Design and Technology of High Power - Couplers

- with a special view on superconducting RF –

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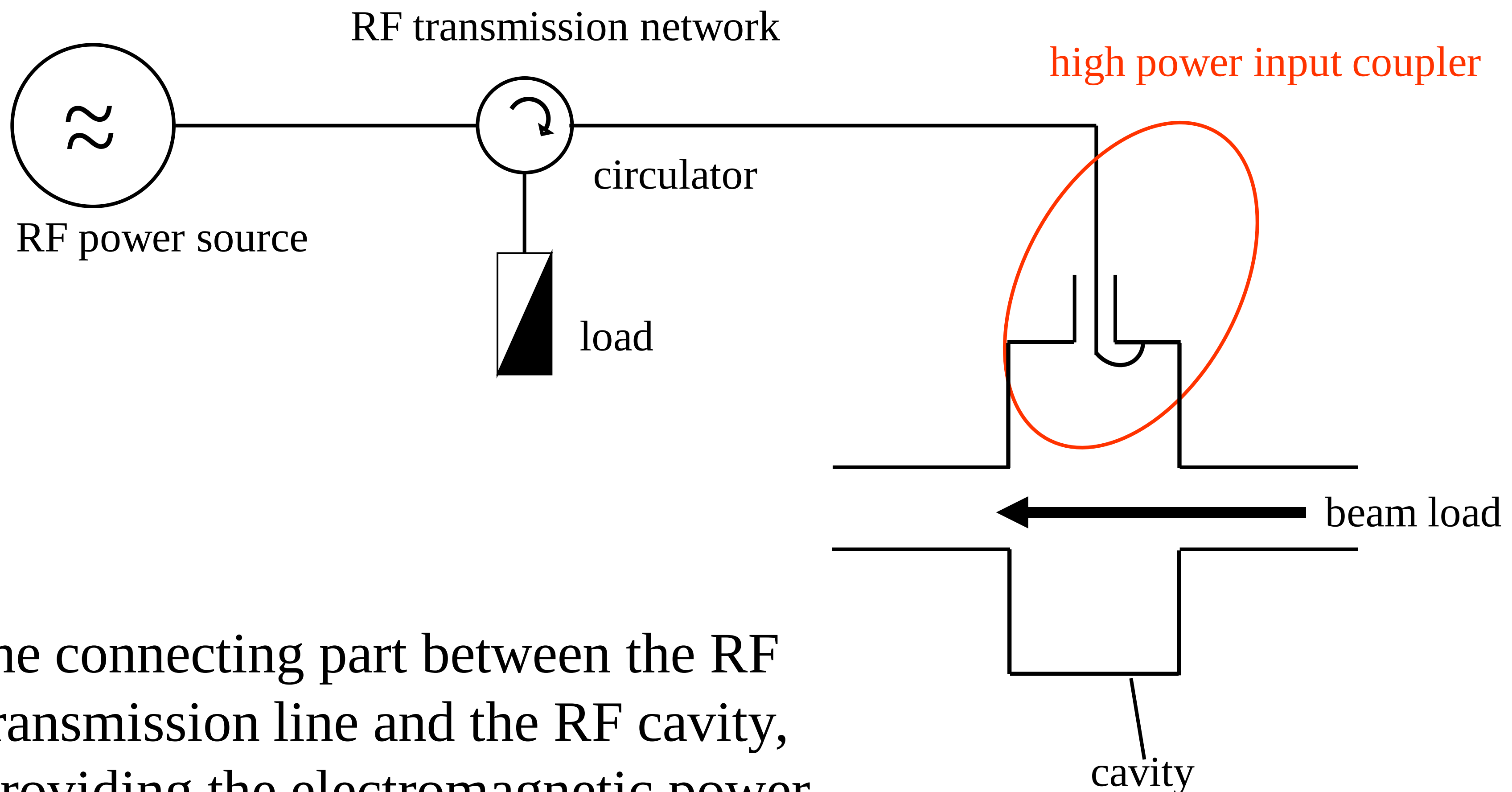
Content:

1.1. Introduction: What is a high power input coupler?



- the connecting part between the RF transmission line and the RF cavity, providing the electromagnetic power to the cavity and beam

1.2. Introduction: RF-Functions of the power coupler

- it has to transfer the power to the cavity field and to the beam at sometimes very high power levels in pulsed or CW operation
- it has to match the impedance of the klystron to the beam loaded cavity
  - take into account: there is a strong mismatch in absence of beam between unloaded cavity and generator → full reflection for SC cavities
  - minimize the wasted power

- possibly allow change of the match for different beam loading
- dimensions should not allow non –TEM modes
- could also be used for HOM damping

1.3. Introduction: Non RF functions of the power coupler

for normal conducting (NC) and superconducting (SC) accelerator structures

Function	important for NC	important for SC
• provide a vacuum barrier for the beam vacuum	yes	yes
• do not contaminate the accelerator vacuum		
– easy cleaning and clean assembly	yes	yes
– clean according to ISO4 (‘dust free’)	no	yes
• bridge the gap between room- and cryogenic-temperature		
– mechanic flexibility for the temperature cycles and thermal expansions	no	yes
– low static thermal losses to cryogenic environment	no	yes
– low dynamic thermal losses to cryogenic environment	no	yes
• Not a function, but important: LOW Costs	yes	yes

1.4. Introduction: The Power Coupler (PC) - one of the most critical parts of a RF cavity system in the accelerator

- Vacuum failure (leak ceramic)
  - bad contamination of the accelerator vacuum system
  - in case of superconducting (SC) RF: contamination of the very delicate SC cavity surface
  - recovery is time consuming and expensive
- Power limitation (arcing, multipacting, window heating)
  - limits the RF cavity performance
  - may damage the coupler over time and makes it inoperable

worst case

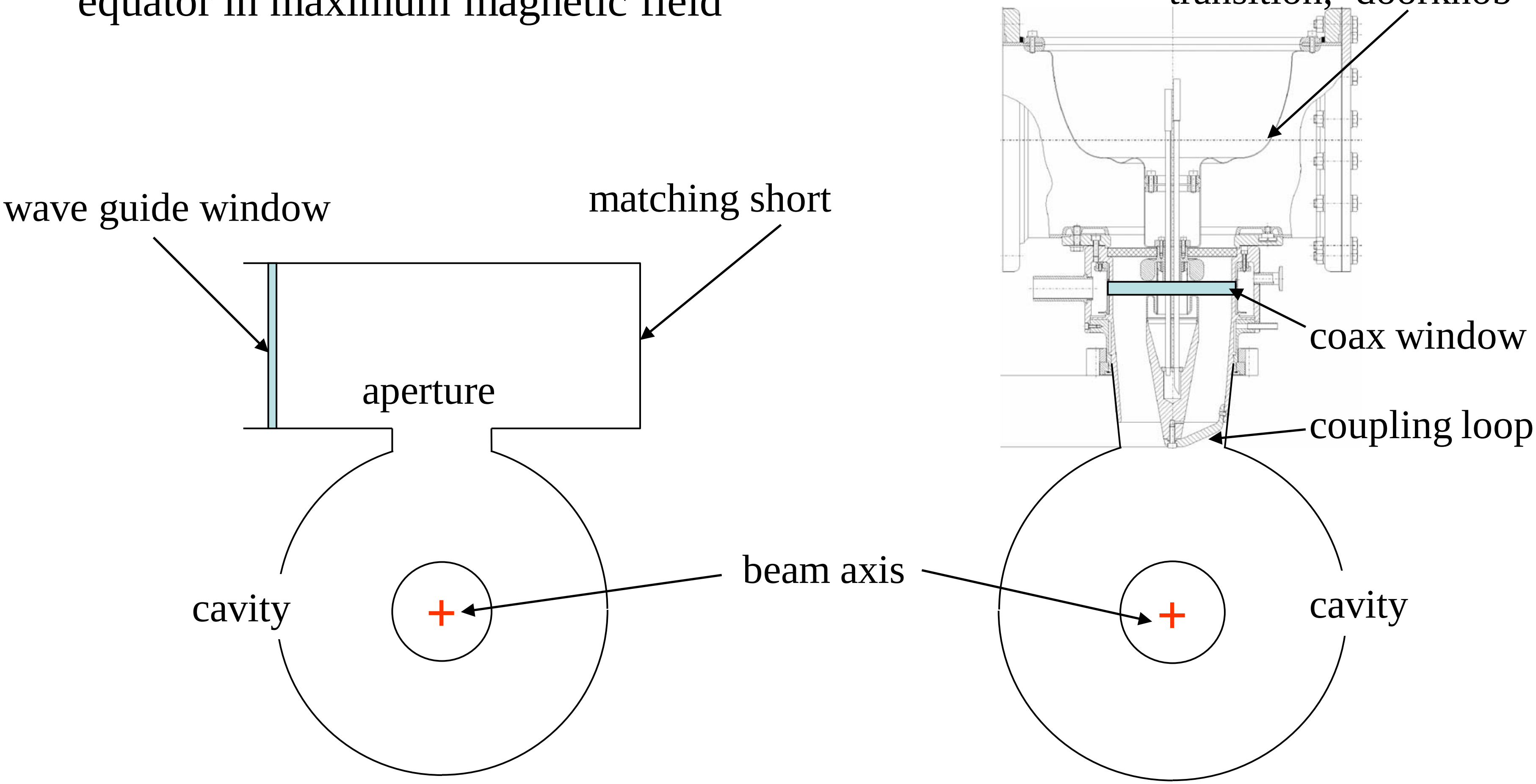
molten by excessive power rise with deactivated technical interlock!!

2. Wave guide vs. coax coupler

- coax:
  - more compact ☺
  - easy tuning of match by changing the penetration of antenna ☺
  - circular parts are easy to machine, assemble and seal ☺
  - RF losses of inner conductor 2/3 to RT or 70K intercept (SC) ☺
  - easy to suppress multipacting by bias on inner conductor ☺
  - asymmetric fields cause kick to the beam ☹
- wave guide:
  - lower surface electric field (1/4) ☺
  - no easy tuning of the match ☹
  - high thermal radiation (SC) ☹
  - machining of big rectangular parts is more extensive ☹

3.1. Coupler ports on normal conducting cavities

NC coupler ports are mostly located at the cavity equator in maximum magnetic field

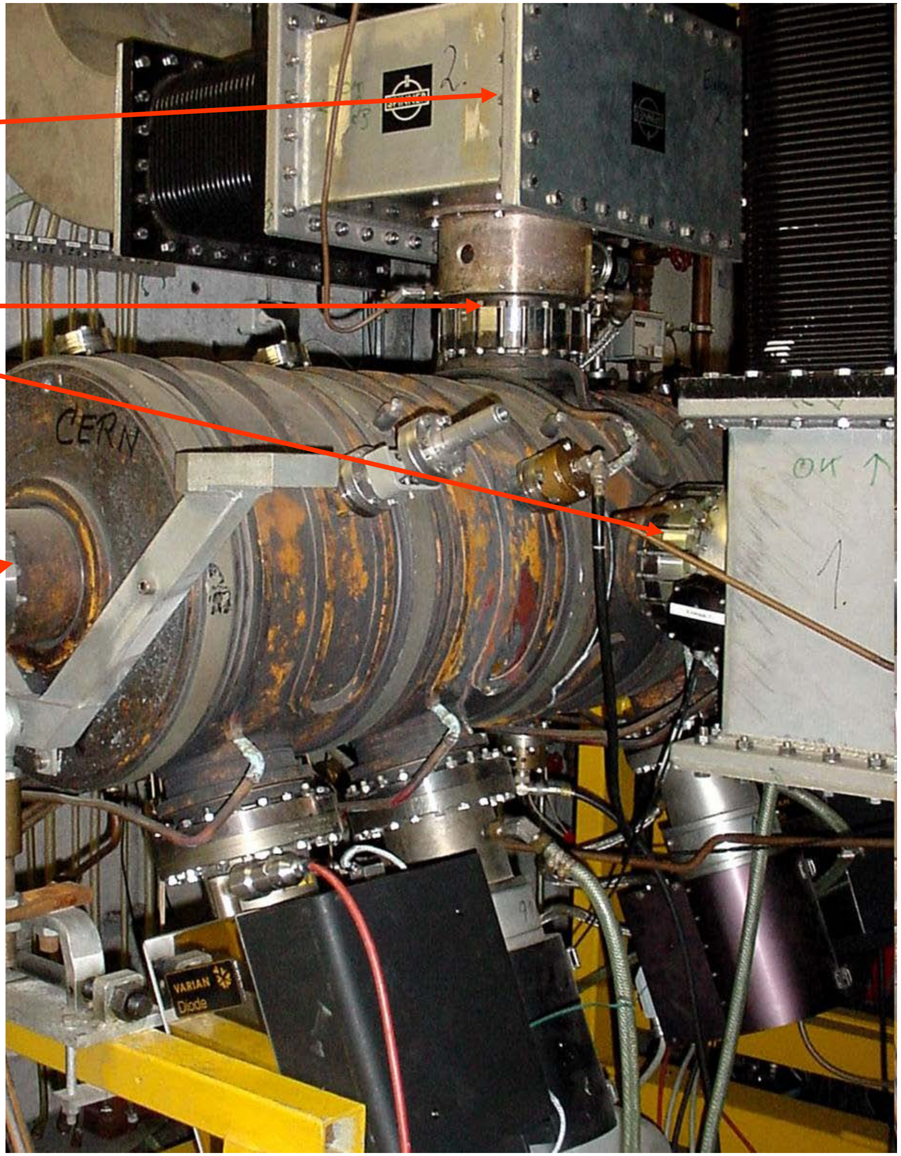


aperture coupling with wave guide

loop coupling with coaxial coupler

3.2. Coupler ports: PETRA NC cavity

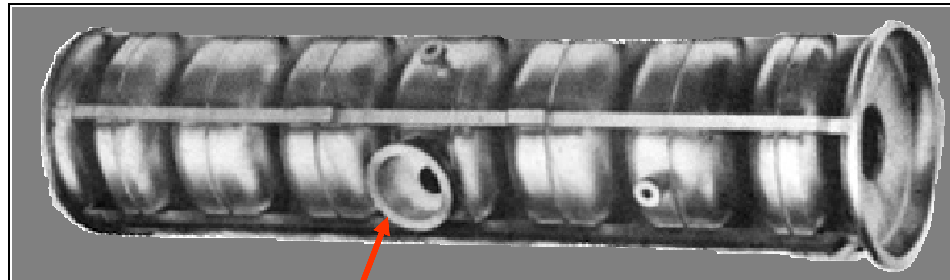
- wave guide with doorknob
- coupler port on cavity
- beam line



3.3. Coupler ports on SC cavities

HEPL cavity (Stanford 1977)

