Lectures for mechanical engineers: Lecture 3

Fundamental power couplers for Superconducting cavity

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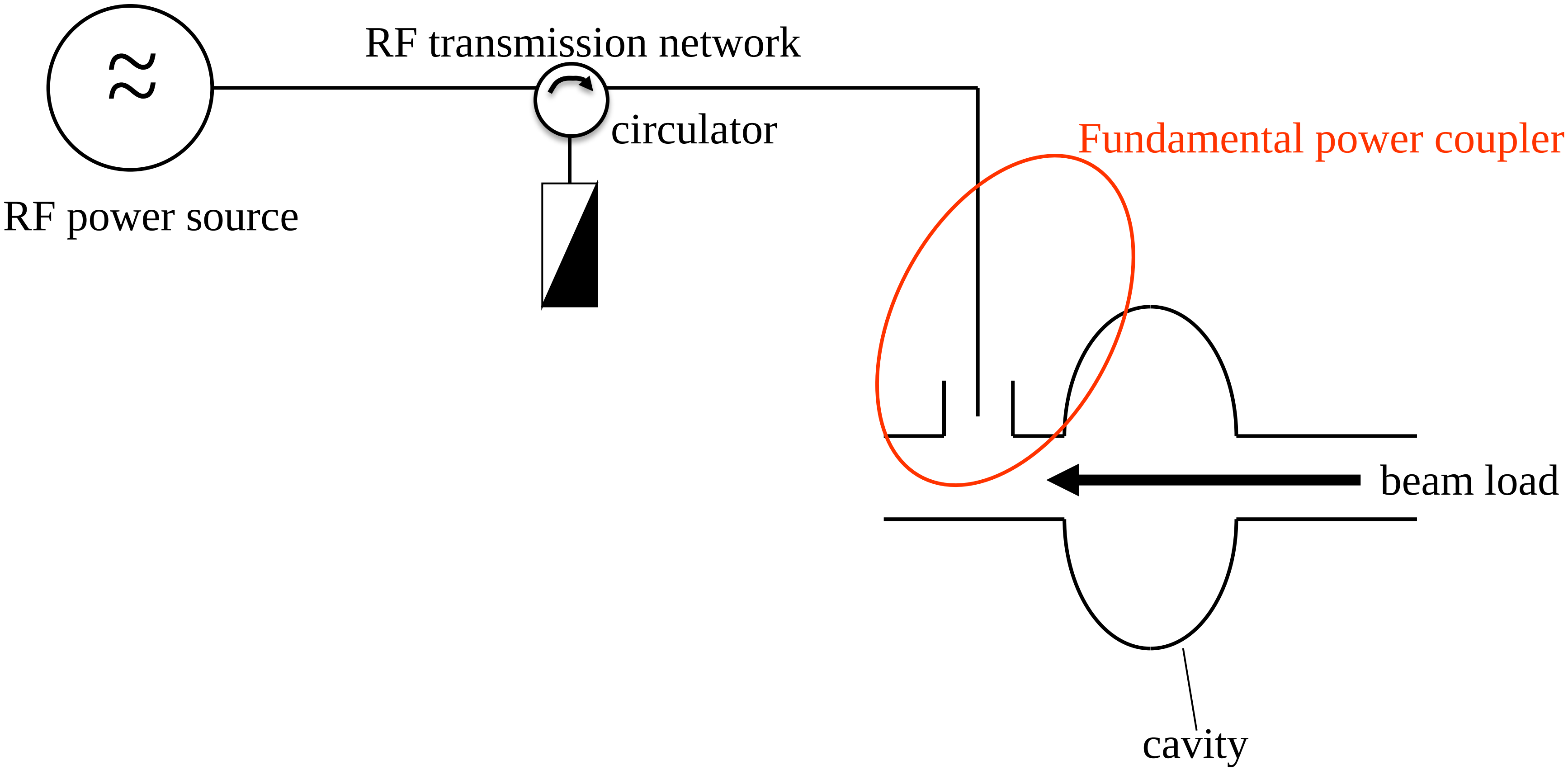
April 28, 2011

Outline

Fundamental Power Coupler(FPC)

- Why do we need fundamental power couplers? What are their functions?
- How to determine the external Q and loaded Q factors, coupling parameter in a RF cavity system?
- How to most efficiently transfer RF power(from RF source) to a cavity w/o beam?
- Show examples of input couplers and RF windows.
- What is multipacting and how to deal with it?
- Why conditioning is important for the operation of FPCs?

What is a fundamental power coupler(FPC)?



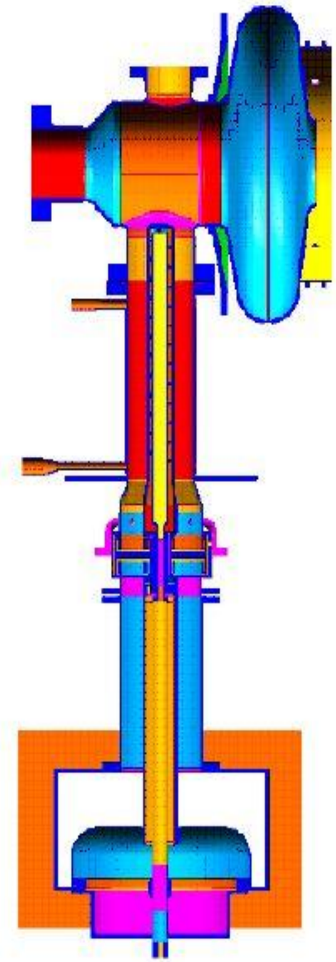
Fundamental power coupler: FPC is the connecting part between the waveguide and the cavity, it provides the electromagnetic power to the *cavity* and *beam*.

It is also called *high power input coupler* in some papers.

Functions of a FPC in the SC system

RF functions:

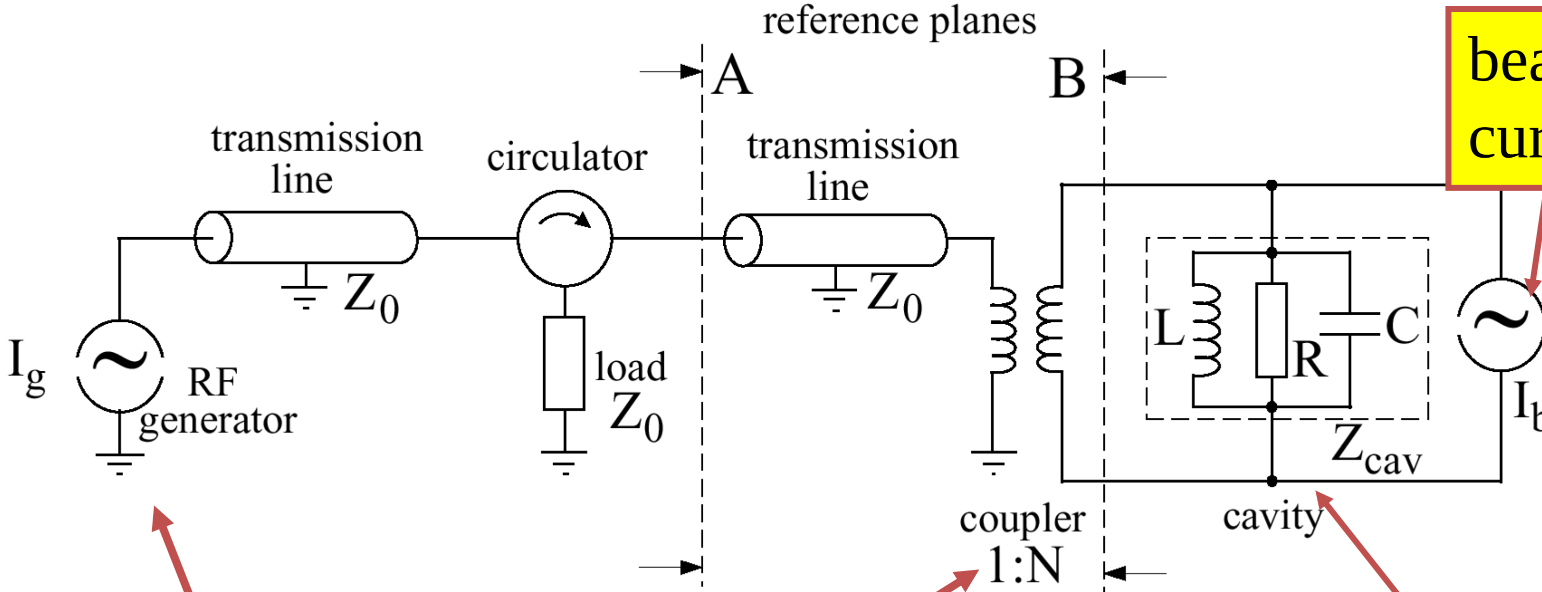
- Transfer the power to the cavity and to the beam at high power levels in pulsed or CW operation. --> The transferred power is limited by arcing, heating, multipacting, etc.
- Match the impedance of the klystron to the *beam loaded* cavity. RF power is fully reflected in the absence of beam.
- Possibly allow to change the match for different beam conditions by tuning the coupling to SC cavity.
- Possibly can be used for HOM damping.



Additional functions

- Bridge the gap between room- and cryogenic- temperature environments, which requires mechanical flexibility and low thermal leak.
- Provide a vacuum barrier between the evacuated cavity and air-filled transmission line. Window failure will cause bad contamination of delicate SC cavity. Recovery is time consuming and expensive.

Equivalent circuit model of SRF system



beam current

Generator:

$$P_g = \frac{1}{2} Z_0 I_g^2$$

Coupler acts like a transformer:

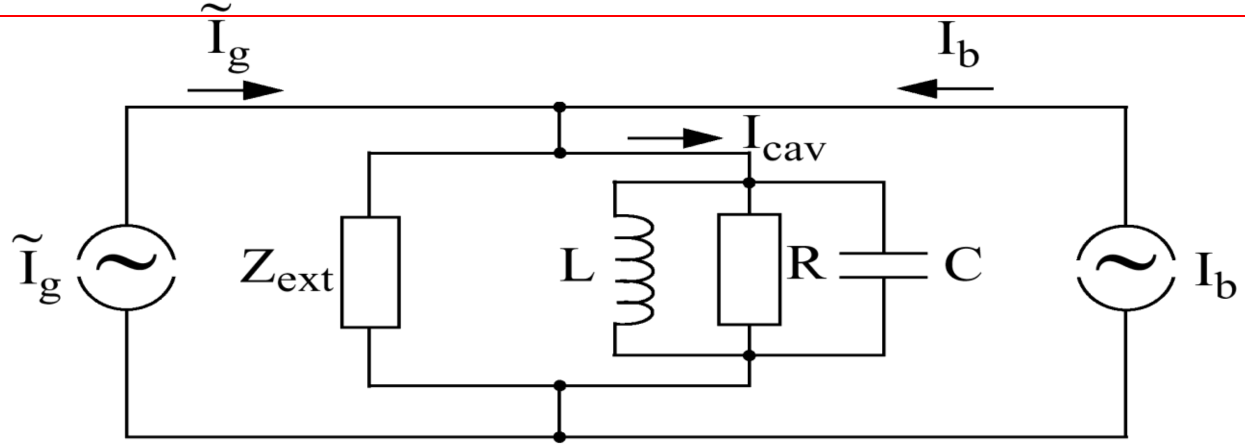
$V_2 = N\ V_1$

$I_2 = 1/N\ I_1$

Cavity modeled as LCR circuit:

Note: R is the shunt impedance, not R_{surf}!

Simplify the circuit model



Resonance frequency: $\omega_0 = 2\pi f_0 \approx 1/\sqrt{LC}$

Intrinsic quality factor(Q0): $Q_0 = \frac{\omega U}{P_{wall}} = \frac{R}{\omega_0 L} = \omega_0 CR$

External quality factor(Qe): $Q_{ext} = \frac{\omega U}{P_{ext}} = \frac{Z_{ext}}{\omega_0 L} = \omega_0 C Z_{ext}$

Loaded quality factor(QL): $Q_L = \frac{\omega U}{P_{total}} = \frac{Q_0}{1+\beta}$

Bandwidth of a mode: $\omega_{1/2} = \omega_0 / 2Q_L$

Cavity detuning: $\Delta\omega = \omega_g - \omega_0$

Coupling factor: $\beta = \frac{R}{Z_{ext}}$

Incident power: $P_g = \frac{1}{8}\frac{1}{\beta} R I_g^2$

Total impedance :

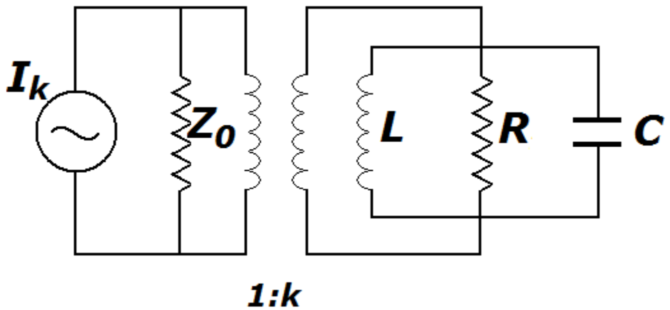
$$Z_{total} = \frac{R}{(1+\beta)[1+i2Q_L \frac{\Delta\omega}{\omega_0}]}$$

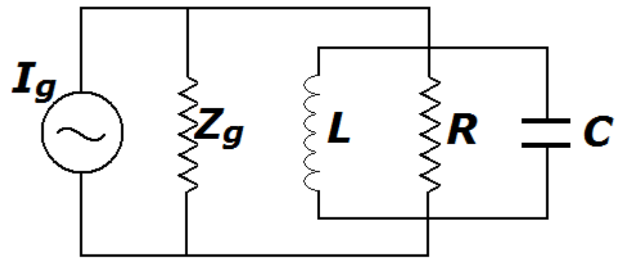
Energy content: $U = \frac{1}{2} C V^2$

Note:

