S. Belomestnykh

Superconducting RF for storage rings, ERLs, and linac-based FELs:

- Lecture 10 *Input couplers*

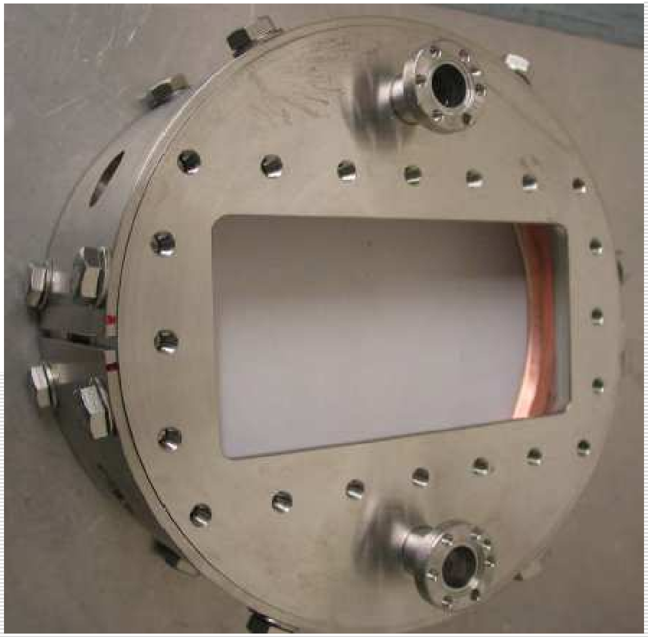
Input couplers

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
- Cavity and coupler should be treated as an integrated system

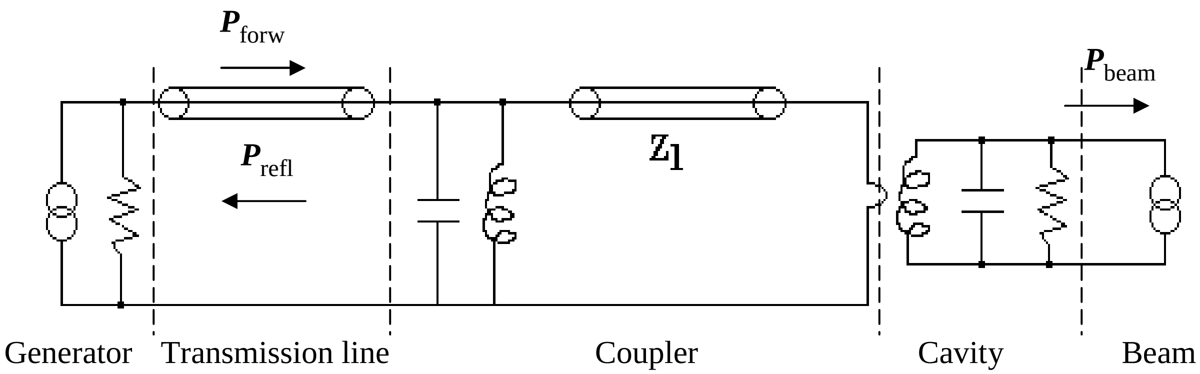
Requirements

- Higher gradients: more standing wave power
- Higher beam currents: more traveling wave power
- Pulsed power: transient conditions, transient gas loads



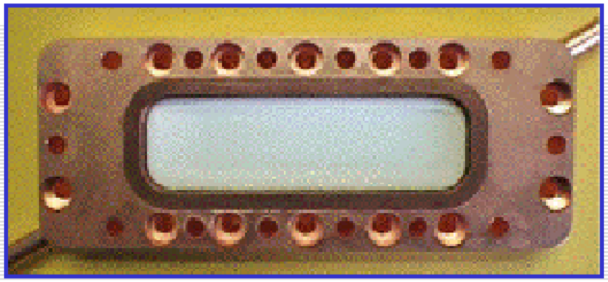
Primary functions: RF

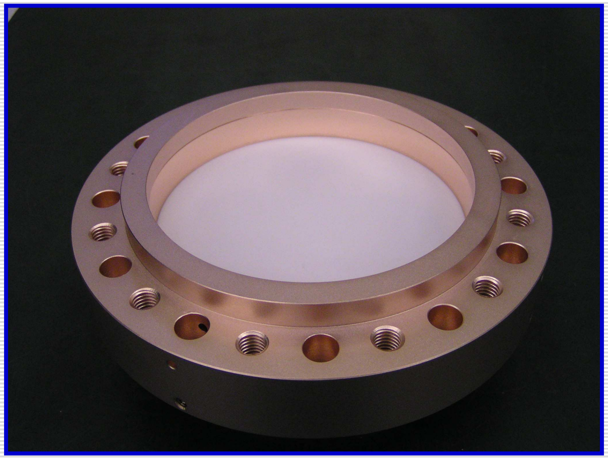
- **Passive impedance matching network.**
- **Designed to efficiently transfer RF power from a source to a beam-loaded cavity.**
- **A cavity-input coupler interface determines how strongly an RF feeder line is coupled to a cavity (β, Q_{ext}).**
- **For many applications are required to transmit megawatts of pulsed RF power and hundreds of kilowatts of average power.**



Primary functions: vacuum

- Separate gas-filled transmission lines (usually air under atmospheric pressure) from Ultra-High Vacuum (UHV) environment of accelerating cavities.
- Incorporate RF-transparent vacuum barriers (RF windows).
- Should conform to clean cryomodule assembly procedures to minimize risk of contaminating the superconducting cavity → using cold window is advisable for high-field applications.





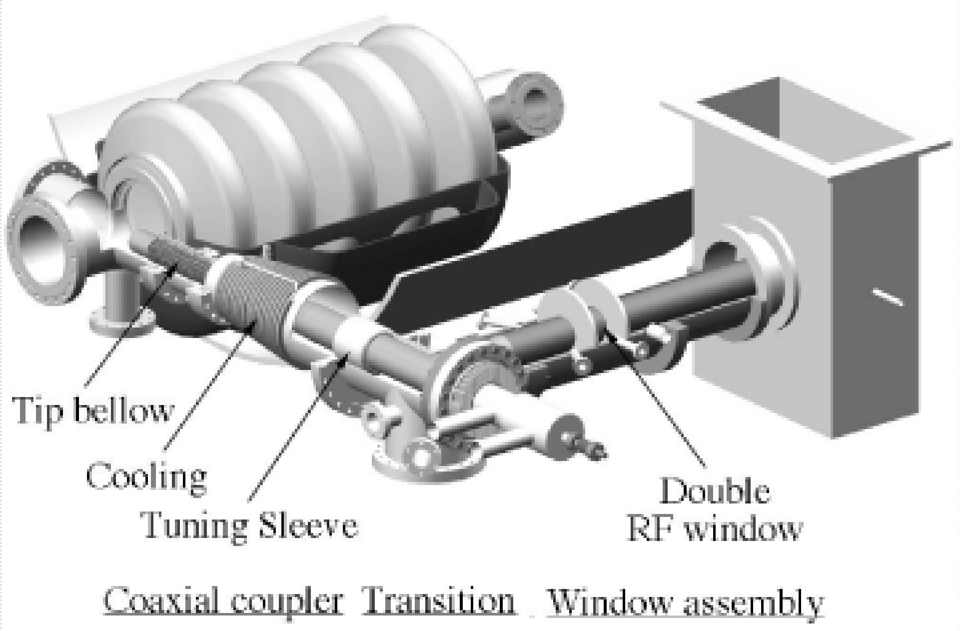
Primary functions: thermo-mechanical

- Must be a low-heat-leak thermal transition between the room temperature environment outside and the cryogenic temperature (2 K to 4.5 K) environment inside the cryomodule → incorporate carefully placed thermal intercepts and/or active cooling.
- Have to withstand multiple thermal cycles.
- Need to withstand large thermal gradients.

