕ54mm

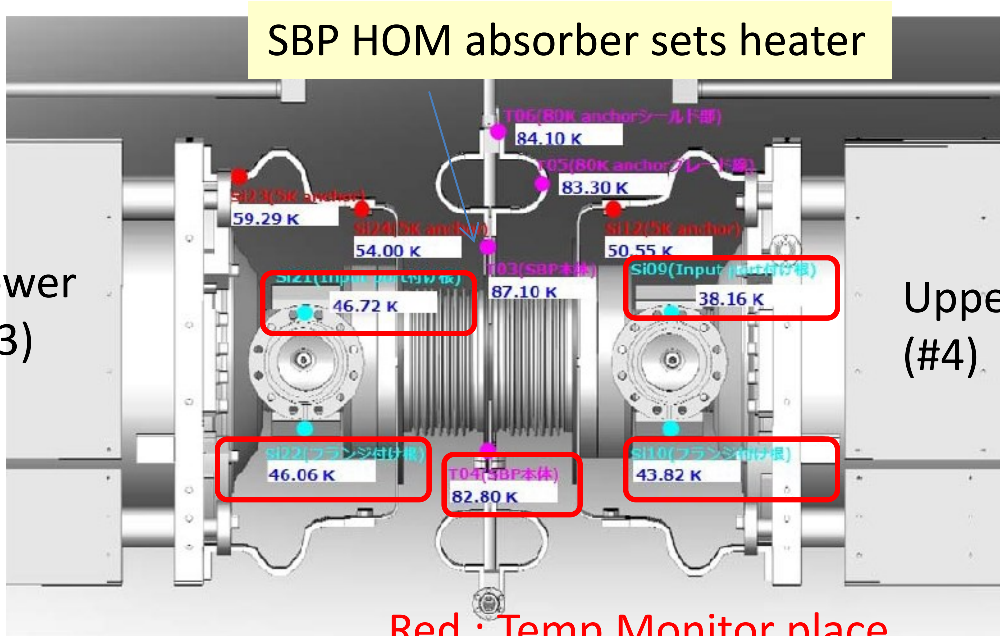
・5K frame is used to suppress heat leak into 2K.

Structure

・5K frame support cavity and alignment target set on frame. By using target, we trace the cavity position under cooling.

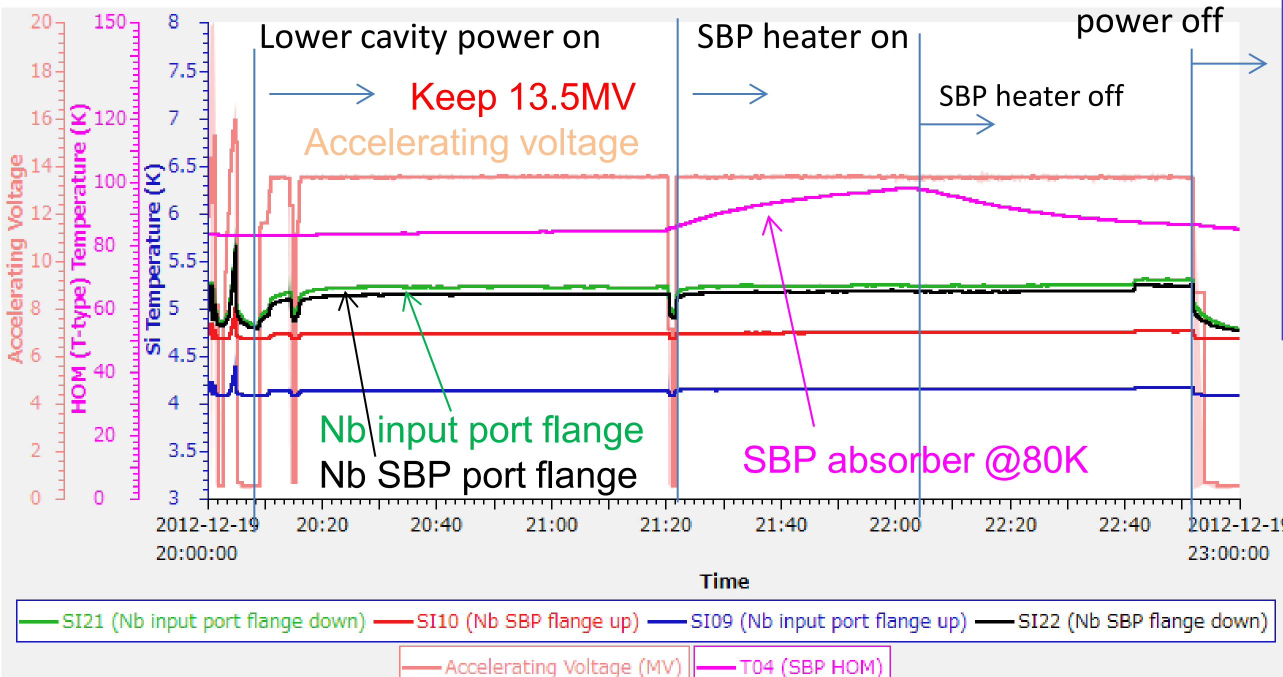
・5K frame was supported from fixed backbone set at 300K via 5K frame supports which reduce the heat leak to 5K frame and thermal shrink .

