Experience in the design of fundamental couplers.

S. Kazakov

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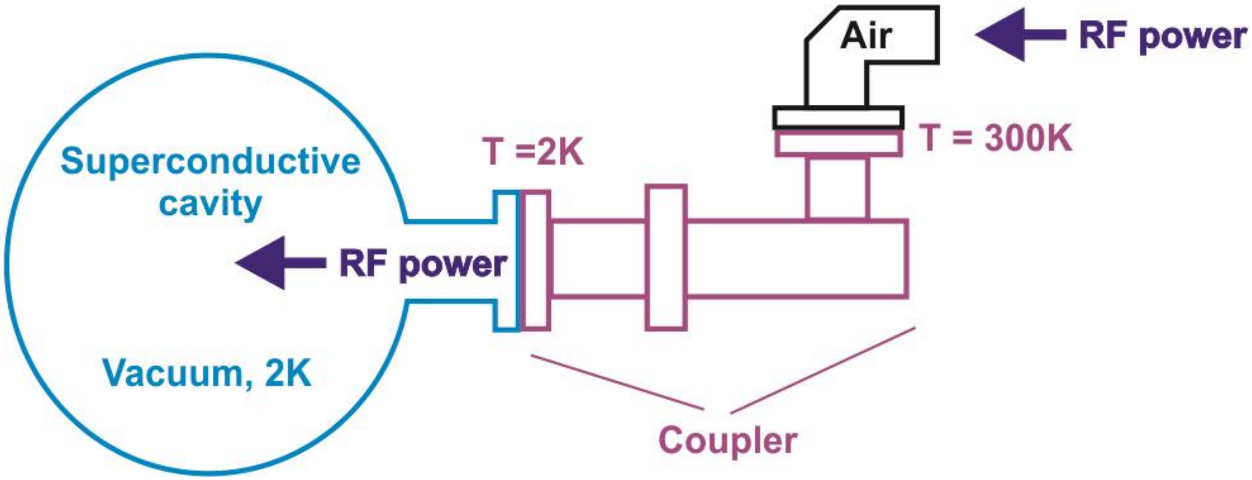
What is the main coupler of superconducting cavity and what is its purpose?

The coupler is device between RF source and superconductive cavity.
One side of coupler is connected to RF source at room temperature and atmospheric pressure. Another side of coupler is connected to cavity at temperature ~ 0K (typically 2K-4K) and vacuum.



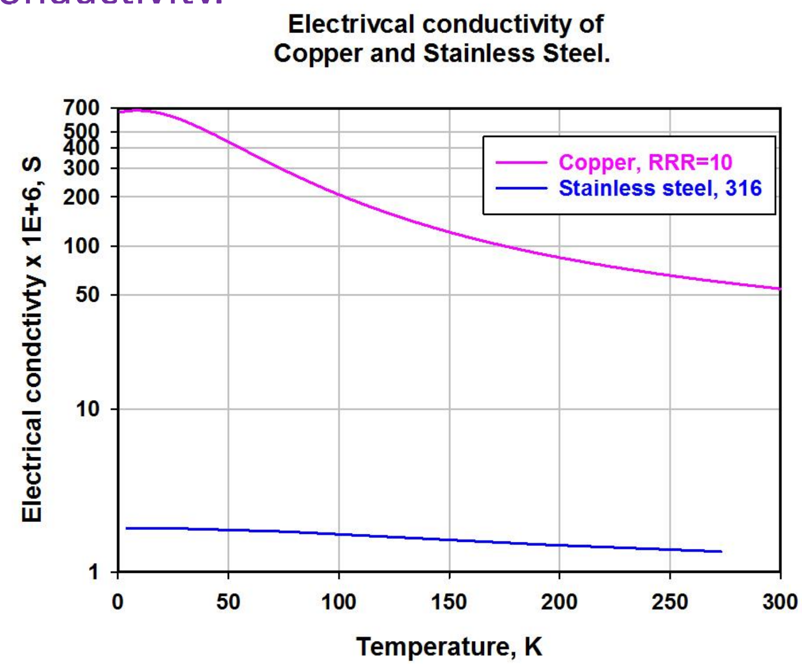
Purpose of coupler is very simple: is to delivery RF power from RF sources into superconductive cavity.

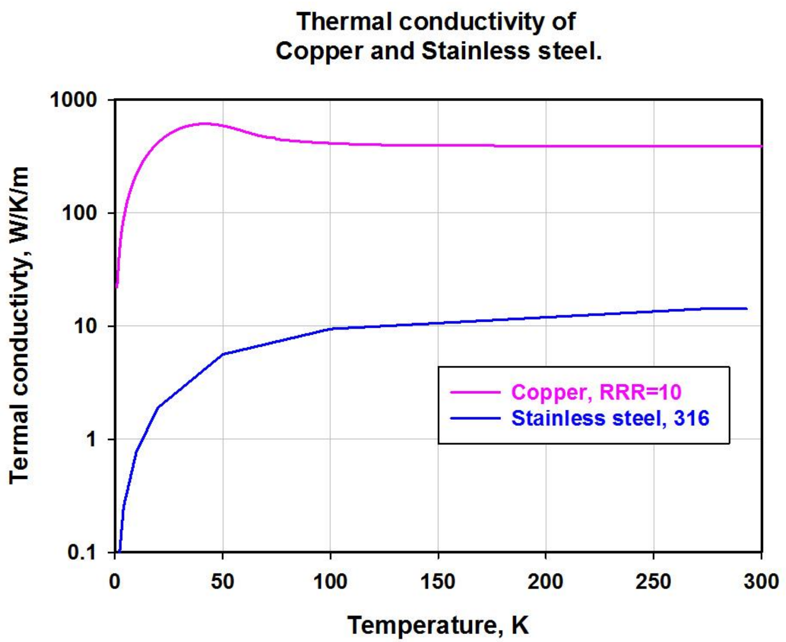
In spite of tis very simple purpose the coupler of the most critical and complicated device of superconducting accelerator. Why so?

This is because the requirements for a coupler are contradictory.

Coupler has to transmute RF power into a cavity with minimum RF losses and not transmit a heat from room temperature to cold cavity to keep cavity in superconductive state.

But the less an electrical losses of material the higher a thermal conductivity. Reducing an electrical loss we increase the thermal loading of cavity by heat flow from room temperature environment and vice versa. Graph of copper and SS electrical conductivity.





Thermal conductivity of SS is about hundred time less then t. conductivity of copper (at 50 K), but electric conductivity is about two hundred time less as well.

To reduce the thermal heat flow from room temperature the walls of coupler have to be as thin as possible. Reducing a wall thickness we reduce a mechanical strength of coupler.

Coupler should be short enough to fit into cryomodule and should be long enough to have high thermal resistance.

Coupler has to transmit RF power with minimum losses and isolate vacuum of cavity from atmosphere. So we need to use material which is transparent for RF and vacuum tight. Typically it is alumna ceramics (Al_2O_3). Ceramics has to be reliably joined with metal environment (brazed). The purer the ceramics, the lower RF the losses. The purer the ceramics, the harder it is to braze.

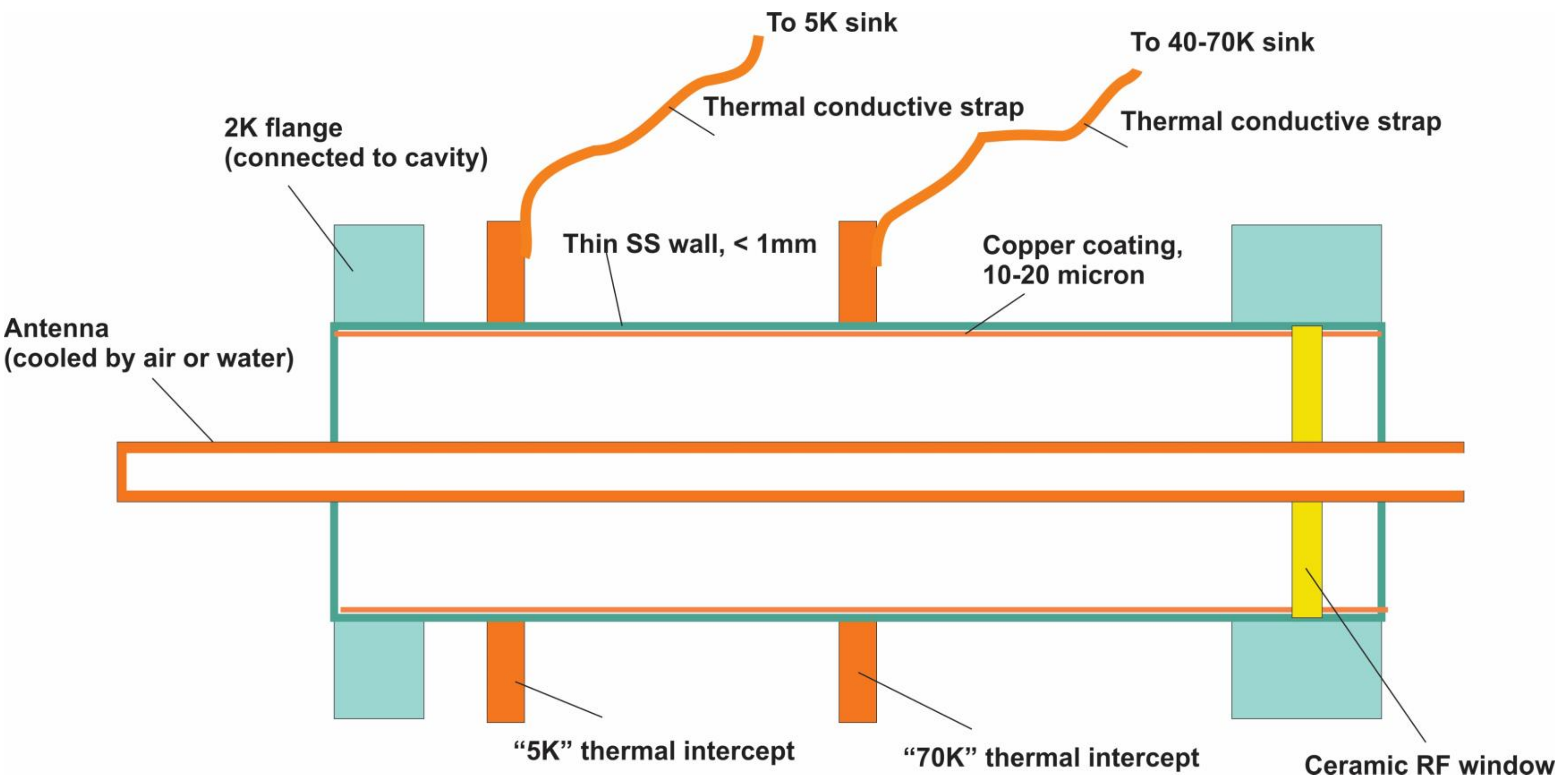
During cool down and warming up the parts of coupler (and cavity) change the sizes. Coupler has to include bellows which changes sizes and isolate cavity or cryomodule vacuum form atmosphere.

Superconductive cavity is sensitive to magnetic field. Coupler has to made of non-magnetic material.

Etc. , etc.

Coupler design is finding compromises.

Typical solution for coaxial coupler, vacuum part:



Thickness of SS wall should be as thin as possible (but enough for mechanical strength) to reduce a heat flow from room temperature to superconductive cavity (typically < 1mm).
Thickness of copper plating should be a thin as possible for the same reason, typically ~10 ~20 microns – several skin depth.
Ceramic diameter (depend on frequency and power) ~ 40 ~ 200mm.

Why we need thermal intercepts?

Cryo-plant efficiency drops rapidly at low temperature:
at 70 efficiency ~ 5%, at 5K ~ 0.5%, at 2K ~ 0.1%

To accommodate 1W of heat power at 70K a cryo-plant spends ~ 20W.
To accommodate 1W of heat power at 5K a cryo-plant spends ~ 200W.
To accommodate 1W of heat power at 2K a cryo-plant spends ~ 1000W.

Heat flow from room temperature to cryogenic temperature(s) without RF power we call "static cryo-loading".

Coupler without thermal intercept will have very high static cryogenic loading at 2K-4K. It will require a lot of power of cryo-plant and can cause probably a quench of superconductive cavity (cavity lost a superconductivity).

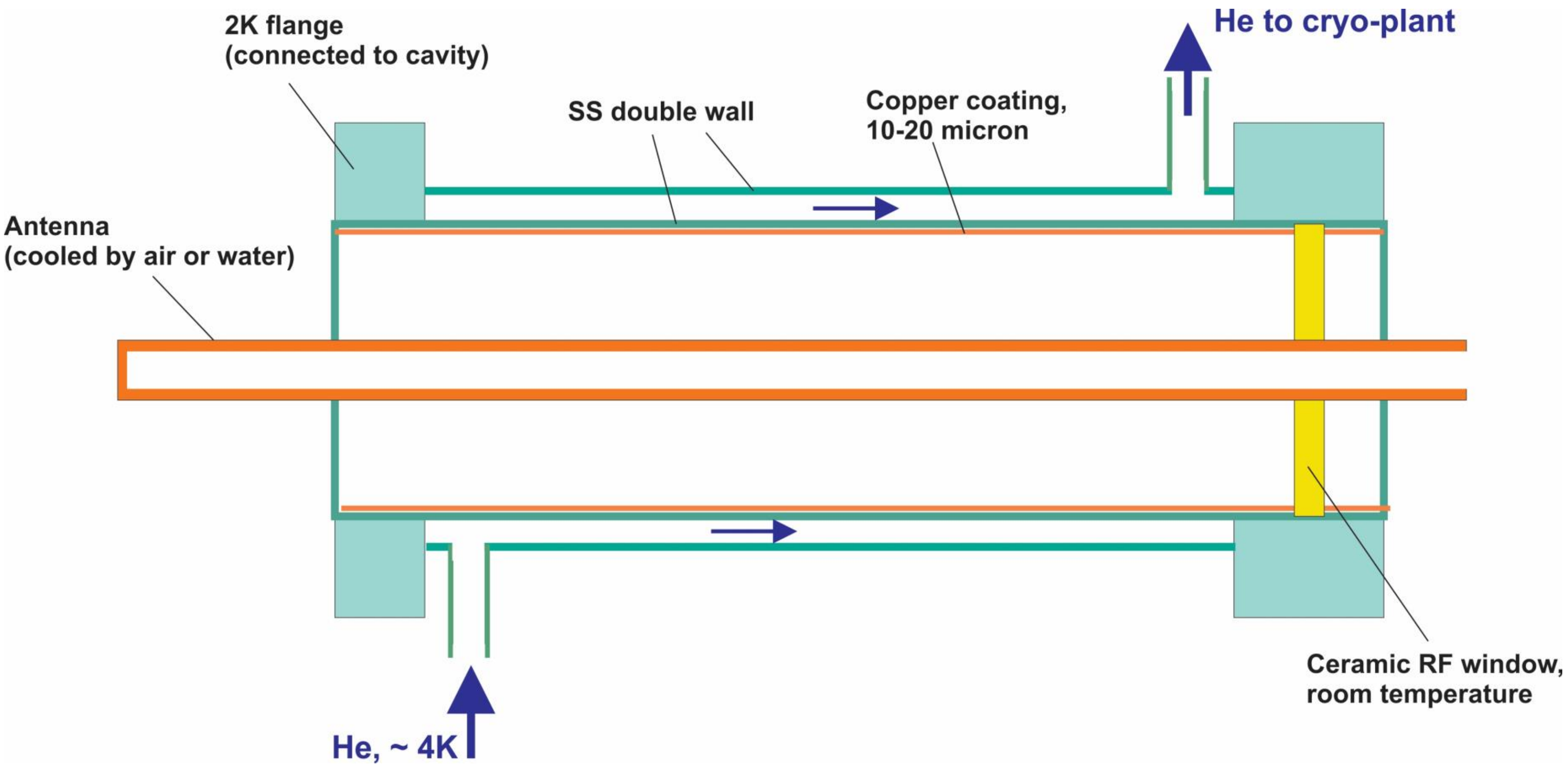
For example, our 325 MHz coupler, power of cryo-plant to compensate static loading

Without thermal intercepts	980 W
With "70K" thermal intercept	215 W
With "70K" and "5K" thermal intercepts	160 W

Thermal intercepts reduce the necessary power of cryo-plant ~ 6 times.

Position of thermal intercepts must be optimized.

Another possible solution is double wall outer conductor.



Advantages - simpler (?).
Disadvantages – efficiency is lower(?), double wall is thicker, no 70K intercept.

What impedance the coaxial coupler has to have?
Or how thick should be antenna?

Typically the people making the couplers with impedance ~ 50 ~75 Ohm (following to optimal impedance for cables).
But, we think, in case of couplers for superconductive cavity the higher impedance the better.
There two reasons: higher impedance means less current for the same power. If the diameter of outer conductor is fixed, the RF losses will be less in outer conductor and cryogenic loading (dynamic and total) will be less because only an outer conductor is connected to the cavity.

I – *wall current*, P_{rf} – *RF power*, Z – *coaxial impedance*,
P_{loss} – *power of losses in outer conductor wall*, R_w – *wall resistanse*,

$$I^2 = \frac{2 * P_{rf}}{Z}, \qquad P_{loss} = I^2 * \frac{R_w}{2}; \qquad \boldsymbol{P_{loss} \sim \frac{1}{Z}}$$

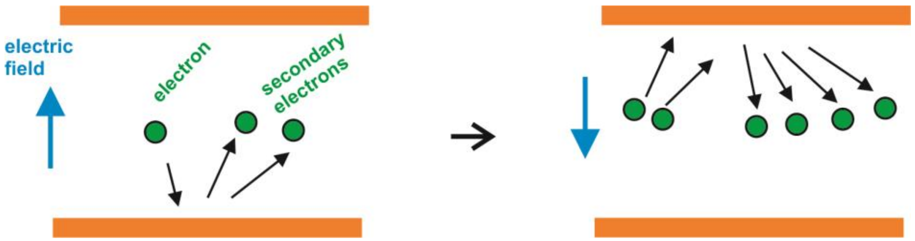
For example, the impedance of our couplers ~ 105 Ohm.

