COUPLERS

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Important Points

- Couplers are critical components of SRF accelerators
- Cost of couplers is often comparable to that of cavities
- Coupler failure can have a dramatic impact on performance and availability of an accelerator
- Coupler engineering is challenging
- (In my opinion) they receive less attention than cavities
- Cavity and coupler should be treated as an integrated system

Requirements

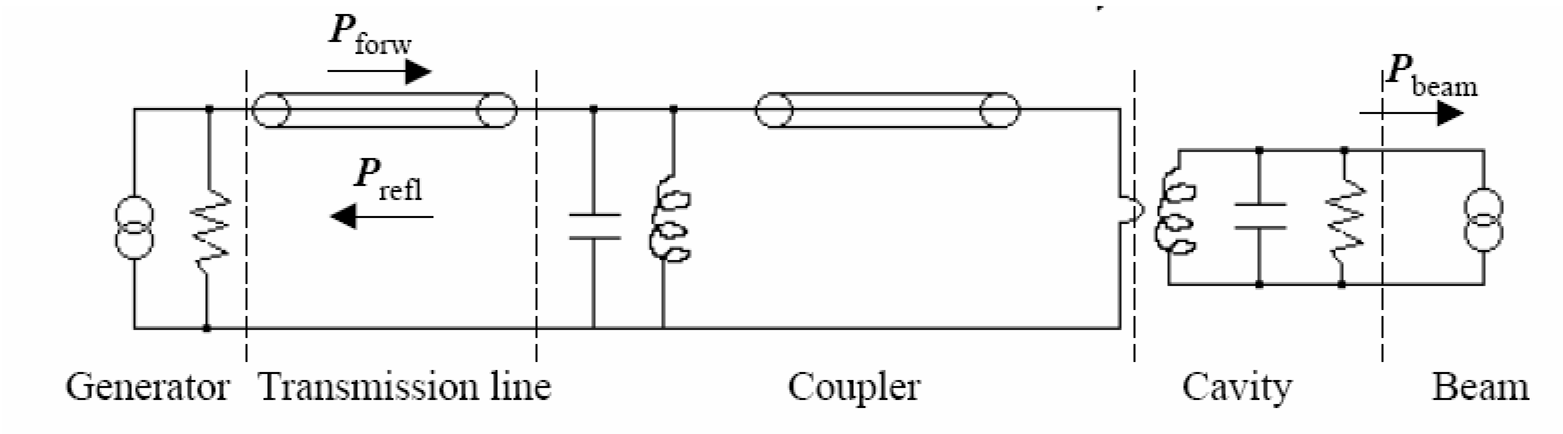
- Requirements on couplers are becoming increasingly more demanding:
  - Higher gradients require more standing wave power
  - Higher beam currents: more traveling wave power
  - Pulsed power: transient conditions, transient gas loads

Main Function (rf)

Efficiently couple rf power from a source to a load

Transmit MW of pulsed power, 100s of kW of average power

Provide efficient matching



Main Function (vacuum)

Provide an interface between atmospheric pressure and ultra-high vacuum

Protect the ultra-clean interior of a superconducting cavity from contamination

Prevent any degradation of the cavity performance

Main Function (thermo-mechanical)

Provide a transition between room temperature and cryogenic temperature

Should be designed to transmit only a very small amount of thermal power from room temperature to cryogenic temperature (100s of mW)

Need to be able to withstand thermal cycling

Need to be able to withstand thermal gradients and differential thermal contraction

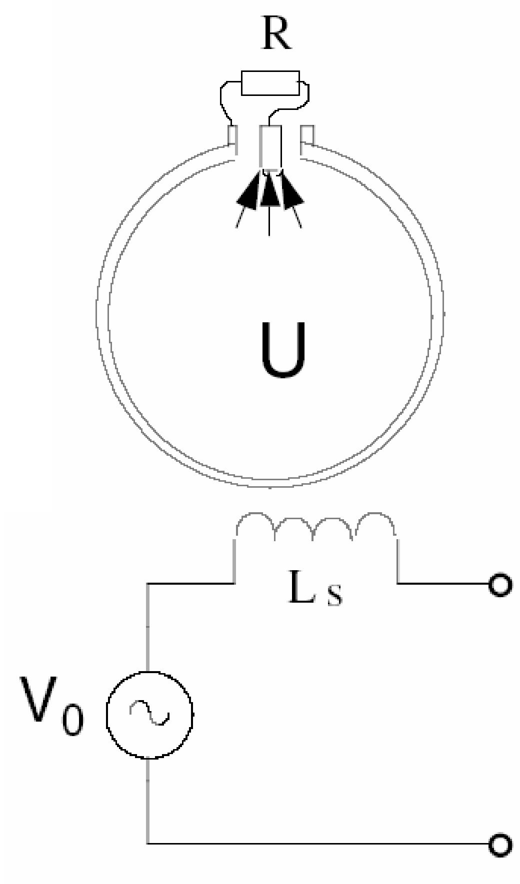
Internal to the coupler

External to the coupler

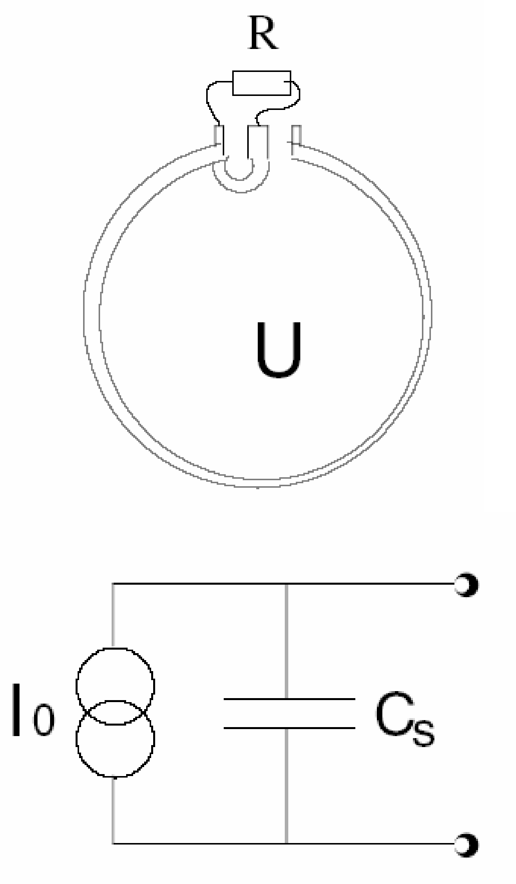
Main Power Coupler Types

	Pros	Cons
Waveguide	• Simpler design • Better power handling • Easier to cool • Higher pumping speed	• Larger size • Bigger heat leak • More difficult to make variable
Coaxial	• More compact • Smaller heat leak • Easier to make variable • Easy to modify multipacting power levels	• More complicated design • Worse power handling • More difficult to cool • Smaller pumping speed