$Z_{ext} = N^2 Z_0$ $\quad R_{sh} = 2R$

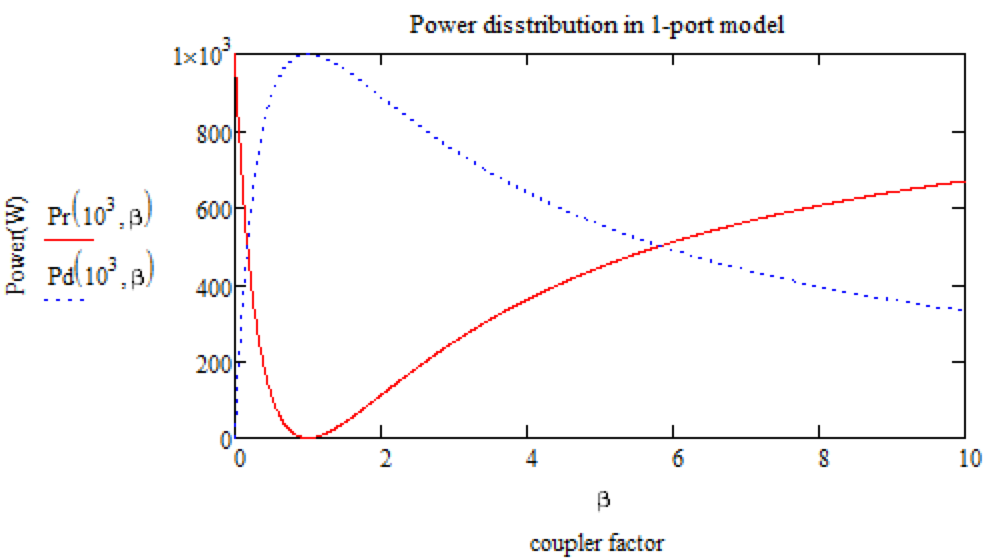
Case1: No beam

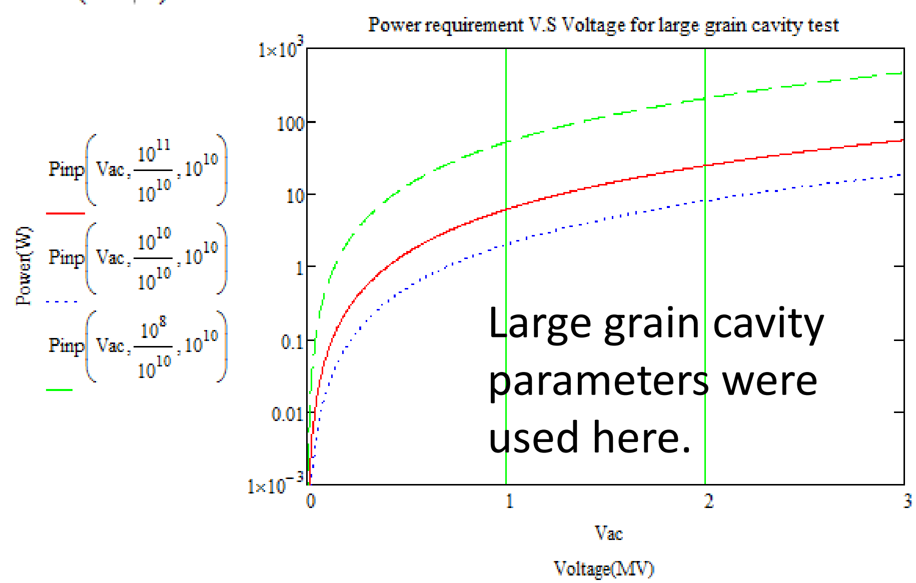




Reflection Power: $$Pr(Pin, \beta 1) := Pin \cdot \left(\frac{1-\beta 1}{1+\beta 1}\right)^2$$

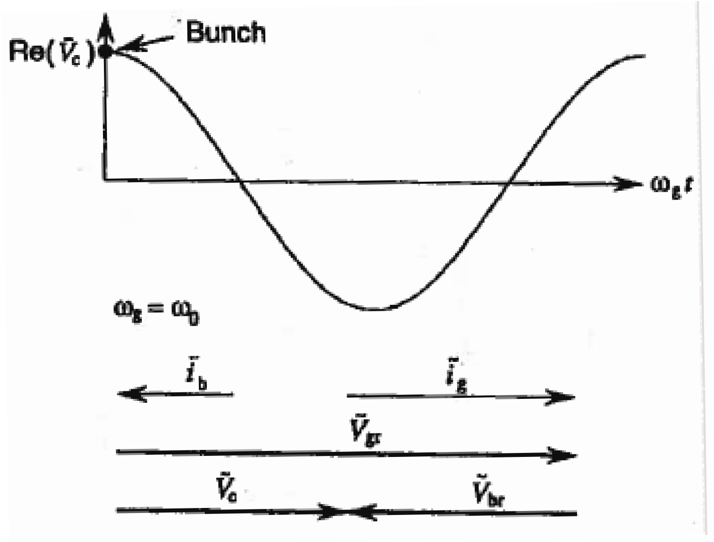
Dissipation Power $$Pd(Pin, \beta 1) := \frac{4\beta 1\, Pin}{(1+\beta 1)^2}$$





- ***Vertical cavity test usually uses a unity coupling or critical coupling (β=1).***
- ***A tunable coupler should be designed for the request.***

Case 2:Resonant and on-crest operation



$$P_r = P_g\left(\frac{\beta-1}{\beta+1} - \frac{I_b\sqrt{R_{sh}\beta}}{(\beta+1)\sqrt{P_g}}\right)^2$$

$$P_c = \frac{4\beta}{(1+\beta)^2}P_g$$

The optimal external Q: $Q_e = \frac{Q_0}{\beta} = \frac{Q_0}{1+\frac{P_b}{P_c}}$

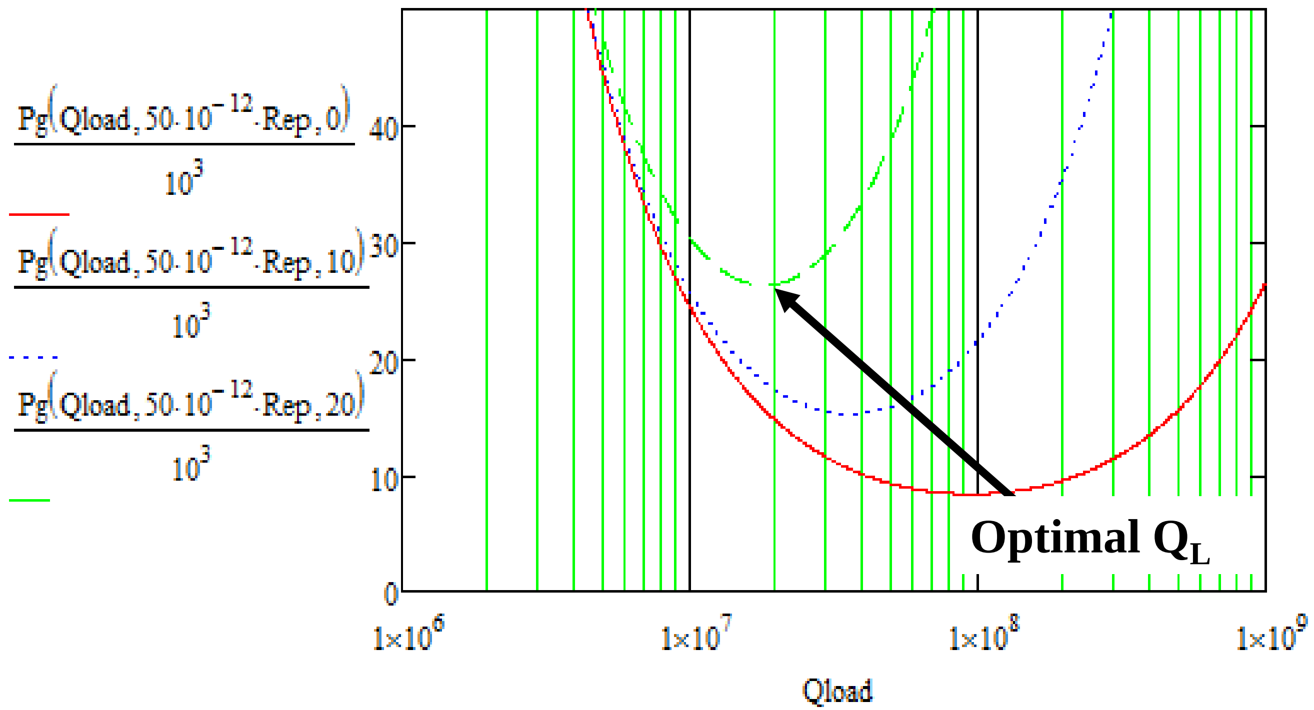
Discussion:

- **For Ib=0, then the formula describes the no-beam case.**
- **If the cavity is matched to generator when there is no beam(critical coupling, Pr=0), it will be no longer matched when a beam is present.**
- **Fixed coupling provides optimal coupling only for one beam current. So if the accelerator needs to operate at different current, it is important to make sure that the reflection power can not exceed the tolerance, or to vary the coupling to keep it always match.**

Case 3: beam, frequency fluctuation - real situation

RF requirement for constant Gradient:

$$P_g = \frac{1+\beta}{4\beta}\frac{V_{acc}^2}{\frac{R_{sh}}{Q}Q_L}\left\{\left(1+\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\cos\phi_b\right)^2+\left(2Q_L\frac{\omega-\omega_0}{\omega_0}+\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\sin\phi_b\right)^2\right\}$$



- BNL3 cavity parameters: R/Q = 503 Ω, Q0 = 3e10.
- RHIC repetition = 9.38 MHz

Optimal detuning:

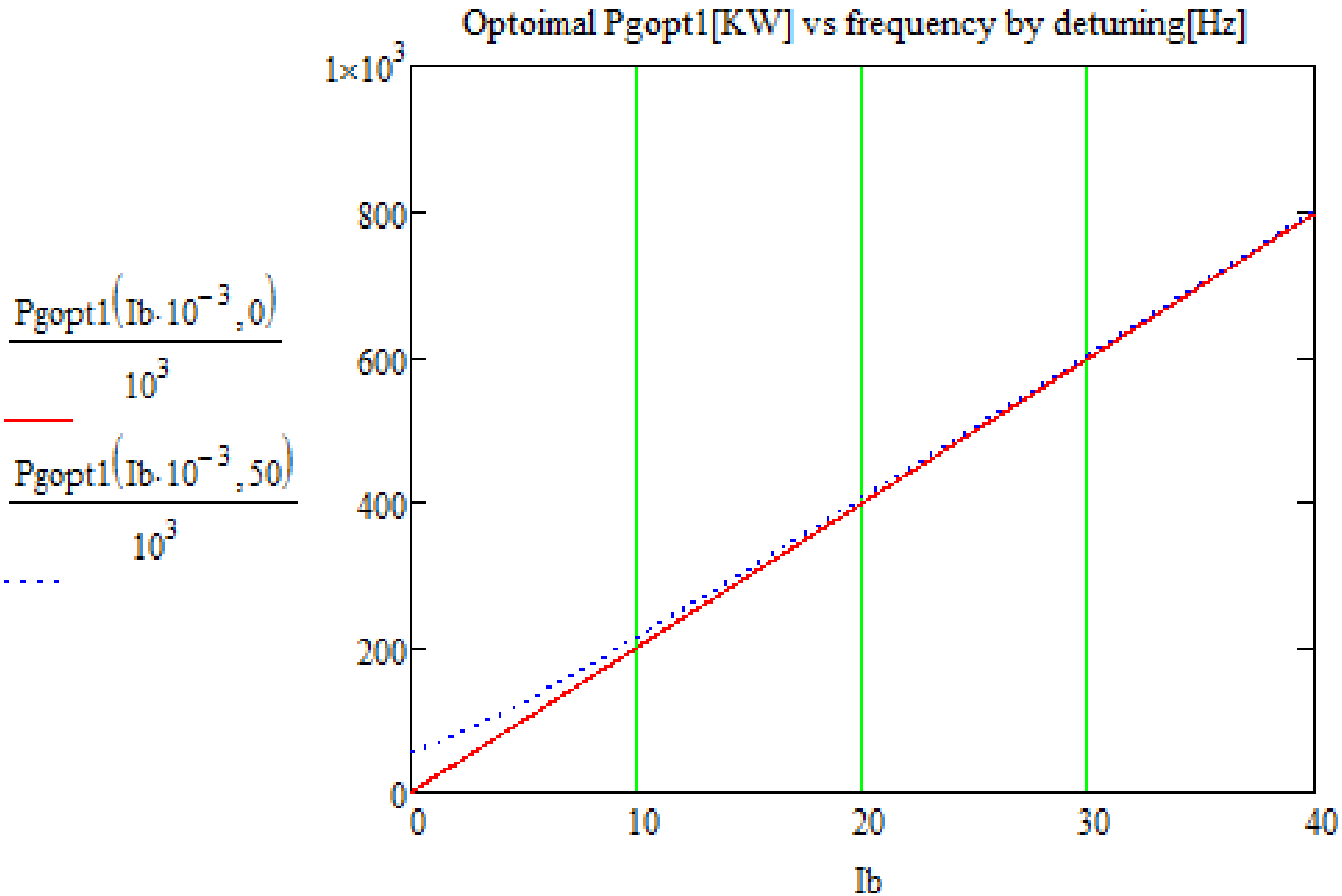
$$\omega-\omega_0 = -\omega_0\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\sin\phi_b$$

Optimal load Q:

$$Q_L = \frac{V_{acc}}{\frac{R_{sh}}{Q}I_b\cos\phi_b}$$

All power is transferred to the beam (no reflected power)