Losses in antenna will be higher, but antenna is not connected to cavity directly and can be cooled by air or water. Limitation of impedance increasing is a difficulty of antenna cooling.

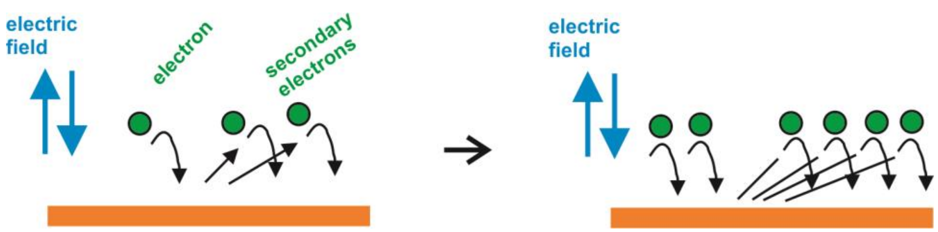
$$P_{ant} \sim \frac{1}{r_{ant} * ln\left(\frac{r_{out}}{r_{ant}}\right)}; \quad r_{ant} \text{ – radius of antenna}, r_{out} \text{ – radius of outer conductor}$$

Second reason to increase impedance: multipactor power threshold becomes higher.
What is multipactor? It is the scourge of God of vacuum electronic devices.

Multipactor is avalanche of electrons:



Two side multipactor



One side multipactor

When electron with energy ~0.05 ~1.5 kV hit a surface of materials, it knocks out a few secondary electrons (n>1). These electrons are accelerated by alternative electrical field and hit the same (one surface multipactor) or opposite side (two side multipactor). Electrons knock out more electrons and under some condition (combination of frequency, electromagnetic field strength, secondary electron yield (SEY), distance between surfaces) an electron avalanche (n>> 1) can be formed. Moving electrons (current) can absorb essential part of RF energy and heat surfaces and can destroy the device.

How to avoid a multipactor?

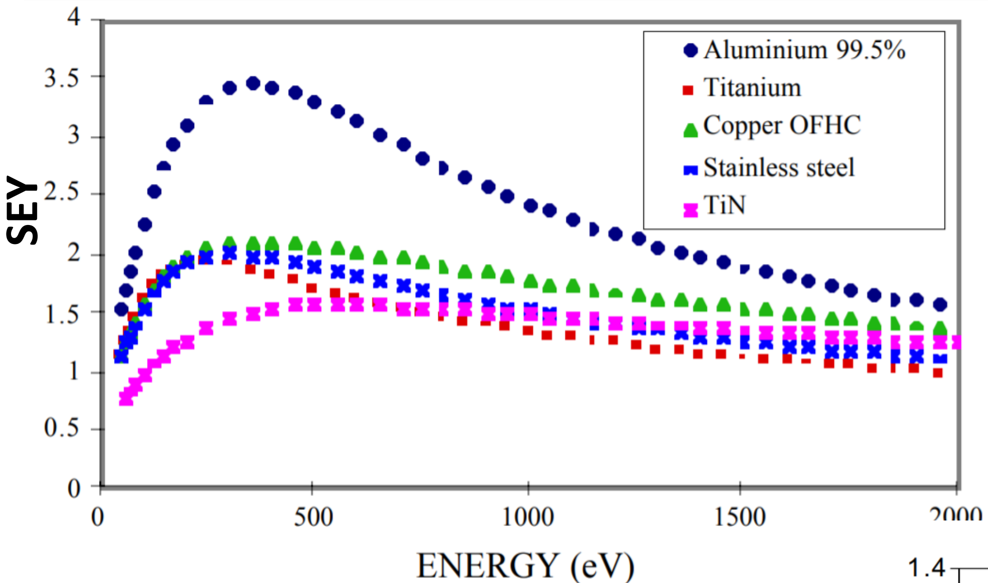
- Use materials with low SEY.
- Avoid multipactor conditions (combination of frequency, power and sizes)
- Destroy multipactor conditions by applying DC electric field (bias)

SEY of different materials:
Typically metals have SEY > 1 and dielectrics SEY >>1

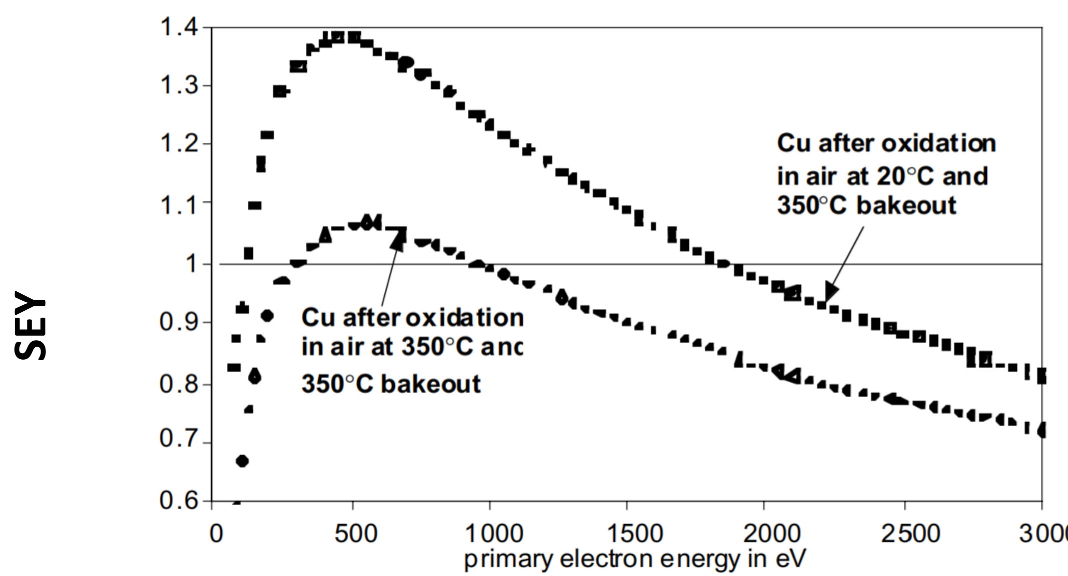
SEY depends on surface condition. Typically pure metal surface has less SEY then contaminated or oxidized surface. As result, multipactor can be conditioning. Election bombardment clean the surface and SYE gradually decrease. Finally multipactor can disappear. We call this procedure “conditioning”.

"THE SECONDARY ELECTRON YIELD OF TECHNICAL MATERIALS AND ITS VARIATION WITH SURFACE TREATMENTS" V. Baglin, J. Bojko1 , O. Gröbner, B. Henrist, N. Hilleret, C. Scheuerlein, M. Taborelli
CERN, Geneva, Switzerland

SEY of different materials



SEY oxidized and pure copper

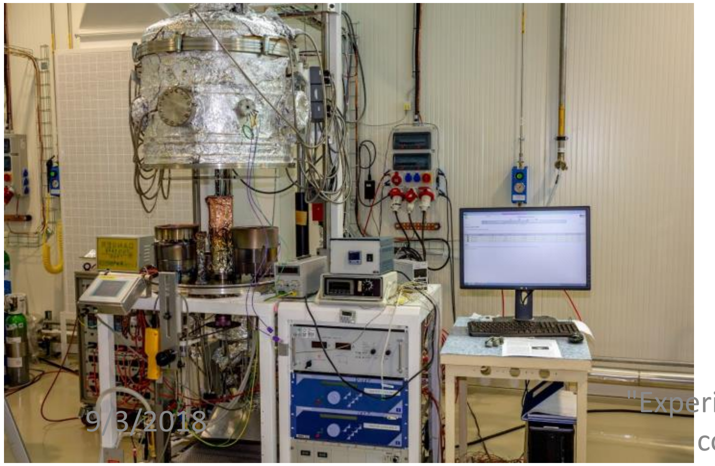


For successful conditioning it is important to have the surface clean as much as possible from the beginning. Baking before an operation helps much. It reduces number of molecules of residual gases and water on the surfaces.
We do 120C baking x 48 hours of cavity and couplers before operation.

The typical material for RF window is alumina ceramics (aluminum oxide). It is dielectric and has rather big SEY ~5 ~10. It makes a surface of ceramics the most probable place of multipactor. To avoid this the surface of ceramics is coated with materials with low SEY. The most commonly used material is Titanium nitride, TiN.
TiN is conductor and film on the ceramic must be rather thin, ~ 1 ~10nm to avoid additional RF losses on the ceramic surface.

CERN uses TiO_2 instead of TiN. Surface is coated by pure Ti in vacuum. Then surface is exposed to atmosphere and Ti is oxidized.

CERN facility for surfaces coating:



We prefer to using a different approach – our couplers works always under high voltage (HV) bias. HV bias suppresses multipactor at the ceramic surface and other parts of coupler.

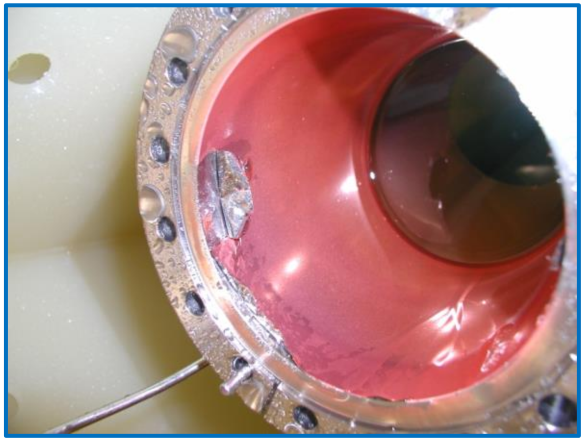
Advantages: technology is simpler, coupler is a bit less expensive. Coupler does not requers conditioning – coupler starts work immediately. The most important thing the strong bias suppress multipactor completely (according to simulations). Without bias a mulipator can be tiny and unrecognizable (it did not disappear completely after conditioning, for example). But during the years of operation it can contaminate the ceramics (evaporating materials from place of multipactoring) and reduce life time of coupler.

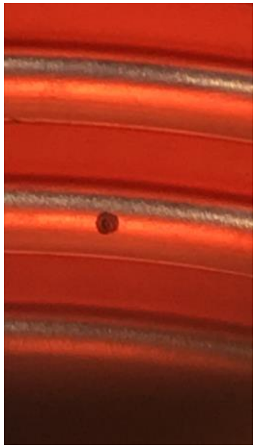
Disadvantage: coupler needs a fast interlock of high voltage bias. RF power must be switched off immediately if high voltage bias disappears for some reasons (failure of HV source, for example). Without HV bias a heavy multipactor can start and can destroy coupler.

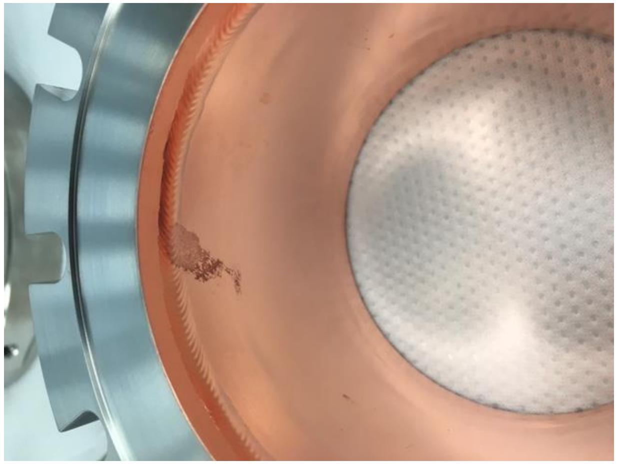
Copper plating of stainless steel.

Some parts of couplers (outer conductors, antenna, bellows…) are made of stainless steel. These parts must be coated with copper to make RF losses acceptable. Copper cplating is another pain of couplers production.
The requirements to copper coating in case of coupler for superconducting cavities are much more tougher then for room temperature device. Any copper flake dropped into a superconducting cavity from kills the cavity. Coating must be extremely reliable and strong.   Technology of coating still is needed to be developed and improved.

Examples of not successful coating:

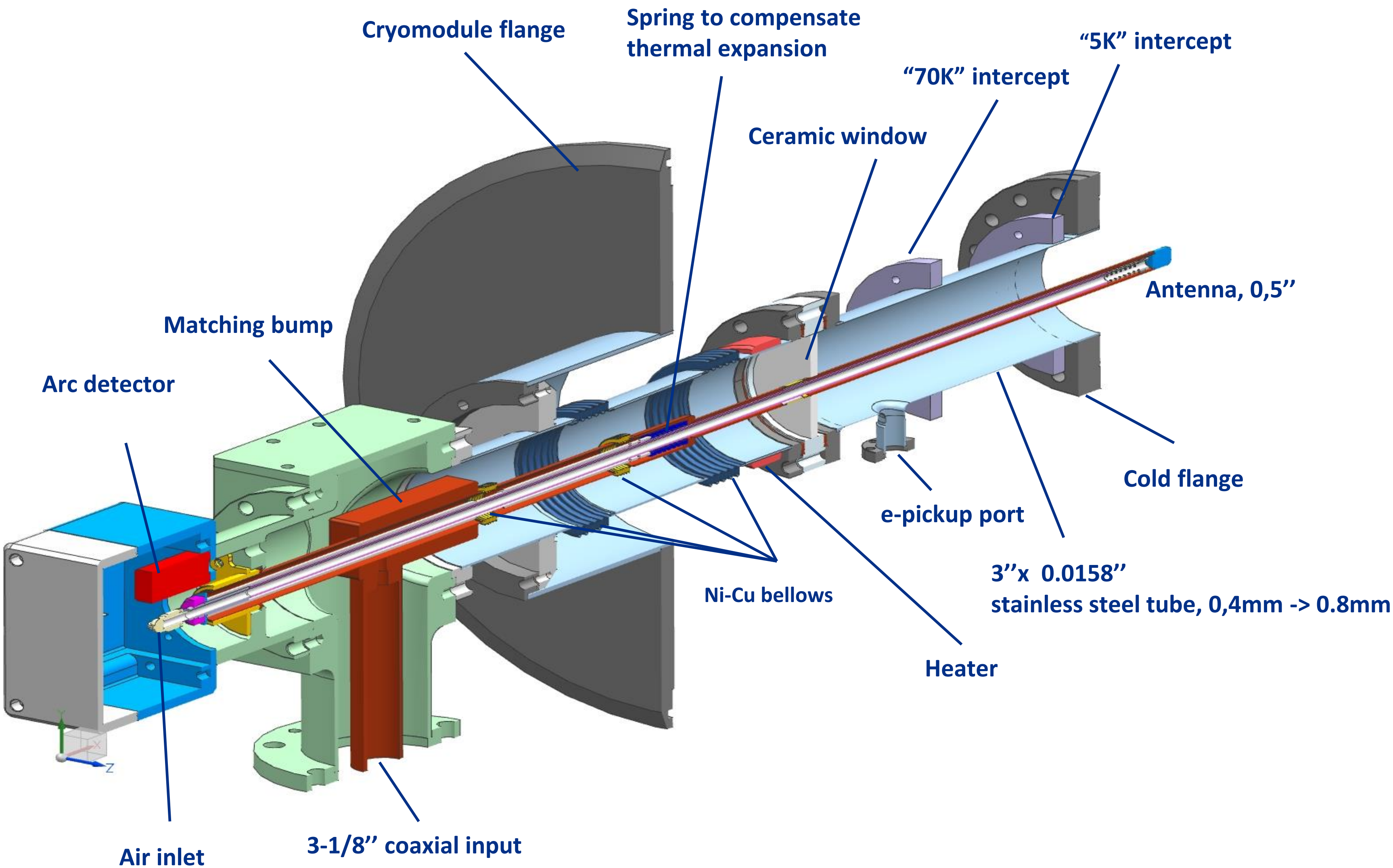




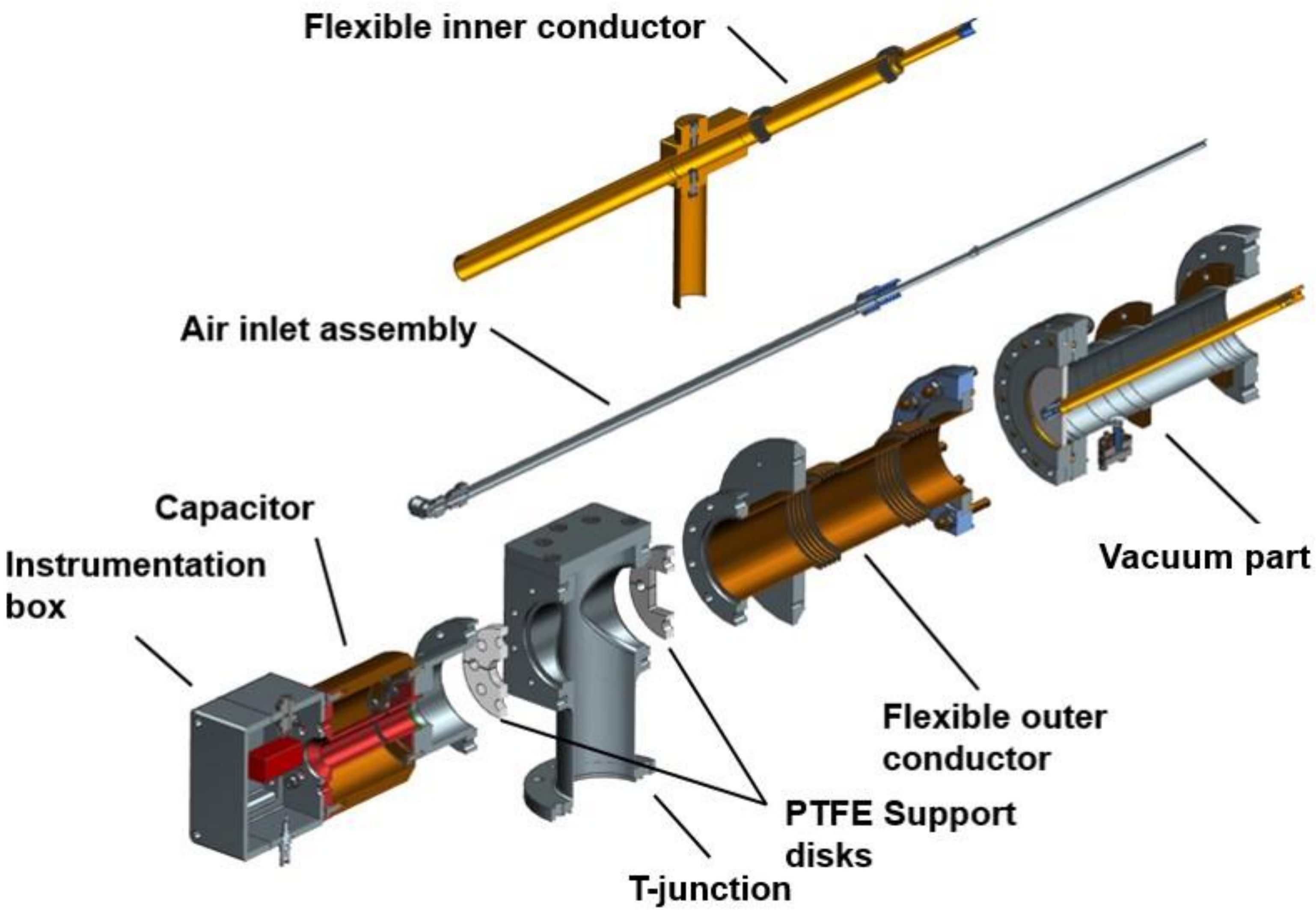


We are trying to avoid a copper coating as much as we can.
How we are doing this?

