cERL 評価専門委員会

（2017年　10月　27日）

超伝導空洞開発

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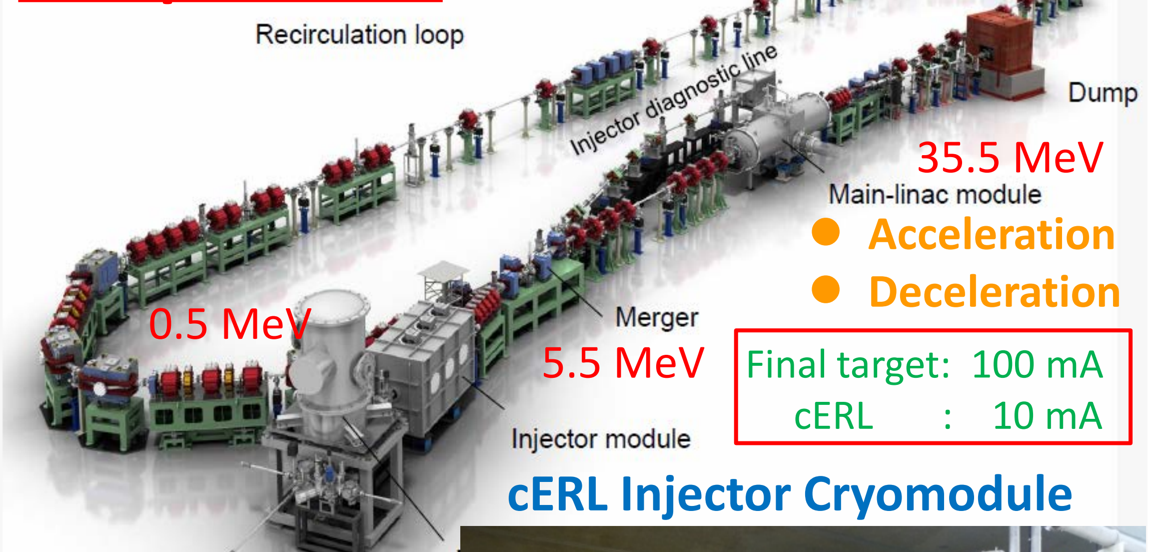
本日の報告内容

1. cERL超伝導空洞システムの概要
2. 入射クライオモジュールの運転状況
3. 主加速クライオモジュールの運転状況
4. 達成された成果と今後の課題
5. まとめ

Superconducting RF Cavity system in cERL

Compact-ERL



Final target: 100 mA
cERL : 10 mA

cERL ML Cryomodule

cERL Injector Cryomodule

1.3GHz 2-cell Cavity

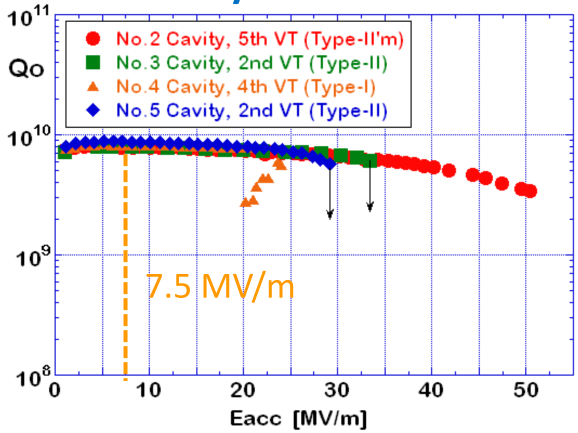
7.5 MV/m x 3 → 5 MV

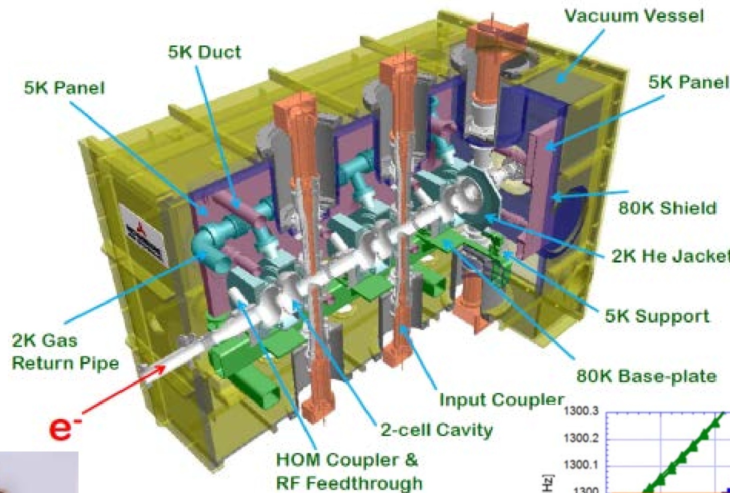
1.3GHz 9-cell Cavity

15 MV/m x 2 → 30 MV

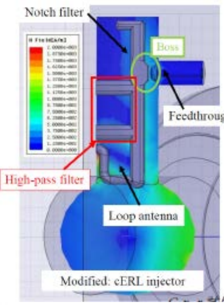
cERL injector cryomodule

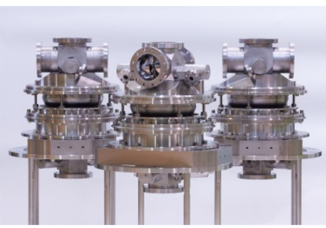
Cavity VT results



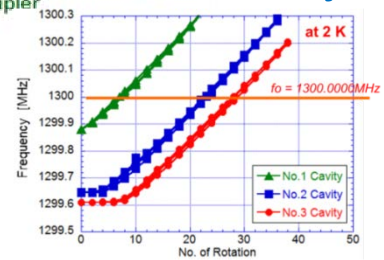


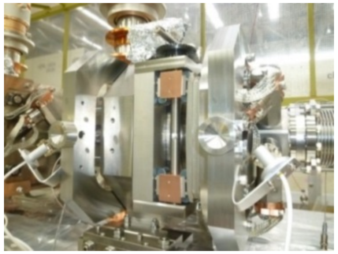
New type HOM couplers



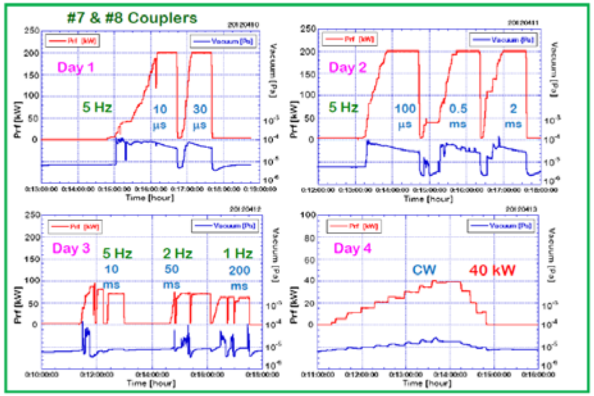


Slide-jack type frequency tuner



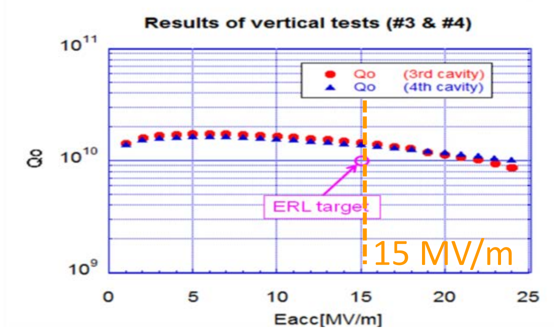


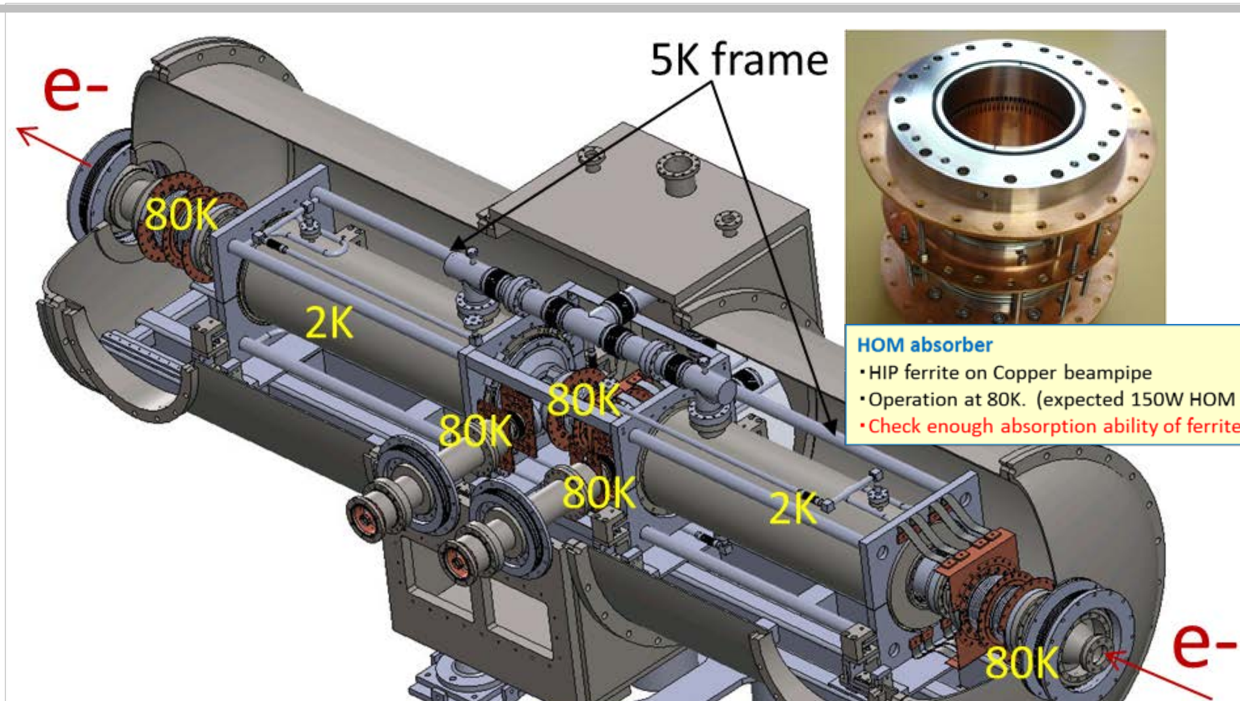
Cavity string assembly in calss-10 clean room



