PIP-II WORKSHOP
CEA COUPLERS

G. Devanz
The development of the 1MW 704 MHz FPC started with EU R&D programme CARE directed towards high power pulsed proton accelerators with 10% duty cycle.

KEK-B, SNS type coupler

- Coaxial coupler
  - 100 mm diameter
  - 50 Ω

- He cooled outer conductor
- Electropolished water cooled inner conductor
- Water cooled RF window
- Vacuum gauge
- Doorknob (air)
- Cryostat flange

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Built one pair of FPC in industry (one for each of the 3 main components), except Cu film done by CERN
Test of the HIPPI power coupler on the HIPPI cavity at 1.8 K, full reflection

1 pair tested up to 1.2 MW, 10% duty factor
This coupler achieves 120 kW average power on test bench and on SRF cavity
HIPPI conclusion (from WWFPC-2015)

What we tested that generally cause worries:

- Assembly on the cavity from the top in the clean room. No particle counting was performed in the 2009 assemblies but FE was not enhanced on the two test SRF cavities.
- Massive antenna resting for years in horizontal position: no deflection observed.
- More recently a new clean room test assembly of 1 HIPPI coupler was carried out in the new ISO5 clean room successfully with particle counting.
- The coupling waveguide aspect indicates it may have been the most difficult part to condition (Cu particulates were present inside).
Designed by CEA-Saclay/IRFU and CNRS/IPNO

- Freq = 704.42 MHz
- $P_{\text{max}} = 1.1 \text{ MW}$, RF pulses at 14 Hz
- Beam pulses duration = 2.86 ms,
- minimum required RF pulse length = 3.1 ms

Medium and high beta differ only by the cavity length and number of cells
- Minor changes for window and double wall tube
- New doorknob with 10 kV HV biasing capability
- Less demanding power-wise (10%DC-> 5%DC)

**Electrical specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency</td>
<td>704.42 MHz</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>14 Hz</td>
</tr>
<tr>
<td>Forward RF power</td>
<td>1.1 MW</td>
</tr>
<tr>
<td>RF pulse width in full reflection (all phases)</td>
<td>500 μs</td>
</tr>
<tr>
<td>RF pulse width in travelling waves</td>
<td>3.6 ms</td>
</tr>
<tr>
<td>Bias Voltage limits</td>
<td>±10 kV</td>
</tr>
</tbody>
</table>

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WINDOW RF PROPERTIES

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pforward= 1.1 MW</td>
<td></td>
</tr>
<tr>
<td>Dielectric losses (travelling wave)</td>
<td>10 W</td>
</tr>
<tr>
<td>Dielectric losses (full reflection)</td>
<td>29.4 W</td>
</tr>
<tr>
<td>RF losses for external choke (travelling wave)</td>
<td>1.2 W</td>
</tr>
<tr>
<td>RF losses for external choke (full reflection)</td>
<td>1.4 W</td>
</tr>
<tr>
<td>RF losses for internal choke (travelling wave)</td>
<td>6.1 W</td>
</tr>
<tr>
<td>RF losses for internal choke (full reflection)</td>
<td>6.8 W</td>
</tr>
</tbody>
</table>

Very wide bandwidth
Same design used for 352MHz RFQ window

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>S11(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε_r=9.3</td>
<td>-55</td>
</tr>
<tr>
<td>ε_r=9.5</td>
<td>-55</td>
</tr>
<tr>
<td>ε_r=9.6</td>
<td>-55</td>
</tr>
<tr>
<td>ε_r=9.4</td>
<td>-55</td>
</tr>
<tr>
<td>ε_r=9.3</td>
<td>-55</td>
</tr>
<tr>
<td>ε_r=9.7</td>
<td>-55</td>
</tr>
</tbody>
</table>

Bandwidth at -55dB: 94 MHz (753-659)

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• Stainless steel 316L
• Cooling circuit manufactured with the shrink-fitting method
• Copper coating with 10µm(-3/+2µm) thickness and $RRR \in [20;40]$
• PEEK Insulation able to provide 10kV insulation
• Actual measured breakdown voltage $\geq 18$kV)
• Estimation of the power dissipated by the coupler

For 1.1 MW peak, duty cycle 5%  
- RF power dissipation of the antenna:  
in travelling wave 58W  
in standing wave 94W  
- RF power dissipation of the ceramic (\(\tan \delta = 3 \times 10^{-4}\))  
in travelling wave 9.3W  
in standing wave 40W (worst case)

