Couplers

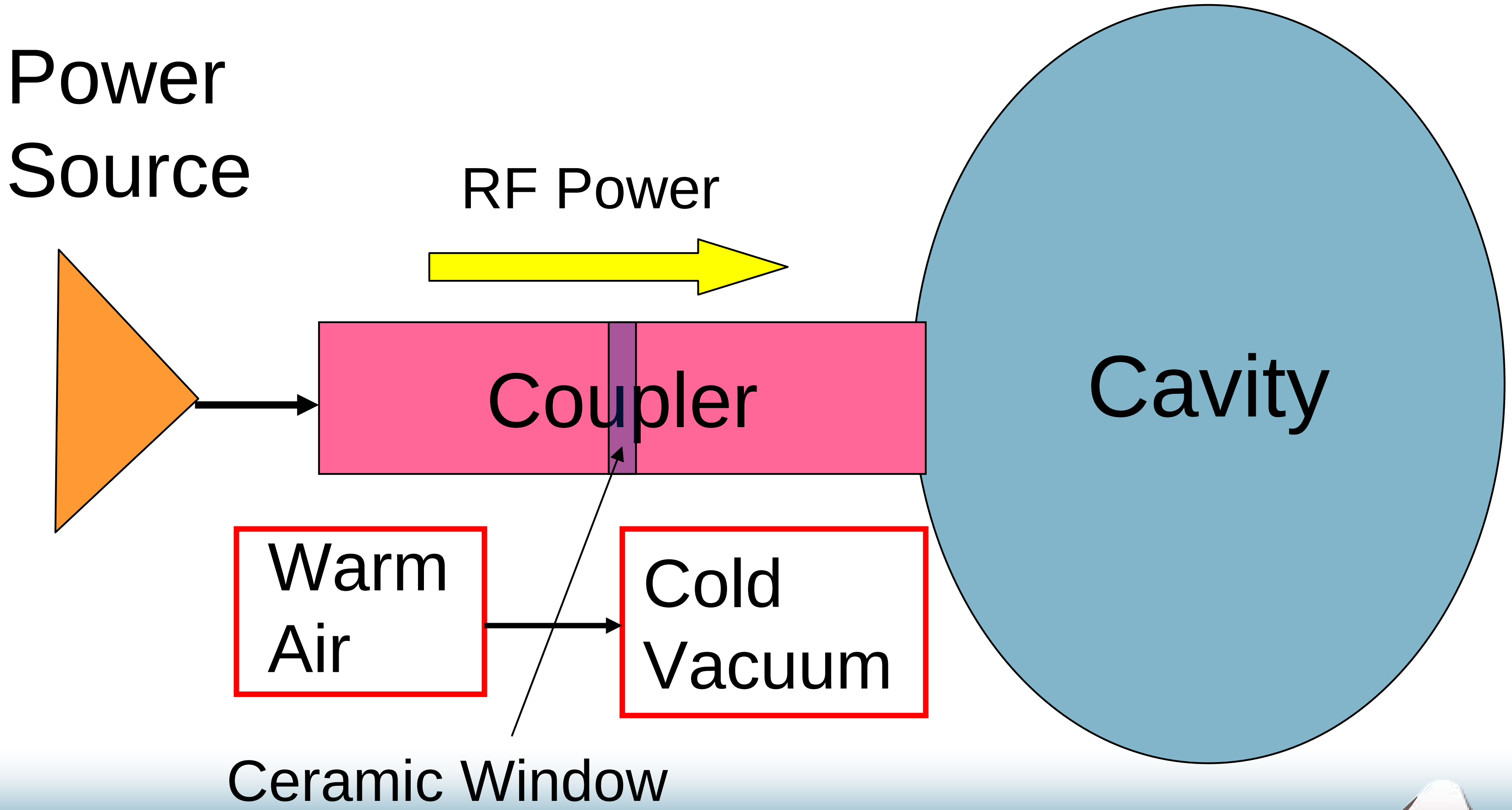
Design and Fabrication Issues of High Power & Higher Order Modes Couplers for Superconducting Cavities

Shuichi Noguchi, KEK

Contents

- Design Issues of Input Coupler
- Design Issues of HOM Coupler

RF Power Input Coupler



Coupler Design & Fabrication

Design	Fabrication	
RF	Geometry	Coaxial Rectangular
Mechanical	Material	Cu Plated SUS
Thermal	Method	Tig Welding Brazing, EBW

Design Issues of Input Coupler

Requirements / Specification

- Frequency
- Maximum Power
- Operation Mode
- Heat Load
- Coupling
  Tune-ability

Choices

- Type ; Coaxial or Wave Guide
- Position ; Cell or Beam Pipe
- Number of Windows ; Single or Double
- Cooling ; Conduction, G-He, L-He, L-N2, Water
- Number of Couplers

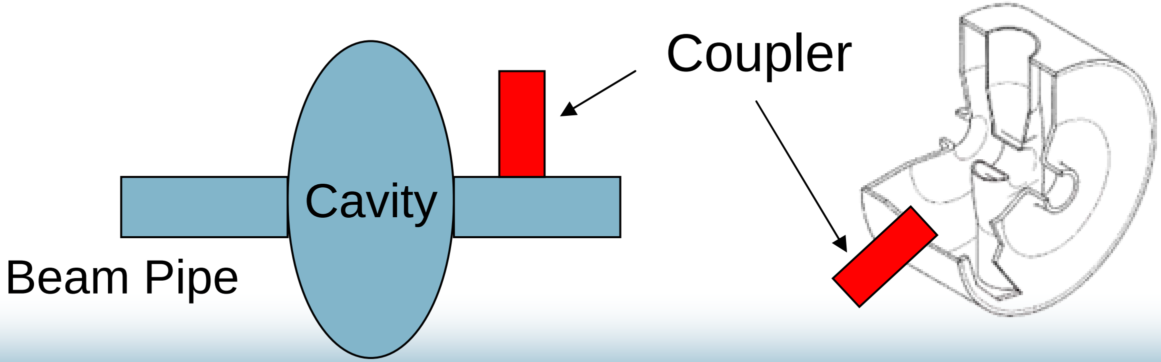
Best Choice for SC

Coaxial Antenna Type Coupler on Beam Pipe is usually the Best Solution.

Exception ;

Low β Cavity ; Coaxial Antenna on Cavity

High Frequency Cavity ; Wave Guide



Major Couplers used

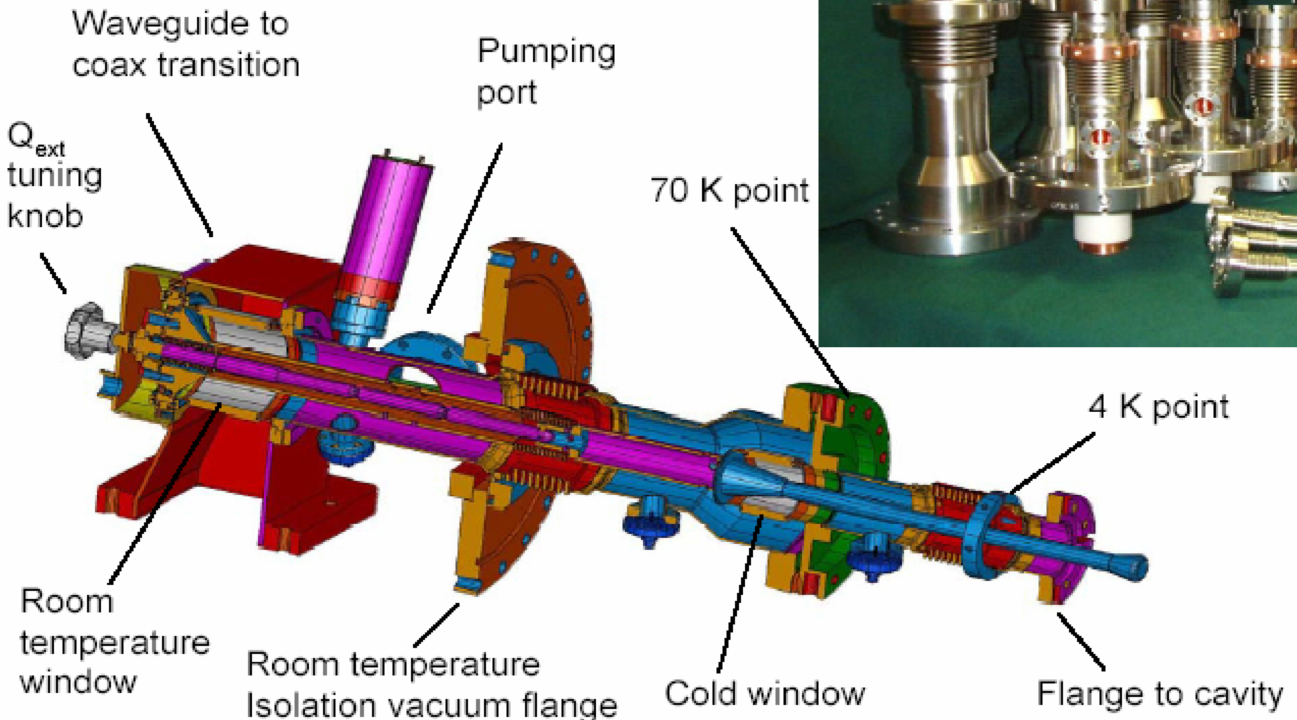
Accelerator	TRISTAN KEKB	SNS	LEP	FLASH	CEBAF
Frequency	508MHz	805MHz	324MHz	1.3GHz	1.5GHz
Power Requirement	CW 400kW	Pulse 400kW	CW 100kW	Pulse 300kW	CW 10kW
Coupler Type	Coaxial Antenna	Coaxial Antenna	Coaxial Antenna	Coaxial Antenna	Wave Guide
Window Type Size	Coaxial Disk	Coaxial Disk	Cylinder	Cylinder	Square
Ceramic Size	ϕ180,t10	ϕ100,t9	ϕ150	ϕ40, ϕ60	60 x 120
Used Coupler	～40	～80	～200	～80	～350

Coaxial Antenna Coupler

- Examples
- Components
- Coupling

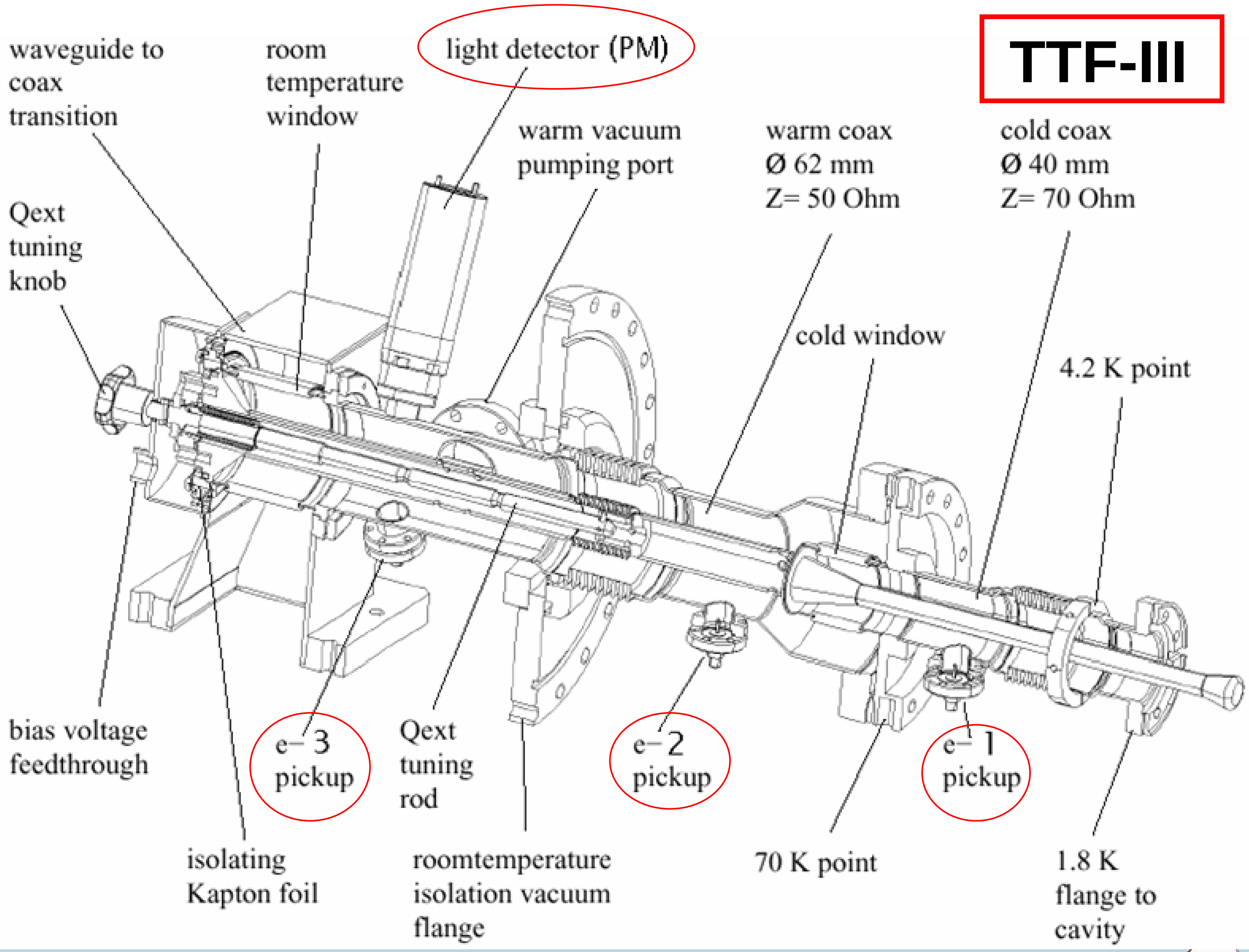
Coax couplers, two cylindrical windows

TESLA Coupler



W.– D. Möller, DESY in Hamburg 12th International workshop on RF Superconductivity 12

