Tutorial Lecture on High power couplers and HOM couplers

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for SRF2019 at HZDR

2019, June 27th

Textbooks for High power couplers and HOM couplers

- **SRF2011 Tutorial:**

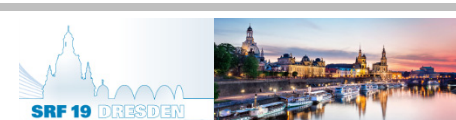
“Design and Fabrication issues of High Power and HOM Couplers for SC Cavities” by W.-D. Moeller (DESY)

- **SRF2015 Tutorial:**

“Fundamental Power Couplers and HOM Couplers” by G. Devanz (CEA-Saclay)

- **SRF2017 Tutorial:**

“High Power Couplers and HOM Couplers” by E. Montesinos (CERN)



Contents of Lecture

1. Introduction
2. High power input couplers
3. HOM couplers and absorbers

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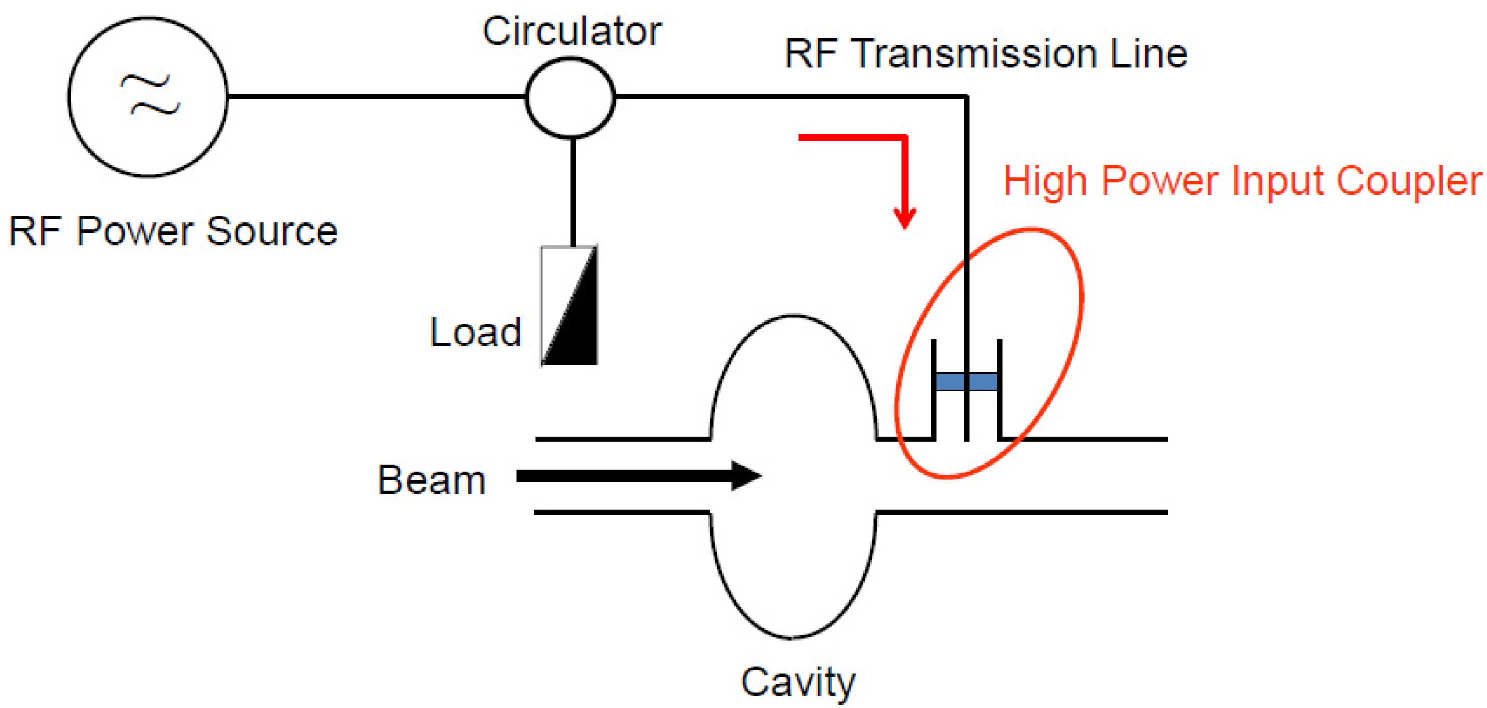
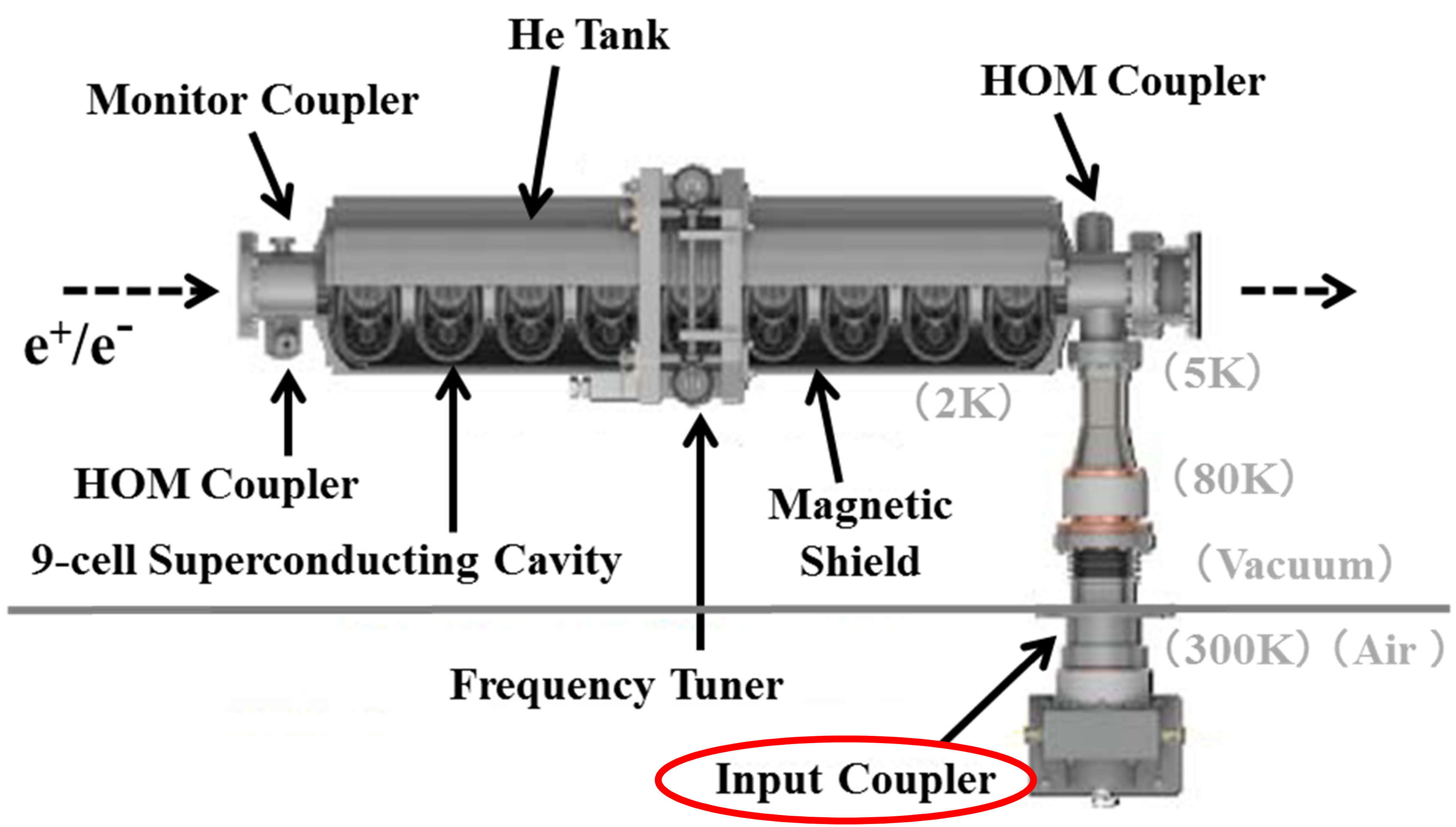
Introduction (1)



The primary role of the input coupler:

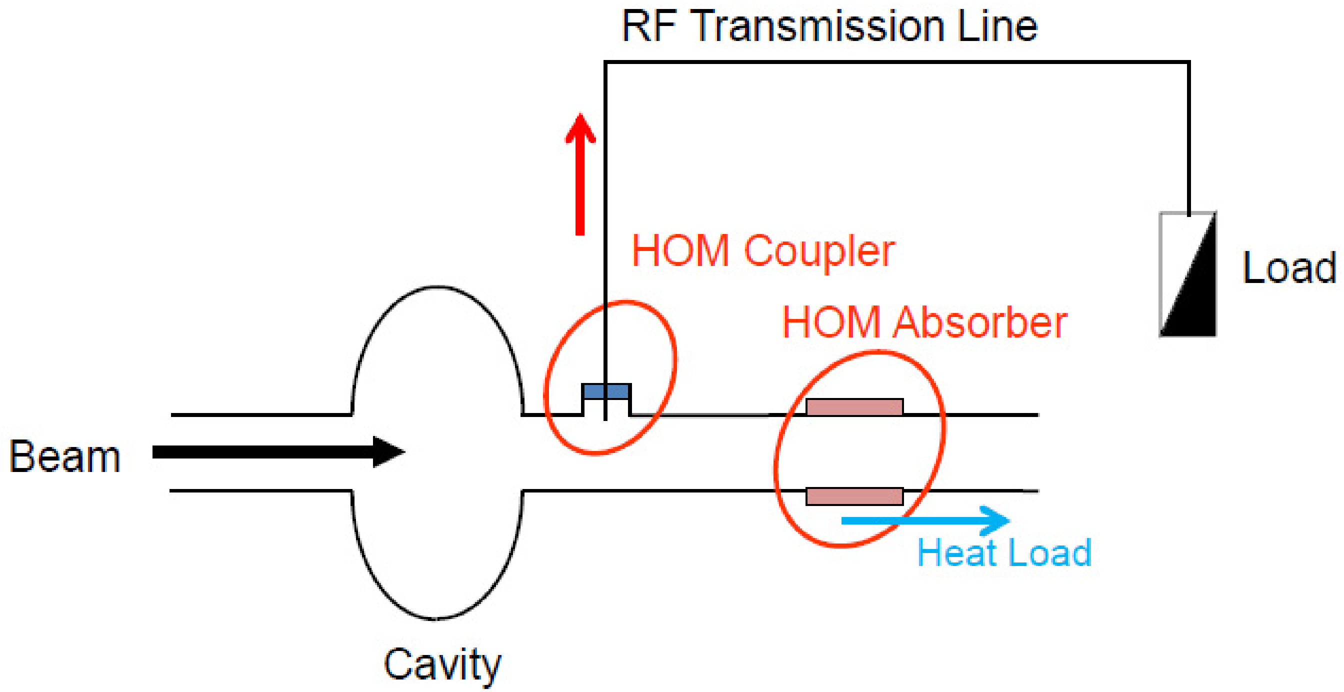
to transfer RF power from the generator to the cavity and to the beam.

Introduction (2)



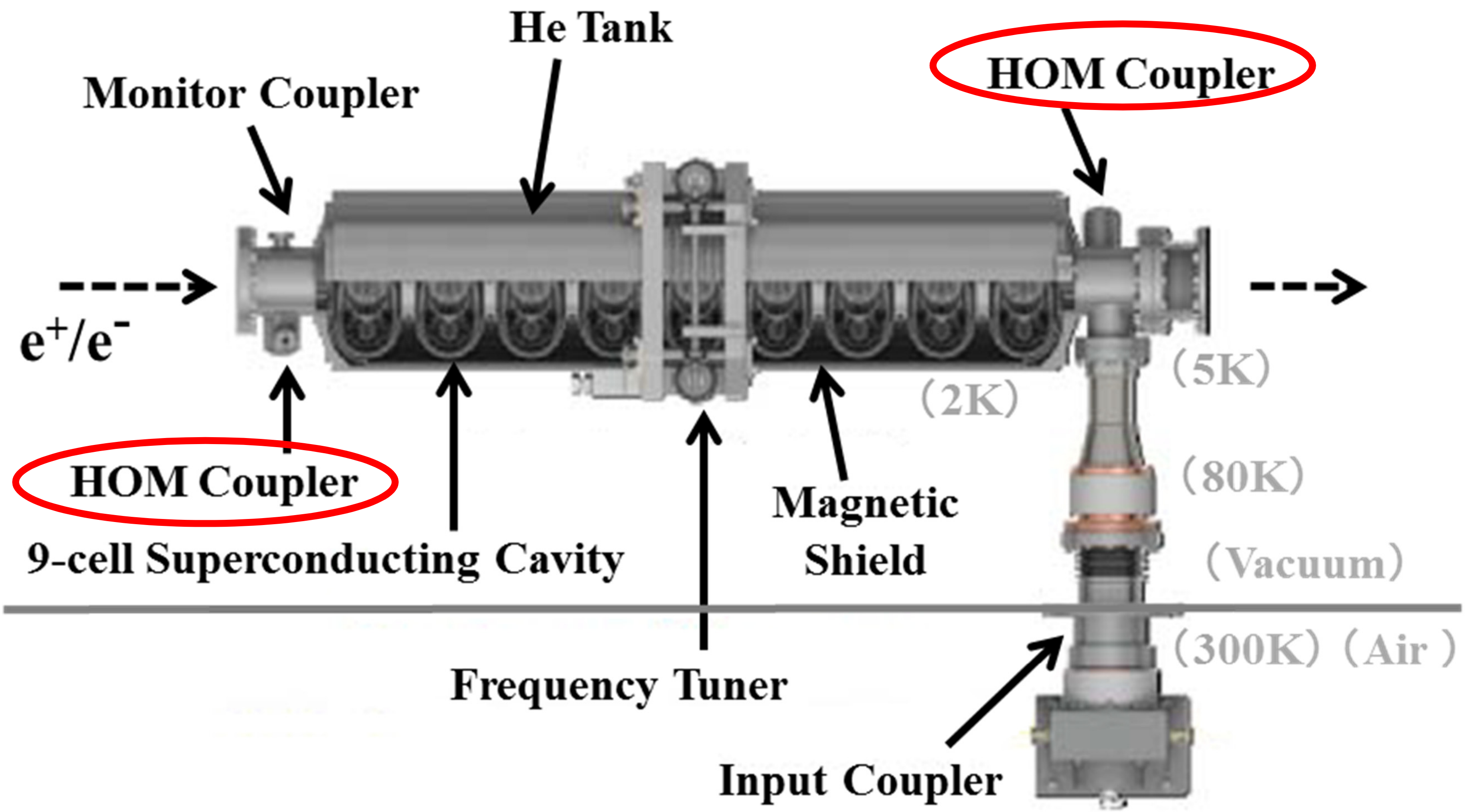
Cavity package of STF 9-cell cavity at KEK for ILC

Introduction (3)



The primary role of the HOM coupler/absorber:
to remove beam induced power from the cavity in order to avoid resonant buildup of beam induced voltage, and in order to avoid beam instabilities.

Introduction (4)



Cavity package of STF 9-cell cavity at KEK for ILC

Introduction (5)

Importance of a Harmonized System Design:

- Only SC cavity is not a special component.
- A harmonized design of a whole cavity package including an input coupler, HOM couplers, a frequency tuner, magnetic shields and a He-tank is a most crucial task for a stable operation in cryomodule with beam.
- Especially, input couplers and HOM couplers are critical components in SC cavity system.

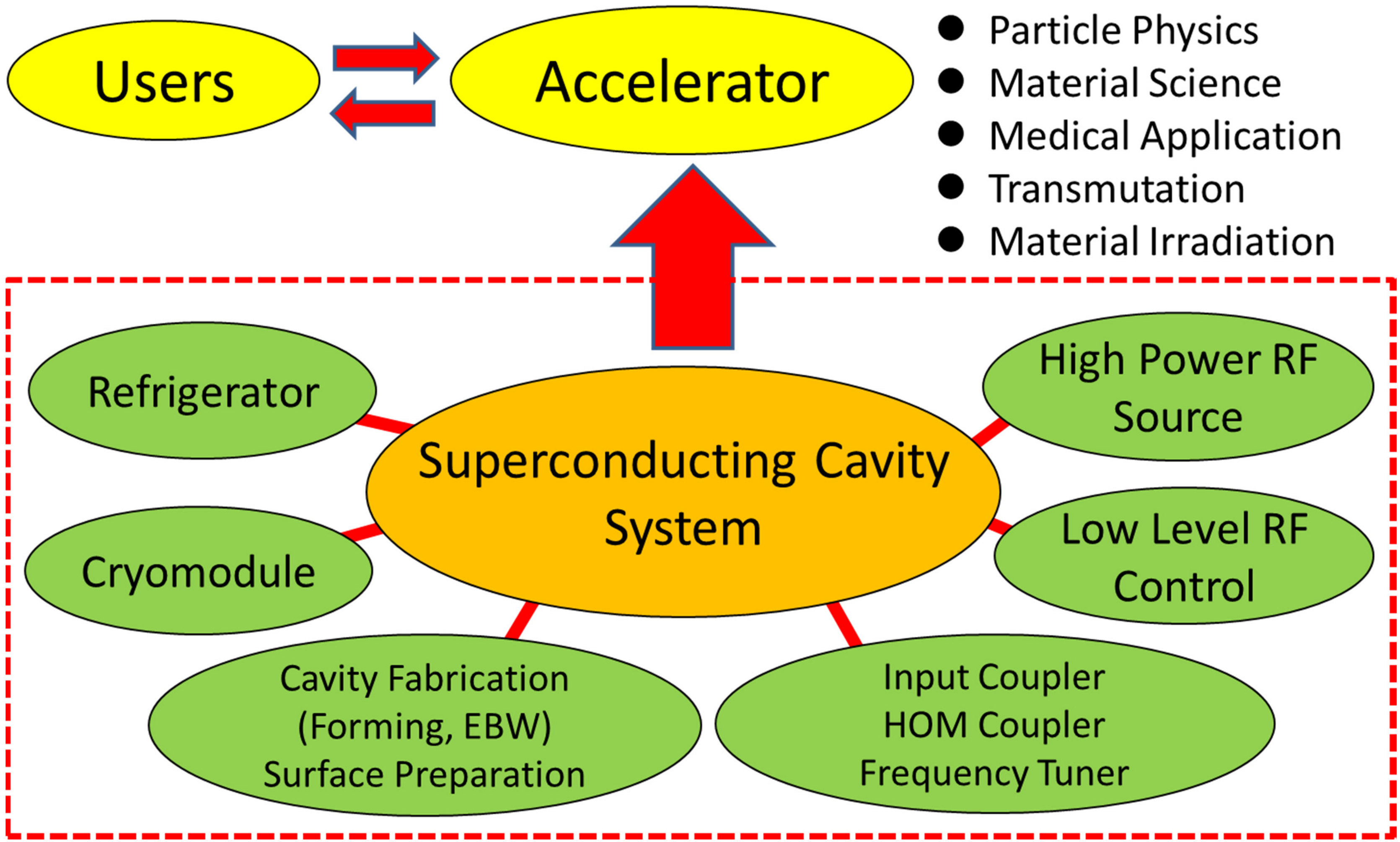
Introduction (6)

High Performance

High Reliability **Low Cost**

<u>Harmonized System Design Concept</u>

Introduction (7)

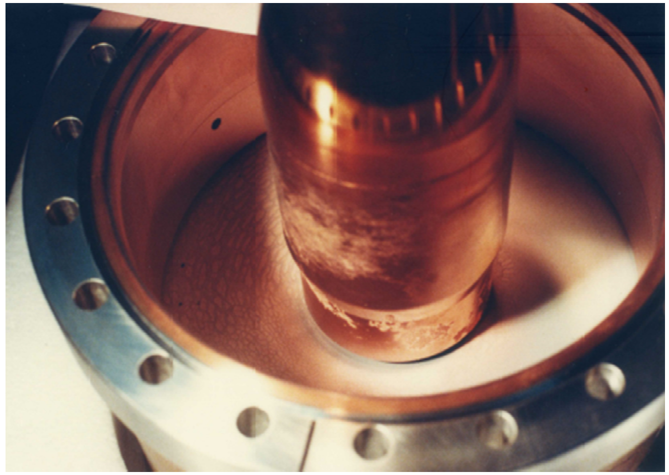


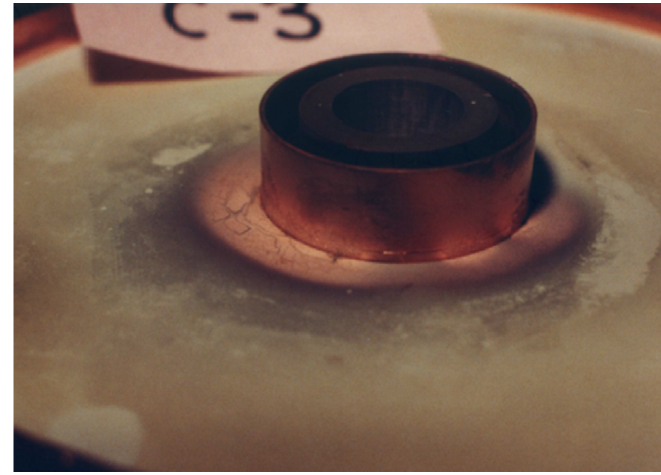
Superconducting RF Cavity System

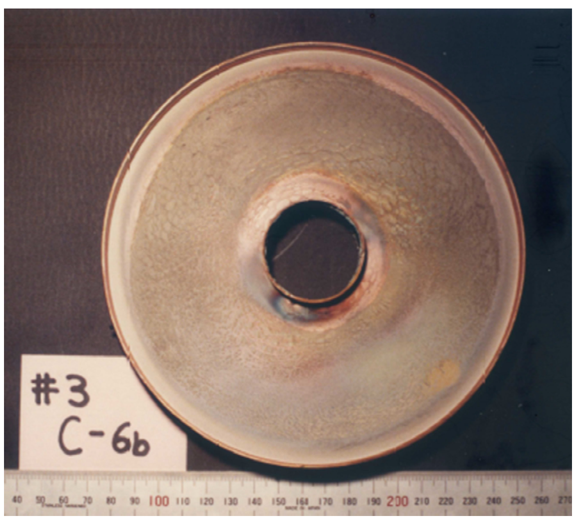
My old experience on Input Coupler (1)

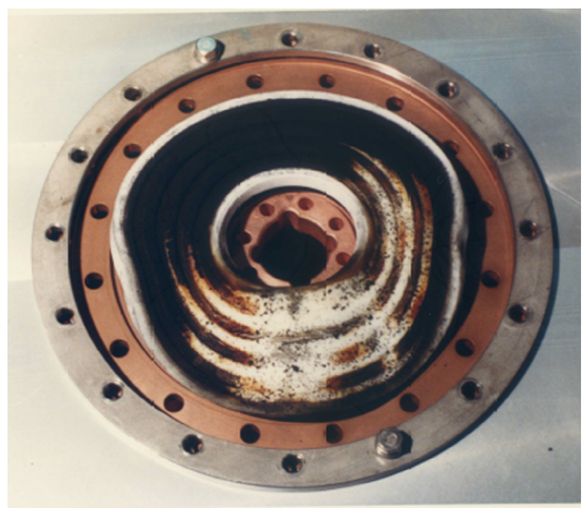
About 30 years ago in TRISTAN at KEK;

508MHz,
CW 50kW
Input coupler with one warm window and water cooling









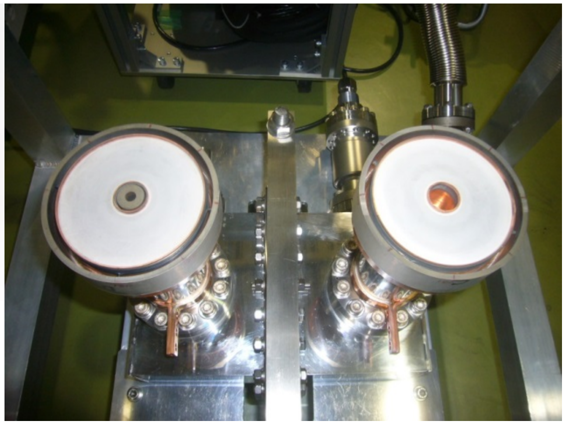
In the initial stage,
no TiN coating
no Arc sensor

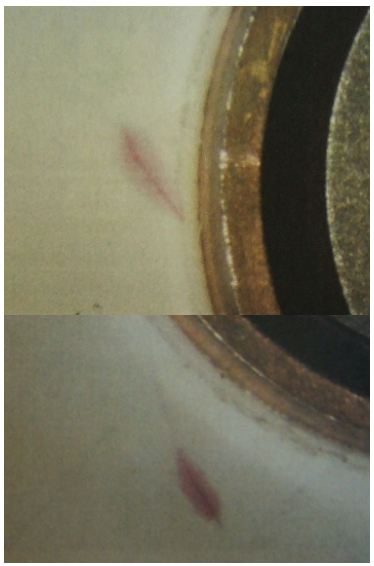
↓

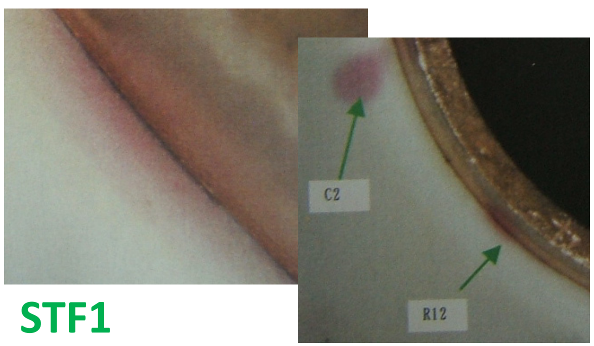
Importance of TiN coating and Interlock system

My old experience on Input Coupler (2)

About 10 years ago in STF1 at KEK;



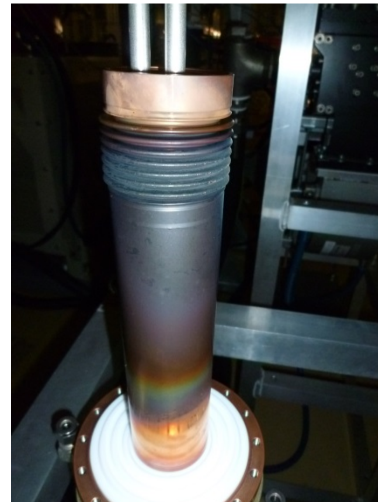


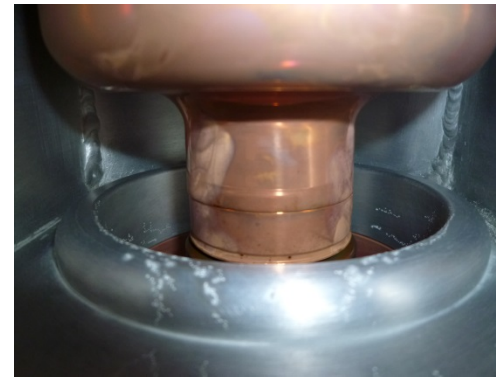


STF1
1.3 GHz, 500 kW
pulsed input coupler

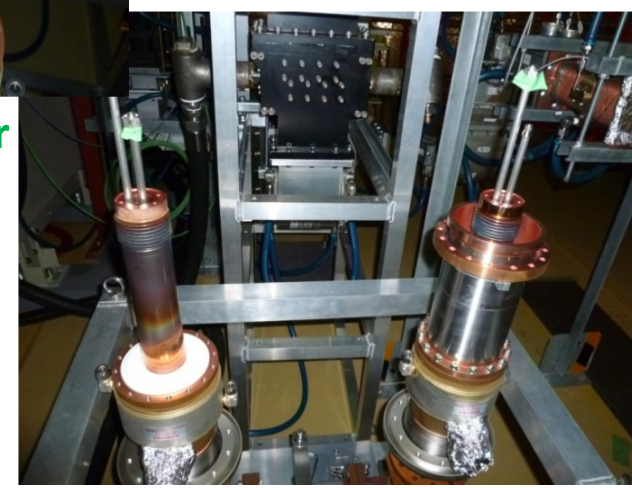
Cracks due to thermal strain at 80 K

About 10 years ago in cERL at KEK;





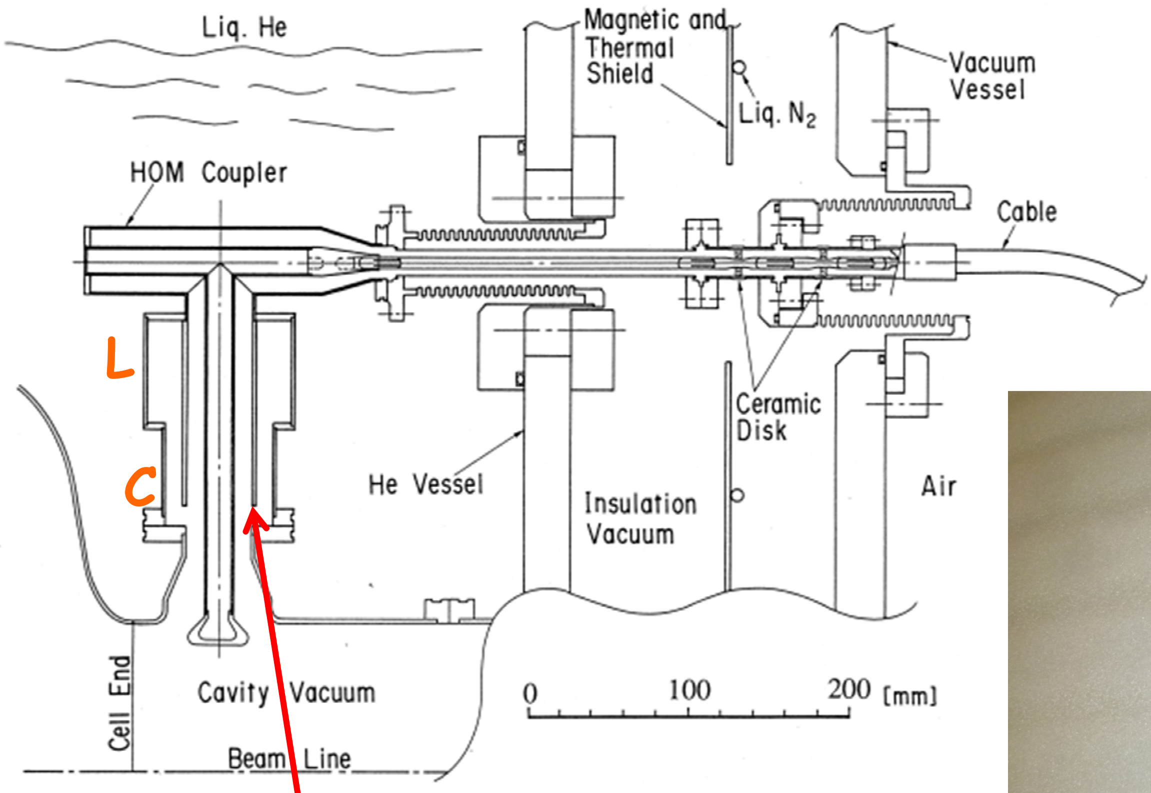
cERL injector
1.3 GHz,
40 kW, CW
input
coupler



Excessive heat-up at coaxial parts

My old experience on HOM Coupler (1)

About 30 years ago in TRISTAN at KEK;

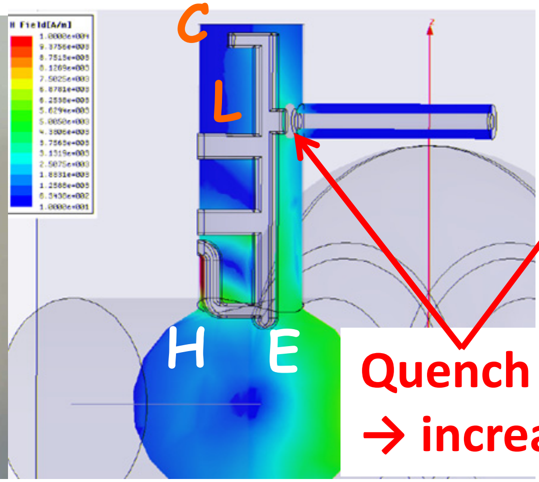


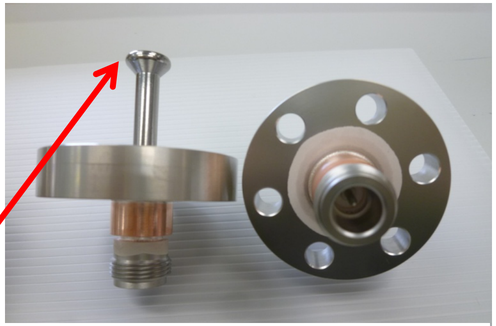
508MHz,
coaxial antenna type,
coupled E-field,
HOM coupler
made of niobium

- heating due to multipacting
- not an efficient cooling
- shift of a rejection frequency
- passing through of accelerating RF power

My old experience on HOM Coupler (2)

About 7 years ago in cERL Injector at KEK;

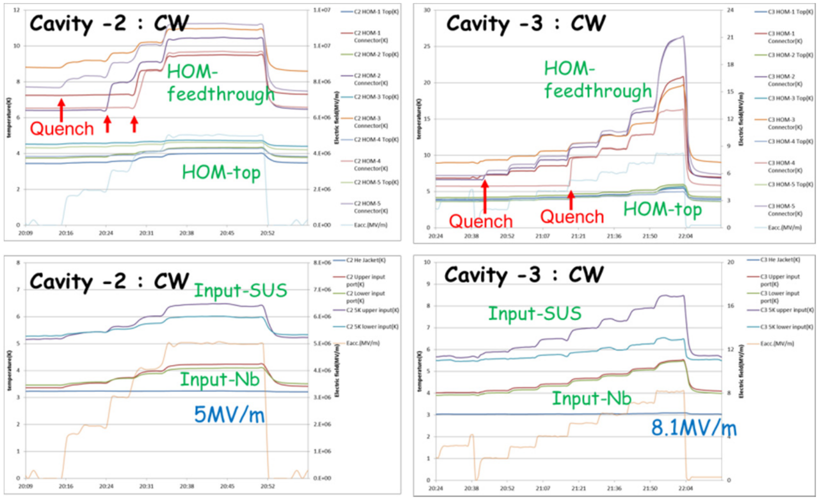




Quench at Nb antenna tip
→ increase of heat load at 2 K

thermal anchors to 2 K

1.3 GHz, 2-cell
cERL injector cavity
with 5 HOM couplers



Contents of Lecture

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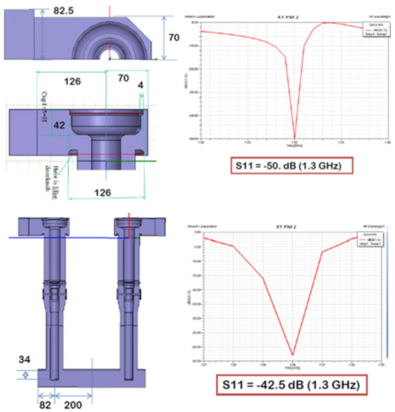
2. **High power couplers**
3. HOM couplers and absorbers