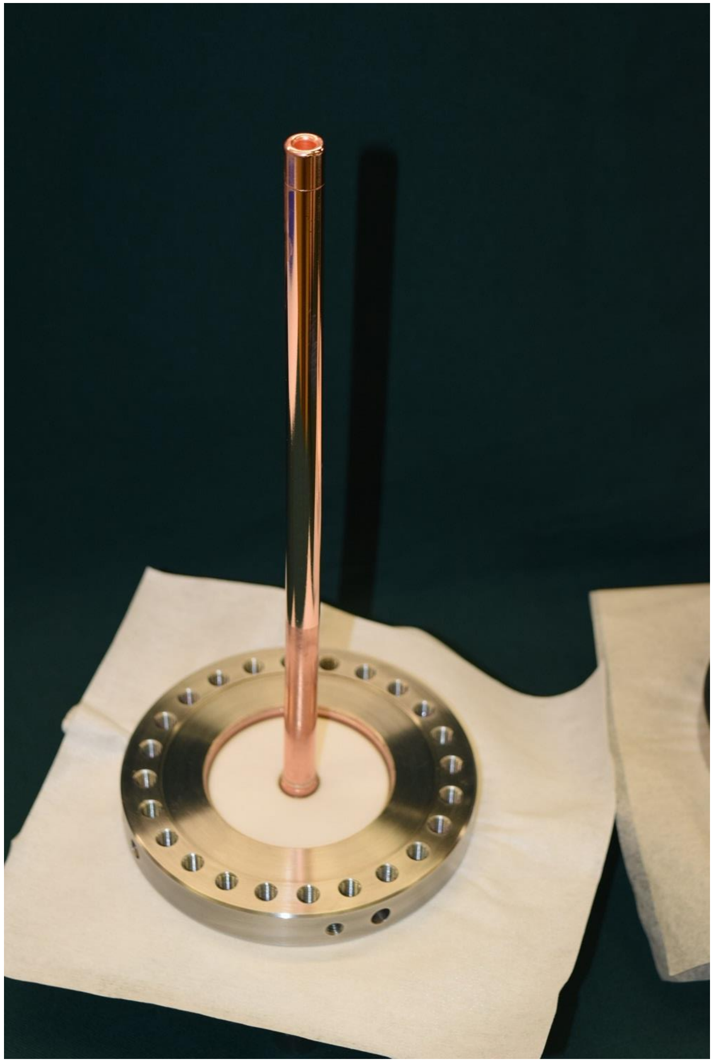
In case of moldered power and not to high frequency it is enough to increase the impedance of coaxial coupler. Example is our 325 MHz coupler for SSR1 and SSR2 cavities.

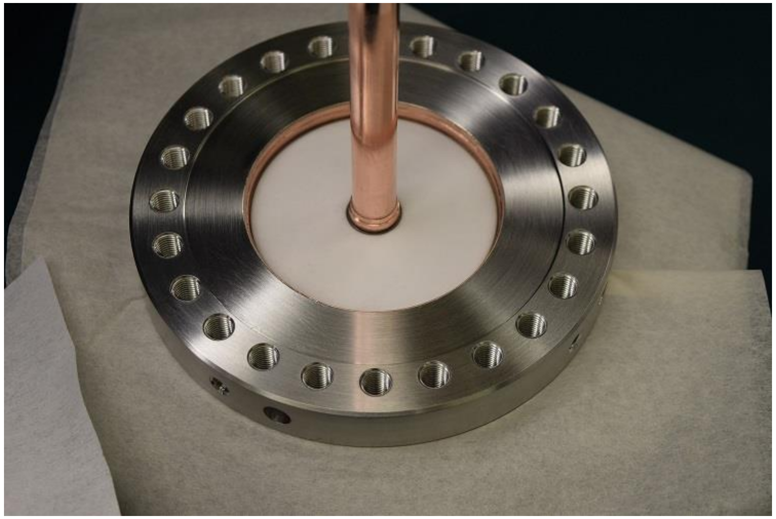


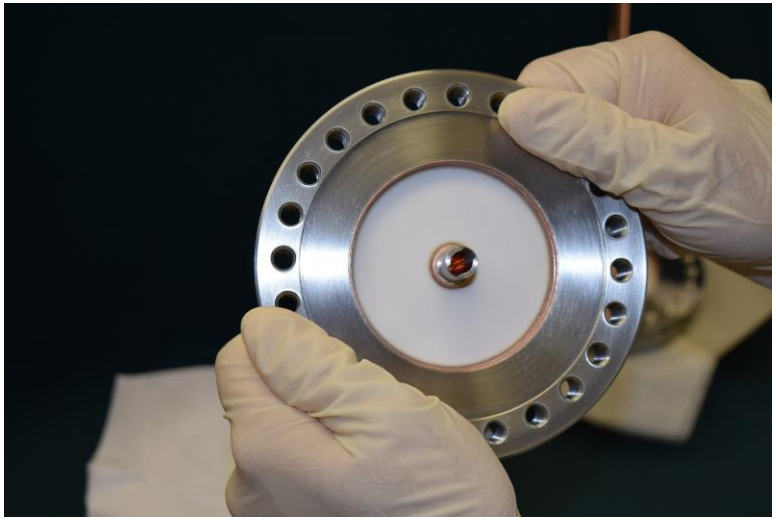
Exploded view of 325 MHz coupler



Antenna of 325 MHz coupler made by CPI

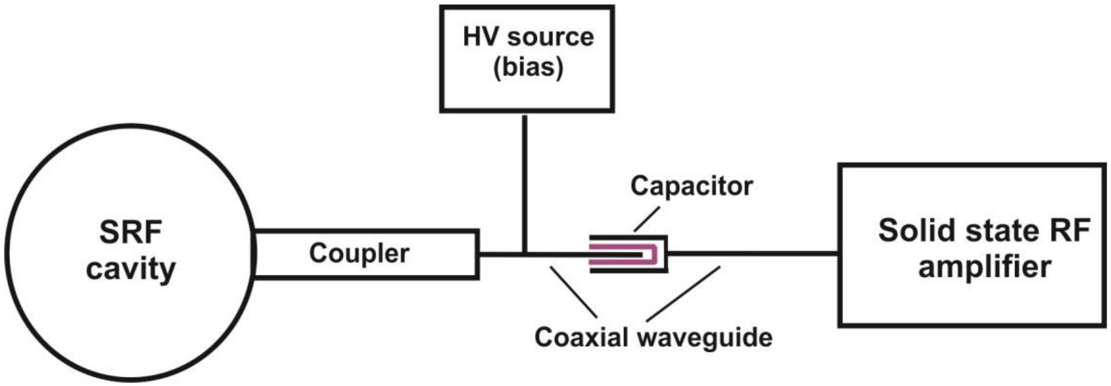




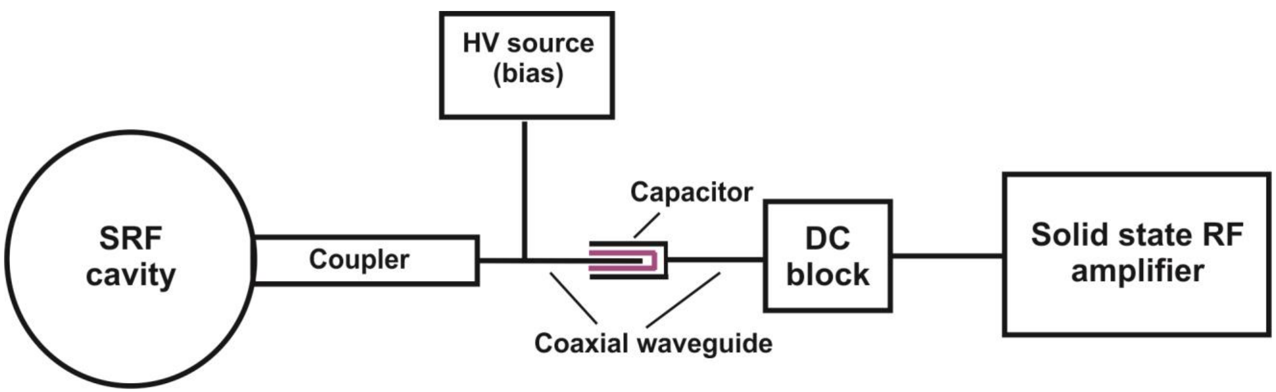


Antenna is electropolished to reduce a thermal radiation into the cavity.

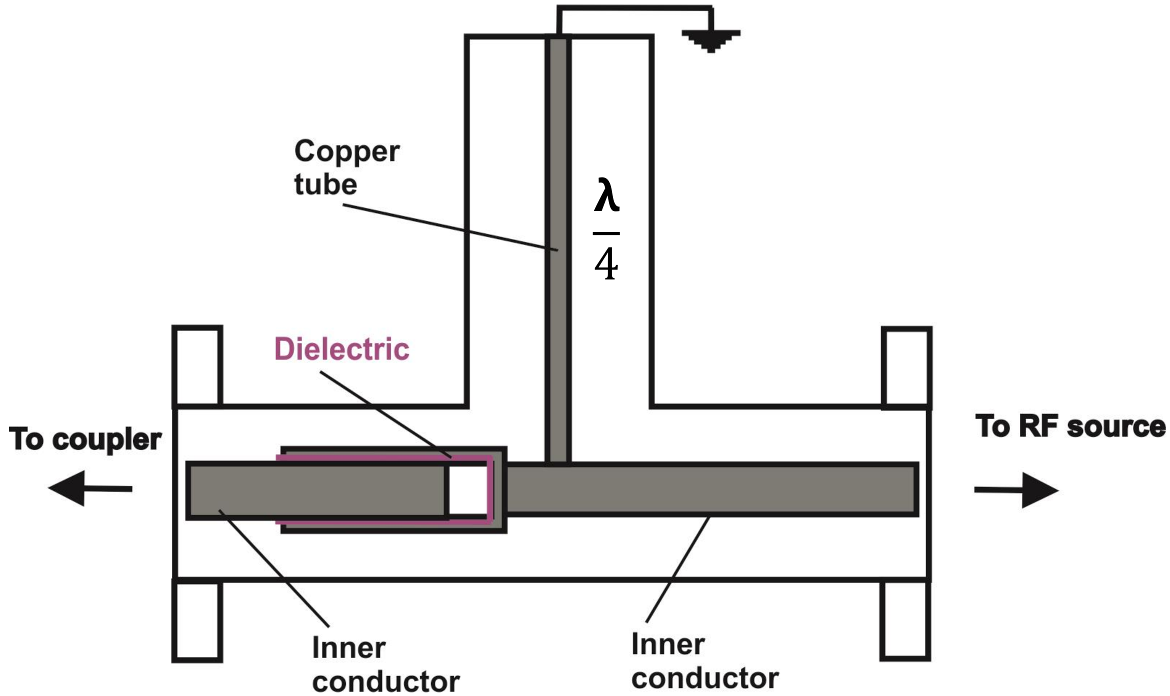
To apply HV bias to coupler antenna, we need to isolate RF source (solid state) from High Voltage (not to destroy an amplifier). Coupler and amplifier can be connected through capacitor, which is transparent for RF and isolate HV.



The problem of this scheme: If the capacity is broken, a high voltage will be applied to the amplifier and amplifier will be destroyed (very expensive device). Additional protection is needed. We use so called " DC block" (it blocks DC voltage and transmits RF).

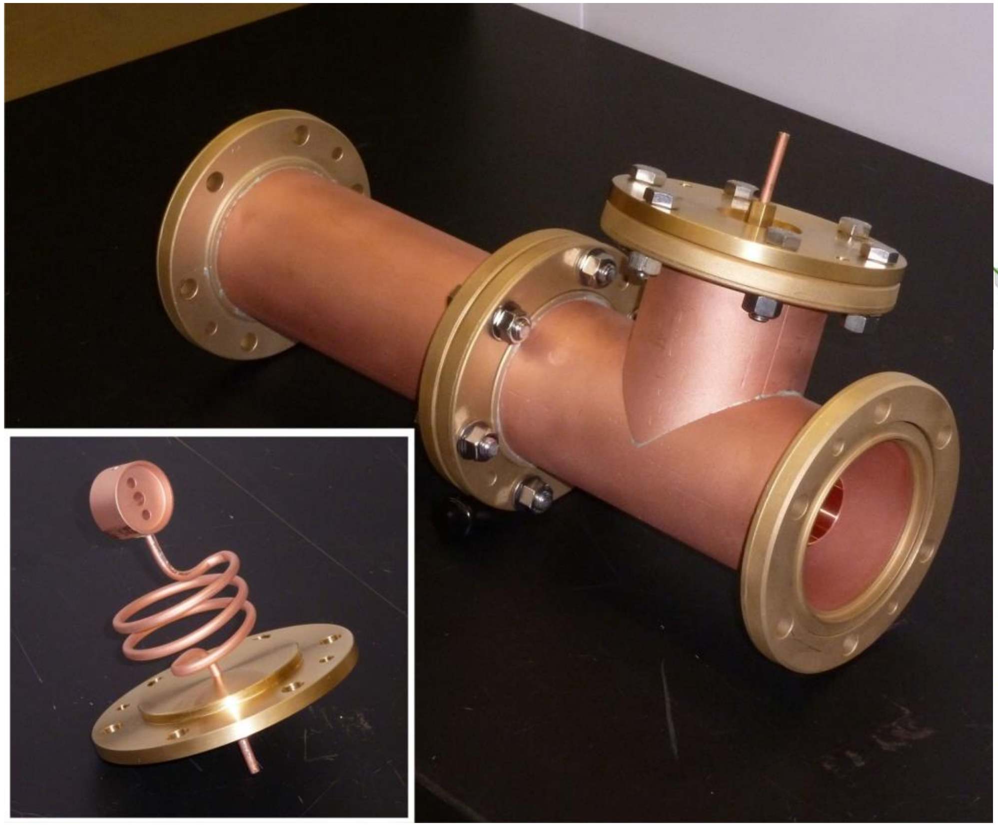


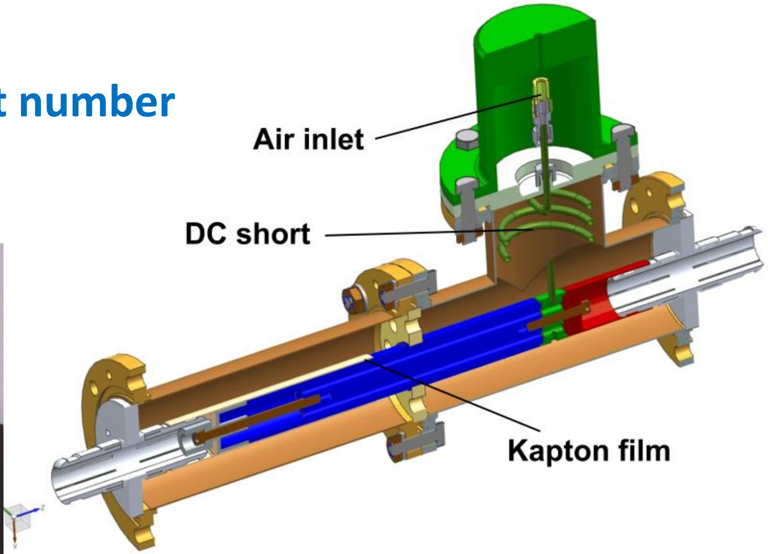
Configuration of DC block

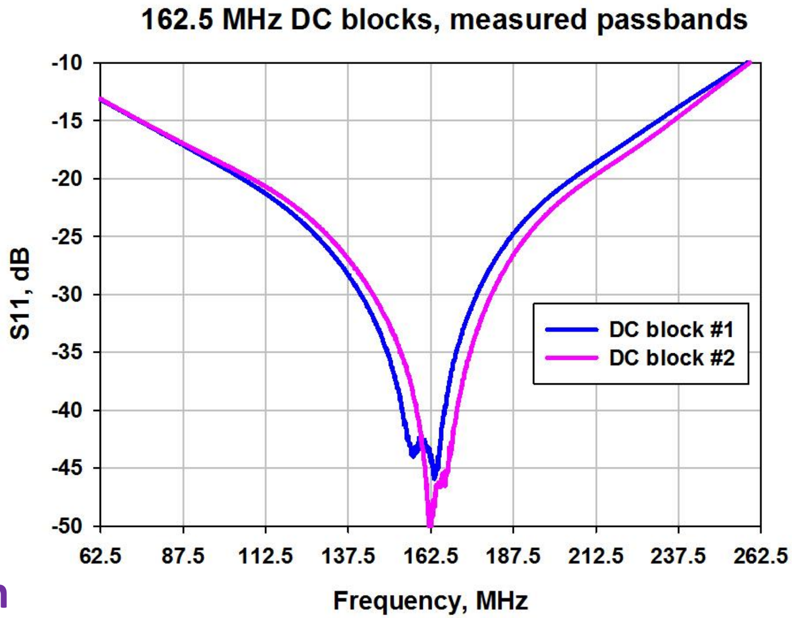


Inner conductor, which is connected to amplifier, is grounded.
In case of dielectric breakdown, the high voltage will not be applied to amplifier.