- ports on equator (like NC cavities)
- limitation by multipacting



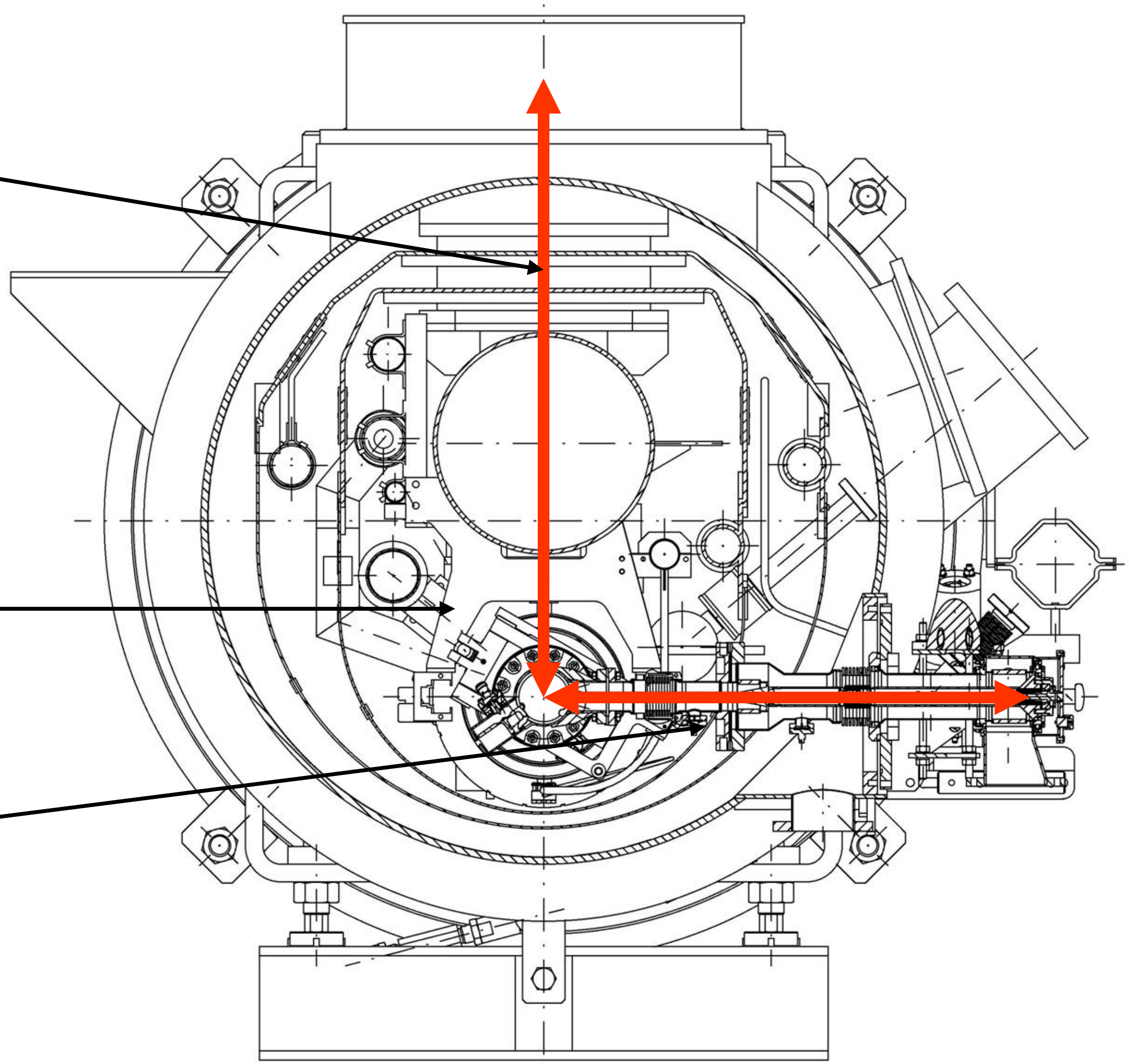
coupler ports

TESLA cavity (DESY 1993)

- ports on beam line
- longer beam lines and smaller filling factor

3.4. e.g. Coupler in the TTF cryo-module

- movement of cavity during cool down in vertical direction
- cavities are supported by the helium gas return pipe
- shrinkage of coupler in length



3.5. e.g.: Coupler in the TTF cryo-module

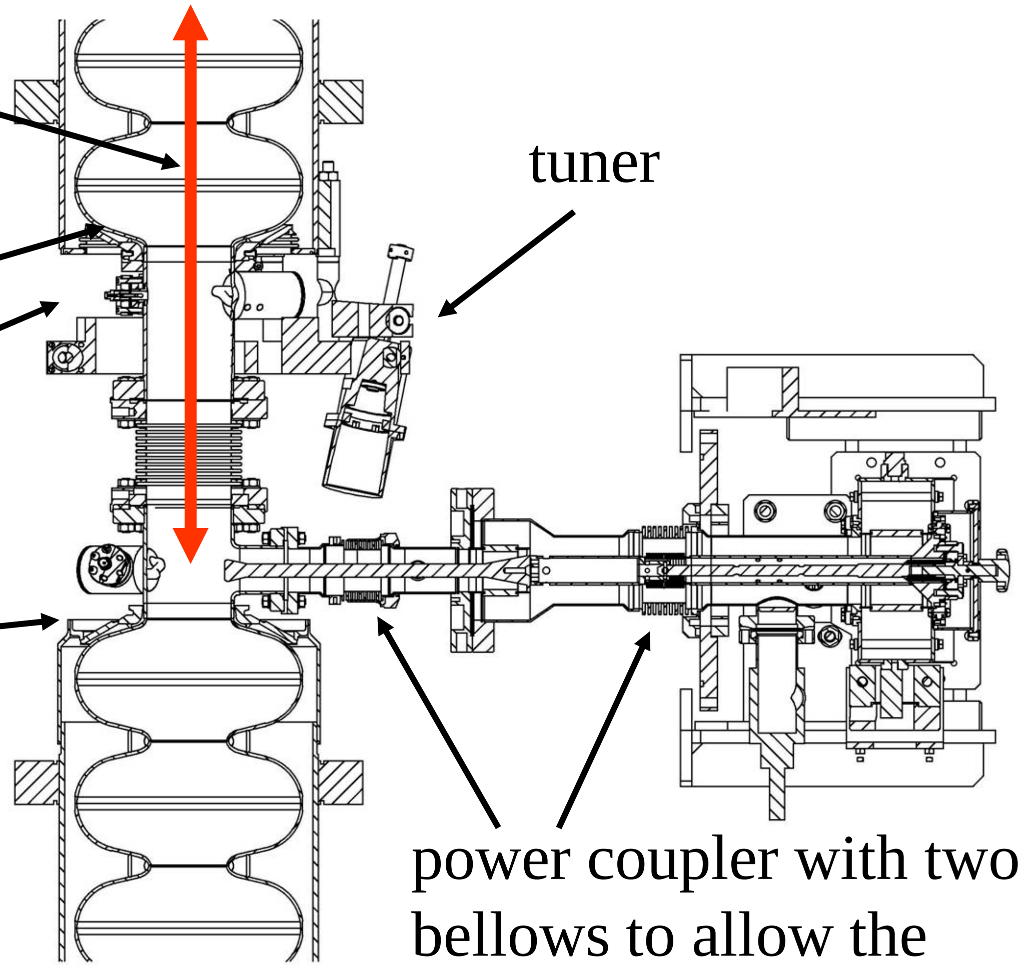
movement/ shrink of cavities

tuner

9 cell cavity

He tank

HOM coupler



cavity support brackets

power coupler with two bellows to allow the z-movement

4. Two vs. one window coupler

For NC cavities the one window solution is preferred

- easy and compact design, no extra vacuum system

For SC cavities:

- at low gradient applications (<15 MV/m) one window coupler with the window at RT is commonly used
- for high gradients (≥ 20 MV/m) two window design is common
  - coupler and cavity have to be assembled in a very clean environment
  - i.e. window has to be close to cavity for geometric restrictions at the cryostat
  - i.e. window is at cryogenic temperature and needs a second window at RT
- safety against window failure during operation (delicate SC cavity surface)

