Performance of the cERL LLRF System

Compact ERL (Energy Recovery LINAC)

Takako Miura (KEK)
[1] **3GeV ERL as VUV and X-ray SR source** (high flux and short pulse)
   (10 mA – 100 mA, $\varepsilon_n$: 0.1 mm-mrad, bunch length: 100fs@min)

[2] **6GeV XFEL Oscillator** (2 times acceleration by 2 circulations)
Compact ERL (cERL) has been constructed as a test facility of a 3-GeV ERL future plan. The commissioning has been started from 2013.

Design parameters of the cERL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal beam energy</td>
<td>35 MeV</td>
</tr>
<tr>
<td>Nominal Injector energy</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>10 mA (initial goal)</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>0.1 – 1 mm·mrad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1-3ps (usual)</td>
</tr>
<tr>
<td></td>
<td>100fs (short bunch)</td>
</tr>
</tbody>
</table>

Circumference ~ 90m

RF frequency= 1.3 GHz

Beam Dump

9-cell SC cavity x 2

QL = 1×10^7

2-cell SC cavity x 3

QL = 5×10^5
## Current status of high power RF sources

<table>
<thead>
<tr>
<th></th>
<th>Buncher</th>
<th>Inj-1</th>
<th>Inj-2</th>
<th>Inj-3</th>
<th>ML-1</th>
<th>ML-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cavity</strong></td>
<td>NC</td>
<td>2cell-SC</td>
<td>2cell-SC</td>
<td>2cell-SC</td>
<td>9cell-SC</td>
<td>9cell-SC</td>
</tr>
<tr>
<td><strong>Cavity Voltage</strong></td>
<td>114 kV</td>
<td>0.7 MV</td>
<td>0.7 MV</td>
<td>0.7 MV</td>
<td>8.6 MV</td>
<td>8.6 MV</td>
</tr>
<tr>
<td><strong>Field Gradient</strong></td>
<td>3 MV/m (7.5 MV/m)</td>
<td>3 MV/m (7.5 MV/m)</td>
<td>3 MV/m (7.5 MV/m)</td>
<td>8.6 MV/m (15 MV/m)</td>
<td>8.6 MV/m (15 MV/m)</td>
<td></td>
</tr>
<tr>
<td><strong>$Q_L$</strong></td>
<td>$1.1 \times 10^5$</td>
<td>$1.2 \times 10^6$</td>
<td>$5.8 \times 10^5$</td>
<td>$4.8 \times 10^5$</td>
<td>$1.3 \times 10^7$</td>
<td>$1.0 \times 10^7$</td>
</tr>
<tr>
<td><strong>Cavity Length</strong></td>
<td>0.068 m</td>
<td>0.23 m</td>
<td>0.23 m</td>
<td>0.23 m</td>
<td>1.036 m</td>
<td>1.036 m</td>
</tr>
<tr>
<td><strong>RF Power</strong></td>
<td>3 kW</td>
<td>0.53 kW</td>
<td>2.6 kW</td>
<td></td>
<td>1.6 kW</td>
<td>2 kW</td>
</tr>
</tbody>
</table>

**<Design>**

100 mA beam & $V_c = 2$ MV at Inj.Cav

200 kW RF power is necessary for each inj. cavity.

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**LLRF’15, Shanghai, Nov 3-6, 2015 (T. Miura)**
Digital LLRF System at cERL

Mechanical tuner: coarse tuning

Frequency Tuner

Tuner board

Field FB board

RF SW

Fast Interlock (Arc, Pref, etc.)

1.3 GHz

KLY/SSA

Cavity pick-up signal

Kly Pf

LO (1.3GHz(1+1/128)≈1310MHz)

IF (≈10MHz)

LO

I

Q

MO(1.3 GHz)

Pc Pf

Requirements of RF stabilities:
0.1%rms, 0.1deg.rms for cERL
0.01%rms, 0.01deg.rms for 3GeV-ERL

Piezo Tuner: fine tuning

Pc

Pf

Digital I/O

Motor driver

DAC

0 ~ 500V

-250V~250V

0 ~ 500V

Digital I/O

(CW/CCW pulse output)

Offset

+250V

-250V~250V

Motor driver

Piezo driver

Digital LLRF System at cERL

LLRF'15, Shanghai, Nov 3-6, 2015 (T. Miura)
Total 11 boards are used for operation.

<table>
<thead>
<tr>
<th></th>
<th>BUN</th>
<th>Inj1</th>
<th>Inj2</th>
<th>Inj 3</th>
<th>ML1</th>
<th>ML2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF FB board</td>
<td>FB0</td>
<td>FB1</td>
<td>FB2 (Vec-sum)</td>
<td>FB4</td>
<td>FB5</td>
<td></td>
</tr>
<tr>
<td>Tuner board</td>
<td>TN0</td>
<td>TN1</td>
<td>TN2</td>
<td>TN3</td>
<td>TN4</td>
<td>TN5</td>
</tr>
</tbody>
</table>

- Embedded Linux is working in the PowerPC on FPGA.
- Each board acts as an EPICS IOC.
- Data acquisition is performed through GbE bus on the backplane.
Frequency Feedback Control

\[ \Delta f = 65 \text{ Hz} \] for ML cavities \((Q_L=10^7)\)

Narrow bandwidth for \(f_0=1.3 \text{ GHz}\)

\[ \Delta \theta = \theta_f - \theta_c \] : The phase difference between the input RF and the cavity pickup signal

\[ \tan \Delta \theta \approx 2Q_L \frac{\Delta f}{f} \]

To keep resonance frequency, tuner should be controlled to maintain \(\Delta \theta\) at zero.