Waveguide coupler for CEBAF upgrade

Other challenges

- Should minimize cavity field perturbations that can affect beam or cavity performance → double couplers, compensating stubs, etc.
- Provide (in some cases, machine dependent) an adjustable coupling for different operating modes → can be supplemented by three-stub tuners in many cases.
- Should be designed taking into consideration multipacting: ideally to be multipactor-free or provide cures such as bias voltage or other mitigating measures.



APT cavity and coaxial input coupler

Coupler options

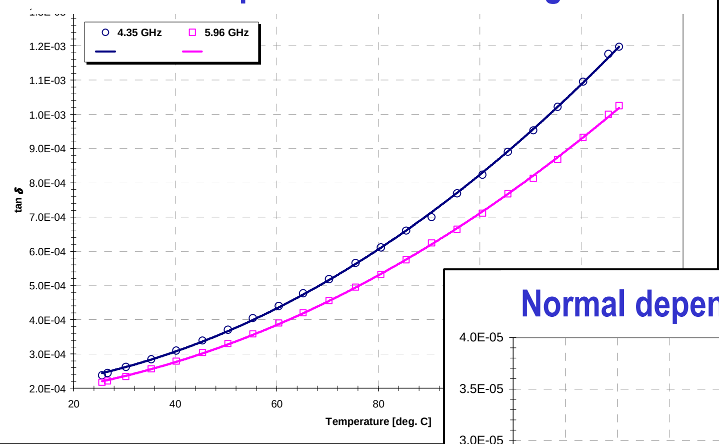
Both waveguide and coaxial coupler designs are used

	Pros	Cons
Waveguide	• Simpler design • Lower RF losses • Easier to cool • Higher pumping speed	• Larger size • Higher thermal radiation • More difficult to make variable
Coaxial	• More compact • Smaller heat leak • Easier to make variable • Easier to handle multipacting	• More complicated design • Need a "doorknob" transition to waveguide • Higher RF losses • More difficult to cool • Smaller pumping speed

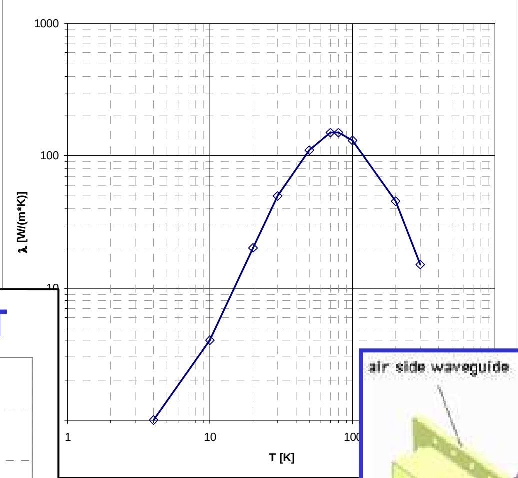
RF windows

- High-purity alumina ceramics (Al_2O_3) is predominantly used for RF windows.
- Low loss tangent ($\sim 10^{-4}$) should have weak dependence on temperature to avoid thermal runaway.
- Alternative materials: BeO (worse yield strength, but better thermal conductivity; dust may be toxic), AIN.
- Window shapes: planar for waveguide couplers; coaxial disk, cylindrical and conical for coaxial couplers.
- To prevent multipacting, vacuum side is coated with titanium nitride or titanium oxide to reduce SEY. Alternative coating: chromium oxide, used on some vacuum tubes.

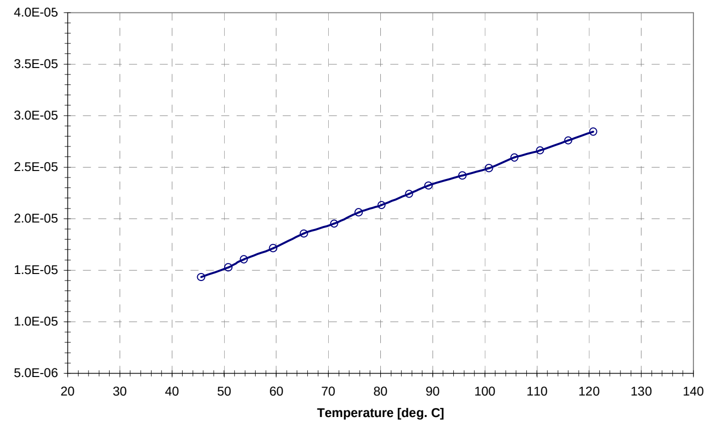
Abnormal dependence of loss tangent on T

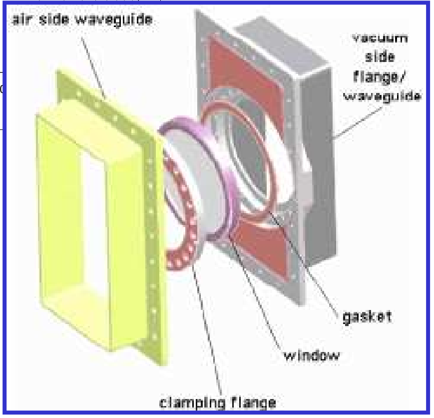


Thermal conductivity of alumina



Normal dependence of loss tangent on T

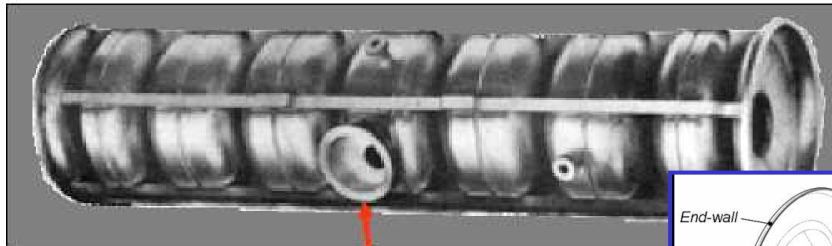




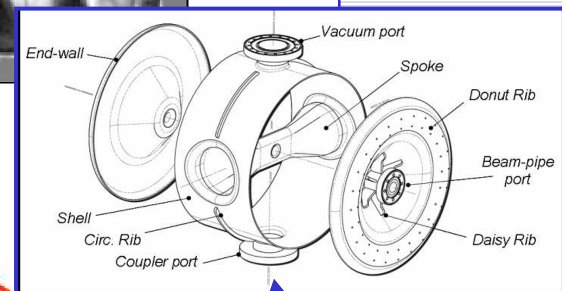
Coupler port location

HEPL cavity 1977

- ports on equator
- limitation by MP



coupler ports



Tesla cavity 1993

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

Coupler port location on a spoke resonator

W.– D. Möller, DESY in Hamburg

13th International Workshop on RF Superconductivity
Peking University, China, Oct. 11-19, 2007

- Beam line port: antenna type coupler → coupling to the electric field.
- Equator port: loop type coupler → coupling to the magnetic field.