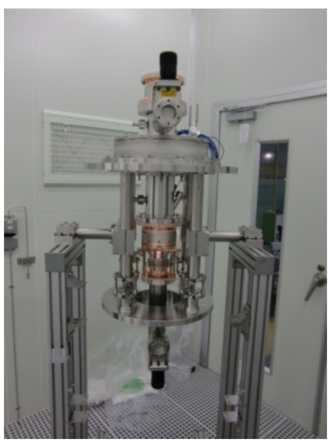
Coupler conditioning at test-stand

cERL main linac cryomodule





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

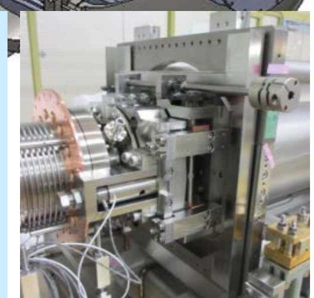


9cell superconducting cavity
Q0 > 1*10^10 @15MV/m

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

(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)



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

Cool-down cycles of injector & main linac cryomodules

Year	2012	2013	2014	2015	2016	2017	Notes
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
4th cool-down		5 – 7					
5th cool-down		11					High RF power tests of Main Linac Cryomodule Beam commissioning of Main Linac section at 20 MeV
6th cool-down			1 – 3				Beam commissioning of Re-circular ring Demonstration of energy recovery
7th cool-down			4 – 6				Beam operation at 20 MeV, ~10 μA
8th cool-down				1 – 4			LCS experiments
9th cool-down				5 – 6			Beam operation at 20 MeV, ~100 μA
10th cool-down					1 – 3		Beam operation at 20 MeV, ~1 mA
11th cool-down						1 – 3	Beam operation at 20 MeV, ~40pC (162.5MHz, 200nsec/5Hz)

Injector Cryomodule

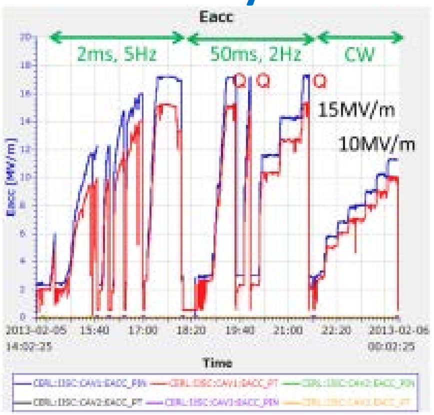
- High power tests
- Beam operation
- Long term cavity performance
- Unexpected discharge phenomenon
- Performance recovery

  by high power pulsed RF conditioning

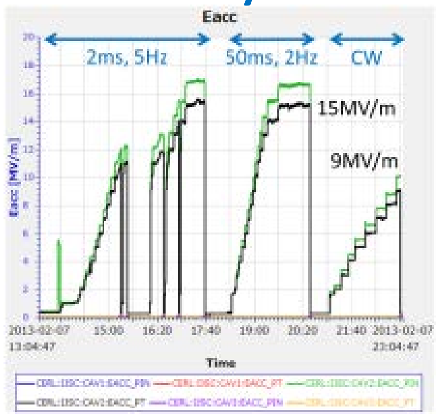
- Design values and achieved results

High power tests of injector cryomodule

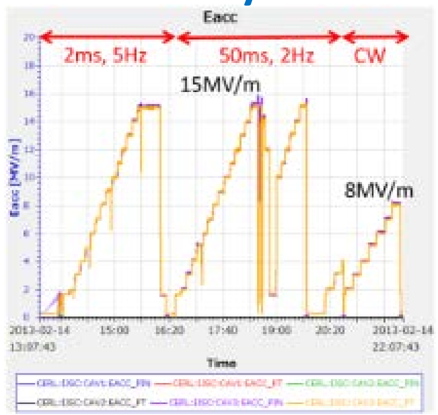
Cavity-1



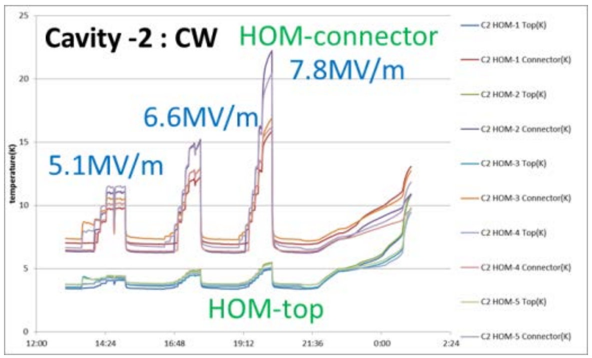
Cavity-2



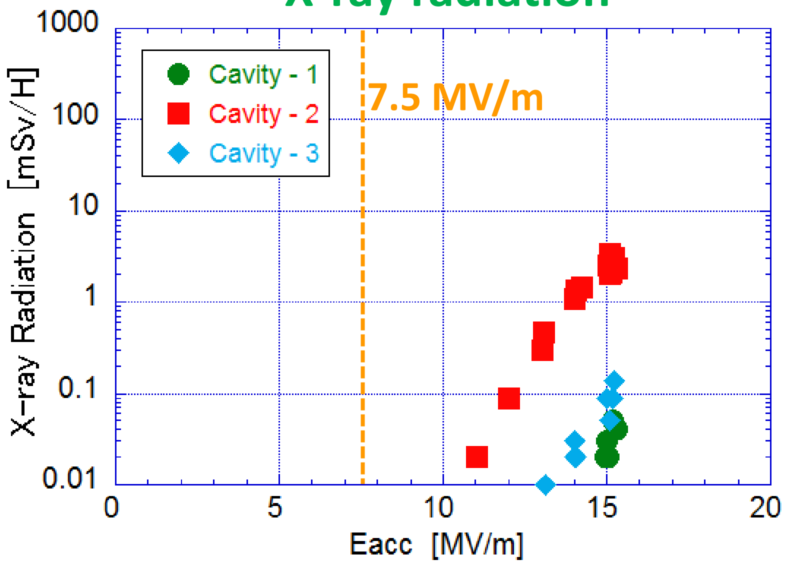
Cavity-3



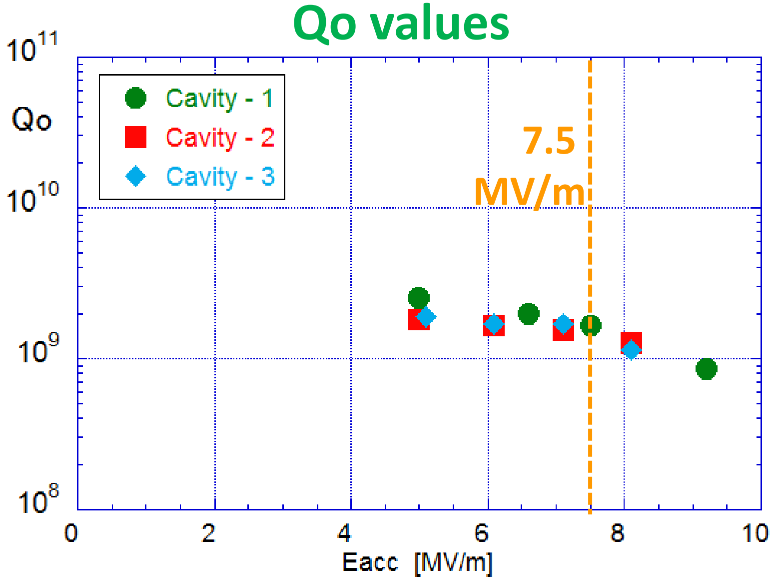
Excessive temperature rises at HOM pick-up connectors



