The Fundamental Power Coupler for CEPC Booster Cavity

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Outline

1. Introduction to CEPC SRF system
2. Design issues of the FPC
3. Fabrication of the FPC
4. High power test of the FPC
5. Summary
Introduction to CEPC SRF system
Three rings in the same channel:
- CEPC & booster
- SppC

1) Injector

L = 1.2 km

2) Booster

C = 100 km

Energy Ramp
10 -> 45/120 GeV

3) Main Ring

C = 100 km
2IP

45/120 GeV

H Mode

W & Z Mode
**Time schedule of CEPC**

**CEPC**

- **Pre-studies (2013-2015)**
- **Construction (2024-2030)**
- **Data taking (2030-2040)**

**1st Milestone:** Pre-CDR (March 2015);  
**2nd Milestone:** R&D funding from MOST (Mid 2016);  
**3rd Milestone:** CEPC CDR Progress Report (April 2017);  
**4th Milestone:** CEPC CDR Report (published in July 2018);  
**5th Milestone:** CEPC TDR Report and Prototype R&D (by the end of 2022);  
**6th Milestone:** CEPC construction start (2024);

**SPPC**

- **CDR and R&D (2014-2035)**
- **Engineering Design (2035-2040)**
- **Construction (2040-2045)**
- **Data taking (2045-2060)**
CEPC SRF Layout

30 MW Higgs:

**Collider:** 240 650 MHz 2-cell cavities in 40 cryomodules (6 cav./ module).

**Booster:** 96 1.3 GHz 9-cell cavities in 12 cryomodules (8 cav. / module).

50 MW Higgs upgrade: add 16 Collider modules.

Courtesy of LCLS-II
## CEPC Booster SRF Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>H</th>
<th>H (HC)</th>
<th>W</th>
<th>Z</th>
<th>Z (HC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10 GeV injection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction beam energy [GeV]</td>
<td>120</td>
<td>80</td>
<td>45.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch number</td>
<td>242</td>
<td>1524</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>0.72</td>
<td>0.576</td>
<td>0.384</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beam current [mA]</strong></td>
<td>0.52</td>
<td>1</td>
<td>2.63</td>
<td>6.91</td>
<td>20</td>
</tr>
<tr>
<td>Extraction RF voltage [GV]</td>
<td>1.97</td>
<td>0.585</td>
<td>0.287</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction bunch length [mm]</td>
<td>2.7</td>
<td>2.4</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity number in use (1.3 GHz TESLA 9-cell)</td>
<td>96</td>
<td>96</td>
<td>64</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Gradient [MV/m]</td>
<td>19.8</td>
<td>19.8</td>
<td>8.8</td>
<td>8.6</td>
<td>8.6</td>
</tr>
<tr>
<td>$Q_L$ (4E6-2E7)</td>
<td>1E7</td>
<td>6.5E6</td>
<td>1E7</td>
<td>4E6</td>
<td></td>
</tr>
<tr>
<td>Cavity bandwidth [Hz]</td>
<td>130</td>
<td>200</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam peak power / cavity [kW] (w/ detuning)</td>
<td>8.3</td>
<td>16</td>
<td>12.3</td>
<td>6.9</td>
<td>20</td>
</tr>
<tr>
<td><strong>Input peak power / cavity [kW] (w/ detuning)</strong></td>
<td>15</td>
<td>22</td>
<td>12.4</td>
<td>7.1</td>
<td>20.1</td>
</tr>
<tr>
<td>Input average power per cavity [kW] (w/ detuning)</td>
<td>0.7</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSA peak power [kW] (one cavity per SSA)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>HOM average power / cavity [W]</strong></td>
<td>0.2</td>
<td>0.2</td>
<td>0.7</td>
<td>4.1</td>
<td>12</td>
</tr>
<tr>
<td>$Q_0$ @ 2 K at operating gradient (long term)</td>
<td>1E10</td>
<td>1E10</td>
<td>1E10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total average cavity wall loss @ 2 K eq. [kW]</td>
<td>0.2</td>
<td>0.01</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Design issues of the FPC
## Requirements and design criteria

