Overview of Input Power Coupler Developments, Pulsed and CW

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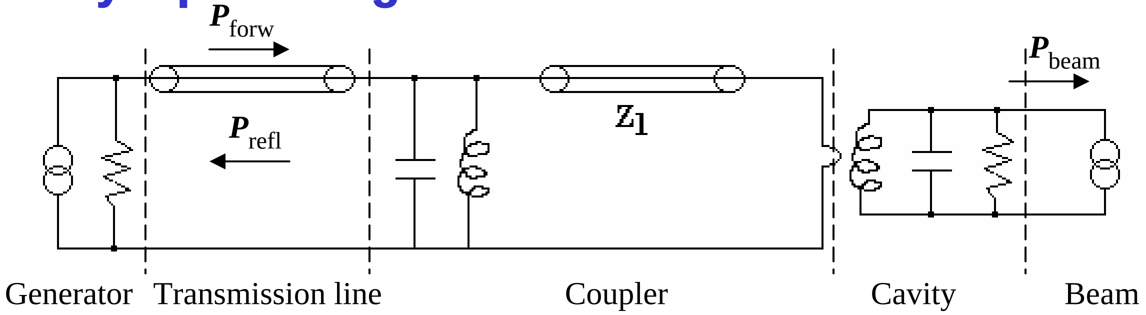
Introduction

- Many successful high power fundamental input couplers have been developed over years for superconducting cavities.
- Projects like the International Linear Collider (ILC), Energy Recovery Linacs (ERLs), Free Electron Lasers (FELs), and Superconducting RF (SRF) guns bring new challenges.
- A number of new coupler designs, both for pulsed and CW operation, was proposed and developed recently.
- In this presentation we will review existing designs with an emphasis on new developments.

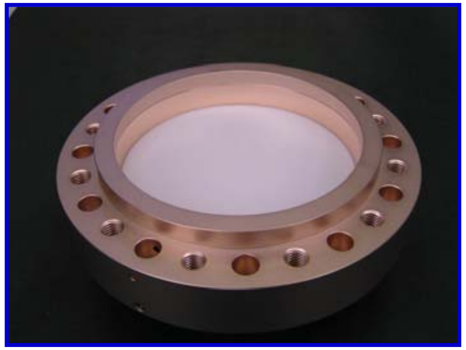
Primary functions

- **RF input couplers are passive impedance matching networks designed to efficiently transfer RF power from a source to a beam-loaded cavity operating under UHV conditions.**



- **As transmission lines (coaxial or waveguide) are usually filled with gas, couplers have to have RF-transparent vacuum barriers (RF windows).**



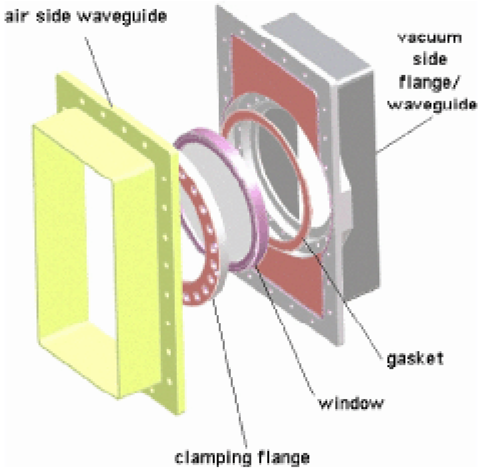


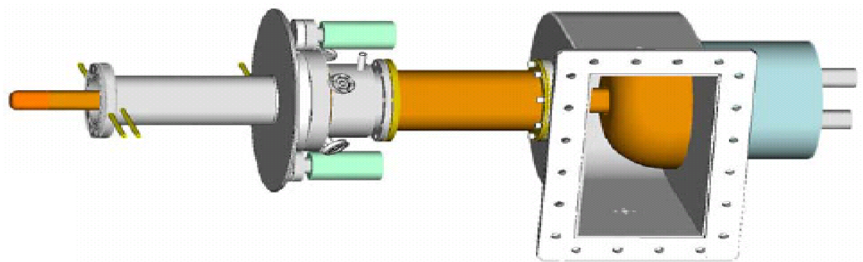
Other requirements/challenges

- Must be a low-heat-leak thermal transition between the room temperature environment outside and the cryogenic temperature (2 to 4.5 K) environment inside the cryomodule → extensive thermal simulations, carefully placed thermal intercepts and/or active cooling.
- Should conform to clean cryomodule assembly procedures to minimize risk of contaminating the superconducting cavity → using cold window is advisable for high-field applications.
- 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 phenomenon: that is to be multipactor-free or provide cures such as bias voltage.
- RF conditioning time is still too long for high-power couplers → need to improve/add new procedures and handling/preparation steps.

Coupler options

Waveguide	Coaxial
• Simpler design • Better power handling • Easier to cool	• More compact • Smaller heat leak • Easier to make variable • Easier to handle multipacting



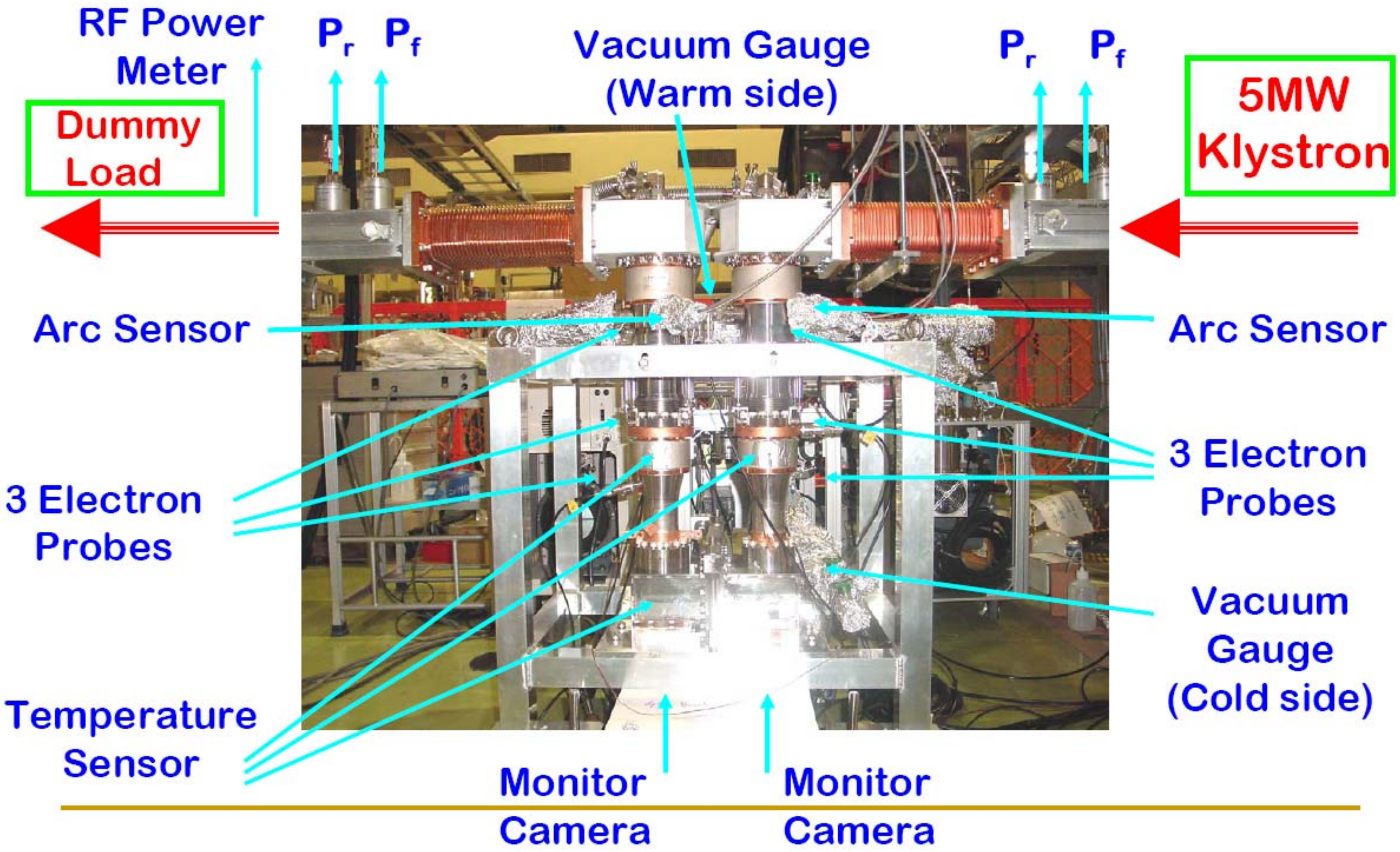


BUT: PEOPLE TEND TO WORK WITH WHAT THEY ARE ACCOSTOMED TO
OR: PICK UP AN EXISTING DESIGN

WITHOUT GIVING MUCH CONSIDERATION TO DIFFERENT OPTIONS

Typical high power test set-up

Set-up for High Power Tests



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

CW couplers

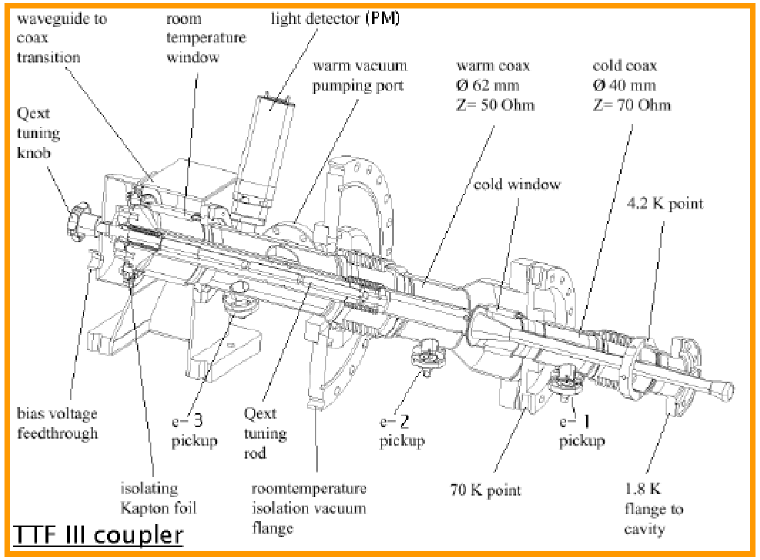
Facility	Frequency	Coupler type	RF window	Q_{ext}	Max. CW power	Comments
LEP2 / SOLEIL	352 MHz	Coax fixed	Cylindrical	2×10^6	Test: 565 kW 380 kW Oper: 150 kW	Traveling wave @ Γ=0.6
LHC	400 MHz	Coax variable (60 mm stroke)	Cylindrical	2×10^4 to 3.5×10^5	Test: 500 kW 300 kW	Traveling wave Standing wave
HERA	500 MHz	Coax fixed	Cylindrical	1.3×10^5	Test: 300 kW Oper: 65 kW	Traveling wave
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 / 3rd generation light sources	500 MHz	WG fixed	WG disk	2×10^5	Test: 450 kW Oper: 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 Oper: 400 kW	Traveling wave Standing wave
APT	700 MHz	Coax variable ($\pm$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 Oper: 35 kW	Very low ΔT

