Couplers design efforts

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Task:
To design, build and test coupler for all types SC cavities of Project X linac

Requirements to RF coupler for ProjectX:

Couplers have to provide reliable operations superconductive accelerating cavities in CW regime of following frequencies and powers:

Section	Energy range MeV	β	Number of cavities	Type of cavities	Maximal power per cavity*, kW
SSR0 (βG=0.11)	2.5-10	0.073-0.146	16	Single spoke cavity.	0.8
SSR1 (βG=0.22)	10-32	0.146-0.261	18	Single spoke cavity.	1.5
SSR2 (βG=0.4)	32-160	0.261-0.52	44	Single spoke cavity.	3.2
650 MHz (βG=0.6)	160-500	0.52-0.758	35	Elliptic cavity	11.5
650 MHz (βG=0.9)	500-2000	0.758-0.95	92	Elliptic cavity	18.5
1300 MHz (βG=1)	2000-3000	0.95-0.97	64	Elliptic cavity	16

Couplers have to allow to make assembling accelerating cavities with coupler in clean room and to be installed in cryomodules then

Couplers should not noticeably to increase the heat load of cavity. Heat load of cavities is estimated as 20W per cavity at 2K.
We can require that heat load of coupler does not excide 1W at 2K

Because the noticeable number of 1300 MHZ cavities and ILC-type cryomodule already made, the new 1300MHz coupler has to fit existing cavities and cryomodules. **It means the diameter of coupler at place of connection to cavity has to be 40mm.**

Because the design of SSR1 cavity already exist and cavity demonstrated reliable operation, the new 325 MHz coupler hast to fit existing design of SSR1. **It means that outer diameter of coupler at place of connection to cavity has to be 76.9 mm**

Cooling of the couplers, if it is necessary, has to be air-type. Water can provoke corrosion at brazing places and decrease life-time of coupler. Water leakage cause more serious damage then air leakage.

Couplers can be made with one "warm" RF window or two "warm" and "cold" windows. Previous experience of working with coaxial couplers in different laboratories shows that coaxial RF windows is reliable element. There is no precedent of coaxial window distraction at SRF facilities. Probably it is no senesce to use two-window type couplers from reliability increasing point of view. Advantage of two-window type coupler is it easer to install coupler to cryomodule. At the same time the one-window coupler is much simpler and cheaper. Because the window is room-temperature element, it has to be placed quite far from 2K cavity flange. It cause some difficulties for assembling and installing in cryomodule. **We think that couplers for ProjectX should be one-window couplers**. If difficulties of assembling are insuperable, a two window approach will be considered.

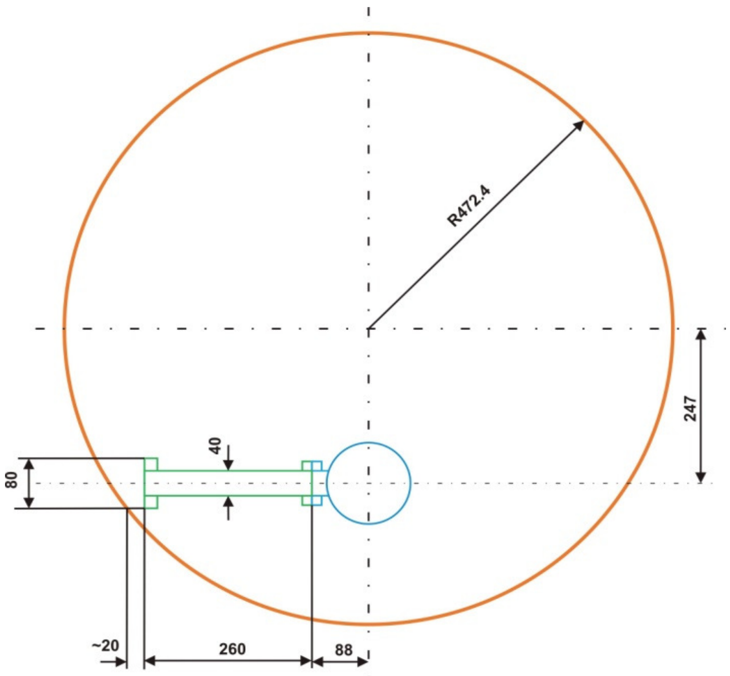
Coupler can be made with adjustable coupling in situ or with fixed coupling. Adjusting is done by moving antenna into cavity volume or moving it out. Not optimal coupling requires additional RF power to keep necessary accelerating gradient of the cavity. At the same time calculations show that power increasing is not significant within quite wide range of coupling changing. For example, if coupling change within 0.6-1.6 (optimal coupling =1), the increasing of power less then 5%. We think the in situ adjusting is not necessary. **Couplers for ProjectX should be with fixed coupling.**

Couplers should be designed for 6 types of cavities and 3 frequencies. **Nevertheless, we has to seek for maximum unification of couplers parts.** We think that one coupler can be used for all 325 MHz cavities. 650MHz and 1300MHz couplers can have common part from cold flange till warm window.

None of existing coupler satisfies these requirements. Couplers have to be design.

A bit more detailed arguments about single window and fixed coupling

Single window



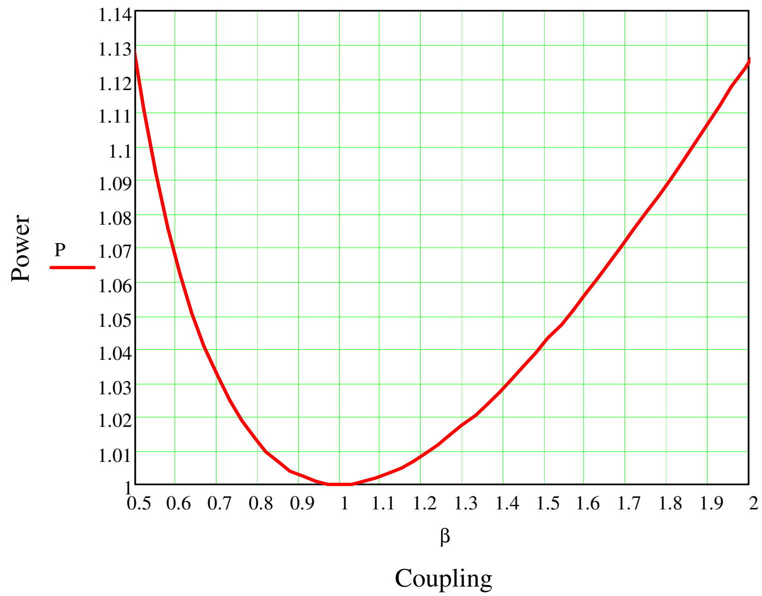
We can install the present 1.3 GHz cavity with RF window in existing ILC-type cryomodule if length from cold flange till window flange is less then ~260mm. Later we will see that it is enough to provide good thermal properties.

Reliability of one window.
Power is rather low for RF breakdown. For example 30kW pulse power can be transmitted without breakdowns through air filled coaxial with 9mm outer diameter. **For all reasonable sizes of coupler we are very far from RF breakdown limit. Window can be destroyed by thermal stress only**. Accurate design and proper cooling will help us to avoid these incidents hopefully.

Fixed coupling

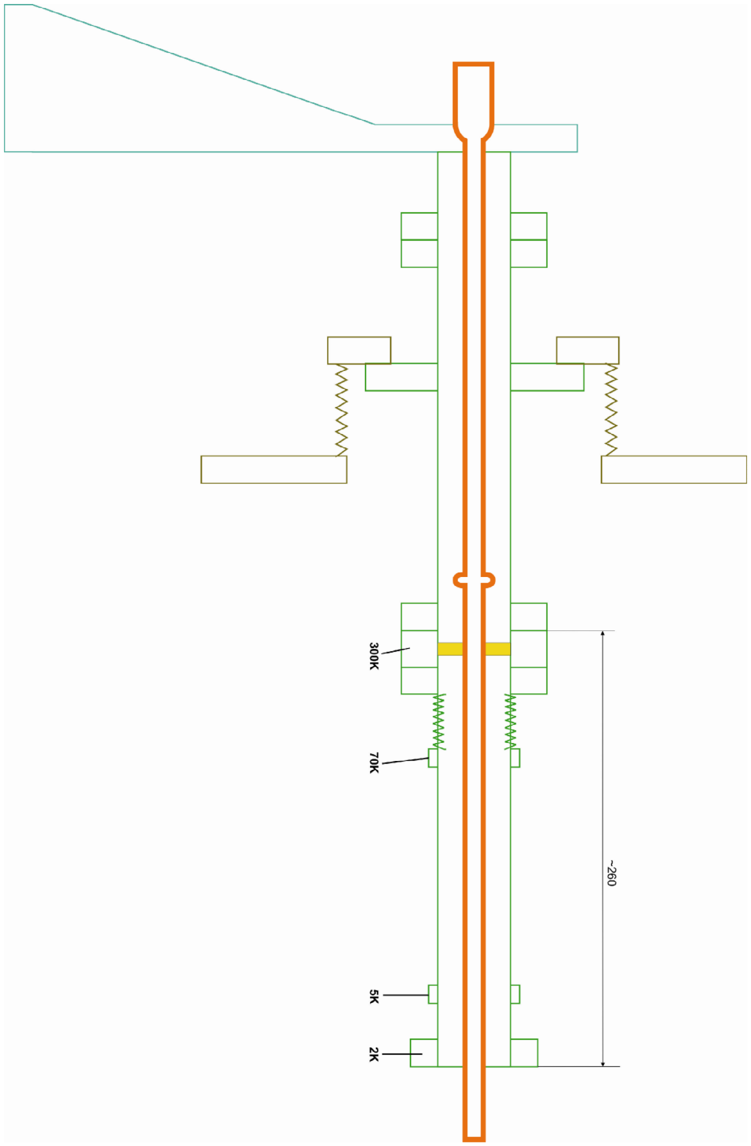
Why do some pulse machine require tunable coupler? The reason that variation of current destroy a pulse fatness if coupling fixed and not optimal (linac works in transient regime). RF power has to adjusted. It is not easy to do because several cavities are fed from one RF source. Cavity is not completely identical , power/coupling of each cavity has to be tuned individually.

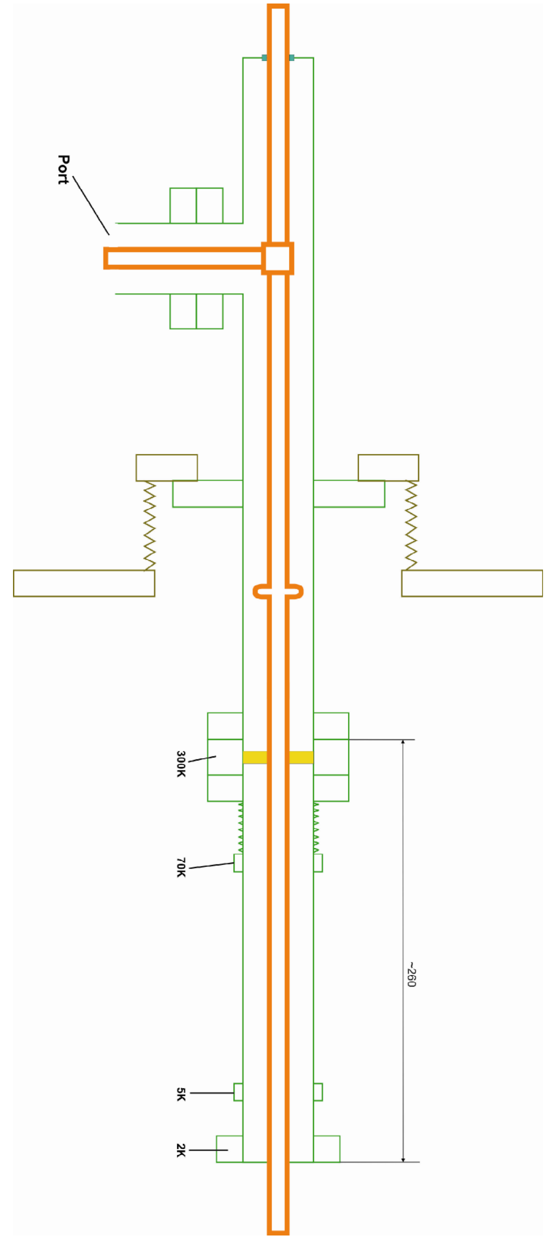
In our case linac works in steady-state regime and each cavity has individual RF source. Payment for wrong coupling is only extra power (part of power reflected back). How much the payment we can understand from graph below:



For example, if we suppose that 5% extra power is exactable, it means that coupling can be in the range 0.64 ≤ β ≤ 1.56. If we make cavity over-coupled from very beginning (β ≈ 1.6) we can increase currant 2.4 times in future (1.56/0.64 = 2.4) without changing the coupling and loosing only 5% power.

As result, possible configurations of coupler with waveguide and coaxial inputs:





Waveguide or coaxial input?

325 MHz – no choice, input is coaxial. Waveguide is too big

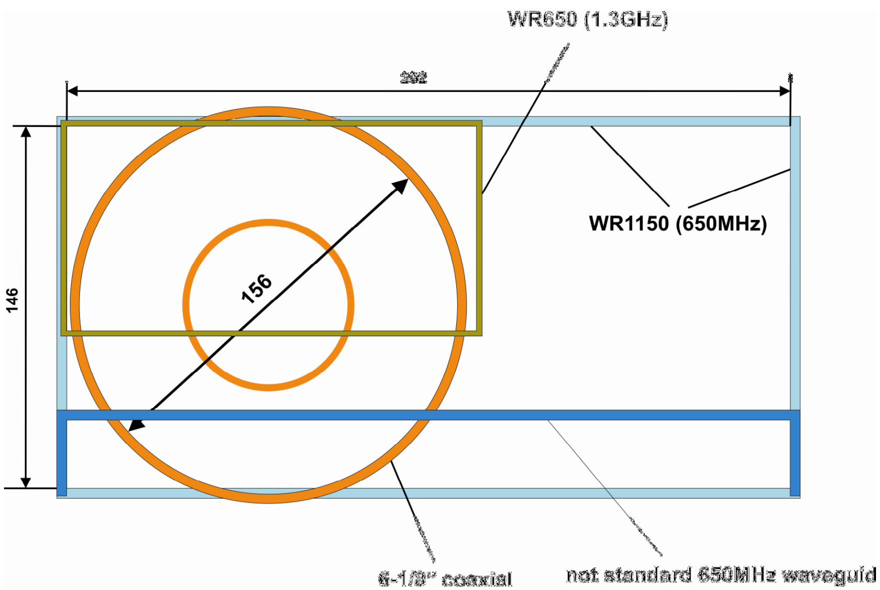
650MHz, 1.3GHz:

RF source will have output power ≈ 30 kW. We need coaxial line, which can operate at this this level of power

Standard coaxial lines:
4-1/16”, Max. CW power (650 MHz) - 33kW
<u>6-1/8’’, Max. CW power (650 MHz) - 57 kW</u>

Standard waveguides:
WR 1150, Max. CW power (650MHz) – 650kW
WR 650,   Max. CW power (1.3GHz) - ≈ 140kW

Cross-section area of feeding line is important: to minimize penetration area in radiation shield.



It is obvious from picture that waveguide has to be used for 1.3GHz

Waveguide with reduced height can be solution for 650 MHz.
(Waveguide has a lot of advantages comparing with coaxial line:
simple topology, higher power, cheaper material
and, probably, line, no problem with oxidation)

Remarks on coupler coaxial sizes choice.

Most important parameter of coupler is heat loading at low temperature. Heat loading depends on RF loss in coupler.

Power loss outer conductor of coaxial line:

$$P_{outer} \sim \frac{1}{R_{2\,\ln\frac{R_2}{R_1}}} \sim \frac{1}{R_2}\frac{1}{Z_L}$$

Power loss in inner conductor of coaxial line:

$$P_{inner} \sim \frac{1}{R_{1\,\ln\frac{R_2}{R_1}}} \sim \frac{1}{R_1}\frac{1}{Z_L}$$

It is important the outer conductor for us because it is connected directly to 2K flange of cavity. With fixed R2, for example, we has to increase Z of coaxial (decrease diameter of inner conductor) as much as possible to decrease loss in outer conductor.

Remarks on choice of window ceramic thickness.

