Power Couplers for Superconducting RF Cavities

Rajesh Kumar
IADD, BARC
Plan of the talk

• Introduction

• Design and manufacturing of power couplers

• High Power test facilities

• Summary
## Indian Institution Fermilab Collaboration (IIFC)

### Schedule of Coupler development

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Major Milestone</th>
<th>Quantity</th>
<th>Delivery date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(a) Design of 325 MHz Power Coupler</td>
<td></td>
<td>Approved design awaited from FNAL</td>
</tr>
<tr>
<td></td>
<td>(b) Design of 650 MHz Power Coupler</td>
<td></td>
<td>Approved design awaited from FNAL</td>
</tr>
<tr>
<td>2</td>
<td>(a) Fabrication of 325 MHz Power Coupler</td>
<td>3</td>
<td>16 months after delivery of 1.a</td>
</tr>
<tr>
<td></td>
<td>(b) Fabrication 650 MHz Power Coupler</td>
<td>6</td>
<td>16 months after 1.b</td>
</tr>
</tbody>
</table>

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RRCAT 18-21 July 2017
<table>
<thead>
<tr>
<th>Cavity</th>
<th>RF Power * (CW)</th>
<th>Nos. Required</th>
<th>Remarks* (Max. power requirement for 30 mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>325 MHz, SSR0 (3-10 MeV)</td>
<td>20kW</td>
<td>19</td>
<td>60 kW for 2 MeV gain per cavity</td>
</tr>
<tr>
<td>325 MHz, SSR1 (10-32 MeV) (10-50)</td>
<td>20 kW max.</td>
<td>10 (26)</td>
<td>60 kW for 2MeV gain per cavity</td>
</tr>
<tr>
<td>325 MHz, SSR2 (32-160 MeV) 50-205)</td>
<td>20 kW max.</td>
<td>20 (53)</td>
<td>~ 90 kW for 3 MeV gain per cavity</td>
</tr>
<tr>
<td>650 MHz, elliptical-beta=.6 (205-440) 1</td>
<td>60 kW max.</td>
<td>18(48)</td>
<td>~180 kW for 6 MeV gain per cavity</td>
</tr>
<tr>
<td>650 MHz, elliptical-beta=.9 (.8) 440-1GeV (up to 1 GeV)</td>
<td>60 kW max.</td>
<td>23(63)</td>
<td>~300 kW for 10 MeV gain per cavity</td>
</tr>
<tr>
<td>650 MHz, elliptical-beta=.9 (1-3 GeV)</td>
<td>60 kW max.</td>
<td>66</td>
<td>For BARC and RRCAT 1 GeV accelerators, couplers are required up to 1 GeV only</td>
</tr>
<tr>
<td>Total couplers per accelerator</td>
<td>* 5 mA current</td>
<td>71(~209)</td>
<td></td>
</tr>
</tbody>
</table>

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Role of RF Power Couplers

- Impedance matching between incoming RF line and cavity
- Couples the incoming RF line’s EM mode to Cavity mode
- Provides Vacuum barrier between cavity and RF line
- Coupling part (probe, loop or iris) projects into cavity
Coupler Classification

Wave guide type
- Side iris coupled
  - with stand alone RF window
- End iris coupled

Coaxial Type
- Loop coupling
  - with planar (disc type) RF window integrated to assembly
- Probe coupling

Waveguide-coax
- Loop coupling
- Probe coupling
  - with planar (disc type) or cylindrical RF window integrated to assembly
Coupler design starts with the choice of coupling mechanism and coupling coefficient calculations using analytical methods and numerical EM Solvers. Further, design of impedance matching, multipacting, thermal, mechanical, fabrication and testing are important.

Ref: Davide Alesini, “Power Coupling”, in CERN Accelerator school, Elbeltoft, Denmark, 2010.
Different type of coupling tuning schemes

Coupling Coefficient ($\beta$) $= 1$ => Critical coupling
$\Rightarrow$ No reflections
$\beta > 1$ => Over-coupling
$\beta < 1$ => under coupling;
$\beta = \frac{Z}{Z_0} = \frac{Q_0}{Q_{ext}}$

$\beta = 1 + \frac{P_b}{P_c}$

Coupling variation by iris rotation, or change of loop area
Coupling variation by changing probe length
Coupling variation by changing iris dimensions or tuner