CW couplers

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

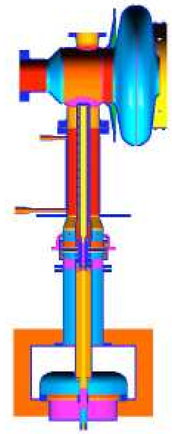
Pulsed couplers

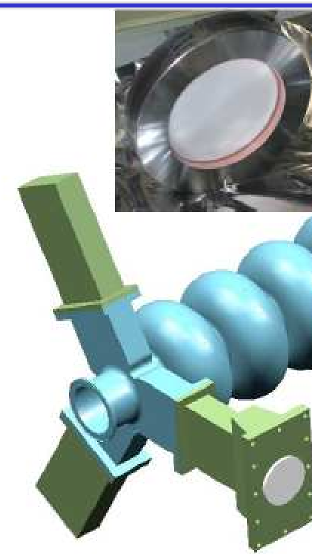
Facility/ Project	Frequency	Coupler type	RF window	Q_{ext}	Max. peak power	Pulse length, rep. rate, etc.
CARE-HIPPI	704 MHz	Coax fixed	Disk, coax	-	Test: 1 MW	2.0 msec, 50 Hz
SNS	805 MHz	Coax fixed	Disk, coax	7×10^5	Test: 2 MW Operation: 550 kW	1.3 msec, 60 Hz 1.3 msec, 60 Hz
J-PARC	972 MHz	Coax fixed	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

**) one pair of couplers was tested to 2 MW, 1.3 msec, 2 Hz*

Power couplers at JLab

- Various coupler configurations are available





CEBAF waveguide
- **Peak power up to 6 kW CW**
- **2K and 300 K windows**
- **Dogleg shields cold window from beam.**

Upgrade WG coupler
- **Peak power in up to 13 kW CW**
- **300 K window**
- **Cooling: WG heat stationed at 50K**
- **Optional active cooling**
- **Optional double warm window**

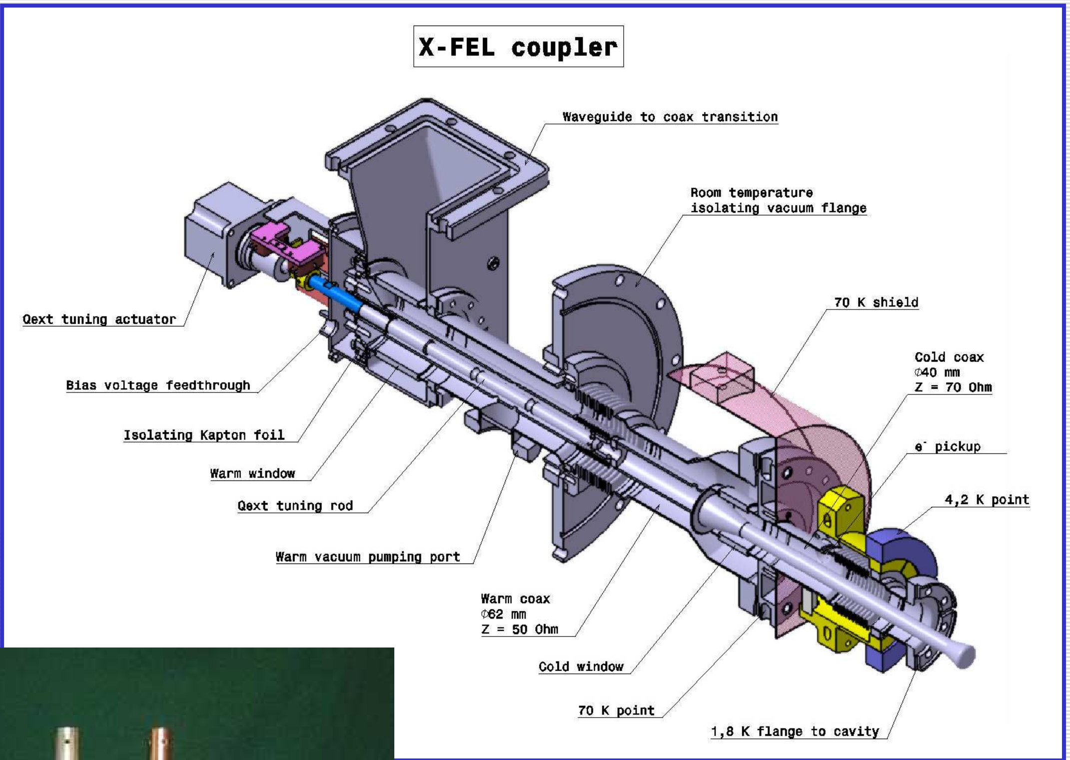
SNS coax coupler
- **Peak power in up to 550 kW (tested up to 2 MW)**
- **1.3 ms RF on. 60 pps**
- **Up to 50 kW average power**
- **Q_{ext} ~ 7 x 10^5**
- **300 K window**
- **Cooling: Inner conductor extension: water. Inner conductor: conduction cooling. Outer conductor: GHe flow**

FEL high-power WG
- **Peak power in up to 200 kW (Window tested to 1 MW CW)**
- **300 K window**
- **Cooling: Window: water. WG transition: GHe flow**
- **Dogleg or bend (not shown) to avoid exposure to beam**

Jefferson Lab   Thomas Jefferson National Accelerator Facility   ERL07, Daresbury 5/2007   JSA

TTF-III / XFEL coupler

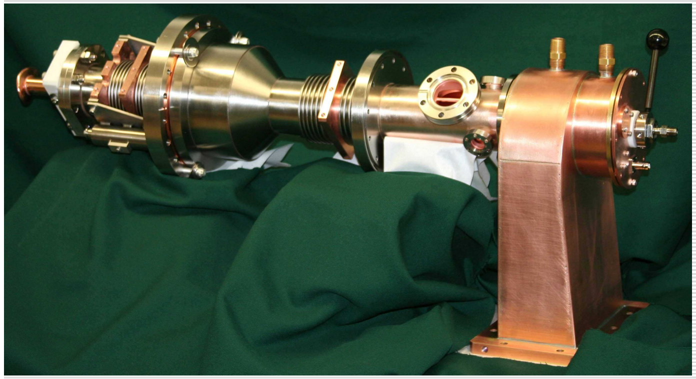
- A "classic" example of a coaxial coupler for high accelerating gradient (>20 MV/m) application: FLASH/XFEL/ILC
- Two cylindrical alumina windows: warm and cold
- Cold windows is assembled on a cavity string in class 100 clean room
- Reached 1 MW (1.3 ms, 2 Hz) on a test stand
- Typically operate at 250 kW (1.3 ms, 10 Hz)



