650 MHz couplers for PIP-II

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PIP-II Fine Tuning Workshop
PIP-II project:

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle species</td>
<td>$\text{H}^-$</td>
<td></td>
</tr>
<tr>
<td>Linac Beam Energy</td>
<td>800</td>
<td>MeV</td>
</tr>
<tr>
<td>Linac Beam Current</td>
<td>2</td>
<td>mA</td>
</tr>
<tr>
<td>Linac Pulse Length</td>
<td>0.55 - CW</td>
<td>ms</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>20 - CW</td>
<td>Hz</td>
</tr>
</tbody>
</table>

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**Diagram:**

- **LEBT**, **RFQ**, **MEBT**
  - $\beta = 0.11$, $\beta = 0.22$, $\beta = 0.47$, $\beta = 0.64$, $\beta = 0.97$

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**Energy Bands:**

- **162.5 MHz**
  - 0.03 - 10.3 MeV
- **325 MHz**
  - 10.3 - 185 MeV
- **650 MHz**
  - 185 - 800 MeV
• **Room temperature cavities:**
  – RFQ.
  – Bunching cavities (4 pc).

• **5 types of superconductive cavities:**
  – Half Wave Resonators, HWR (8 pc).
  – Superconductive Spoke Resonator 1, SSR1 (16 pc).
  – Superconductive Spoke Resonator 2, SSR2 (35 pc).
  – Low Beta 650 MHz Cavity, LB 650 (33 pc).
  – High Beta 650 MHz Cavity, HB 650 (24 pc).

**Total number of couplers: 122.**
**Requirements to couplers:**

(Requirements meets CW version of PIP-II with 5 mA current.
Requirements are revised now for 2 mA version.)

**RFQ coupler:**
- Frequency: 162.5 MHz
- Power: 75 kW, CW

**SSR1 & SSR2 coupler:**
- Frequency: 325 MHz
- Power: 30 kW, CW

**Bunching coupler:**
- Frequency: 162.5 MHz
- Power: 3 kW, CW

**LB & HB 650 coupler:**
- Frequency: 650 MHz
- Power: 110 kW, CW

**HWR coupler:**
- Frequency: 162.5 MHz
- Power: 10 kW, CW

All couplers were designed and all, except 650 MHz couplers, were built and tested.
Principles of design:

- Simplicity of vacuum part of coupler: no moving parts, no bellows. simple configuration – more reliable, easy to clean, less expansive.

- Air cooling of antennas (no water)

- Ability to apply high voltage bias to suppress a multipactor.

- Avoid a copper coating of stainless steel.

Based on this principles the RFQ, SSR1 & SSR2, LB & HB 650 couplers were designed.

RFQ and SSR1 & SSR2 couplers were built and tested.
Main features of new design:
- no copper coating
- ceramics is protected by shields
- better cryogenics properties
In backup design the vacuum outer conductor is ‘conventional’ type: SS tube coated by copper.
Vacuum part of coupler, new design
Backup geometry with copper coating, vacuum part:
Limitation of power level and life time are mechanical stresses.

Aluminum and copper are B-type material. If stresses are cyclic, a coupler with copper will be broken always. Only question is when. Number of cycles has to bigger then lifetime of accelerator.
CW accelerator is really pulse accelerator with long pulses.

How many cycles will see a coupler during accelerator life time?

Suppose the accelerator life time is ~ 30 years

One trip per day ~ $10^4$ cycles.
One trip per hour ~ $10^5$ cycles

Coupler has to sustain ~ $10^5$ cycles even in case of CW machine.
Copper fatigue

Average (148 measurements) for annealed copper at 295K:

\[ S(\text{MPa}) = 271 \times N^{-0.074} \]

or

\[ N = \left(\frac{S(\text{Mpa})}{271}\right)^{-13.514} \]

Worst:

\[ S(\text{MPa}) = 192 \times N^{-0.074} \]

or

\[ N = \left(\frac{S(\text{Mpa})}{192}\right)^{-13.514} \]