• Cooling of the antenna

Estimation of the water flow

<table>
<thead>
<tr>
<th>(\Phi) (l/min)</th>
<th>(\Delta T) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.97</td>
</tr>
<tr>
<td>2.5</td>
<td>0.78</td>
</tr>
<tr>
<td>3</td>
<td>0.65</td>
</tr>
</tbody>
</table>

During the conditioning: for \(\Phi = 2.4\) l/min  
\(T_{\text{water input}} = 25.6^\circ\text{C}\)  
\(T_{\text{water output}} = 26.2^\circ\text{C}\)

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• Steady state in TW 120kW avg power (HIPPI test case)
  ▪ 2.5 x the ESS average RF power
  ▪ pressure, convection for air and water are modeled
  ▪ RF dissipations

**HIPPI test case**

| RF PEAK POWER (MW) | 1.2 |
| Duty cycle (%)     | 10  |
| Regime             | TW  |
• Lesson learned from HIPPI previous design (copper coated welded SS cavity) and E. Montesinos dismountable cavity, we tried to simplify a step further by not having any copper layer.
• Thermal design with margins showed fin heat exchangers and fan system were required.
• In use, the box was operated with good thermal stability with only air circulation on the cover plate (air channels)
• Pumping port and port for arc detection
• Aluminum wire used as seal between cover and bottom for vacuum tightness
Assembly has been performed in three different clean areas:
- ISO5
- ISO4
- Clean booth
without any noticeable change in conditioning time

Top gun+Particle counter on all cavuum components

Particle free pumping and venting systems

<table>
<thead>
<tr>
<th>Double wall tube</th>
<th>window</th>
<th>Coupling Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside of clean room</td>
<td>Us+tikopur</td>
<td>Antenna Deox T310+rinsing</td>
</tr>
<tr>
<td>De-oxidation RBS T310</td>
<td>Ethanol cleaning of ports, outer shell</td>
<td></td>
</tr>
<tr>
<td>rinsing</td>
<td>drying</td>
<td>drying</td>
</tr>
<tr>
<td>Clean room</td>
<td>Top gun+particle counter</td>
<td>Top gun+particle counter</td>
</tr>
</tbody>
</table>
NEW CONDITIONING INFRASTRUCTURE

- 2 klystrons
  - existing CPI klystron + cea modulator upgraded to 1.2MW 3.6ms pulses
  - Additional 1.6 MW Thales klystron+modulator (not yet operational)

- 2 FPC pairs can be conditioned in parallel

- 2 conditioning systems w EPICS control/DAQ/hardware interlocks

- 2 Baking ovens with N2 atmosphere

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170°C baking current setup

New N₂ atmosphere baking oven

Back-to-back configuration

Standing wave setup

- Line 1: CPI 1.2 MW klystron
- Line 2: Thales 1.6 MW klystron (HVPS to be delivered)
CAVITY STRING WITH PROTOTYPE FPCS

ESS M-ECCTD cavity string in Saclay clean room

3 CEA cavities

1 LASA CAVITY

Jan. 2017

March 2017
No bias during conditioning
Typical conditioning time 45-100hrs
CONDITIONING SEQUENCE :: STANDING WAVE EXAMPLE

Min. E-field on both ceramics
Max. E-field on both ceramics

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• Reach the peak power of 1.2 MW, 3.6 ms pulses at 14 Hz TW *in less than 120 hrs* with applied RF
• Sustained application of max. power for 1 hour
• Full reflection
  – up 1.2 MW for 500μs pulses at 14 Hz
  – Up to 300 kW for 3.6 ms pulses at 14 Hz

- 2 most arcing-prone short-circuit positions
- 4 other short circuit positions
- No time limit
MANUFACTURING PREPARATION FOR 120 UNITS

- Single vendor for 120 units
- ESS FPC Prototypes (before call for tender):
  - 8 window antenna assemblies from supplier 1
  - 4 double wall tubes from supplier 2, Cu coating subcontracted by supplier 3
  - 4 doorknob transitions from supplier 2
  - 2 complete FPCs including doorknob from supplier 3
- RF conditioning passed with success involving windows from 1 and 3
- Being aware of the successful RF test of 2 pairs, 3 companies presented offers for the series (supplier 1, 3 and 4)
- Two major companies involved in FPC manufacturing did not build any prototype, nor RF window:
  - One did not even participate to the first round of the CfT (publicity)
  - The other did
• Initially FPC prototypes have been fabricated in a different context than the series production (FPC procurements for ESS CM prototypes)
• The series manufacturing company agrees by contract to have the coupler accepted based on high power performance
• It was not required to have them built ESS FPC prototypes beforehand in order to be part of the call for tender for the series. The bid-winning company did build a pair of prototypes
• Having a power test of the prototypes was anyway necessary to prove them the level of risk of FPC failure is acceptably low, and at least that the design (RF, thermo-mechanical) is valid
• Pres-series of 6 couplers delivered in spring 2018
After the production readiness review is passed, manufacturer capability is assessed based on