5.1. Coaxial PC examples for NC cavities

power coupler with coupling loop

for PETRA

f = 500 MHz

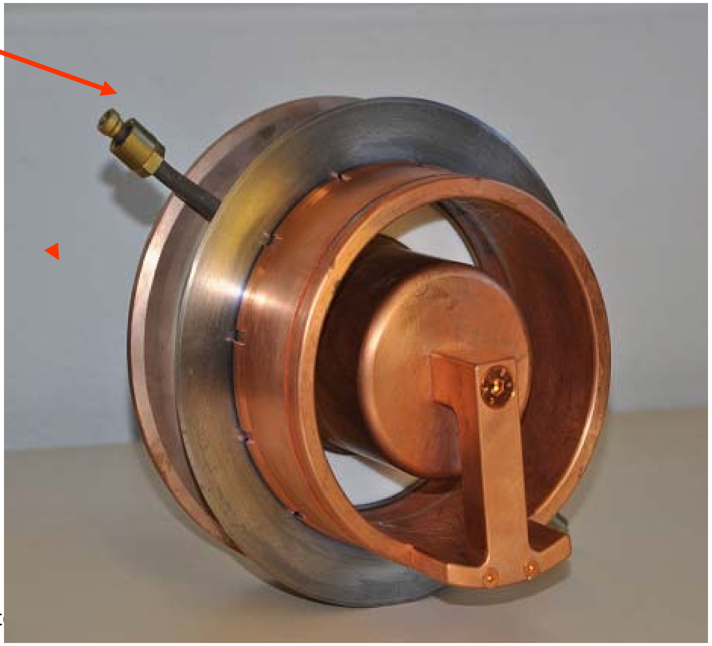
P = 250 kW, cw

and

HERA –P

f = 208.19 MHz

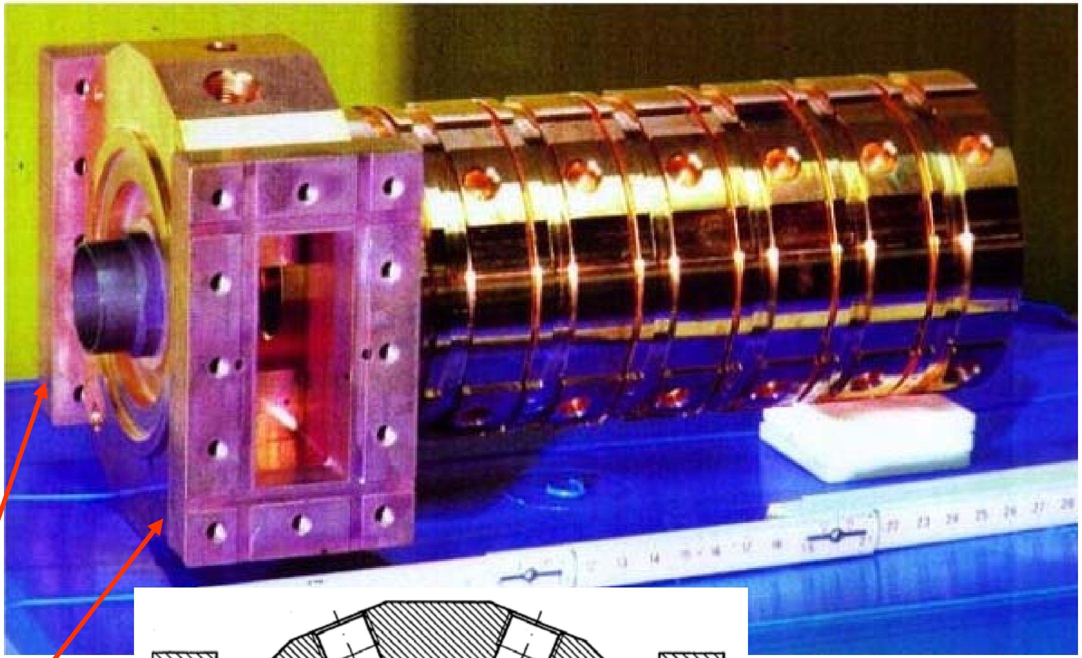
P = 25kW, cw

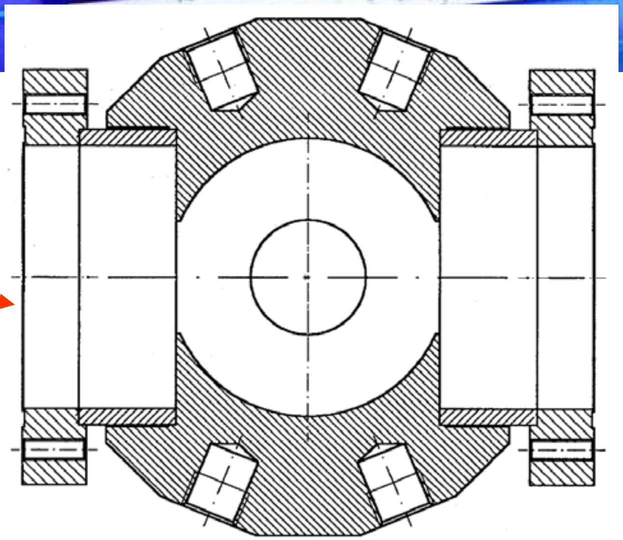


5.2. Wave guide PC examples for NC cavities

S-band structure

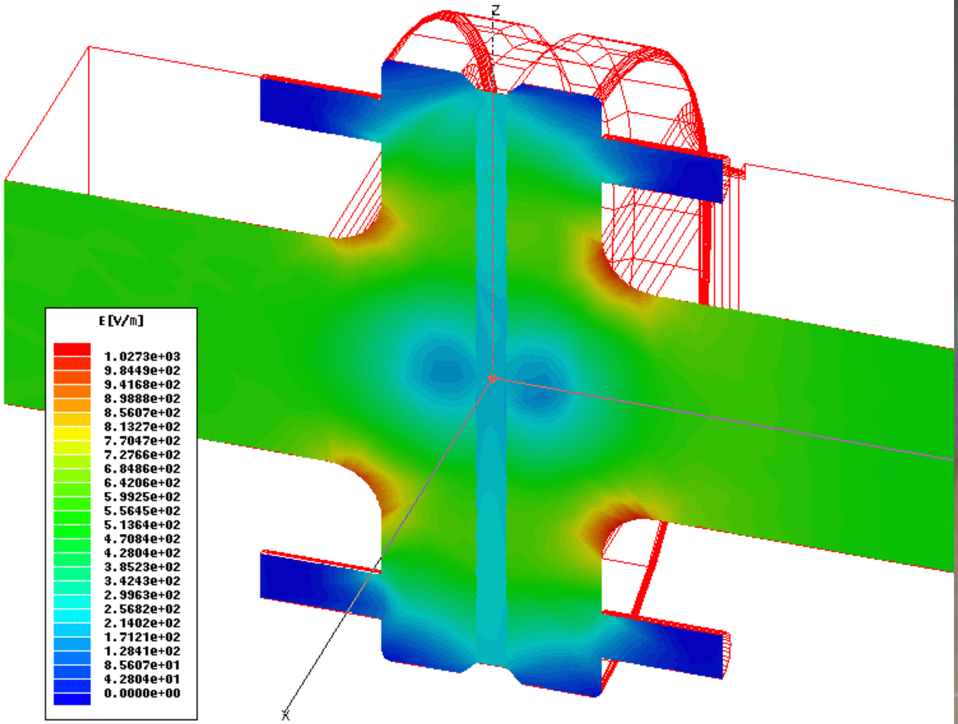
- f = 2.998 GHz
- P = 100 MW
- pulsed

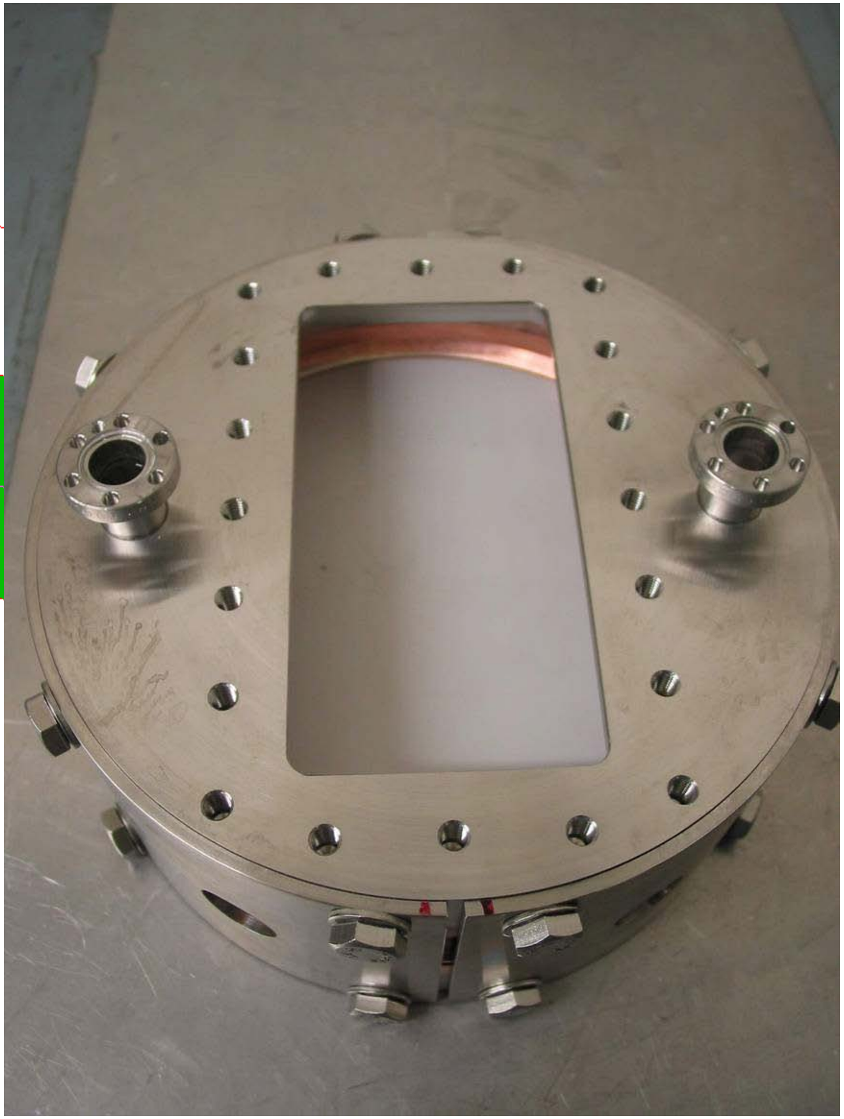




wave guide coupler ports

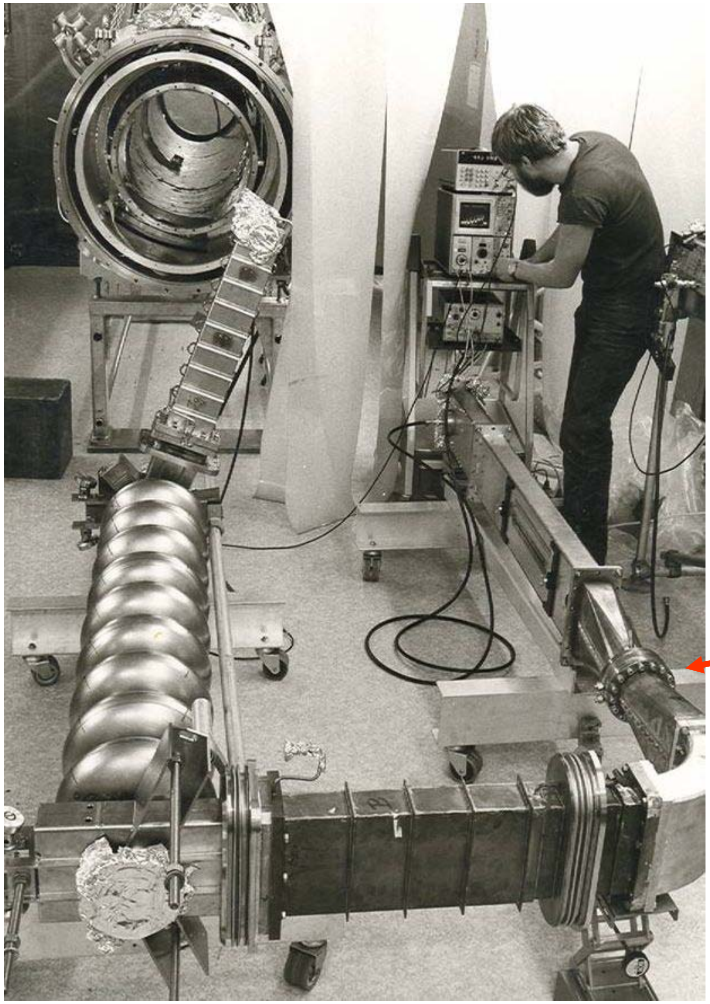
5.3. Wave guide window

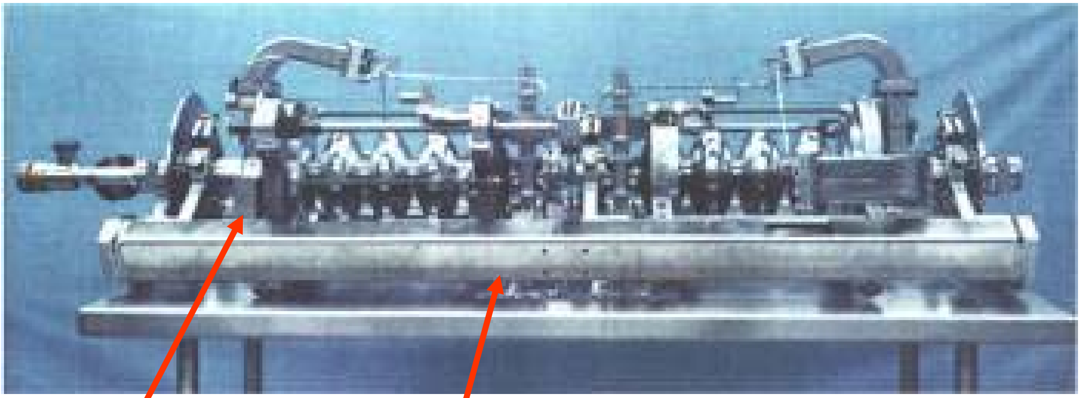




window with diagnostic ports
(TTF 2 coupler)
f = 1.3 GHz
P = 1 MW
Pulse: 1.3ms, 10 Hz

5.4. Wave guide couplers at SC cavities

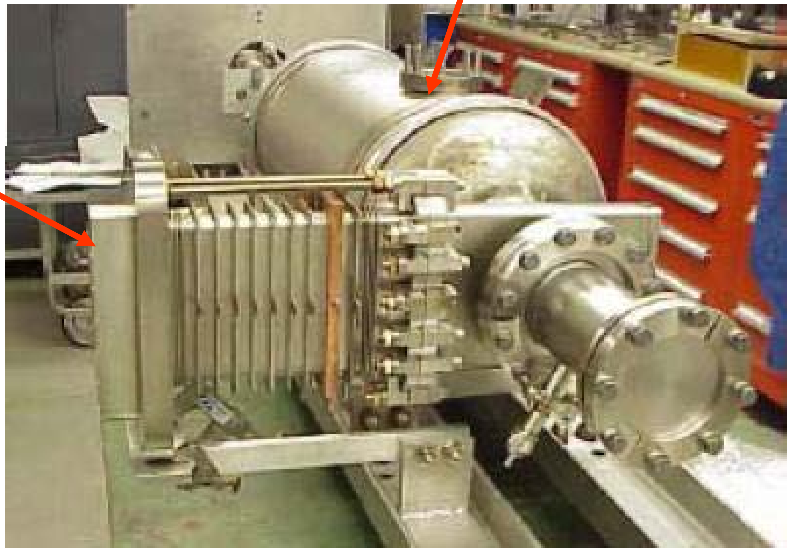




CEBAF cavity pair and new upgrade cavity

window

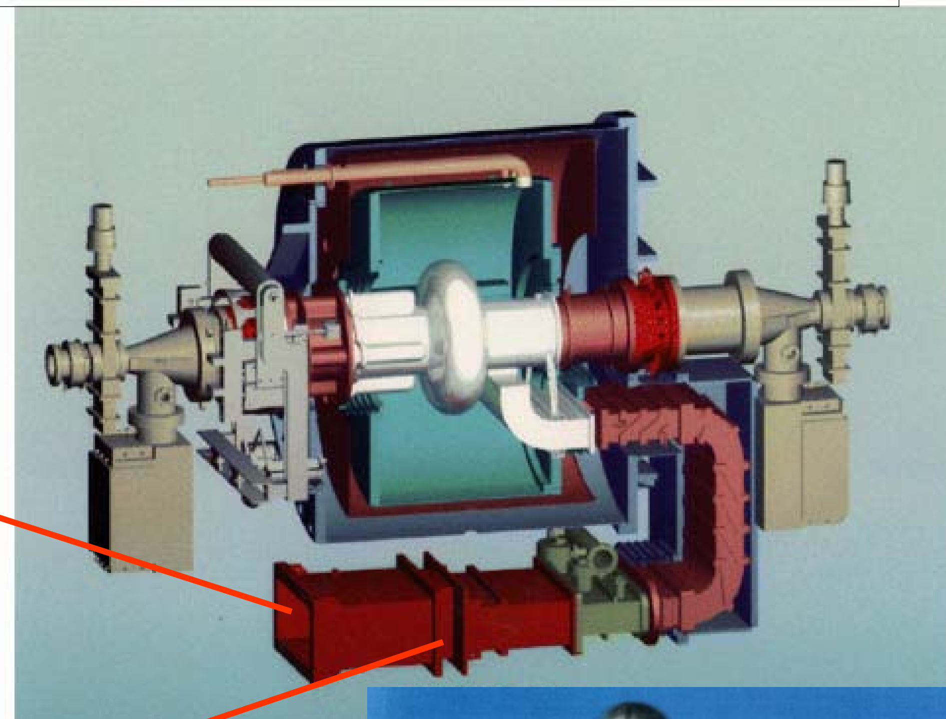
f = 1.5GHz
P = 35kW, cw



1 GHz Petra test cavity

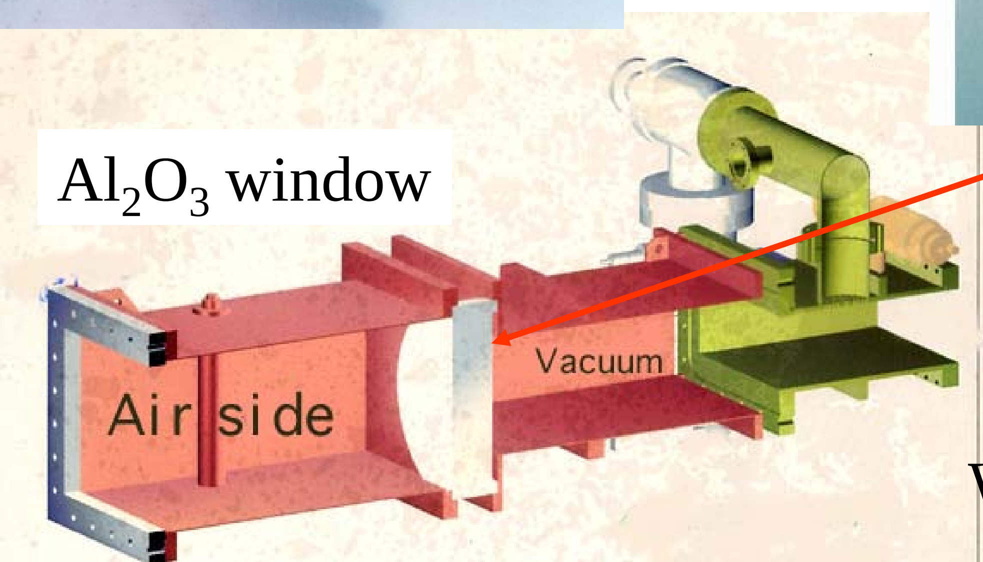
5.5. Wave guide couplers for SC cavities

CESR – B cavity
f = 499.65 MHz
P = 250 kW, cw

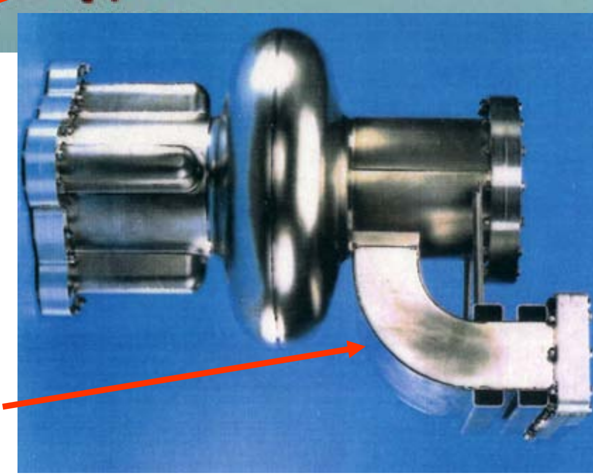


backup Kapton window

Al_2O_3 window



WG coupler

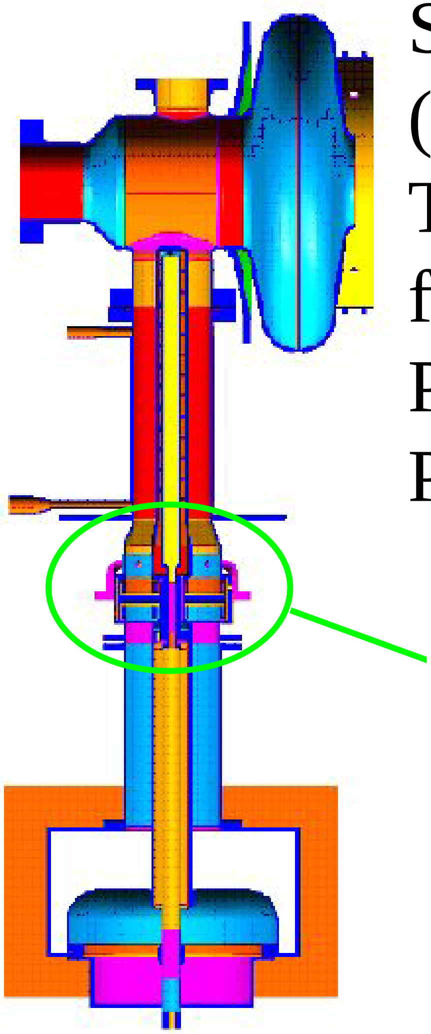


5.6. Coax couplers, one cylindrical window for SC cavities

HERA
f = 500 MHz
P = 65 kW, cw

LEP2 coax to wave guide transition
f = 352 kHz
P = 150 kW, cw

5.7. Coax couplers, flat window for SC cavities

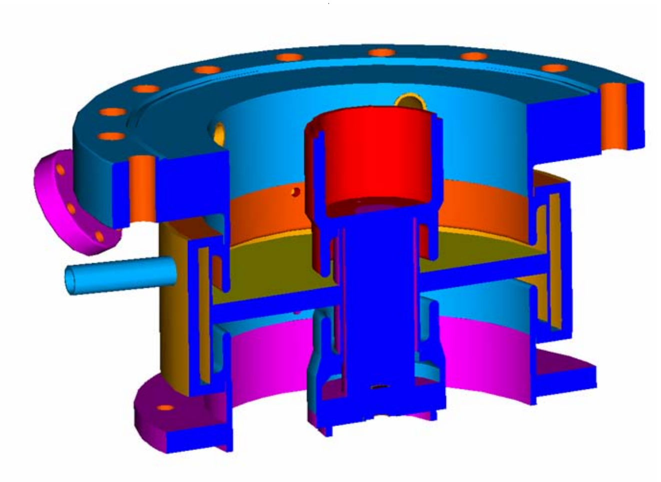


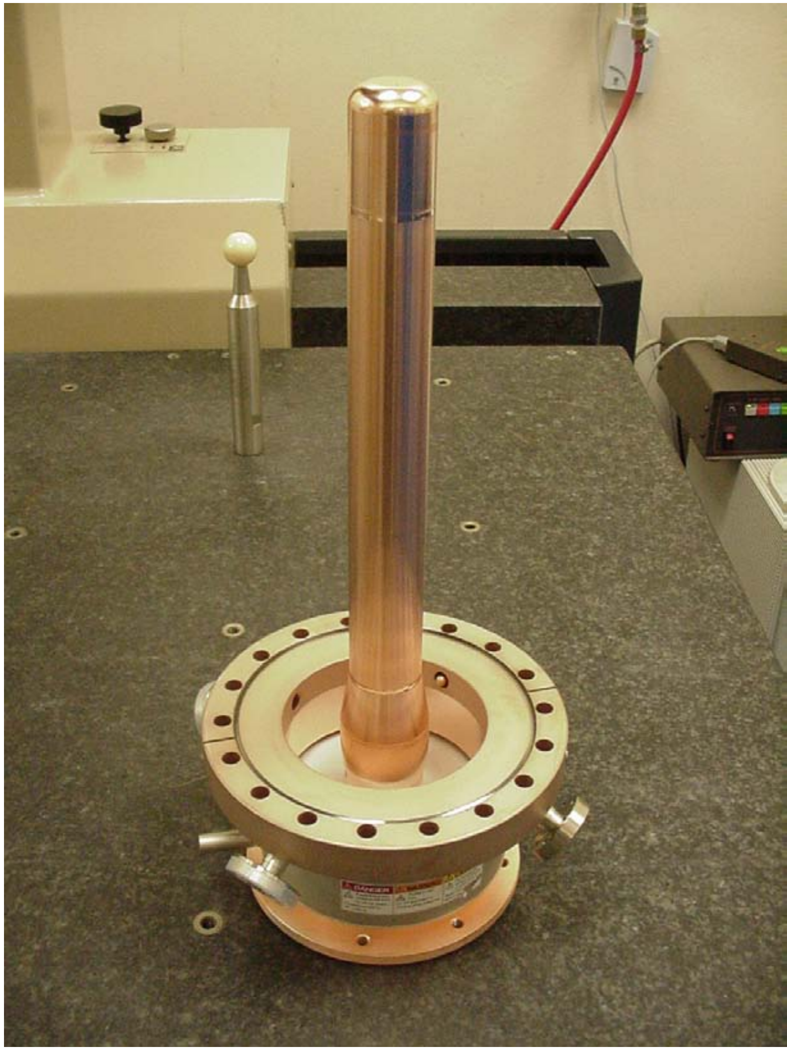
SNS "Choke" window (scaled from KEK-Tristan)