Pulsed couplers

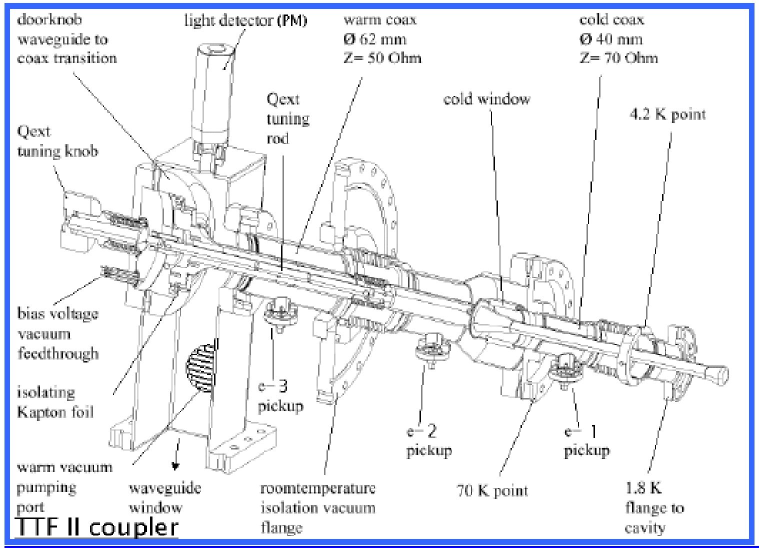
Facility	Frequency	Coupler type	RF window	Q_{ext}	Max. peak power	Pulse length, rep. rate, etc.
SNS	805 MHz	Coax fixed	Disk, coax	7×10^5	Test: 2 MW Oper: 550 kW	1.3 msec, 60 Hz 1.3 msec, 60 Hz
J-PARC	972 MHz	Coax fixed	Disk, coax	5×10^5	Test: 2.2 MW 370 kW	0.6 msec, 25 Hz 3.0 msec, 25 Hz
FLASH	1300 MHz	Coax variable (FNAL)	Conical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 250 kW Oper: 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 Oper: 250 kW	1.3 msec, 10 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: 1.5 MW 1 MW Oper: 250 kW	1.3 msec, 2 Hz 1.3 msec, 10 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 for LL cavity, ILC)	Disk (cold), cylindrical (warm)	2×10^6	Test: 2 MW 1 MW	1.5 msec, 3 Hz 1.5 msec, 5 Hz

Input couplers for FLASH/XFEL/ILC

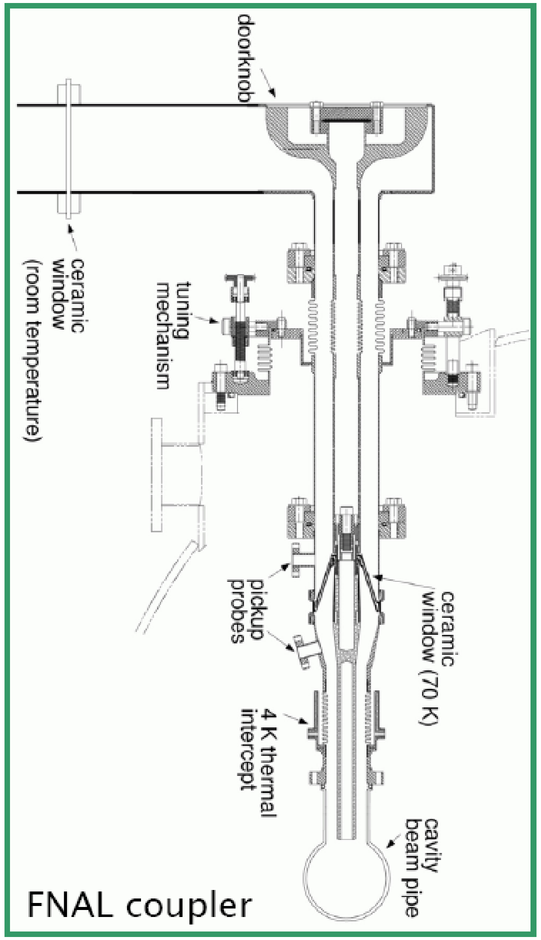
RF Coupler Types



TTF III coupler



TTF II coupler



FNAL coupler

Denis Kostin, MHF-sl, DESY September 2007

WEP05
WEP22

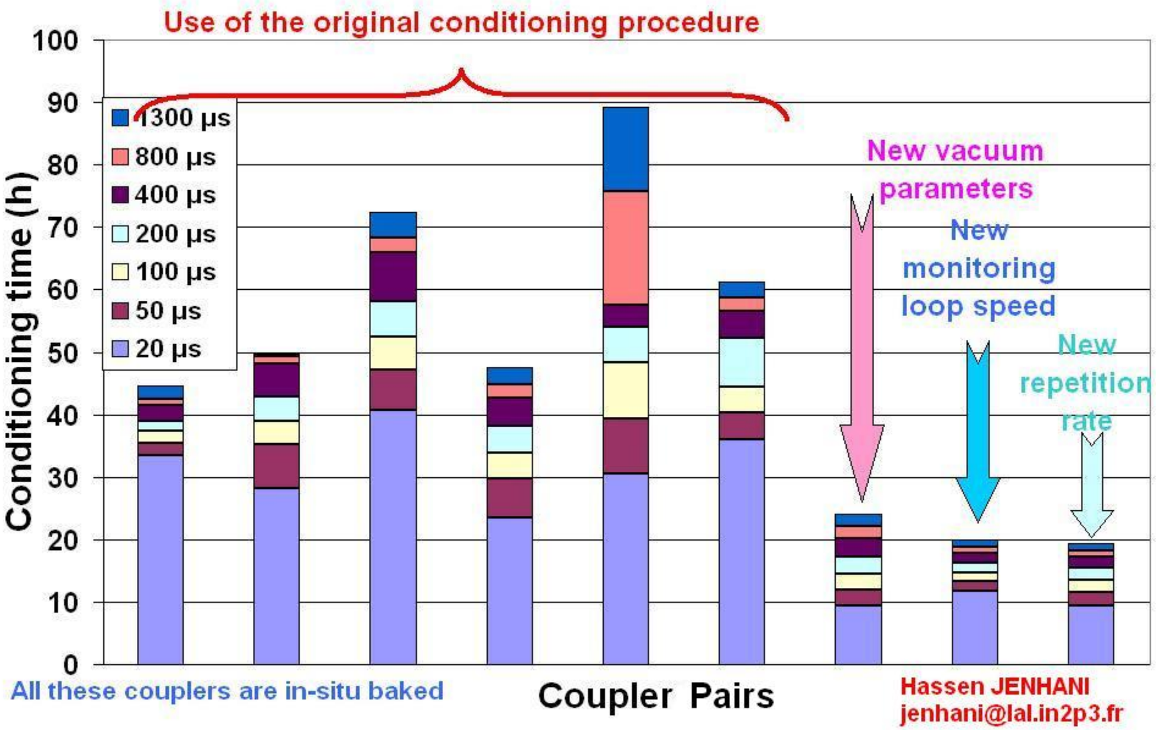
RF conditioning (1)

TTF-III Couplers (DESY and LAL/Orsay):

- **Baseline for XFEL. At present industrialisation studies for 800 couplers to reduce the costs.**
- **Baseline coupler for ILC.**

Basic problem: long conditioning time.

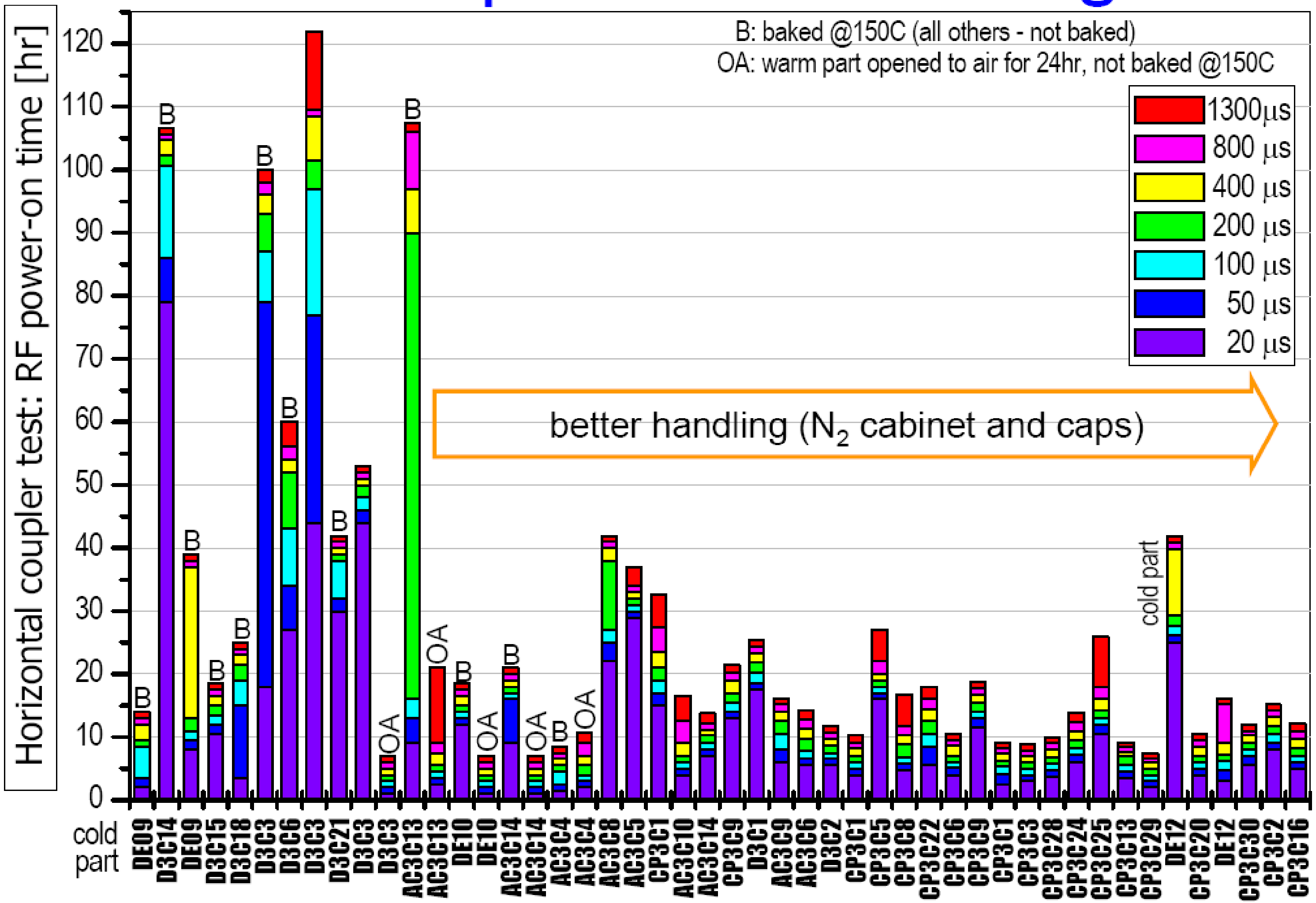
A long experimental program has been carried out to reduce the conditioning time



