CW and Pulsed Power Couplers – Design and Performance Review

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Orsay

Will treat mainly SNS, TTF, ERL

- Will concentrate on linac projects in progress or under study.
  - i.e. no discussion of KEK-B, HERA, CESR, CEBAF, LEP….

Pulsed Power Couplers

There are few examples in operation to date

- TESLA Test Facility
  - FNAL coupler
  - TTF-II
  - TTF-III
- Spallation Neutron Source

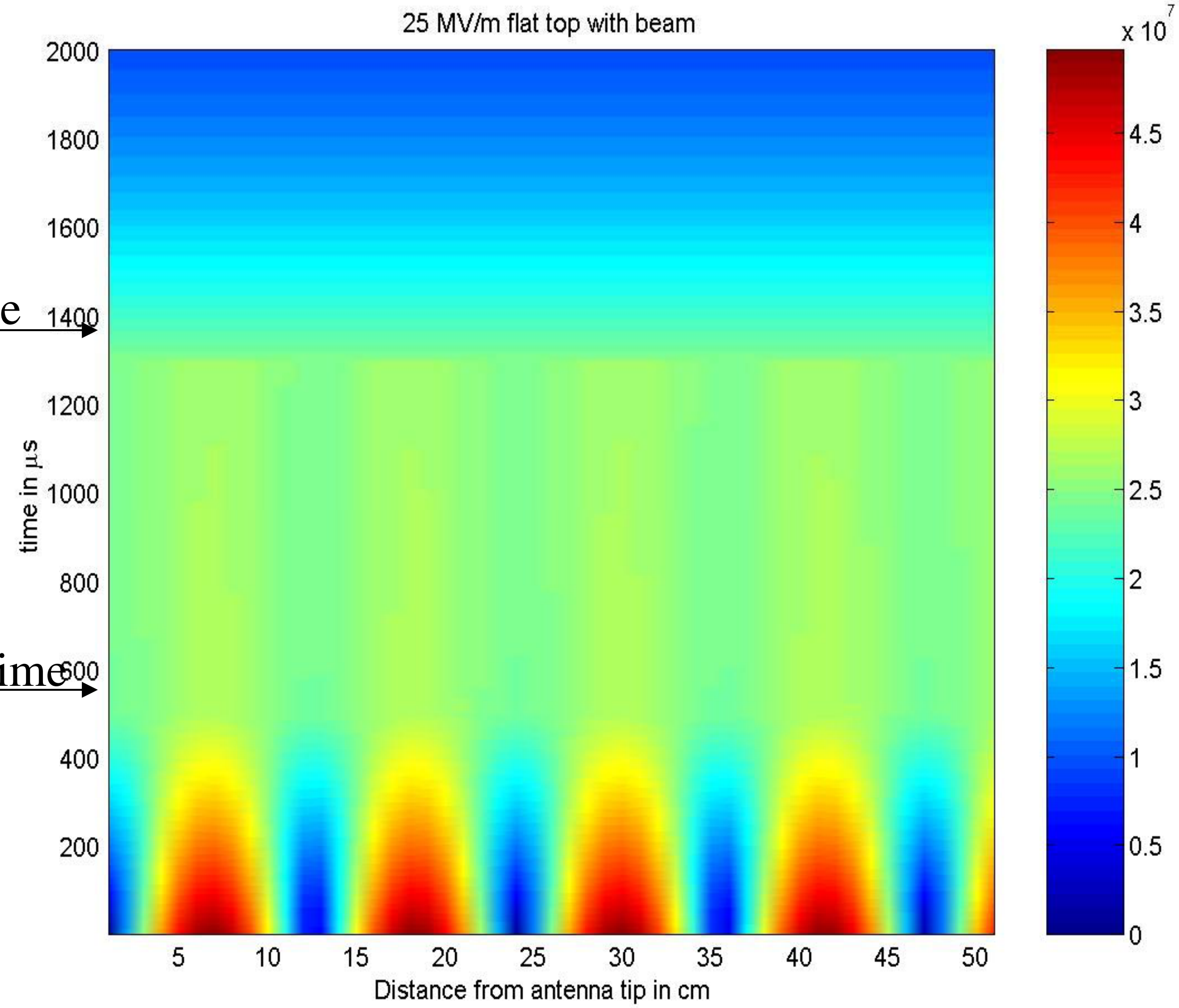
Consequences of pulsed operation

- Lower average power
- Full transient reflection for each pulse
  - transient standing wave
    - higher electric fields
  - continuous phase changes
    - gas desorption

Standing wave pattern in the coupler coax line

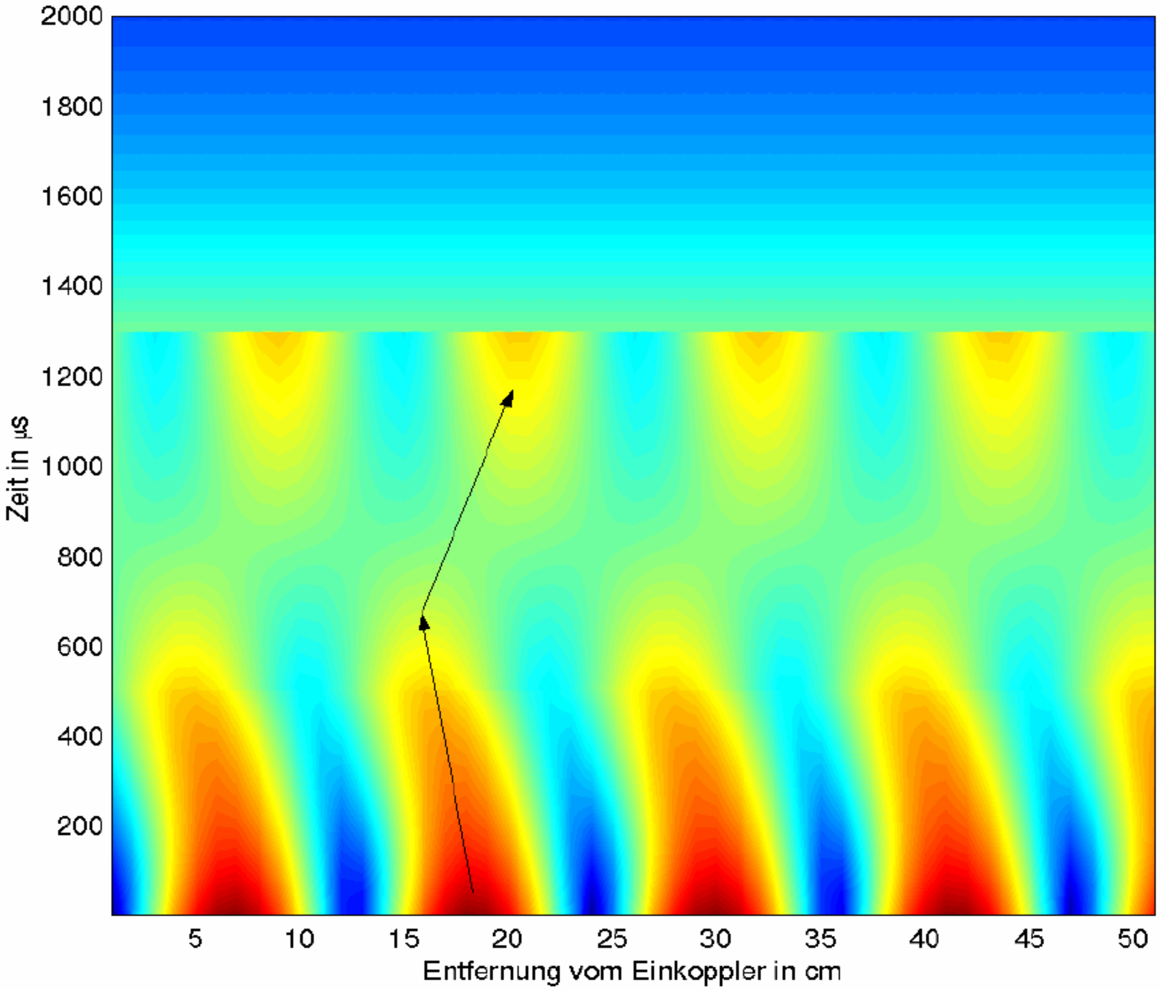
End of RF pulse

End of filling time



Nikolay Sturm

Standing wave pattern with Lorenz Force detuning at 25MV/m



-The standing wave pattern is changing due to the Lorenz Force detuning

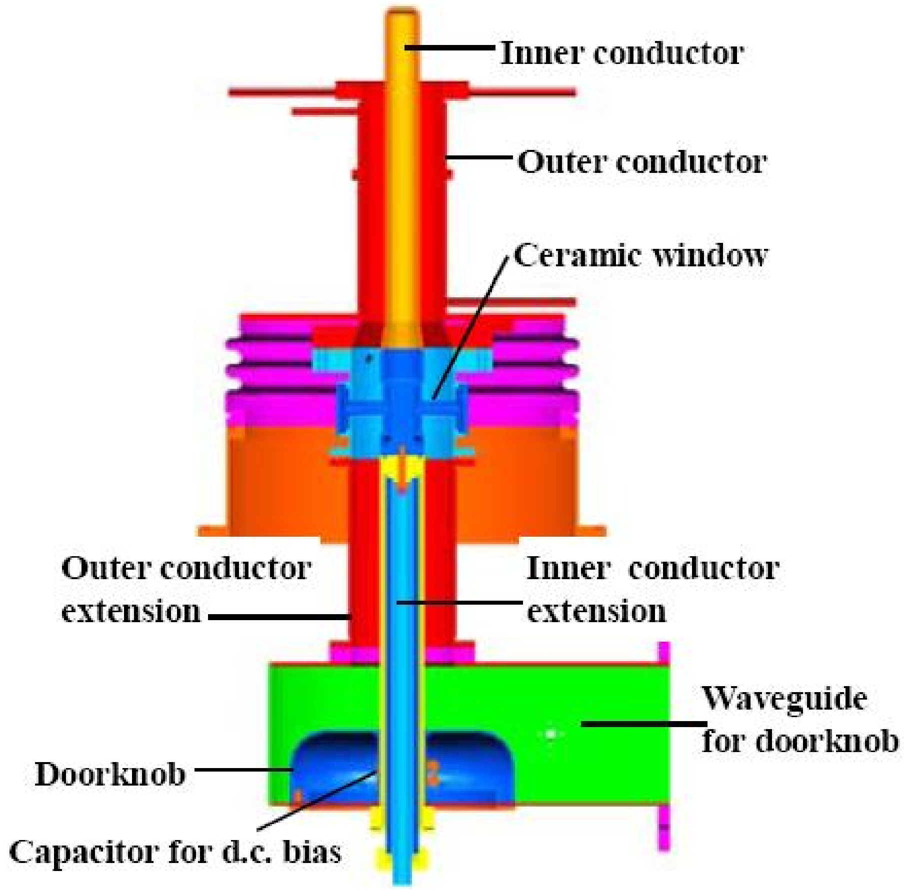
- the high field areas are moved to areas with normally lower fields

Proposed and existing projects using pulsed couplers

	frequency	Peak power	Average power	Coax diameter	Number of windows	Cavity gradient	electric field in coax, TW
J-PARC KEK/JAERI	972 MHz	300 kW	22.5 kW	80 mm	1	10 MV/m	0.4 MV/m
SNS, J-Lab	805 MHz	550 kW	48 kW	96 mm	1	12 MV/m	0.6 MV/m
VUV-FEL DESY	1.3 GHz	250 kW	3.25 kW	40/60 mm	2	25 MV/m	0.8 MV/m
X-FEL	1.3 GHz	150 kW	3.25 kW	40/60 mm	2	25 MV/m	0.8 MV/m
ILC	1.3 GHz	500 kW	3.25 kW			35 MV/m	

SNS Power Coupler Specification

Parameter	Operation	Processing
Impedance	50 Ω	50 Ω
Peak power	550 kW	2.4 MW
Pulse length	1.3 ms	1.3 ms
Repetition rate	60 Hz	60 Hz
Average power	Max. 53 kW	klystron limit
D.C. bias	2.5 kV	± 2.5 kV



DC bias against multipactor – shown to be useful during tests

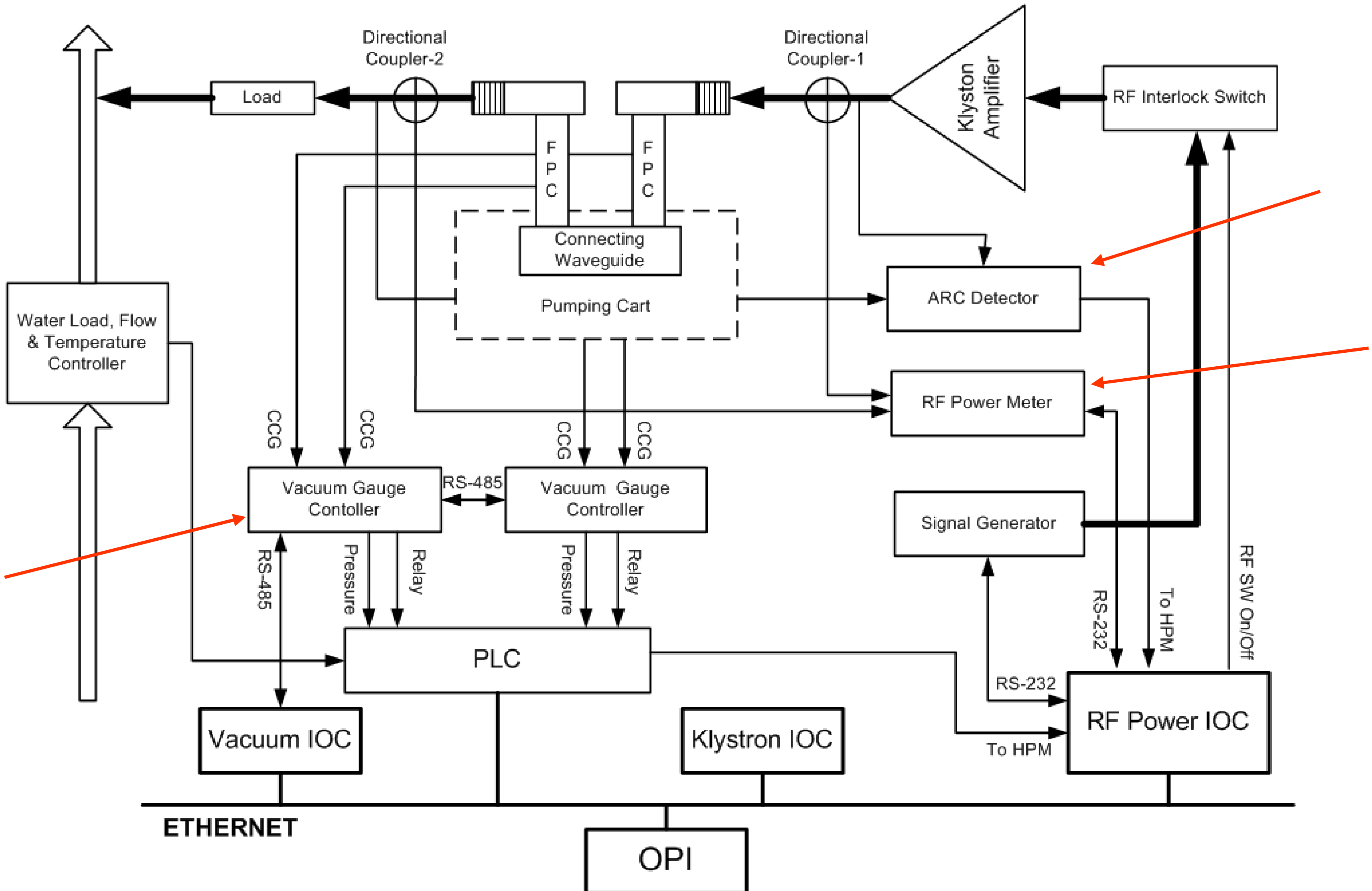
Based on coupler developed for KEK B-factory SC cavities.

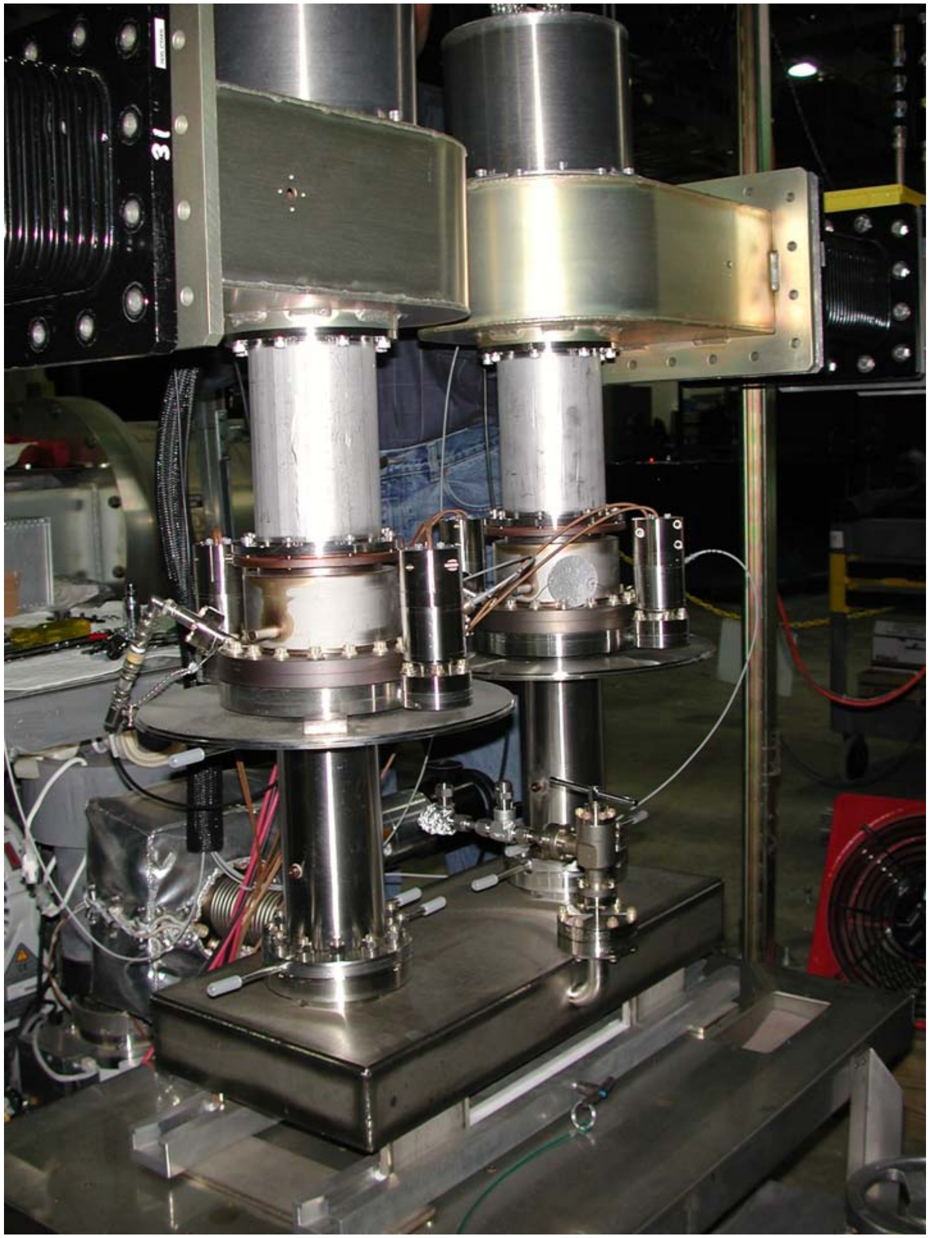
Modified for SNS constraints

- vacuum side has double walled outer conductor cooled by He gas. Made from Cu-coated stainless steel. Inner conductor is made from OFE copper.
- Air side – OC is Cu-coated stainless steel. Water cooled IC is made of OFE copper.
- 4 diagnostic ports on vacuum side – 1 arc, 1 e-p.u., 2 vacuum gauges.