Example 2: Linac optimal Qe operation



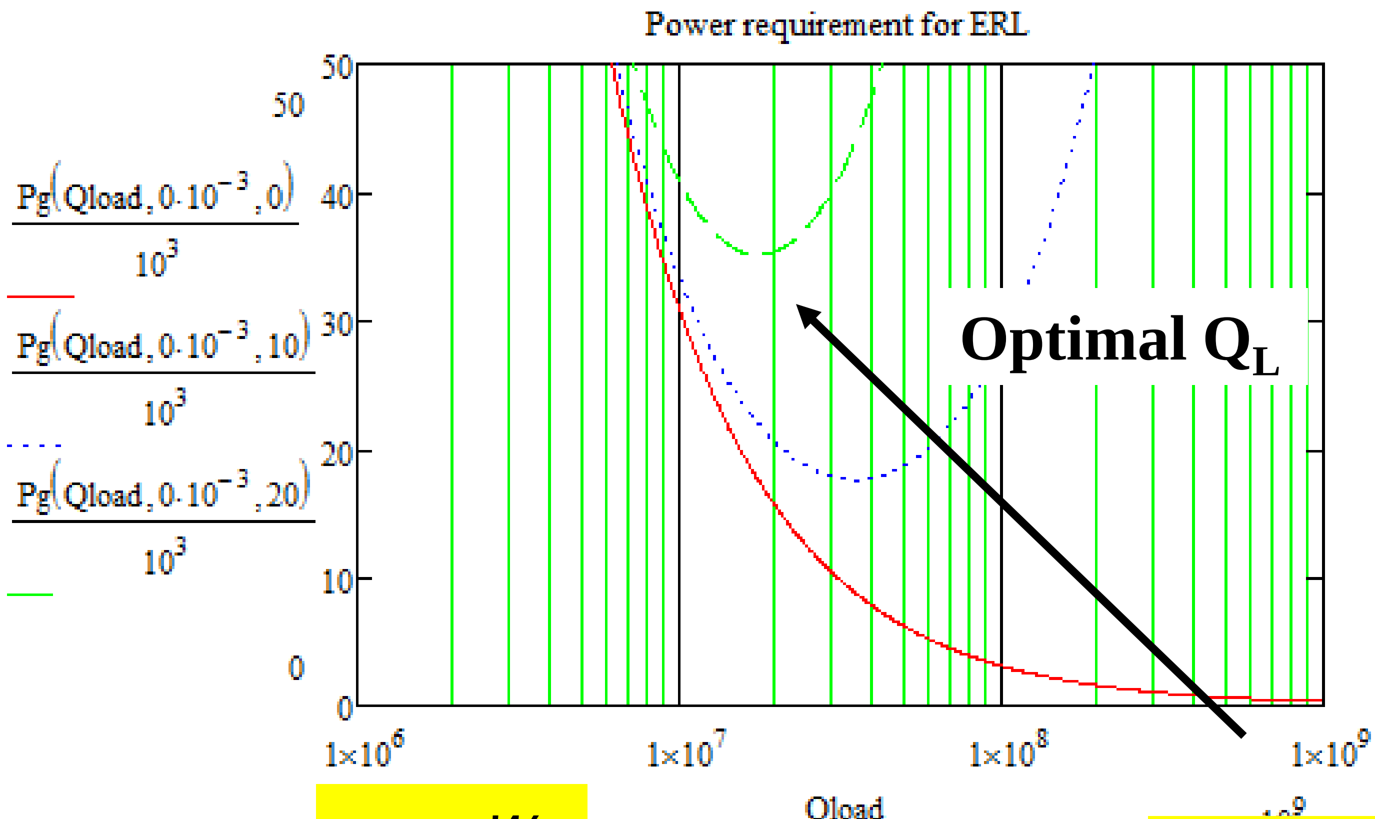
BNL3 cavity parameters: R/Q=503Ω , Q0=3e10.

- For high beam current Linac, most power is to provide for the beam.
- For low current, the power required for compensating the frequency vibration is big.

Example3 : ERL

ERL: the accelerating bunch is in phase and decelerating beam is off phase, so cavity see 0 beam current

$$P_g = \frac{1+\beta}{4\beta}\frac{V_{acc}^2}{\frac{R_{sh}}{Q}Q_L}\left\{1+\left(2Q_L\frac{\omega-\omega_0}{\omega_0}\right)^2\right\}$$



BNL3 cavity parameters: R/Q=503Ω , Q0=3e10.

Optimal load Q: $Q_L = \frac{\omega_0}{2\Delta\omega}$

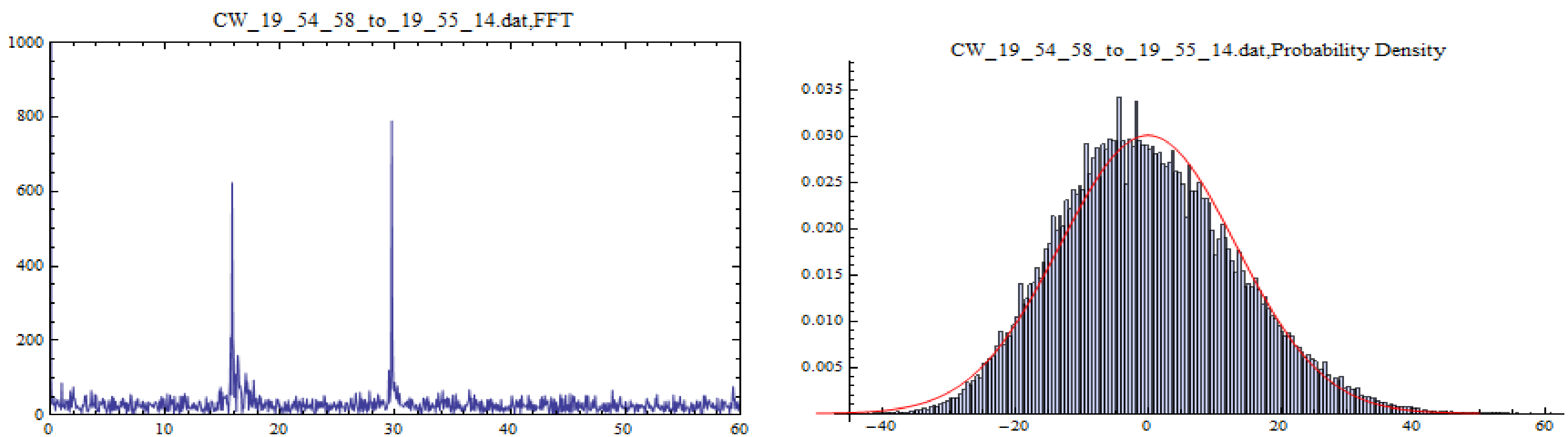
Optimal Power: $P_g^{opt} = U\Delta\omega$

Frequency vibration in SRF cavity

• *Environmental effects*.
These include drifts induced by changes of temperature or pressure of the cryogens, and are usually compensated by tuners, mechanical or otherwise.

• *Lorentz detuning* : Coupling between the electromagnetic and mechanical modes of the cavities through the radiation pressure.

•*Microphonics* :These can be either stochastic (ambient vibrations with a white or pink noise frequency spectrum) or composed of some well-defined frequencies.

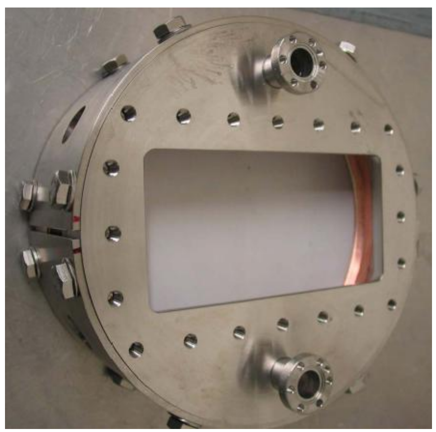


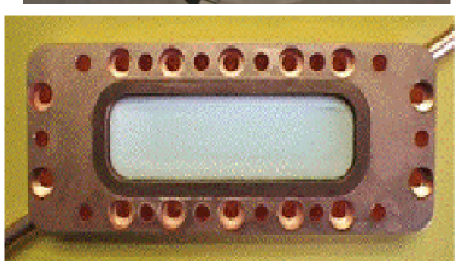
Example of microphonics measurement in ECX cavity at BNL

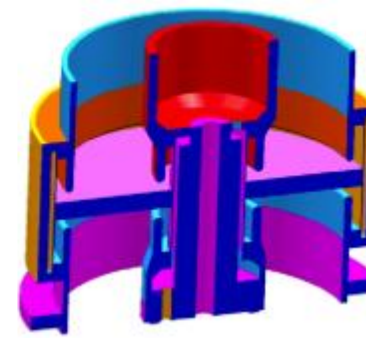
Ideally, the RF power requirement for ERL is only to compensate the microphonics. However, it may still be much power if the bandwidth is big.

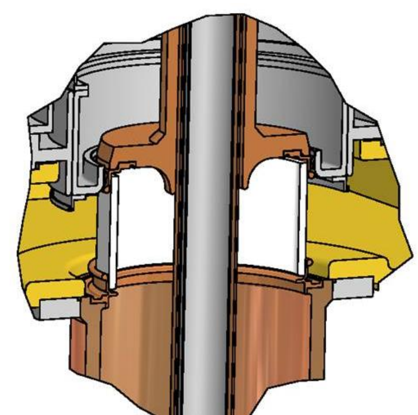
Fundamental power coupler overview

Waveguide	Coaxial
❑ Simpler design	❑ More compact
❑ Lower RF losses	❑ Smaller heat leak
❑ Lower surface electric field	❑ Easier to make variable
❑ Easier to cool, but higher thermal radiation	❑ Easier to handle multipacting
❑ Fixed Qext	❑ Tunable Qext, but is complicated