- Not only for CEPC, but also a pure R&D project aiming for CW, variable and clean assembly.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Design criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency: 1.3 GHz</td>
<td>• Satisfy the interfaces:</td>
</tr>
<tr>
<td></td>
<td>--Power source side: WR650 waveguide</td>
</tr>
<tr>
<td></td>
<td>--Cavity side: 1.3GHz 9-cell cavity and cryo-module</td>
</tr>
<tr>
<td>Power:</td>
<td>• Sufficient cooling to remove the high RF power dissipation</td>
</tr>
<tr>
<td>• R &amp;D: CW 75kW</td>
<td></td>
</tr>
<tr>
<td>• CEPC Booster: Peak, 20 kW; Average, 4 kW</td>
<td></td>
</tr>
<tr>
<td>Variable Qext: 4E6~1E7</td>
<td>• Coaxial type is determined for easy coupling adjusting;</td>
</tr>
<tr>
<td></td>
<td>• With bellows and tuning mechanism.</td>
</tr>
<tr>
<td>Dynamic 2K heat load:</td>
<td>• Optimized thermal intercepts design</td>
</tr>
<tr>
<td>• R &amp;D: 0.5W (TW,CW,75kW)</td>
<td></td>
</tr>
<tr>
<td>• CEPC Booster: 0.06W (TW,CW,4kW)</td>
<td></td>
</tr>
<tr>
<td>Clean assembly</td>
<td>• Two windows:</td>
</tr>
<tr>
<td></td>
<td>--Cold window assembly to the cavity in class 10 clean room</td>
</tr>
<tr>
<td></td>
<td>--Warm window double the vacuum safe</td>
</tr>
<tr>
<td>Multipacting free</td>
<td>• RF structure optimization to avoid MP at nominal power;</td>
</tr>
<tr>
<td></td>
<td>• TiN coating of ceramic</td>
</tr>
<tr>
<td></td>
<td>• A DC bias voltage is adopted to suppress MP.</td>
</tr>
<tr>
<td>Safe operation</td>
<td>• With sufficient diagnostic monitors.</td>
</tr>
</tbody>
</table>
Design features

- The warm window is derived from TTF-III coupler and the cold window is belong to the Tristan-type family;
- In order to handle a higher average power, a series of modifications are made:
  - The warm window size is enlarged (OD=87mm);
  - Air cooling is added to the IC of the warm coax;
  - Both air and water cooling are applied to the warm window;
  - Larger coaxial size for a larger cold window (OD=90mm);
- A DC bias voltage mechanism is arranged to suppress Multipacting;
- The travel range of the antenna is designed to be 20mm to meet the coupling adjusting requirement.
Power transferring optimization

- The measured $S_{11} = -45.4\, \text{dB} \, @1.2989\, \text{GHz}$;
- The measured $S_{21} = 0.166\, \text{dB} \, @1.3\, \text{GHz}$
The E-H field distribution at CW 75kW in TW mode was calculated. And the peak E-field is one forth of the air break value.

- $E_{\text{max}} = 7 \times 10^5$ → far away air break → safe!
Multipacting Simulation

- Free of MP at the power range of 0~80kW!
The thickness and RRR of copper plating were determined to minimum the cryogenic heat load.

Final decisions:
- Copper plating thickness:
  - Cold OC: 5um
  - Warm OC: 30um
  - Warm IC: 150um
- Optimum RRR value:
  - RRR=30 for average 4kW
  - RRR=50 for CW 75kW

2K heat load at different RRR values
Cooling design

- The cooling was optimized based on the required heat load and temperature rise.

<table>
<thead>
<tr>
<th>2K heat load</th>
<th>Requirements</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 4kW</td>
<td>0.06 W</td>
<td>0.04 W</td>
</tr>
<tr>
<td>CW 75kW</td>
<td>0.5 W</td>
<td>0.4 W</td>
</tr>
</tbody>
</table>
Temperature distribution at CW 75kW, TW

- Warm window: 90°C
- Warm IC: 125°C
- Cold window: 37°C
Divided into six sub-assemblies:

- Cold part: cold window, cold IC, cold OC
- Warm OC
- Warm IC
- Warm window
- Doorknob
- Tuning unit

Warm window is demountable: easy to be replaced once damaged.
Fabrication issues of the FPC
Copper plating

- **Challenges**
  - Uniform copper plating on bellows
  - Very thick (~150um) plating on warm inner conductor
  - High RRR required (RRR>30)
- Copper plating after brazing or welding

Electrodes optimization

Warm OC: 30um copper plating

Warm IC: 150um copper plating  
**Very difficult!**
Copper plating quality test

- Thickness tolerance < 20% achieved
- RRR was largely improved by using purer electroplating bath and reducing the annealing temperature (400°C → 350°C).
- The adhesiveness was tested by liquid nitrogen shocking and ultrasonic cleaning.
- No bubbles and peeling!

### RRR

<table>
<thead>
<tr>
<th>Bath condition</th>
<th>Annealing T</th>
<th>thickness</th>
<th>RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original electroplating bath (low purity)</td>
<td>400°C</td>
<td>20 μm</td>
<td>&lt;10</td>
</tr>
<tr>
<td>New electroplating bath (high purity)</td>
<td>400°C</td>
<td>10 μm</td>
<td>&lt;10</td>
</tr>
<tr>
<td></td>
<td>350°C</td>
<td>20 μm</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 μm</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 μm</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 μm</td>
<td>40</td>
</tr>
</tbody>
</table>
Window brazing