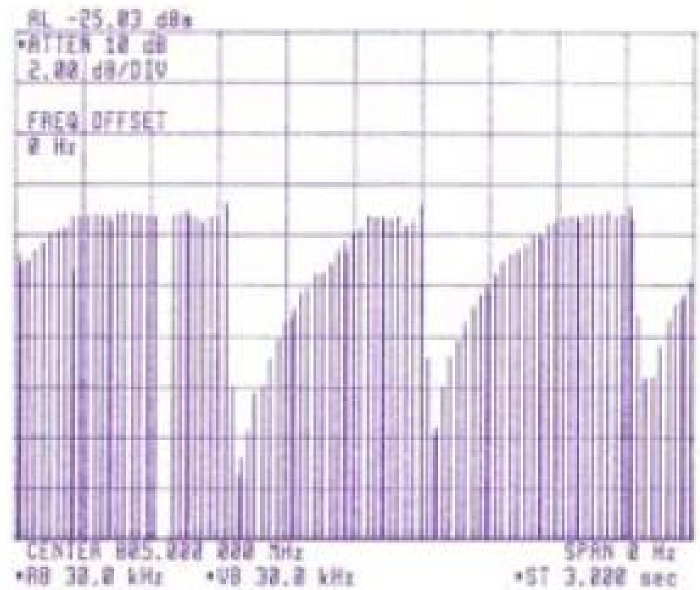
SNS RF Test Facility

RF Conditioning System



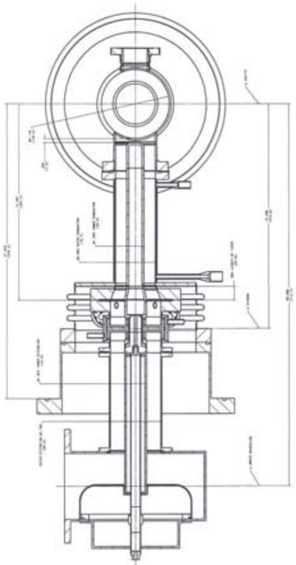


SNS Couplers under test at room temperature. All now tested between JLab and ORNL.

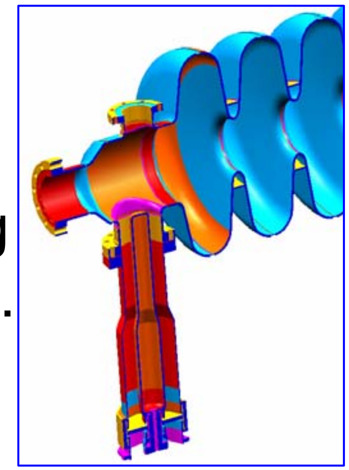


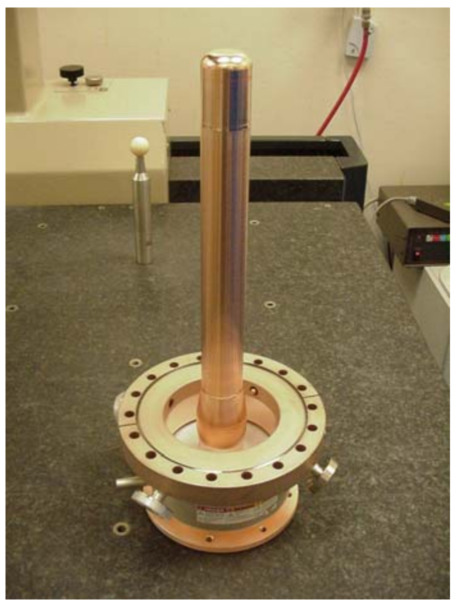
Vacuum level modulation of RF power during conditioning. ~ 50 hours needed.

SNS Fundamental Power Coupler Performance



All couplers have been pre-processed at JLab or SNS to nearly 1 MW peak power traveling wave and full reflection to 500 kW.





During testing of cryomodules in the SNS tunnel one coupler has transferred more than **500 kW** peak power, in full reflection and with the 2 MW traveling wave peak at the end of the RF pulse

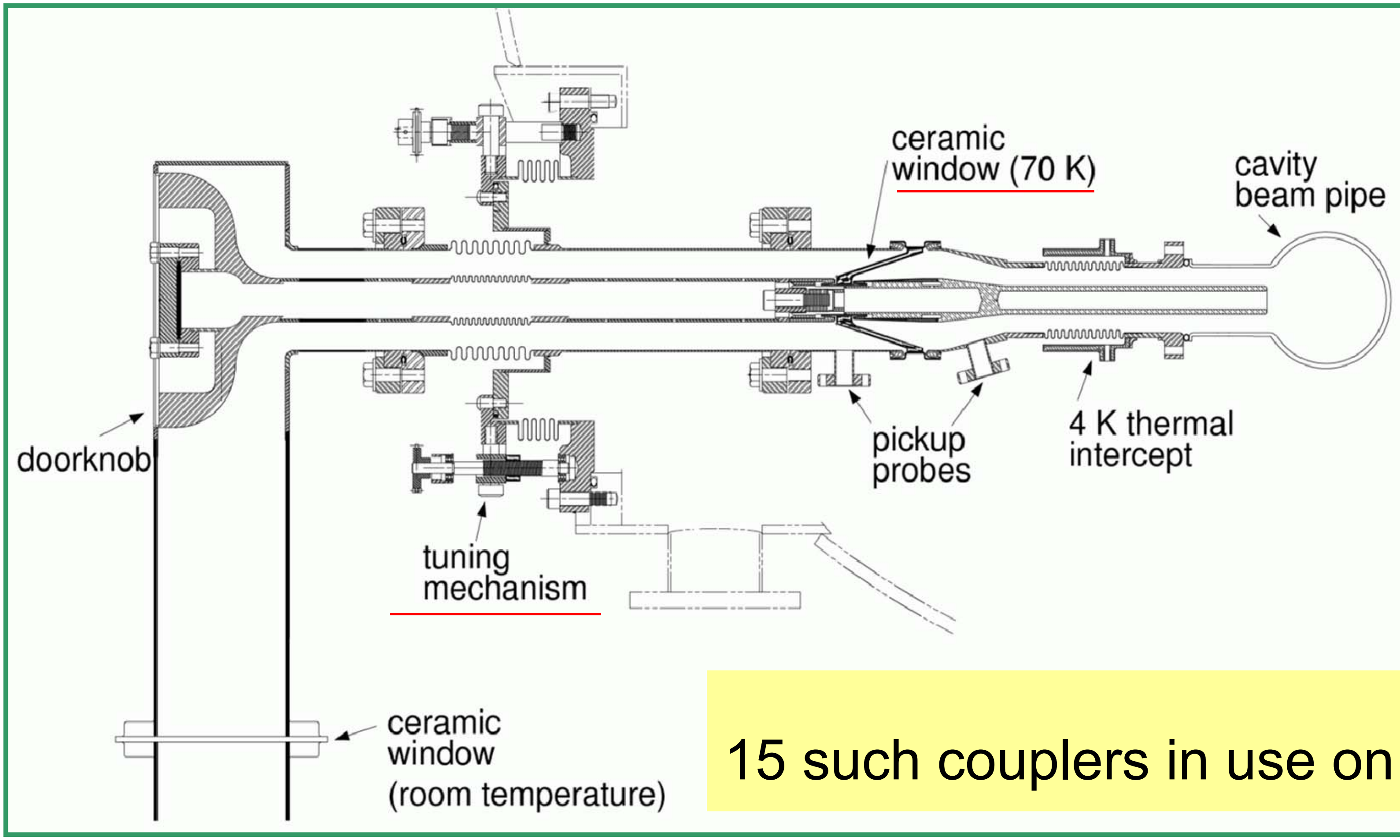
TTF Coupler Specification (1/2)

frequency	1.3 GHz
operation	pulsed: 500 μsec risetime, 800 μsec flat top with beam
Two windows !! TiN coated	• safe operation • clean cavity assembly for high Eacc
2 K heat load	0.06 W
4 K heat load	0.5 W
70 K heat load	6 W
isolated inner conductor	bias voltage, suppressing multipacting
Diagnostics / interlocks	sufficient for safe operation and monitoring

TTF Coupler specification (2/2)

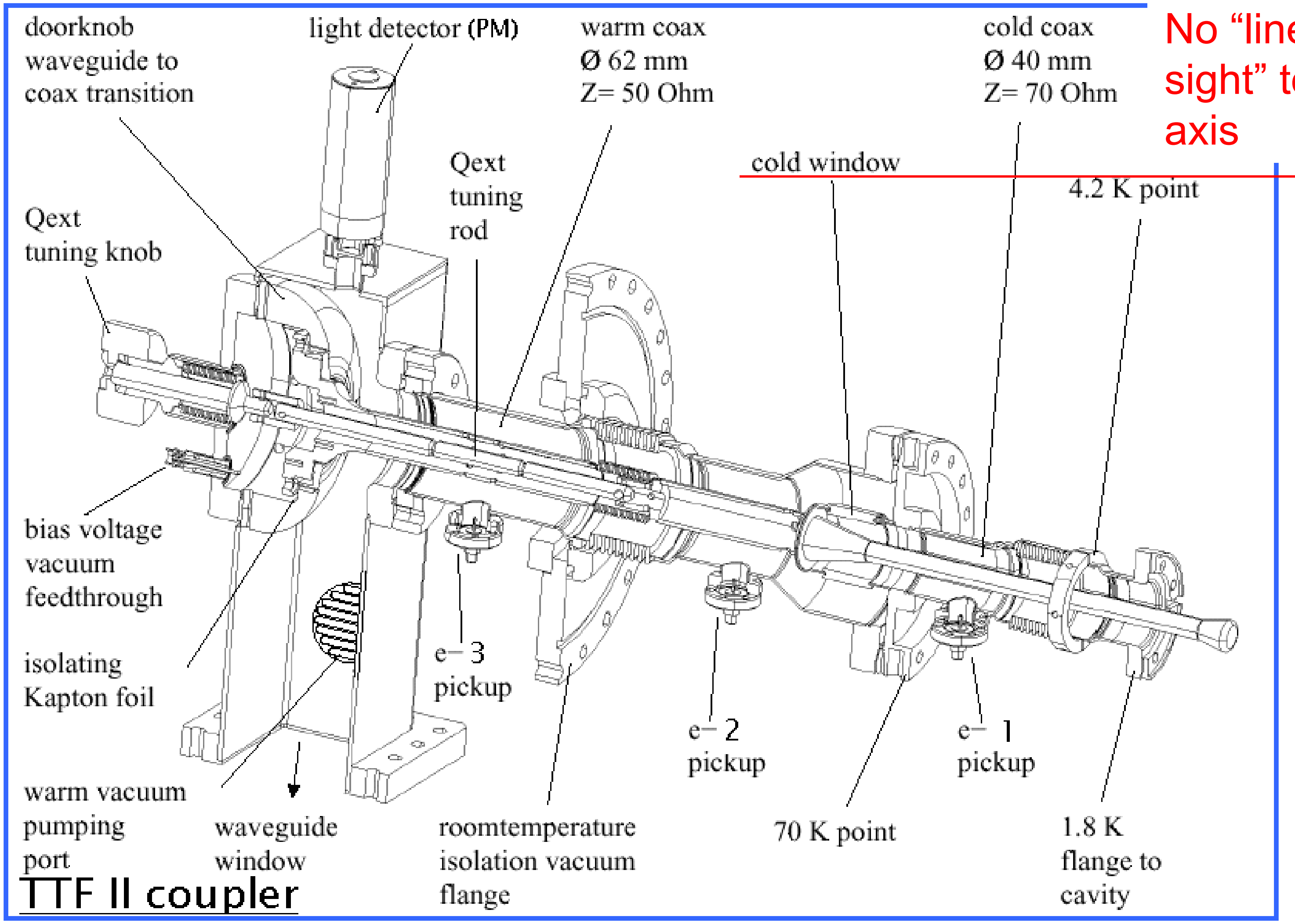
	TTF	**TESLA** 9cell / upgrade	**XFEL**
Peak power + control margin	250 kW	250 kW / 500 kW	150 kW
Repetition rate	10 Hz	5 Hz	10 Hz
Average power	3.2 kW	3.2 kW / 6.4 kW	1.9 kW
Coupling (Qext)	adjustable (10^6 - 10^7)	fixed ($3*10^6$)	adjustable (10^6 - 10^7)

