Power Couplers for Superconducting RF Cavities

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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

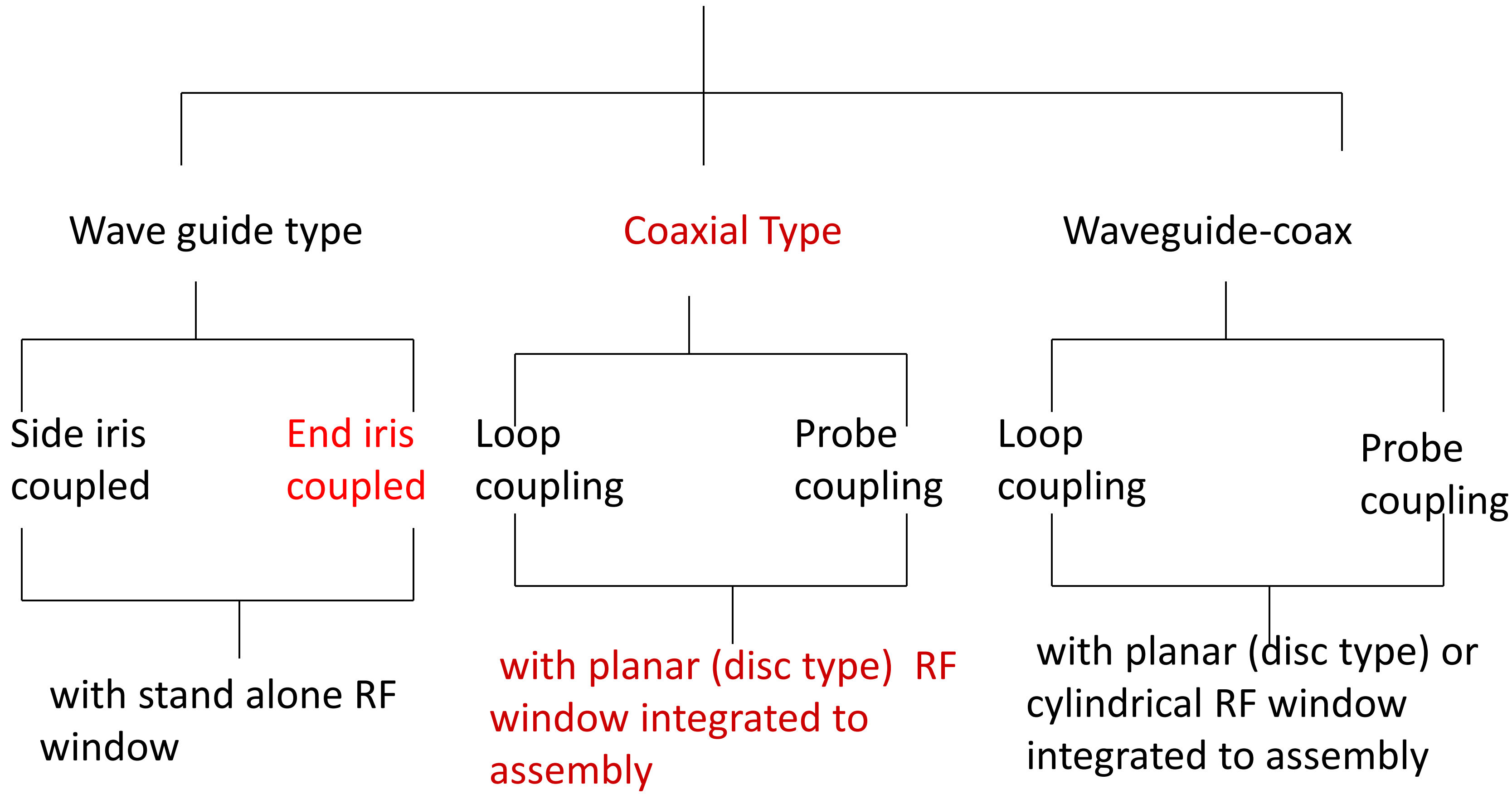
S. No.	Major Milestone	Quantity	Delivery date
1	(a) Design of 325 MHz Power Coupler		Approved design awaited from FNAL
	(b) Design of 650 MHz Power Coupler		Approved design awaited from FNAL
2	(a) Fabrication of 325 MHz Power Coupler	3	16 months after delivery of 1.a
	(b) Fabrication 650 MHz Power Coupler	6	16 months after 1.b

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

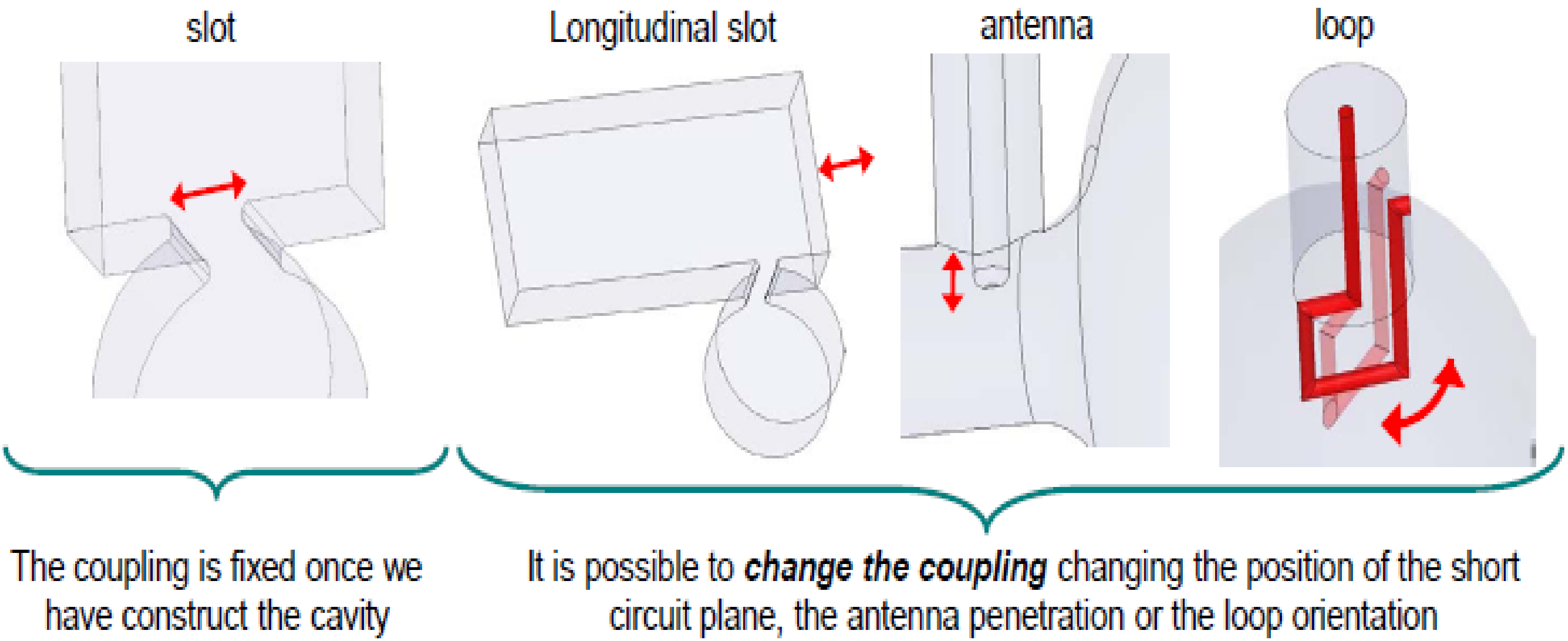
Role of RF Power Couplers

- 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



RF coupling mechanisms



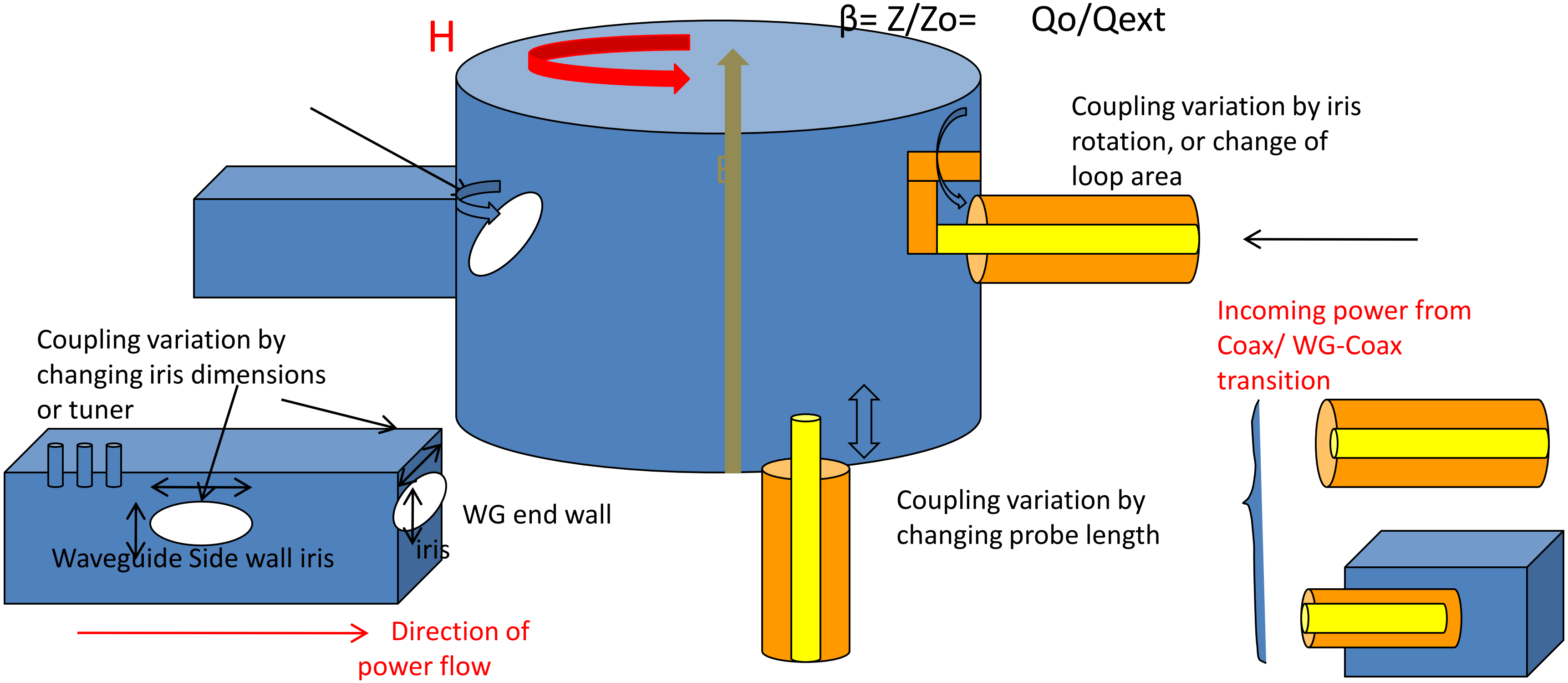
Ref. Davide Alesini," Power Coupling", in CERN Accelerator school, Elbeltoft, Denmark, 2010.

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.

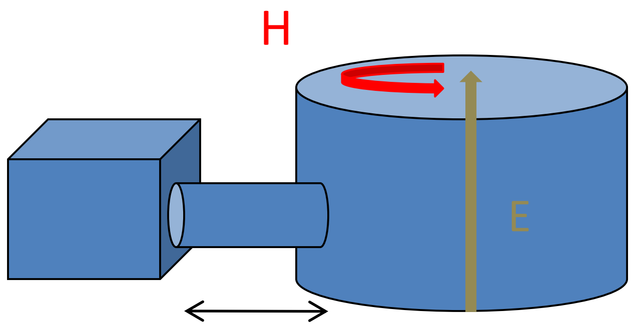
Different type of coupling tuning schemes

Coupling Coefficient (β)= 1 => Critical coupling
=> No reflections
β> 1 => Over-coupling
β < 1 => under coupling;
β= Z/Zo= Qo/Qext

β= 1+Pb/Pc

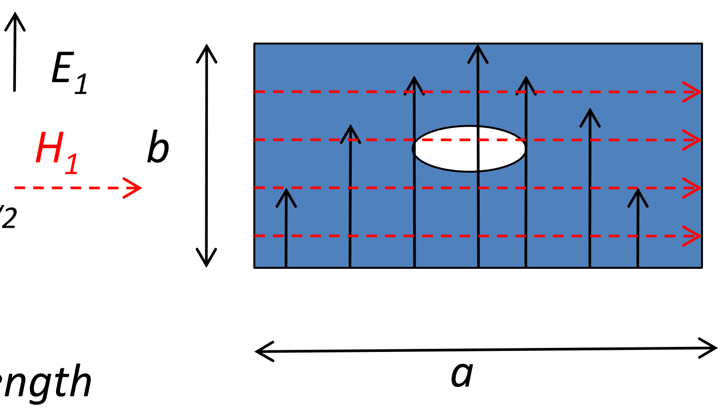


Electromagnetic analysis of RF Coupling



$e_o = (1 - l_2^2/l_1^2)^{1/2}$

Rectangular WG TE_{10} mode

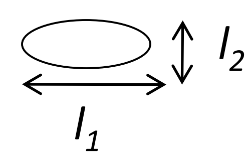


d= iris length

H_1 = *H*exp(-αd) => β decreases with iris length*

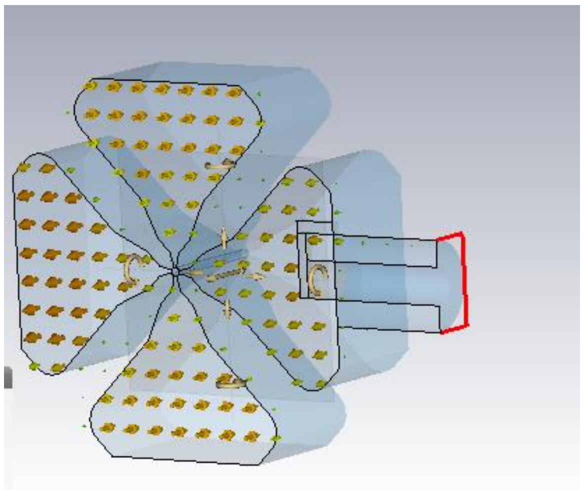
$$\beta = \frac{16 Z_o k_o \Gamma_{10} e_o^{4} l_1^{6} e^{-2\alpha d}}{9ab\left(1+\frac{3}{8}e_o^{2}+\frac{15}{64}e_o^{4}+\frac{315}{3072}e_o^{6}+..\right)^{2}} \frac{H_1^{2}}{Po}$$

iris dimensions

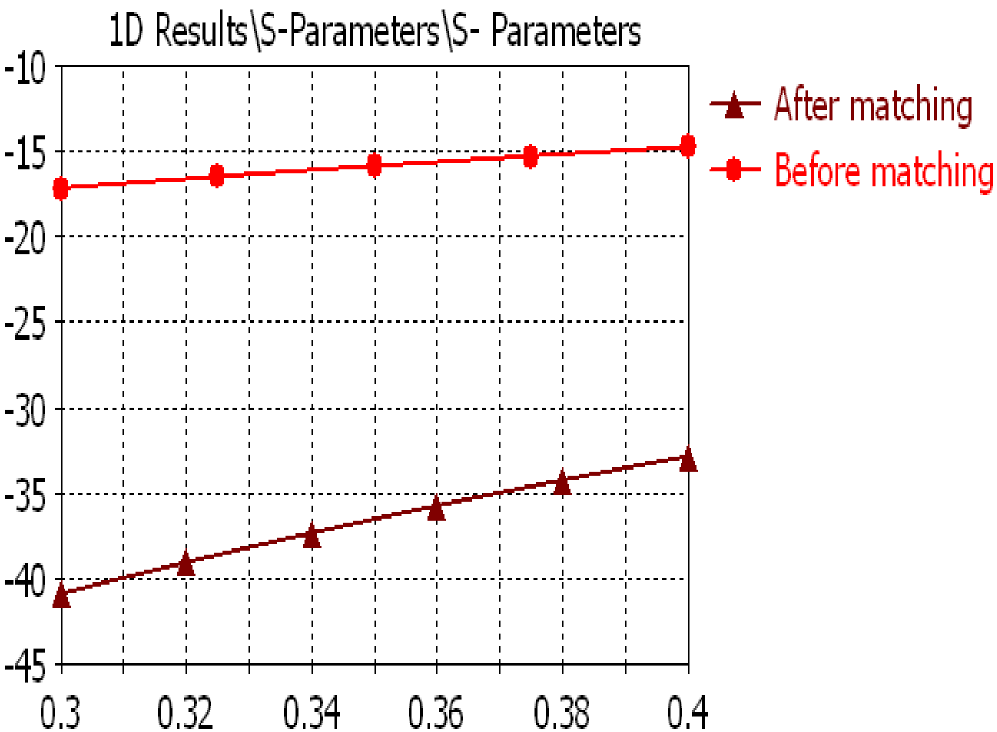


Ref. *J.Gao, Nuclear Instr. and Meth. A-309(1991) p. 5-10*

Q external simulations of Coaxial couplers

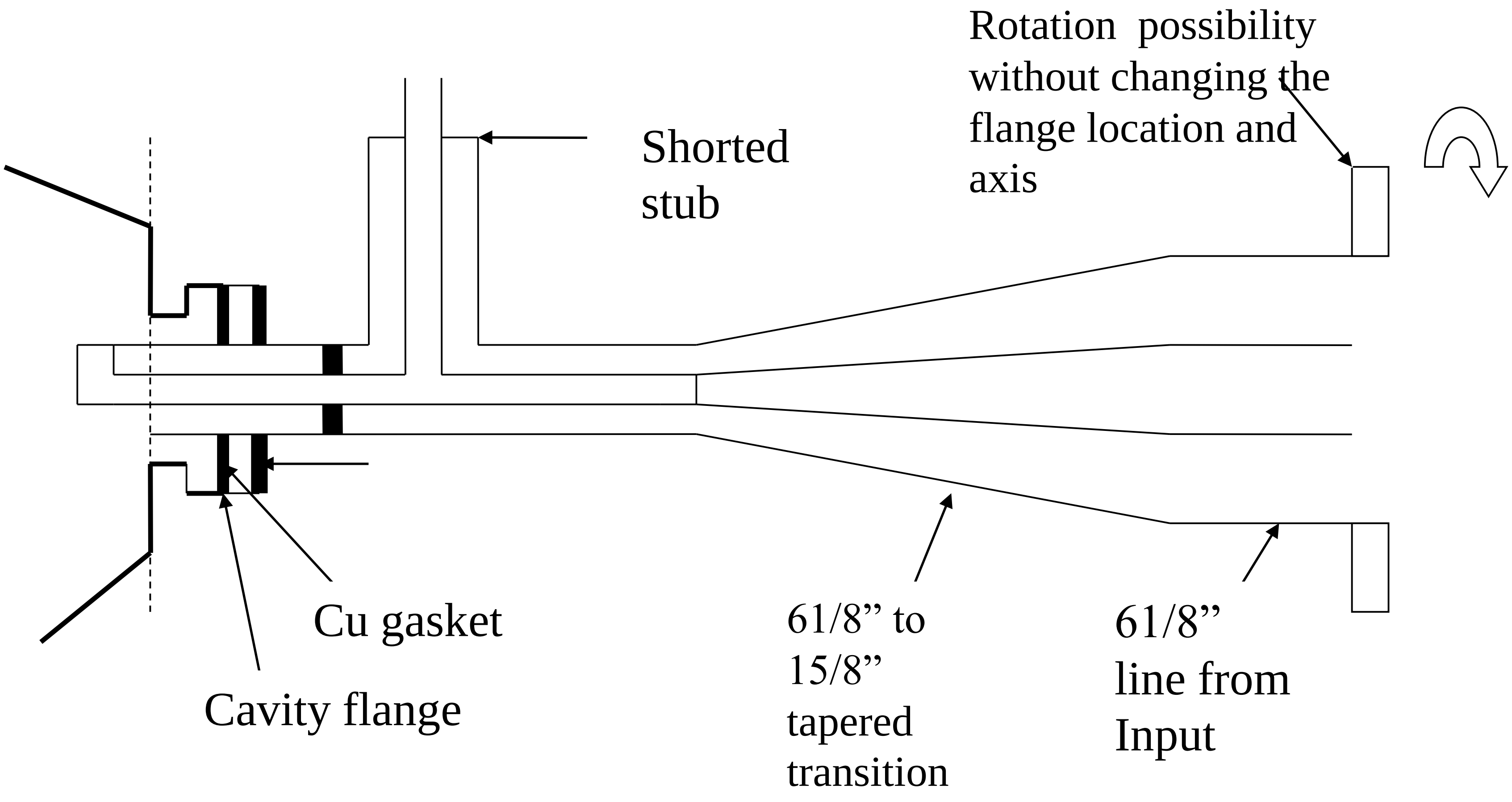


External Q simulation of loop coupler on RFQ cavity. Loop area is designed to obtain an External Q of about 5000.