Firs version of DC block for 162.5 MHz RFQ.
325 MHz DC block has the same configuration but number of coil turns is less.

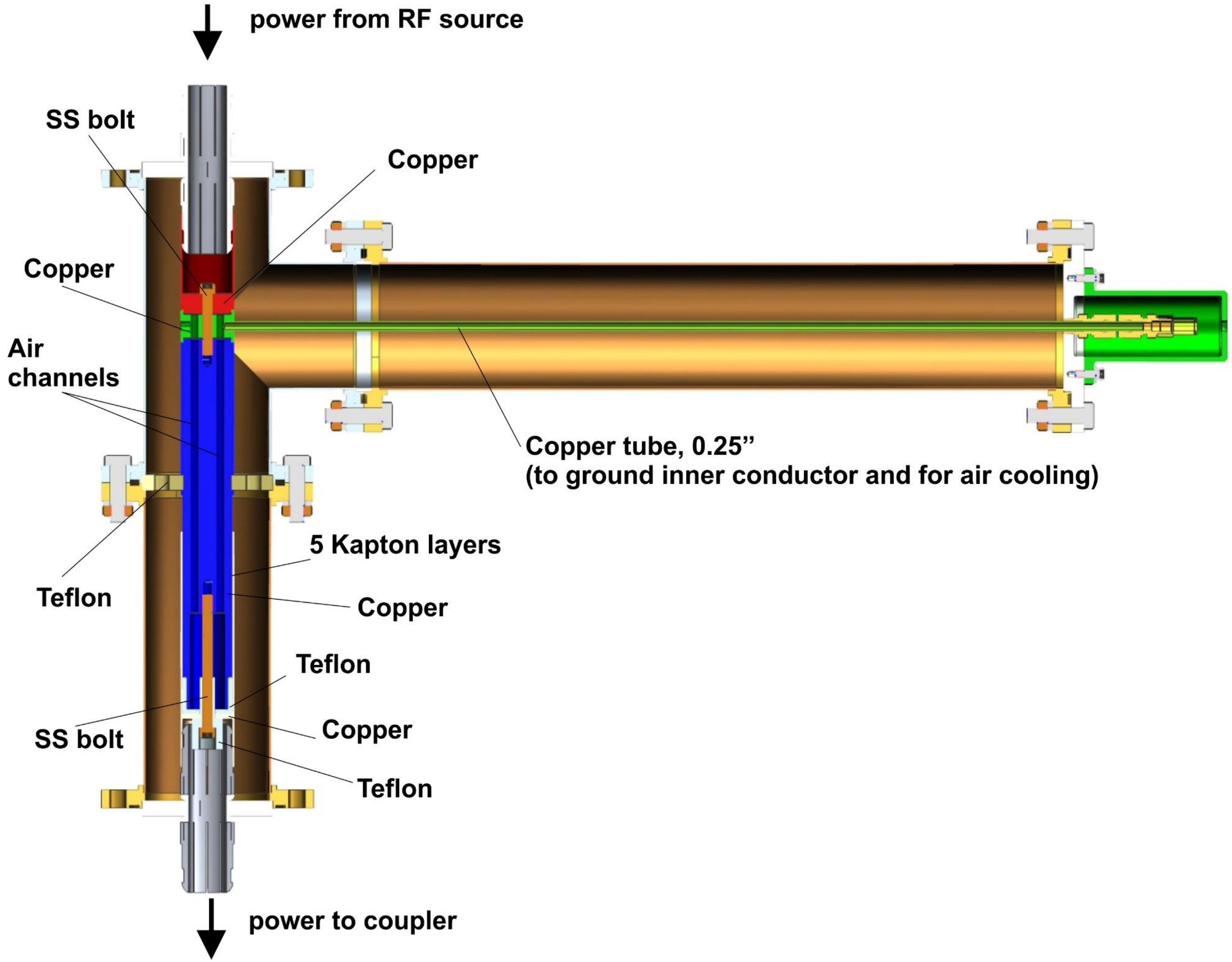






There were problems with breakdowns between Coils turns and outer conductor. New version was designed and built.

Second version of DC block. Coil was replaced by straight waveguide.
DC block was tested up to 5 kV and more then 50 kW, CW RF power (162 and 325 MHz)

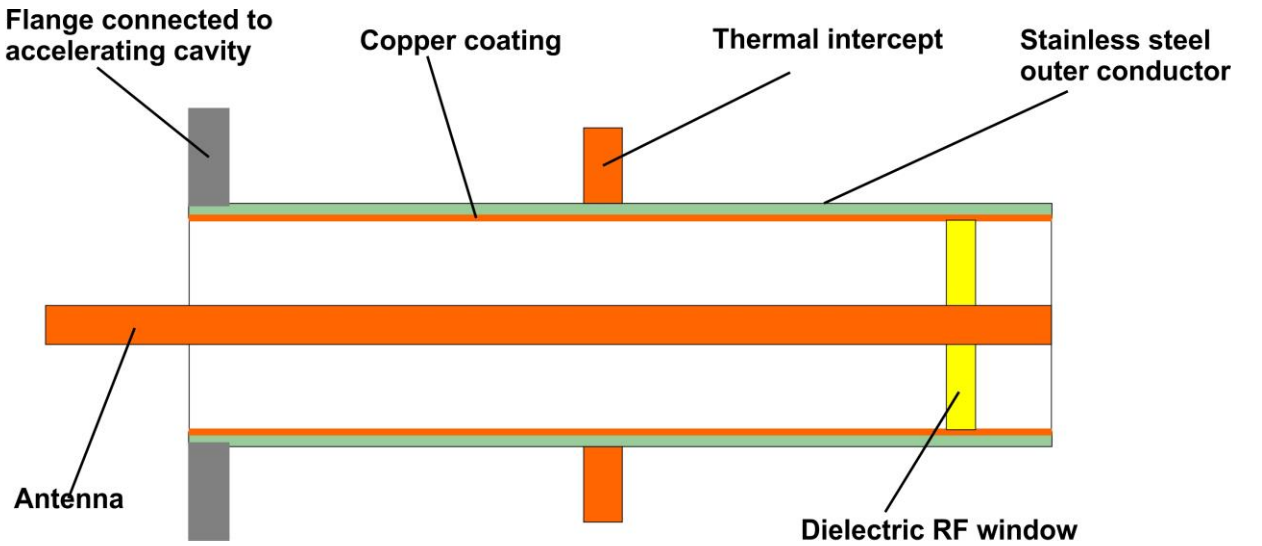


We know how to avoid a copper plaiting in case of coupler for moderate power and frequency. How to avoid copper coating in case of more powerful couplers.

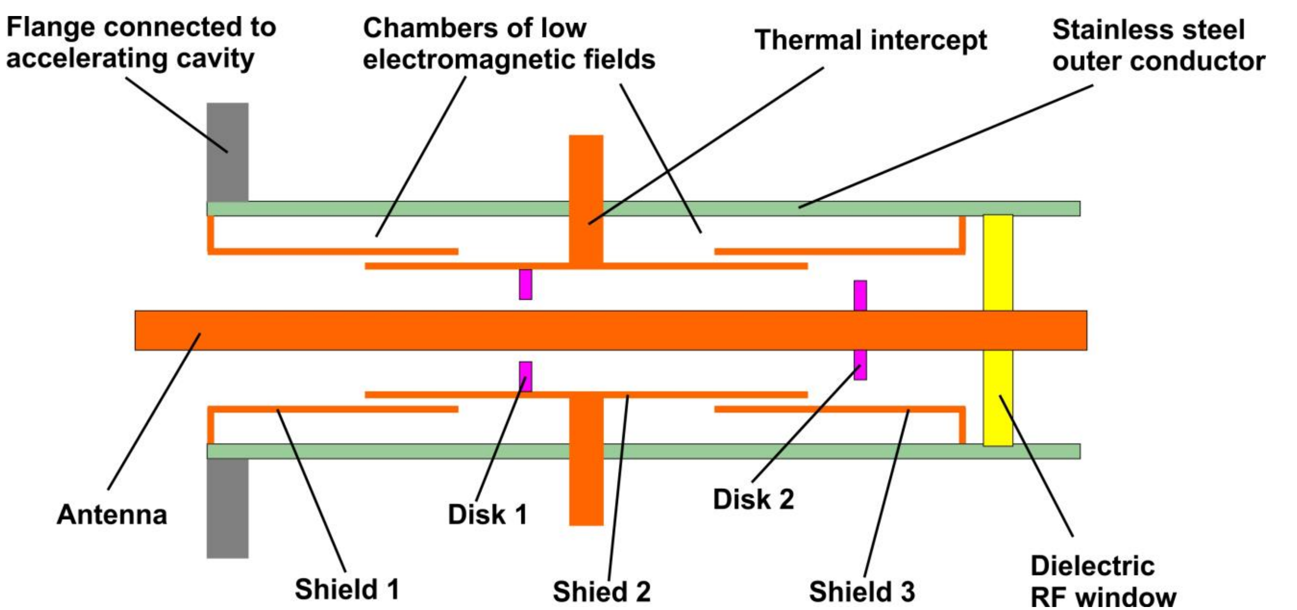
For example, PIP-II 650 MHz coupler has higher frequency, higher power. Outer conductor cannot be made of pure SS.

New approach was developed, which allows to avoid a copper coating and improves cryogenic properties of couplers.

Conventional coupler



New approach



Idea is to replace a copper coating with electromagnetic shields made of solid copper.

Advantages:

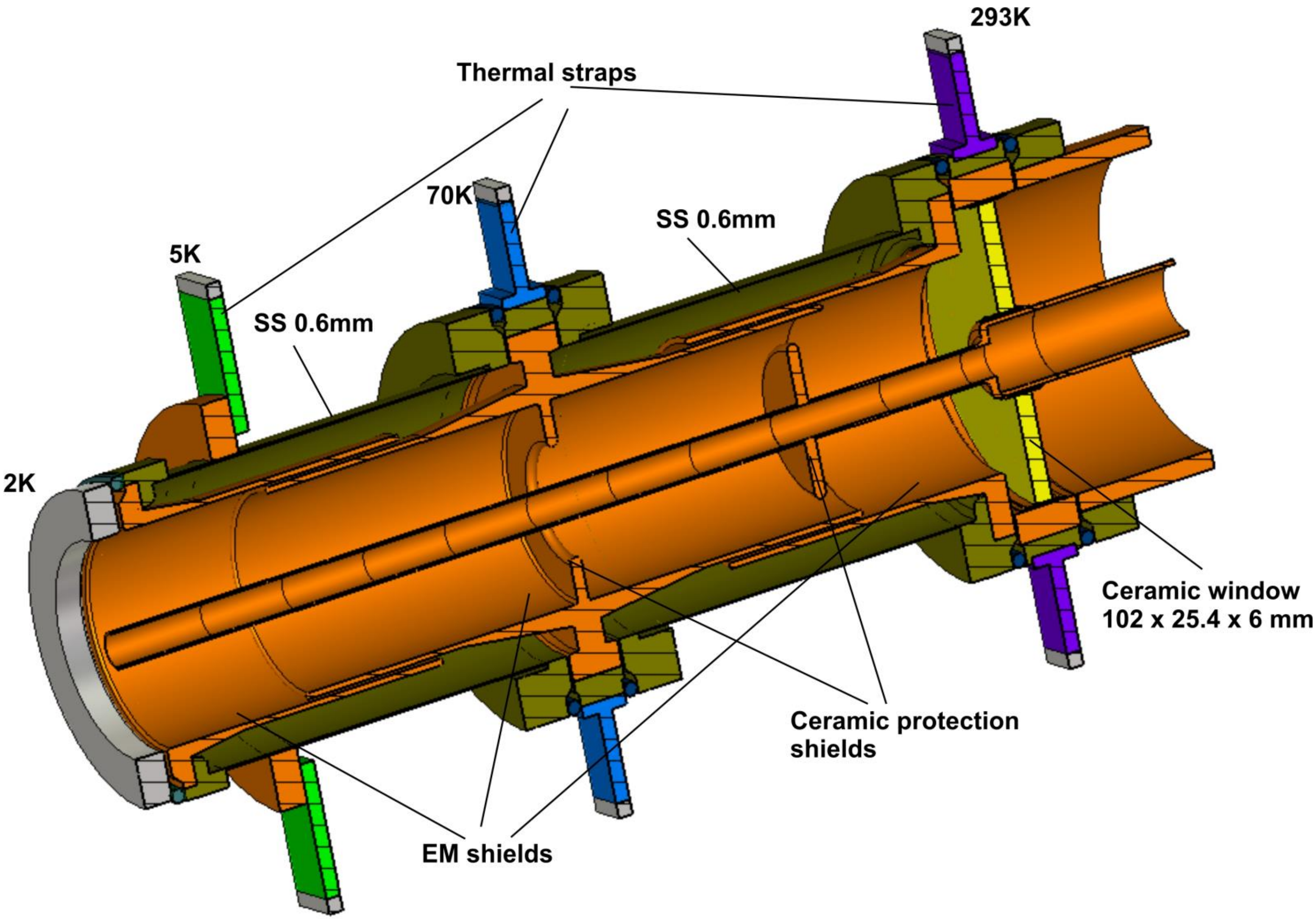
- Avoiding not well developed technology of copper coating. The is no problem with copper flacking.
- Shields are made of solid copper with high RRR. As result, the RF loses are less.
- Main part of RF loses are translated to 70K (from 5K and 2K).

As result, total cryo-loading of new coupler is less then conventional coupler.

Possible problem:

- Configuration is more complicated, higher probability to generate particles during assembling.
- Gaps between shields must be small, < 1mm, to avoid a multipactor in the gaps. (There is no multipactor in the chambers between SS wall and shields - EM fields are too low. Multipactor in other parts is suppressed by HV bias.)

Vacuum part of 650 MHz coupler, new design (configuration for EM and thermal simulation).



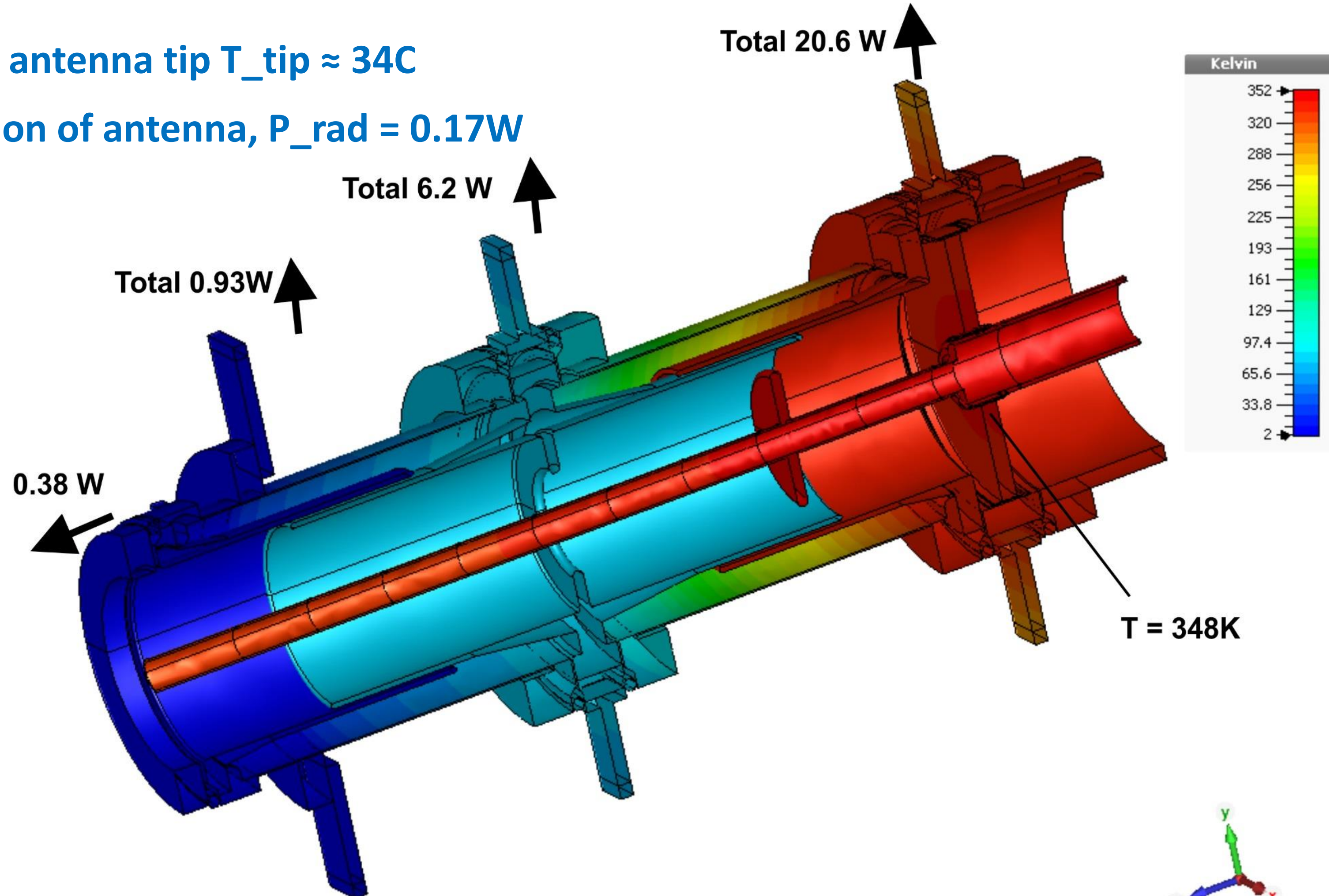
Results of simulations for P =100 kW, TW (cooling air rate 3 g/s)