10^5 cycles \(\sim\) 120 MPa

Worst:

10^5 cycles \(\sim\) 80 MPa
Samuli Heikkinen “Fatigue of Metal, Copper Alloys”, CERN, 06/26/2003

**Pure Copper Properties, annealed and cold worked**

<table>
<thead>
<tr>
<th></th>
<th>Annealed</th>
<th>Cold Worked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength [MPa]</td>
<td>240</td>
<td>380-415</td>
</tr>
<tr>
<td>Yield Strength [MPa]</td>
<td>70</td>
<td>345-380</td>
</tr>
<tr>
<td>Fatigue Strength at $10^8$ cycles [MPa]</td>
<td>75</td>
<td>126</td>
</tr>
</tbody>
</table>

Annealed copper, 20°C, $10^5$ cyc. -> 120 MPa

Annealed copper, 130°C, $10^5$ cyc. -> 80 MPa
Alumina


**Compressive strength**  min 690  max 5500
**Tensile strength**  min 69  max 665

http://www.matweb.com/search/datasheet.aspx?matguid=0654701067d147e88e8a38c646dda195

**Tensile strength**  260 MPa

https://www.memsnet.org/material/aluminumoxidel2o3bulk/

**Tensile strength**  255-261 MPa


**Tensile strength**  280-370 MPa

**Tensile strength limit**  250 MPa – good estimation
Typical pictures of stresses (linear scale). Maximal stresses are localized in place of ceramic-metal brazing. Stresses caused by temperature gradient in ceramic are noticeably smaller.
### Stresses in copper and ceramics for 100kW and 300kW, TW, CW

<table>
<thead>
<tr>
<th>Power, Air rate</th>
<th>Inner, Cu</th>
<th>Inner, Cer</th>
<th>Outer, Cu</th>
<th>Outer, Cer</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kW, TW, 3g/s</td>
<td>87 MPa, T = 74°C</td>
<td>100 MPa</td>
<td>125 MPa, T = 60°C</td>
<td>160 MPa</td>
</tr>
<tr>
<td>100 kW, TW, 4g/s</td>
<td>65 MPa, T = 65°C</td>
<td>92 MPa</td>
<td>97 MPa, T = 55°C</td>
<td>128 MPa</td>
</tr>
<tr>
<td>300 kW, TW, 5g/s</td>
<td>160 MPa, T = 124°C</td>
<td>220 MPa</td>
<td>280 MPa, T = 112°C</td>
<td>250 MPa</td>
</tr>
</tbody>
</table>

Design is good for 100 kW, TW, CW. For 300 kW it has to be improved.
Pass band of “new” vacuum part
Pass band of "backup" vacuum part.
$P = 0.5W, \text{ TW}$

Max. $E$ (100 kW, TW) = 1.22 MV/m  
Max. $E$ (300 kW, TW) = 2.13 MV/m

Max. $H$ (100 kW, TW) = 1.81 kA/m  
Max. $H$ (300 kW, TW) = 3.14 kA/m

Strength of electric field is not high, even less then breakdown threshold for air.
$P = 0.5W, TW$

Max. $E$ (100 kW, TW) = 1.09 MV/m
Max. $E$ (300 kW, TW) = 1.88 MV/m

Max. $H$ (100 kW, TW) = 1.78 kA/m
Max. $H$ (300 kW, TW) = 3.08 kA/m
Passband and losses of total coupler

Total losses = 4.0E-3 (0.4%)

100 kW <-> 400 W
300 kW <-> 1.2 kW

Losses:
~ 50% - aluminum waveguide
~ 25% - antenna
Multipactor simulations.
Multipactor in gaps of shields:

Gap ~ 1mm, D ~ 73mm

E-field in slot 1, P = 0.5W TW

0.5 W => ~ 300 V/m

E-field in slot 2, P = 0.5W TW
Coaxial slots (~1mm) was replaced by flat slots for multipactor simulations (1mm << R = 36.5mm):