Coaxial Power Coupler Types

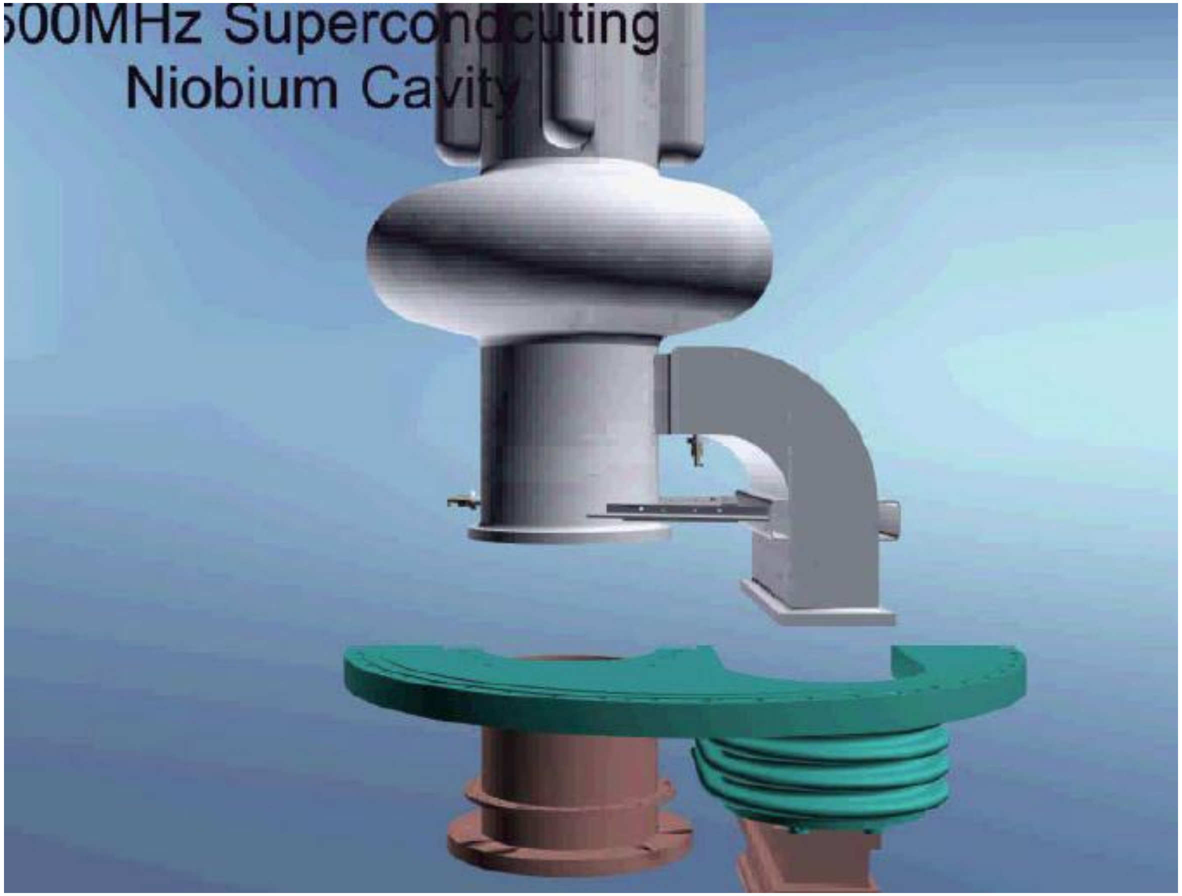


Coupling to the electric field

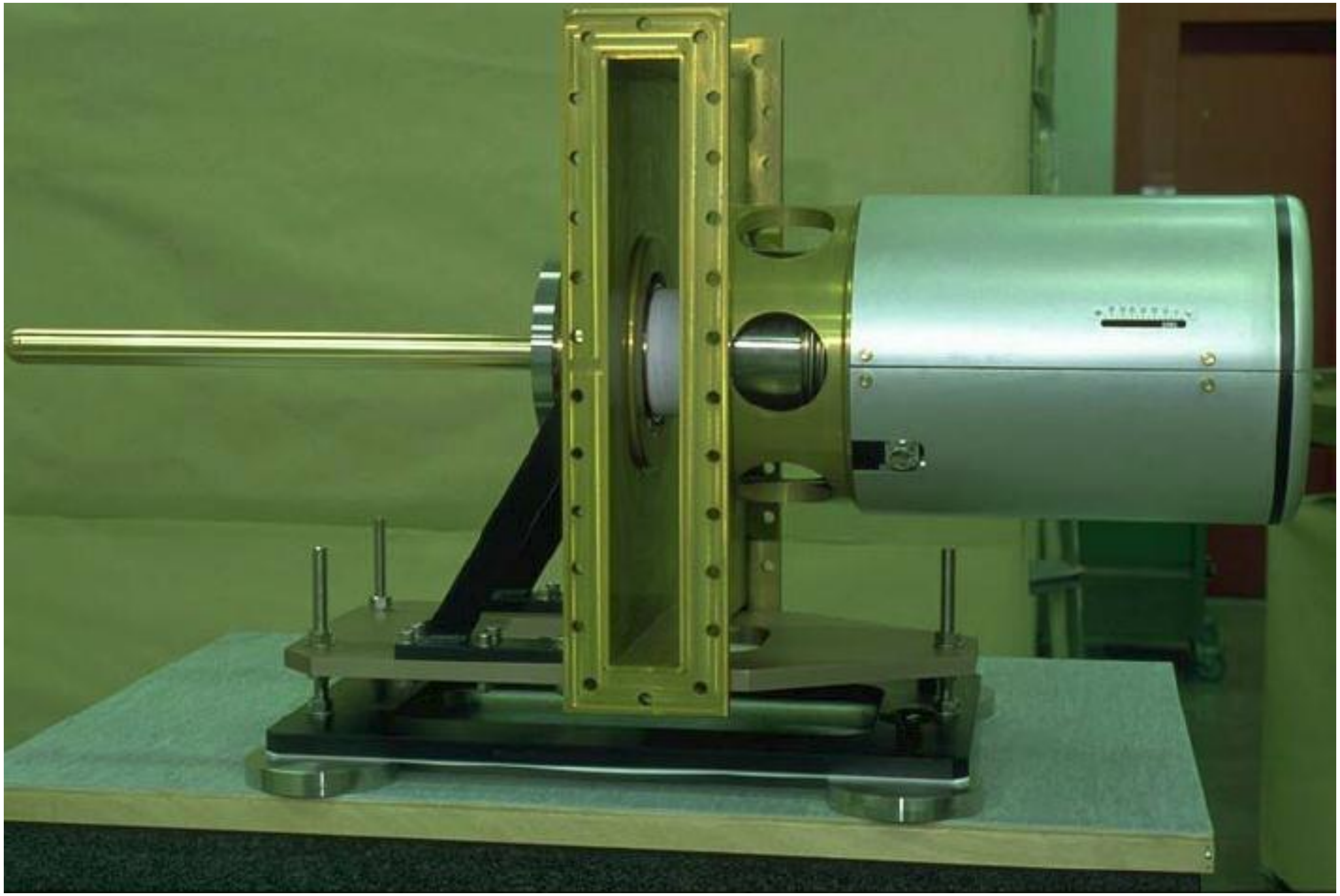


Coupling to the magnetic field

CESR II Waveguide Coupler



Variable Power Coupler for LHC



Windows

Two main types of windows

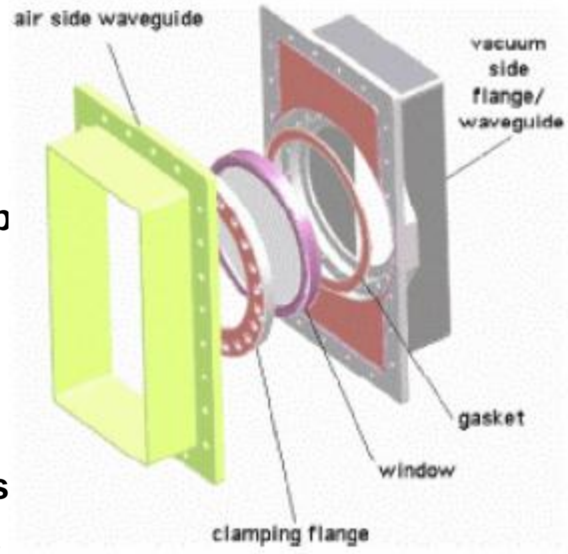
Planar windows for waveguides (JLab

Coaxial windows

Disks (APT, KEKB, Tris

Cylindrical (HERA, LEP2,

Conical



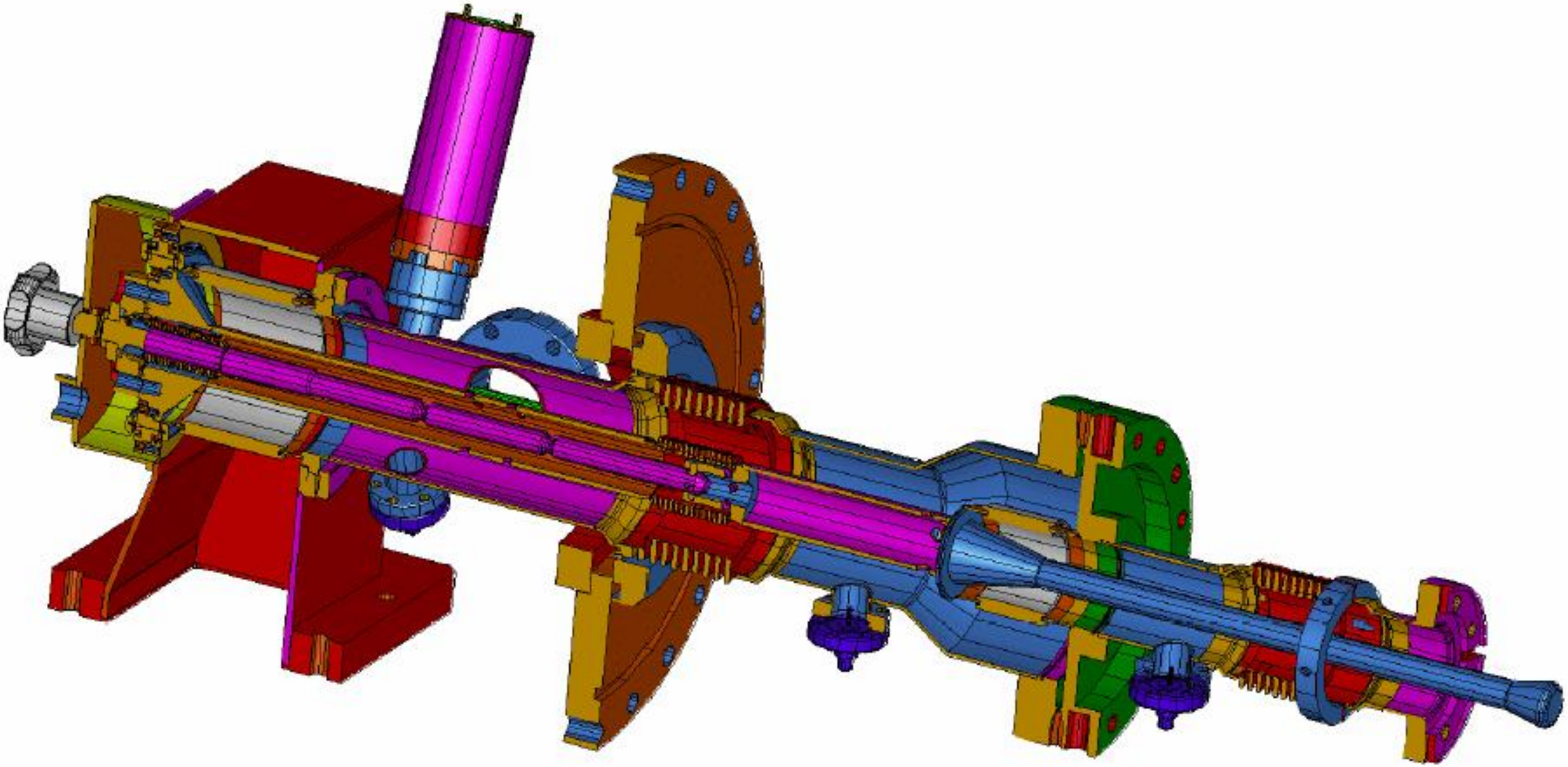
High Power CW Couplers

Facility	Frequency	Coupler type	RF window	Q_{ext}	Max. power	Comments
LEP2	352 MHz	Coax fixed	Cylindrical	2×10^6	Test: 565 kW 380 kW Oper: 100 kW	Traveling wave @ Γ=0.6 288 couplers
LHC	400 MHz	Coax variable (60 mm stroke)	Cylindrical	2×10^4 to 3.5×10^5	Test: 500 kW 300 kW	Traveling wave Standing wave
HERA	500 MHz	Coax fixed	Cylindrical	1.3×10^5	Test: 300 kW Oper: 65 kW	Traveling wave 16 couplers
CESR (Beam test)	500 MHz	WG fixed	WG, 3 disks	2×10^5	Test: 250 kW 125 kW Oper: 155 kW	Traveling wave Standing wave Beam test
CESR	500 MHz	WG fixed	WG disk	2×10^5	Test: 450 kW Oper: 300 kW 360 kW	Traveling wave 4 couplers Forward power
TRISTAN	509 MHz	Coax fixed	Disk, coax	1×10^6	Test: 200 kW Oper: 70 kW	32 couplers
KEKB	509 MHz	Coax fixed	Disk, coax	7×10^4	Test: 800 kW 300 kW Oper: 380 kW	Traveling wave Standing wave 8 couplers
APT	700 MHz	Coax variable (±5mm stroke)	Disk, coax	2×10^5 to 6×10^5	Test: 1 MW 850 kW	Traveling wave Standing wave
JLAB FEL	1500 MHz	WG fixed	WG planar	2×10^6	Test: 50 kW Oper: 35 kW	Very low ΔT 2 couplers