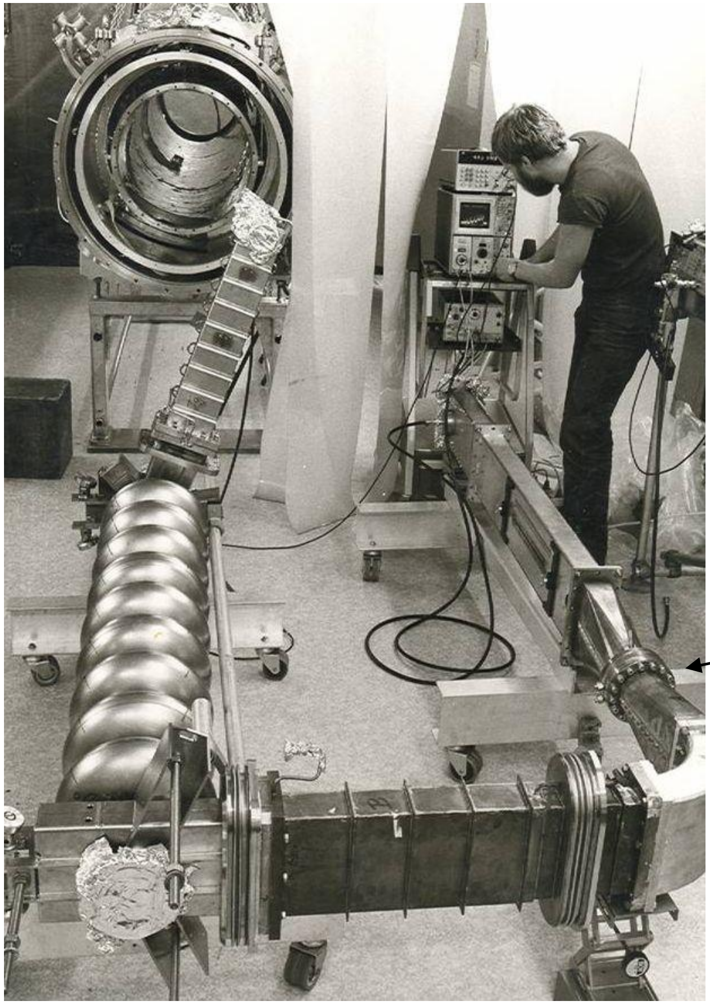


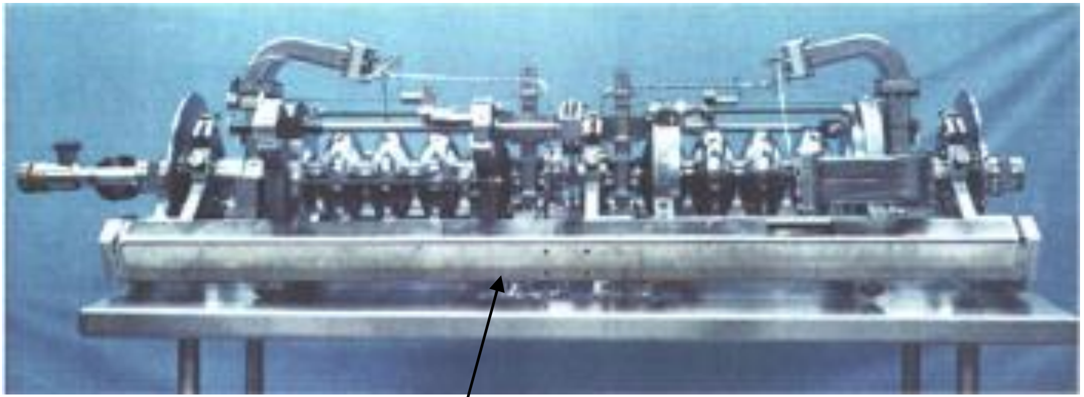






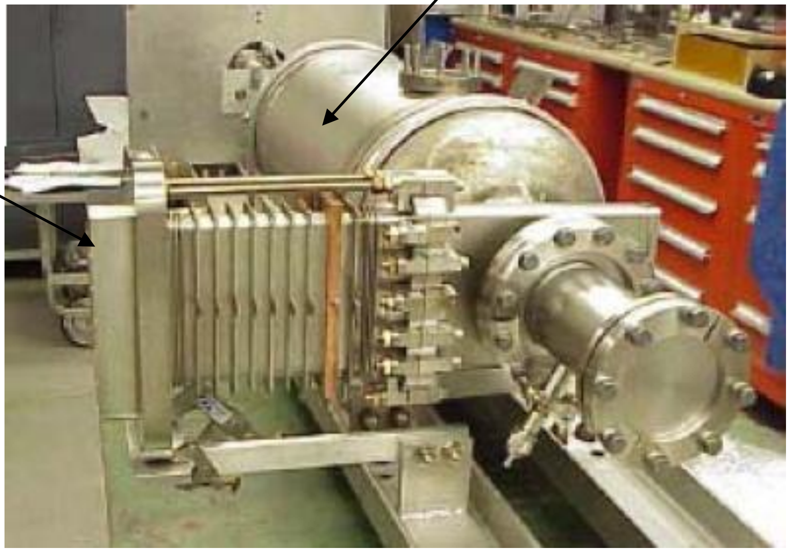
Waveguide couplers





CEBAF cavity pair and new upgrade cavity

window

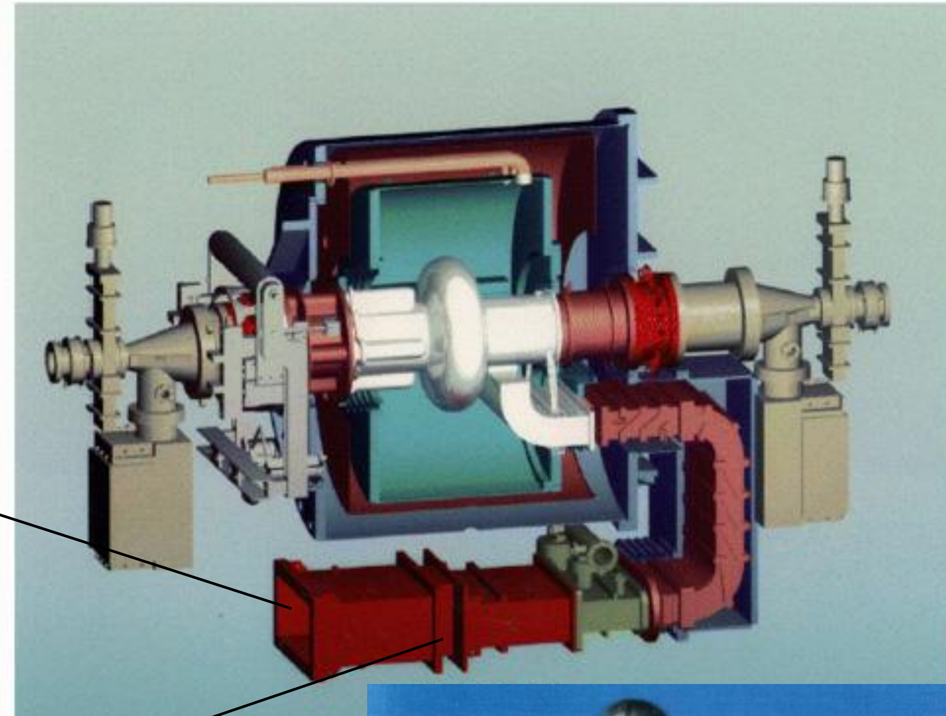


1 GHz PETRA test cavity

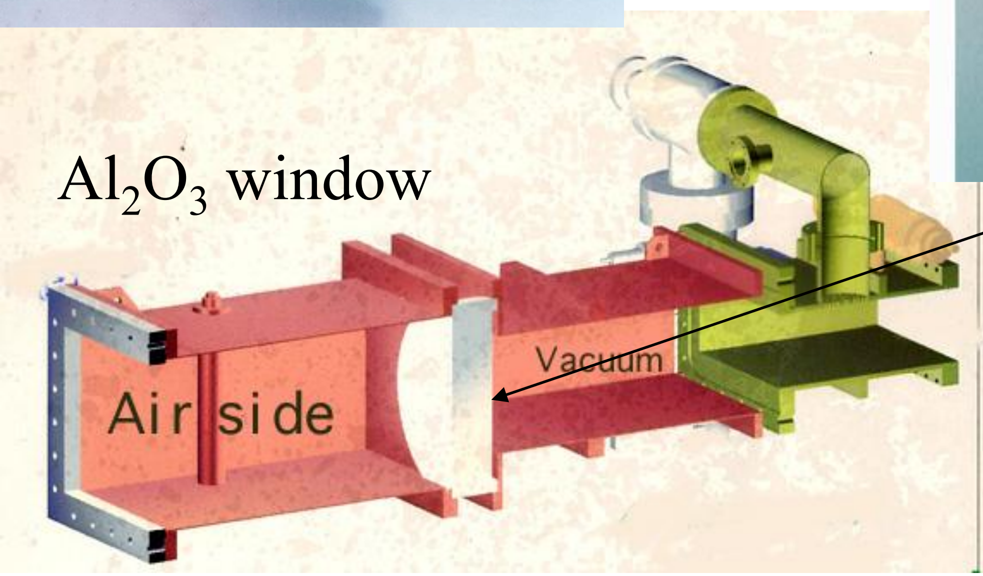
Waveguide couplers, cont.