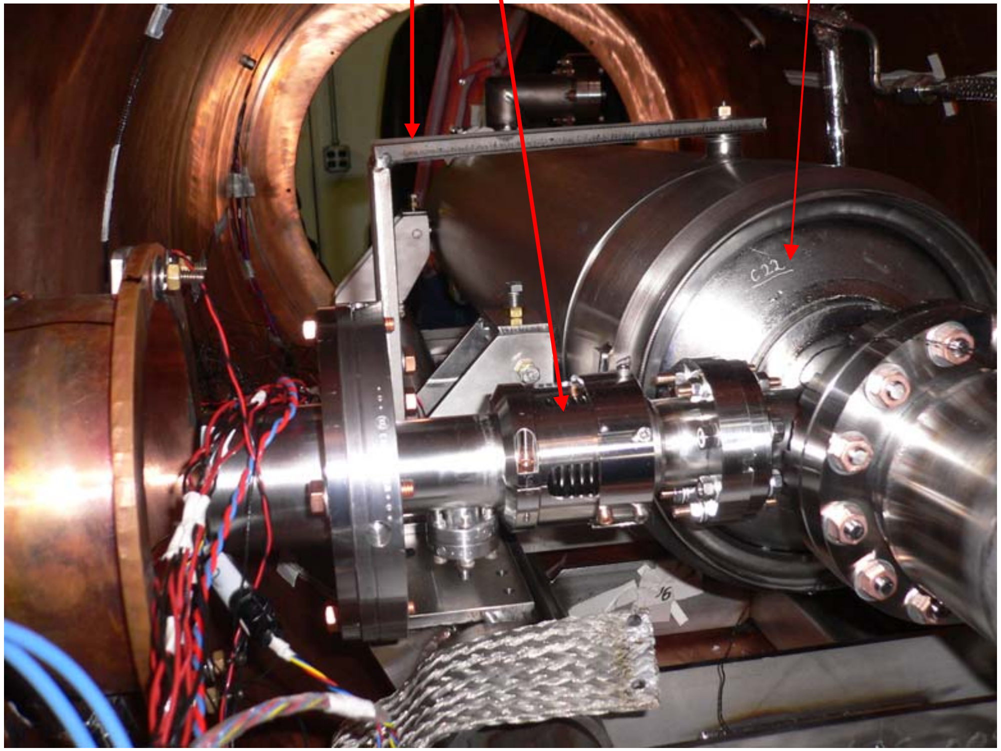
TTF-III



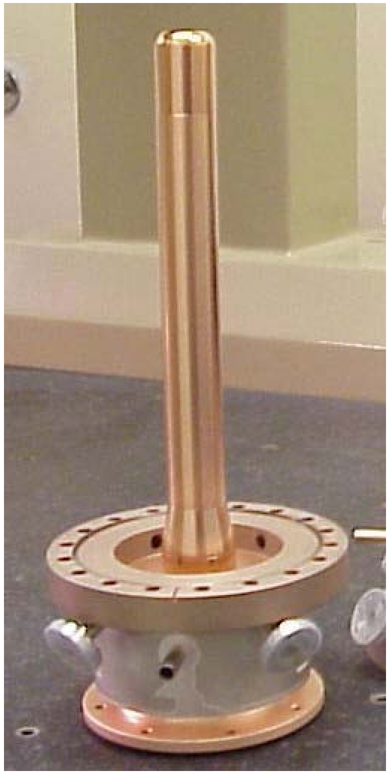
waveguide to coax transition
room temperature window
light detector (PM)
warm vacuum pumping port
warm coax
Ø 62 mm
Z= 50 Ohm
cold coax
Ø 40 mm
Z= 70 Ohm
Qext tuning knob
cold window
4.2 K point
bias voltage feedthrough
e− 3 pickup
Qext tuning rod
e− 2 pickup
e− 1 pickup
isolating Kapton foil
roomtemperature isolation vacuum flange
70 K point
1.8 K flange to cavity

