Design and Optimization of Radio-Frequency Pulse Compressor Systems for High Brightness Linacs

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OUTLINE

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Passive pulse compressors
SLED
Brief BOC Theory

The EuPRAXIA@SPARC_LAB project

Main design parameters and power distribution network

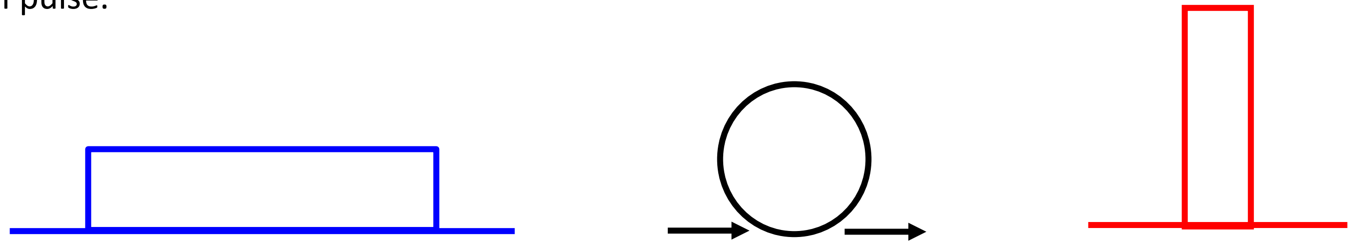
Design and optimization of The BOC

Electromagnetic Simulations
Mechanical Design
Preliminary Thermo-Mechanical Simulations

RF pulse compressors

In klystron technology it is easier to produce moderate peak power long pulses, rather than short and high peak.

Normal conducting linacs need high peak and relatively short pulses, factor 3-10 shorter then the convenient klystron pulse.



Pulse from RF sources

Pulse compressor

Pulse need by linacs

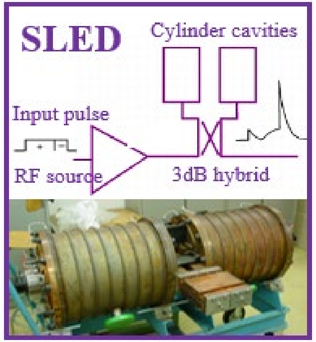
The pulse compression is way to increase the peak rf power in exchange for the rf pulse length shortening. Although this method has a limited efficiency for two reasons.

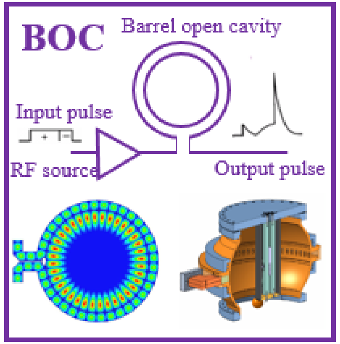
- due to the ohmic losses in the RF storage element
- System parameters are kept constant during the pulse (passive method), because of the transient processes in a system.

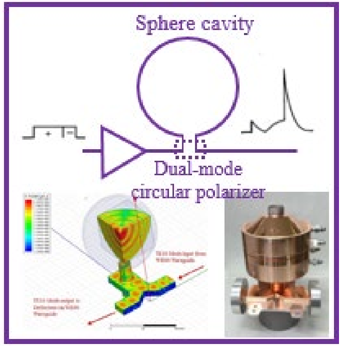
Passive RF pulse compressors

Passive pulse compressors can be realized with cavity or delay lines

Cavity



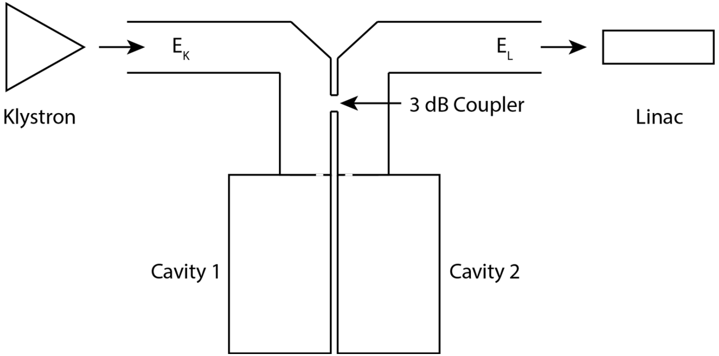




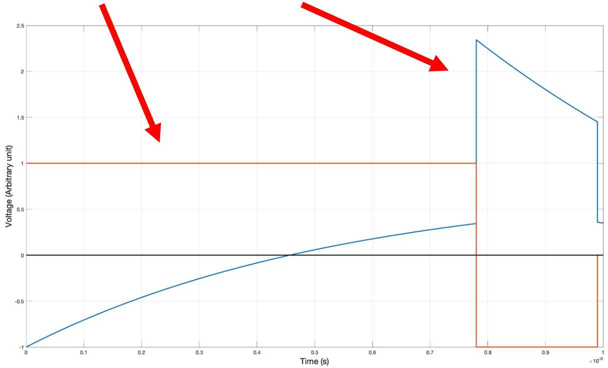
Delay lines

SLED

General schematics



Input and output pulse shape



First rf pulse compressor named SLED was invented at SLAC in 1973.

Energy from the klystron builds up in two high quality cavities. Which is later extracted by reversing input pulse in shorter time interval, amplitude is much higher, but decaying exponentially

$$\text{Input pulse} \begin{cases} 1 & \text{if } 0 < t < t_f \\ -1 & \text{if } t_f \leqslant t \leqslant t_e \\ 0 & \text{if } t > t_e \end{cases}$$

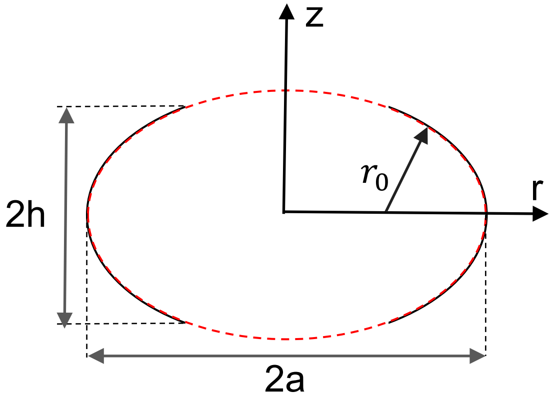
Solutions for output pulse

$$V_{out}(0 \leqslant t < t_f) = \alpha\left(1 - e^{-t/T_c}\right) - 1$$

$$V_{out}(t_f \leqslant t \leqslant t_e) = \alpha[(2 - e^{-t_f/T_c})e^{-(t-t_f)/T_c} - 1] + 1$$

$$V_{out}(t > t_e) = \alpha[(2 - e^{-t_f/T_c})e^{-(t_e-t_f)/T_c} - 1]e^{-(t-t_e)/T_c}$$

Brief Theory



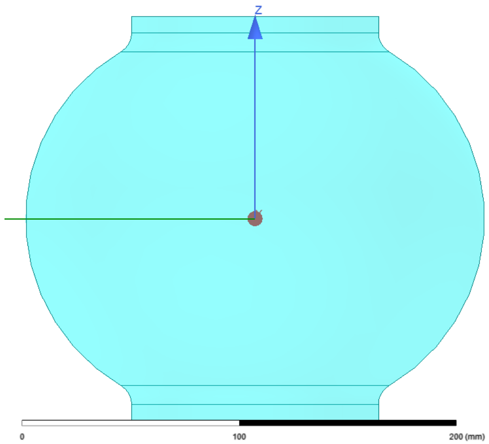
Wave equation: $ka = \nu_{mn} + \frac{\alpha \cdot (q-1/2)}{sin\alpha}$

ν_{mn} is Bessel function, a and r_0 are cavity axises.