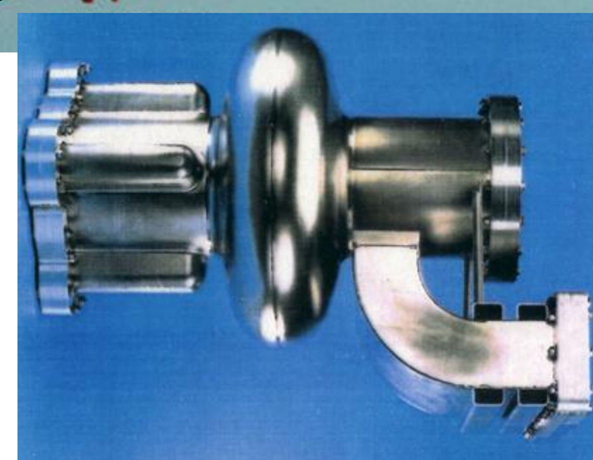
CESR – B cavity, 500 MHz

backup Kapton window

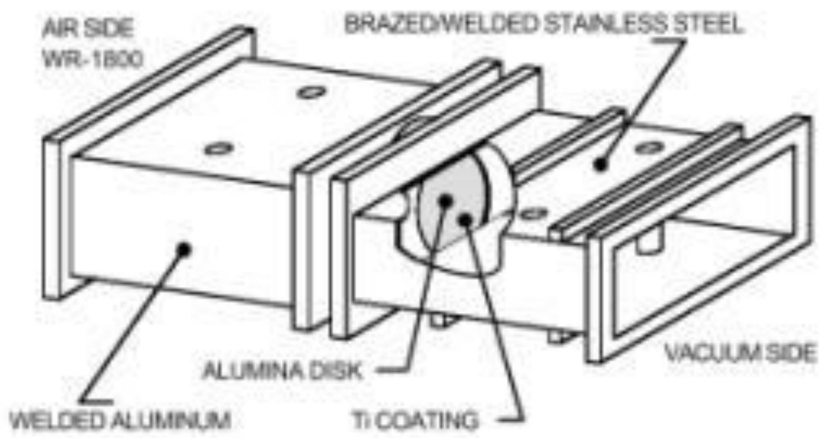


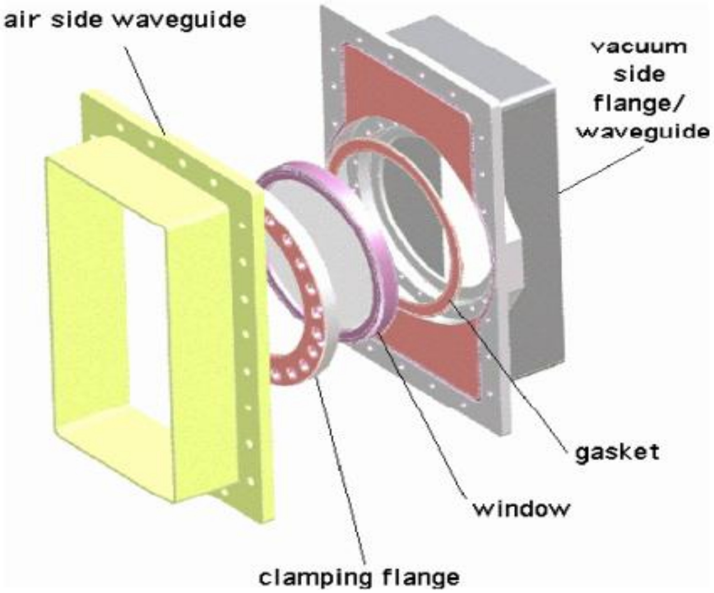
Al_2O_3 window

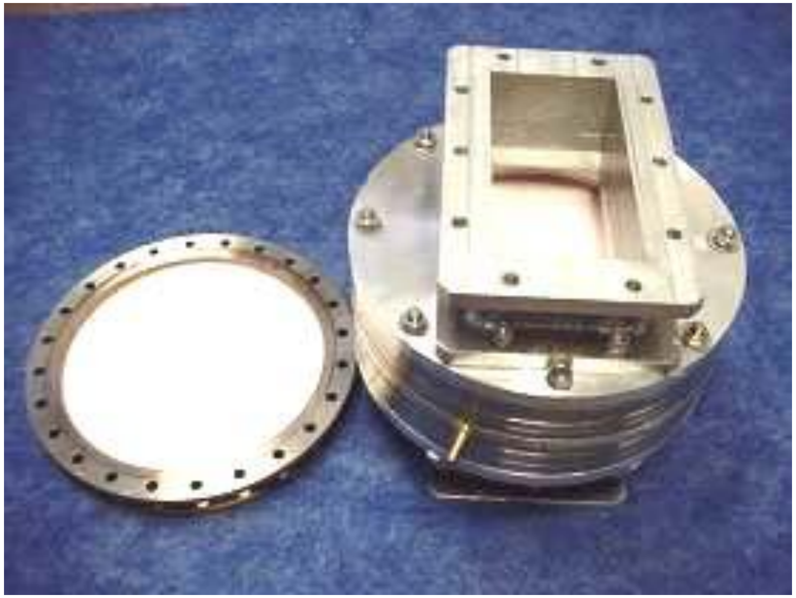


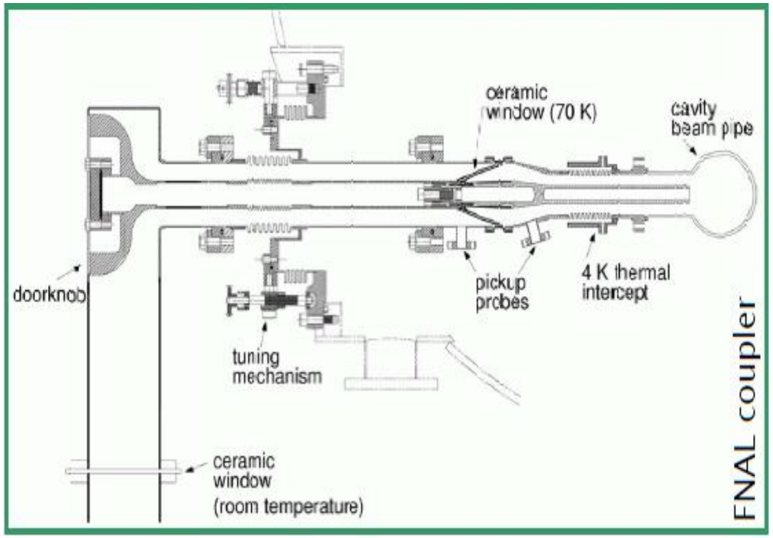


Waveguide window



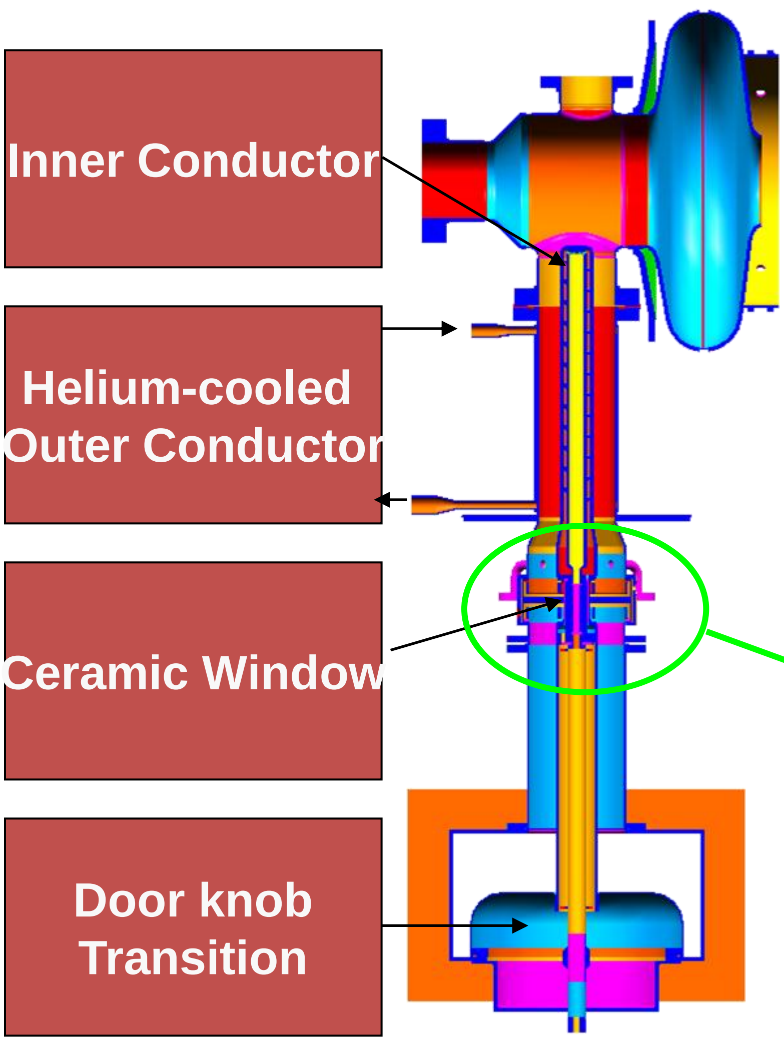


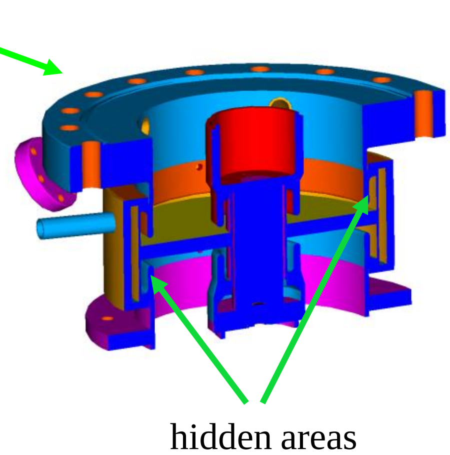




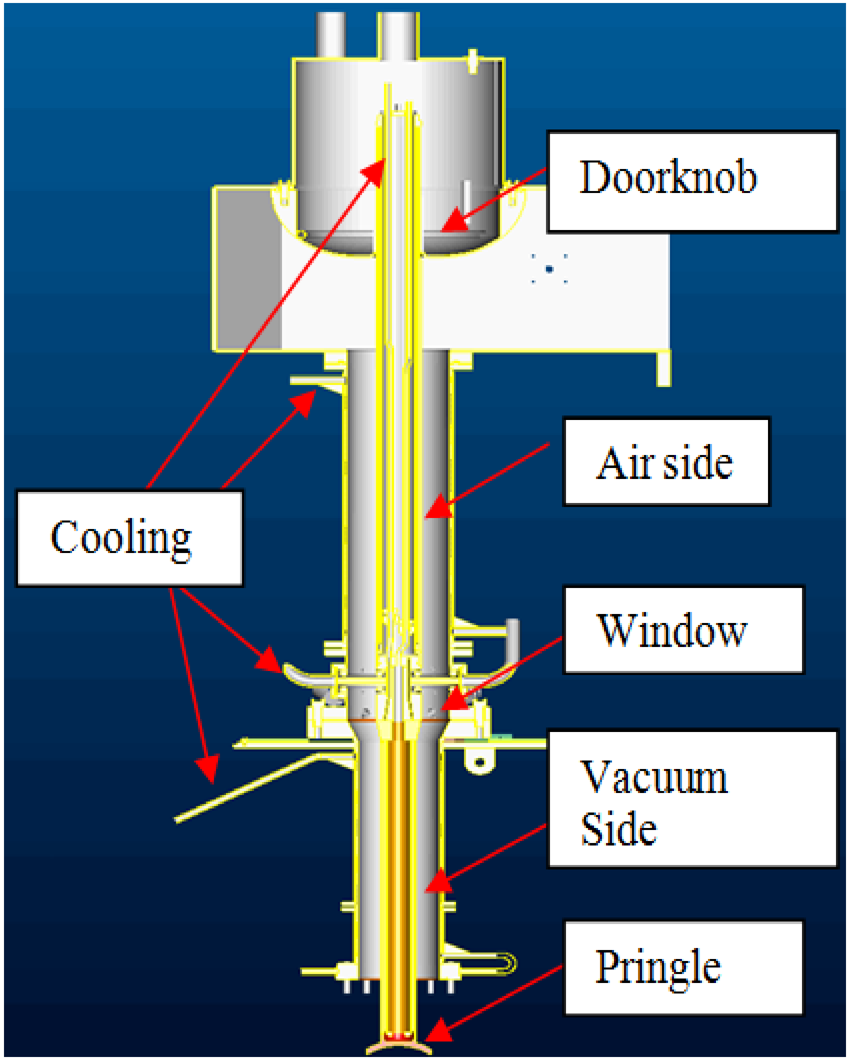
SNS coupler, one disc window

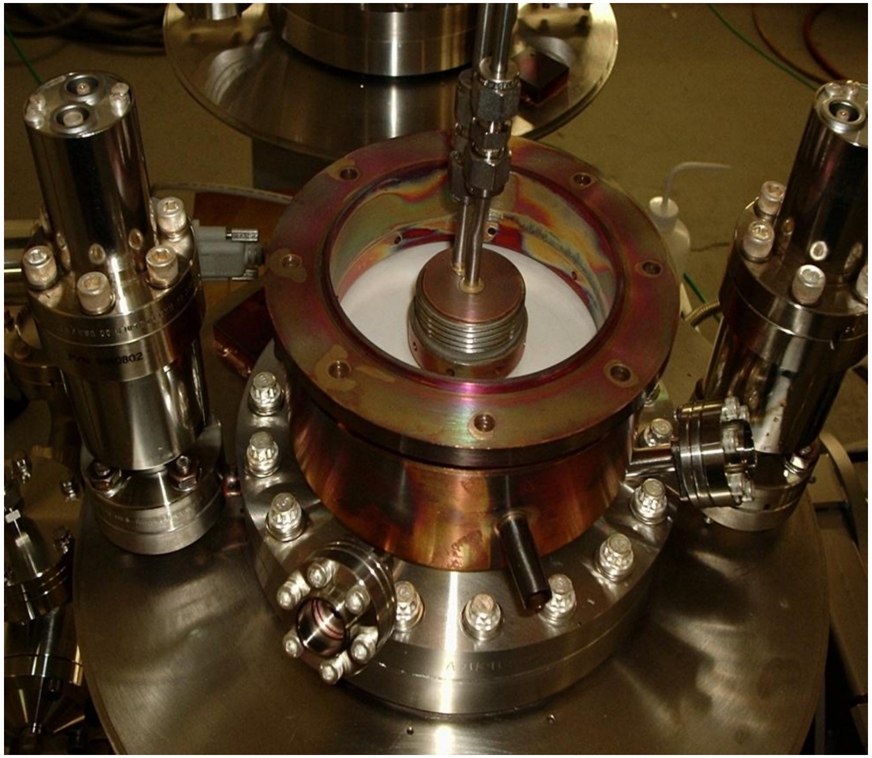
- **Derived from KEKB design, "choke" window**
- **Present specifications:**
  - **550 kW peak**
  - **48 kW average**
- **Performance:**
  - **Tested up to 2 MW peak power on a test stand**
  - **Over 500 kW peak power in real cavity operation**
- **Higher average power for the upgrade & more stable operation at 60 Hz may require additional cooling**



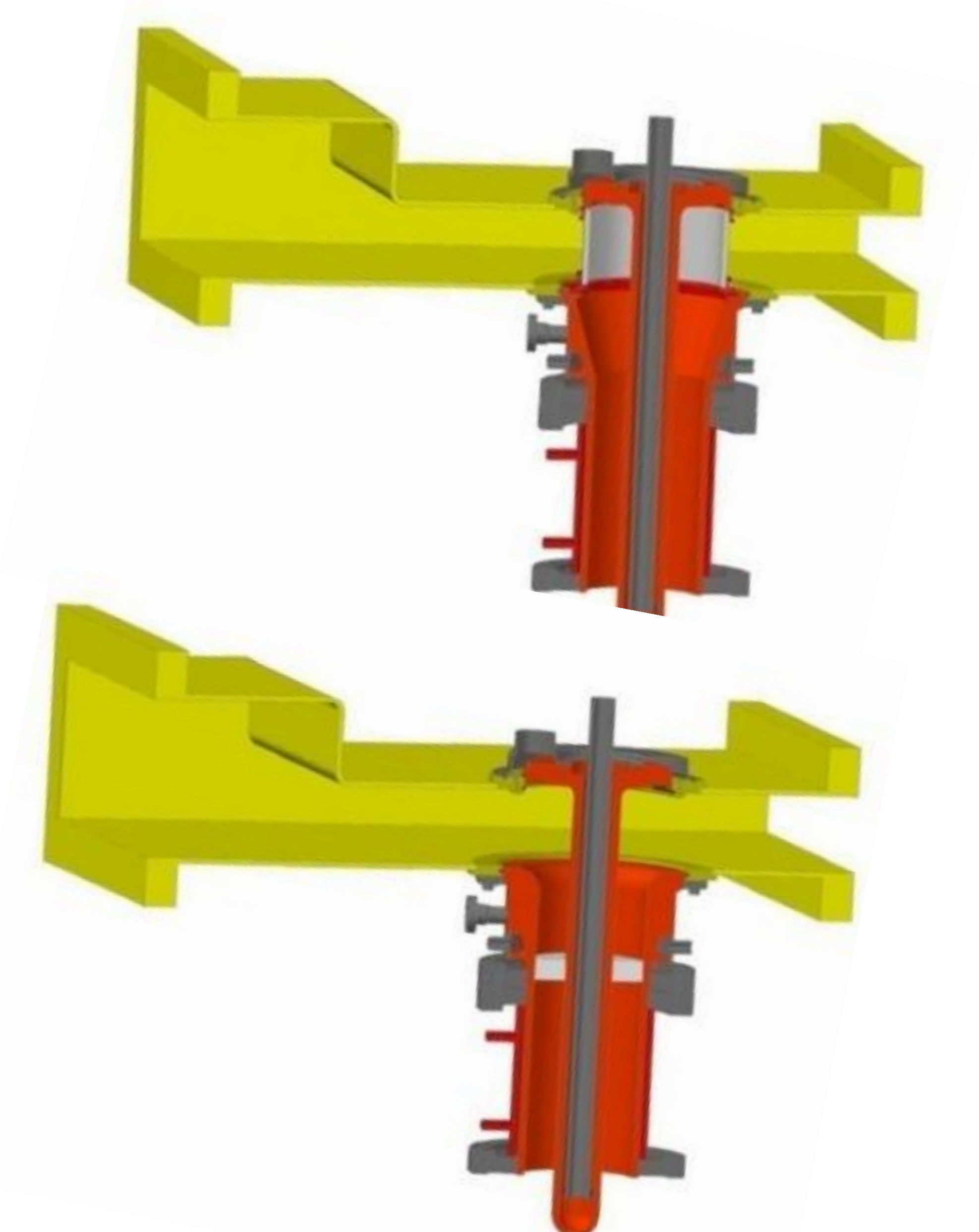


BNL Gun cavity's FPC, one window



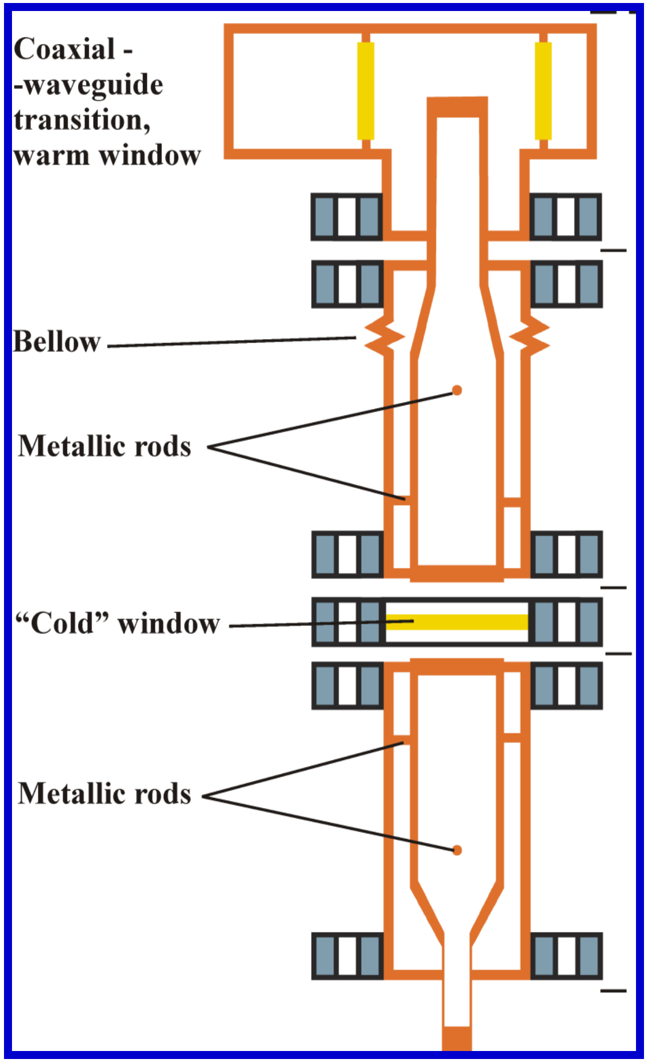


SPL coupler design, one window

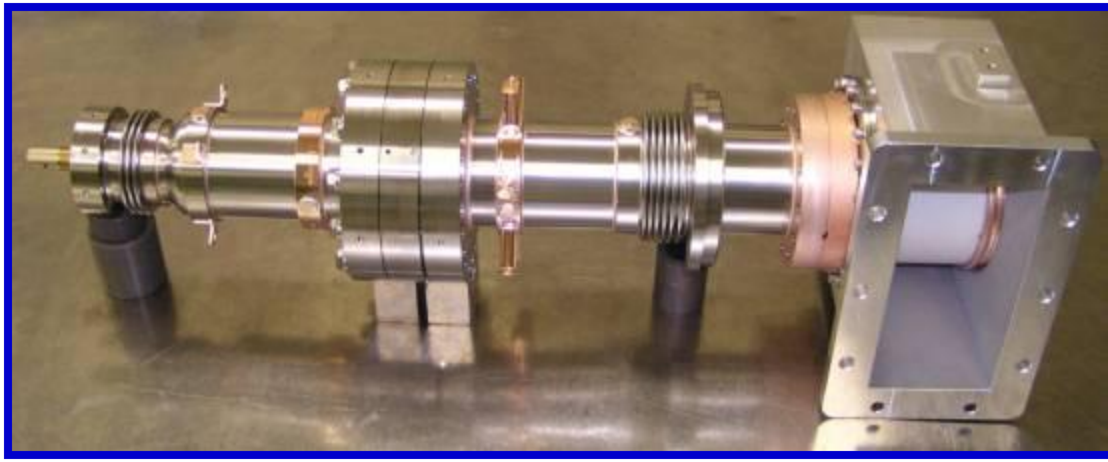


Coupler Parameters	
f_0	704.4 MHz
High Power SPL	1000 kW pulsed 0.4 + 1.2 + 0.4 = 2.0 ms 50 Hz (20 ms) 100 kW average
Cavity design gradient	19-25 MV/m
Q_{ext} of input coupler	1.2×10^6
Input line Ø	100 / 43.5 mm = 50 Ω (from the cavity design)
Waveguides	WR 1150

Coax couplers, two cylindrical windows



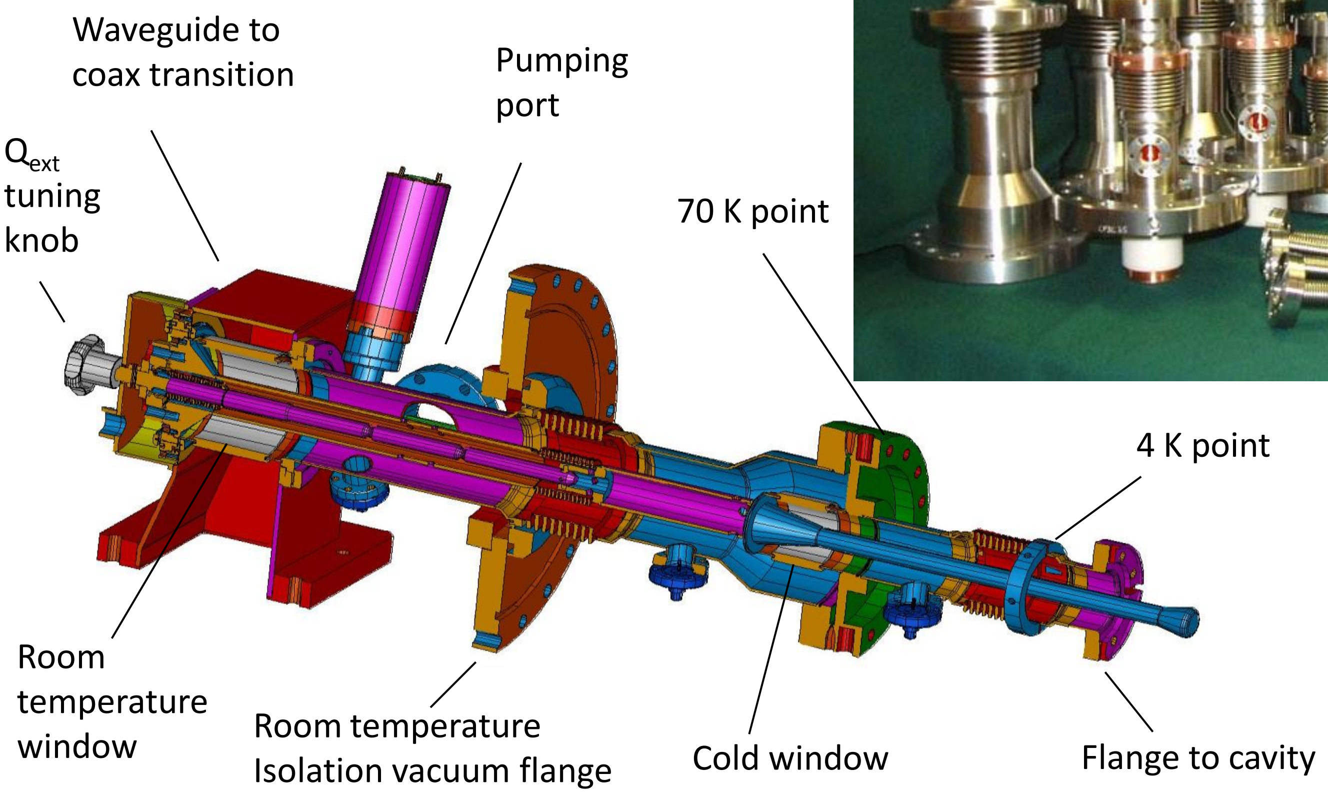
- Window is a disk without inner conductor penetration.
- Each pair of rods is mounted in the gap between the inner- and outer-conductors, and are rotated 90 degrees from each other.