Fermilab TTF coupler



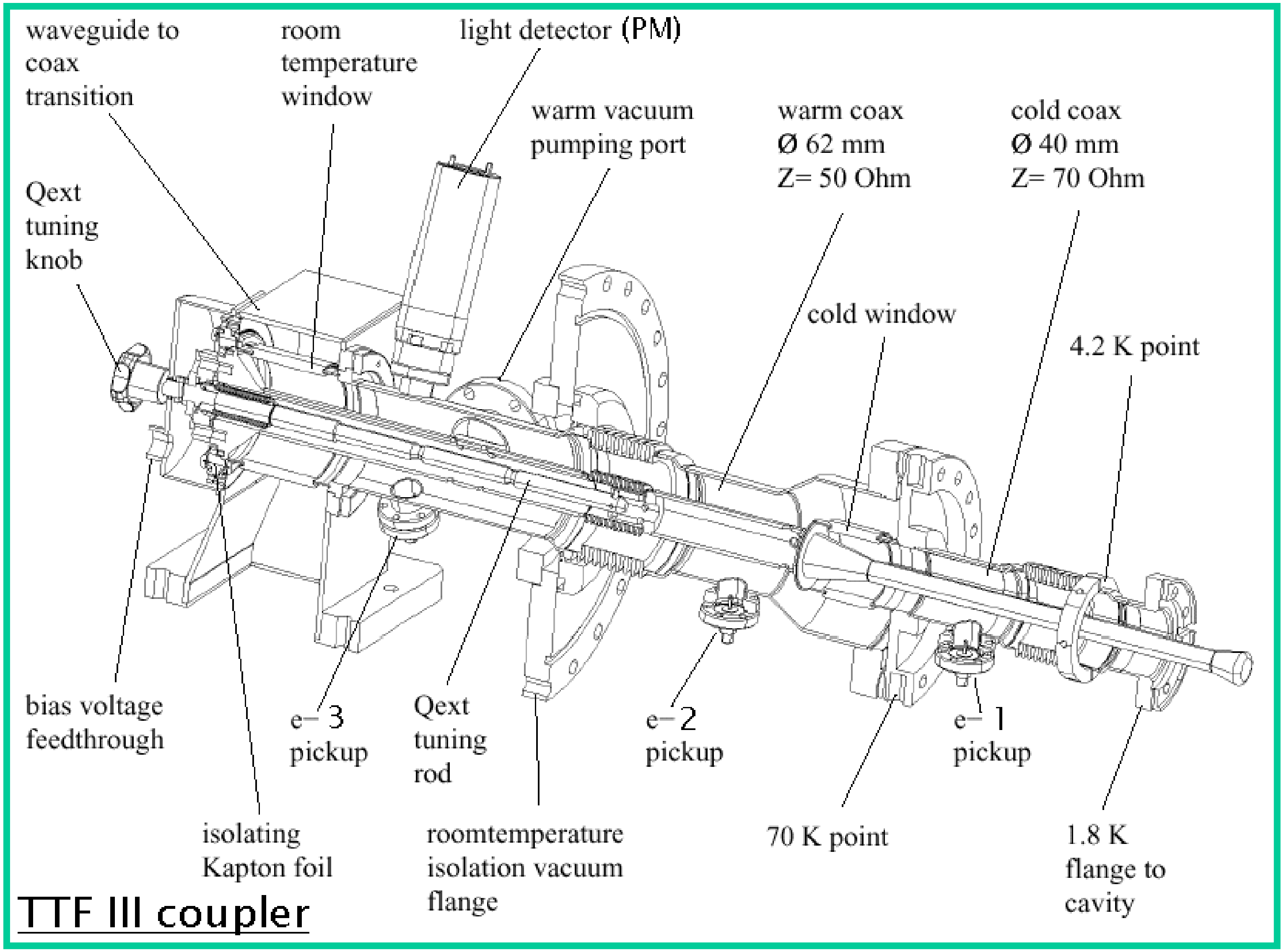
15 such couplers in use on TTF

TTF-II Coupler schematic



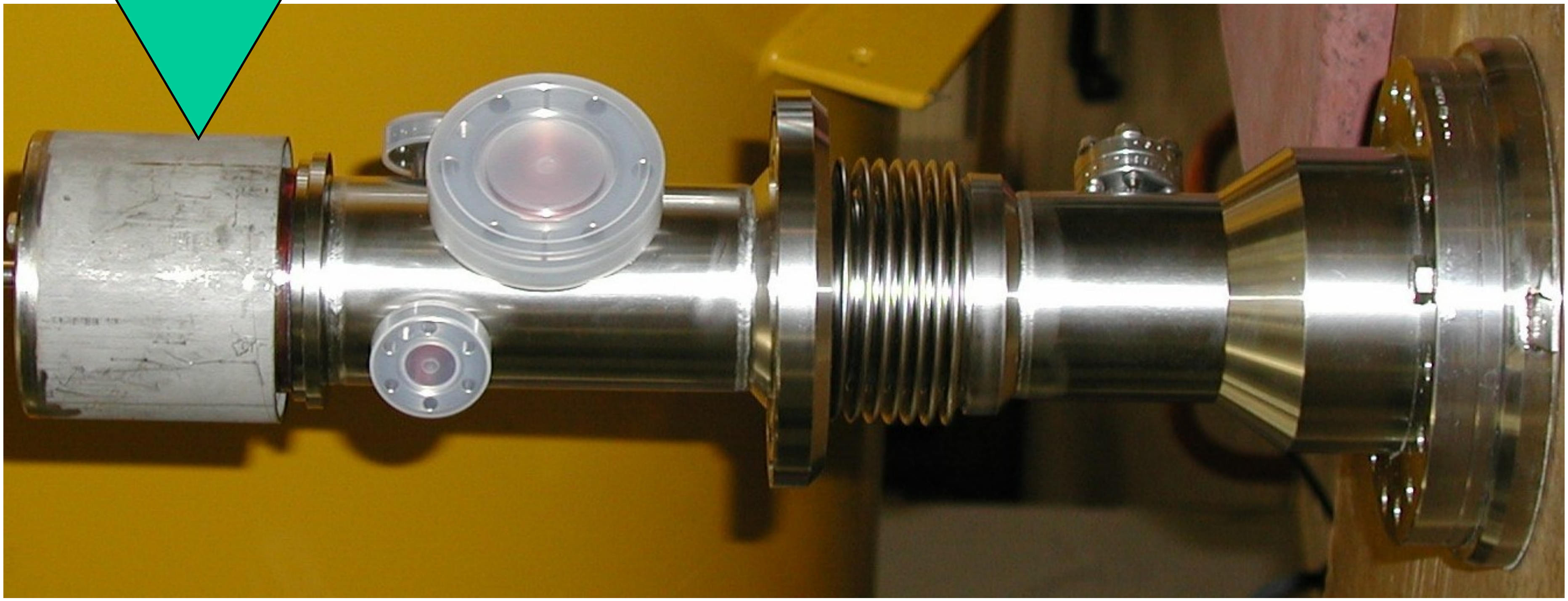
No "line of sight" to cavity axis

Meet the champ! The TTF-III Coupler

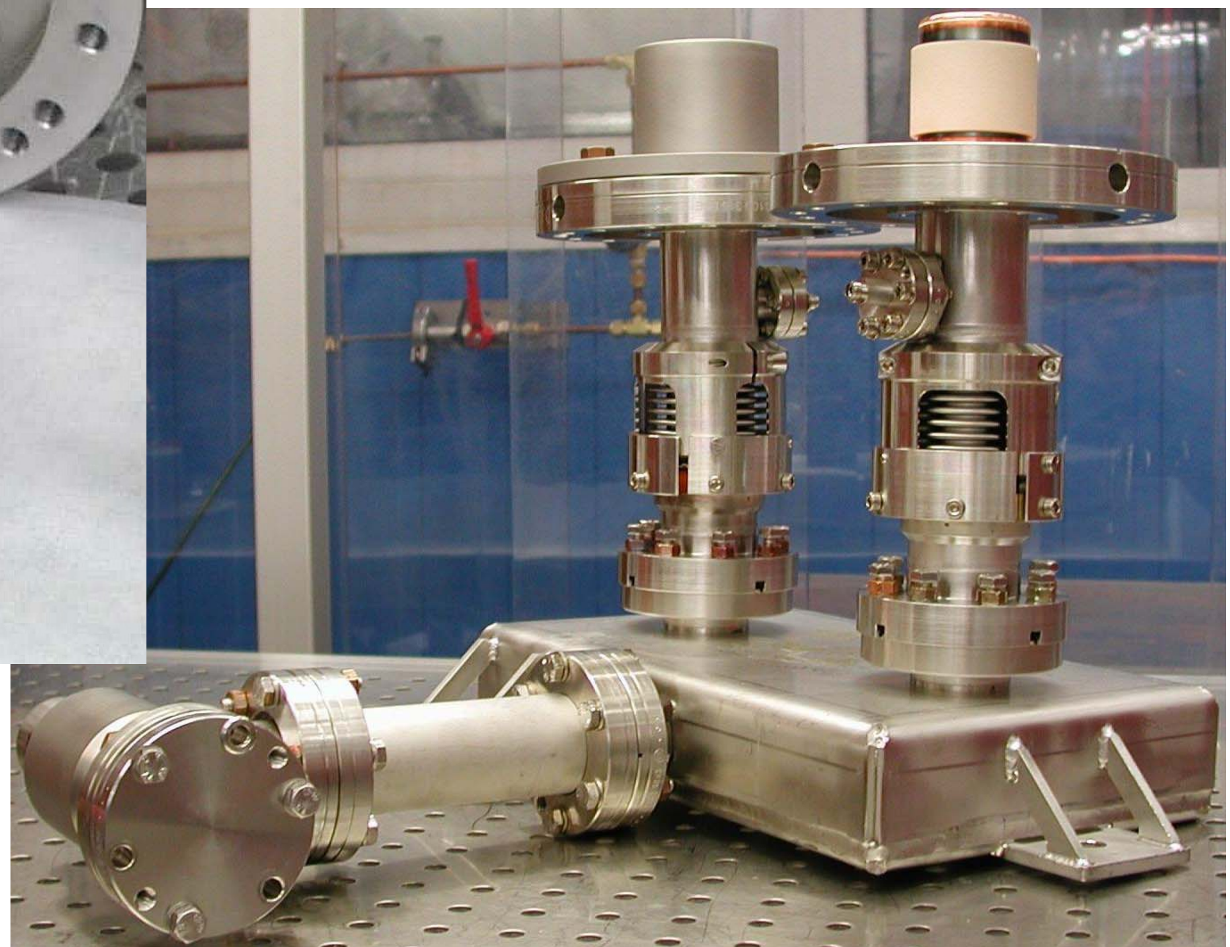


Warm assembly

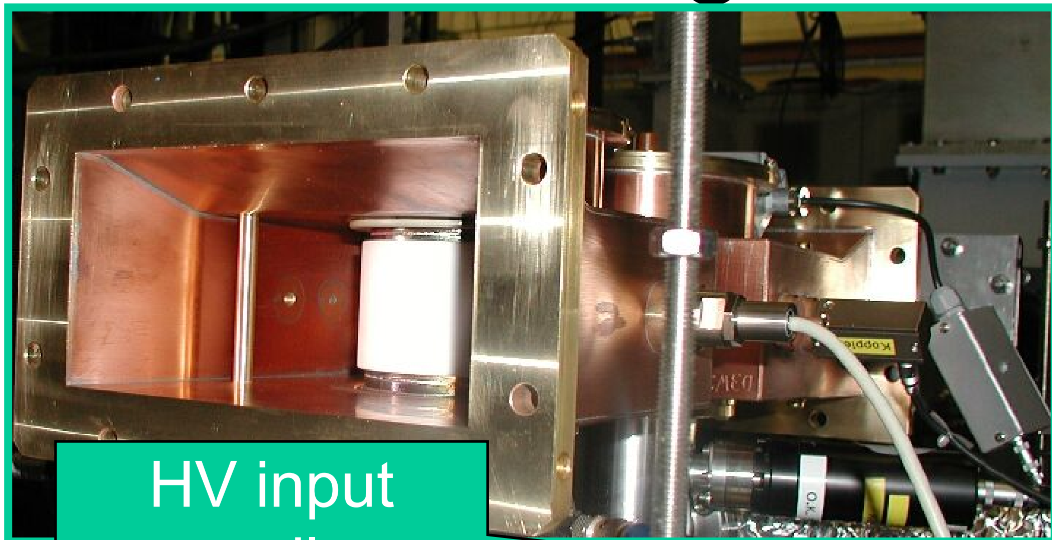
Warm ceramic protection cap

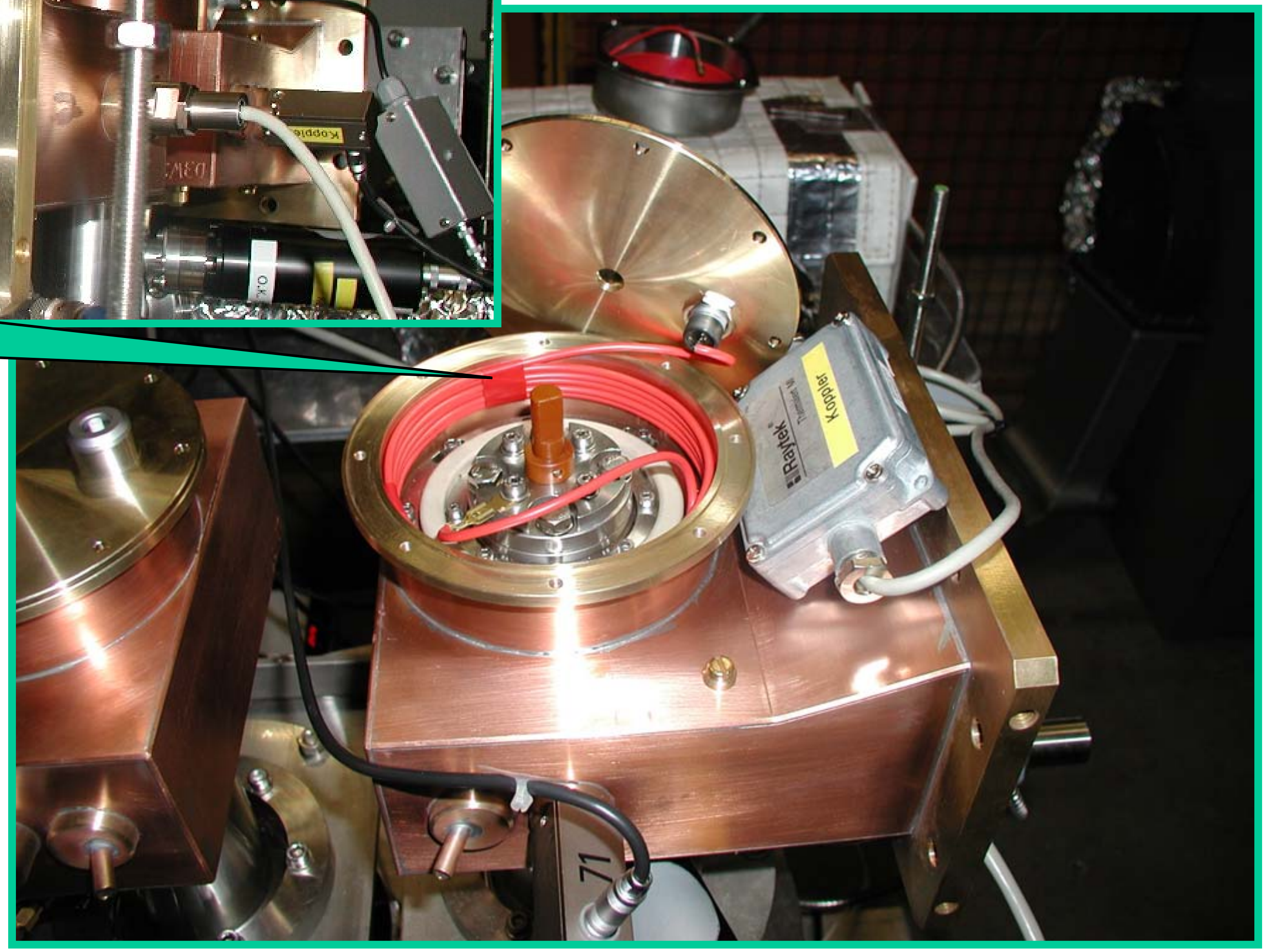


Cold assembly

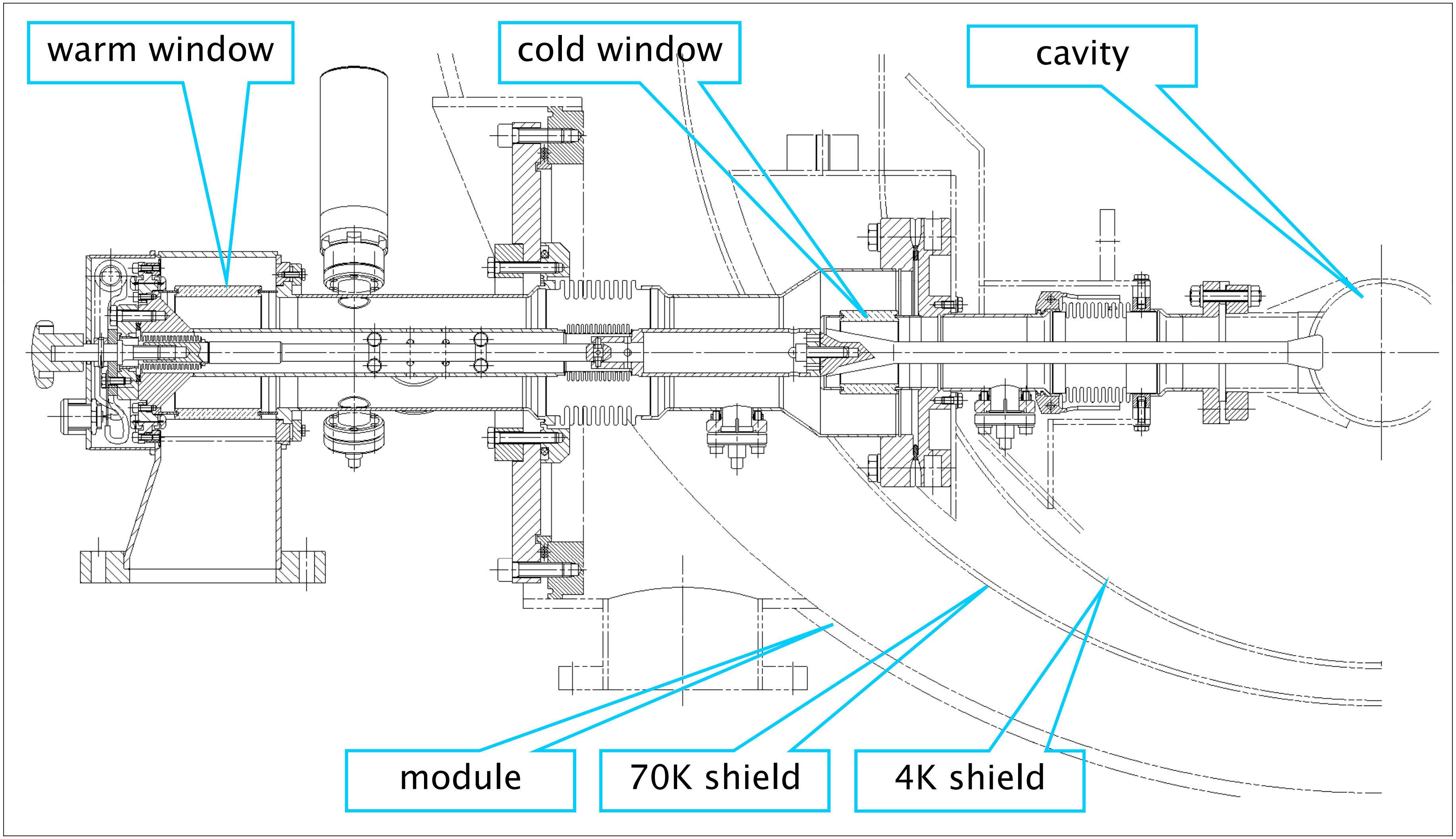


Wave-guide assembly

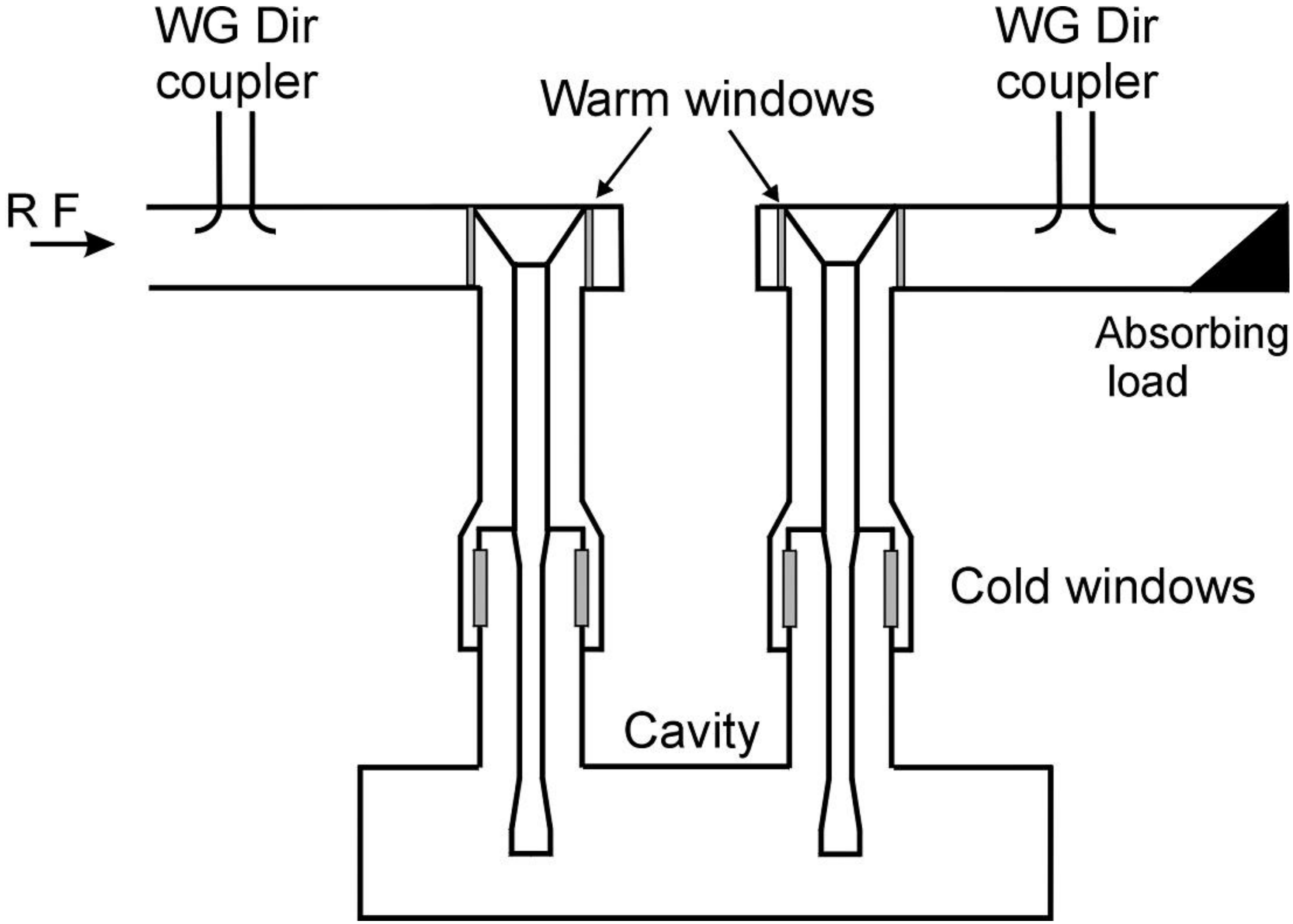




RF Coupler in Module



Test stand layout

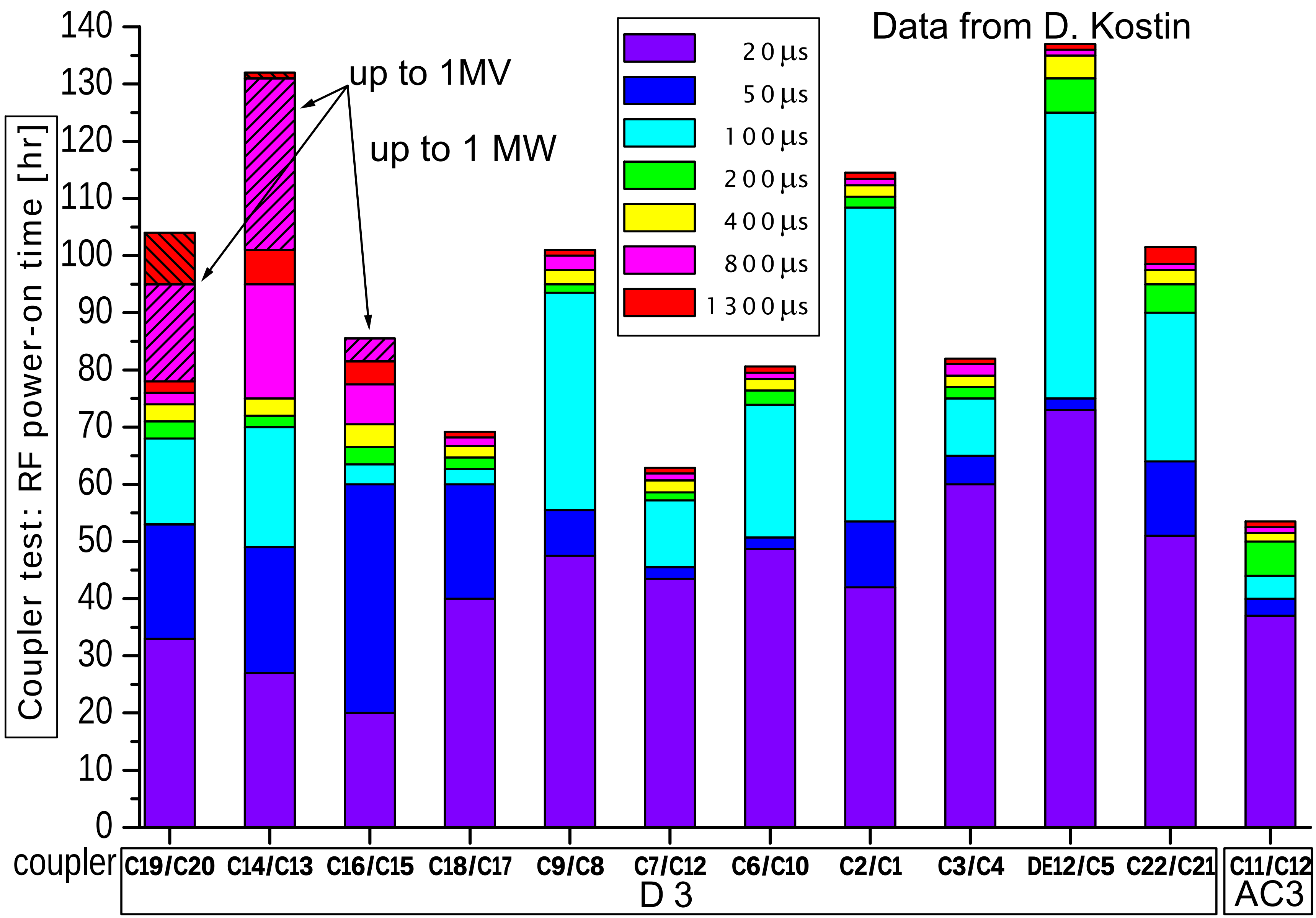


Conditioning procedure

Most labs use warm conditioning routines, and preparation procedures, which differ in detail but which are, by and large, very similar.
Here is the DESY example.

- Pulse length 20 μs, ramp power to 1.0 MW in 0.2 dB steps
- Pulse length 50 μs, ramp power to 1.0 MW in 0.2 dB steps
- Pulse length 100 μs, ramp power to 1.0 MW in 0.2 dB steps
- Pulse length 200 μs, ramp power to 1.0 MW in 0.2 dB steps
- Pulse length 400 μs, ramp power to 1.0 MW in 0.2 dB steps
- Pulse length 800 μs, ramp power to 0.5 MW in 0.2 dB steps
- Pulse length 1300 μs, ramp power to 0.5 MW in 0.2 dB steps
- Sweep power @ 1.3 ms, 50 to 500 kW.

- **Interlocks**
- e- pick-ups, photo-multiplier, vacuum, ceramic temperature
- Wave-guide sparks – stop operation!



T. Garvey – LAL – Orsay
12th International Workshop on RF Superconductivity
Cornell, USA, July 10 – 15, 2005.

Performance summary from coupler operation on TTF

- All couplers in the TTF linac have been processed and operated up to the cavity performance limits.
- RF power couplers were tested up to 1 MW of pulsed power at 1.3 ms pulse length 2 Hz at the test stand.
- RF power couplers operated > 270,000 coupler*hours .
- Latest coupler design, TTF-III has simplified assembly, shown better performance and has shorter conditioning.
- TTF-III couplers have been tested together with cavities at gradients of 35 MV/m (600 kW) 5 Hz without degradation of cavity or coupler. Important for ILC !!!

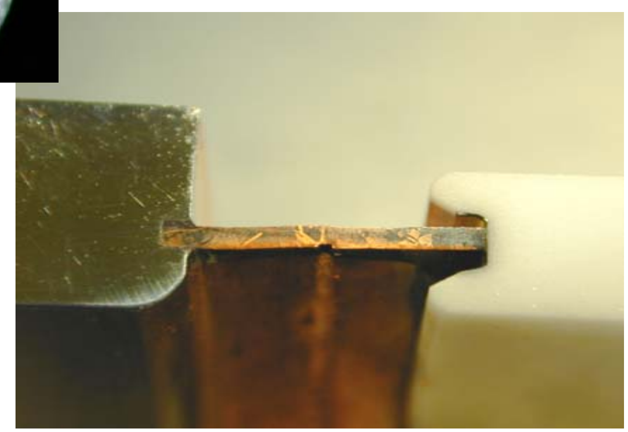
30 TTF-III Couplers ordered from Industry

Series TTF-III coupler production – present design requires many technologies.