X-ray radiation

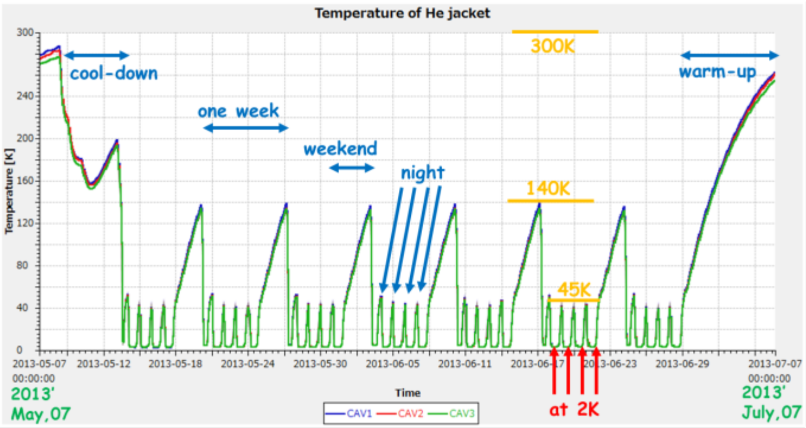


Qo values

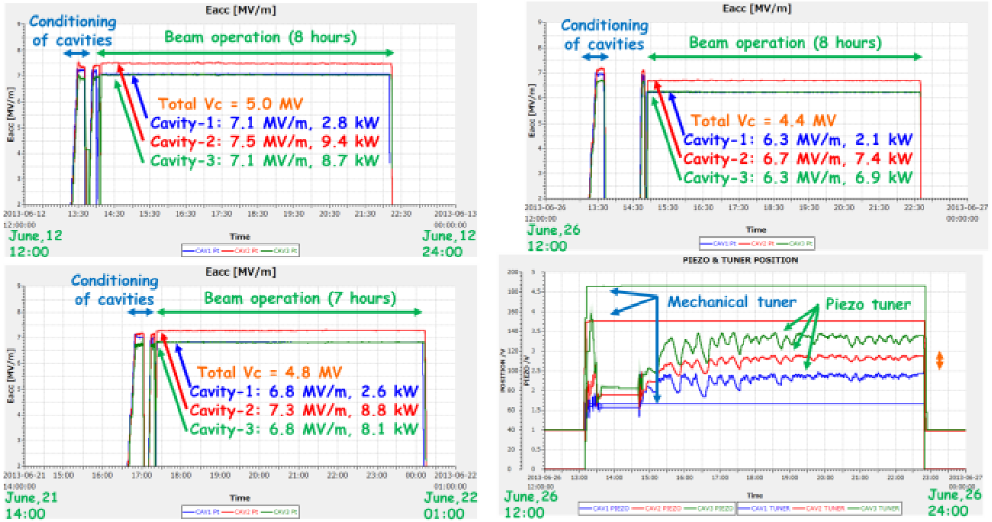


Beam operation of injector cryomodule

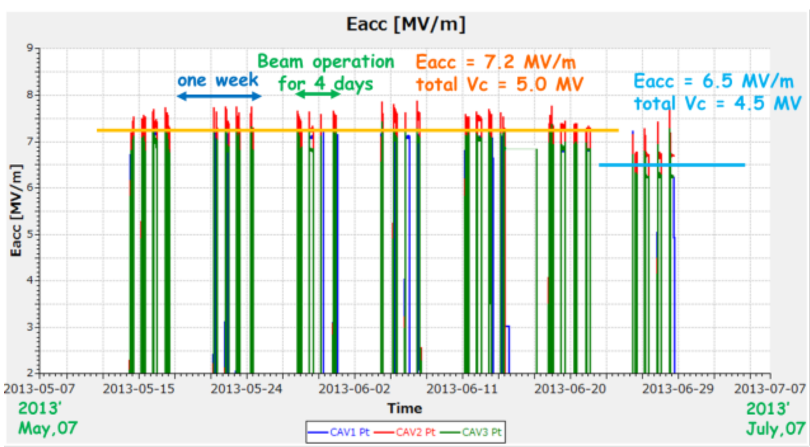
History of thermal cycles in May-July, 2013

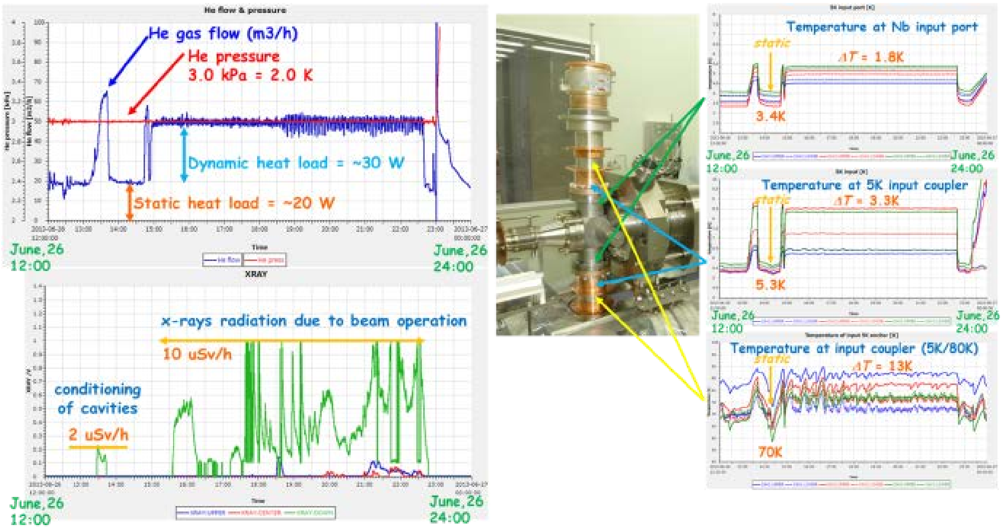


Stable beam operation at Vc = 4.4~5.0 MV/m



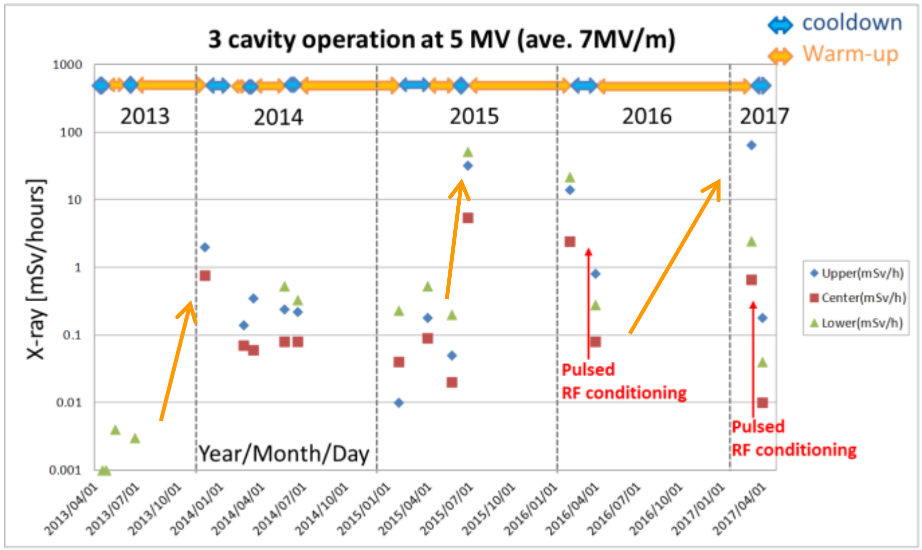
Operating accelerating gradient (Eacc)



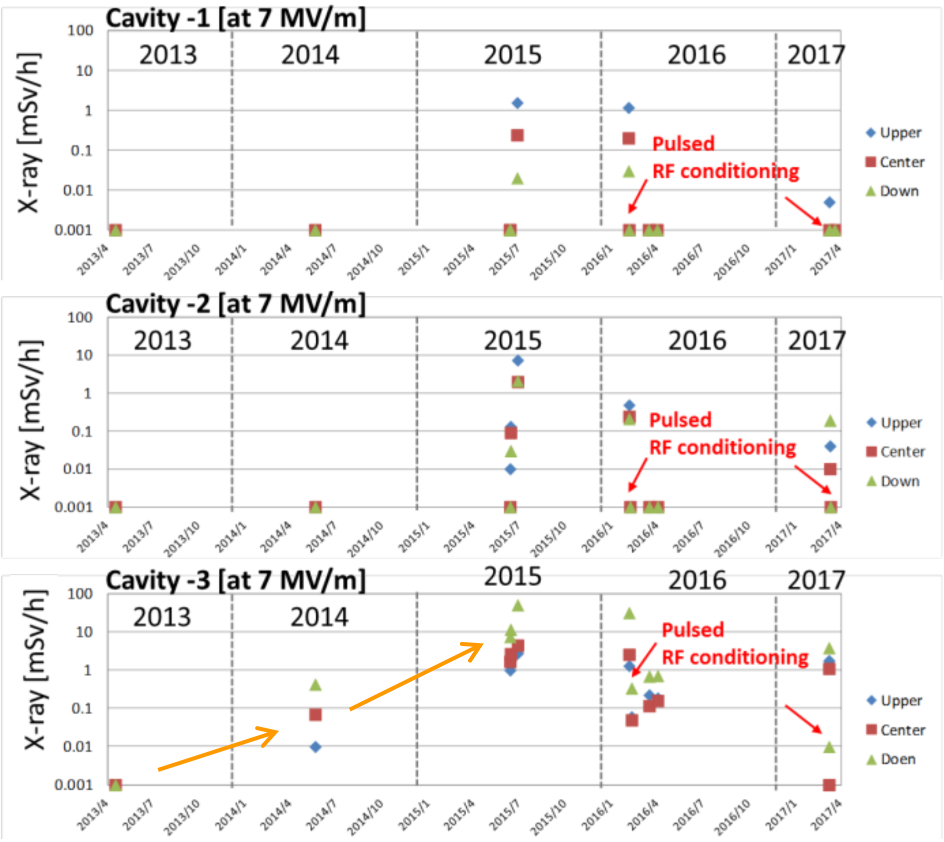


Long term cavity performance in injector cryomodule

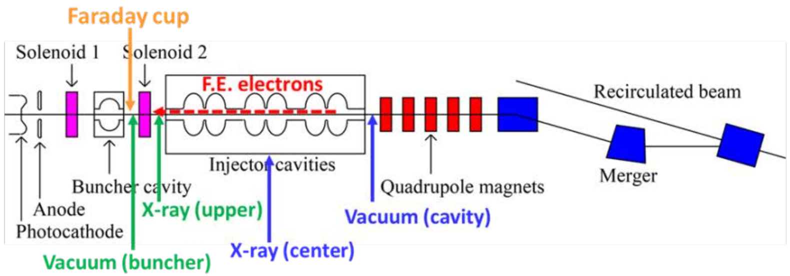
Observation of x-ray radiation in 2013-2017

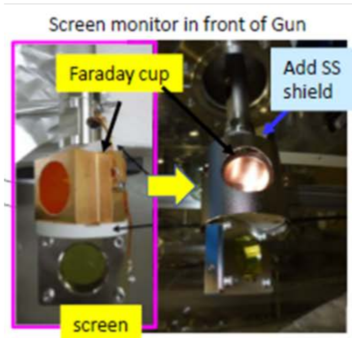


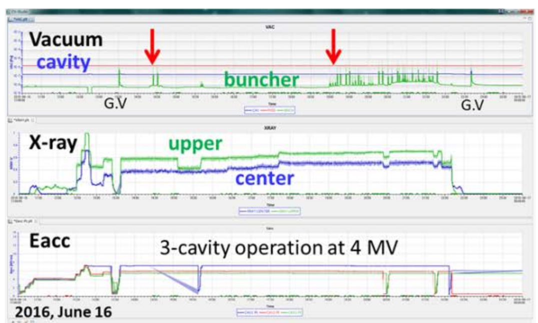
X-ray of individual cavity operation at 7 MV/m