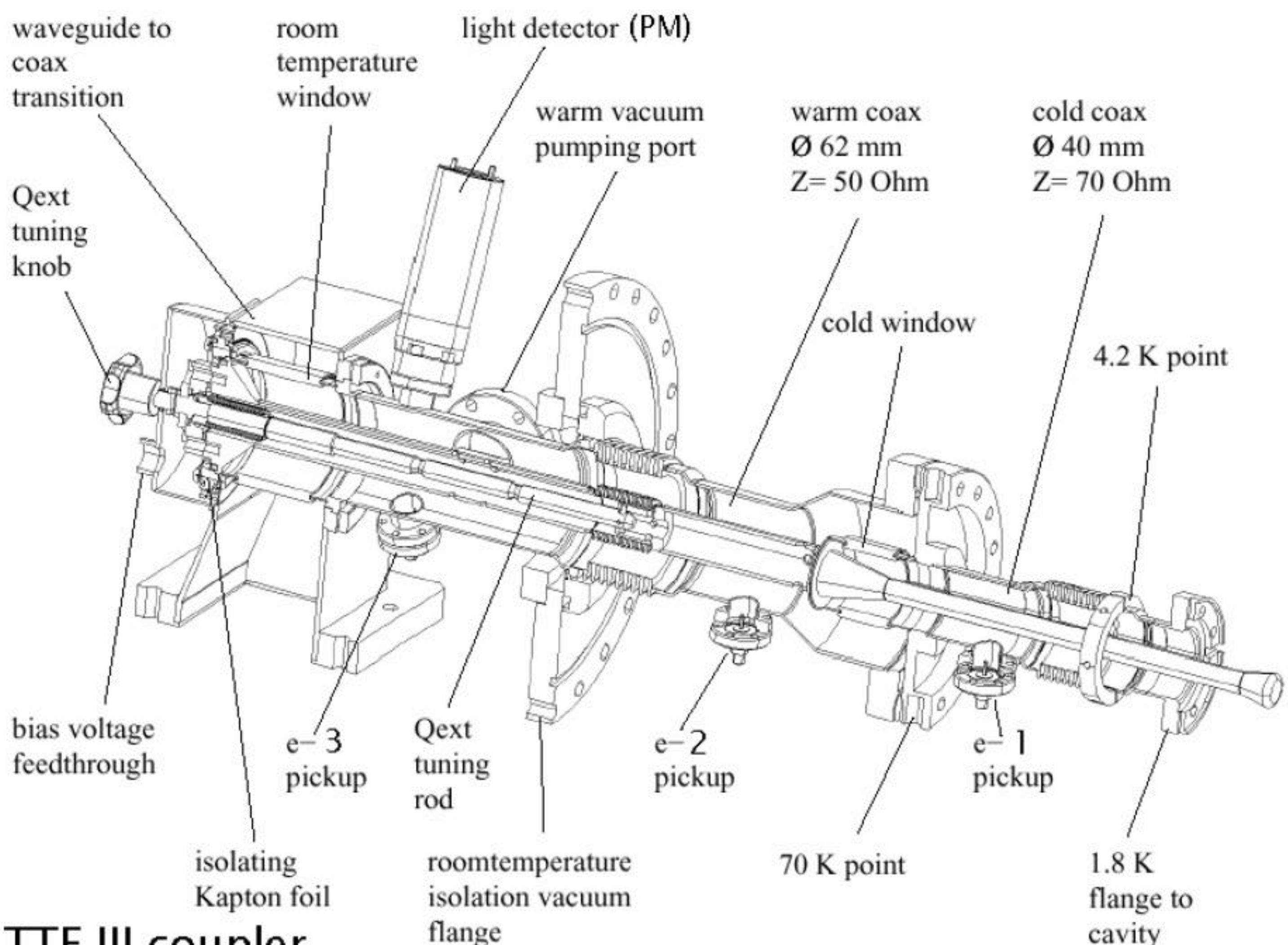
High Power Pulsed Couplers

	frequency	Peak power	Average power	Coax diameter	Number of windows	Cavity gradient	electric field in coax, TW
SC proton linac, KEK, JAERI	0.9 GHz	250 kW	6.25 kW	80 mm	1	10 MV/m	0.4 MV/m
SNS, JLab	0.8 GHz	550 kW	48 kW	96 mm	1	12 MV/m	0.6 MV/m
Tesla 500, TTF, TESLA collaboration	1.3 GHz	250 kW	3.25 kW	40 mm	2	25 MV/m	0.8 MV/m

Example: TTF3 Coupler



Example: TTF3 Coupler

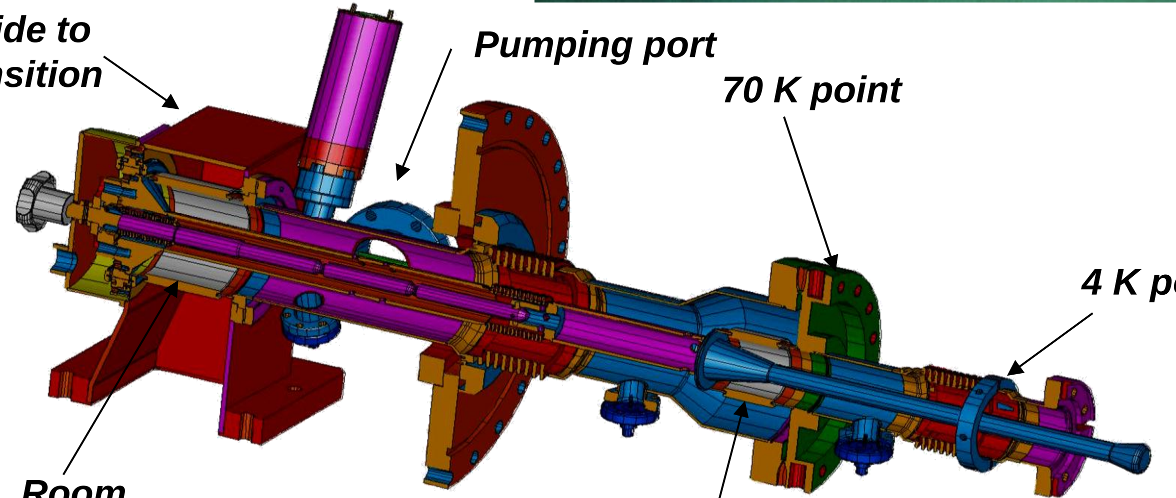


TTF III coupler

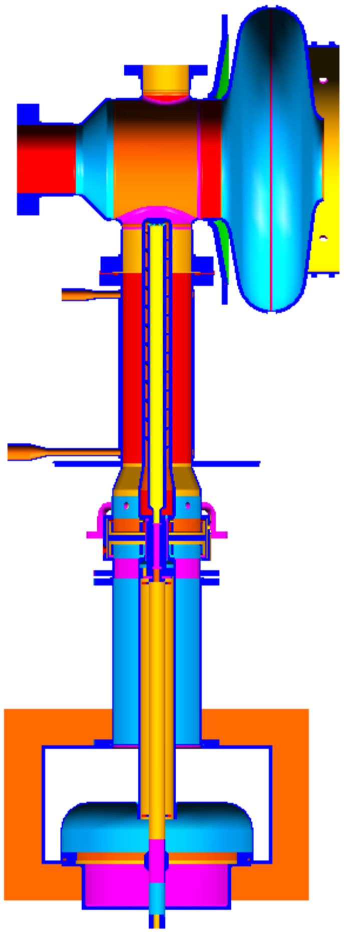
Fundamental Power Coupler

Test showed that FPC (TTFIII)

- ***Power capability is 1 MW in the TW mode.***
  - ***SW capability is at least 1 MW***
  - ***Processing time is of concern***