First conditioning on coupler station

RF conditioning (2)

RF Couplers Conditioning



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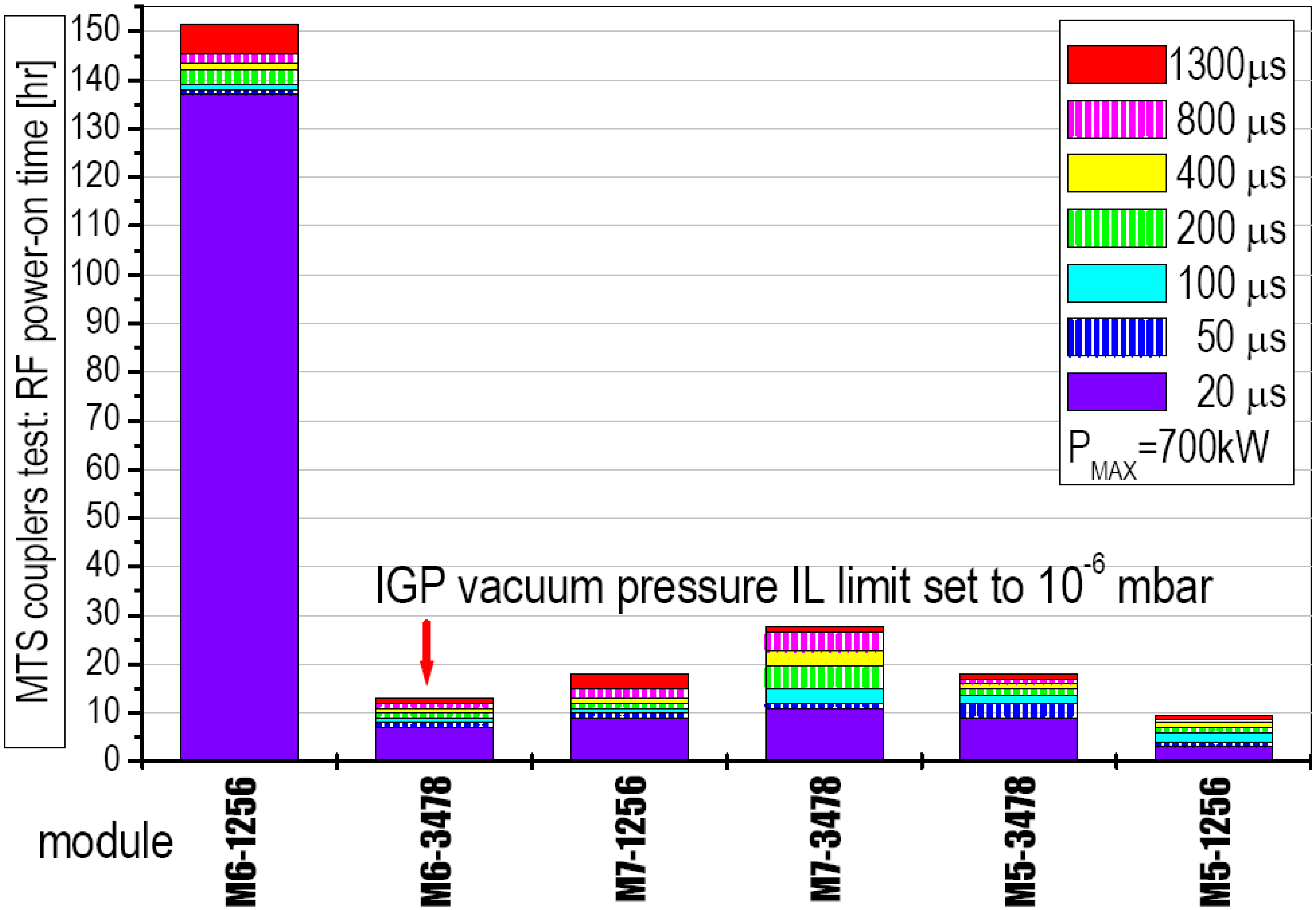
RF conditioning (3)

RF Couplers Conditioning



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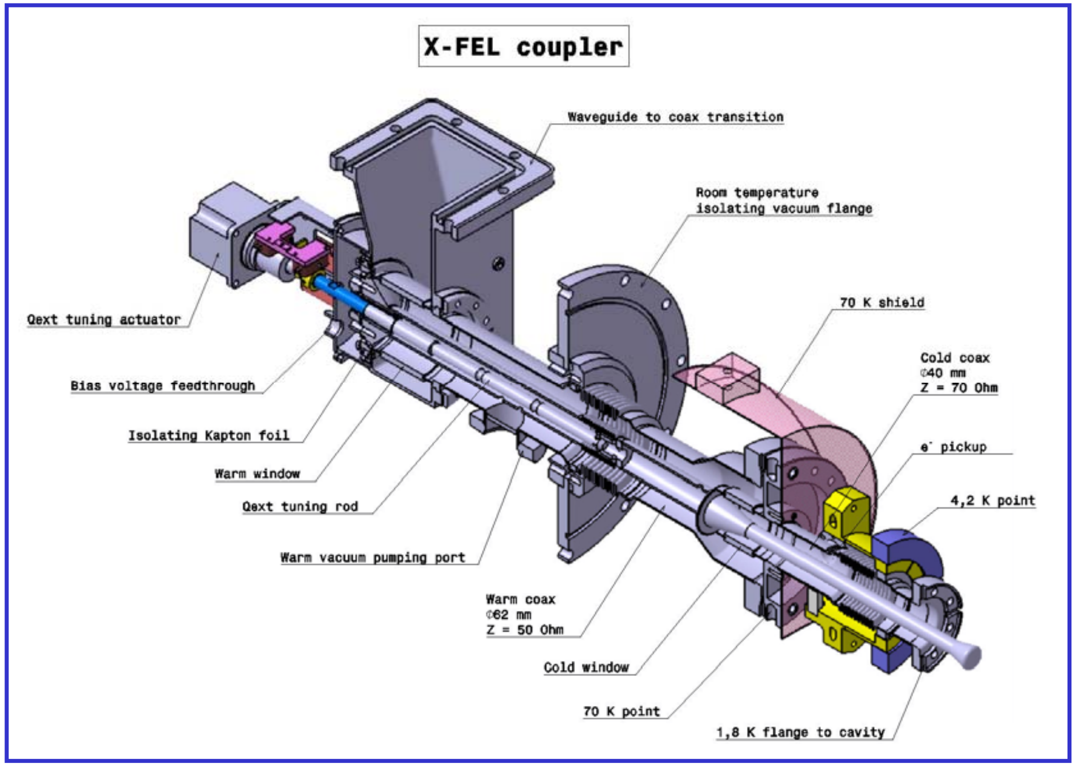
Industrialization study

At LAL-Orsay the XFEL team is developing a method of industrialization studies for input couplers. Three companies were awarded study contracts to define the manufacturing processes and produce 2 prototypes in 2008. This is a necessary and useful step towards the mass production of input couplers (800 for XFEL, 16000 for ILC). Action plans, anticipation and organization will ensure fabrication, assembly and tests with minimum risks and at an optimized cost.

A call for tenders for the production of XFEL couplers will be initiated by LAL in the middle of 2008, based on functional specifications.

LAL will perform extensive process control and close monitoring of the mass production through recorded data and indicators, in view to guarantee that the 800 input couplers for XFEL show a constant quality with full traceability, reliable components and replaceable assemblies.

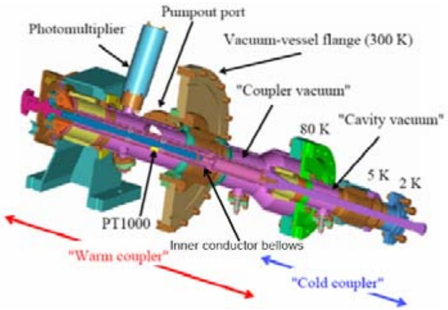


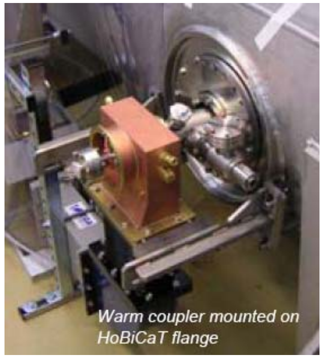
TH202

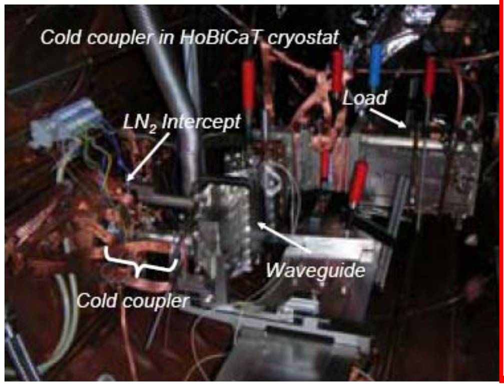
TTF-III coupler in CW

TTF-III input coupler was tested in CW regime

BESSY / ACCEL / Cornell / DESY / Rossendorf collaboration, PAC'05 presentation




Warm coupler mounted on HoBiCaT flange



5. Results and Conclusions

- Thermal time constant is very long (50 mins), see Fig. 4
- Inner conductor bellows region becomes very hot. We imposed a limit of 300 C.
- Interlock trips due to vacuum and reflected power limited the tests (but these are not a fundamental limit).
- Extrapolation of Fig. 5: 10 kW TW and 5 kW SW operation with existing coupler should be possible.
- *No significant difference seen between warm and cold tests* (Fig. 5) → Cold window ceramic is not the limiting item for heat conduction
- *Tests up to 10 kW (klystron limited) were also done with the inner conductor air cooled. If the results are extrapolated, 25 kW SW operation is feasible (Fig. 5)*

While the conclusion is that 5 kW SW operation should be possible, the prudent way is to upgrade cooling of the coupler center conductor to lower its temperature and improve vacuum.

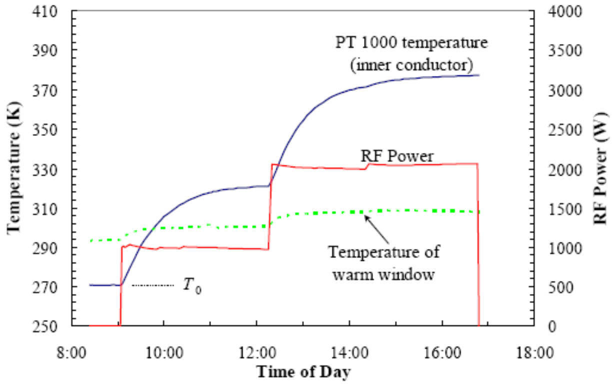


Figure 4: Example of the temperature rise as a function of time as RF power is applied.