The optimal radius r_0, when the external caustic has the smallest height comes when $r_0 = 2asin\theta$

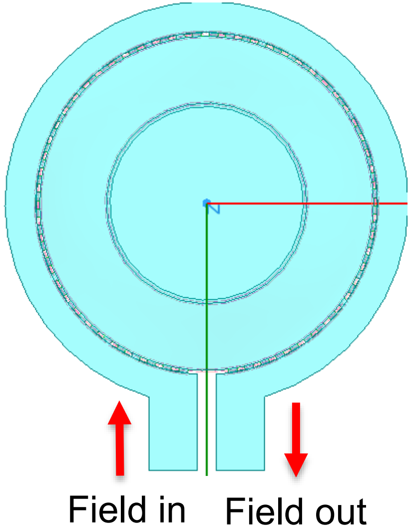
a and q are derived from:

$$\sin \alpha = \sqrt{\frac{a}{r_0}} \sin \theta \qquad \cos \theta = \frac{m}{\nu_{mn}}$$



Why BOC?

- Requires only one cavity
- No 3-dB coupler
- Applicable in X-band



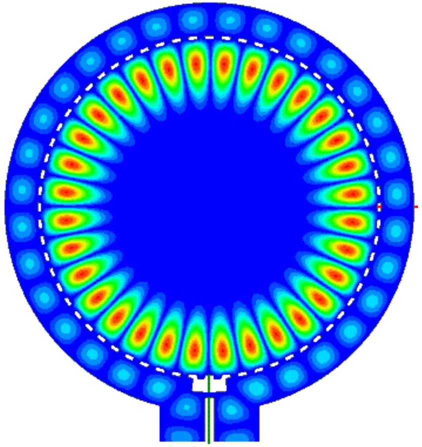
How does it work?

Waveguide around the cavity, excites two modes inside the cavity through coupling irises.

Distance between irises $\lambda/4$ ensures that these two Modes are orthogonal in space.

If waveguide width is chosen in such way that phase velocity in the waveguide and cavity are the same, modes will be orthogonal also in space.

So these two mode will cancel each other in input port and sum up in the output port. These will avoid reflections back to the source.

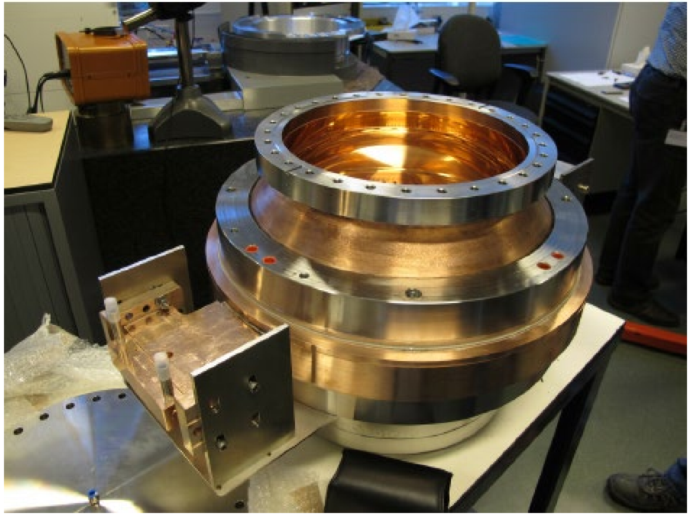


Field propagation

BOCs built so far

1990 KEK TM_{25,1,1} X Band

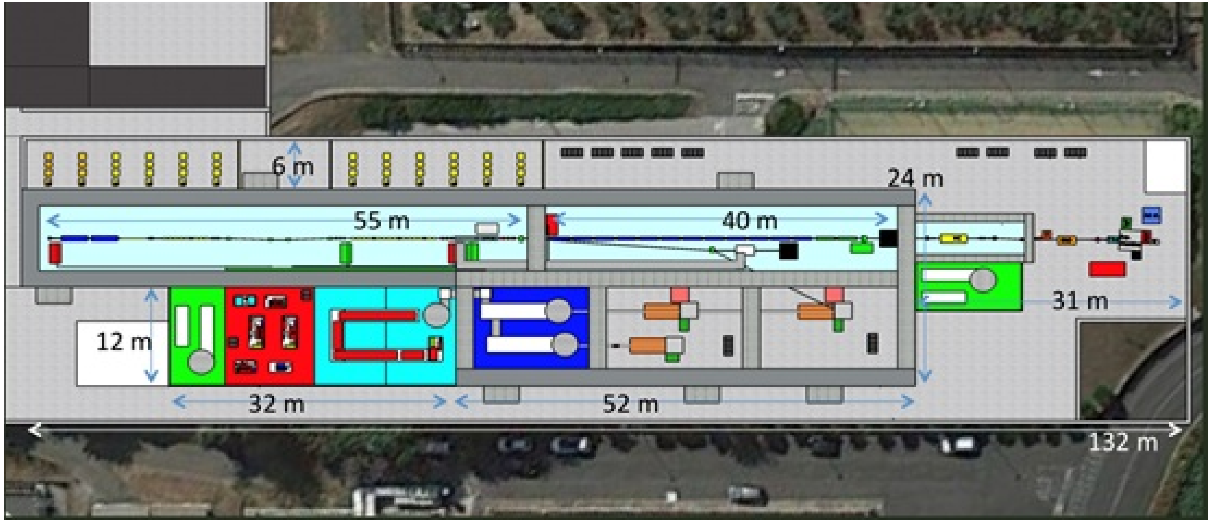
2001 CERN TM_{10,1,1} S Band



2012 PSI TM_{18,1,1} C Band

EuPRAXIA@SPARC_LAB: A COMPACT FEL SOURCE

EuPRAXIA@SPARC_LAB project is a proposal for a new national facility as an expansion of the **SPARC_LAB** activities, based on the combination of a high gradient compact linac and high-power lasers for plasma acceleration oriented to FEL with user beam line at 3 nm wavelength, synergic with the EU **EuPRAXIA** design study. **EuPRAXIA** is a design study which goal is to demonstrate the feasibility to drive an **FEL** with a beam accelerated in a plasma stage.



