Input coupler development for KEK ERL main linac

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- Design of input coupler for ERL main linac
- High power test at test stand
- compact ERL(cERL) cryomodule test
- Summary

Compact ERL(cERL) @KEK

Main linac

TTC CW SRF workshop @Cornell Univ. (2013.June.12-June.14)
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 ($Q_{\text{ext}} = 1 \times 10^7 – 1 \times 10^8$)
  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 $Q_L$

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

KEK case:
$Q_L = 2 \times 10^7$

More severe case
$\Delta f = 50\text{Hz}$
Basic parameters & design of input coupler for main linac at KEK

- **Basic parameters**
  - **frequency**: CW, 1.3GHz
  - **Accelerating gradient**: Max 20MV/m (First)
  - **input power**: max 20kW, standing wave (Δf=50Hz)
  - **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
  - 99.7% purity of ceramic window are used. make variable and add cold bellows

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**Basic design**

- **Cold window**
  - Vacuum
  - Copper plate: 30um
  - Bellows
  - Cu plate: 10um
  - Variable (±5mm)

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

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Coaxial disk type ceramic window was used
Input coupler heat load (per cavity) (calculation)

10kW+10kW(=20kW) standing wave Dynamic loss

<table>
<thead>
<tr>
<th>Dynamic loss</th>
<th>2K</th>
<th>5K</th>
<th>80K</th>
<th>300K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner conductor</td>
<td>-</td>
<td>-</td>
<td>14.7W</td>
<td>6.8W (forced gas cool)</td>
</tr>
<tr>
<td>Outer conductor</td>
<td>-</td>
<td>0.79W</td>
<td>1.3W</td>
<td>2.1W</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>0.79W</td>
<td>16.0W</td>
<td>8.9W</td>
</tr>
</tbody>
</table>

20kW+20kW(=40kW) standing wave Dynamic loss

<table>
<thead>
<tr>
<th>Dynamic loss</th>
<th>2K</th>
<th>5K</th>
<th>80K</th>
<th>300K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner conductor</td>
<td>-</td>
<td>-</td>
<td>29.4W</td>
<td>13.7W (forced gas cool)</td>
</tr>
<tr>
<td>Outer conductor</td>
<td>-</td>
<td>1.55W</td>
<td>2.5W</td>
<td>4.1W</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>1.55W</td>
<td>31.9W</td>
<td>17.8W</td>
</tr>
</tbody>
</table>

Ceramic window heat <1W

(Static loss)

<table>
<thead>
<tr>
<th>calc</th>
<th>5K→2K</th>
<th>80K→5K</th>
<th>300K→80K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static loss Qc</td>
<td>&lt; 0.3W (depend on sealing)</td>
<td>1.6W</td>
<td>(inner conductor) 5.5W (outer conductor) 10W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total = 15.5W</td>
</tr>
</tbody>
</table>

Come from N2 gas cooling
**Setup**

- Coupler test stand for cERL cryomodule
- N2 gas into inner conductor to forced cooling
- Doorknob (Up)
- Doorknob (Down)
- 1.3GHz 300kW CW klystron
- Warm window (Up)
- Warm window (down)
- Cold window (Up)
- Arc sensor of warm window
- Arc sensor of cold window of both sides
- Coupling wave guide

**Aim**

- Assembly work on class 4 clean room and bake 150degree for 24h
- Processing coupler before assembly: SW 20kW -> TW 80kW (1/2 duty)
- 1.3GHz CW 300kW klystron used → Try TW 100kW to get margin for CW arc sensor using fiber was tested for cryomodule power fast ITL < 10 us

**RF calc of test stand was done by HFSS**

- Arc sensor of cold window of both sides
- CCG1 (warm both)
- CCG2 (cold)

**Calc vs low level measurement**

- Measurement
- Calc by HFSS

- S11 parameters measured and these measurements were also agree well with calc of HFSS.
  → set S11 < -25dB
Fiber Arc sensor and its logic

Interlock from sudden discharge of ceramic for cERL beam operation (<10us required)
- fast arc sensor by using fiber and PMT → allow less than 1us response