TUP40

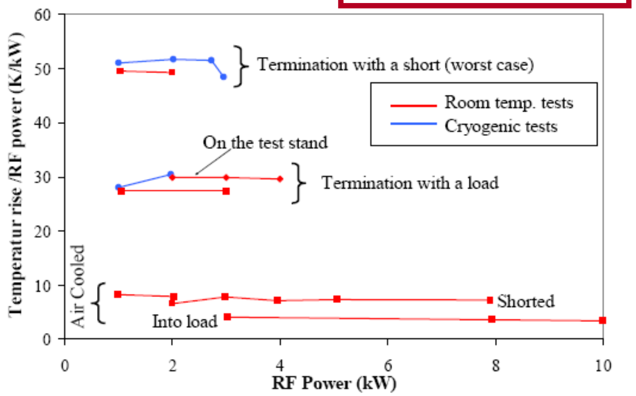
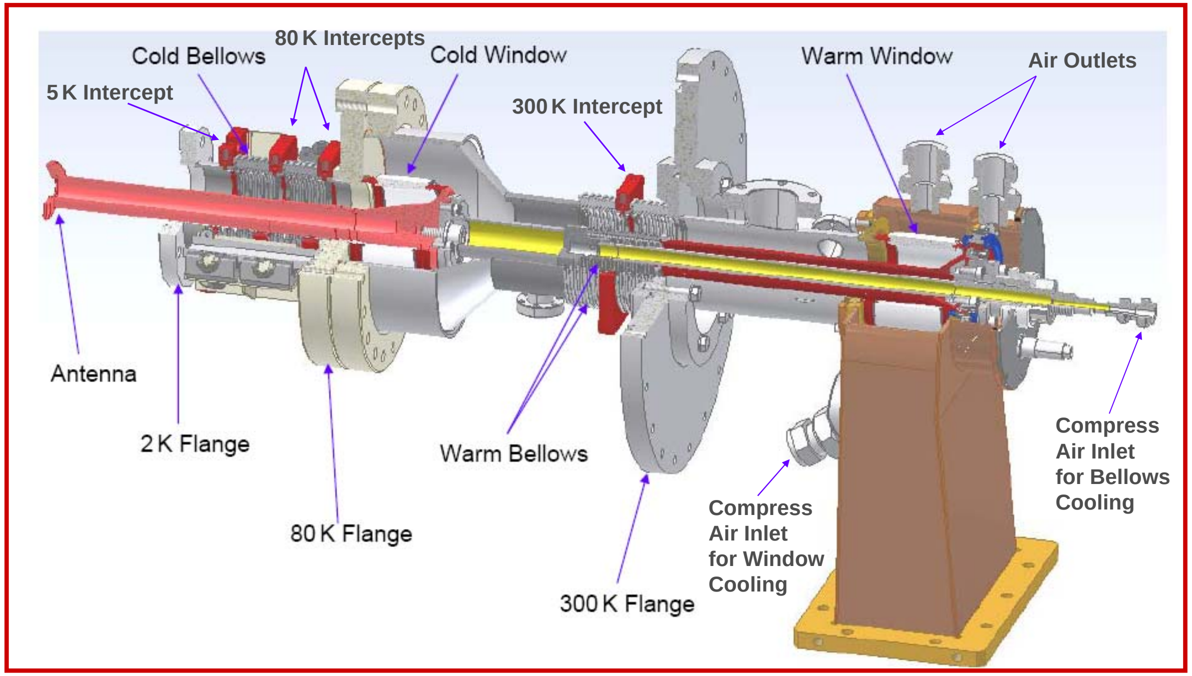


Figure 5: Temperature rise per kW of applied power at the PT1000 sensor in the inner conductor (see Fig. 1). All tests in HoBiCaT except the one marked „on the test stand.“

Cornell ERL injector input coupler

Design features:

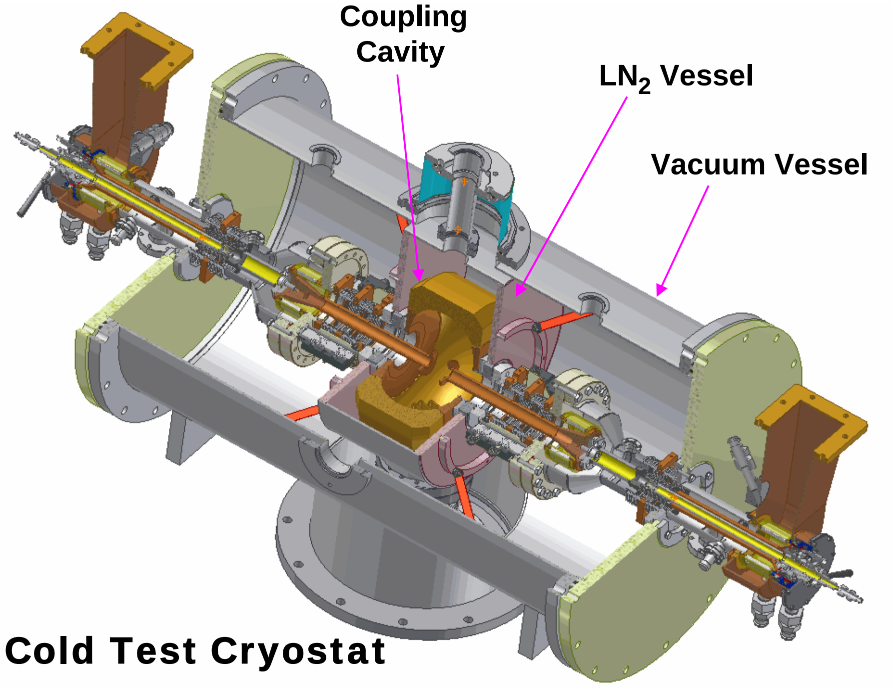
- Design derived from the TTF-III coupler
- The cold part was completely redesigned using a 62 mm, 60 Ohm coaxial line for stronger coupling, better power handling and avoiding multipacting
- Antenna tip was enlarged and shaped for stronger coupling
- “Cold” window was enlarged to the size of “warm”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



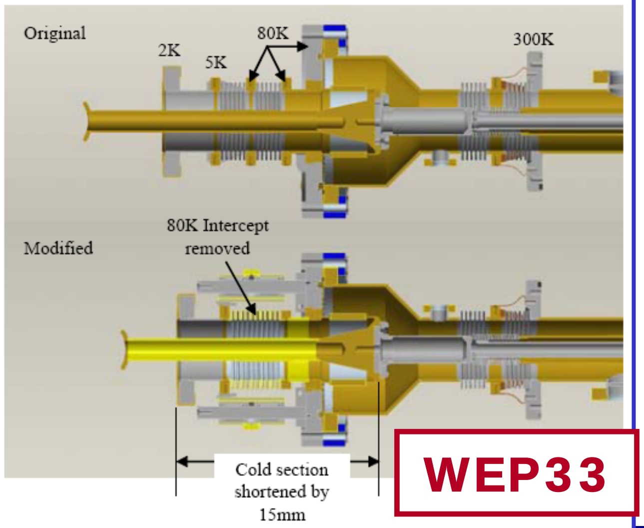
Sattus and test results

- Two prototype and eight production couplers have been manufactured by CPI to date. Two prototypes and two production couplers were tested.
- A special Cold Test Cryostat (CTC) was designed and built for input coupler testing.
- After testing prototype couplers some design changes were implemented to further improve cooling.
- *In situ* baking to 120° C was implemented to facilitate quicker processing.
- Production couplers reached 61 kW CW level after pulsed RF conditioning up to 85 kW (above 36 kW CW).
- Exposure of RF surfaces to room temperature air for 4 hours did not degrade performance: couplers "remember" processing!
- These couplers (slightly modified) will be used in the ERL cryomodule (collaboration Daresbury/Cornell/LBNL/Rossendorf/Stanford).

WEP26

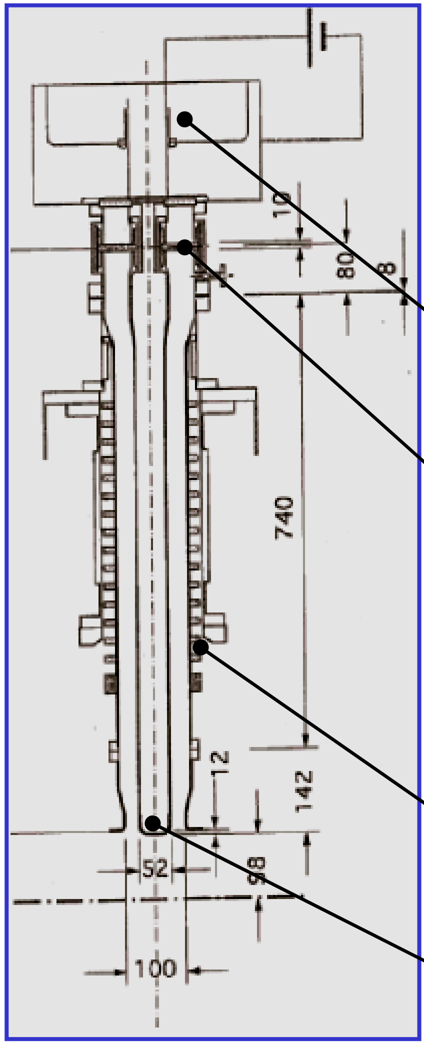


Cold Test Cryostat



WEP33

TRISTAN / KEKB coupler



- Based on the long-term operation of 32 SC cavity couplers in TRISTAN
- 50 Ohm coaxial line
- Fixed coupling @ $Q_{ext} = 7 \times 10^4$
- Improved monitoring, cooling, choke structure around window
- Record power delivered to beam: 400 kW
- Used on BEPC-II cryomodules

Biased doorknob (±2 kV)