Loss in antenna = 97W

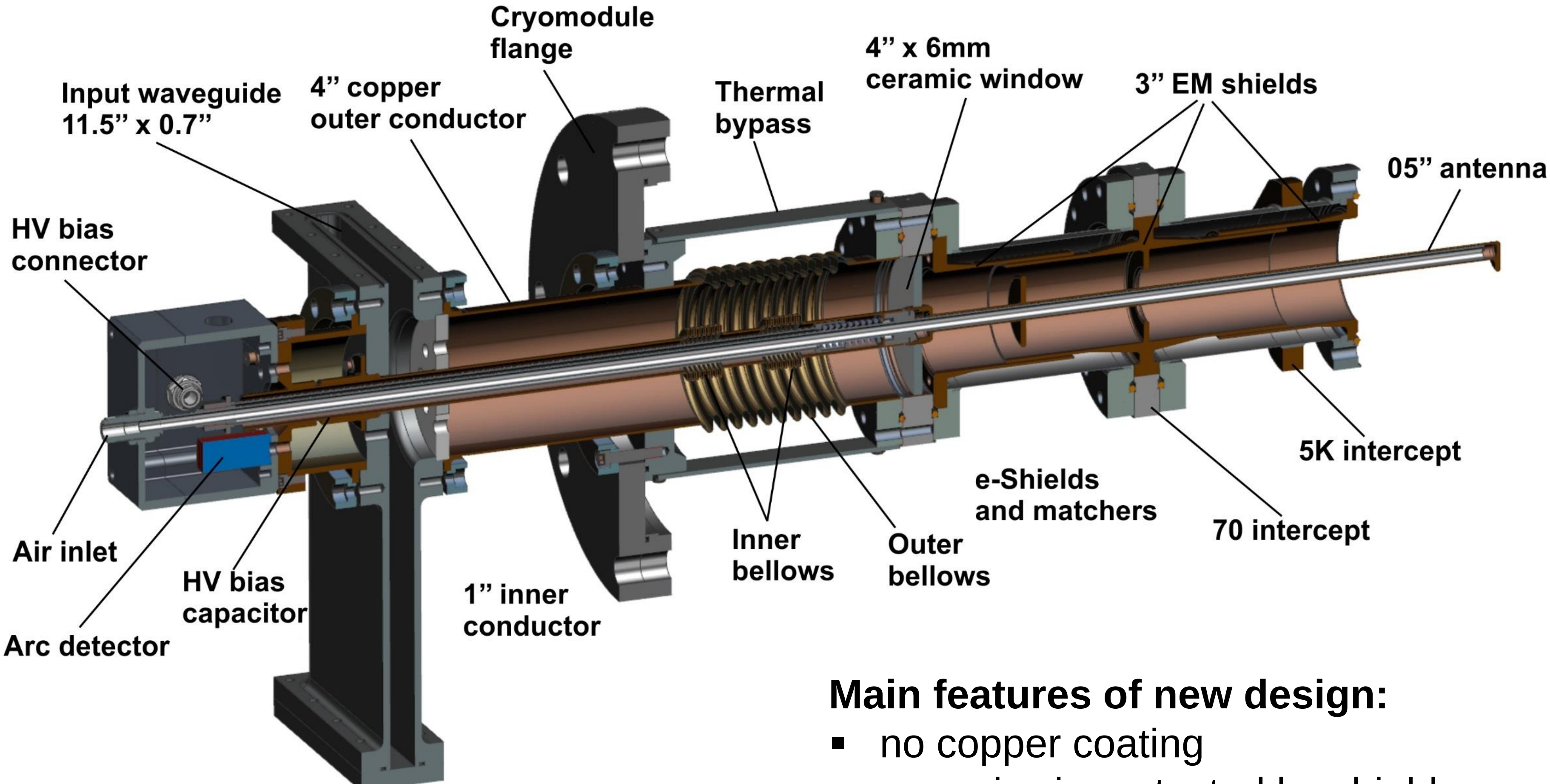
ΔT_air ≈ 38C

Temperature of antenna tip T_tip ≈ 34C

Thermal radiation of antenna, P_rad = 0.17W



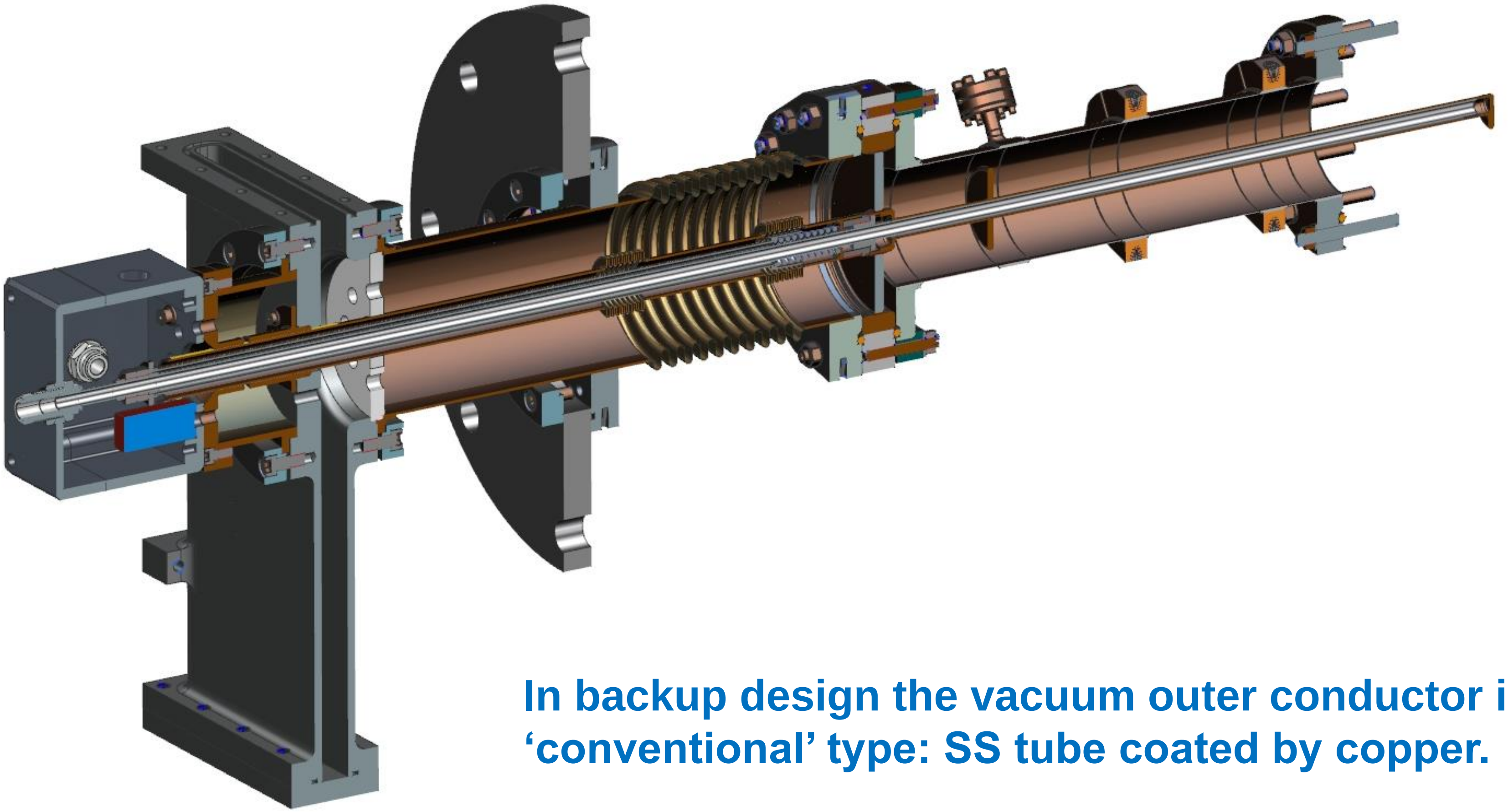
Configuration of 650 MHz couplers, new design.



Main features of new design:

- no copper coating
- ceramics is protected by shields
- better cryogenics properties

650 MHz coupler, conventional (backup) design.



In backup design the vacuum outer conductor is ‘conventional’ type: SS tube coated by copper.

Thermal properties of 650 MHz couplers

	2K, W	5K, W	70K, W	293K, W
New, 0 kW	0.15	0.6	3.3	-2.7
New, 100 kW	0.55	0.93	6.2	21
Bckp, 0 kW	0.41	1.46	3.0	-3.1
Bckp, 100 kW	0.97	4.1	11.4	20

100 kW:

New = 0.55*960 + 0.93*220 + 6.2*20 = **857 W** of cryo-plant
Bckp = 0.97*960 + 4.1*220 + 11.4*20 = **2061 W** of cryo-plant

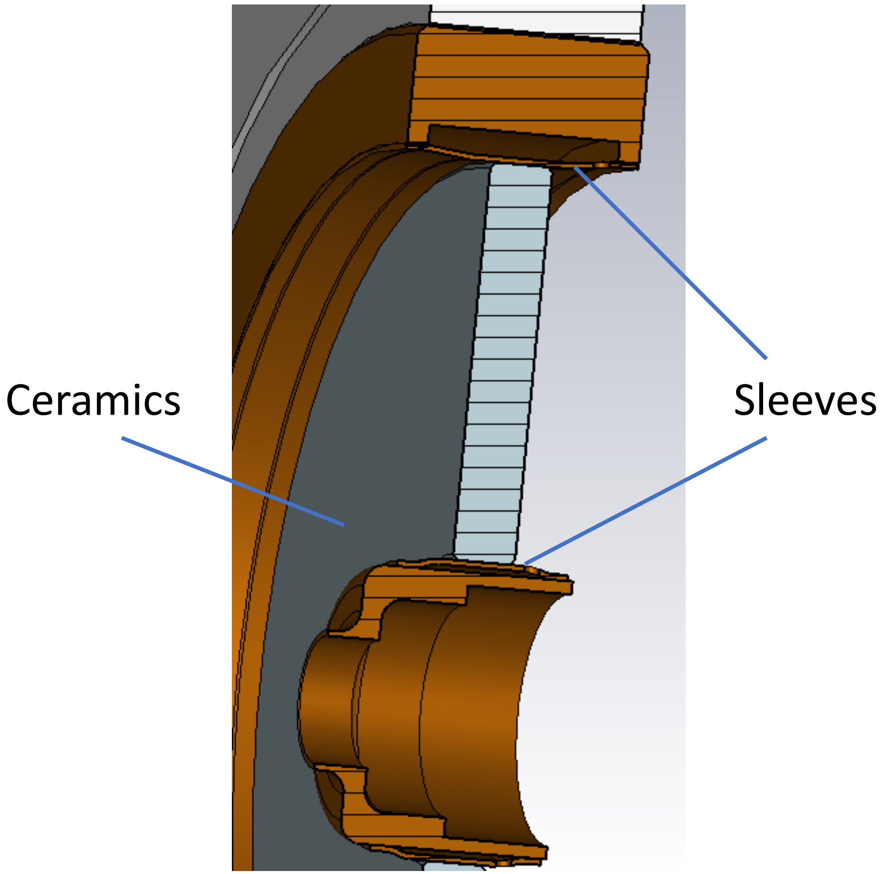
New design requires ~ 2.4 times less power of cryo-plant.

Vacuum parts of 650 MHz couplers made by CPI.

New

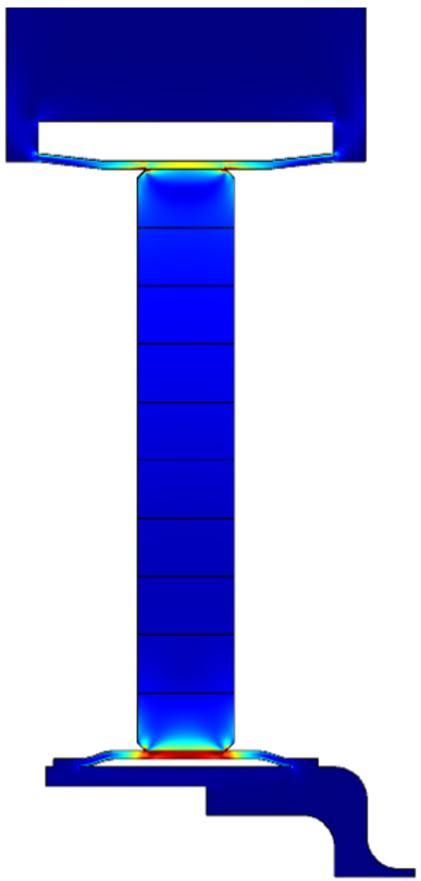
Conventional

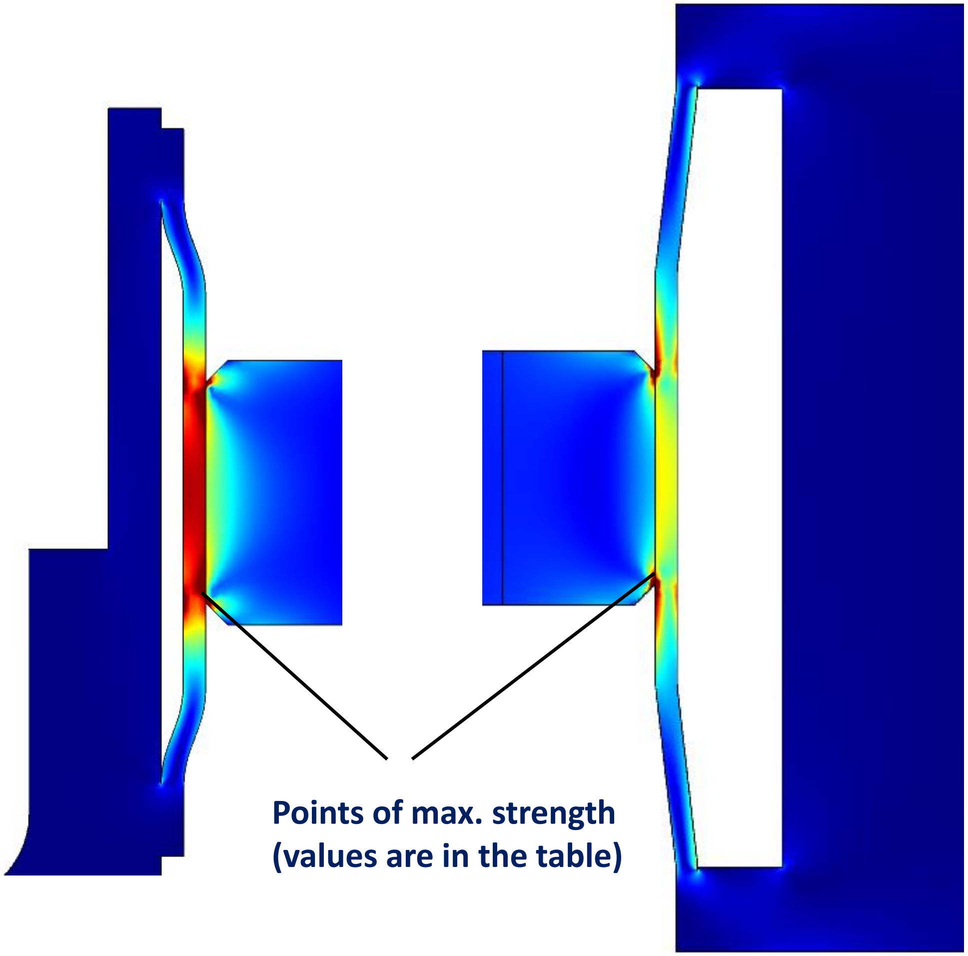
The critical part of coupler, which determines the reliability, is ceramics window. Ceramics brazed into metal shell and metal antenna. Problem is that thermal expansions of ceramic and metal are different and ceramics is brazed to metal through thin flexible sleeves. Sleeves accommodates relative ceramics and shell displacement. Sleeves are made of copper typically.



Simulation shows that maximum mechanical stresses, which determine window reliability and lifetime, are localized in place of ceramic-metal brazing. Stresses are caused by changing temperature during operation.