Previous experience with Al203 ceramic plain RF window:

S-band pill-box windows.
Ceramic diameter ~80mm, ceramic thickness < 3mm.
Typical pulse power - several tens MW
Average power - several kW

X-bend pill- box window
Ceramic diameter ~50mm, ceramic thickness < 3mm.
Tested pulse power – 80MW
Tested average power - several kW

S-band pill-box TW window
Ceramic diameter ~80mm, ceramic thickness ~ 7mm.
Tested pulse power ~ 500 MW
Tested average power ~ 50 kW

X-bend pill- box TW window
Ceramic diameter ~70mm, ceramic thickness < 3mm.
Tested pulse power – 25MW
Tested average power - several kW

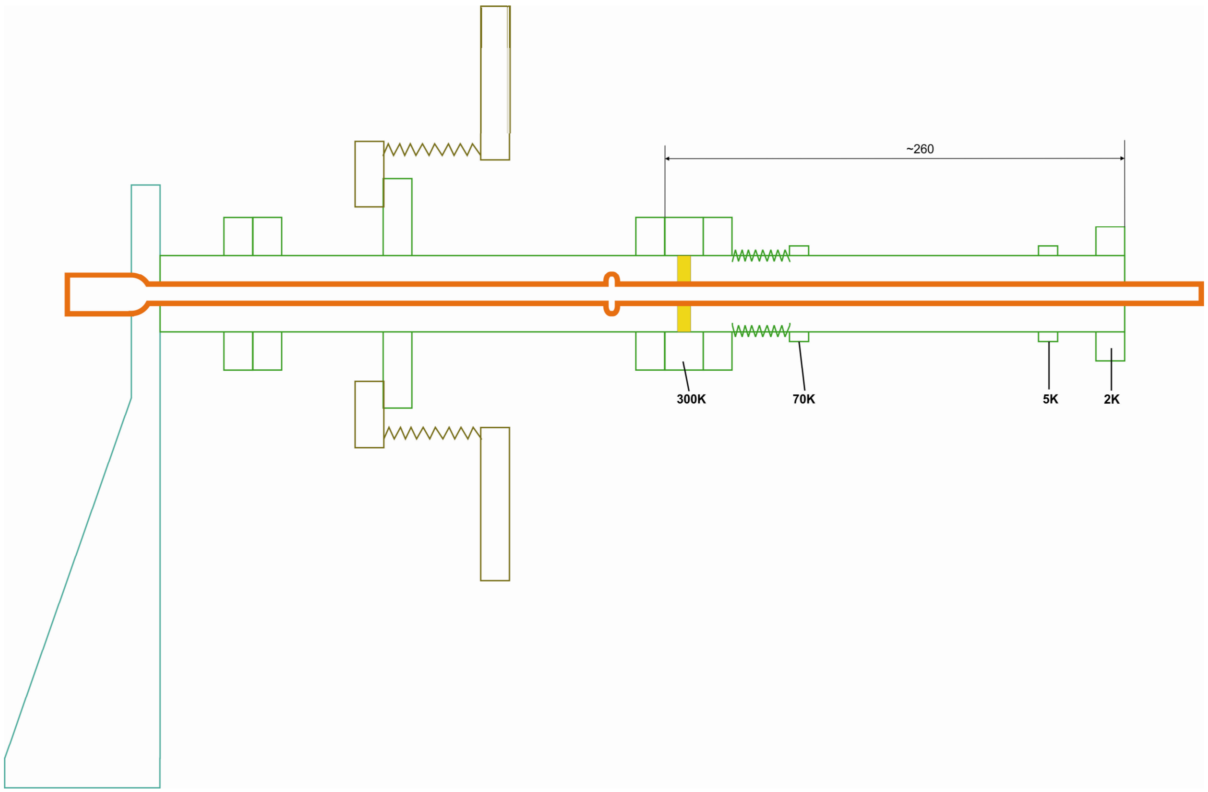
Windows with ceramic D ≈ 80mm and thickness ≈ 3mm work reliably.

In coupler case a thick window decreases passband, decreases transparency at other frequencies.

Thickness of ceramic for coupler was chosen 5 mm (it can not be too thin, it supports and aligns inner conductor)

Boundary conditions for design 1.3 GHz coupler.

- has to be comparable with present 1.3 GHz cavity (D40mm input);
- has to be compatible with ILC type cryomodule;
- 20-30 kW power level;
- less then ≈ 1W heat load at 2K;
- single window;
- waveguide input;



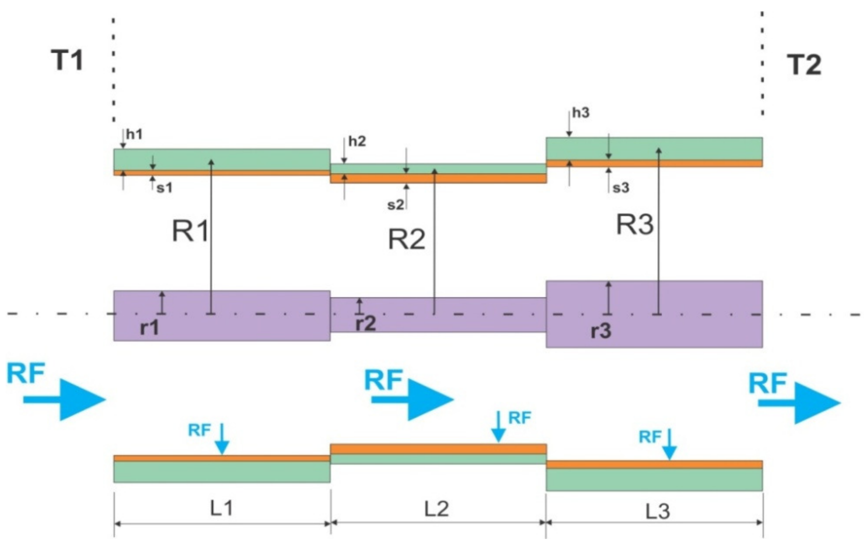
Chose of coaxial sizes.

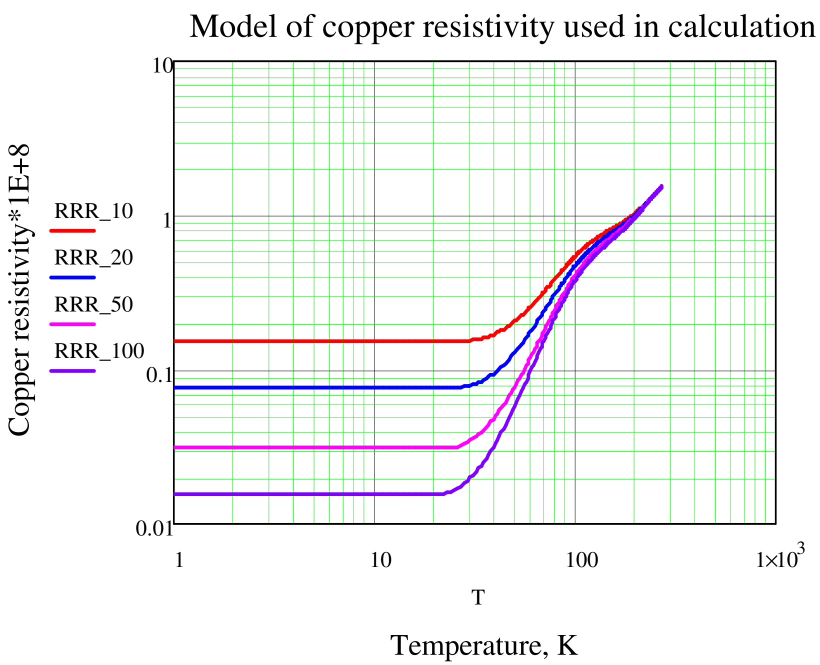
Outer pipe is standard stainless steel pipe with diameter closest to 40mm. It is 1-3/4'' pipe.
Outer diameter 1-3/4'' (44.45mm)
Wall thickness   0.065'' (1.651mm)
Inner diameter   (41.148mm)
Pipe coated by copper ≈ 0.01mm

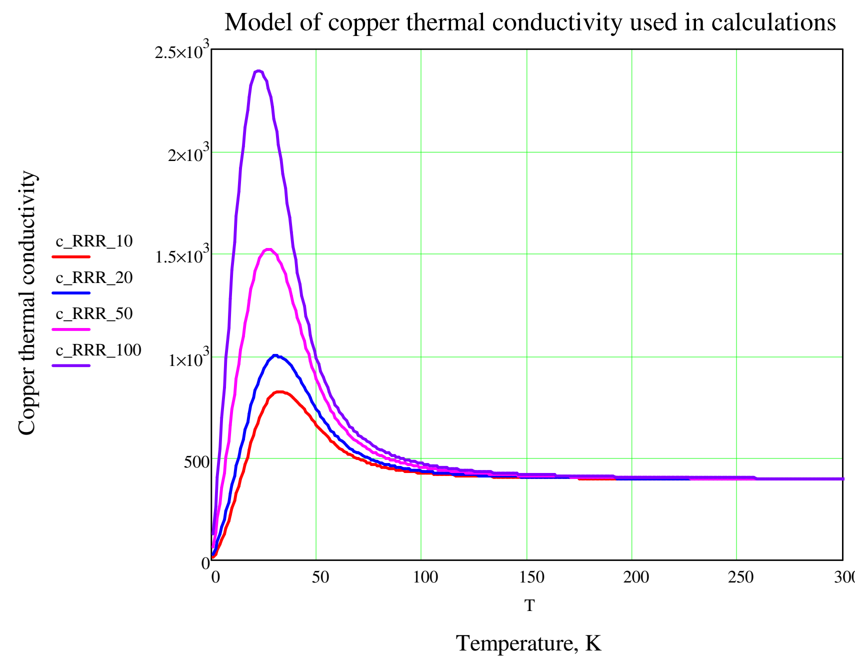
Inner conductor.
It is supposed that inner conductor will be air-cooled. Probably it is difficult to install air-cooling system if diameter too small, < 10mm. Standard OFC pipe with diameter 1/2'' (12.7mm) was chosen as inner conductor.
Wall thickness 0.0625'' (1.59mm) or 0.035''(0.89mm)

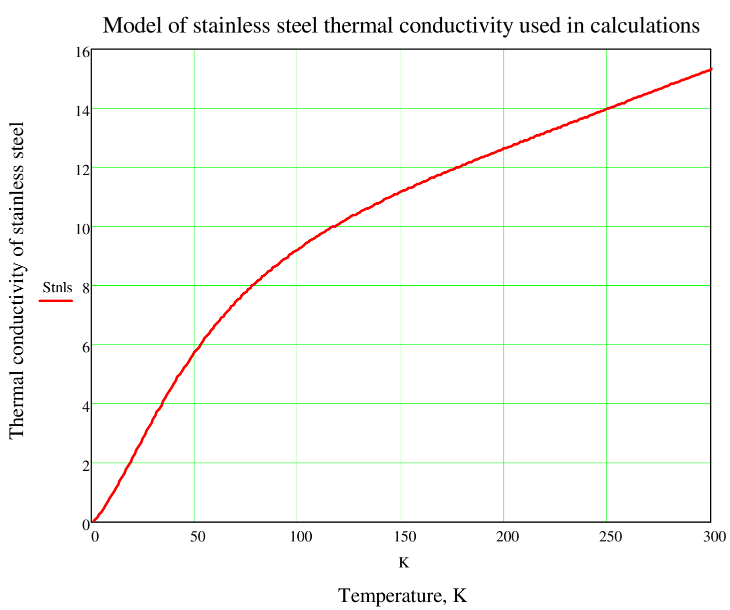
Thermal analyses of outer conductor.

It was written code to simulate heat flow in coaxial which consist of several macro-parts. Each macro-parts is divided into many (~100) micro –parts. Each micro-parts consist of two materials with different thermal properties.





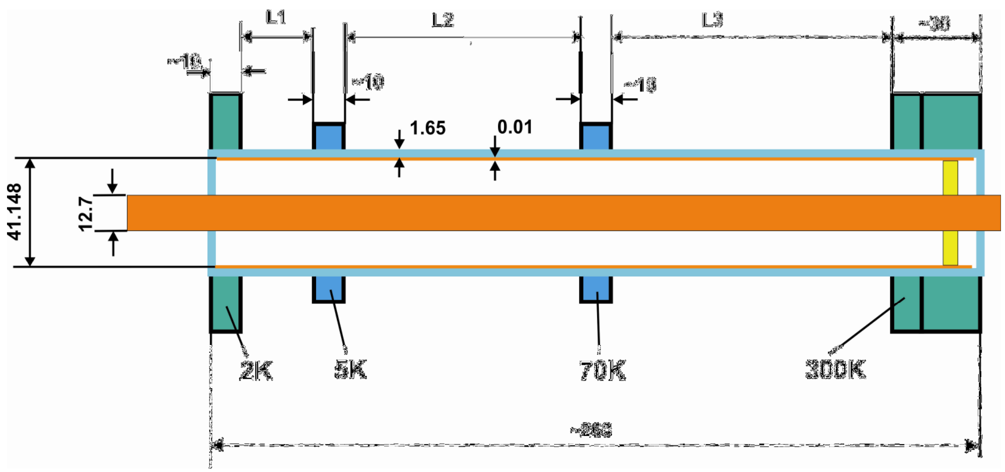


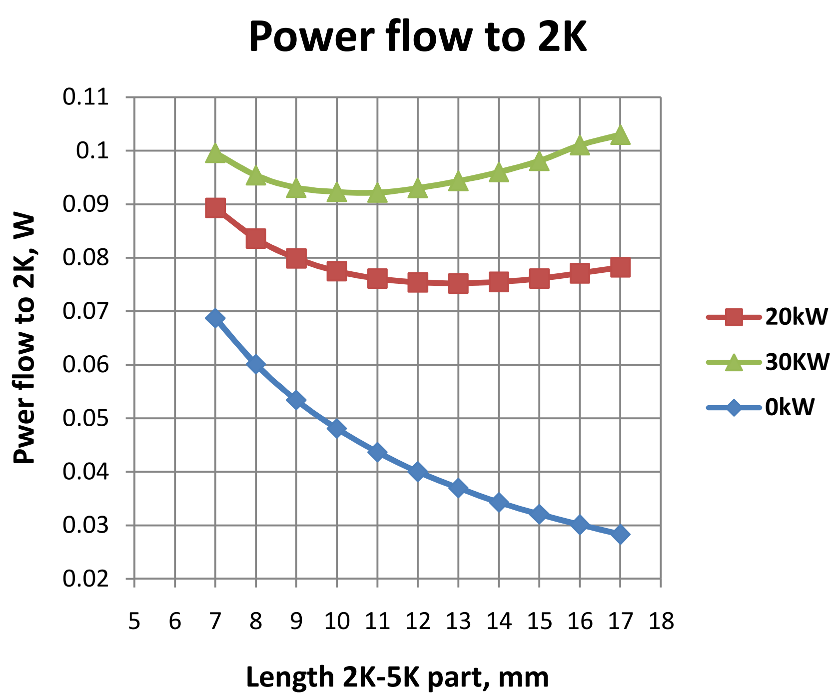


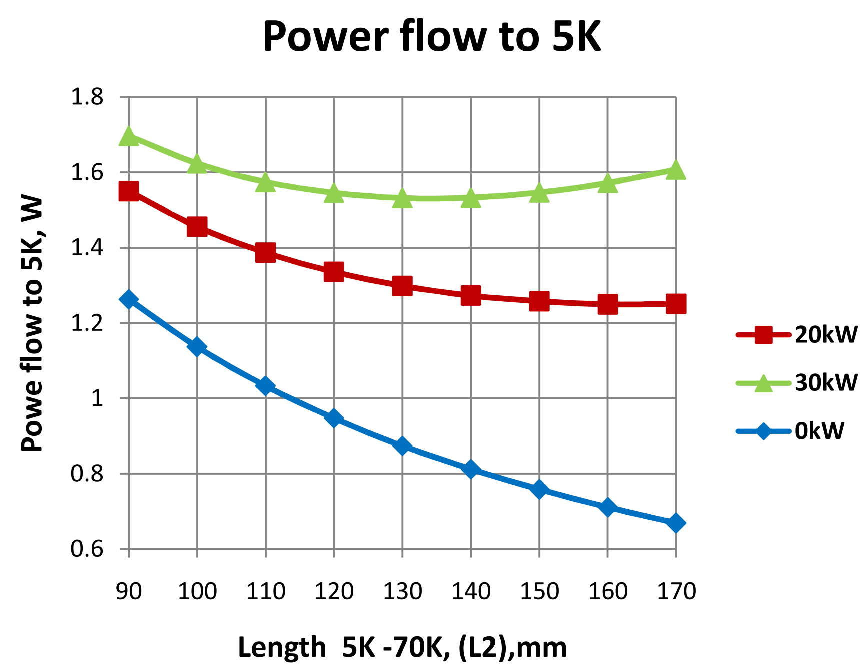
For simulation of thermal conductivity RRR of copper was chosen as 15. It is coating and to get good RRR is not easy.