Temperature rise around cavity on high power feeding & SBP HOM heater test



Measure the temperature rise on cavity flange when the accelerating voltage of lower cavity was kept at 13.5MV .Furthermore, we add 30W (equal to the 50mA beam current HOM power)to SBP absorber by Heater to estimate the heat leak to 2K cavity and Nb flange.

4.5kW of Pin power fed into lower cavity



- Temperature rise of Nb input and SBP flange is from 4.8K to 5.2K (ΔT =0.4K) by power feeding of 4kW
- 30W of SBP HOM heater did not contribute the temperature rise of the Nb flange of cavity.

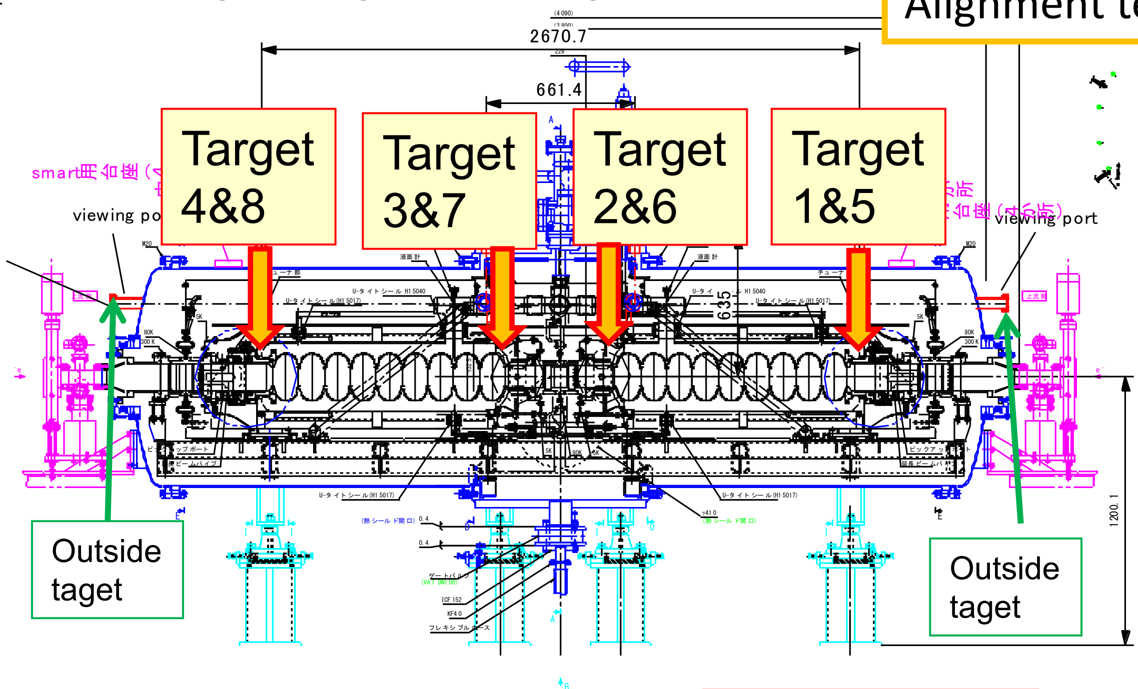
•Heat leak to 2K was absorbed by 80K & 5K anchor and isolated by bellows of SBP HOM absorber as expected by design of cryomodule.