TTF-3 Coupler

Processing Stand



Coaxial Disk Type Window Coupler



SNS

KEK-JAEA

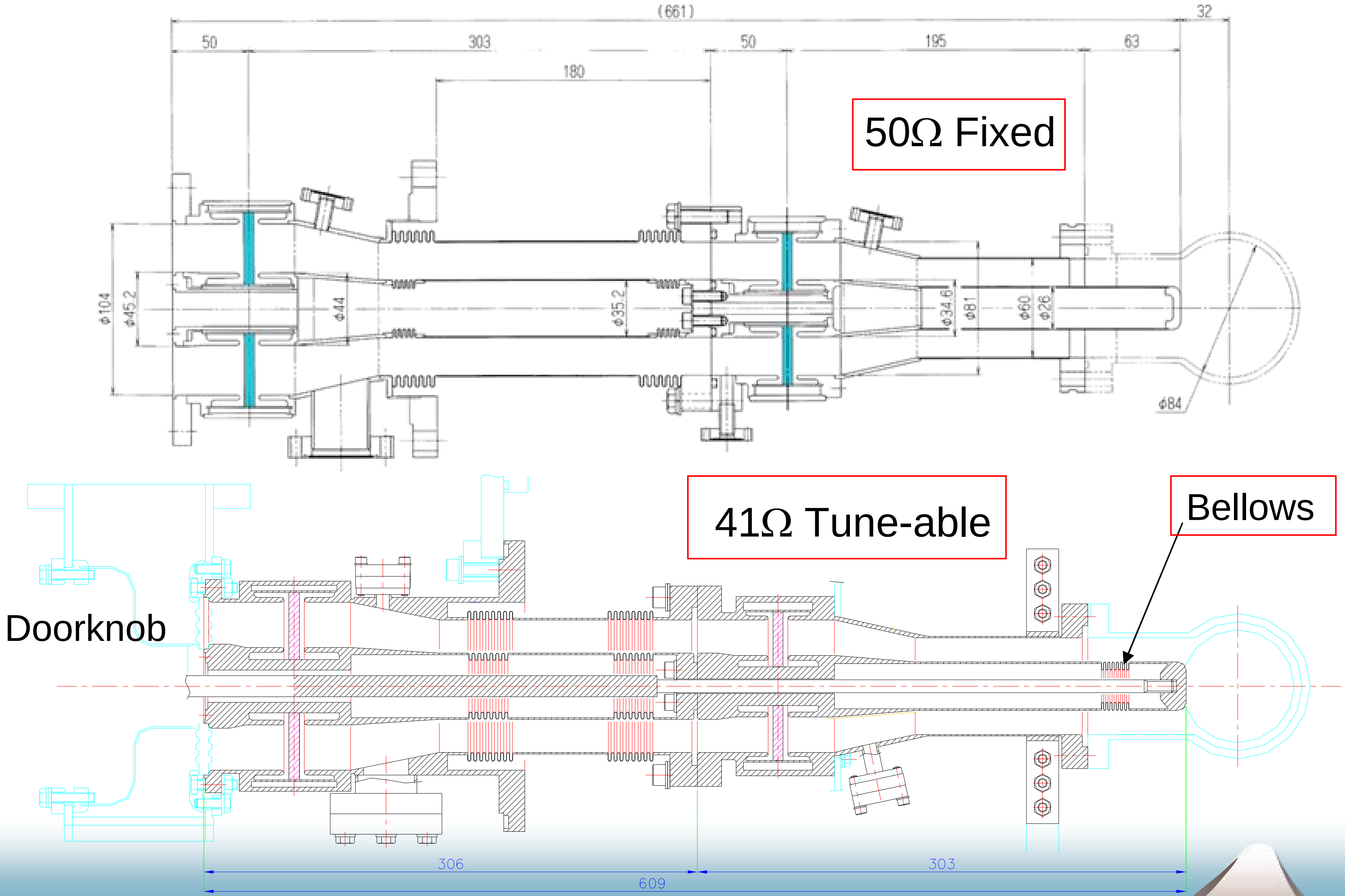
STF-1

STF-2

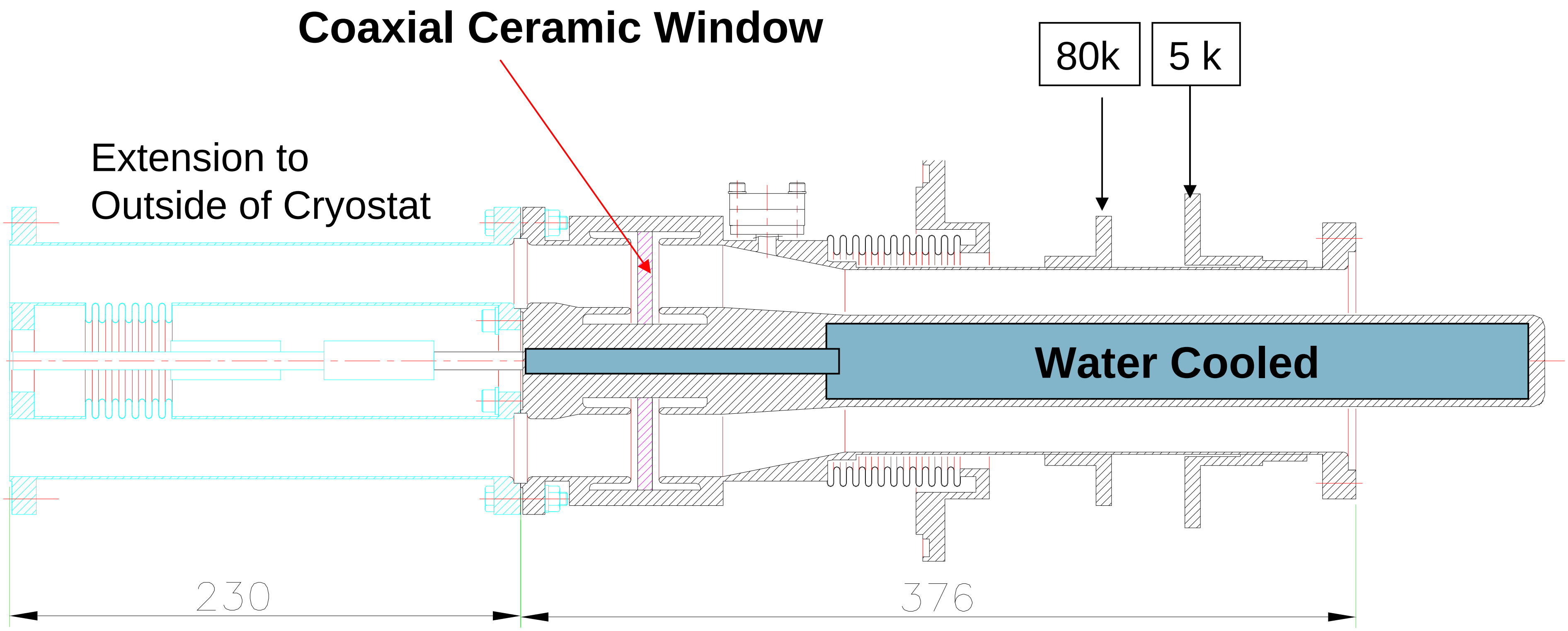
TTF-V

KEK-ERL

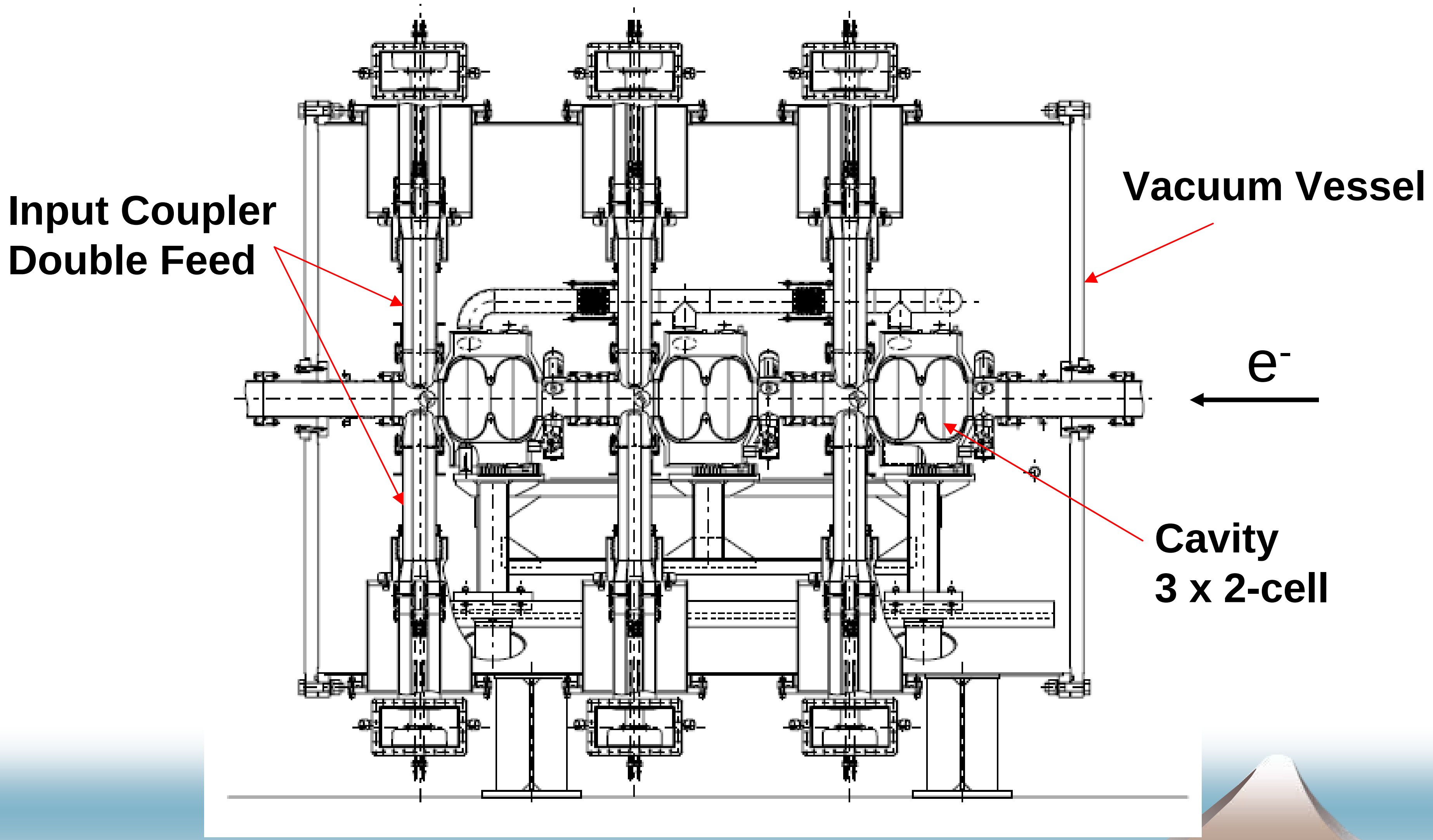
STF-I & II Couplers



CW Input Coupler for KEK-ERL



ERL Injector Cryomodule



Components of Coaxial Antenna Coupler

- Coaxial Line (Cu Plated SUS)
- Window (High Purity Al_2O_3)
- Wave Guide to Coaxial Transformer
- Diagnostics

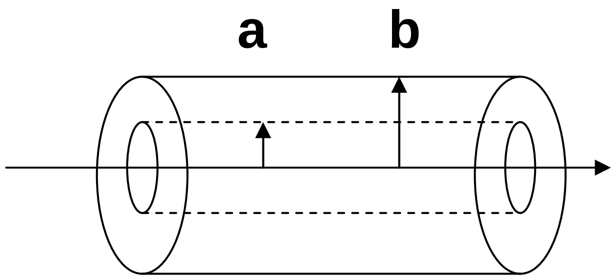
  Vacuum, Arcing, Electron

RF Design Criteria

- Maximum Peak E (Pulse High Power Application)
- Loss (CW Application)
- Reflection
- Multipacting

Fabrication, Assembly, Risk, etc.

Coaxial Waveguide (TEM-Modes)



$$E_\theta = 0\,, \quad H_r = 0\,,$$

$$\frac{\partial}{\partial r}\left(r\,E_r\right) = 0\,, \quad \frac{\partial}{\partial r}\left(r\,H_\theta\right) = 0$$

$$E_r = \frac{\mathrm{A}}{r} e^{-j\beta z}\,, \quad H_\theta = \frac{1}{Z_i}\frac{\mathrm{A}}{r} e^{-j\beta z}$$

$$V = \int_a^b E_r\, dr = \mathrm{A} \ln\frac{b}{a} e^{-j\beta z}\,, \quad I = \int_0^{2\pi} J_S\, a\, d\theta = 2\pi \frac{\mathrm{A}}{Z_i} e^{-j\beta z}$$

$$Z_0 = \frac{V}{I} = \frac{Z_i}{2\pi} \ln\frac{b}{a}\,;$$

Characteristic Impedance

Power Loss

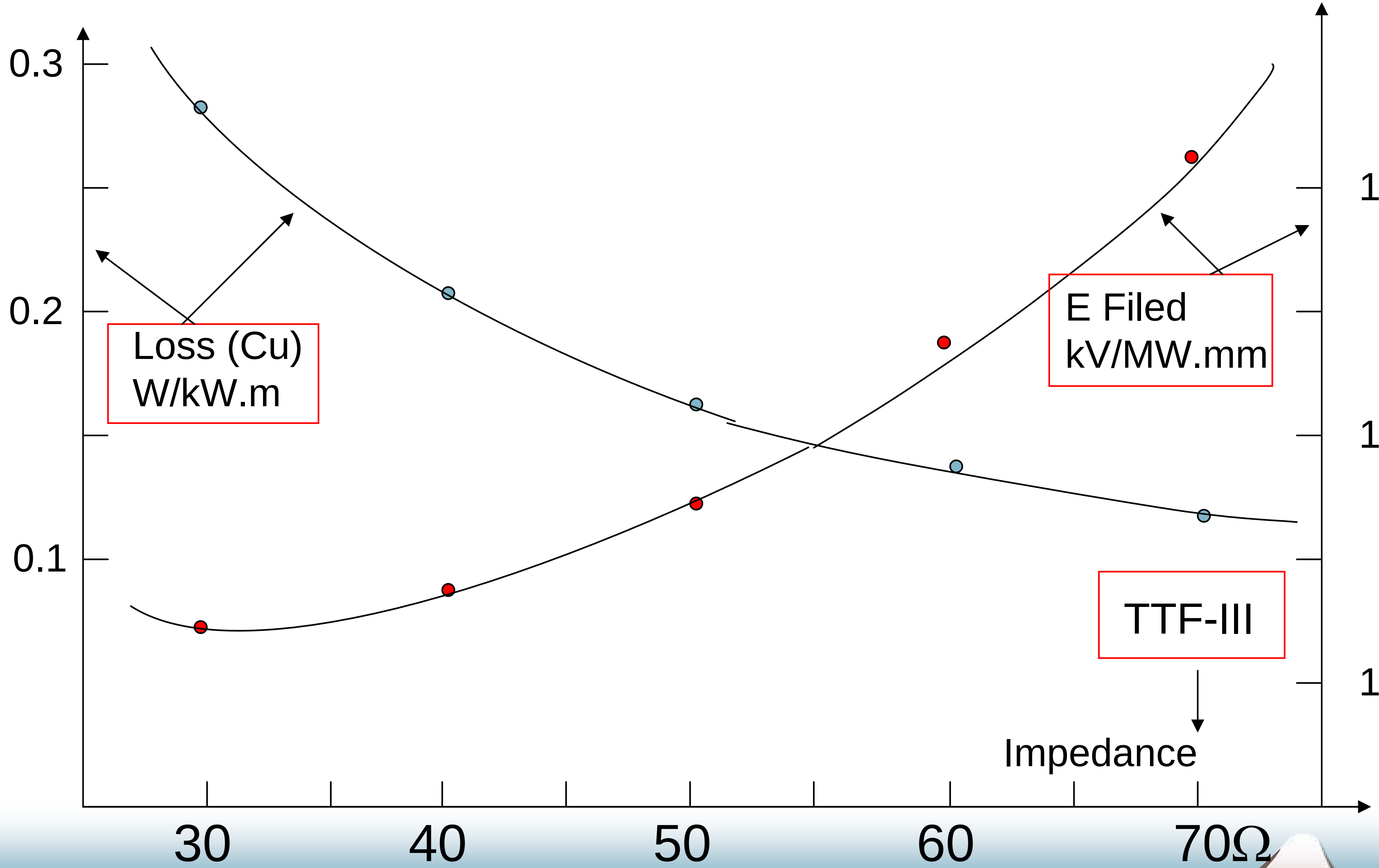
$$P_f = \int_0^{2\pi}\int_a^b \frac{1}{2}\mathrm{Re}\left(E_r H_\theta^*\right) r dr d\theta = \frac{\mathrm{A}^2}{Z_i}\pi \ln\frac{b}{a}$$

$$P_{loss} = \frac{1}{2}R_S\left[\int_0^{2\pi}\left|H_\theta\right|_{r=a}^2 a d\theta + \int_0^{2\pi}\left|H_\theta\right|_{r=b}^2 b d\theta\right] = R_S\frac{\mathrm{A}^2}{Z_i^2}\pi\left(\frac{1}{a}+\frac{1}{b}\right)$$

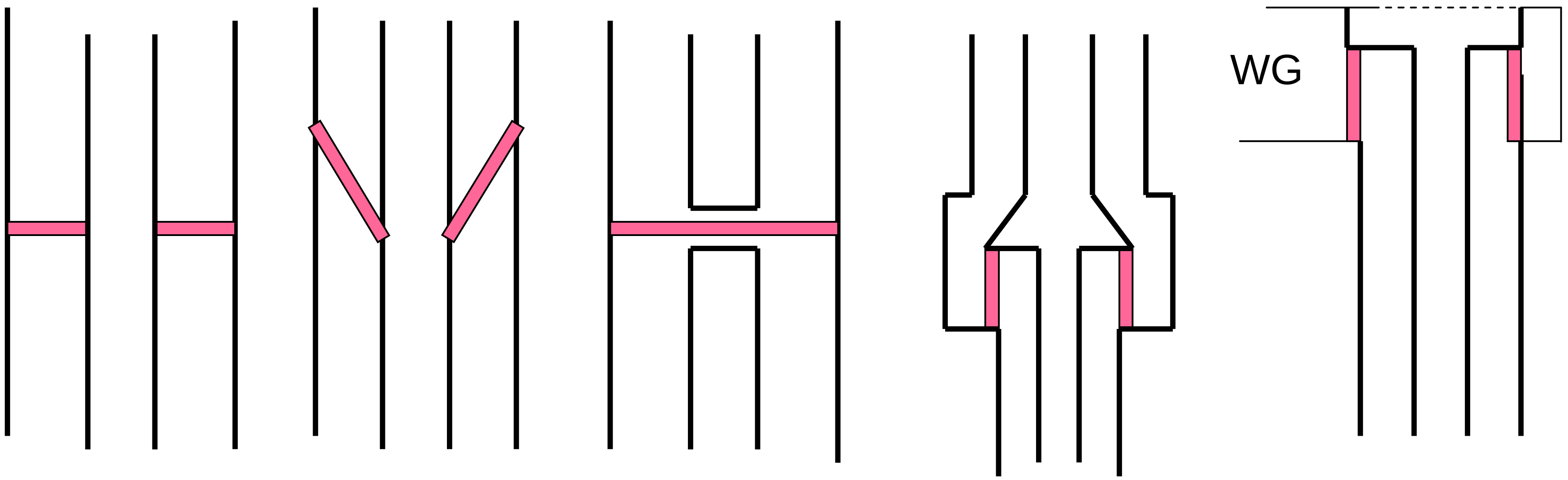
$$= R_S\frac{P_f}{Z_i}\left(\frac{1}{a}+\frac{1}{b}\right)\Big/\ln\frac{b}{a} = \frac{R_S P_f}{2\pi Z_0}\left(\frac{1}{a}+\frac{1}{b}\right)$$