Unexpected vacuum discharge phenomenon

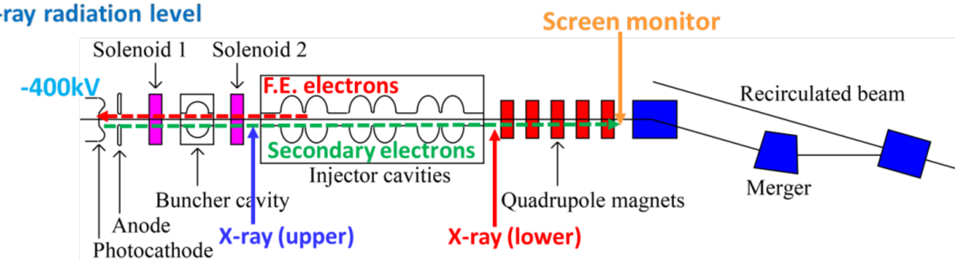




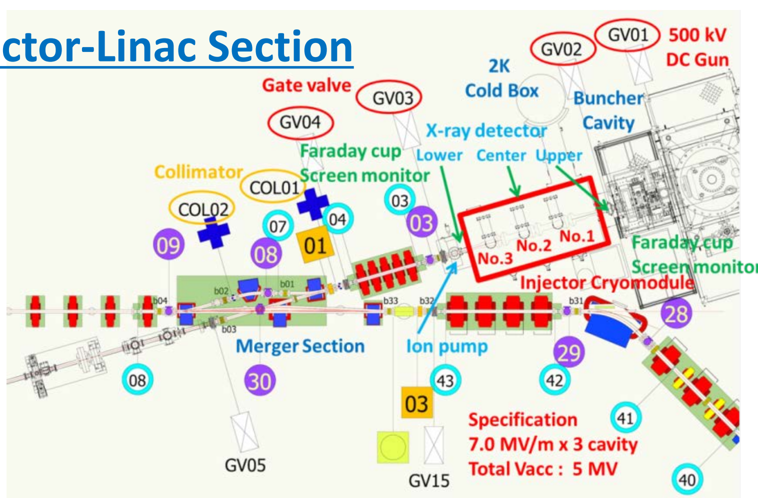


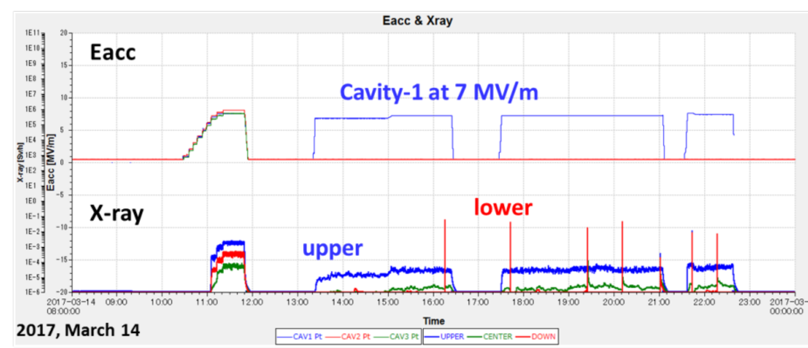
Many bursts of vacuum pressure

Gradual increase of x-ray radiation level



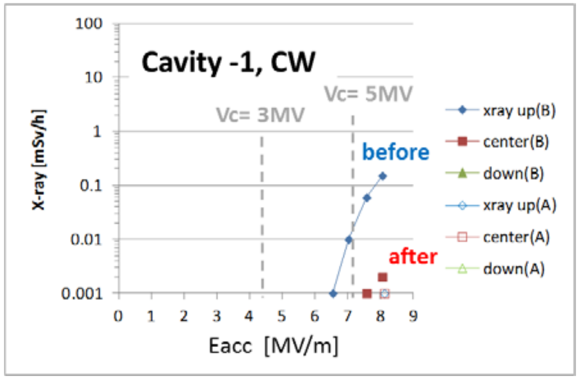
Injector-Linac Section

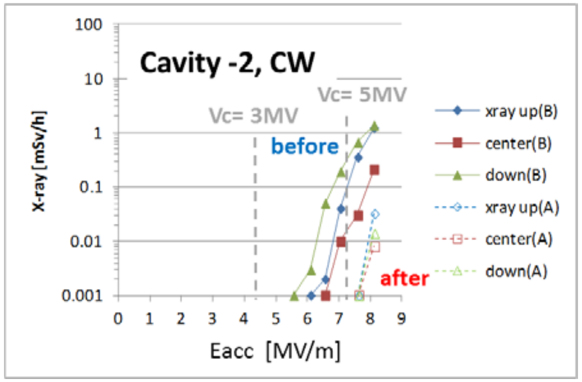


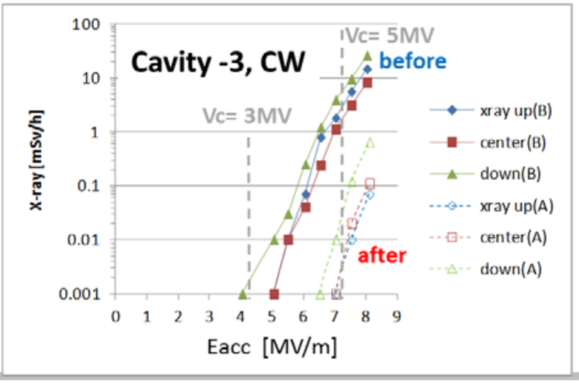


Performance recovery by high power pulsed RF conditioning

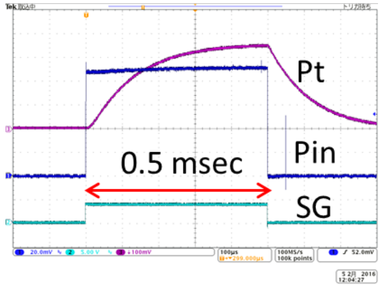
	No.1 cavity	No.2 cavity	No.3 cavity
Q_L	1.2 x 10^6	5.3 x 10^5	5.4 x 10^5
τ -filling	0.15 msec	0.07 msec	0.07 msec
15 MV/m	12 kW	27 kW	27 kW
20 MV/m	21 kW	47 kW	47 kW



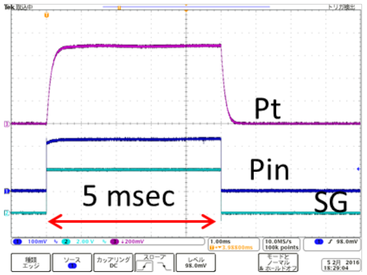


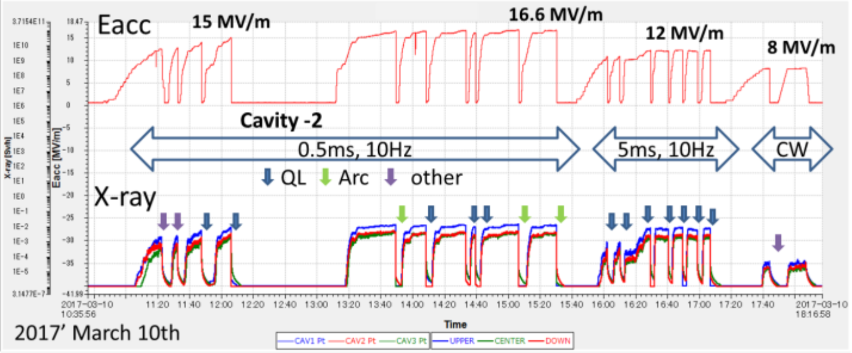


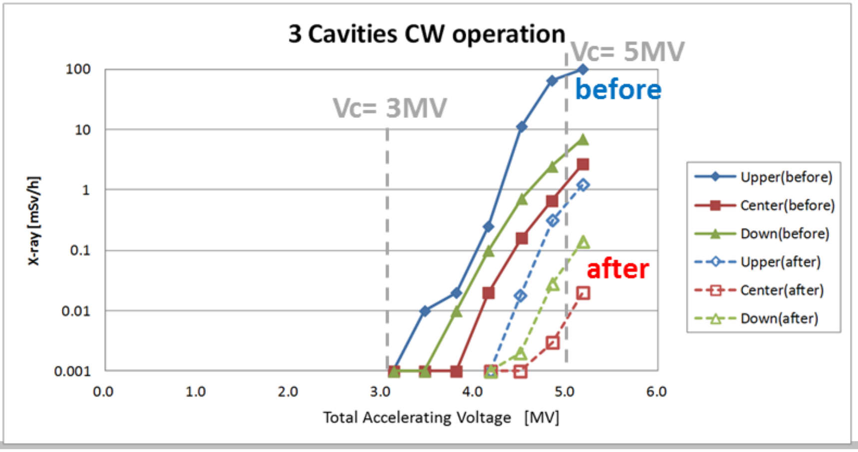
0.5 msec x 10 Hz



5 msec x 10 Hz







Summary of design values and achieved results

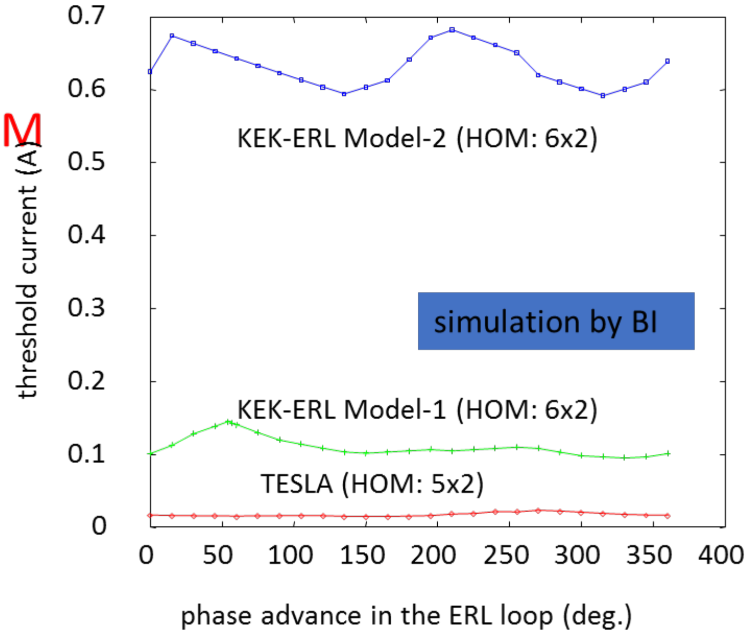
Injector Cryomodule	Design	Result
Static heat load at 4.2 K	33 W	36 W
Static heat load at 2 K	11 W	14 W
Dynamic heat load at 2 K (7 MV/m per cavity)	< 1.0 W	8.5 W
Qo at 2 K (7 MV/m)	> 1.0×10^{10}	1.8×10^{9}
Operating total Vc	5 MV	5 MV
Conditioning RF power at RT	---	40 kW
Operating RF power at 2K	---	10 kW
Tuner stroke	> 500 kHz	600 kHz
Piezo stroke	> 1 kHz	2 kHz