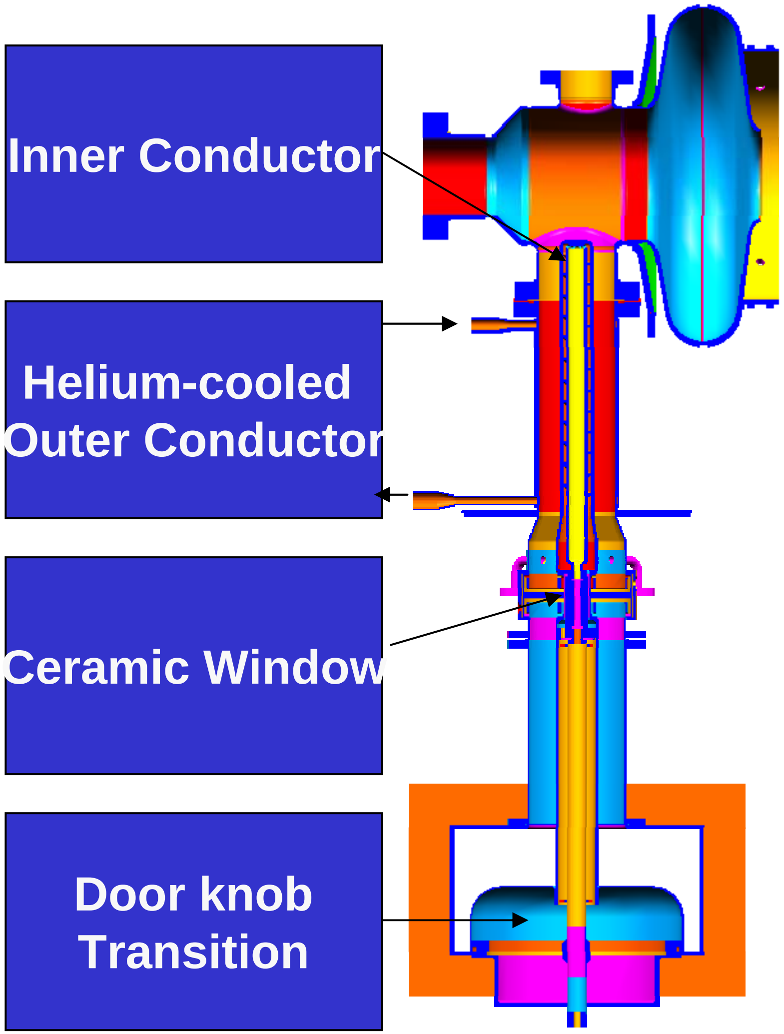
Alumina (99.5%) coaxial disk window, coated with 100 Å of TiN_xO_{1-x}, air cooled outside

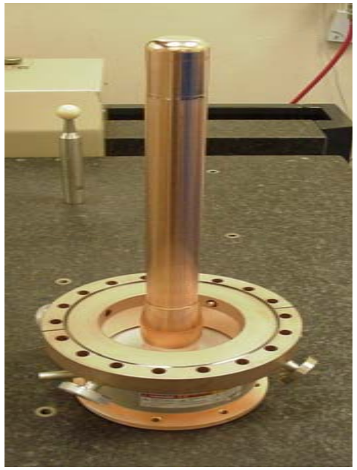
Copper plated SS,
4 K He gas cooling at 8 l/min

Water cooled inner conductor, electropolished copper

KEKB coupler upgrade to 500 kW [TUP23]
KEKB crab cavity coupler [WEP50]
BEPC-II [TUP09], [WEP51]

SNS coupler



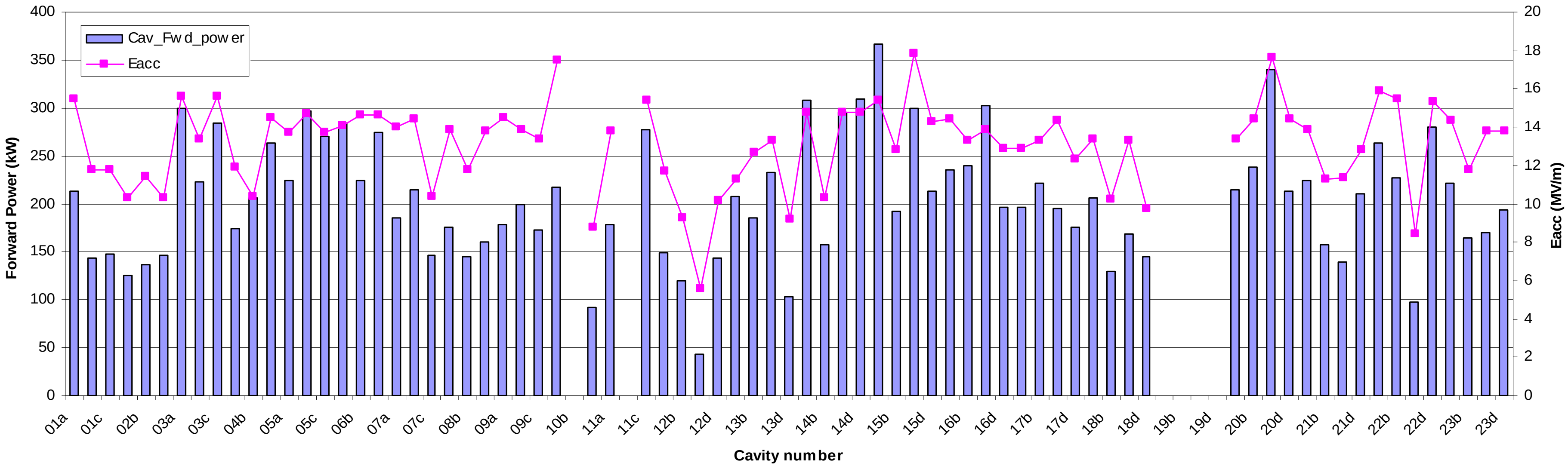


Present specifications:
550 kW peak
48 kW average

Performance:
- Tested up to 2 MW peak power in 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

SNS couplers: operational experience



10b; disabled (noisy filed probe signal)
11b; disabled
(large fundamental mode coupling thru HOM coupler)

CM19
Removed
for HOM coupler repair

- **Cavity-coupler interaction**
  - **Electron current at the full traveling wave**
  - **Radiation spikes at the same time**
- **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**

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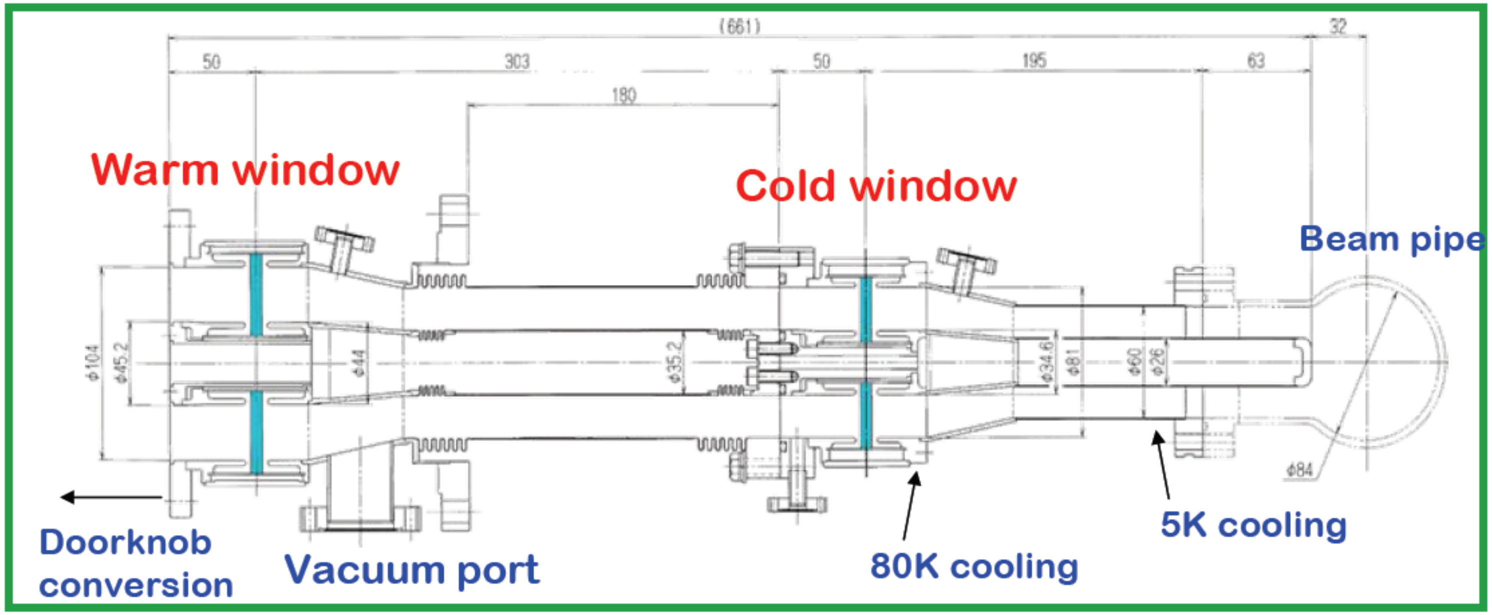
STF baseline cavity input coupler

Input Coupler for STF Baseline Cavities

Improved design for simplicity with no tuning mechanism.

TRISTAN Type Coaxial Disk Ceramic ;

(KEKB 1 MW/cw, JPARC-ADS 2.2 MW/pulse)