$$\mathrm{A} = \sqrt{\frac{Z_i P_f}{\pi \ln\frac{b}{a}}}$$

Power Loss & E-Field Strength



RF Windows of Coaxial Coupler



Coaxial Disk

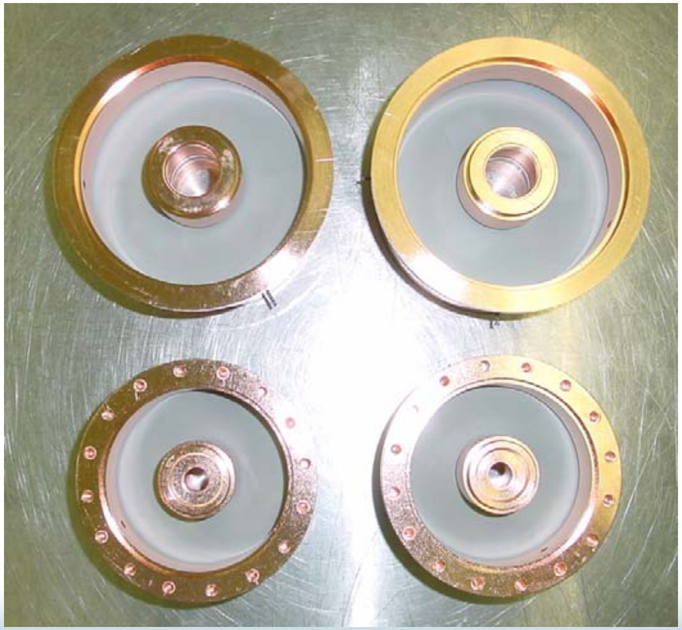
Conical

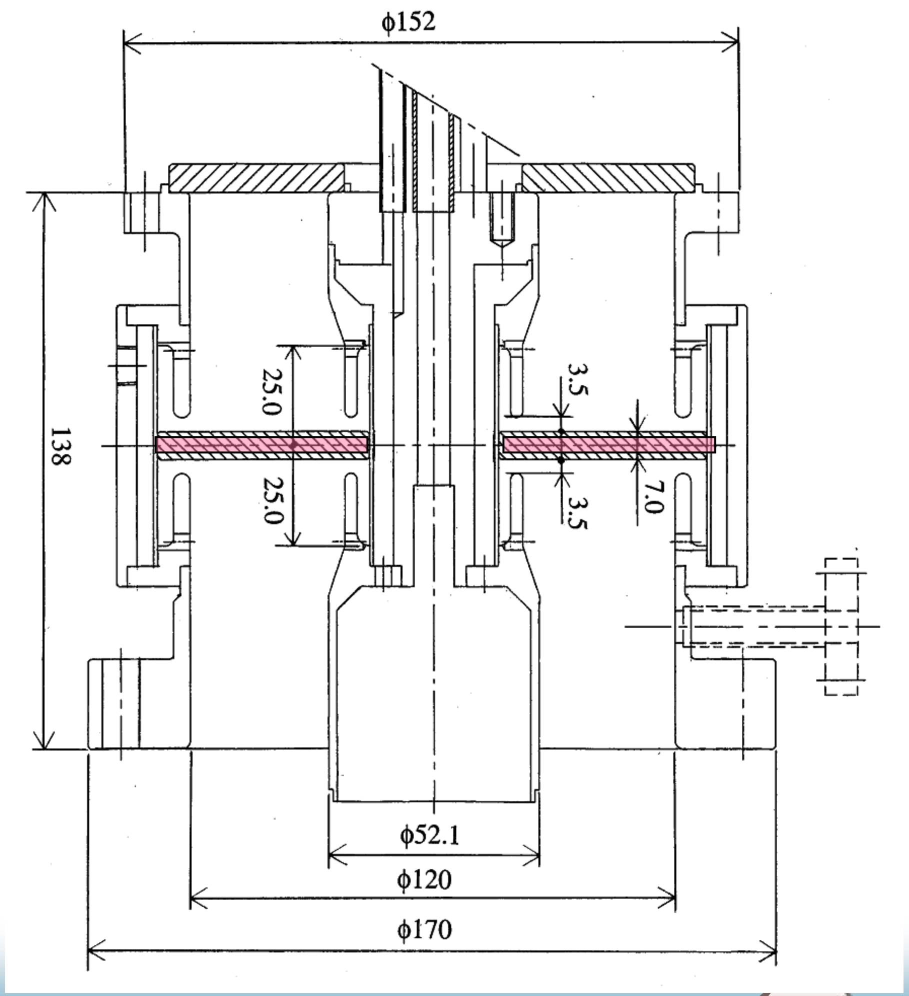
Capacitive

Cylinder

Cylinder at WG Transformer

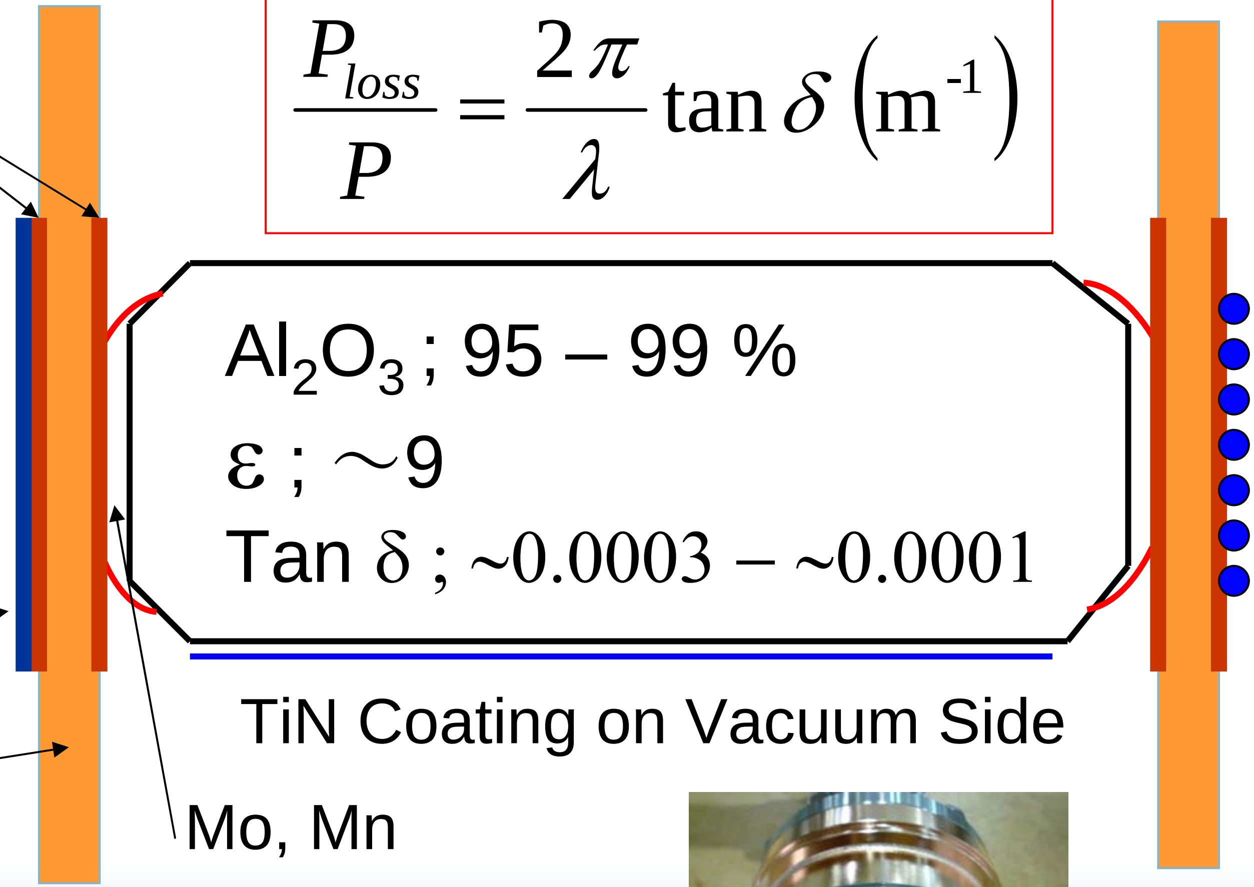
Coaxial Disk Window





Ceramics Window

$$\frac{P_{loss}}{P} = \frac{2\pi}{\lambda}\tan\delta\ \left(\mathrm{m}^{-1}\right)$$



Al_2O_3 ; 95 – 99 %

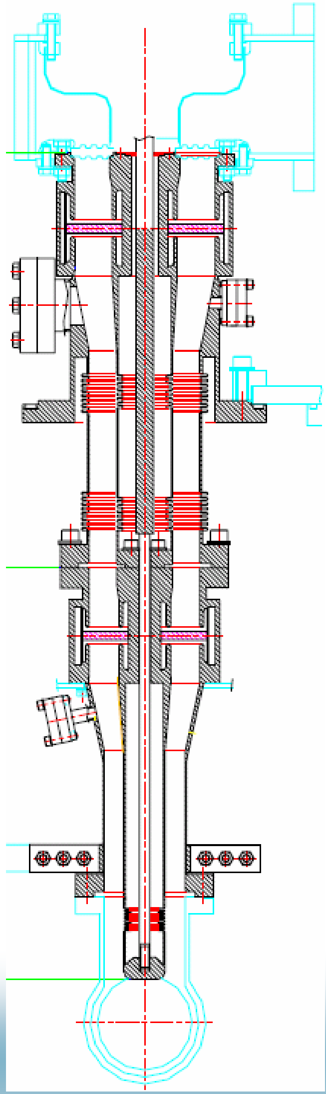
ε ; ~9

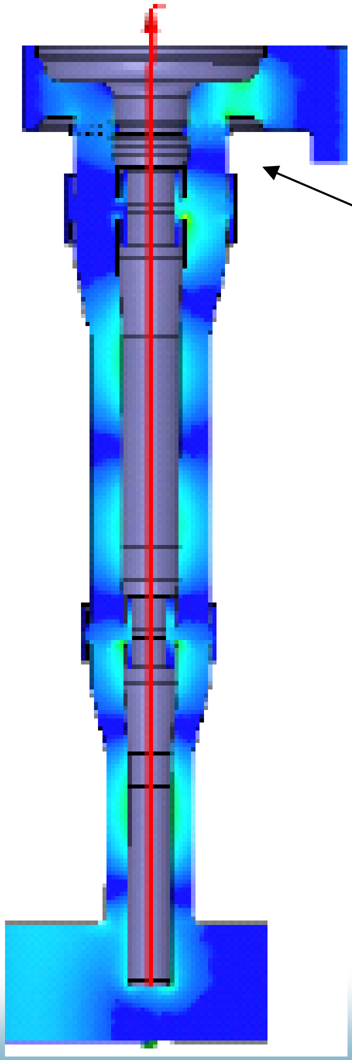
Tan δ ; ~0.0003 – ~0.0001

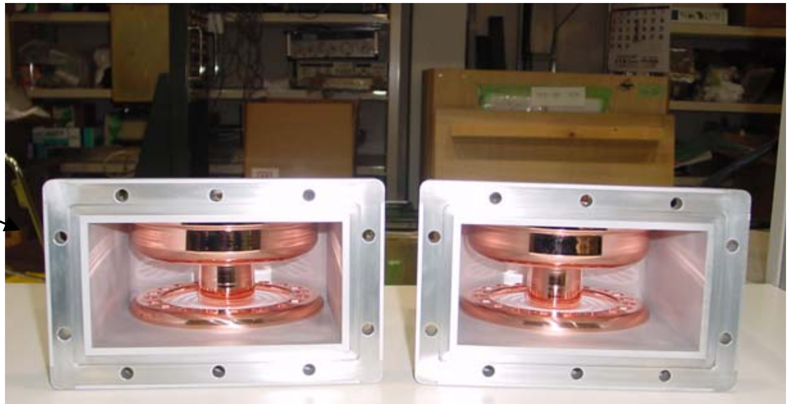
TiN Coating on Vacuum Side

Difference in thermal expansion coefficient is key.