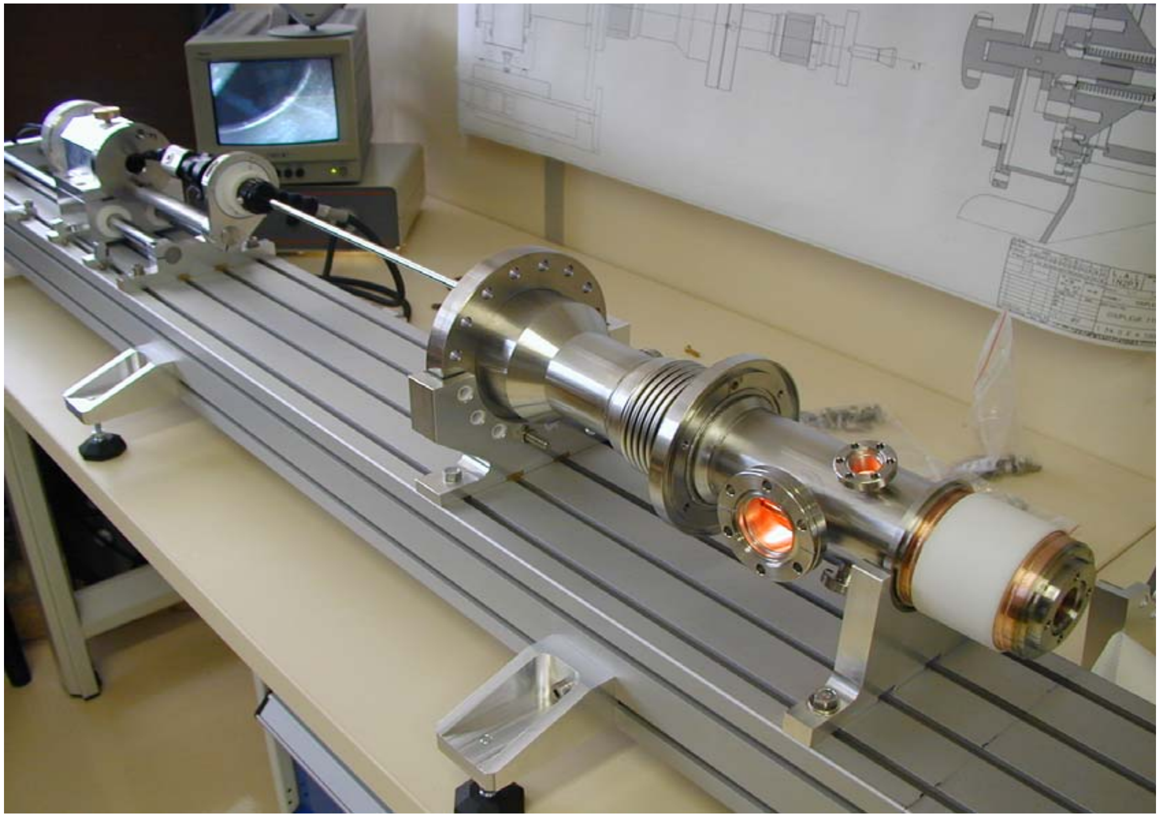
Laser weld of bellows

Copper coated bellows

Ceramic-metal brazing



E-beam welding



Non-destructive examination by endoscopy at LAL

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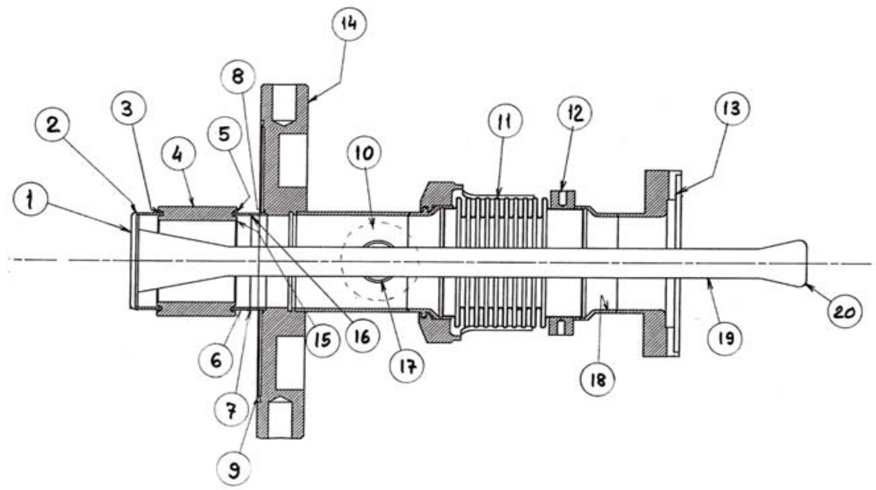
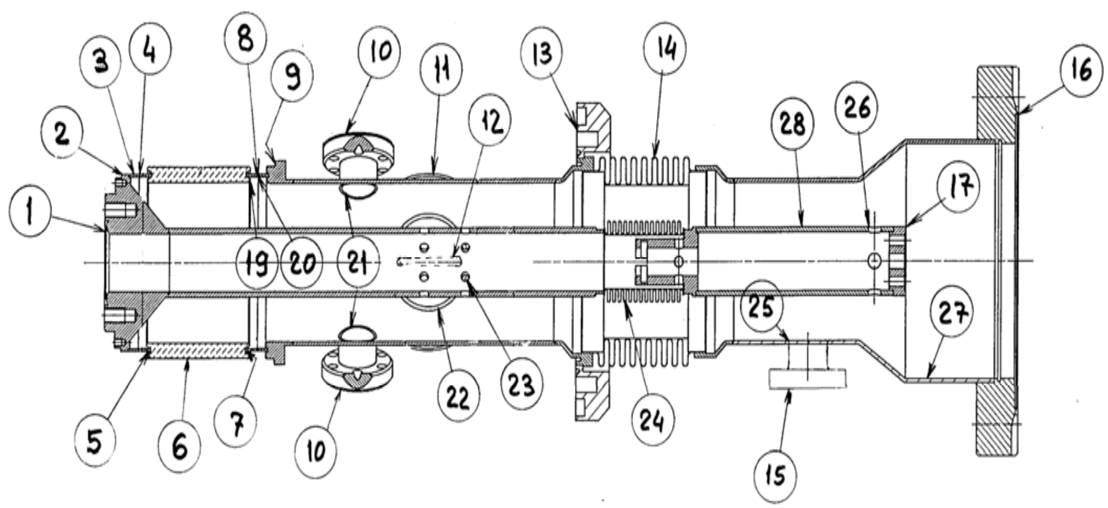
12th International Workshop on RF Superconductivity
Cornell, USA, July 10 – 15, 2005.

Points of visual inspection



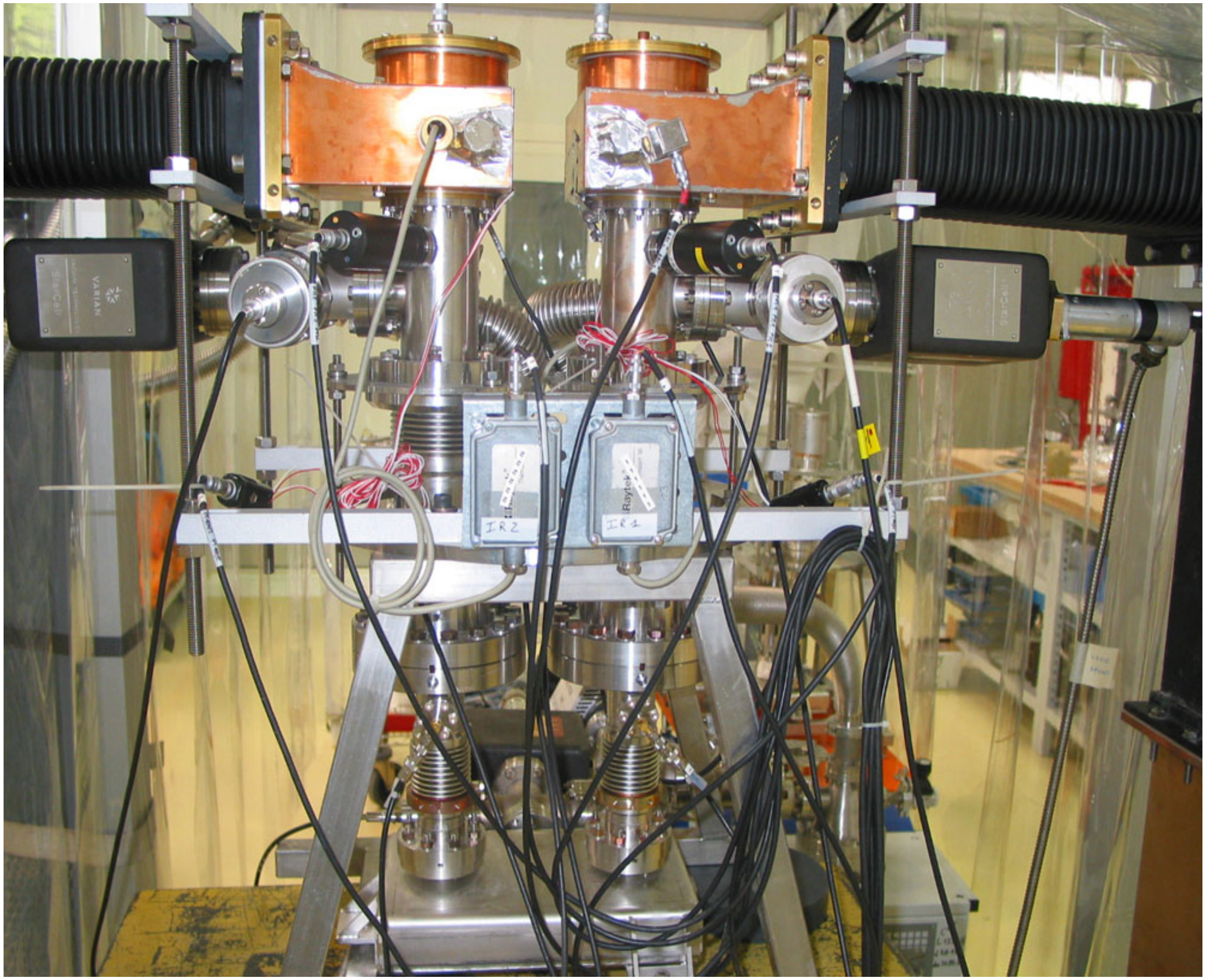
Cold assembly



Warm assembly

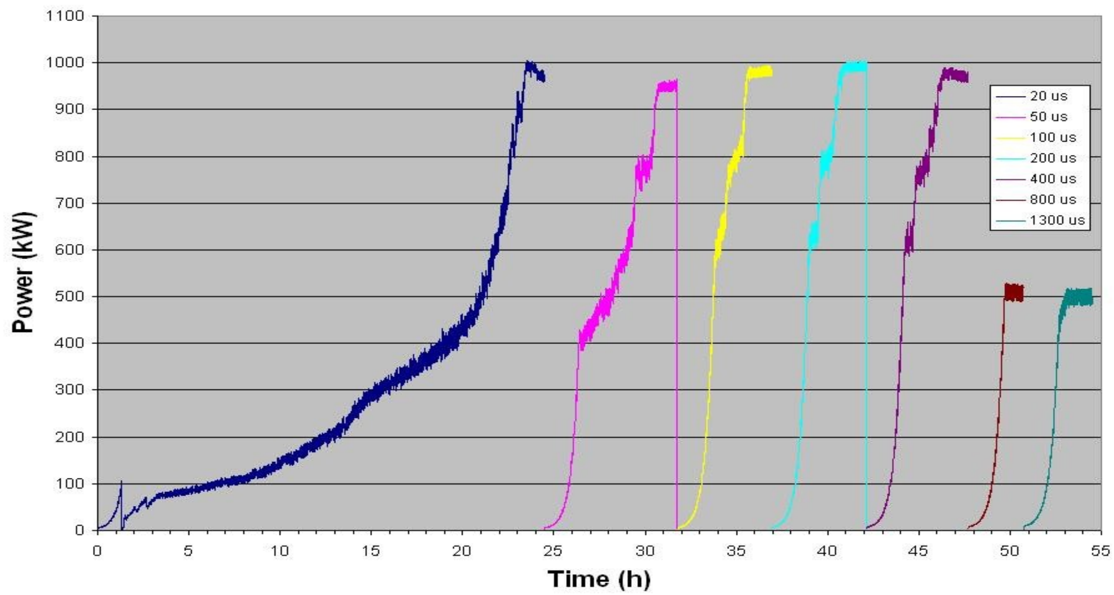
Observations → EXCEL files → data base

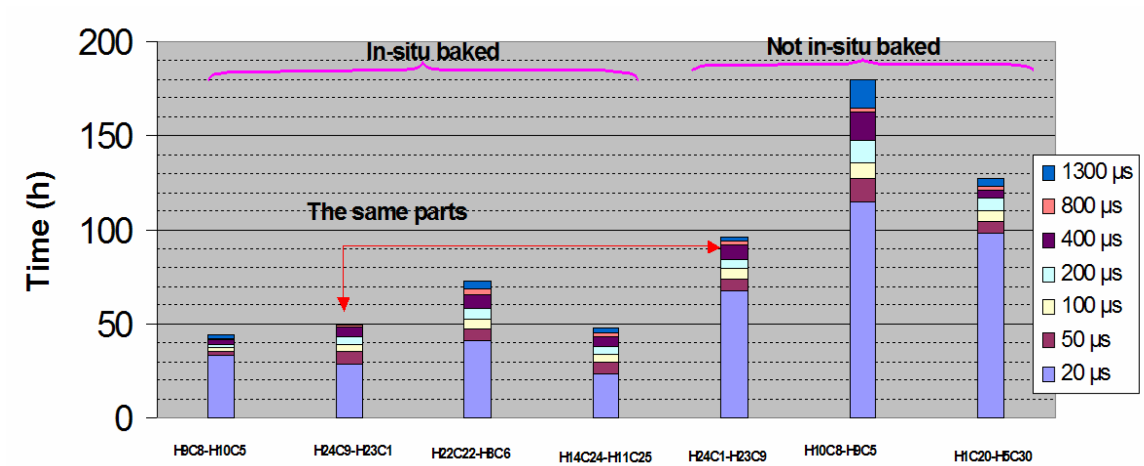
Assembly of cold part in class 10 clean room



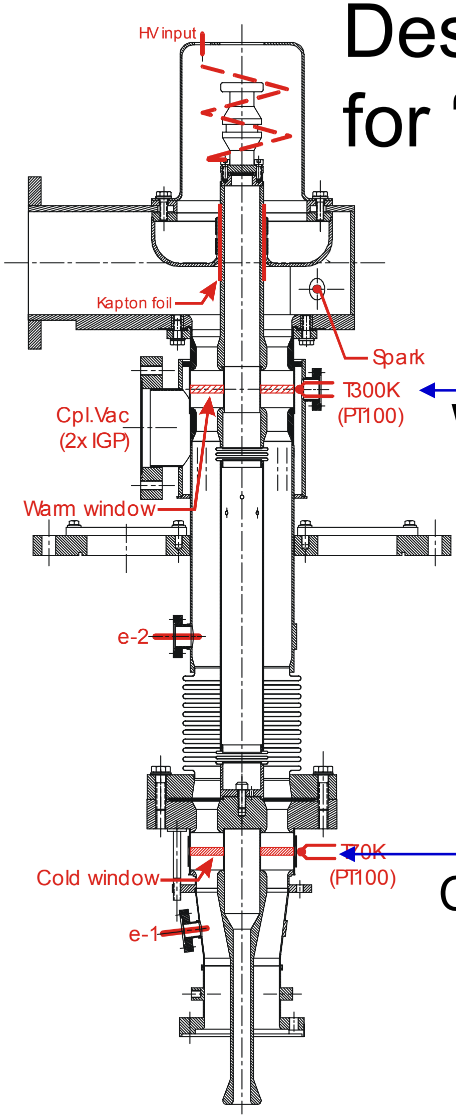
2 couplers under test at LAL-Orsay

TTF-III coupler conditioning at Orsay.
See poster ThP48 by H. Jenhani





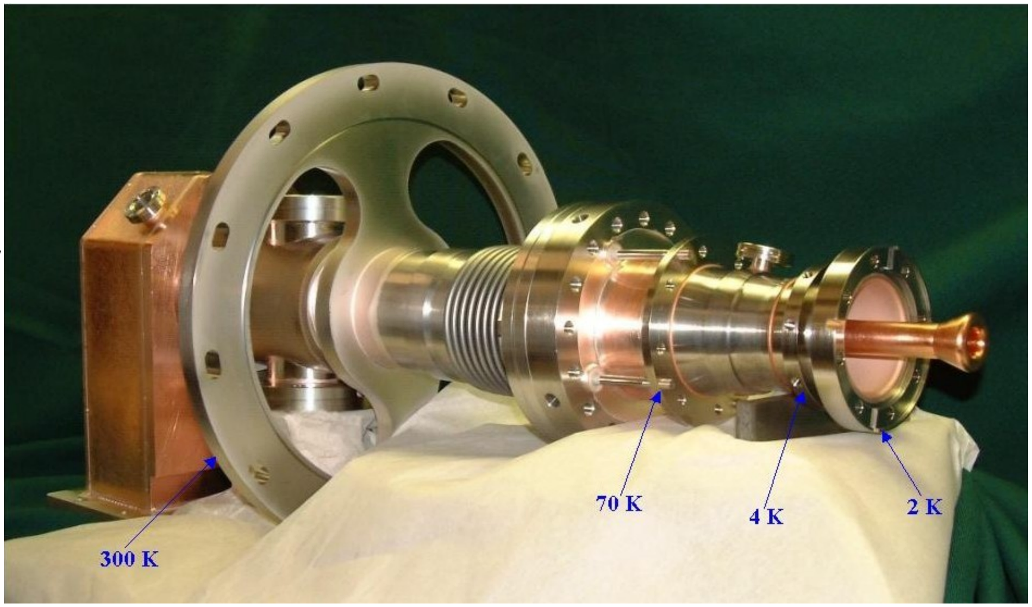
Alternative "TESLA" coupler design



Designed by AMAC International Inc. for "superstructure", ~1.1 MW. Two disk windows

Warm window

Cold window



Couplers presently being tested at DESY. Results encouraging. See poster session ThP47.

CW operation tests of TTF-III coupler

TESLA Technology considered for BESSY FEL - as well as other 4th Generation light sources

See J. Knobloch et. al., PAC'05 – collaboration ACCEL, BESSY, Cornell, DESY, Rossendorf

Room temperature tests at Rossendorf, cryogenic tests on HoBiCaT (BESSY). Limiting component is warm inner bellows.

(cooled only by radiation and conduction)

Coupler can safely operate at 10 kW CW TW;
Minor modification to allow cooling of inner conductor will allow this to increase to 25 kW.
Further tests to be held at BESSY with new transmitter.

Coupler for ERL Injector Cavities

- Injector uses five 2-cell 1300 MHz cavities providing 1 MeV/cavity for 100 mA beam.
- Based on TTF-III coupler but with much higher average power – 2 x 75 kW CW.
  - Twin coupler chosen to reduce transverse kick to beam.

Main issue is higher power → extensive thermal and RF simulations see Sobenin et. al. (EPAC04) and Belomestnykh et. al. (LINAC04) for details.

