High Power RF Coupler design for Accelerator Cavities

Rajesh Kumar
IADD, BARC
Plan of the talk

• Introduction
• Coupler Design
• Coupler Manufacturing
• RF measurements
• High power Conditioning /Test facilities
• Summary
Introduction

Power coupler

- Transfers or couples the required RF power to the accelerator cavity
- Provides required impedance matching (to minimize reflections)
- Provides required Coupling (coefficient-β) to the cavity
- Separates the air side from vacuum side
Typical RF – Coupler-Cavity system for accelerators

- RF Amplifier
- Circulator
- Matched load
- DC
- RF Coupler
- E field in cavity
- 50 kW, 350 MHz Coupler
- 50 keV beam
- 400 keV beam
- High vacuum Components

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Equivalent circuit of coupler cavity system

Ref. J.P. Holzbauer, Ph.D.
USPAS – Applied Electromagnetism Lecture 5
1/27/2016
Different types of coupling schemes

\[ \beta = 1 + \frac{P_b}{P_c} \]

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

Waveguide Side wall iris

WG end wall iris

Coupling variation by iris rotation, or change of loop area

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RF coupling mechanisms

The coupling is fixed once we have construct the cavity.

It is possible to change the coupling by changing the position of the short circuit plane, the antenna penetration or the loop orientation.

RF coupling mechanisms contd.

Technical Considerations

• RF Power (Coax Vs WG)

• Frequency

• Pulsed/CW

• Stand alone vacuum barrier (window) or integrated to assembly
Waveguide & Coaxial windows

Coaxial Conical Capacitive Cylinder Cylinder at WG transformer

Waveguide window Choke type window
Waveguide & Coaxial lines

WG Cut off:

\[ f_c = \frac{c}{2\pi} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \]

- Waveguide size becomes very large for lower frequencies, hence preferred for frequencies generally above UHF

Eg. WG size for 352 MHz (WR2300 Hh) is 584.2 mm by 146.05 mm

Ref. Microwave Engineering, D.M. Pozar

Attenuation of various modes in a rectangular brass waveguide with \( a = 2.0 \) cm.

- for WG

\[ \alpha_c = \frac{R_s}{a^3 b \beta \kappa} \left(2b \pi^2 + a^3 k^2\right) \]

- for Coax

\[ \alpha_c = \frac{R_s}{2\eta \ln b/a \left(\frac{1}{a} + \frac{1}{b}\right)} \]

Ref. Microwave Engineering, D.M. Pozar
Basics of coupling calculations

\[ Q_o = \omega_o \frac{U}{P_o} \]
\[ Q_{ext} = \omega_o \frac{U}{P_{rad}} \]
\[ \frac{1}{QL} = \frac{P_o}{\omega U} + \frac{P_{rad1}}{U} + \frac{P_{rad2}}{U} + \ldots \]
\[ Q_L = \frac{f_o}{BW} \]
\[ Q_o = \frac{1}{QL} (1 + \beta_1 + \beta_2 + \ldots) \]
Coupling calculations contd.

\[ Z_{in} = \frac{R}{n^{2}} \]

\[ \beta = \frac{Z_{in}}{Z_{o}} = \frac{R}{Z_{o}n^{2}} \]

\[ \Gamma = \frac{Z_{in} - Z_{o}}{Z_{in} + Z_{o}} \]

\[ \beta = \frac{(1 + \Gamma)}{(1 - \Gamma)} \]
Procedure for Coupling measurements (frequency domain)

- Vector Network Analyzer (VNA) is generally used for measuring the coupling and quality factor.
- Using VNA, S11 measurement gives reflection coefficient value which can be used to calculate reflection coefficient. From 3 dB points, QL and Qo can be calculated.
- From Smith chart, impedance circle size tells whether the system is under coupled or overcoupled.
- Transmission measurements are useful for overcoupled and undercoupled systems as 3 dB point in Return loss (S11) may not be available.
- Time domain methods are useful in SC cavities and for dynamic measurements.
Quality factor using measurements using Transmission method