Typical fiber arc sensor signal from light (pulse width less than 1us)

Machine protection module (FPGA)
Latch TTL pulse and RF off (< 10us)

If count TTL pulse > N or >9us → TTL out (against cosmic ray event)

If Pulse height increase the finite threshold, make TTL pulse with same width

Set sensor faced each window and detect light

Cold window
Fiber arc sensor
Arc sensor module (PMT)
Arc decision module (FPGA)
Power test results with pulse processing (10us → 200us)

Typical processing of 10us 5Hz (70kW → 85kW)

Start pulse processing with 10us width. On 27kW, vacuum was increased but processing level was gradually increased until 80kW with 6kW/h and many arc signal ITL. From 80kW to 100kW, sudden vacuum increase of cold window led the processing speed decreased to 2.5kW/h; processing level was slowly increased with many vacuum ITL (>1*10^-4Pa). Finally reached the 100kW with 10us width.

Next we lengthen pulse width 30us → 100us → 200us Continuing the processing and lengthen the pulse width suddenly vacuum level was better and finally we reached 105kW with 200us of 20Hz and no ITL was detected with arc and vacuum. → OK.TW 100kW pulse processing → continue lengthening.
During processing with 10us, we see the arc signal event with ITL and gradually decreased this pulse height.

After processing with short pulse and apply long pulse

Arc signal was delayed if processing down with short pulse

If processing was done, we detected no arc signal
Processing time of coupler test stand

• Pulse processing
  – 10us 5Hz--20Hz (->100kW) (21h 40min)
  – 30us 5Hz (->100kW) (2h 10min)
  – 100us 5Hz (15Hz) (->102kW) (1h 50min)
  – 200us 10Hz (20Hz) (->105kW) (1h 20min)
  – 500us 20Hz (->102kW) (1h 7min)
  – 2ms 5Hz (100kW) (1h 11min)
  – 10ms 5Hz (95kW) (1h 7min)
  – 50ms 2Hz (92kW) (1h 4min)
  – 200ms 1Hz (88kW) (1h 5min)
  – 1s 0.5Hz (85kW) (1h 25min)

• CW (43kW) (4hours)

Power increase with processing and finally get no vacuum increase and arc event

Search the stable field level of no ITL event for 1hour by lengthen the pulse width . 85kW of 1s pulse width of 0.5Hz (duty 50%) achieved.

Total pulse processing time (from 10us to 1s 0.5Hz) = 34hours
Final results of coupler power test

- RF power up to 105 kW (pulse) (200 μs 20 Hz)
  and done < 80 kW TW processing with long pulse (1 s 5 Hz)
  43 kW (CW) -> same as 20 kW SW heat load

- Keep 43 kW CW, 4 hours \(\rightarrow\) 50 kW increased the vacuum after 20 min due to the lack of outer cooling fan ability.

- Highest Temp: bellows of inner conductor \((\Delta T \sim 60\text{ degree}, \text{OK})\)
  with N2 gas cooling of 120 l/min
Module assembly of input coupler for cERL main linac

Leak check (no leak) & keep test stand in vacuum in clean room

Connection of input coupler cold window in clean room (class 4)

Doorknob , inner rod, arc sensor & RF cable wereequipped

Connection of input coupler warm window in clean boose
QL optimization & measurement

- Input coupler has variable mechanism for Qext tuning.
- Measured Qext followed design values.
  - $1.5 \sim 5.3 \times 10^7$ for upper (#4 cavity)
  - $8.7 \times 10^6 \sim 3.3 \times 10^7$ for lower (#3 cavity)
  - design: $1 \sim 4 \times 10^7$
Coupler aging of each cavities of cyromodule & power test

Aging history after module assembly (at room temperature)

- After assembly, first we start aging at room temperature, 8 hours was needed for processing again in cryomodule.
- After finish processing, we did not meet the continuous electron activity under warm and 2K condition.
- Aging up to 15kW with CW detune condition @ 2K. Thanks to the processing of room temperature, aging time is much small (< less then 10min).
- Finally in high power test, power fed into 4.5kW with on resonance with QL=1.5*10^7
- Microphonics is Δf = 7Hz of pk-pk
- Vacuum level is less than 1*10^-6 Pa.