High Power Input Coupler

The input coupler:

1. has to transfer RF power from the generator to the cavity and to the beam.
2. must provide a match between the generator impedance and the combined impedance of the cavity-beam system, so as to minimize the wasted reflect power.
3. may need to be an adjustable coupling.
4. has to minimize the heat transfer from 300 K to 2 K.

from coupler design to stable beam operation

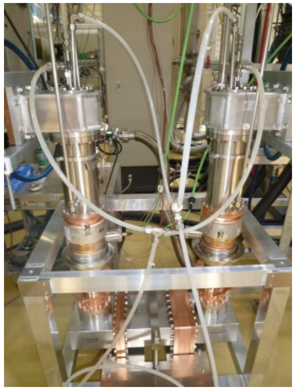


Design/Calculation

Fabrication

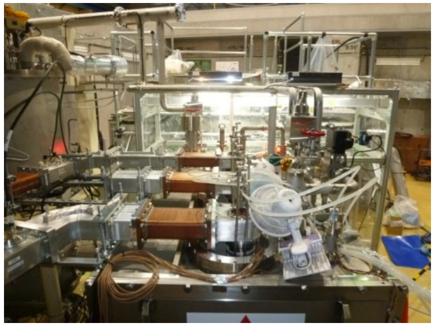
RF measurement

Cleaning/Assembly
Pumping/Baking



Conditioning at test stand

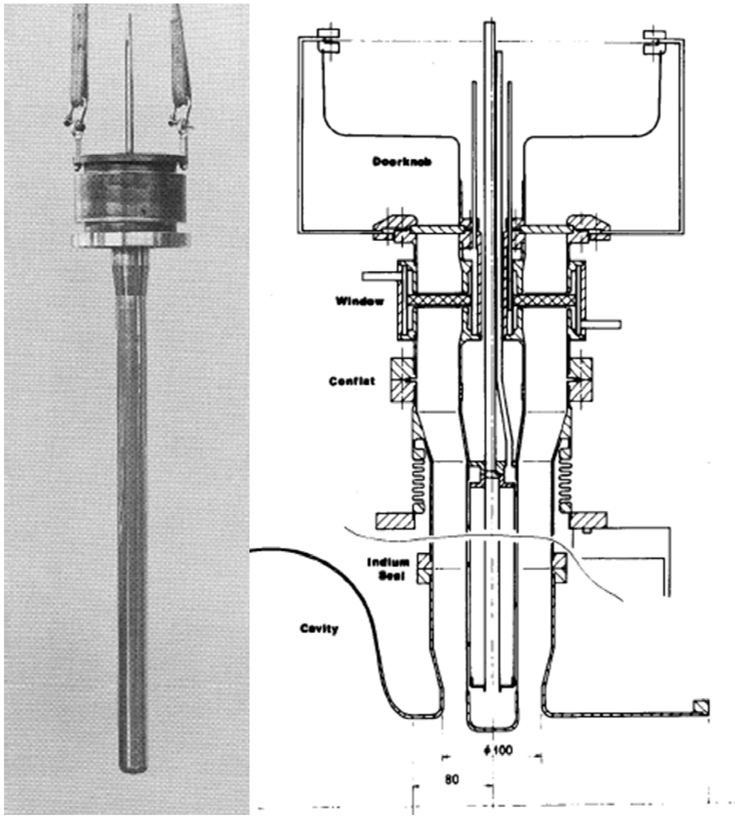
Cavity string assembly



Conditioning at RT in cryomodule

High power operation with beam

TRISTAN-type High Power Input Couplers at KEK



Original design :
508 MHz TRISTAN Input Coupler
S. Noguchi, E. Kako, K. Kubo
(4th SRF-WS, 1989)

972 MHz J-ADS
Input Coupler (KEK)

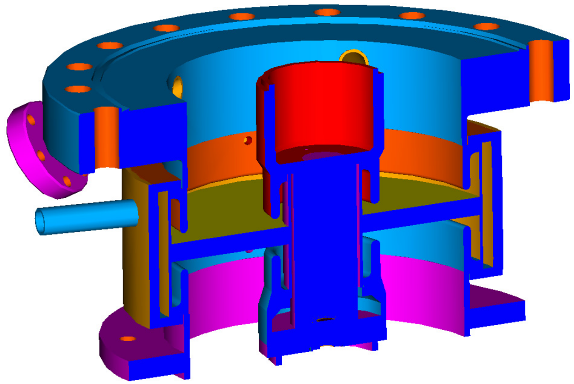
1.3 GHz cERL Injector
Input Coupler (KEK)

1.3 GHz STF-1
Input Coupler (KEK)

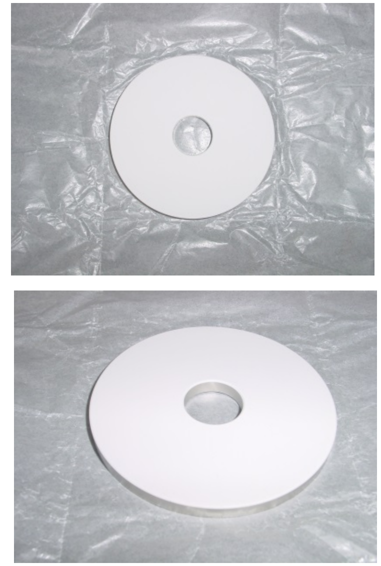
1.3 GHz STF-2
Input Coupler (KEK)

TRISTAN-type RF Windows

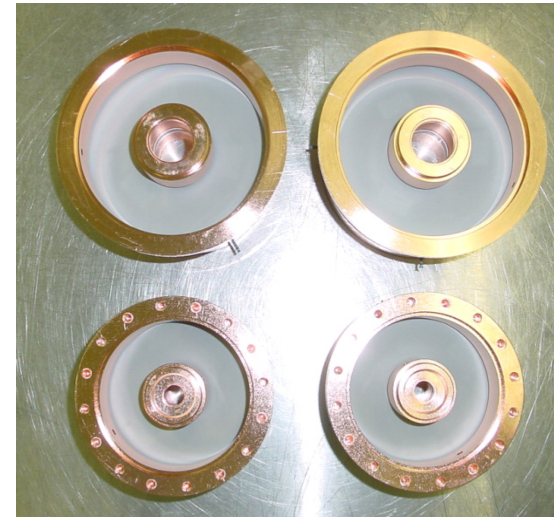
Tristan-type coaxial disk ceramics RF window with choke structure



Canon
CANON ELECTRON TUBES & DEVICES CO., LTD.

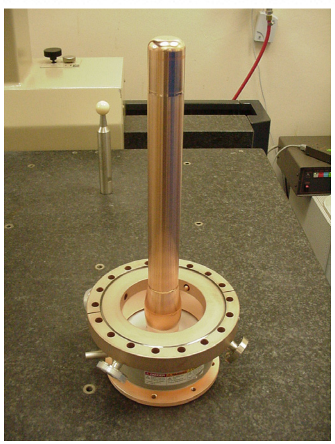


Al_2O_3 ceramics with metalizing



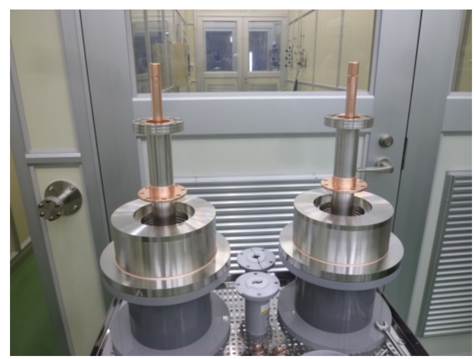
RF windows after 1st brazing

CW input couplers with TRISTAN-type RF window in many projects



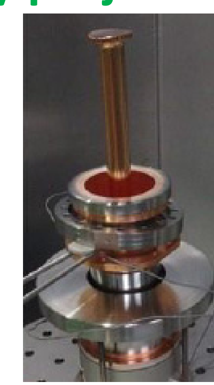
SNS, 805 MHz

CEA, 704 MHz



IBS-QWR, 81.25 MHz

MSU-HWR, 322 MHz



HZB, 1.3GHz

High Power Performance of TRISTAN-type Couplers

Facility	Frequency	Window type Coupling	Maximum RF Power
TRISTAN /KEK	508 MHz	1, Coax. Disk Fixed	Test-stand, 200 kW, CW Operation, 70 kW, CW
KEKB /KEK (T. Mitsunobu)	508 MHz	1, Coax. Disk Fixed	Test-stand, 800 kW, CW Operation, 380 kW, CW
J-ADS /KEK-JAEA	972 MHz	1, Coax. Disk Fixed	Test-stand, 2.0 MW, pulse Operation, 350 kW, pulse
cERL-Inj. /KEK	1300 MHz	1, Coax. Disk Fixed	Test-stand, 40 kW, CW Operation, 10 kW, CW
cERL-ML /KEK (H. Sakai)	1300 MHz	2, Coax. Disk Variable	Test-stand, 40 kW, CW Operation, 15 kW, CW
STF-2 /KEK	1300 MHz	2, Coax. Disk Variable	Test-stand, 1.5 MW, pulse Operation, 450 kW, pulse

Important Technical Issues for Input Couplers

- Ceramics window : material, purity
- Metalizing of ceramics
- Copper plating : thickness, RRR, adhesion, pits, uniformity
- TiN coating : thickness, uniformity
- Joining by Brazing
- Welding by TIG, Laser, E-beam

- RF properties
- Thermal characteristics
- Mechanical analysis
- Multipacting simulation

- Cleaning procedure
- Assembly in clean room

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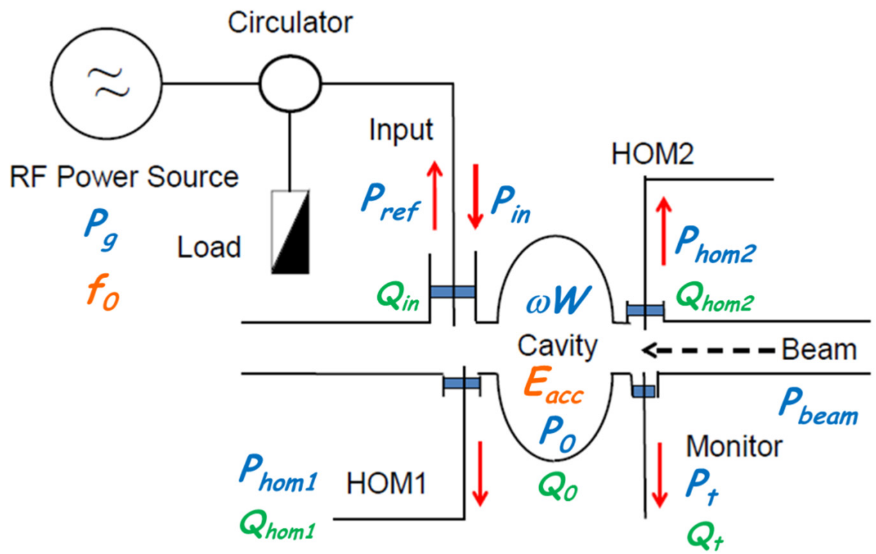
1. Coupling to a cavity
2. Choice of Coupler Type
3. Design Issues
4. Fabrication Issues
5. RF Conditioning Issues
6. Trouble shooting
7. State of the Arts

Contents

External Q Values (1)

A typical conceptual structure of an SC cavity with an input coupler port, two higher-order mode (HOM1 and HOM2) ports, and a monitor coupler port is shown in Figure. An input coupler is used for suppling RF power from a power source into the SC cavity. Harmful RF power induced by beams is extracted by HOM couplers. The purpose of the monitor coupler is to estimate the accelerating gradient in the cavity.



External Q value of a cavity with a beam. Q_{in}, Q_{hom1}, Q_{hom2} and Q_t are the external Q values of the input coupler, the HOM1 coupler, the HOM2 coupler, and the monitor coupler, respectively. RF power from the input coupler (incident and reflected), the HOM1 coupler, the HOM2 coupler, and the monitor coupler are represented by P_{in}, P_{ref}, P_{hom1}, P_{hom2}, and P_t.

External Q Values (2)

Cavity RF loss (P_0) in an SC cavity is usually negligible as it is smaller than the beam power (P_{beam}). Therefore, the following condition holds for the generator power (P_g) from an RF power source:

$$P_g \approx P_{beam} >> P_0 \qquad (1)$$

(This is one of important advantages in SRF cavities.)

This condition states that almost all of the generator RF power is dissipated for beam acceleration. A sum of the power balance from each port of the cavity shown in Figure (p25) can be expressed by the following equation:

$$P_{in} - P_{ref} = P_0 + P_{beam} + P_t + P_{hom1} + P_{hom2} \qquad (2)$$

Furthermore, the following relations of the external Q values are desirable in the optimum design of each coupler:

$$Q_{in} << Q_0 << Q_t \, , Q_{hom1} \, , Q_{hom2} \qquad (3)$$

Coupling Factor of Input Coupler (1)

The external Q value (Q_{in}) of an input coupler can be determined by using the following RF parameters:

R/Q: Impedance of accelerating mode [Ω]
L_{cavity}: Effective cavity length [m]
W: Energy stored inside the cavity [J]
Z_{cavity}: Constant parameter given by R/Q and L_{cavity}
Q_0: Unloaded cavity quality factor
V_C: Cavity accelerating voltage [V]
I_{beam}: Beam current [A]
ϕ: Beam phase

- Accelerating gradient (E_{acc})

$$E_{acc} = \frac{\sqrt{R/Q}}{L_{cavity}} \sqrt{\omega W} = Z_{cavity} \sqrt{P_0 \cdot Q_0} \tag{4}$$

- Cavity RF loss (P_0)

$$P_0 = \frac{\omega W}{Q_0} \tag{5}$$

Coupling Factor of Input Coupler (2)

- Beam power (P_{beam})

$$P_{beam} = I_{beam} \cdot V_C \cdot \cos\phi$$
$$= I_{beam} \cdot E_{acc} \cdot L_{cavity} \cdot \cos\phi \qquad (6)$$

- Generator RF power (P_g)

$$P_g = P_0 + P_{beam} + P_{ref} \qquad (7)$$

Here, the following conditions are assumed:

$P_{ref} \approx 0$ (no refection),
$P_g = P_{in}$ (no RF loss in transmission lines),
$P_0 + P_{beam} >> P_t, P_{hom1}, P_{hom2}$.

- Coupling constant (β)

$$\beta = \frac{P_g}{P_0} = 1 + \frac{P_{beam}}{P_0} \cong \frac{Q_0}{Q_L} \qquad (8)$$

Coupling Factor of Input Coupler (3)

$$\frac{1}{Q_L} = \frac{1}{Q_{in}} + \frac{1}{Q_0} + \frac{1}{Q_t} + \frac{1}{Q_{\mathrm{hom1}}} + \frac{1}{Q_{\mathrm{hom2}}} \qquad (9)$$

$$Q_L \cong Q_{in} \qquad (10)$$

In this case, the following condition holds: $Q_{in} << Q_0 << Q_t$, Q_{hom1}, Q_{hom2}.
Therefore, the loaded Q value (Q_L) can be described as follows:

- Loaded Q value (Q_L)

$$Q_L = \frac{Q_0 \cdot P_0}{P_{beam}} \cong \frac{Q_0}{\beta} \qquad (11)$$

When an actual beam operation given by E_{acc} = 30 MV/m, I_{beam} = 10 mA, L_{cavity} = 1.0 m, P_0 = 100 W and $Q_0 = 1.0 \times 10^{10}$ is considered, the following quantities can be obtained:

From Eq. (6) → P_{beam} = 300 kW, (in the case that $\phi = 0$),
From Eq. (11) → $Q_{in} \approx Q_L = 3.3 \times 10^6$,
From Eq. (8) → β = 3,000.

Coupling Factor of Input Coupler (4)

Therefore, in the case of the matching condition ($P_g \approx P_{beam}$),

- Optimum coupling ($Q_L \approx Q_{in} << Q_0$):

$$Q_{in} \cong \frac{V_c}{(R/Q) \cdot I_{beam} \cdot \cos\phi} \tag{12}$$

- Required generator RF power (P_g) , in the case of no refection (P_{ref} =0),

$$P_g = \frac{V_c^2}{4 \cdot (R/Q) \cdot Q_L} \left[1 + \frac{I_{beam} \cdot (R/Q) \cdot Q_L \cdot \cos\phi}{V_c} \right] \tag{13}$$

- In the case of no beam current (I_{beam} = 0):

$$E_{acc} = \frac{\sqrt{R/Q}}{L_{cavity}} \cdot \sqrt{4 \cdot P_g \cdot Q_L} \quad = Z_{cavity} \sqrt{P_t \cdot Q_t} \tag{14}$$

- In the case of the optimum conditions:

$$\frac{1}{Q_{in}} = \frac{1}{Q_0} \left(1 + \frac{P_{beam}}{P_0} \right) = \frac{1}{Q_0} + \frac{1}{Q_{beam}} \tag{15}$$

Coupling Factor of Input Coupler (5)

Therefore, the optimum coupling factor of an input coupler is strongly dependent on the beam current:

$$P_{beam} >> P_0 \; ; \quad Q_{in} = Q_{beam} \qquad (16)$$

In light of these results, it can be seen that a variable input coupling is preferable for minimizing the reflected RF power from the cavity in an SC accelerator in which the beam current is frequently changed.

The bandwidth of the resonant frequency (Δf) is given by:

$$\Delta f = \frac{f}{2Q_{in}} \qquad (17)$$

Accordingly, in the case of the following Q_{in} values, the bandwidth can be calculated as follows:

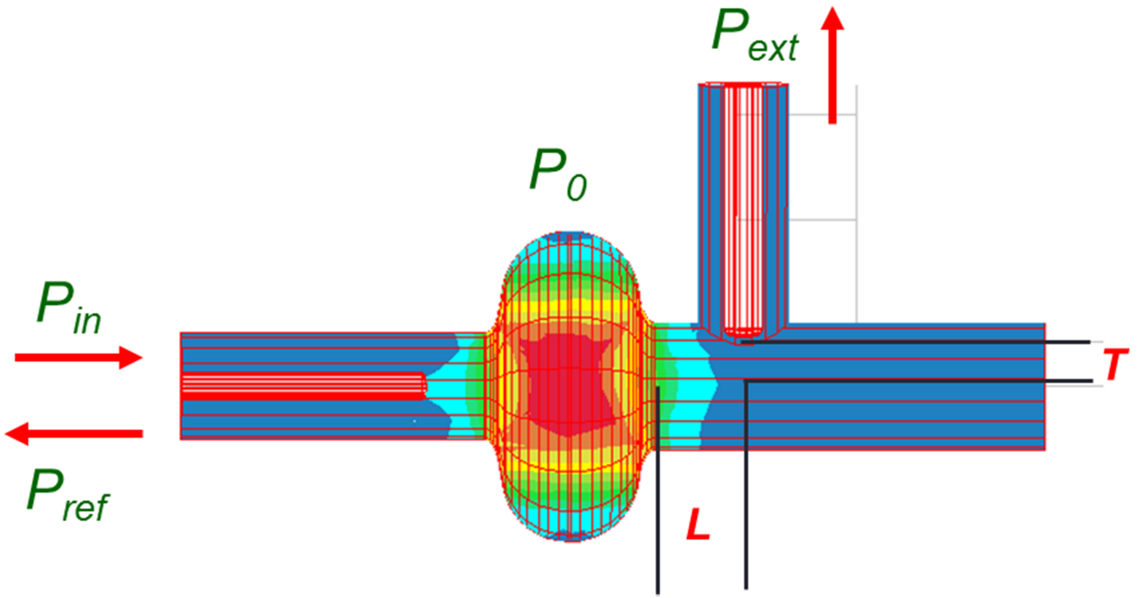
f = 1.3 GHz, Q_{in} = 3 x 10^7 → Δf = 22 Hz,
f = 1.3 GHz, Q_{in} = 3 x 10^6 → Δf = 220 Hz,
f = 1.3 GHz, Q_{in} = 3 x 10^5 → Δf = 2.2 kHz.

The bandwidth is an important parameter in achieving stable beam operation. A preferable coupling factor for the input coupler for a stable frequency control is as follows:

$$Q_{in} \leq 10^7 \qquad (18)$$

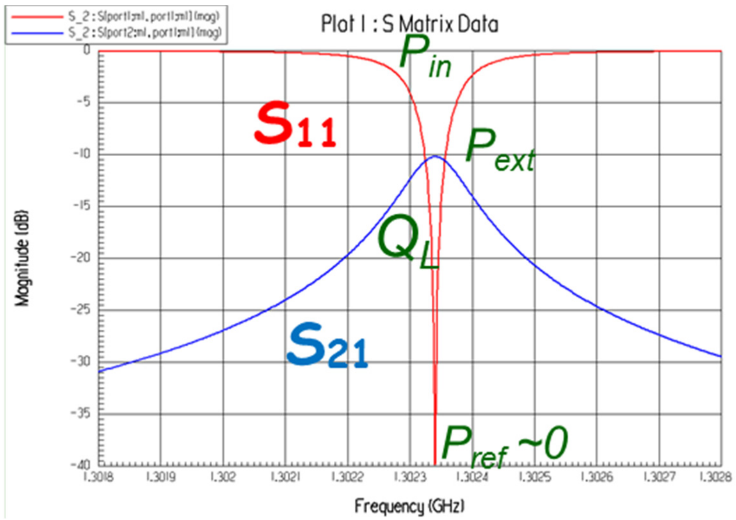
Calculation of Coupling Factor of Input Coupler (1)

A model copper single-cell cavity with an end-cell shape is shown in Figure in order to guide the design of the coupling factor between a cavity and an input coupler. The relationship between the external Q values of the input coupler and the location of the antenna tip is calculated using HFSS code . One example of the calculation results is shown in Figure (P33).



A model cavity for the calculation of external Q values of an input coupler: Here, *L* is the distance between the cell end and the coupler center, and *T* is the space between the beam axis and the antenna tip of the input coupler.

Calculation of Coupling Factor of Input Coupler (2)



$$P_{in} = 0\ dBm\ = 1\ [mW]$$

$$P_{ref} = 10^{\frac{S_{11}}{10}} \cdot P_{in}\ [W]$$

$$P_{ext} = 10^{\frac{S_{21}}{10}} \cdot P_{in}\ [W]$$

$$Q_L = \frac{f}{\Delta f}$$

One example of calculation results using HFSS. Here, S_{11} is the reflected power from the cavity, and S_{21} is the transmitted power through the cavity.

The values of S_{11}, S_{21} and Δf (bandwidth of P_{ext}) are given by the calculation results. The input power (P_{in}), reflected power (P_{ref}), transmitted power (P_{ext}), and loaded Q value (Q_L) are obtained from Figure. The cavity RF loss (P_0) and unloaded Q value (Q_0) are calculated from Eqs. (19) and (23), respectively. Finally, the external Q value (Q_{ext}) of the input coupler is estimated by Eq. (24). The result of the external Q values as a function of the location of the antenna tip is shown in Figure (P35).

Calculation of Coupling Factor of Input Coupler (3)

$$P_o = P_{in} - P_{ref} - P_{ext} \quad (19)$$

$$\beta^* = \frac{1 \pm \sqrt{P_{ref} / P_{in}}}{1 \mp \sqrt{P_{ref} / P_{in}}} \quad (20)$$

$$\beta_{in} = \beta^* \cdot (1 + \beta_{ext}) \quad (21)$$

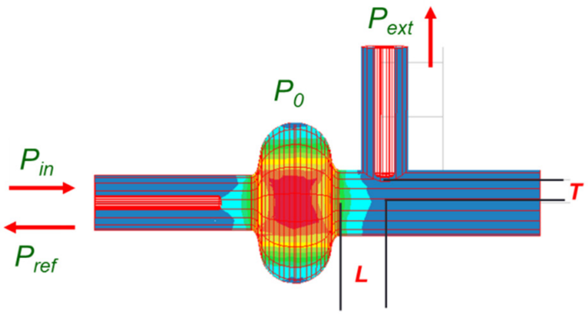
$$\beta_{ext} = P_{ext} / P_o \quad (22)$$

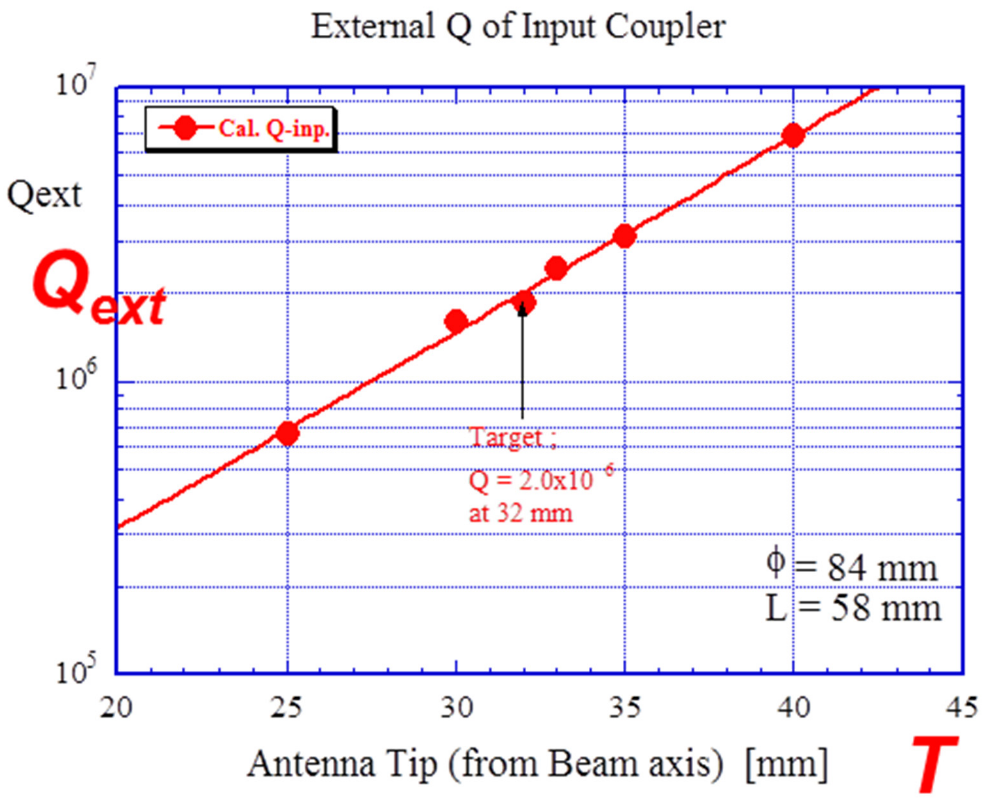
$$Q_o = Q_L \cdot (1 + \beta_{in} + \beta_{ext}) \quad (23)$$

$$Q_{ext} = P_o \cdot Q_o / P_{ext} \quad (24)$$

This calculation method using these equations is just the same as the VT measurements.

Calculation of Coupling Factor of Input Coupler (4)





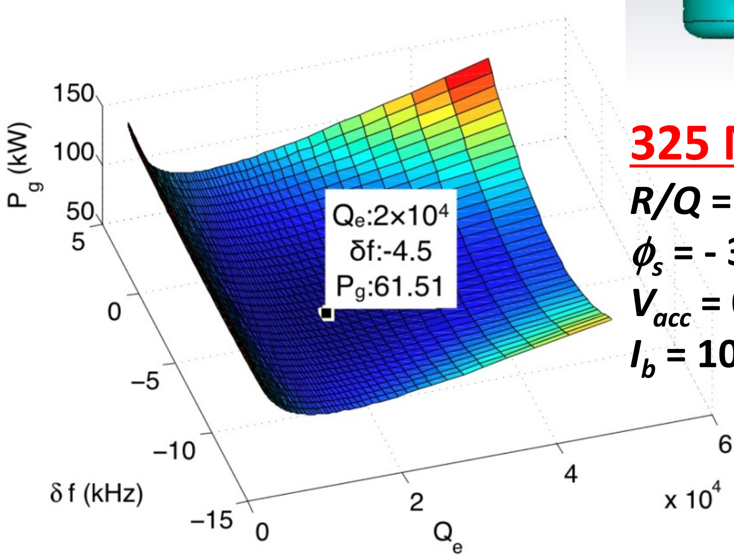
External Q values (Q_{ext}) as a function of the location of the antenna tip (T).

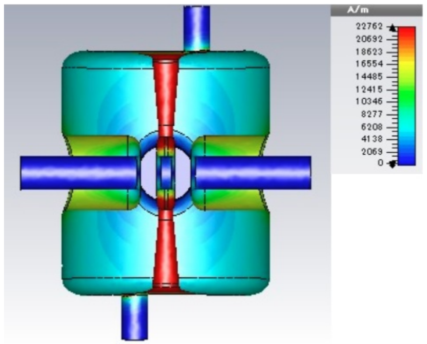
Calculation of Coupling Factor of Input Coupler (5)

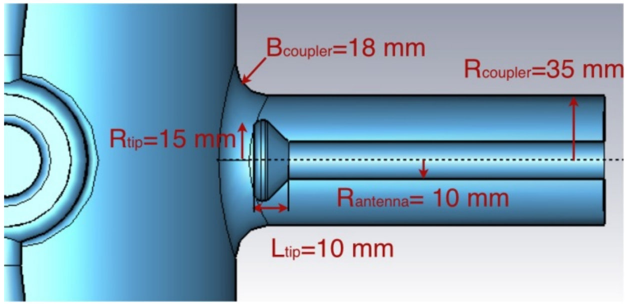
- Required generator RF power (P_g) : input coupling (Q_e), frequency shift (δf)

$$P_g = \frac{V_{acc}^2}{4\frac{R}{Q_0}}\frac{Q_e}{Q_L^2}\left[\left(1+\frac{R}{Q_0}Q_L\frac{I_b}{V_{acc}}\cos\phi_S\right)^2+\left(2Q_L\frac{\delta f}{f}-\frac{R}{Q_0}Q_L\frac{I_b}{V_{acc}}\sin\phi_S\right)^2\right] \quad (25)$$

Calculation by CST-MWS







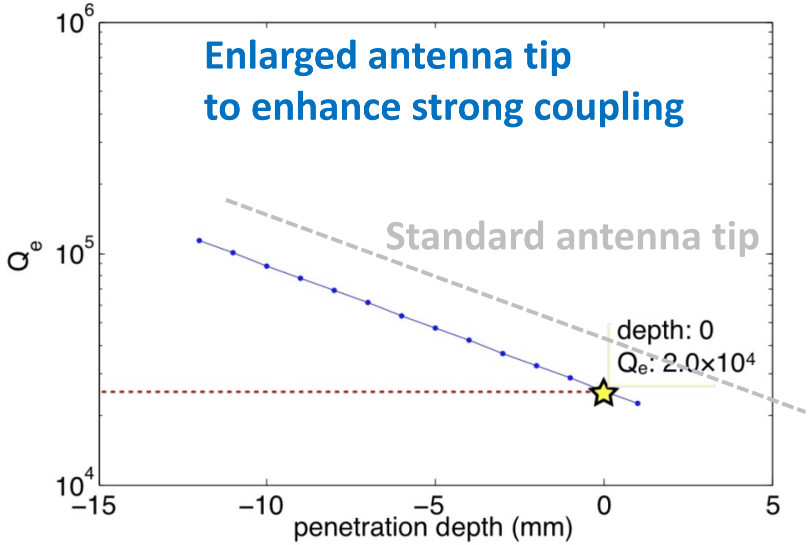
325 MHz HWR

***R/Q* = 198 Ω**

ϕ_s = - 30 degree

V_{acc} = 0.66 MV

I_b = 100 mA



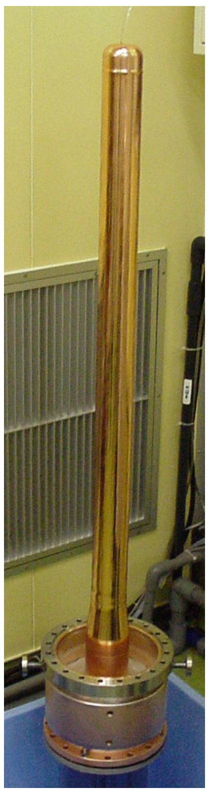
Contents

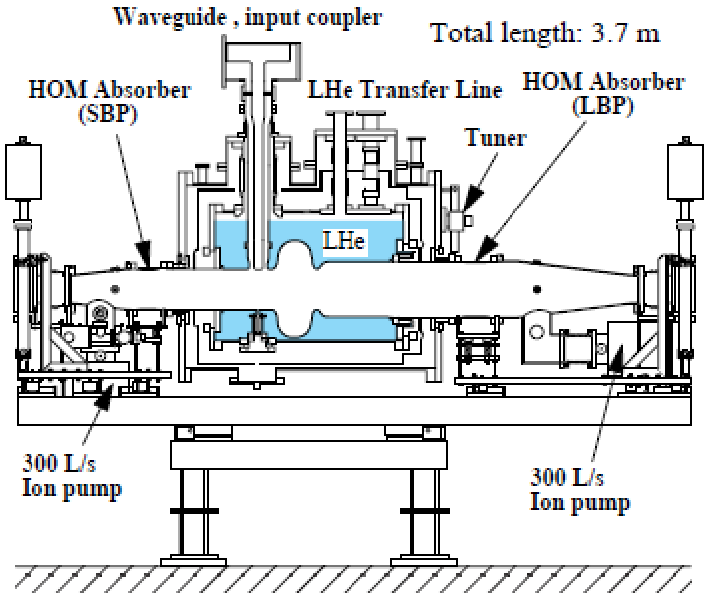
1. Coupling to a cavity
2. **Choice of Coupler Type**
3. Design Issues
4. Fabrication Issues
5. RF Conditioning Issues
6. Trouble shooting
7. State of the Arts