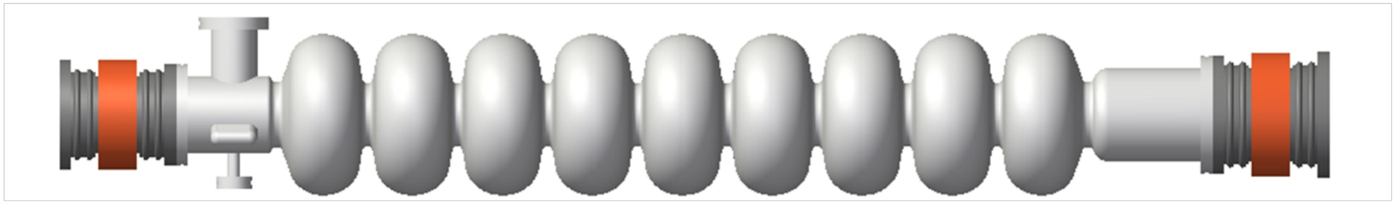
Main linac Cryomodule

- HOM damped cavity design
- High power test of input couplers
- Performance test of tuner & HOM damper
- Typical one day operation of main linac
- Demonstration of energy recovery
- Cavity performance in VT and cryomodule test
- Long term cavity performance before 1 mA
- Performance recovery by pulse processing
- Trip statistics of ML cavities for 2 years

HOM damped cavity design for ML cryomodule

1) Cell shape is optimized to reduce HOM impedances
   - Iris diameter 80mm, elliptical shape at equator
   - Cell diameter 206.6mm
2) Large beampipes mounted with RF absorber
   - Bempipe diameter 100mm and 123mm



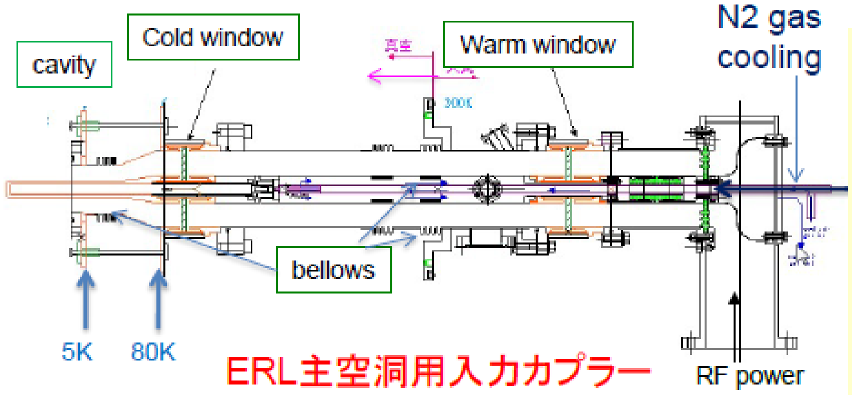


Main parameters for the acceleration mode

Frequency	1300 MHz	Coupling	3.8 %
Rsh/Q	897 Ω	Qo x Rs	289 Ω
Ep/Eacc	3.0	Hp/Eacc	42.5 Oe/(MV/m)

High power test of ML input couplers

ERL主空洞用の入力カプラー（cERL用カプラーのハイパワーテストとモジュール評価）



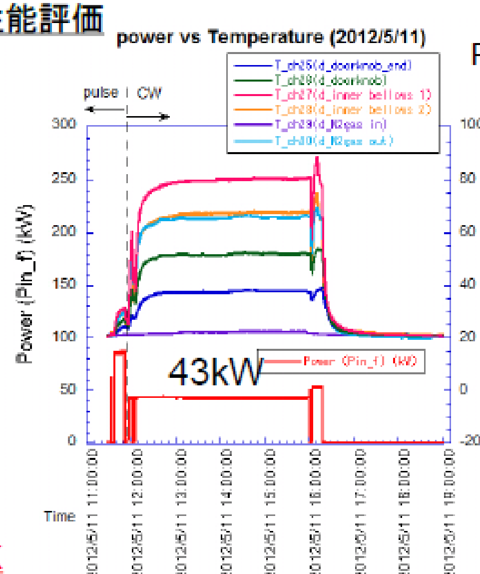
- Basic parameters
  - 加速勾配: Max 20MV/m (1.3GHz)
  - 入力パワー：max 20kW，定在波 (Δf<50Hz)
  - 負荷Q(Q_L): (1-4) * 10^7 (variable coupling)
- Points (STF-BL coupler からの修正 >CW対応)
  - 内導体をN2 gasで強制空冷
  - Impedance を50Ω から60Ωに変更
  - 99.7% の純度のセラミック窓を使用.
  - cold 窓にbellows追加。+-5mm可変。

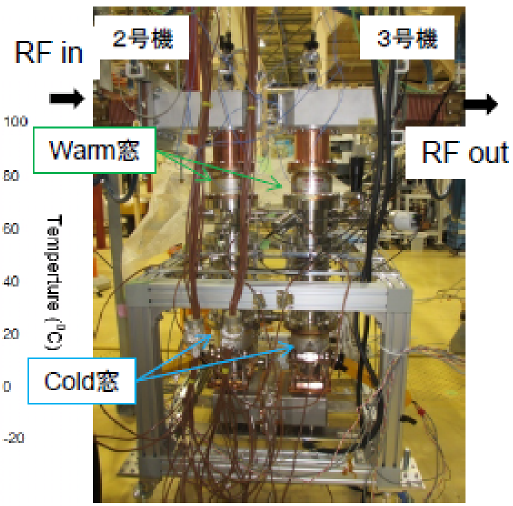
cERL用入力カプラー(#2,3号機)の性能評価

・テストスタンドでの評価：
到達パワー 105kW (pulse)
43kW(CW)
・Keep 40kW CW, 4hours
・一番温度が高い場所:
内導体のベローズ（80℃）
(ΔT~60degree, OK)

・モジュール組込み2K冷却後：
pulse：25kW、CW：15kW
でモジュール試験にて真空＆温度上昇もΔT<60Kで問題なし

➡ cERLモジュールへの組込OK





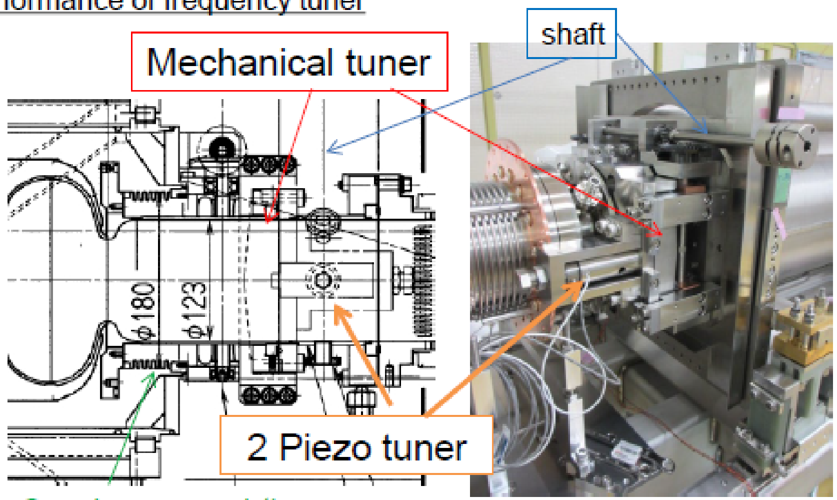
cERL用のカプラーテストスタンド

Performance test of ML cryomodule (tuner & HOM damper)

Performance test of cERL cryomodule (tuner & HOM damper)

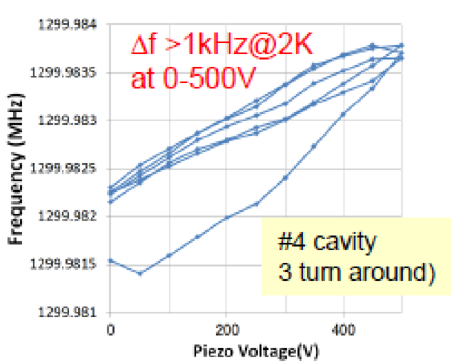
Detail 江波＆沢村

Performance of frequency tuner

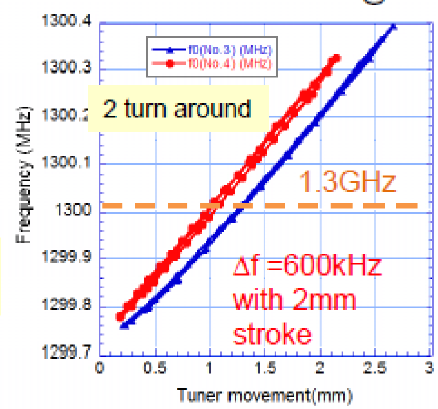


Cancel pressure variation

Piezo performance @ 2K

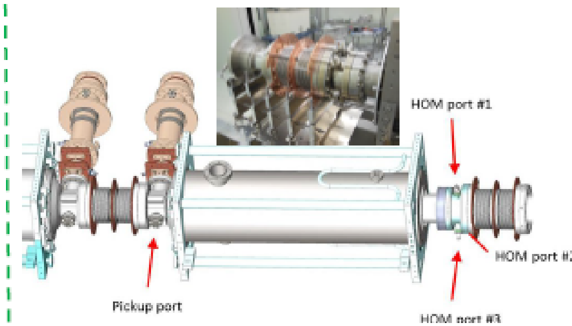


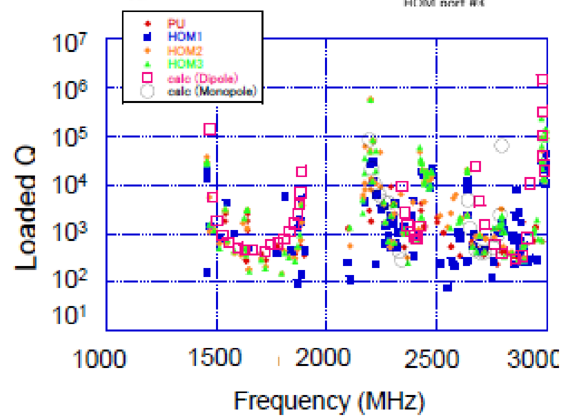
Coarse mechanical tuner stroke @ 2K



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.