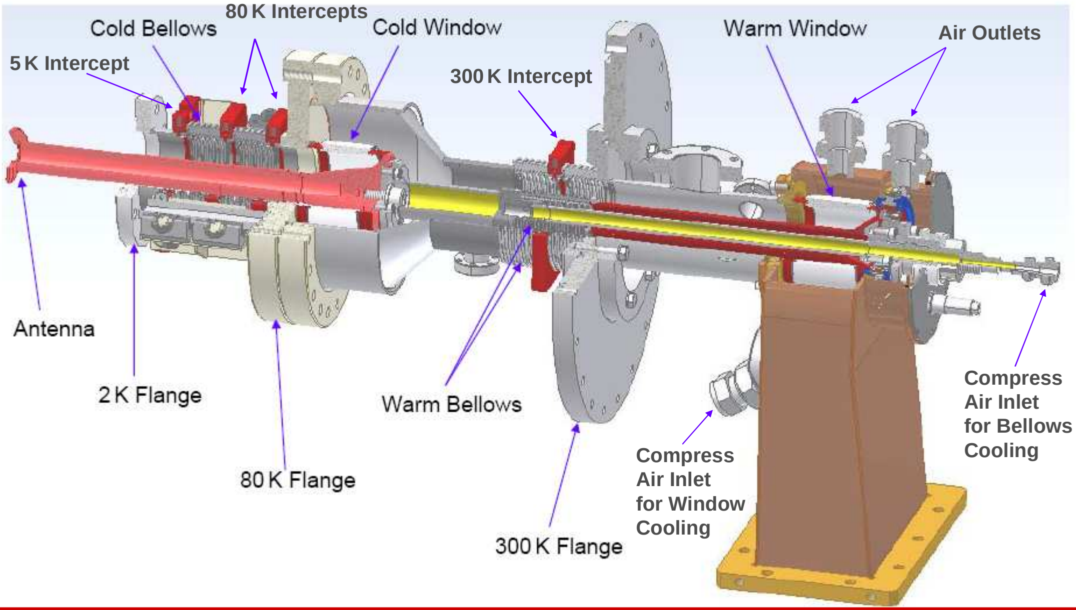
Cornell ERL injector input coupler

Design features:

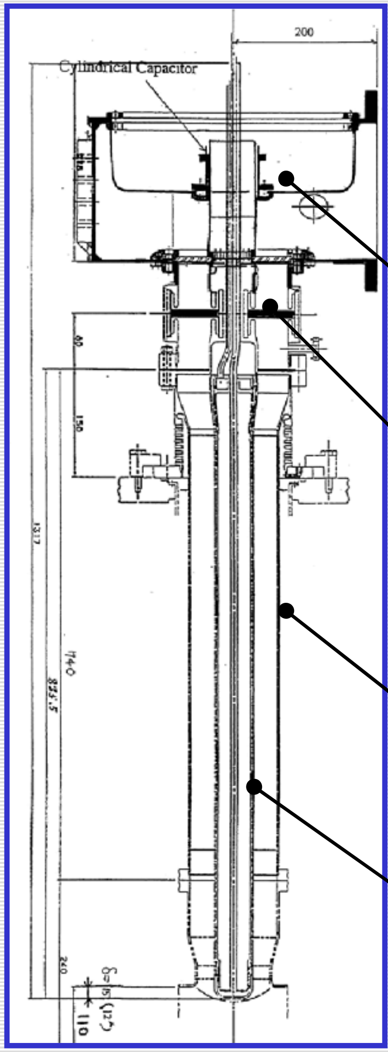
- Design derived from the TTF-III coupler with improvements necessary to handle high average RF power of 75 kW
- The cold part was completely redesigned using a 62 mm, 60 Ohm coaxial line for stronger coupling, better power handling and avoiding multipacting
- Antenna tip was enlarged and shaped for stronger coupling
- "Cold" window was enlarged to the size of "warm" window
- Outer conductor bellows design was improved for better cooling (added heat intercepts)
- Air cooling of the warm inner conductor bellows was added



- Production couplers reached 61 kW CW level on a test stand
- This couplers should be able to handle at least as high peak power as TTF-III couplers: 1 MW



TRISTAN / KEKB coupler



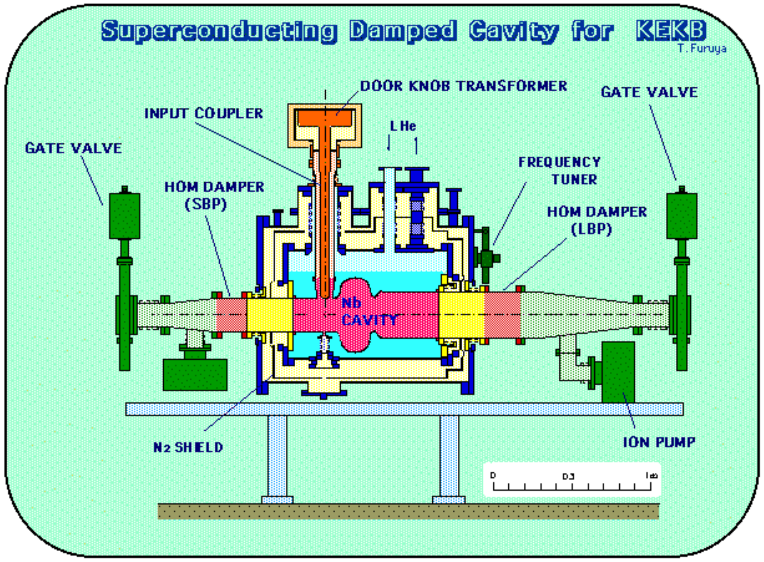
- Based on the long-term operation of 32 SC cavity couplers in TRISTAN (operating frequency of 509 MHz)
- 50 Ohm coaxial line
- Fixed coupling @ $Q_{ext} = 7\times10^4$
- Improved monitoring, cooling, choke structure around window
- Record power delivered to beam: 400 kW
- Used on KEKB crab cavities and BEPC-II cryomodules
- This very successful coaxial coupler design was adapted for other frequencies and pulsed operation (SNS, CARE-HIPPI, …)

Biased doorknob (±2 kV)

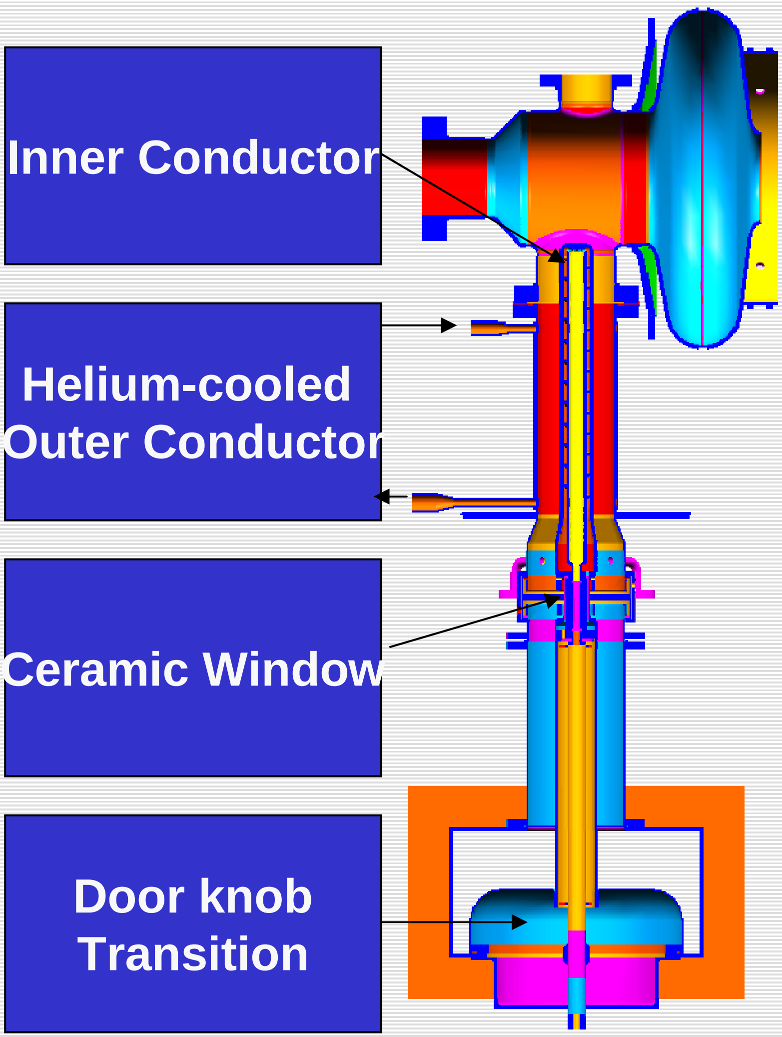
Alumina (99.5%) coaxial disk window, coated with 100 Å of TiN_xO_{1-x}, air cooled outside