Direction of power flow

Incoming power from Coax/ WG-Coax transition

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Electromagnetic analysis of RF Coupling

\[ e_o = (1 - \frac{l_2^2}{l_1^2})^{1/2} \]

\[ d = \text{iris length} \]

\[ H_1 = H \exp(-\alpha d) \Rightarrow \beta \text{ decreases with iris length} \]

\[ \beta = \frac{16Z_o k_o \Gamma_{10} e_o}{9ab(1 + \frac{3}{8} e_o^2 + \frac{15}{64} e_o^4 + \frac{315}{3072} e_o^6 + \ldots )^2} \frac{4l_1^6 e^{-2\alpha d}}{Po} \]

Q external simulations of Coaxial couplers

External Q simulation of loop coupler on RFQ cavity. Loop area is designed to obtain an External Q of about 5000.

Return loss of under-cut type coupler before and after matching

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Schematic of 50 kW CW, 350 MHz Coaxial Coupler

- Cu gasket
- Cavity flange
- Shorted stub
- Rotation possibility without changing the flange location and axis
- 61/8” line from Input
- 61/8” to 15/8” tapered transition

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Simulation model of 50 kW Coaxial Coupler

Electromagnetic waves- frequency domain (emw) module is used.
• 6 1/8” rigid coaxial line made up of Copper is tapered to 1 5/8” using a 160 mm long tapered transition.
• Capacitive discontinuity of alumina discs is cancelled by quarter wave shorted stub.
• Shorted stub is used to circulate cooling water to inner conductor
• Return loss is optimized for 350 MHz.
Simulations with COMSOL for E field
Return loss simulations

-19
-20
-21
-22
-23
-24
-25
-26
-27
-28
-29
-30
-31
-32

freq

3
3.2
3.4
3.6
3.8
x10^8

S-parameter, dB, 11 component (dB)

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RF Simulations for Coupling Coefficient

- Half Height WR2300 waveguide is reduced to small cross-section on the RFQ cavity
- Ridge loading is used to maintain the same cut-off and impedance match
- Cavity Frequency shift caused by the coupler is < 0.03%

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Straight ridge transition based coupler for 352.2 MHz

Top view of the coupler  Cross-section view of coupler
Proposed tuners on straight ridge transition based coupler

CST Microwave studio model of coupler with tuners

Return loss variation with frequency

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Straight ridge transition based coupler for 352.2 MHz

(a) Top view of the coupler       (b) cross-section view of coupler
Optimized dimensions for straight ridge transition based coupler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$</td>
<td>WR2300 width</td>
<td>584.2</td>
</tr>
<tr>
<td>$h$</td>
<td>WR2300 height</td>
<td>146.05</td>
</tr>
<tr>
<td>$wl$</td>
<td>Input Port length</td>
<td>160</td>
</tr>
<tr>
<td>$c$-$ow$</td>
<td>Central section- overall width</td>
<td>334</td>
</tr>
<tr>
<td>$cw$</td>
<td>Central ridge width</td>
<td>69.4</td>
</tr>
<tr>
<td>$cl$</td>
<td>Central ridge length</td>
<td>315</td>
</tr>
<tr>
<td>$cg$</td>
<td>Central ridge gap</td>
<td>11.5</td>
</tr>
<tr>
<td>$ch$</td>
<td>Central ridge height</td>
<td>64</td>
</tr>
<tr>
<td>$ew$</td>
<td>End ridge width</td>
<td>89</td>
</tr>
<tr>
<td>$e$-$ow$</td>
<td>End section- overall width</td>
<td>189</td>
</tr>
<tr>
<td>$eg$</td>
<td>End ridge gap</td>
<td>1.55</td>
</tr>
<tr>
<td>$eh$</td>
<td>End ridge height</td>
<td>35</td>
</tr>
<tr>
<td>$el$</td>
<td>Output Port length</td>
<td>20</td>
</tr>
</tbody>
</table>
RF Simulations for Return loss of coupler transition and fields

Iterative simulations are performed in Microwave Studio to reach at optimized dimensions of different coupler sections to meet the design goals.