f = 850 kHz

P = 550 kW

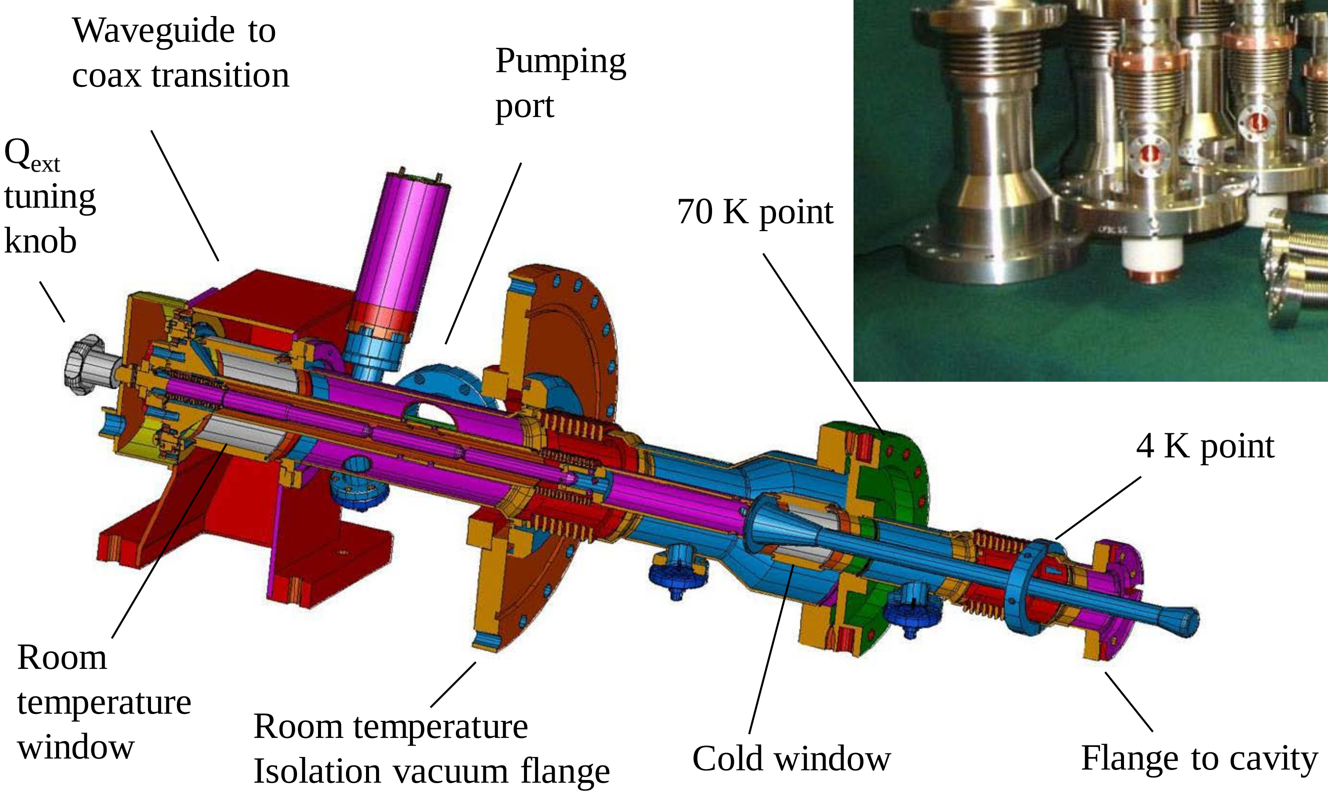
Pulse: 1.3ms, 60Hz



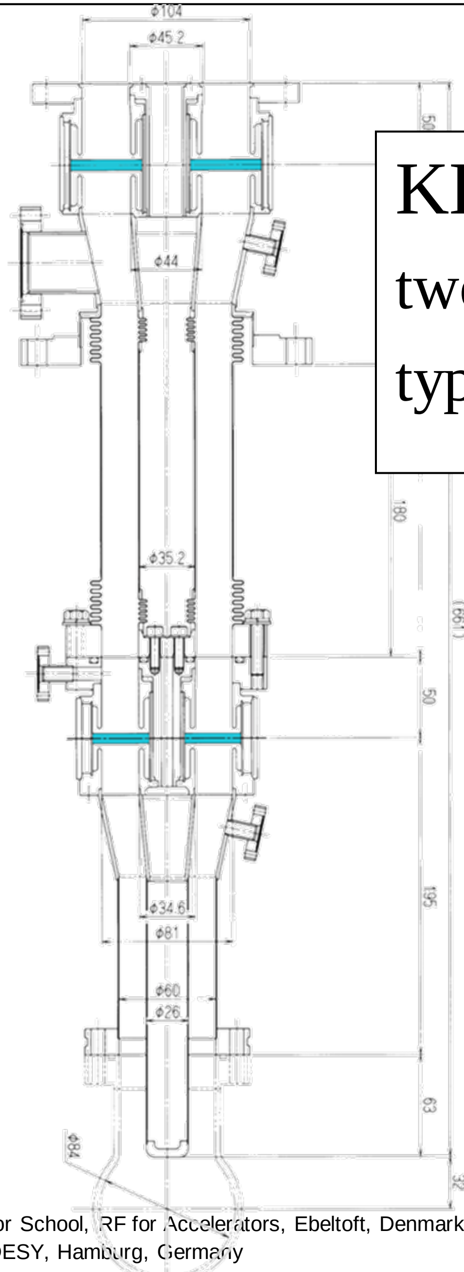


5.8. Coax couplers, two cylindrical windows for SC cavities

TTF3 Coupler
f = 1.3 GHz
P = 1MW
Pulse: 1.3ms, 10Hz



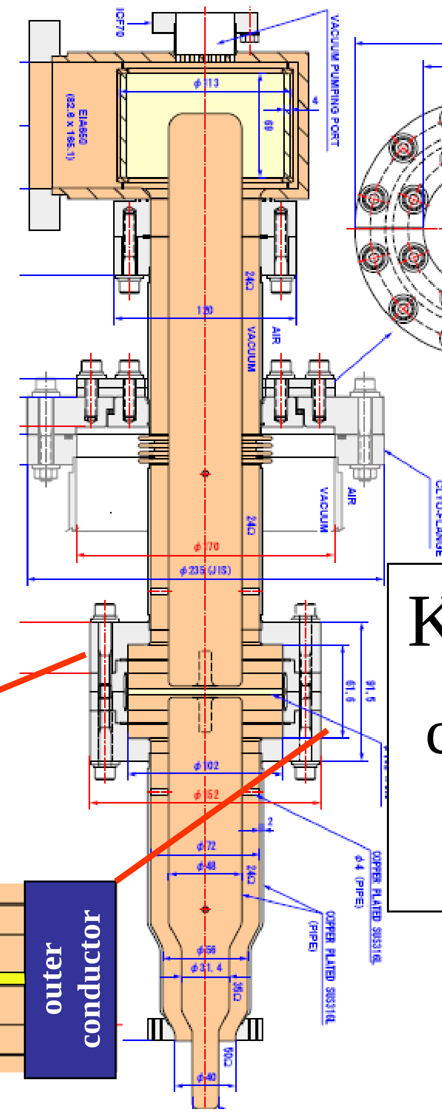
5.9. Coax couplers, two flat windows for SC cavities



KEK1:

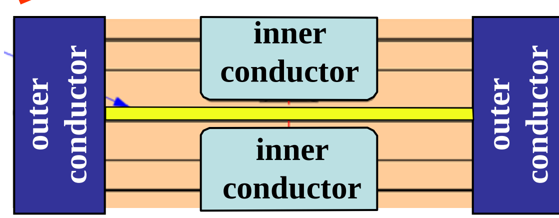
two TRISTAN type disks

f = 1.3GHz



KEK2:

capacitive coupling



6.1. Design specification

Parameters for the coupler design:

- frequency
- peak power, average power
- fix or variable coupling
- coax or wave guide
- one vs. two windows
- NC vs. SC resonator (cryostat design)
- window layout according to geometrical restrictions or available technology: disc, cylinder
- …

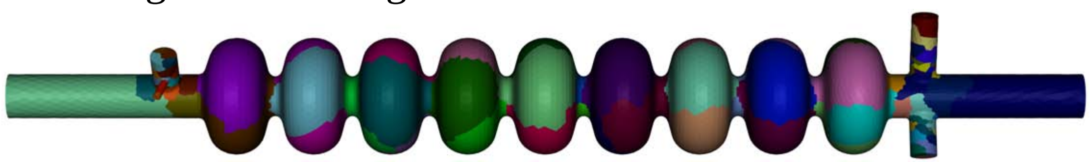
6.2. RF simulation codes

- Today the design is done by FEA
- many codes are available:
  - SUPERFISH
  - URMEL
  - **MAFIA™**
  - HFSS™
  - **CST MICROWAVE STUDIO®**
  - …

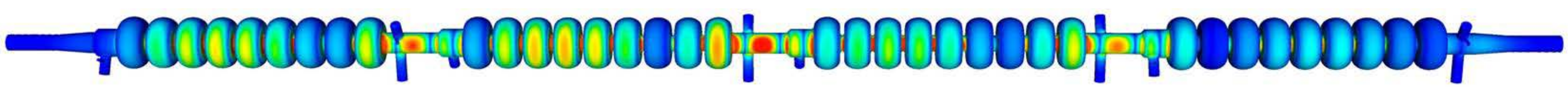
6.3. SLAC 3D Parallel FEM EM Codes

Zenghai Li et al., SLAC

- Tetrahedral Mesh with Finite-Element
  - Up to 6th order basis for field accuracy
  - Unstructured grid for modeling geometry with large variation in dimensions
- Parallel implementation (10^2-10^3 processors, 10^2GB memory)
  - Modeling details with great realism



  - Simulating large systems such like multi-cavity cryomodule

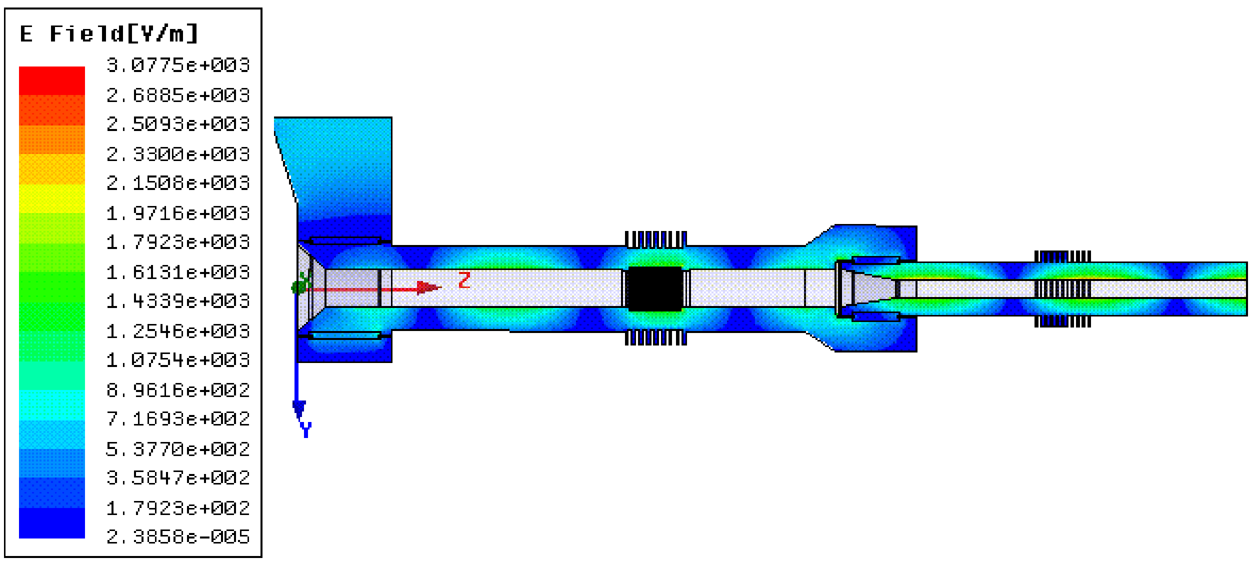


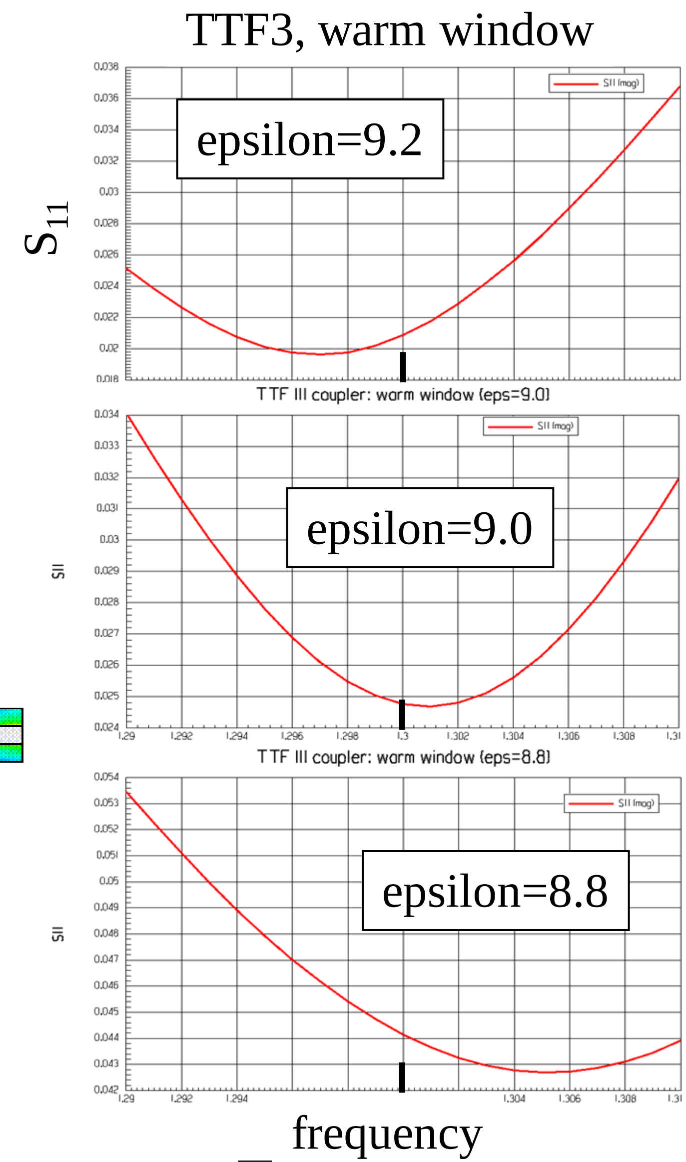
- A suite of solvers including frequency domain and time domain