- Vacuum furnace, Ag72Cu28
- Optimize the temperature evolution curve
- Special fixture for support
- The cold window brazing processes were reduced from 3 steps to 2 steps. It greatly increased the success rate of cold window brazing.
The fabricated components

- Warm window
- Warm OC
- Doorknob
- Warm IC
- Cold part
- Whole assembly
High power test of the FPC
Cleaning, assembly, baking and on site installation

- **Cleaning**: ultra-sonic cleaning with detergent at 50 °C → pure water rinsing → pure N2 blowing
- **Assembly**: processed at class 10 clean room
- **Baking**: 120 °C for 48 hours

Ultra-sonic cleaning  
Clean assembly and vacuum leak check  
Baking  
On site installation
Setup for high power test

- The high power test has been processed at a resonant ring platform developed at Peking University.*
- Power source: 10kW SSA; The input power can be amplified about 5~8 times.

*An alternative way to increase the power gain of resonant rings*, REVIEW OF SCIENTIFIC INSTRUMENTS 89, 034702 (2018)
The cold OC was cooled by the thermal intercepts connected to liquid Nitrogen cooled copper plates.
Antenna excursion test

- The antenna excursion tested: $\pm 10\text{mm} \rightarrow \text{Qe variable range: } 1.5\times10^6\text{~}1\times10^8 \text{ (Spec: } 4\times10^6\text{~}1\times10^7\text{);}$
- Before high power test, S11 of the whole test bench was adjusted by tuning the penetration depth of the antenna tip into the connecting test box.

![Graph showing Antenna tip traveling range for Qe adjusting](image1)

- S11 adjusting before high power test
  (After tuning: $-45.4\text{dB@1.2989GHz}$)

![Graph showing S11 adjusting of the whole test bench](image2)
Conditioning time

- After 60 hours conditioning, two prototypes reached CW 70kW.
Conditioning process

10Hz, 10us

10Hz, 100us

10Hz, 200us

10Hz, 500us

10Hz, 1ms

10Hz, 2ms

10Hz, 5ms

10Hz, 10ms

10Hz, 10us

10Hz, 100us

10Hz, 200us

10Hz, 500us

10Hz, 1ms

10Hz, 2ms

10Hz, 5ms

10Hz, 10ms

10Hz, 10us

10Hz, 100us

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10Hz, 500us

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10Hz, 5ms

10Hz, 10ms

10Hz, 10us

10Hz, 100us

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10Hz, 500us

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10Hz, 10ms

10Hz, 10us

10Hz, 100us

10Hz, 200us

10Hz, 500us

10Hz, 1ms

10Hz, 2ms

10Hz, 5ms

10Hz, 10ms
High power test result

- It's difficult to keep the resonant ring tuned for more than 30 minutes as the power above CW 50kW due to thermal drift.
- So we lowered the RF power below 50kW for power keeping test: stayed at 30kW for 60 minutes; stayed at 40kW for 30 minutes.
Temperature rise at CW 40kW

- A high warm IC temperature observed during test:
  - Test result: 100 ºC
  - Simulation result: 72 ºC
  - Poor copper plating or insufficient cooling?

<table>
<thead>
<tr>
<th>Location</th>
<th>Equilibrium T up./down. (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet water</td>
<td>21.1/22.5</td>
</tr>
<tr>
<td>Outlet water</td>
<td>21.7/23.7</td>
</tr>
<tr>
<td>Doorknob WG up</td>
<td>25.2/27.2</td>
</tr>
<tr>
<td>Doorknob WG down</td>
<td>24.7/25.3</td>
</tr>
<tr>
<td>Warm inner conductor</td>
<td><strong>97.2/102.7</strong></td>
</tr>
<tr>
<td>Warm outer conductor</td>
<td>19.1/30.0</td>
</tr>
<tr>
<td>Warm outer bellow</td>
<td>58/74.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Equilibrium T up./down. (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold window up</td>
<td>18.9/-24.6</td>
</tr>
<tr>
<td>Cold window down</td>
<td>15.6/-35.4</td>
</tr>
<tr>
<td>Cold outer bellow</td>
<td>14.4/-35.5</td>
</tr>
<tr>
<td>Connecting box</td>
<td>52.5/50.7</td>
</tr>
</tbody>
</table>
Summary

• 1.3GHz variable, double-window, CW 75kW coupler developed at IHEP
  - Demountable cylindrical warm window + Tristan-type cold window
• Two prototypes fabricated and high-power tested on test bench
• CW 70kW RF power reached on both couplers
• Warm-part inner conductor overheating observed (30°C higher than simulation)
• FPCs fulfill CEPC booster cavity requirements
• Further optimization foreseen: cooling of warm inner conductor
Thanks for your attention

Thanks to Peking University for the great contribution to the coupler test.

Thanks to Eiji Kako (KEK), Eric Montesinos (CERN), Wencan Xu (BNL), Denis Kostin (DESY), Sergey Kazakov (FNAL),... for useful discussion.