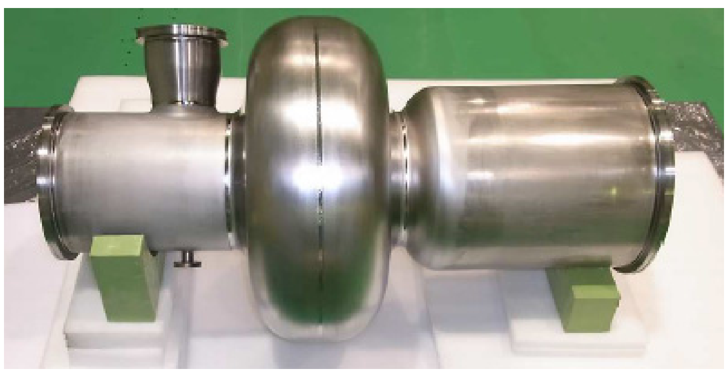
Choice of Coupler Type

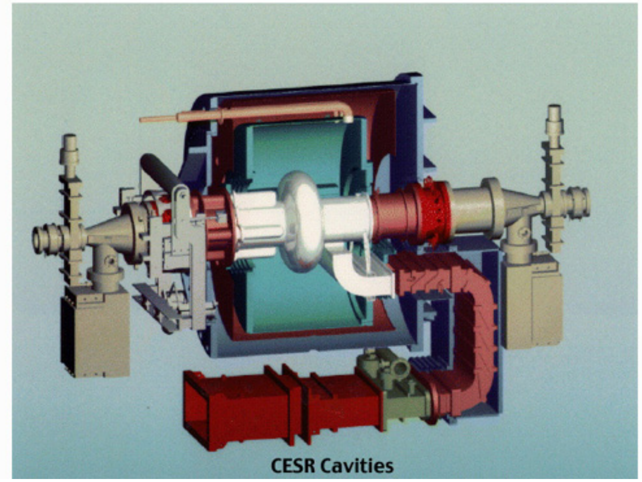
- Coaxial or Waveguide
- Disk or Cylindrical Window
- Single or Double Windows
- Fixed or Variable Coupling
- CW or Pulsed operation
- Double Feed Couplers

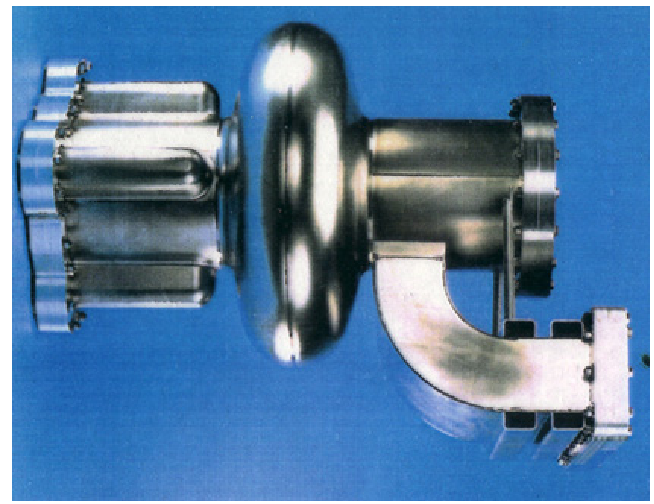
Coaxial or Waveguide







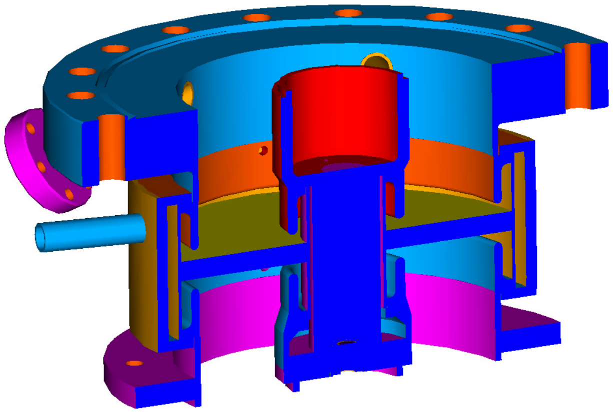


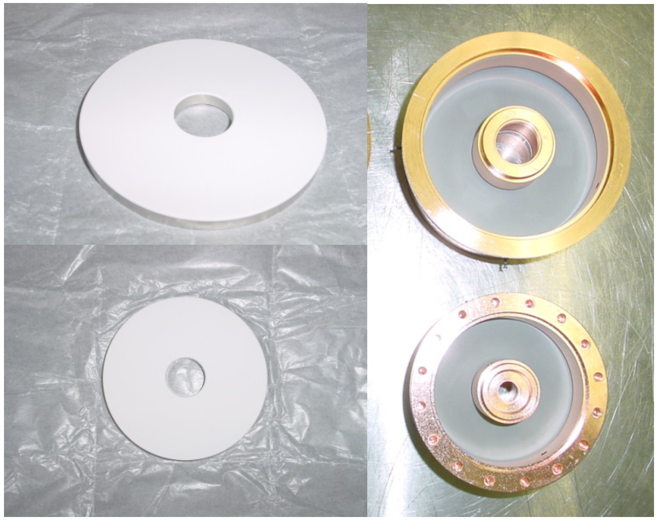


KEK-B Cavity (508MHz)
with a coaxial coupler

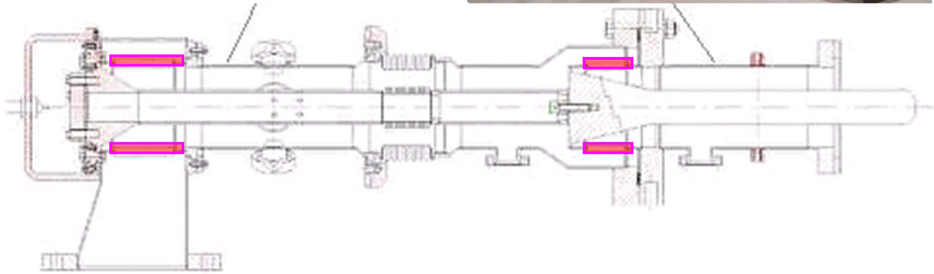
CESR-B Cavity (500MHz)
with a waveguide coupler

Disk or Cylindrical Window





Tristan-type coaxial disk ceramics
RF window with choke structure

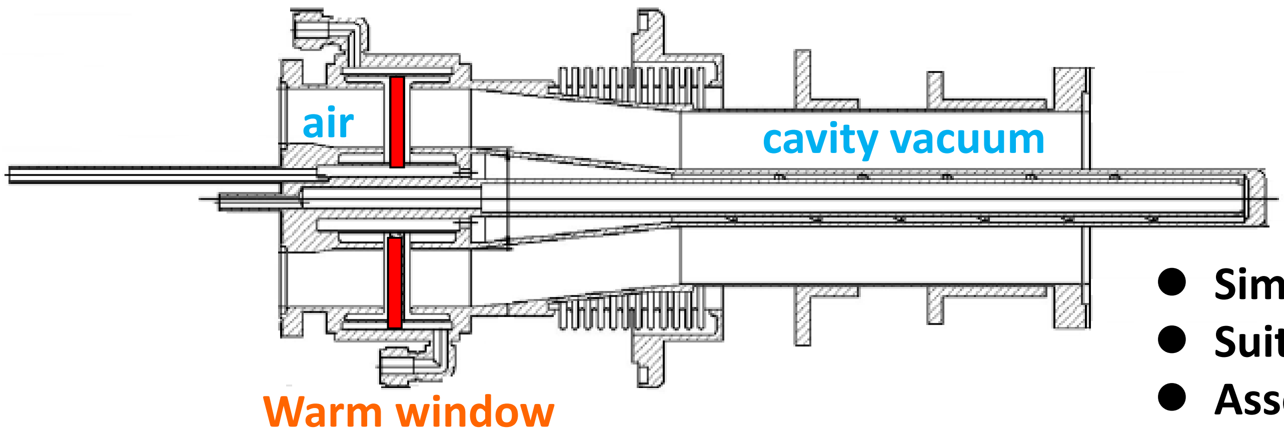


TTF-V input coupler for ILC
with cylindrical ceramic windows

Single or Double Windows

CW Input Coupler for cERL Injector

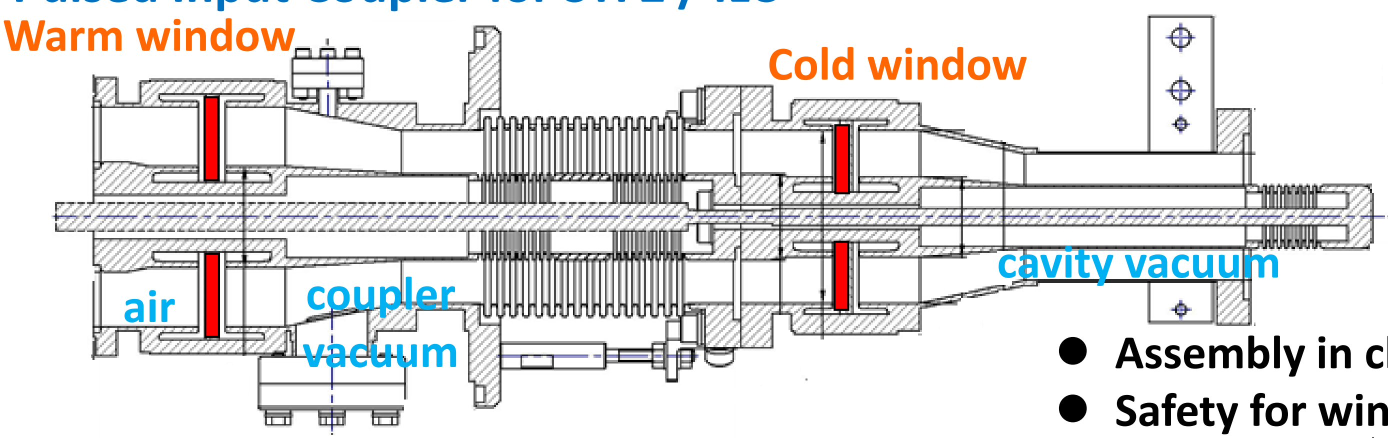
(Single Window)



- Simple structure
- Suitable for cooling
- Assembly with cryomodule

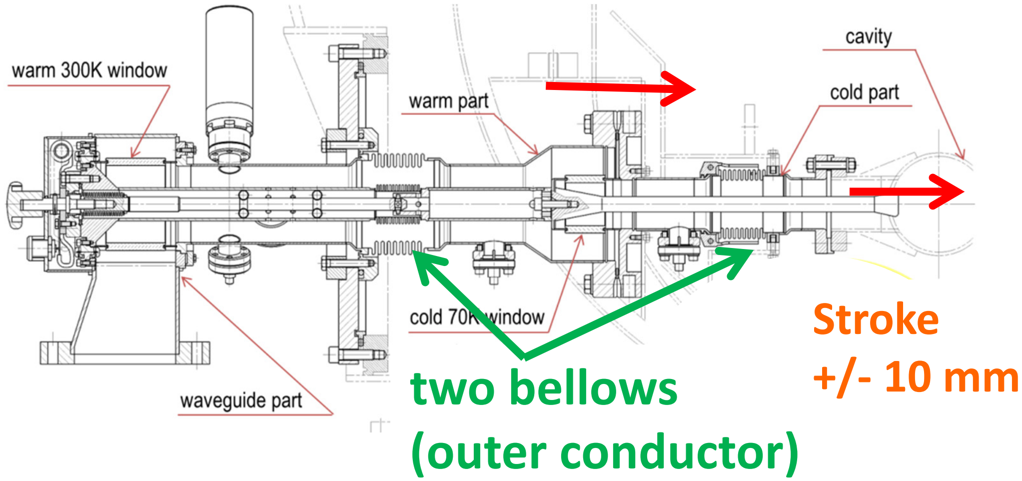
Pulsed Input Coupler for STF2 / ILC

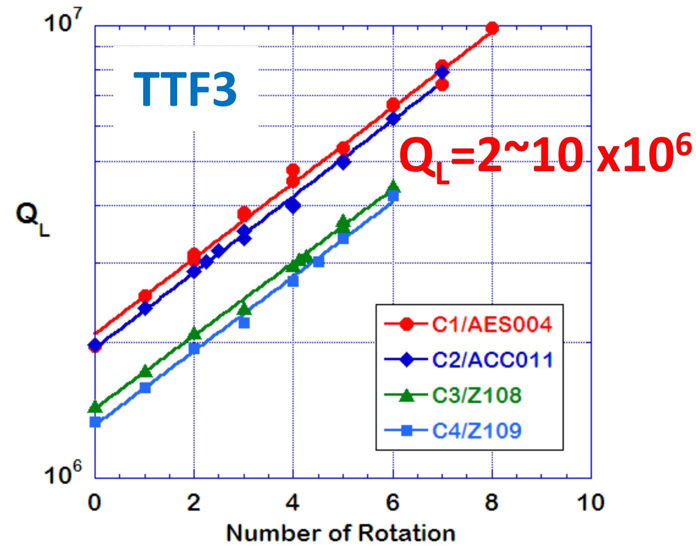
(Double Windows)



- Assembly in clean room
- Safety for window failure
- Coupler vacuum for cold window

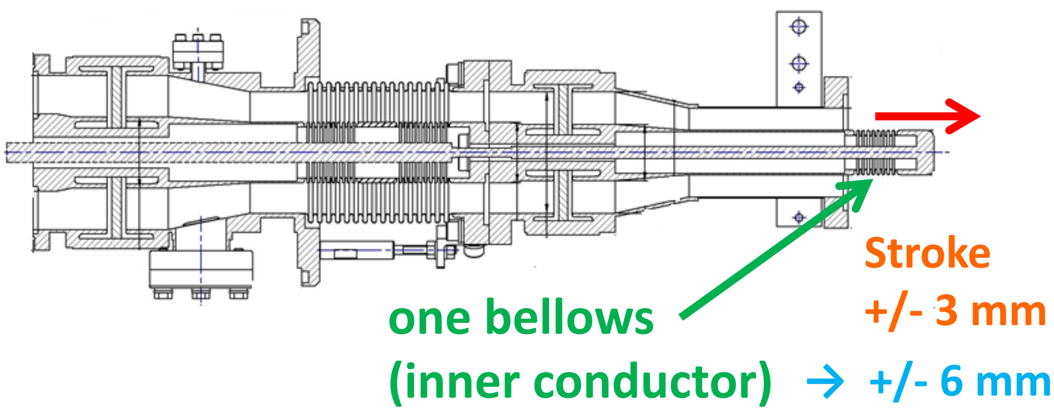
Fixed or Variable Coupling

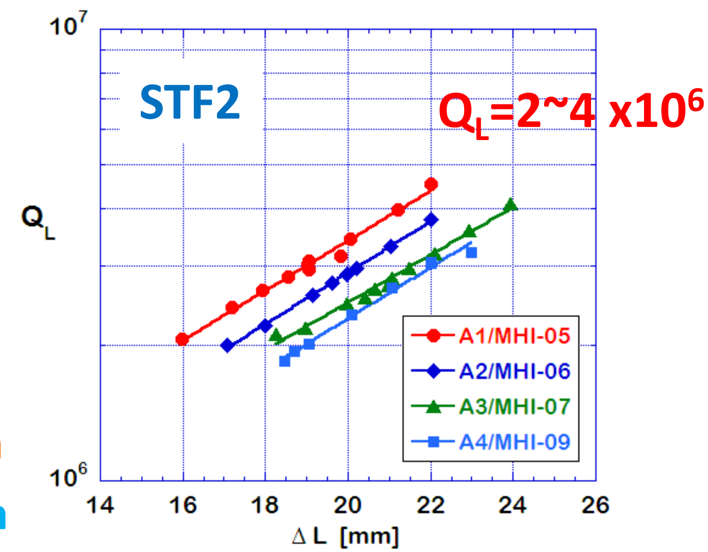




TTF3 Input Coupler for XFEL

STF2 Input Coupler for ILC

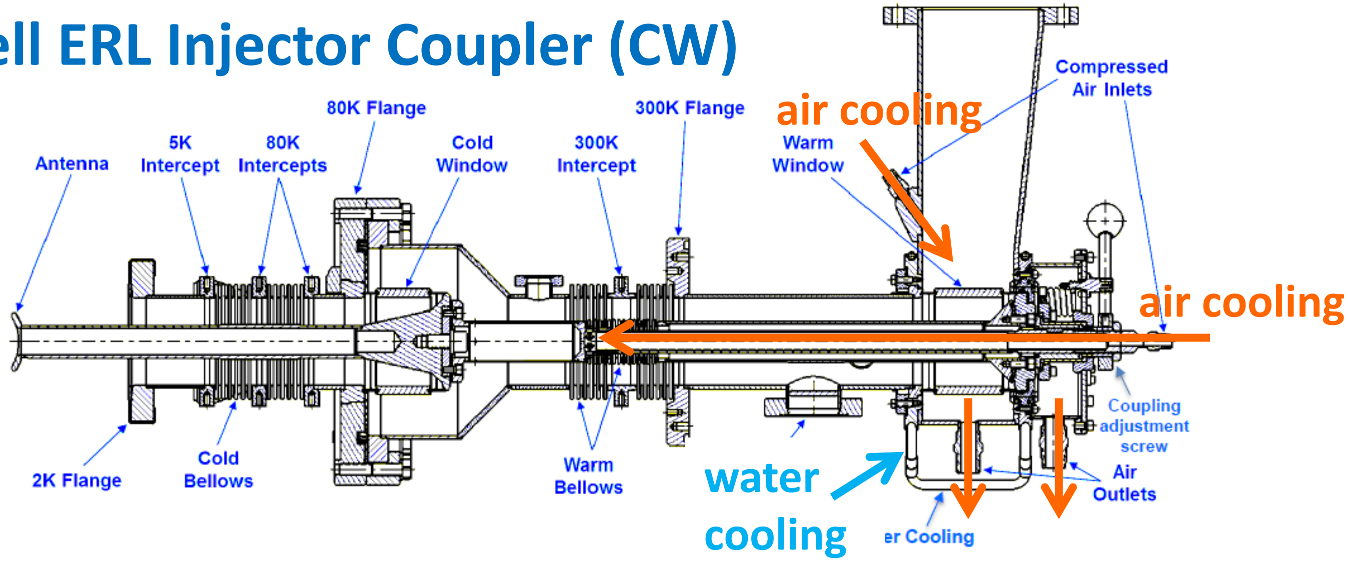




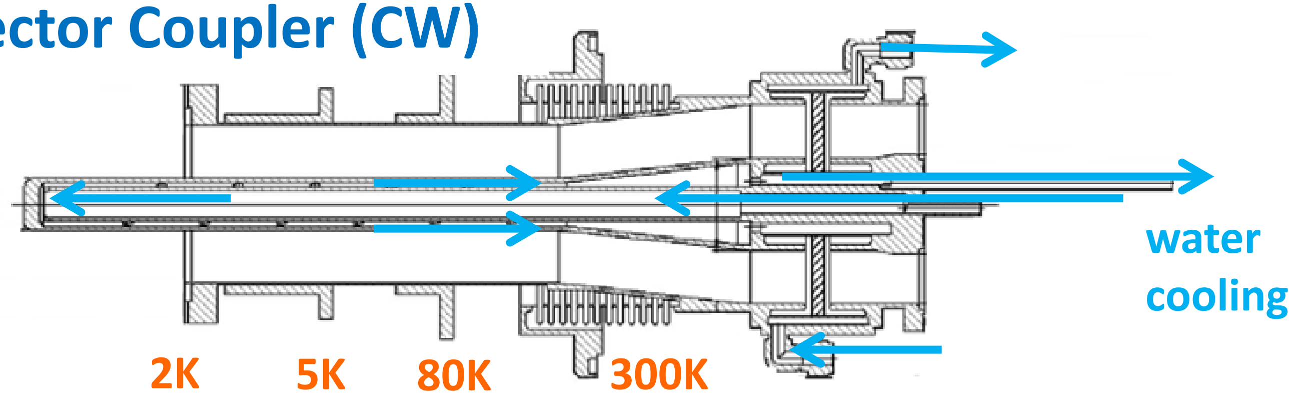
CW or Pulsed Operation

Cooling of inner conductor is necessary in ave. P_{RF} > 3 kW.

Cornell ERL Injector Coupler (CW)

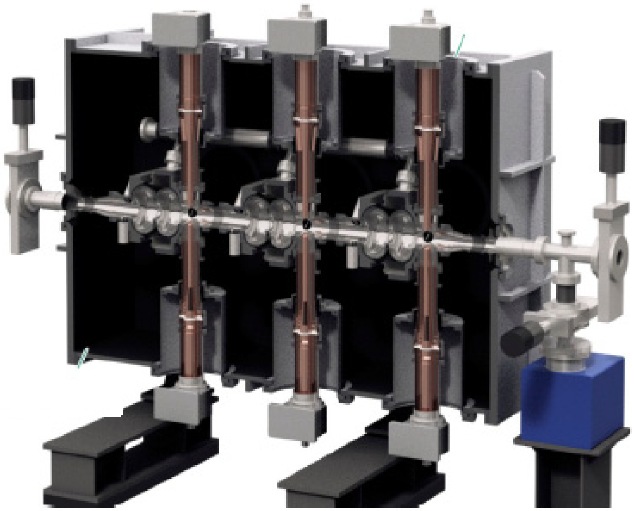


KEK cERL Injector Coupler (CW)

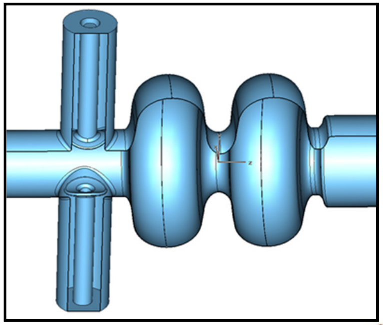


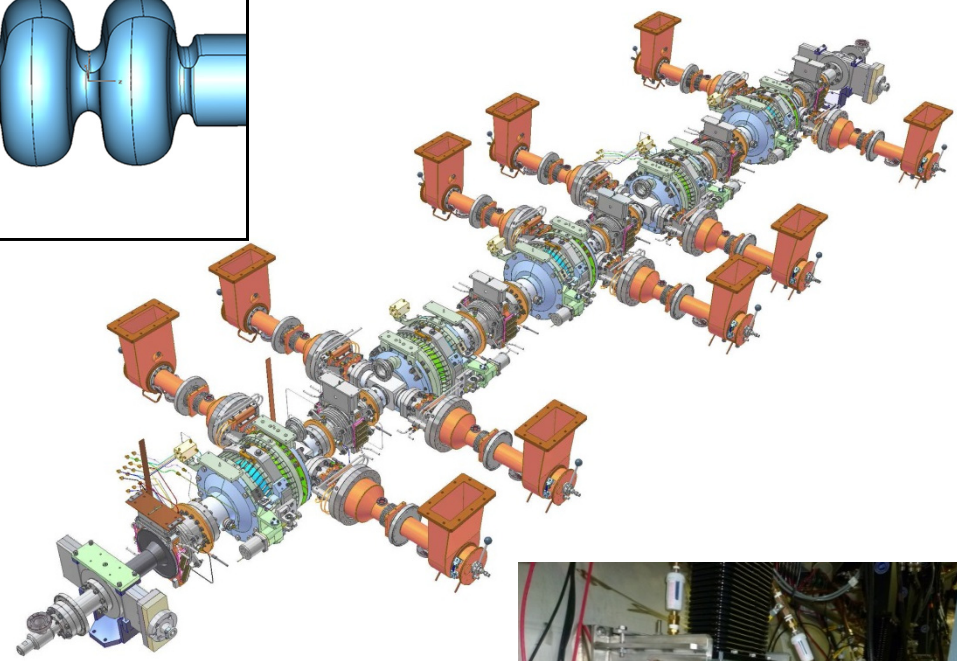
Double Feed Couplers

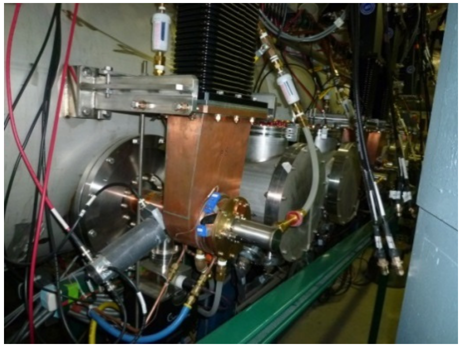
Vertical-type double feed couplers for cERL Injector (KEK)



Horizontal-type double feed couplers for ERL Injector (Cornell)







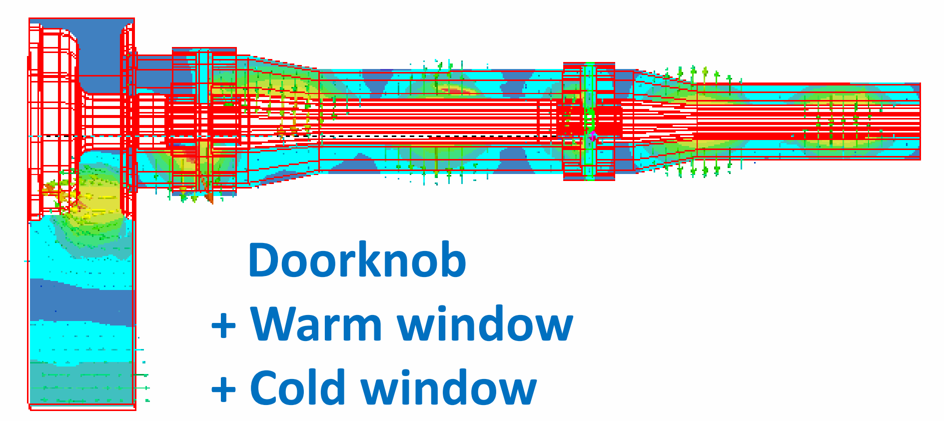
- **Power handling capability (1/2)**
- **Suppression of coupler kick by symmetry structure**
- **Choice of vertical or horizontal**

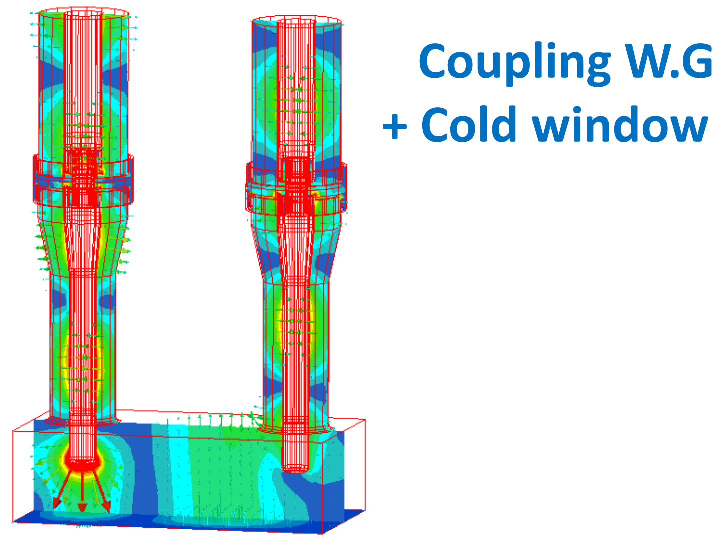
Contents

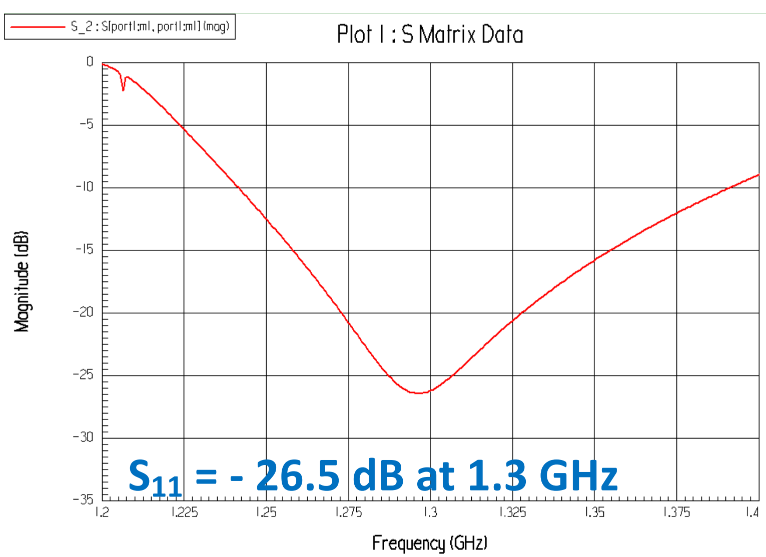
Design issues

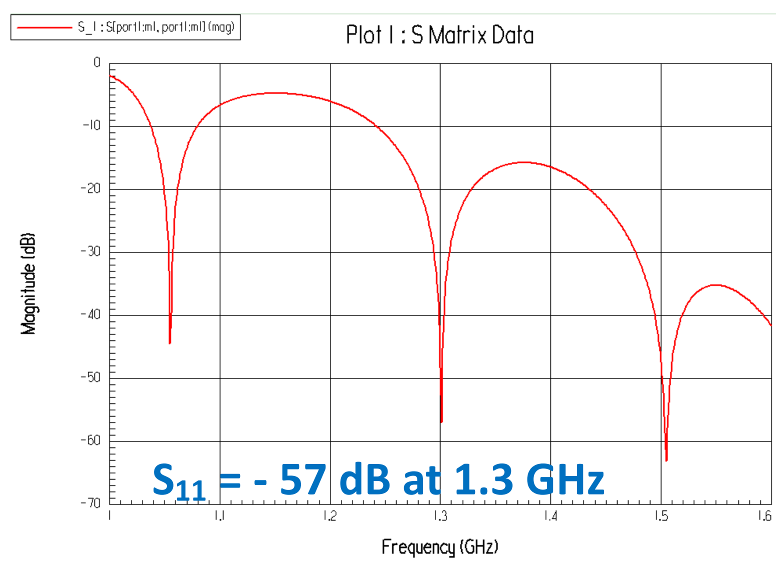
- RF Design
- RF Power Dissipation
- Thermal Calculation
- Mechanical Analysis
- Multipactor Simulation

RF Design (HFSS) (1)

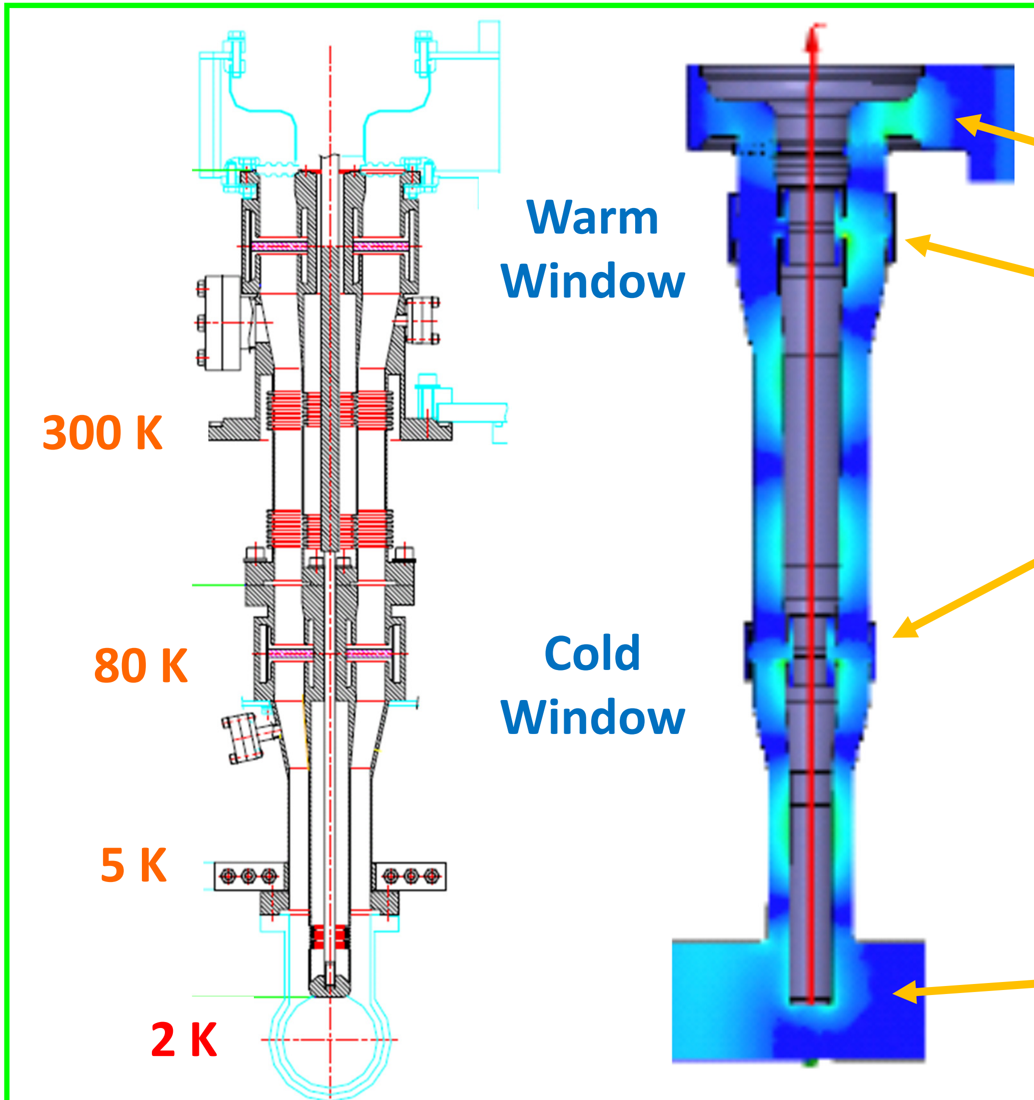




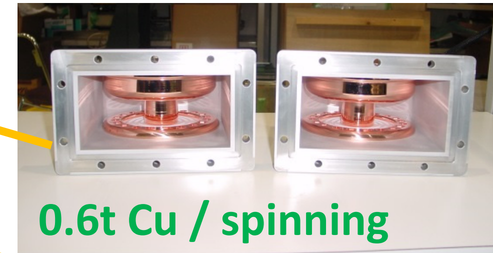




RF Design (HFSS) (2)