Slot 1mm:
Simulated equivalent of TW powers, kW (power in coupler): 5, 10, 15, 20, 25, 30, 50, 100, 200, 300

Slot 0.9mm:
Simulated equivalent TW powers, kW: 5, 10, 12.5, 15, 20 – no multipactor

Conclusion: multipactor does not exist at 650 MHz for slots ≤ 0.9 mm
Multipactor near shielding disk:

Multipactor exists (no bias) \( P > 20 \text{ kW, TW} \)

Bias \( \pm 4 \text{ kV} \) suppresses multipactor for \( P < 700 \text{ kW, TW} \)

Multipactor near the window:

Multipactor exists (no bias) at \( P \geq 100 \text{ kW, TW} \)

-5 kV suppresses multipactor up to 300 kW, TW

+5 kV does not suppress multipactor (300 kW, TW)

This is true for Port 1 and Port 2 excitation (both directions of TW)

Multipactor near shielding iris:

Multipactor exists (no bias) at \( P > 50 \text{ kW, TW} \)

\( \pm 5 \text{ kV} \) bias suppresses multipactor up to 300 kW, TW

Multipactor in regular part:

Multipactor exists (no bias) at \( P > 40 \text{ kW, TW} \)

+2 kV and – 3.6 kV bias suppresses multipactor up to 300 kW, TW
Multipactor in low-field volumes:

No multipactor at $P < 2$ MW, TW

Conclusion:

-5kV bias suppresses multipactor in all parts of coupler up to 300 kW, TW
Thermal properties
In simulations all thermo-intercepts are connected through copper straps like these:

**Performance Data & Mass**  
(at braid length = 10 cm):

| Conductance (at 300K) | 0.43 W/K  
| Projected Conductance (at 20K) | 1.80 W/K  
| Approximate Weight | 260g

**30 cm**

- 36x OFHC Cu ropes
- 1.00 in [25.4 mm]
- 0.35 in [8.9 mm]
- 2.00 in [50.8 mm]

**Performance Data & Mass**  
(at braid length = 10 cm):

| Conductance (at 300K) | 0.21 W/K  
| Projected Conductance (at 20K) | 0.93 W/K  
| Approximate Weight | 130g

**15 cm**

- 18x OFHC Cu ropes
- 1.00 in [25.4 mm]
- 0.35 in [8.9 mm]
- 1.00 in [25.4 mm]
Static thermal loading, RF power = 0 kW

\[ T_{\text{tip}} \approx 20 \, \text{C} \]
\[ P_{\text{rad}} \approx 0.14 \, \text{W} \] (Polished copper \( \varepsilon = 0.05 \))
P = 100 kW, TW, Air = 3.0g/s

Loss in antenna = 77W + 20W = 97W

ΔT_air ≈ 38°C (T_out = 331 K)

T_tip ≈ 34°C

P_rad = 0.17W
$P = 300 \text{ kW}, \text{ TW, Air} = 5 \text{ g/s}$

Loss in antenna = $230W + 58W = 288W$

$\Delta T_{\text{air}} \approx 72^\circ C \ (T_{\text{out}} = 365K)$

$T_{\text{tip}} \approx 44^\circ C$

$P_{\text{rad}} = 0.19W$

$P = 1.33W$

Total 1.6W

Total 11.5W

Total 47.8W
Distribution of temperature and temperature gradient along ceramics

\[ P = 100 \text{ kW, TW, } \]
\[ \text{Air} = 3.0 \text{g/s} \]

\[ P = 300 \text{ kW, TW, } \]
\[ \text{Air} = 5 \text{g/s} \]
Static thermal loading, RF power = 0

Tip $\approx 20$ C

$P_{\text{rad}} \approx 0.14$W
\[ P = 100 \text{ kW}, \text{TW, Air} = 3.0 \text{ g/s} \]