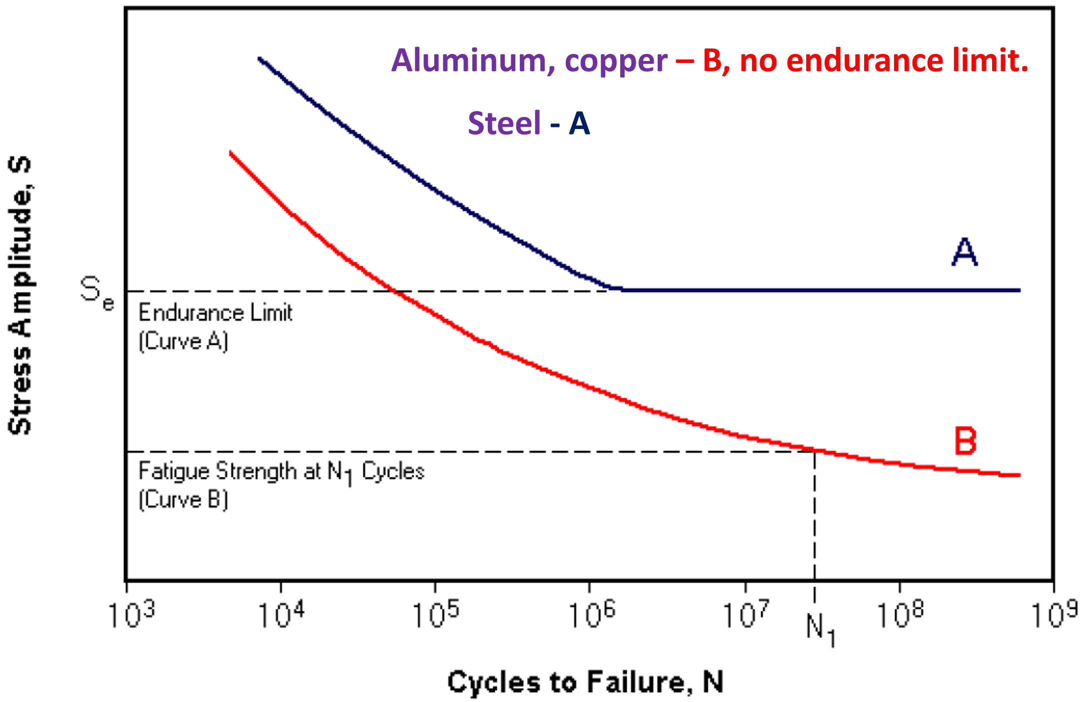
What level of stresses are acceptable?





Window ceramics and sleeves experience periodical stresses even in case of accelerator works in CW mode. For example, life time of accelerator 20-30 years. If accelerator experience 1 trip per day, total number of on/off cycles will be ~ 1e+4. 1 trip per 2 hours corresponds ~ 1e+5 cycles. CW accelerator is pulse accelerator with very long pulses. So, coupler has to be able to sustain ~ 100 thousands on/off cycles.
Cycling stresses caused material fatigue.

Typical S-N fatigue curves



In case of cycling stress the copper sleeve will be broken soon or later. It is important that this will not happen within the life time of the accelerator.

Copper fatigue

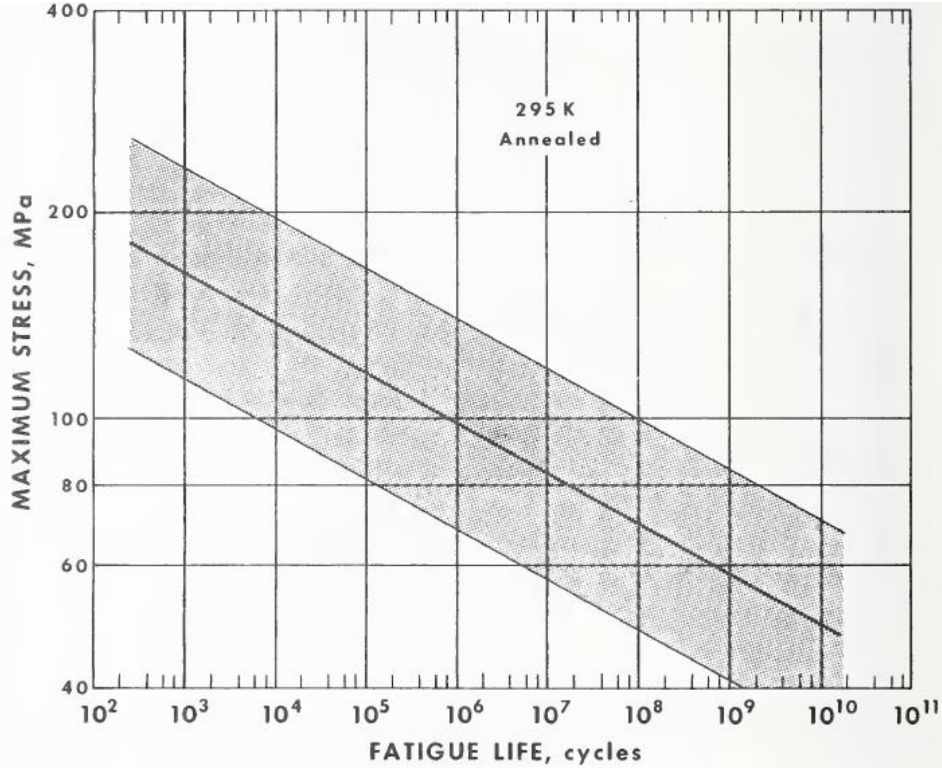


Figure 4.2. Dependence of maximum stress at 295 K upon number of cycles to failure. The scatter band represents two standard deviations about a linear regression equation based upon 148 measurements. The regression equation is

$$\sigma_m(\text{MPa}) = 271\ N^{0.074}.$$

S-N depends on some para**meters**: temperature, grain sizes, frequency of cycles.

Average (148 measurements) for annealed copperat 295K:

S(MPa) = 271*N^(-0.074)
or
N = (S(Mpa)/271)^(-13.514)

Worst:

S(MPa) = 192*N^(-0.074)
or
N = (S(Mpa)/192)^(-13.514)

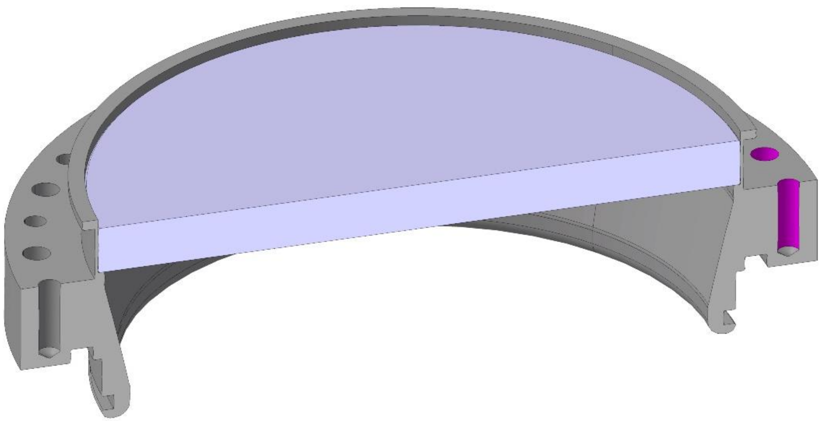
Example of window stresses of 650 MHz coupler

Stresses in copper and ceramics for 100kW and 300kW, TW, CW

Power, Air rate	Inner, Cu	Inner, Cer	Outer, Cu	Outer, Cer
100 kW, TW, 3g/s	87 MPa, T = 74C	100 MPa	125 MPa, T = 60C	160 MPa
100 kW, TW, 4g/s	65 Mpa, T = 65C	92 MPa	97 Mpa, T = 55C	128 MPa
300 kW, TW, 5g/s	160 Mpa, T = 124C	220 MPa	280 Mpa, T = 112C	250 MPa

Design is good for 100 kW, TW, CW.
For 300 kW it has to be improved.

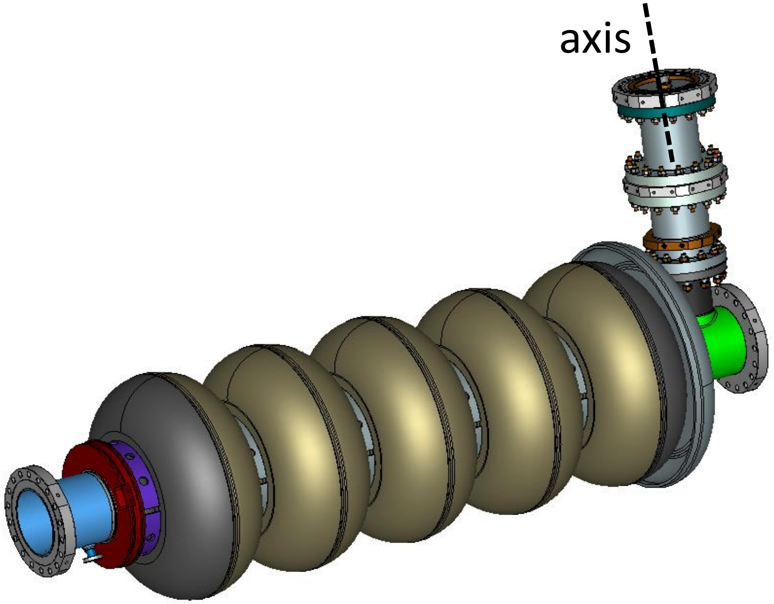
Another approach is use for shell materials with the thermal expansion close to ceramic thermal expansion. Example – RF window for SPS 200, CERN. Shell made of Titanium. Ceramics is brazed directly into shell without sleeves.



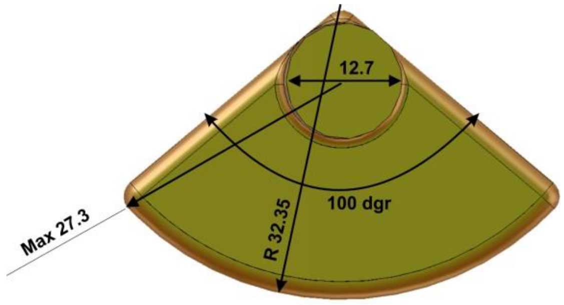
(eric.montesinos@cern.ch, CERN FPC status and perspectives)

Antenna tip and coupling.

Configuration of 650 MHz cavity and coupler is not axial symmetrical (relative to axis of antenna).

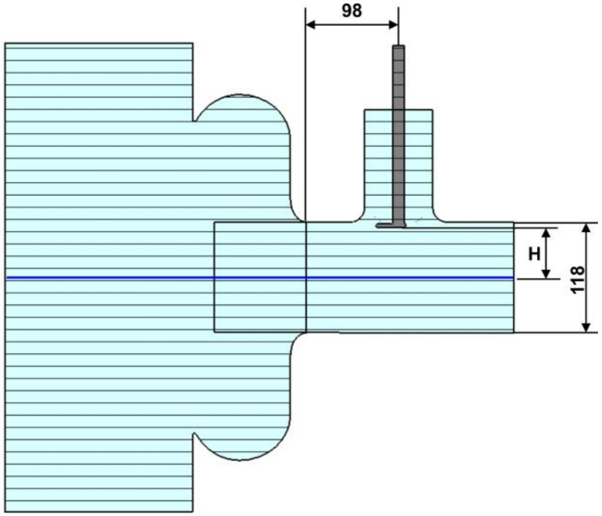


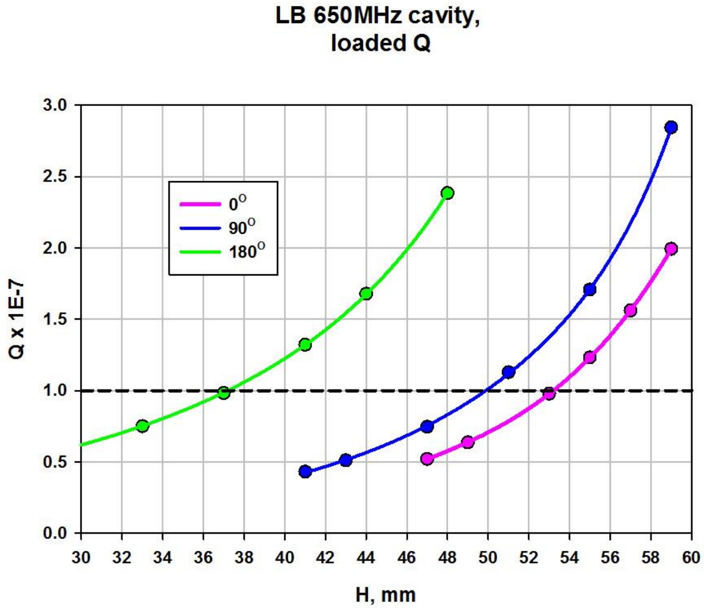
We found that optimal (maximum coupling) shape of antenna tip should be non axial symmetrical as well. Optimal shape, “goose foot”, is presented on drawing.



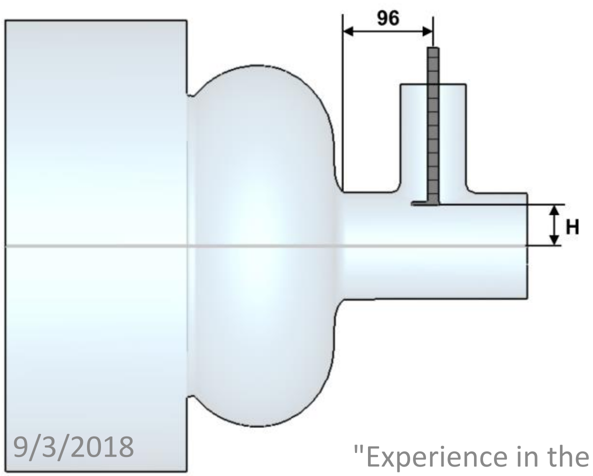
“Goose foot” increase coupling, decries antenna penetration and heating, allow to change coupling by antenna rotation. As simulations show the coupling can be change by more then 4 times.

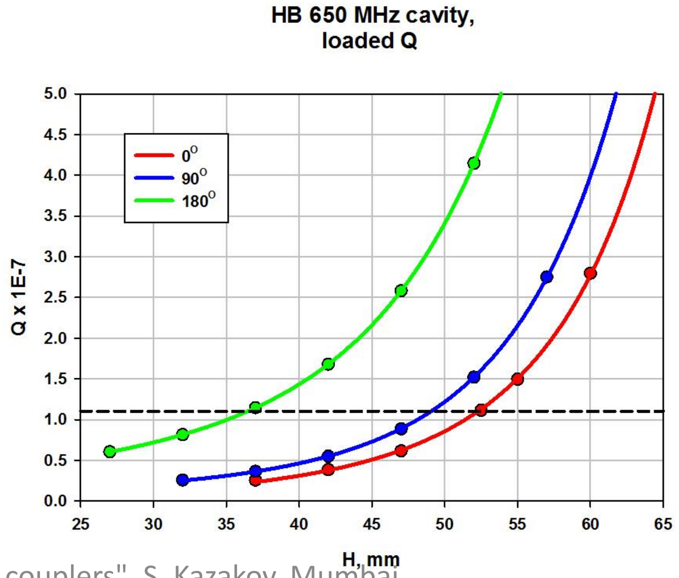
LB 650 MHz cavity coupling:





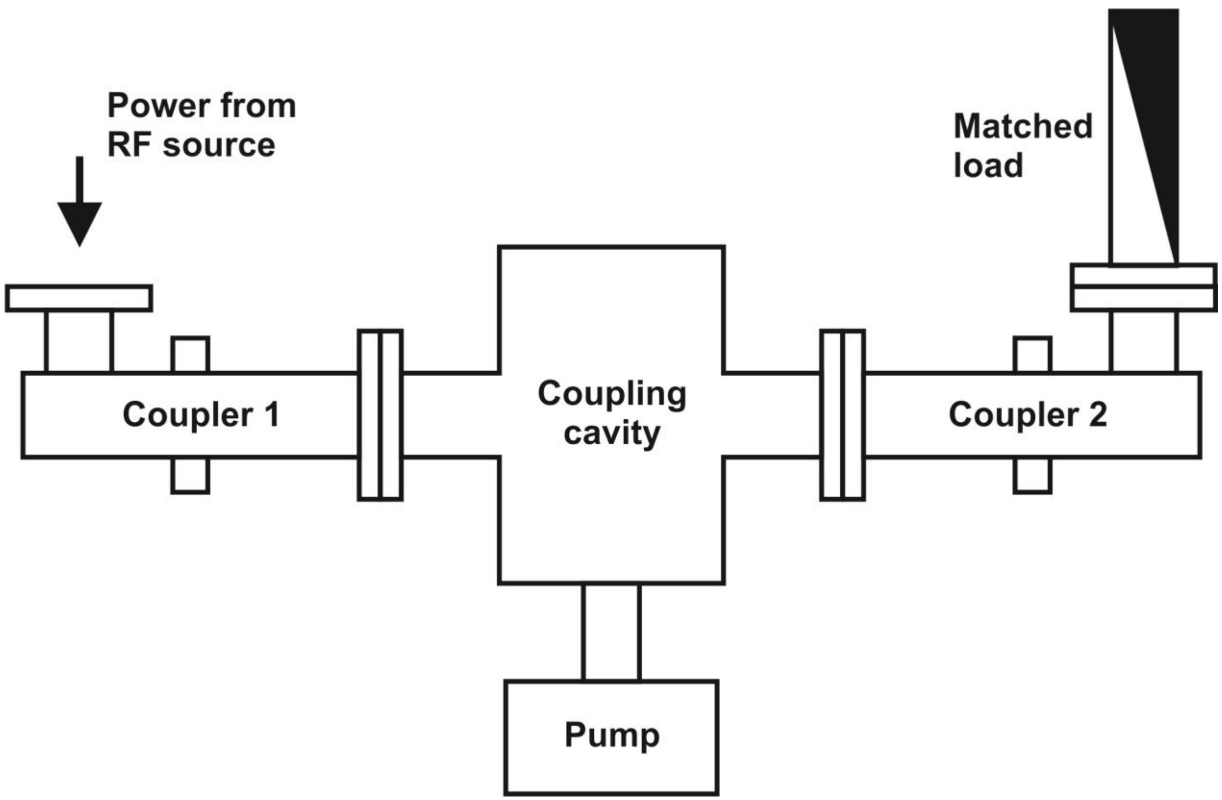
HB 650 MHz cavity coupling:



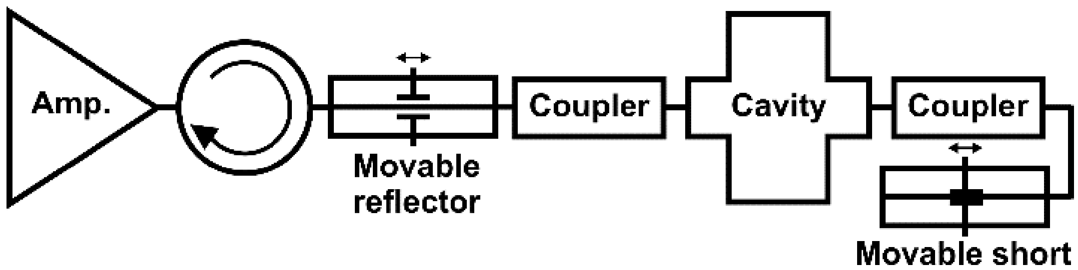


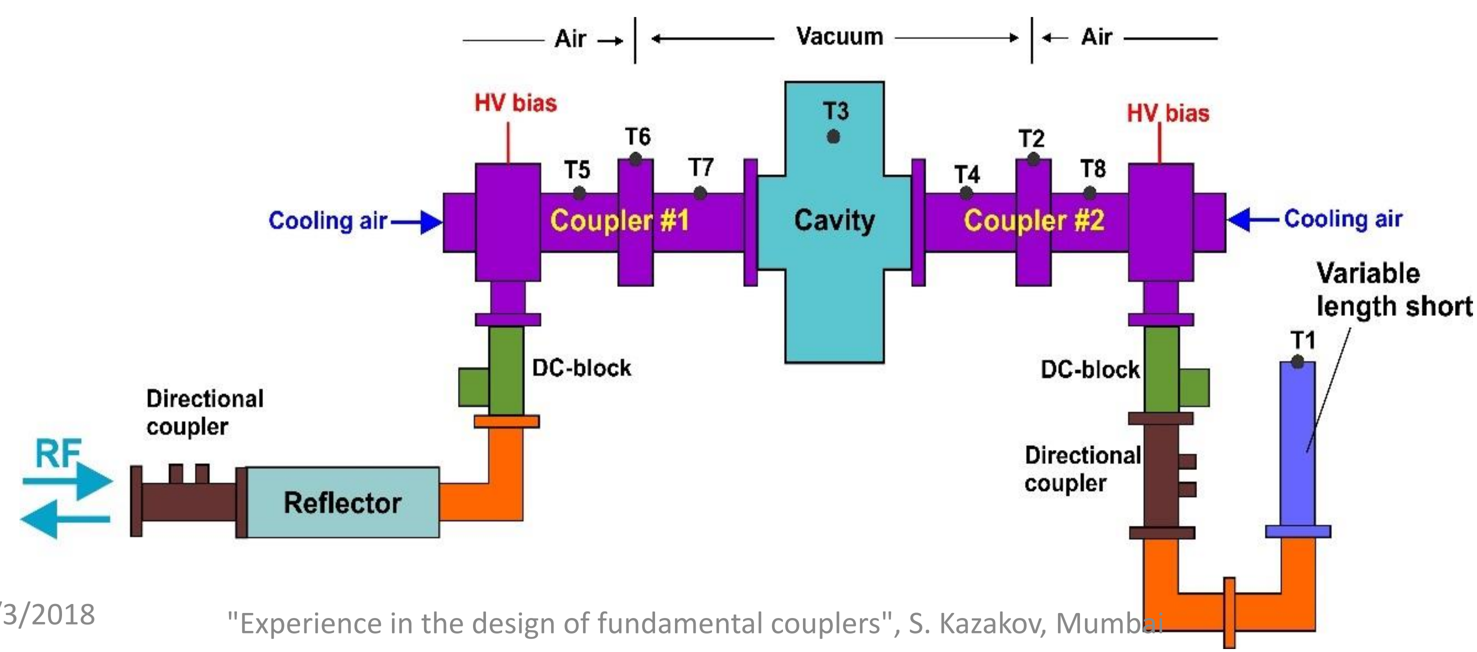
Coupler testing.

Usually couplers are tested in pairs to provide vacuum between couplers.
Typical configuration is presented at the drawing:



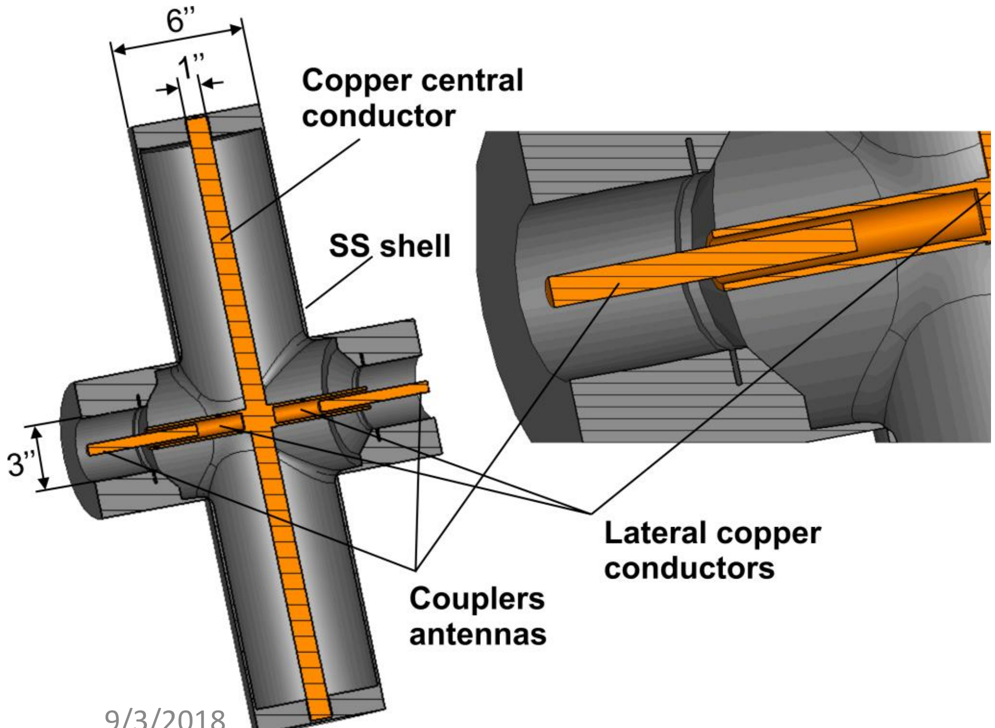
In our test of 325 MHz couplers we use the similar configuration, but instead of matched load we use movable short and installed the mobile reflector between RF source and test setup. Reflector partly transmits RF power and partly reflects. This configuration allows to organize a resonance between short and reflector. It increases testing power by several times, about 5 times in our case. Using 10 kW solid state amplifier we can test couplers up to 50 kW, full reflection.

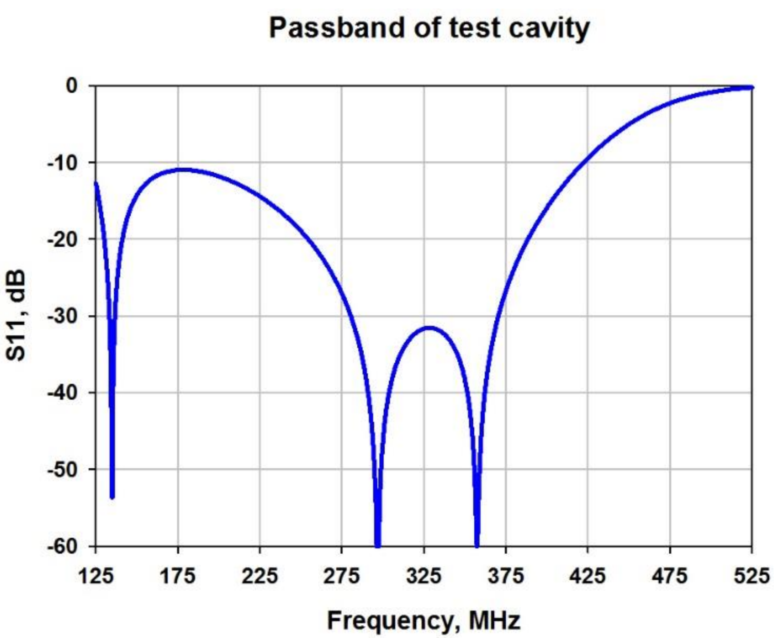




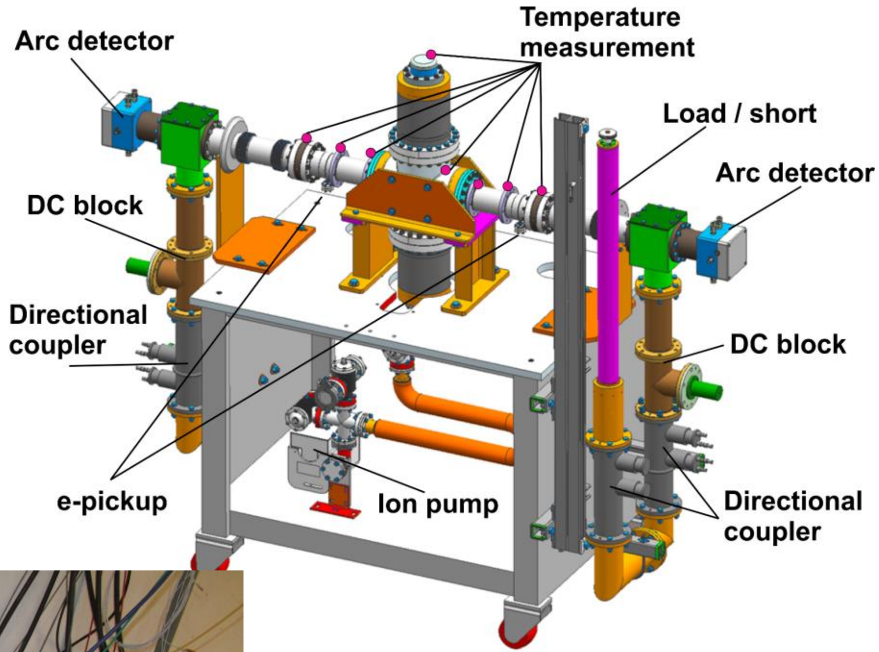
In our case the coupling cavity is rather transmission line with two quarter–wave supports then cavity. It provide wide passband, low fields and losses. Cavity made of pure stainless steel (no copper coating). Internal rods and supports are made of copper. Antennas of couplers have no mechanical contacts with internal copper rods. Electrically they connected through small capacitive gaps. Diameter of cavity was chosen as 6’’ to avoid multipactor in operating range of power.

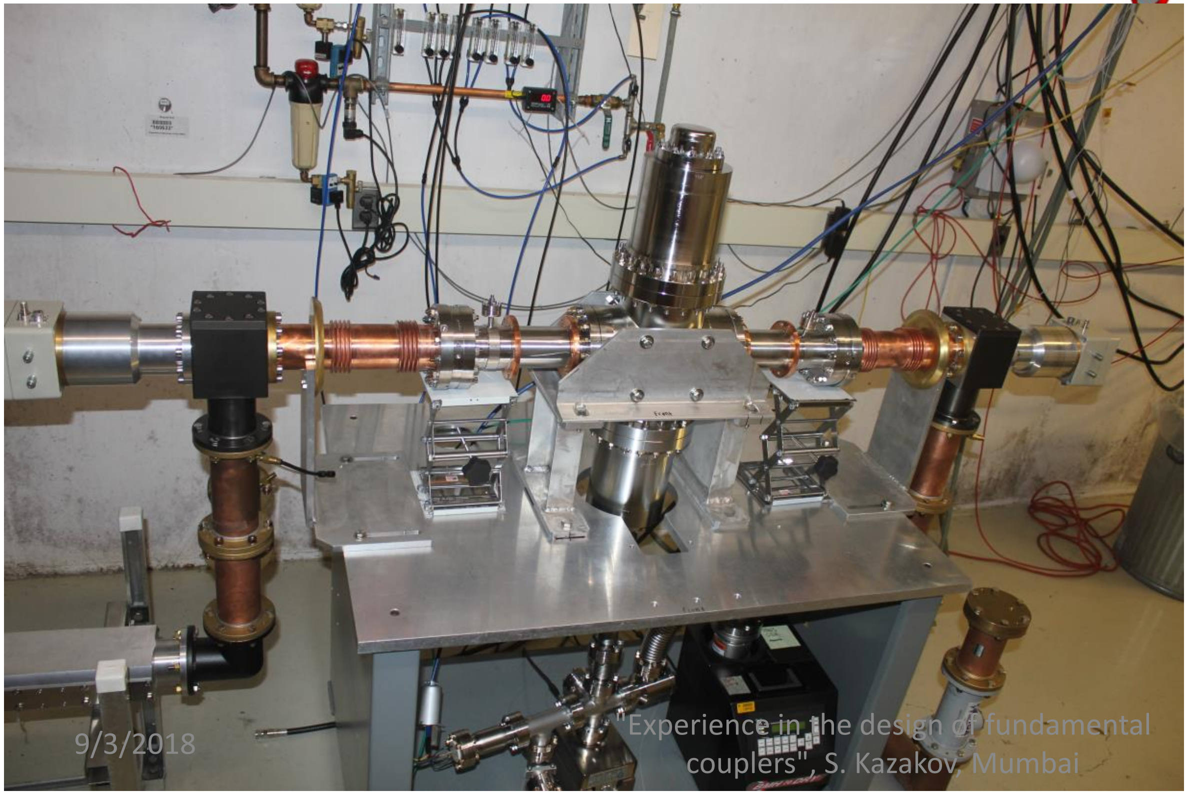
Configuration of coupling cavity.



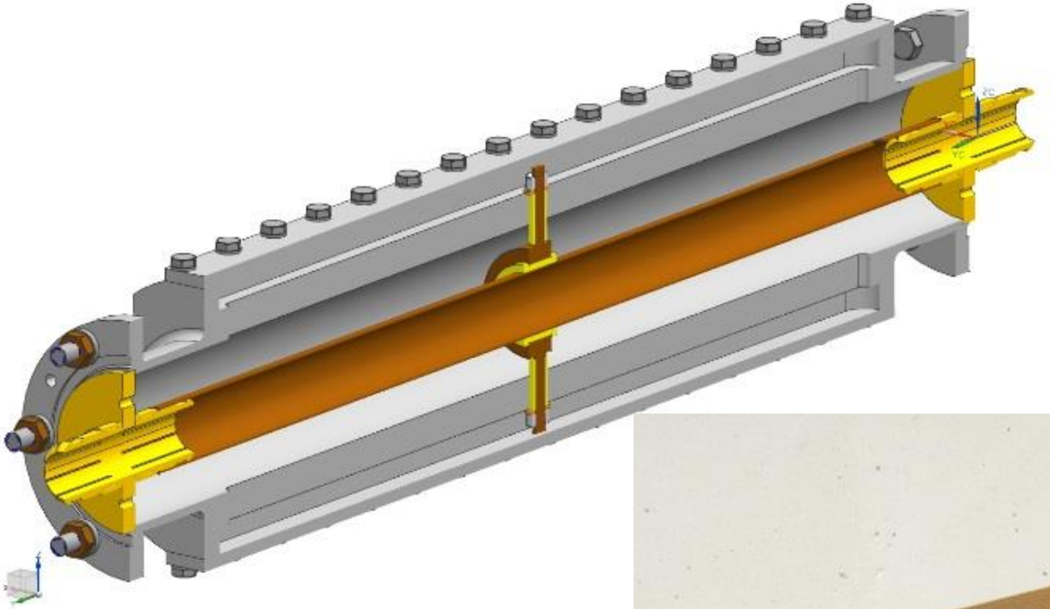


325 MHz coupler test stand





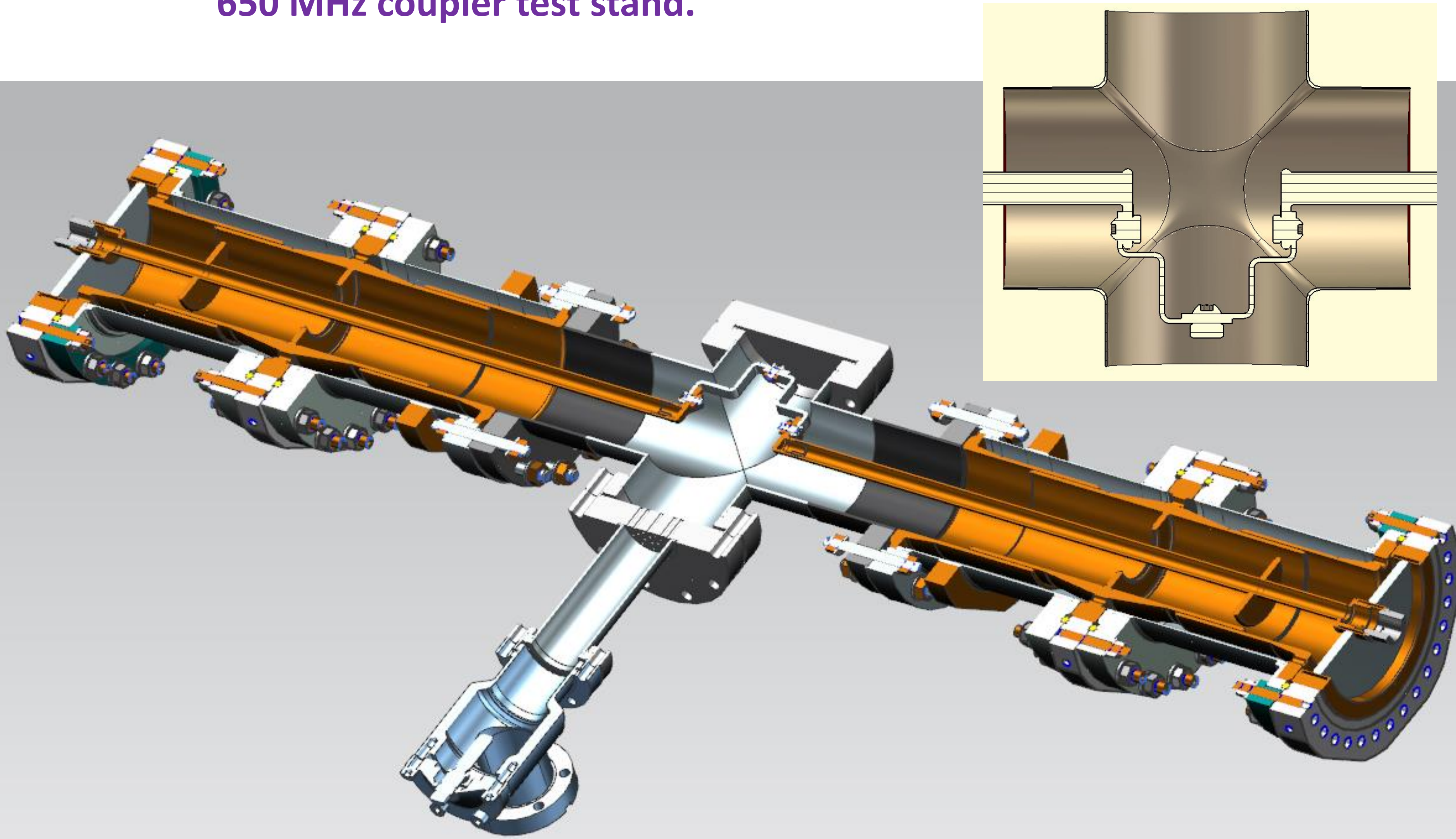
Coaxial reflector. It allows to increase testing power up to 5 times.