Coupler works well in cryomodule

Aging history (at 2K condition) detune
Temperature rises of input coupler under high power test in cryomodule

Results of temperature measurements

- No significant temperature rise was observed. → works well
- 80K thermal anchor works well. Temperature of 5K thermal anchor increased. Come from some other heat load to 5K?
- Bellows of cold part and warm part isolate temperature rise come from higher temperature as expected.
- N2 gas cooling also works well to suppress the temperature rise of inner conductor. \( \Delta T = 38\) K when cooled by 60l/min flow

Plot upper side cavity
- Detune condition
- 15kW CW power
- standing wave (before nopower → after 15kW power)

We note temperature of coupler on resonance with 5kW was less than these measurements results
Summary

- We fabricated two input couplers for cERL main linac cryomodule, especially to meet CW high power feeding of 20kW standing wave.
- High power test at coupler test stand for cERL
  - 1.3GHz 300kW klystron used for more than 80kW traveling wave (=20kW SW)
  - we reached 105kW(20Hz,200us) under pulse processing.
  - Total pulse processing time is 34 hours.
  - 43kW CW power with traveling wave also feed and can keep for 4hours
  - Fiber arc sensor works effectively for ITL within 10us and see processing.
- cERL cryomodule test
  - QL of both couplers also met the design values of \((1-4) \times 10^7\).
  - processing were also applied up to 25kW with 0.2s pulse width within a half day.
  - Thanks to the processing of room temperature again, aging time is much small for cryomodule test of 2K condition (< less then 10min) up to 15kW SW on detune condition.
  - Finally we can keep 14MV with 4.5kW power feeding in high power test of QL=1.5 \times 10^7
  - Michrophonics of \(\Delta f=7\)Hz of pk-pk. This is much smaller than expected.
  - No significant temperature rise was observed under 15kW power feeding.

These input couplers worked well in cERL main linac cryomodule.
(Open) Issues for coupler

• How to suppress the heat leak to 2K or lower temperature?
  – Optimum Copper plating (thickness (-10um) ) can reduce heat load. It’ll be a technical issue to make thin plating.
  – Bellows (with cu plating) can separate the thermal heat load source. But temperature increase if dynamic loss is high.
  – Inner conductor cooling is necessary even if power decreased below 5kW CW power.

• How much will be expected on microphinics?
  – I think 50Hz overestimated for safety. Now Δf=7Hz of pk-pk for our cryomodule. Maybe 20Hz-30Hz is desirable? But this depend on the cryomodule design.

• Is Cold window needed to prevent the sudden ceramic broken for main linac and to absorb the heat load at 80K? → I think yes.

• Not only power ITL but also fast sensor (like arc sensor and/or electron sensor) (< a few us) is needed on coupler to beam, when the recovery condition break by sudden trip of coupler.

• Optimum & fast coupler conditioning
backup
KEK-ERL main linac coupler high power test by prototype coupler (v1) with LN2 cooling

- High power test of prototype of input coupler under liquid Nitrogen cooling with vacuum insulator
  
  Add pulse processing for 8 hours, (easy to process)
  
  Finally achieve 25 kW power feeding with standing wave.

Can keep 20 kW power for 16 hours with standing wave.

Temperature of inner conductor is 120°C.

Temperature rise of cold bellows is 100K

works well especially on the viewpoint of the RF and heat load

Prototype of input coupler

High power test setup with liquid Nitrogen

Vacuum insulator

Liq. N2 tank

Input couler

Doorknob exchanger

Warm window

Cold window

Sudden power down is mainly caused by noise of arc
Thermal cycle tests of cold window of prototype coupler (v1)

Setup of thermal cycle test

We applied the thermal cycle test by using LN2 cooling high power test stand as shown above. After 10 thermal cycle, no leak and crack was observed.