HFSS Simulation

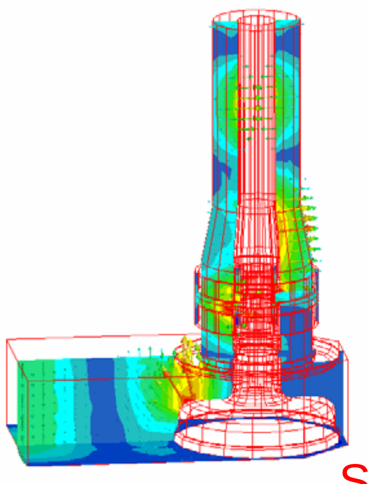


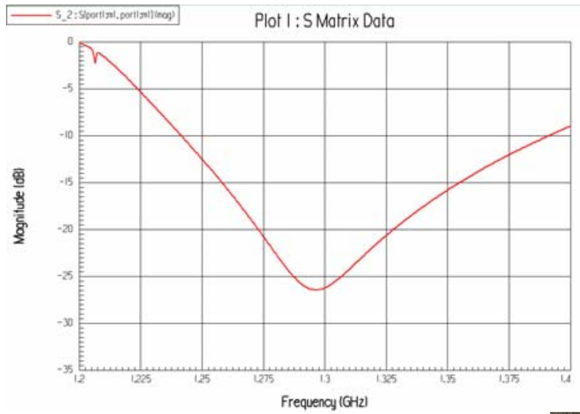


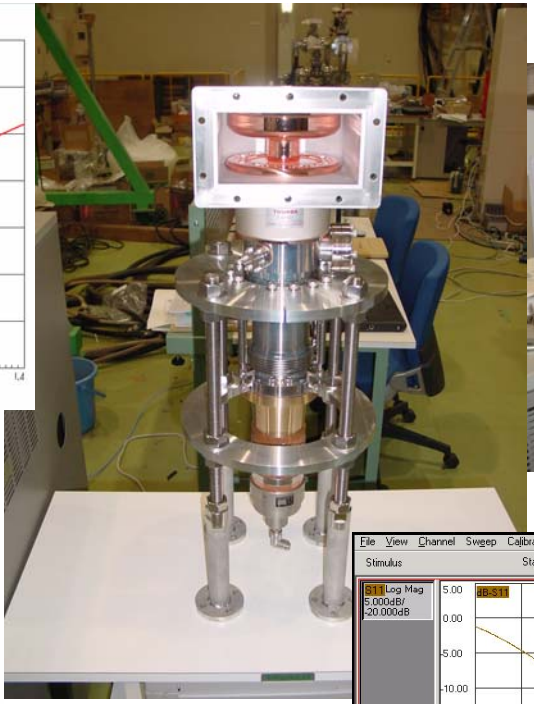


WG Transformer

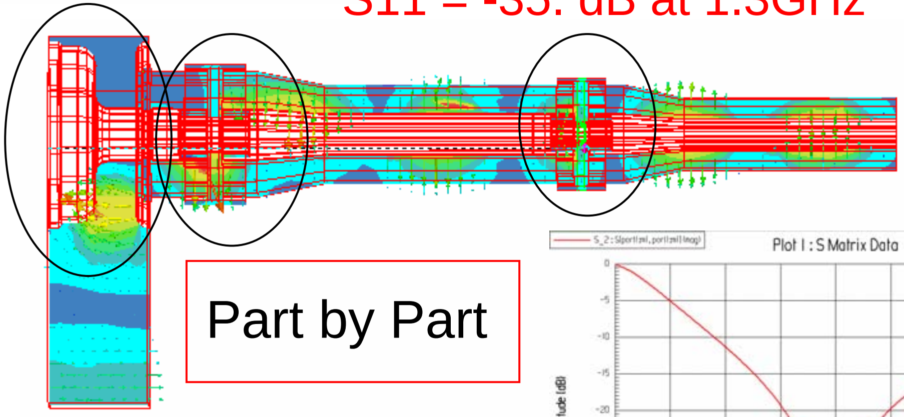
Warm window and Doorknob



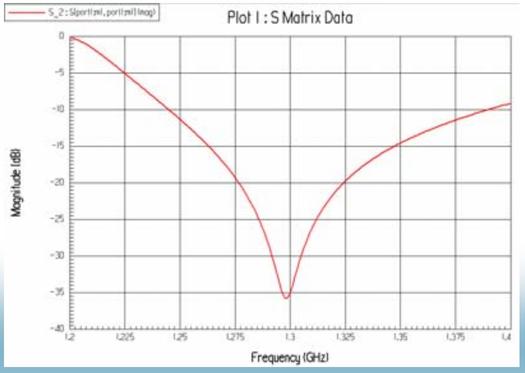


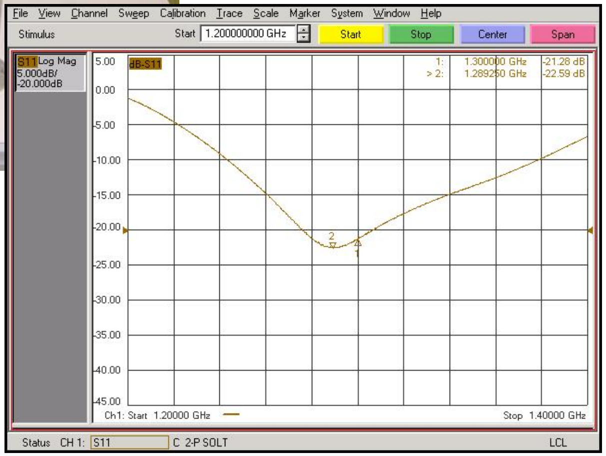


S11 = -35. dB at 1.3GHz



Part by Part





S11 = -26. dB at 1.3GHz

S11 = -21.3 dB at 1.3GHz

Coupling / Tune-ability

Optimum Coupling ; $\dfrac{1}{Q_{in}} = \dfrac{1}{Q_0}\left(1 + \dfrac{P_{beam}}{P_0}\right) = \dfrac{1}{Q_0} + \dfrac{1}{Q_b}$

$P_{beam} >> P_0$; $Q_{in} = Q_b$, depends on Beam Current

Coupling Tune-ability may be useful.

$Q_{in} \leq 10^7$ is desireble for better RF controll.

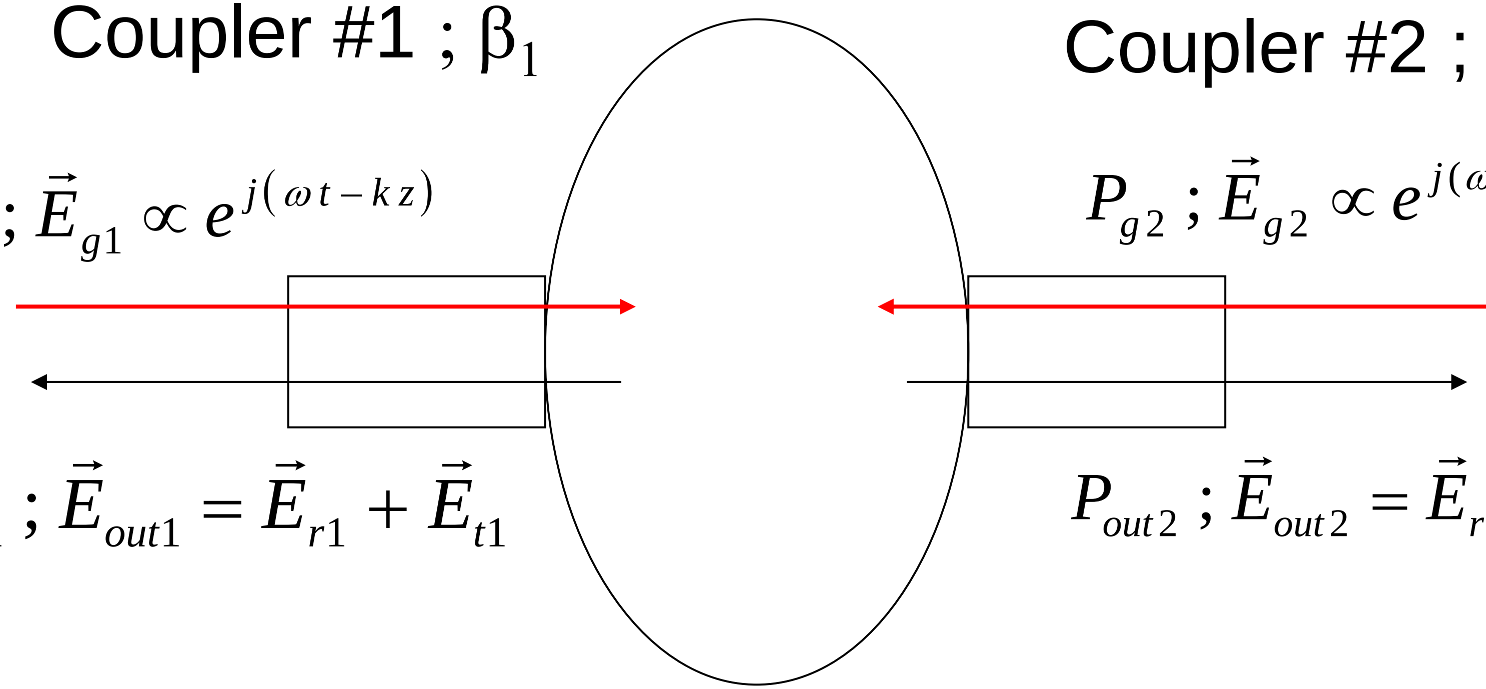
Double Couplers

Coupler #1 ; β_1

Coupler #2 ; β_2

$$P_{g1} \; ; \; \vec{E}_{g1} \propto e^{j(\omega t - kz)}$$

$$P_{g2} \; ; \; \vec{E}_{g2} \propto e^{j(\omega t + kz + \Psi)}$$

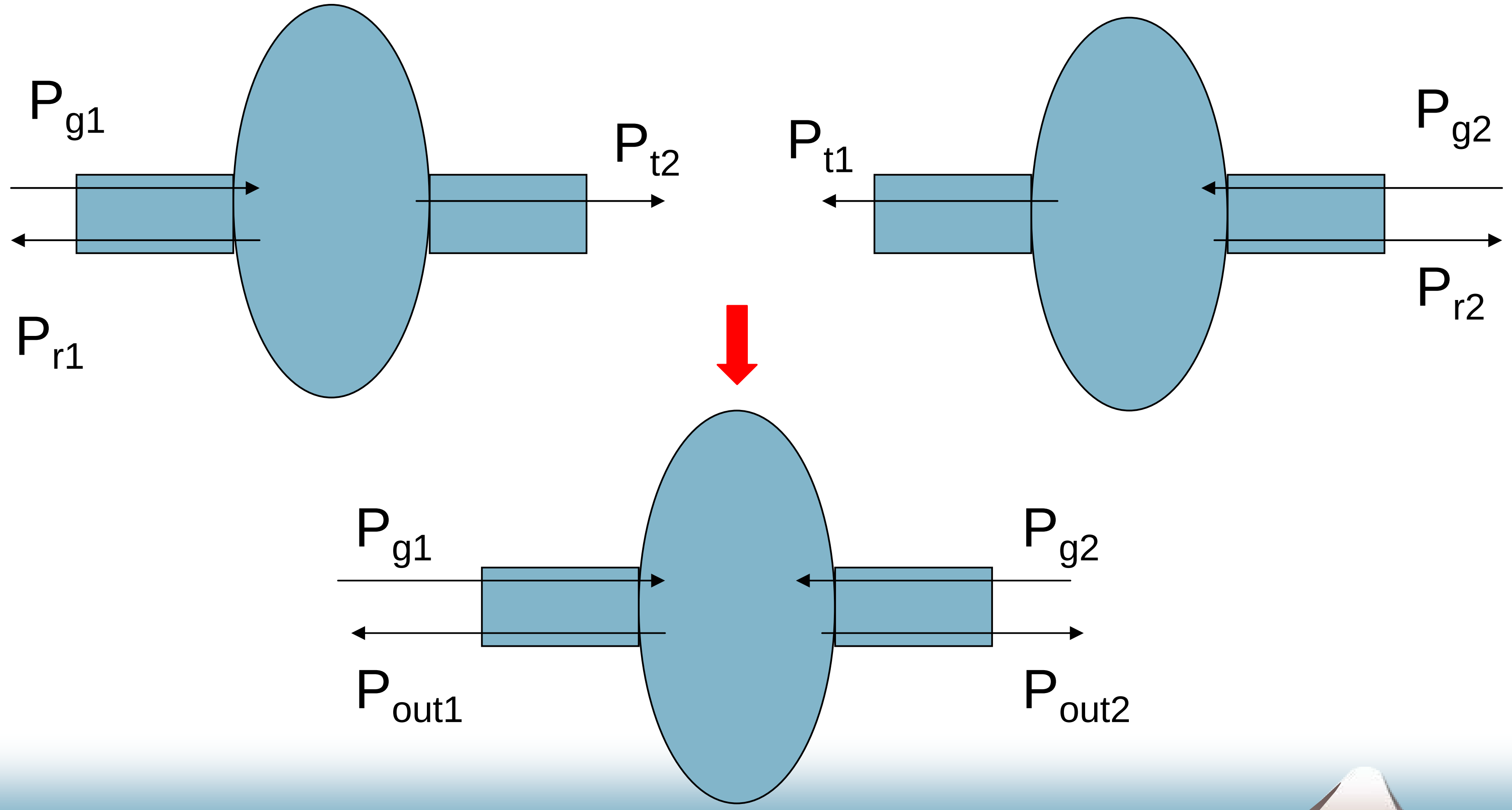


$$P_{out1} \; ; \; \vec{E}_{out1} = \vec{E}_{r1} + \vec{E}_{t1}$$

$$P_{out2} \; ; \; \vec{E}_{out2} = \vec{E}_{r2} + \vec{E}_{t2}$$

Optimum Coupling ; $P_{out\,1} = P_{out\,2} = 0$

Superposition



At Resonance

$$\sqrt{\frac{P_{r1}}{P_{g1}}} = \frac{E_{r1}}{E_{g1}} = \left| \frac{1+\beta_2-\beta_1}{1+\beta_1+\beta_2} \right| \qquad \sqrt{\frac{P_{in1}}{P_{g1}}} = \frac{2\sqrt{(1+\beta_2)\beta_1}}{1+\beta_1+\beta_2}$$

$$\sqrt{\frac{P_{t2}}{P_{g1}}} = \frac{E_{t2}}{E_{g1}} = \frac{2\sqrt{\beta_1\beta_2}}{1+\beta_1+\beta_2} \qquad \sqrt{\frac{P_{01}}{P_{g1}}} = \frac{2\sqrt{\beta_1}}{1+\beta_1+\beta_2}$$

$$\vec{E}_{g1} = E_{g1}\, e^{j(\omega t - kz)} \qquad \vec{E}_{acc1} = E_{acc1}\, e^{j\omega t}$$

$$\vec{E}_{r1} = E_{r1}\, e^{j(\omega t + kz + \phi)} \qquad \vec{E}_{t2} = E_{t2}\, e^{j(\omega t + kz' + \Phi)}$$

$$\phi = 0\,;\ \text{Overcouple}\left(\beta_1^* > 1\right) \qquad \phi = \pi\,;\ \text{Undercouple}\left(\beta_1^* < 1\right)$$

Optimum Coupling

$$P_{out1} = P_{out2} = 0$$

$$P_{out1} \propto \left| \vec{E}_{r1} + \vec{E}_{t1} \right|^2 = E_{r1}^2 + E_{t1}^2 + 2E_{r1}E_{t1}\cos\left[\phi - \left(\Psi - \Phi\right)\right]$$

If $\phi = \pi$ and $\Psi = \Phi$ $\qquad P_{out1} \propto \left(E_{r1} - E_{t1}\right)^2$

If $P_{g1} = P_{g2}$ $\qquad P_{out1} \propto \left(\dfrac{1 - \beta_1 + \beta_2 - 2\sqrt{\beta_1 \beta_2}}{1 + \beta_1 + \beta_2} \right)^2$

$$P_{out2} \propto \left(\frac{1 + \beta_1 - \beta_2 - 2\sqrt{\beta_1 \beta_2}}{1 + \beta_1 + \beta_2} \right)^2$$