Omega3P	- Frequency Domain Mode Calculation
S3P	- S-parameter Computation
T3P	- Time Domain With Beam Excitation
Track3P	- Particle Tracking, MP and dark current
V3D	- Visualization
…	

6.4. RF simulation for individual coupler components

- matching of the coupler components
  - the influence of the ceramic epsilon is shown
  - epsilon will change with temperature (70K)

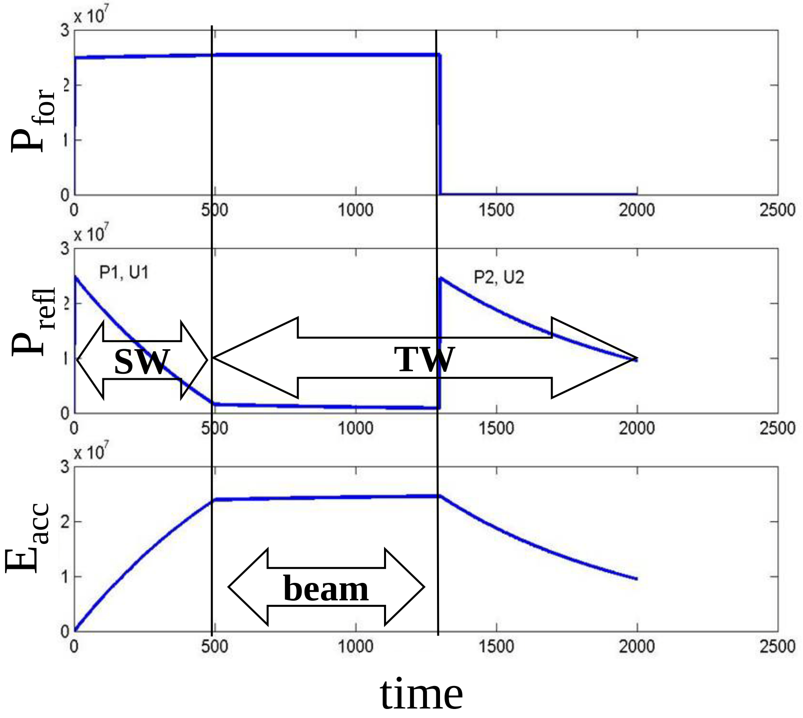


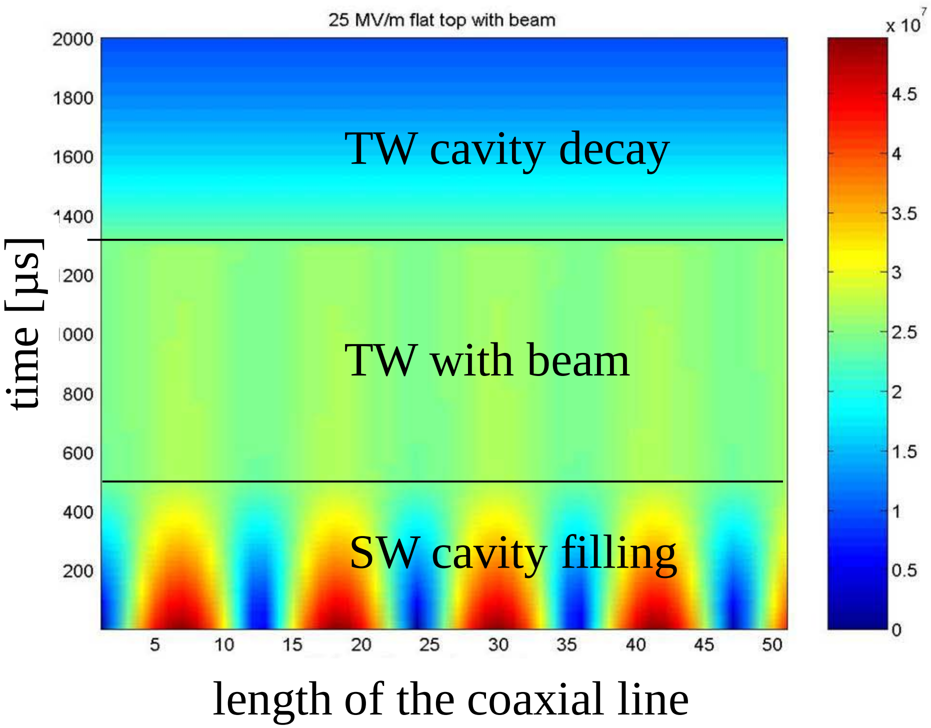


6.5. Standing waves in PC at SC cavities

pulsed operation:

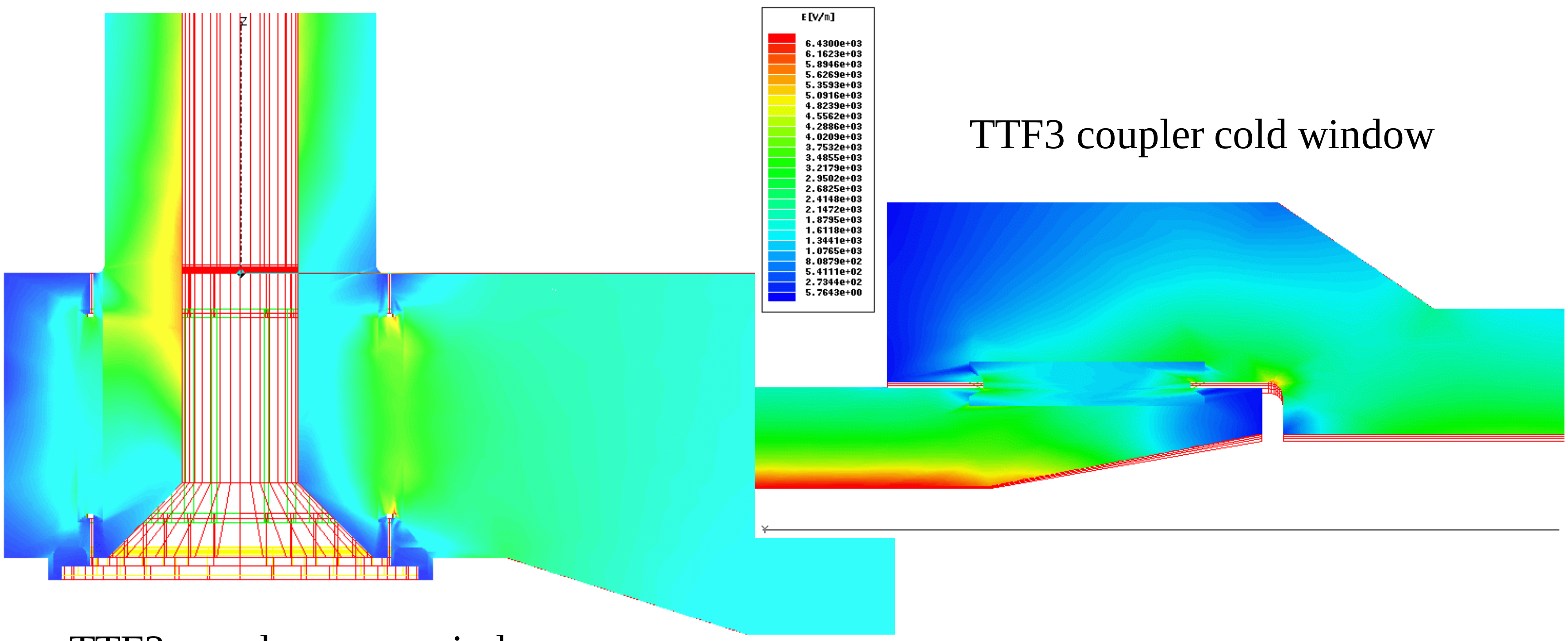
- during filling time of cavity and at absence of beam: standing waves (SW) in coupler, this increases the voltage in the coupler





6.6. RF simulation, window position

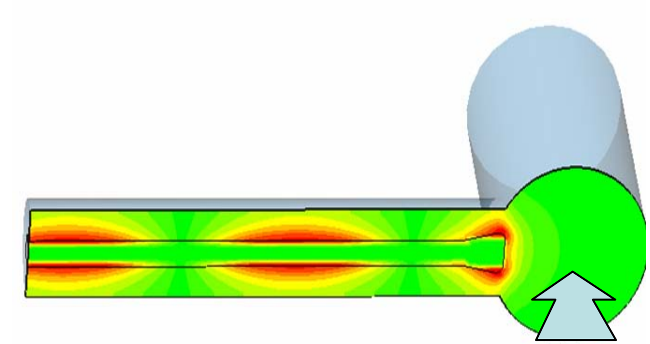
- for pulsed operation: placing the window in the minimum electrical field



TTF3 coupler cold window

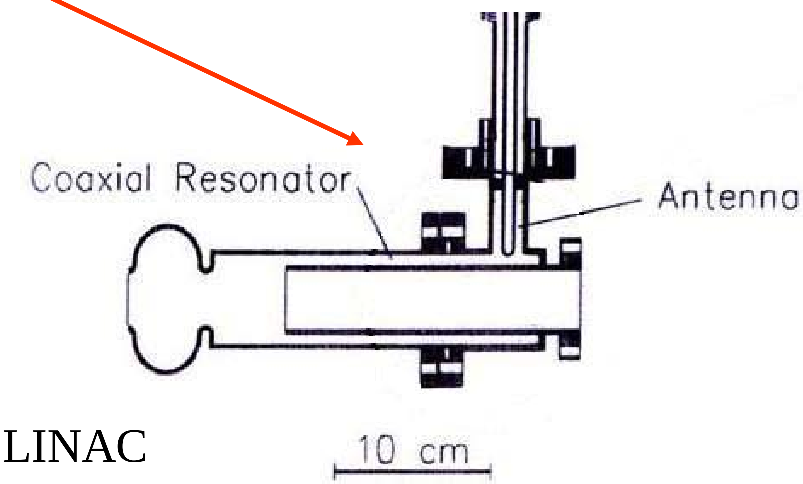
TTF3 coupler warm window

6.7. RF simulation, kick to the beam

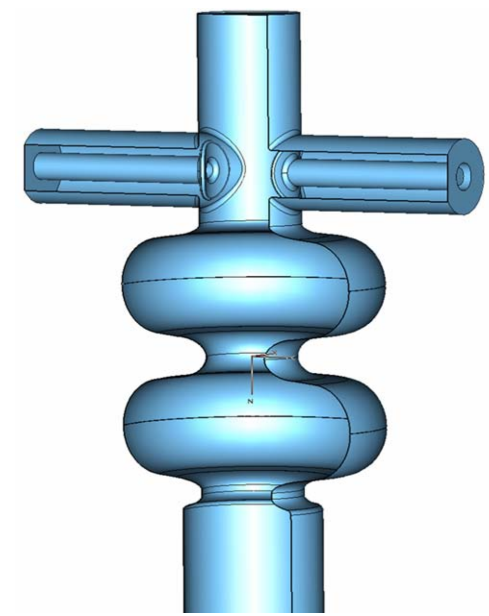


the asymmetric field at the coaxial coupler antenna – beam pipe transition causes an unwanted kick to the beam

- symmetric (2 couplers) or alternating coupler positions
- wave guide coupler
- coax resonator in beam line