M. Ferrario EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF

ACCELERATING STRUCTURE AND MODULE: PARAMETERS

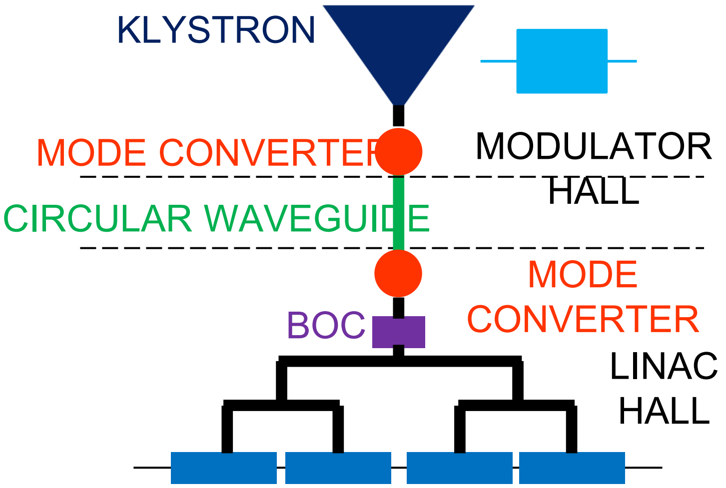
Parameter	Value
Frequency [GHz]	11.9942
Phase advance per cell [rad]	$2\pi/3$
Shunt impedance R [MΩ/m]	90-131
Effective shunt Imp. R_s [MΩ/m]	387
Group velocity v_g [%]	4.7-1.0
P_{out}/P_{in}	0.215
Filling time [ns]	144
Number of cells per structure	108
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23000
# structures per module N_m	4
Module active length L_{mod} [m]	3.6
Average iris radius <a>	3.5
Iris radius input-output [mm]	4.3-2.7
Structure length L_s [m]	0.9
Accelerating cell length [mm]	8.332

	Rep. rate [Hz]		
	100	250	1000
Average gradient <G> [MV/m]	65	32	30.4
Max klystron available output power [MW]	50	50	10
Required klystron power per module P_K [MW]	39	42.5	8.5
RF pulse [µs]	1.5	0.15	1.5
SLED	ON	OFF	ON
Av. diss. power per structure [kW]	1	0.31	2.2
Peak input power per structure [MW]	68	10.6	14.8
Av. Input power per structure [MW]	44	10.6	9.6
Module energy gain [MeV]	234	115	109

RF MODULE MODULE

Ref. CPI VKX-8311A

50 MW, 1.5 μs, 100 Hz



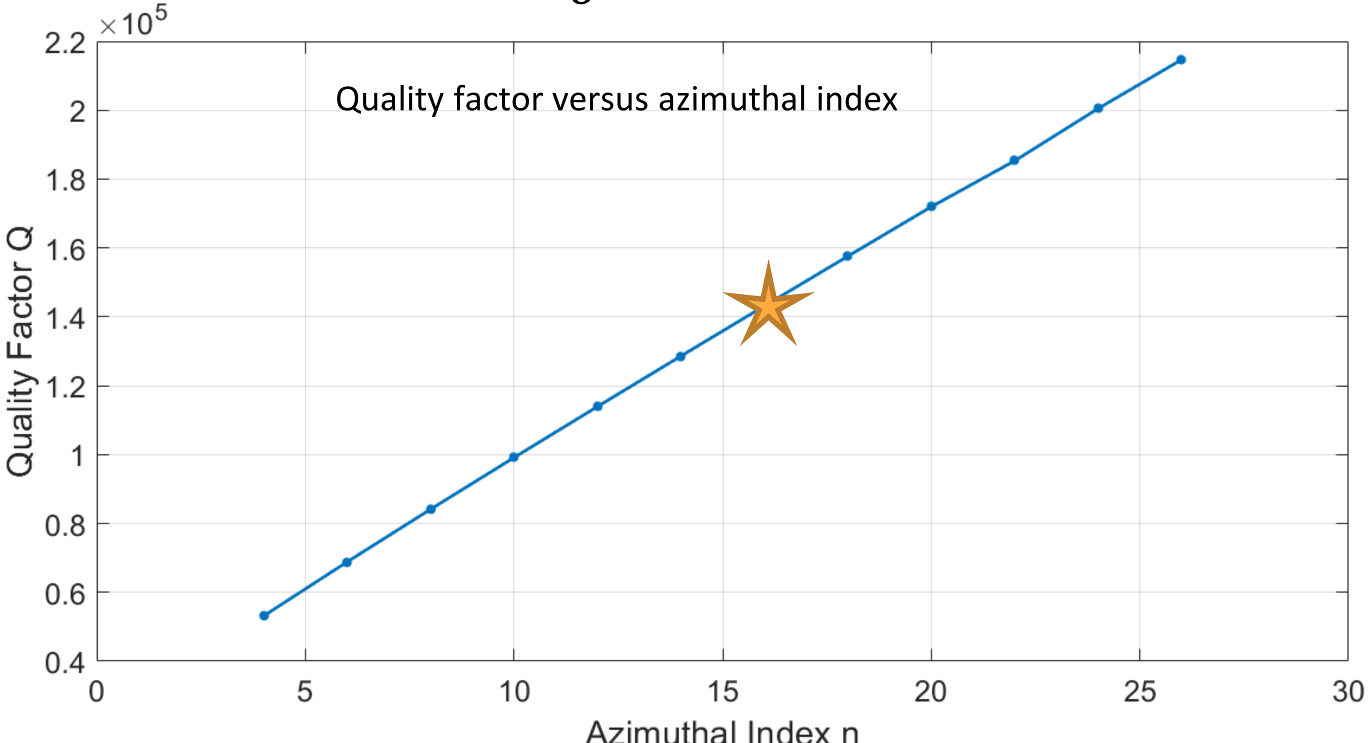
1 klystron x LINAC Module

$\langle E_{acc} \rangle = 65$ MV/m

Quality Factor

To reduce cost and the difficulties in the design and realization of the BOC and simulation time, we decided to choose unloaded Q_0= 150 000, at this value BOC can provide still efficient compression and we don’t have much derivation in linac performance.

Quality factor is calculated as for spherical cavity $\frac{a}{\delta}$



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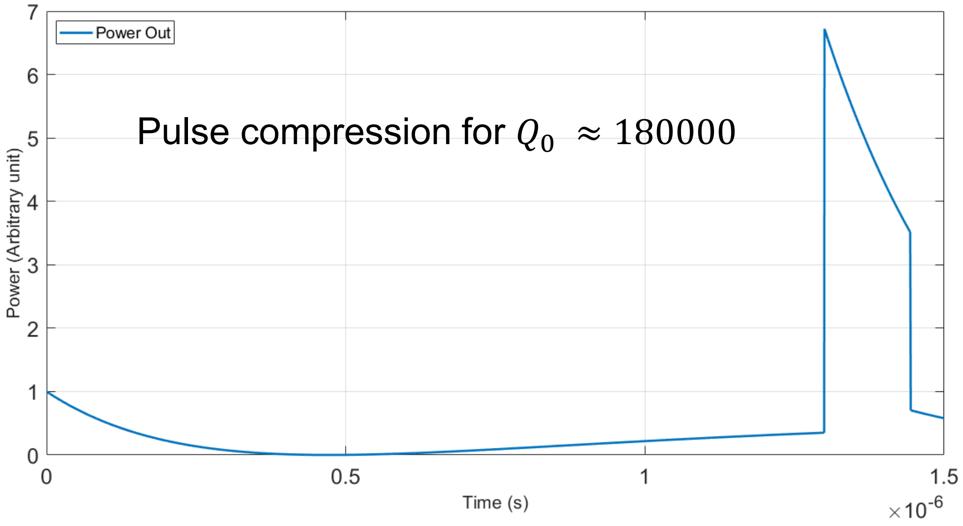
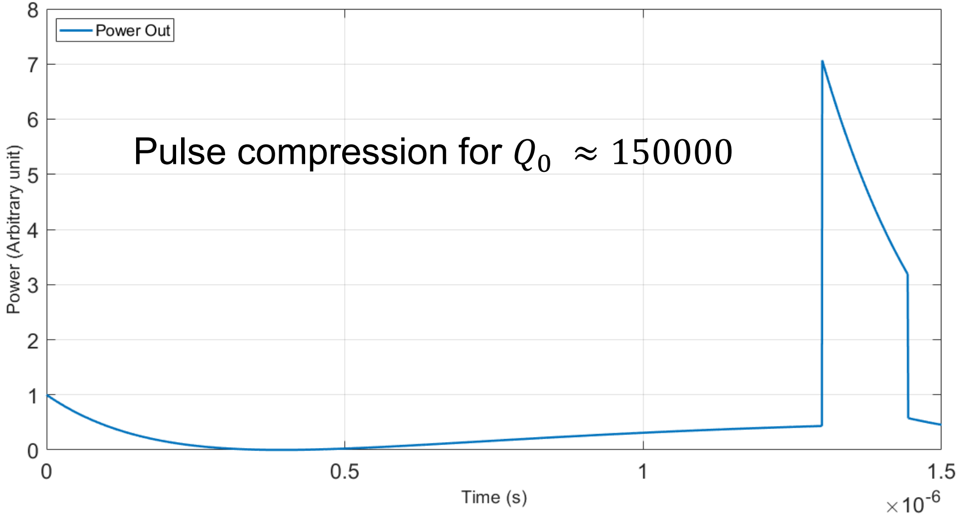
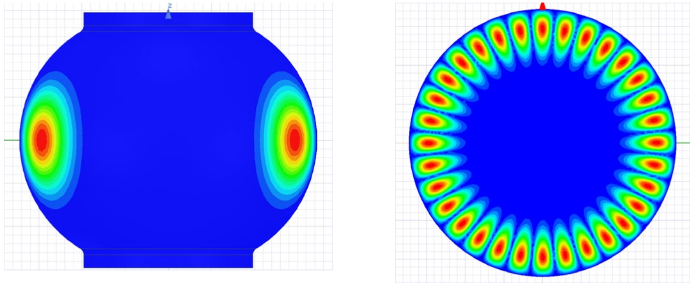
So mode 16,1,1 was chosen as an Operational mode