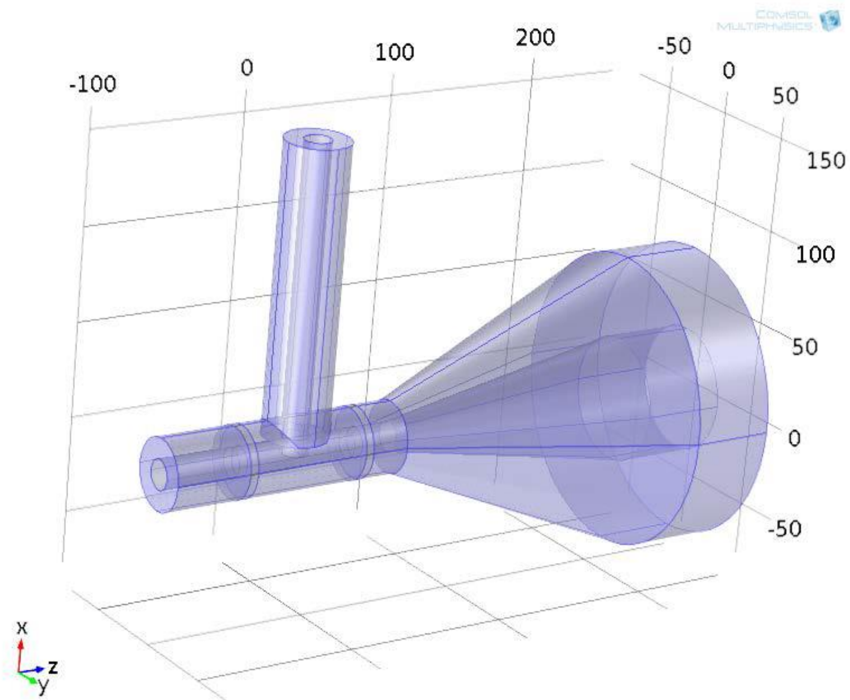


Return loss of under-cut type coupler before and after matching

Schematic of 50 kW CW, 350 MHz Coaxial Coupler



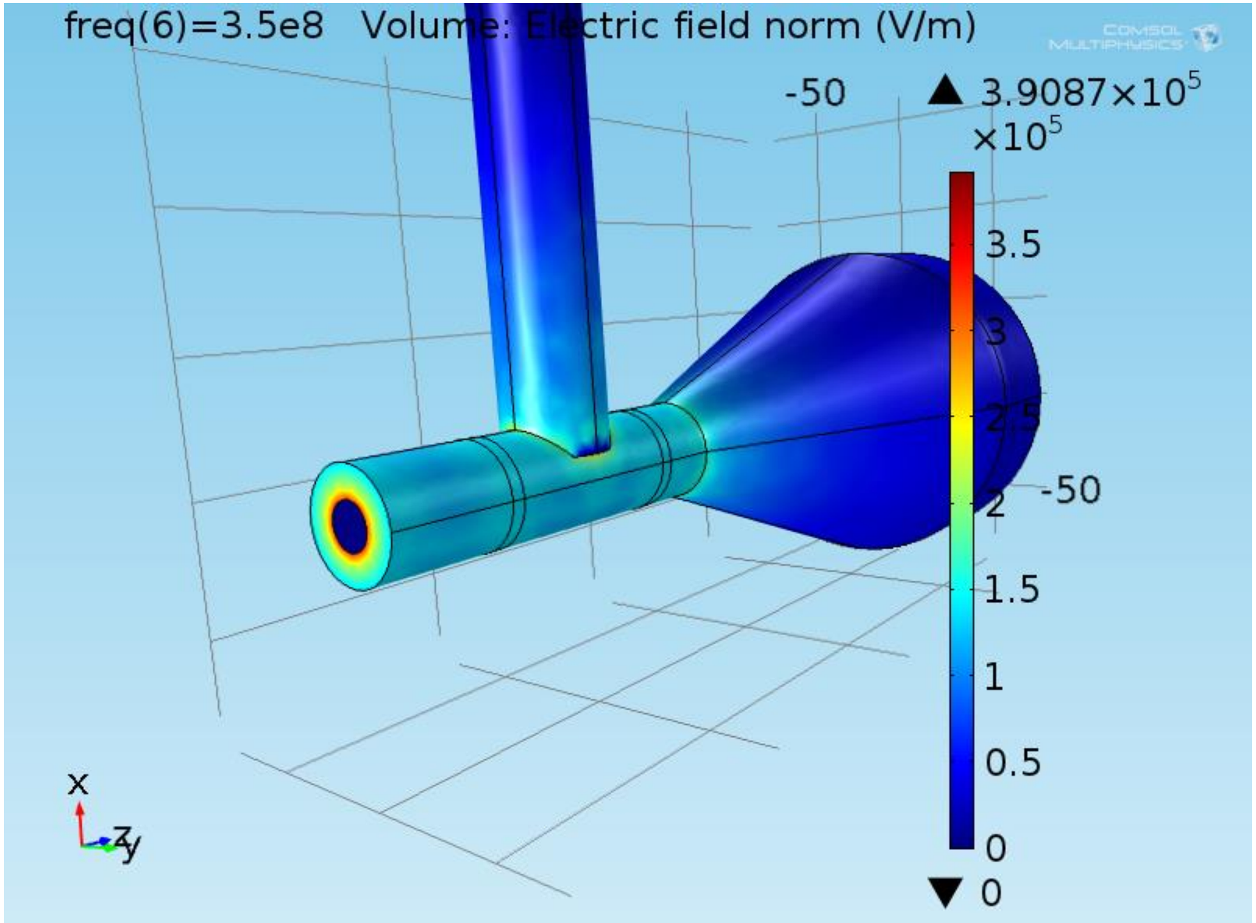
Simulation model of 50 kW Coaxial Coupler



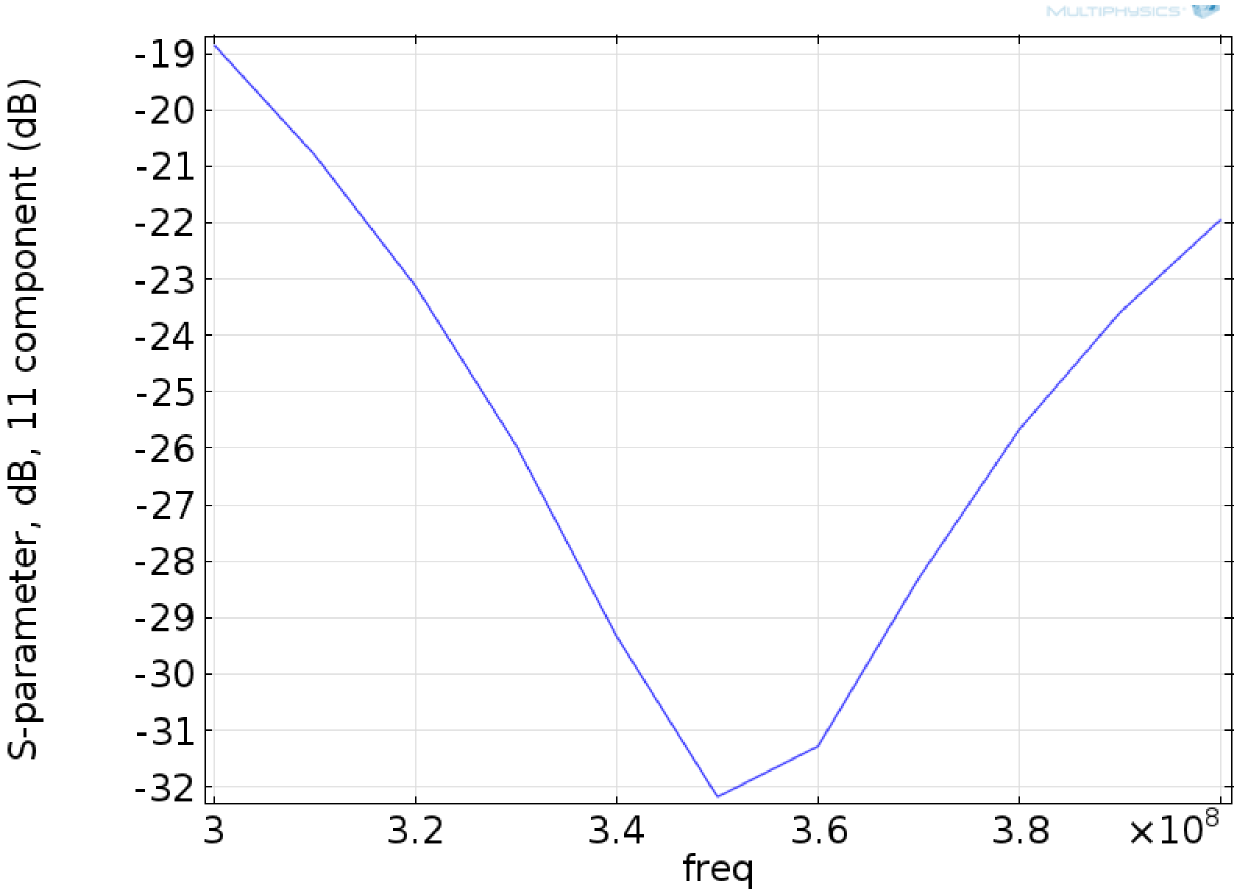
Electromagnetic waves- frequency domain (emw) module is used.

- 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

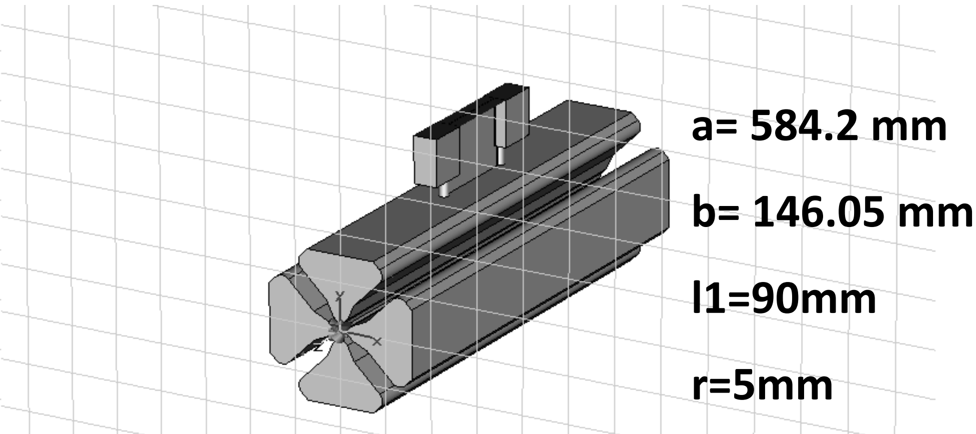


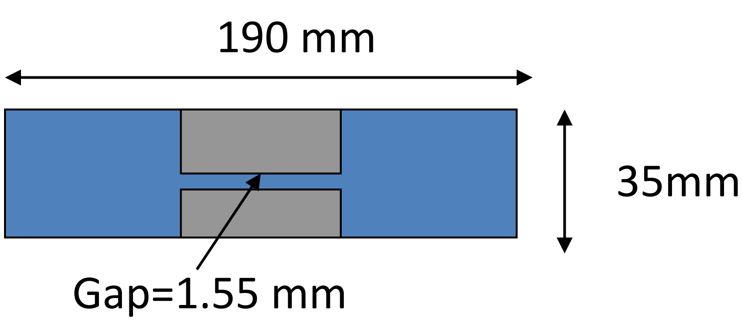
Return loss simulations

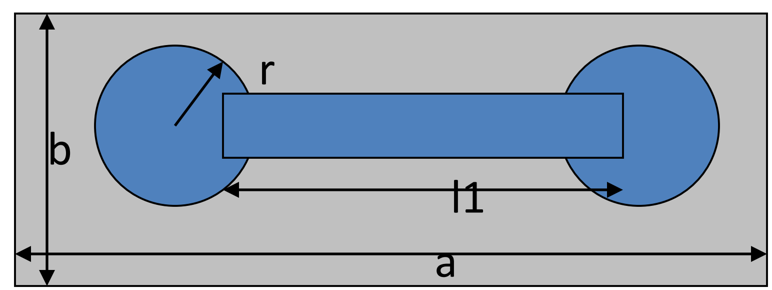


RF Simulations for Coupling Coefficient

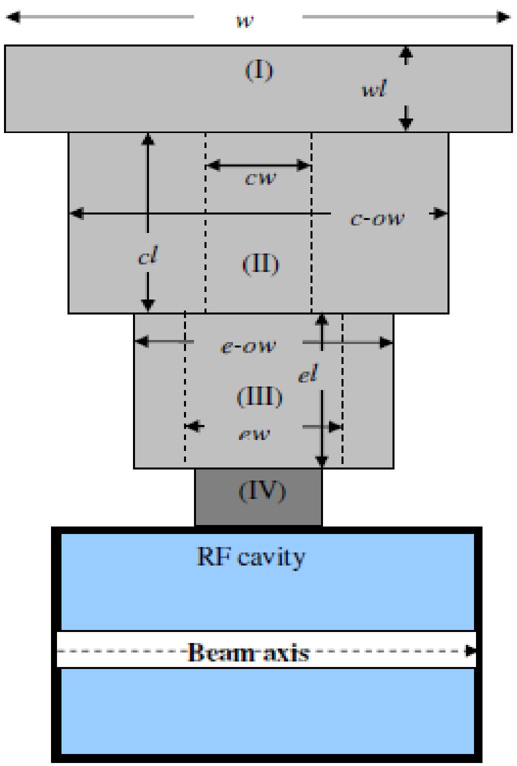
- Half Height WR2300 waveguide is reduced to small cross-section on the RFQ cavity
- Ridge loading is used to maintain the same cut-off and impedance match
- Cavity Frequency shift caused by the coupler is < 0.03 %



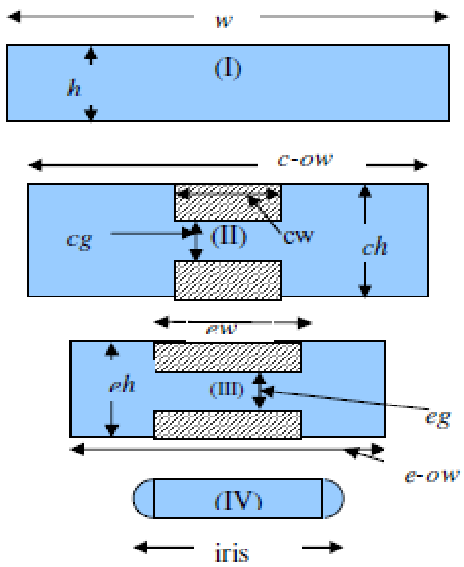




Straight ridge transition based coupler for 352.2 MHz

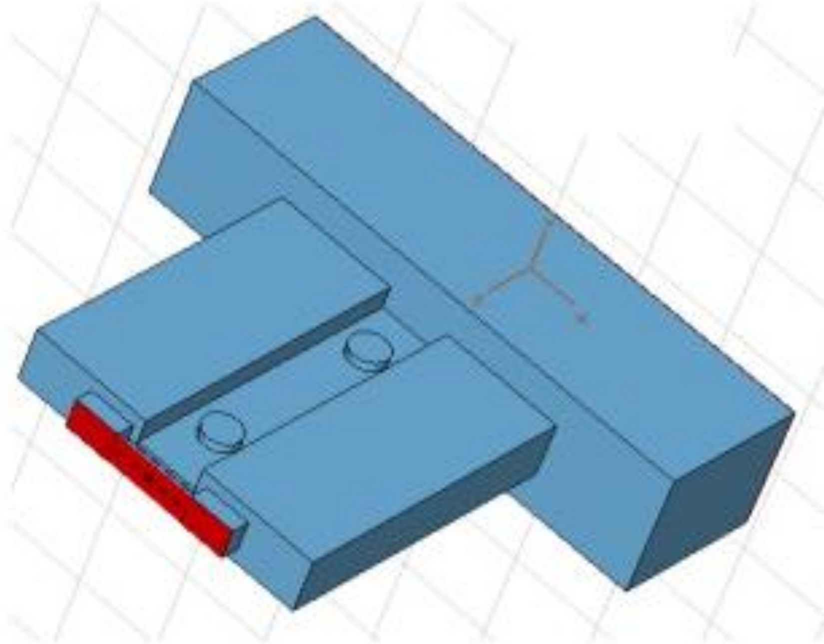


Top view of the coupler

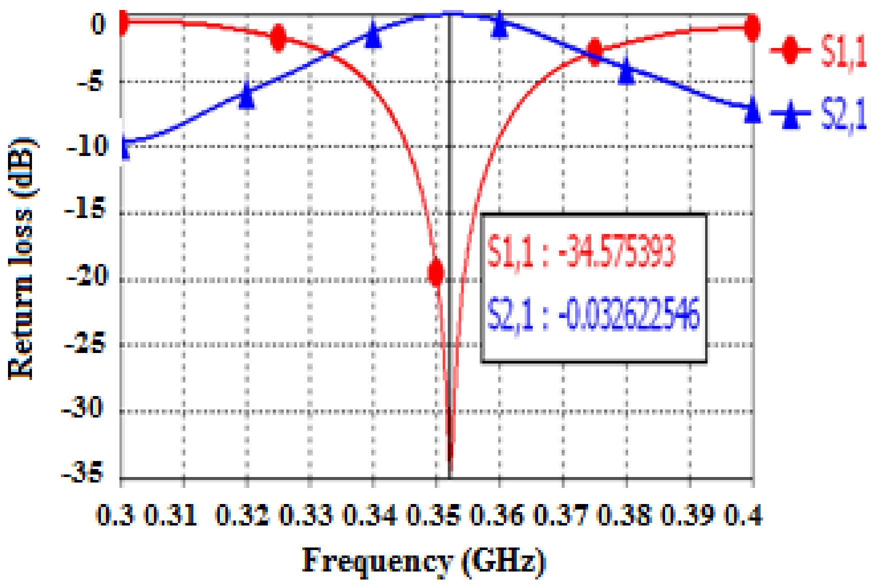


Cross-section view of coupler

Proposed tuners on straight ridge transition based coupler

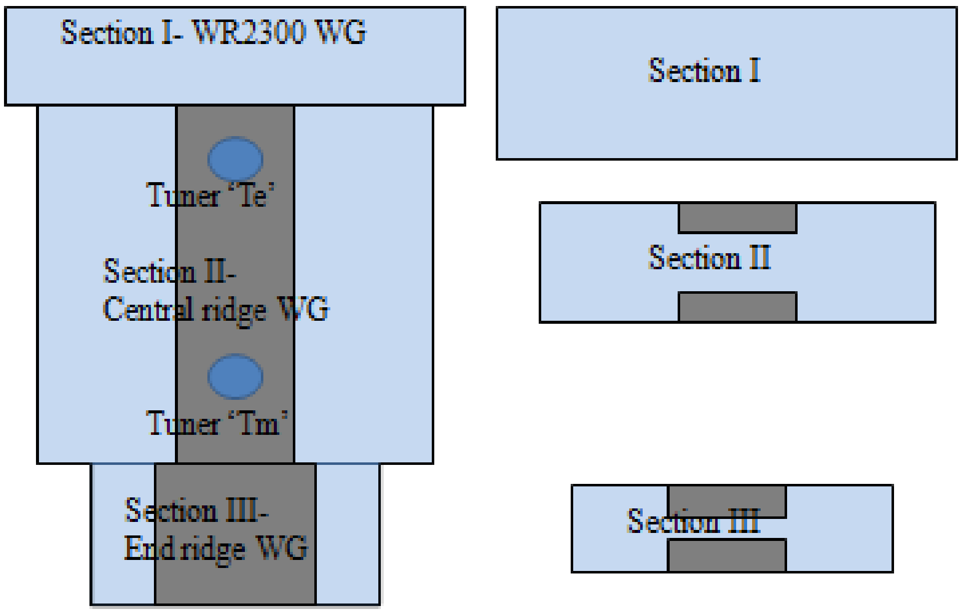


CST Microwave studio model of coupler with tuners



Return loss variation with frequency

Straight ridge transition based coupler for 352.2 MHz

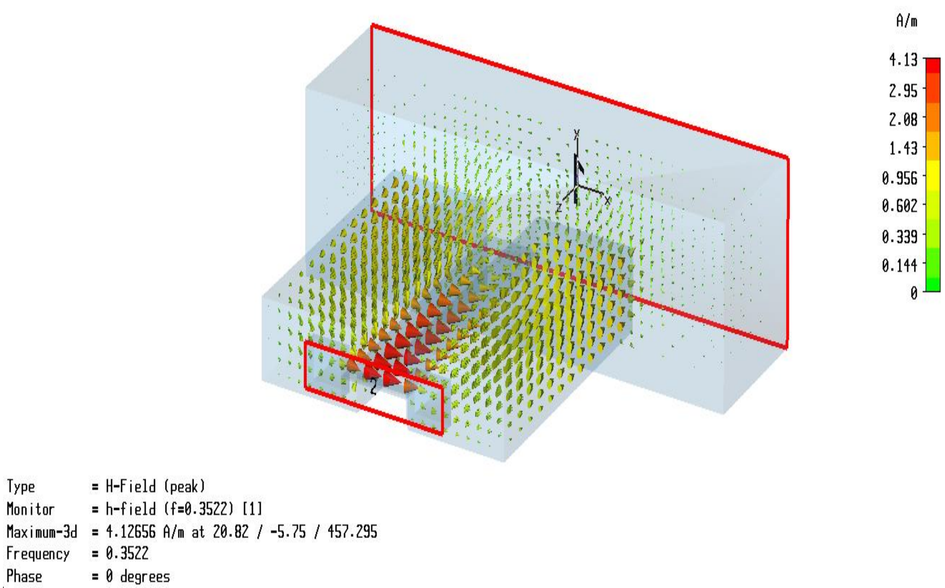


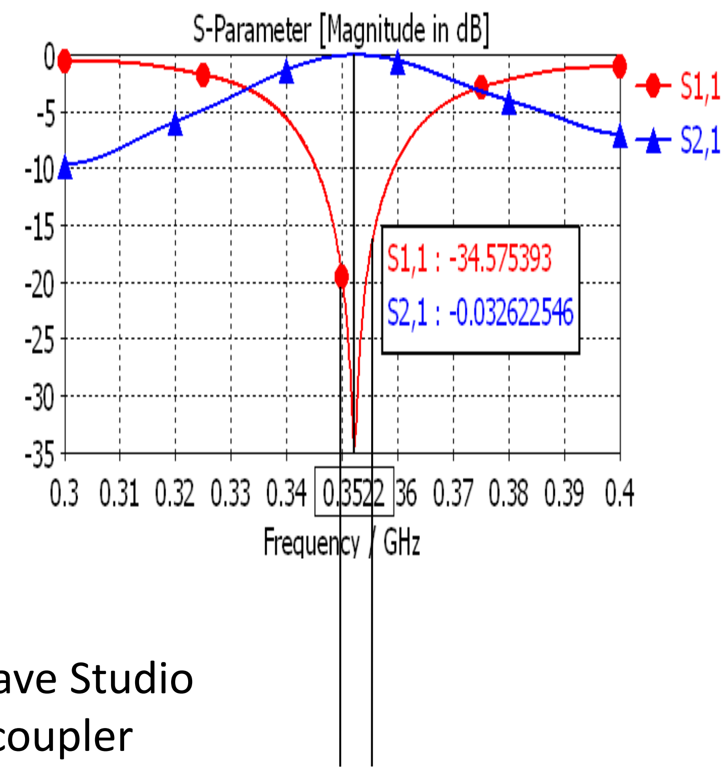
(a) Top view of the coupler **(b) cross-section view of coupler**