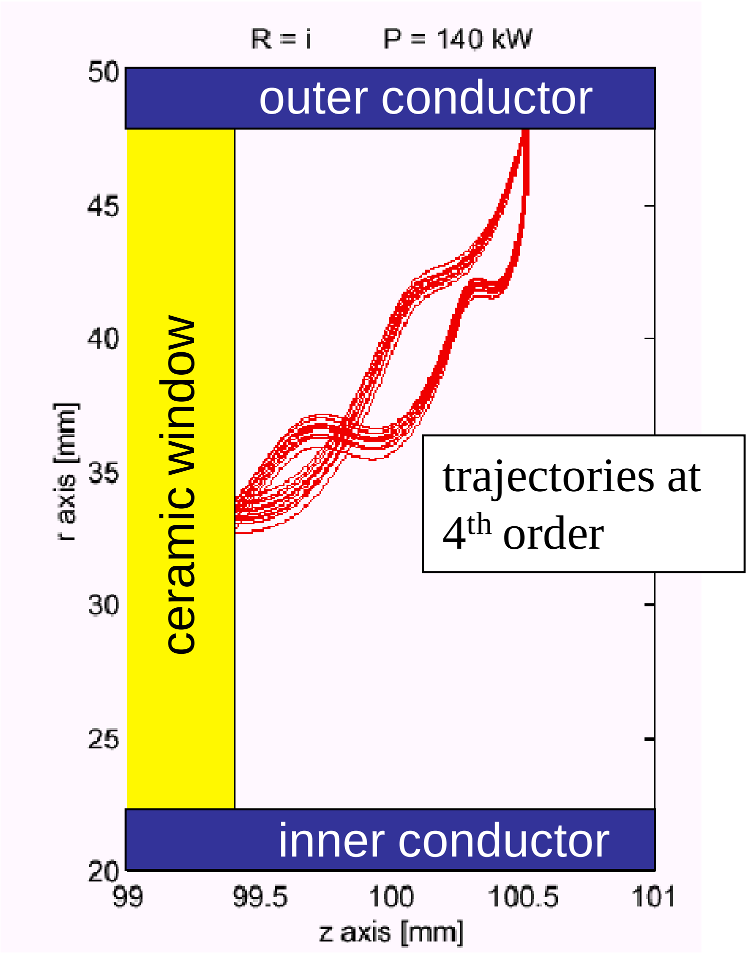
S-Darmstadt LINAC



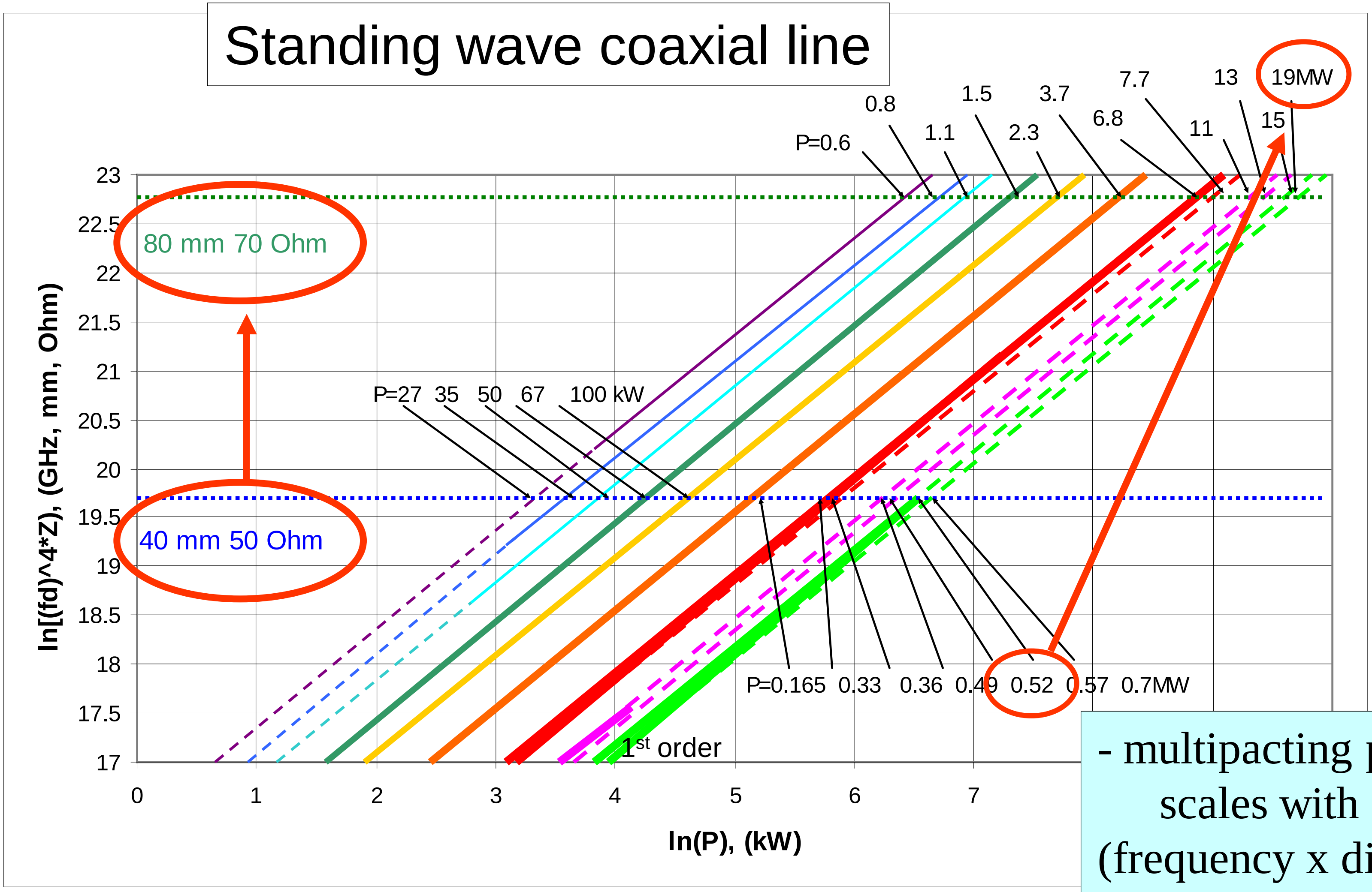
Cornell ERL Injector Cryomodule

7.1. Multipacting (MP) in the coupler vacuum

- Resonant multiplication of electrons caused by:
  - electron trajectories (1 point or 2 point) determined by RF field and geometry
  - secondary electron emission coefficient (SEC) >1
  - order = traveling time over RF periods, lower order more stable (i.e. more difficult to condition)



7.2. Multipacting analytical calculations



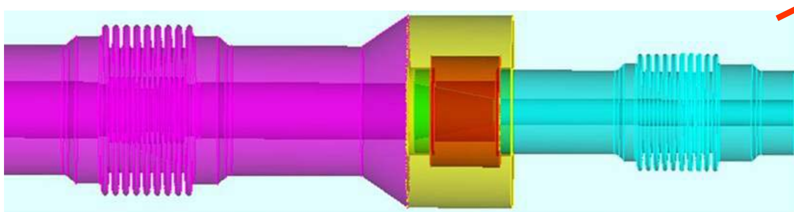
- multipacting power level scales with (frequency x diameter)^{4}

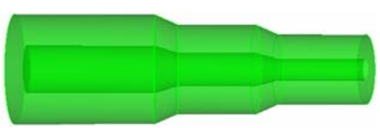
- diameter is limited (excitation of TEM-modes)

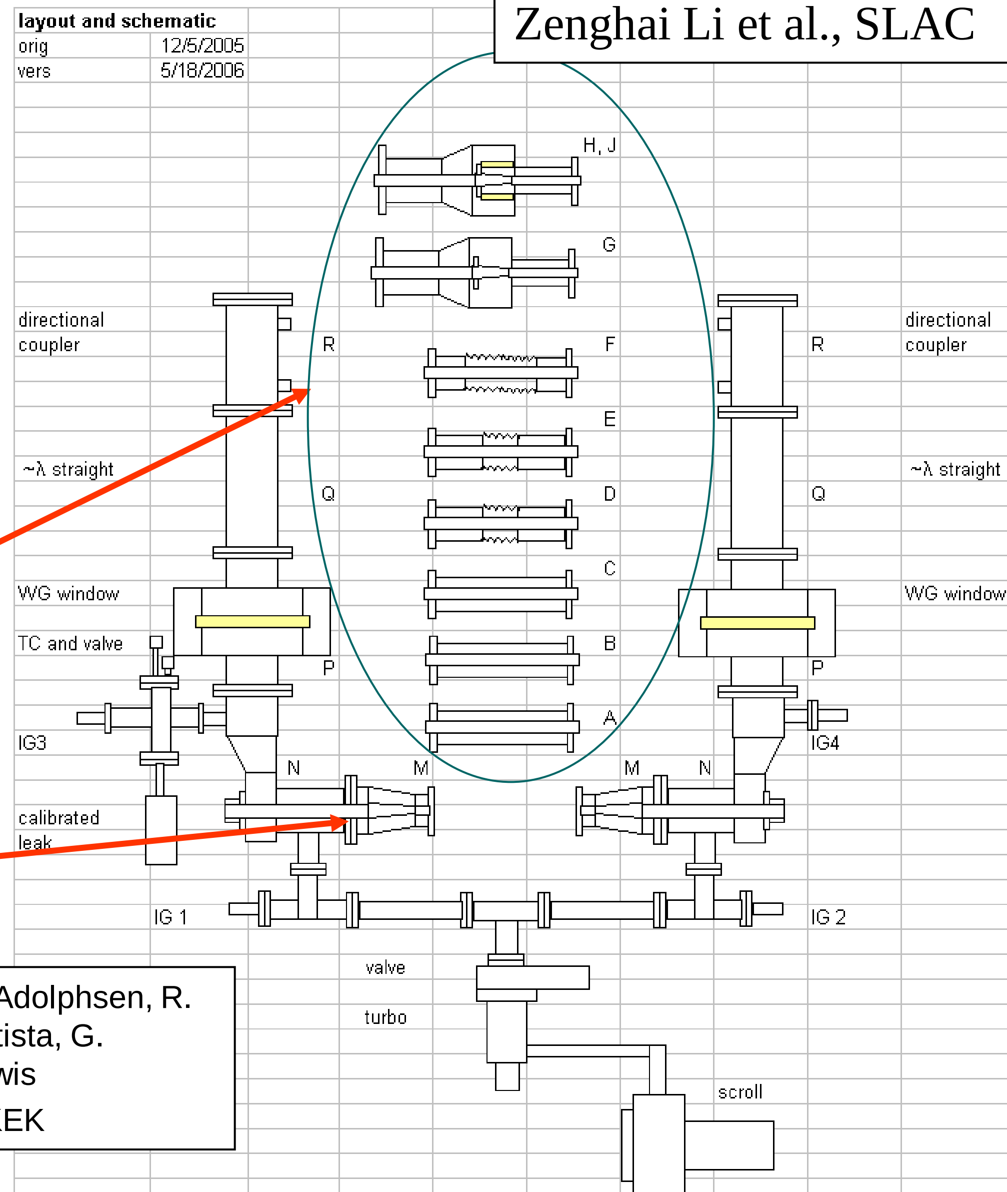
7.3. Coupler test setup @ SLAC

- test components of PC
- measure the MP behavior
- compare with and help to understand the high power test results

Zenghai Li et al., SLAC



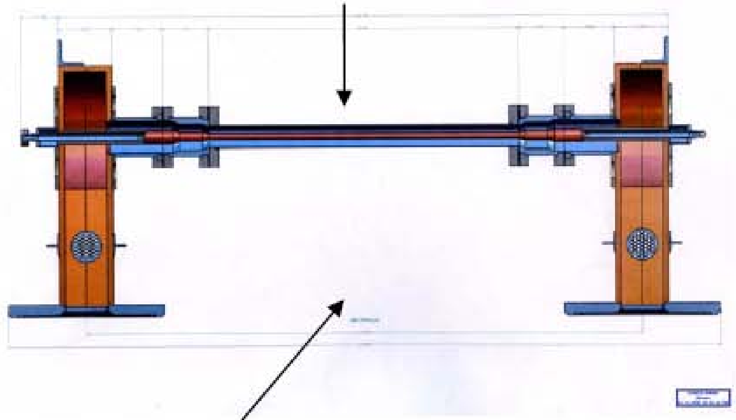


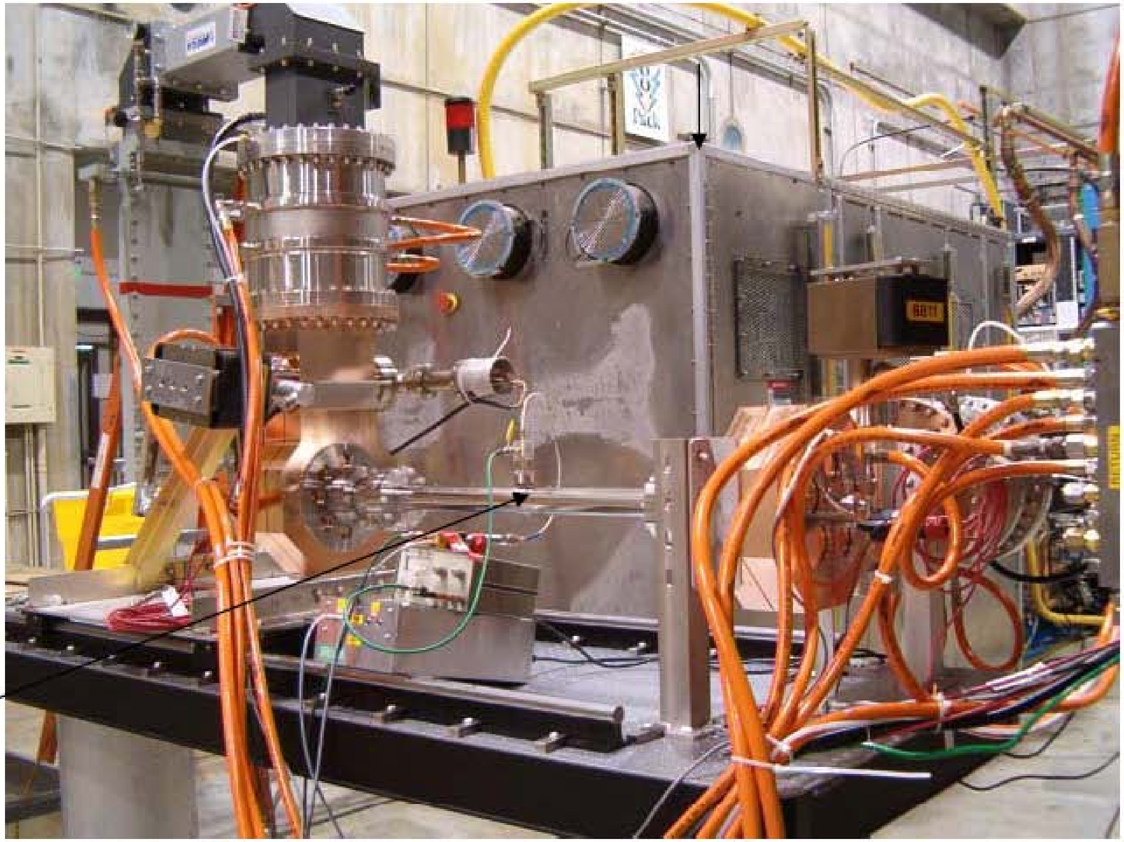


B. Rusnak, C. Adolphsen, R. Swent, C. Nantista, G. Bowden, J. Lewis
TTC meeting KEK

7.4. Coupler test setup @ SLAC

Component
Under Test



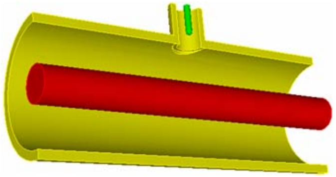


Concept and hardware of test set up for measuring components – first test component is a 40 mm straight tube

7.5. Multipacting in coax of TTF3 coupler

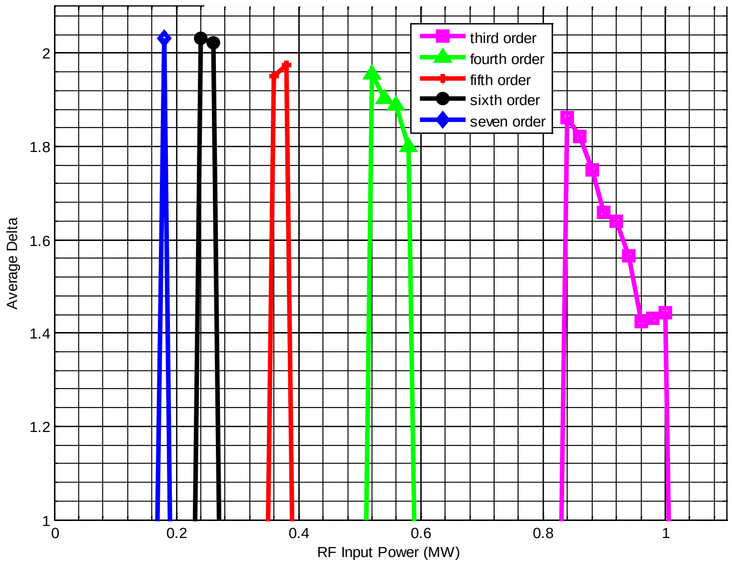
Zenghai Li et al., SLAC

Cold coax, 40mm diameter

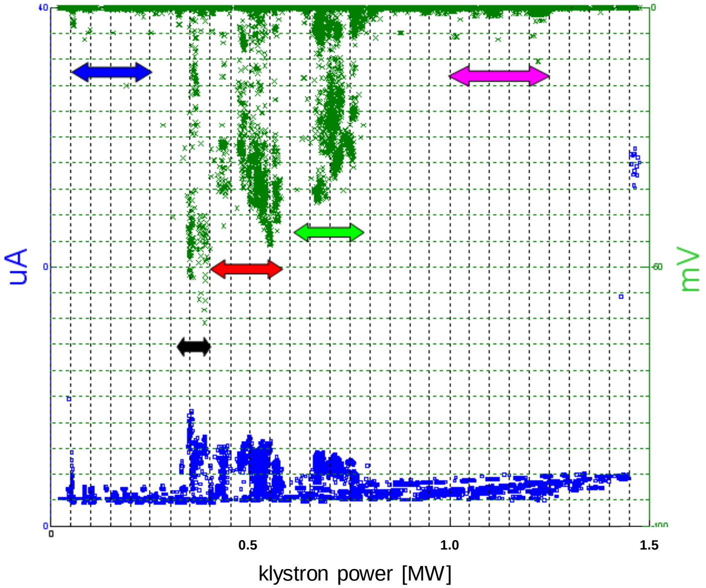


(F. Wang, C. Adolphsen, et al.)