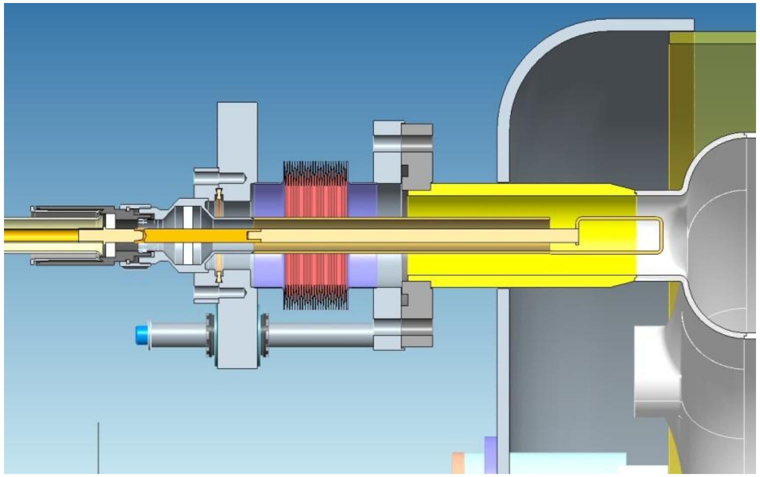
2 MW, pulse

Coax couplers, two cylindrical windows

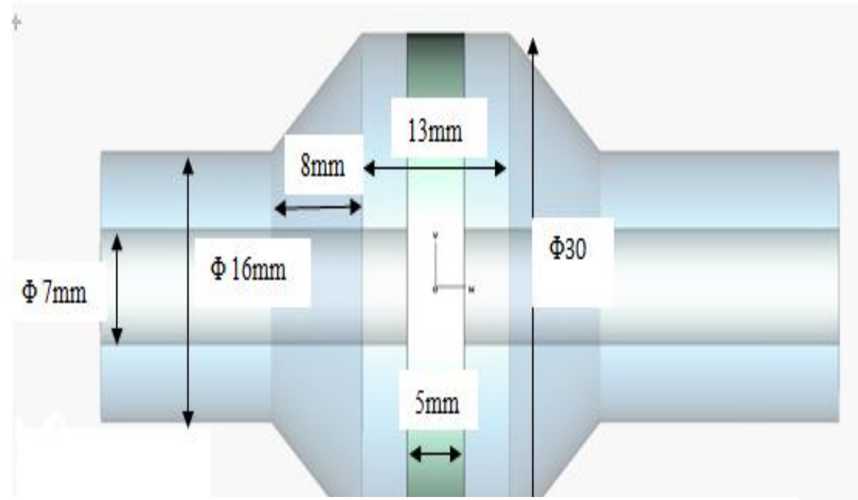
TTF-III Coupler

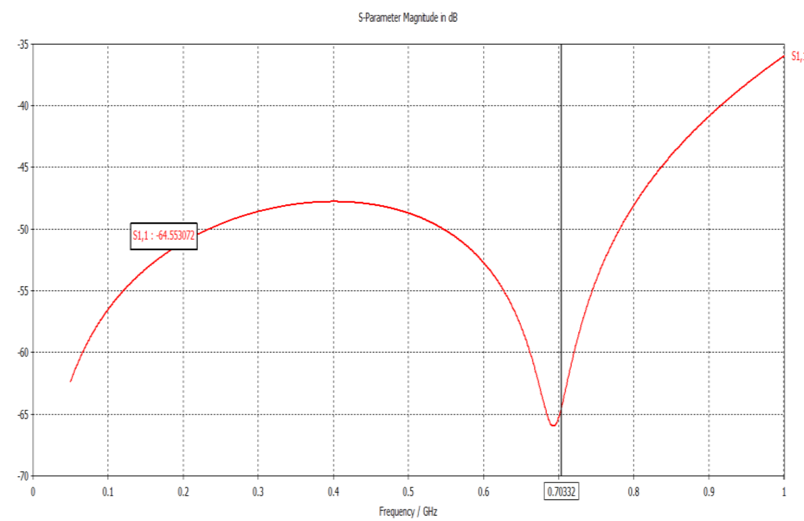


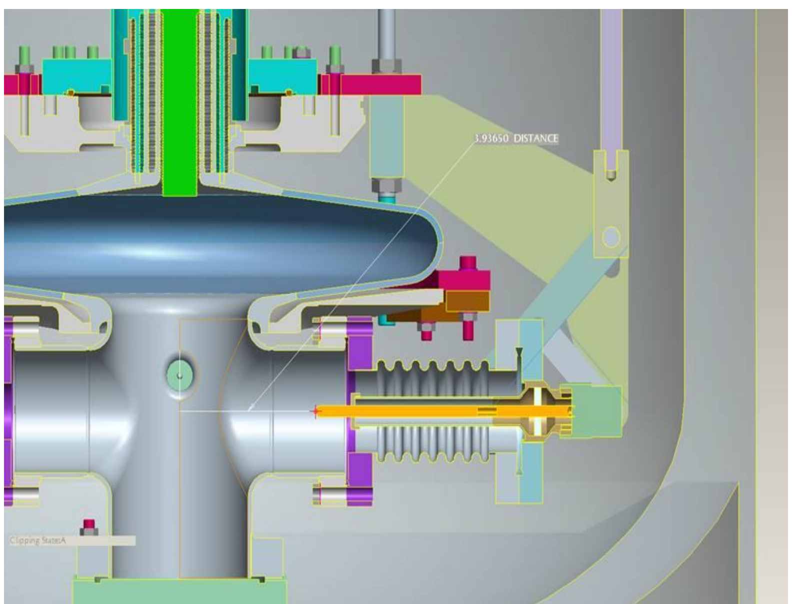
Broadband window



56 MHz FPC







Large Grain cavity tunable FPC

Overview: CW couplers on machines

Facility/ Project	Frequency	Coupler type	RF window	Q_{ext}	Max. CW power	Comments
LEP2 / SOLEIL	352 MHz	Coax fixed	Cylindrical	2×10^{6}	Test: 565 kW 380 kW Operation: 150 kW	Traveling wave @ Γ=0.6
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 Operation: 65 kW	Traveling wave
CESR (Beam test)	500 MHz	WG fixed	WG, 3 disks	2×10^{5}	Test: 250 kW 125 kW Operation: 155 kW	Traveling wave Standing wave Beam test
CESR / 3rd generation light sources	500 MHz	WG fixed	WG disk	2×10^{5}	Test: 450 kW Operation: 300 kW 360 kW	Traveling wave Forward power
TRISTAN / KEKB / BEPC-II	509 MHz	Coax fixed	Disk, coax	7×10^{4}	Test: 800 kW 300 kW Operation: 400 kW	Traveling wave Standing wave
APT	700 MHz	Coax variable (±5 mm stroke)	Disk, coax	2×10^{5} to 6×10^{5}	Test: 1 MW 850 kW	Traveling wave Standing wave
Cornell ERL injector / ERL cryomodule collab.	1300 MHz	Coax variable (>15 mm stroke)	Cylindrical (cold and warm)	9×10^{4} to 8×10^{5}	Test: 61 kW	Traveling wave
JLAB FEL	1500 MHz	WG fixed	WG planar	2×10^{6}	Test: 50 kW Operation: 35 kW	Very low ΔT
BNL R&D ERL Gun	703.75MHz	Coaxial	Disk, coax	4.5×105	Operation: 500kW	Traveling wave

Overview: Pulse mode couplers on machines

Facility/ Project	Frequency	Coupler type	RF window	Q_{ext}	Max. peak power	Pulse length, rep. rate, etc.
CARE-HIPPI	704 MHz	Coax fixed	Disk, coax	-	Test: 1 MW	2.0 msec, 50 Hz
SNS	805 MHz	Coax fixed	Disk, coax	7×10^5	Test: 2 MW Operation: 550 kW	1.3 msec, 60 Hz 1.3 msec, 60 Hz
J-PARC	972 MHz	Coax fixed	Disk, coax	5×10^5	Test: 2.2 MW 370 kW	0.6 msec, 25 Hz 3.0 msec, 25 Hz
FLASH	1300 MHz	Coax variable (FNAL)	Conical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 250 kW Operation: 250 kW	1.3 msec, 10 Hz 800 usec, 10 Hz
FLASH	1300 MHz	Coax variable (TTF-II)	Cylindrical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 1 MW* Operation: 250 kW	1.3 msec, 2 Hz 1.3 msec, 10 Hz
FLASH / XFEL / ILC	1300 MHz	Coax variable (TTF-III)	Cylindrical (cold and warm)	1×10^6 to 1×10^7	Test: 1 MW Operation: 250 kW	1.3 msec, 2 Hz 1.3 msec, 10 Hz
KEK STF	1300 MHz	Coax fixed (baseline ILC)	Disks, coax (cold and warm)	2×10^6	Test: 1.9 MW 1 MW	10 usec, 5 Hz 1.5 msec, 5 Hz
KEK STF	1300 MHz	Coax fixed (capacitively coupled)	Disk (cold), cylindrical (warm)	2×10^6	Test: 2 MW 1 MW	1.5 msec, 3 Hz 1.5 msec, 5 Hz

- CW or Pulse mode?
- RF power requirement ?
- Waveguide or coaxial ?
- Single window or double windows ?
- Water cooling, He cooling or air cooling?
- Coating ?

Prior to installation: FPC conditioning

Prior to installation on the cavities, the couplers need to be RF high power processed. The goals of the processing are:

1. To help remove any surface imperfections from the fabrication step.
2. To check for, and process through, any *multipacting* barriers that may be encountered.
3. To ensure the copper plating on the outer conductor is well adhered.
4. To help outgas the UHV components prior to installation.
5. To ensure the parts are capable of handling the designed power level prior to installation.
6. To verify the cooling circuits function properly and provide adequate cooling to the respective parts.

What is multipacting?

'Multiple Impact'* *of electrons: Multipacting is a resonant process, when a large number of electrons build up under influence of RF field in evacuated equipment (couplers, cavities, etc.)

- *Electrons*

  - are omnipresent on couplers' or cavities' wall (from field emitters for example)

  - are accelerated in the RF field

  - hit the surface

  - can produce more electrons (depends on the secondary electron emission coefficient)

- *Resonance condition* depends on frequency, rf-phase, geometry, surface conditions (adsorbed gases => water !!),

  - If in resonance (same place and RF phase), they produce an avalanche

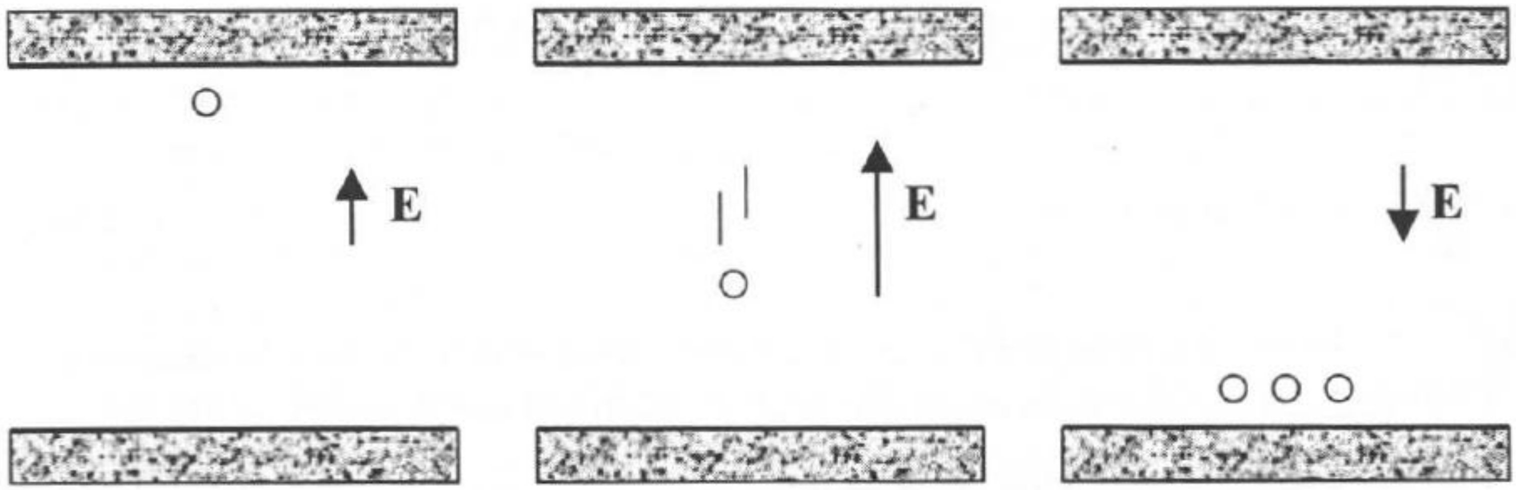
⇒ breakdown of rf-field, window-break

⇒ MP is processable (depending on type and order)

Multipacting example: parallel plates

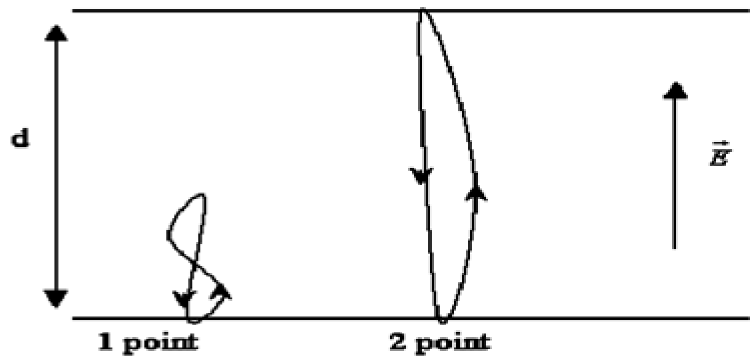
1. A free electron inside a microwave device is accelerated by an electric field.
2. In a strong field, the electron will quickly reach a high velocity and upon impact with one of the device walls, secondary electrons may be emitted from the wall.
3. If the field direction reverses at this moment, the newly emitted electrons will start accelerating towards the opposite wall and, when colliding with this wall, knock out additional electrons.