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Max. E field is ~1.6 MV/m at 250 kW in straight ridge
RF loss at 250 kW input is about 700 W in tapered coupler and 800 W in straight ridge coupler.
Comparison of multipacting in two couplers

<table>
<thead>
<tr>
<th>Coupler Type</th>
<th>Multipacting onset Power level in rectangular WG (kW)</th>
<th>Multipacting onset Power level in central ridge WG (kW)</th>
<th>Multipacting onset Power level in end ridge WG (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight ridge</td>
<td>22.4</td>
<td>.57 to 17</td>
<td>.38</td>
</tr>
<tr>
<td>Tapered ridge</td>
<td>22.4</td>
<td>.38 to 17</td>
<td>.38</td>
</tr>
</tbody>
</table>
Multipacting analysis of waveguide coupler

Simulations with CST Particle studio showing electron cloud inside coupler at 0.6 kW, 352.2 MHz

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Thermal analysis of high power waveguide couplers for LEHIPA


Temperature plot in the Iris and end ridge waveguide (flow velocity 2.0m/sec, material Copper)
IIFC 325 MHz Coupler

Material:
- Coaxial coupler parts, antenna: OFE Copper, ETP Copper, brass
- Vacuum Flanges facing cryogenic system: SS 316LN

3 1/8 inch Coaxial line (79.3 mm OD)

Coupler part under cavity vacuum and cryogenic system

View of 325 MHZ coupler

928 mm

325 MHz Main Coupler Specification Document
Fermilab Specification: 5500-ES-371114
Fermi National Accelerator Laboratory
May 09, 2012

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Cut view of 325 MHz Coupler

Bellows material changed now

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May 09, 2012
Simulation model of 325 MHz Coupler

RF in

Standard 3 1/8” line, Zo = 50 Ohm

Coax. OD: 72.3 mm, ID: 12.7 mm, Zo = 100 Ohm

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RF simulations on 325 MHz Coupler

S1,1dB

shorting_length=47 : -20.166282
shorting_length=48 : -20.710999
shorting_length=49 : -21.143255
shorting_length=50 : -21.25674
shorting_length=51 : -21.606642
shorting_length=52 : -21.675223
shorting_length=53 : -21.744788
shorting_length=54 : -21.830317
shorting_length=55 : -21.980289
shorting_length=56 : -21.650262
shorting_length=57 : -21.372576

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Multipacting simulation on 325 MHz Coupler

Multipacting is a resonant electron multiplication in RF fields under vacuum and it can cause undesired effects like reflections, arcing, temperature rise etc. in couplers and cavities.

Pin = 7.2 kW

Pin = 8.4 kW

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Heat load studies

Cavity end  

warm side

CST Microwave Studio Simulation model
Temperature distribution along coupler length

Temperature distribution along the length of PX 325 cold coupler part

- **Dynamic temperature distribution with graded material parameters (P30kW)**
- **Dynamic temperature distribution with nonlinear thermal conductivity (P30 kW)**
- **Static analysis with graded thermal conductivity**
- **Static analysis with non-linear thermal conductivity cst option**

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Non linearity in material conductivities

Thermal conductivity of copper

Electrical conductivity of Copper

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325 MHz Coupler Cold part

+  

Temperature range spans from 2 K to room temperature

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Status of Power Coupler prototype fabrication

325 MHz Power Coupler’s Cold part being assembled for brazing at CEERI PILANI.

- Based on the prototype coupler design received from Fermilab for 325 MHz Coupler, fabrication has been initiated at CDM and CEERI-PILANI
- A draft MOU is under preparation with CEERI-PILANI for fabrication of cold part of 325 MHz and 650 MHz Couplers
3 D Model of 650 MHz Coupler
RF Simulation model of 650 MHz Coupler
Dimensional sensitivity studies on 650 MHz coupler

**Return loss Vs WG short position**

- **X-axis:** WG short position in mm
- **Y-axis:** Rloss(dB) at 650 MHz

**Frequency (MHz) Vs WG short position**

- **X-axis:** WG short position in mm
- **Y-axis:** Min. RLoss Frequency (MHz)
RF Couplers (325 MHz) mounted on Cryomodule
650 MHz Coupler mounted on Cryomodule

650 MHz coupler installed in cryomodule
Typical Test stand for 325 MHz coupler testing at room temperature (IIFC)
Typical Test stand for 650 MHz coupler testing at room temperature (IIFC)
Horizontal Test stand for 1.3 GHz cavity and coupler at Fermilab
RF Coupler Manufacturing

• Coaxial or waveguide coupler assemblies generally include RF window as they operate in high vacuum environment
• Vacuum/hydrogen furnace brazing
• Alumina brazing
• Requirement of Sub micron surface finish
• Strict dimensional tolerances
• Water or air cooling
50 kW coaxial coupler with coolant channels