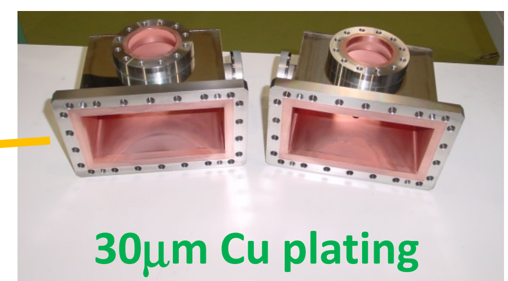


Doorknob Coax/WG transition

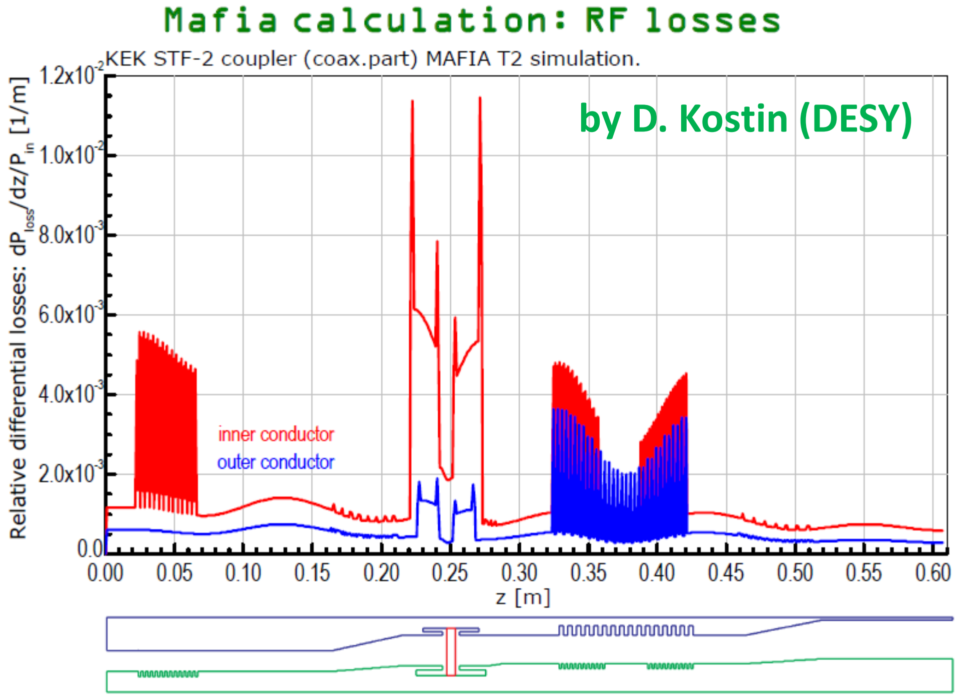


Cold and warm windows

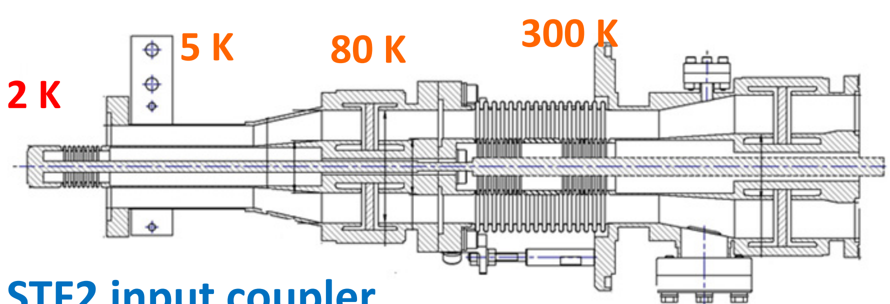
Coupling Waveguide



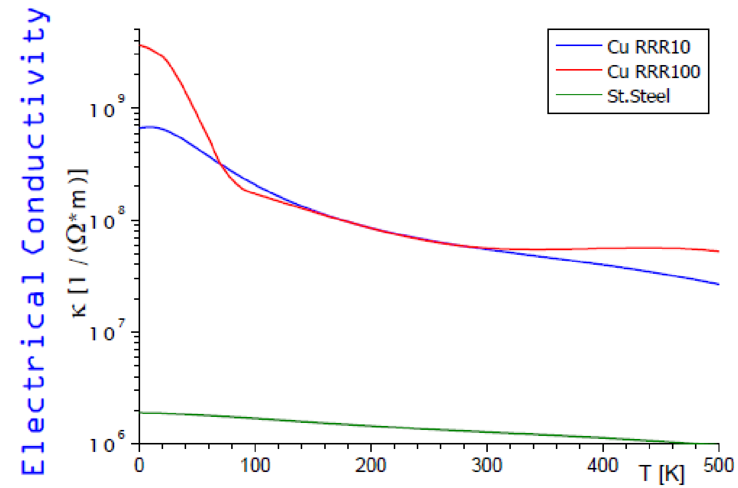
RF Power Dissipation (MAFIA-T2)

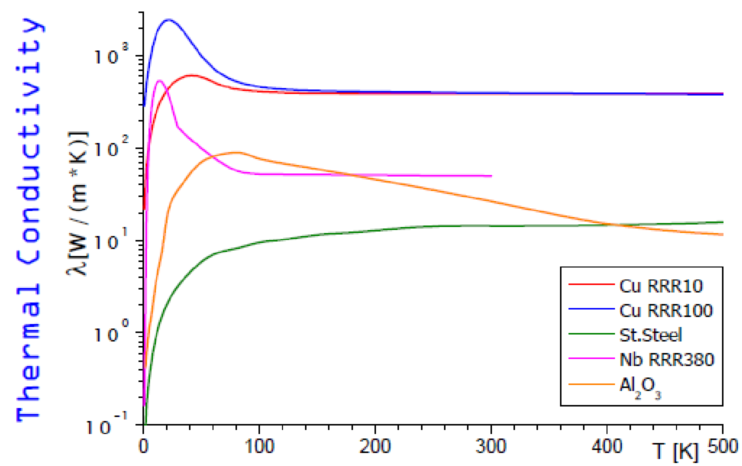


Material: Cu, $\kappa_0 = 5.8\times10^7$ 1/(Ω×m) (300 K)
Power Losses in the 70K ceramic window
(ε=9.2, tgδ=10^{-4}): $P_{loss.win}/P_{in} = 1.39\times10^{-4}$



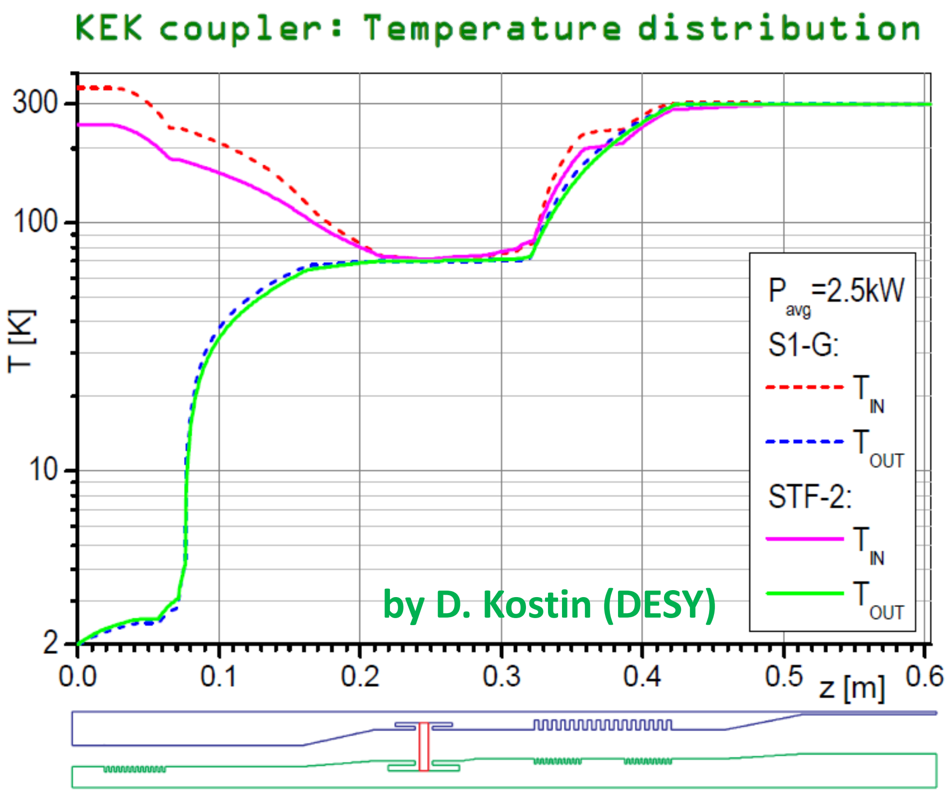
STF2 input coupler

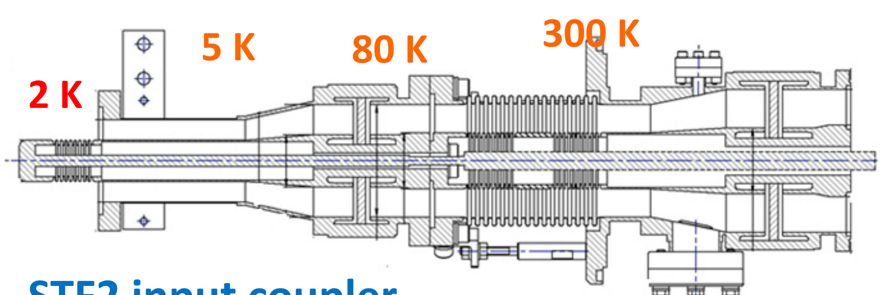




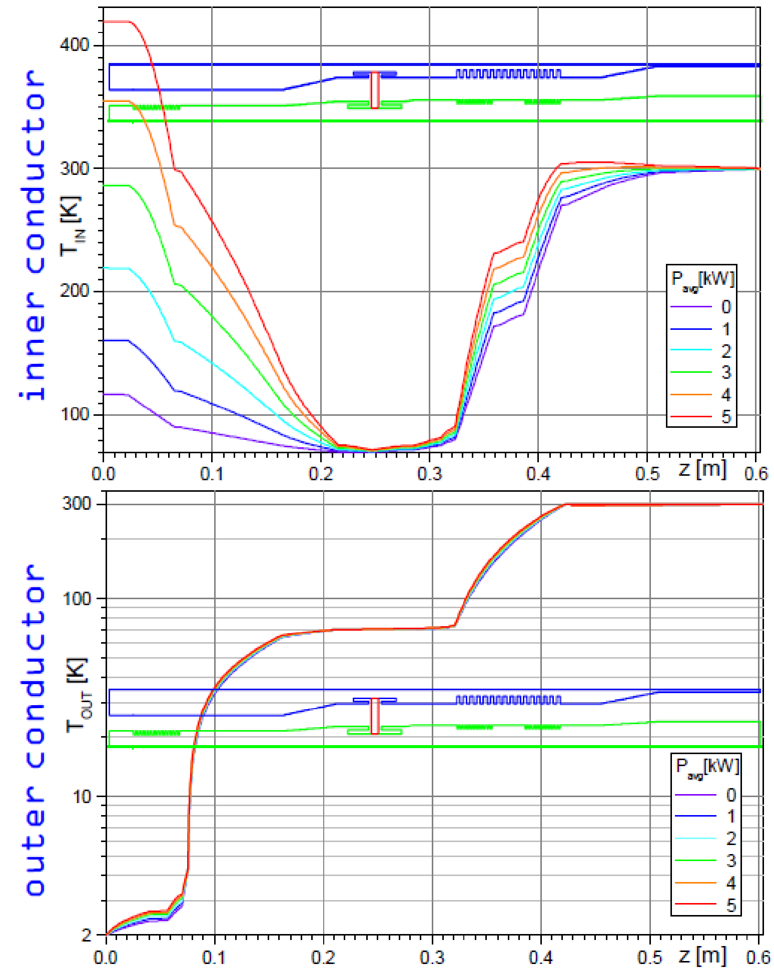
To reduce dynamic loss, high RRR Cu-plating is preferable.

Thermal Calculation (MAFIA-T2)



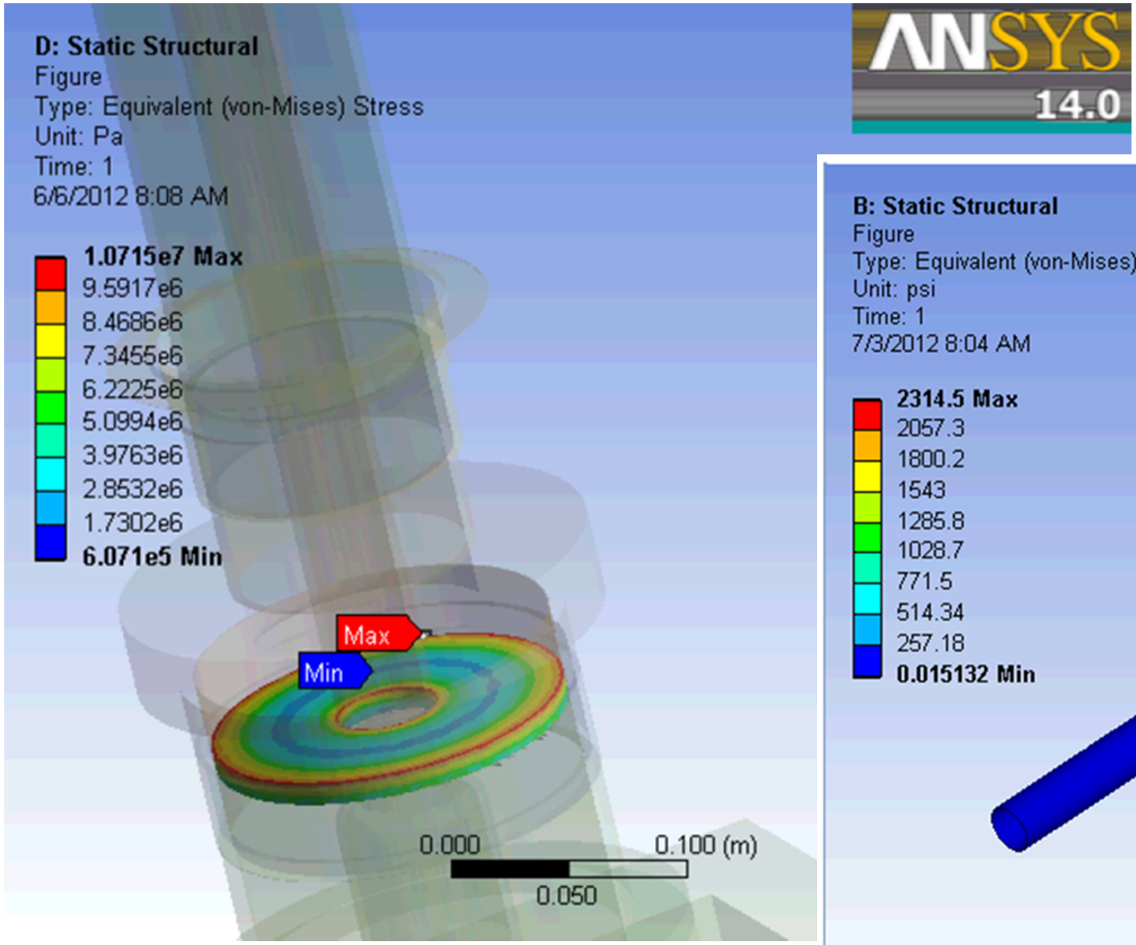


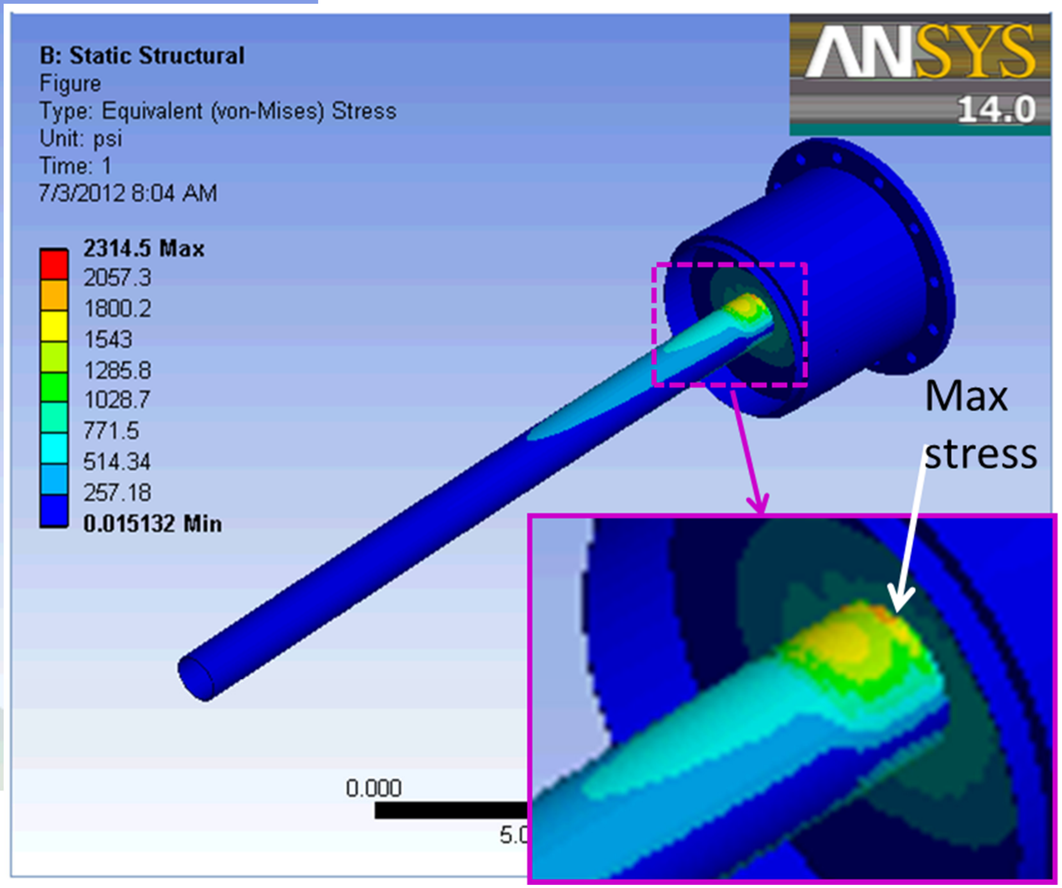
STF2 input coupler



To reduce static loss, thin and low RRR Cu-plating is preferable.

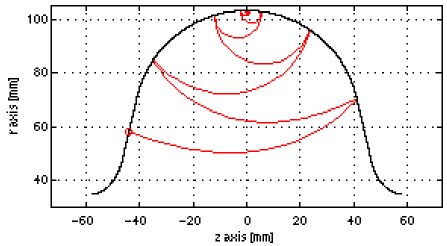
Mechanical Analysis (ANSYS)



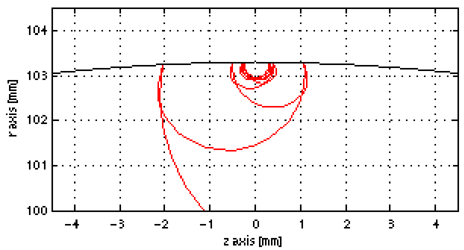


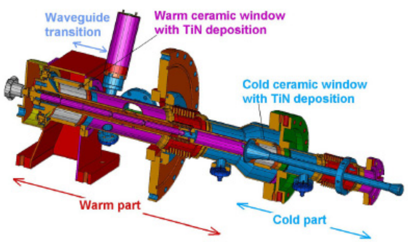
IFMIF Coupler (CEA-Saclay / CPI Beverly) by H. Jenhani

Multipacting Simulation

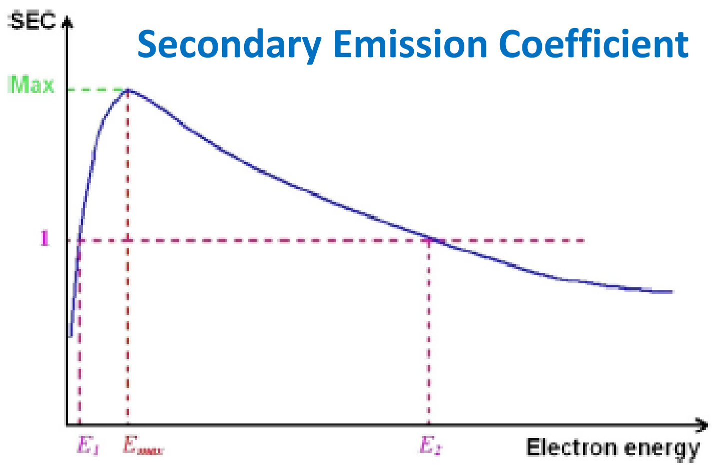


Resonant process of electrons in RF structure



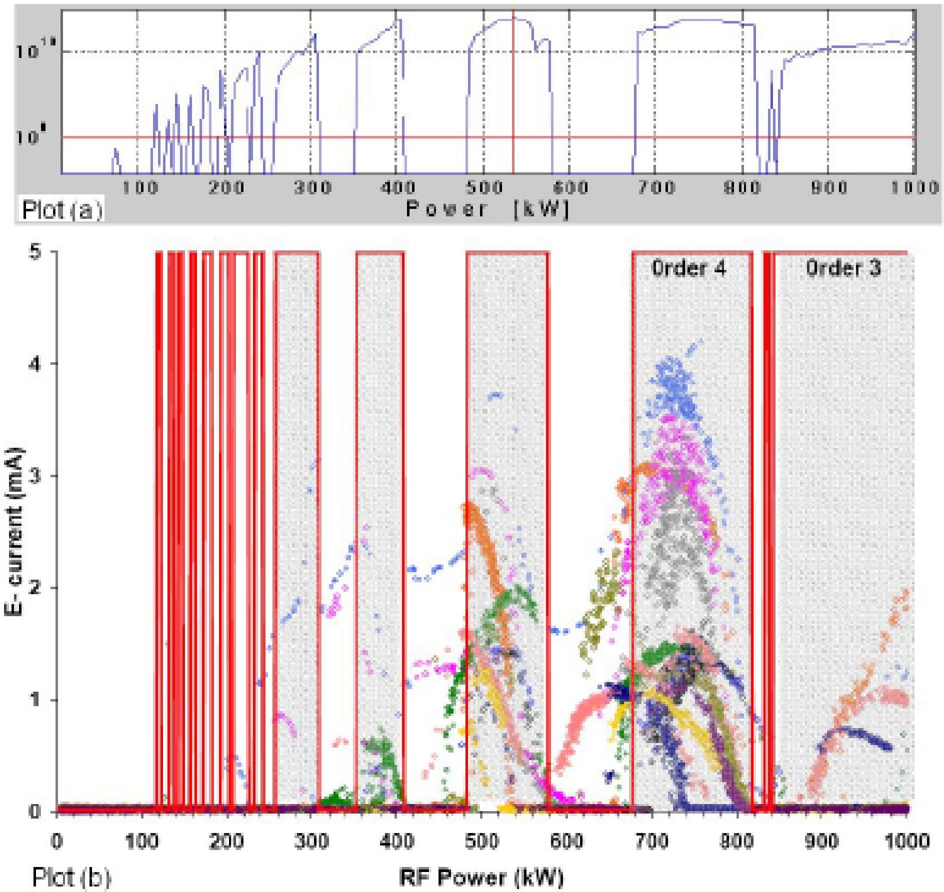


Secondary Emission Coefficient



~100eV **~1000eV**

Comparison between MP simulation and e- current measurement in TTF3 coupler



by H. Jenhani (LAL-Orsay)

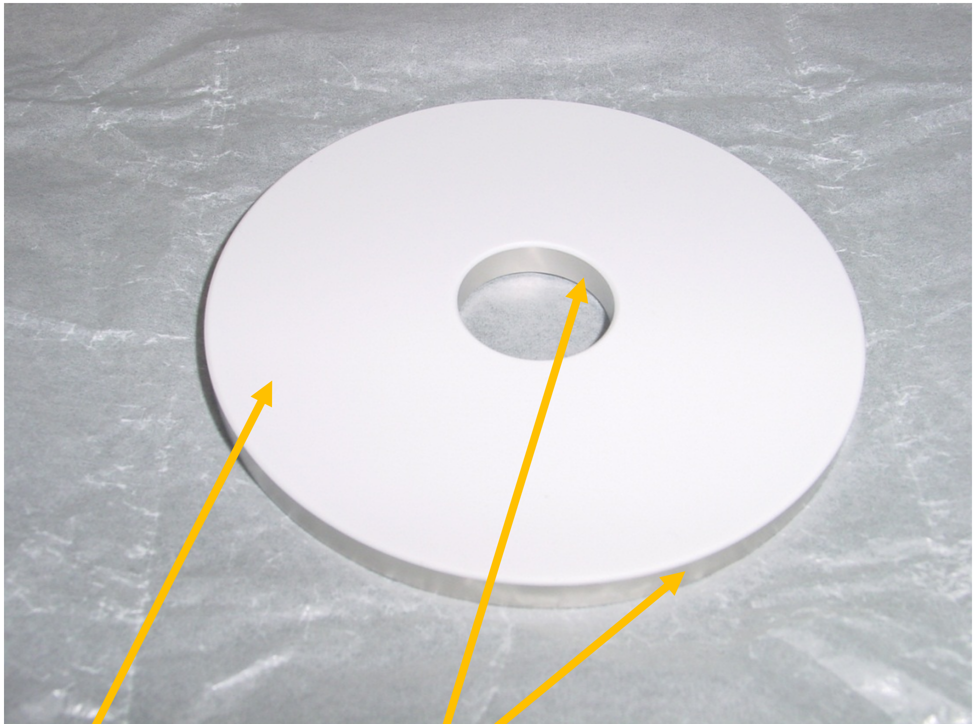
Contents

Fabrication issues

- Ceramics Window
- Metalizing
- Brazing
- Copper Plating
- Bellows
- TiN Coating

These are essential technologies for coupler fabrication.
But, the details are usually not opened
by fabrication companies!!

Ceramics Window



Al_2O_3 ceramics
Purity;
HA95 ~95%
HA99 ~99%
ε* = 9.0 ~ 9.8

Metalizing by sintering of Mo-Mn paste

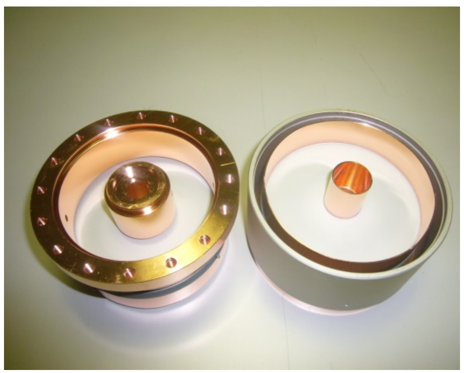
Dielectric loss: 1~6 x 10^{-4} (1MHz)
Loss tangent = tan $\delta = (\varepsilon''/\varepsilon')$

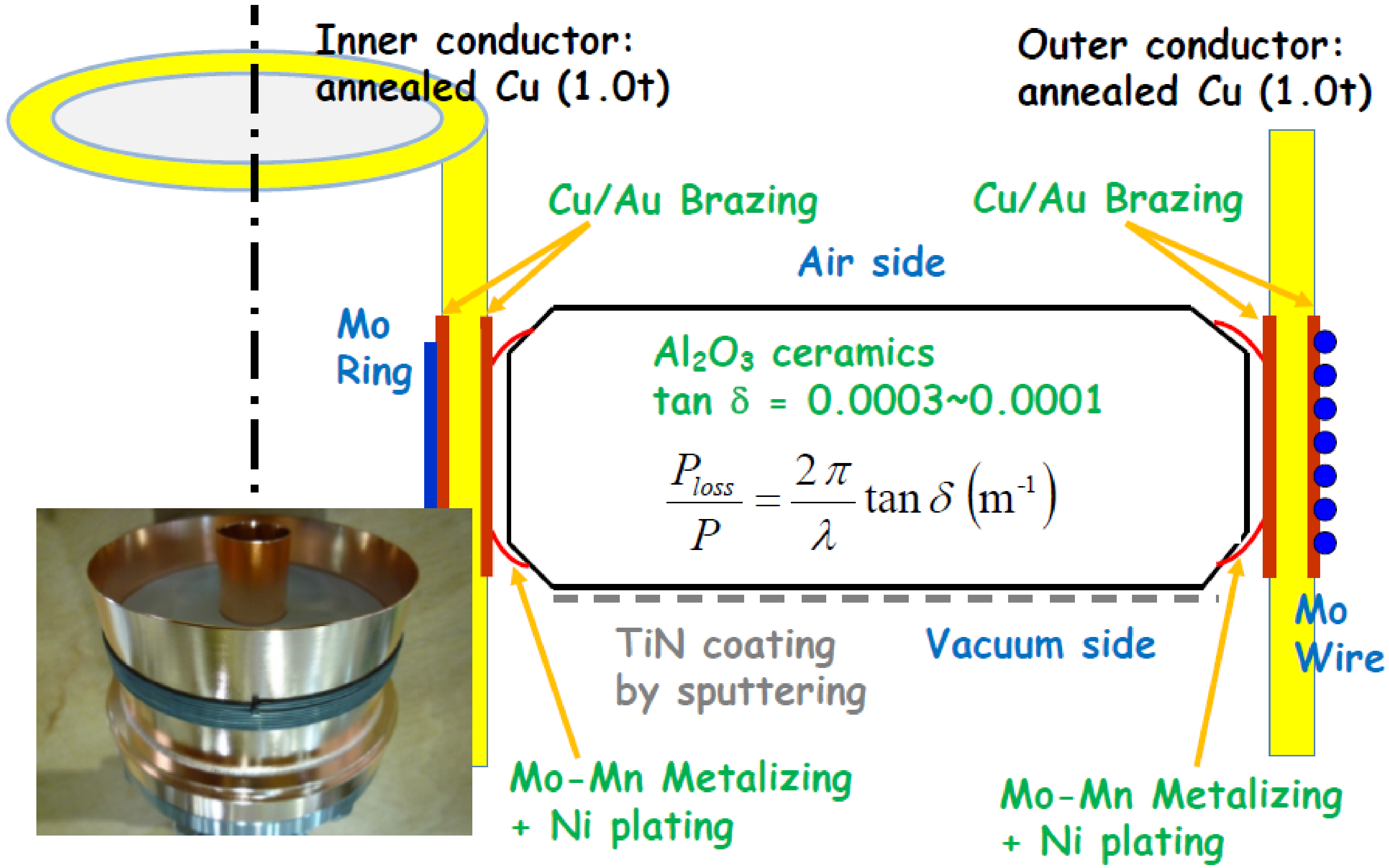
Thermal cycle tests by liquid N_2 of ceramic-disks & thin Cu-plating.