	80 K	5 K	2 K
Static Loss	5 W	1.1 W	0.05 W
Dynamic Loss	3 W	0.2 W	0.03 W

E. Kako (KEK)

Meeting at LAL-Orsay, 2007' Feb. 28

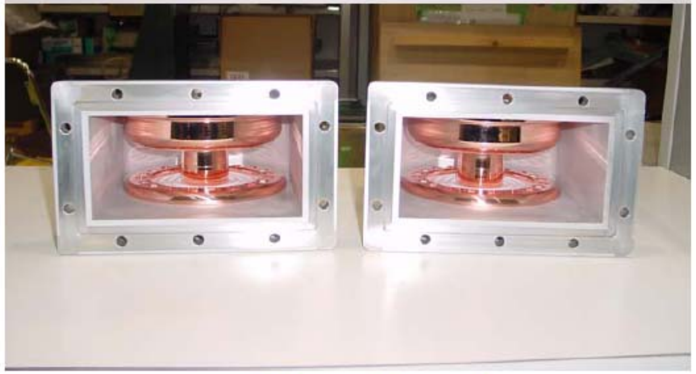
TUP60

Input coupler components

Components for High Power Test Stand

Input Couplers

Coupling Waveguides



Doorknobs

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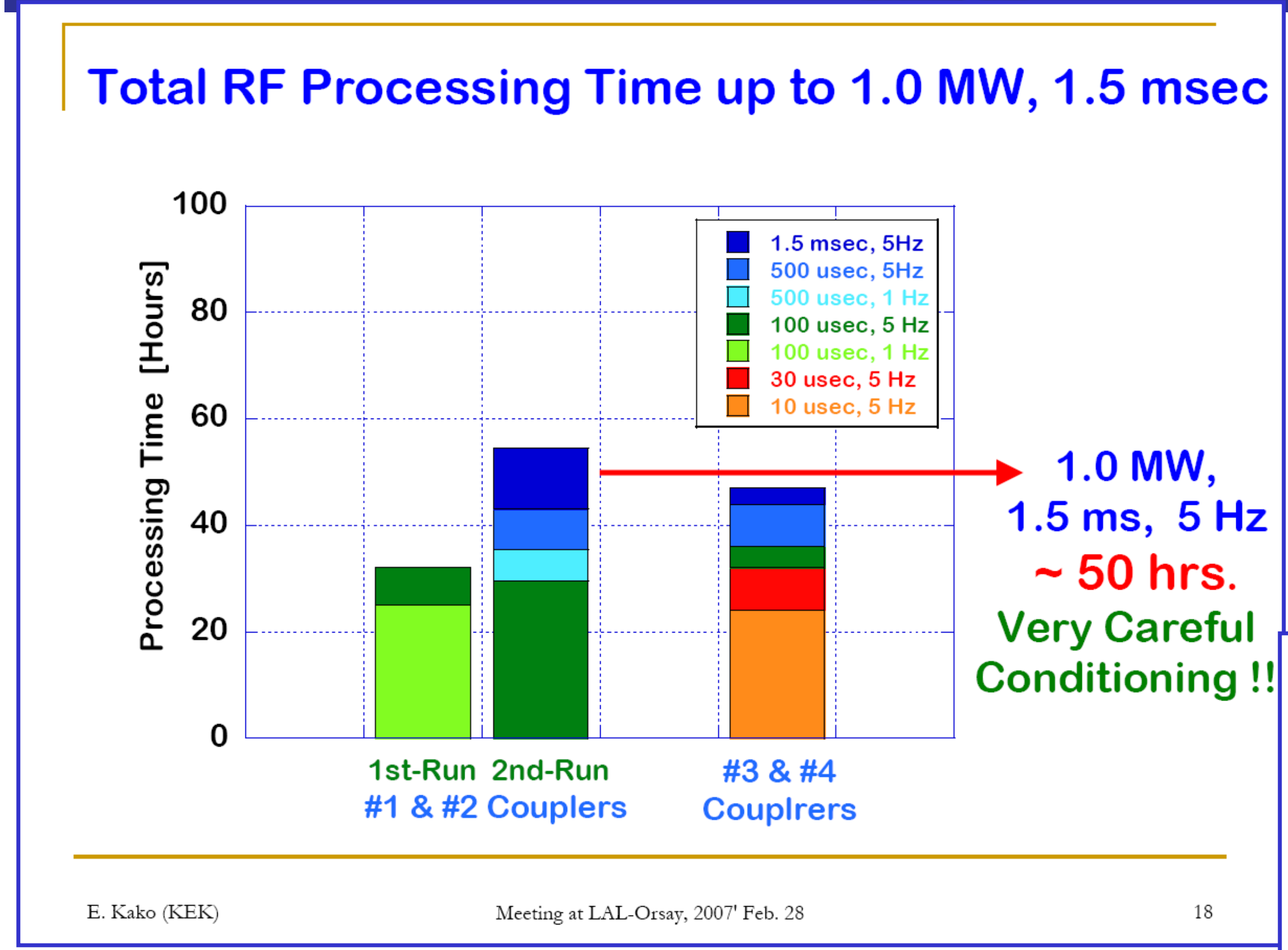
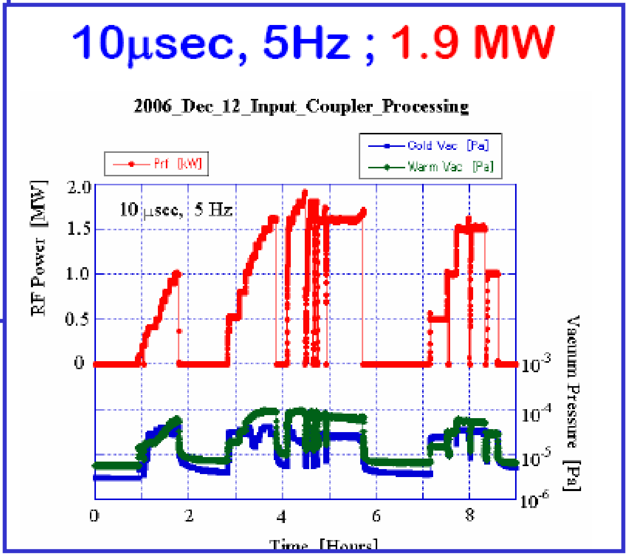
STF baseline cavity input coupler





ERL main linac input coupler

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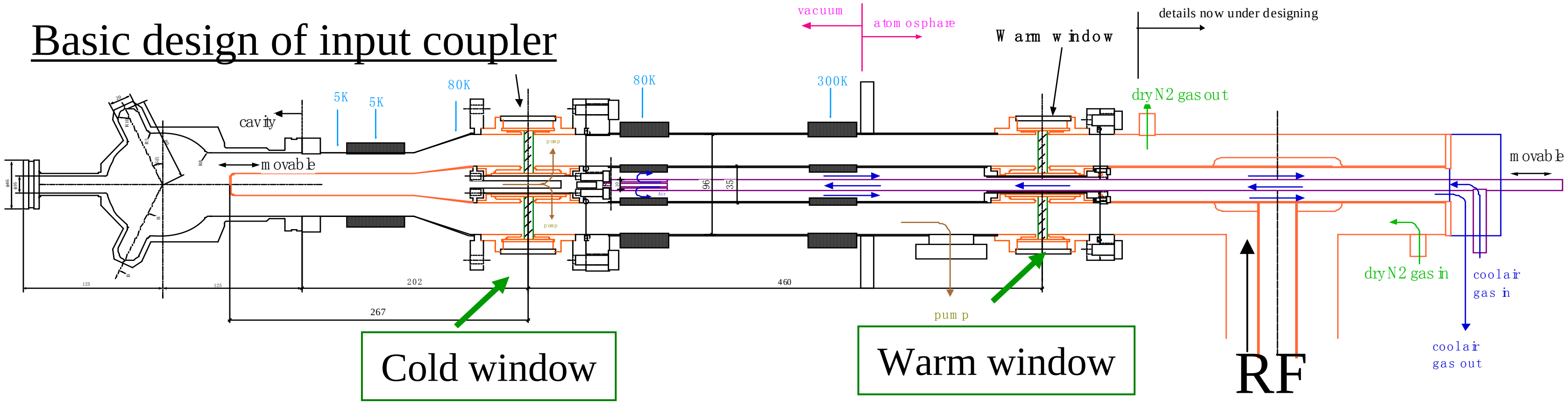
Design of the input coupler for the ERL main linac in Japan
(Hiroshi Sakai, et. al.)

- Input coupler design is just started for ERL main linac.
  - Input power : 20kW
  - Gradient : max 20MV/m
  - QL : $5 \times 10^{6} - 2 \times 10^{7}$
- Design is based on ILC coupler at KEK-STF. Especially, disk type ceramic was applied. Some modifications are applied.
- In order to check the heating of ceramic and bellows during the 20kW operation.we now make a test stand for component test.

Concepts

- **20kW CW input power**
- **variable coupling add bellows on cold part**
- **gas cooling in inner conductor**
- **double ceramic of same size**
- **disk type ceramic window (HA997)**
- **60Ω impedance**

