Development of input coupler for cERL main linac

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• Design of input coupler
• High power test of input coupler under LN2.
• Other measurements
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Coupler requirements & properties for CW-ERL main linac

ERL design based on compact ERL (cERL)

Main linac case (compared with injector)
- Low RF power thanks to Energy Recover weak coupling (Q_{ext} = 1*10^7 – 1*10^8)
- which depend on microphonics effect basically 5-20kW will be needed.
- Reliabilities are another important points due to fabricate large number of couplers.

Calculation of \( \Delta F \) vs \( P_g \) with different QL

\[
P_g = \frac{V_c^2}{4(R/Q)Q_L} \left(1 + 4Q_L^2 \left(\frac{\Delta f}{f}\right)^2\right)
\]

KEK case:
QL = 2\times10^7

\( \Delta f = 50\text{Hz} \)

More severe case
Basic parameters & design of input coupler for main linac at KEK

- **Basic parameters**
  - **frequency**: CW, **1.3GHz**
  - **Accelerating gradient**: Max 20MV/m
  - **input power**: max 20kW, standing wave
  - **loaded Q(Q_L)**: (1-4) * 10^7 (variable coupling)

- **Points** (modified from STF-BL coupler for CW)
  - **Forced N2 gas cooling of inner conductor**
  - **Impedance from 50Ω to 60Ω**
  - Two 99.7% purity of ceramic windows are used.
  - Make variable (+-5mm) with cold bellows

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**Basic design**

- **Cold window**
  - **Cavity**
    - **Cu plate**: 30um
    - **Cu plate**: 10um
    - **Bellows**
    - **5K 80K**

- **Warm window**
  - **N2 gas cooling**
  - **Cu plate**: 150um

- **coaxial disk ceramic window was used**
Prototype of input coupler (v1) & assembly in clean room for high power test

Cold window

Warm window

(Toshiba TETD)

ultra pure water rinsing at class 10

Assembly in clean room of class 10

Prototype of input coupler

Warm window

Cold window
**KEK-ERL main linac coupler high power test with liquid Nitrogen**

- High power test of prototype of input coupler under liquid Nitrogen cooling with vacuum insulator to know the real temperature rises under vacuum insulation as same as the cryomodule by feeding the high power.
- To simulate the same standing wave condition of cryomodule, Bellows and ceramic windows were set not to stand the peak field in high power test.
Detail setup of high power test

Arc sensor1

Overview

Inside vacuum insulator

Liq. N2 tank

Thermo coupler

Cold window

Braid lines

All are surrounded with super insulator

Arc sensor2

Warm window

N2 gas in

N2 gas out

E-pick3

E-pick1

E-pick2
At 20kW, suddenly arc (arc2) and vacuum (CCG2) interlocks worked. feeding power could not overcame 10kW level under CW power feeding.

→ Change pulse processing. feeding power gradually increased under keeping the lower vacuum pressure than $1 \times 10^{-4}$ Pa for 8 hours and finally we reached the 25kW power level.

・After changing to the CW power feeding at 25kW, the vacuum pressure of cold window (CCG1) slightly increased and however decreased under keeping the 25kW level. The processing was smoothly carried out by using the pulse processing.
Can keep 20kW with standing wave for 16 hours.

- Vacuum of cold part is near $1 \times 10^{-6}$ Pa and decreased while keeping 20kW.
- Temperature of inner conductor with bellows are $130^\circ$C under feeding N2 gas of 116 l/min.
- Temperature rise of cold window is $83^\circ$C, but temperature of cold window is $-81^\circ$C.
- Temperature rises of bellows of outer conductors of cold window and warm window are about 100K, which is largest point of temperature rise under keeping 20kW standing wave.
- Measured heat load at Cold window was roughly estimated to 53W. This was slightly higher than expected value of 30-40W by calculation.
Details of measured temperatures under 20kW power feeding