Coaxial Coupler parts before brazing of final assembly

Coaxial coupler assembly after brazing
High power testing of coaxial coupler

Coaxial Couplers have been tested up to 58 kW RF power at 1 ms, 1 Hz duty cycle (for deuteron beam experiments from RFQ)

CW Power has been raised up to 1 kW

50 kW, CW, 350 MHz RF Power Coupler developed in collaboration with CEERI PILANI
Multipacting suppression studies using magnetic field in coaxial coupler

For Axial B Field

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Multipacting suppression studies using magnetic field in coaxial coupler contd.

Particle Number (at the end of simulation) $\times$ Peak Power

- Red line: No field
- Green line: $B_x = 30$ G
- Blue line: $B_x = 50$ G
- Orange line: $B_x = 100$ G

For Azimuthal B Field

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Coupler Fabrication and Testing status

50 kW Peak power Coaxial coupler used during beam acceleration from RFQ

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RF Coupler Testing/Conditioning

- Vacuum leak testing
- RF laboratory equipped with VNA, test cavities
- High Power conditioning
Coupler Fabrication and Testing status contd.

Coupler view from window side

Vacuum Leak Testing at CEERI-PILANI

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RF cavity for coupler testing

RF Cavity developed for Coaxial Coupler Conditioning

RF Coupler leak tested at LEHIPA, BARC

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RF cavity for coupler testing
Coaxial couplers testing on RFQ cavity

RF Coupler, tested up to 15 kW, with 0.5% duty cycle & 58 kW, 350 MHz with 0.1% duty cycle
Prototypes of ridge waveguide couplers

250 kW, 352.2 MHz ridge loaded waveguide iris coupler prototypes for RFQ and DTL cavities
RF Measurements on ridge waveguide couplers (without tuners)
RF Measurements on ridge waveguide couplers (with tuners)

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Waveguide coupler (250 kW, 352.2 MHz) for 20 MeV proton accelerator LEHIPA

250 kW, CW, 352 MHz RF waveguide Coupler under development

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Different type of couplers have been developed indigenously for LEHIPA. Development of 325 MHz, 650 MHz is in progress for IIFC.

250 kW CW, 352.2 MHz, Waveguide Coupler for LEHIPA with all ports

These waveguide couplers are fabricated by vendors in Mumbai & Pune. The iris part of couplers is fabricated at CEERI Pilani.
Development of high power RF couplers at IADD, BARC

Two copper halves and S/steel flange before brazing

Brazed iris coupler at CEERI Pilani
Waveguide couplers testing on RFQ cavities of LEHIPA

These couplers have been successfully tested for more than 200 kW RF Power in pulsed mode and used for proton beam acceleration to 1.24 MeV energy. Presently, two couplers are being used to feed more than 400 kW RF Power to RFQ cavities at low duty cycles. The beam energy analysis is being carried out.

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Vacuum signals during RF Conditioning on RFQ cavities of LEHIPA

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High Power Test facilities for Couplers
Basic layout of high power resonant ring
Main components required for setup

• RF amplifier of minimum output power 3 kW @325 MHz
• Primary line Directional coupler (coupling factor 15 dB)
• RF load
• Secondary line Directional coupler (coupling factor 50 dB)
• Waveguide tuners
• Waveguide H bends
• Waveguide to coaxial transitions
• Test cavity
• DC Block
• RF couplers to be tested (02 nos)
RF Cavities for test facilities

Test cavity for 250 kW, 352.2 MHz Waveguide Couplers

Test cavity for 325 MHz IIFC Couplers (presently under fabrication)
TiN coating system for RF window of SC Couplers

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Status of SC Coupler development

• Detailed analysis of 325 MHz Fermilab Couplers design is in progress
• Metallized alumina discs, OFE Copper rods have been procured
• CDM-BARC has initiated machining of coupler parts.
• TiN coating set-up order is placed
• Most of the RF components for 40 kW resonant ring for coupler testing have been designed, fabricated and characterized with VNA.
Summary

• High power couplers for warm and SC cavities are under development at IADD, BARC.

• RF Power Couplers developed so far (for warm cavities) have been successfully used in beam experiments at low duty cycles.

• The design aspects of SC couplers are being studied.

• High power test facilities are being developed at IADD, BARC for testing of these couplers.
Thanks