- As this procedure is repeated, the electron density grows quickly and within fractions of a microsecond a fully developed multipactor discharge is obtained.



Multipacting: some definitions

- **One-point multipacting:** When the trajectory is such that the electrons returns to their initial position;
- **Two-point (two-surface) multipacting**: the trajectory of the electrons loop between two impact points;



- **The order of the multipacting** is defined as the number of RF periods taken for the electron to transit from its creation to its impact with a wall (in the case of two point multipactor, the electron takes 2n-1 half periods to reach the other wall, where n is the order).

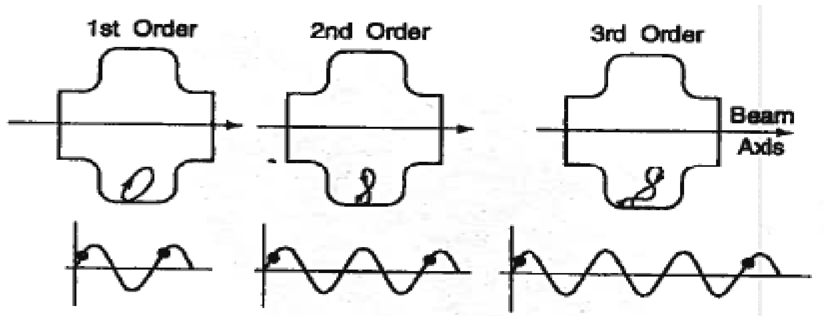
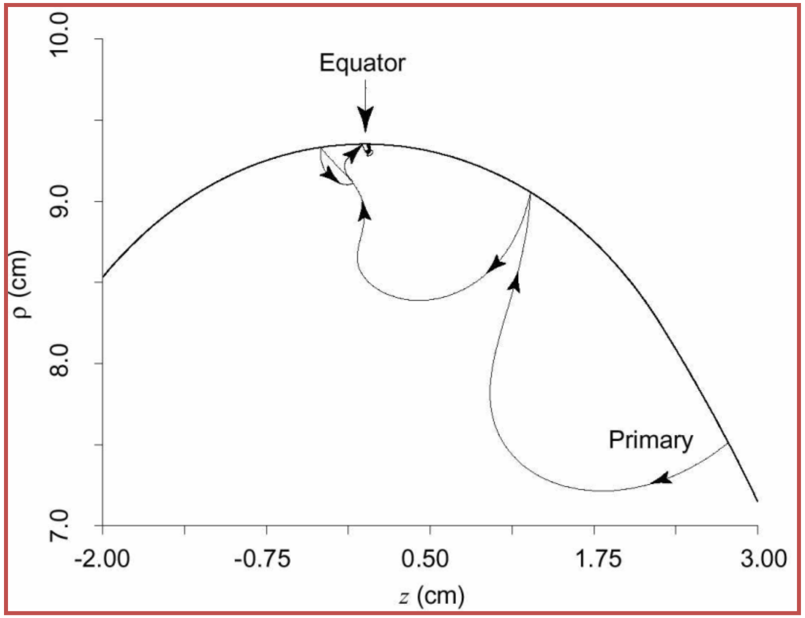
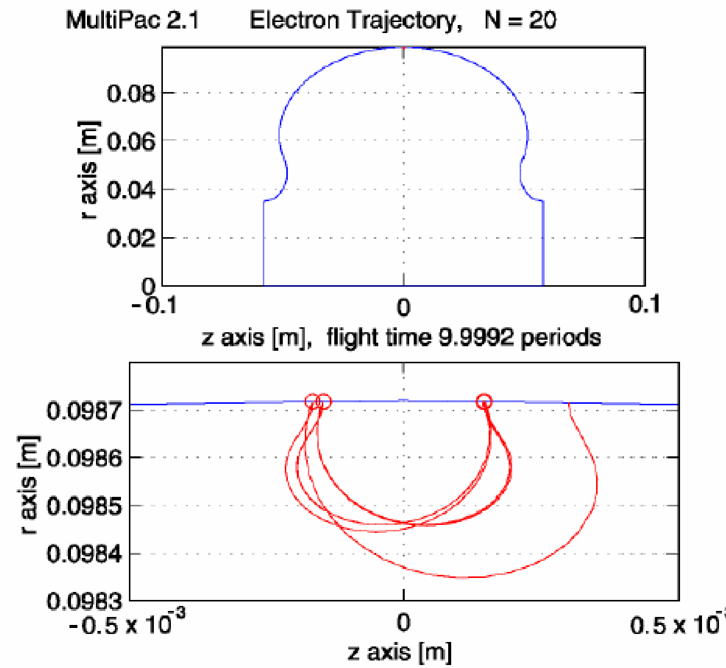


Figure 10.7: Typical one-point multipacting trajectories for orders one, two, and three.

Multipacting in cavities

- In a spherical/elliptical geometry electrons drift to equator region, where electric field is near zero. As a result MP electrons gain very little energy and MP stops.
- However, at high gradients conditions exist for stable MP though it is usually very weak and easily processed.

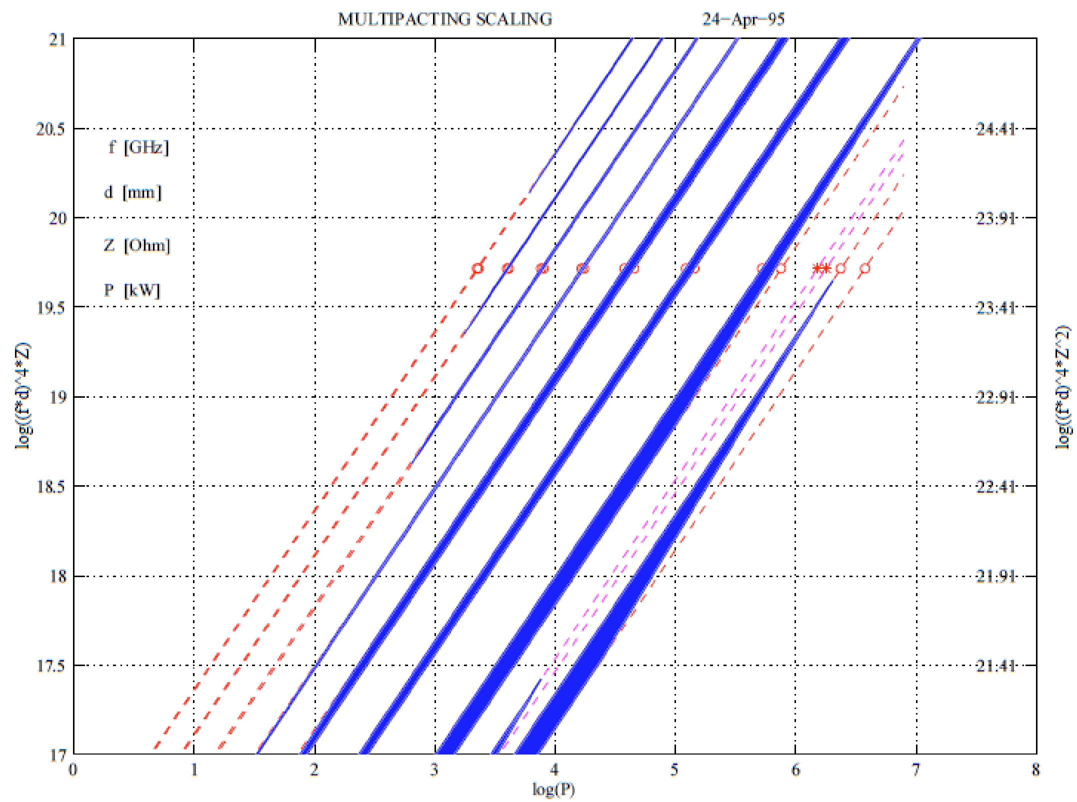




Multipacting in couplers

- MP can be a limiting factors in RF input and HOM couplers.
- In input couplers it causes vacuum degradation and limits power delivered to cavities. If RF is not interlocked properly, MP can damage RF windows.
- It is very important to carefully simulate MP during the design stage.
- In HOM coupler excess heating can cause severe stress at weld junctions and fracture in the cold.
- In rectangular waveguides MP zones can be predicted relatively well using parallel-plate model.
- In coaxial lines both one- and two-surface MP can exist. One-surface MP is stronger and more difficult to condition.
- Simple rules give the scaling of levels for one-point MP and two point MP, as these vary with frequency *f*, gap-size *d* and coaxial line impedance *Z*:

Power ~ (fd)^4*Z* (one point MP)
Power ~ (fd)^4*Z*^{2} (two-point MP)



Show MP movie!

Suppression of multipacting

1. **Geometry** : Optimization for less susceptible to MP (elliptical cavity shape, large radius of beam line transitions, larger dimensions of transmission lines…)
2. **Materials:** Selecting lower SEY materials, coating RF windows with thin layer (~10 nm) of anti-multipacting material like TiN.
3. **DC bias** (electric or magnetic) to disturb the trajectories of electrons.
4. **RF conditioning → cleaning surfaces → reducing SEY.**

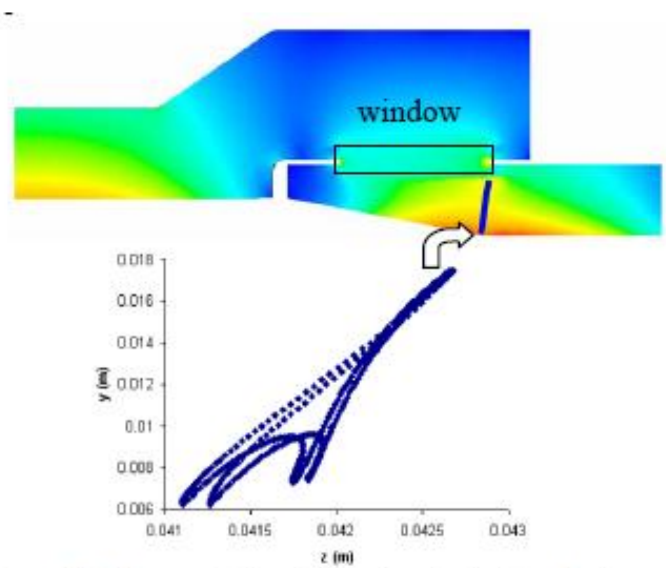


Figure 7: A two-point multipacting trajectory between the ceramic window and the inner conductor of the coax.

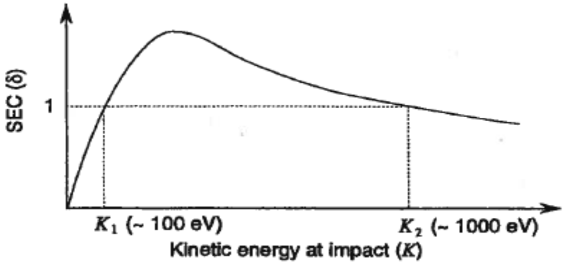


Figure 10.4: Generic dependence of the secondary emission coefficient (δ) on the impact kinetic energy (K).

Table 10.1: Secondary emission coefficient for a variety of materials

Material	δ_{max}	K_{max} (eV)	K_1 (eV)	K_2 (eV)
Ag	1.5	800	200	> 2000
Al	1.0	300	300	300
Au	1.4	800	150	50
C (diamond)	2.8	750		> 5000
C (graphite)	1.0	300	300	300
C (soot)	0.45	500	None	None
Cu	1.3	600	200	1500
Fe	1.3	400	120	1400
Nb	1.2	375	150	1050
Pb	1.1	500	250	1000
Ti	0.9	280	None	None
Al_2O_3 (layer)	2–9			
MgO (layer)	3–15			

Source: *CRC Handbook of Chemistry and Physics*, 65th edition.

How to do FPC conditioning?