Copper plated SS,
4 K He gas cooling at 8 l/min

Water cooled inner conductor, electropolished copper



SNS coupler



Derived from KEKB design

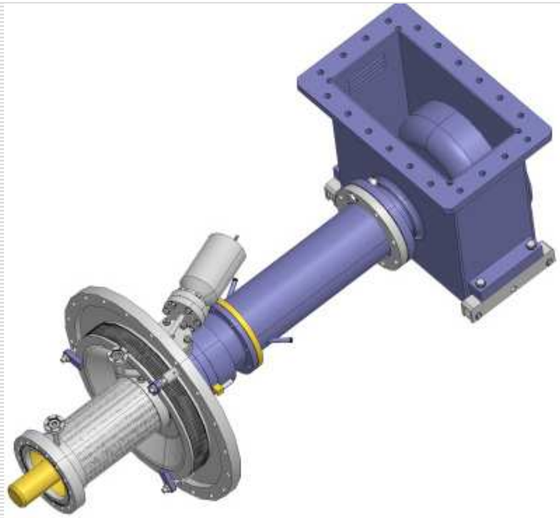
Present specifications:
- 550 kW peak
- 48 kW average

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

CARE-HIPPI coupler

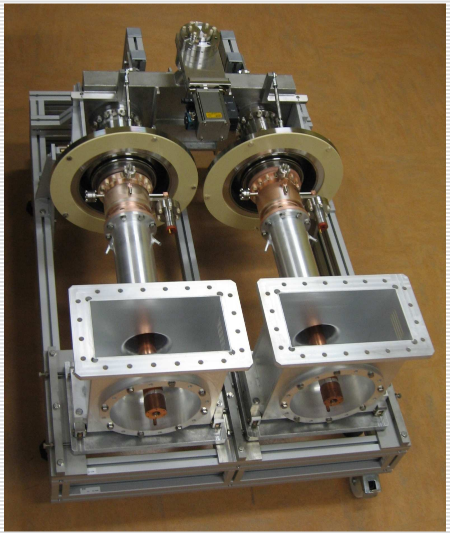
- 704 MHz fundamental power coupler is developed at Saclay in the framework of the CARE-HIPPI program
- The coupler is designed to transmit RF power of 1 MW at 10% duty cycle (2 ms, 50 Hz)
- The design is similar to KEKB and SNS with coaxial disk window, 100 mm 50 Ohm coaxial line and WR1150 waveguide
- In recent test reached 1.2 MW at 2 ms, 50 Hz (120 kW average), limited by the klystron



He cooled outer conductor

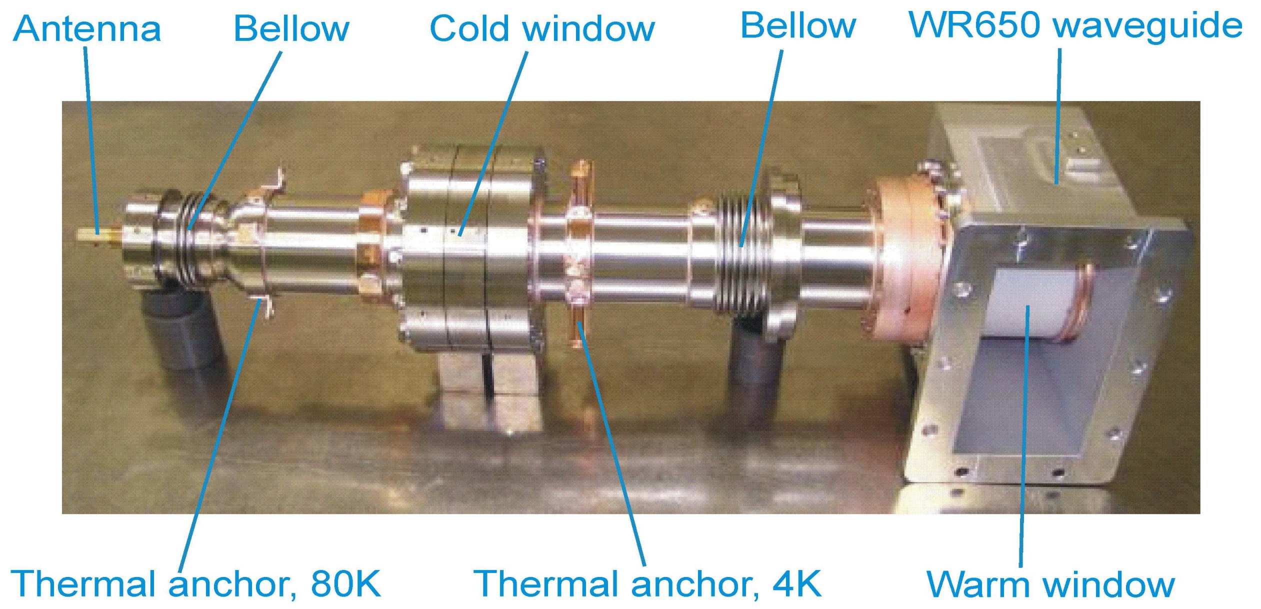
Ceramic disk window with an integrated antenna