Optimized dimensions for straight ridge transition based coupler

Parameter	Description	Value (mm)
w	WR2300 width	584.2
h	WR2300 height	146.05
wl	Input Port length	160
c-ow	Central section-overall width	334
cw	Central ridge width	69.4
cl	Central ridge length	315
cg	Central ridge gap	11.5
ch	Central ridge height	64
ew	End ridge width	89
e-ow	End section- overall width	189
eg	End ridge gap	1.55
eh	End ridge height	35
el	Output Port length	20

RF Simulations for Return loss of coupler transition and fields

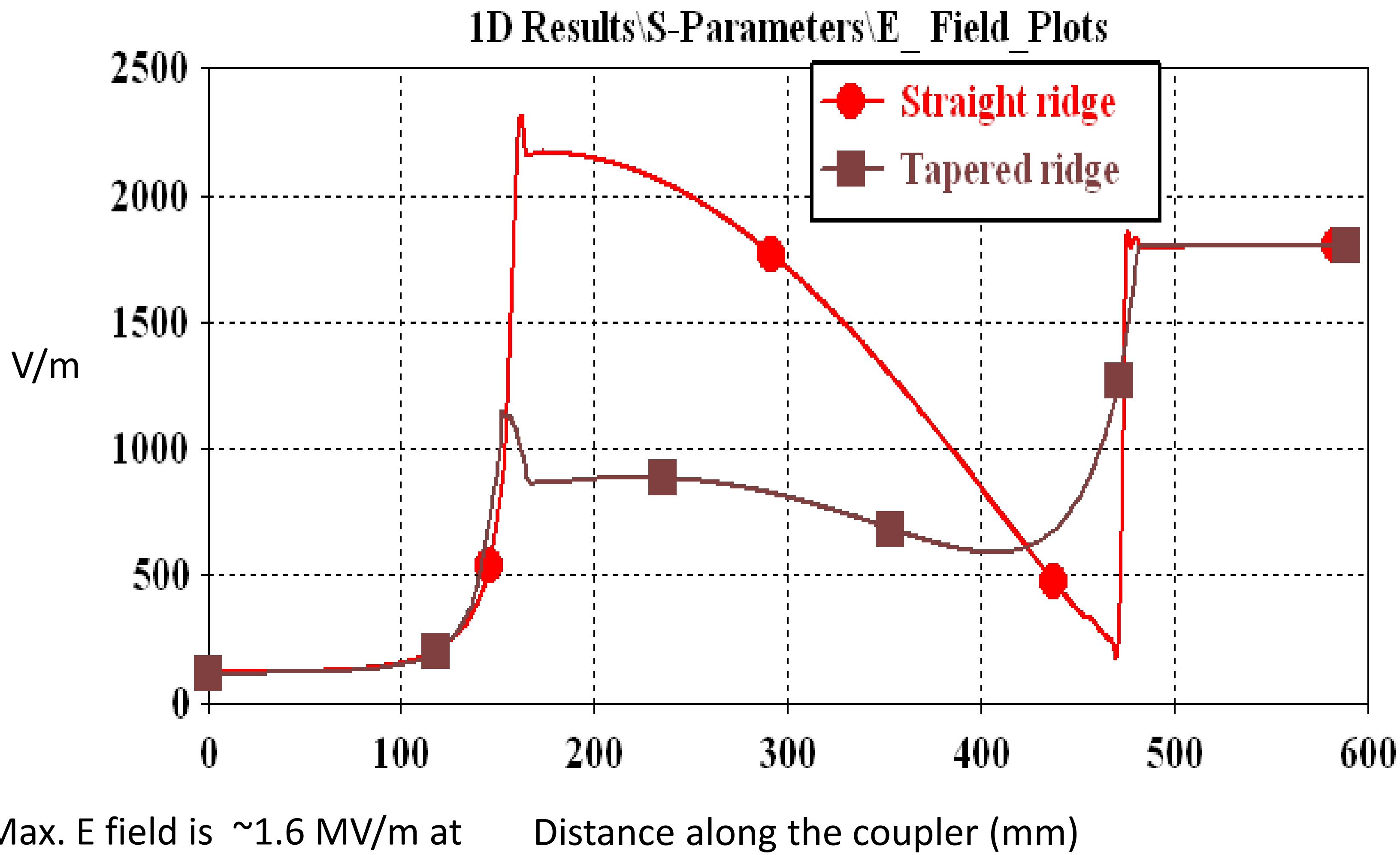




Iterative simulations are performed in Microwave Studio to reach at optimized dimensions of different coupler sections to meet the design goals.

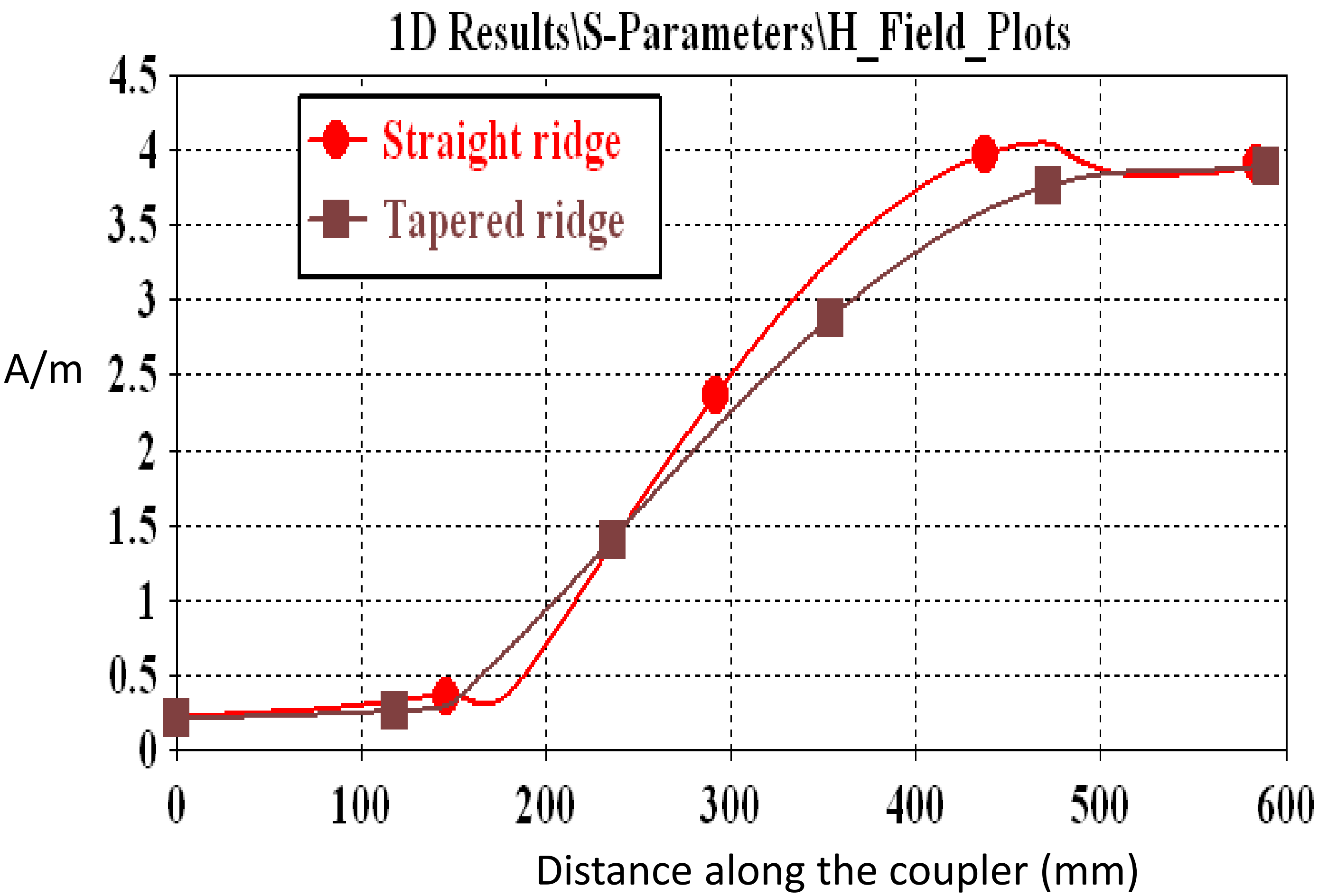
BW ~ 3 MHz

Plot of electric field inside the couplers



Max. E field is ~1.6 MV/m at 250 kW in straight ridge

Plots of magnetic field inside the couplers



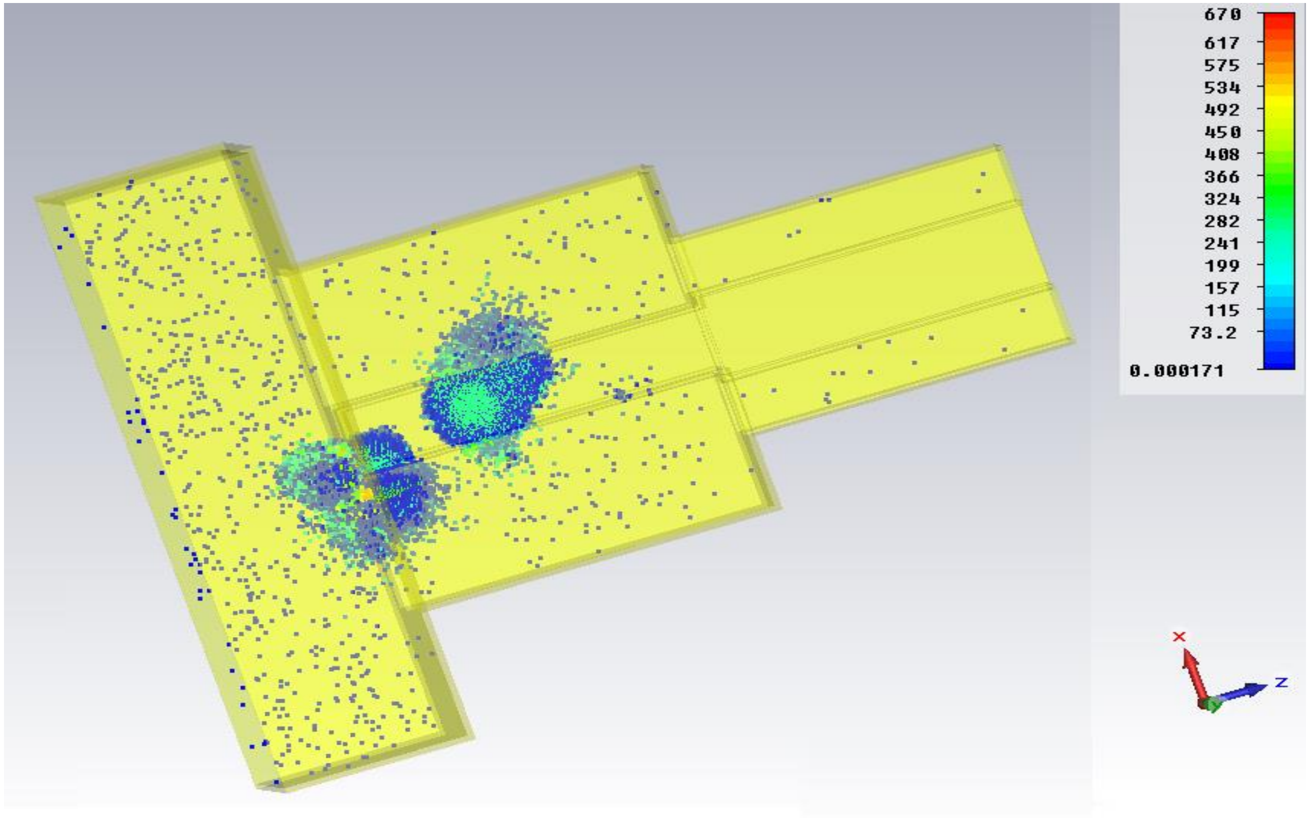
$$P_{surface} = \frac{R_s}{2} \iint H^2 dS$$

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

Coupler Type	Multipacting onset Power level in rectangular WG (kW)	Multipacting onset Power level in central ridge WG (kW)	Multipacting onset Power level in end ridge WG (kW)
Straight ridge	22.4	.57 to 17	.38
Tapered ridge	22.4	.38 to 17	.38

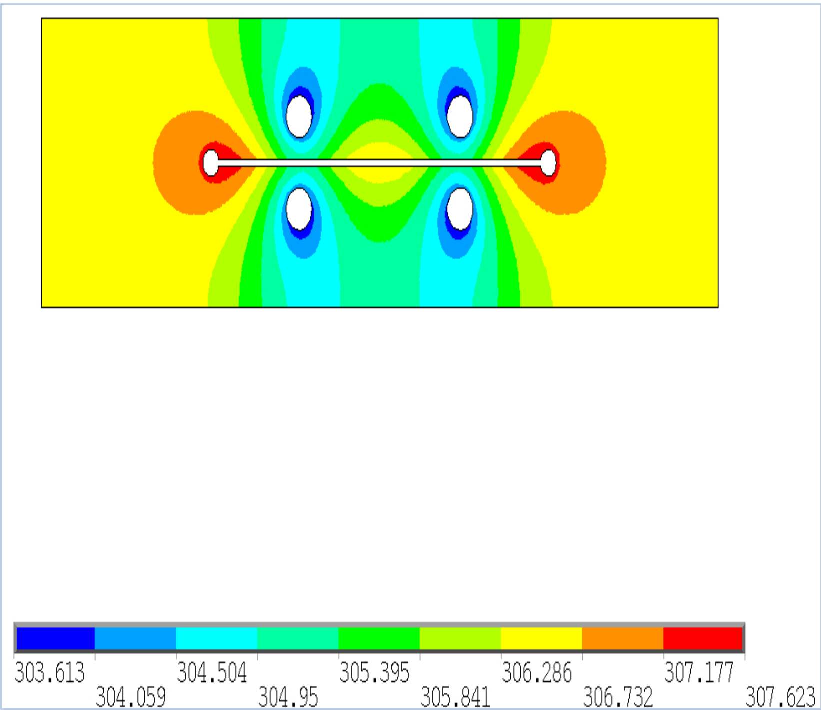
Multipacting analysis of waveguide coupler

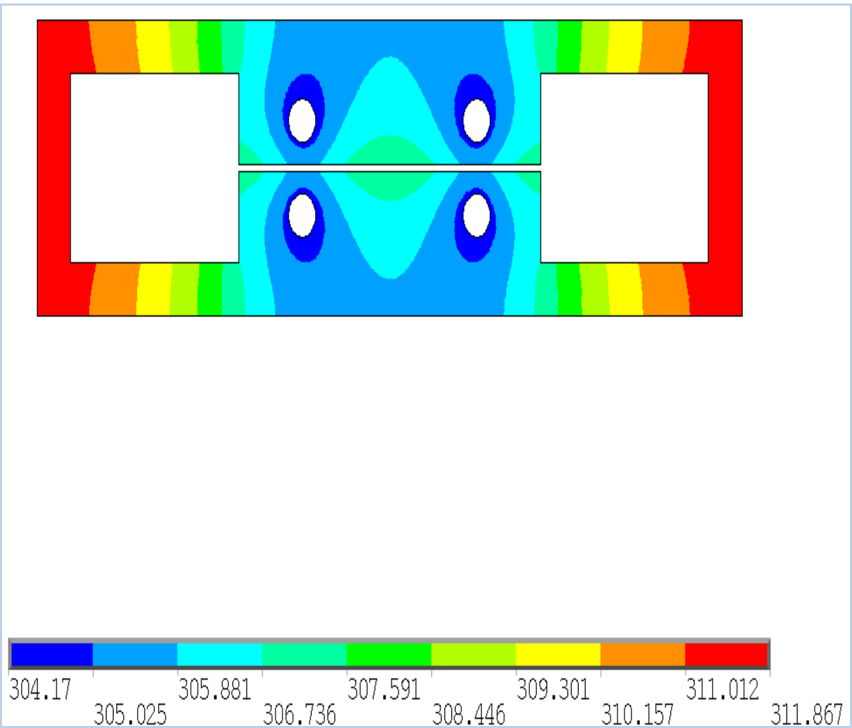


Simulations with CST Particle studio showing electron cloud inside coupler at 0.6 kW, 352.2 MHz

Thermal analysis of high power waveguide couplers for LEHIPA

Ref. Vishnu Verma and R. K. Singh, *Reactor Safety Division, BARC*



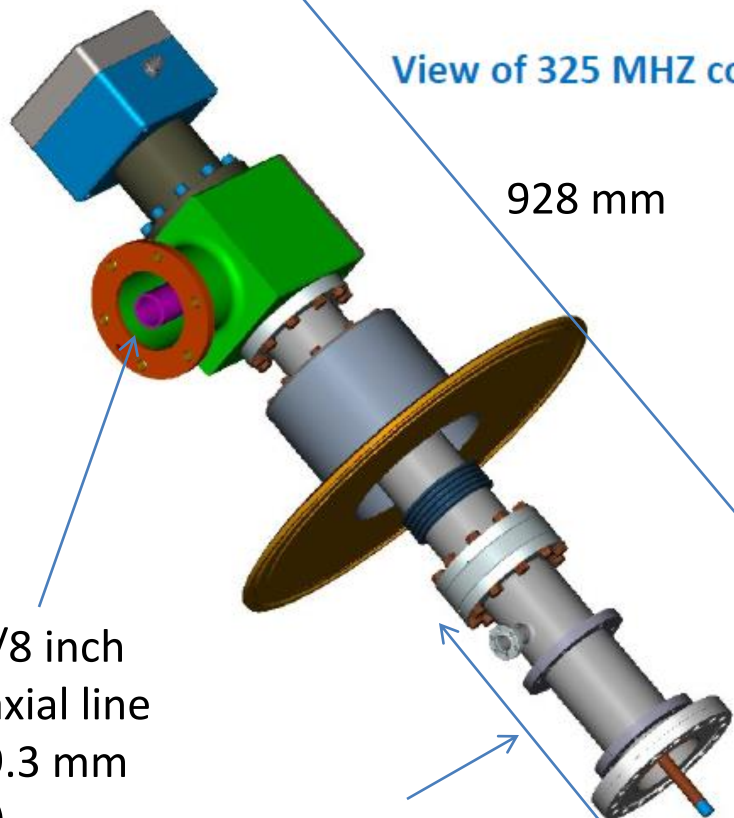


Temperature plot in the Iris and end ridge waveguide (flow velocity 2.0m/sec, material Copper)

IIFC 325 MHz Coupler

View of 325 MHZ coupler

928 mm



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

Coupler part under cavity vacuum and cryogenic system

Material:

- Coaxial coupler parts, antenna : OFE Copper, ETP Copper, brass

- Vacuum Flanges facing cryogenic system: SS 316LN

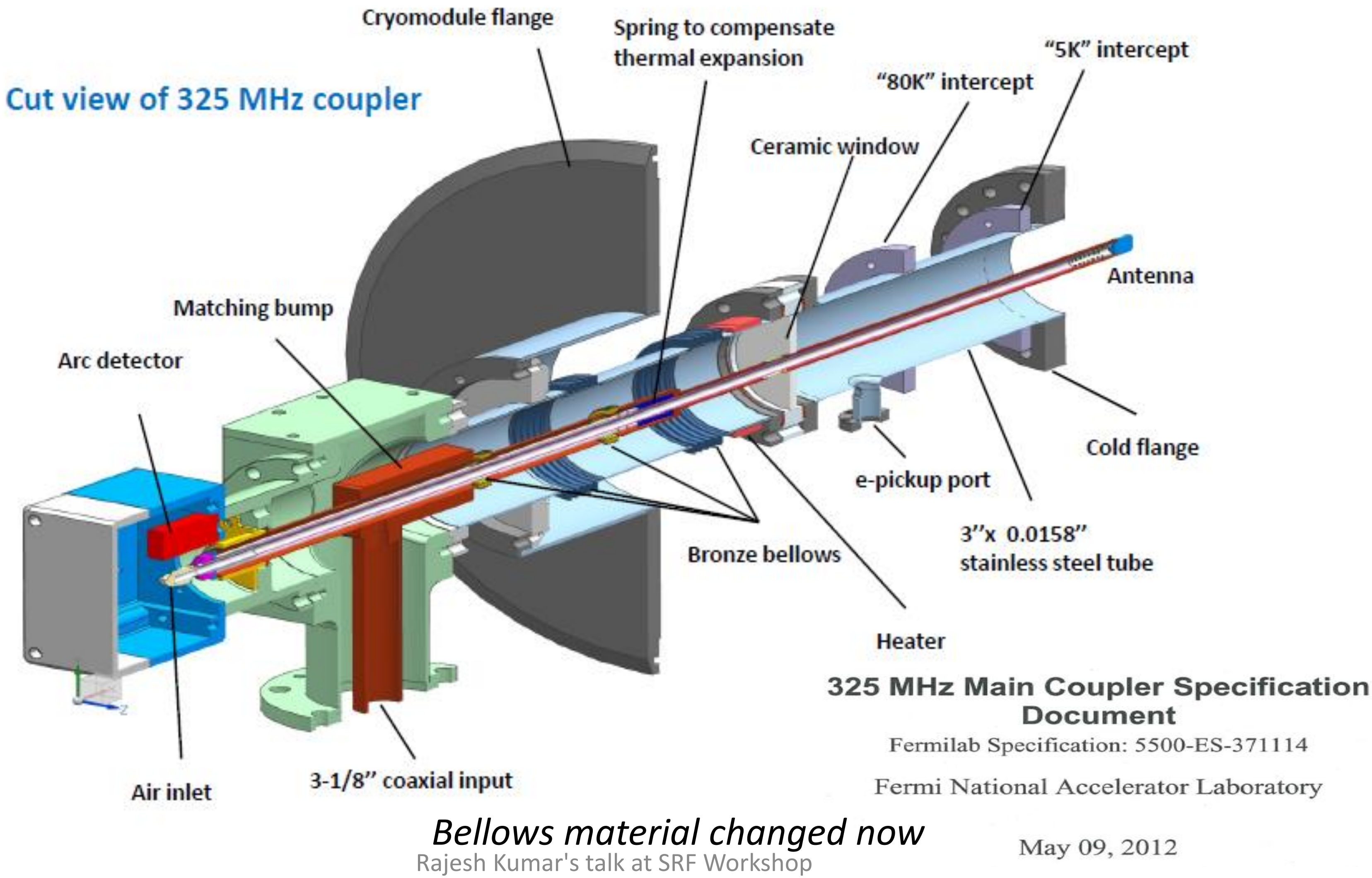
325 MHz Main Coupler Specification Document