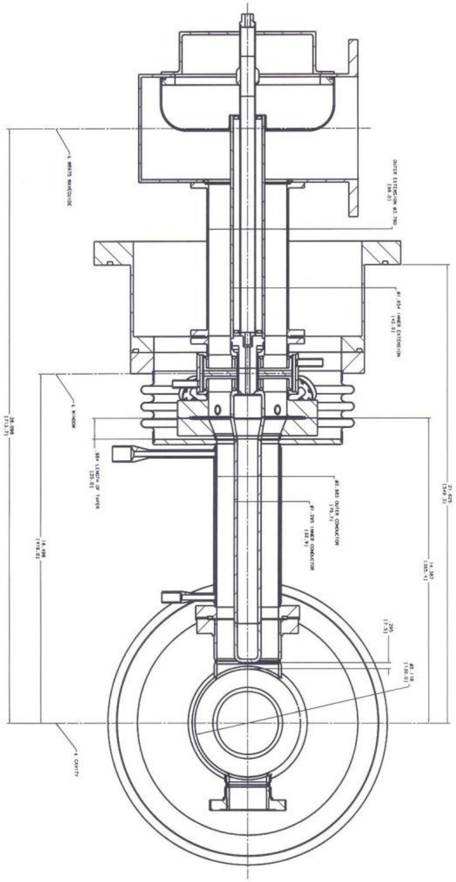
Example: SNS Power Coupler

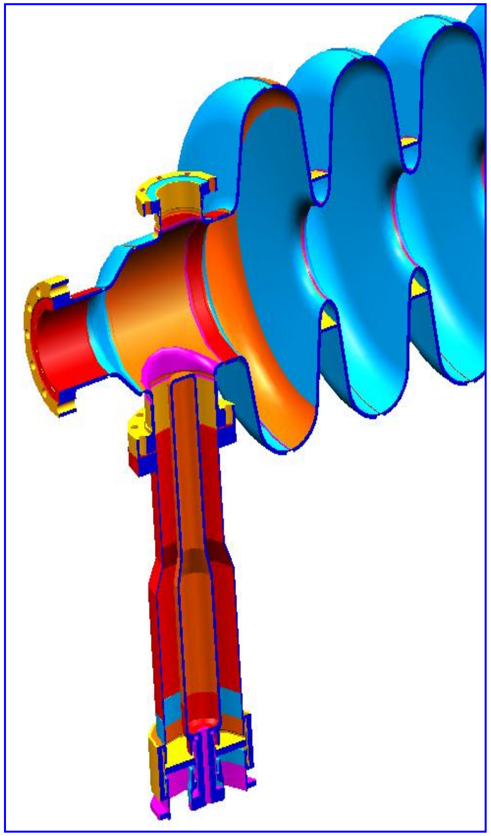


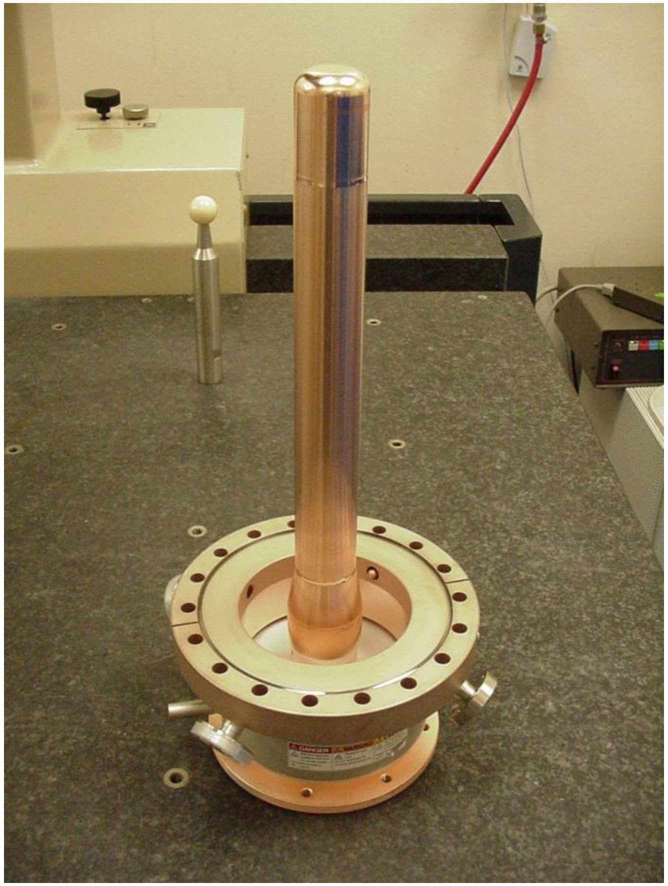
- Coupler transfers RF Power from klystron to beam
  - Normal Operation (1.0 GeV): 320 kW at 7% Duty Cycle
  - Upgraded operation (1.3 GeV): 400 kW at 11% duty cycle
- Coupler scaled from KEKB coupler (508 to 805 MHz)
  - Length: ~ 20.6 in.
  - Weight: ~ 23 lbs
- Ratio of inner conductor to outer conductor: 2.3 (to maintain 50 Ohm impedance)

SNS Fundamental Coupler (Fixed)

Design is scaled from KEK design







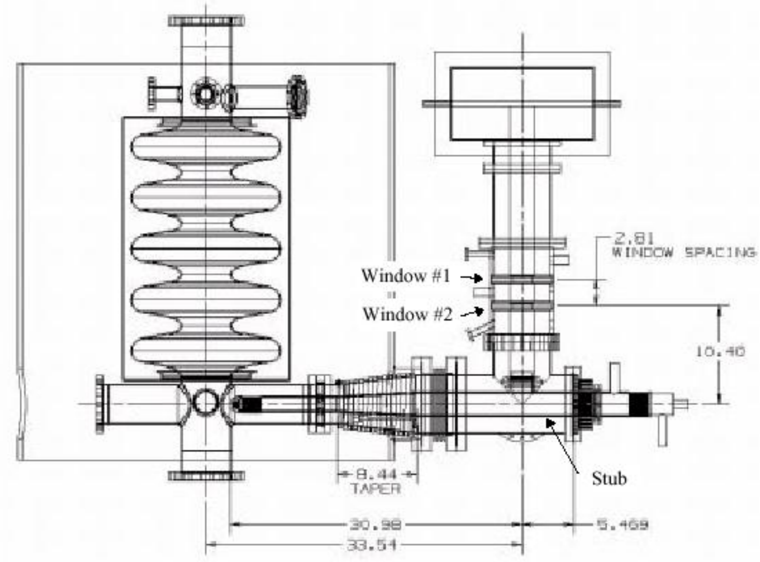
APT Coupler (Variable)

More compact at lower frequencies

Allows variability

More complicated geometry and manufacturing

High Power: > 400 kW CW
Variable coupling: 2 - 6 E5
High-speed pumping
Double window
Tested up to 1 MW TW CW
850 kW SW



CW and Pulsed Power Couplers

- Couplers for cw operation
  - High average power
  - Stable operation
  - Gas discharge requires complete shutoff of rf power

- Couplers for pulsed operation
  - Lower average power
  - Coupler events (discharge) are easier to handle
  - Transient dynamics
    - Dynamic Lorentz detuning causes frequency and phase shifts
    - Electromagnetic fields in the coupler displays transient and standing wave patterns

Coupler Failures

- Cracked windows due to mechanical stresses
- Cracked windows due to thermal stresses
- Punctured windows due to electron activities
- Leaking brazes and welds
- Leaking flanges
- Burned bellows
- Cracked bellows

Coupler Degradation

- Increased heating
- Increased arcing
- Multipacting barriers
- Window metalization
- Passband detuning

Physics Causes of Failure or Degradation

- Undesirable rf modes
  - Higher order modes
  - Transients
  - Passband modes
  - Harmonics from rf source
- Electronics activity
  - Multipacting
  - Plasma discharge
- Sputtering
- Gas condensation

Engineering Causes of Failure or Degradation

- Insufficient thermal margin
  - Overheating
  - Thermal stresses
- Inadequate mechanical design margin
  - insufficient stress relief
  - Insufficient tolerances
- Inadequate pumping
- Poor process control
  - Plating
  - Ceramic manufacturing and qualification
- Inadequate interlocks
  - Electron activity
  - Gas discharges
  - overheating

Multipacting in Couplers

e.g. P. Ylae-Oijala; "Analysis of Electron Multipacting in Coaxial Lines with Traveling and Mixed Waves", TESLA-Report 97-20

Electron Multipacting is a significant problem in coaxial lines and requires in most cases extensive "conditioning": As in cavities, certain conditions have to be satisfied to generate multipacting:

- An electron emitted from a wall of the line is under the influence of the EM fields returning to its origin within an integer number of rf cycles
- The impacting electrons produce more than one electron, if the impact energy is high enough

Because in coax lines standing, traveling and mixed wave pattern can exist depending upon the load conditions, MP is very complex in these systems

Multipacting

Traveling Wave case

- Multipacting power bands occur at 4 times higher power levels than in SW case

$$P\,(TW) = 4\,P\,(SW)$$

- Only orders 2-9 multipactor because of impact energy dependence of secondary yield
- Trajectories of MP electrons are different in SW and TW operation: stationary in SW, traveling with wave in TW, app.1 mm between wall impacts

$$V(\text{traveling}) \sim d^2 f / (1+n)$$

- MP may appear in entire line in TW, only at discreet points in SW (max. of E-field)

TW/Mixed Wave case occurs, when reflected wave vanishes

and is more complicated

Multipacting

Standing Wave case (E.Somersalo, P.Ylae-Oijala, D.Proch; ”Analysis of MP in Coaxial Lines”, PAC 95, pp.1500-1502)

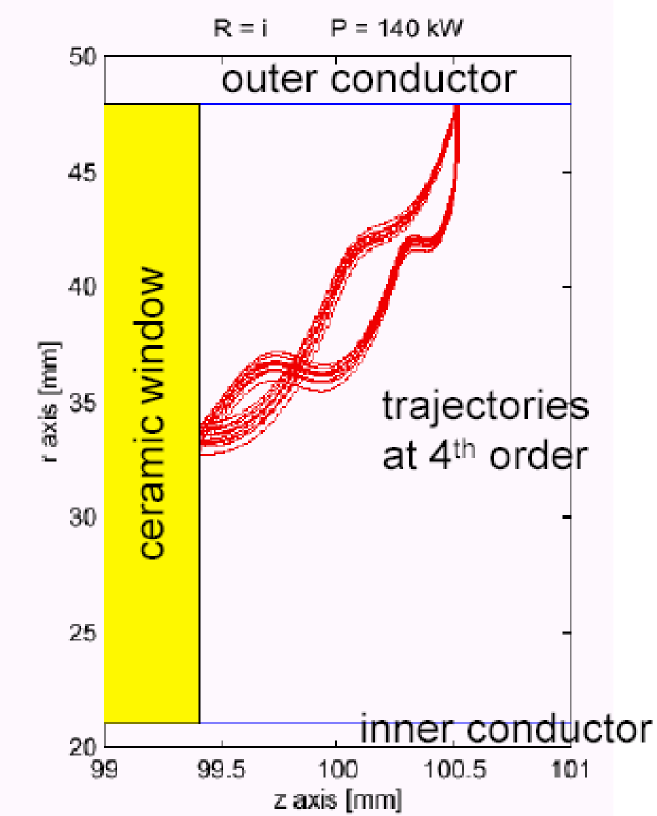
- Multipacting always occurs close to the electric field maximum and close to zero in magnetic field: electric multipacting
- Two types of MP:
  - 1-point of different order on outer conductor
  - 2-point of different order between outer and inner conductor
- Simple scaling laws for MP in straight coax lines (f, diameter d and impedance Z)

1-point: $P \sim (f\,d)^4\,Z$

2-point: $P \sim (f\,d)^4\,Z^2$

Multipacting 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)



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Cures for multipacting

- the right choice of the geometry:
  - bigger coax diameter, higher impedance
- reduction of SEC:
  - coating of critical surfaces (e.g. ceramic 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

Coupler Processing Stands

SNS main power coupler test cart

The test cart is design to allow simultaneously processing (baking or RF conditioning and high power testing) of two main power couplers at room temperature.