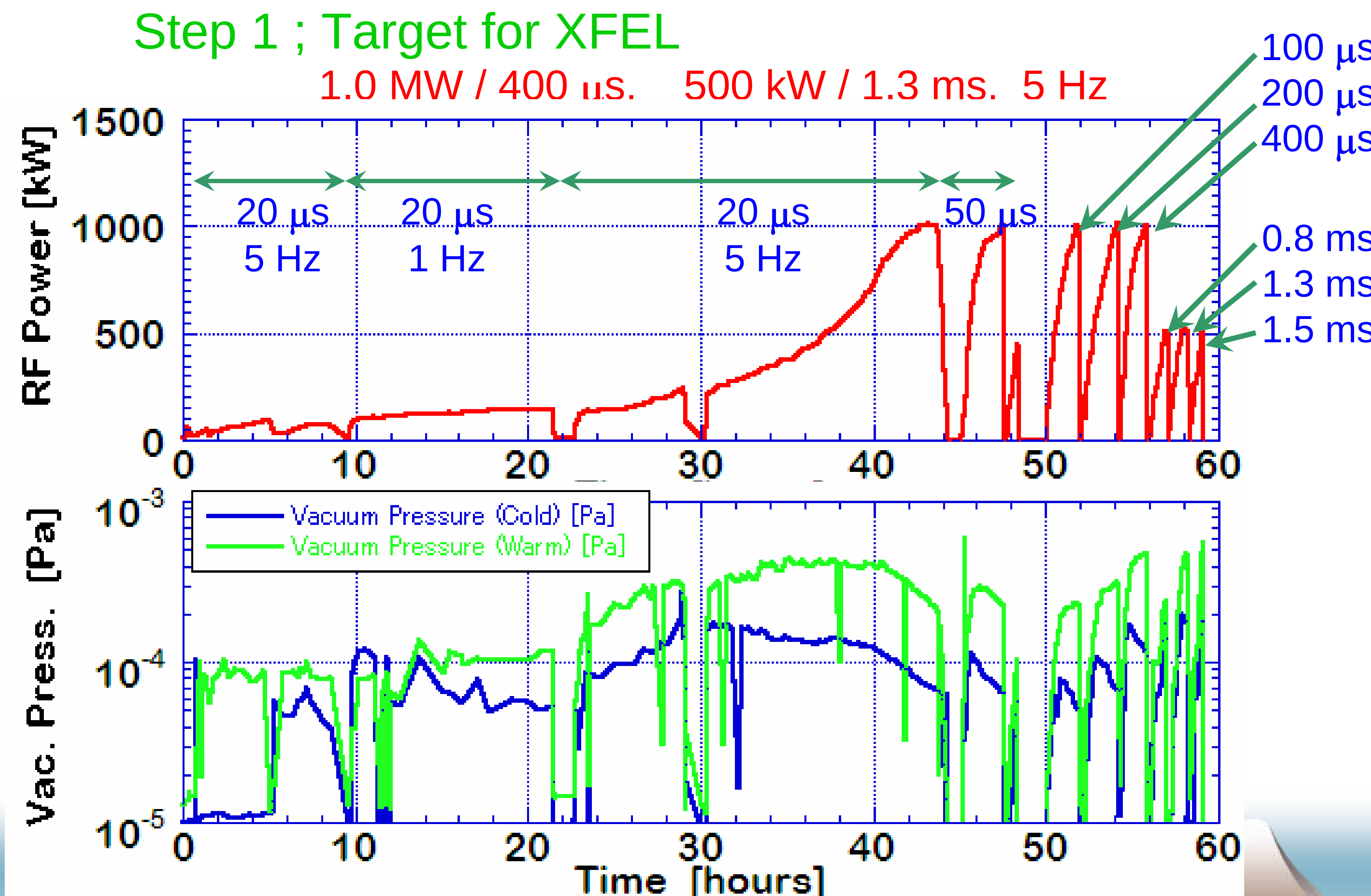
$$\boxed{\beta_1 = \beta_2 = \frac{1}{2}}$$

Processing (Acceptance Test)

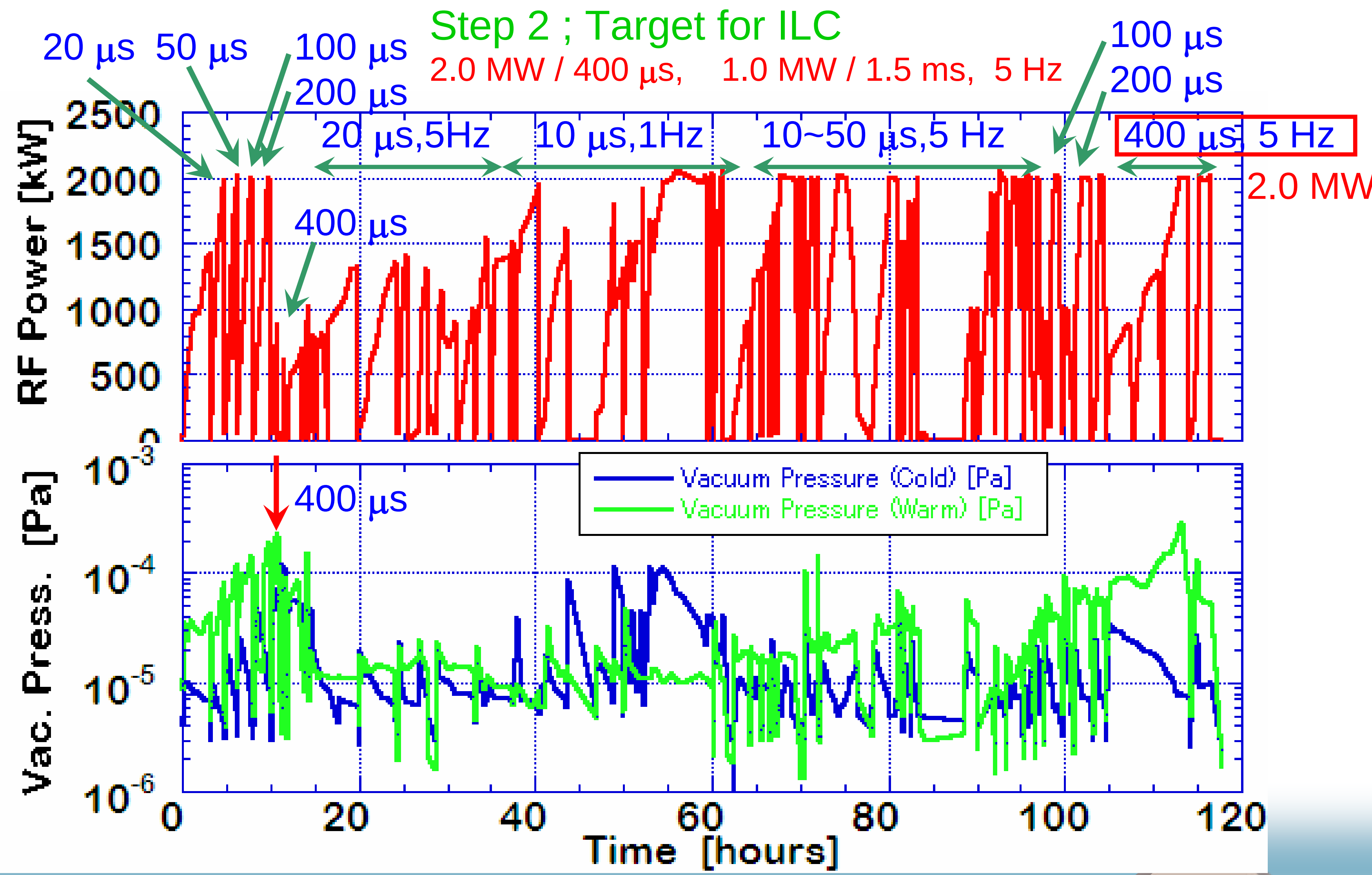
- Make them Clean
- Keep them Clean
- Careful Processing with Diagnostics

  Arc Detector, Electron Monitor, Vacuum

Processing of TTF-V Couplers at KEK



TTF-V Couplers at KEK



HOM Coupler

- Device to lower Q-Values of HOM's
- Output Coupler for HOM's excited by Beam
- Need Filter for the Operating Mode
- So Many HOM Couplers have been designed and used.
- Beam Pipe Absorber is an Alternative.

Design Issues of HOM Coupler

Requirements / Specification

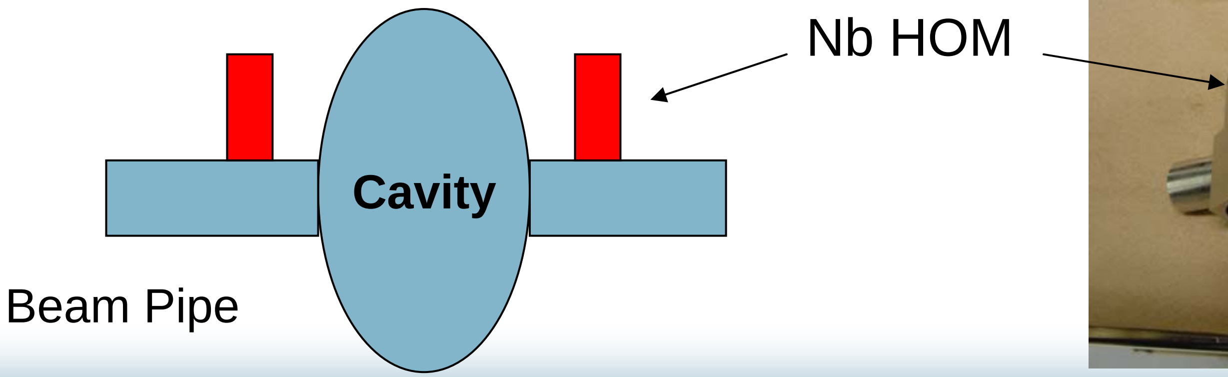
- Frequency
- Dumping
- Maximum Power
- Operation Mode
- Heat Load

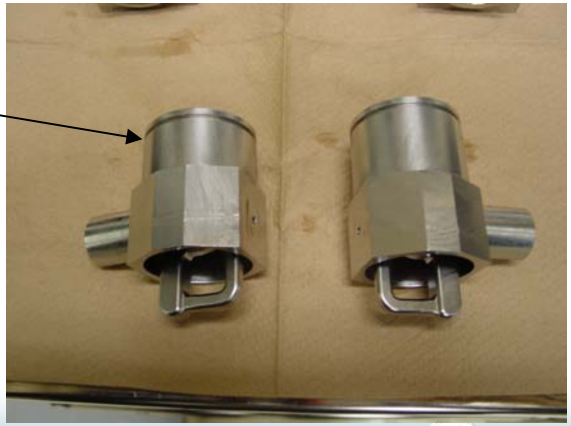
Choice

- Type ; Coaxial or Wave Guide
- Position ; Cell or Beam Pipe
- Welded or Flange
- Number of Couplers
- Cooling
- Position of Loads

Best Choice

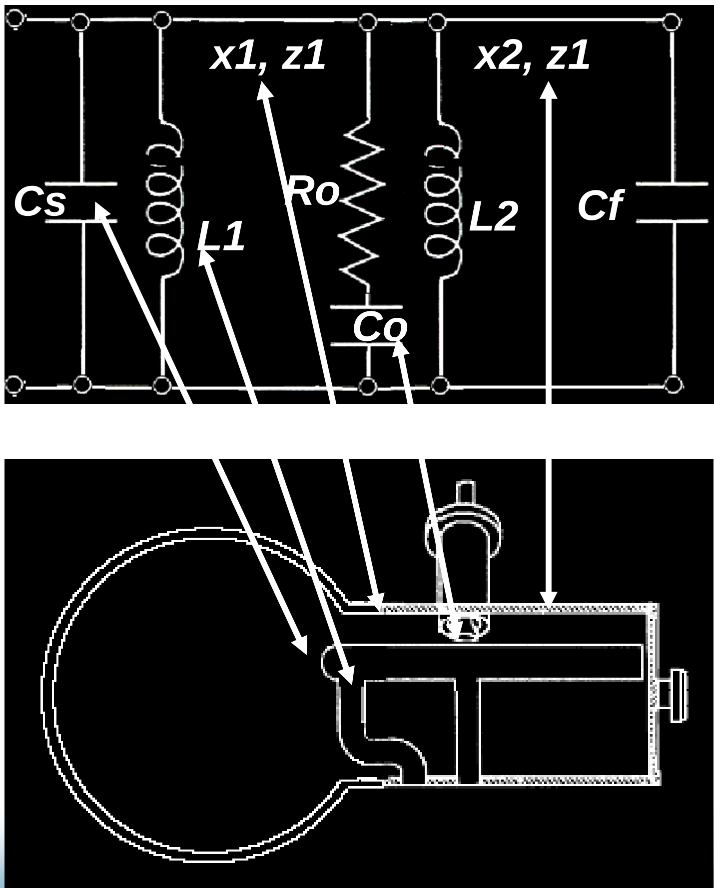
Coaxial Loop Type Coupler on Beam Pipe
is the Best Solution. (TESLA-like)
Being used up to 3.9GHz Cavity.