Loss in antenna = 73W + 20W = 93W

\[ \Delta T_{\text{air}} \approx 37^\circ \text{C} \]

\[ T_{\text{tip}} \approx 34^\circ \text{C} \]

\[ P_{\text{rad}} \approx 0.17 \text{W} \]
$P = 300 \text{ kW, TW, Air } = 5 \text{ g/s}$

Loss in antenna $= 220 + 58 = 278 \text{W}$

$\Delta T_{\text{air}} \approx 65^\circ \text{C}$

$T_{\text{tip}} \approx 44^\circ \text{C}$

$P_{\text{rad}} \approx 0.19 \text{W}$
Distribution of temperature and temperature gradient along ceramics

Backup design, $P = 100$ kW, TW, 
Air = 3.0 g/s

Backup design, $P = 300$ kW, TW, 
Air = 5 g/s
Thermal properties of 650 MHz couplers

<table>
<thead>
<tr>
<th></th>
<th>2K, W</th>
<th>5K, W</th>
<th>70K, W</th>
<th>293K, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>New, 0 kW</td>
<td>0.15</td>
<td>0.6</td>
<td>3.3</td>
<td>-2.7</td>
</tr>
<tr>
<td>New, 100 kW</td>
<td>0.55</td>
<td>0.93</td>
<td>6.2</td>
<td>21</td>
</tr>
<tr>
<td>Bckp, 0 kW</td>
<td>0.41</td>
<td>1.46</td>
<td>3.0</td>
<td>-3.1</td>
</tr>
<tr>
<td>Bckp, 100 kW</td>
<td>0.97</td>
<td>4.1</td>
<td>11.4</td>
<td>20</td>
</tr>
</tbody>
</table>

100 kW:

New = 0.55*960 + 0.93*220 + 6.2*20 = \(857\) W of cryo-plant
Bckp = 0.97*960 + 4.1*220 + 11.4*20 = \(2061\) W of cryo-plant

New design requires \(~2.4\) times less power of cryo-plant.

(without thermal radiation from ceramic window)
Air cooling of antenna

Pressure drops:

Inner pipe: OD 9.5 mm, ID 7.7 mm, Length ~ 1m
Antenna ID 10.9 mm, Length ~ 0.41 m

Pressure drop at inner pipe:
3 g/s: ΔP = 0.06 bar, V = 64 m/s
5 g/s: ΔP = 0.16 bar, V = 107 m/s

Pressure drop at antenna:
3 g/s: ΔP = 1.3 bar, V = 113 m/s, Convection ~ 550 W/(K*m²)
5 g/s: ΔP = 3.2 bar, V = 189 m/s, Convection ~ 830 W/(K*m²)

Inlet pressure ~ 2 bar for 3 g/s
  ~ 4 bar for 5 g/s
Mechanical design
650 MHz Main Coupler assembly F10056895

- Air inlet with pusher F10059980
- Inner conductor with bellows F10058374
- Waveguide assembly with instrumentation box F10059948
- Outer conductor with bellows F10058374
- Cold end Assembly F10056896

Length ~ 1 meter, Weight ~ 50 kg
HB 650 MHz Main Coupler assembly F10056895 exploded view

- Inner conductor with bellows F10057202
- Waveguide assembly with instrumentation box F10059948
- Teflon support disk
- Air inlet with pusher F10059980
- Cold end Assembly F10056896
- Outer conductor with bellows F10058374
Last modification (it is under production now):
Last modification (it is under production now):
Main components of Coupler Cold End Assembly
EM shields outer conductor version F10056896

- 4”OD x 6mm thick ceramic window
- 4”OD SS outer conductor
- 3”OD EM copper shields
- 0.5”OD antenna
- 1”OD inner conductor
- 70K Intercept
- 5K Intercept

Length ~ 450 mm, Weight ~ 18 kg
Ceramic window with Antenna assembly
Exploded view