Brazing

Two steps of Brazing ; 1st brazing by Cu/Au-composition at ~1000°C
2nd brazing by Cu/Ag-composition at ~800°C

Vacuum Furnace or Hydrogen Furnace





TiN Coating

- Al_2O_3 has a high SEC:
  - coating of the surface on the vacuum side is a must
- TiN has a low SEC and is a stable composition
- Deposition processes are
  - sputtering **KEK**
  - evaporating → **DESY**
- Ammonia is used to convert the Ti to TiN

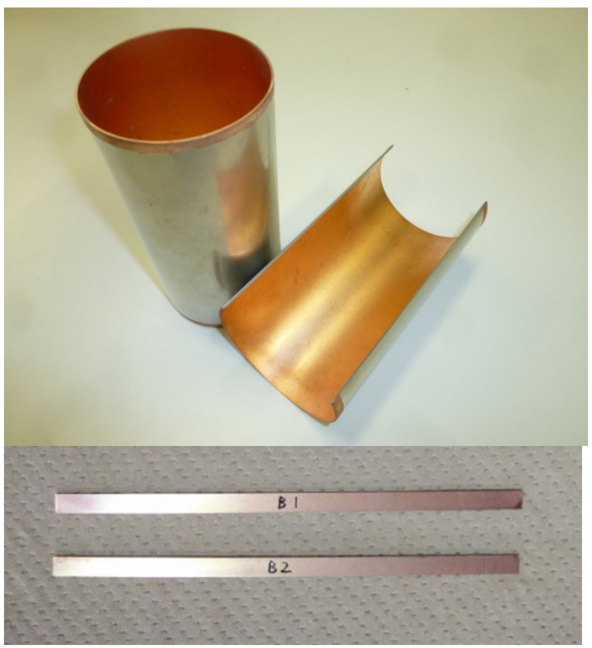
W.– D. Möller, DESY in Hamburg

15th International Conference on RF Superconductivity
Chicago, July 25 -29, 2011

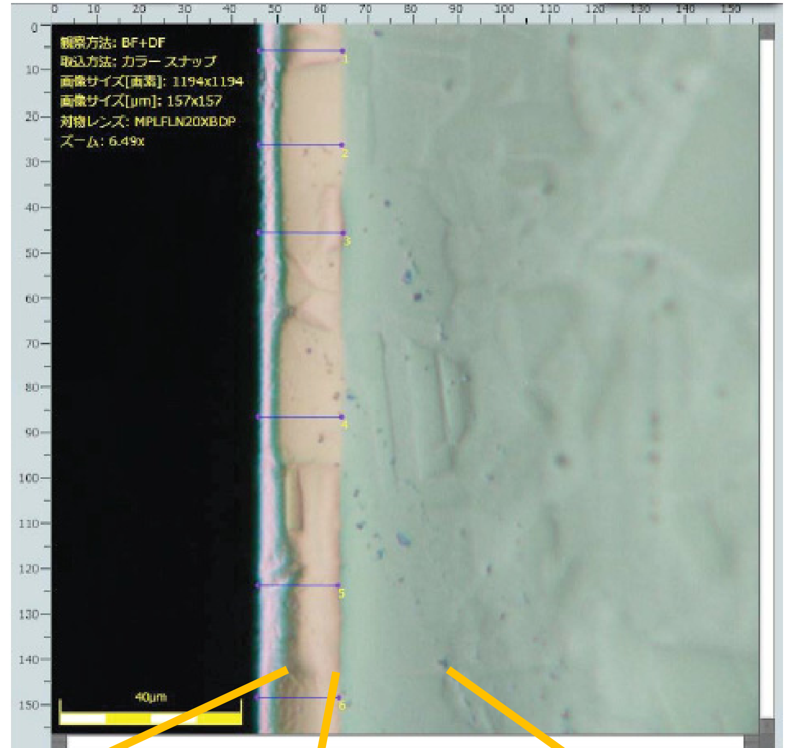
W.-D. Moeller, DESY, Hamburg

Copper Plating (1)

Cu-plating
Samples :
SUS 1.0t
Ni-strike
0.2 μm
Cu 5 μm



after anneal
at 800 °C
in hydrogen
furnace



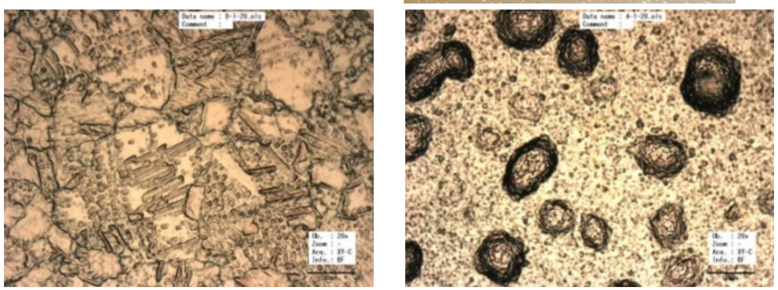
18μm Cu Plating
- $Cu_2P_2O_7$
- CuCN
- $CuSO_4$

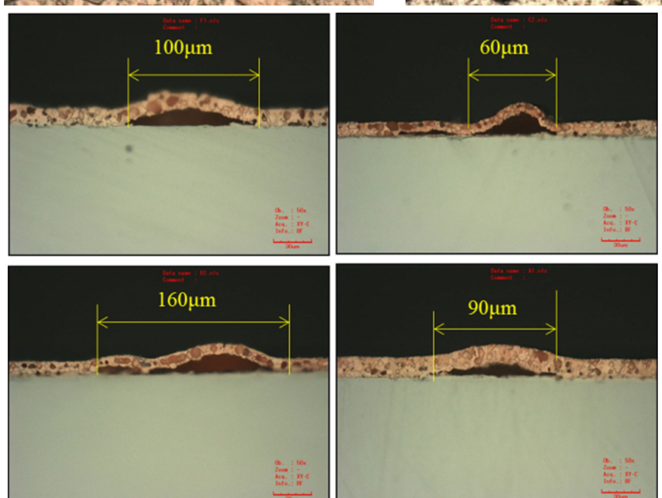
0.2μm
Ni or Au
Strike-plating

SUS316L
1.0t,
annealed

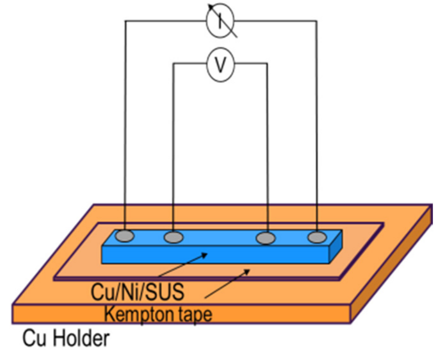
Copper Plating (2)

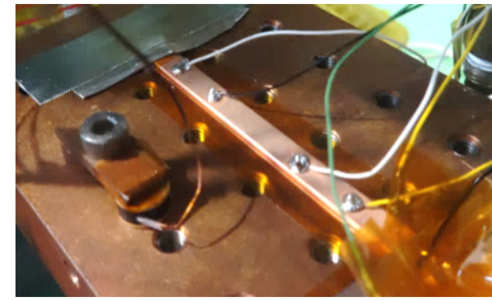
Quality control (adhesion)



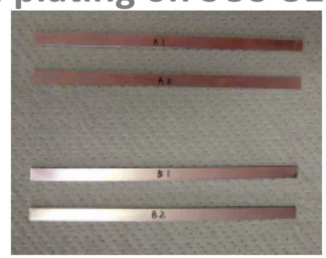


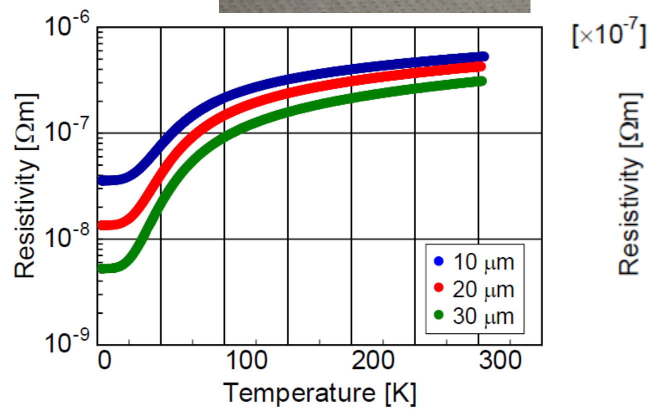
Quality control (RRR measurement)



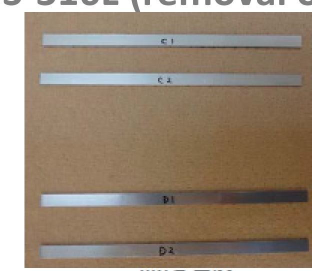


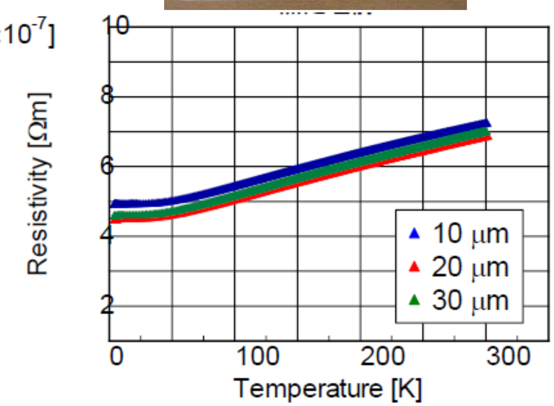
Cu plating on SUS-316L

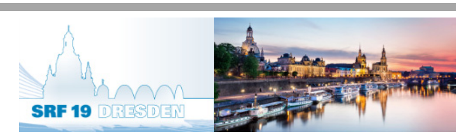




SUS-316L (removal of Cu)

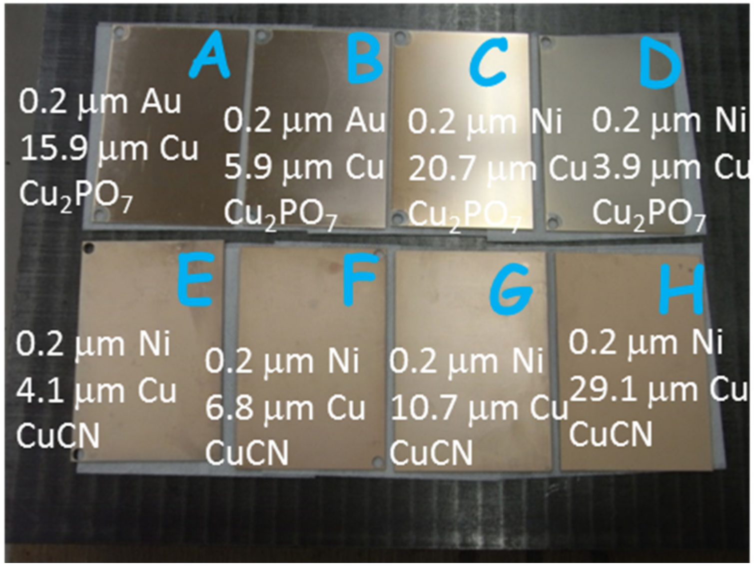






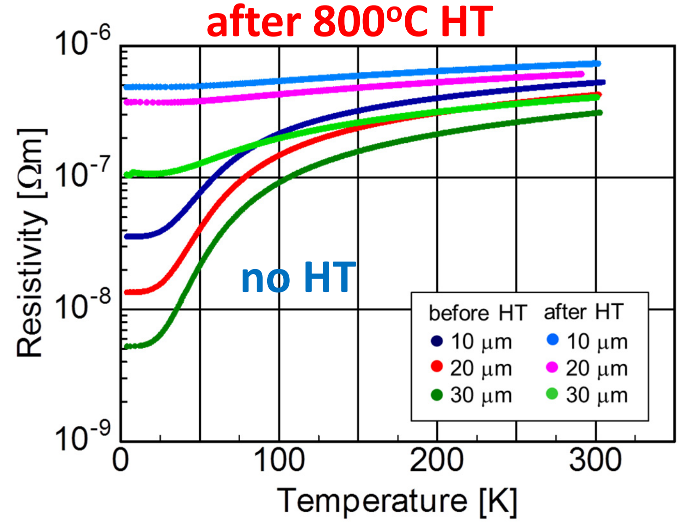
Copper Plating (3)

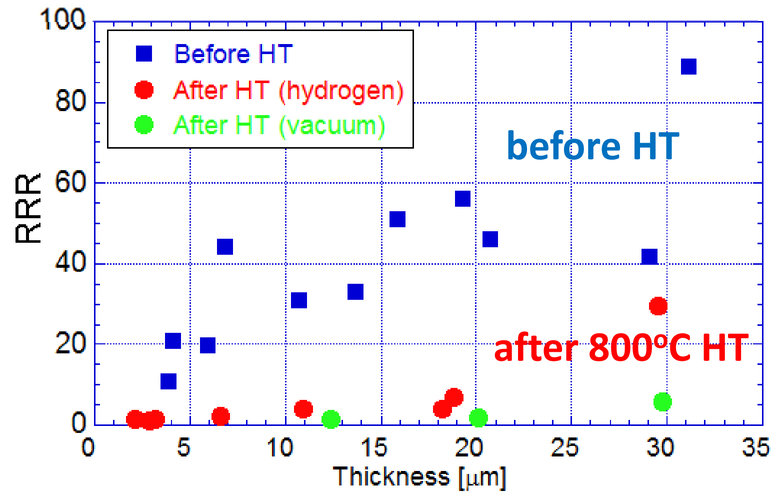
Sample tests of Cu-plating

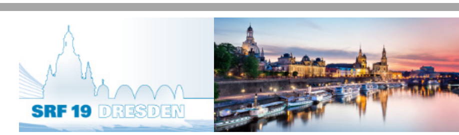


Sample	Plating vender	Target thickness	Measured thickness	Strike plating	Solution for copper-plating
A	X	20 μm	15.9 μm	Au	Copper-Pyrophosphate
B	X	5 μm	5.9 μm	Au	Copper-Pyrophosphate
C	X	20 μm	20.7 μm	Ni	Copper-Pyrophosphate
D	X	5 μm	3.9 μm	Ni	Copper-Pyrophosphate
E	Y	5 μm	4.1 μm	Ni	Copper-Cyanide
F	Y	20 μm	6.8 μm	Ni	Copper-Cyanide
G	Z	10 μm	10.7 μm	Ni	Copper-Cyanide
H	Z	35 μm	29.1 μm	Ni	Copper-Cyanide
I	V	10 μm	13.7 μm	Ni	Copper-Sulfate
J	V	20 μm	19.3 μm	Ni	Copper-Sulfate
K	V	30 μm	31.1 μm	Ni	Copper-Sulfate

Comparison between before/after HT







Contents

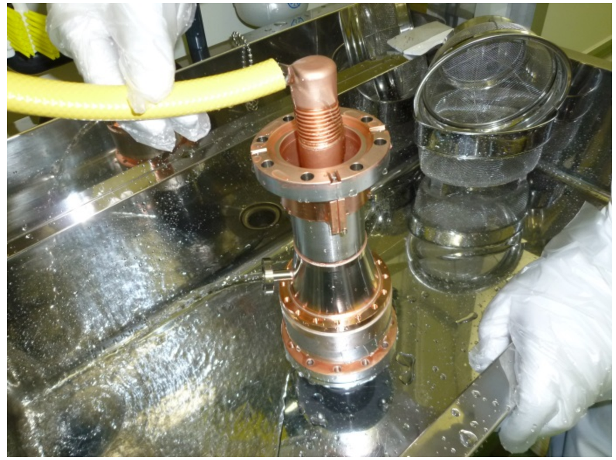
1. Coupling to a cavity
2. Choice of Coupler Type
3. Design Issues
4. Fabrication Issues
5. **RF Conditioning Issues**
6. Trouble shooting
7. State of the Arts

RF Conditioning issues

- Cleaning Procedure and Assembly
- High Power Test Stand
- Diagnostics and Interlocks
- Conditioning Time at Test Stand
- Cryomodule Assembly
- Conditioning Time in Cryomodule
- Dynamic Heat Loads

Cleaning Procedure and Assembly

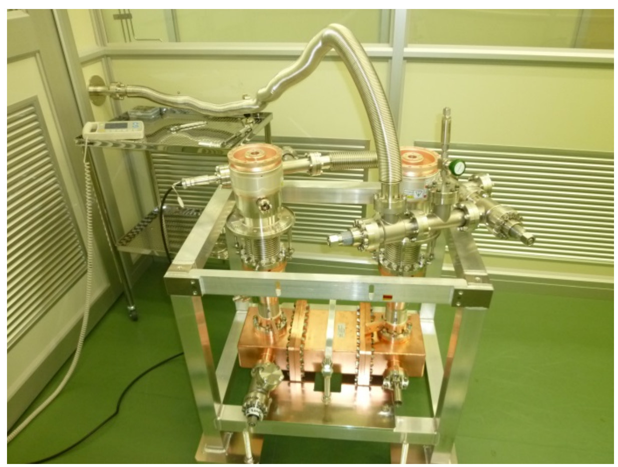
Ultra-pure water rinsing with ultra-sonic agitation



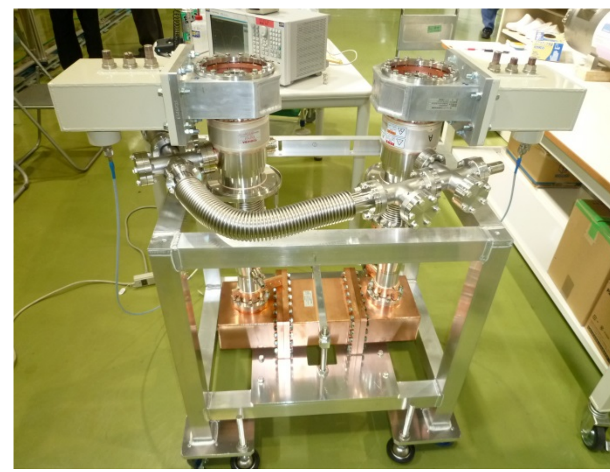
Low pressure water rinsing with ultra-pure water

Drying by ionized air gun

Installation of cold parts

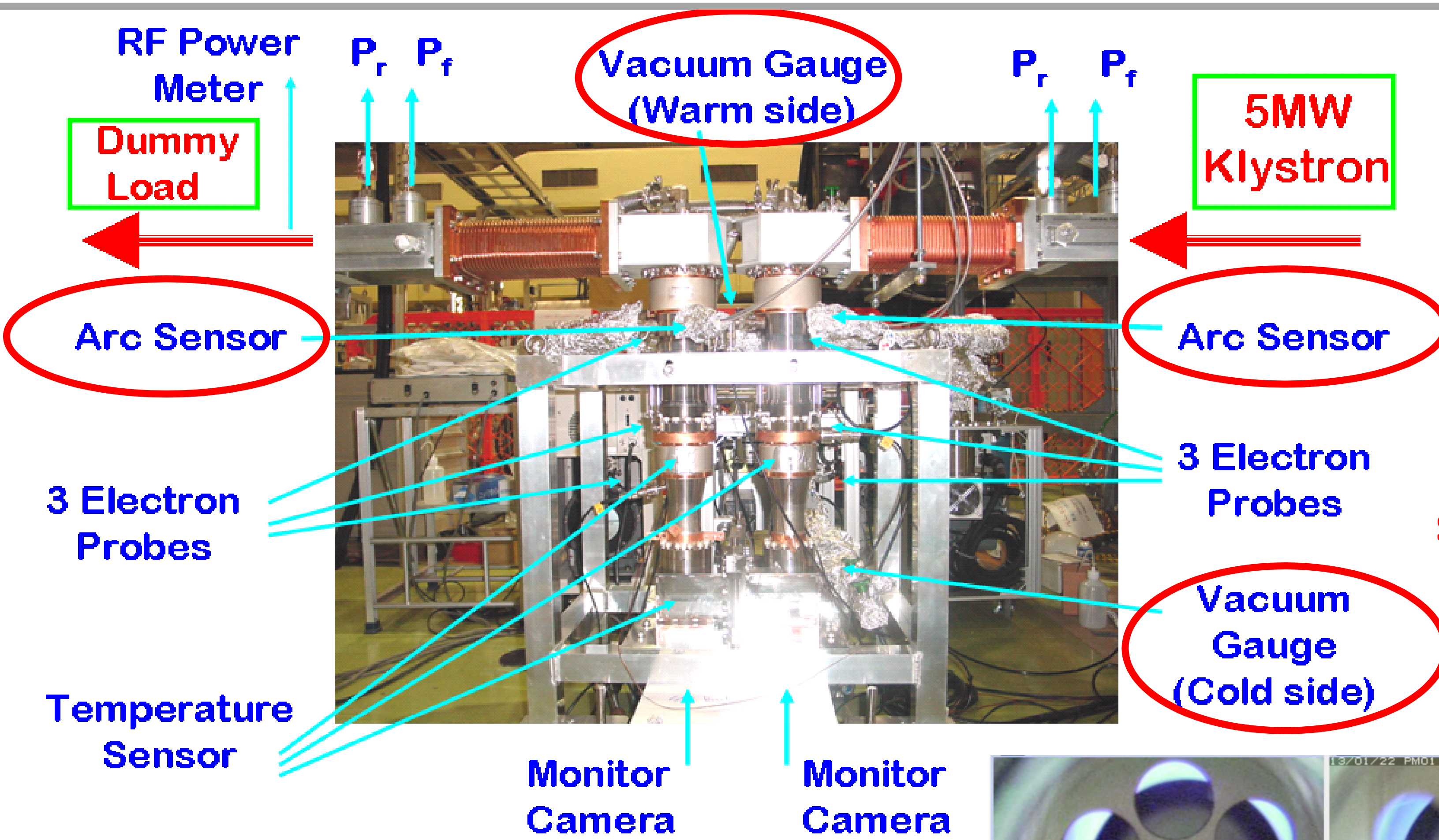


Pumping and leak-check

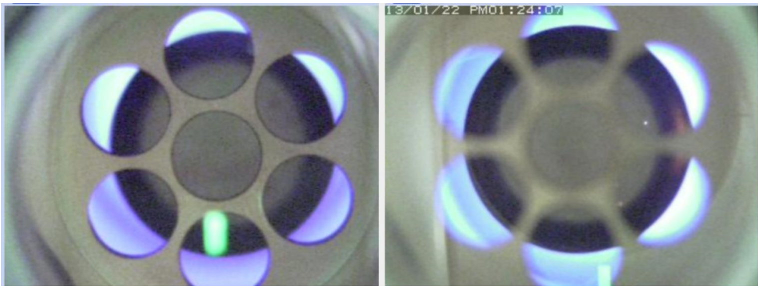


RF measurements

Diagnostics and Interlocks (1)



Interlock system



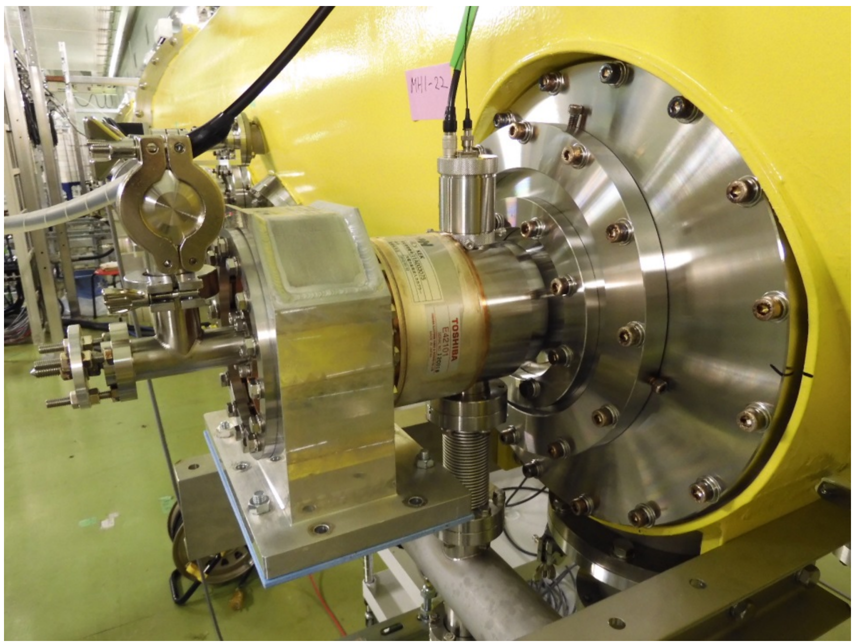
Observation of multipacting

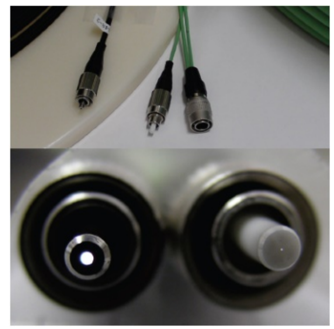
Diagnostics and Interlocks (2)

Vacuum I/L system is not a fast response to shut-down RF power;
(several tens ms) → cause a fatal damage to the RF windows

Arc sensor I/L system has a sufficient fast response. → a few μs

Arc sensor modules for STF at KEK

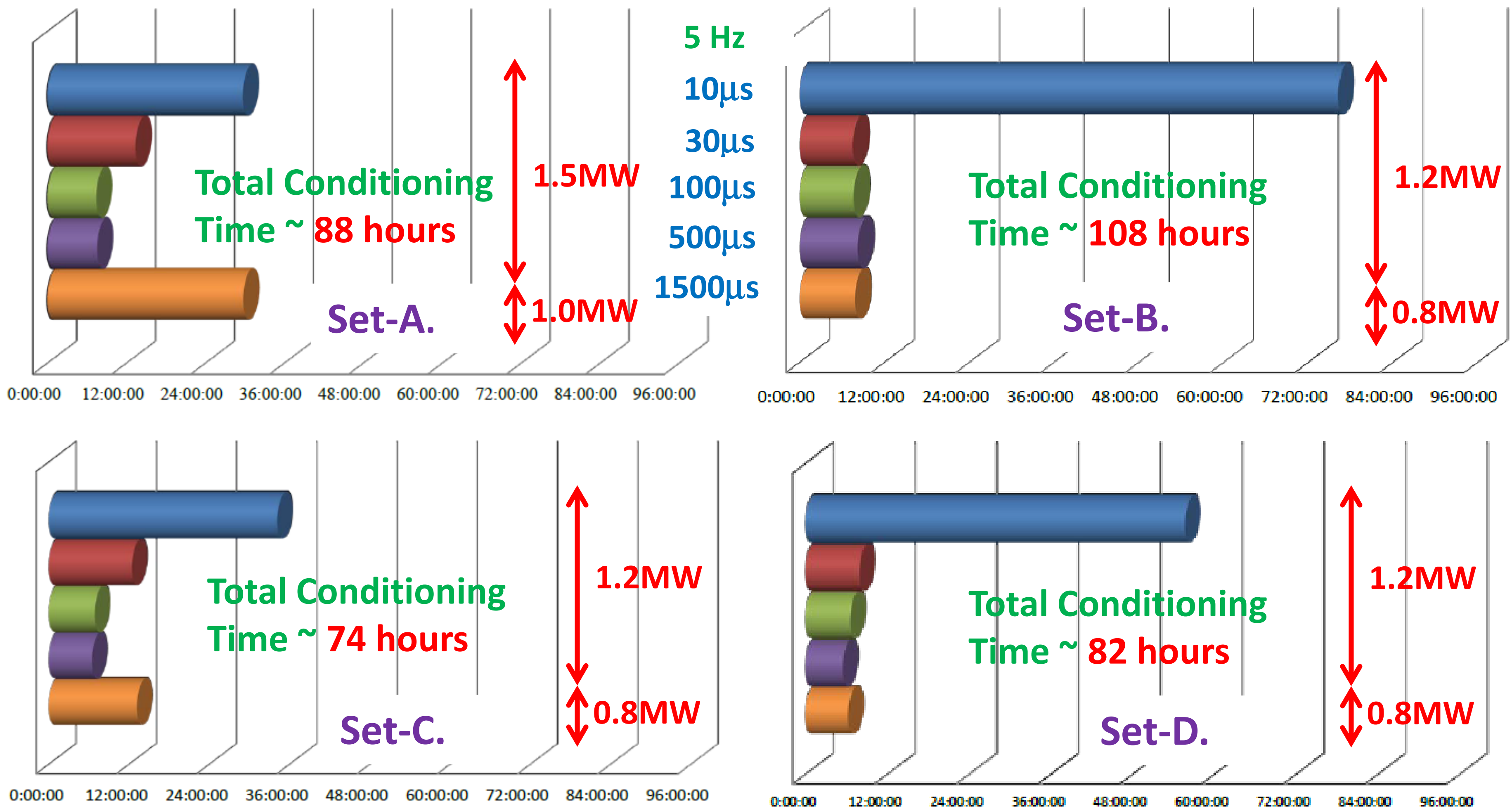




Conditioning Time at Test Stand

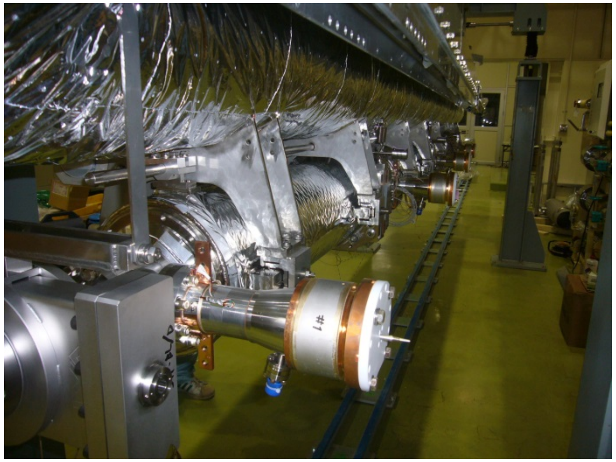
4 pairs of STF2 input couplers

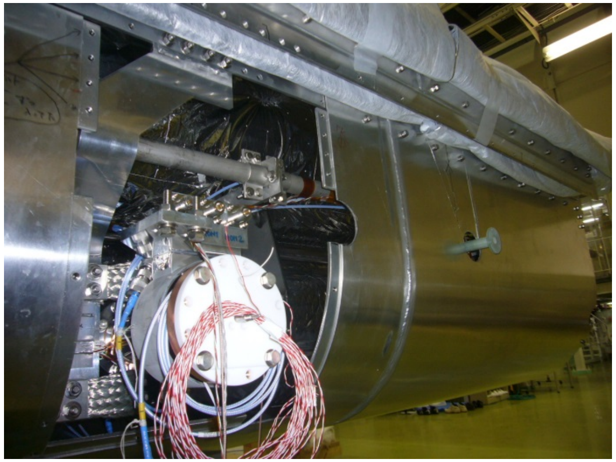
2013’ Jan. ~ May

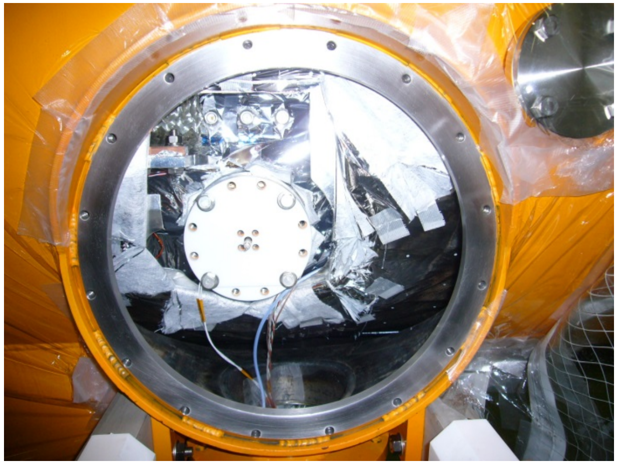


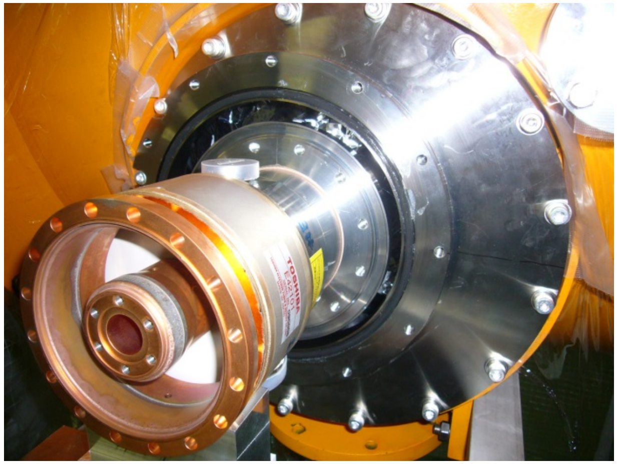
S1-G Cryomodule Assembly (STF2 coupler)

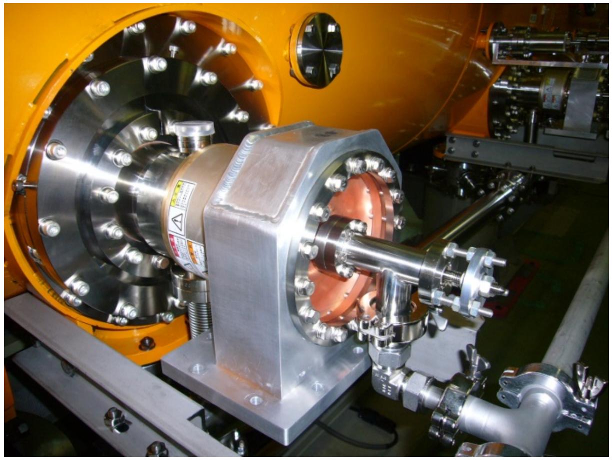

Cavity string assembly


Hanging under He-GRP


5K, 80K thermal anchor

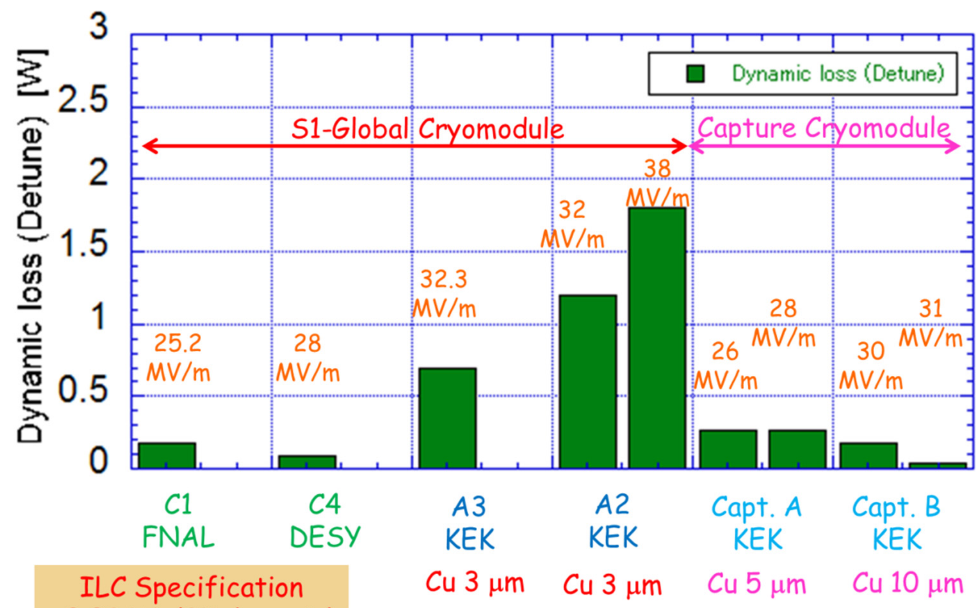

Installation into vacuum vessel


Warm coupler assembly

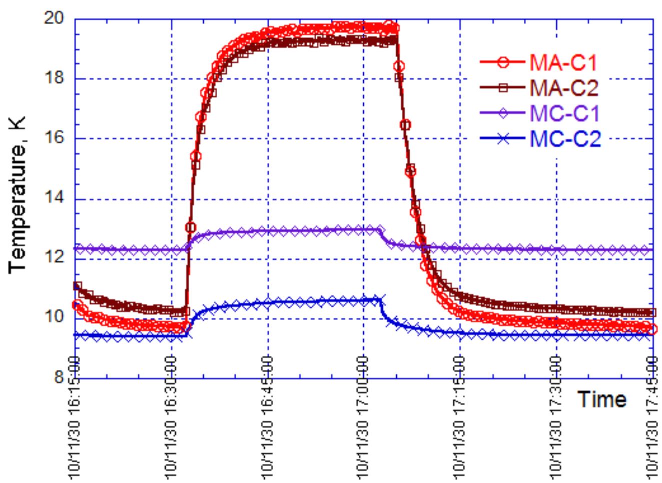

Attachment of doorknob WG

Dynamic Heat Load measurements

Cavity	Z-109	AES-004	MHI-07	MHI-06
Coupler	TTF-III	TTF-III	STF-2	STF-2
Eacc [MV/m]	28	25	32	32
$P_{loss-(Total)}$ [W]	0.8	1.4	2.8	2.6
$P_{loss-(Detune)}$ [W]	0.1	0.2	0.7	1.2
$P_{loss-(Cavity)}$ [W]	0.7	1.2	2.1	1.4
Q_0	8.8×10^9	4.3×10^9	4.3×10^9	6.5×10^9

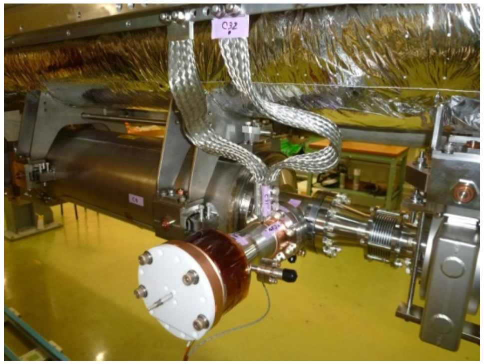


ILC Specification
< 0.02 W (2K dynamic)



1. **Static loss (RF/off)**
2. **Tune (total dynamic loss)**
3. **Detune (coupler loss)**
4. **Static loss (RF/off)**
5. **Static/Cavity/Coupler loss**

STF-2 Input Coupler



5 K thermal anchor

Quality control of Cu-plating and thermal anchors with efficient cooling are also important to reduce heat loads.