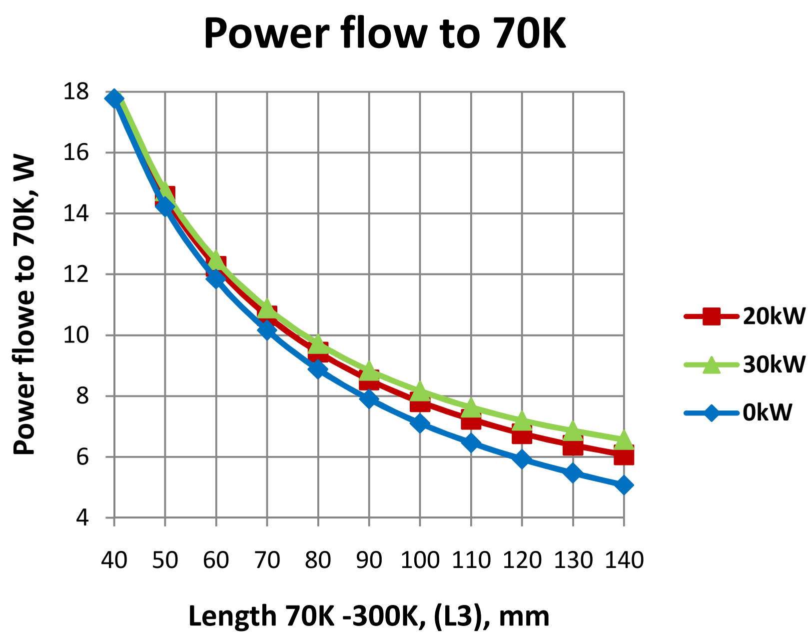
For electro-conductivity of copper the limit was chosen 12 –abnormal skin-effect.

Several different configuration were analyzed. Conclusion: two thermo-anchors are necessary:



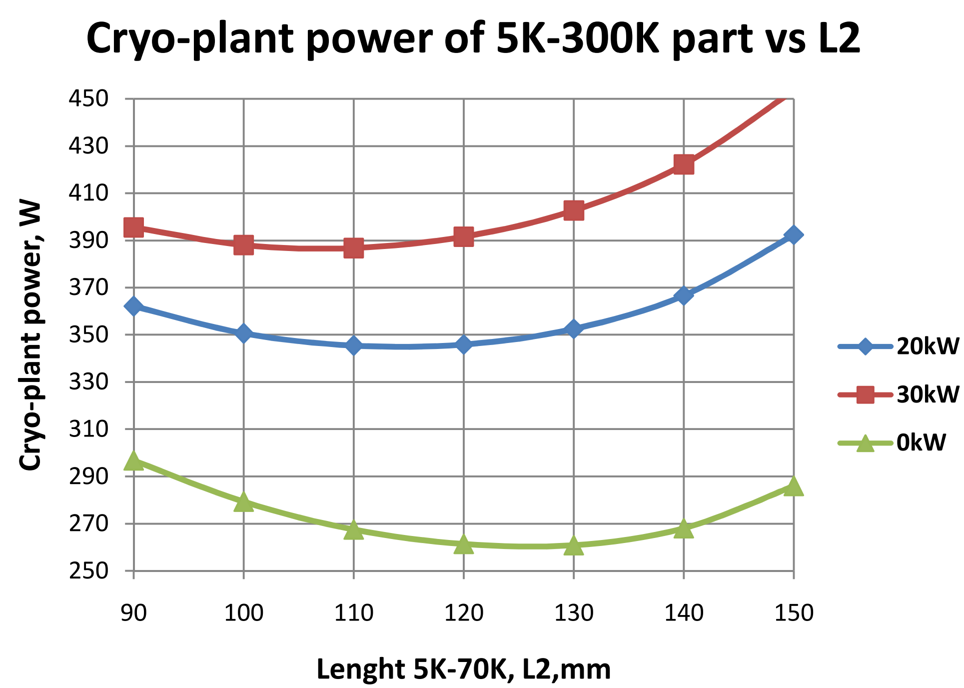




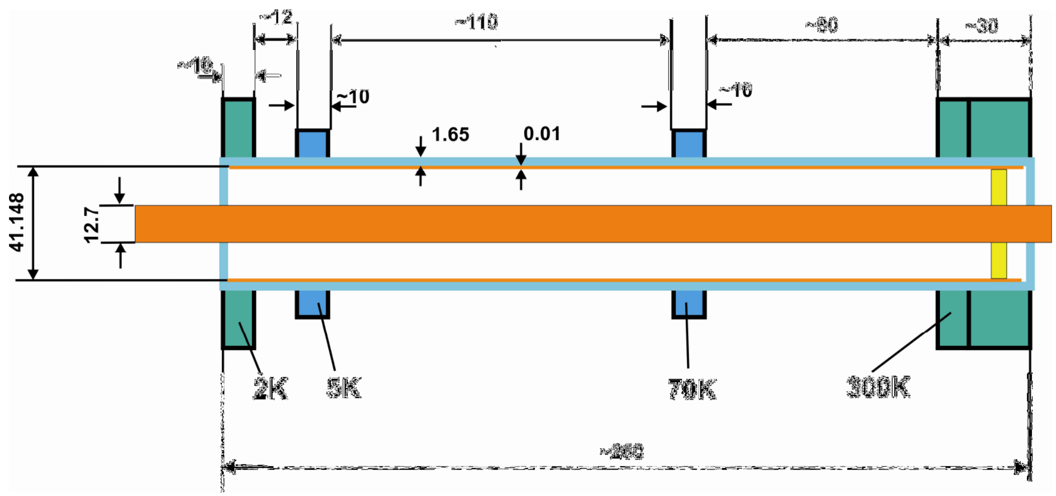


We should minimize total power of kryo-plant.

Converting coefficient were chosen as:
703 for 2K, 198 for 5K, 16 for 40K (Slava Yakovlev).
For 70K the coefficient 8 was chosen.



Optimum geometry of "cold" part.



1.3 GHz

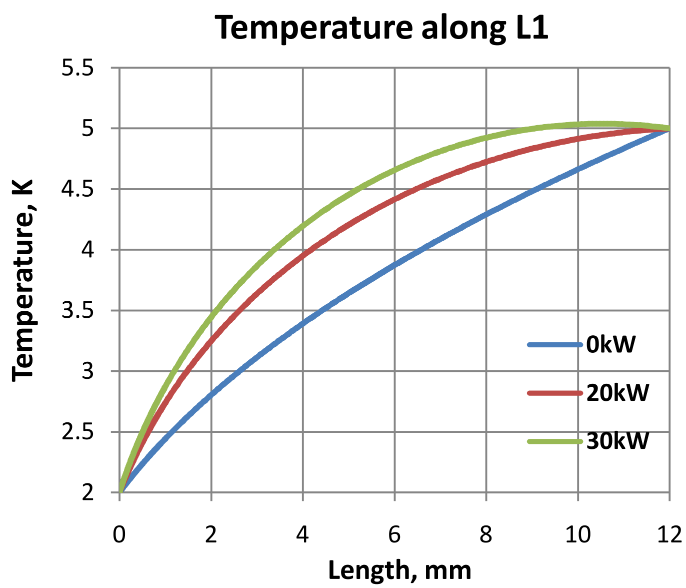
	2K (Flow/Plant),W	5K(Flow/Plant),W	70K(Flow/Plant),W	Total plant,W
RF = 0kW	0.04 / 28.1	0.99 / 196	7.85 / 62.8	287
RF = 20kW	0.075 / 52.7	1.38 / 273.2	8.84 / 70.7	397
RF = 30kW	0.093 / 65.4	1.59 / 314.8	9.36 / 74.9	455

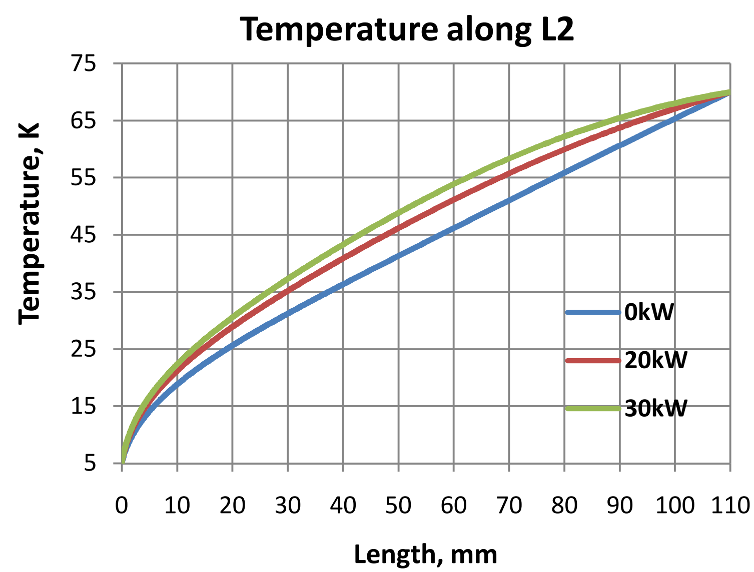
650 MHz

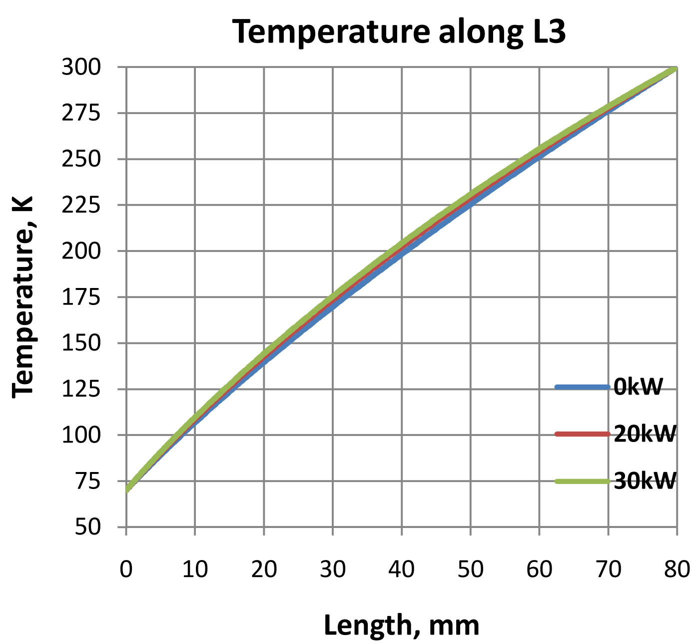
	2K (Flow/Plant),W	5K(Flow/Plant),W	70K(Flow/Plant),W	Total plant,W
RF = 0kW	0.04 / 28.1	0.99 / 196	7.85 / 62.8	287
RF = 20kW	0.065 / 45.7	1.27 / 251.5	8.55 / 68.4	366
RF = 30kW	0.078/ 54.8	1.41 / 279.2	8.87 / 71.0	405

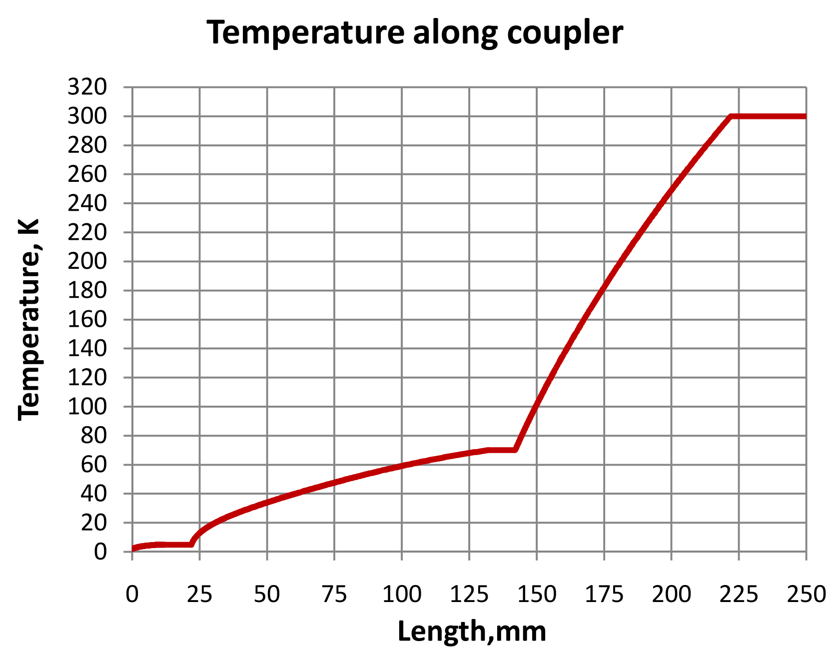
Expected power plant for cavity cooling is ≈20W x 703 ≈ 15kW.
Coupler contribution will be 3-4 % .

Temperature distribution





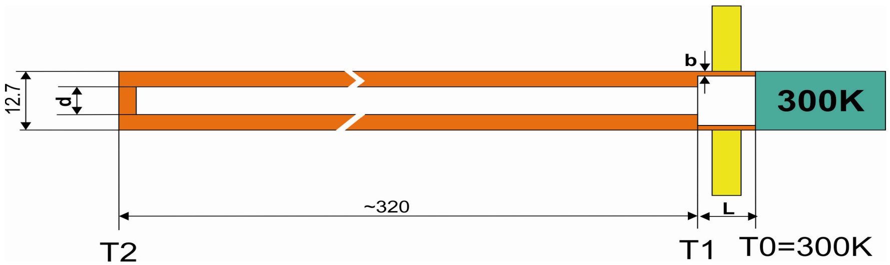




Inner conductor

Diameter	12.7mm
Length	≈ 320mm
Loss 1.3GHz	21.4W/20kW, 32.1W/30kW
Loss 650MHz	15.1W/20kW, 22.7W/30kW

Let's consider inner conductor without air cooling. Cooling is done through end of conductor:

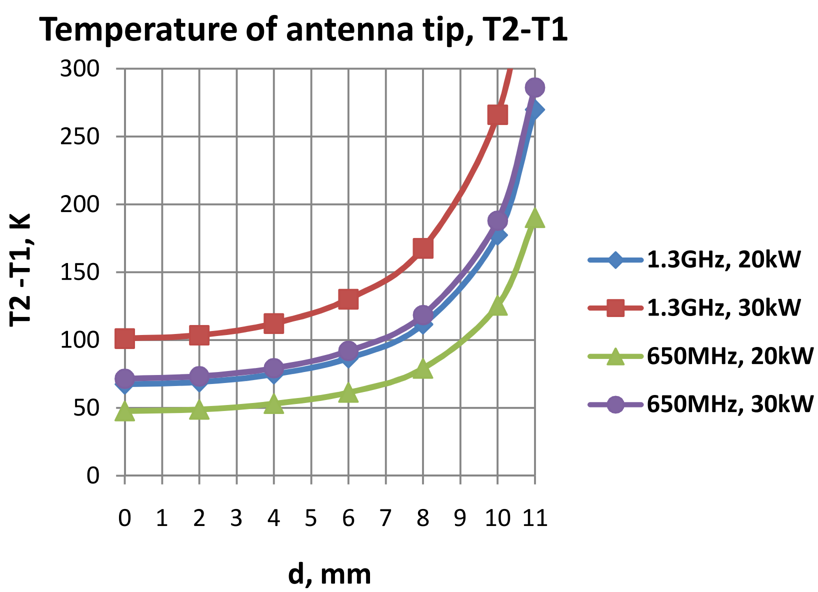


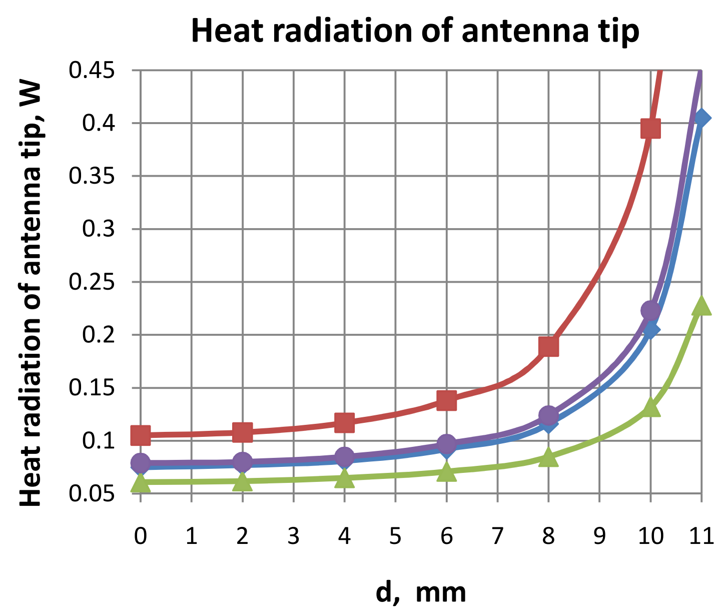
$$\Delta T1 = T1 - T0 = \frac{P * L}{\lambda * 2\pi R b}$$