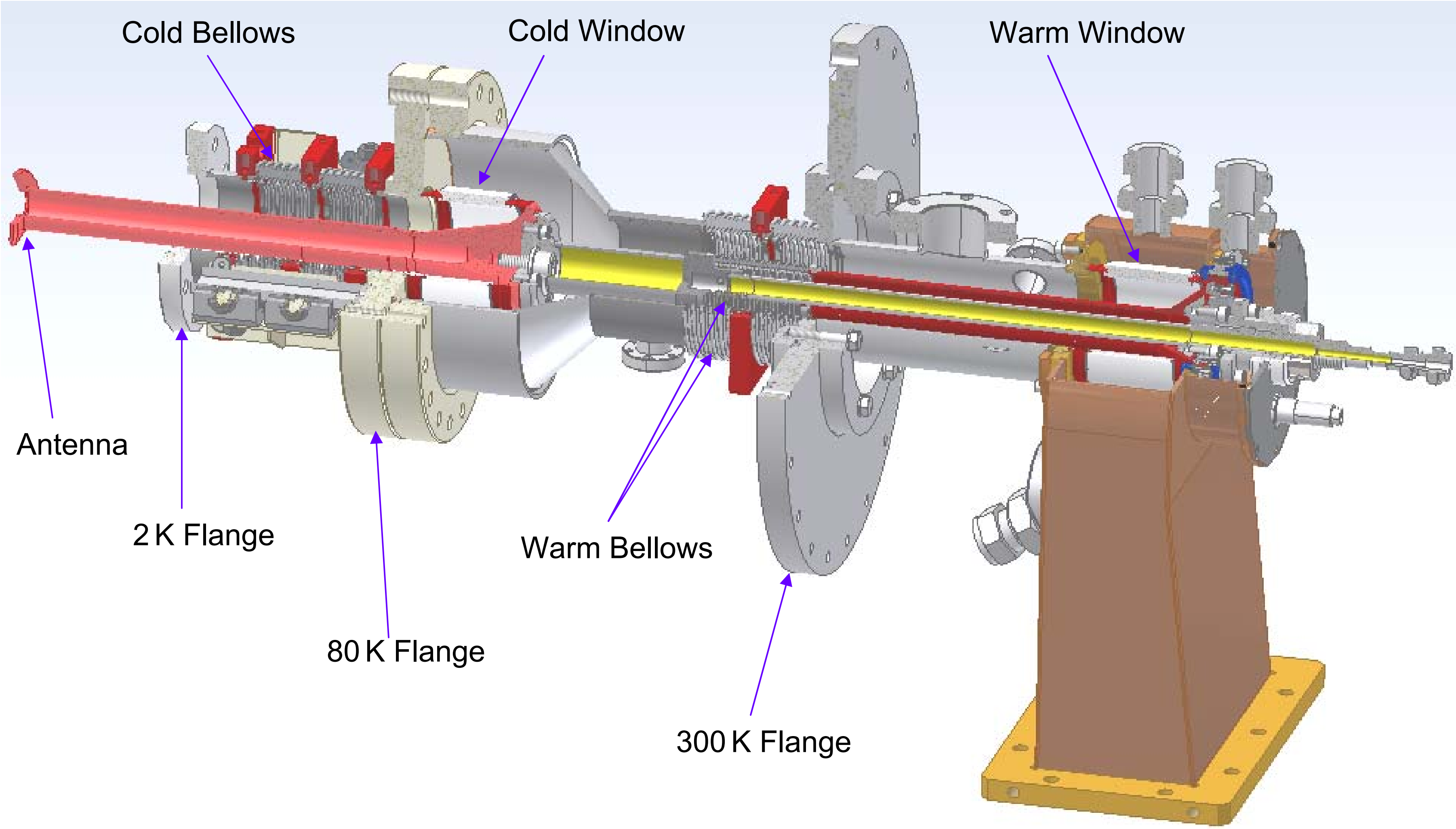
  - 40 mm, 70 Ω co-ax replaced by 62 mm, 60 Ω co-ax
    - Stronger coupling, higher power capability, better for multipactor.

- Re-design of bellows to handle CW power: forced air cooling of inner conductor bellows of warm assembly; additional heat intercepts to cold + warm outer bellows.

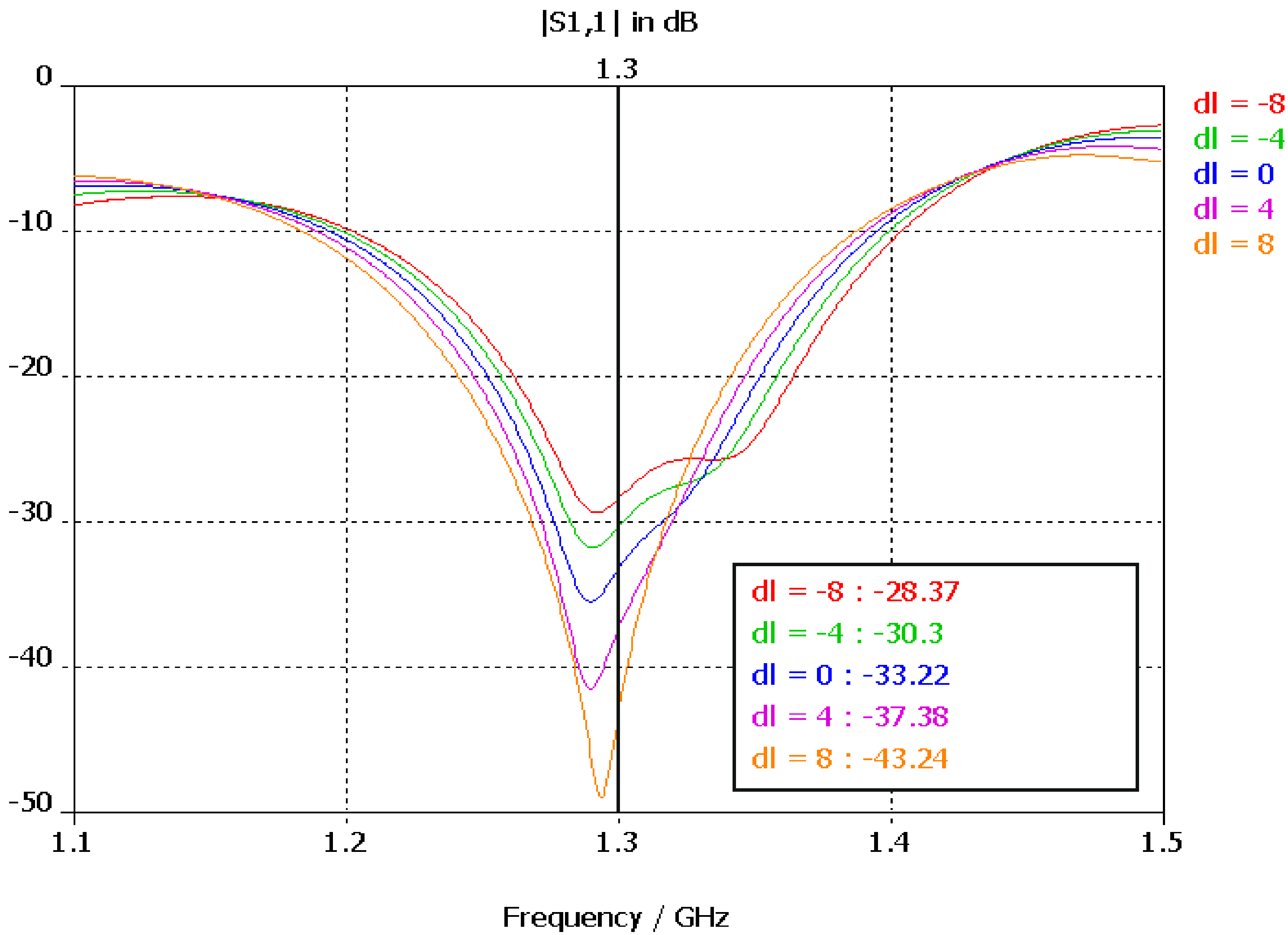
Parameters of the ERL Injector Cavity Coupler

Central frequency	1300 MHz
Bandwidth	±10 MHz
Maximum power transferred to matched load	75 kW
Number of ceramic windows	2
Cold coaxial line impedance	60 Ohm
Warm coaxial line impedance	46 Ohm
Coaxial line OD	62 mm
Q_{ext} range	9.2×10^{4} … 8.2×10^{5}
Antenna stroke	≥ 15 mm
Heat leak to 2 K	< 0.2 W
Heat leak to 4.2 K	< 3 W
Heat leak to 80 K	< 75 W

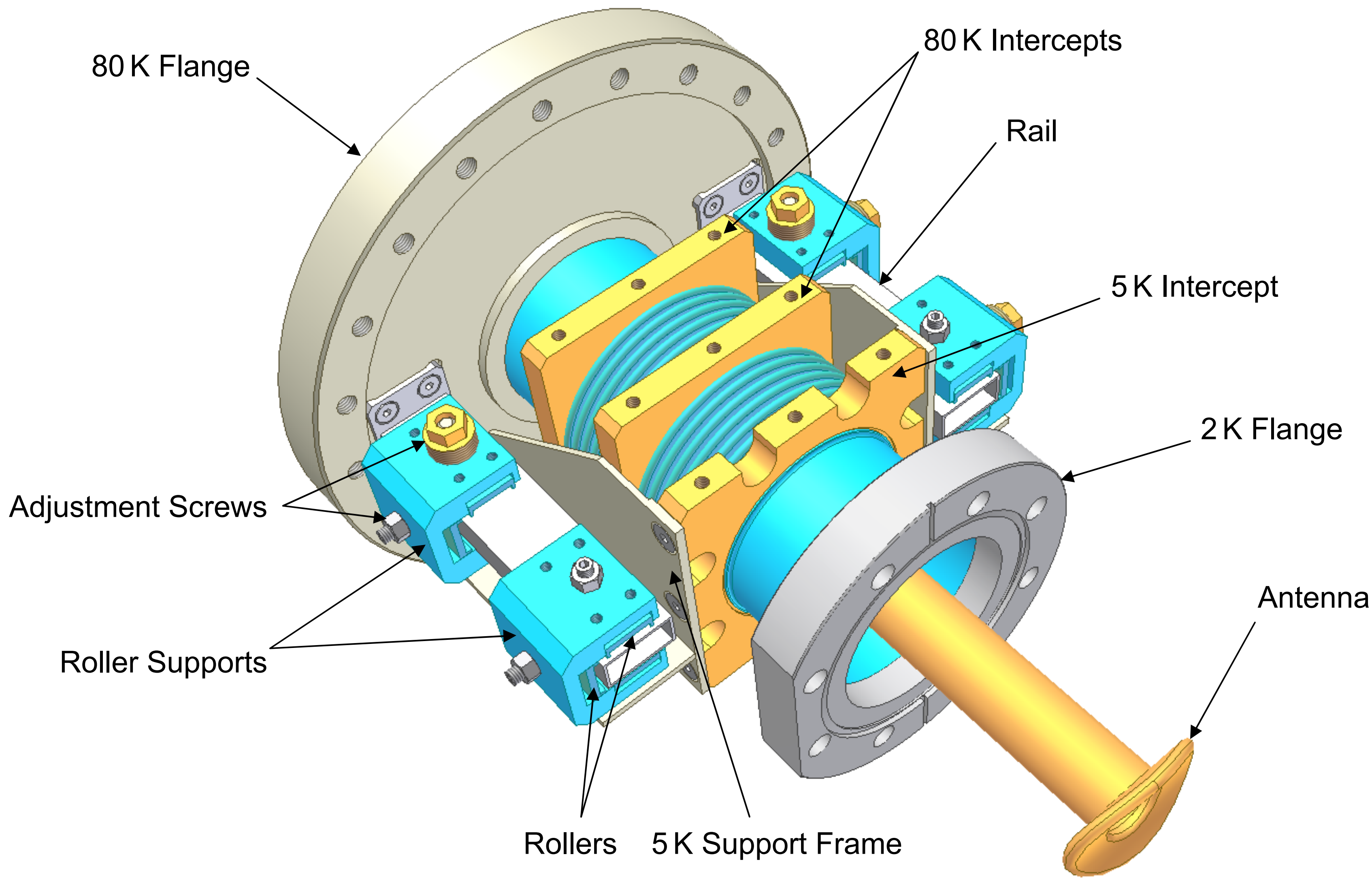
ERL Injector Cavity Coupler



Reflection from the Coupler



Cold Part of the Coupler

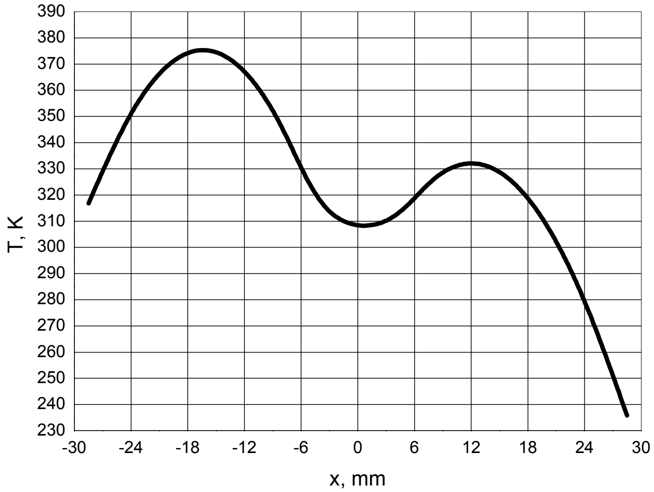


ANSYS Results

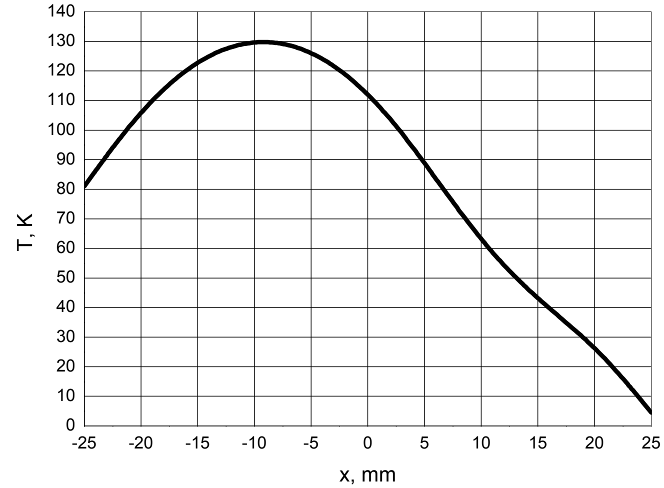
Heat load, W	Regular Bellows		Intercepted Bellows		Requirements
	Static	With RF	Static	With RF	
2 K flange	0.04	0.18	0.03	0.17	0.2
5 K intercept	0.98	3.50	1.46	2.45	3.0
80 K intercept (before bellows)	4.66	59.86	4.19	56.29	—
80 K intercept (between bellows)	—	—	–1.43	0.93	—
80 K flange	3.53	12.13	3.84	12.00	—
Total load at 80 K	8.18	71.99	6.60	69.22	75.0
300 K intercept (between bellows)	–3.57	11.14	–3.57	11.14	—
300 K flange	–0.03	13.39	–0.03	13.39	—
Total load at 300 K	–3.60	24.53	–3.60	24.53	—