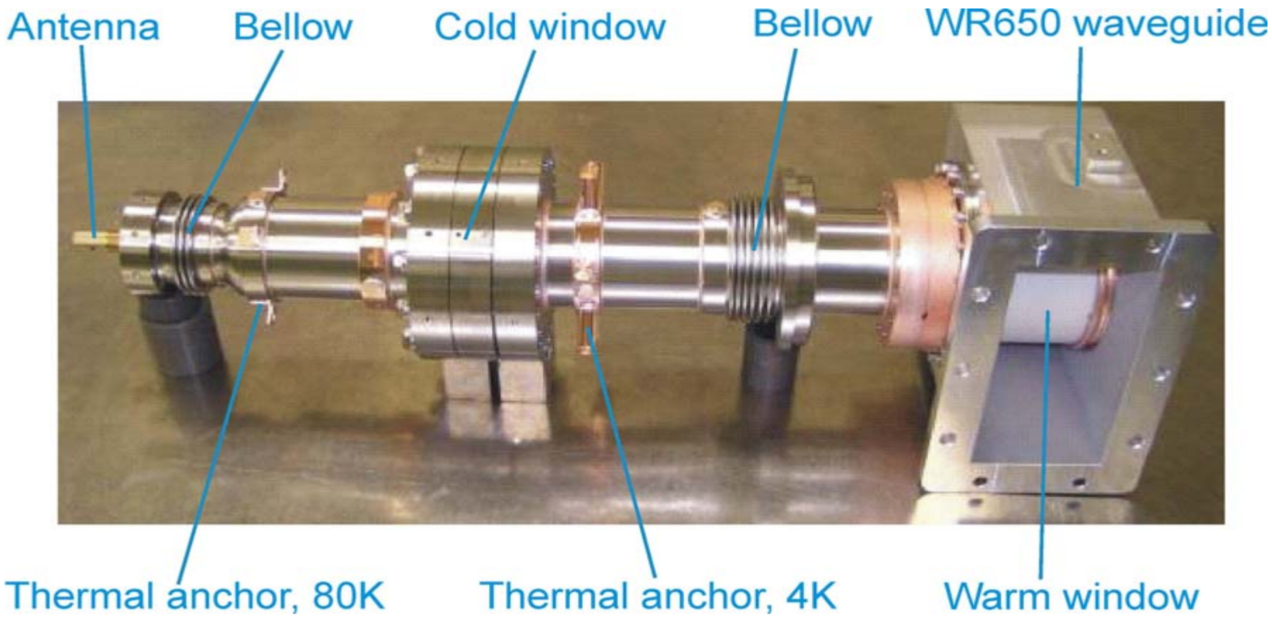
Basic design of input coupler

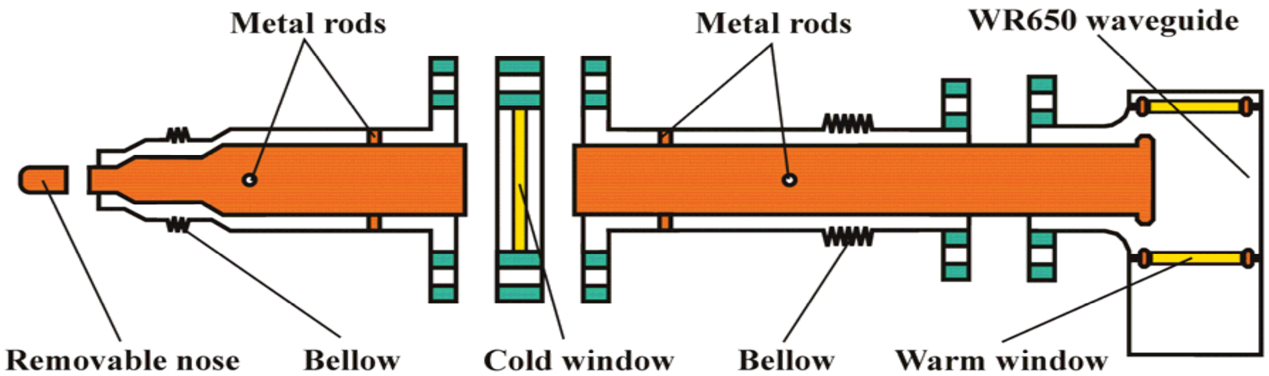


STF capacitively coupled input coupler for LL cavity

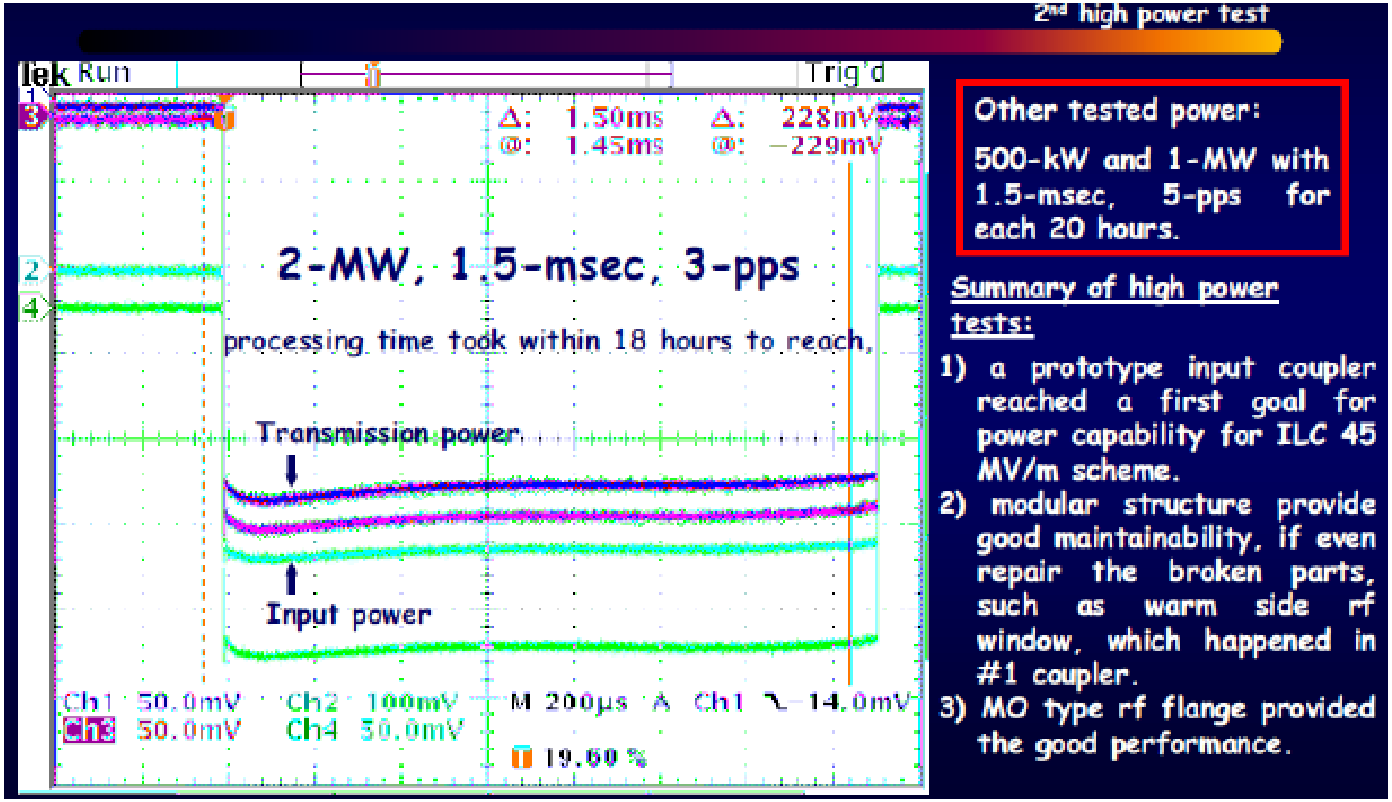
- **Modular design with capacitively coupled window**
- **Low heat leak**

WEP45



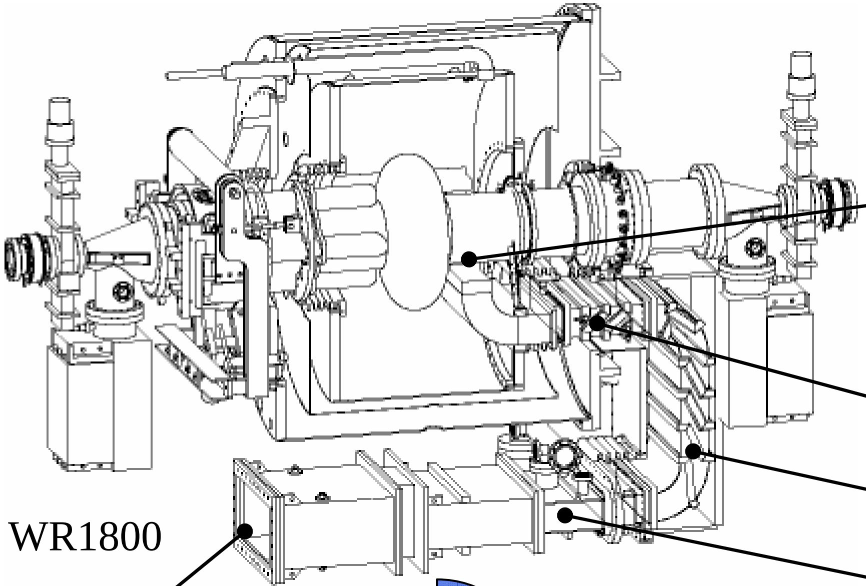


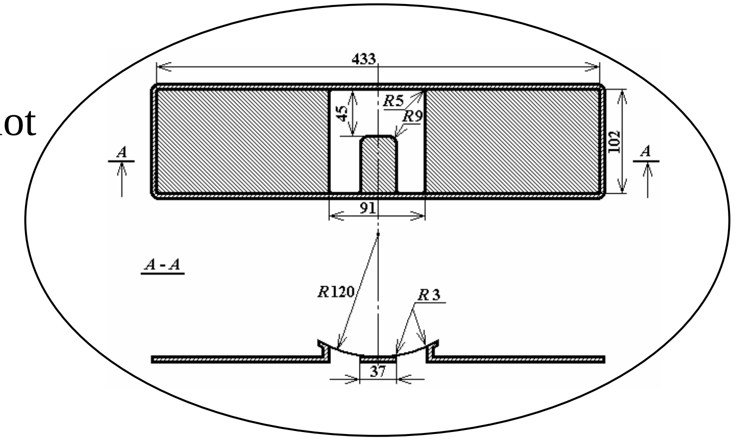
STF capacitively coupled input coupler test results

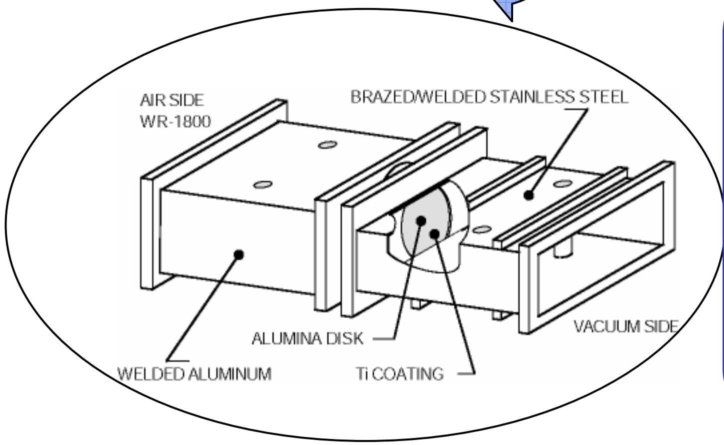


High power test demonstrated that couplers can successfully operate with pulse 1MW x 1.5 x 5pps and 2MW x 1.5ms x 3pps for matching load and pulse 500kW x 1.5ms x 5pps for short. Effect of multipactor is weak. Upper limit of multipactor is about 200 kW.

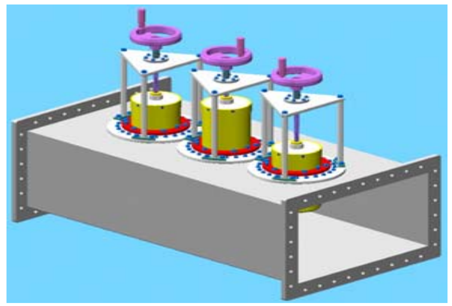
CESR waveguide input coupler







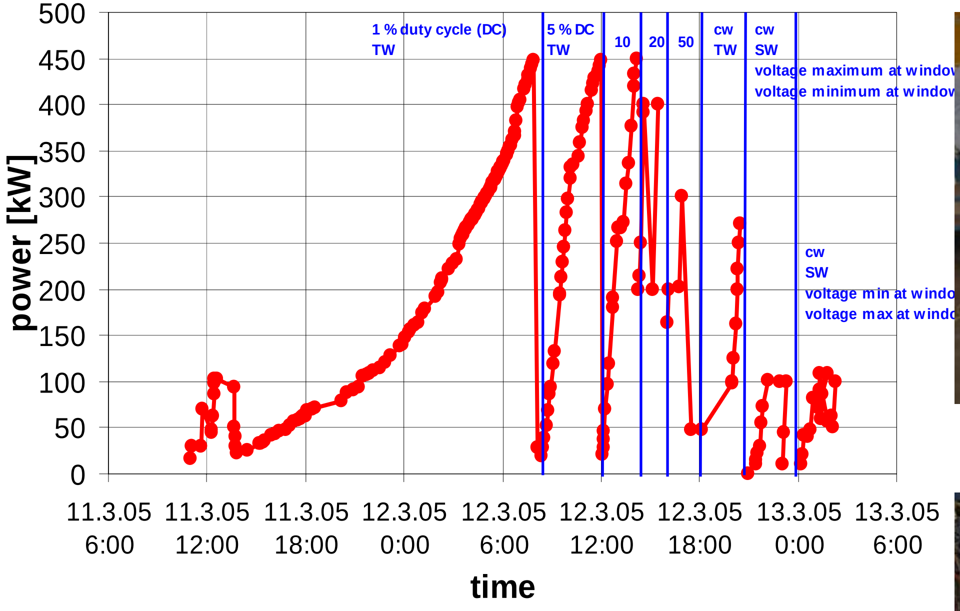
- **Fixed coupling @ Q_{ext} = 2×10^5**
- **Magnetic bias of the WG to suppress multipacting**
- **Adjustability is possible via a 3-stub WG transformer**
- **This coupler is used at TLS, CLS, Diamond and SSRF 3rd generation light sources**



WG window conditioning

ACCEL

Window conditioning



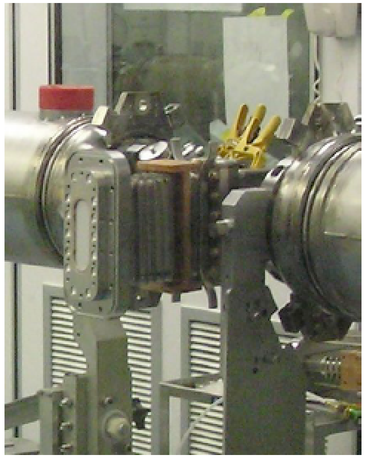
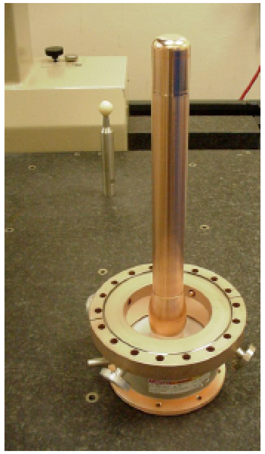
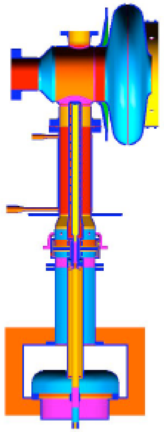
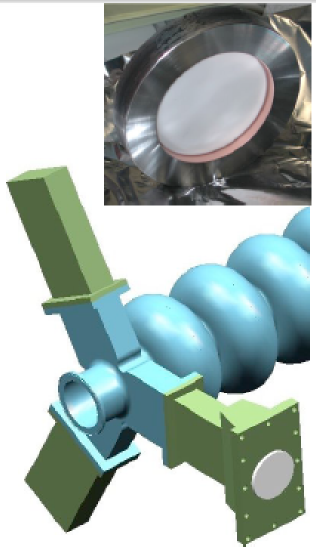
Windows cleaned, assembled and baked at ACCEL