Track3P simulation



Test: After high power processing



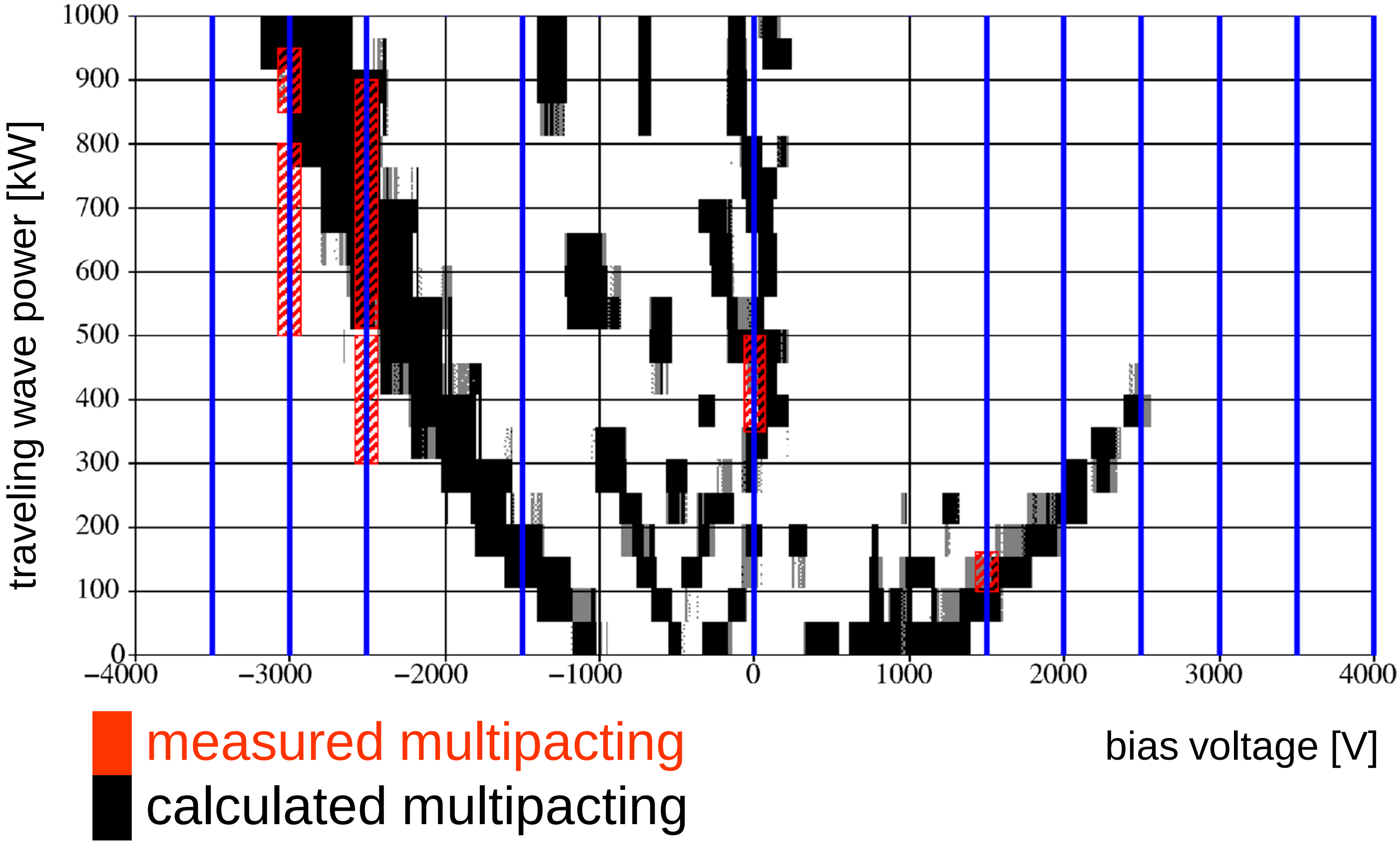
Simulated power (kW)	170~190	230~270	350~390	510~590	830~1000
Power in Coupler (kW)	43~170	280~340	340~490	530~660	850~1020
klystron power (kW)	50~200	330~400	400~580	620~780	1000~1200

More simulations being carried out to understand measurement details

7.6. Cures for multipacting

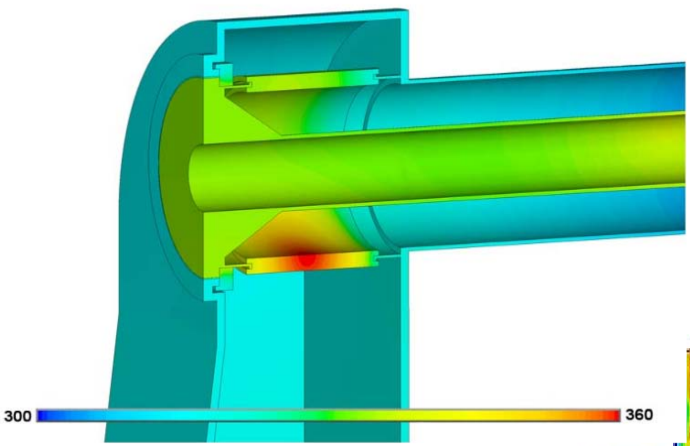
- the right choice of the geometry:
  - bigger coax diameter and higher impedance shift the MP levels to higher power ranges
- reduction of SEC:
  - coating of critical surfaces (e.g. Al_2O_3 SEC≈8) with Ti or TiN (SEC≈1)
  - cleaning RF surfaces before or by conditioning
- shift resonant conditions by additional fields:
  - electrical bias on inner coax
  - magnetic bias on wave guide

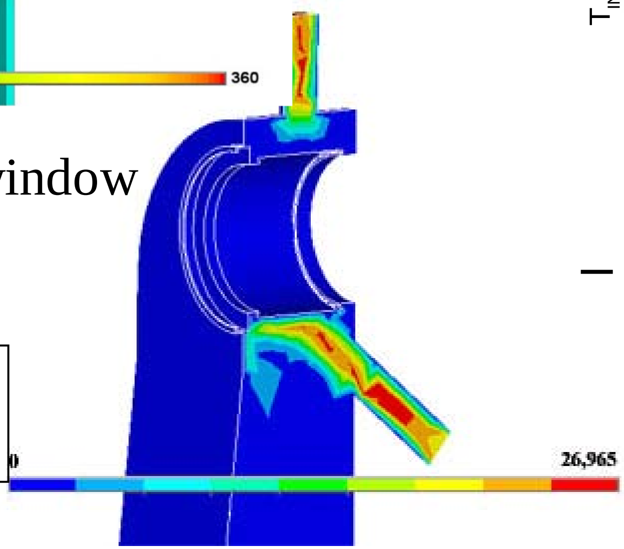
7.7. Multipacting measurements, influence of bias voltage (TTF2 Coupler)



8. Thermal simulations

75 kW CW Coaxial Input Coupler for Cornell ERL Injector Cryomodule

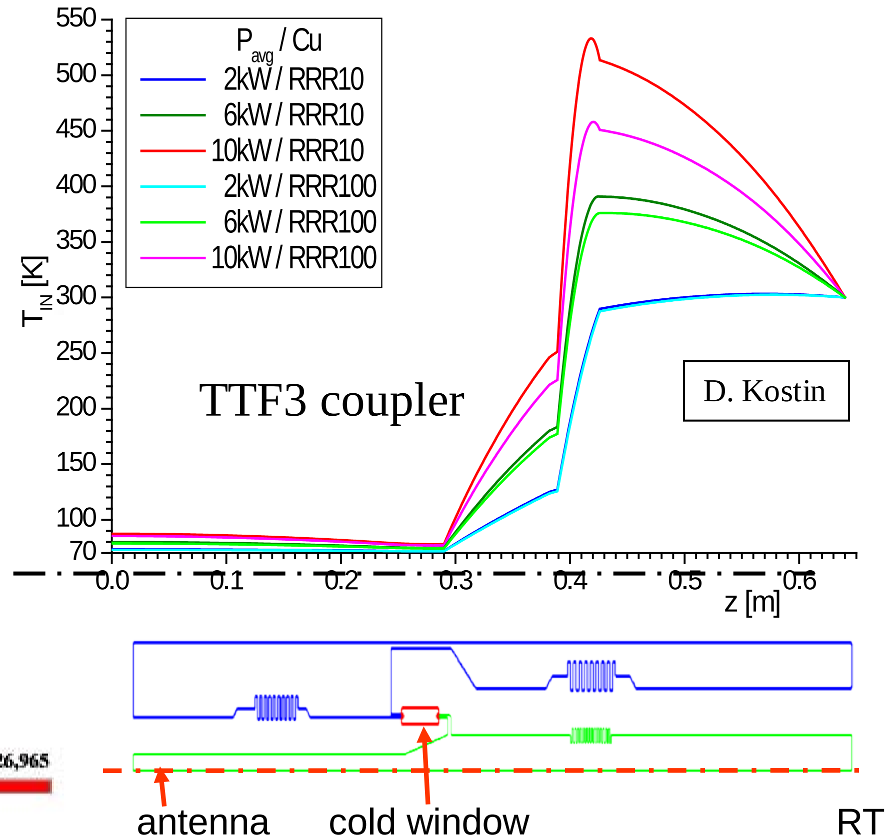




heating of the window and air cooling

Московский инженерно-физический институт and “ИНТРОСКАН”

heating of the inner conductor for different quality of the copper plating



9.1. Fabrication issues, general

- A good RF design is a precondition for a reliably working coupler.
- To realize a good coupler, the RF design has to consider the fabrication, assembly and costs:
  - use standard material qualities (316LN, Cu-OFHC, Al_2O_3)
  - use standards sizes (tubes, bellows, flanges)
  - use standard fabrication techniques
  - use fabrication techniques according to the abilities of the industries involved
  - decide on acceptable tolerances
  - clean handling during the fabrication

  - close collaboration with the manufacturer as early as possible and during the fabrication is a must

9.2. Fabrication issues, stainless steel

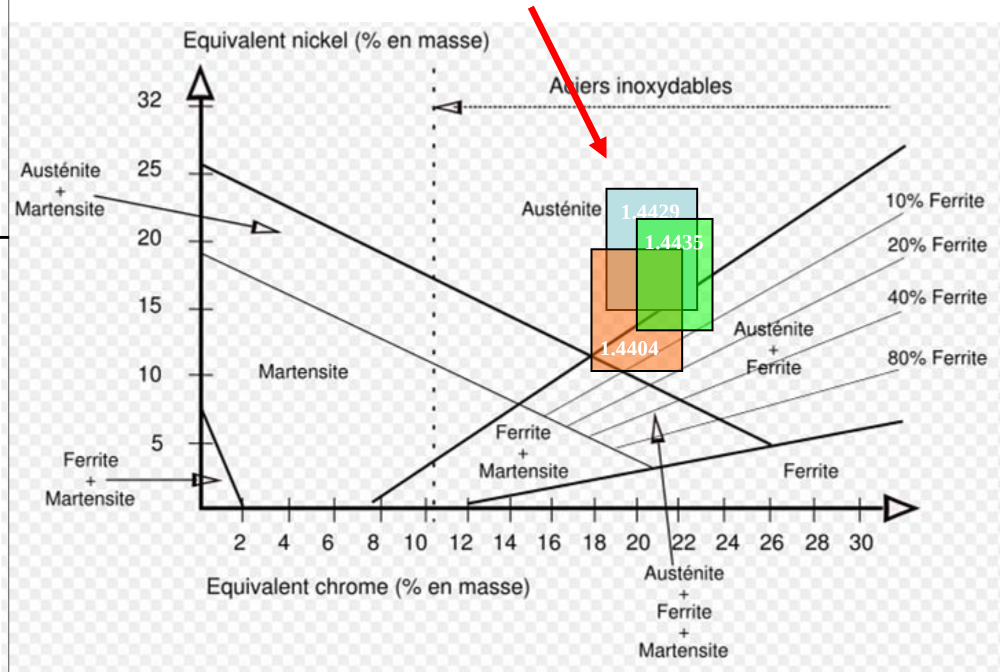
Low permeability (≤1.01) is essentialy close to SC cavity and beam

S. Prat, LAL, Orsay

EN 1.4404 X2 Cr Ni Mo 17-12-2 (316L) • ferrite number ~ 2 • easy to procure	Tubes, bellows, fixation parts
EN 1.4435 X2 Cr Ni Mo 18-14-3 (316L also) • ferrite number ~ 0 • $\mu r < 1.01$ • less easy to procure	Tubes in cold part
EN 1.4429 X2 Cr Ni Mo 17-13-3 (316LN) • $\mu r < 1.005$ • N2 enriched → Hardness 150 / 190 HB • refined by electro slag process • forged in bars • stands baking 2h at 950°C • difficult to procure	• CF flanges • cavity flange

Verify the real chemical composition !
Standards have a wide range

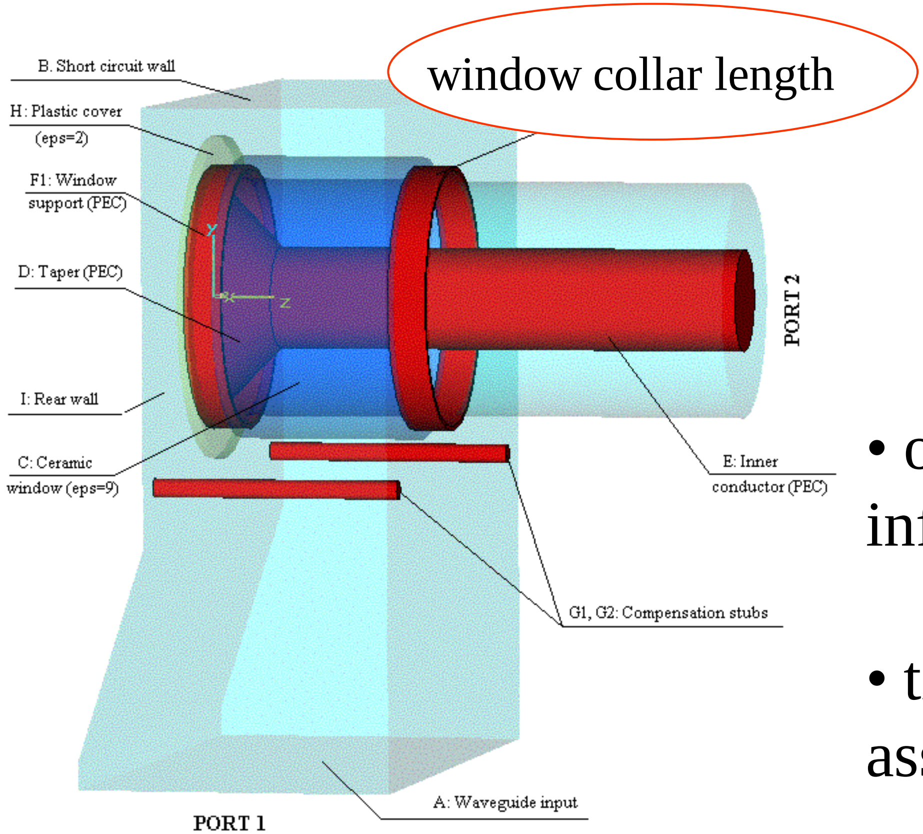
European standard: EN 10088

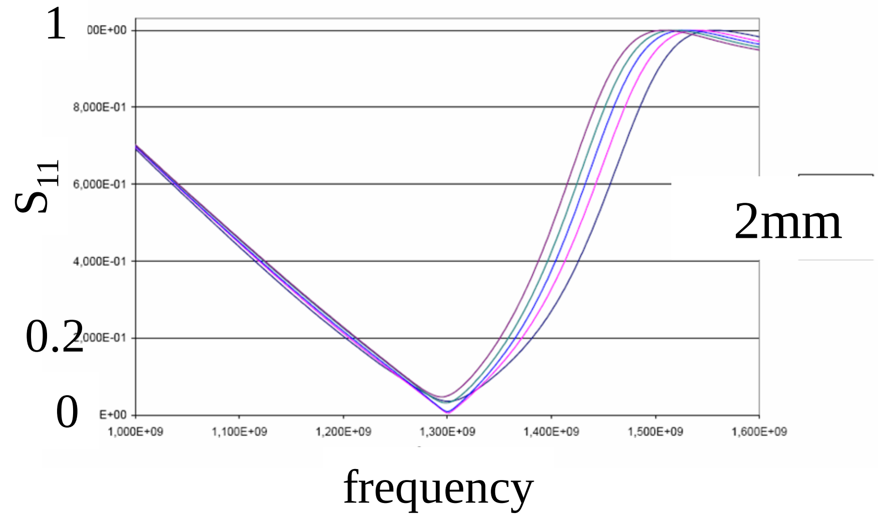


Delong model: Equivalent Chrome : (Cr)eq= (%Cr) + 1,5(%Si) + (%Mo) + 0,5(%Nb)
Equivalent Nickel : (Ni)eq= (%Ni) + 0,5(%Mn) + 30(%C) + 30(%N)