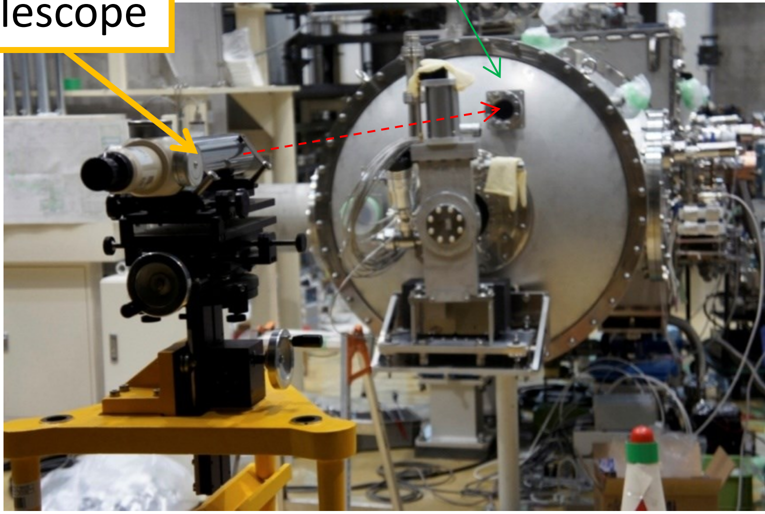
Cavity alignment setting under cooling

Setting of alignment targets

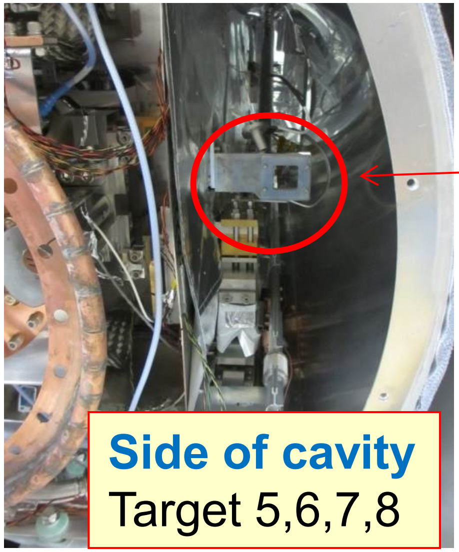
4 outside targets on R.T to make base lines of telescope