Design criteria :

- mechanical : robustness, invariant dimensions as a function of temperature, pressure and mechanical deformation, sustaining repeat utilization, modularity and mobility.

- clean room : possibility of applying cleaning procedure for admission in clean room class 100 or better.

- pressure range : from over atmospheric 10^3 Torr to 5 10^{-9} Torr

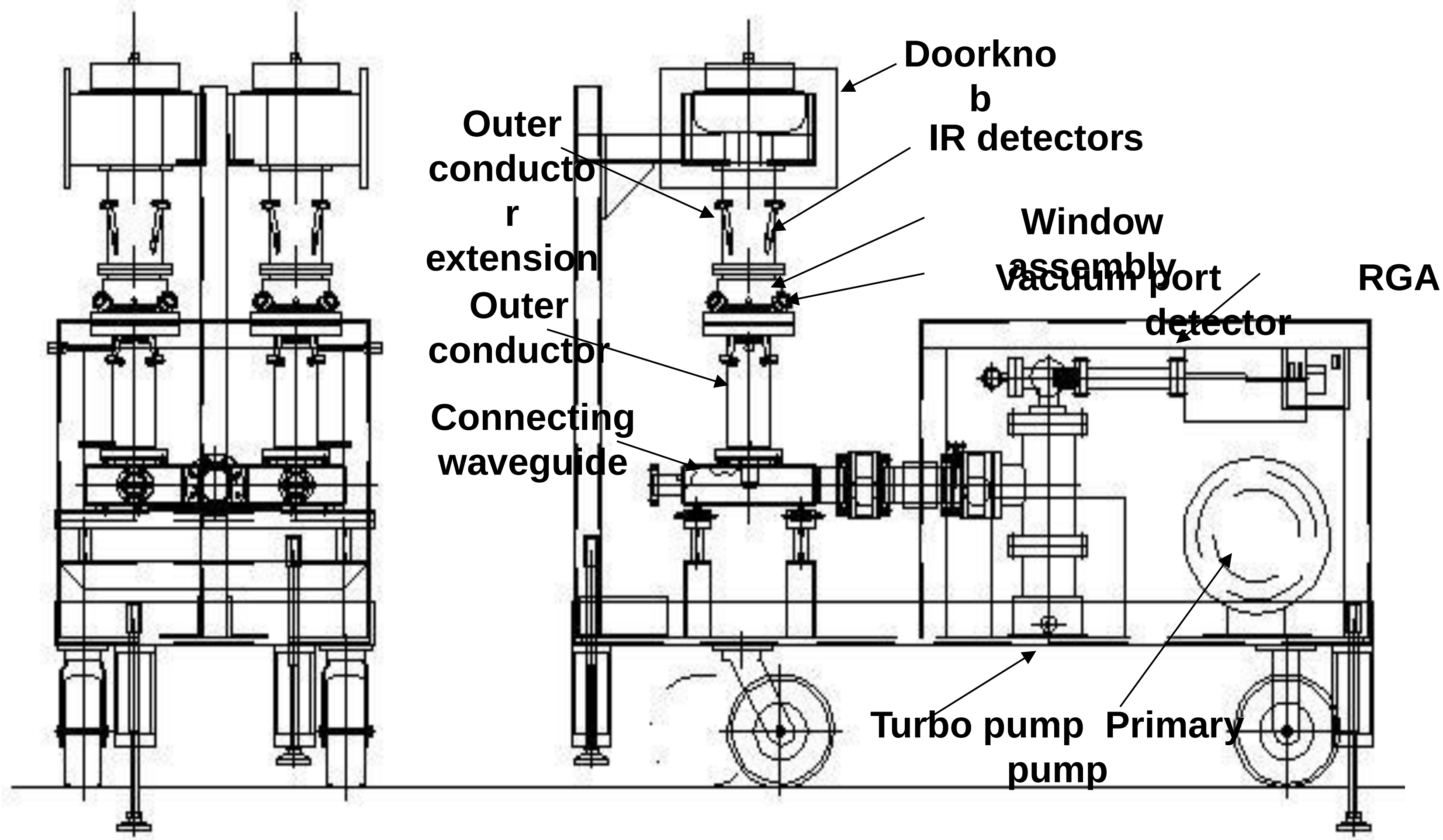
- RF

- controls and instrumentation

- safety aspects (HV, RF, temperature, pressure, cooling agents)

Test Cart

Cart for testing the SNS power couplers



Processing

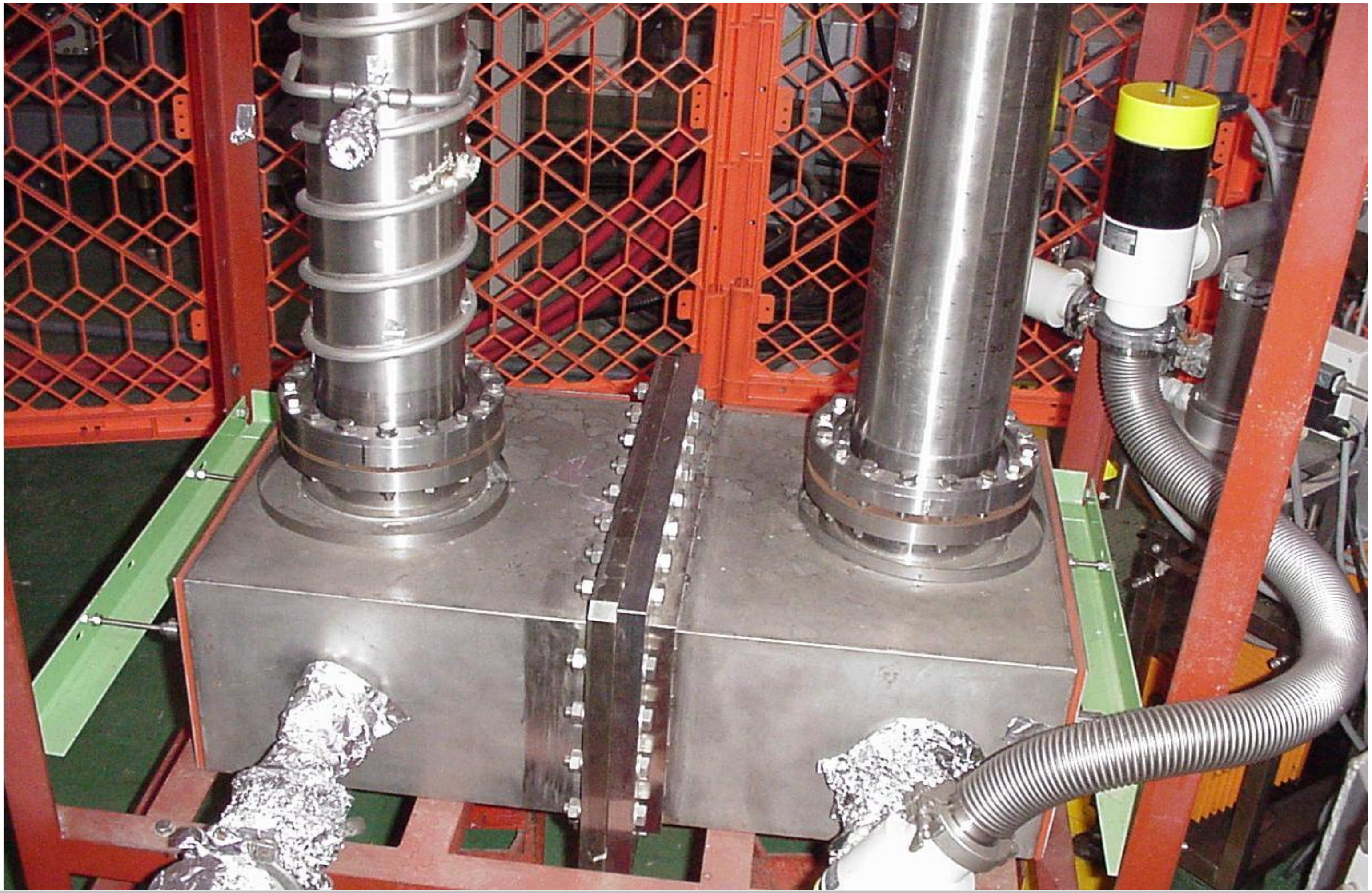
- There does not exist a "Standard" conditioning procedure
- Each lab has developed or is in the process of developing an optimum procedure for its coupler
- Many different methods are applied in succession such as TW processing, SW (off resonance) processing, frequency sweeping, power sweeping, bias voltage processing, warm and "cold" processing, vacuum interlocking at different vacuum levels
- The objective is always to "touch" as much surface area with rf as possible to desorb residual gas layers (they enhance the secondary electron emission coefficient and cause "desorption outbursts")