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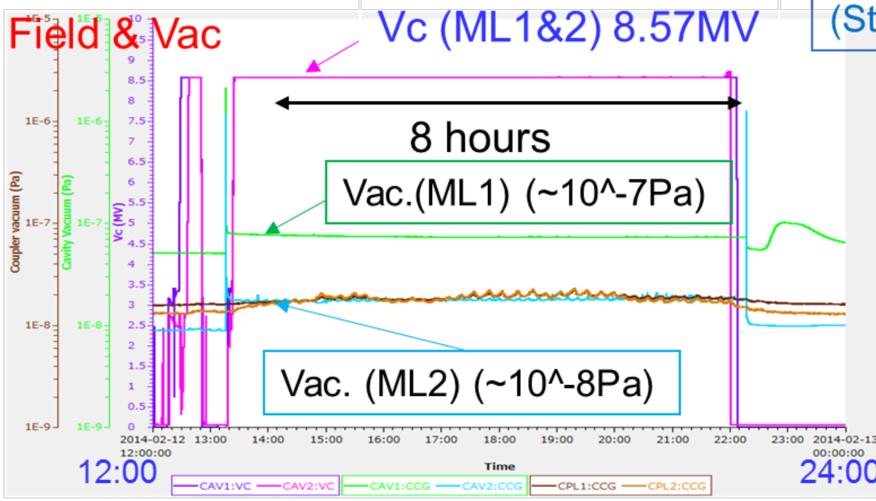
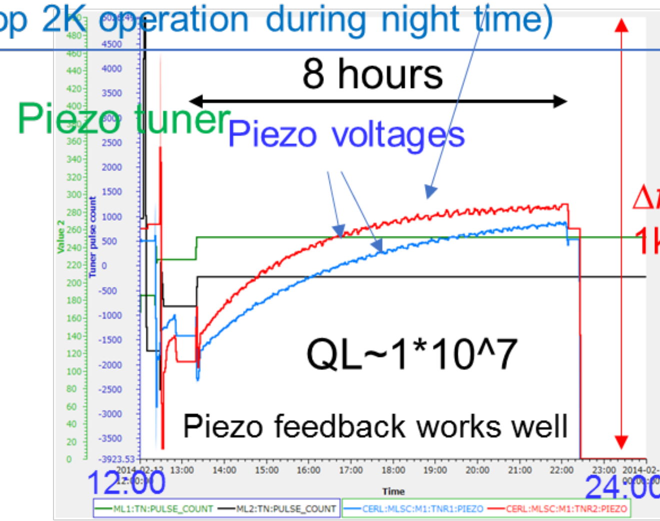
Typical one day operation of main linac

Main linac

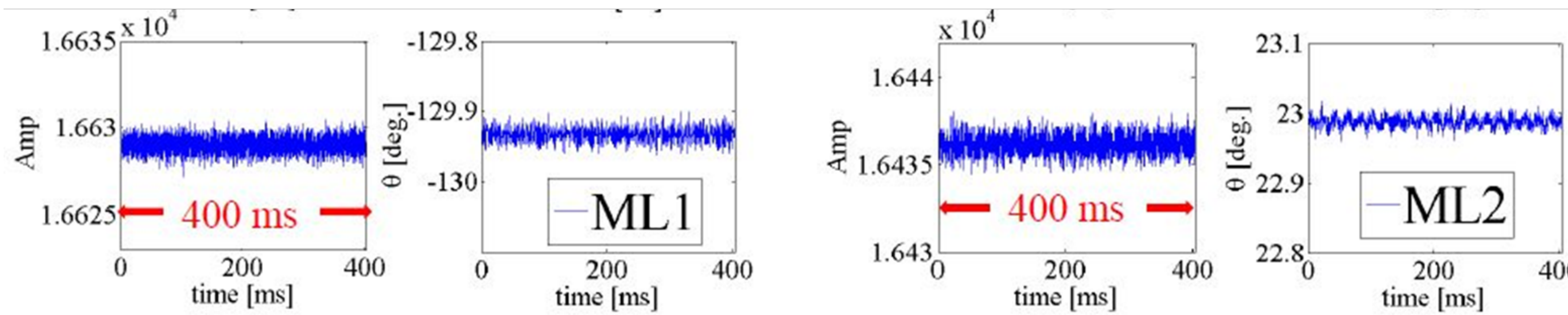


Drift due to temperature change of tuner system
(Stop 2K operation during night time)

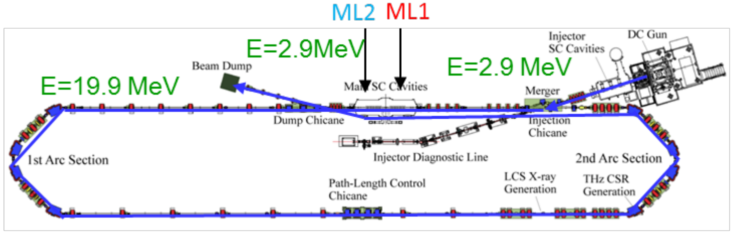


RF stability

$\Delta A/A$(% rms) ~ 0.003, $\Delta\theta$(deg rms) < 0.01 deg

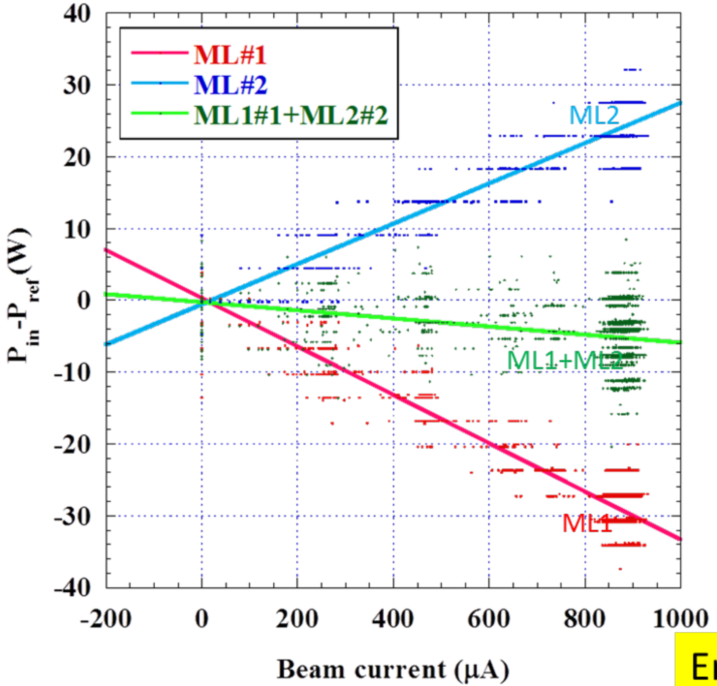


Demonstration of energy recovery in ML cryomodule

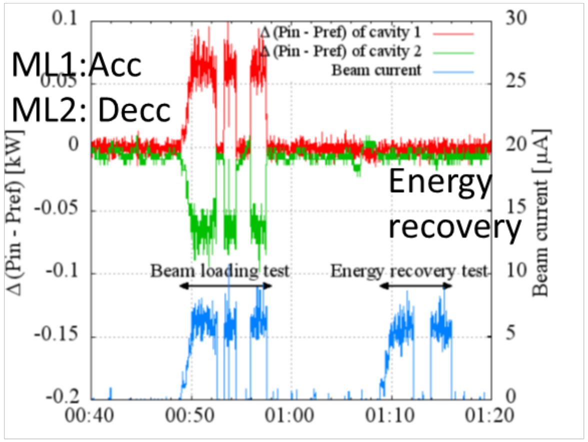


Pin – Pref ~ Ploss + Pbeam

Δ(Pin – Pref) ~ Pbeam ← Beam loading



ML



Cavity voltage :
8.56 MV (ML1), 8.57 MV (ML2)
Current: 0 ~ 900uA

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%)

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

Cavity performance in VT and cryomodule test

cERL用の主加速部超伝導空洞の性能評価試験 (縦測定＆cryomodule試験)

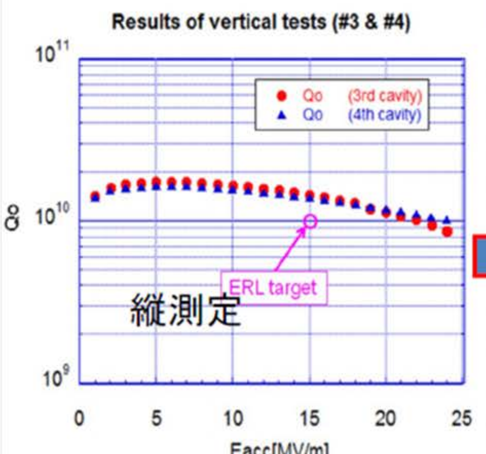
Summary of performance

•縦測定では単体で25MV/m達成。特に要求値の1x10^10@15MV/mを達成。

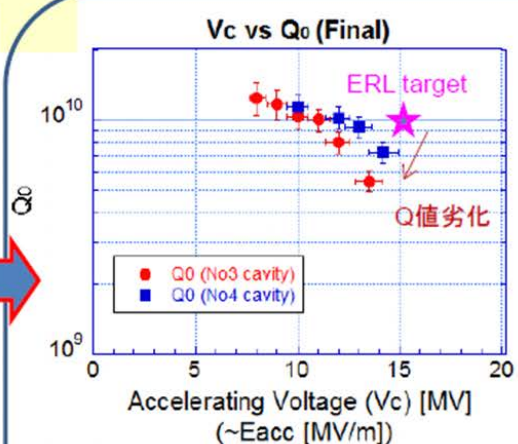
- Cryomodule組込み後は
- 2空洞とも Vc = 16MVまで印加可能であったが、8-10 MVからfield emissionが始まる。
- 冷凍機負荷に至るまでのVc=13.5-14 MVで1時間keep可能。
- 但し、Low field (<10MV/m) ではQ0>1*10^10.を達成しており、磁気シールドの効果は低温で十分確保されていることがわかった。またHOM damperや入力カプラーからの入熱はない。