Fermilab Specification: 5500-ES-371114

Fermi National Accelerator Laboratory

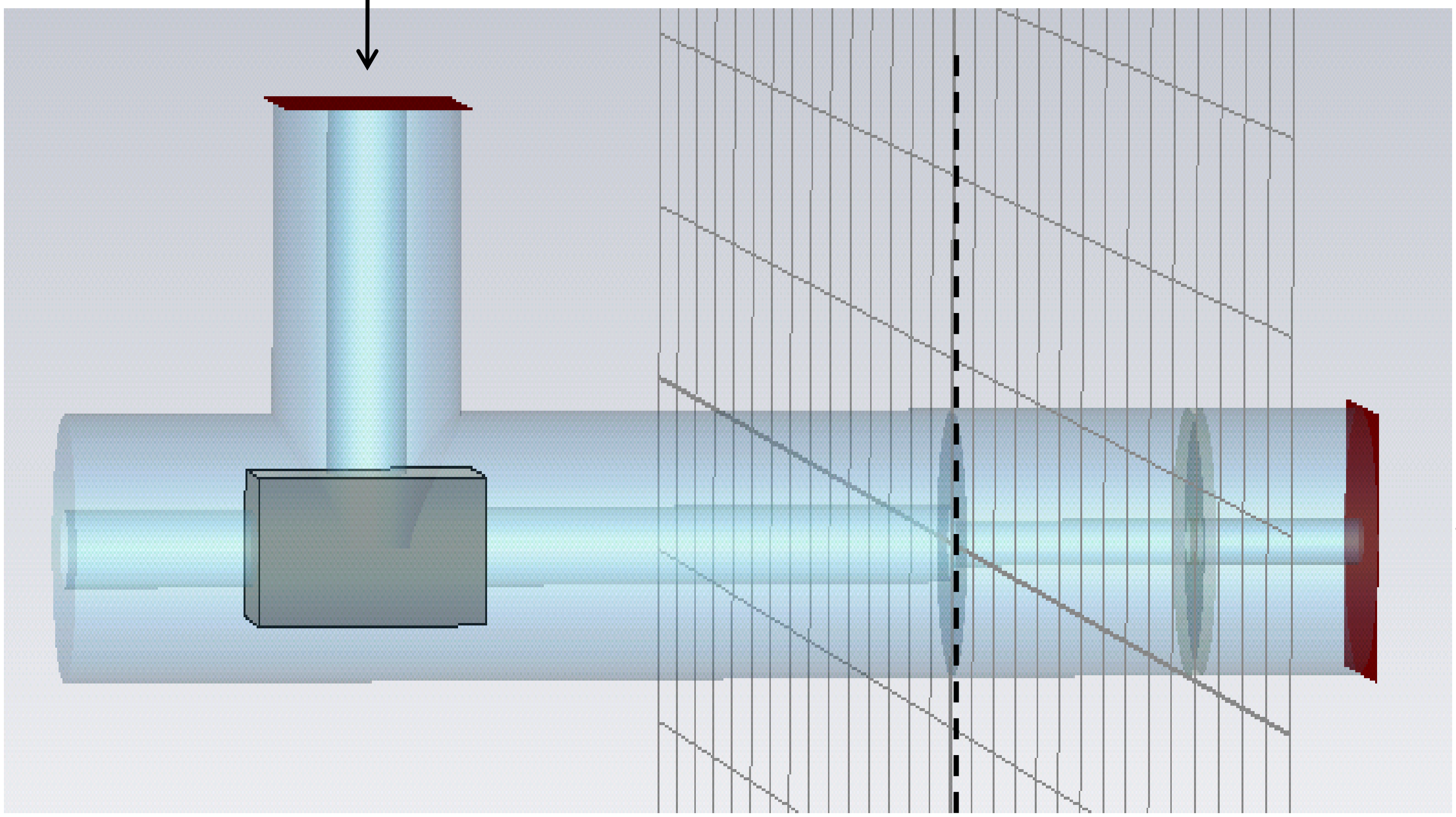
May 09, 2012

Cut view of 325 MHz Coupler



Bellows material changed now

Simulation model of 325 MHz Coupler



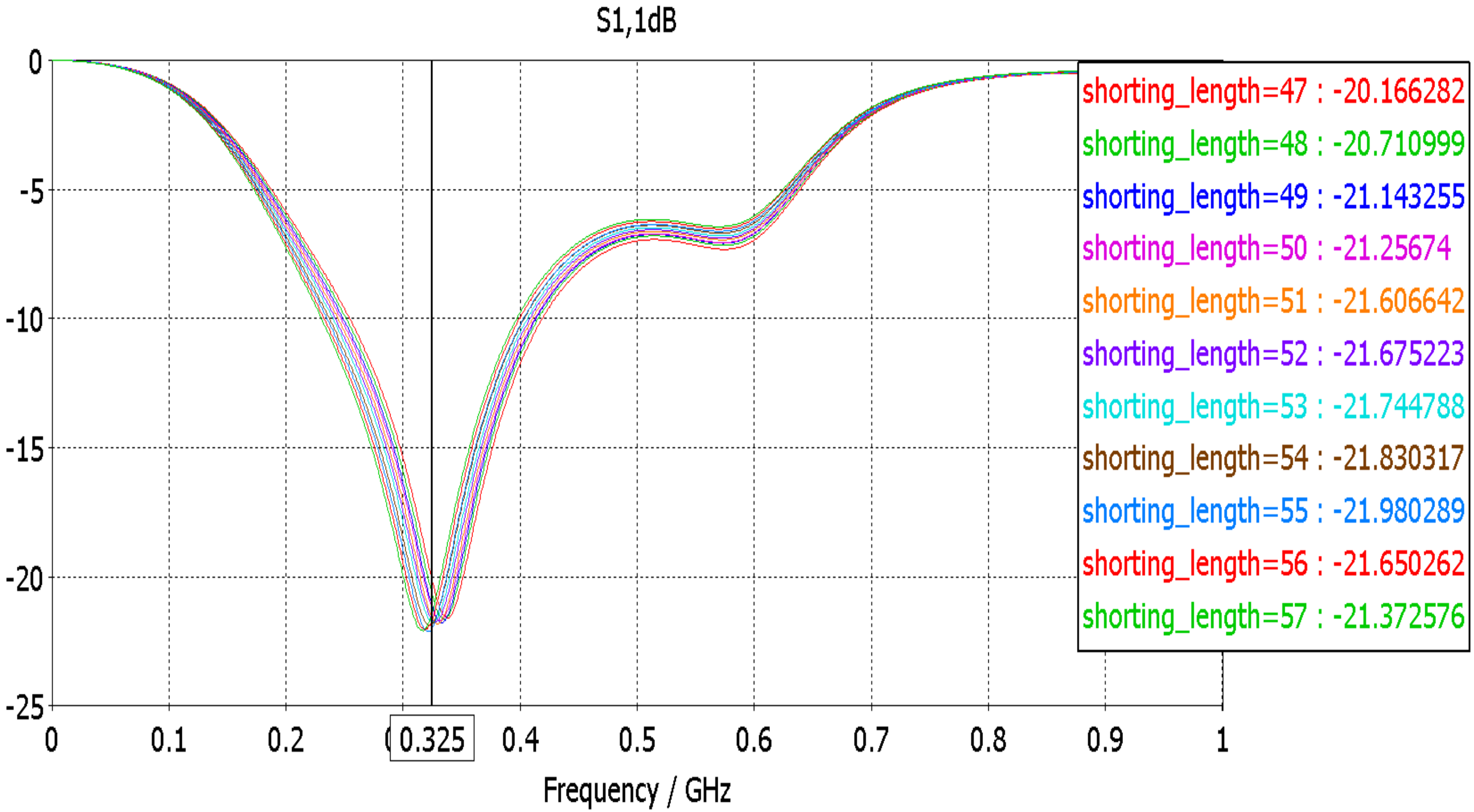
RF in

To RF cavity

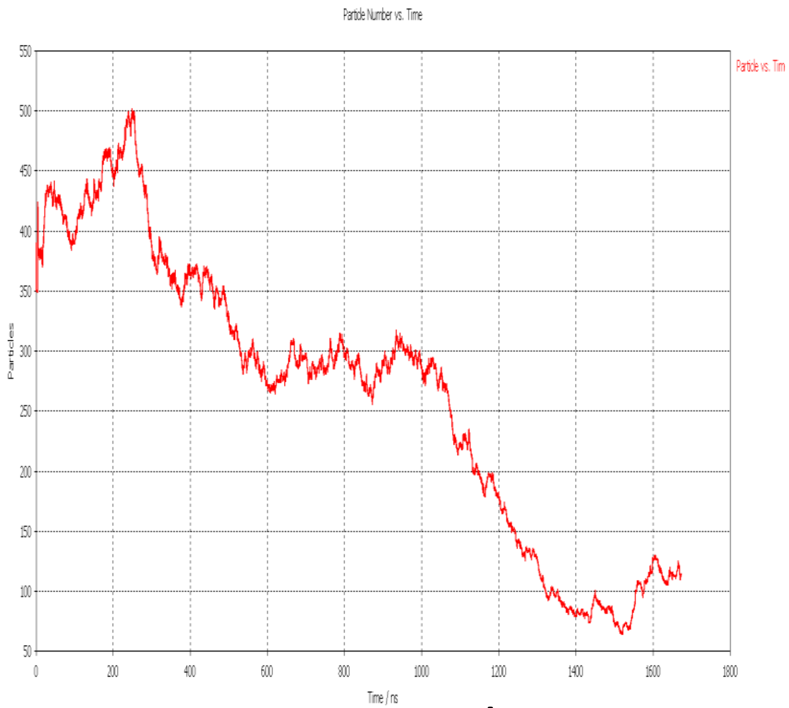
Standard 3 1/8”line, Zo= 50 Ohm

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

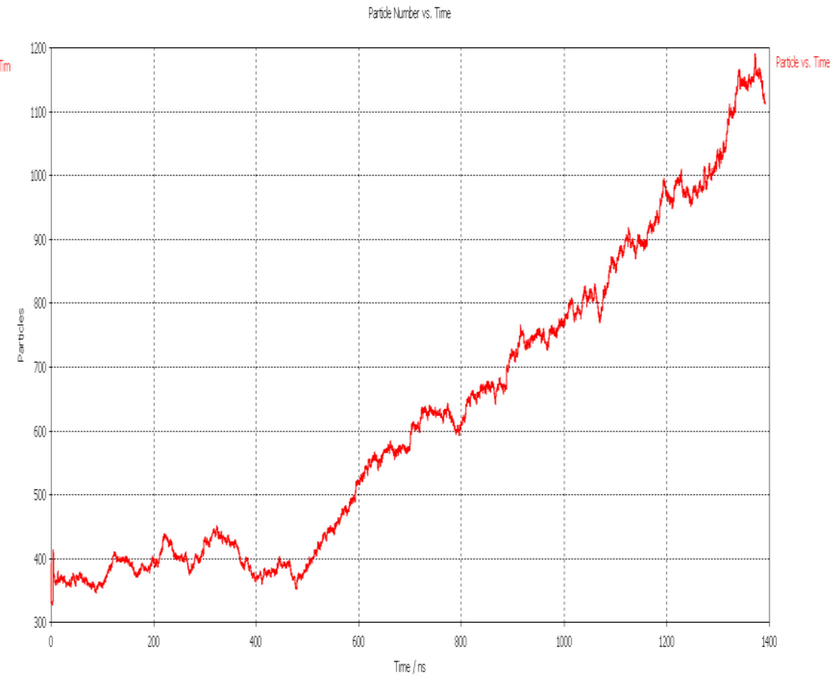
RF simulations on 325 MHz Coupler



Multipacting simulation on 325 MHz Coupler



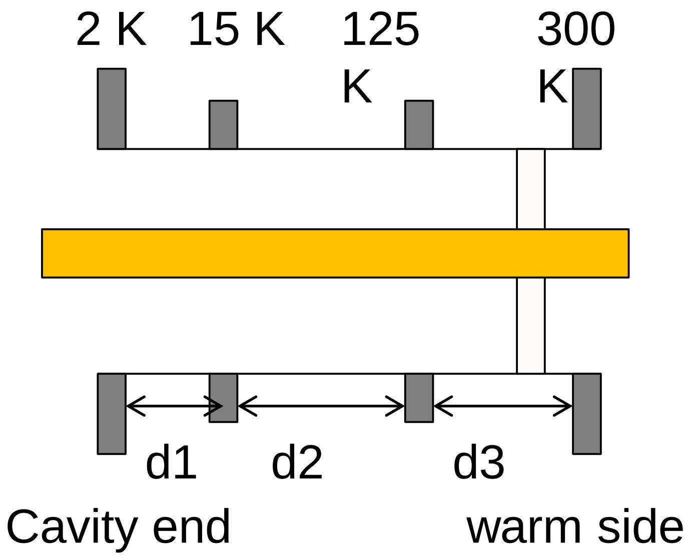
Pin = 7.2kW

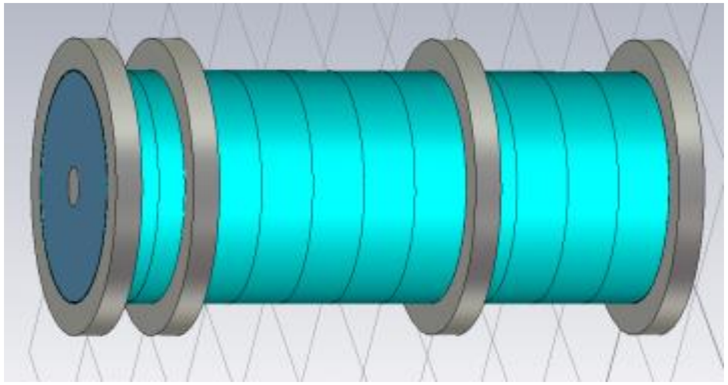


Pin= 8.4 kW

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.

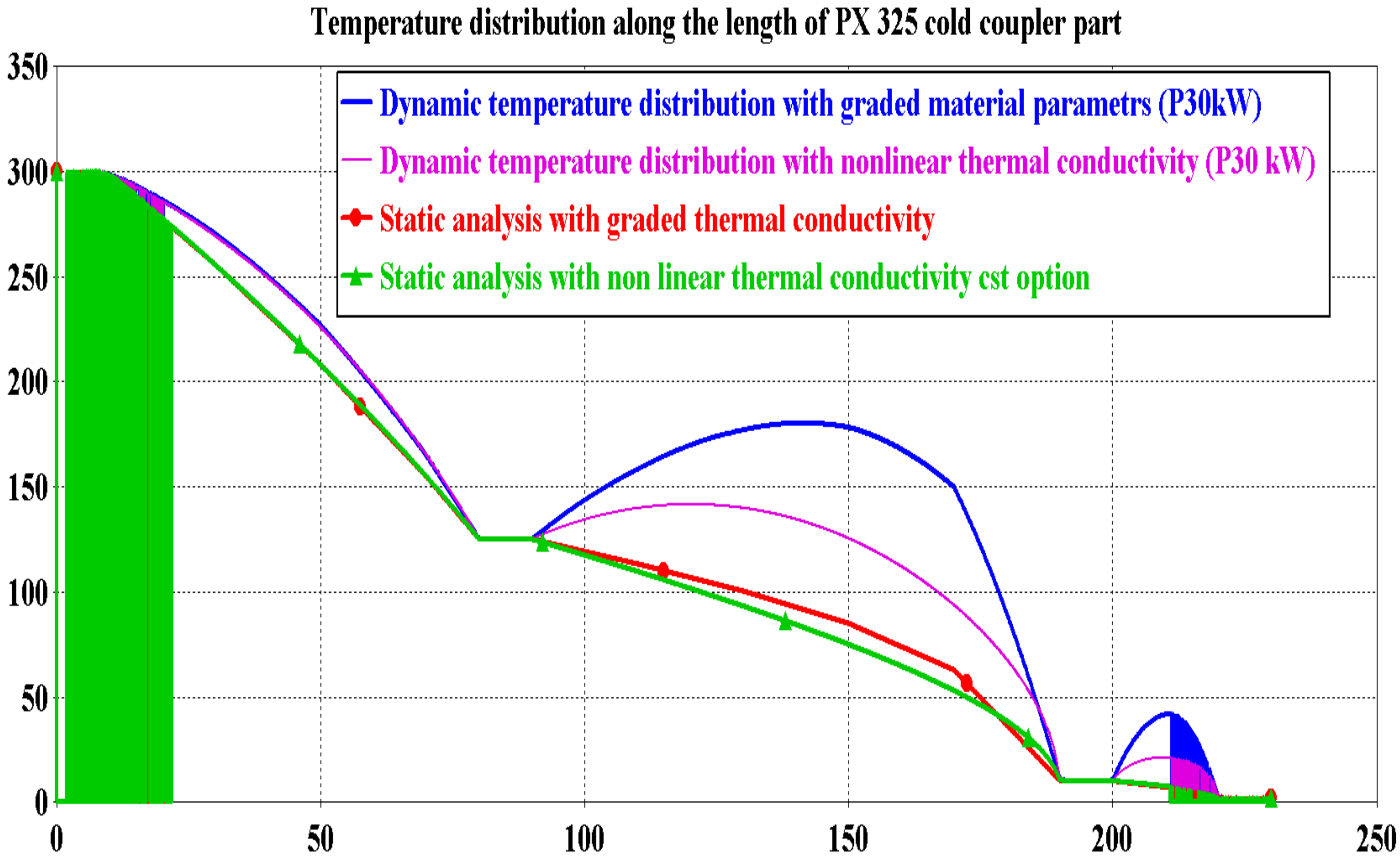
Heat load studies



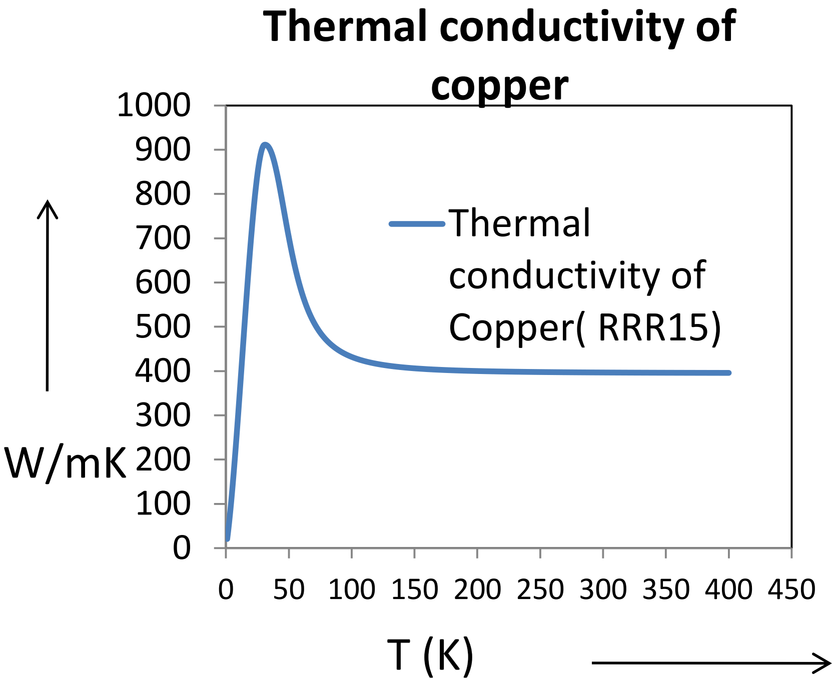


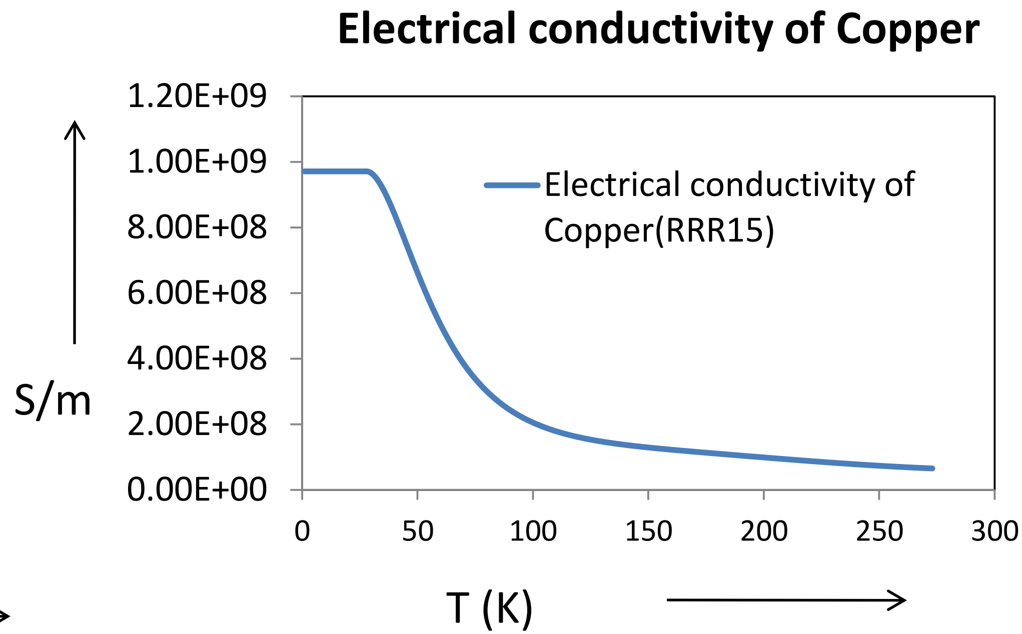
CST Microwave Studio Simulation model

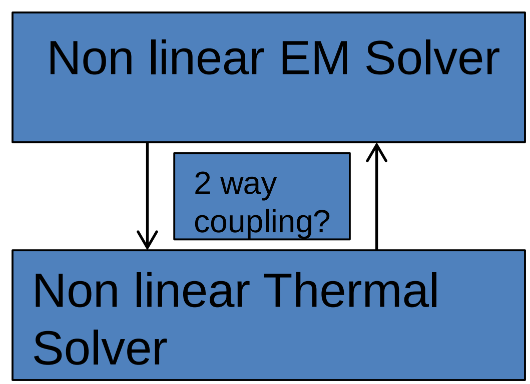
Temperature distribution along coupler length