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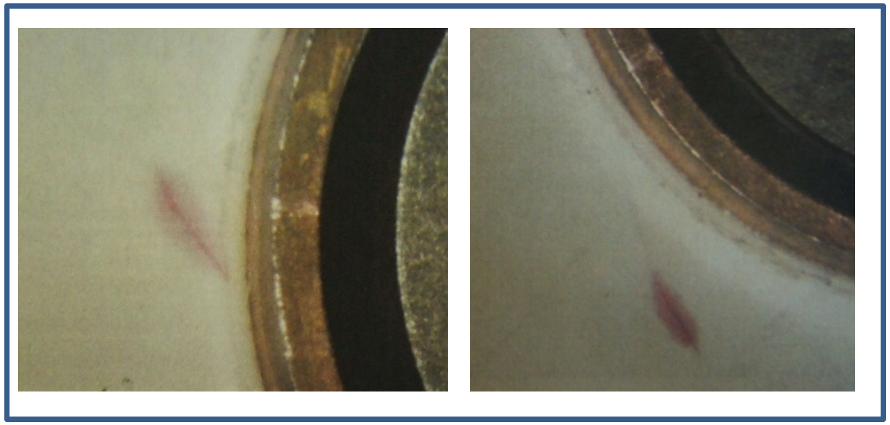
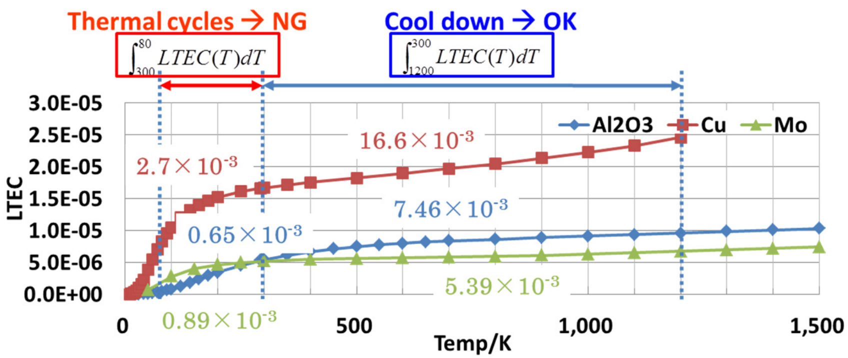
Vacuum leaks at 80K cold windows

No.1 Coupler

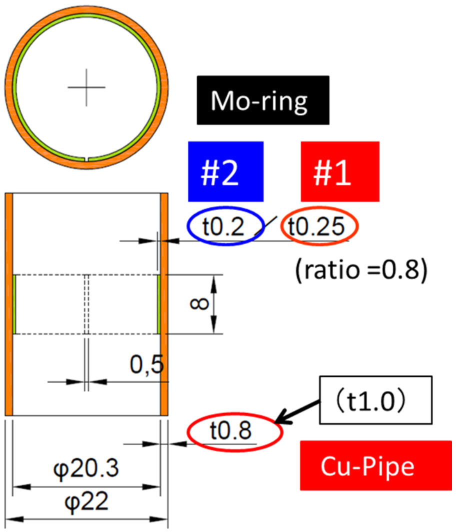


Linear Thermal Expansion Coefficient of Cu, Ceramics, Mo

Actual shrinking amount : - Δ length=length × ∫LTEC dT



Thermal cycle tests of 4 sample windows



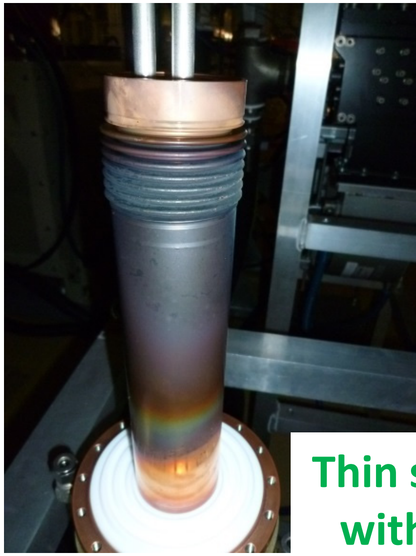
Mo-ring : 0.25 t
Cu-pipe : 1.0 t

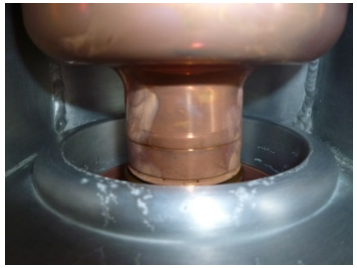
To reduce thermal stress

Mo-ring : 0.25 t
Cu-pipe : 0.8 t

OK, no leak:
20 thermal cycles between 80K and 300K

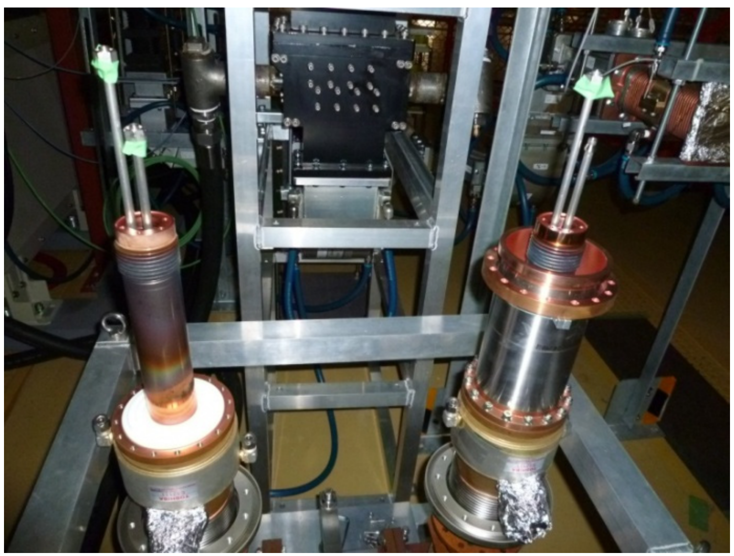
Excessive heating at coaxial parts





Excessive heat-up

Thin stainless tube with Cu-plating



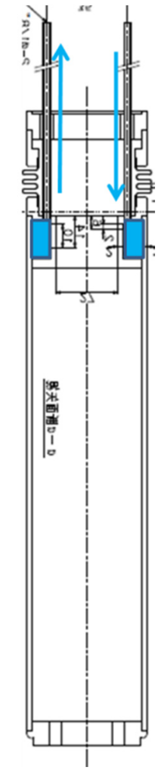
Efficient water cooling

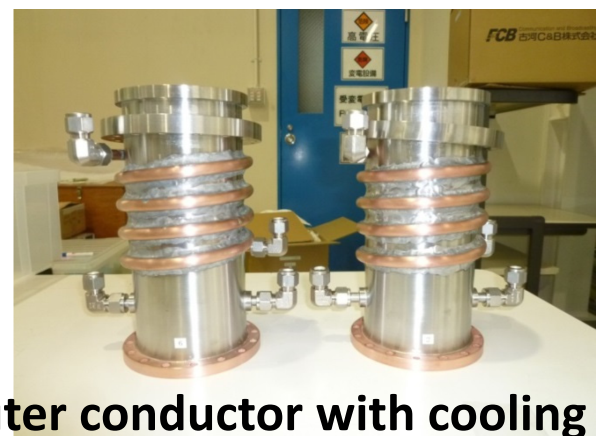
Cu-bellows and Cu-tube

high thermal conductivity

Inner conductor

Water cooling channel

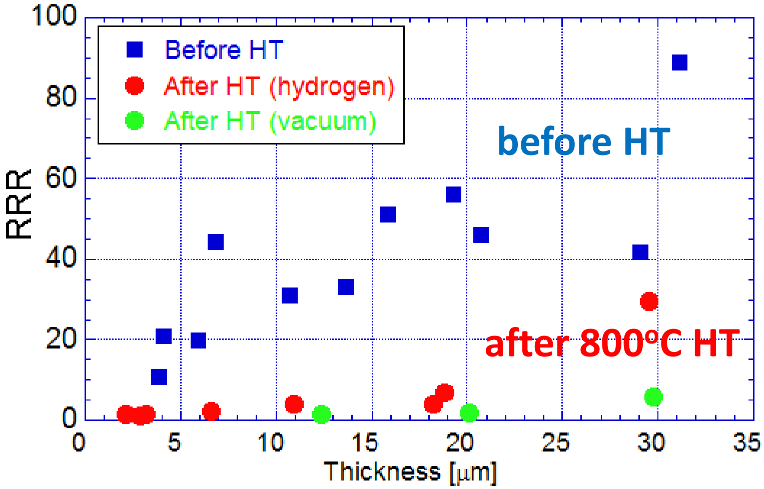




Outer conductor with cooling pipe

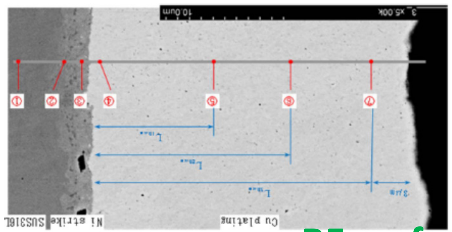
Degradation of RRR in Cu-plating

DC measurement



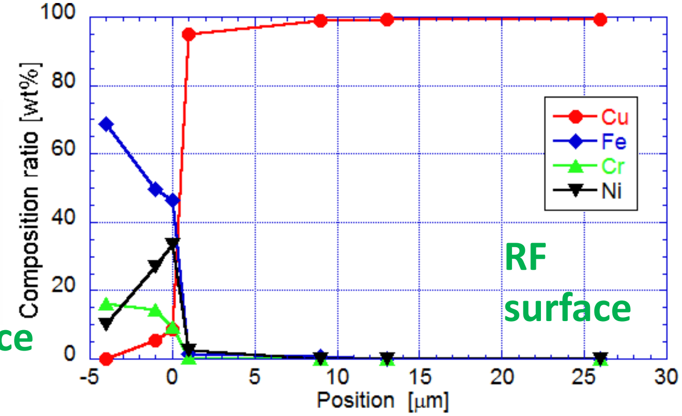
Impurity composition diffused into Cu-plating of 30 μm after 800°C HT

SUS : Cu-plating

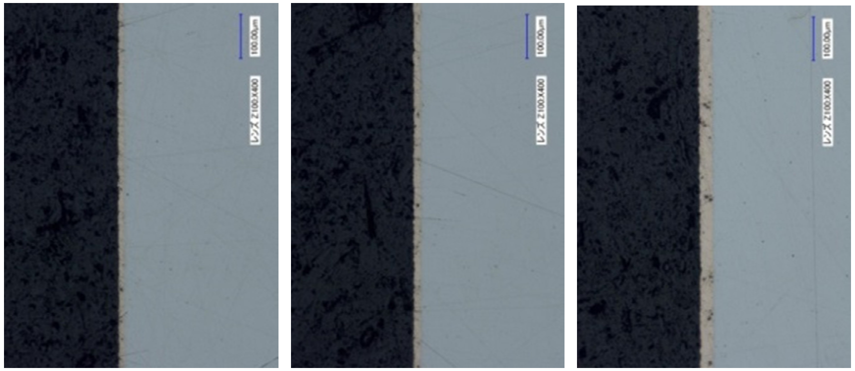


[by SEM]

RF surface



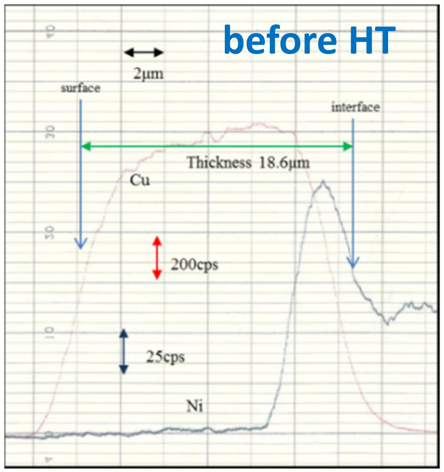
Cross-section of Cu-plating on SUS-316L



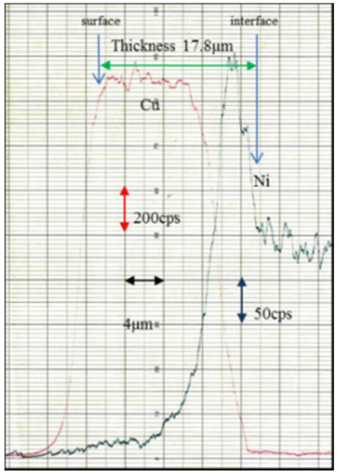
14 μm 19 μm 31 μm

[by laser microscope]

Ni diffusion into Cu-plating after 800°C HT



after 800°C HT



Contents

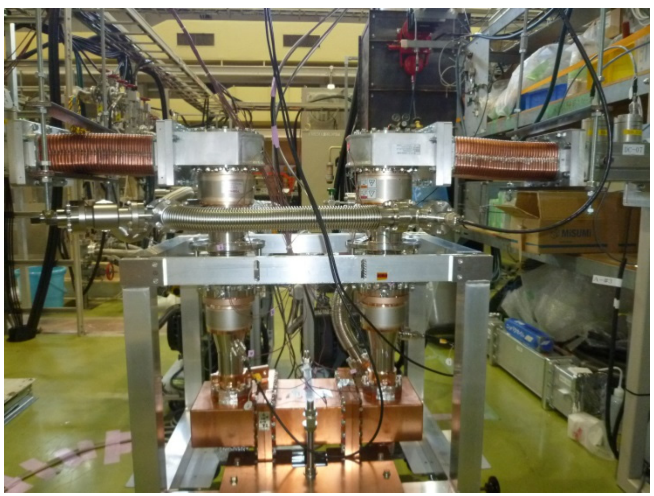
State of the Arts

- Pulsed coupler for XEFL/ILC
- CW coupler for ERL
- CW/HD coupler for Proton Linac
- CW coupler for Low-*b* structure
- CW waveguide input coupler
- High power performance

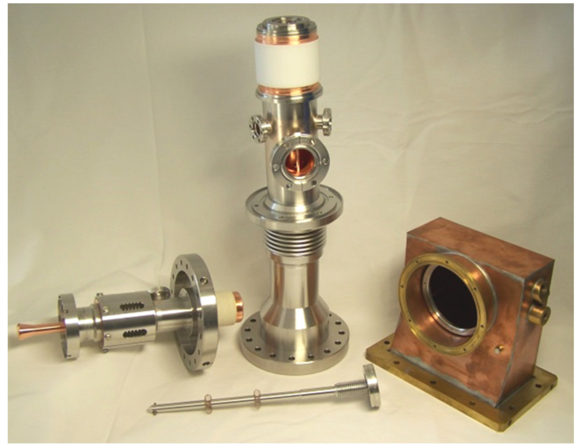
Pulsed coupler for XEFL/ILC (1.3GHz)

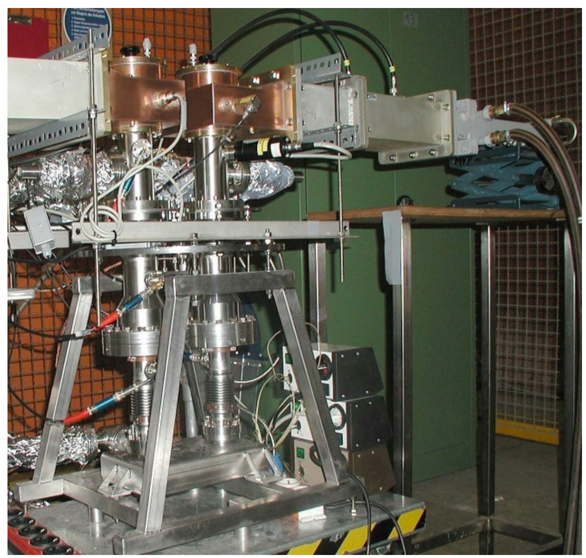
2 windows, no cooling

STF2 Coupler (KEK)



TTF3 Coupler (DESY)

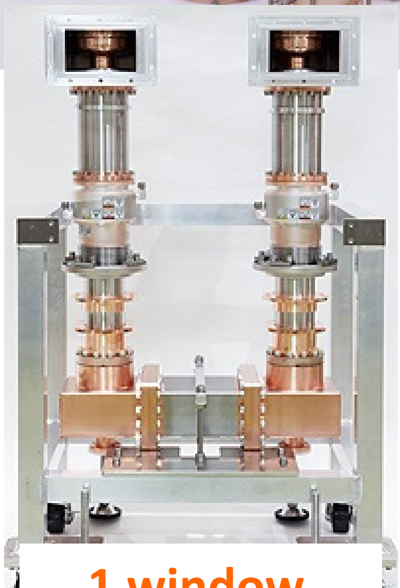




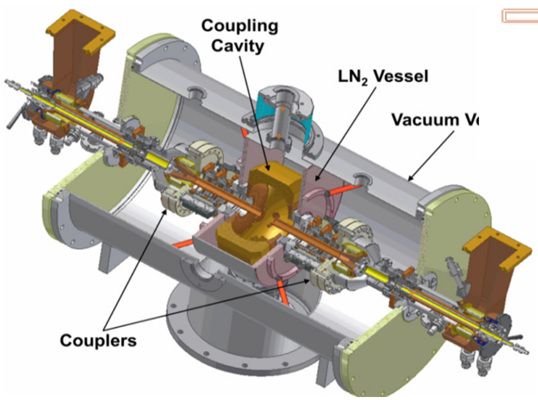
TTF-V Coupler (LAL)

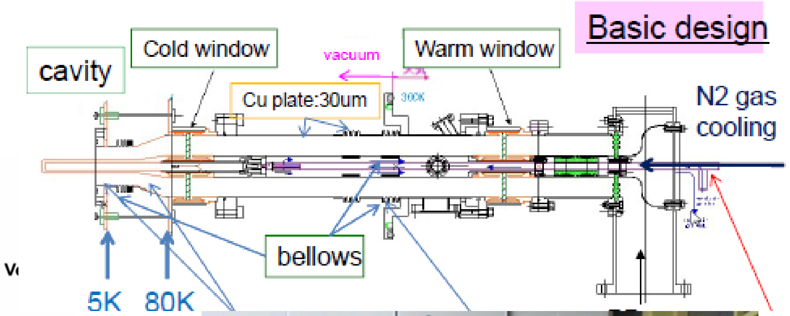
CW coupler for ERL (1.3GHz)

cERL Injector Coupler (KEK)

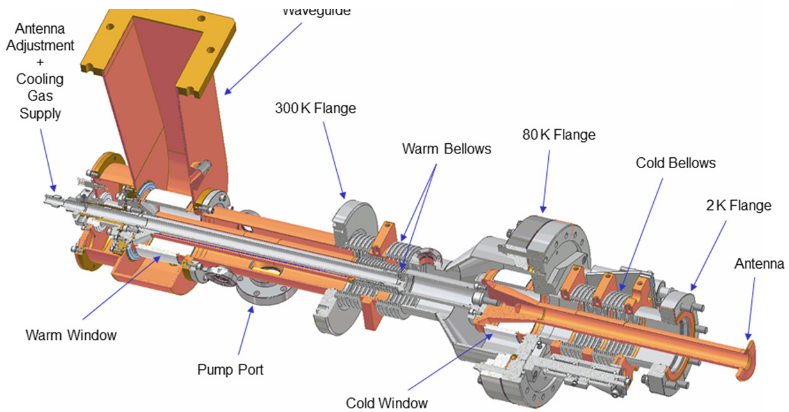


1 window,
water cooling

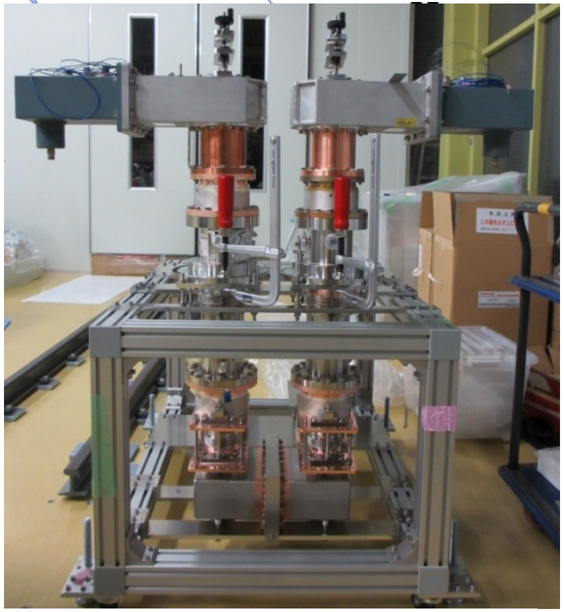




ERL Injector Coupler (Cornell)



2 windows, air cooling

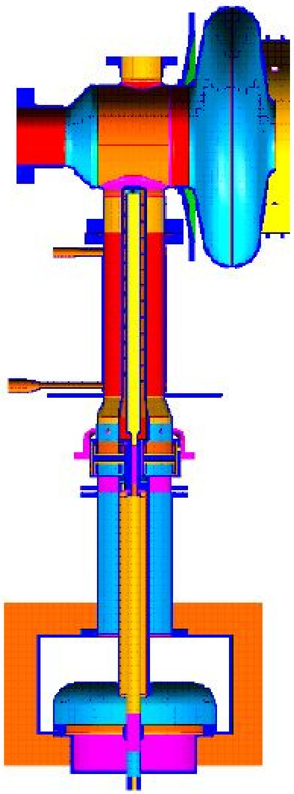


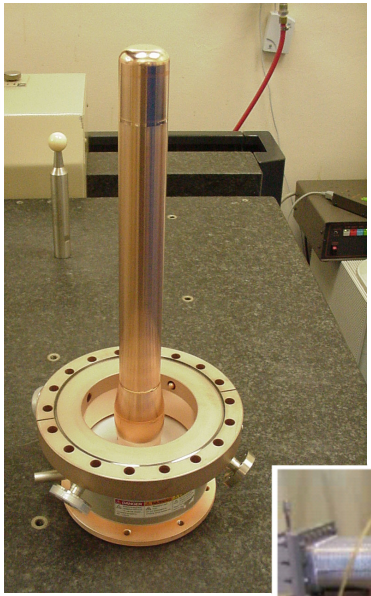
cERL ML Coupler (KEK)

2 windows,
N_2 gas cooling

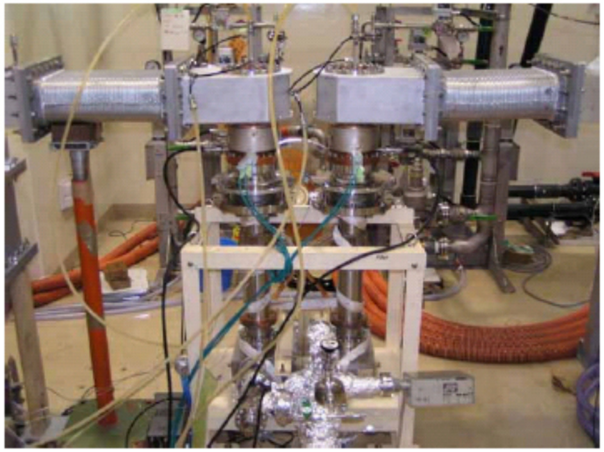
CW/high-duty coupler for Proton Linac

SNS Coupler (ORNL) 805MHz





J-ADS Coupler (KEK) 972MHz

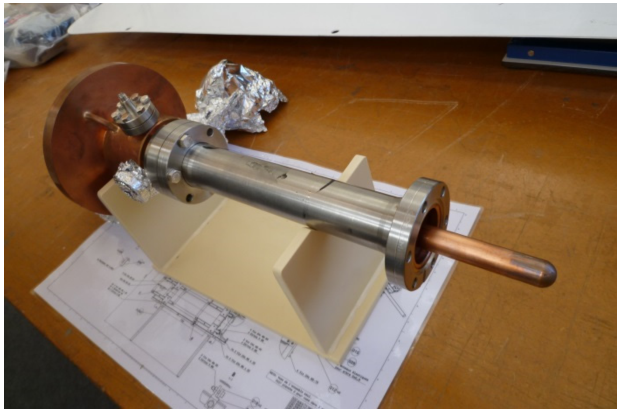


HIPPI Coupler (CEA-Saclay) 704 MHz

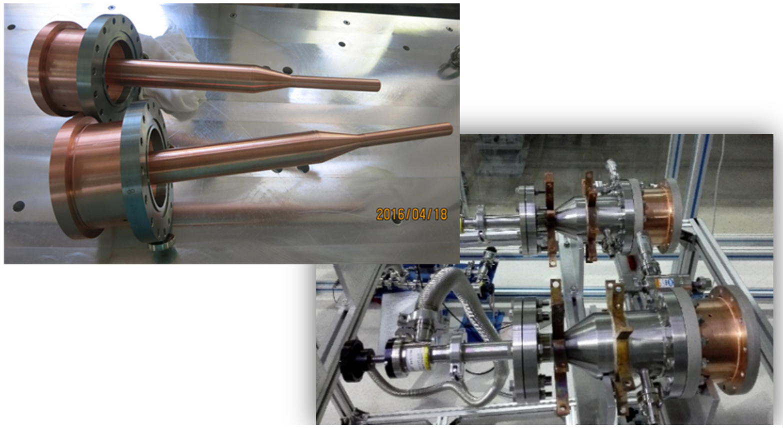
PIP-II Coupler (FNAL) 650MHz

CW coupler for Low-β structure

QWR Coupler for SPIRAL-2 (CEA-Saclay) 88MHz



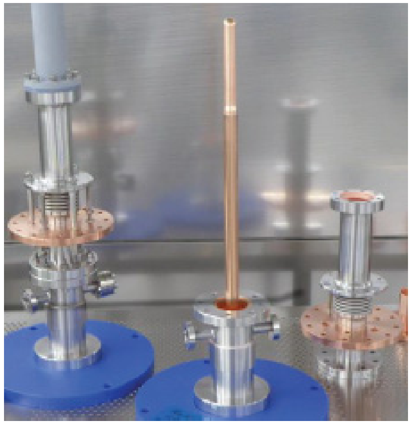
Spoke Cavity Coupler for CADS (IHEP) 325MHz



HWR Coupler for IFMIF (Saclay) 175MHz

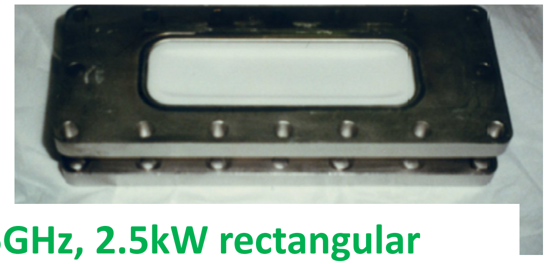
QWR Coupler for RAON (IBS/RISP) 81.25MHz

QWR Coupler for SRILAC (RIKEN) 73MHz



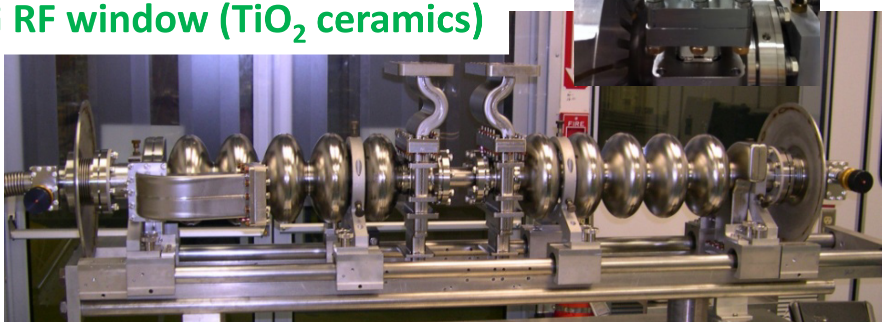
CW Waveguide Input Coupler

Original CEBAF 5-cell cavity (JLab) 1.5GHz

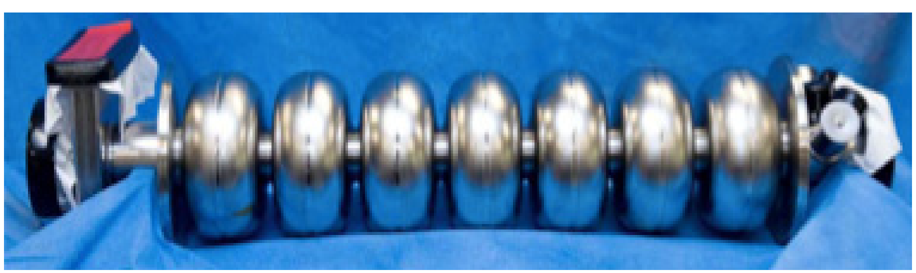


1.5GHz, 2.5kW rectangular WG RF window (TiO_2 ceramics)

Dogleg waveguide

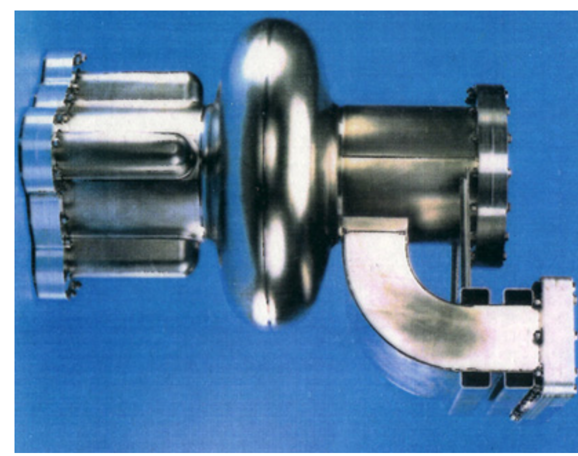


CEBAF upgrade 7-cell cavity (JLab) 1.5GHz



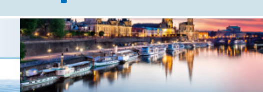
High current cavity for ERL/FEL (JLab) 1.5GHz

CESR-B cavity (Cornell) 500MHz



High power performance of single-window couplers

Facility	Frequency	Coupler type	RF window	Qext	Max. power
TRISTAN /KEK	508 MHz	Coaxial, Fixed	Coaxial disk	$1x10^5$	test 200kW, CW oper. 70kW, CW
KEK-B /KEK	508 MHz	Coaxial, Fixed	Coaxial disk	$7x10^4$	test 800kW, CW oper. 380kW, CW
ADS /KEK	972 MHz	Coaxial, Fixed	Coaxial disk	$5x10^5$	test 2.0MW pulse oper. 350kW pulse
SNS /ORNL	805 MHz	Coaxial, Fixed	Coaxial disk	-	test 2.0MW pulse oper. 350kW pulse
SPL/Saclay	704 MHz	Coax Fix	Coax. disk	-	test 1.2MW pulse
cERL-Inj. /KEK	1300 MHz	Coaxial, Fixed	Coaxial disk	$1x10^6$	test 40kW, CW oper. 10kW, CW
SPIRAL-2	88 MHz	Coaxial, Fixed	Coaxial disk	$5x10^5$	test 10kW, CW oper. 10kW, CW
IFMIF	175 MHz	Coax Fix	Coax. disk	$6x10^4$	spec. 200kW, CW
B*ERL*inPro	1300 MHz	Coax Fix	Coax. disk	$1x10^5$	spec. 130kW, CW



High power performance of double-window couplers

Facility	Frequency	Coupler type	RF window	Qext	Max. power
TTF3 /DESY	1300 MHz	Coaxial, Variable	Cylindr.	0.1-2x10^7	test 1.0MW pulse oper. 350kW pulse
TTF-V /LAL	1300 MHz	Coaxial, Fixed	Cylindr.	3x10^6	test 2.0MW pulse oper. - pulse
STF2 /KEK	1300 MHz	Coaxial, Variable	Coaxial disk	2-4x10^6	test 1.5MW pulse oper. 450kW pulse
ERL Inj. /Cornell	1300 MHz	Coaxial, Variable	Cylindr.	0.9-8x10^5	test 60kW, CW oper. 40kW, CW
cERL-ML /KEK	1300 MHz	Coaxial, Variable	Coaxial disk	1-4x10^7	test 40kW, CW oper. 15kW, CW
TT3-CW /HZB	1300 MHz	Coaxial, Variable	Cylindr.	3.6x10^6	test 8kW, CW spec. 10kW, CW

Summary

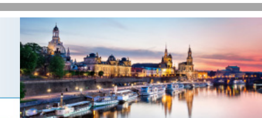
- High power input couplers are one of the most critical components of a superconducting RF cavity system.
- High power input coupler includes varieties of key technologies in design, fabrication, conditioning and operation.

Contents of Lecture

1. Introduction
2. High power input couplers
3. HOM couplers and absorbers

Higher Order Modes Coupler (1)

1. A charge passing through a cavity can excite modes.
2. The mode excited by bunches can seriously affect subsequent charges passing through the cavity.
3. If not sufficiently damped, they can lead to beam instabilities and beam loss.
4. Even without beam break-up, HOMs can degrade the beam quality, leading to loss of luminosity or loss of brightness.



Higher Order Modes Coupler (2)

5. HOMs increase the cryogenic losses due to the additional power dissipation in the cavity wall.

<u>The HOM coupler/absorber:</u>

- must remove beam induced power from the cavity in order to avoid resonant buildup of beam induced voltage, and in order to avoid beam instabilities.
- Three types of HOM coupler/absorber;

  1. waveguide, 2. coaxial, 3. beam tube.

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1. Design Considerations
2. Waveguide HOM Coupler
3. Coaxial HOM Coupler
4. Beam-tube HOM Absorber
5. RF Feedthrough

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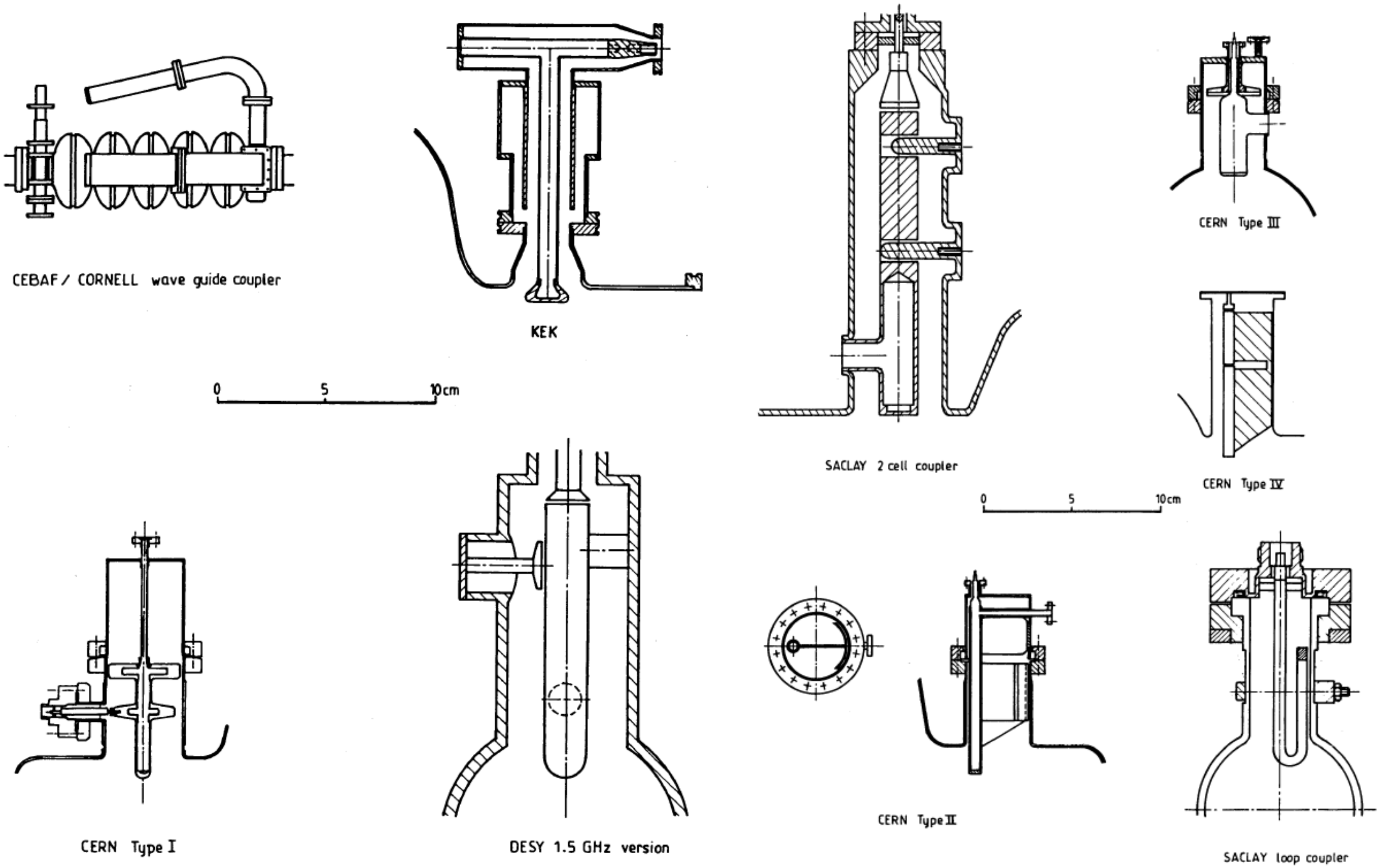
5. RF Feedthrough

Design Considerations (1)



SRF1989, by A. Mosnier (CEA-Saclay)

Design Considerations (2)

Requirements for a HOM coupler:

- Damping of all dangerous higher order modes.
- Very small coupling with the fundamental mode.
- Precise tuning of the filter; Qext $>10^{11}$.
- Effective cooling of superconducting parts to avoid excessive heating.
- Simple design for easy cleaning to remove dusts.
- Cost reduction.