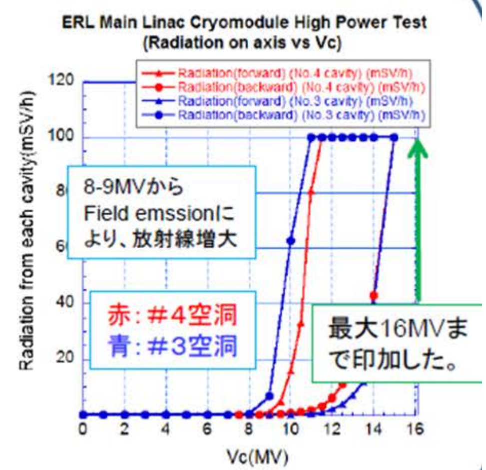
組立のdetailや劣化対策の今後詳細は梅森氏発表から

cERLモジュール組込後性能劣化
今後性能劣化原因詳細(sub-umレベルのゴミや埃の混入？)を調べ、cERL用モジュールの空洞の性能回復を目指すことが今後の課題。



モジュール組込前空洞単体テスト(縦測定)->**性能OK。**

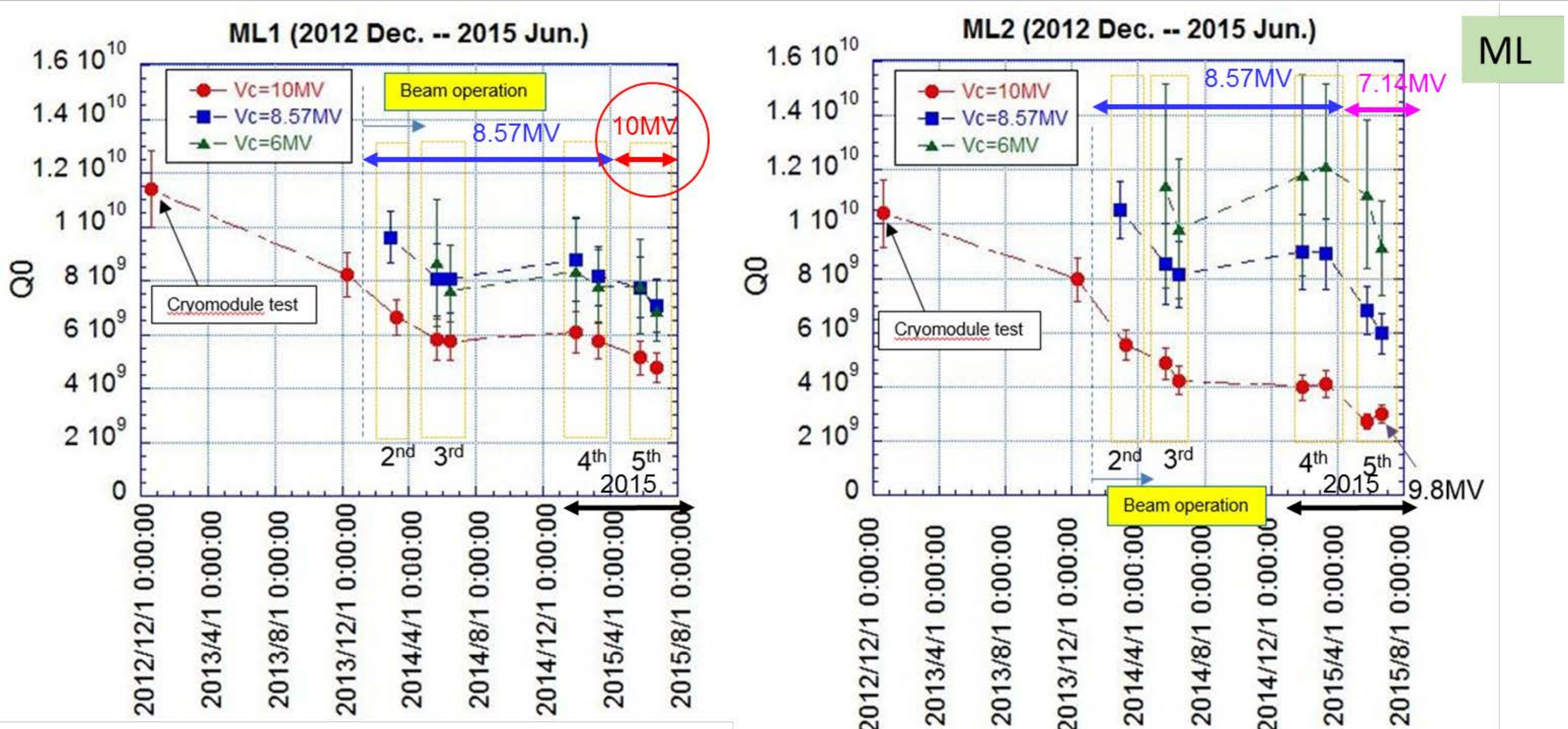




モジュール組込後**性能劣化**

field emissionによるradiation増加がみられる。

Long term cavity performance of ML cavities before 1mA

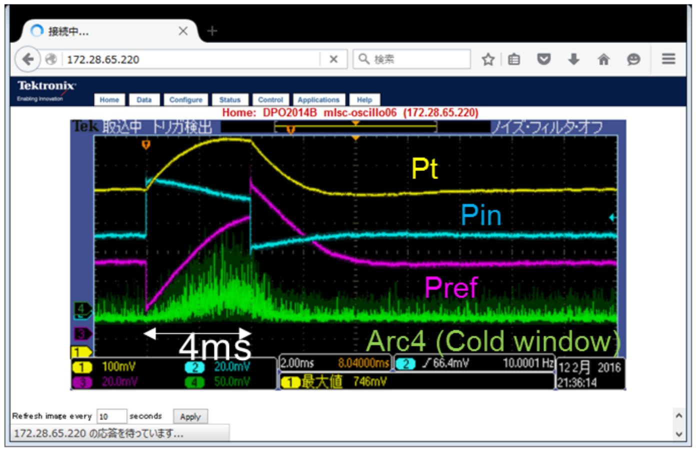


We met Q degradation during beam operation. But we kept same performance within error bars after degradation from May 2014 to March 2015 and no trip was observed for 1.5 months, even if no pulse processing was applied in 2015. So in 5th phase in May – June 2015, one cavity of ML1 increase the field from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

Performance recovery by pulse processing in ML cavities

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

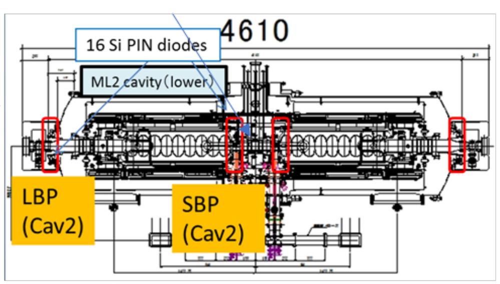


History of pulse processing: In ML, we were processing by monitoring side 32 PIN diodes