Processing

- In all cases the windows are conditioned in a test stand (or cavity) at a factor of 2 higher power levels than needed in operation

- If a cavity "quenches" in operation or trips by some other reason, all the forward power in the coupler is reflected and some areas in the coupler "see" 4 times the power level. Therefore, it seems important to "age" couplers at higher powers

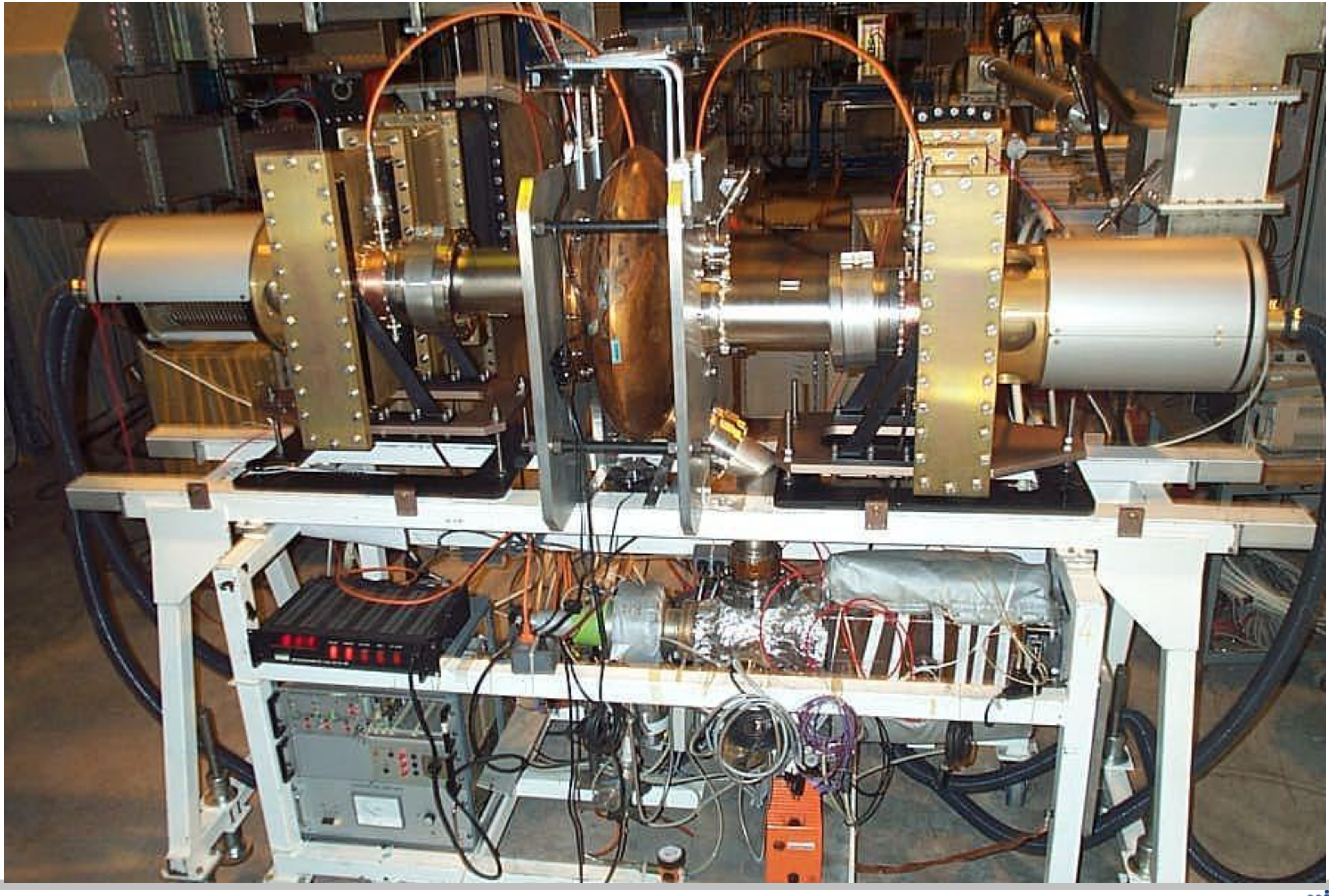
KEK connecting waveguide



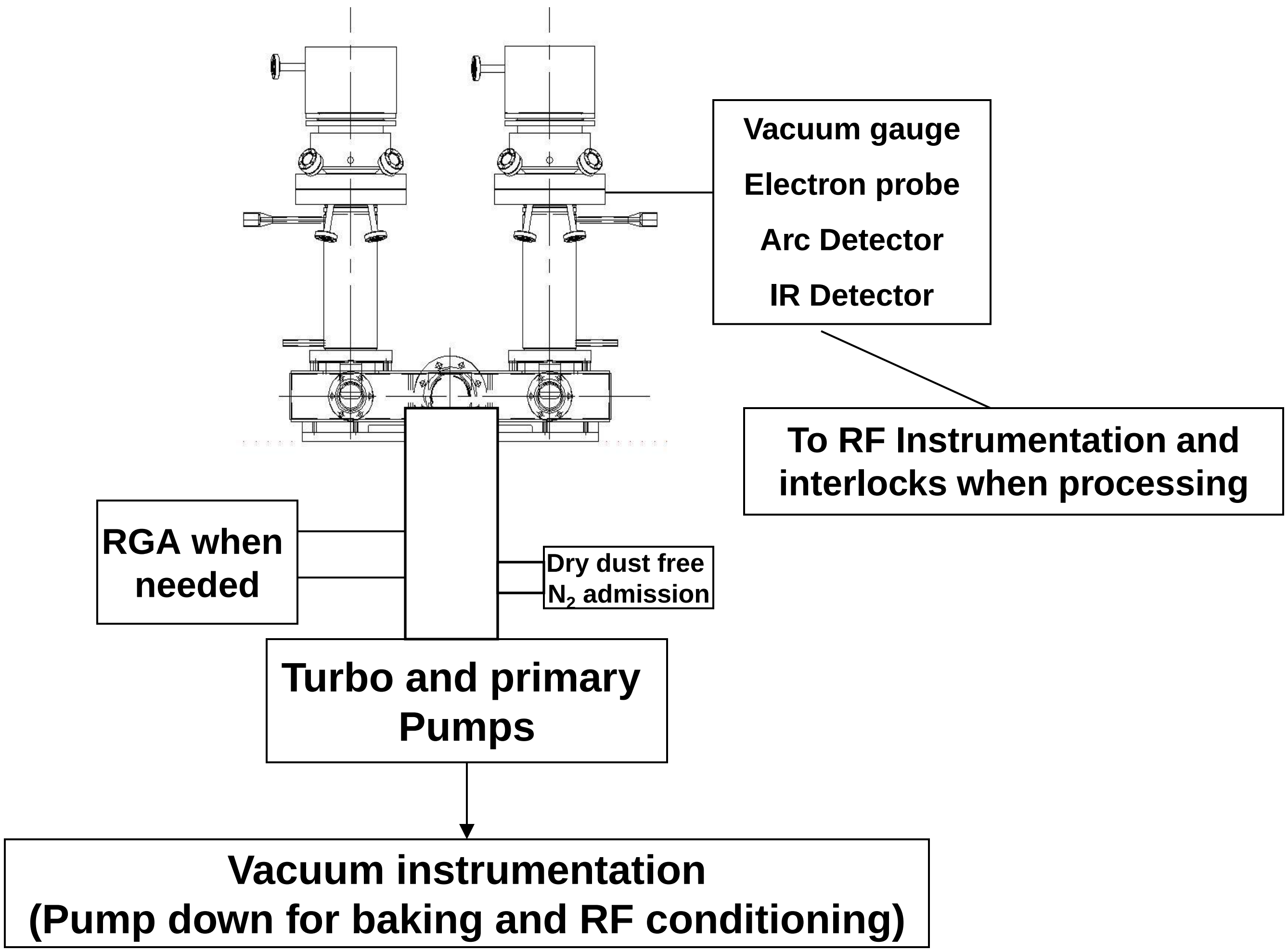
KEK baking stand

Test stand for LEP main power couplers

Test stand for LHC main power couplers



Instrumentation for bake out



Fundamental Power Coupler

What is 'RF-processing'

- 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 certain period of operation

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Fundamental Power Coupler

Testing and processing 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

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RF conditioning

Start RF conditioning in TW with the capacitor for DC bias short-circuited:

- use pulses with short duration and small amplitude.

- increase RF pulse amplitude (fast vacuum feedback loop and computer assisted).