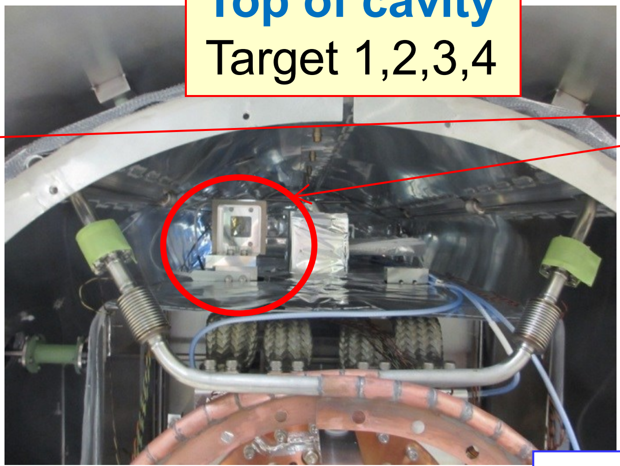
Alignment telescope

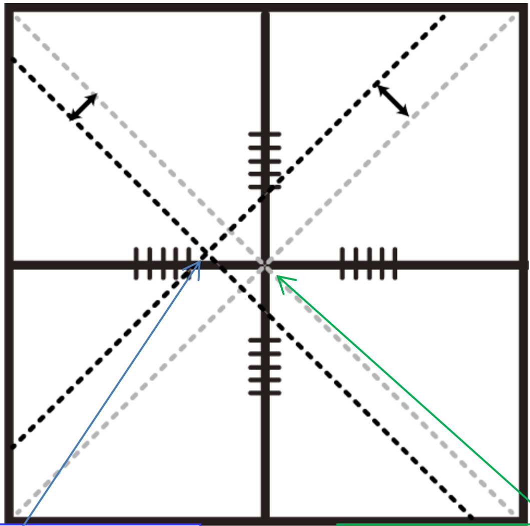




8 Qurtz targets with markers were set around 5K frame at known position from caity centor mechanically along cavity axis





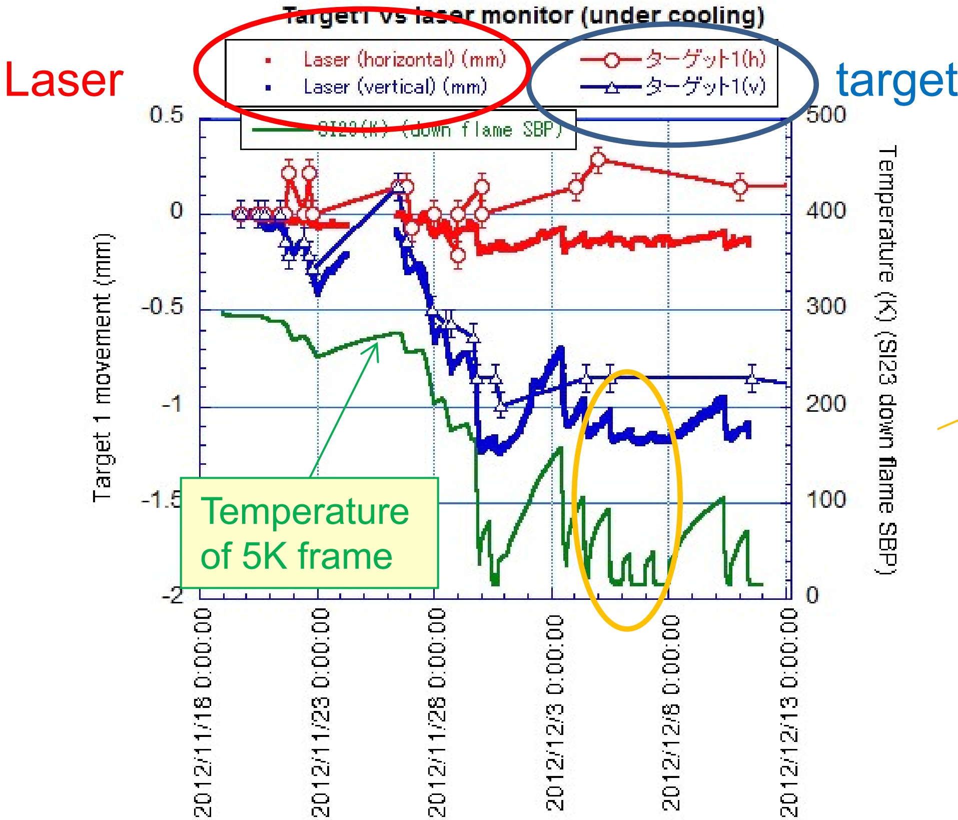


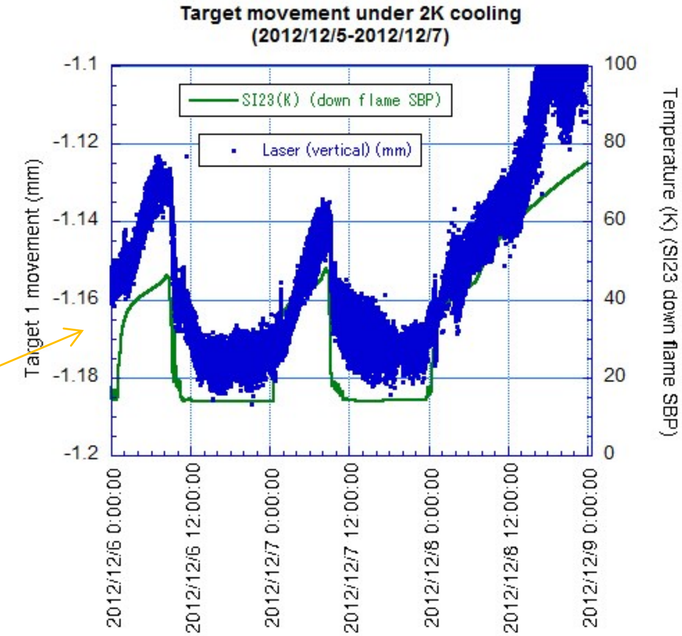
Center of telescope

Target center

Precise measurement of cavity movement by laser position monitor