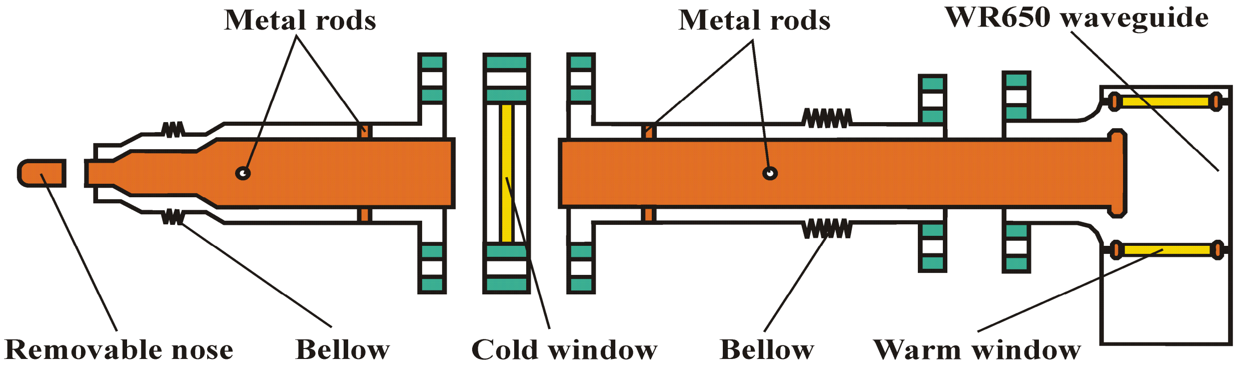
Assembled couplers



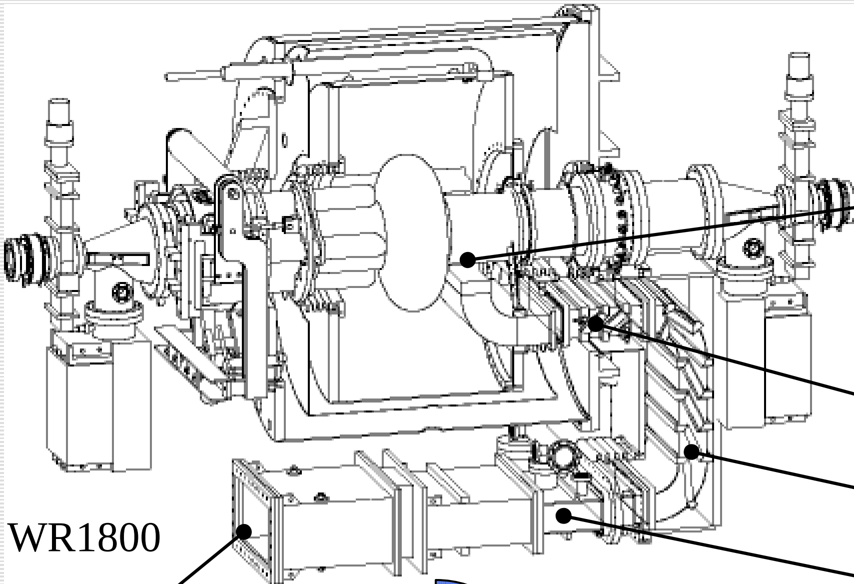
Capacitively coupled coupler (KEK)

- Modular design
- Low heat leak

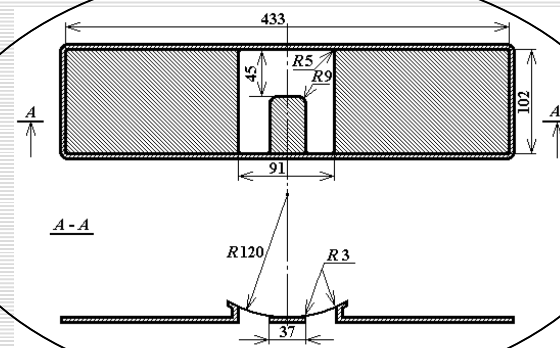




CESR waveguide input coupler



Coupling slot



Cold He gas cooled WG

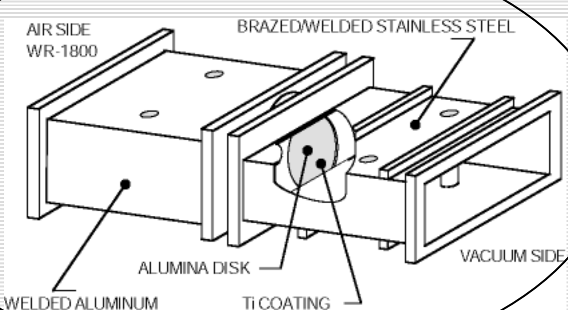
Liquid nitrogen cooled WG

Pumping section

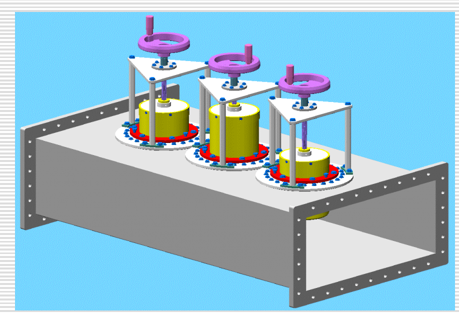
WR1800

Kapton window

Warm RF window



- Fixed coupling @ $Q_{ext} = 2\times10^5$
- Magnetic bias of the WG to suppress multipacting
- Adjustability is possible via a 3-stub WG transformer
- This coupler is used at TLS, CLS, Diamond and SSRF 3rd generation light sources



Coupler failures

***Typical coupler failures & performance degradation*:**

- 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
- Increased heating
- Increased arcing
- Re-activation of MP barriers

***Some causes of failures & performance degradation*:**

- Beam-induced higher-order modes
- Transient effects
- Harmonics from RF source
- Gas condensation on cold surfaces
- Sputtering due to intense MP or arcing
- Insufficient thermal margin in design
- Inadequate mechanical design margin
- Inadequate vacuum pumping
- Poor quality control during fabrication
- Inadequate interlocks

destroyed by excessive power rise with deactivated interlock!!

Coupler RF conditioning

Prior to installation in a cryomodules high-power couplers are usually RF conditioned (processed) on a test stand with parameters matching or exceeding those expected in operation with beam.

- **Using vacuum bake and clean room techniques helps to reduce processing time.**
- **RF conditioning allows to control desorption of absorbed gases.**
- **Protection interlocks should be set as a compromise between conditioning speed and risk of sparking.**
- **Traveling wave operation cleans all surfaces, standing wave operation utilizes sliding shorts to do the same.**

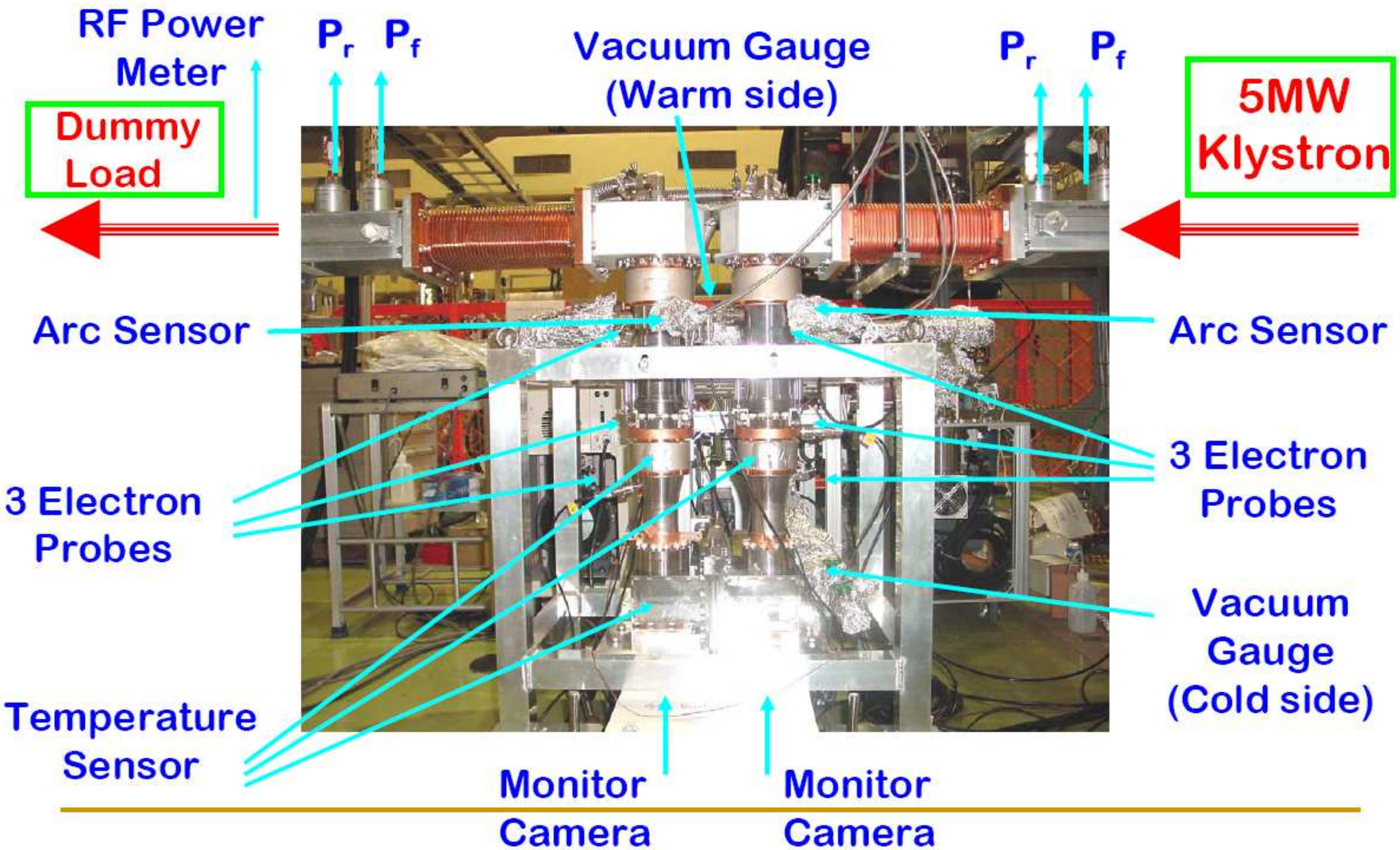
After installation in a cryomodule, couplers may need to be re-conditioned in situ as they may become re-contaminated during the assembly process and/or the cold surfaces may collect condensed gases.