- 4”OD x 6mm thick Ceramic disk
- 1”OD copper inner conductor
- copper sleeves
- copper ring
- 316L stainless flange
- 0.5” OD copper Antenna
- copper Antenna Tip
Main components of Coupler Cold End Assembly
EM shields outer conductor version F10056896
Exploded view

All parts will be cleaned separately and assembled together in Clean room.
Cold Outer conductor assembly

We will use F10069409 Alignment jig for Cold Outer Conductor assembly.
Main components of Coupler Cold End Assembly
copper coated outer conductor version F10056896

- 4”OD x 6mm thick ceramic window
- E-pickup
- 3”OD SS copper coated outer conductor
- 1”OD inner conductor
- 0.5”OD antenna
- 5K Intercept
- 70K Intercept

Length ~ 450 mm, Weight ~ 9 kg
Outer and inner conductors with bellows

- Stainless steel flanges
- Copper tubing
- Copper coated nickel alloy electrodeposited bellows
Air Inlet with Pusher
Waveguide assembly

Instrumentation box
Kapton tape
Capacitor
Waveguide
HB 650 MHz Main Coupler Cold End Assembly on the cavity
HB 650 MHz Main Coupler on the Cryomodule
HB 650 MHz Main Coupler on the Cryomodule
Current status

- Two coupler prototypes with four vacuum parts are under production.
- Four vacuum parts are already made by CPI.
- Test infrastructure is under constriction.
Couplers test bench.

Couplers will be tested in resonance mode with full reflected power. It will allow to increase the level of testing power more then 100 kW using 30 kW RF source.
During the test (qualification the antennas will be connected electrically and mechanically.

After the test couplers will be re-cleaned.
Good news from 1.3 GHz coupler testing
1.3 GHz prototype coupler was successfully tested up to 27 kW, TW, CW. Design is similar to 650 MHz coupler design.
Main features:

- Single room temperature window, 2.6 inch (66 mm), no TiN coating
- No copper coating.
- Window protection against charged particles.
- Low static and dynamic cryo-loading.
- HV bias for multipactor suppression.
- Air cooling of antenna.
Gaps 0.5mm

Al diamond seals

Copper

SS
Configuration of high power test.
Assembling test stand
Coupler at test stand

- Waveguide to 30 kW, CW source.
- Matched load
- RF vacuum window
- Coupler
Test results:

Coupler was tested in pulse and CW modes. + 3kV bias was applied in all tests.

- In pulse mode the coupler was tested up to 15 kW/ 10ms only. RF source (IOT) was not stable in pulse mode.
- There was no sign of any vacuum activity (no evidences of multipactor) during the pulse mode test. Vacuum level was ~ 2E-8 Torr.

Test in CW mode.

- Maximum power 27 kW, CW, TW was reached.
- Power level was limited by RF source (IOT).
- Time was limited by temperature (vacuum level) of waveguide RF window. Window became hot and vacuum level reached upper limit 1E-6 Torr.

It is good sign for 650 MHz coupler. Scaling coefficient ~ 4.
Chambers, no multipactor

Gaps, no multipactor

MP is suppressed by HV bias
Improved design
Design power - 250 kW, CW (TW)

Cryogenic load at 2K-5K < 1 W (!)
Geometries of copper shields and antenna were changed.
Geometry of RF window was change
Back up
325 MHz coupler qualification:

Each couplers (each pair of couplers) is qualified at test stand. Qualification: running coupler at full reflection mode, CW, at qualification power level for ~ 2 hours at each reflecting phase point. It is 4 phase point with 90 dgr. steps. Total time ~ 8 hours. Qualification power depends on operating power. It is still debated how much it shall be. Qualification is not conditioning. After qualification the couplers are re-cleaned and installed to cavity without conditioning. **Really, the couplers do not require a conditioning. HV bias suppresses any activity.**
Each ceramic disk is measured before to be brazed.
CoorsTek ceramic measurements, $F \sim 2.7$ GHz

Some times ceramics is extremely good: loss tangent $\sim 1.5E-5$ at 2.7 GHz