Pulse compression for $Q_0 \approx 180000$



Pulse compression for $Q_0 \approx 150000$

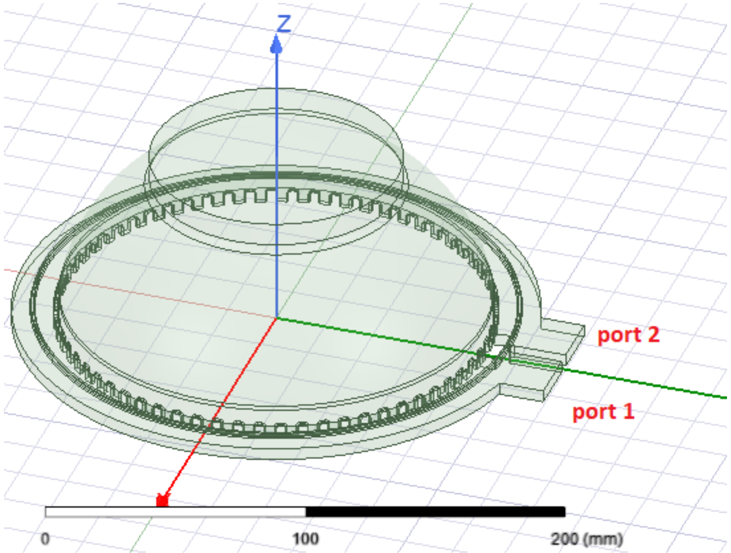


Side view

Top view

Field distribution in the cavity

Simulations

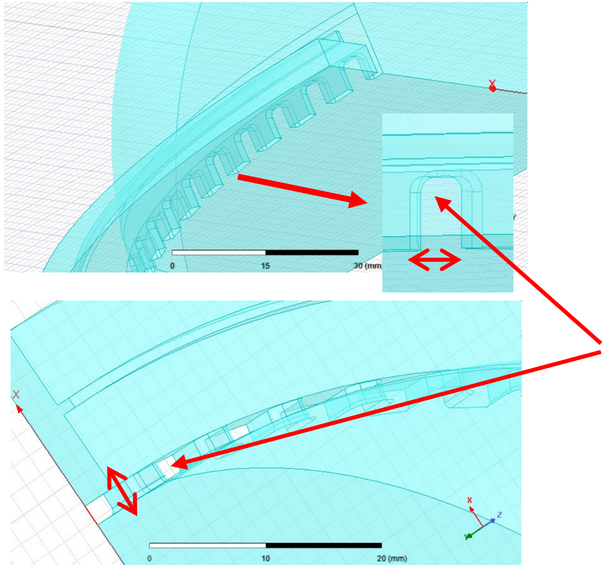


Geometry we have simulated
(Half symmetry)

All electromagnetic simulations were done using **ANSYS-HFSS**.

Common wall thickness between cavity and waveguide and dimensions of the coupling hole's define the coupling.

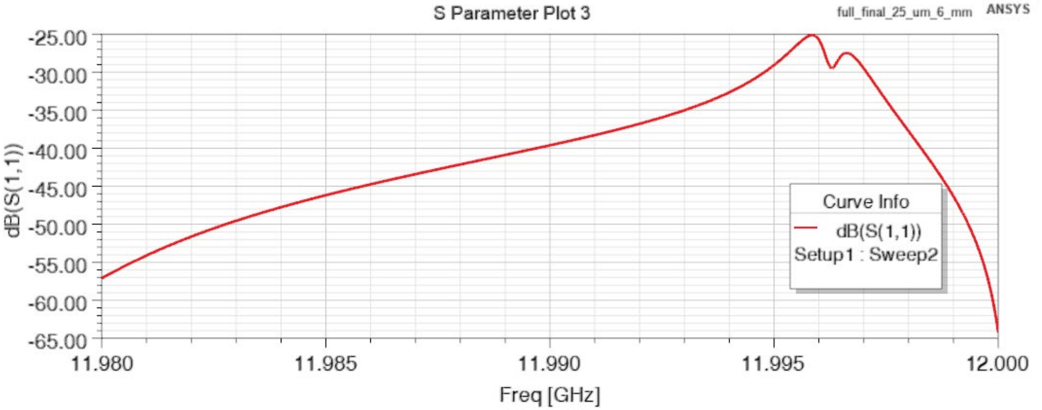
Another important parameter is waveguide width, which must be tuned to avoid reflection back to the source.



These are the parameters
which defines
the coupling β

Simulations results: summary

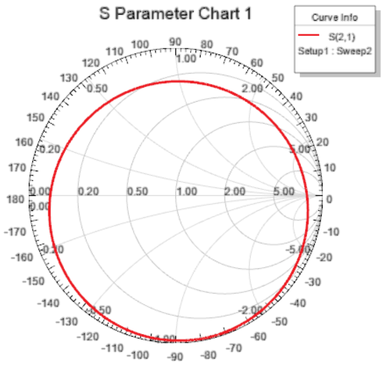
S_{11} < 25 -dB which is more than acceptable.