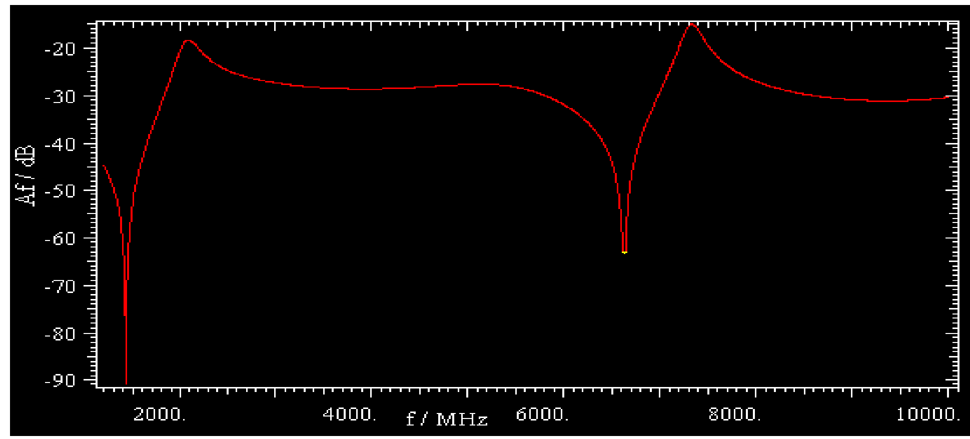


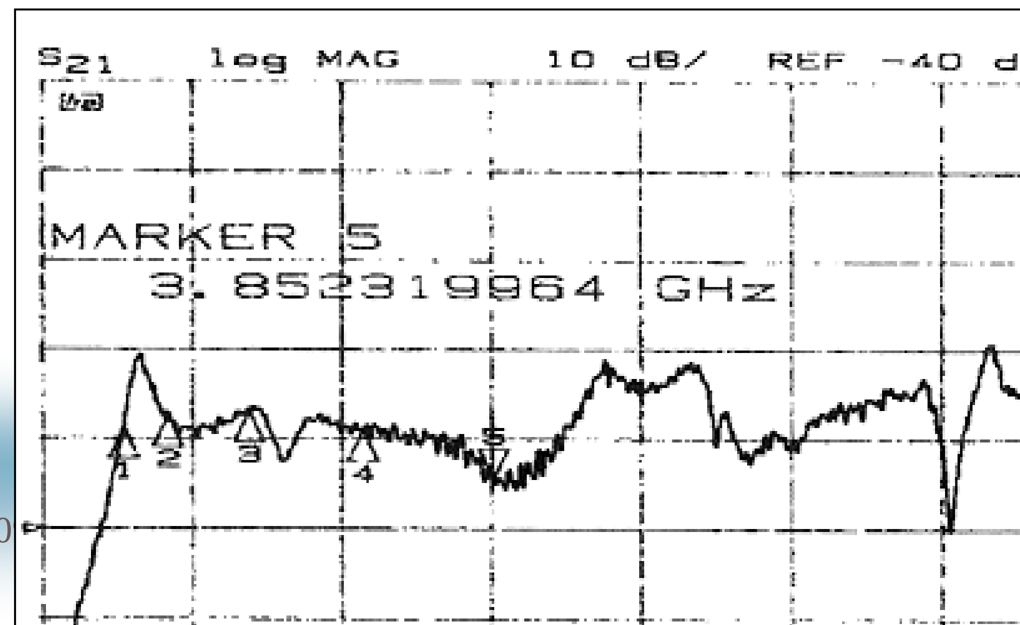


The TESLA –like HOM couplers are nowadays designed in frequency range: 0.8-3.9 GHz

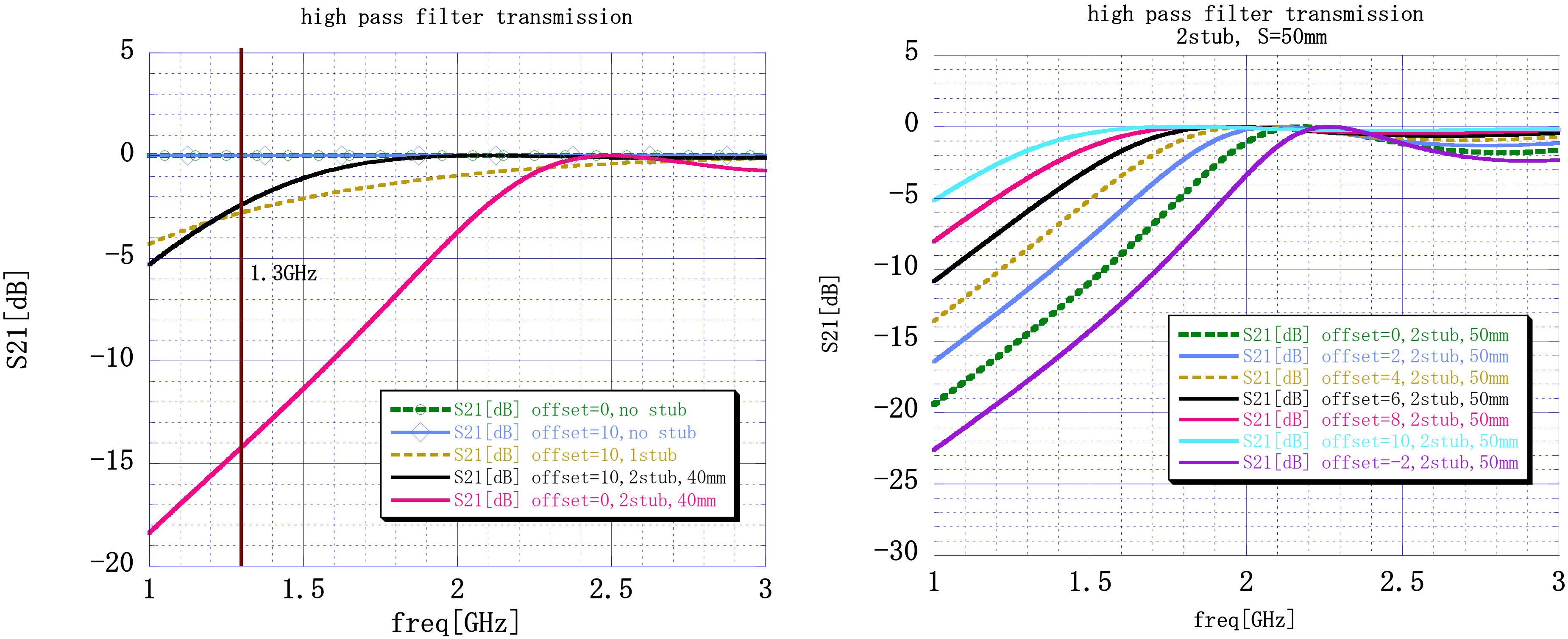
J. Sekutowitz DESY





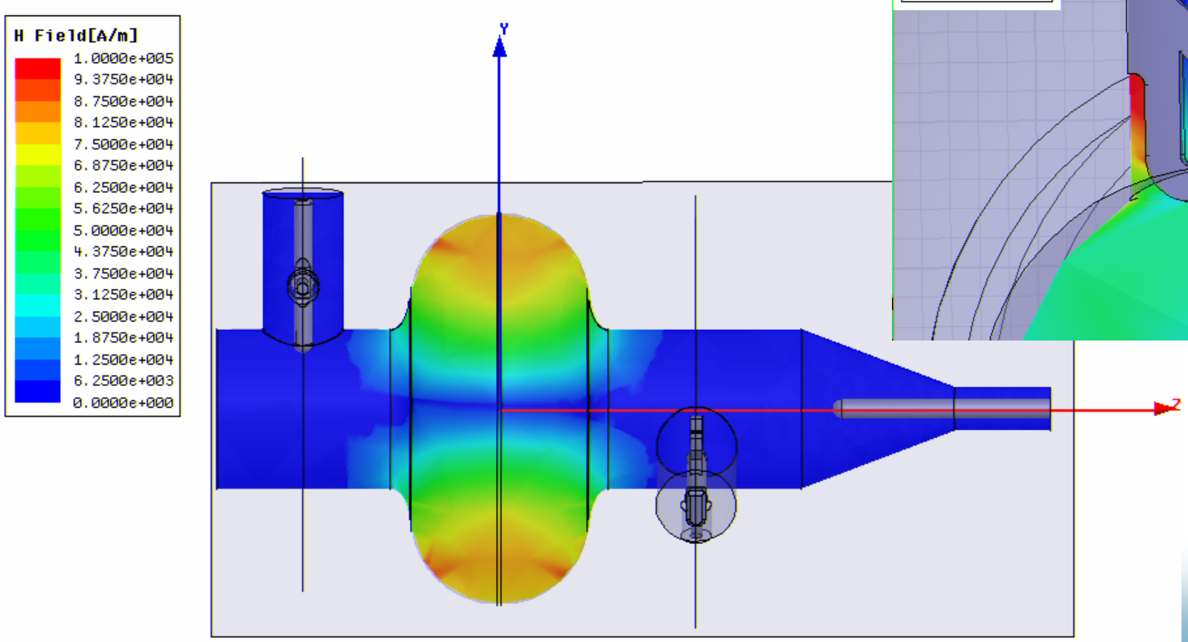


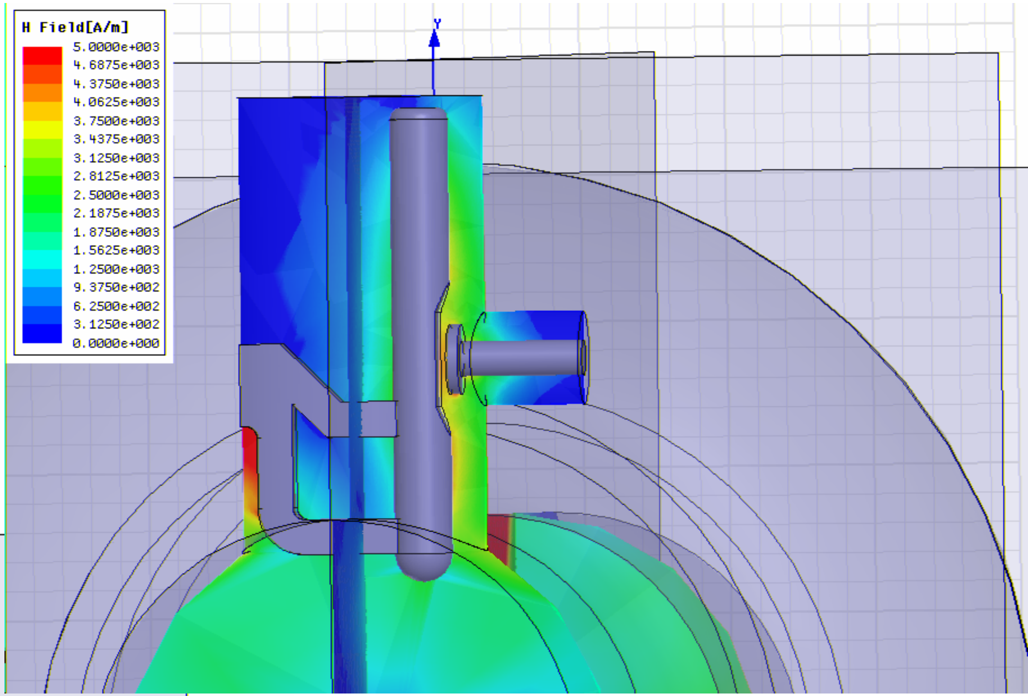
High-pass Filter (+ Notch Filter)



HFSS Simulation HOM Coupler

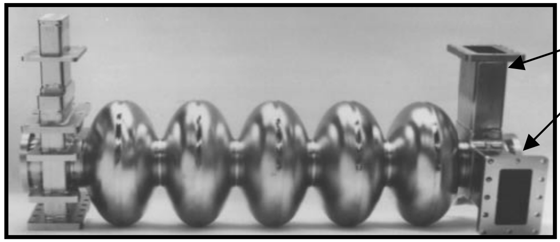
H Field





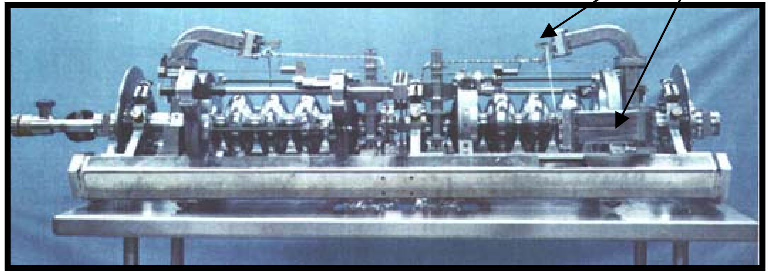
Waveguide HOM couplers

CEBAF/Cornell 1.5 GHz



HOM ports

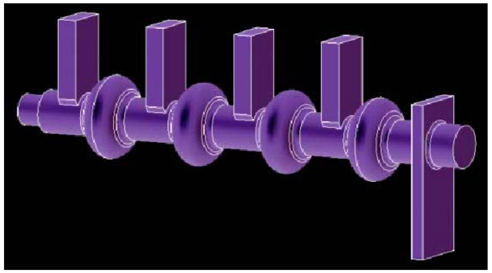
HOM loads



Design (1982) works at present in CEBAF both linacs with

I_{beam} ~ 80μAx4 @ Eacc 7 MV/m

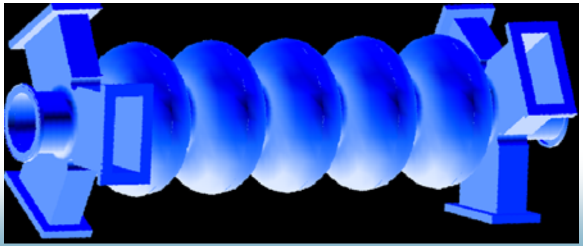
HOM power is very low. It can be dissipated inside cryomodule.