<table>
<thead>
<tr>
<th>Changing point</th>
<th>Old Cold window</th>
<th>New Cold window (coupler v1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic thickness</td>
<td>6.2mm</td>
<td>5.4mm</td>
</tr>
<tr>
<td>Cu thickness of inner conductor</td>
<td>1mm</td>
<td>0.8mm</td>
</tr>
<tr>
<td>Mo thickness</td>
<td>100%</td>
<td>200%</td>
</tr>
<tr>
<td>Max stress</td>
<td>100%</td>
<td>76%</td>
</tr>
</tbody>
</table>

10 thermal cycle test is OK. → decide to fabricate two input coupler for cERL cryomodule

Prototype of input coupler (v1) & assembly in clean room for high power test

(Toshiba TETD)

ultra pure water rinsing at class 10

Assembly in clean room of class 10
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.
Coupling measurements

Connecting the input coupler to 9cell ERL cavity, we measure the coupling directly.
Slope of $Q_{ext}$ change with coupler length agree well with calculation with $\pm 5\text{mm}$.
However, the measured value of $Q_{ext}$ with doorknob exchanger is 1.3 times higher than calculation.

<table>
<thead>
<tr>
<th>Qext coupler</th>
<th>$5.0 \times 10^6$</th>
<th>$2.0 \times 10^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas 0deg (doorknob)</td>
<td>52.83mm</td>
<td>62.38mm</td>
</tr>
<tr>
<td>Calc (MW-Stdio)</td>
<td>51.20mm</td>
<td>60.64mm</td>
</tr>
<tr>
<td>Calc (HFSS)</td>
<td>51.09mm</td>
<td>60.88mm</td>
</tr>
</tbody>
</table>

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

Calc by HFSS

TE mode stands inside

Caution for using to cold window

Max Thermal stress

Inner conductor

outer conductor

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

Broken profile

By changing the thickness of window, peak was shifted.

Please calculate not only S-parameter but also eigenmode of disk ceramic itself.


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

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.

JLAB (CEBAF, JLAB-FEL)

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

KEKB coupler
- >400kW (operation)
- 509MHz
- Disk ceramic with choke

Disk ceramic (TRISTAN type)

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**Cylinder ceramic (TTF type)**

KEKB coupler
- >400kW (operation)
- 509MHz
- Disk ceramic with choke

TTF-III
- 1.3GHz
- 2 Windows
- Adjustable Qext

Cornell, Daresbury, HZB

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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

Vt/Vs NonFlute
Vt/Vs Flute
Vt/Vs Chamfer NonFlute
Vt/Vs Chamfer Flute

Kick Voltage

1.2 \times 10^{-3}
1 \times 10^{-3}
8 \times 10^{-4}
6 \times 10^{-4}

E-field H-field

Blue: beam

Single cell case

9cell case : Vt/Vs \sim 1 \times 10^{-4}

Coupler kick will canceled with setting symmetry with optimum length

By T. Muto
Typical data of fiber arc and e-pick after interlock (2012/4/26)

Pin_f = 23kW

F-arc ⑤、⑥が反応、そのさいに⑤と関係するe-pick 4も信号が大きくなる。
もちろん、これに応じて真空も前々ページのように増大。（warm,Cold両方とも）

Fiberでarc interlockがかかった時は1us以下でpowerは落ちる。
ちなみにMPS moduleのこの時の設定は0.24usのdelay

Interlockとしては十分

下流

CCG2 (Cold 真空)
E-pick 4 (cold window)
E-pick 3 (warm window)
Cautions about disk ceramic with choke (about TRISTAN type coupler)

When modify the impedance or diameter from original

By using for cold window

Calc by HFSS

TE mode stands inside

Max Thermal stress

Inner conductor

outer conductor

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

By changing the thickness of window, peak was shifted.

Please calculate not only S-parameter but also eigenmode of disk ceramic itself.

modify the blazing of conditions

→ 10 thermal cycle is OK now.
2K microphonics measurements

- Measured by oscilloscope and FFT analyzer
  - LLRF Feedback loop off
  - Field set to 2.5MV/m
  - Measured by #3 cavity

- **Pk-pk = 7Hz** by oscilloscope. It allows us to increase the QL higher than several *10^7 \(\rightarrow\) 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.
- It might come from backbone and/or 5K flame resonance frequency??

We need to continue measuring microphonics on next cERL operation