RF source: SS, 10 kW, CW, 325 MHz.

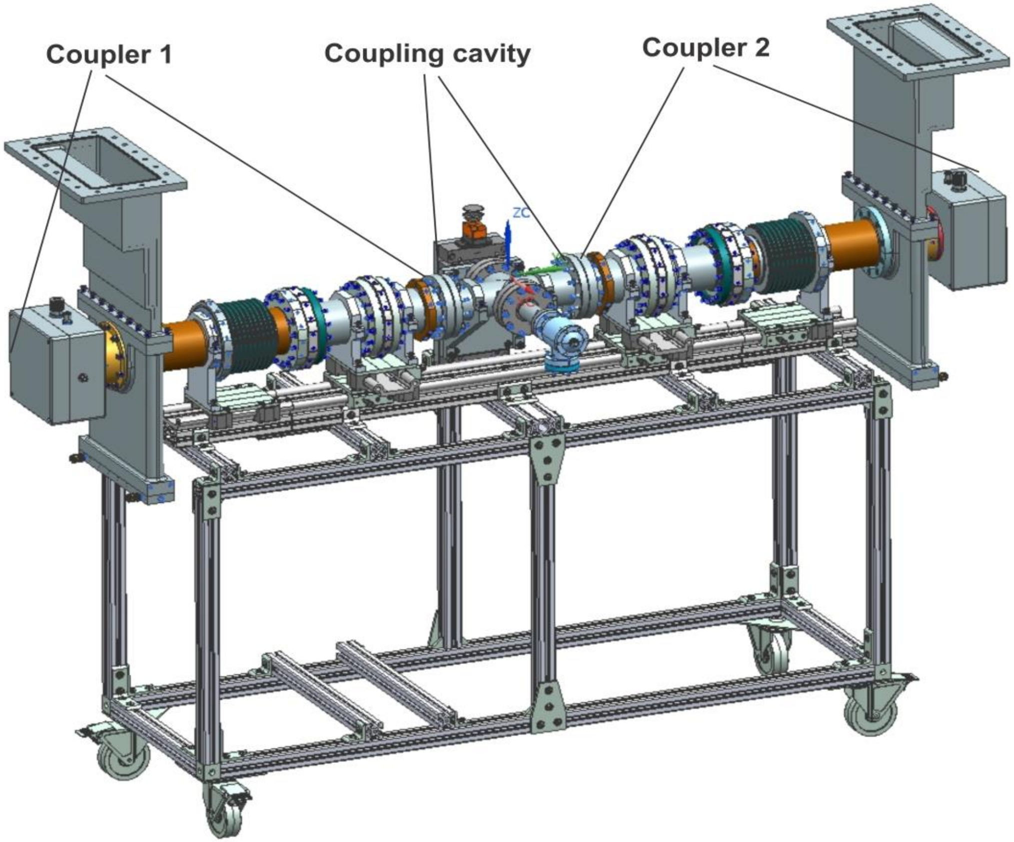
Testing power: up to 50 kW, CW

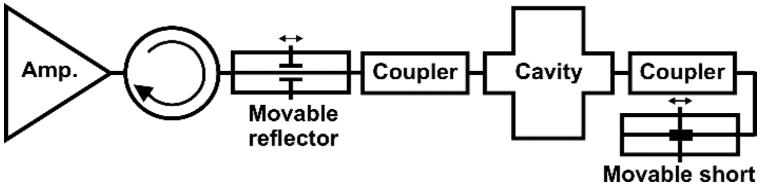
650 MHz coupler test stand.



In case of 650 MHz test stand the couplers will be connected mechanically to make things easer and less expensive.

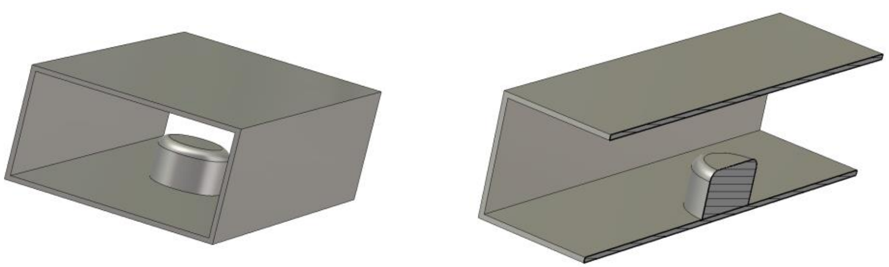
650 MHz couplers test bench.





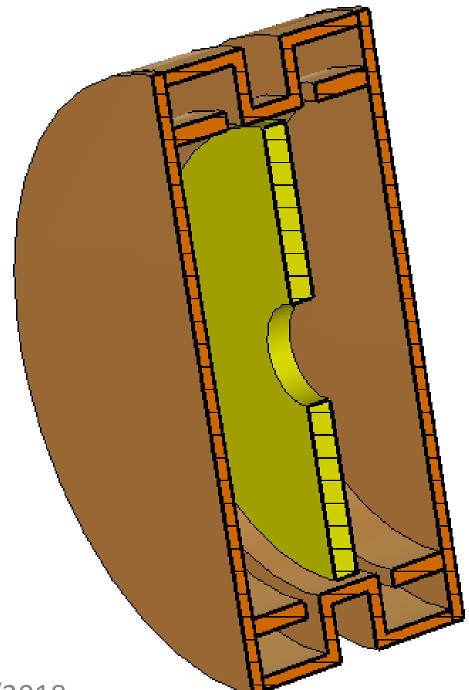
Couplers will be tested in resonance mode with full reflected power. It will allow to increase the level of testing power more then 100 kW using 30 kW RF source.

Waveguide reflector

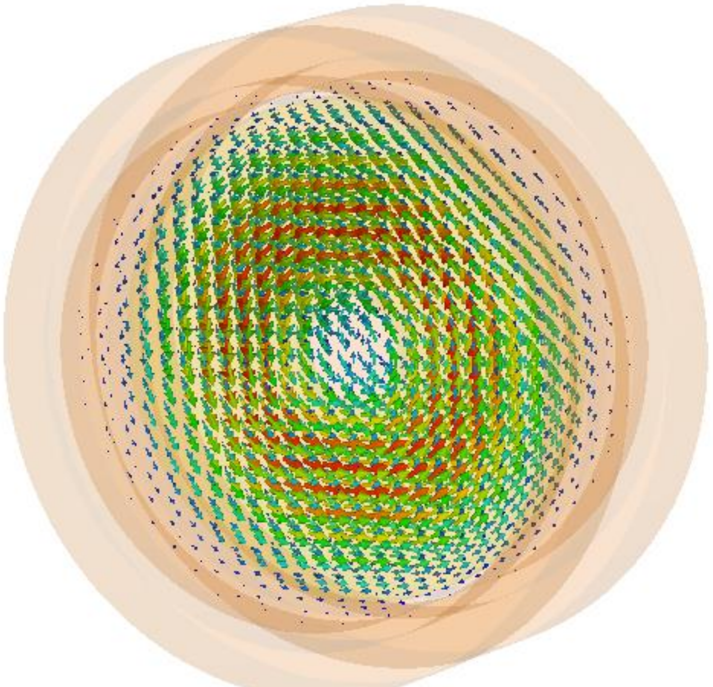


Quality of ceramics is very impotent for reliable operation of coupler. We verify the loss tangent of each ceramic dick. Disk is placed in special copper cavity and quality factor of resonance is measured. Based on this value the loss tangent is calculated.
Cavity has the special shaper to move side resonances form operating resonance.
Operating resonance is TE_011 type. TE_011 most sensitive to loss tangent of ceramic and has no angle variation. It increase the accuracy of measurements (no double peaks).
Measures are performed at different temperatures to verify dependence of loss tangent on temperature. Measurements are performed at not operating frequency of coupler but several times higher ~ 2.5 GHz.

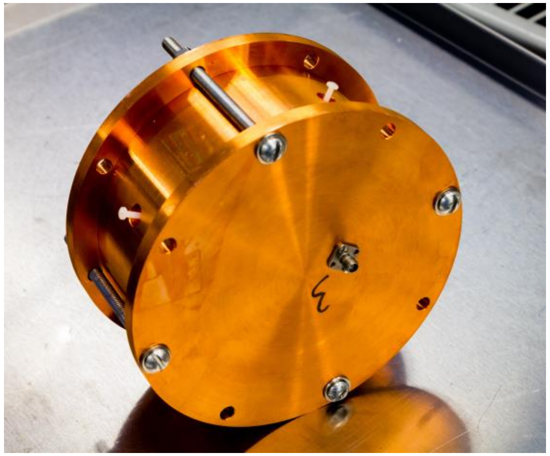
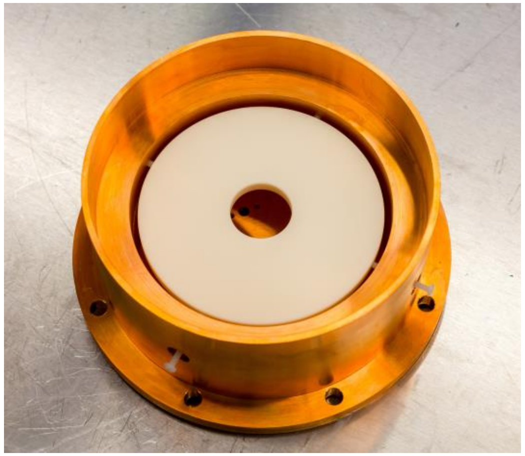
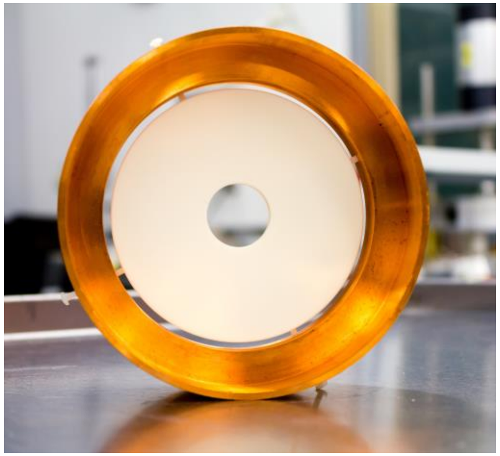
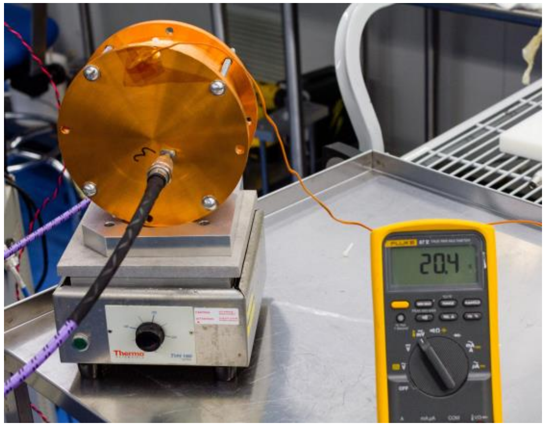
Cut view of cavity with ceramic disk.

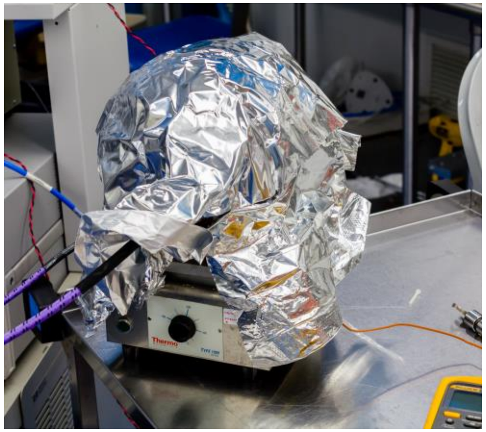
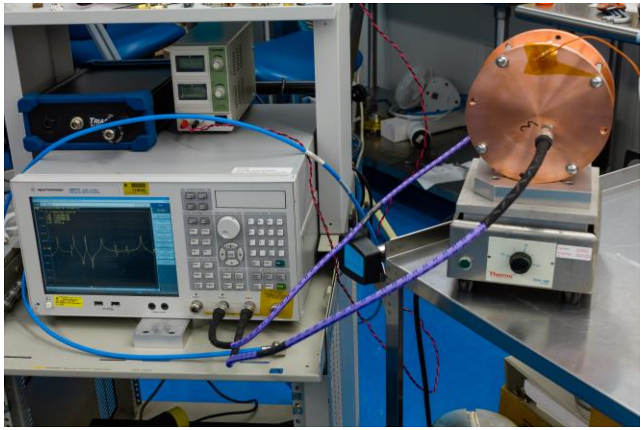


Electric field of measured mode



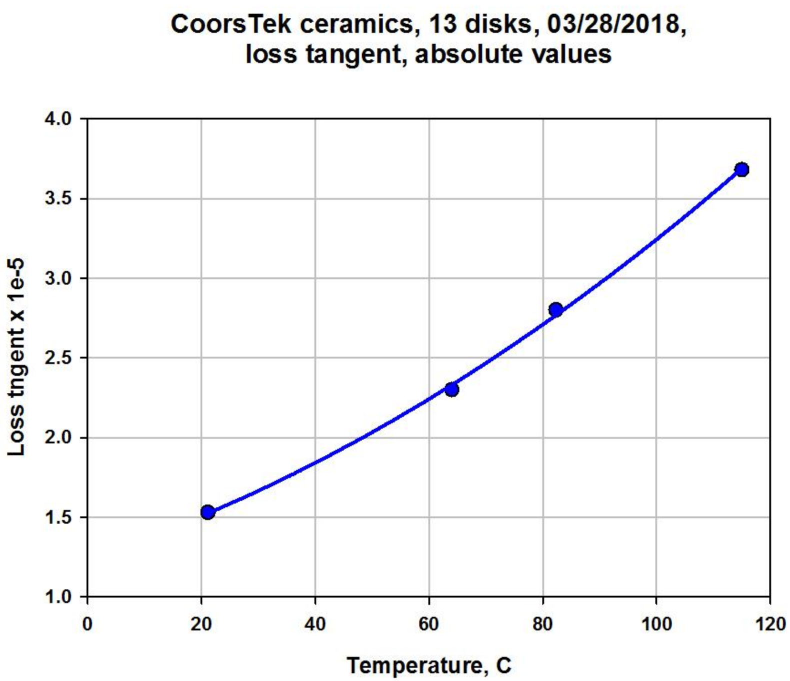
Measurements of loss tangent of ceramics disks.

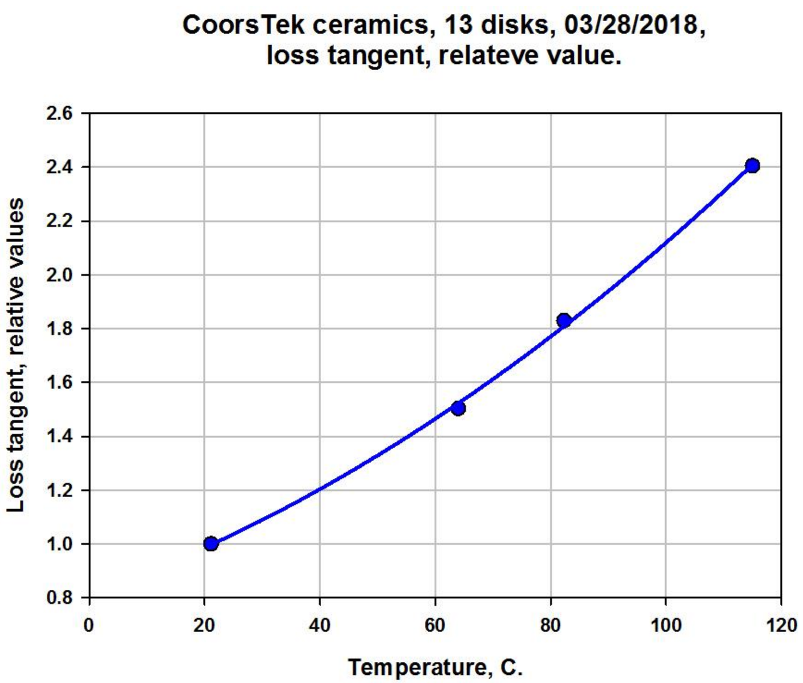





Example of results of measurements

CoorsTek ceramic measurements, F ~ 2.7 GHz





Some times ceramics is extremely good: loss tangent ~ 1.5E-5 at 2.7 GHZ

Thank you for attention!