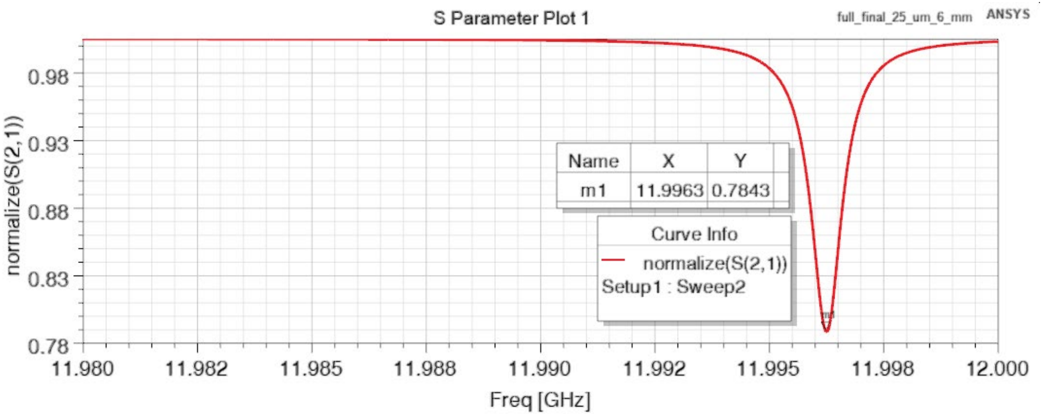


Coupling coefficient is equal to:

$$\beta = \frac{1 + S_{21}}{1 - S_{21}} = 7.8$$

Cavity is strongly overcoupled

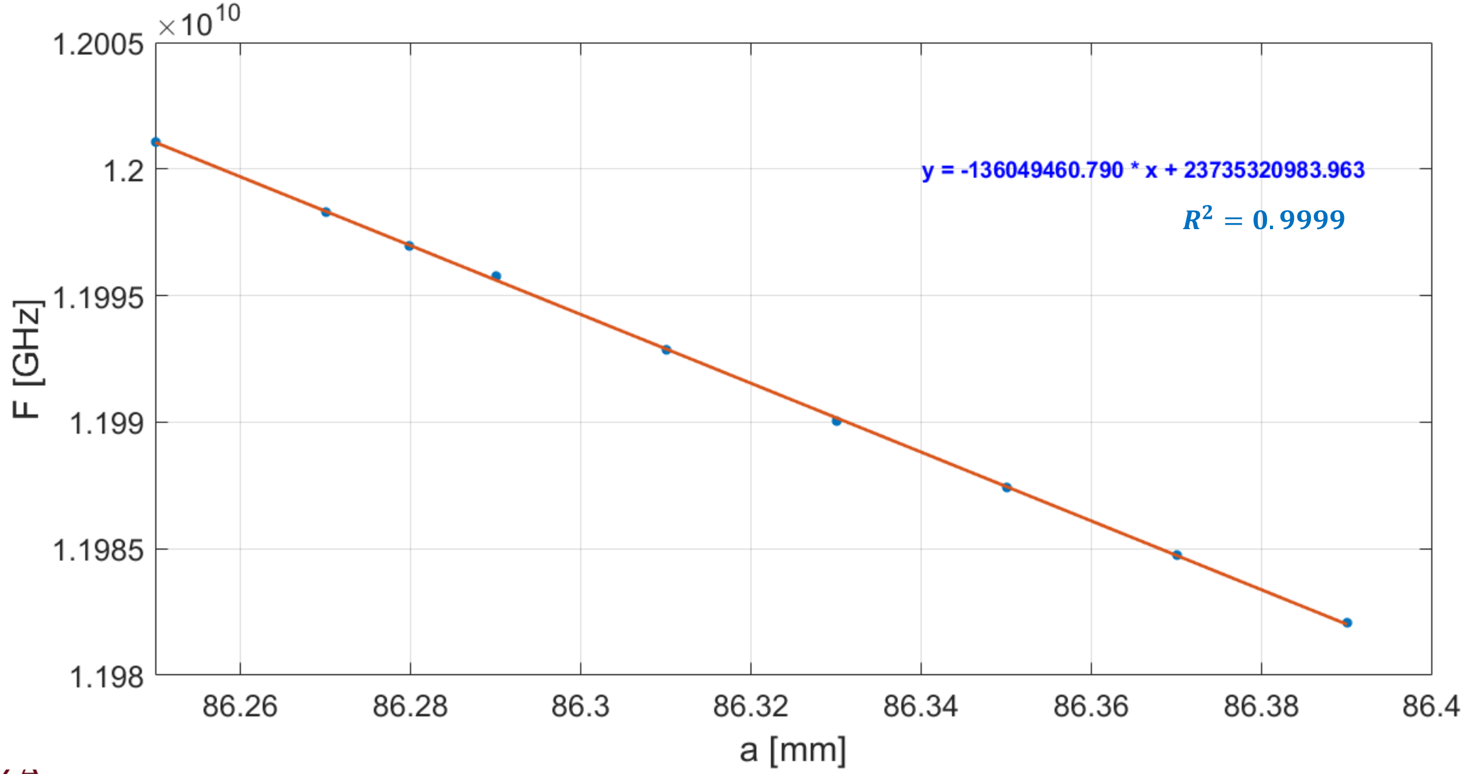




Name	X	Y
m1	11.9963	0.7843

Sensitivity studies

A sensitivity study has been done considering all main geometrical parameters. As an example in the picture below it is reported the case of the most critical parameter “a”.



Considerations on the Sensitivity study

The most critical parameters in the sensitivity is the cavity large radius **a**.

Sensitivity studies allow to establish which is the required precision we need in the machining of the structure if tuning is not available. More precisely it is possible to tune the structure by changing the temperature of the cooling system within a range of few degrees (+/-5 °C).

If we can tune the resonance frequency of the cavity by changing the temperature by +/-5 °C this means that we have a range of tunability of about +/-1 MHz.

If we fit data on the previous with linear function $f = A \times a + B$,
we will have $f = 136049461 \times a + 23735320984$ => $\frac{\Delta f}{\Delta a}$ = 136 MHz/mm

So $\Delta a = \frac{\Delta f}{136049461} = \frac{1 \cdot 10^6}{136049461} \approx 7\ \mu m$

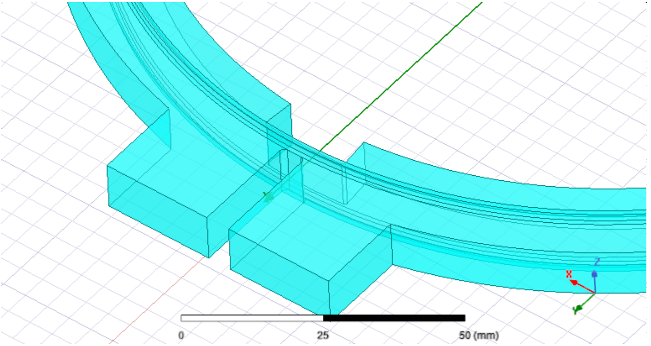
Required is precision 7 μm.

Brazeless realization of Accelerating Structures

The accelerating structures and components are, in general, realized by a brazing/welding process of the machined parts. The brazing process requires a large vacuum furnace, is very expensive and poses a not negligible risk of failure. Furthermore, BDR studies in X-band indicated that, avoiding the high temperature thermal stress of copper associated with brazing, one can reduce the BDR probability.