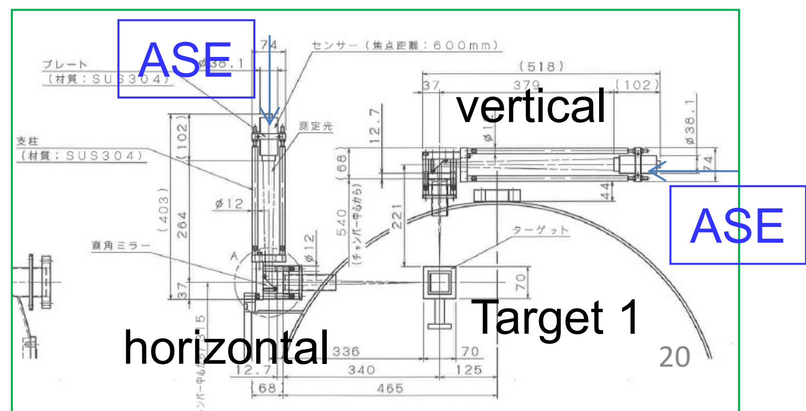
To confirm the measurement accuracy of target, we also measure the movement by newly developed laser position monitor with 10um level accuracy by setting one target.





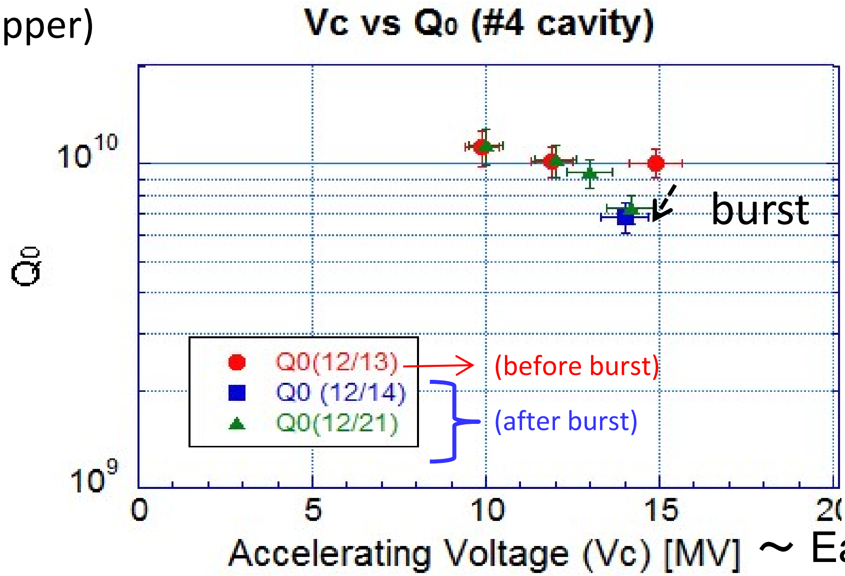
This monitor based on interference of ASE light between target and reference position. By measuring reference position movement we know the target position movement