λ – copper thermal conductivity

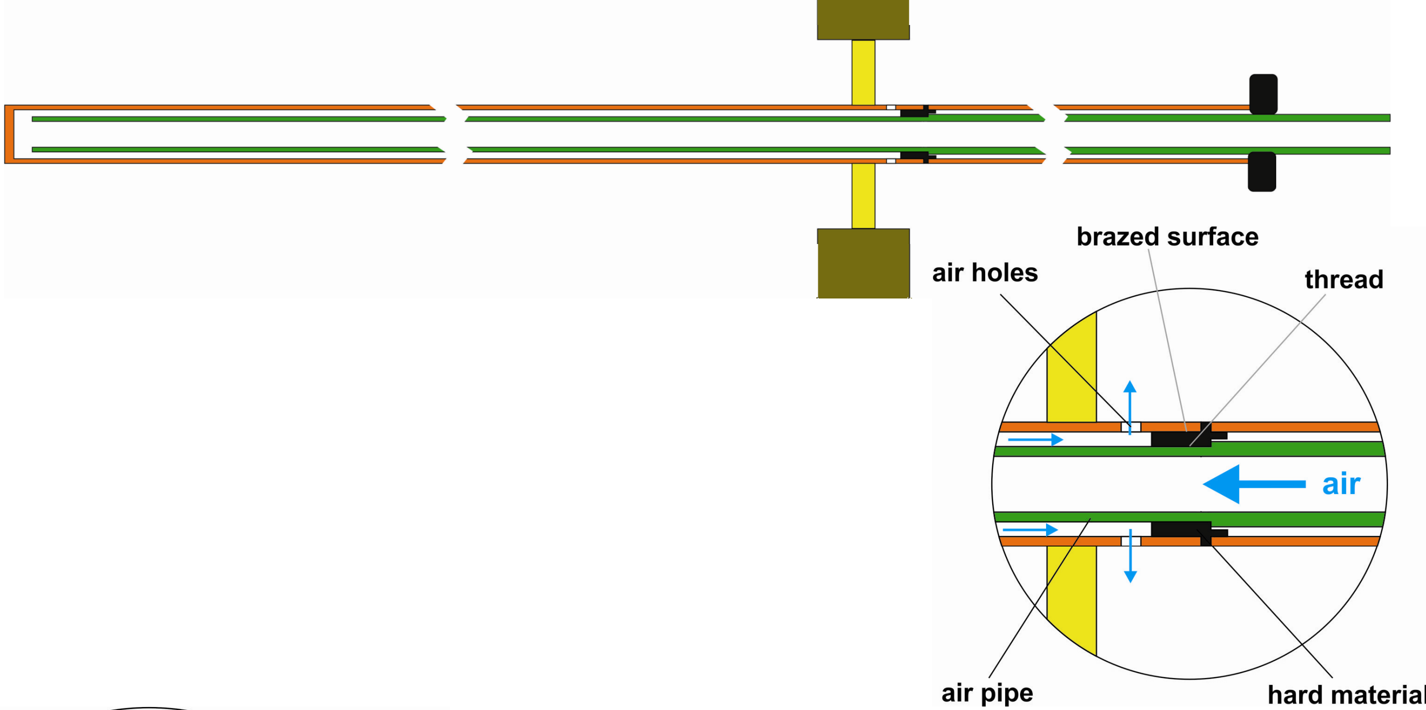
ΔT1(20W) = 14K, ΔT1(30W) = 20K

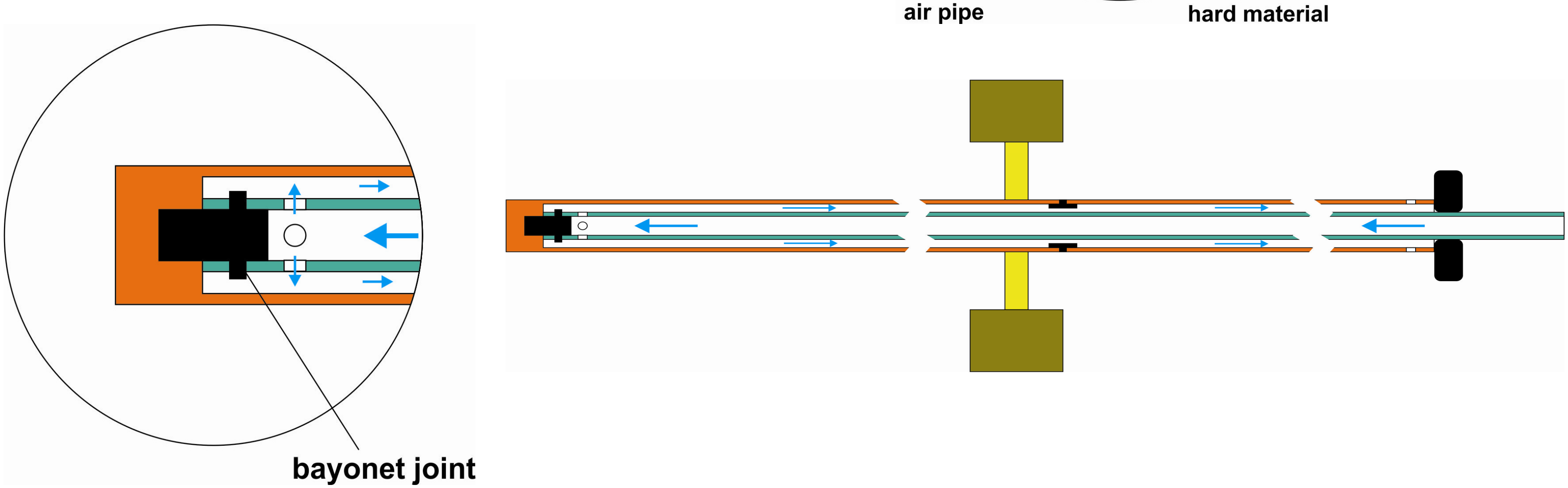
Emissivity of copper was chosen as 0.02. This value corresponds mirror polished copper (electro-polished).
Length of radiating part is 75mm





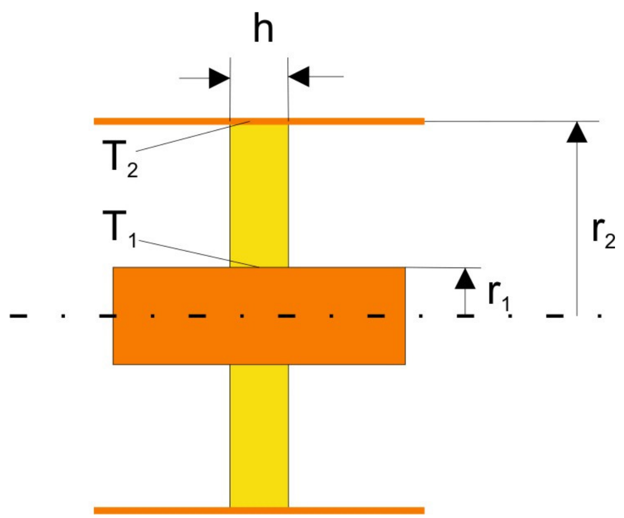
Possible air-cooling schemes of antenna:





Loss in ceramic window, ceramic heating.

Window geometry:



r1 = 5 mm
r2 = 20 mm
h = 6 mm

Ceramic properties:

$\varepsilon = 9.8$ Permittivity

δ Loss tangent

k Thermal conductivity

Pin = 20kW – transmitted power

$P_{lss} = 1.49 \cdot \delta \cdot P_{in}$ Loss in ceramic window (HFSS)

T1, T2 – temperatures of inner and outer surfaces of ceramic

Solution of thermal conductivity equation in case of the electric field dependence E(r) = E0/r:

$$T(r) = T_1 + \frac{\ln\left(\frac{r}{r_1}\right)}{\ln\left(\frac{r_2}{r_1}\right)}\left(T_2 - T_1 + \frac{P_{lss}}{4\pi hk}\ln\left(\frac{r_2}{r}\right)\right)$$

Power flow through inner surface: $$P_1 = -\frac{2\pi kh(T_2 - T_1)}{\ln\left(\frac{r_2}{r_1}\right)} - \frac{P_{lss}}{2}$$

Power flow through outer surface: $$P_2 = -\frac{2\pi kh(T_2 - T_1)}{\ln\left(\frac{r_2}{r_1}\right)} + \frac{P_{lss}}{2}$$

Good ceramic:

$$\delta = 0.0001$$

$$k = 35$$

T1 = T2 = 300K

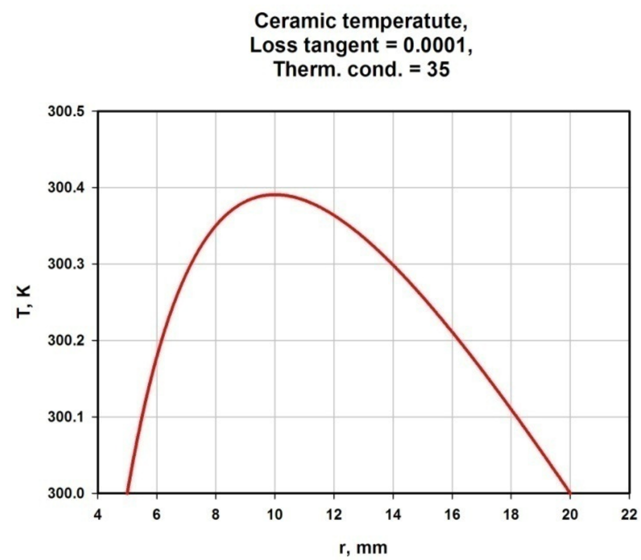
Ploss = 2.98 W

P1 = P2 = 1.49 W

Density of power flow:

P1/S1 = 0.79 W/cm2

P2/S2 = 0.20 W/cm2



Not so bad ceramic:

$$\delta = 0.0003$$
$$k = 30$$

T1 = T2 = 300K

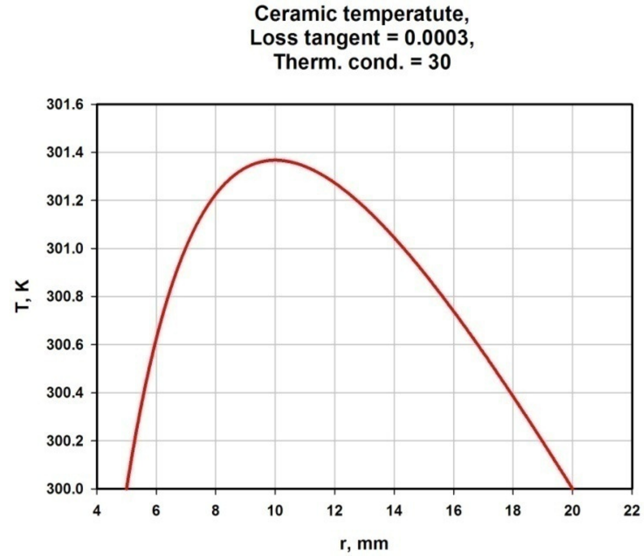
Ploss = 8.92 W

P1 = P2 = 4.46 W

Density of power flow:

P1/S1 = 2.37 W/cm2

P2/S2 = 0.59 W/cm2



Bad ceramic:

$$\delta = 0.001$$
$$k = 20$$

T1 = T2 = 300K

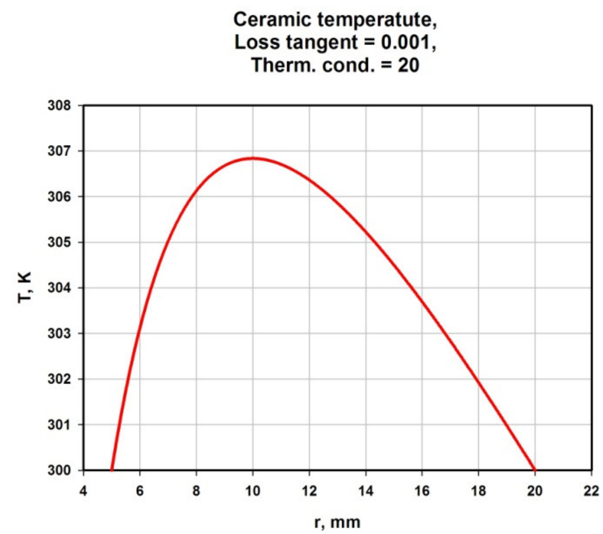
Ploss = 29.8 W

P1 = P2 = 14.9 W

Density of power flow:

P1/S1 = 7.90 W/cm2

P2/S2 = 2.0 W/cm2



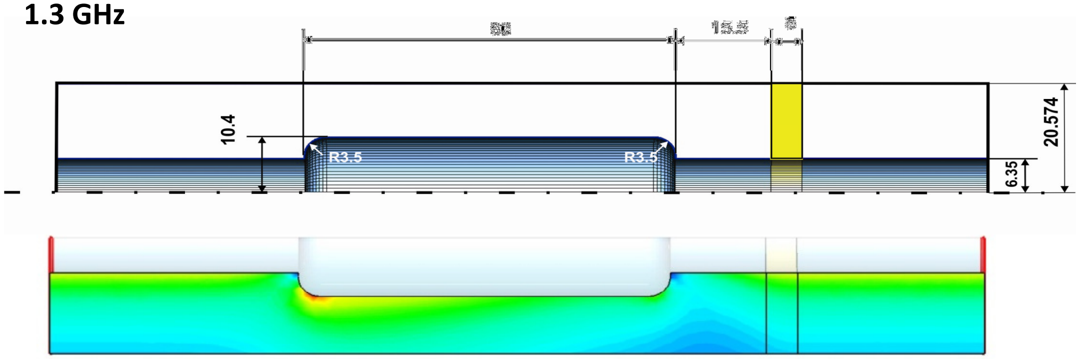
Conclusions:
It seems we have no problem with ceramic window in case of good ceramic

Air side of coupler

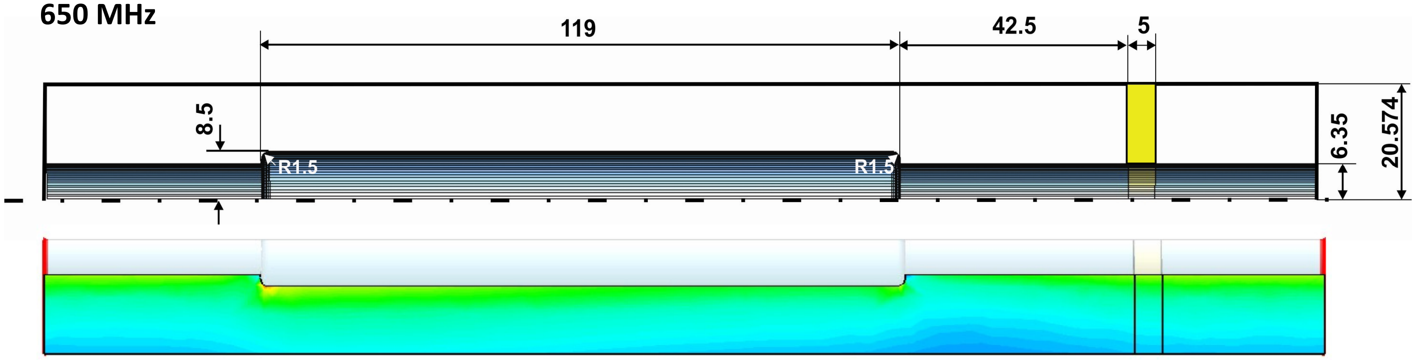
Coaxial window has to be matched. All matching elements were decided to put in air side to keep vacuum side geometry as simple as possible – to avoid multifactor in complicated geometry. Second – the simpler geometry, the better quality of surface (coating) , less RF loss.