• Initial Samples of each critical manufacturing step:
  – Cu coating on real size ss tube
  – Window
  – Antenna weld and electropolishing
  – Bias insulator
• a pre-series of 6 couplers: they must pass acceptance test

For each pair acceptance is based on:
• Dimension control
• Leak test, RGA
• Visual inspection
• RF performance

After preseries acceptance, and QC control audit, series production is authorized

Sampling of critical processes is maintained but is set at a different rate
STATUS OF ESS COUPLERS

• 6 pre-series FPC manufactured; currently conditioning the 2nd pair

• All but 2 existing couplers have been conditioned and part of the medium beta technology demonstrator cryomodules and acceptance of preseries

• 1 FPC has gone through installation on a ESS high beta 5-cell cavity, and installed at UPPSALA in horizontal test cryostat HNOOS; passed room temp conditioning, final conditioning with cavity at 2K, and cavity on –tune operation at 2K
Limitations of the setup:
- Max pulse length of RF source is 2.6 ms
- Reduced pumping speed

Room temp. operation

2K operation

Courtesy H.Li, T. Hamelin
MANUFACTURING OF PROTOTYPES AND PRE-SERIES CONCERNS

• Copper coating requires most follow-up

• In our manufacturing scheme, Cu coating is produced by a level2 sub-contractor

• At least 3 iteration on the tooling and process has been necessary in order to obtain 2+4+6 = 12 double-wall tubes with good quality.

• The coating process is operator-dependant, our experience is that each change of operator involves quality problems for the first batch this person produces.

• Doorknob Al waveguide welding repeated issues have been canceled by switching to a mechanically assembled WG
LIPAC CRYOMODULE

- **Requirement for IFMIF EVEDA phase:** 8 Power Couplers are needed with a maximum nominal operating RF power of 70 kW CW.

- **RF power validation needs for the Power Coupler:** 100 kW CW in TW and SW modes.

- **Frequency** 175 MHz / $Q_{ext} = 6.5 \times 10^4$.

H. JENHANI, PIP-II Fine Tuning Workshop | June 25-27, 2018
MAIN VALIDATION STAGES FOR THE PROTOTYPING PHASE

Validation of processes based on samples:
- **Copper plating validation**: RRR, thickness, adhesion
- **TiN validation**: Thickness measurements

Validation based on mock-up:
- Assembling processes validation
- RF measurements
- Easy cleaning of vacuum parts

Validation based on a single prototype coupler pair:
- **Acceptance tests:**
  - Desorption test
  - Surface aspect controls
  - Dimension controls
  - Thermal shocks + Vacuum leak tests
  - Water cooling hydrostatic pressure and tightness tests
  - Assembling and disassembling test
- RF conditioning up to 100 kW CW TW/SW

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The cleaning and assembly aspects were considered since the design stage.

Cleaning tests were performed on samples and couplers parts before the final cleaning.

Assembly of the series couplers

Assembly of the coupler parts in ISO5 cleanroom with adapted tools (CEA procedures)

Systematic cleanliness control

Assembly of a coupler pair on their test box in ISO5 cleanroom
RF POWER TESTS PROGRESS

RF conditioning test operating conditions:

- TW and SW configuration
- Several SW RF configuration allowing to have the maximum RF field on the critical parts
- Gradual increase of power
- E-current, vacuum and light detection diagnostics near the ceramic and fast hardware interlocks
- Particle free vacuum pumping and venting systems
- Efficient and hydrocarbon free pumping system

RF conditioning results:

- 2 prototype couplers RF conditioned successfully
- 1 prototype coupler RF tested successfully on HWR cavity.
- 4 series couplers RF conditioned successfully
- 4 series couplers cleaned and assembled to be tested soon

The RF conditioning procedure allowed to have a low degassing of the surfaces (<10^-7 mbar) at the operation power and even at 100 kW CW and TW and SW configurations.
IFMIF MANUFACTURING PHASE ISSUES

• Several years hiatus between prototyping and series manufacturing, covered within a single contract with the same manufacturer

• Copper coating quality issues, requiring stripping of layer and re-process for most of parts

• Company did not provide the top level QC due to the low number (8) of couplers

• Repeated cleanliness issues, dimension control issues