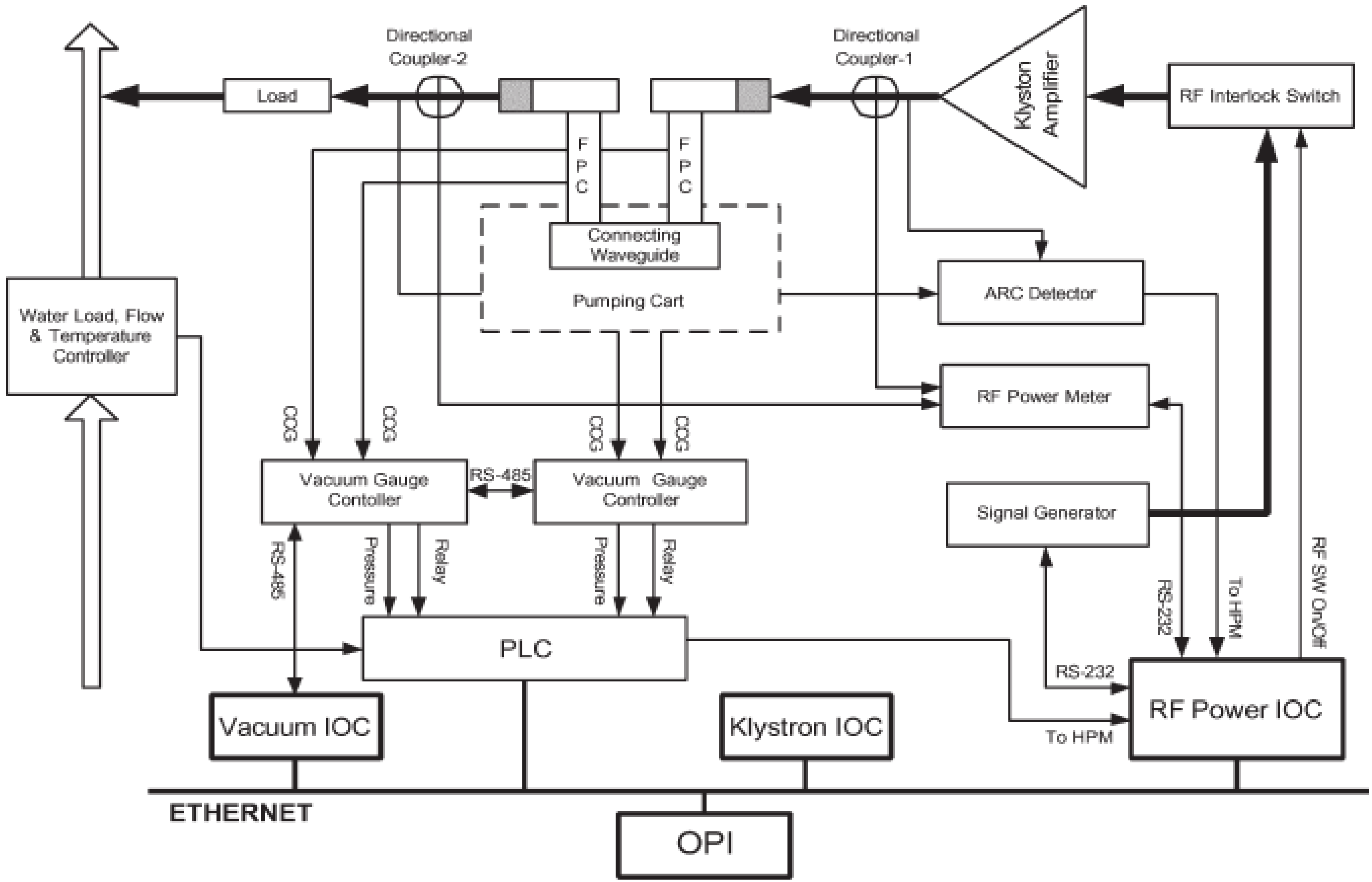
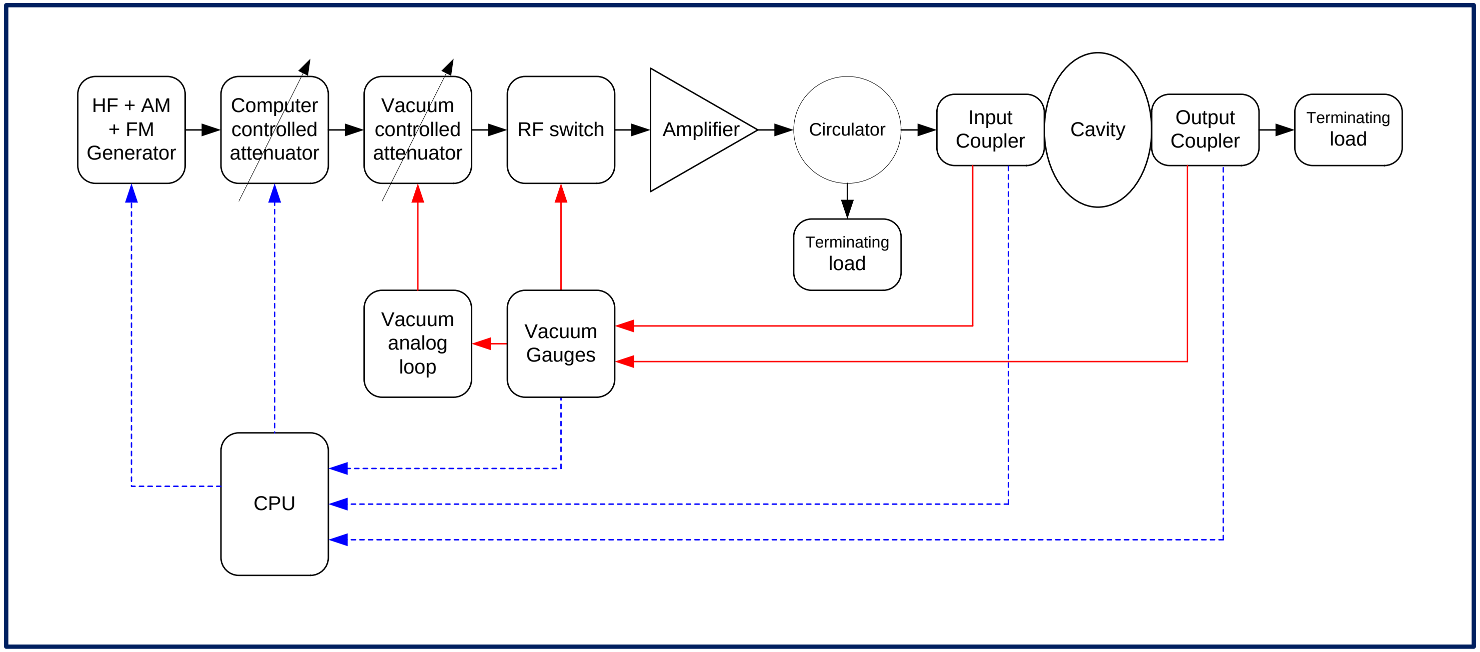


Fig. 3. Block diagram of the RF conditioning system.

FPC conditioning layout photo

FPC conditioning control loop

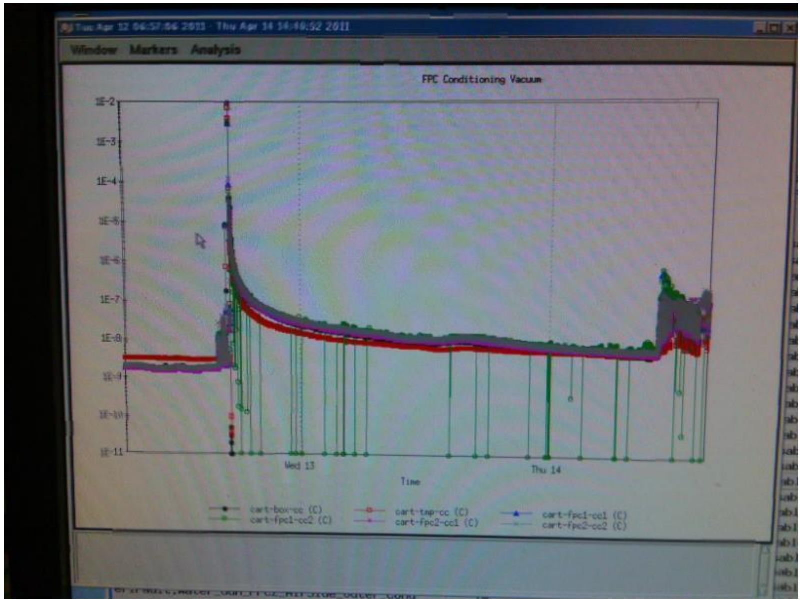


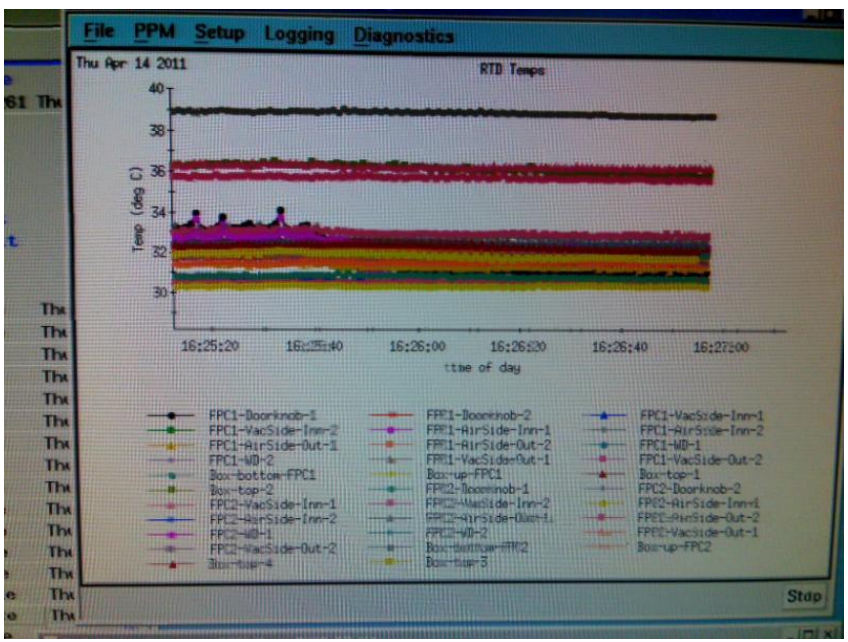
With two couplers mounted face to face on a test cavity (or coupling box) :

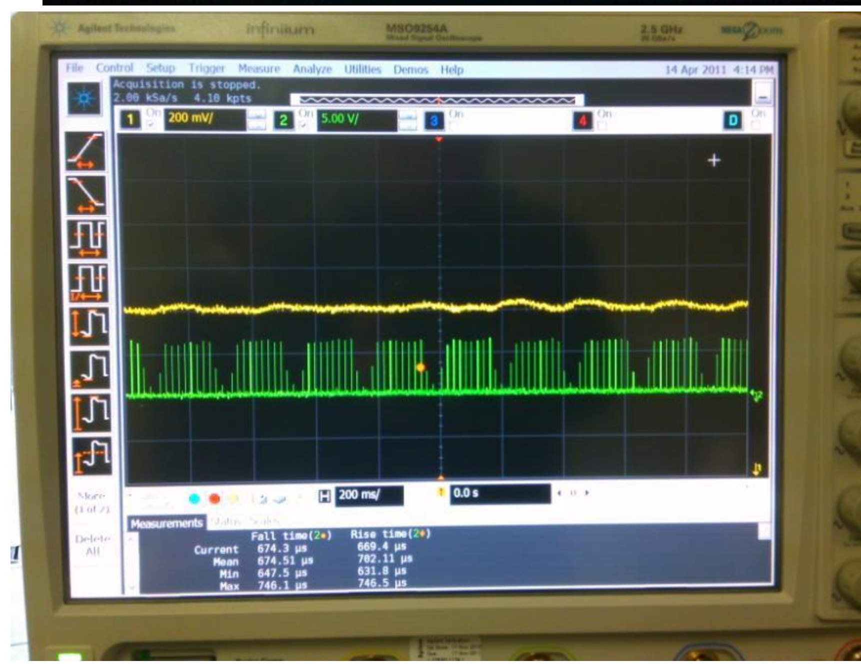
- A first direct vacuum loop (red) ensures RF is never applied if pressure exceeds 2.0 x10^{-7} torr (Vacuum Controlled Attenuator for lower values, RF switch as interlock for higher values)

- A second vacuum loop (dashed blue), cpu controlled, executes the automated process

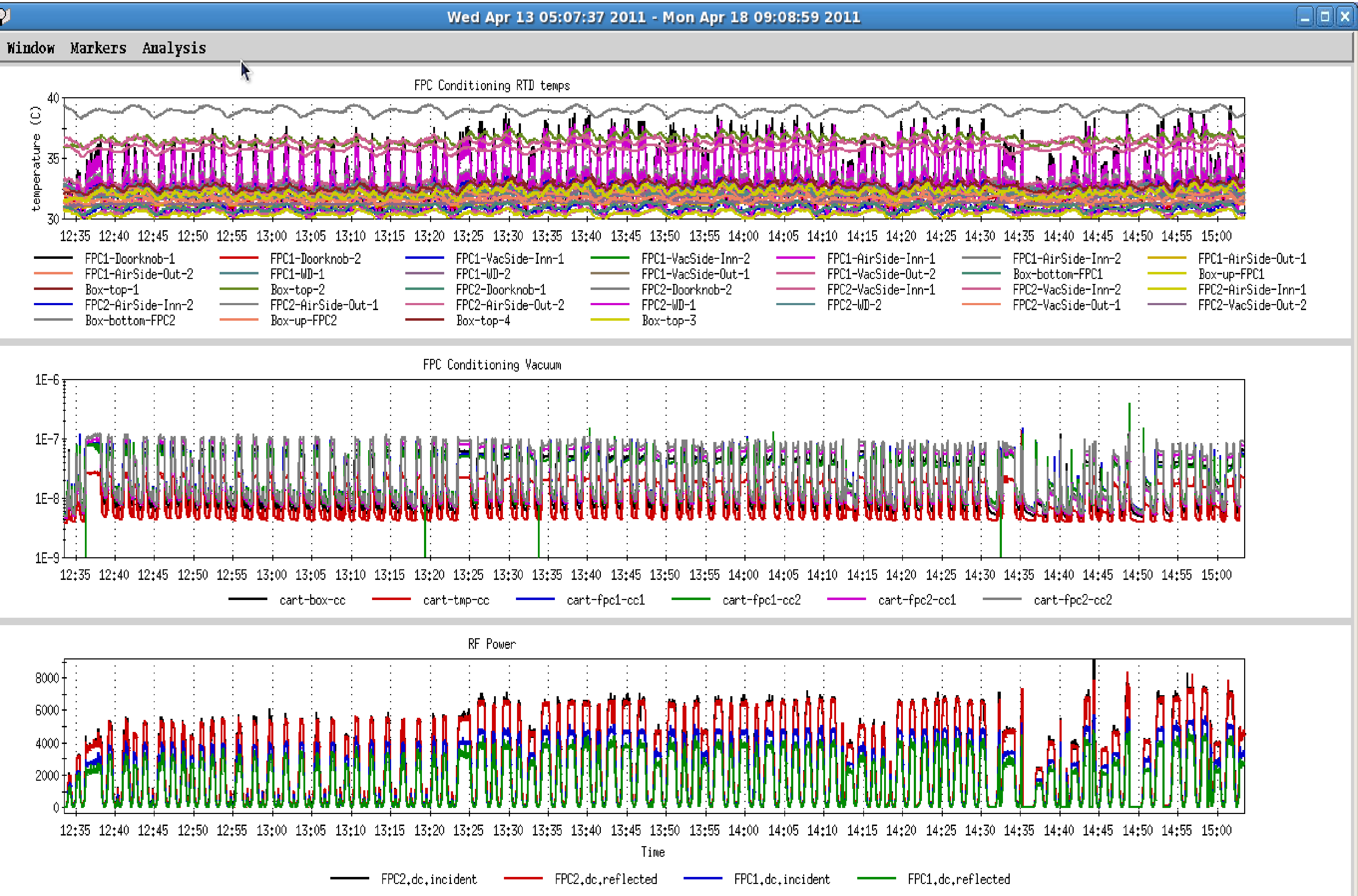
Watching signals







Conditioning Progress



Summary of FPC

- What is FPC, what are its Functions?
- How to transfer the RF power cavity w/o beam
- Types of FPCs: waveguide, cylinder
- What is multipacting? How to suppress it?
- Why FPC conditioning is important?

Thank you for you attention!