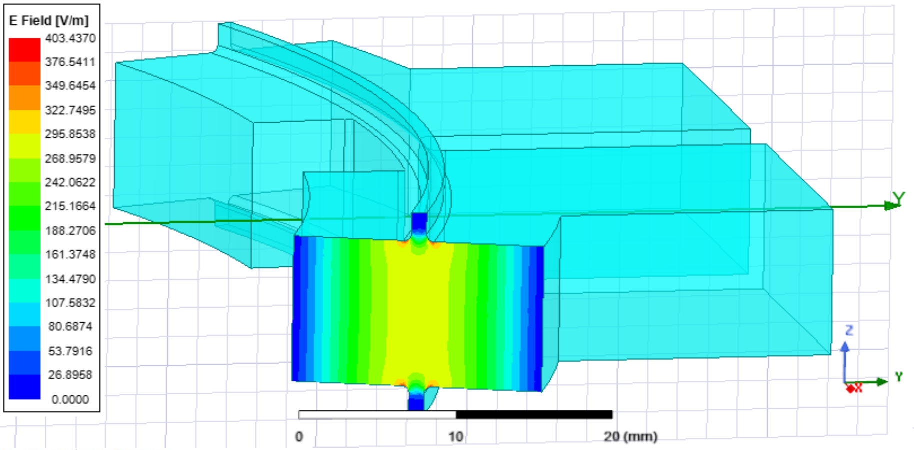
For this reason at LNF-INFN was developed novel method assembly of structures which involves special gaskets that guarantee (simultaneously) the vacuum seal and perfect rf contact when the structure is clamped. **This method excludes expensive brazing process, large volume vacuum furnace, so that saves assembly time and reduces prototype price.**

Bend and waveguide design

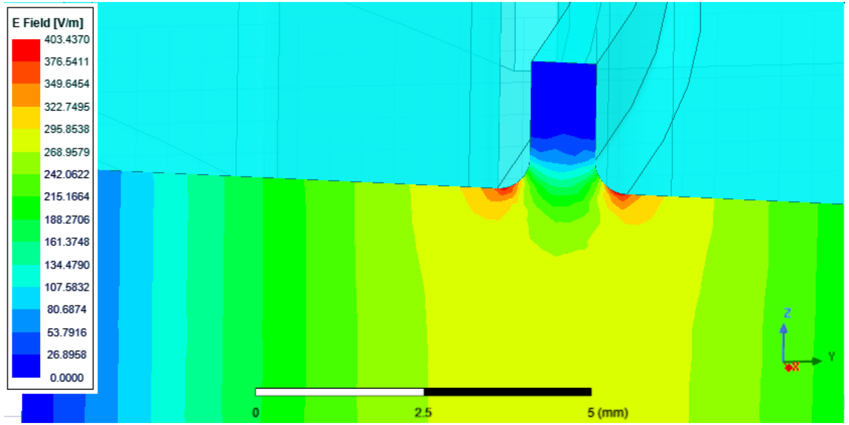


We implemented gap in the middle of the waveguide. The dimensions of the gap was chosen in such way to minimize field penetration and to avoid possible em field peaks near clamps.

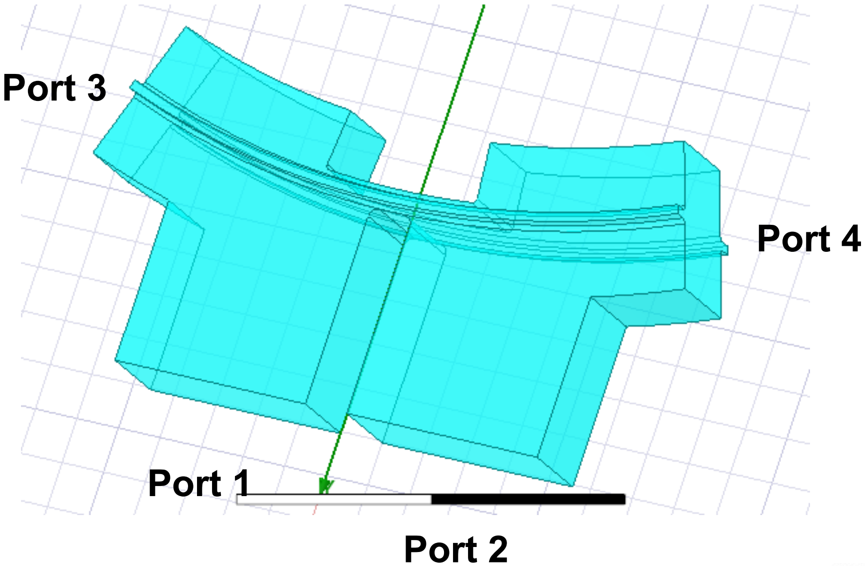
Field distribution in the waveguide



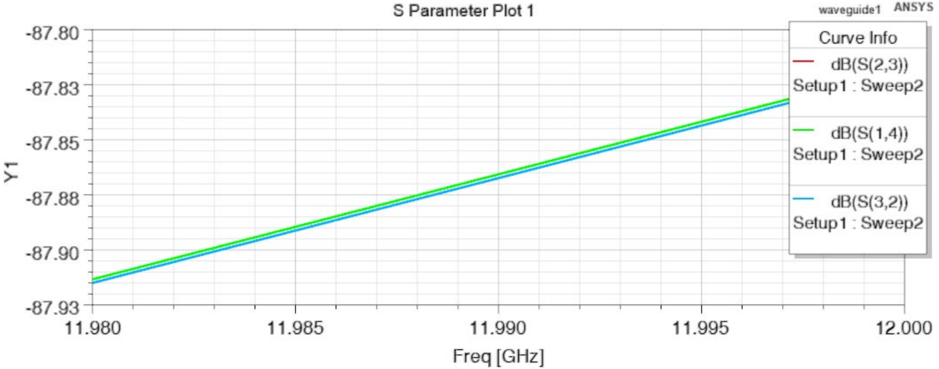
Field penetration in the gap



Bend and waveguide design

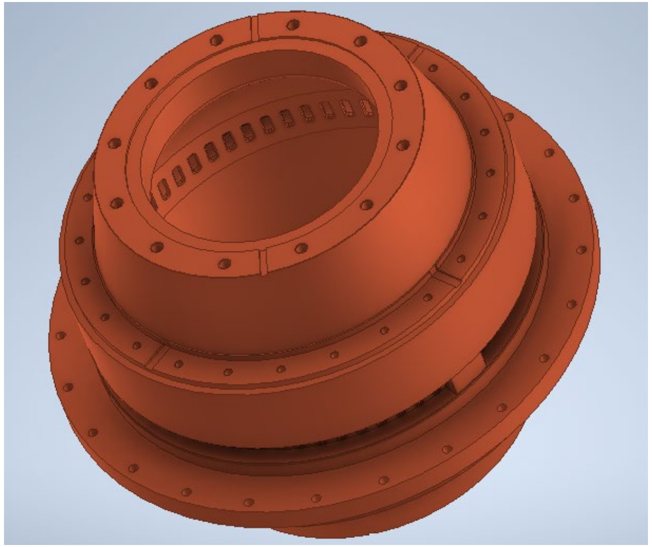


In our new design from mechanical point of view bend's ports are not isolated from each other, but from em point of view crosstalk between the ports are negligible.