Design Considerations (3)

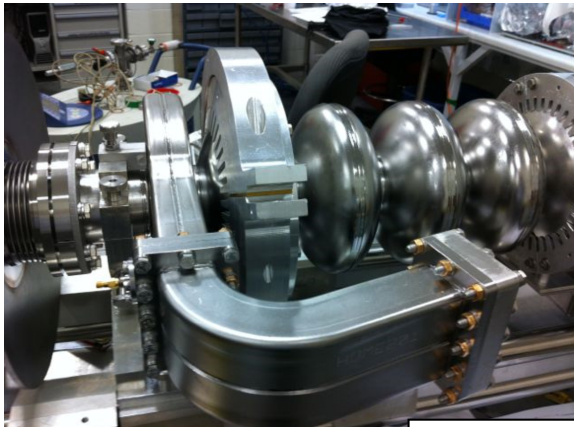
Requirements for a HOM absorber:

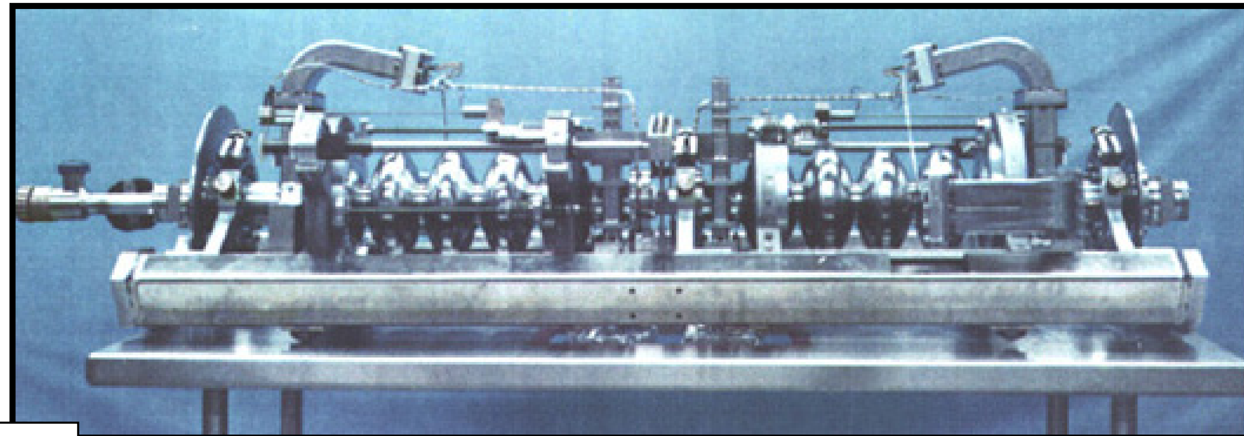
- Damping of all dangerous higher order modes.
- Choice of broad-band absorbing material; Ferrite, SiC, AlN, Glassy carbon, etc...
- Preferable operating temperature for cooling.
- Efficient cooling method.
- Low outgassing property in vacuum.
- Reliable cleaning procedure for dust free.
- Cost reduction.

Contents

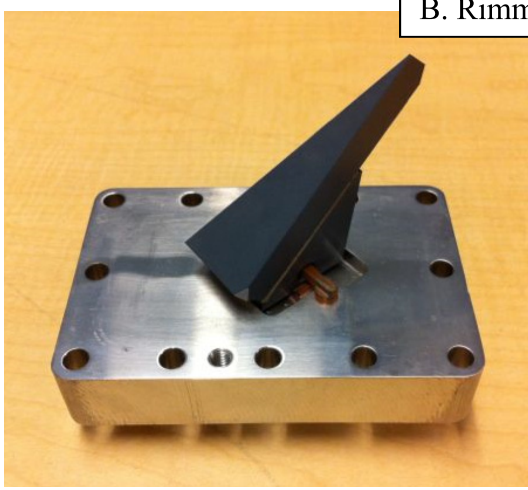
Waveguide HOM Coupler

Original CEBAF waveguide HOM couplers at 2K (JLab)





B. Rimmer, JLab



Glassy-carbon ceramic

AlN-based composites

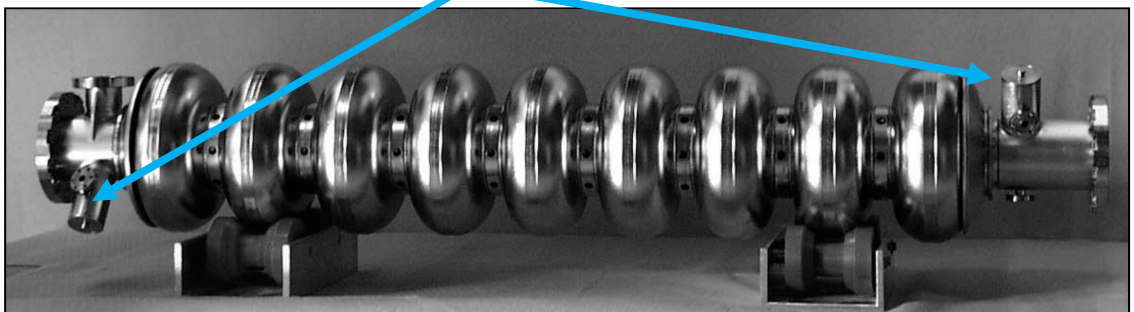
- **Cut-off frequency of WG; no tuning in the high pass filter.**
- **WG flange to be far enough from beam tube.**
- **Matching stub on beam tube in opposite side.**

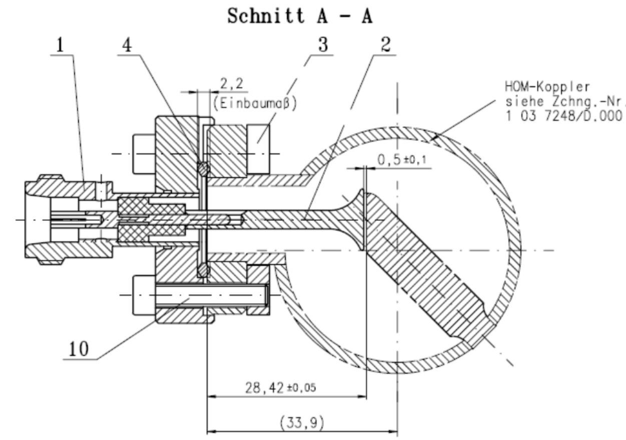
Contents

Coaxial HOM Coupler (1)

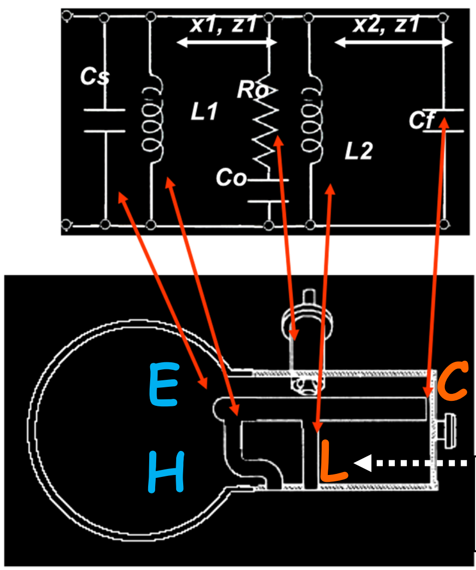
HOM Couplers for 1.3GHz TESLA 9-cell Cavity (DESY)

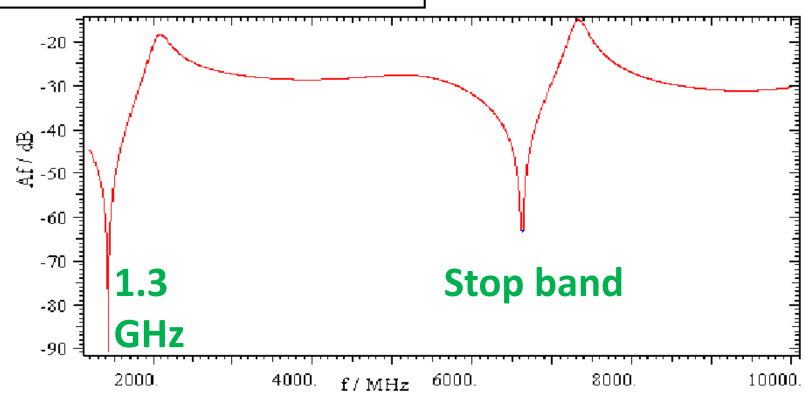
2 HOM couplers (welded) <P_{HOM}> ~ few watts





J. Sekutowicz, DESY, Hamburg





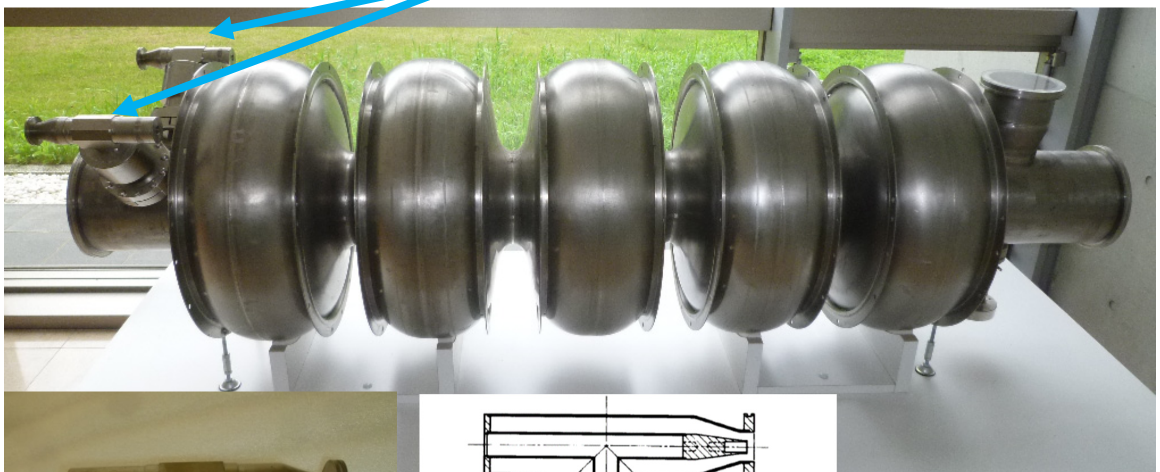
FM rejection filter

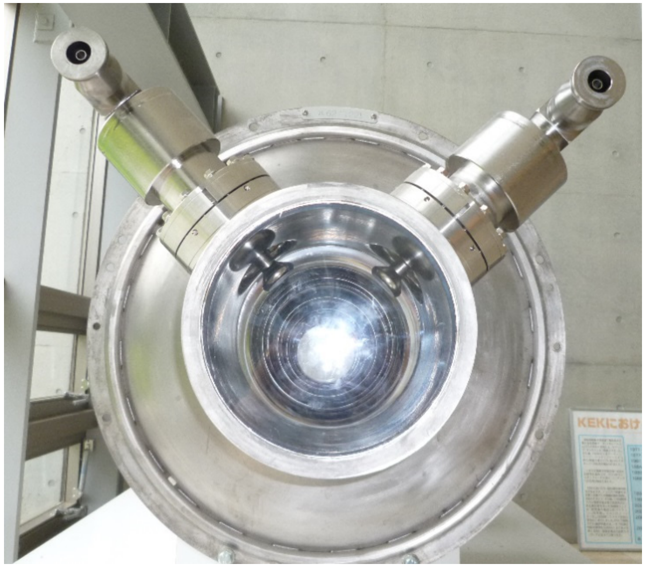
$f_{rej.} = 1/2\pi(LC)^{0.5}$

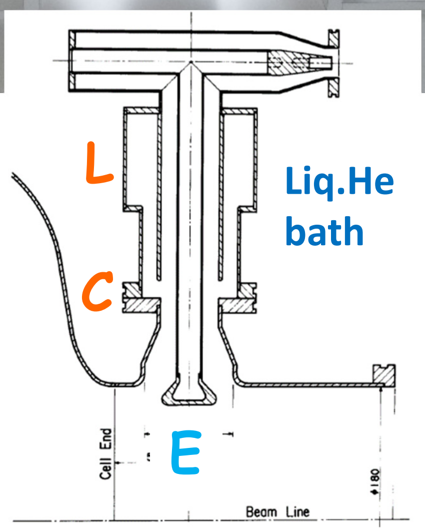
Coaxial HOM Coupler (2)

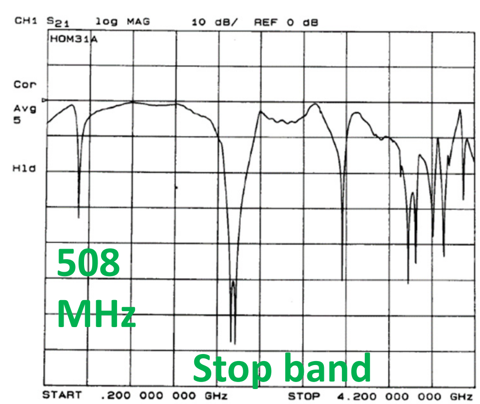
HOM Couplers for 508MHz TRISTAN 5-cell Cavity (KEK)

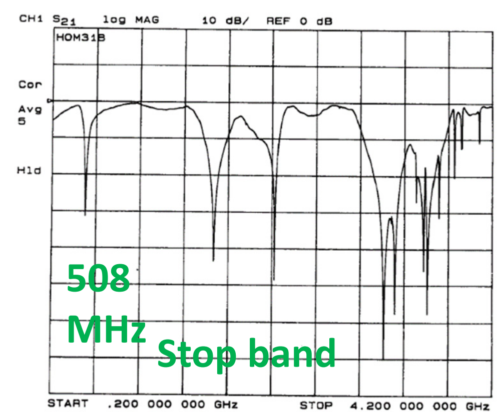
2 HOM couplers (demountable)







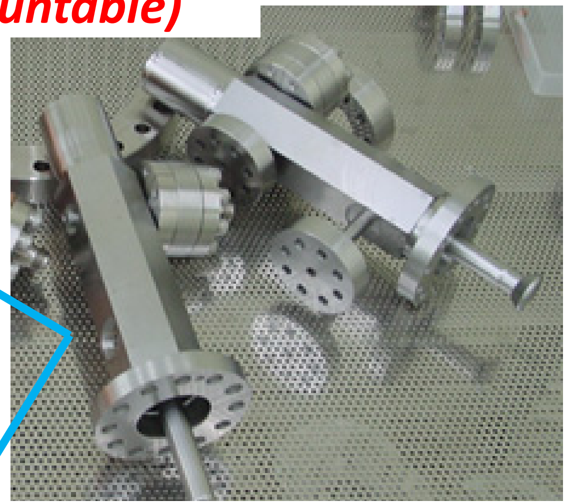


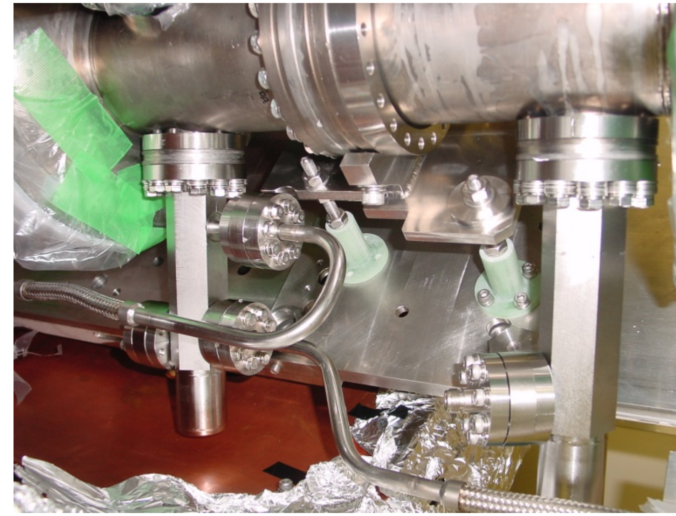


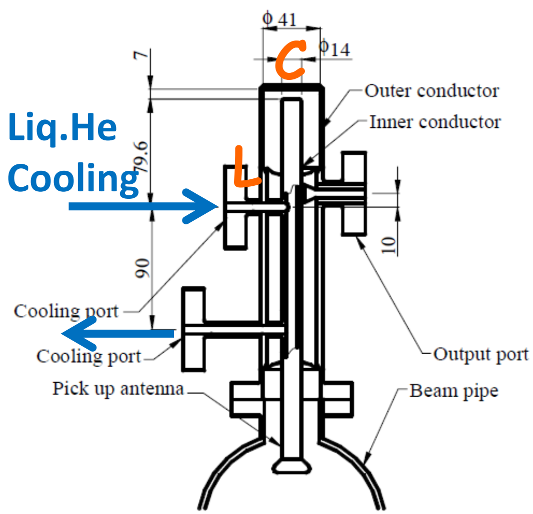
Coaxial HOM Coupler (3)

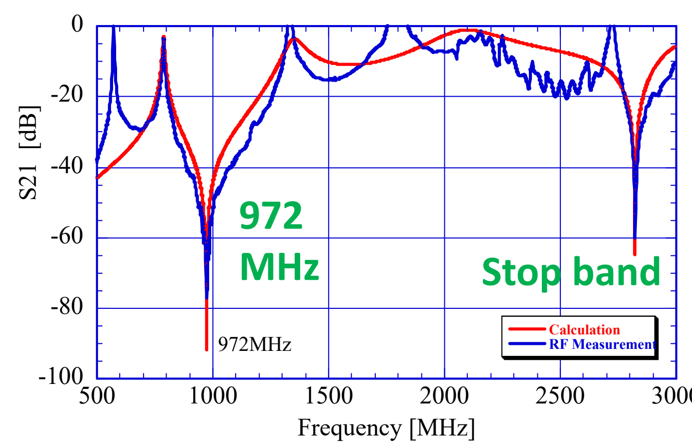
HOM Couplers for 972MHz ADS 9-cell Cavity (KEK)

2 HOM couplers (demountable)







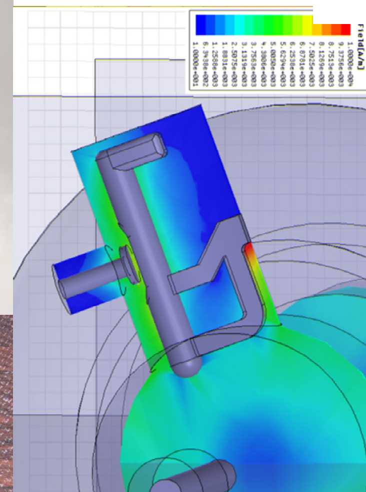


Coaxial HOM Coupler (4)

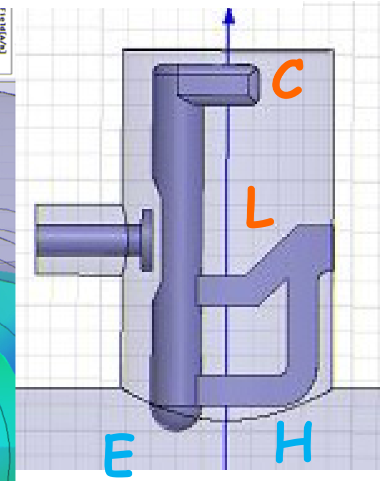
HOM Couplers for 1.3GHz STF 9-cell Cavity (KEK)

2 HOM couplers (welded)

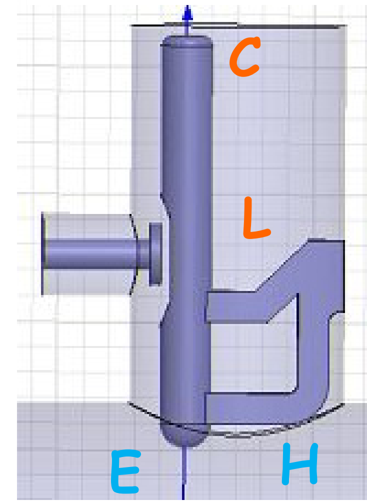
Two types of HOM couplers

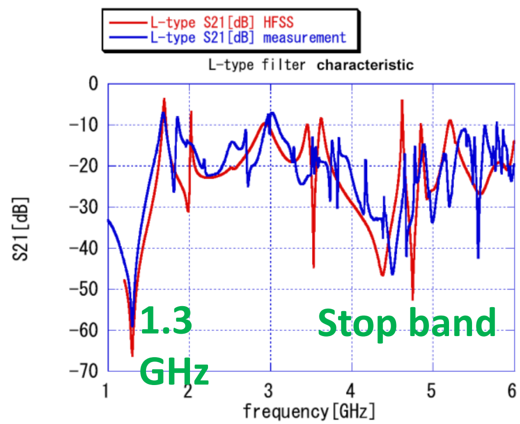


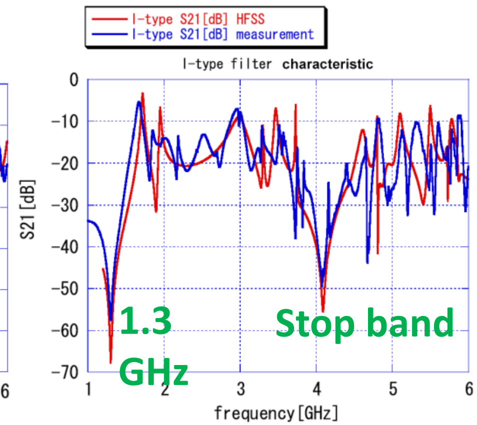
HOM L-type



HOM I-type





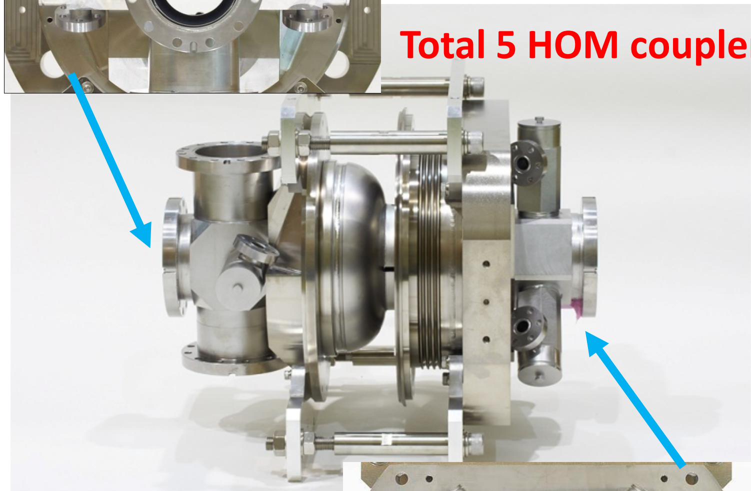


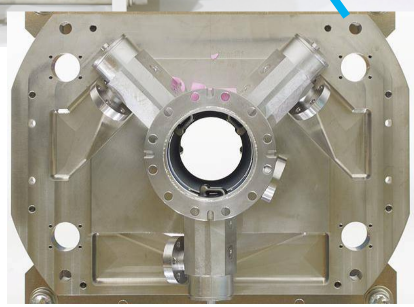
Coaxial HOM Coupler (5)

HOM Couplers for 1.3GHz cERL 2-cell Cavity (KEK)

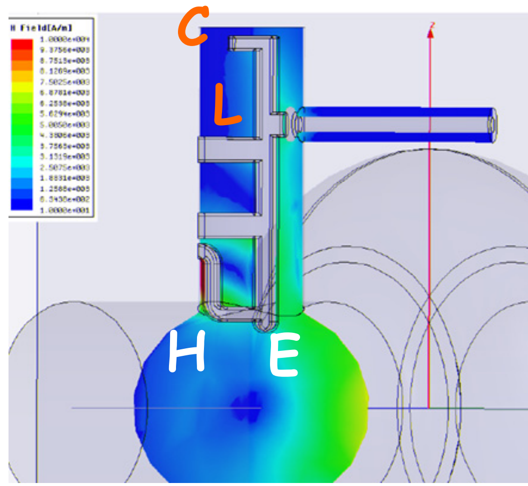
2 HOM & 2 Input couplers

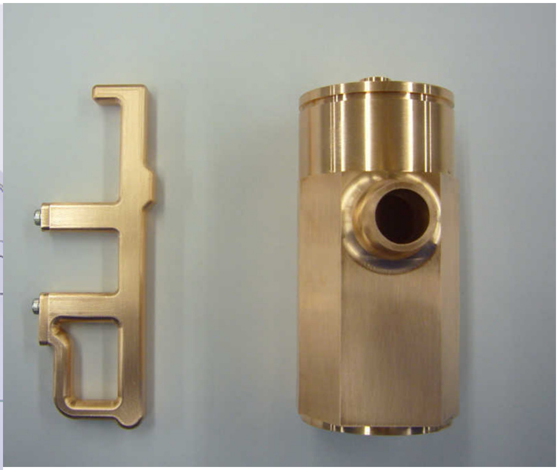
Total 5 HOM couplers

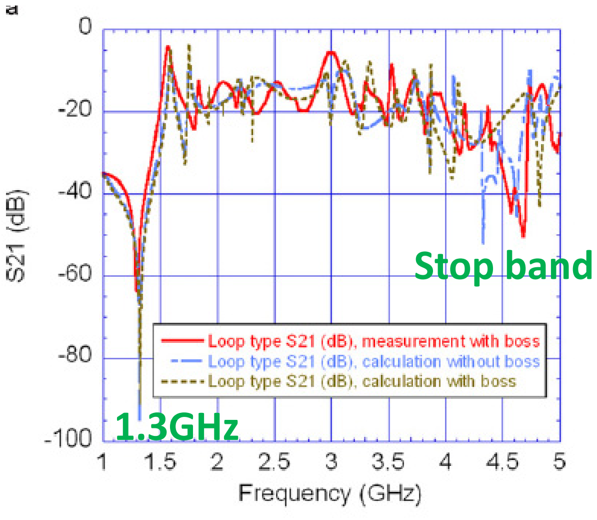




3 HOM couplers







Contents

Consideration for HOM absorbers

- Absorbing materials: (ε and μ)
- Fabrication : (bonding by brazing or HIP)
- Mechanical strength and porosity: (cleaning)
- Outgassing rate: (residual gas components)
- Thermal conductivity: (efficient cooling)
- Thermal expansion rate: (thermal stress)
- Operational temperature: (cooling method)
- Dust contamination:

Characteristics of HOM absorbers

- <u>Mechanisms of absorption:</u>

  1. Dielectric loss, (ε : permittivity)

     $\varepsilon = \varepsilon_0 (\varepsilon' - j \varepsilon'')$, $W_d = ½ \, \omega E^2 \varepsilon_0 \varepsilon''$

  2. Magnetic loss, (μ : permeability)

     $\mu = \mu_0 (\mu' - j \mu'')$, $W_m = ½ \, \omega H^2 \mu_0 \mu''$

- <u>Materials for absorbing RF power</u>

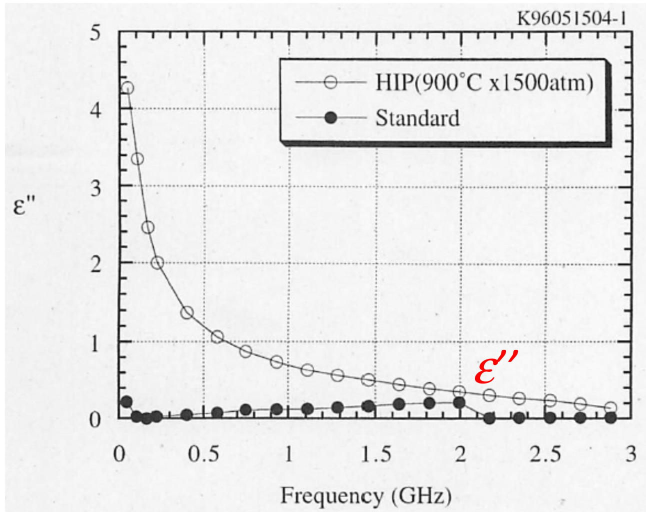
  1. Ferrite (dielectric and magnetic loss)
  2. SiC (dielectric loss)
  3. AlN (dielectric loss)

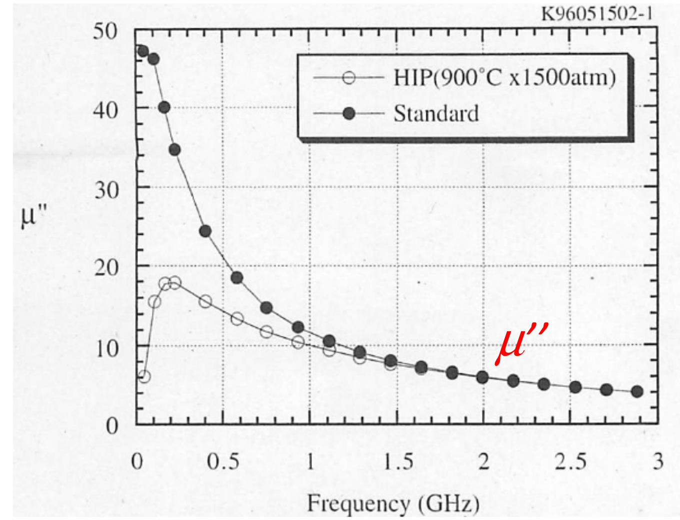
Properties of absorber materials

Ferrite IB-004

(at room temp.)