Block diagram of frequency FB control

Forward RF

\[ V_f \]

ADC \(\rightarrow\) I/Q \(\rightarrow\) ROT \(\rightarrow\) \(\Delta \theta\) \(\rightarrow\) LPF \(\rightarrow\) Ki \(\rightarrow\) \(\Sigma\) \(\rightarrow\) DAC

Cavity pickup

\[ V_c \]

ADC \(\rightarrow\) I/Q \(\rightarrow\) ROT \(\rightarrow\) \(\Delta \theta\) \(\rightarrow\) LPF \(\rightarrow\) Kp

Ki

FB On/Off Offset

0 < 0 > CW CCW

Digital I/O

Piezo tuner

Mechanical tuner

Stepping motor

LLRF'15, Shanghai, Nov 3-6, 2015 (T. Miura)
Field Feedback Control

\[ I = \frac{1}{4} \sum_{n=0}^{7} \cos \left(2\pi \frac{n}{8}\right) \cdot V(n), \quad Q = \frac{1}{4} \sum_{n=0}^{7} \sin \left(2\pi \frac{n}{8}\right) \cdot V(n) \]
Results of Frequency Control

\[ \Delta \theta = \theta_f - \theta_c \]

\[ \Delta \theta \approx 2 Q_L \frac{\Delta f}{f} \]

\[ \Delta \theta = \pm 3 \text{deg.} \quad Q_L \approx 10^7 \Rightarrow \Delta f \approx \pm 3.4 \text{ Hz} \]
Performance of RF Feedback Control

Waveforms of cavity pick-up

ML1

Amplitude

Phase

Vc: FB ON

Vc: FB OFF

Phase noise measurement using signal source analyzer

ML1

ML2

Amplitude

Phase

Vc: FB ON

Vc: FB OFF

50Hz peak in Pf is fake: leakage from reflection port in directional coupler.

Fluctuations by microphonics have been well suppressed by FB control.
# RF Stabilities

<table>
<thead>
<tr>
<th></th>
<th>Inj1</th>
<th>Inj2 &amp; Inj3</th>
<th>ML1</th>
<th>ML2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>0.006% rms</td>
<td>0.007% rms</td>
<td>0.003% rms</td>
<td>0.003% rms</td>
</tr>
<tr>
<td>Phase</td>
<td>0.009° rms</td>
<td>0.025° rms</td>
<td>0.010° rms</td>
<td>0.009° rms</td>
</tr>
</tbody>
</table>

Monitored with IIR LPF(5kHz)

**Requirements:**
- 0.1% rms, 0.1° rms for cERL
- 0.01% rms, 0.01° rms for 3GeV-ERL

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**ML2**

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>0.003349% rms</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Phase</th>
<th>0.0085591 deg.rms</th>
</tr>
</thead>
</table>

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LLRF'15, Shanghai, Nov 3-6, 2015 (T. Miura)
Stability of Beam Momentum (1)

Screen Monitor
CAM14

Injector
Main Linac

Beam diagnostic line

Dispersion: \( \eta_X = 0.487 \text{m} \)

Beam: 5Hz, 3ps rms, 23 fC, total Energy = 19.9 MeV

\( dP/P = 0.013115 \% \text{rms} \)

Momentum drift in the period of \(~15\) minutes was observed.
Reduction of the Effect of Vector-sum Error

\[ \tan \Delta \theta \approx 2Q_L \frac{\Delta f}{f} \]

The time interval of detuning is similar to the interval of energy drift.

\[ \Delta \theta = \theta_f - \theta_c \]

\(~15\ \text{min.}\)

Higher tuner FB gains were adopted in Inj2 & Inj3.

The amount of phase variation became small.

If error is included in vector-sum calibration, energy drift can occur.
In the region of Inj2 and Inj3 cavities, \( \beta < 1 \). Transit time is different in each cavity.

\[ \Rightarrow \text{weight of vector-sum is different between Inj2 and Inj3.} \]
Stability of Beam Momentum (2)

Measurement after modification of tuner feedback gain for Inj2 and Inj3

Large momentum drift disappeared.

Good stability of beam momentum was achieved.

=> It was confirmed that the RF field for the beam is stable.
Demonstration of Energy Recovery ($I_0 = 30 \mu A$)

**Non-ERL operation**

- Cavity 2: deceleration (Vc=8.57 MV/cavity)
- Cavity 1: acceleration (Vc=8.57 MV/cavity)

**ERL operation**

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

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**Beam current**

- Cavity 1: $P_{in} - P_r$
- Cavity 2: $P_{in} - P_r$

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

By H. Sakai
Summary

- RF stabilities satisfied the requirement for cERL, and almost satisfied the requirement for 3GeV ERL.

- The beam momentum jitter of 0.006% rms was achieved.

Future Plan

- Tuner feedback parameters have not been optimized enough. We will optimize the tuner control parameters.

- Beam current will increase and burst mode operation is planned. Beam loading compensation is necessary. [Feng Qiu (KEK), this afternoon]

- The evaluation of the long-term stability is necessary.
Thank you for your attention.