<table>
<thead>
<tr>
<th>Thermosensors (channel &amp; locations)</th>
<th>Temp. (℃)</th>
<th>ΔT (K)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>T1-1 (cold end plate in vac.)</td>
<td>-11.7</td>
<td>46.1</td>
<td>T2-1 (Liq. N2 tank)</td>
<td>-193.1</td>
<td>0.8</td>
<td>T3-1 (warm outer outside)</td>
<td>28.2</td>
<td>25.2</td>
</tr>
<tr>
<td>T1-2 (cold outer bellows down)</td>
<td>-47.7</td>
<td>82.5</td>
<td>T2-2 (outer 125mm H-bottom)</td>
<td>32.6</td>
<td>111.8</td>
<td>T3-2 (warm window)</td>
<td>78.9</td>
<td>74.7</td>
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<tr>
<td>T1-3 (cold outer bellows middle)</td>
<td>-30.5</td>
<td>113.2</td>
<td>T2-3 (Blade (3) to Cold window)</td>
<td>-179.0</td>
<td>10.5</td>
<td>T3-3 (inner conductor down)</td>
<td>50.9</td>
<td>47.7</td>
</tr>
<tr>
<td>T1-4 (cold outer bellows up)</td>
<td>-32.6</td>
<td>117.6</td>
<td>T2-4 (outer bellows (middle) cold side)</td>
<td>55.3</td>
<td>99.5</td>
<td>T3-4 (inner conductor middle)</td>
<td>127.5</td>
<td>124.1</td>
</tr>
<tr>
<td>T1-5 (cold window upper)</td>
<td>-81.2</td>
<td>82.7</td>
<td>T2-5 (Blade (4) to Cold Box)</td>
<td>-188.2</td>
<td>3.2</td>
<td>T3-5 (N2 gas in)</td>
<td>8.8</td>
<td>1.9</td>
</tr>
<tr>
<td>T1-6 (cold window lower)</td>
<td>-62.9</td>
<td>97.0</td>
<td>T2-6 (Blade (3) at Cold Window)</td>
<td>-93.4</td>
<td>72.6</td>
<td>T3-6 (N2 gas out)</td>
<td>108.2</td>
<td>103.7</td>
</tr>
<tr>
<td>T1-7 (outer 10mm) (H-bottom)</td>
<td>-31.5</td>
<td>106.6</td>
<td>T2-7 (Cold Box top)</td>
<td>-108.8</td>
<td>53.4</td>
<td>T3-7 (doorknob)</td>
<td>91.7</td>
<td>86.7</td>
</tr>
<tr>
<td>T1-8 (outer 67.5mm) (H-top)</td>
<td>11.5</td>
<td>117.9</td>
<td>T2-8 (Cold Box side 1)</td>
<td>-59.0</td>
<td>54.9</td>
<td>T3-8 (doorknob end plate)</td>
<td>77.7</td>
<td>72.4</td>
</tr>
<tr>
<td>T1-9 (warm outer bellows middle1)</td>
<td>56.9</td>
<td>67.7</td>
<td>T2-9 (Cold Box side2)</td>
<td>-67.3</td>
<td>68.3</td>
<td>T3-9 (cold end plate)</td>
<td>7.8</td>
<td>2.9</td>
</tr>
<tr>
<td>T1-10 (warm outer bellows middle2)</td>
<td>57.9</td>
<td>69.2</td>
<td>T2-10 (Cold Box bottom)</td>
<td>-55.8</td>
<td>66.0</td>
<td>T3-10 (room temperature)</td>
<td>5.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Red: ΔT=100K points, these points are only connected with thermal anrhos of Liq. N2. Therefore it is difficult to cool down.

Orange: T > 100℃ points. These come from heating inner conductors.

We will add more braid s for cryomodule.

**Setup of thermosensors**

115l/min N2 gas

These temperature rises are acceptable.
After warming up and exposing to air for 4 hours, the coupler was cooled down to Liq. N2 temperature again and we fed the power. We can feed the power up to 24kW smoothly. Processing effects could keep the coupler.
Connecting the input coupler to 9cell ERL cavity, we measure the coupling directly. The slope of $Q_{ext}$ change with coupler length agree well with calculation with +/-5mm. However, the measured value of $Q_{ext}$ with doorknob exchanger is 1.3 times higher than calculation.

Change the length of 2mm short for cryomodule from measurement results.
Cautions and learn from previous ceramic window test for ERL about disk ceramic with choke.

When modify the impedance or diameter from original:
- TE mode stands inside.
- By changing the thickness of window, peak was shifted.
- Please calculate not only S-parameter but also eigenmode of disk ceramic itself.

Caution for using to cold window:
- Inner conductor
- Outer conductor
- Max Thermal stress
- Cross section of ceramic near inner conductor
- Leak point
- Molybdenum
- Copper
- Broken cold window

After 5th thermal cycle test between 80K and 300K, old ceramic was broken.

Modify the blazing conditions → 10 thermal cycle is OK now.

Calc by HFSS

S21 data (cold window broken)

H. Sakai or M. Sato et al., Proc. of 15-th SRF, Chicago (2011)
Summary

- We carried out high power test by using input coupler prototype for cERL main linac. After pulse processing for 8 hours, we finally achieved 25kW with standing wave in the high power test and could keep the 20kW SW for 16 hours.

- The maximum temperature rise was measured at the bellows of the inner conductor. However, the temperature rise was suppressed down to 120K by N₂ gas cooling of 115 l/min flow. The temperatures rises of bellows of outer conductors are also high, but these were suppressed by the liq. N₂ cooling.

- The vacuum pressure was suppressed at ~10⁻⁶ Pa under 20kW power feeding.

- We noted that we could smoothly increase up to 24kW power level again after warming up to room temperature and exposing the inside of the input coupler to the air for 4 hours.

- By changing the brazing condition of the cold window, we could stand the thermal cycles up to 10 times and no crack or leak was observed.

- The thermal and RF power tests were successfully done and the basic design of the input coupler has satisfied our requirements by these tests.

- In this year, we will fabricate the two input couplers for the main linac to prepare the compact ERL construction.
Thank you
backup
Coupler choices for ERL

**Waveguide**
- Lower surface electric field
- Higher thermal radiation
- No easy tuning

CESR waveguide
- >250kW
- 500 MHz
- WG Bend shields cold window from beam.

**Coaxial**
- Smaller heat leak
- Easier to make variable
- Easier to handle multipacting

**Cylinder ceramic (TTF type)**
- KEKB coupler
  - >400kW (operation)
  - 509MHz
  - Disk ceramic with choke
- TTF-II
  - 1.3GHz
  - 2 Windows
  - Adjustable Qext

**Disk ceramic (TRISTAN type)**
- JLAB (CEBAF, JLAB-FEL)
- Cornell, Daresbury, HZB
- KEK, BNL (SNS), HZB

This coaxial disk ceramic window is reliably operated at KEKB applying up to CW 400kW with 1A beam current and STF with high peak power more than 1MW at 1.3GHz. This is our choice.
Coupler kick & cancelation

Calc case

E-field

H-field

Blue: beam

9cell case: Vt/Vs ~ 1*10^-4

Coupler kick will canceled with setting symmetry with optimum length