<u>Basic RF conditioning procedure for pulsed couplers (SNS)</u>:

- ***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.***

Typical high-power test set up

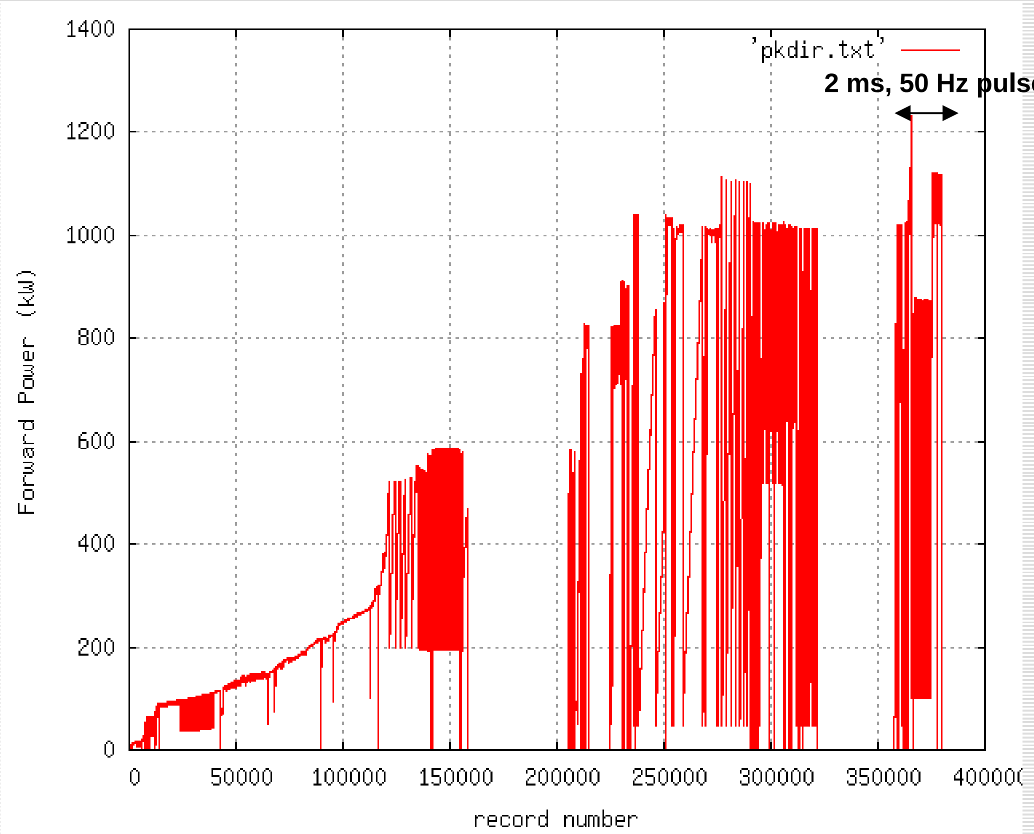
Set-up for High Power Tests



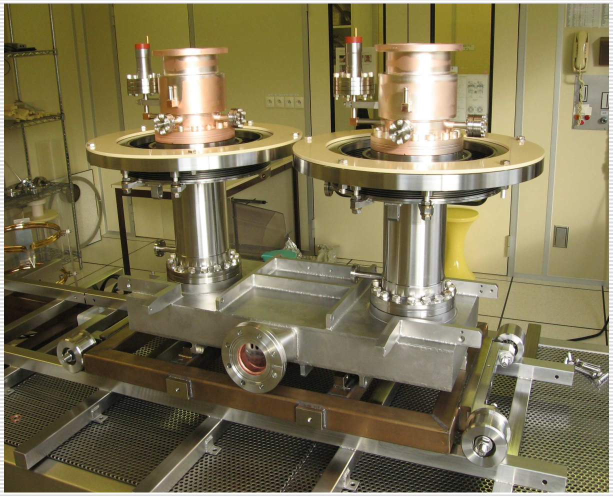
E. Kako (KEK) Meeting at LAL-Orsay, 2007' Feb. 28 13