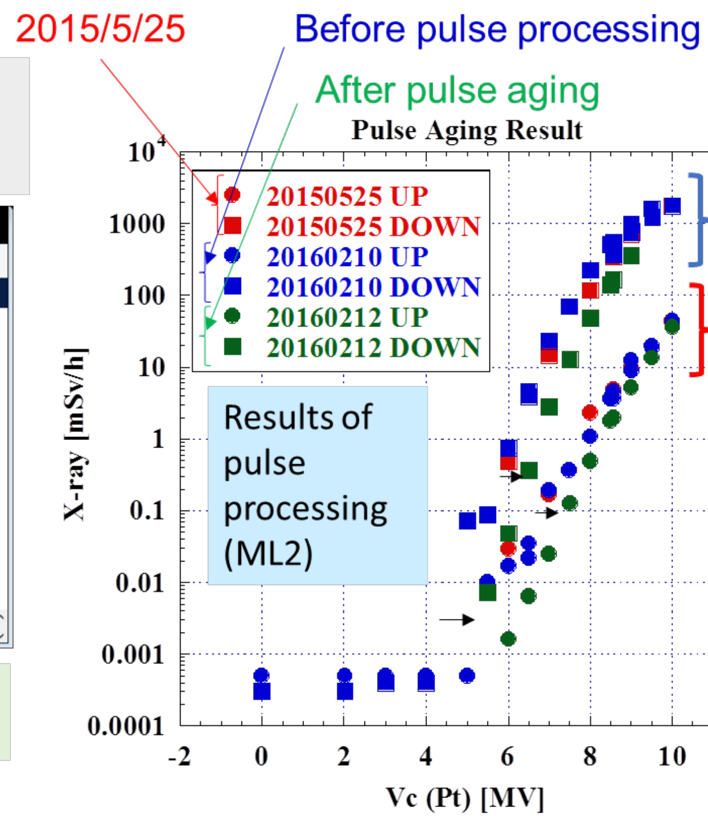
Arc sensor

SBP side

Under pulse processing



ML



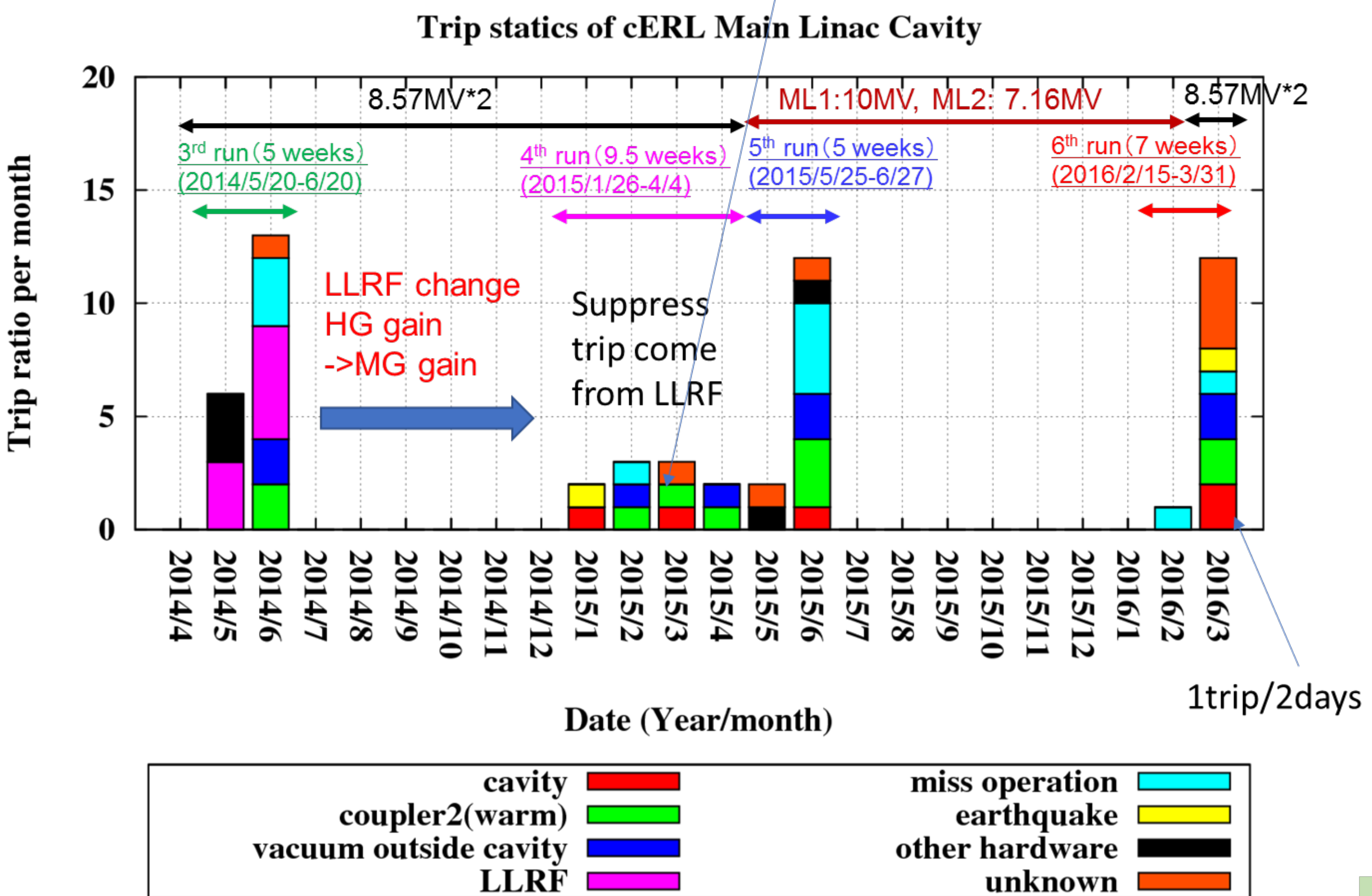
ML2 Vc vs ALOKA monitor

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

→Pulse processing works well.

Trip Statistics of Main Linac cavities for 2 years

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



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

ML

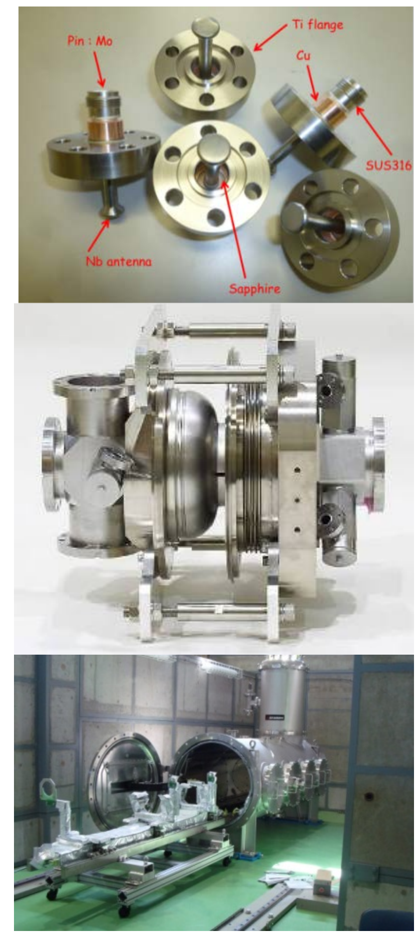
達成された成果と今後の課題:

- 入射超伝導空洞
- 主超伝導空洞

達成された成果と今後の課題（1）: 入射空洞

Components	評 価	対応 ・ 対策
Cavity	○ (stable)	
Field emission (x-ray)	× → △	空洞性能回復手段の確立
Tuner	○ (stable)	
Input coupler	○ (<10 kW → 100kW)	テストスタンドでの試験
HOM coupler	○ (stable)	
HOM RF feedthrough	× (改良必須)	横型クライオでの試験 →
Static heat load	△	低減のための改善の余地あり
Dynamic heat load	△	低減のための改善の余地あり
Q_{HOM}, HOM power	△	電流増加での観測
Beam operation	○ (stable)	電流増加での検証

Off-line tests of RF feedthroughs in horizontal cryostat



達成された成果と今後の課題（2）： 主空洞

- **空洞**
  - HOM-BBU抑制のため、HOM減衰型空洞を設計
  - 表面電場が大きくなりField emissionが問題に
- **HOM減衰器**
  - 1mA運転での問題はなし。
    （ただし、クラックが入るなどの製作上の問題がある。）
- **入力カップラー**
  - 設計値のCW 15kWまで、投入可能であった。
- **周波数チューナー**
  - ビーム運転中、問題無く周波数調整がなされていた。
- **クライオモジュール**
  - クライオモジュールとして、ビーム運転までうまくもっていけた。

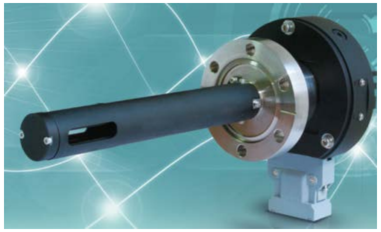
【課題】

- 劣化を起こさないアセンブリ技術の開発
- 劣化した空洞を回復させる技術の開発→
- 量産化に向けた対応

He processing at low temperature
Ne plasma processing at room temp.
High power RF pulsed processing

達成された成果と今後の課題 （3）

Dust free clean assembly technology for suppression of field emission

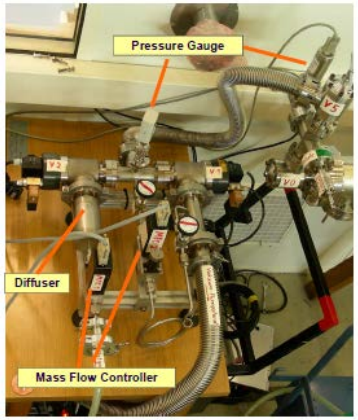


Vacuum particle sensor

0.1um particle counter

Collaboration with IFMIF/ QST-Rokkasho

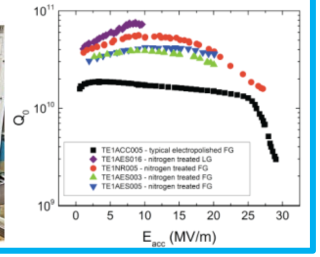
Local clean-booth



Slow venting/ pumping system

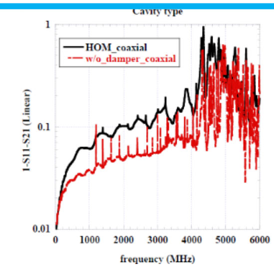
High-Q/ N-doping

Collaboration with FNAL

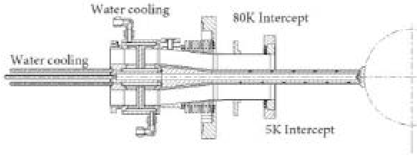


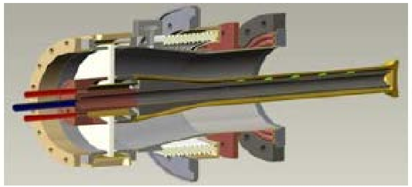
AlN HOM absorber

Collaboration with Toshiba



CW, 130 kW Input coupler

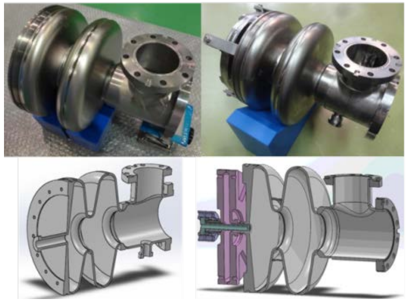




bERLinPro (HZB)

1.3 GHz, SRF-Gun

2 MeV, 100 mA, CW e-beam



Collaboration with MHI

ま と め

- 入射空洞での熱損失の低減、主空洞でのビームエネルギーの増強が主たる改善点ではあるが、安定なビーム運転に対しては大きな実績となった。

- 将来のEUV／FELへの応用に関して、幾つかの考えられる今後の課題について、その解決策に対応した共同研究をもとにして、すでにR＆Dに着手している。

- 世界で唯一稼働しているERLであるcERLの継続的なビーム運転は、将来の加速器計画にとって、必要不可欠な経験と実績を生み出すことを認識して頂きたい。

Thank you for your attention.