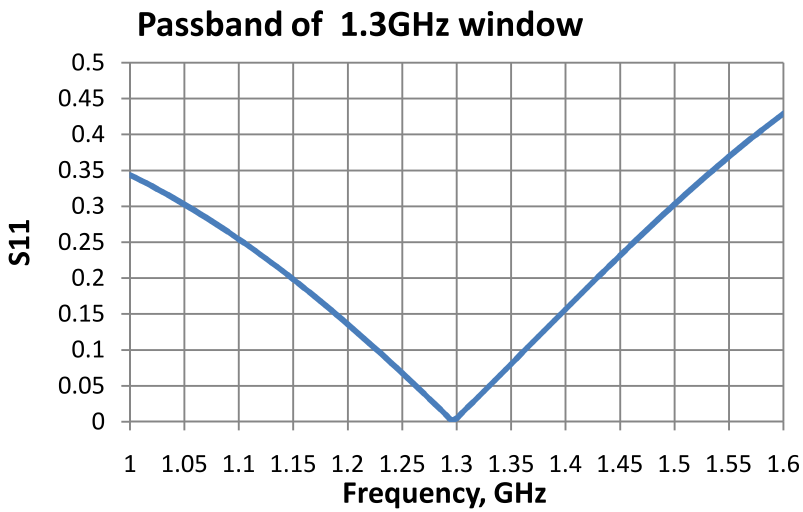
Several matching geometries were considered. It was found that optimal ones are long 1/4 wavelength matchers. They provide maximum transparency at different frequencies (to load HOMS) and minimum electric field in the surface.

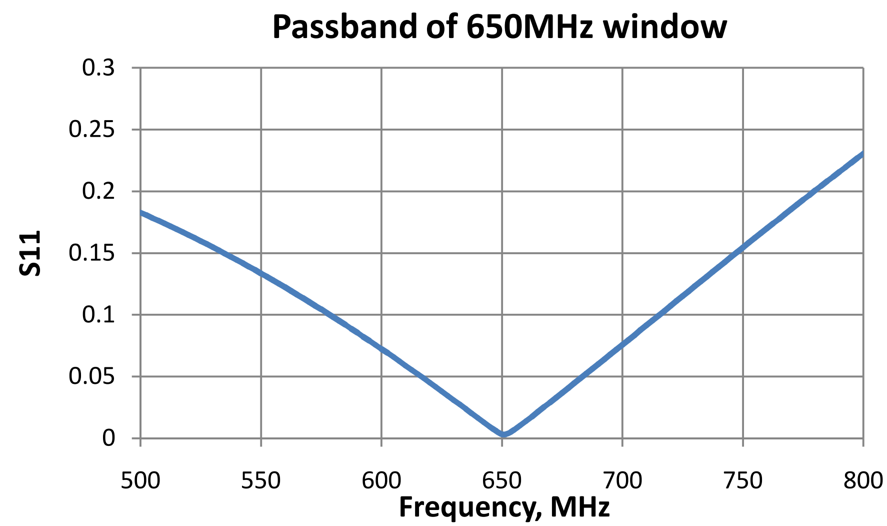
1.3 GHz

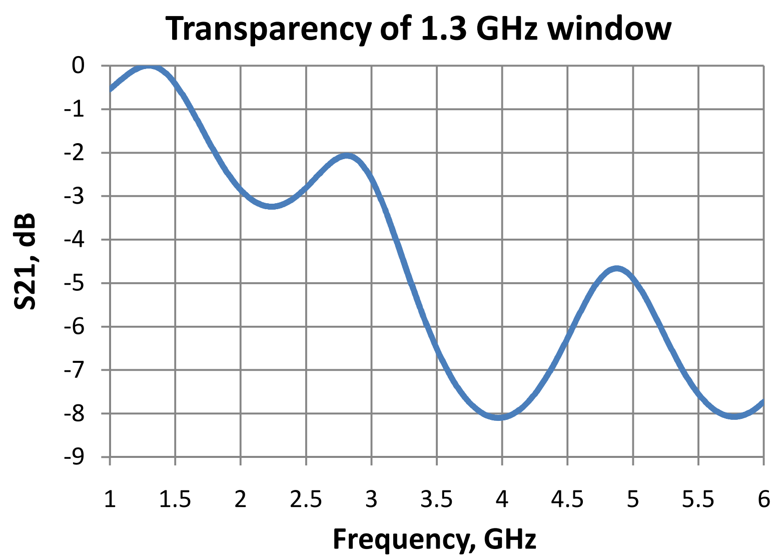


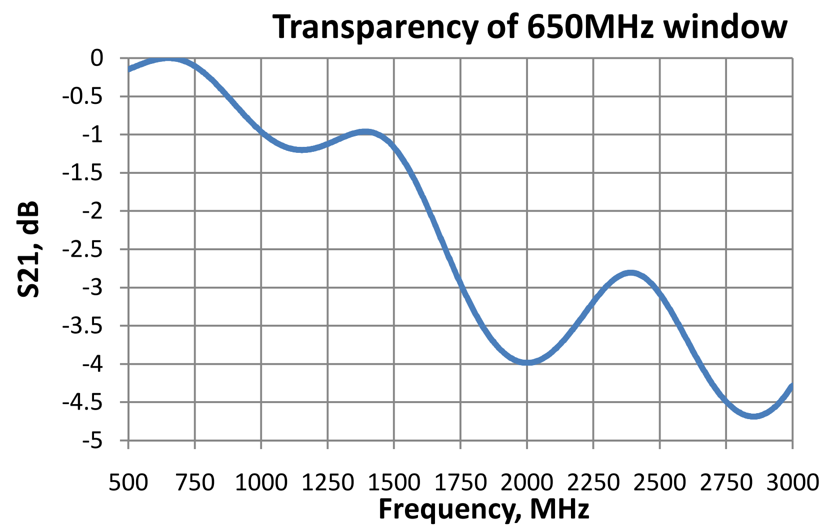
650 MHz







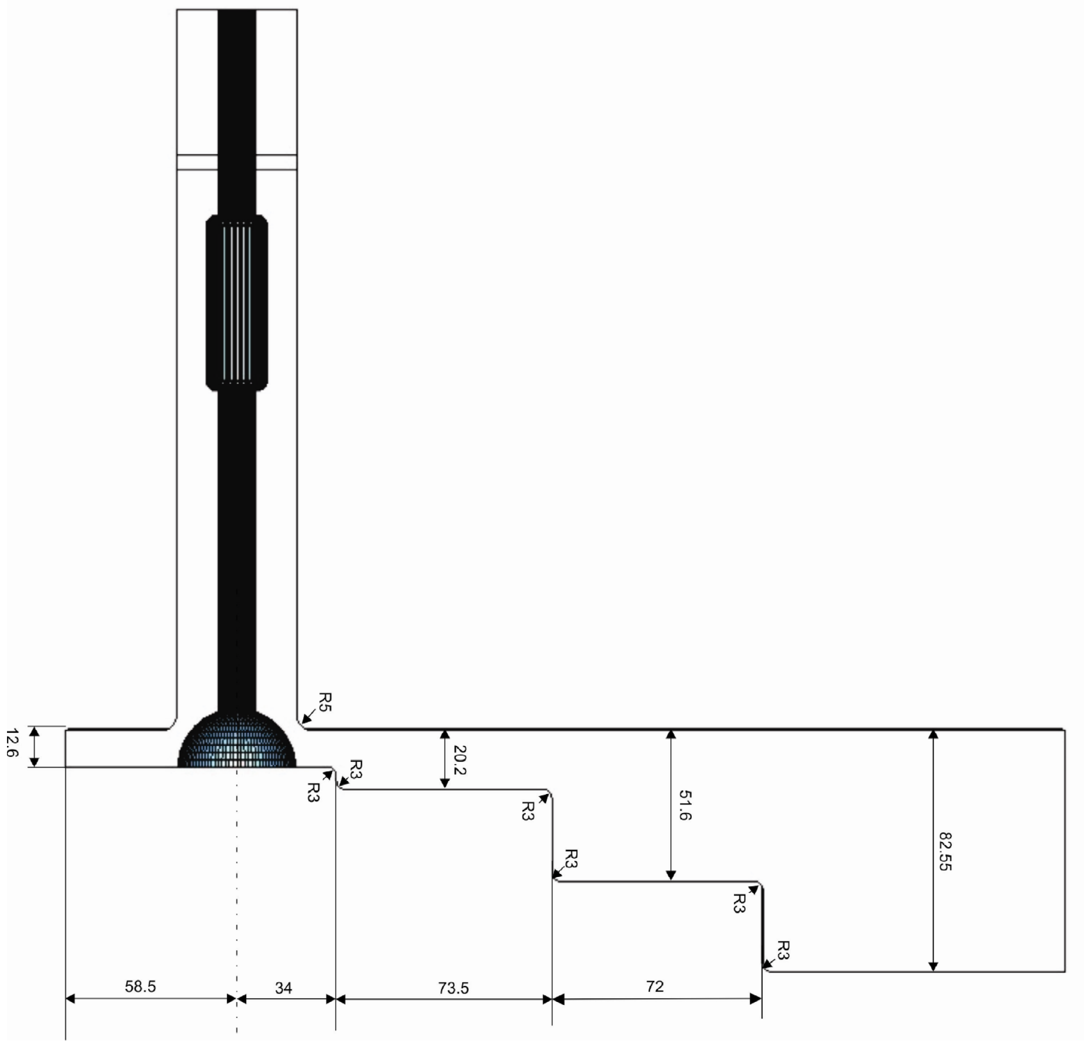


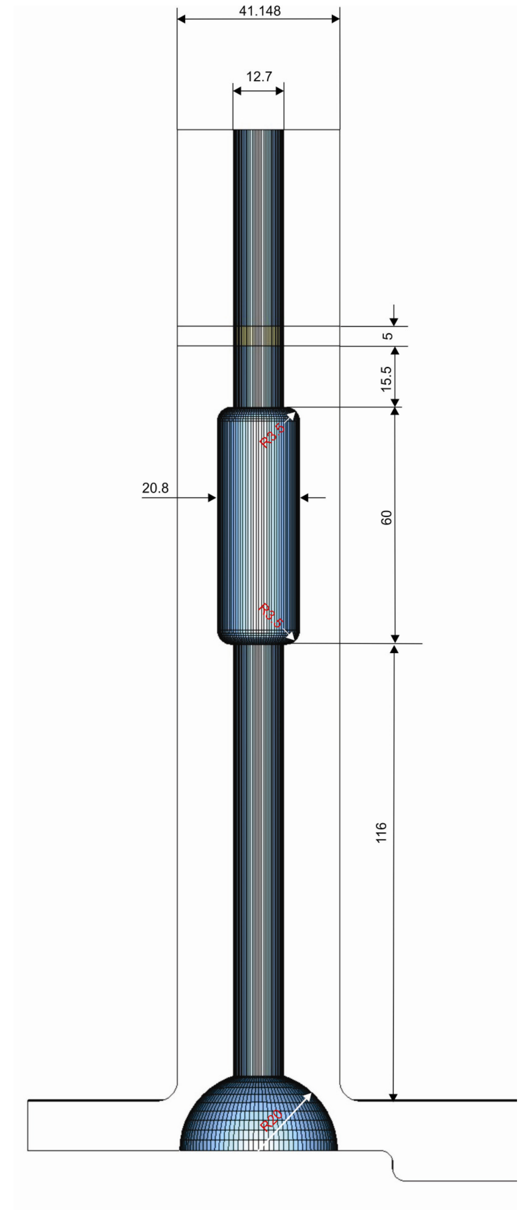


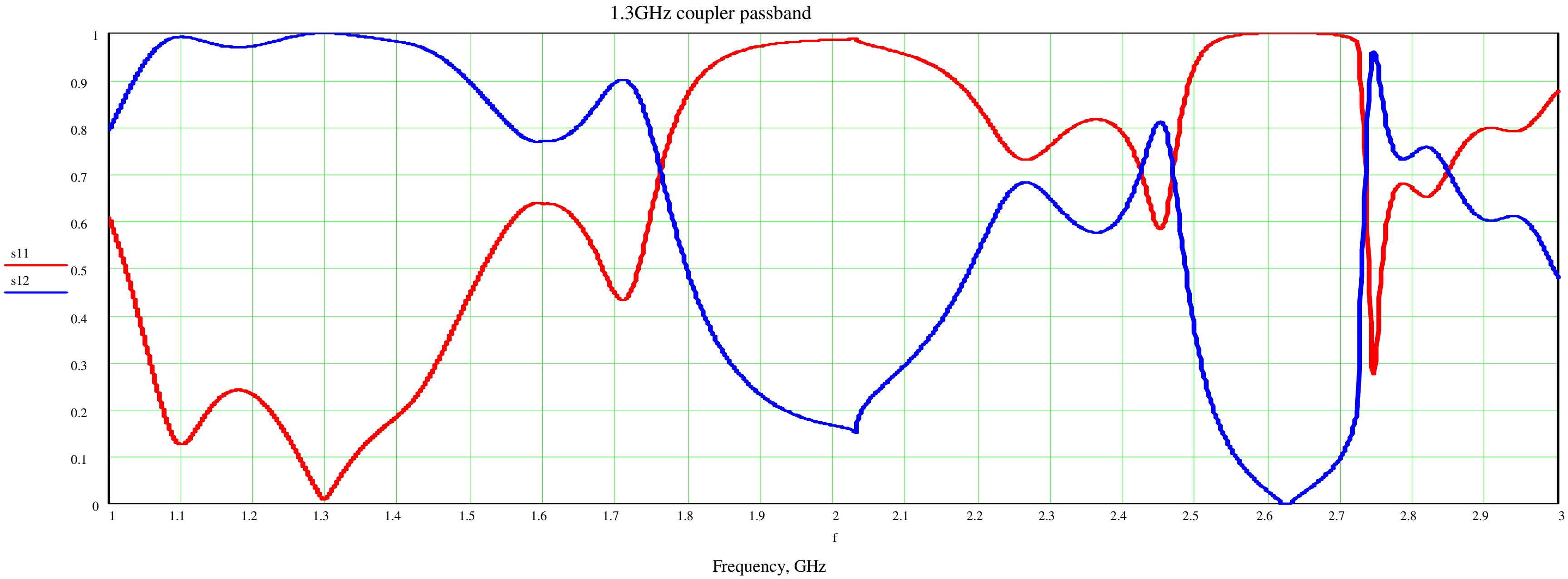
	Passband , S11<0.1, MHz	Max. E-field on the surface, RF power = 20 kW, kV/cm
1.3 GHz window	140	3.27
650 MHz window	140	3.36