[Thesis by T. Tajima (KEK)]

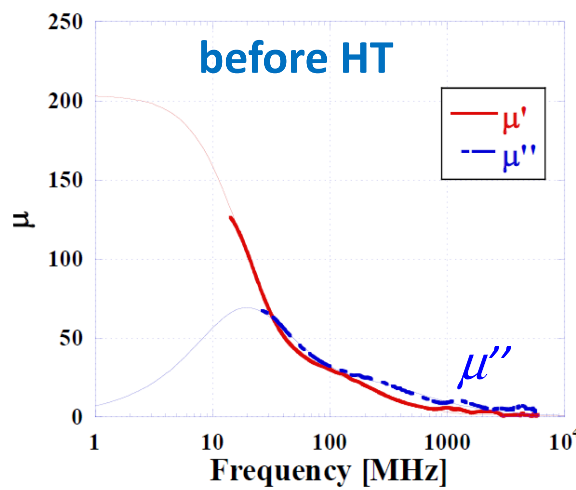


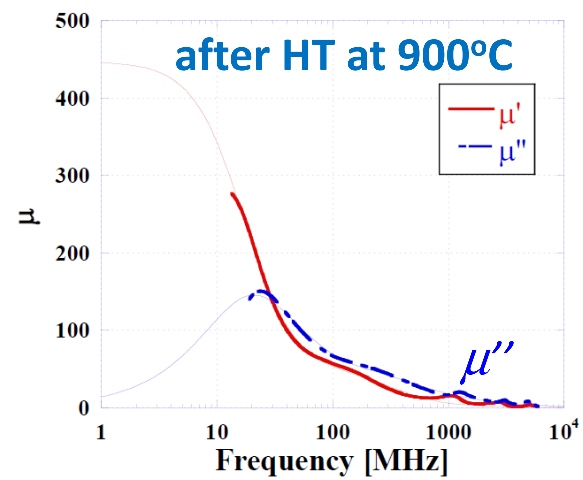


Ferrite CMD10

(at 77 K)

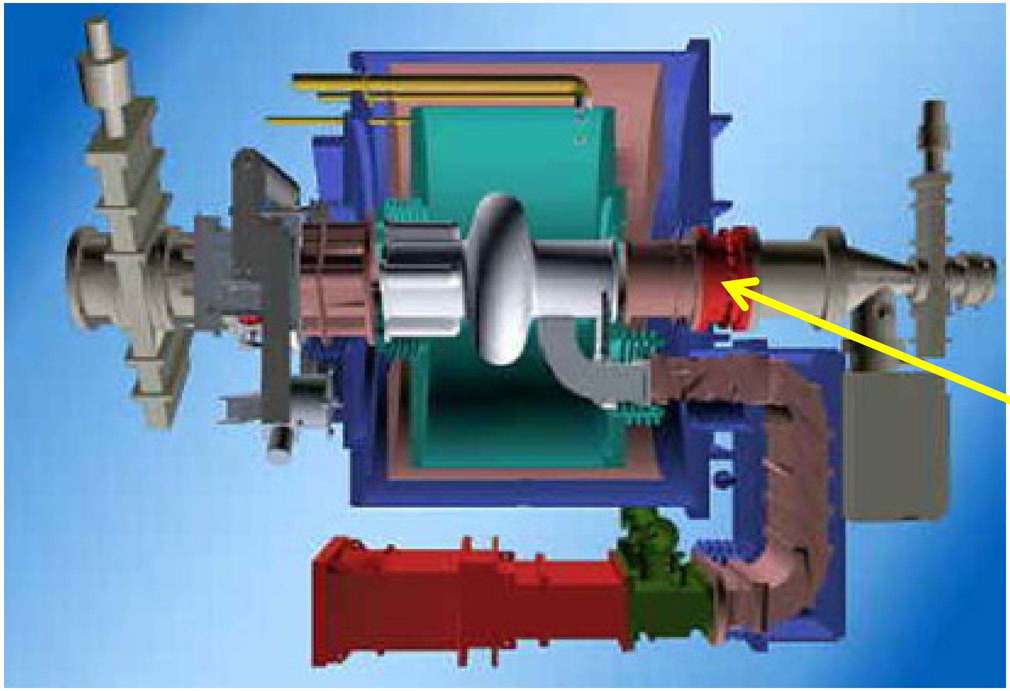
[Thesis by T. Konomi (KEK)]





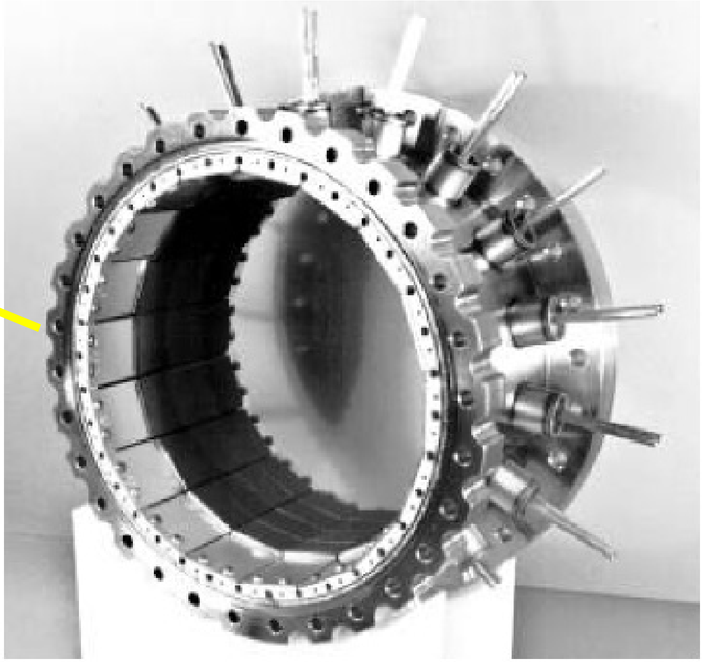
Beam Tube HOM Absorber (1)

HOM absorber for 500MHz CESR-B Cavity (Cornell)



S. Belomestnykh, Cornell

Cornell CESR HOM Load

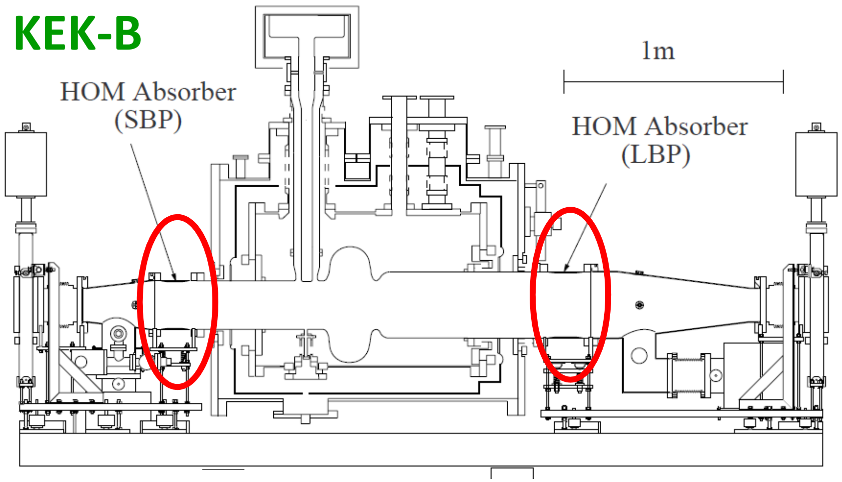


- Ferrite absorber tiles
- Water cooled

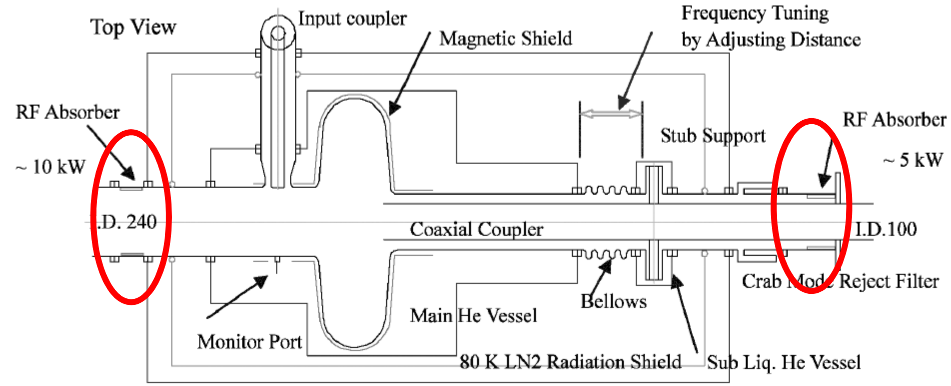
Beam Tube HOM Absorber (2)

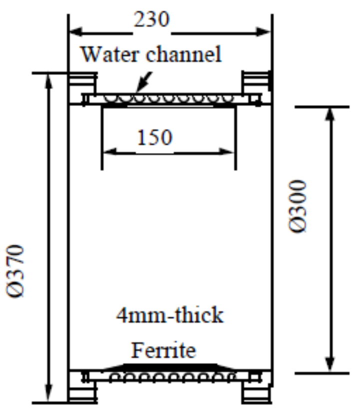
HOM absorber for 508MHz KEK-B and Crab Cavity (KEK)

KEK-B



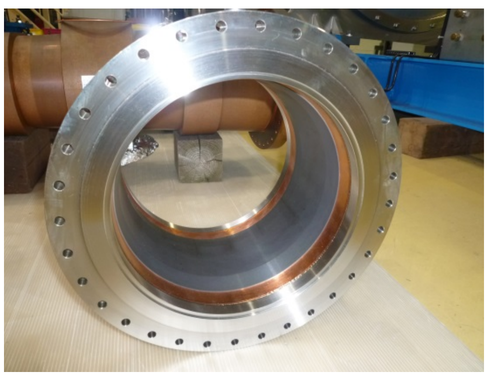
Crab Cavity



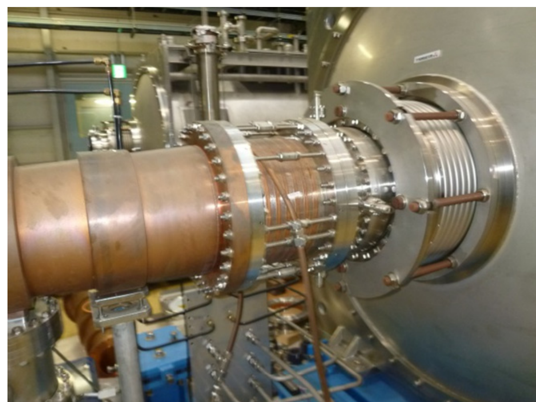


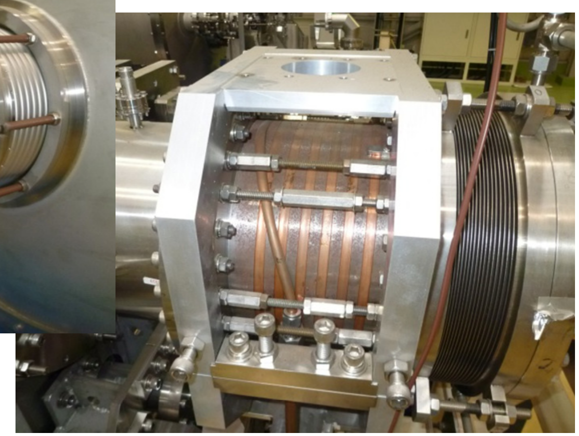
Absorber (L)

T.Tajima, KEK



- HIP Ferrite absorber
- Water cooled





H. Nakai, KEK

Beam Tube HOM Absorber (3)

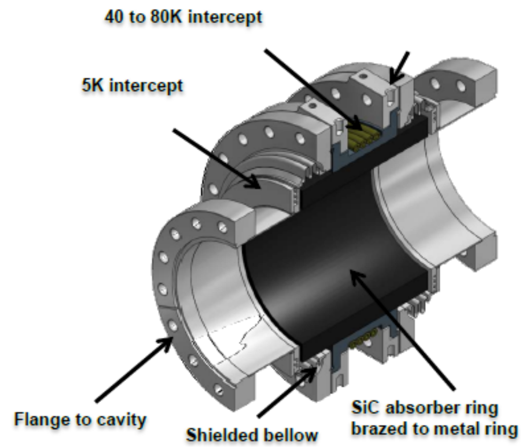
HOM absorber for 1.3GHz ERL Injector and ML Cavity (Cornell)

Cornell ERL injector HOM Load

- 3 types of absorber tiles
- One was charging up ☹
- Operated at 80 K
- Complicated to mount

- **Ferrite tile absorber**
- **Cooled at 80K**

Main Linac HOM Absorbers



- **SiC ring absorber**
- **Cooled at 40-80K**

- Full-circumference heat sink to allow >500W dissipation @ 80K
- Broadband SiC absorber ring
- Includes bellow sections
- Flanges allow easy cleaning
- Zero-impedance beamline flanges

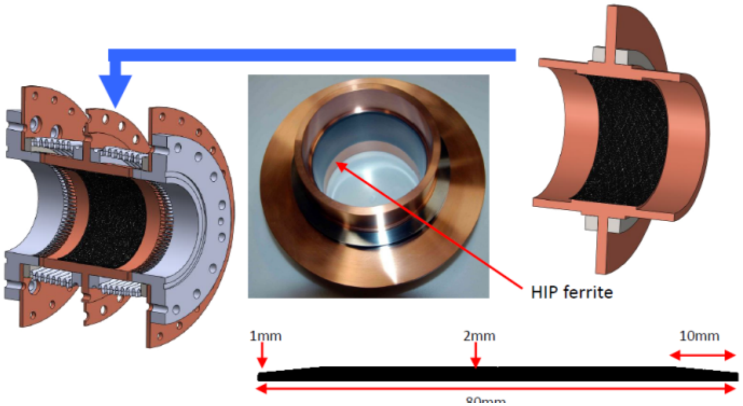
R. Eichhom, Cornell

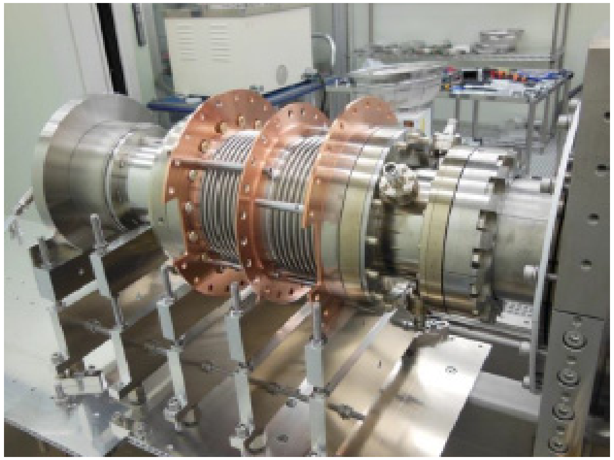
Beam Tube HOM Absorber (4)

HOM absorber for 1.3GHz cERL ML 9-cell Cavity (KEK)

HIP ferrite model

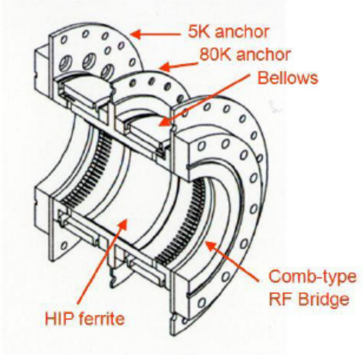
- Center part of HOM absorber before manufacturing Comb-type bridge and 80K anchor

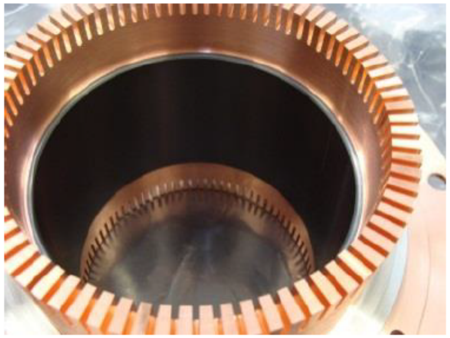




HOM absorber

- HOM absorber located on 80K region
- Heat load of 150W/cavity is estimated for 100 + 100mA electron beam with 3ps bunch length
- New IB004 ferrite is HIP bonded on Cu pipe
  - Original IB004 is used for KEKB HOM absorber
- Outside: bellows, Inside: Comb-type RF bridge





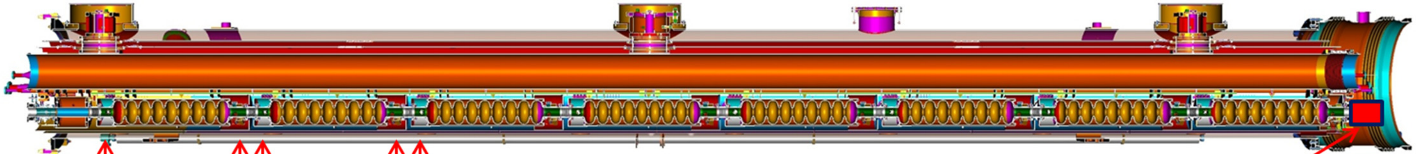
K. Umemori, KEK

- **HIP Ferrite absorber**
- **Cooled by nitrogen, 80K**
- **Very slow cool-down speed**

Beam Tube HOM Absorber (5)

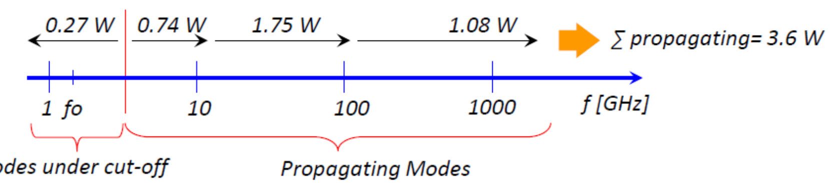
HOM absorber for 1.3GHz XFEL 9-cell Cavity (DESY)

J. Sekutowicz, DESY, Hamburg

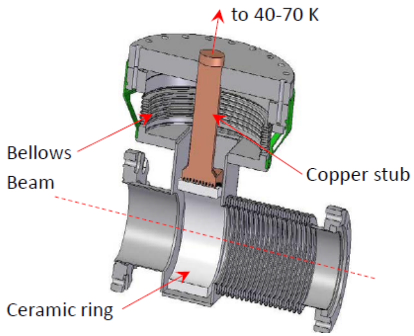


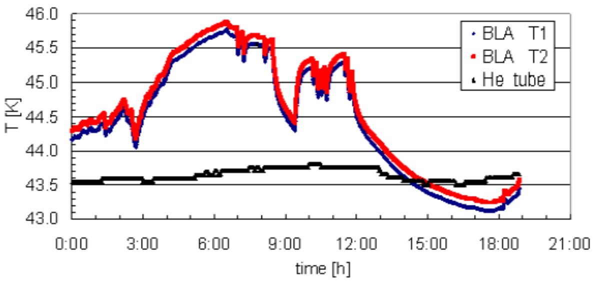
Beam Line Absorber Concept:

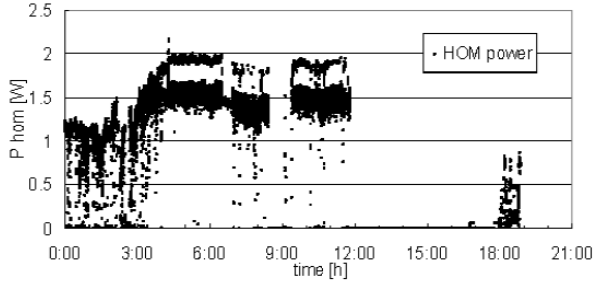
Nominal beam with 27000 short bunches will generate HOM power of 3.9 W/CM



The XFEL beam line absorbers suppressing propagating modes have capacity of 100 W, which makes them suitable for large DF operations .

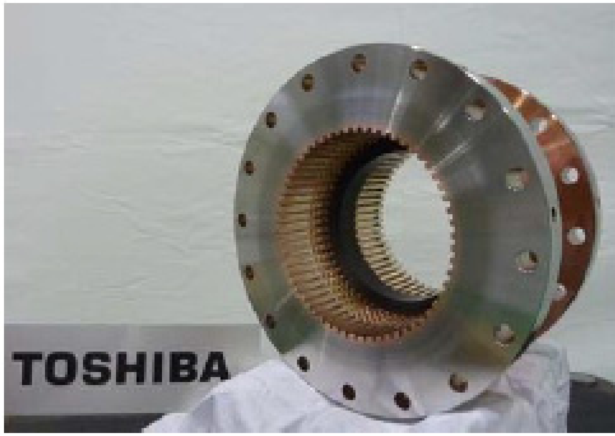


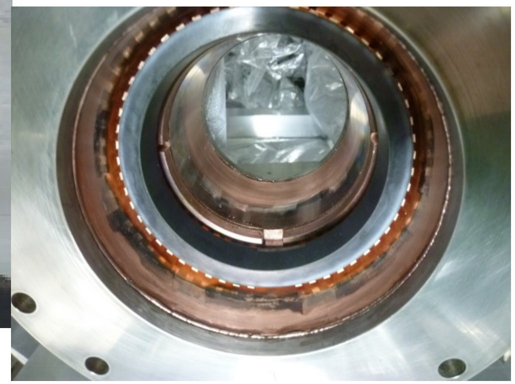




- **Special ceramic ring absorber (AlN)**
- **Cooled to 40-70K**

Beam Tube HOM Absorber (6)



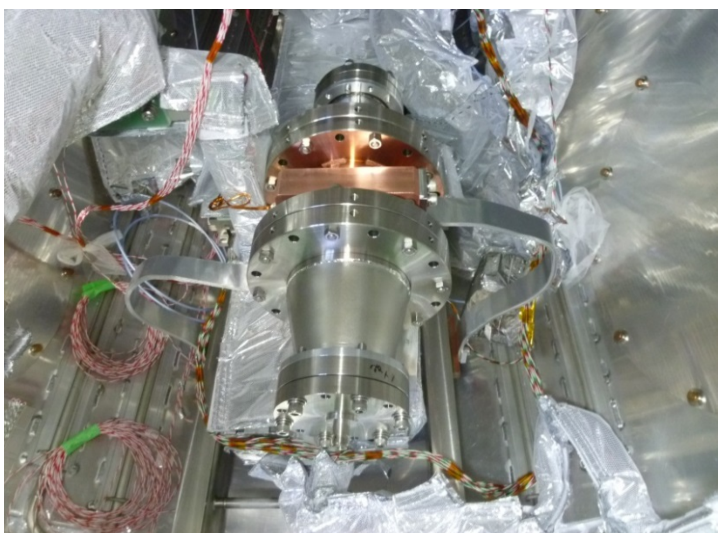


AlN HOM Absorber for ERL cryomodule

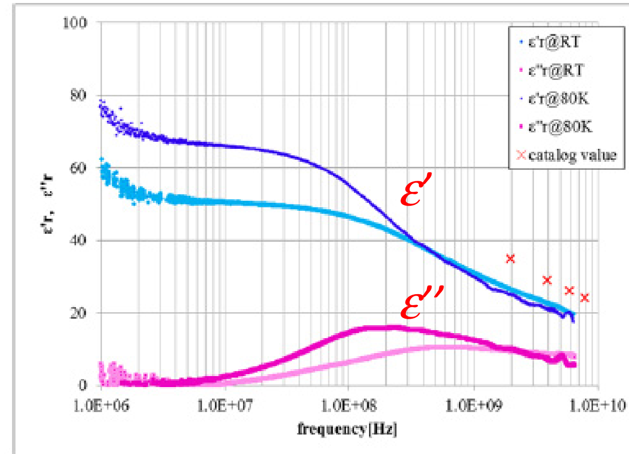
KEK/Toshiba

TOSHIBA
Leading Innovation >>>

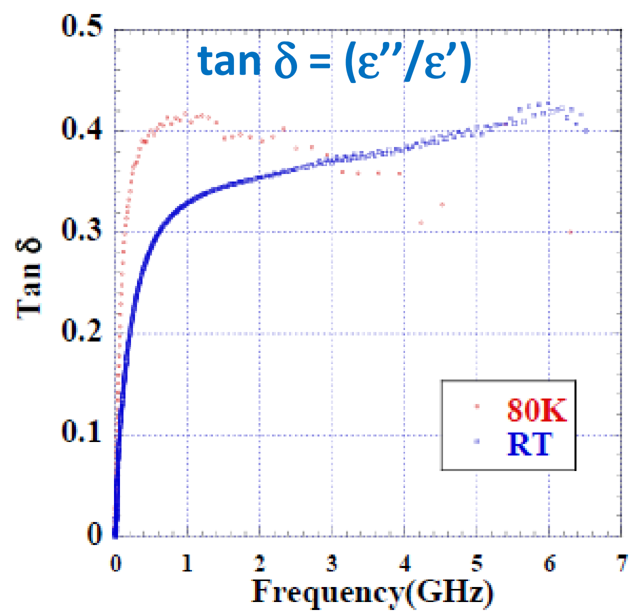
[by T. Ohta (Toshiba)]



Relative dielectric constant



Dielectric loss



Contents

RF Feedthrough (1)

RF Feedthrough for 1.5GHz CEBAF-Upgrade 7-cell Cavity (JLab)

Cooling of HOM coupler, 3rd
Feed through

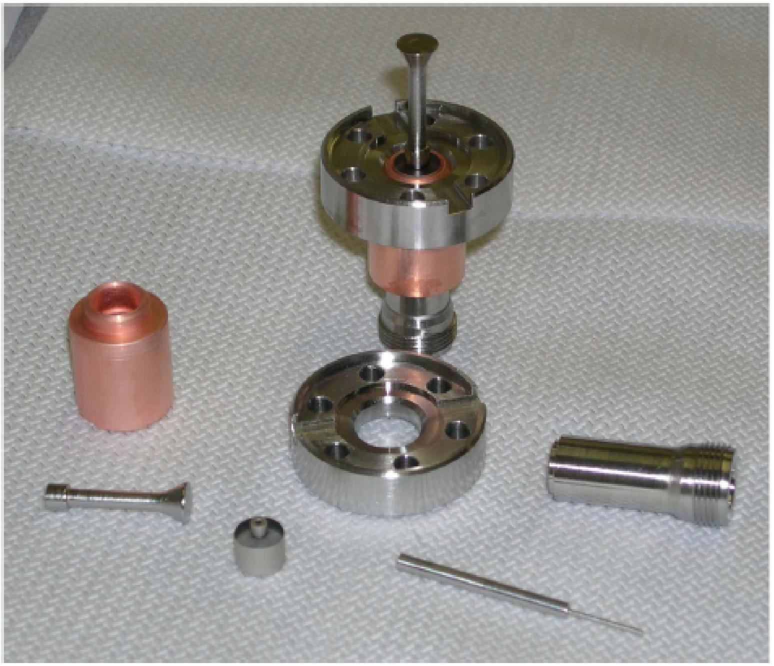
High heat conductivity feedthrough, ensuring thermal stabilization of Nb antenna below the critical temperature (9.2 K) at 20 MV/m for the cw operation.

Jefferson Lab development for the 12-GeV CEBAF upgrade

- Al_2O_3 replaced by single crystal sapphire directly brazed to a copper sleeve

⇒ higher thermal conductivity

- copper interface for 2K connection



W.–D. Möller, DESY in Hamburg

15th International Conference on RF Superconductivity
Chicago, July 25 -29, 2011

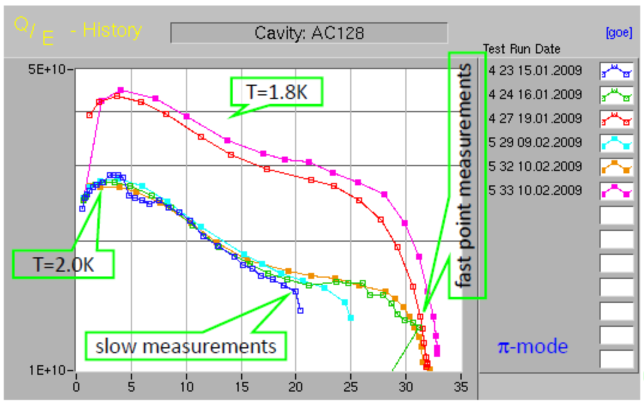
W.-D. Moeller, DESY, Hamburg

RF Feedthrough (2)

RF Feedthrough for 1.3GHz XFEL 9-cell Cavity (DESY)

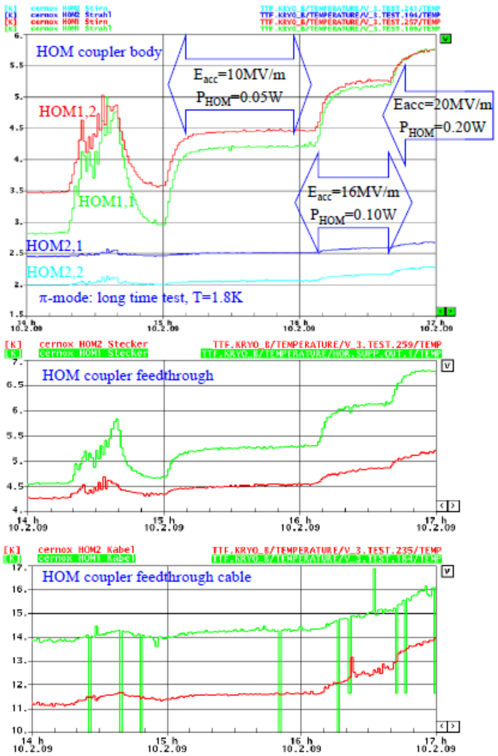
HISTORY:

CW test on cavity AC128 in the horizontal cryostat



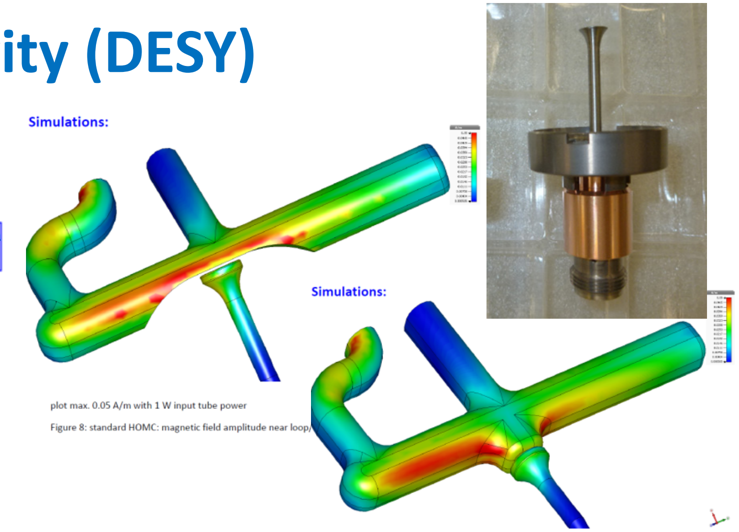
Heat load from HOM couplers / HOM couplers temperature increase

D.Kostin, at.al, **TESLA Type 9-Cell Cavities Continuous Wave Tests**, SRF2009



D. Kostin, DESY, Hamburg

Simulations:



plot max. 0.05 A/m with 1 W input tube power

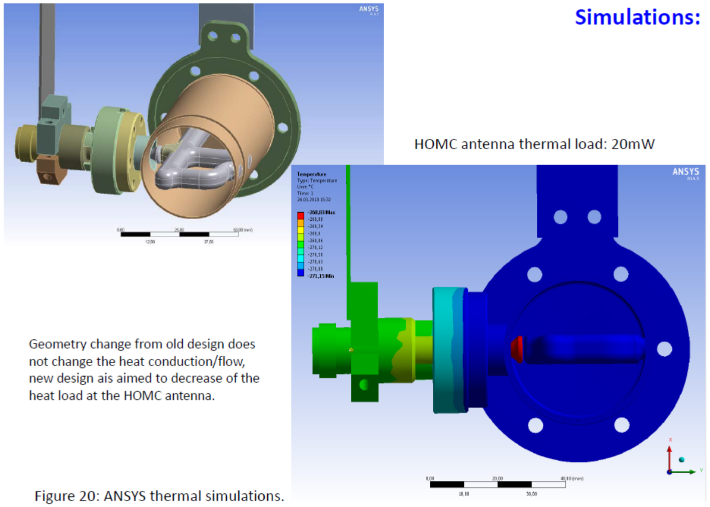
Figure 8: standard HOMC: magnetic field amplitude near loop

Simulations:

plot max. 0.05 A/m with 1 W input tube power

Figure 9: new HOMC: magnetic field amplitude near loop/feed surfaces

Simulations:



HOMC antenna thermal load: 20mW

Geometry change from old design does not change the heat conduction/flow, new design ais aimed to decrease of the heat load at the HOMC antenna.

Figure 20: ANSYS thermal simulations.

RF Feedthrough (3)

RF Feedthrough for 1.3GHz cERL 2-cell Cavity (KEK)

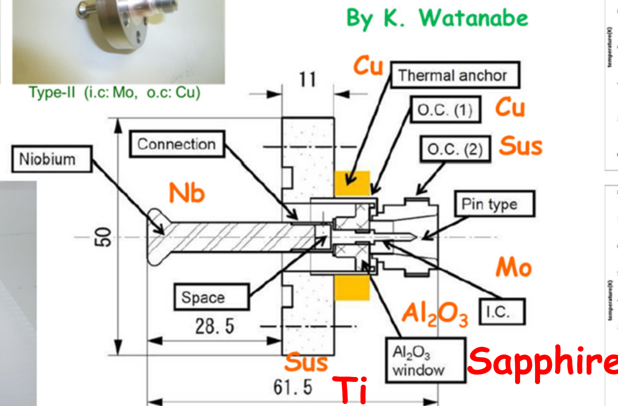

Type-0 (i.c: Kovar, o.c: Kovar)

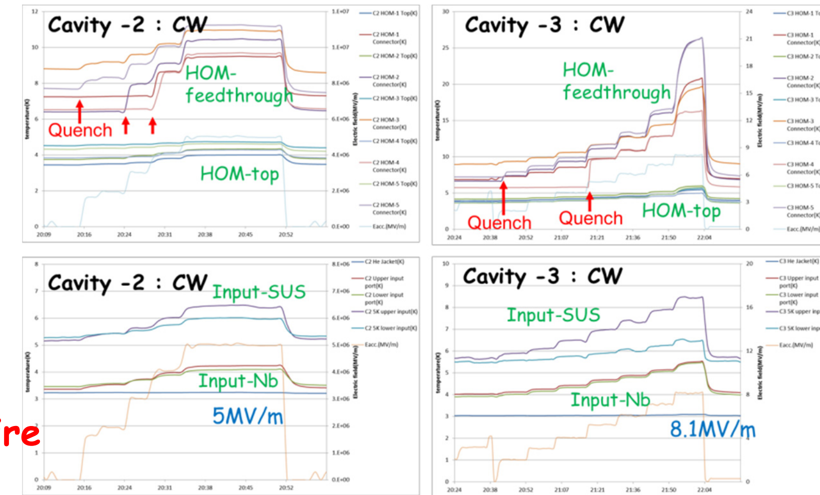

Type-I (i.c: Mo, o.c: Kovar)

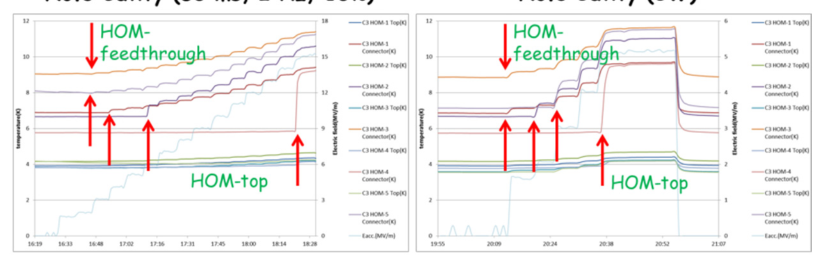

Type-II (i.c: Mo, o.c: Cu)

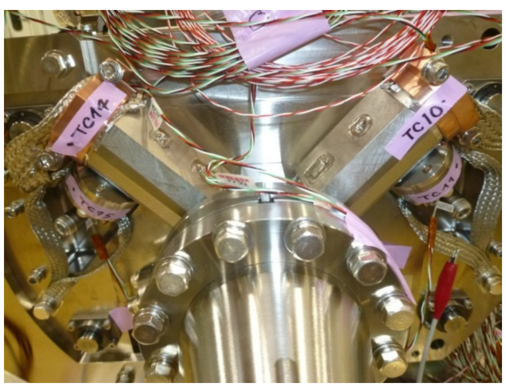

Type-II'm (i.c: Mo, o.c: Cu) "male pin"

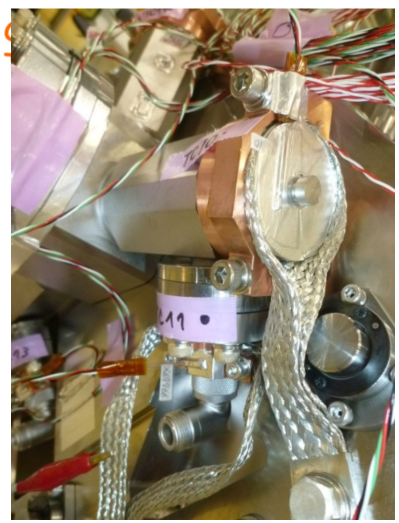
By K. Watanabe



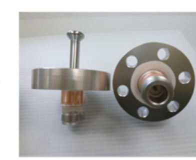








Eacc at antenna quench	No.3 Cavity (10% Duty)	No.3 Cavity (CW)
	HOM-1: 4 MV/m	HOM-1: 1.7 MV/m
	HOM-2: 6 MV/m	HOM-2: 2 MV/m
	HOM-3: 3 MV/m	HOM-3: 1.7 MV/m
	HOM-4: 15 MV/m	HOM-4: 5 MV/m
	HOM-5: 3 MV/m	HOM-5: 3 MV/m



Summary

- Higher order modes couplers are one of the most critical components of a superconducting RF cavity system.

- Higher order modes coupler includes varieties of key technologies in design, fabrication, conditioning and operation.

Thank you for your attention.

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