CARE-HIPPI coupler test

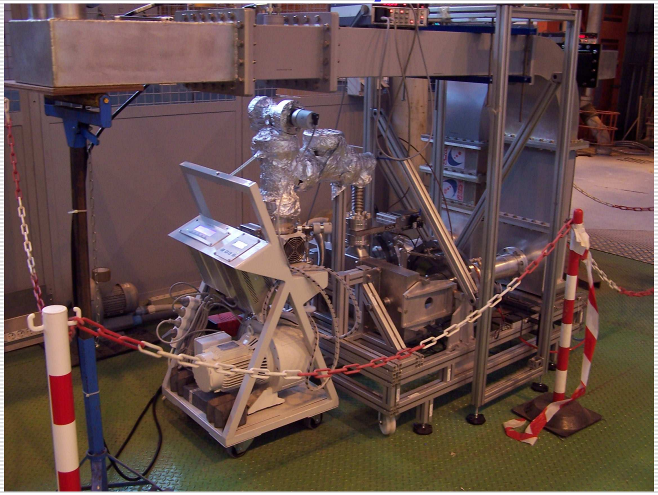
Power conditioning



Test stand assembly in the clean room

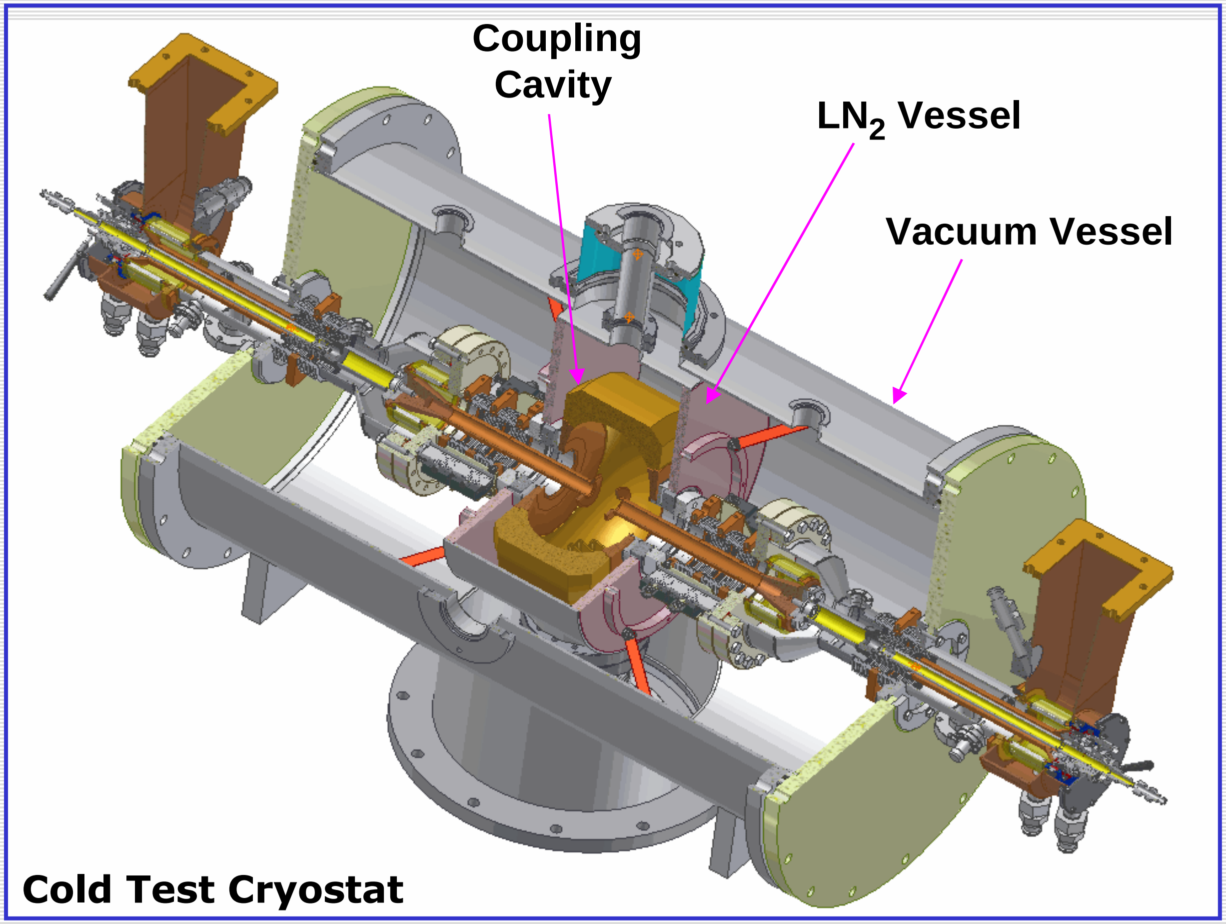


Test stand connected to 1 MW klystron



Cold test set up of CW couplers

- CW or high-average-power pulsed coupler with cold windows may require testing in a special cryostat as they rely on high thermal conductivity of ceramics at temperatures ~80 K



Handling after processing

Handling after processing

goal is to maintain the processing effect

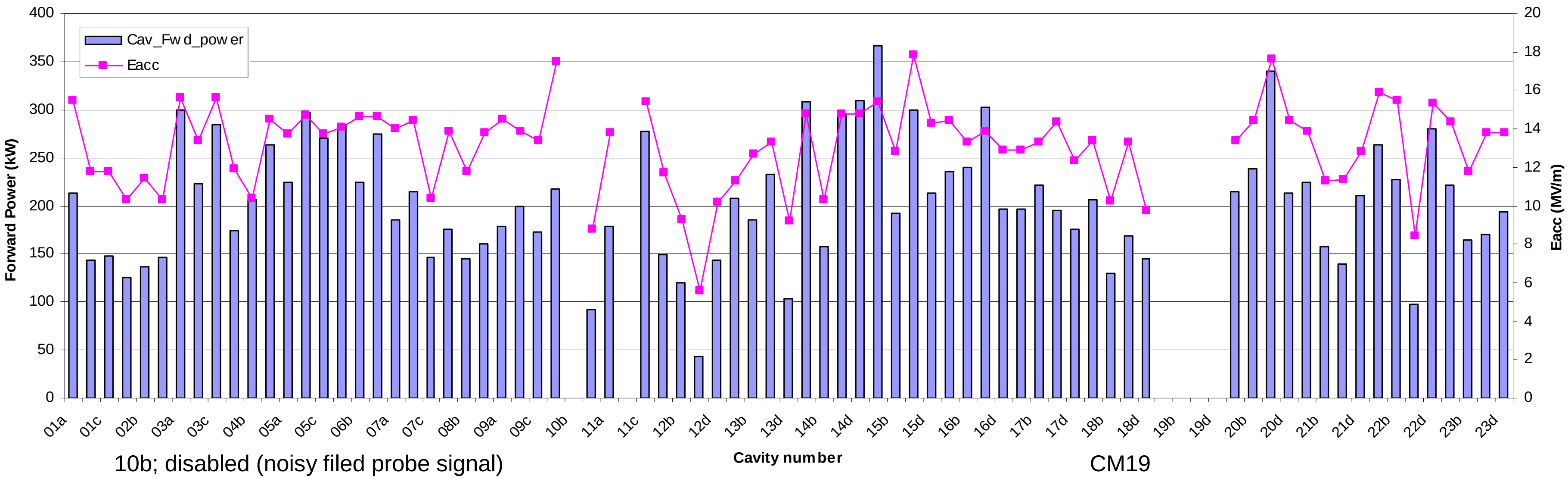
– disassembly from test stand and assembly to the cavity & module under clean conditions

– store always under dry Nitrogen to avoid contamination by water

sealing cap for cold window

W.– D. Möller, DESY in Hamburg   12th International workshop on RF Superconductivity   36

SNS couplers: operational experience



- **Cavity-coupler interaction**
  - **Electron current at the full traveling wave**
  - **Radiation spikes at the same time**
  - **Can cause multipacting**
- **Cold cathode gauge (interlock to protect coupler window)**
  - **Sleeping and wake-up with erratic signals**
  - **Made turn-on difficult before new procedure were implemented**
  - **Moving towards interlocking on electron probe signals**
- **Coupler outer conductor cooling circuit**
  - **Difficult adjustment of helium flow under changing average power**
  - **Cross-interactions between cavities in a cryomodule**
- **Multipacting (MP) in FPCs**
  - **As the beam power is increased, the multipacting purely in the FPC in several cavities is observed**
  - **DC biasing will help to suppress MPs**
- **Otherwise the FPCs are working fine and very robust.**

What have we learned?

- Input couplers are critical and complex components.
- Their cost is comparable to the cost of cavities.
- A cavity with input coupler(s) should be treated as an integrated system.
- Couplers perform several functions: RF matching network, vacuum barrier, low-loss thermal transition from room temperature outside the cryomodule to cryogenic temperature environment inside.
- There are several very successful designs of waveguide and coaxial input couplers.
- High power couplers should be RF conditioned prior to installation.

✪ We will discuss HOM dampers in the next lecture