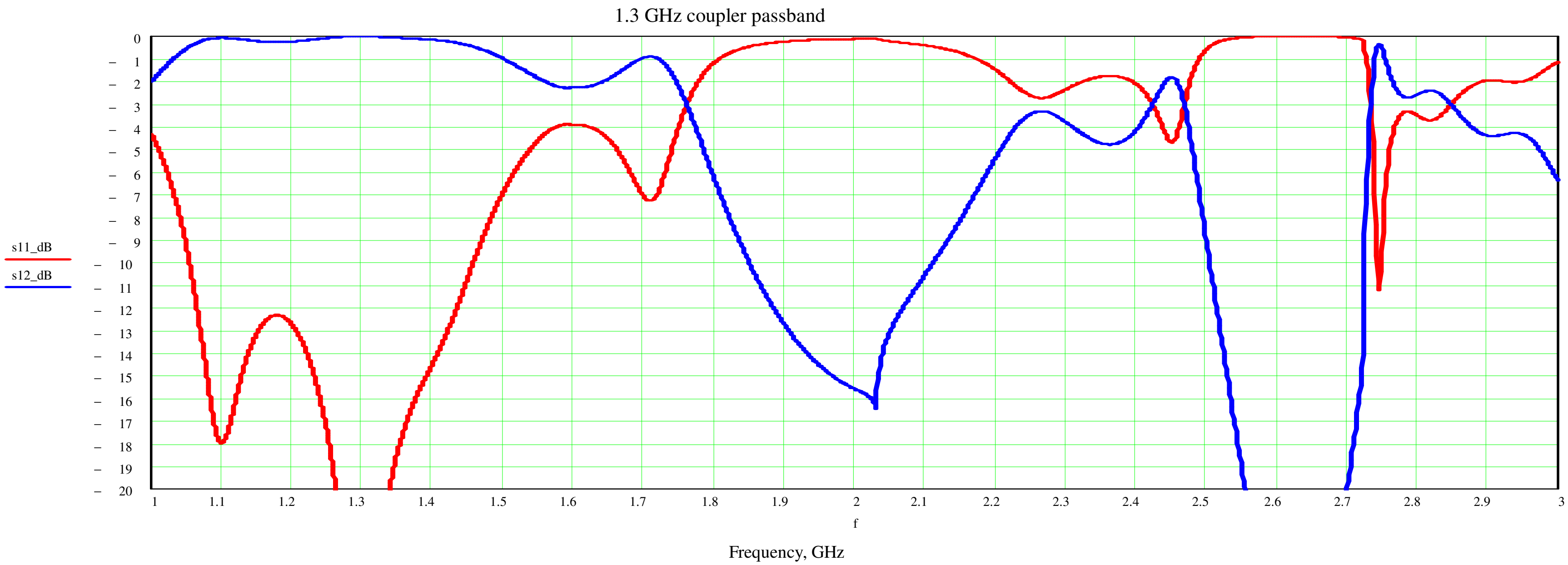
Waveguide – to – coaxial adapter (WCA)

Skipping details, final geometry:

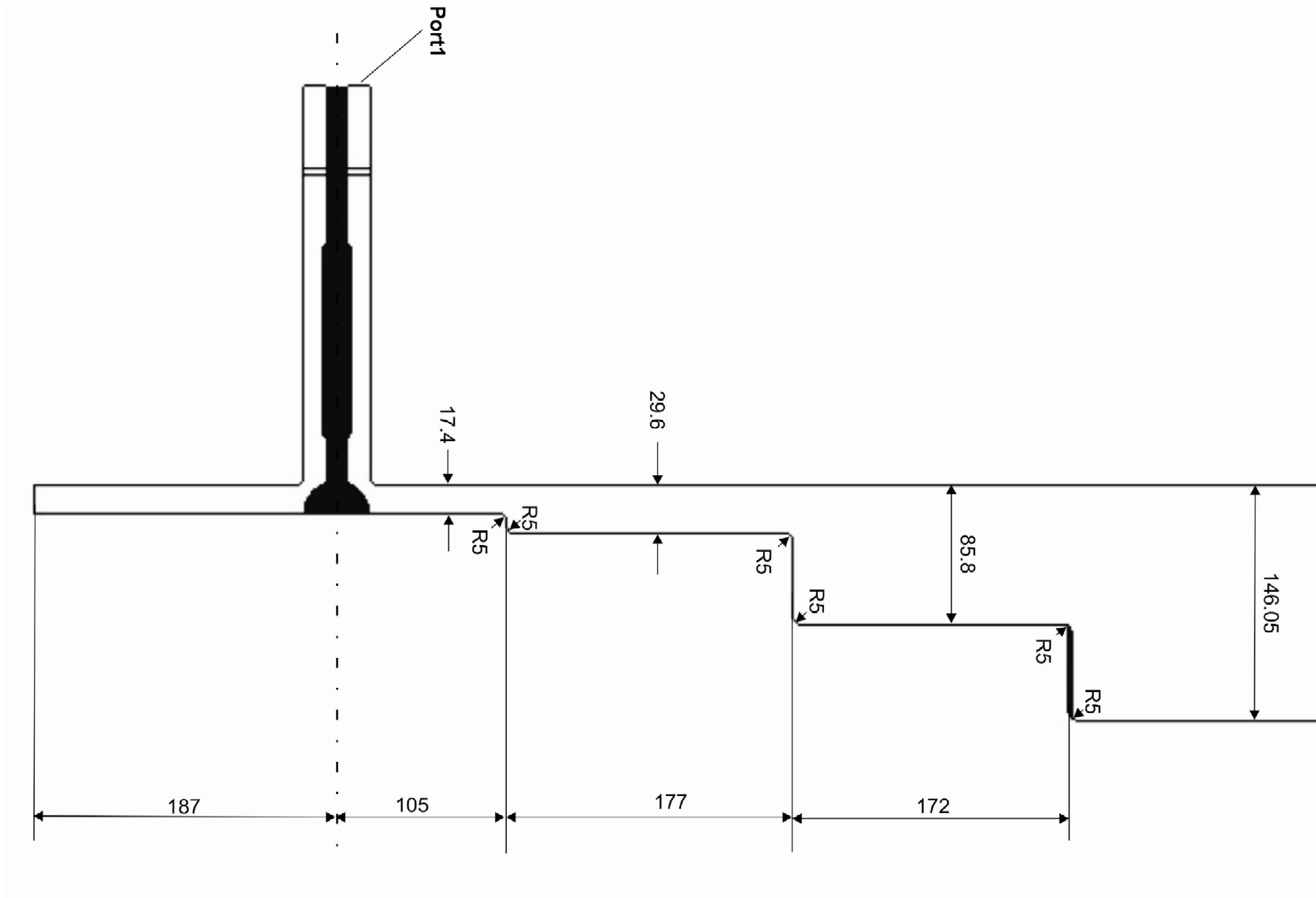


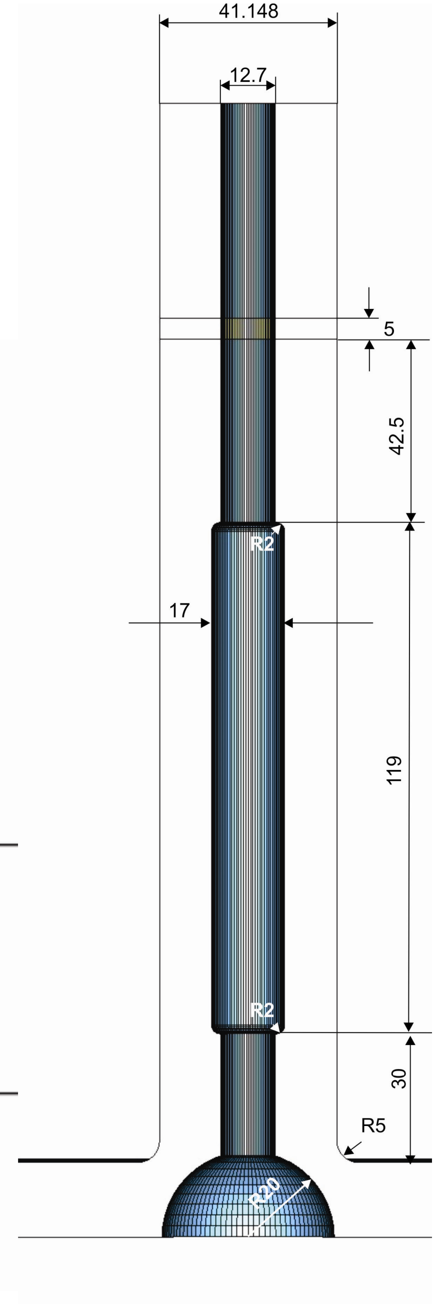


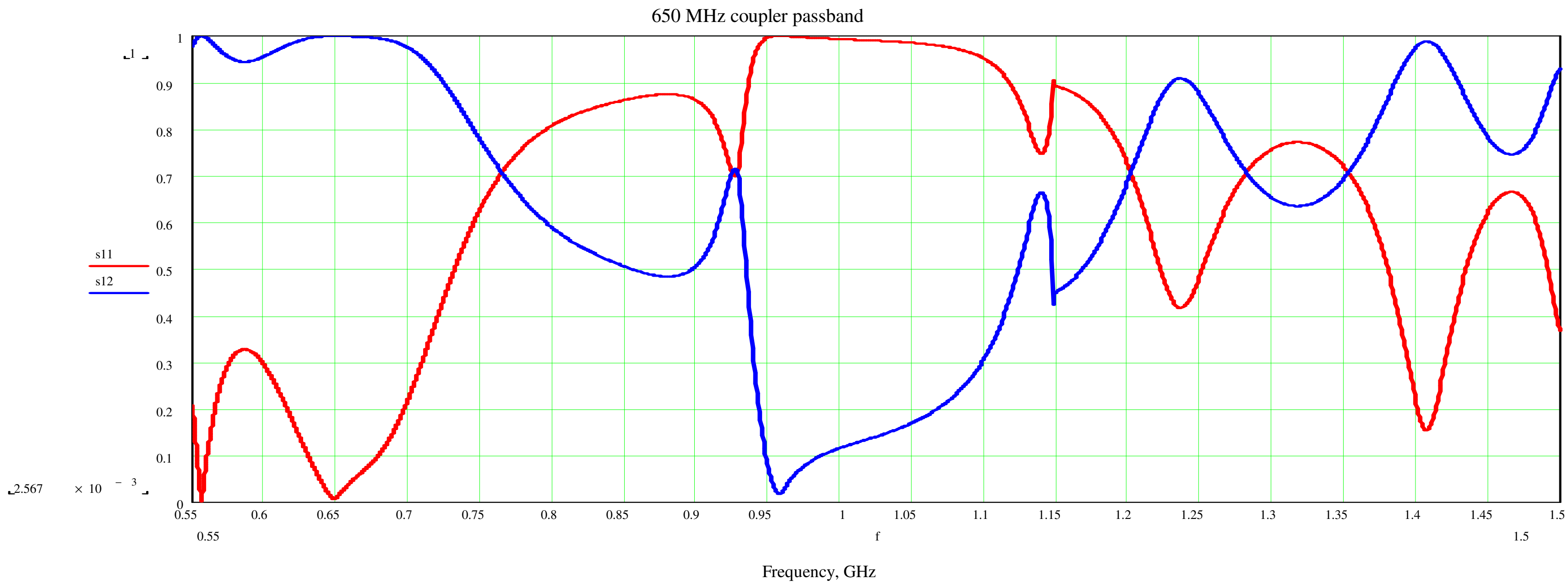

1.3GHz coupler passband
s11
s12
f
Frequency, GHz


1.3 GHz coupler passband
s11_dB
s12_dB
f
Frequency, GHz

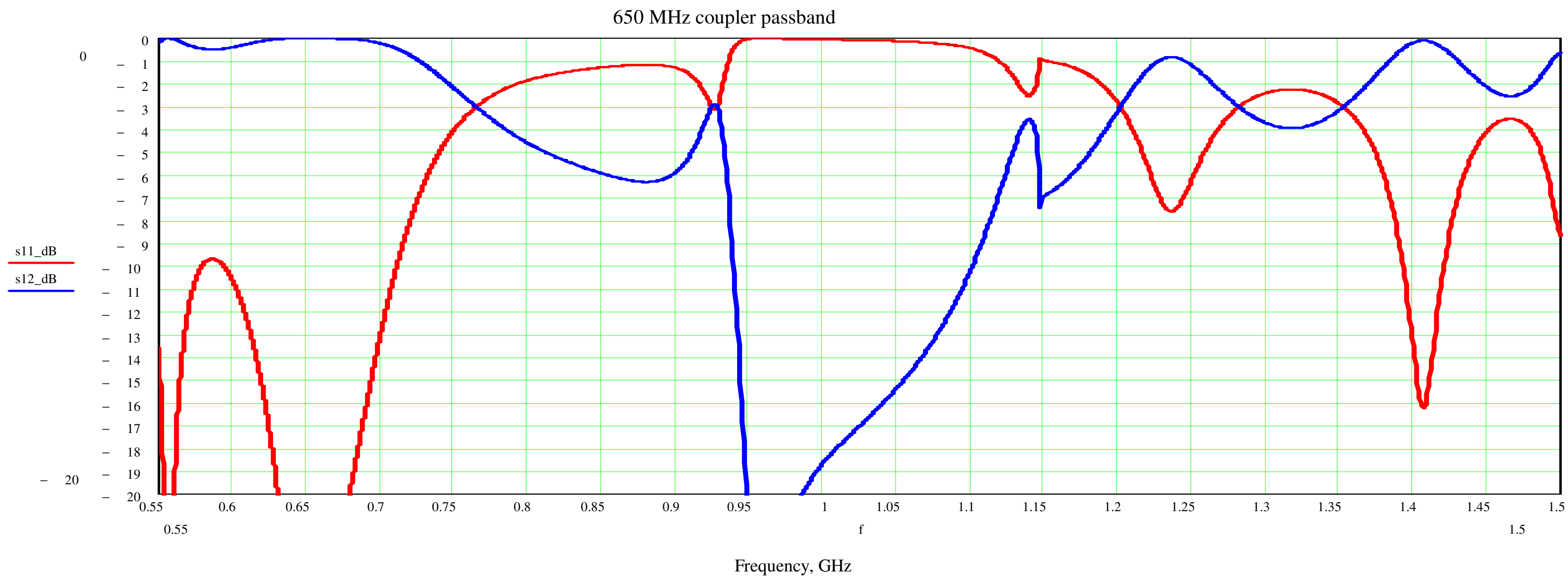
Geometry was optimize to provide maximum transparency around 1230MHz (bad HOM)







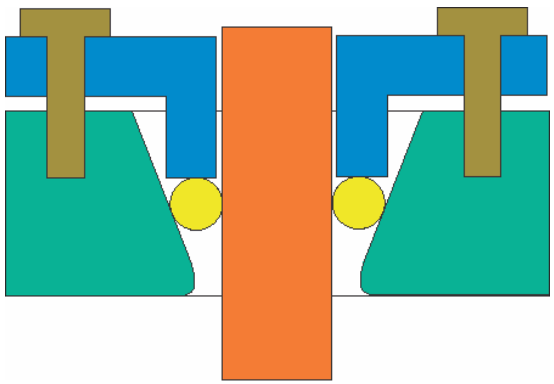
650 MHz coupler passband
s11
s12
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2.567 × 10 − 3
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5
f
Frequency, GHz

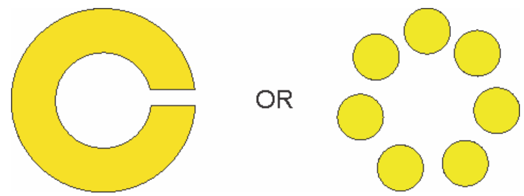


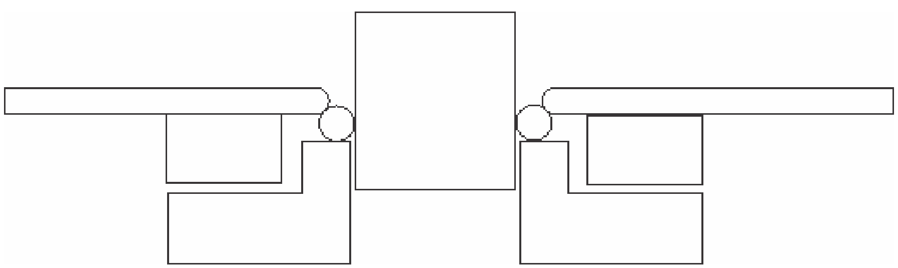
650 MHz coupler passband
s11_dB
s12_dB
0
− 20
0
− 1
− 2
− 3
− 4
− 5
− 6
− 7
− 8
− 9
− 10
− 11
− 12
− 13
− 14
− 15
− 16
− 17
− 18
− 19
− 20
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5
f
Frequency, GHz

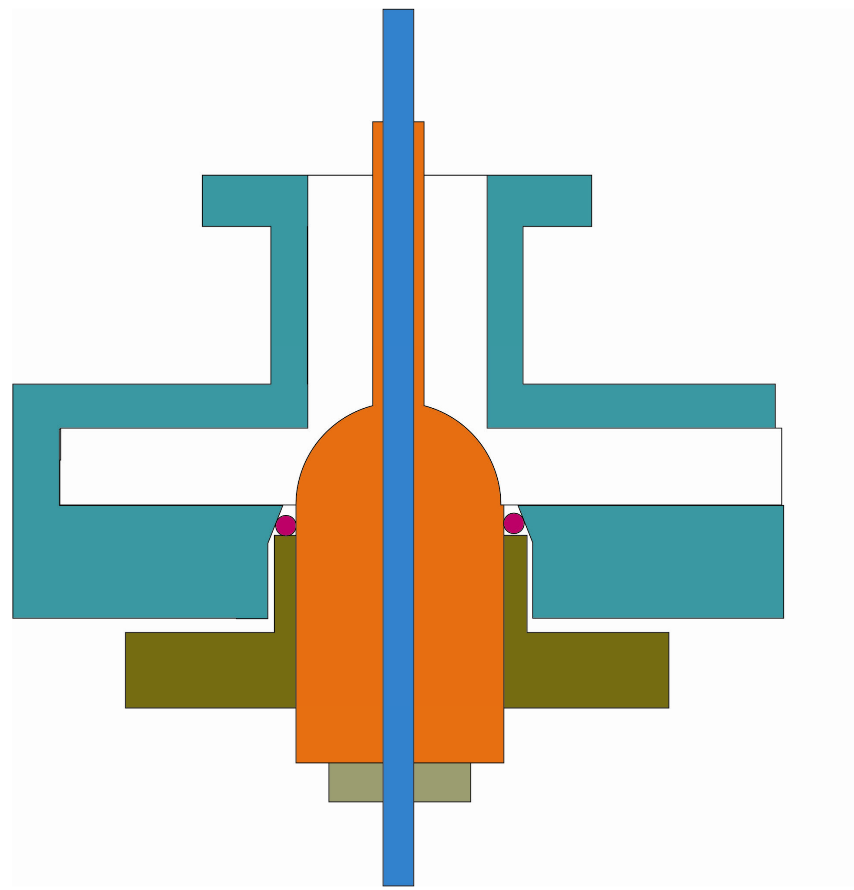
WCA must be demountable.