9.3. Fabrication issues, mechanical tolerances

TTF3 WG to coax transition





- one detail might not have a big influence, but they might add up

- tight tolerances at welding assemblies require great care

low tolerances = high costs

A. Labanc

9.4. Fabrication issues, copper plating

Challenges:

- high electrical conductance for low RF losses
- small thickness-low thermal conductance for low static losses (SC cavities)
- good uniformity of thickness especially on bellows
- no blisters or stripping
- low surface roughness

9.5. Fabricating issues, brazing

- ‘Microwave tube industry prefers to braze fixtures and self- fixtured assemblies’[CPI]
- miscellaneous parts can be brazed at one time
- metalized ceramic must be brazed to joining parts
- but:
  - protect the ceramic from evaporated metal (vacuum brazing)
  - avoid brazes with a high vapor pressure
  - notice: copper grain size grows at high temperatures

9.6. Fabricating issues, TiN coating

- Al_2O_3 has a high secondary electron emission coefficient (SEC):
  - coating of the window surface on the vacuum side is a must
- TiN has a low SEC and is a stable composition
- deposition processes are
  - sputtering
  - evaporating
- ammonia is used to convert the Ti to TiN

10.1. RF test and conditioning (aging)

- high power coupler tests are needed for
  - acceptance test
  - preconditioning prior to the operation on cavity
- usually test stands of two couplers at RT
- interlock is needed to protect the coupler and investigate the behavior
- couplers for SC-cavities have to be cleaned up to the ISO4 standard

10.2. What is ‘RF-conditioning’

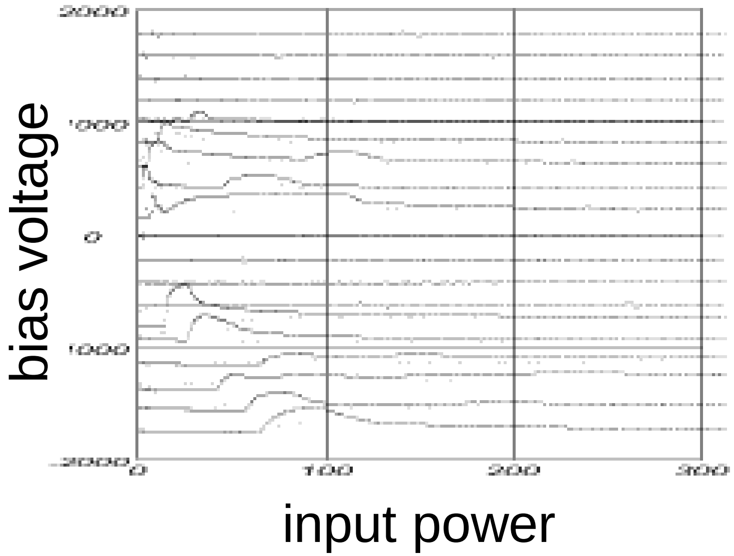
- controlled desorption of absorbed gases by accelerated ions and electrons
- compromise must be found between conditioning speed and sparking risk
- traveling wave cleans all surfaces, at standing waves additional tricks are required
- cold surfaces collect gas after a certain period of operation, maybe reconditioning is necessary

10.3. Testing and conditioning procedure

- low power to high power
- short to long pulses
- low to high repetition rate
- limitation of power rise by thresholds of vacuum, e-, light
- ‘analog processing’: vacuum feedback loop to keep the power level close to the thresholds developed at CERN

10.4. Other processing ‘tricks’

- at KEK the bias voltage on inner coax was used to process the multipacting levels
- controlled discharge processing with Argon or Helium



Pressure increase in coupler at different bias voltage levels

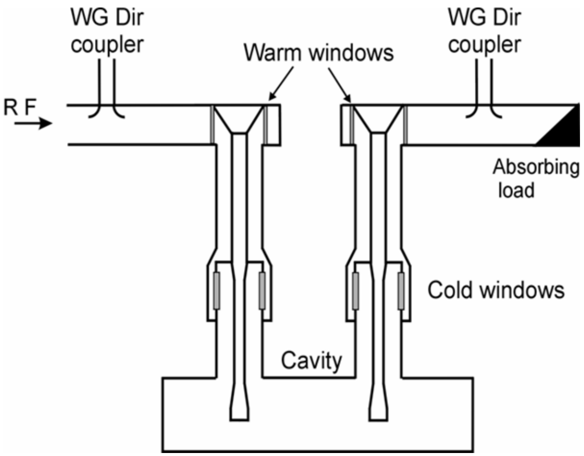
10.5. Technical interlock

The technical interlock system protects the coupler against discharge and other degradation

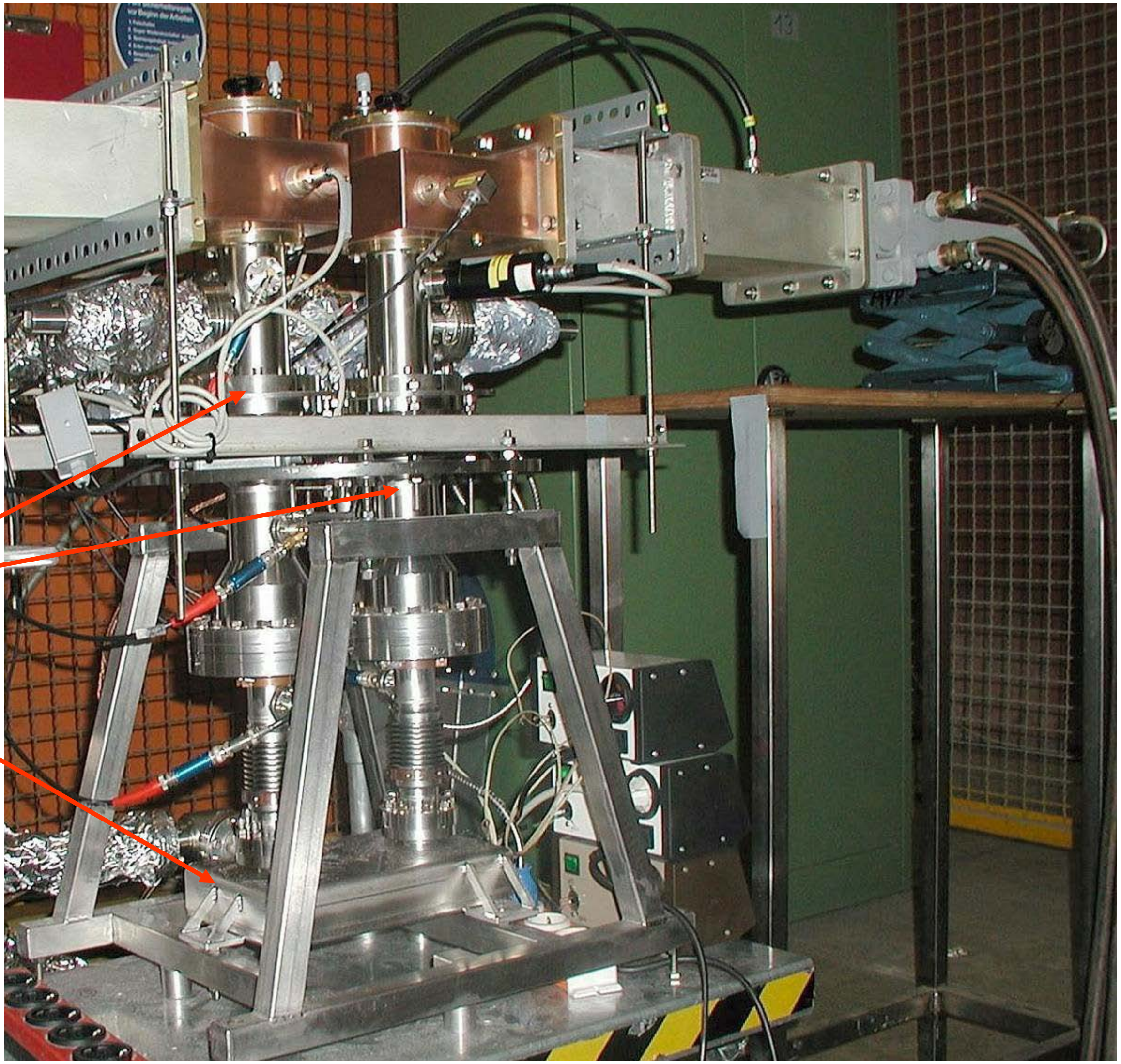
- hardware interlock:
  - vacuum read out
  - e- pick up
  - light detectors in vacuum and on the air side
  - temperature on windows
  - reflected power
- software interlock:
  - all the above mentioned
  - but, thresholds are tighter than hardware interlock in order to avoid RF off time

10.6. TTF 3 Coupler on Test Stand

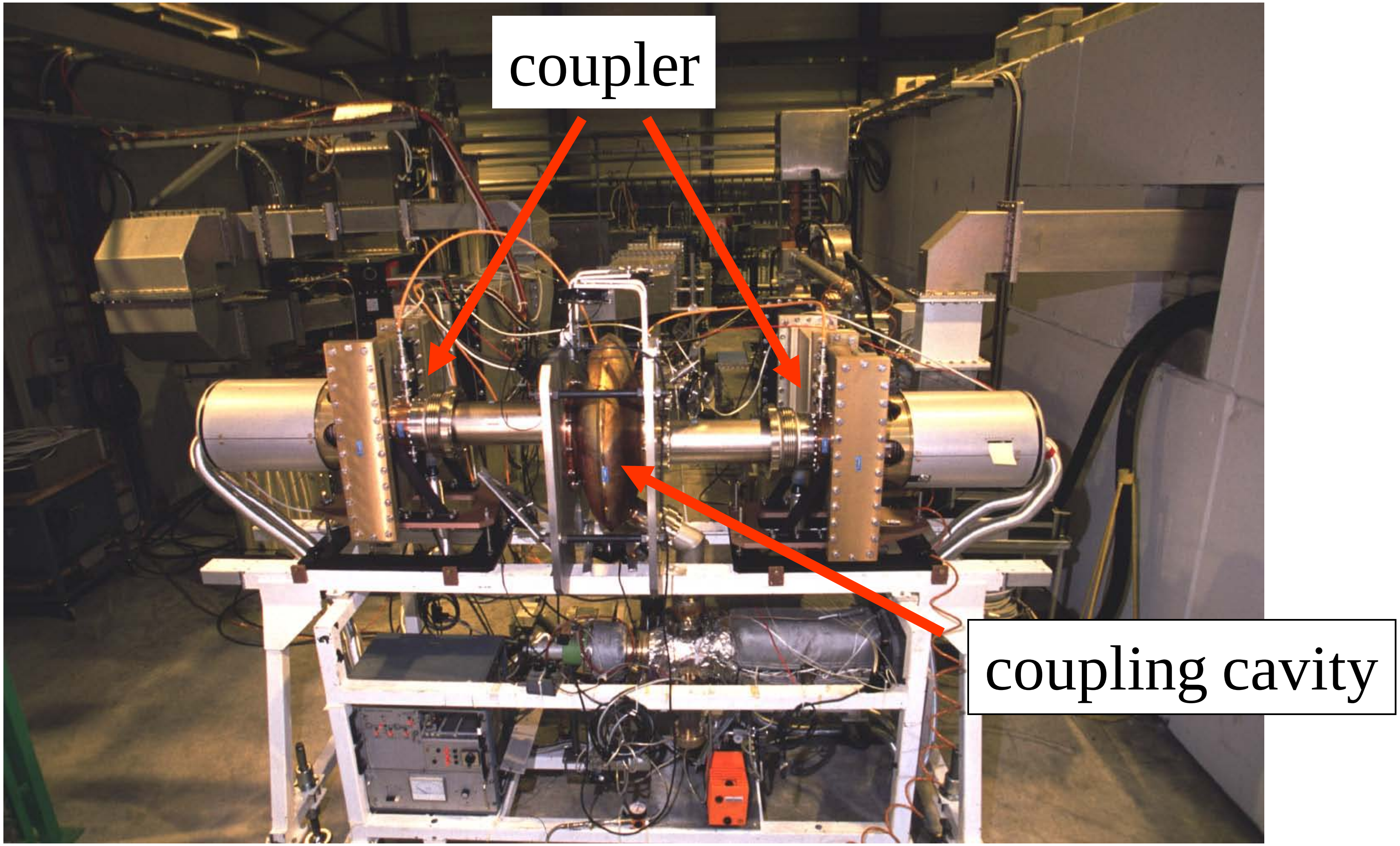
Teststand



- two couplers
- WG coupled
- traveling wave or standing wave
- room temperature



10.7. LHC power coupler test stand



11.1. Handling before processing

- storage of all coupler parts always under dry Nitrogen in order to avoid oxidation and contamination
- after assembly baking of the test stand in situ

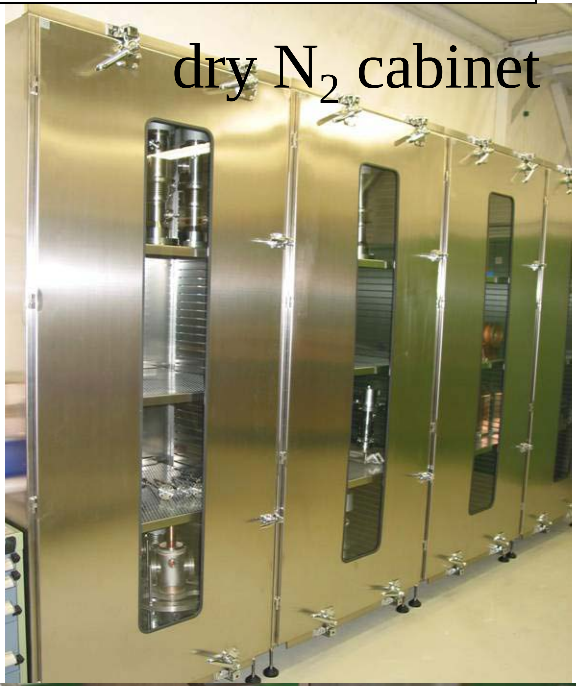
For SC cavities:

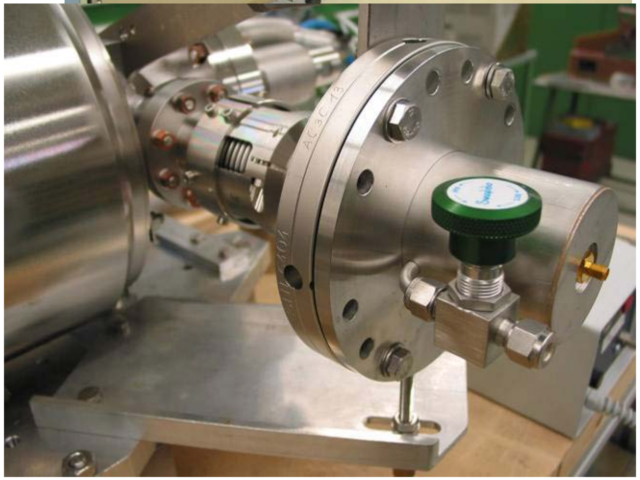
- cleaning to the SC cavity standard, ultra pure water
- assembly in class 10 clean room

11.2. Handling after conditioning

Goal is to maintain the processing effect

- disassembly from test stand and assembly to the cavity & module under clean conditions
- store always under dry nitrogen to avoid contamination by water and others





sealing cap for cold window

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