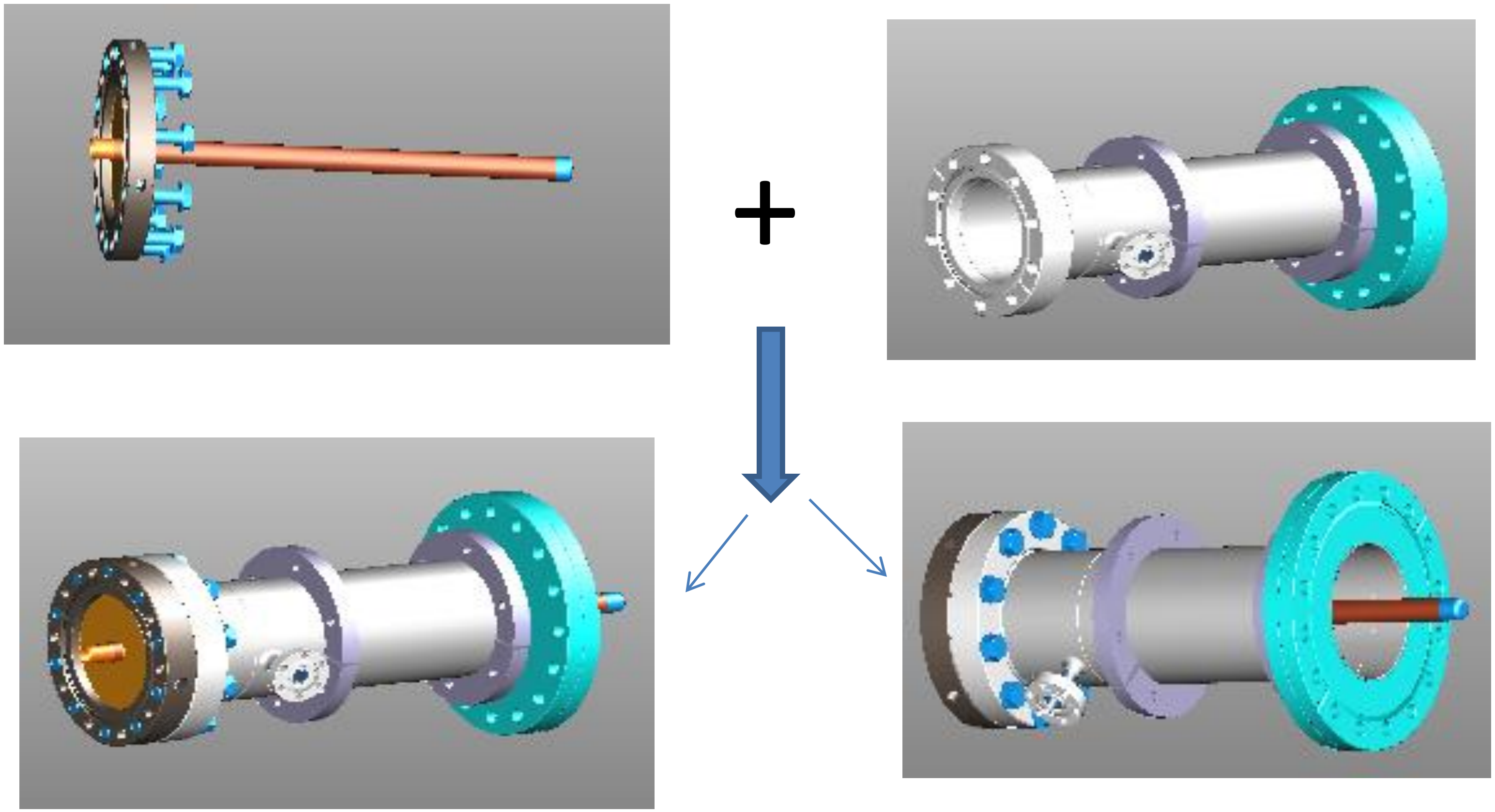
Non linearity in material conductivities







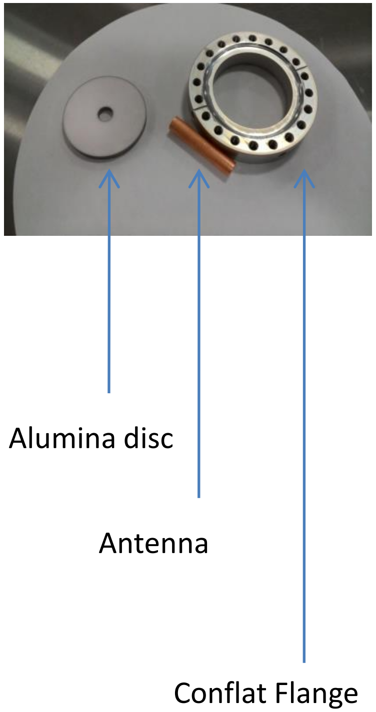
325 MHz Coupler Cold part



Temperature range spans from 2 K to room temperature

Status of Power Coupler prototype fabrication

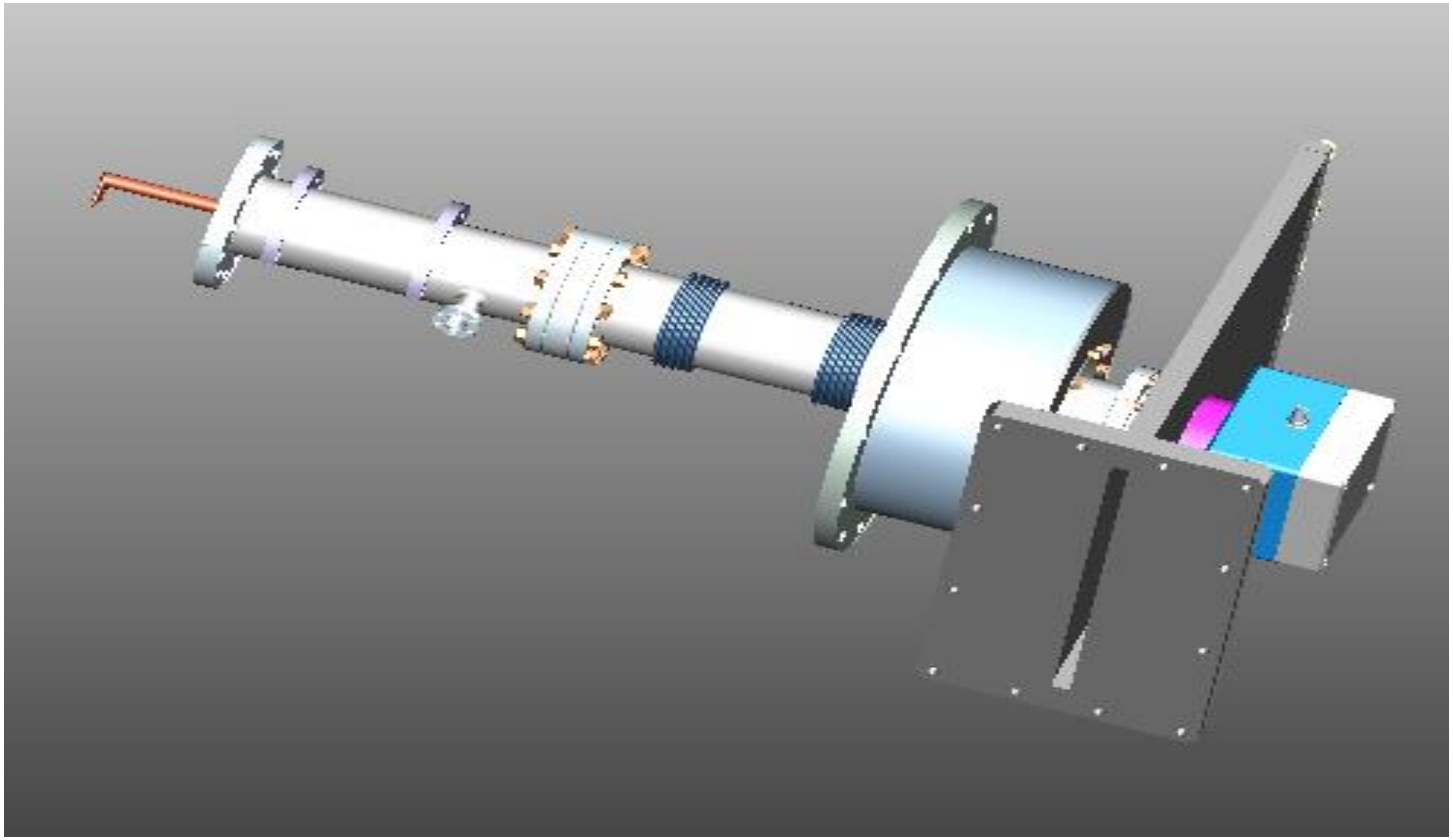
325 MHz Power Coupler's Cold part being assembled for brazing at CEERI PILANI.



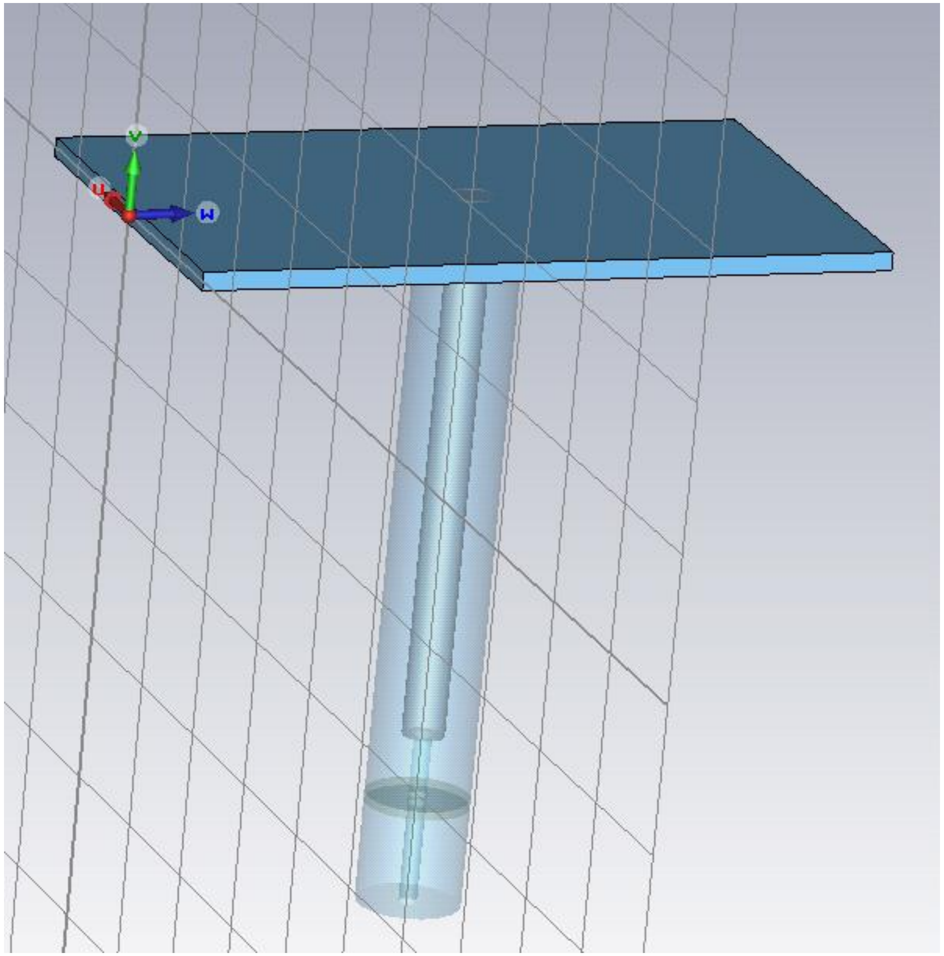
•Based on the prototype coupler design received from Fermilab for 325 MHz Coupler, fabrication has been initiated at CDM and CEERI-PILANI

•A draft MOU is under preparation with CEERI-PILANI for fabrication of cold part of 325 MHz and 650 MHz Couplers