Temperature Distributions on Bellows

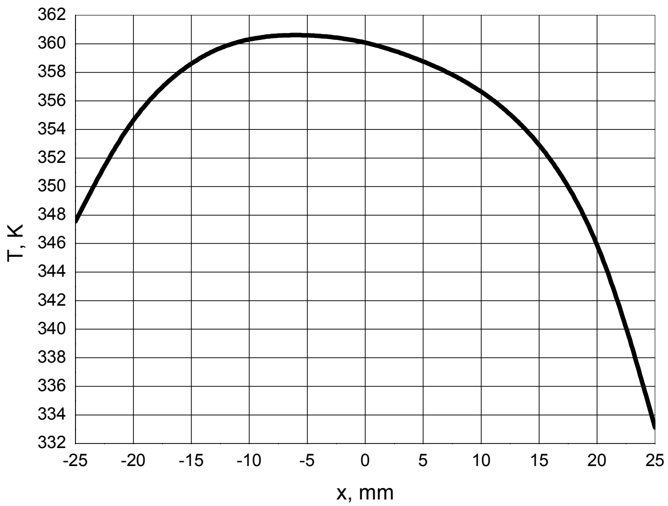
outer warm bellows



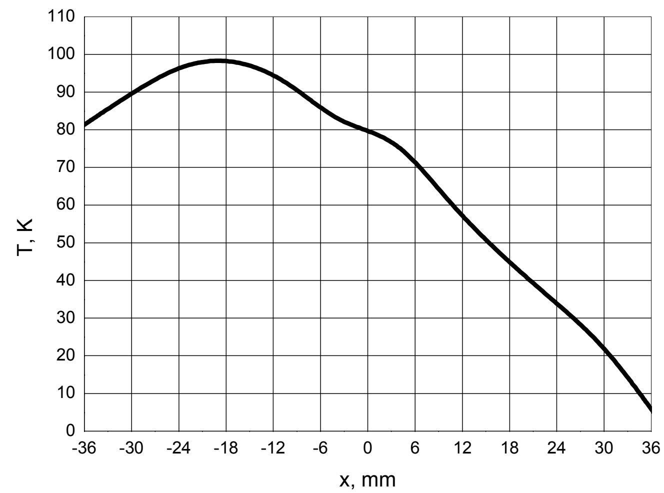
regular cold bellows



inner warm bellows

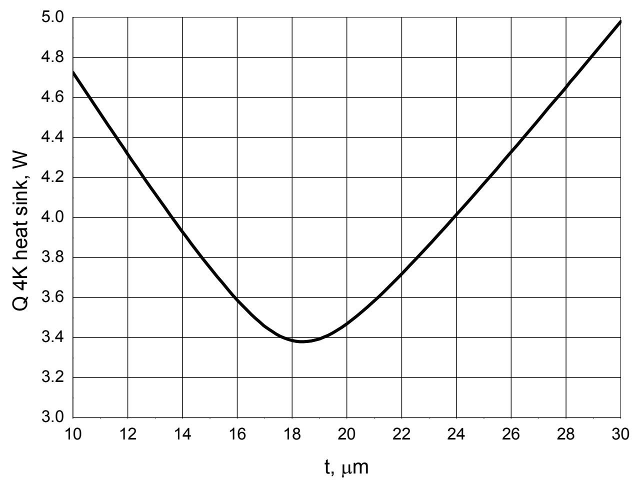


intercepted cold bellows

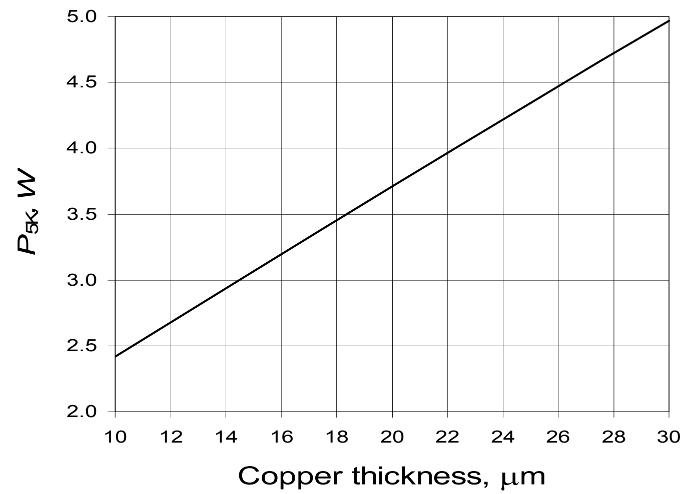


Optimizing the Coating and Wall Thickness

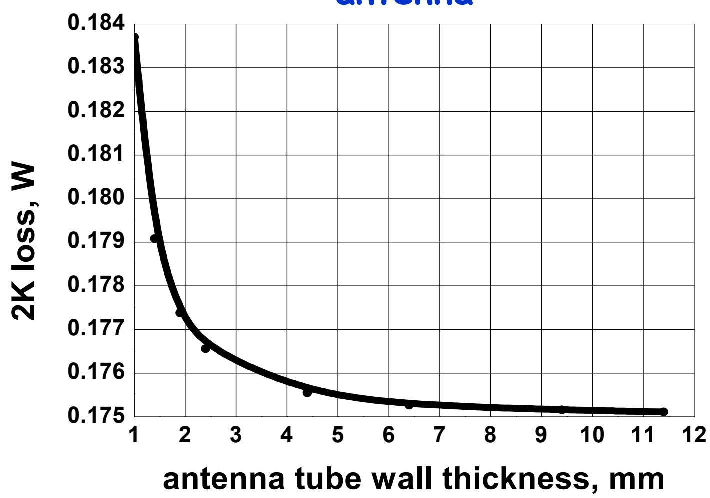
regular cold bellows



intercepted cold bellows



antenna

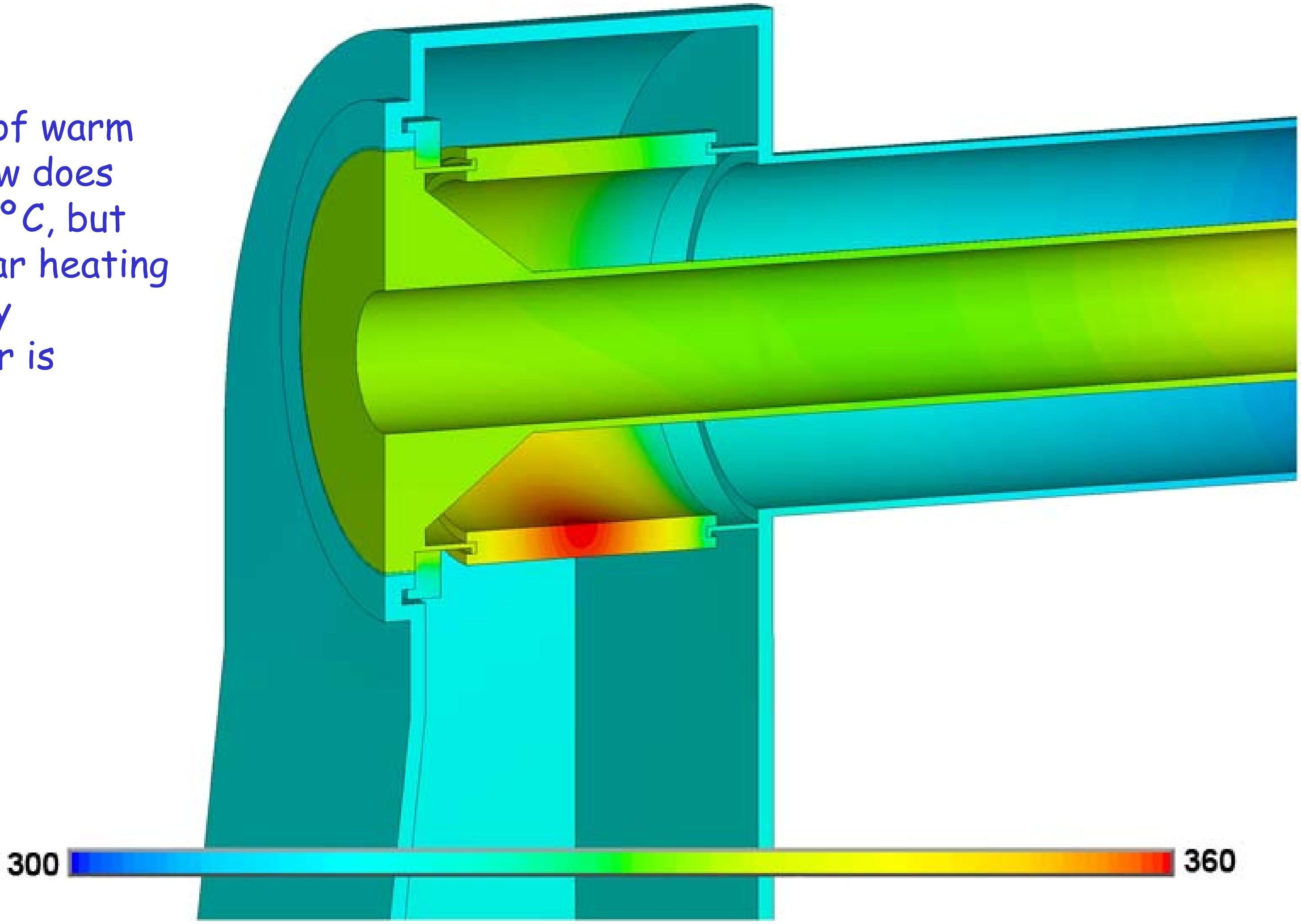


The thickness of copper coating on cold bellows was optimized to obtain the minimum heat load on 5 K zone. It is **18 µm** for the regular bellows and **10 µm** for the intercepted bellows.

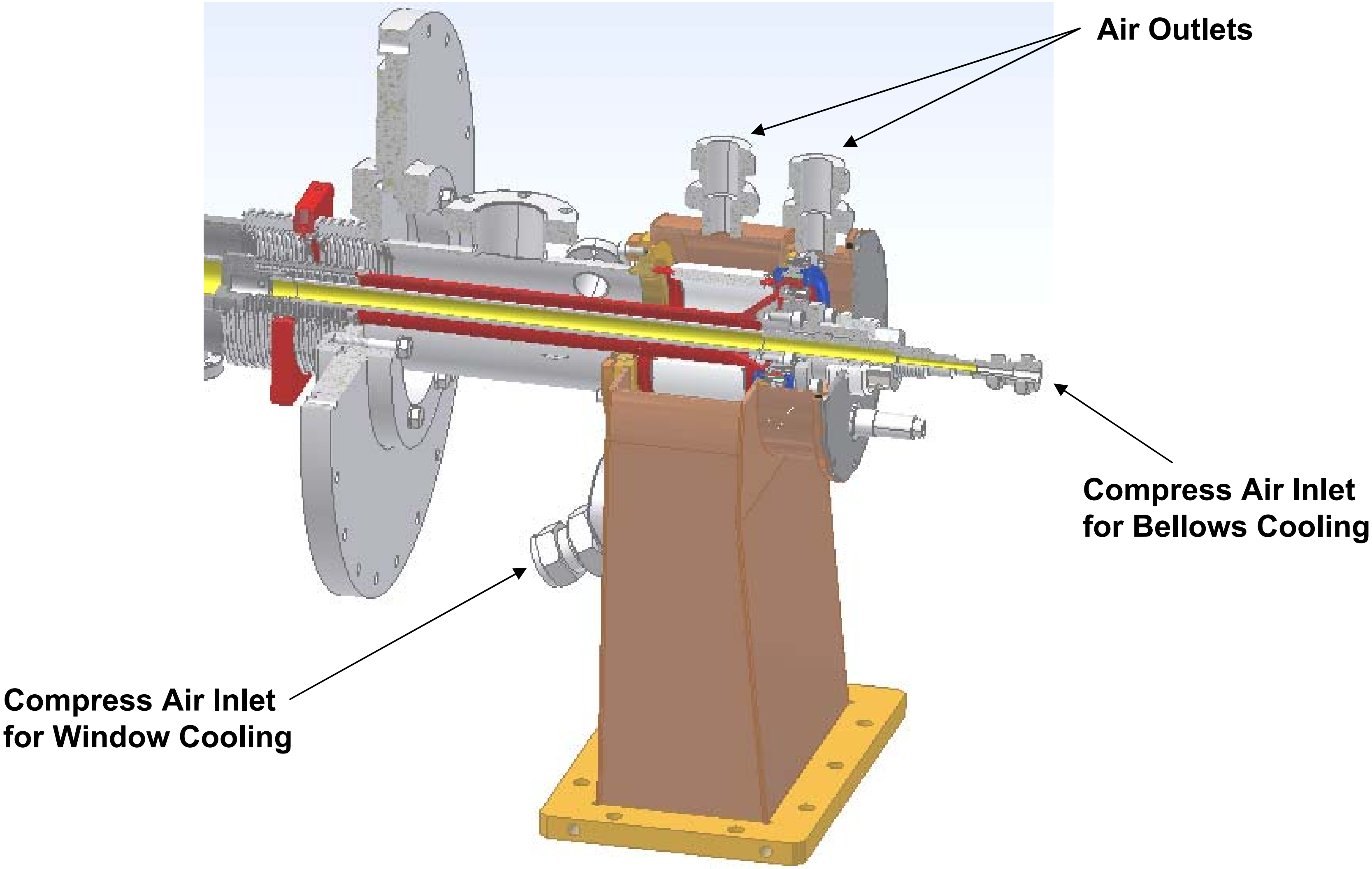
The wall thickness of antenna tube should not be too small to avoid increase of heat load on 2 K due to infrared radiation.

Temperature Map of the Warm Window

Temperature of warm ceramic window does not exceed 90°C, but due to irregular heating local cooling by compressed air is required



Air Cooling of Warm Part of the Coupler



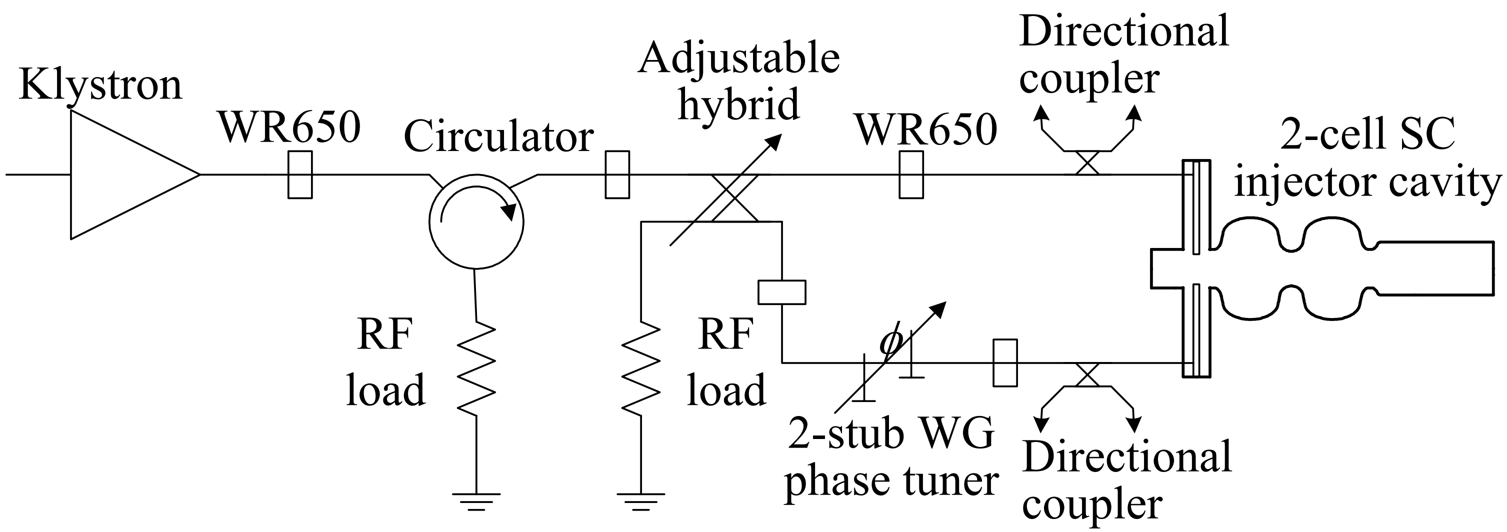
RF Power Splitting for the ERL Injector Cavity

Very strict requirements to the power dividing system:

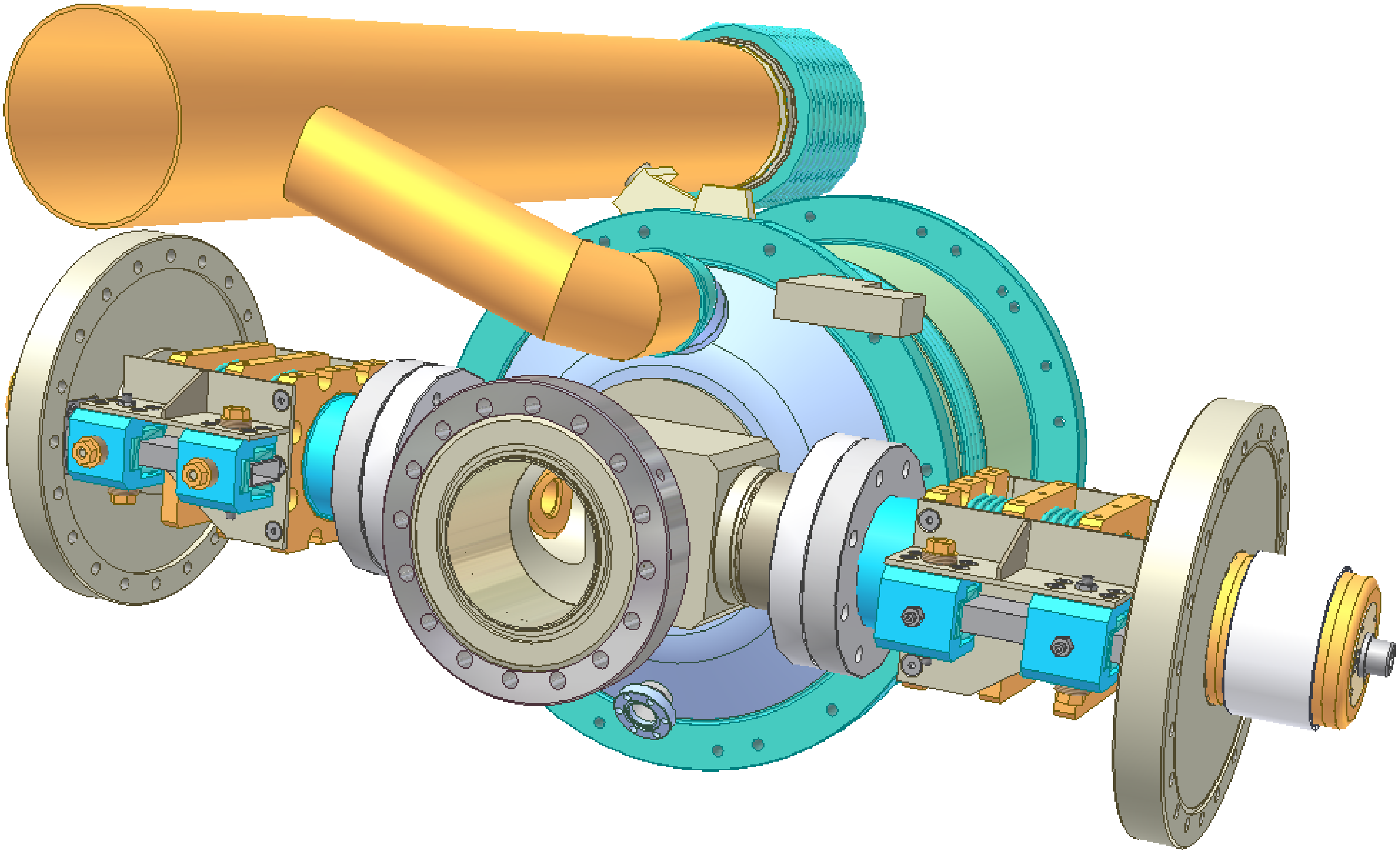
- Difference of field magnitudes on individual coupler antennae ≤ 1-2 %
- Phase difference ≤ 1°

Solution:

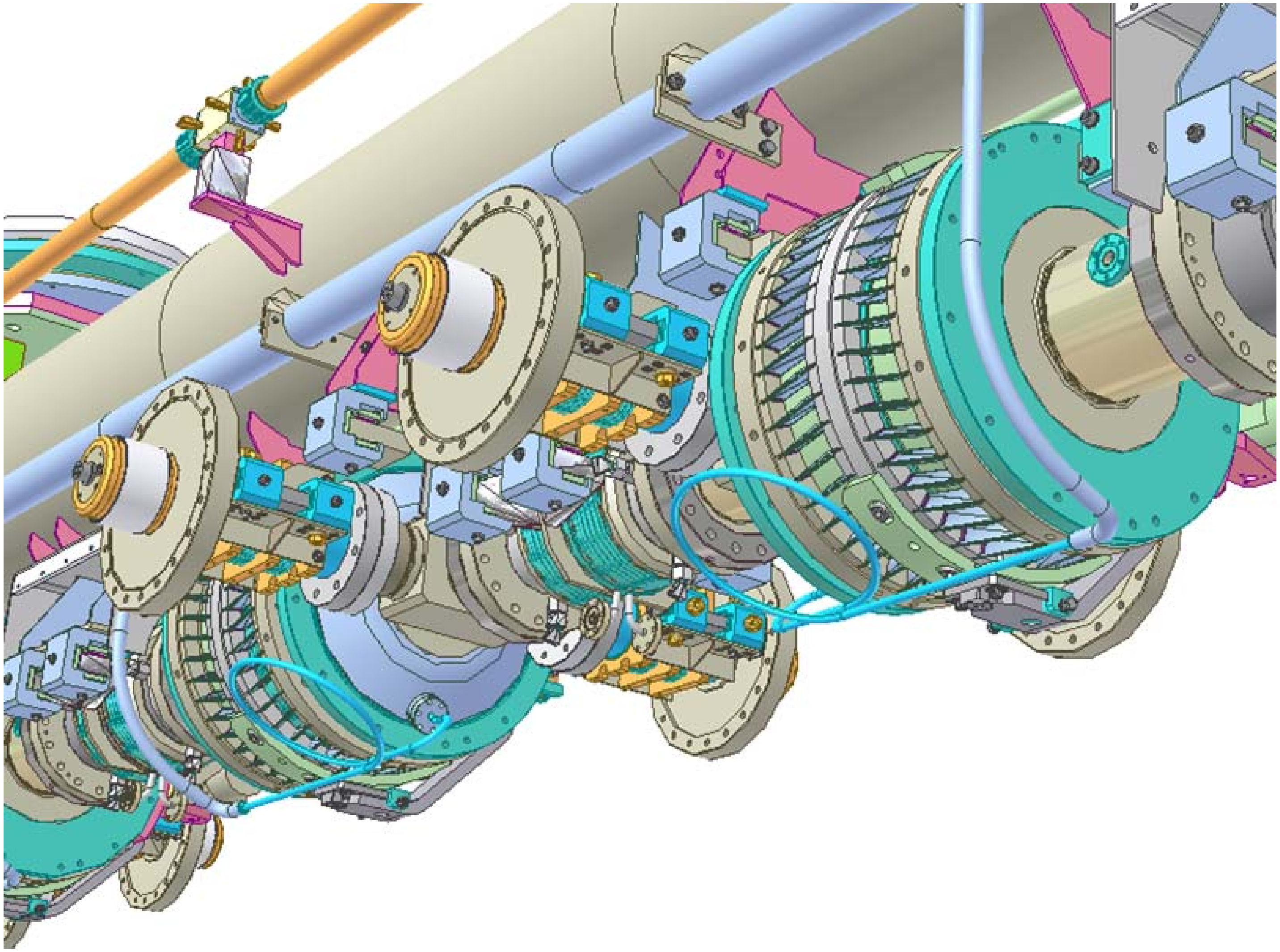
- Precision adjustable power divider
- Fine phase tuner
- No flexible waveguide parts between power divider and cavity couplers



Twin Coupler Attached to the Cavity

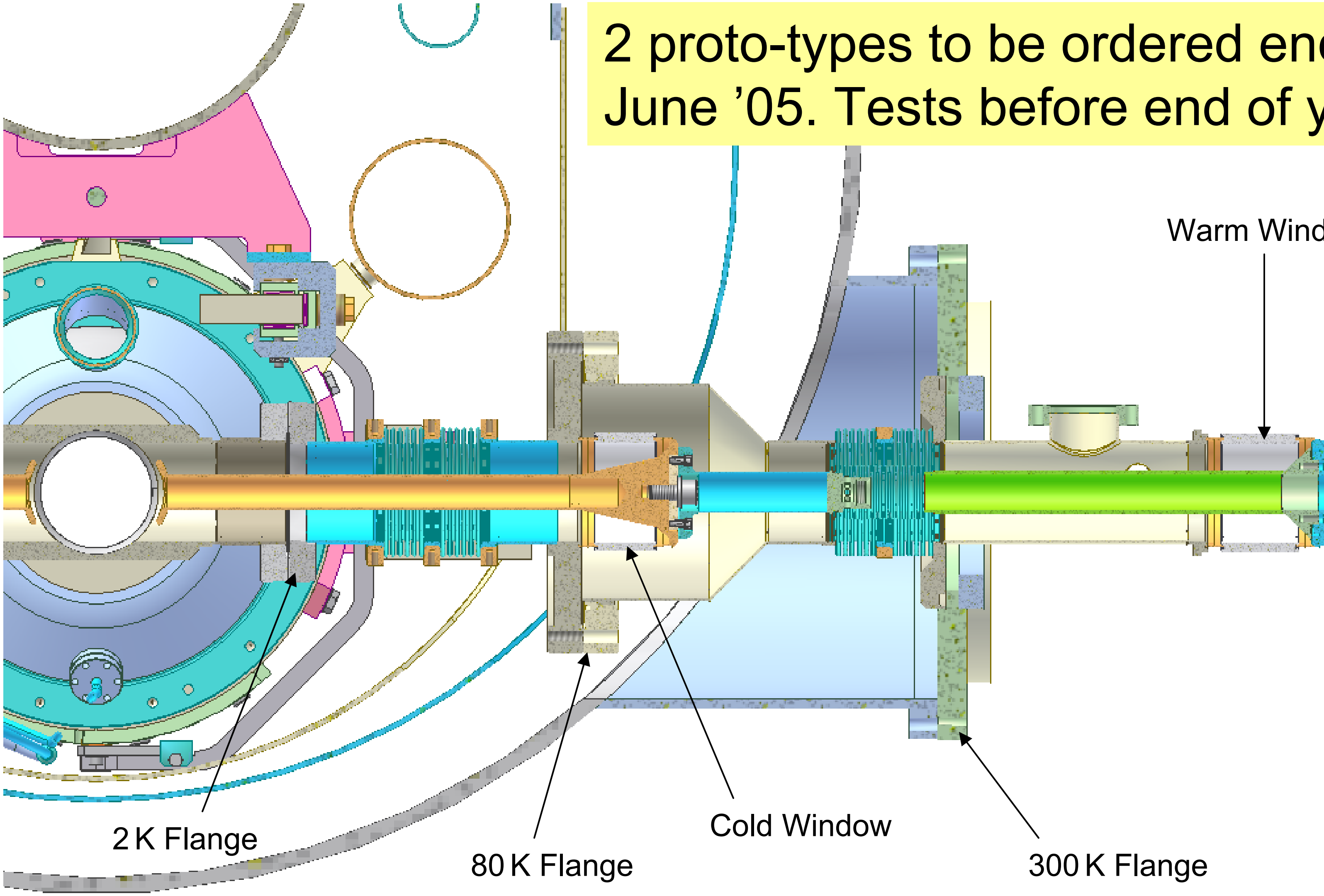


Twin Couplers in the Cryomodule



Coupler Mounted in the Cryomodule

2 proto-types to be ordered end of June '05. Tests before end of year.