- Laser monitor roughly agree with target measurement by telescope with ±0.1mm
- While keeping 2K , target movement was stable within 10um → cavity was stable within 10um
- Temperature of 5K frame is sensitive for 5K frame movements by laser position monitor.

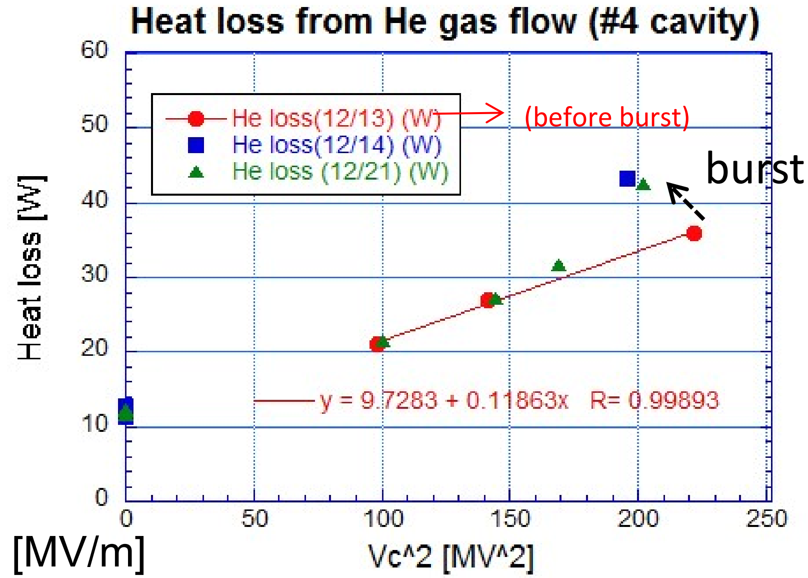


Dynamic loss measurements

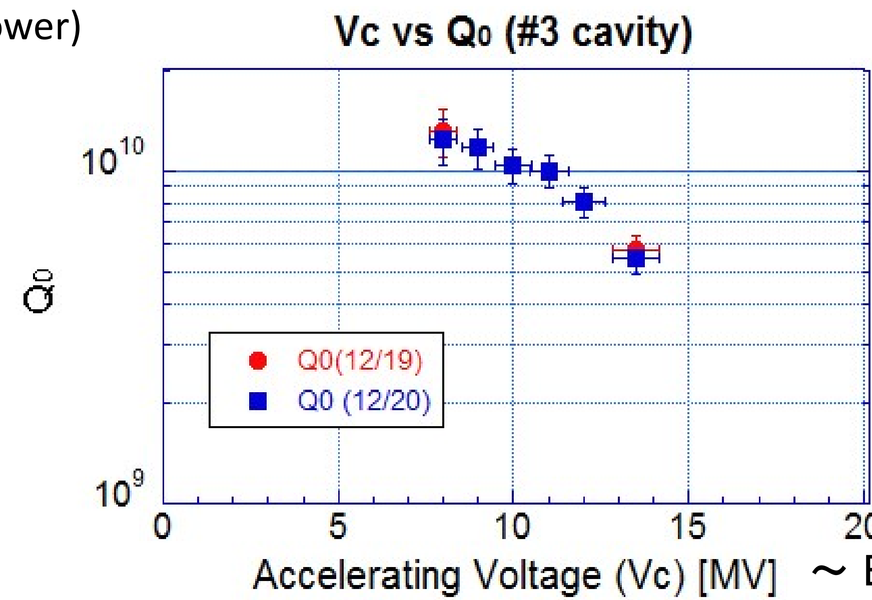
#4 (Upper)