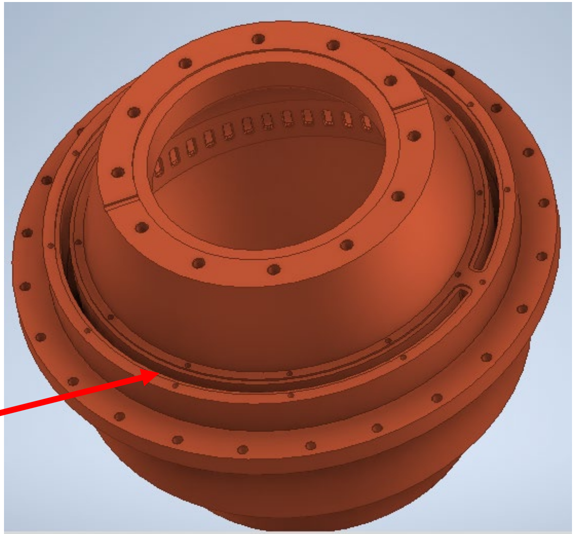
Scattering parameters $S_{23},\ S_{32},\ S_{14},\ S_{41}$ < -87 dB

no crosstalk

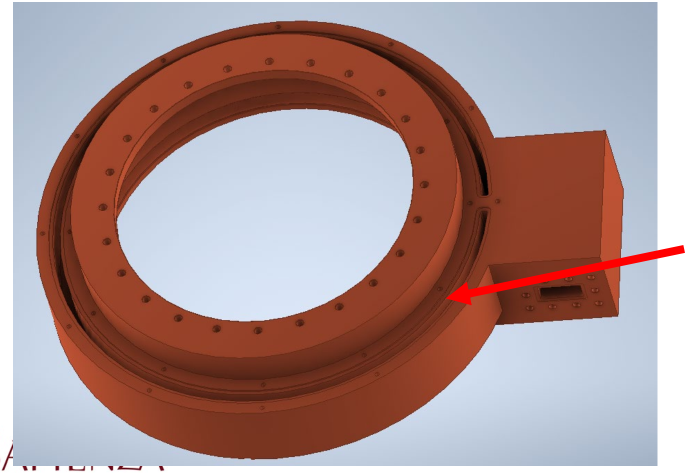


Cavity body,
top view

Cavity body
Bottom view



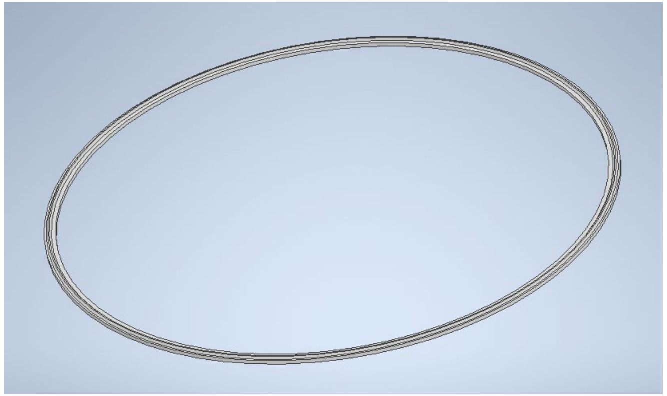
cooling channel



Waveguide

cooling channel

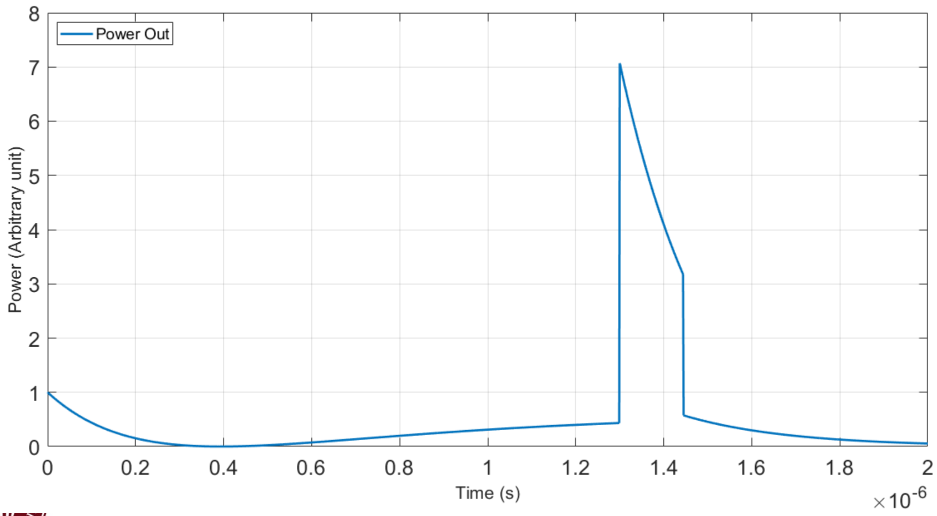
Gaskets Clamp



Preliminary thermal studies

BOC compressor power source will be powered by 50 MW Toshiba ET3702 klystron. Pulse duration is 1.5 μs.
Accelerator repetition rate 100 Hz (actually 50 Hz).

Power dissipated in the BOC is difference between the input and output power.



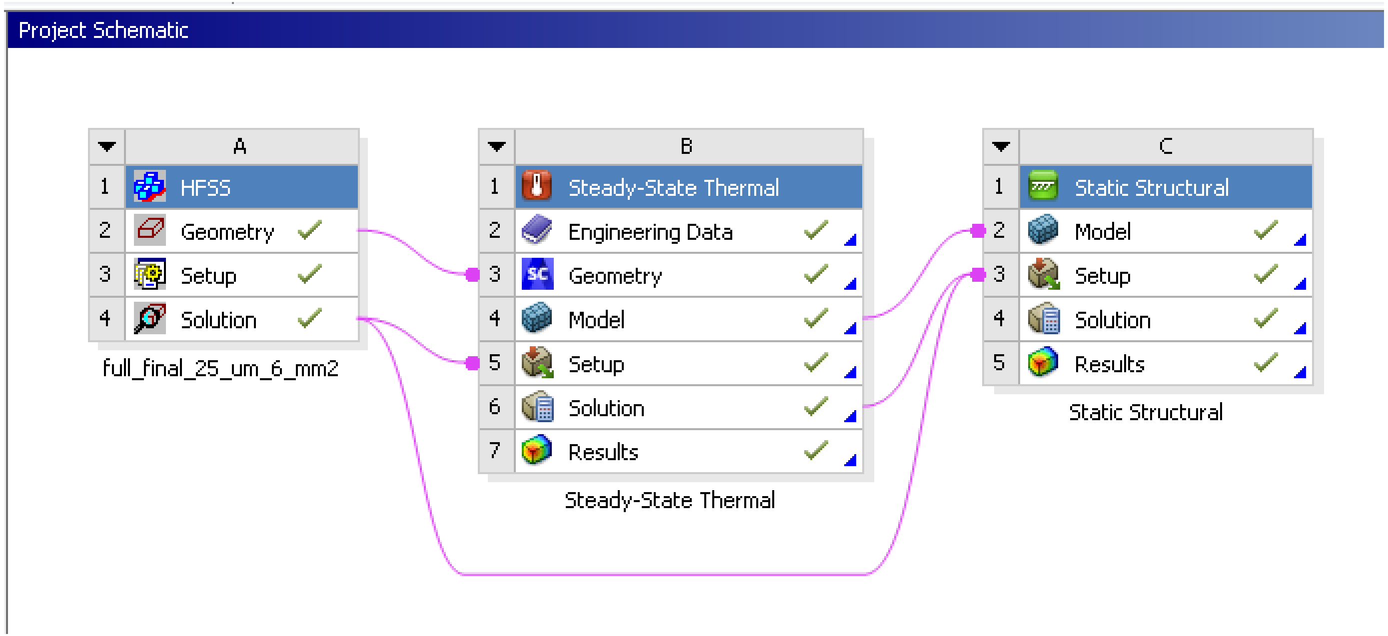
Output power from the klystron

Average power from klystron is equal 7.5 × 10^3 W

The losses in the BOC is equal to difference between average klystron power and the output pulse, in our case the total loss is 1.6 × 10^3 W