SPIRAL-II DESIGN PERFORMANCE

- Transmission of 20 kW nominal power to the beam for a 100% duty cycle.
- External quality factor of $1.06x10^6$ (for 1.39 MV gap voltage and QWR cavity of $\beta = 0.12$).

- Reflection coefficient of -32 dB for coupler with cylindrical ceramic and – 50 dB with disk ceramic.

Dissipation at thermal interfaces

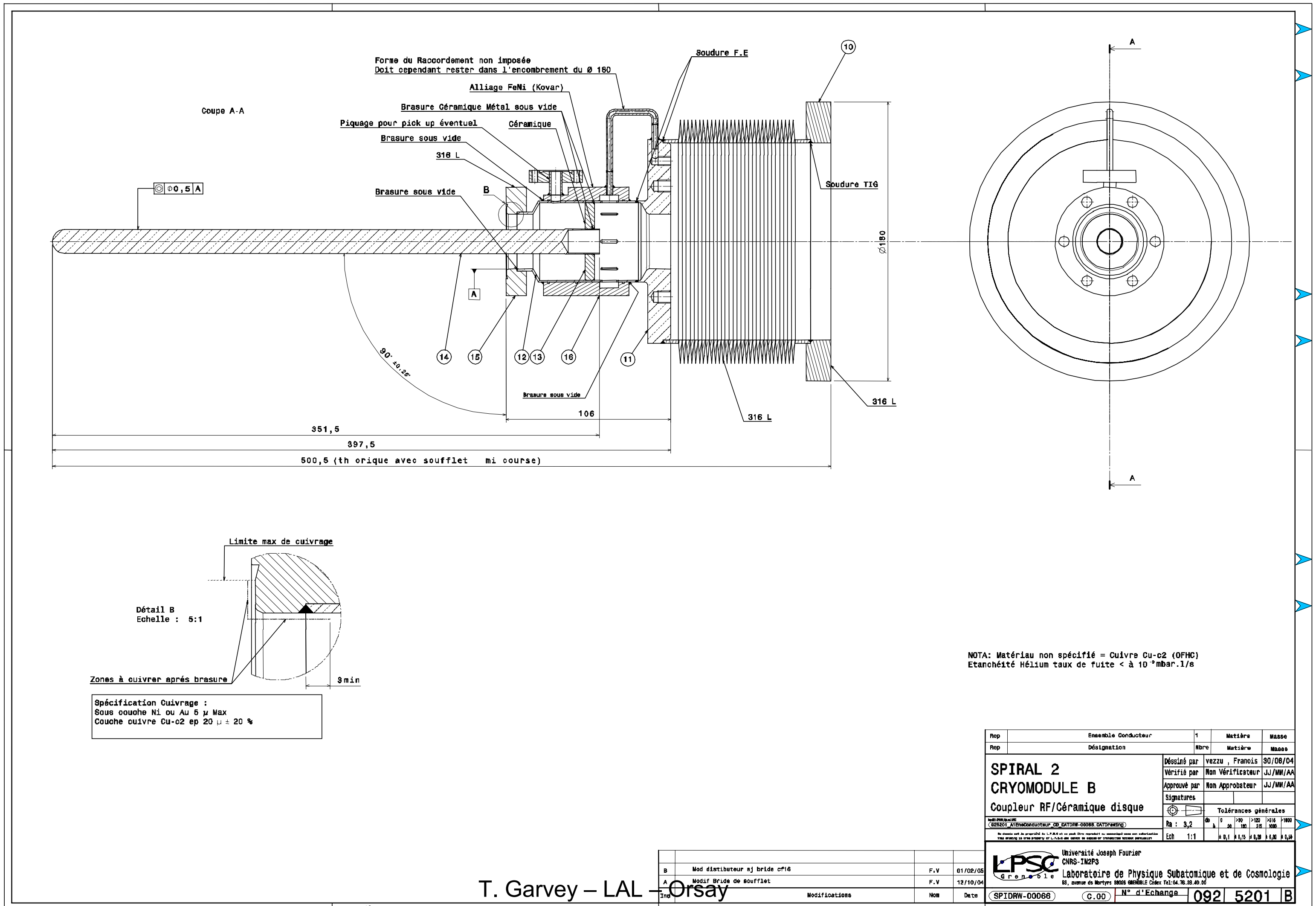
	Transmitted power 0 kW (W)	Transmitted power 20 kW (W)
Liaison 4.2 k (1)	0.66	1.1
Liaison 70 k	7.0	8.3
Cavity (2)	0.1	0.2

SPIRAL-II Design Performance

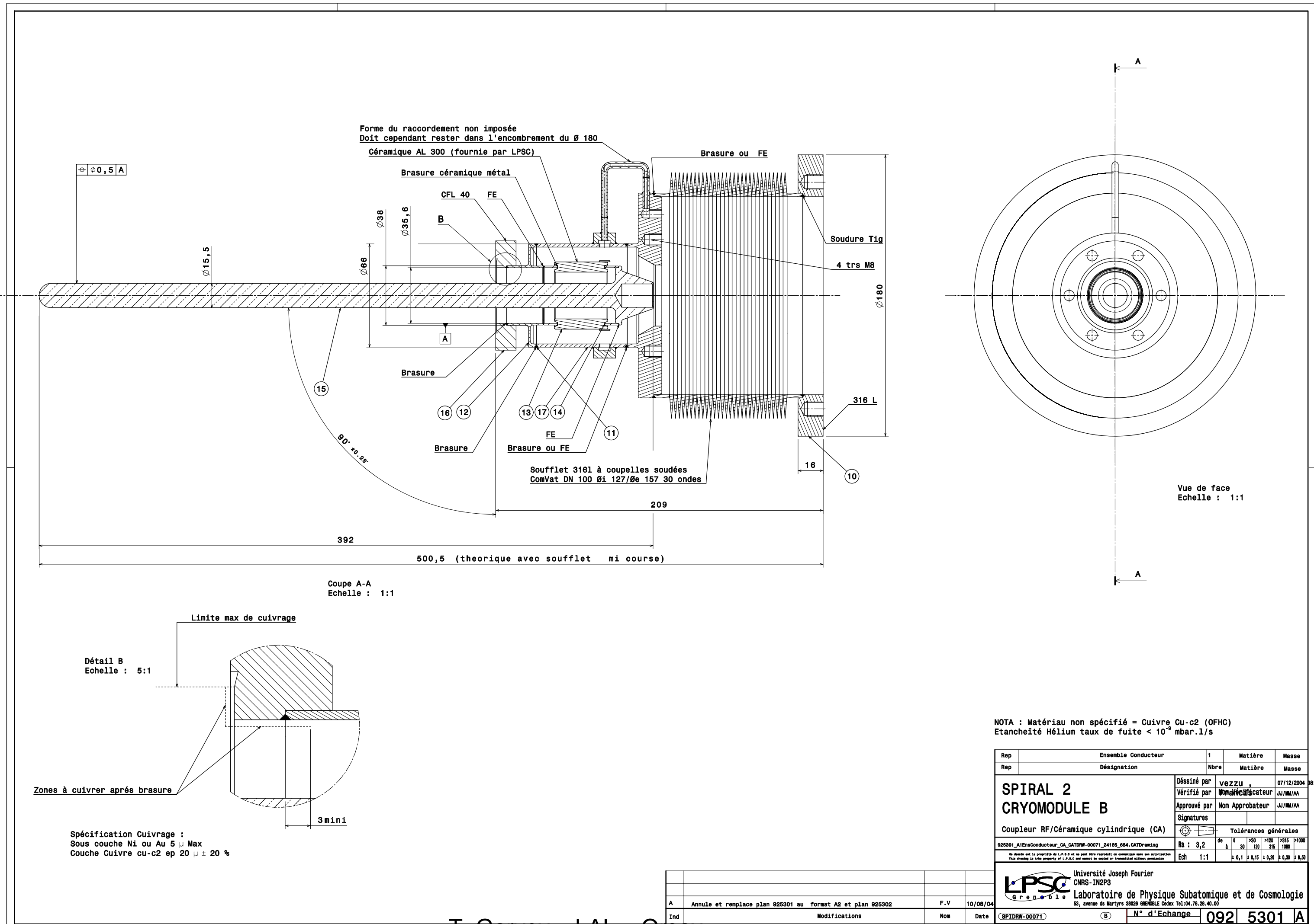
Temperatures for 0 et 20 kW transmitted power.

	Transmitted power (kW)	Temperature at the antenna tip (K)	Maximum temperature within the ceramic (K)	Minimum temperature within the ceramic (K)
Cylindrical ceramic	0	288	288	286
	20	345	324	309
Disk ceramic	0	288	288	287
	20	340	315	305

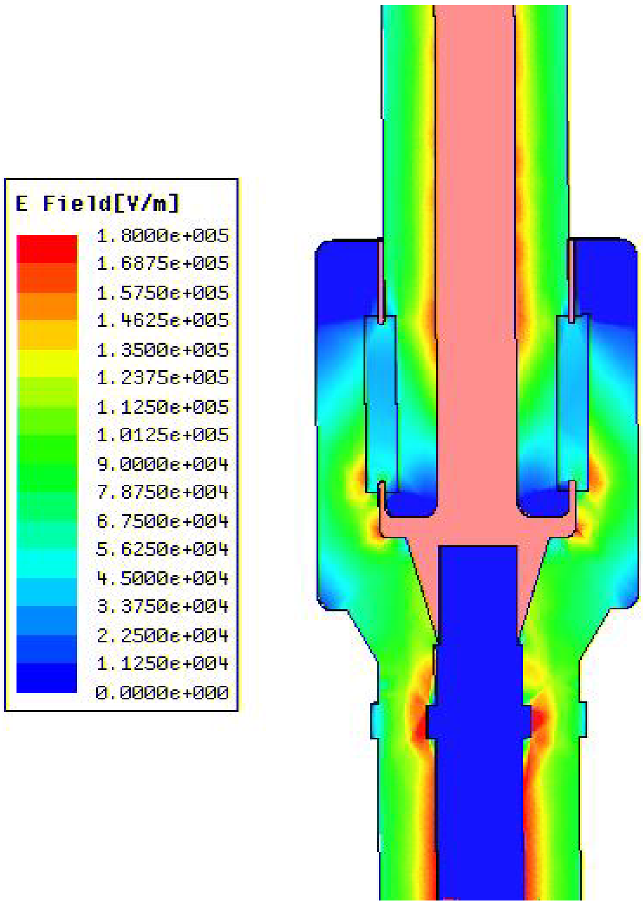
Ceramic disk window

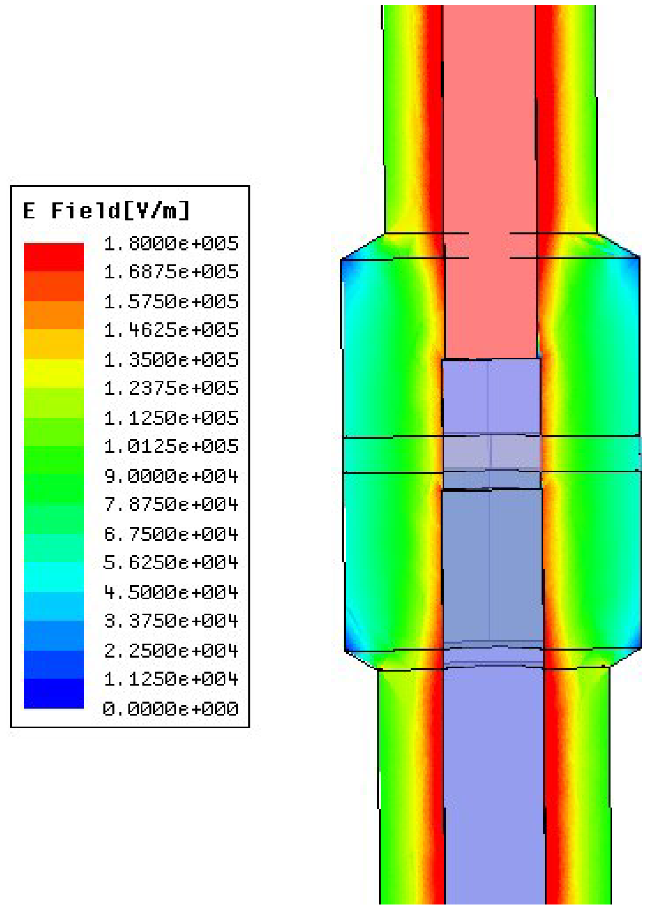


Cylindrical ceramic window



Fields in the Couplers



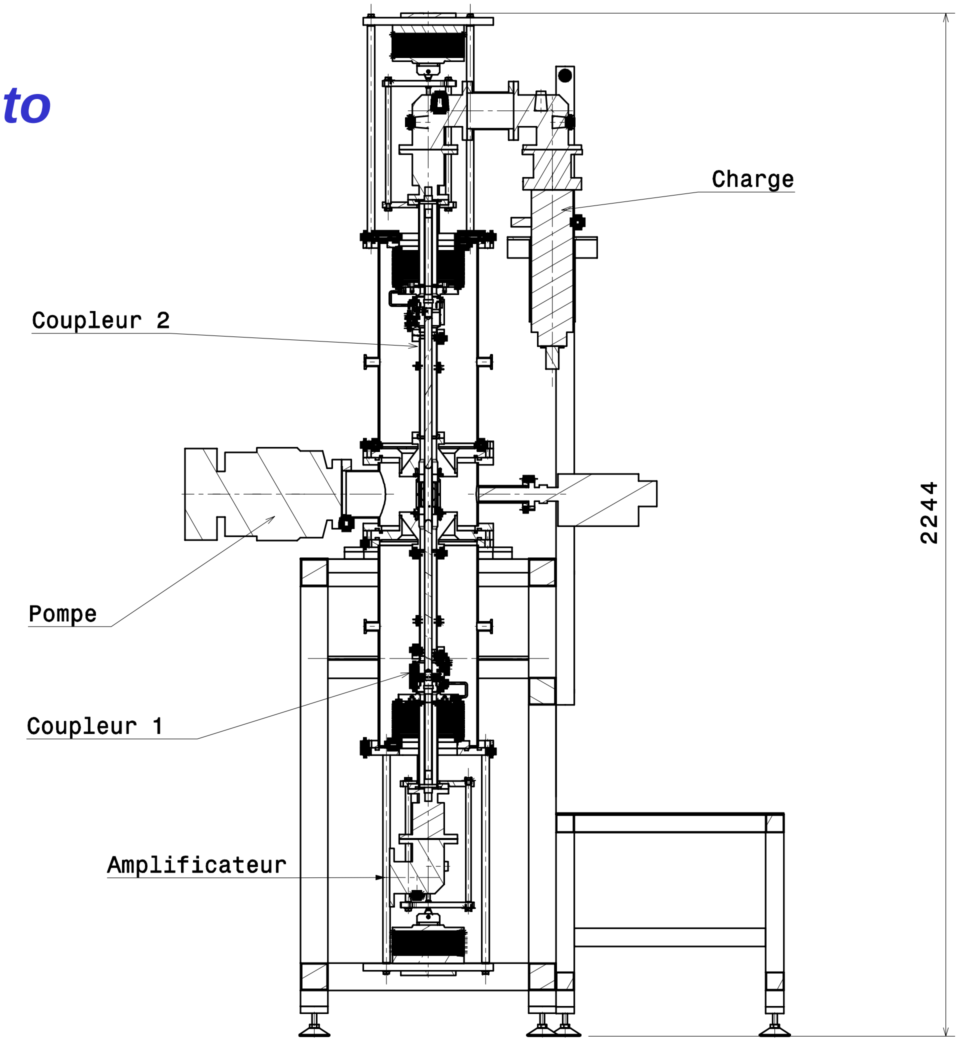


Input power - 20 kW

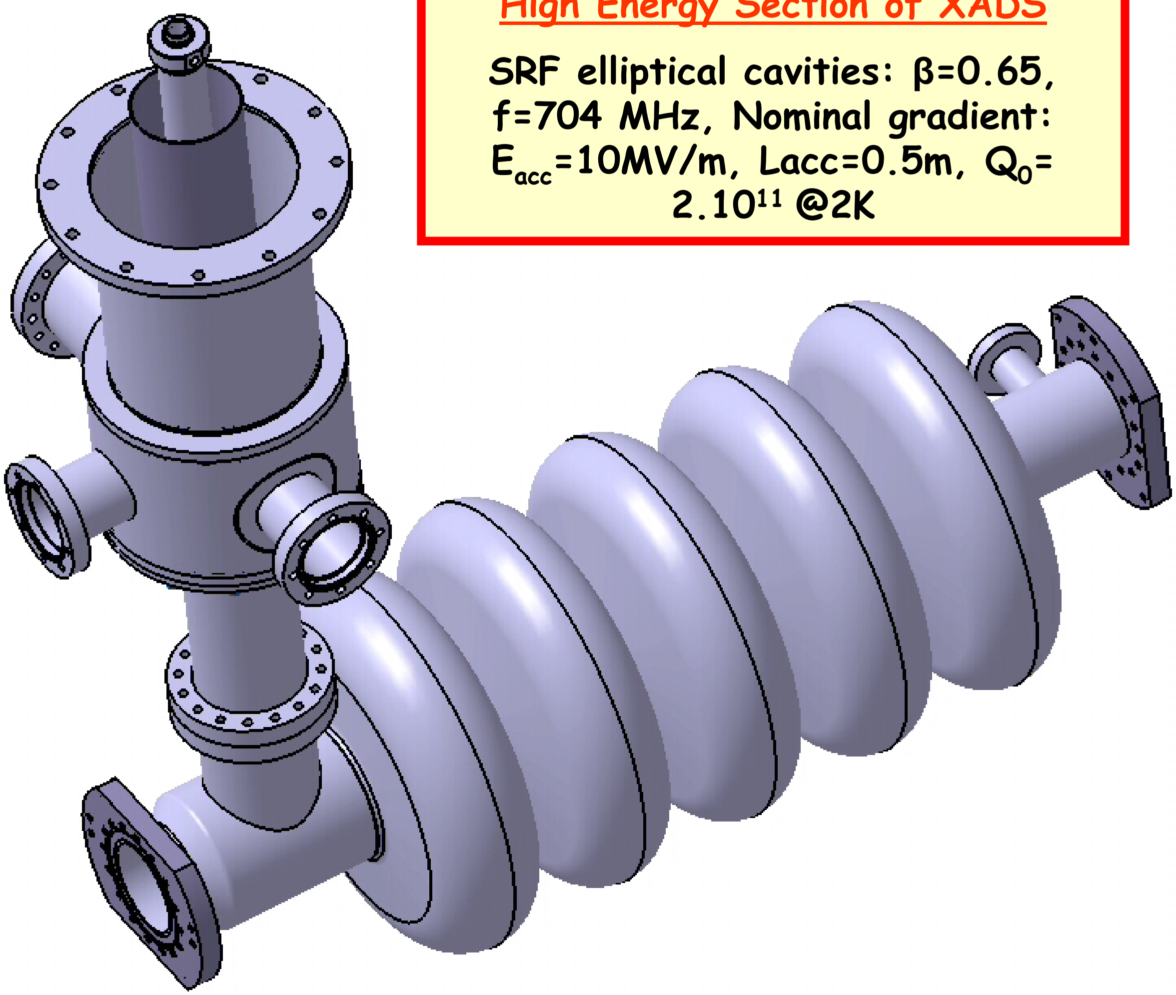
LPSC (Grenoble) windows

TEST BENCH

Couplers tested in pairs into 50 kW load.