- ramp up and down pulse amplitude around multipacting level.

- gradually increase pulse duration (up to 1.8 ms) and duty cycle. Check for average RF power. Use different ramping steps.

- at chosen power levels (550 kW, 1.1 MW) continue pulsing for several hours.

- perform RF conditioning with DC bias (500 V, 1 kV, 1.5 kV and 2.5 kV).

Continue RF conditioning in SW using a sliding RF short circuit.

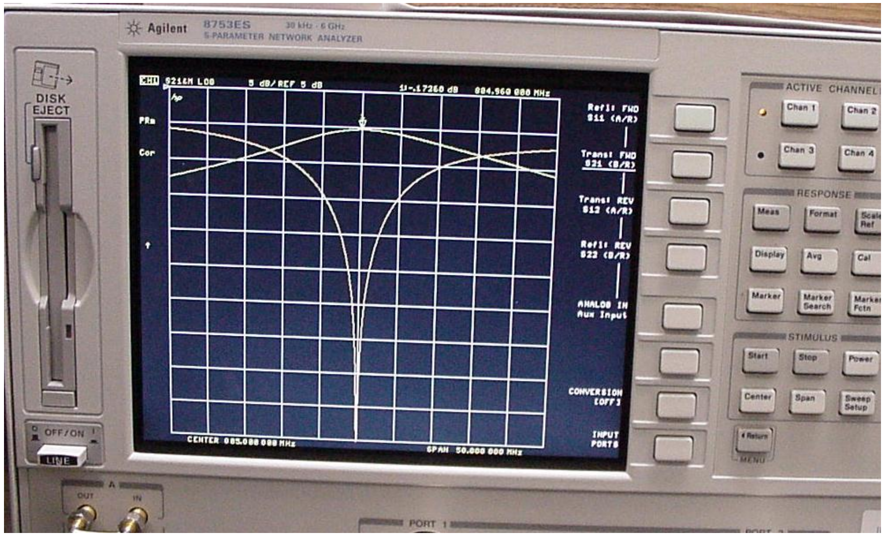
- use short pulse duration, start with small amplitude then increase the pulse amplitude to reach power levels approaching 4.4 MW.

- change position of the short circuit in steps of 10 mm.

- Continue conditioning until pulsing at maximum power there is no more RF induced outgassing and the nominal DC bias is effective in controlling multipacting events.

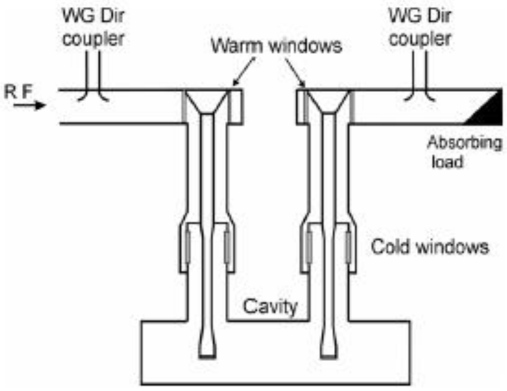
Controls for conditioning LEP main power couplers

JLAb SNS FPC Processing Test Stand

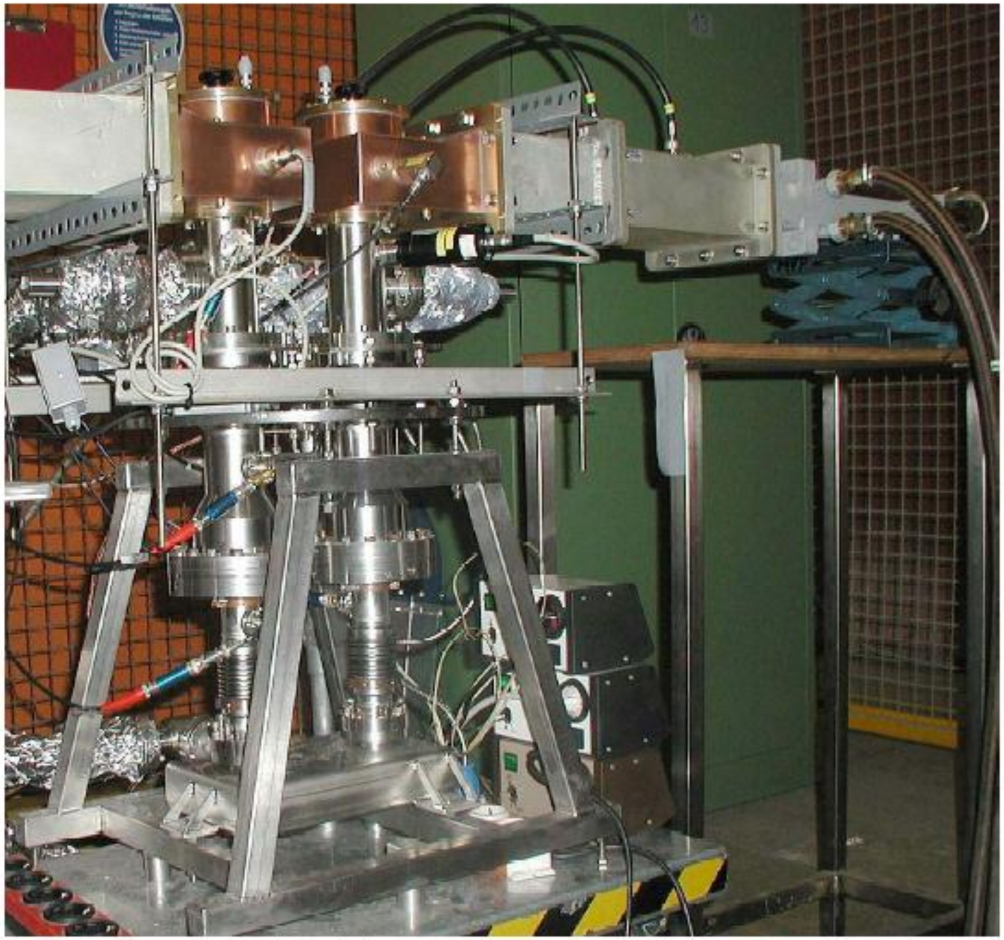


TTF 3 Coupler on Test Stand

Teststand



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



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Handling after processing

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

dry N_2 cabinet

sealing cap for cold window