Possible solution for contact waveguide – coaxial.
Configuration provide minimum force in ceramic direction









ANALYSIS OF MULTIPACTING IN COAXIAL LINES

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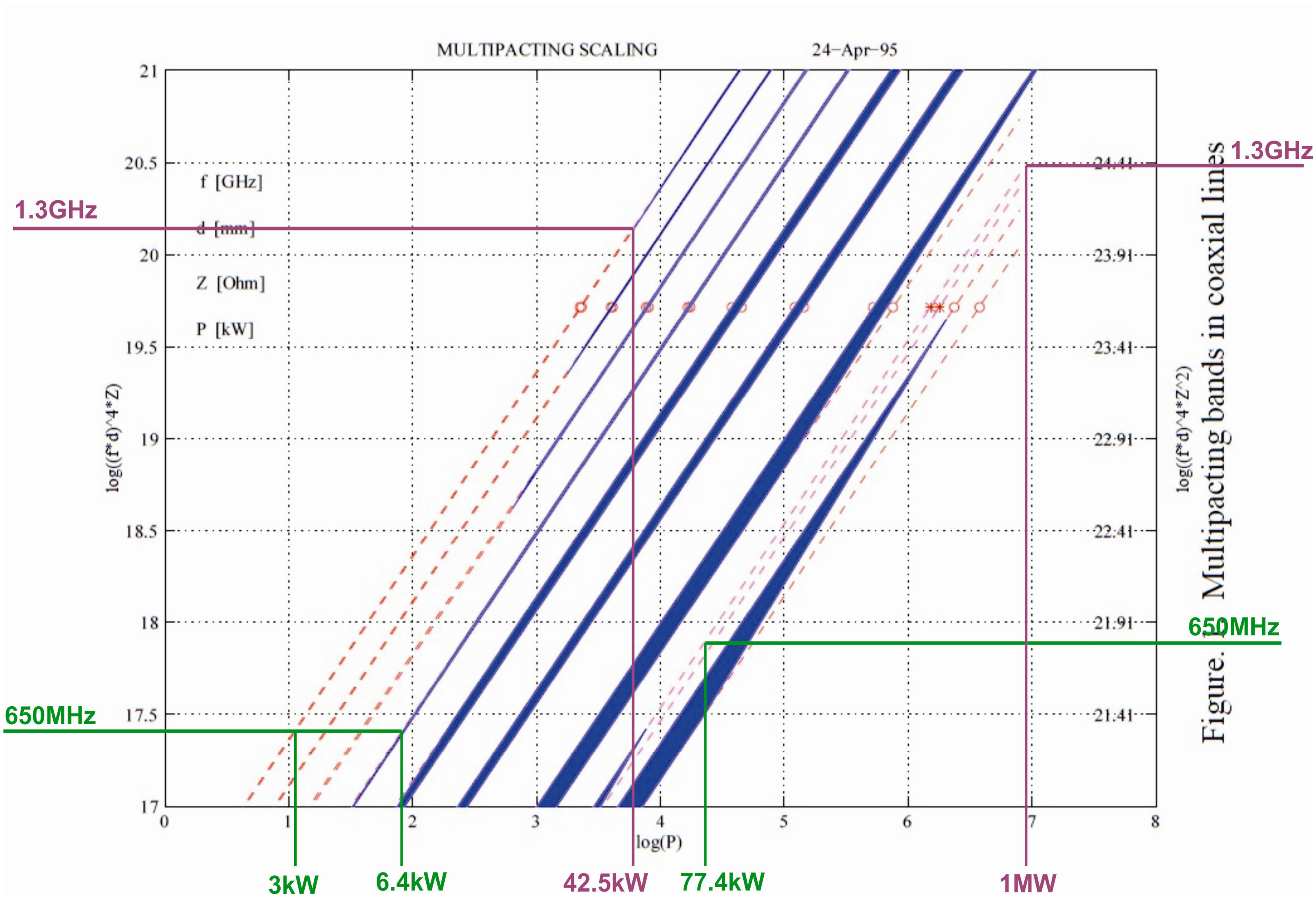
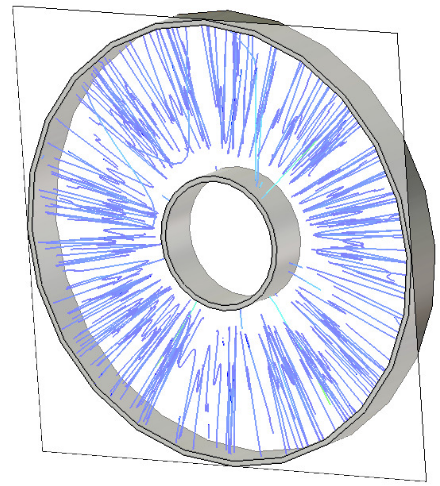
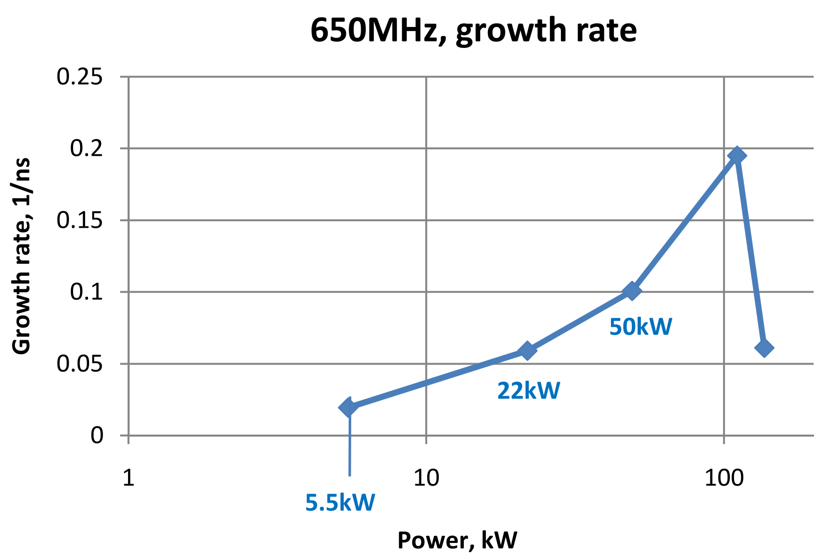
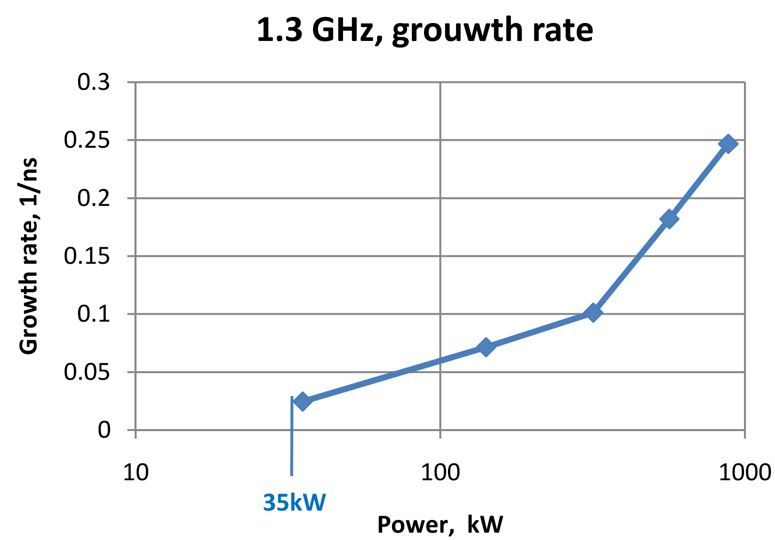


Figure. Multipacting bands in coaxial lines

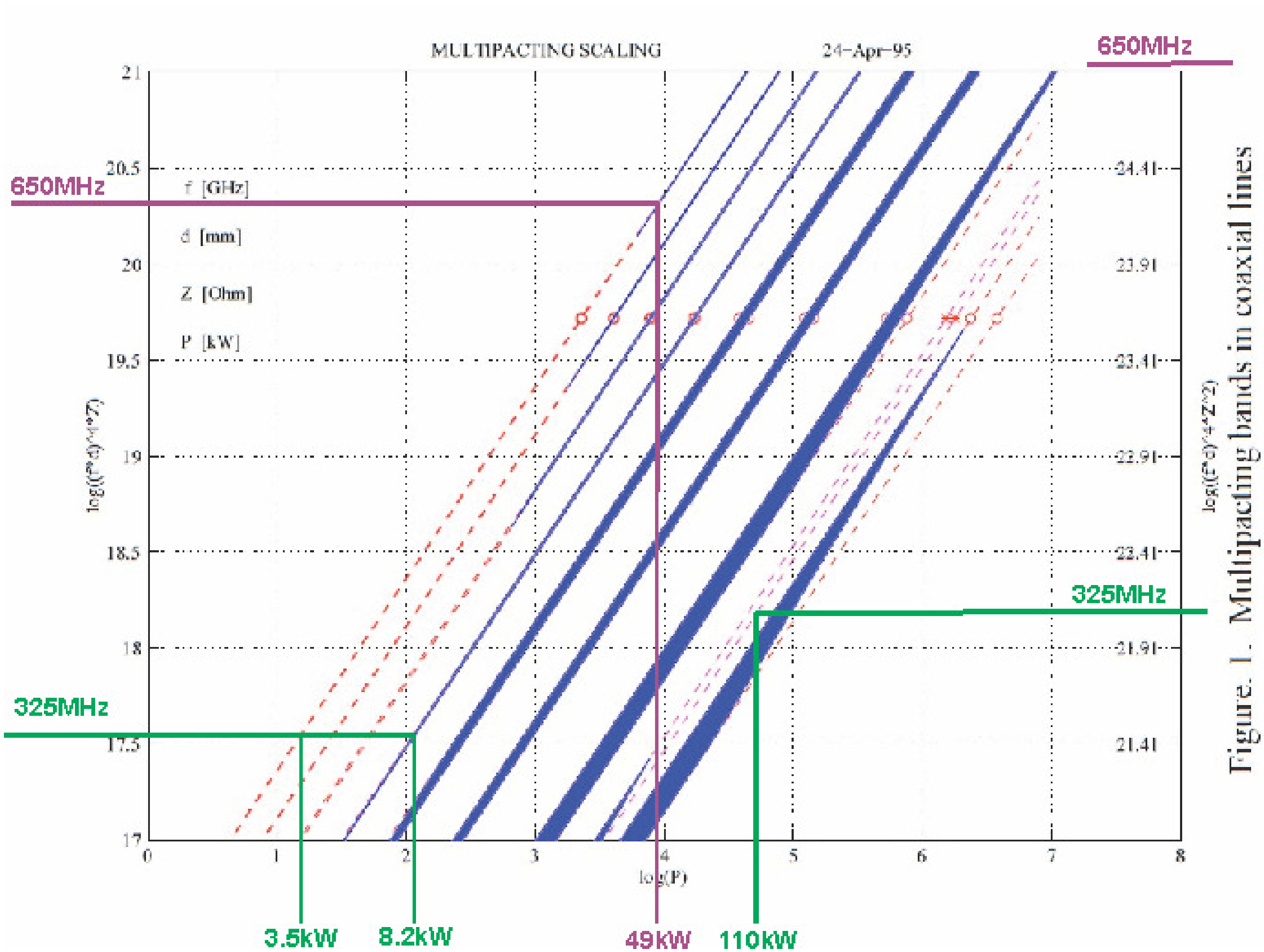
CST multipactor simulations (G. Romanov)