Power coupler development for the high energy section of high power proton LINAC (IPNO / CEA Saclay)



High Energy Section of XADS

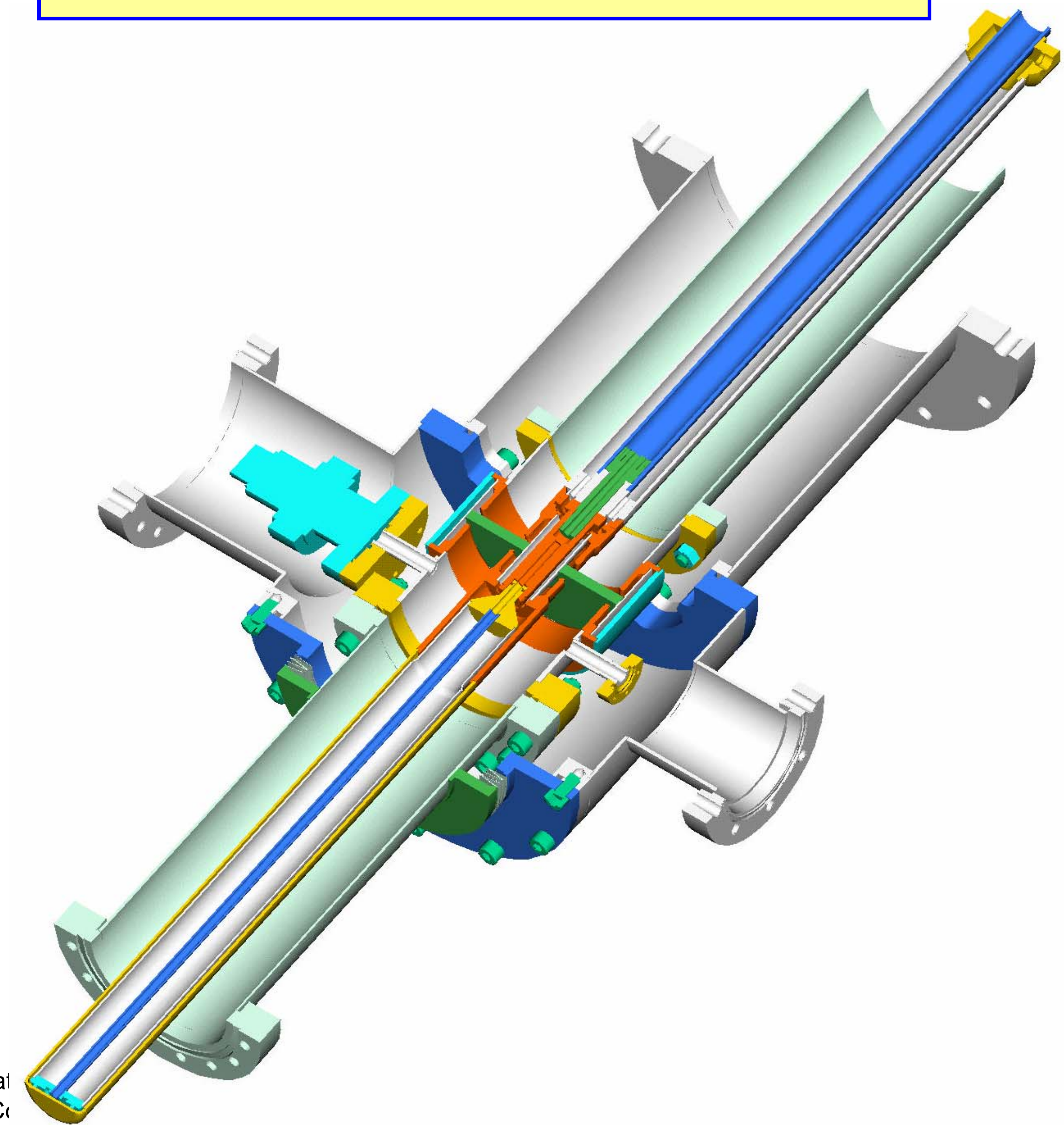
SRF elliptical cavities: β=0.65, f=704 MHz, Nominal gradient: E_{acc}=10MV/m, Lacc=0.5m, Q_0= 2.10^{11} @2K

Characteristics

Frequency (MHz)	**704**
RF Power (kW)	**150(CW)**
Impedance (Ω)	**50**
External conductor **Inner Diameter (mm)** **Wall Thickness (mm)**	**Cu/S.S** **100** **2**
Inner Conductor	**Φ43 OFHC copper**

Overview of power coupler components

2 Windows built by TOSHIBA



__Calculated Average RF losses (Joule Heating)__

-Inner conductor (IC) :

PCI= 65 W (TW mode)

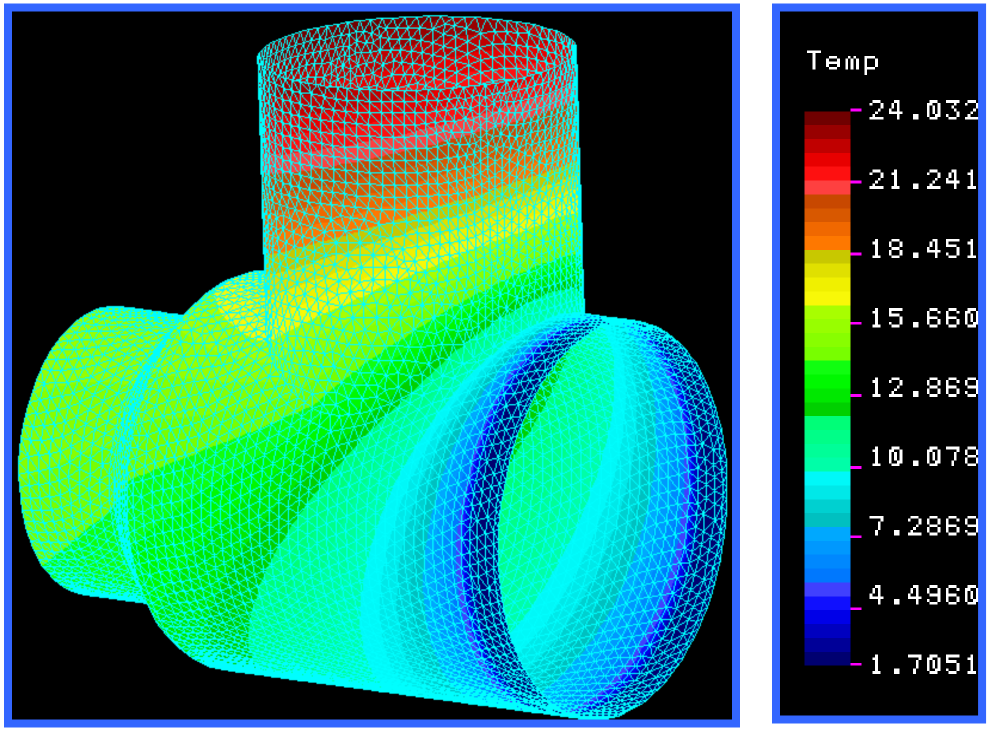
and 256 W (SW mode)

-Outer conductor (OC):

PCX= 23 W (TW mode)

and 92W (SW mode)

Thermal Modeling using Finite Element Thermal Analysis COSMOS/M GEOSTAR



2 cooling circuits to remove RF Joule Losses

Beam Tube Temperature Distribution for a Residual Heat Load PH = 8.5W

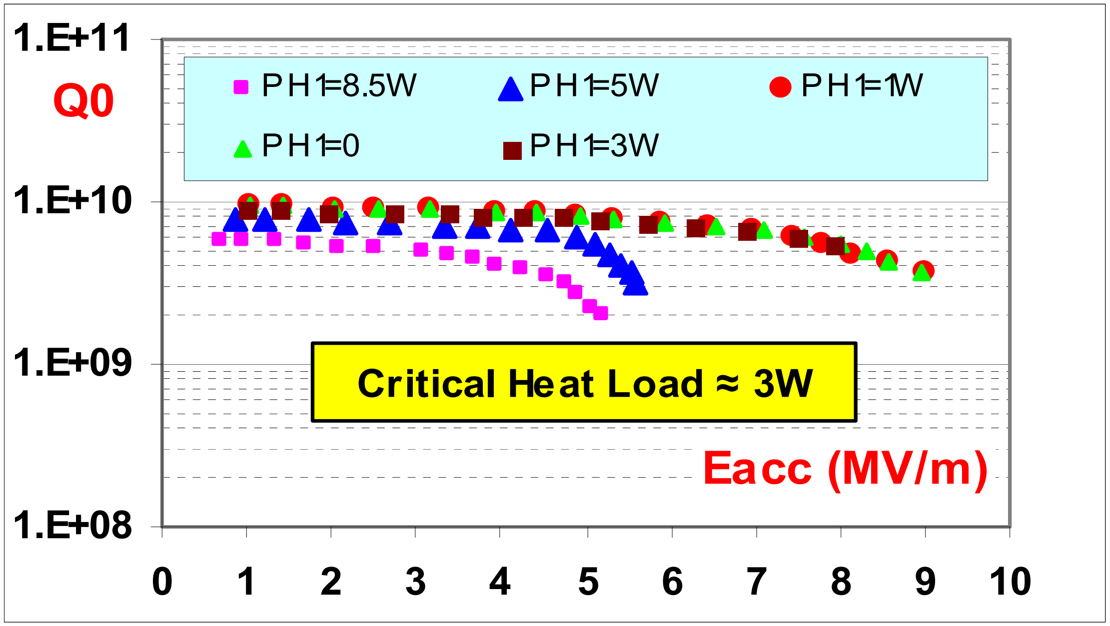
1) **Water circulation at 288K in annular space around the IC**

2) **Helium (5 K- 250 K) through a copper coil brazed around the OC**

Recent experimental results

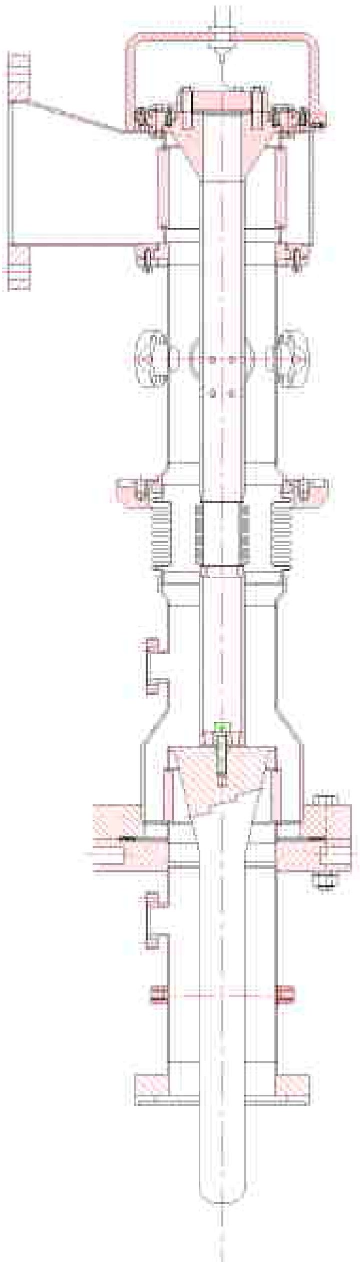
Critical heat load on 704 MHz SRF cavity

(CRYHOLAB Measurements March 2005)



Posters ThP53: Mehdi SOULI

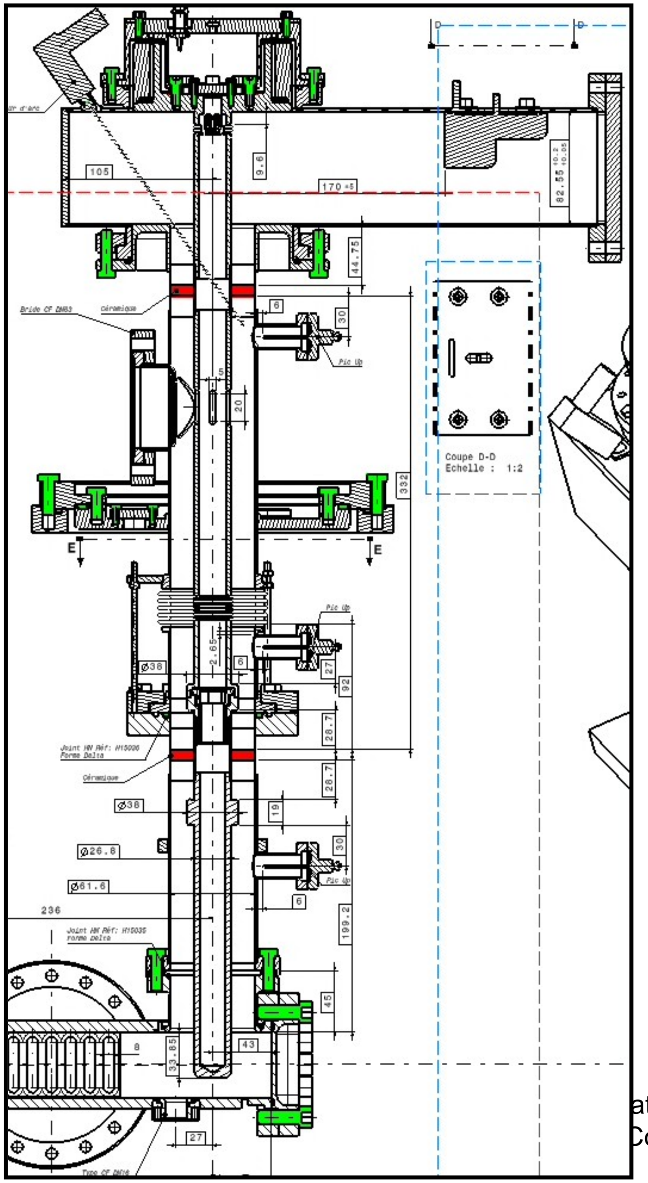
Study of Thermal Interaction Between a CW 150 kW Power Coupler and a Superconducting 700 MHz Elliptical Cavity



TTF-V Proto-type

- Essentially = TTF-III “warm” part + 62 mm ϕ “cold” part.
- Larger diameter – transmit more power, push multipactor levels to higher power
- Candidate coupler for a two x 9 cell TESLA/ILC cavity
- Engineering drawings and technical specifications completed.
- Four such couplers will be built in 2005 (by ACCEL) for high power tests in early 2006.
- Will be subsequently used for studies on RF conditioning times.

TW60 Coupler Proto-type



Radically different from TTF-III coupler,
uses “thin” planar ceramic windows.

Easy to braze, low dielectric loss.

Insensitive to multipactor

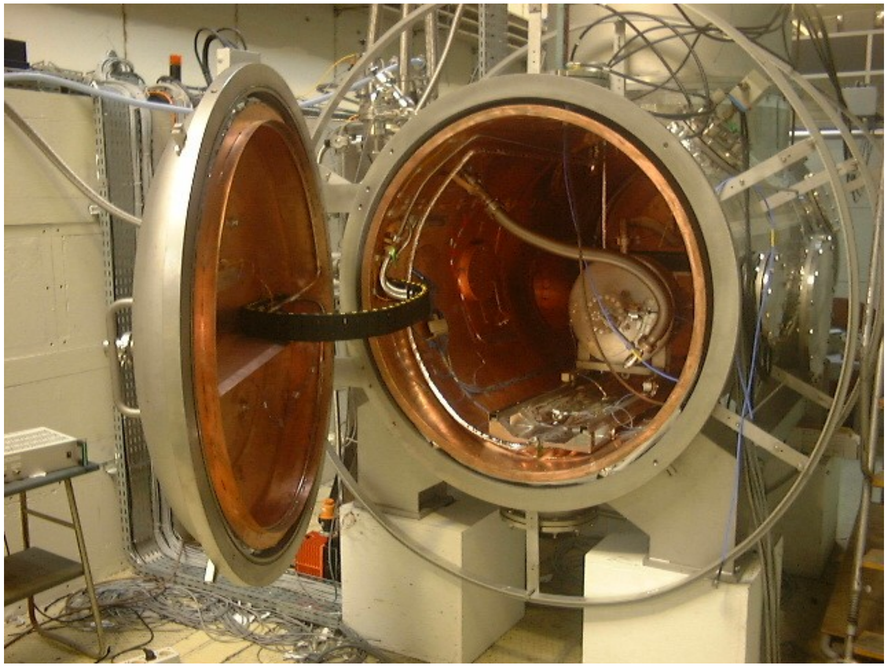
Warm transition is matched with reduced-height wave-guide → standing wave.

“Line of sight to cavity”

Cold window matched with reactive impedance elements on inner co-ax.

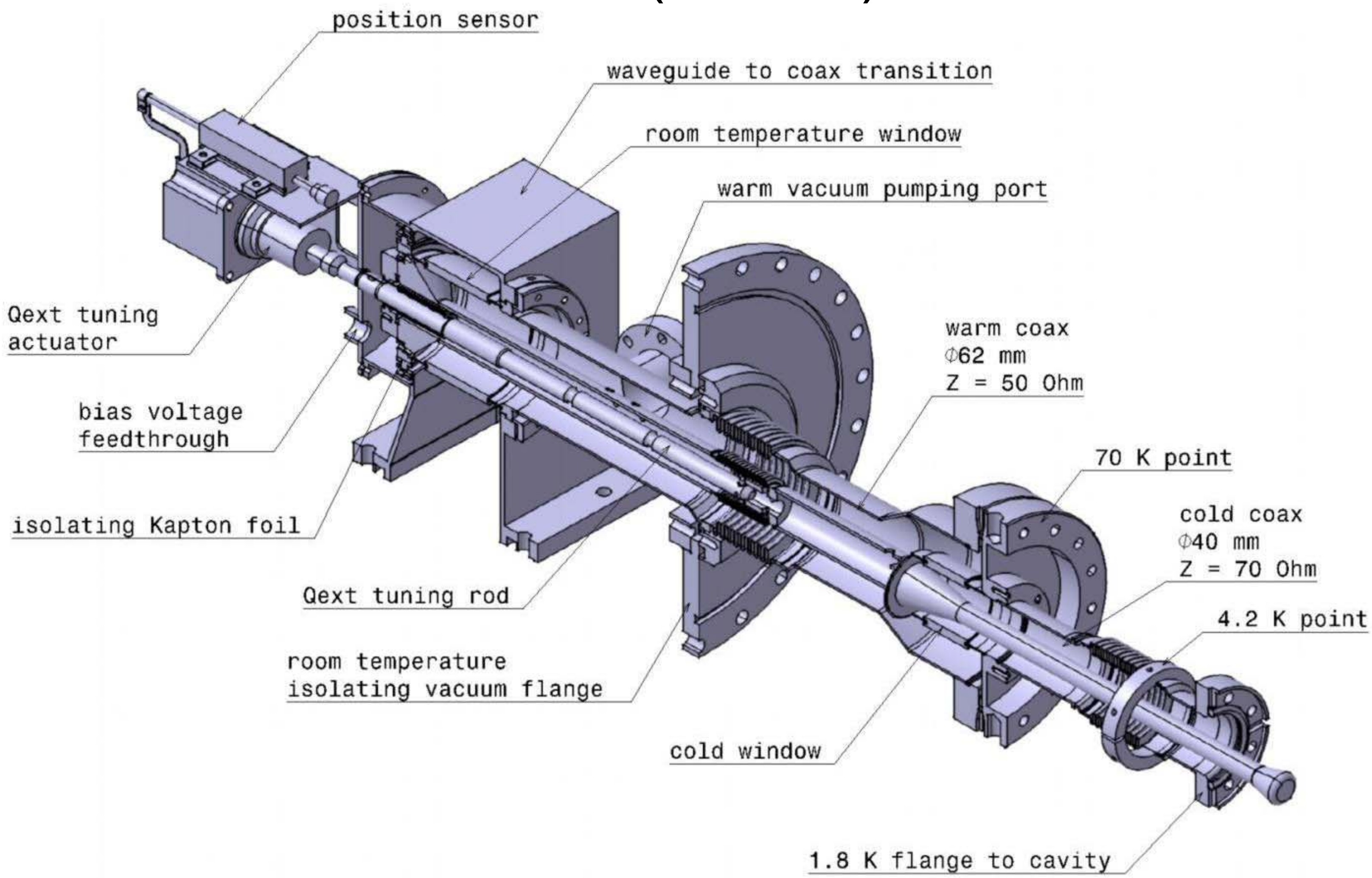
Low power measurements already performed. High power tests planned for 2006 on four proto-types to be built by ACCEL.

Cold tests using CryHoLab



- Cryostat – Built by IPN - Orsay
- Installed at CEA-Saclay to benefit from existing cryogenic infra-structure

Schematic of modified TTF-III coupler for X-FEL industrialisation studies (S. Prat).



Closing remarks

- Power couplers remain one of the major challenges of SC RF.
- However, recent designs appear to meet technical requirements (e.g. SNS, TTF-III).
- Extensive use of codes (mechanical, thermal, RF, multipactor) are crucial for success.
- Much remains to be understood about conditioning.
- Cost still an issue for projects requiring very large numbers of couplers (X-FEL, ILC).
  - *Industrialisation !!*

Acknowledgments

I should like to thank the following people who provided me with information on the coupler projects with which they are associated –

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And thank you all for your attention !