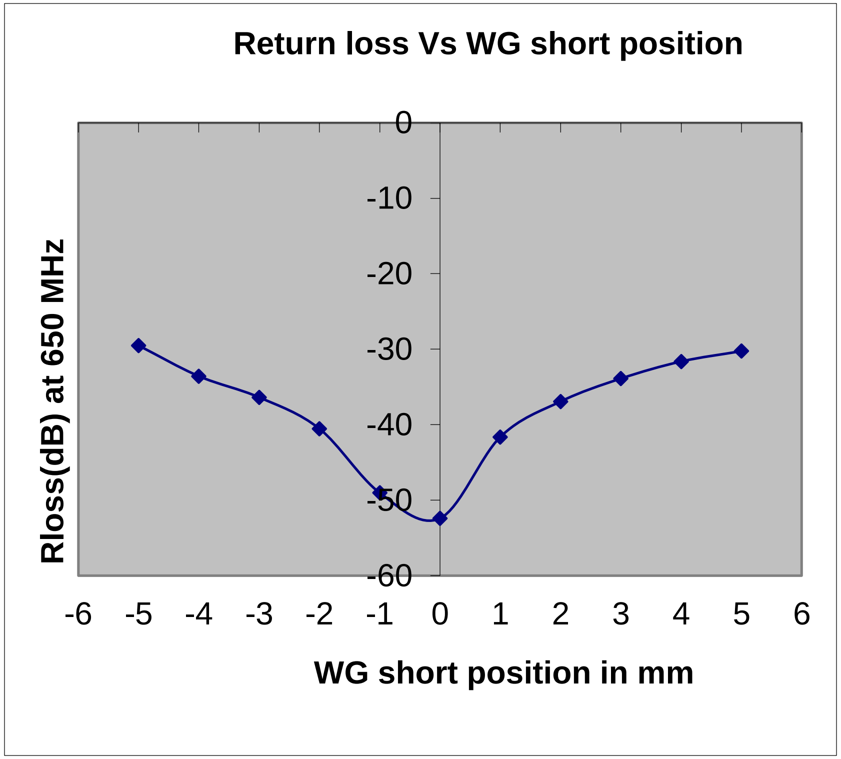
3 D Model of 650 MHz Coupler

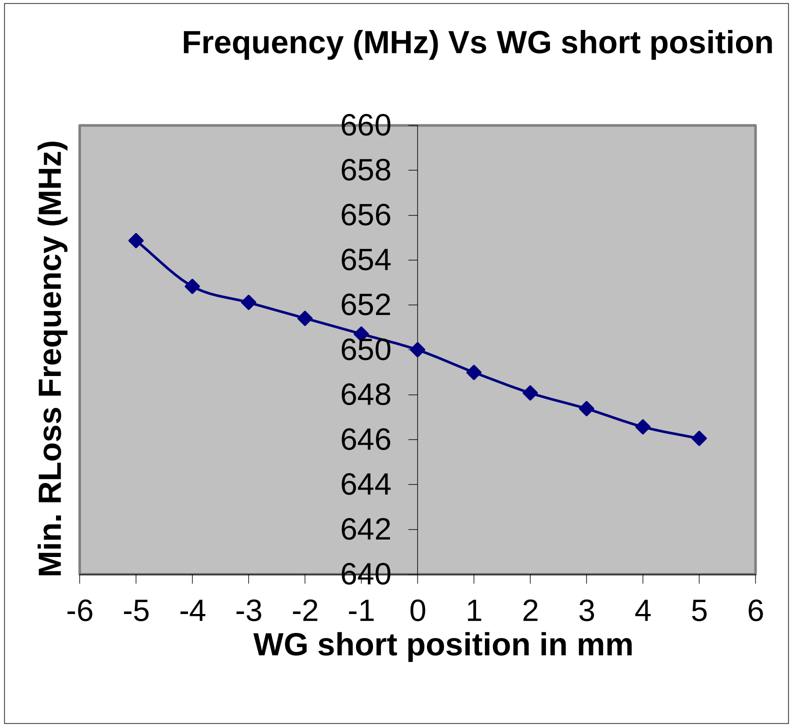


RF Simulation model of 650 MHz Coupler

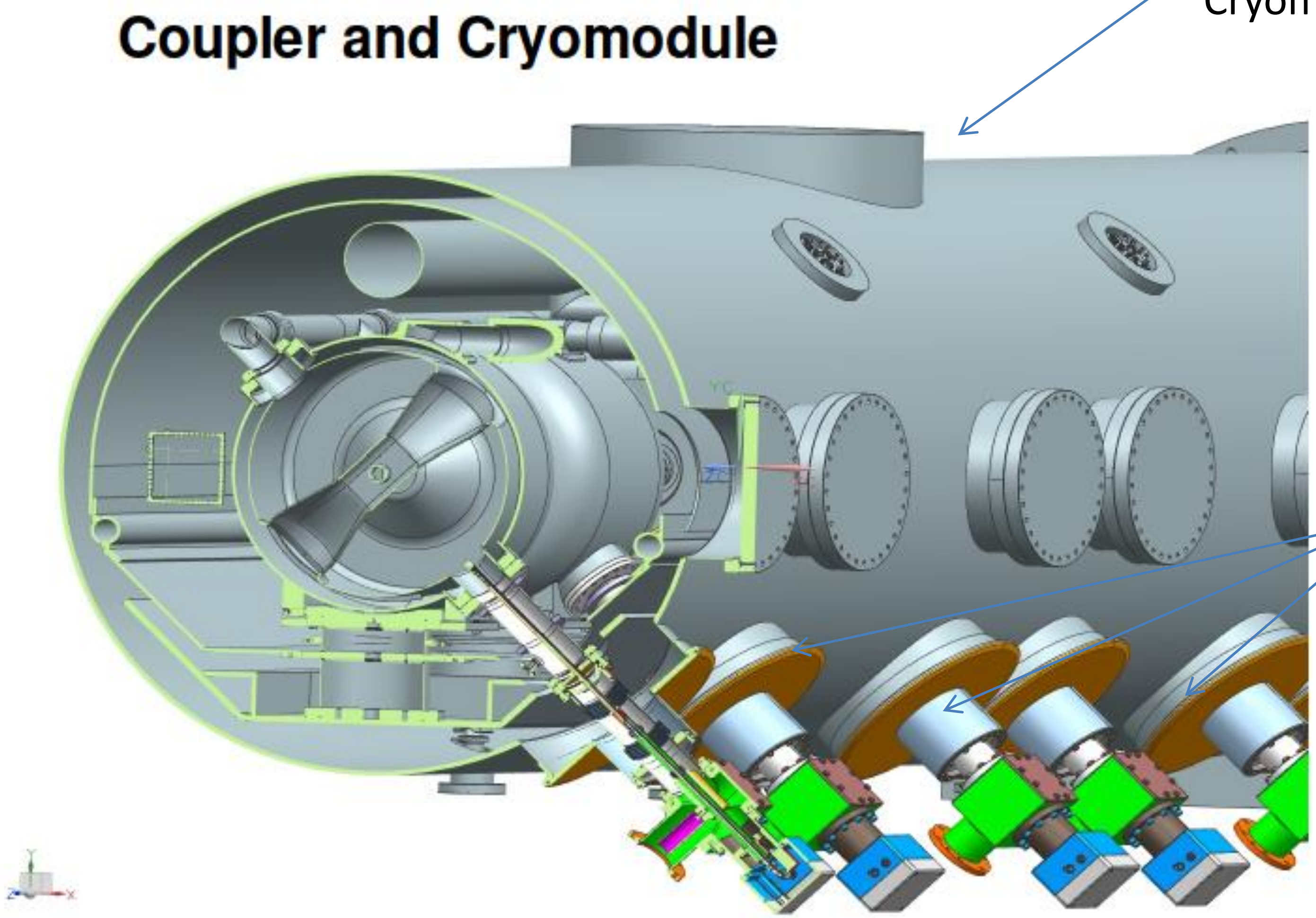


Dimensional sensitivity studies on 650 MHz coupler





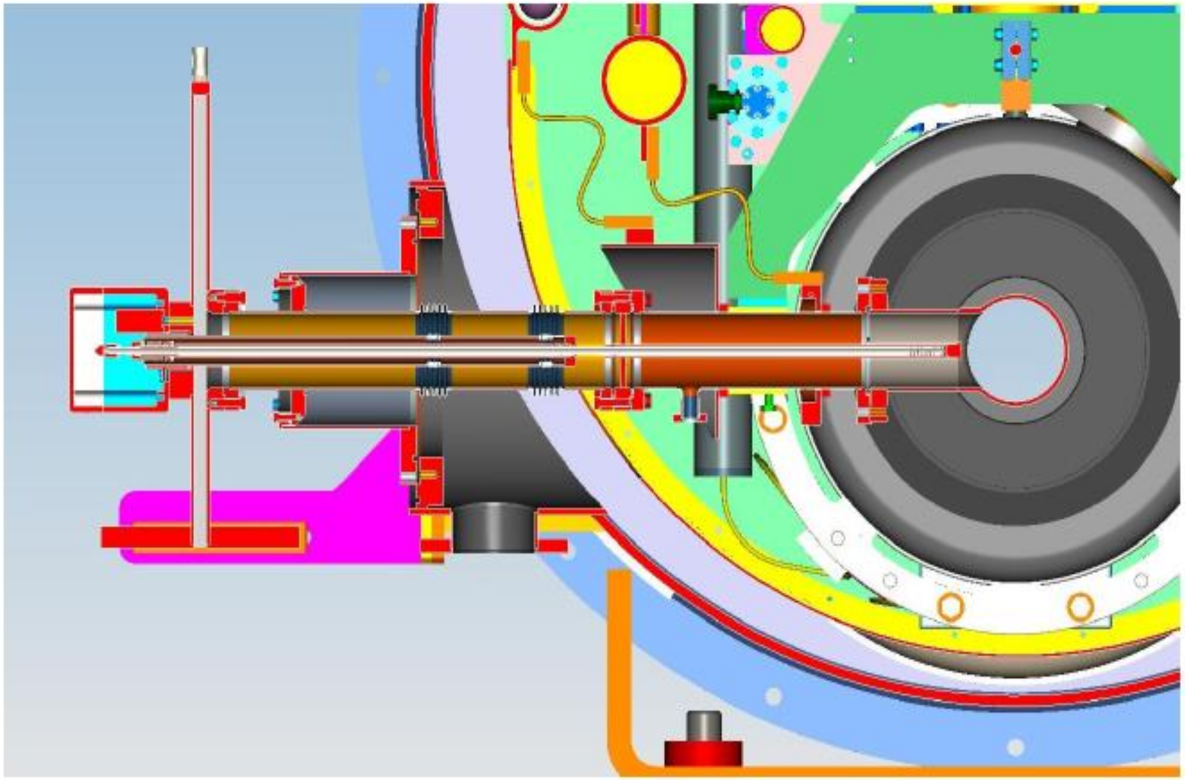
RF Couplers (325 MHz) mounted on Cryomodule



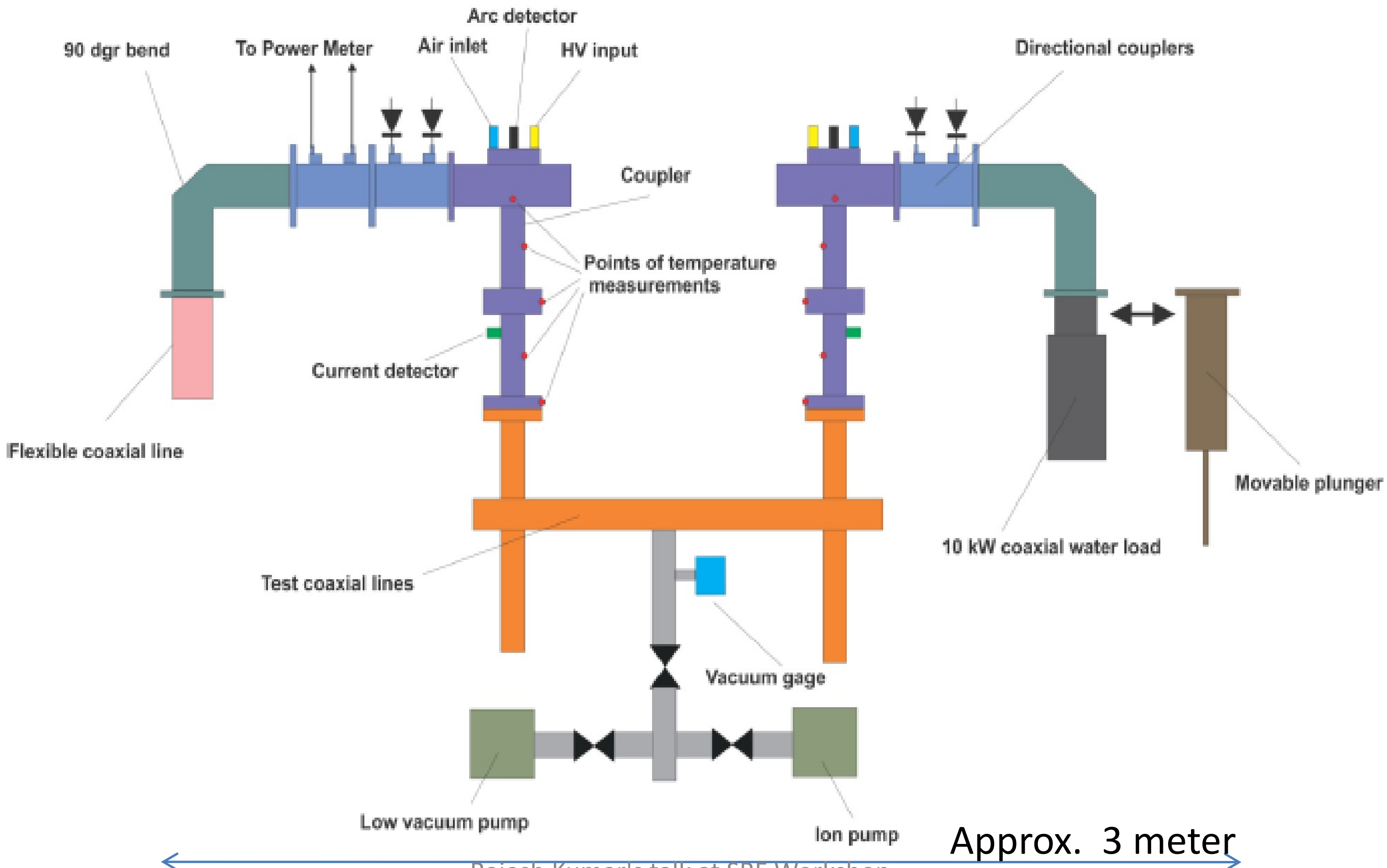
Rajesh Kumar's talk at SRF Workshop
RRCAT 18-21 July 2017

650 MHz Coupler mounted on Cryomodule

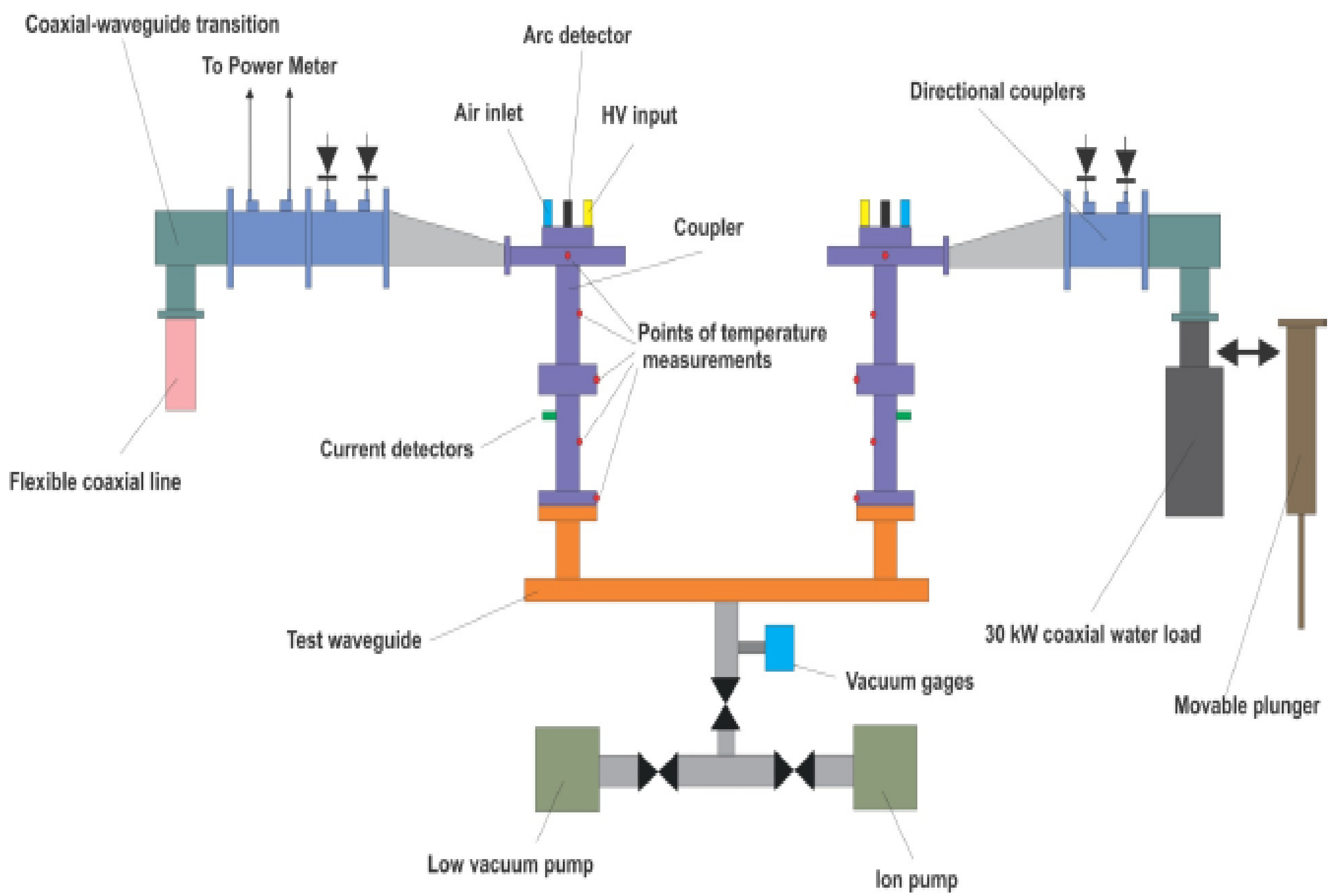
650 MHz coupler installed in cryomodule



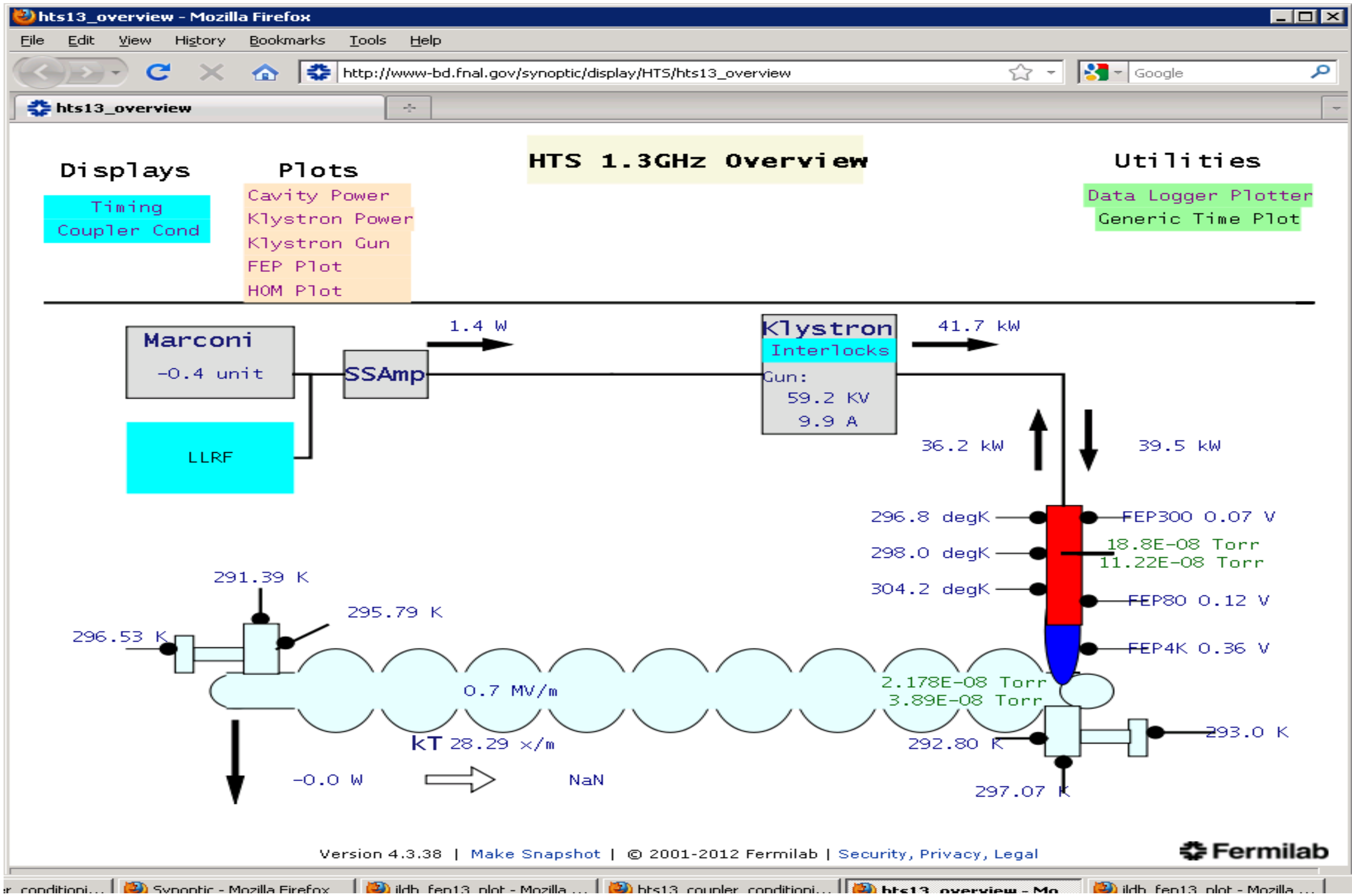
Typical Test stand for 325 MHz coupler testing at room temperature (IIFC)



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

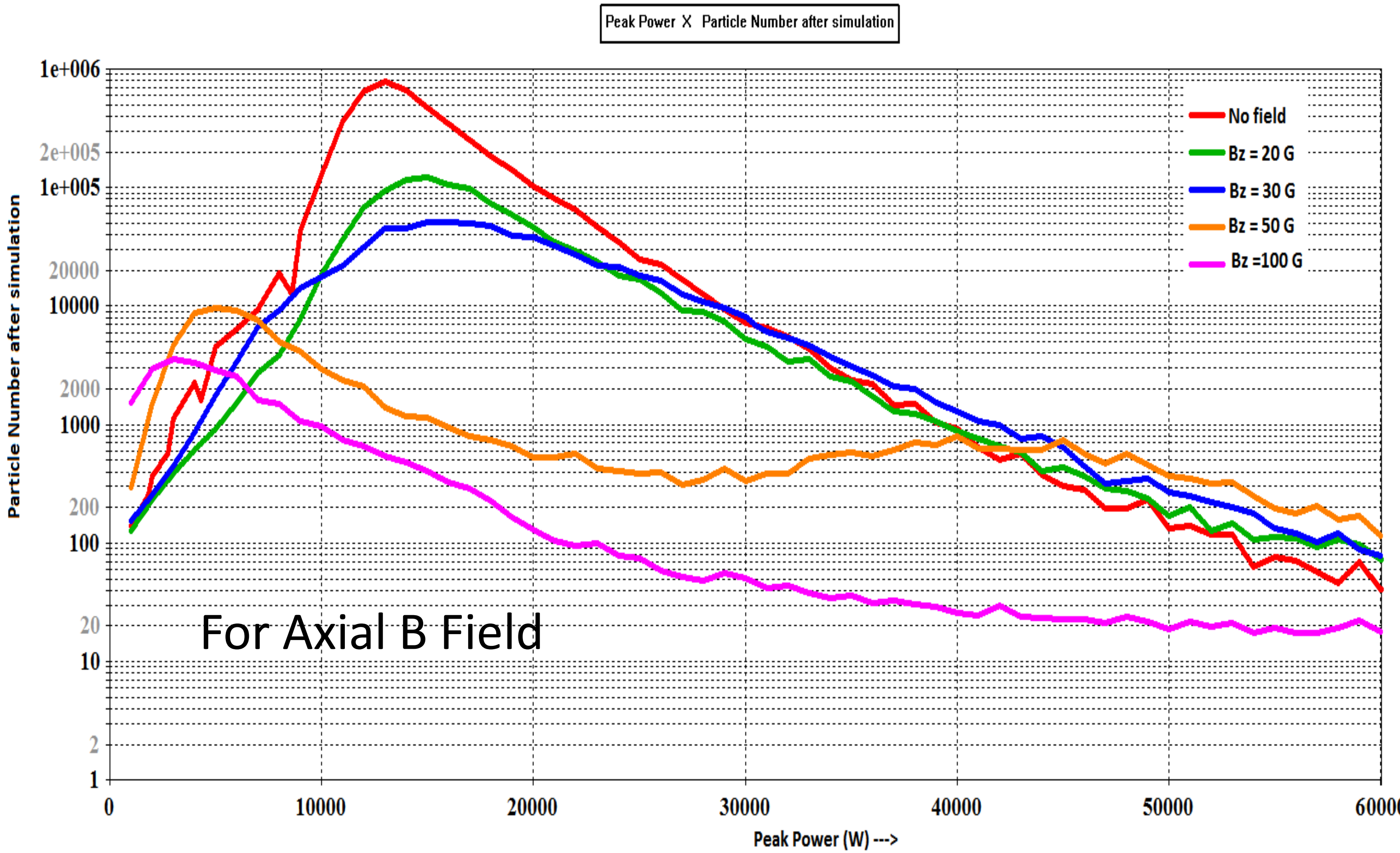
High power testing of coaxial coupler

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

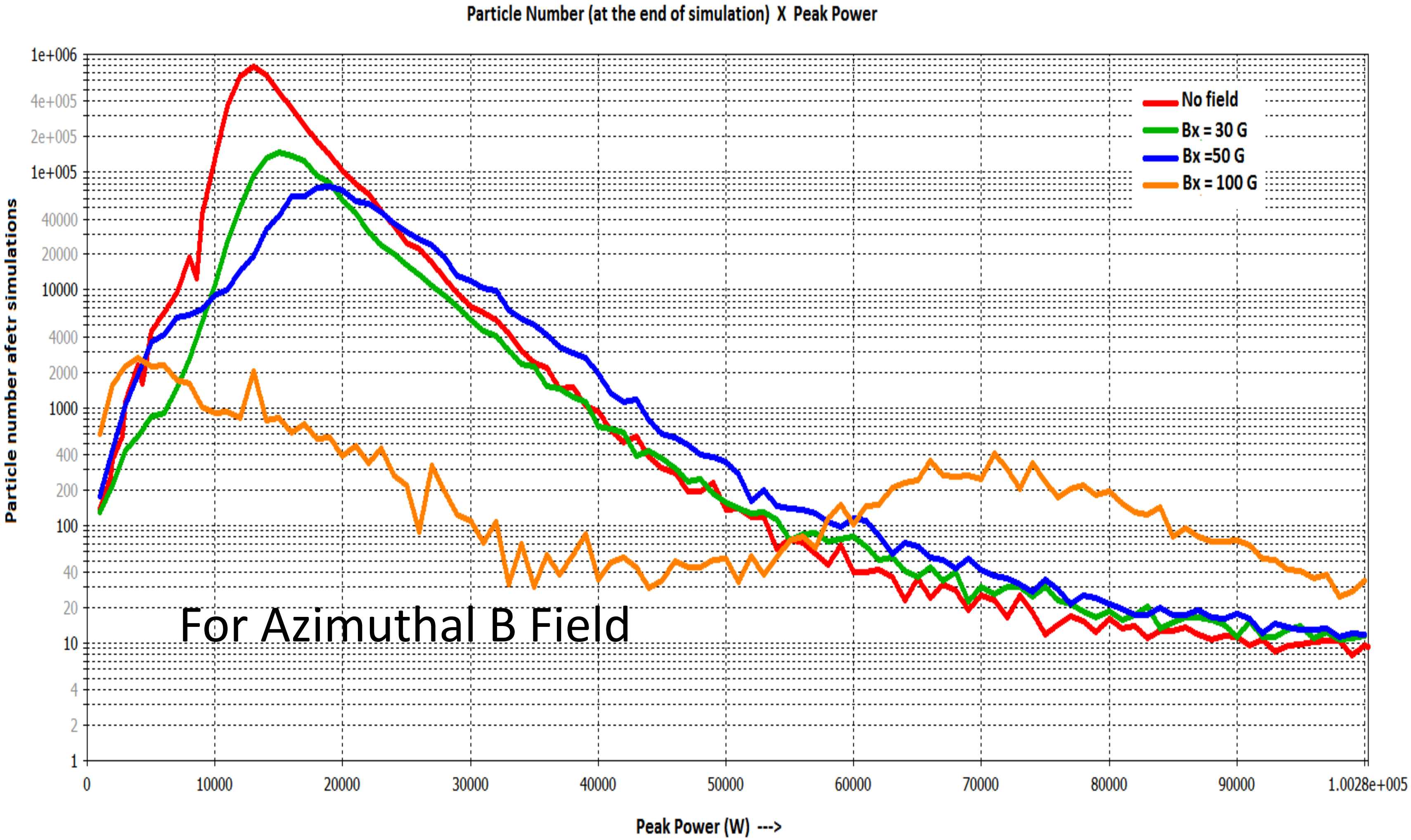
• CW Power has been raised up to 1 kW

50 kW, CW, 350 MHz RF Power Coupler developed in collaboration with CEERI PILANI

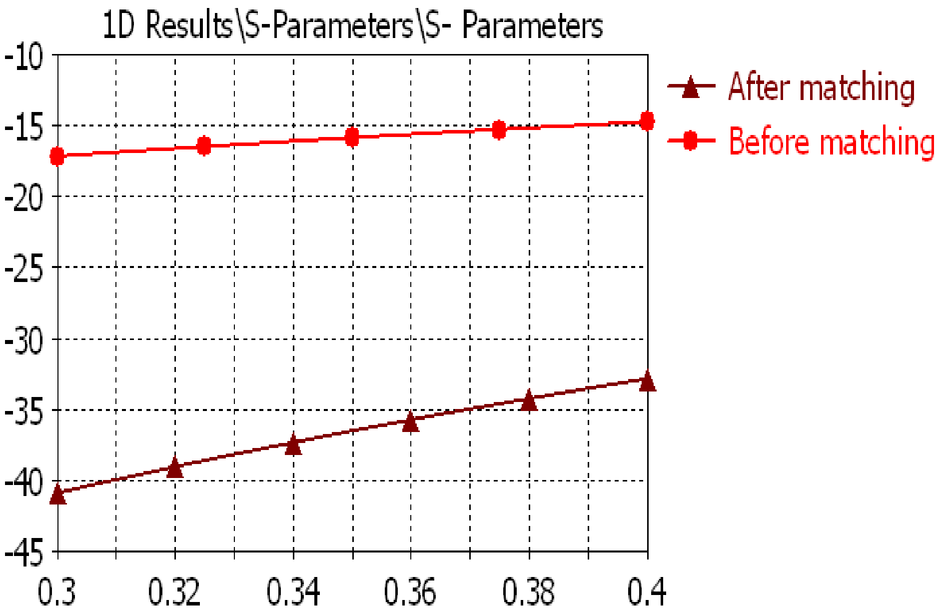
Multipacting suppression studies using magnetic field in coaxial coupler



Multipacting suppression studies using magnetic field in coaxial coupler contd.