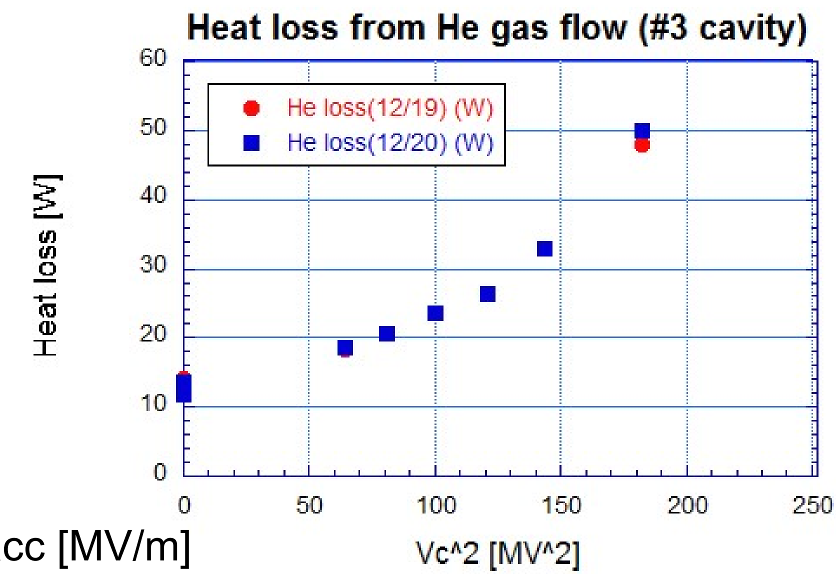
~ Eacc [MV/m]



#4(Lower)



~ Eacc [MV/m]

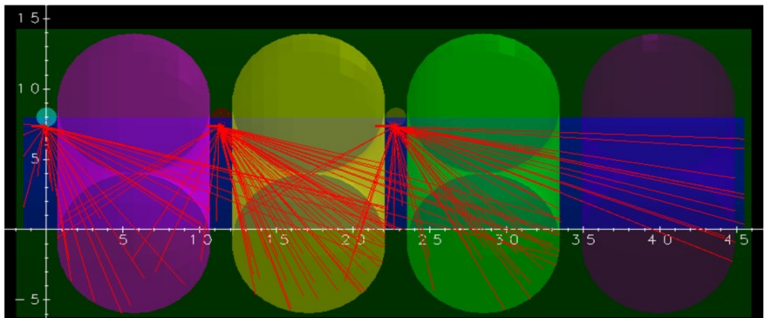


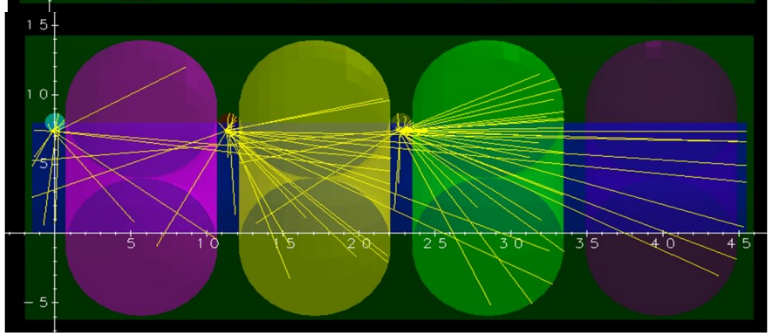
Q-value was dropped by field emission ← Cryogenic loss drastically increased.
Q-value is higher than 1*10^10 at low field of less than 10MV of Vc.
Magnetic shield works well .

2K Static loss :
11W at final (little large)

Radiation calculation (EGS5)

electron





photon