High power CW tests of cERL main-linac cryomodule

Hiroshi Sakai, Kazuhiro Enami, Takaaki Furuya, Masato Sato, Kenji Shinoe, Kensei Umemori (KEK) Masaru Sawamura (JAEA), Enrico Cenni (Soken-dai)

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• cool down to 2K and performance test at 2K
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Compact ERL (cERL) at KEK

Parameters of cERL main linac
- Frequency: 1300 MHz
- Eacc: 15-20MV/m
- Q0: $1 \times 10^{10}$
- Beam current: max 100mA (100mA (in)+ 100mA(out))

Apparatus of cERL

Requirements of cERL main linac
- Frequency: 1.3 GHz
- Gradient: 15MV/m
- Q0: $>1 \times 10^{10}$
- Beam current: max 100mA
- Bunch length: 0.1-3ps

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

HOM absorber

HOM-BBU calculation (w/o HOM randomization)

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


All HOMs damped to both end

- $\Phi 100$ (SBP)
- Iris: $\phi 80$
- $\Phi 120$ (LBP)

Phases advance in the ERL loop (deg.)

Threshold current (A)

Calc by R. Hajima, R. Nagai

TESLA (HOM: 5x2)

KEK-ERL Model-1 (HOM: 6x2)

Simulation by BI

KEK-ERL Model-2 (HOM: 6x2)

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

Beam dump

Main SC cryomodule

Injector SC cryomodule

Photocathode

DC gun

Chicane for path-length adjustment

HOM absorber

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

$R_{sh}/Q = 897 \Omega (1007\Omega)$

$E_p/E_{\text{acc}} = 3.0 (2.0)$

$E_p/E_{\text{acc}} = 42.5 \text{ Oe/(MV/m)}$
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

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

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)

Frequency: 1.3 GHz
Input power: 20kW CW (SW)
Gradient: 15MV/m
Q0: >1*10^10
Beam current: max 100mA (against HOM-BBU instability)
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 : $Q_0 > 1 \times 10^{10} @ 15$ MV/m

For module assembly

ERL 9-cell #3 cavity

• X-ray onset : 14 MV/m

ERL 9-cell #4 cavity

• X-ray onset : 22 MV/m

Field emission profile by rotating X-ray mapping

Candidate of source

Broad signals

Sharp traces on cell

Simulation (with Fowler Nordheim eq.)

Field emission Profile on Nb surface simulated with including EGS5 (radiation with material 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.

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

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

Backbone set at 300K

5K frame

Keep alignment within 0.2mm

2012/Mar

2012/Aug

2012/Oct

2012/Sep
Setup of high power test at cERL beam line

PIN radiation profile monitor set around beam axis

16 Si PIN diodes at each position

Installed in cERL beam line
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(N₂) lines.

**History of 2k cooling**
Performance test of cERL cryomodule

**Performance of frequency tuner**

- 2 Piezo tuner
- Cancel pressure variation
- Piezo performance @ 2K

- Δf >1kHz@2K at 0-500V
- #4 cavity 3 turn around)

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

**Coarse mechanical tuner stroke @ 2K**

- 2 turn around
- 1.3GHz
- Δf =600kHz with 2mm stroke

**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.
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.
- Q0 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)

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

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

Measured radiation of each cavities at final state

Ref: #4 (upper)
Blue: #3 (lower)

Max field 16MV applied.
Detail radiation profile measurement

- Radiation pattern was changed from VT
- Radiation pattern also changed after X-ray burst

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

Sudden burst event was observed under keeping field of 14.5MV

Before burst

After burst
Survey location of field emission source by NaI

Measured spectrum (at 8.5MV)

Cavity #3 (up)
Cavity #4 (down)

Comparison between measured data and simulation with different Eacc

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 ??
We can keep the following voltages of Upper cavity:
- 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)

Accelerating voltage was kept stably

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 displacement under 2K cooling

**Summary of displacements of targets and cavities between RT to 2K**

<table>
<thead>
<tr>
<th>Summary of displacements of targets and cavities between RT to 2K</th>
<th>Horizontal (mm)</th>
<th>Vertical (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target 1-4 (Average)</td>
<td>-0.11</td>
<td>-1.06</td>
</tr>
<tr>
<td>Target 5-8 (Average)</td>
<td>0.87</td>
<td>-0.37</td>
</tr>
<tr>
<td>Average movement of cavity center (from target 5-8)</td>
<td>0.39</td>
<td>-0.37</td>
</tr>
</tbody>
</table>

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

**Measurement target (#1) for WLI monitor**

**Alignment telescope**

**Measurement of displacement under 2K cooling**

**Alignment target**

**Move same way with targets at same transverse position**

**Measured displacements of targets**

**H.S. Sakai et al., MOP069 in SRF2013**

- About 0.4mm of cavity center movement was evaluated horizontally and vertically, which agreed with expected values of thermal shrink of 5K supports.
- These values were within alignment error from beam requirement of 1mm.
2K microphonics measurements

- Example of #3 cavity, $QL = 1.15 \times 10^7$

- Pk-pk = 7 Hz by oscilloscope. It allows us to increase the QL higher than several $10^7 \rightarrow$ lower power
- Main peak was observed at 49.5 Hz (not 50 Hz of electrical noise) by FFT analyzer, which was not come from cavity resonance frequency.

- We need to continue measuring microphonics on next cERL operation

- Measure $\Delta\phi$ (Pin and Pt)
- LLRF Feedback loop off
- Field set to 2.5 MV/m
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 severe field emission by newly produced emitter which came from the cryomodule assembly work and during high power test.
- We can keep 13.5-14MV 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.
- Main linac stable operation of cERL is next issues for our module by Digital LLRF for beam operation.
- 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 commissioning was done at April-June in 2013.

Obtained beam profile @5.5MeV

18.4 mm
7.7 pC/bunch
Backup
Detailed design of Cryomodule of cERL main linac

Cross section of cryomodule

Central tower

Superconducting cavity with jacket

80K thermal shield

Vacuum insulator

Input coupler

He level

Inside jacket

Requirements

Dynamic loss \(\text{(need margin 80W @ 2K of cooling ability)}\)
- Cavity: 25 W (for 2K) / cavity (@15MV/m)
- Input coupler: 1.5 W (for 5K) / coupler
- HOM absorber: 150 W (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

Alignment target

Magnetic shield equipped just outside 5K frame with 1.5t thickness

Vacuum insulator

Input coupler

5K frame support

Backbone at R.T

Central tower

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.
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

**Target 4&8**

**Target 3&7**

**Target 2&6**

**Target 1&5**

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

8 Quartz targets with markers were set around 5K frame at known position from cavity center mechanically along cavity axis

**Outside taget**

**Outside taget**

**Top of cavity**
**Target 1,2,3,4**

**Side of cavity**
**Target 5,6,7,8**

**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.

- 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.

This monitor based on interference of ASE light between target and reference position. By measuring reference position movement we know the target position movement.
Q-value was dropped by field emission \( \leftrightarrow \) Cryogenic loss drastically increased.

Q-value is higher than \( 1 \times 10^{10} \) at low field of less than 10MV of \( V_c \).

Magnetic shield works well.

2K Static loss:

11W at final (little large)
Radiation calculation (EGS5)

- electron
- photon