Coupler Fabrication and Testing status

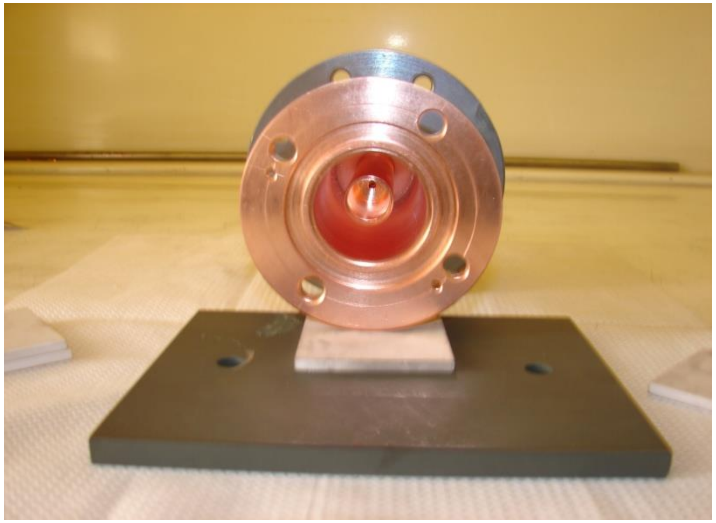


50 kW Peak power Coaxial coupler used during beam acceleration from RFQ

RF Coupler Testing/Conditioning

- Vacuum leak testing
- RF laboratory equipped with VNA, test cavities
- High Power conditioning

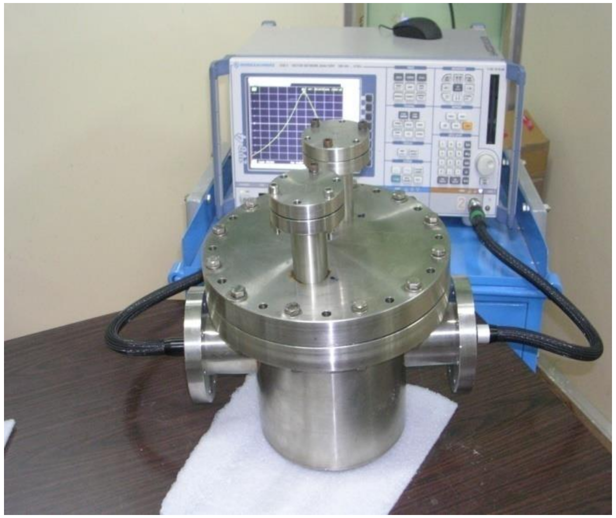
Coupler Fabrication and Testing status contd.



Coupler view from window side

Vacuum Leak Testing at CEERI-PILANI

RF cavity for coupler testing

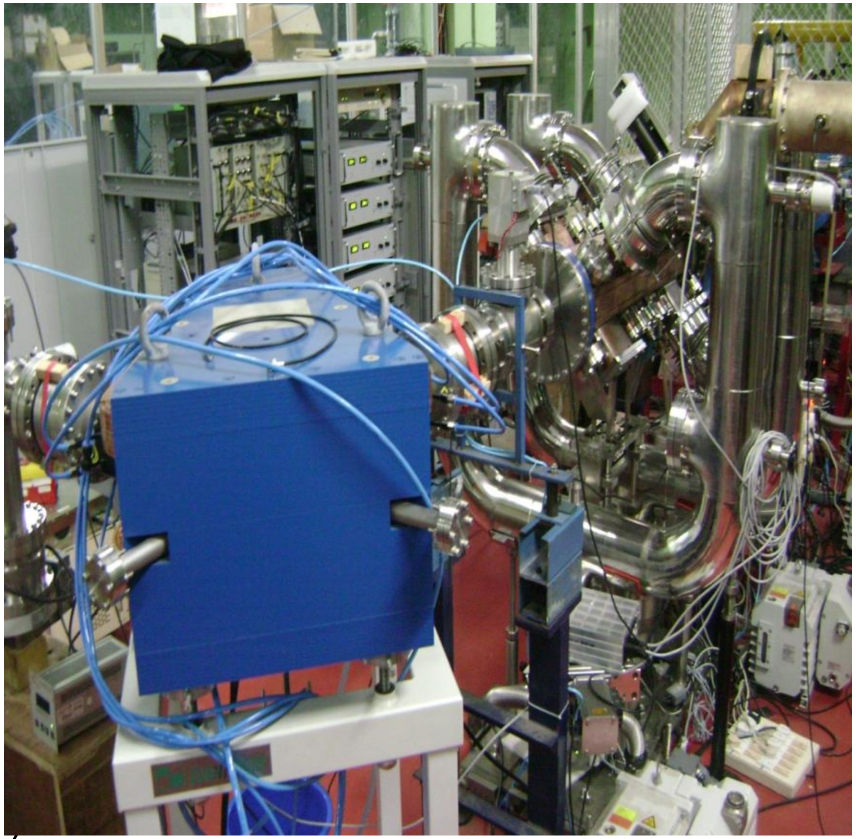


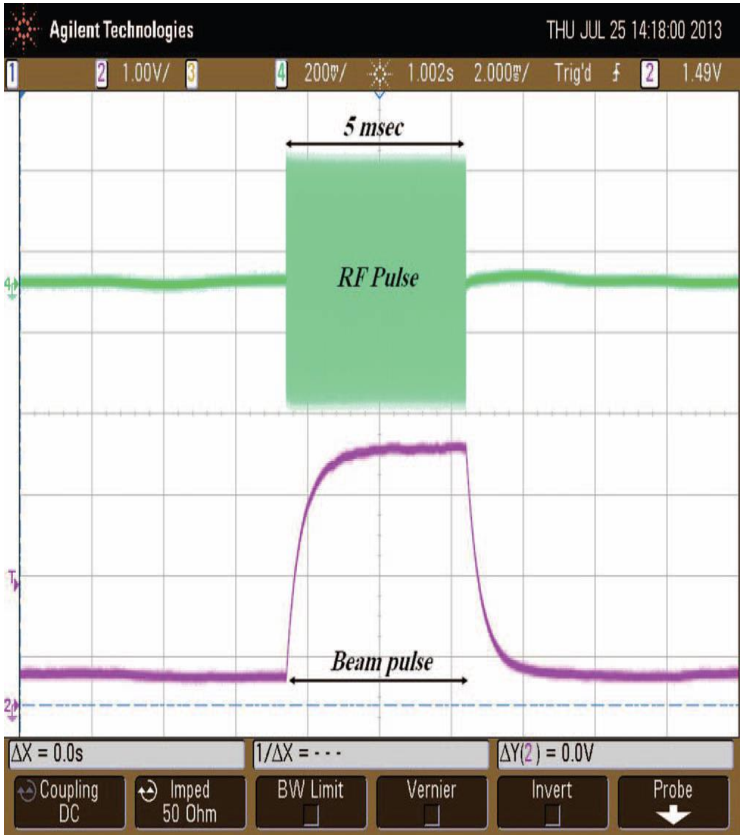
RF Cavity developed for Coaxial Coupler Conditioning

RF Coupler leak tested at LEHIPA, BARC

RF cavity for coupler testing

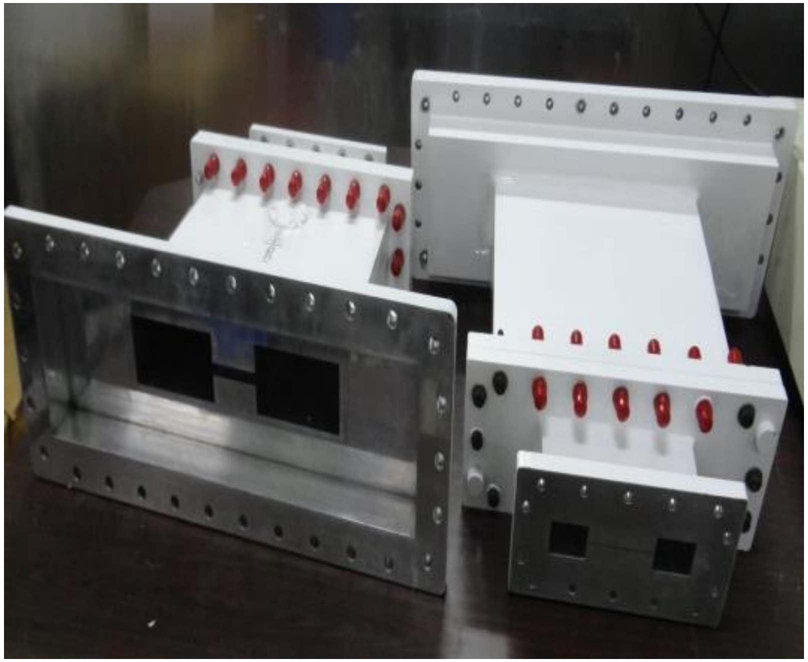
Coaxial couplers testing on RFQ cavity





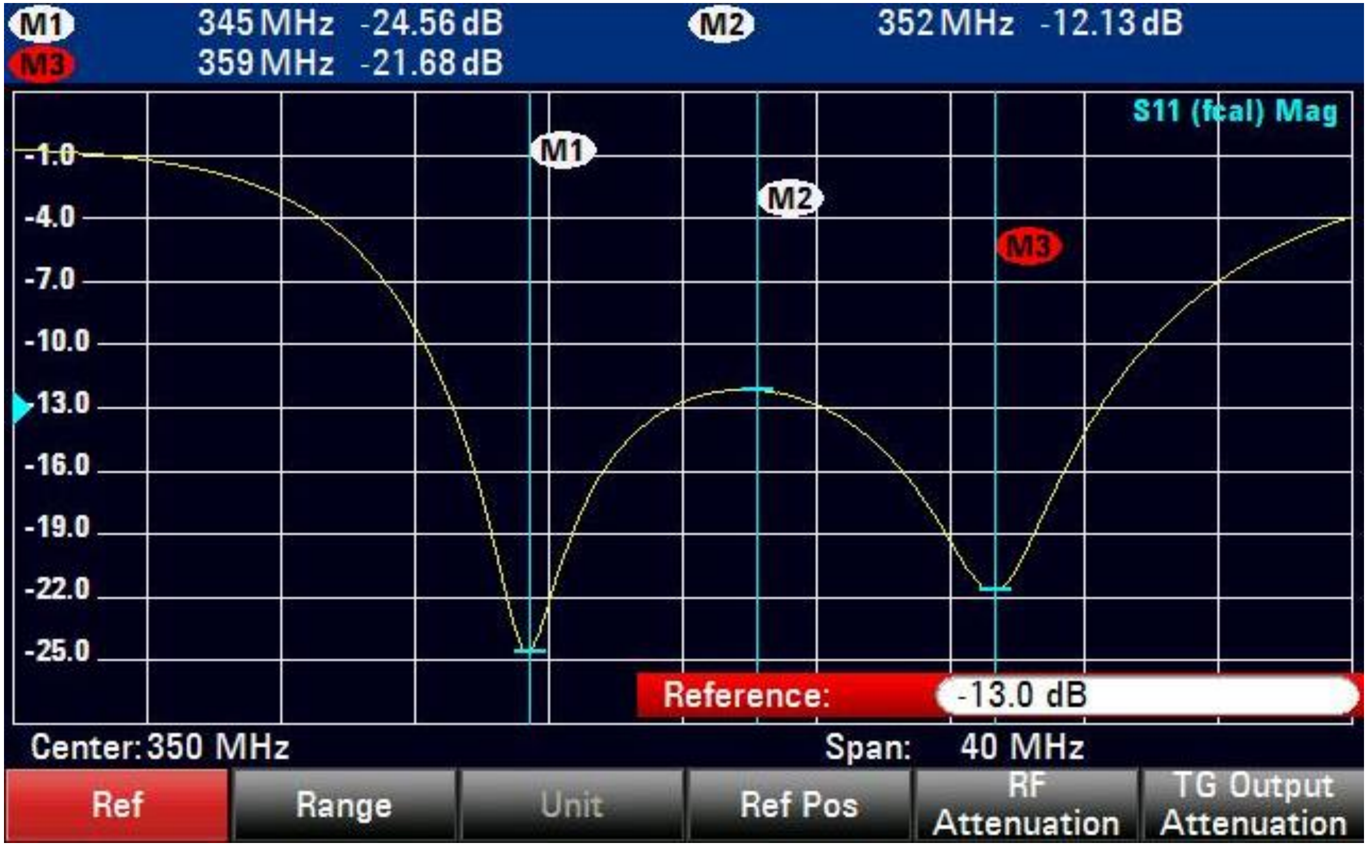
RF Coupler, tested up to 15 kW, with 0.5% duty cycle & 58 kW, 350 MHz with 0.1 % duty cycle

Prototypes of ridge waveguide couplers

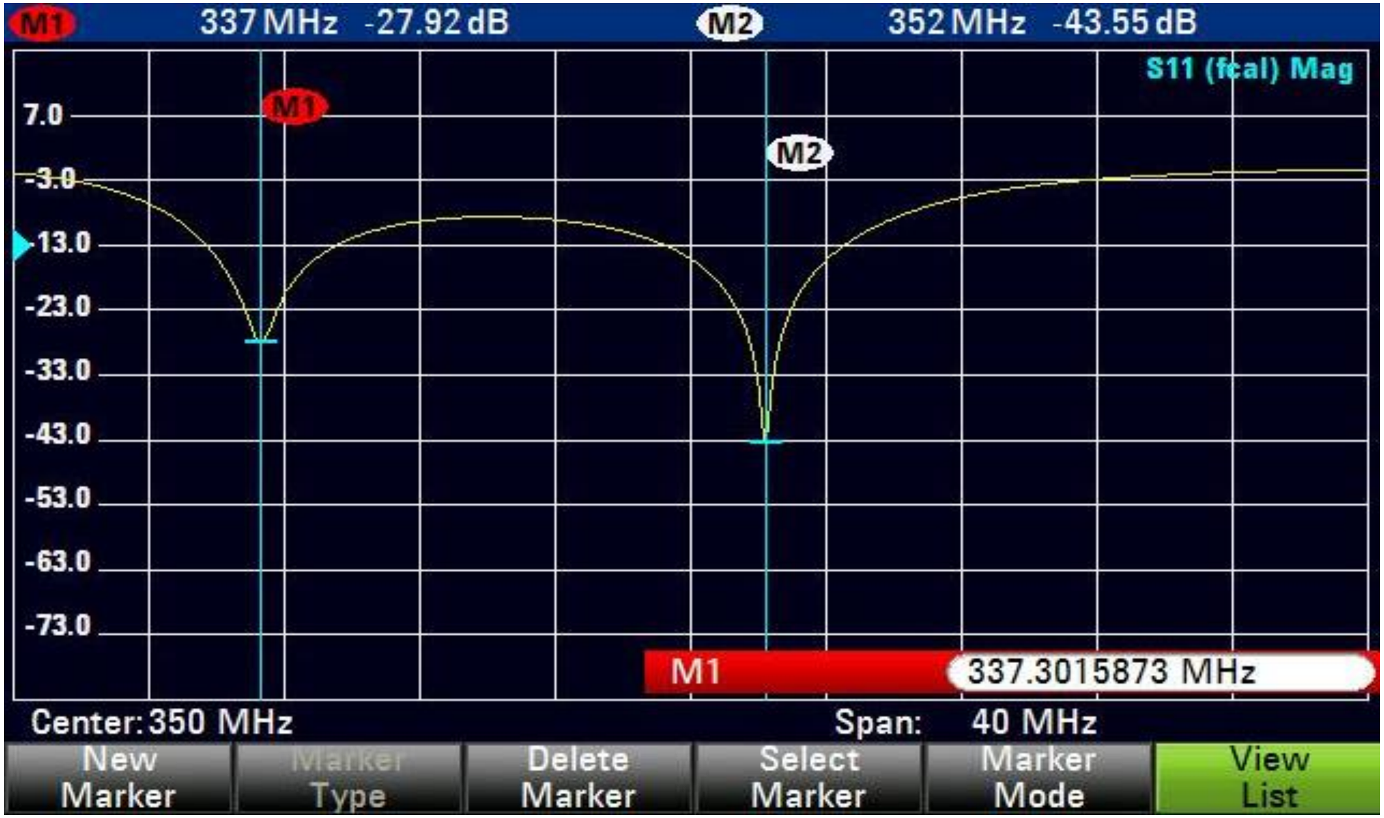


250 kW, 352.2 MHz ridge loaded waveguide iris coupler prototypes for RFQ and DTL cavities

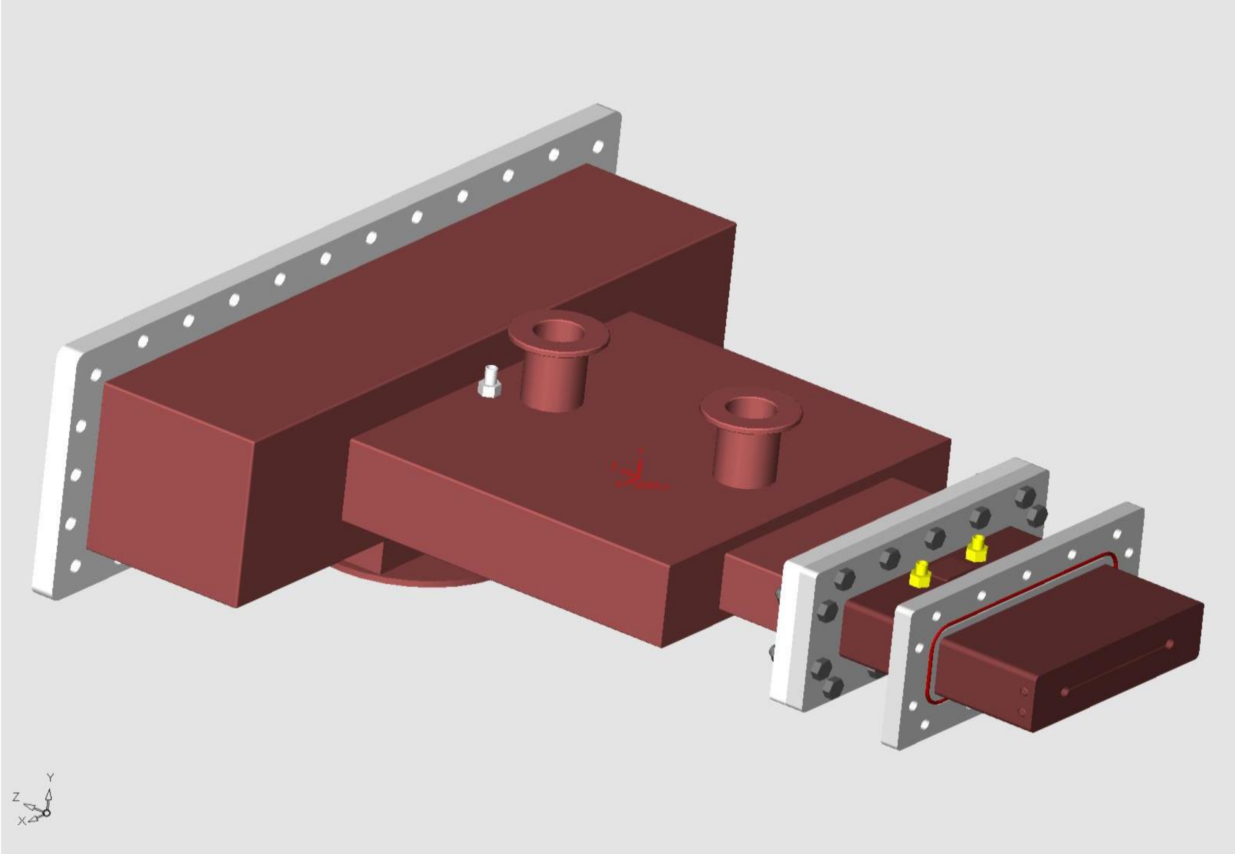
RF Measurements on ridge waveguide couplers (with out tuners)