Design proposed by G. Wu (JLab)

1500 MHz for 100 mA class ERLs

LINAC2004

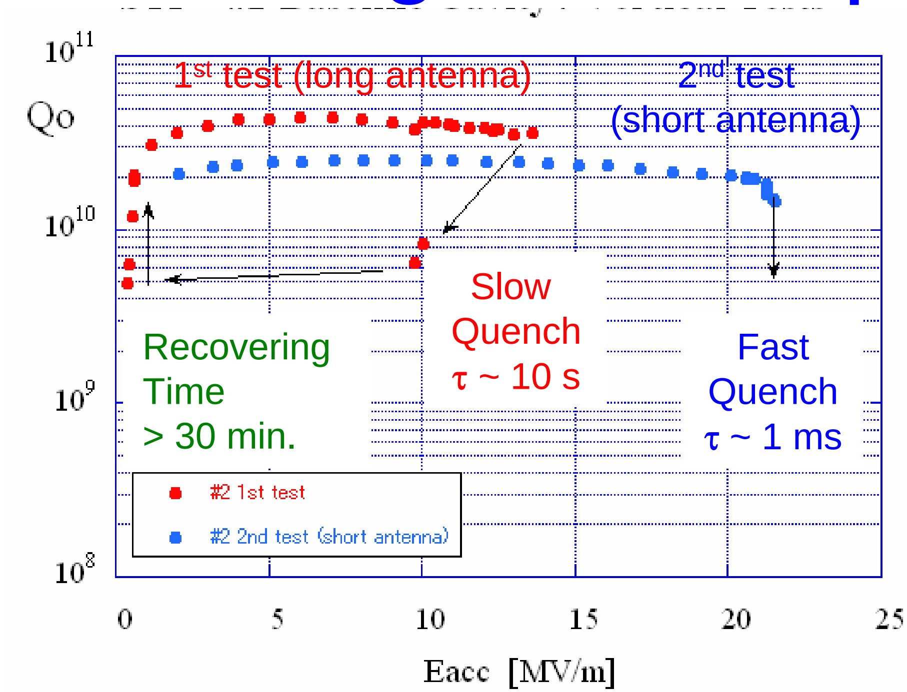


Design proposed by R. Rimmer (JLab)

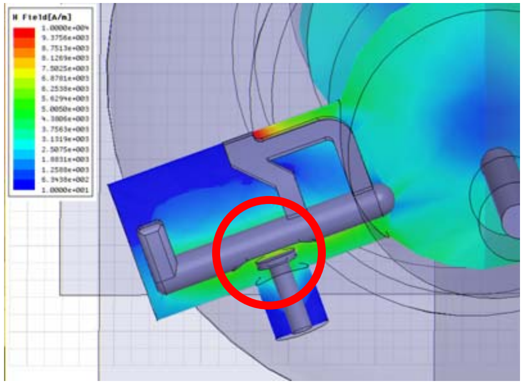
750 MHz for 1A class ERLs

PAC2005

Heating at HOM pick-up antenna

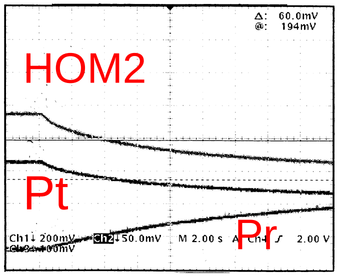


$H_{antenna\text{-}tip} \sim Hsp / 20.$



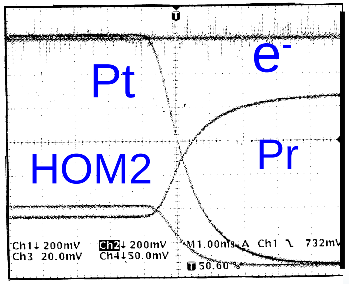
At Eacc = 10 MV/m,
ΔPo = 8 W
P-loss (cal.) = 2 W x 2

Slow Quench ~ 10 sec.



2 sec/div.

Fast Quench ~ 1 msec.



1 msec/div.

1st test
(long antenna)

2nd test
(short antenna)

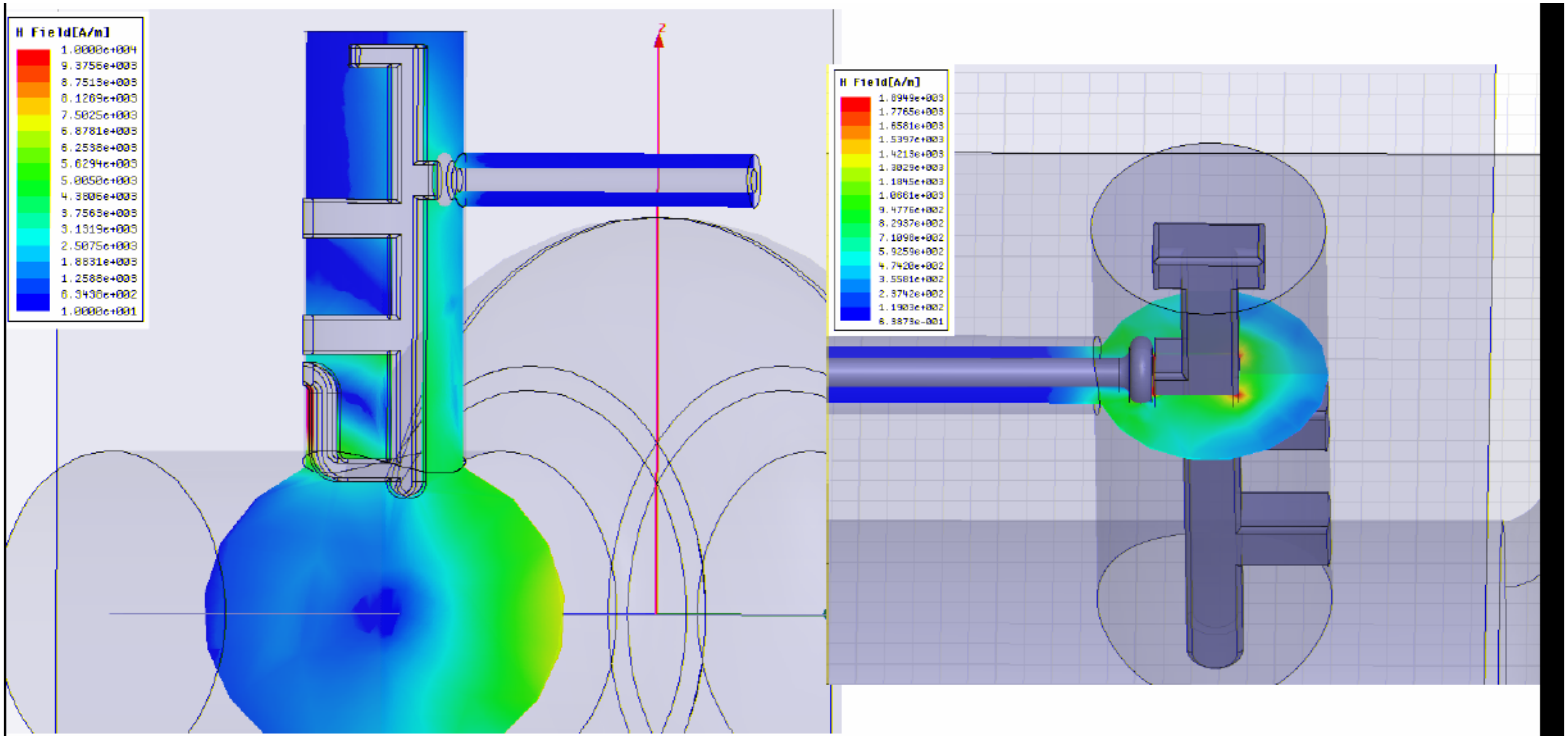
Transition from SC state to normal state occurred
at the location isolated thermally.

Design for CW Application needs

- Lower the Magnetic Field at an Antenna.
- Improved Thermal Design

KEK cERL Design

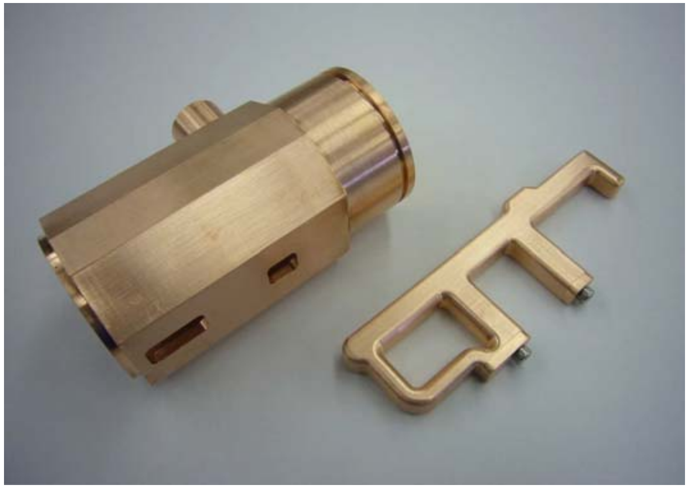
H-Field Distribution



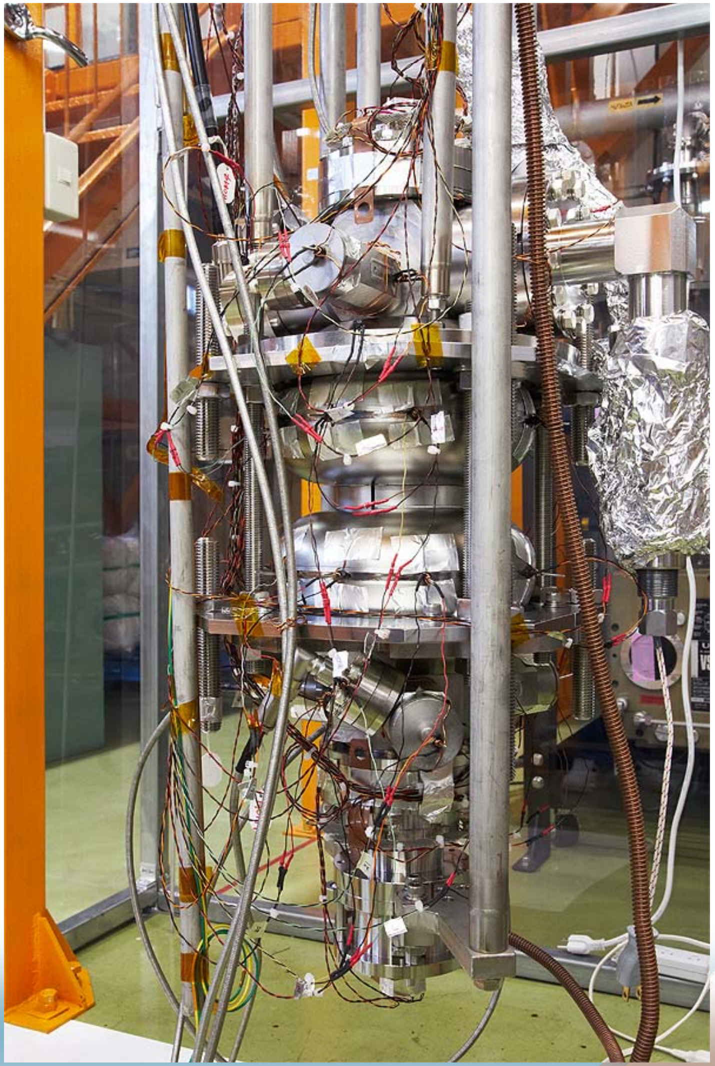
H-field distribution at 1.3 GHz (acceleration load)

conditions	15MV/m	20MV/m	25MV/m	other
Antenna type : New , improve inner conductor (probe tip = 10 mm from HOM coupler center)				
(1)c=10mm, u=5mm	850～1000 A/m	1150～1350 A/m	1400～1650 A/m	Probe gap=0.5mm Offset = 0mm
Antenna type : old c=0mm, u=0mm (probe tip = 5 mm from HOM coupler center)				
(0)c=0mm, u=0mm	2400～2850 A/m	3000～3500 A/m	3700～4400 A/m	0.5mm Offset = 0mm
loop type : New , improve inner conductor (probe tip = 13 mm from HOM coupler center)				
(1)c=10mm, u=3mm	1800～2050 A/m	2400～2720 A/m	3000～3360 A/m	0.5mm Offset = 6mm
loop type : old c=0mm, u=0mm (probe tip = 10 mm from HOM coupler center)				
(0)c=0mm, u=0mm	2200～2400 A/m	2900～3150 A/m	3500～3850 A/m	0.5mm Offset = 6mm
STF type : New , improve inner conductor (probe tip = 17 mm from HOM coupler center)				
(1)c=10mm, u=2mm	-----	-----	-----	Offset=10 mm
STF model : old c=0mm, u=0mm (probe tip = 13 mm from HOM coupler center, due to cut 2mm inner conductor)				
(0)c=0mm, u=0mm	4000～4250 A/m Heating limit at CW	5200～5600 A/m Not use ? CW operation	6800 ～ 7200 A/m Not use ? CW operation	0.5mm Offset=10 mm

2 Stub HOM coupler for cERL




Vertical Test



Q_0-E_{acc} Curve for ERL 2-cell #1 @1.5K & 4.2K