Shipped to Cornell for RF conditioning

Coupler developments at JLab

Power couplers

- 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
- $Q_{ext} \sim 7 \times 10^5$
- 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

TUP65
WEP85

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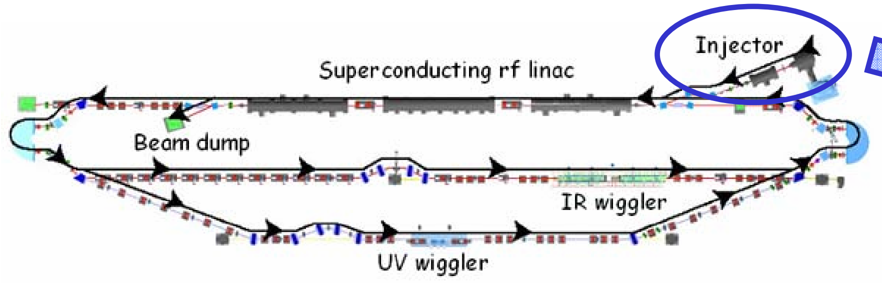
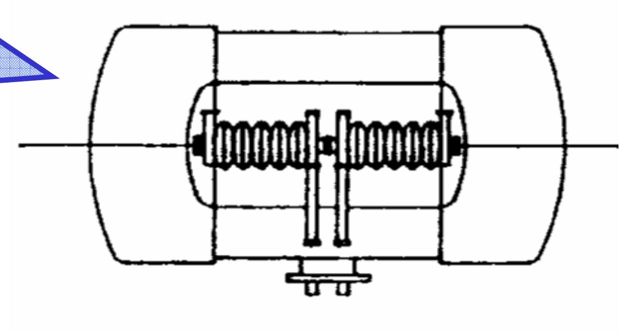
JLab FEL injector WG coupler

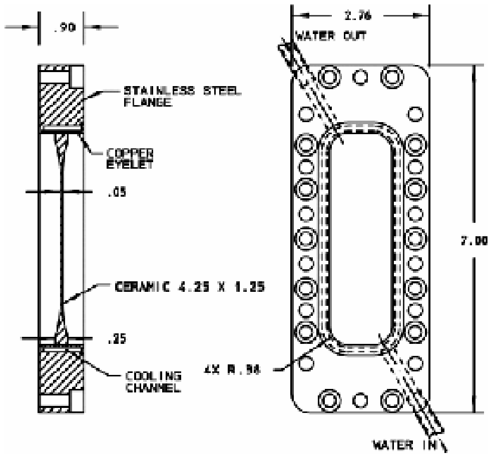
JLAB FEL ¼ cryomodule

At JLAB FEL a ¼ - cryomodule (similar to ones used in CEBAF injector) was equipped with a 50 kW waveguide windows. The result is an injector capable to deliver 10 mA, 10 MeV beam.

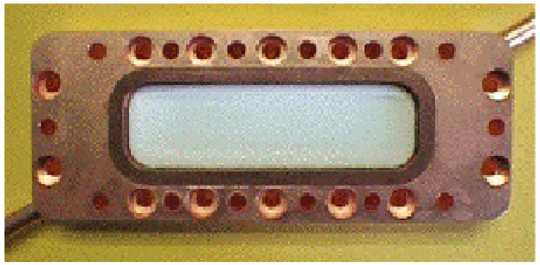


10 mA, 10 MeV





50 kWCW waveguide window

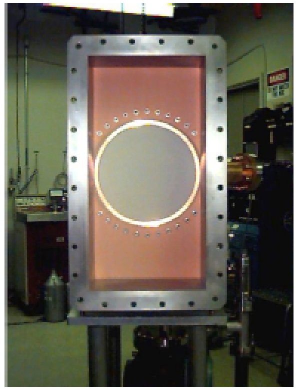


JLab FPC for 1 A cryomodule

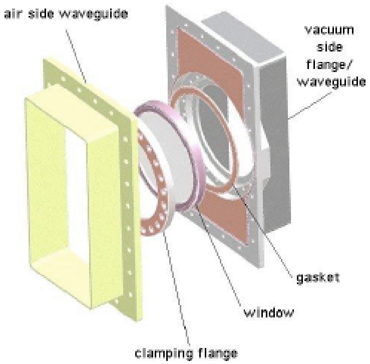
Fundamental power coupler for 1 A CM

- Operating frequency: **748.5 MHz**
- Max FWD RF power **200 kW CW***
- Sustain local peak RF power of **800 kW**
- No line of sight from the beam to the ceramic window
- Adopt proven pre-stressed waveguide window design
- Coupling set by distance from beam center line to waveguide step

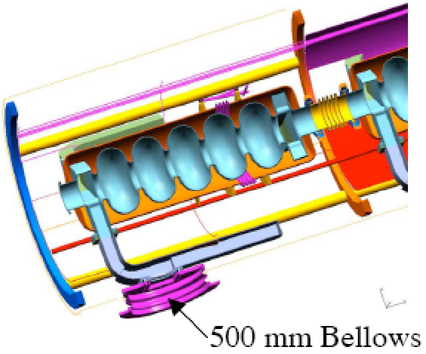
* could go higher because of transient demands

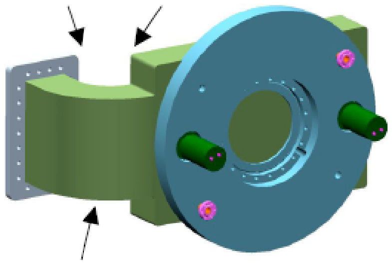


PEP-II window 476 MHz
600 kW, (WR2100)



LEDA 700 MHz, 1 MW
(WR1150)





1ACM 748.5MHz concept

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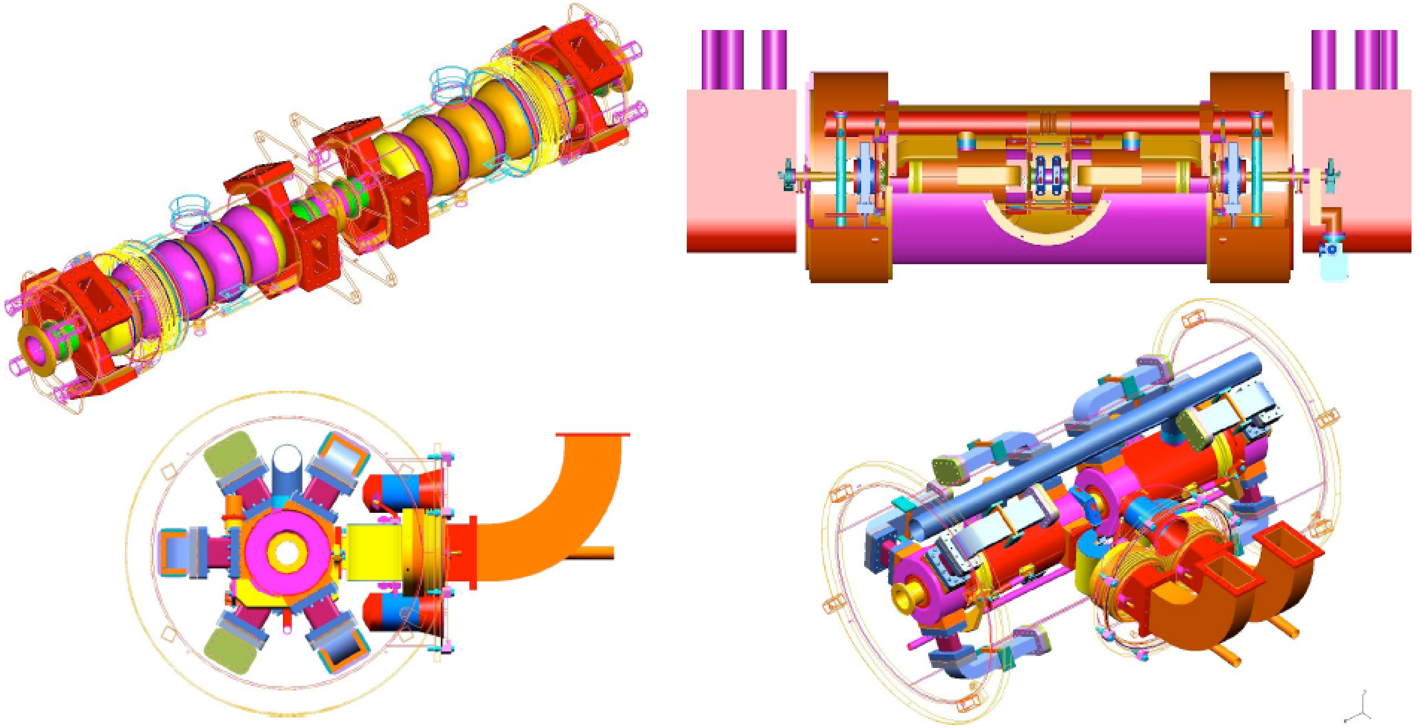
1497 MHz "100 mA" cryomodule

- All 1A components being tested at half scale to use existing infrastructure
- Can use to build FEL a new quarter module based on 1497 MHz prototypes.
- Get beam test of BBU and all important concepts years earlier than other paths.
- Full module ~80 MV in CEBAF length (more if stretched), ~0.25 A BBU threshold



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Developments at other labs

Other developments presented at SRF2007:

i) 500 kW input coupler design for BNL photoinjector (AES) [TUP43]

ii) Prototype couplers for SPIRAL2 [WEP06]

iii) Design of power couplers for 325 MHz spoke cavities (AMAC) [WEP20]

iv) Conditioning and processing of LHC couplers [WEP60]

v) 100 kW resonant ring for window testing (Rossendorf) [WEP81]

Summary

- While new projects present ever more demanding requirements, new designs appear to be able to meet the challenges in terms of RF and thermal performance.
- Several new input coupler designs, both pulsed and CW, have been tested recently with very good results.
- In some cases the designs were based on adopting successful existing designs (TTF-III, TRISTAN coupler) though often with significant upgrades/modifications.
- Progress is being made to improve coupler handling, preparation and RF conditioning time.
- Efforts to reduce the construction cost are under way, including industrialization study for XFEL couplers.
- In the era of large-scale projects like ILC and XFEL close cooperation between laboratories is extremely important.

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