RF Measurements on ridge waveguide couplers (with tuners)



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



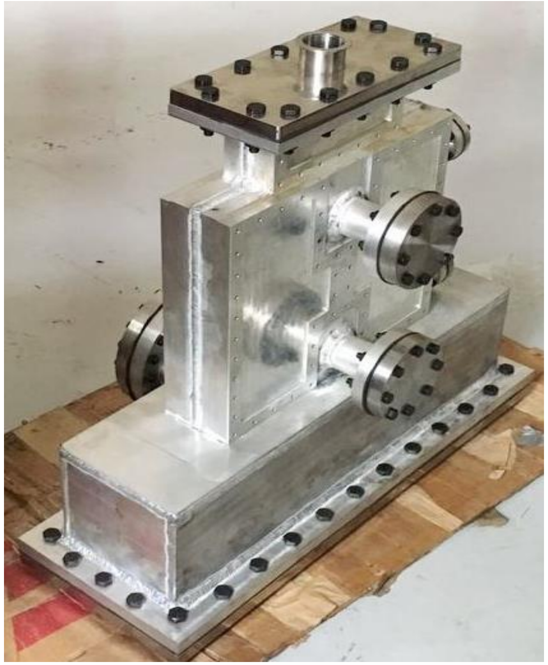
250 kW, CW, 352 MHz RF waveguide Coupler under development

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

250 kW CW, 352.2 MHz Waveguide Coupler for LEHIPA

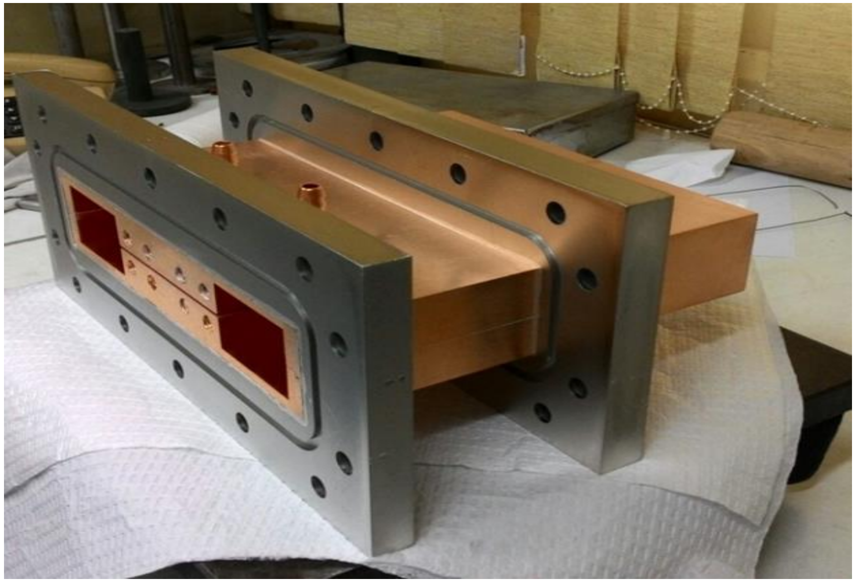


250 kW CW, 352.2 MHz, Waveguide Coupler (Aluminium) for LEHIPA with all ports

These waveguide couplers are fabricated by vendors in Mumbai & Pune. The iris part of couplers is fabricated at CEERI Pilani.

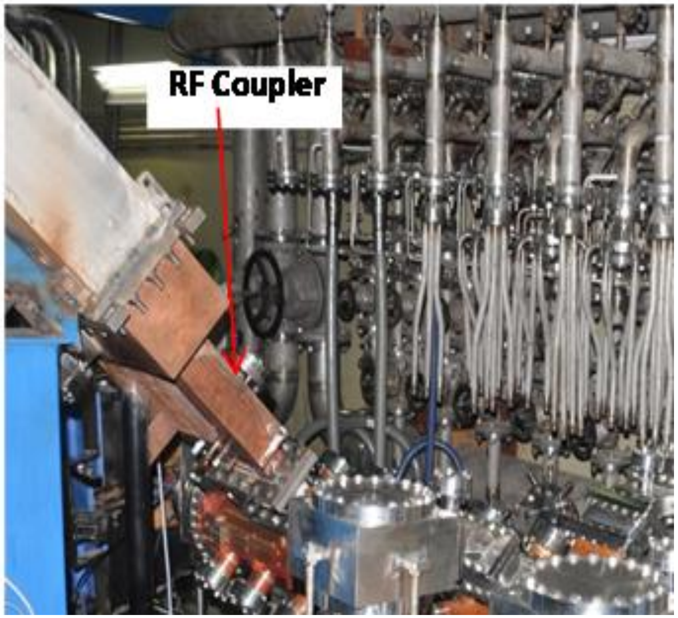
Development of high power RF couplers at IADD, BARC

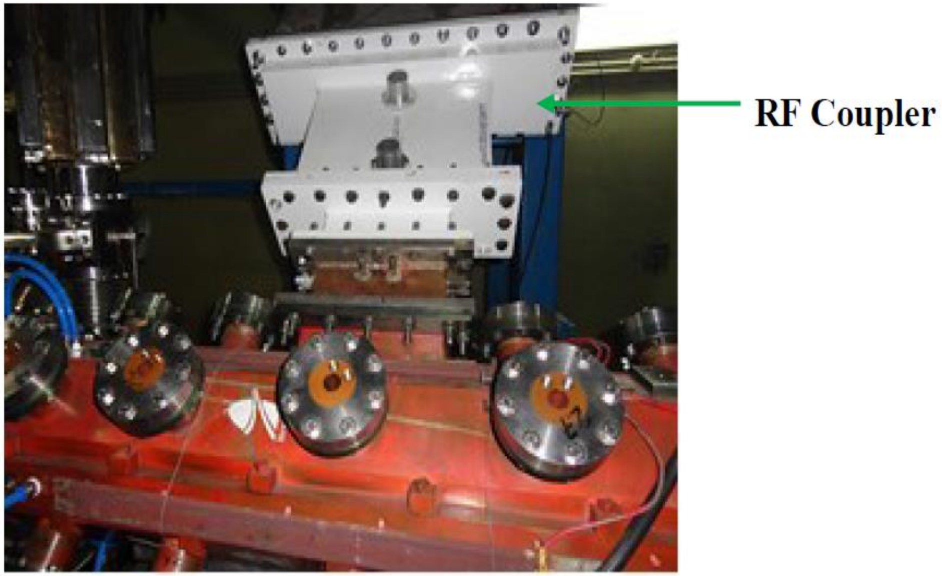
Two copper halves and S/steel flange before brazing



Brazed iris coupler at CEERI Pilani

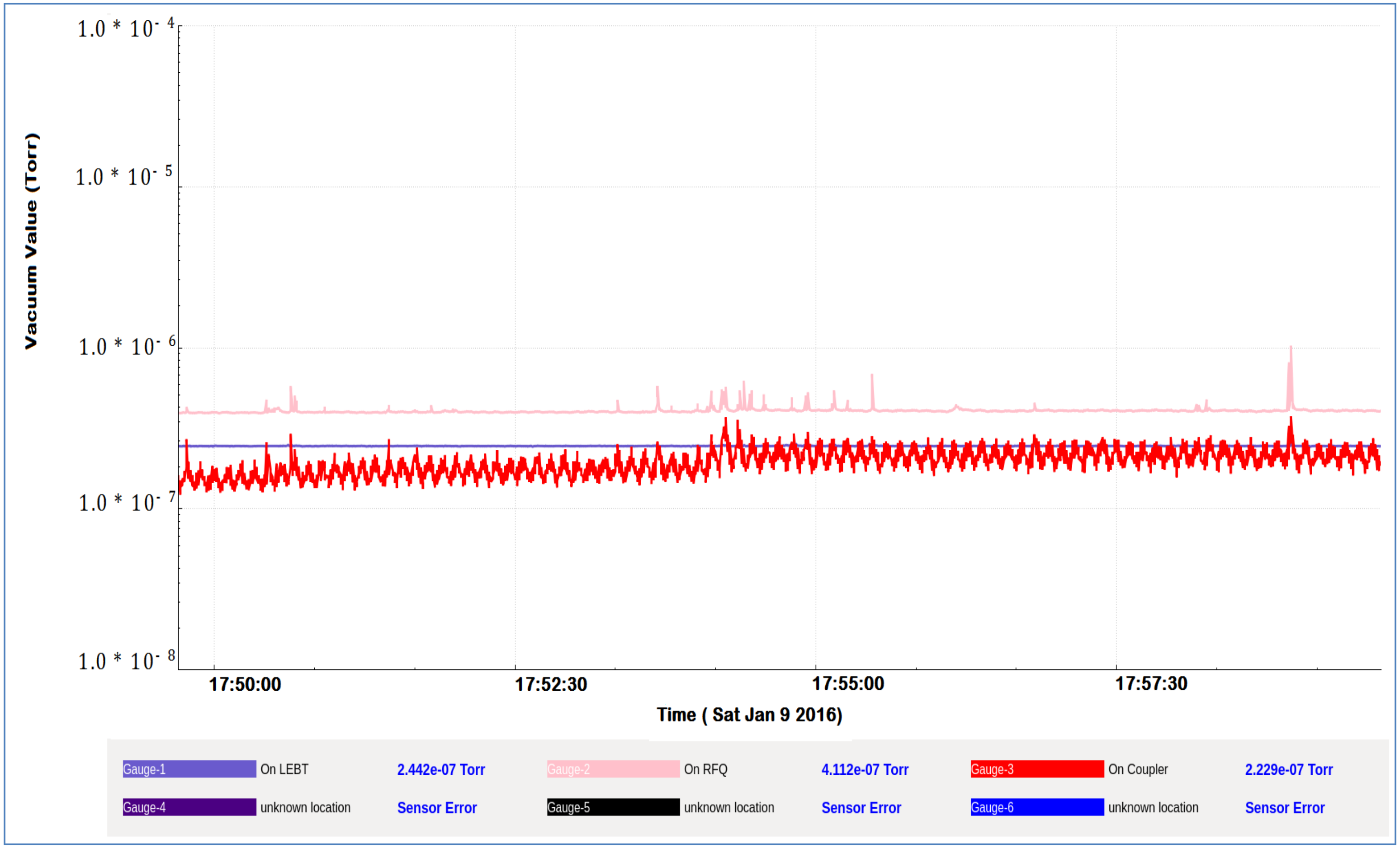
Waveguide couplers testing on RFQ cavities of LEHIPA





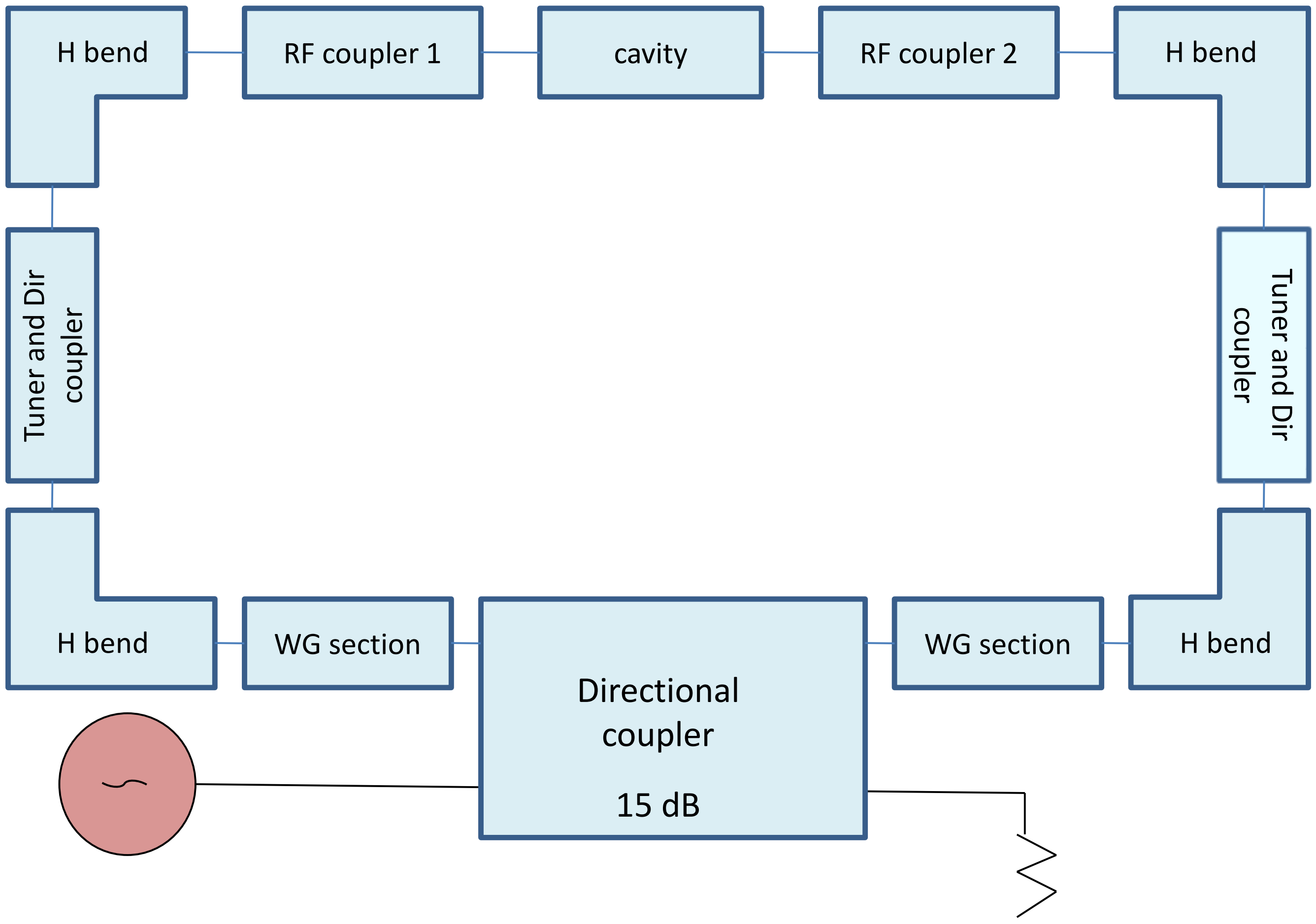
These couplers have been successfully tested for more than 200 kW RF Power in pulsed mode and used for proton beam acceleration to 1.24 MeV energy. Presently, two couplers are being used to feed more than 400 kW RF Power to RFQ cavities at low duty cycles. The beam energy analysis is being carried out.

Vacuum signals during RF Conditioning on RFQ cavities of LEHIPA



High Power Test facilities for Couplers

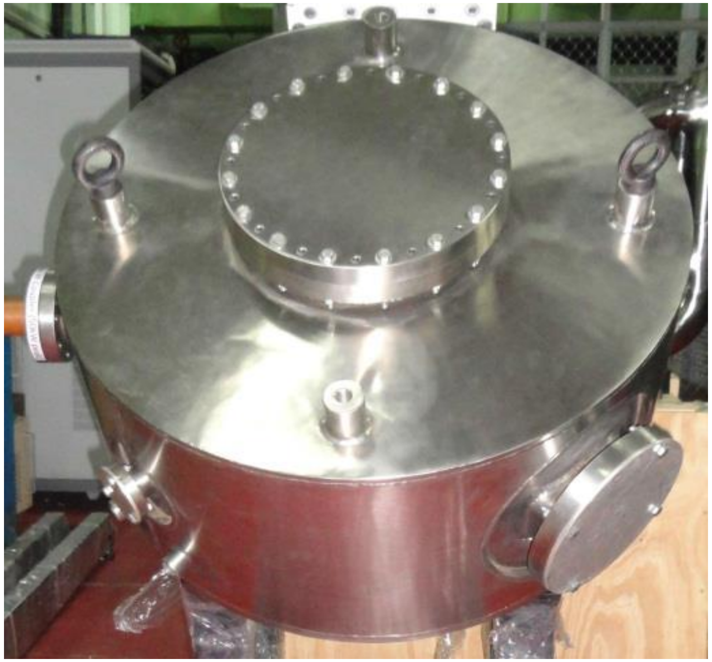
Basic layout of high power resonant ring



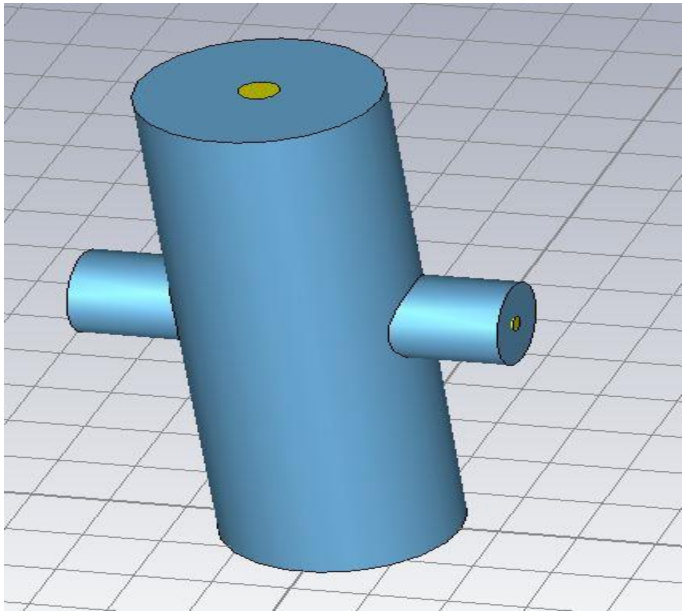
Main components required for setup

- 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

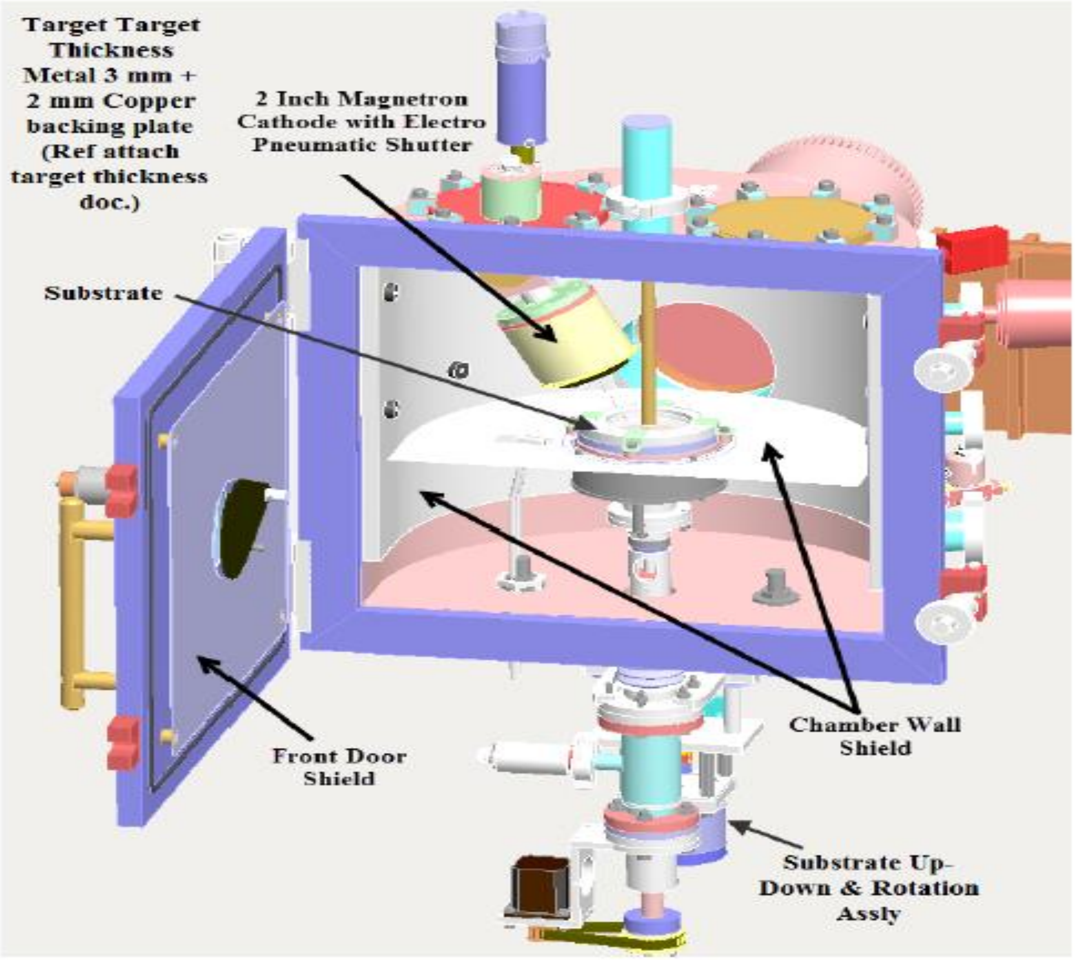


Test cavity for 250 kW, 352.2 MHz Waveguide Couplers



Test cavity for 325 MHz IIFC Couplers (presently under fabrication)

TiN coating system for RF window of SC Couplers



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