Ray Kwok & Ji-Fuh Liang
*Characterization of High-Q Resonators for Microwave-Filter Applications*
IEEE Trans MTT vol.47, p111-114, 1999
Case 1: Critical coupling

sharp & high return loss

radius ~ 1 circle

Ref. Q factors - Dr. Ray Kwok

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Case 2: Over coupling

lower return loss

Ref. Q factors - Dr. Ray Kwok

radius > 1

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Case 3: Under coupling

lower return loss

radius > 1

Ref. Q factors - Dr. Ray Kwok
Time domain coupling measurements

\[
\begin{array}{ccc}
\beta < 0.5 & \beta = 1 & \beta > 2 \\
\hline
P_f & P_t & P_r & P_r & P_r & P_r \\
V_f & V_t & V_r & V_r & V_r & V_r \\
\end{array}
\]

Ref. J.P. Holzbauer, Ph.D.
USPAS – Applied Electromagnetism Lecture 5
1/27/2016

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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.
Different type of coupling tuning schemes

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

- Coupling variation by iris rotation, or change of loop area
- Coupling variation by changing probe length
- Coupling variation by changing iris dimensions or tuner
- Waveguide Side wall iris
- Coupling variation by changing probe length
- Waveguide End wall iris

$\beta$ = 1 + $P_b/P_c$
Electromagnetic analysis of RF Coupling

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

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

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

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


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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.
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

freq(6) = 3.5e8  Volume: Electric field norm (V/m)

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Return loss simulations

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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

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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

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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>

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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.

Iterative simulations are performed in Microwave Studio to reach at optimized dimensions of different coupler sections to meet the design goals.
Max. E field is ~1.6 MV/m at 250 kW in straight ridge

Distance along the coupler (mm)
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>0.57 to 17</td>
<td>0.38</td>
</tr>
<tr>
<td>Tapered ridge</td>
<td>22.4</td>
<td>0.38 to 17</td>
<td>0.38</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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Temperature plot in the Iris and end ridge waveguide (flow velocity 2.0m/sec, material Copper)

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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.

For Azimuthal B Field

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IIFC 325 MHz Coupler

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

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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

S11, dB

Frequency / GHz

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 = 7.2kW

Pin = 8.4 kW

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Heat load studies

2 K  15 K  125 K  300 K

Cavity end  d1  d2  d3  warm side

CST Microwave Studio Simulation model

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Temperature distribution along the length of PX 325 cold coupler part

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

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Non linearity in material conductivities

Thermal conductivity of copper

Electrical conductivity of Copper

T (K)

W/mK

S/m

Non linear EM Solver

2 way coupling?

Non linear Thermal Solver

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325 MHz Coupler Cold part

Temperature range spans from 2 K to room temperature
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**

- Rloss(dB) at 650 MHz
- WG short position in mm

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

- Min. RLoss Frequency (MHz)
- WG short position in mm

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RF Couplers (325 MHz) mounted on Cryomodule

Coupler and Cryomodule

Spoke resonator
Cryomodule

RF Couplers

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650 MHz Coupler mounted on Cryomodule

650 MHz coupler installed in cryomodule
Typical Test stand for 325 MHz coupler testing at room temperature (IIIFC)

Approx. 3 meter
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
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
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 (with out tuners)
RF Measurements on ridge waveguide couplers (with tuners)
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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Development of high power RF couplers at IADD, BARC

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

250 kW, 352.2 MHz Ridge waveguide couplers in Aluminium

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

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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

- H bend
- RF coupler 1
- cavity
- RF coupler 2
- H bend
- Tuner and Dir coupler
- H bend
- WG section
- Main Directional coupler
- WG section
- H bend

- 15 dB

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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
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.
Other Team Members:
Sonal Sharma, Mentes Jose, G.N. Singh

Thanks for your kind attention