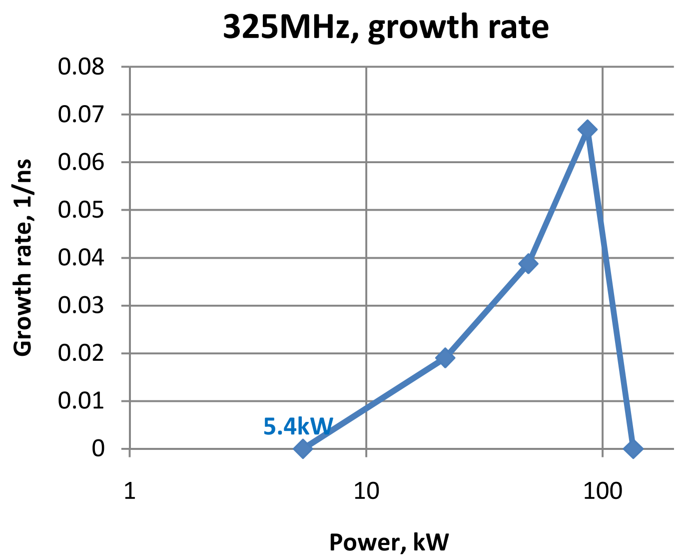


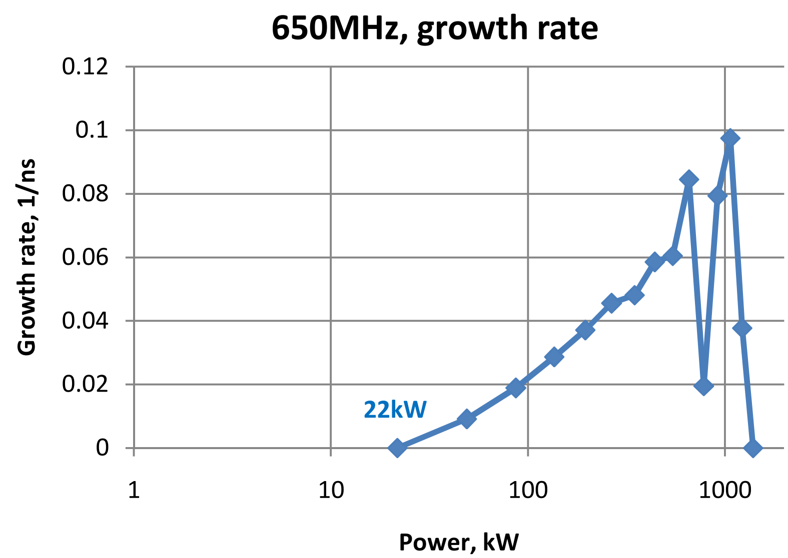


Multipactor in coaxial 12.7mm / 76.9 mm at 325MHz and 650MHz

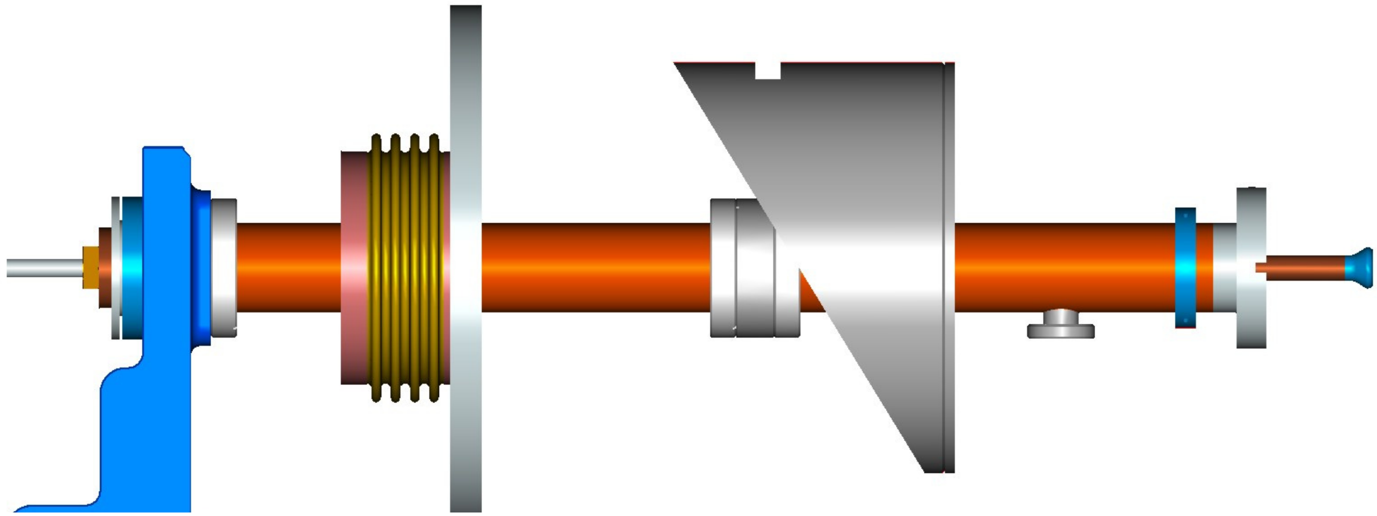


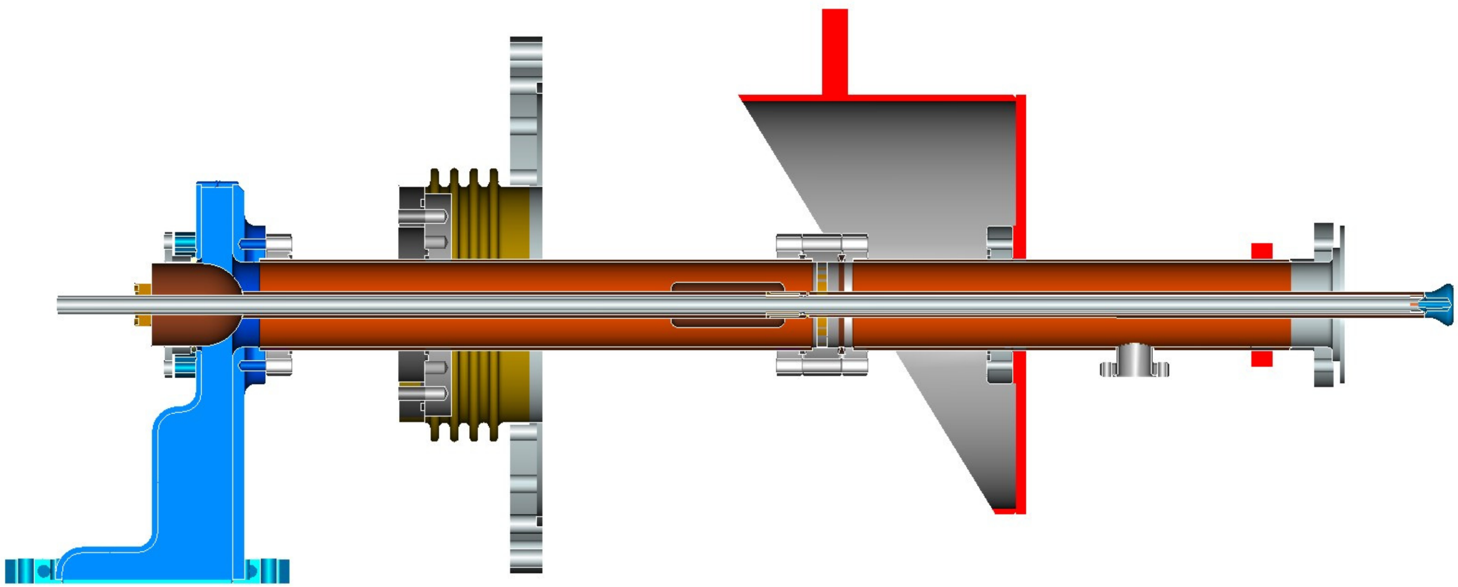
CST multipactor simulations of 12mm/76.9mm
(G. Romanov)





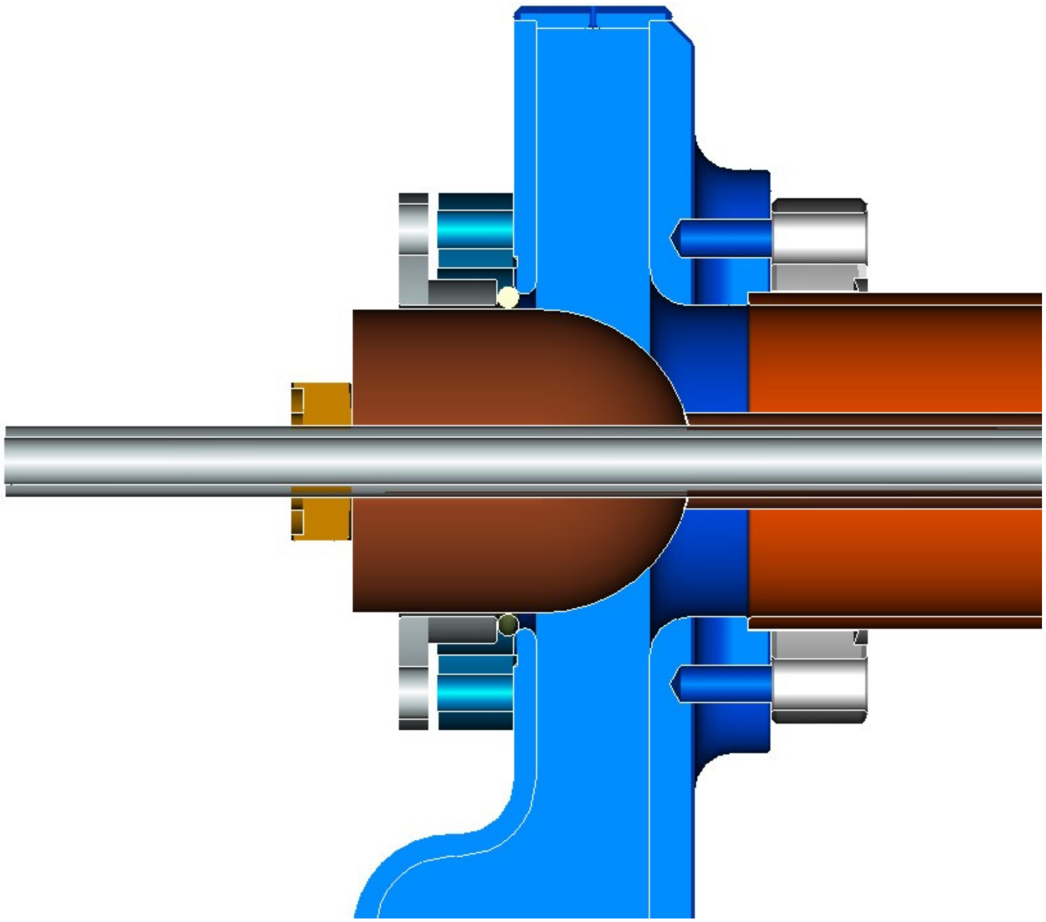
1.3 GHz coupler, preliminary mechanical design (M. Kramp)



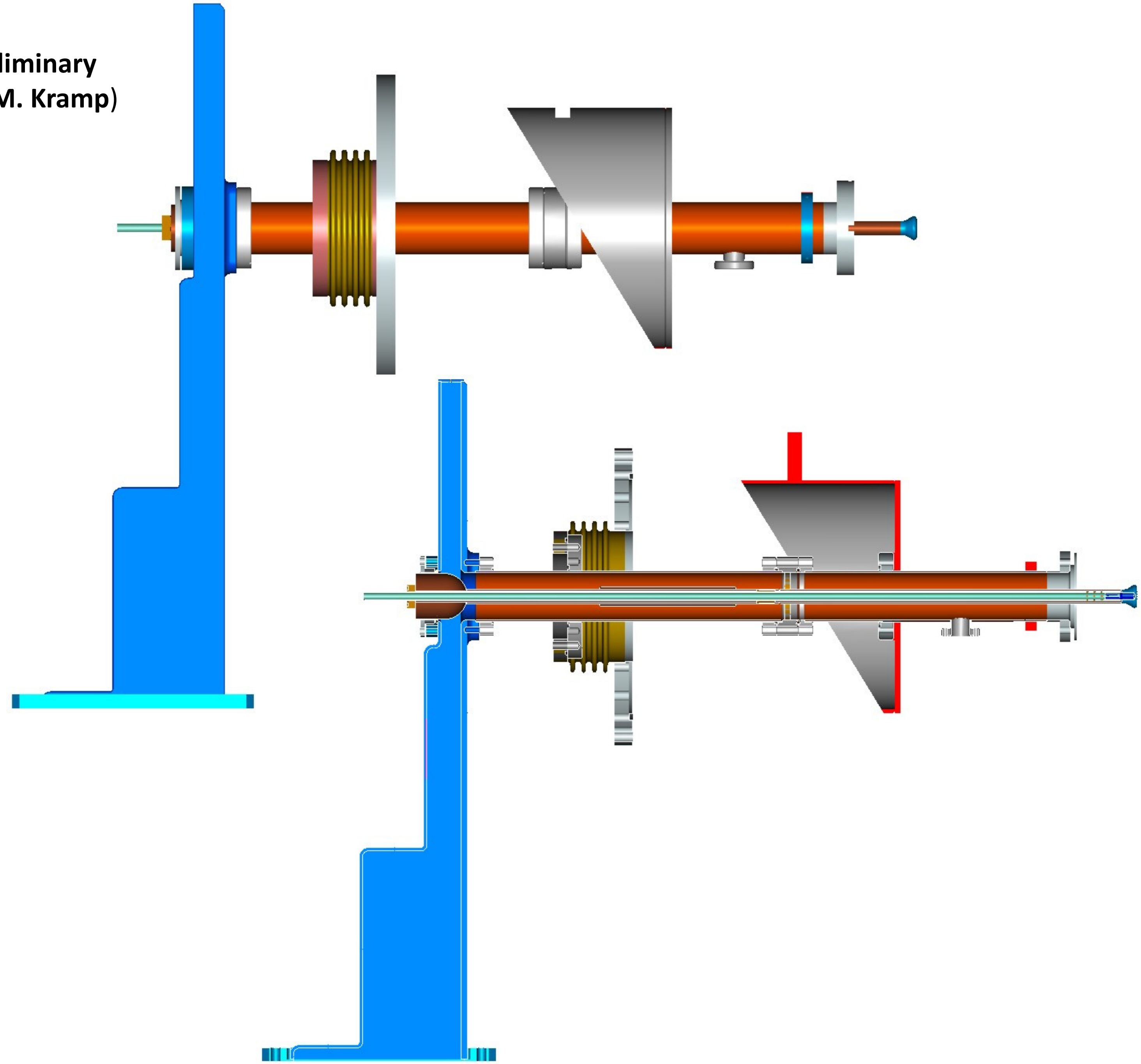


Coaxial-waveguide connection.

Door knob can have a thin insulator on the surface.
In this case we can apply HV bias to suppress multipactor.

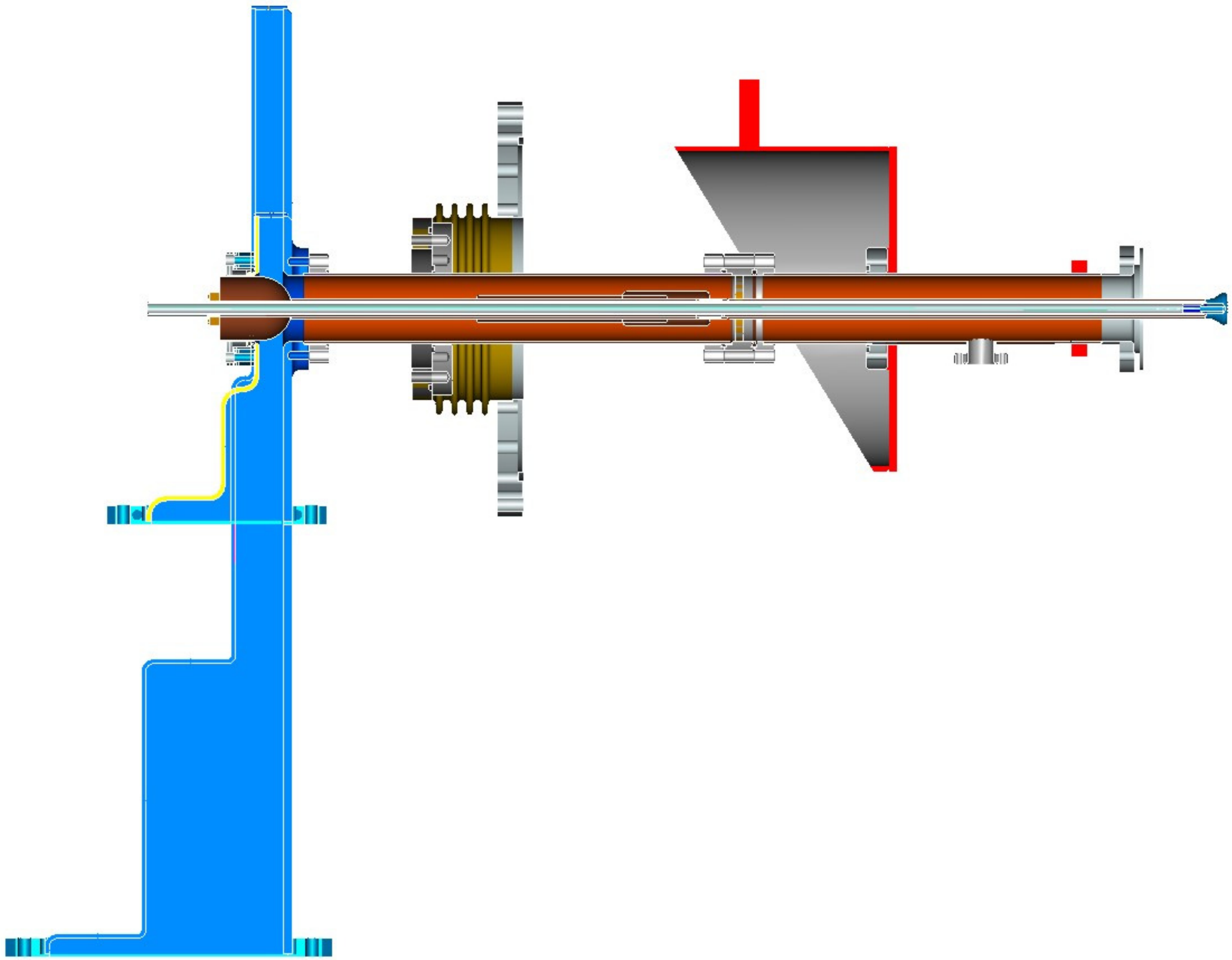


650MHz coupler, preliminary mechanical design (M. Kramp)



1.3 GHz and 650MHz couplers.

Differences are only two details: waveguide and pipe with matching element!



Conclusion:

1.3GHz coupler

Electrical design is done:
Coupler is compatible with present cavity and cryomodue.
Heat load – 3-4% of heat load of cavity
No multipactor

Preliminary mechanical design is done

What to do:
Additional mechanical analyses are required:
Thermal stress of ceramic
Parameters of big bellow to provide proper transverse freedom.
(During cooling cavity shrinks and coupler moves transversally).

650 MHz coupler.

Preliminary electrical and mechanical designs are done:
1.3 GHz coupler easily can be transformed to 650MHz coupler.

There is a problem with multipactor, expected power threshold ≈ 5kW.

What to do:
New preliminary design with bigger coaxial (Preliminary – no information about kryomodule yet) .
Probably joint design for 350MHz and 650MHz with coaxial 76.9mm / ??mm

325 MHz coupler

What to do:
To start a work