Thermal studies

To find out thermal heating affects on the performance of the BOC, we jave carried out simulations in **ANSYS- Workbench**



Project Schematic

	A	
1	HFSS	
2	Geometry	✓
3	Setup	✓
4	Solution	✓

full_final_25_um_6_mm2

	B	
1	Steady-State Thermal	
2	Engineering Data	✓
3	Geometry	✓
4	Model	✓
5	Setup	✓
6	Solution	✓
7	Results	✓

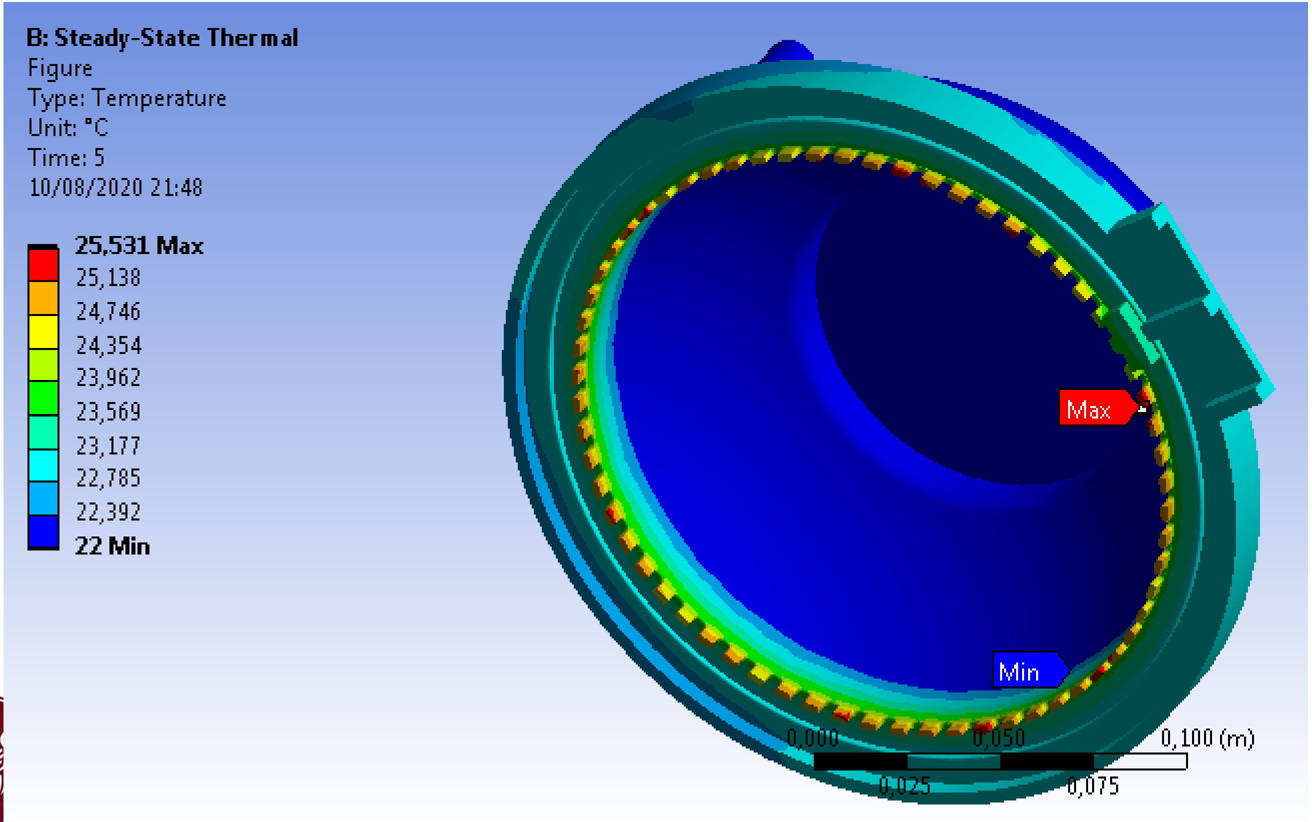
Steady-State Thermal

	C	
1	Static Structural	
2	Model	✓
3	Setup	✓
4	Solution	✓
5	Results	✓

Static Structural

This is the setup

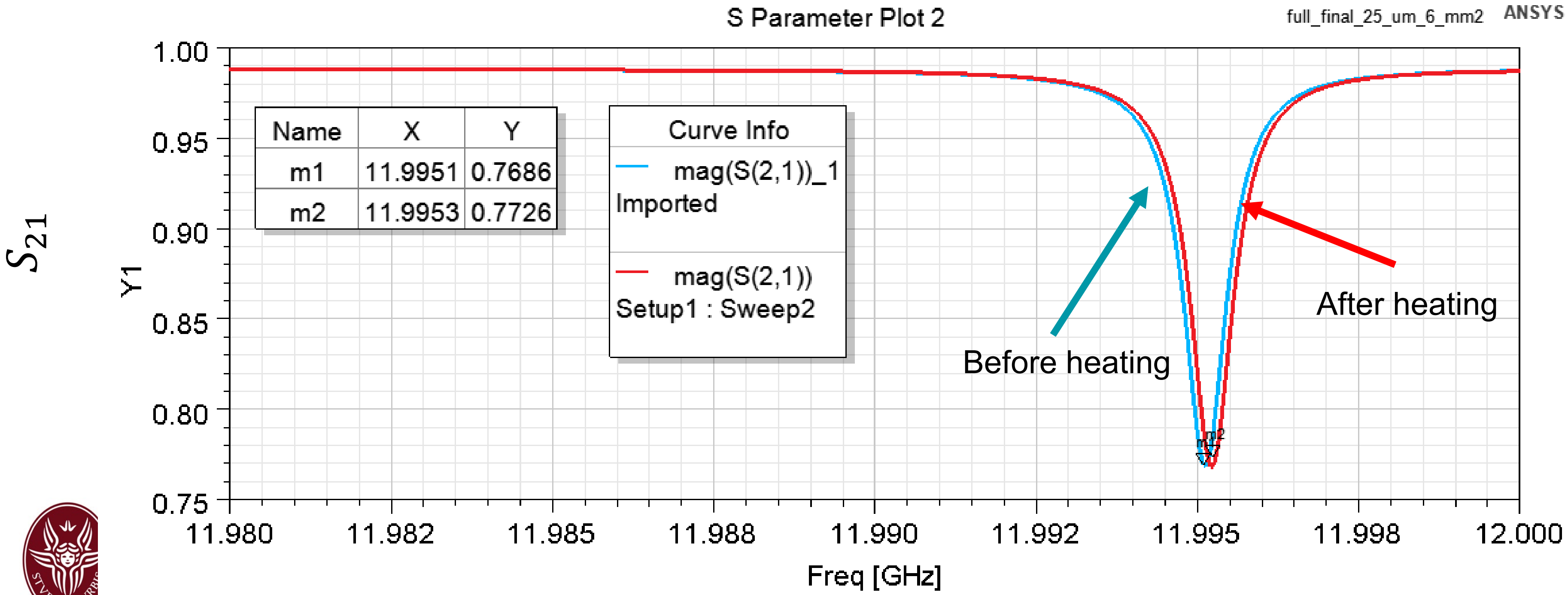
Temperature distribution



As we see the most incread temperature happens in coupling holes around 14°C

This slide shows detuning due to heating

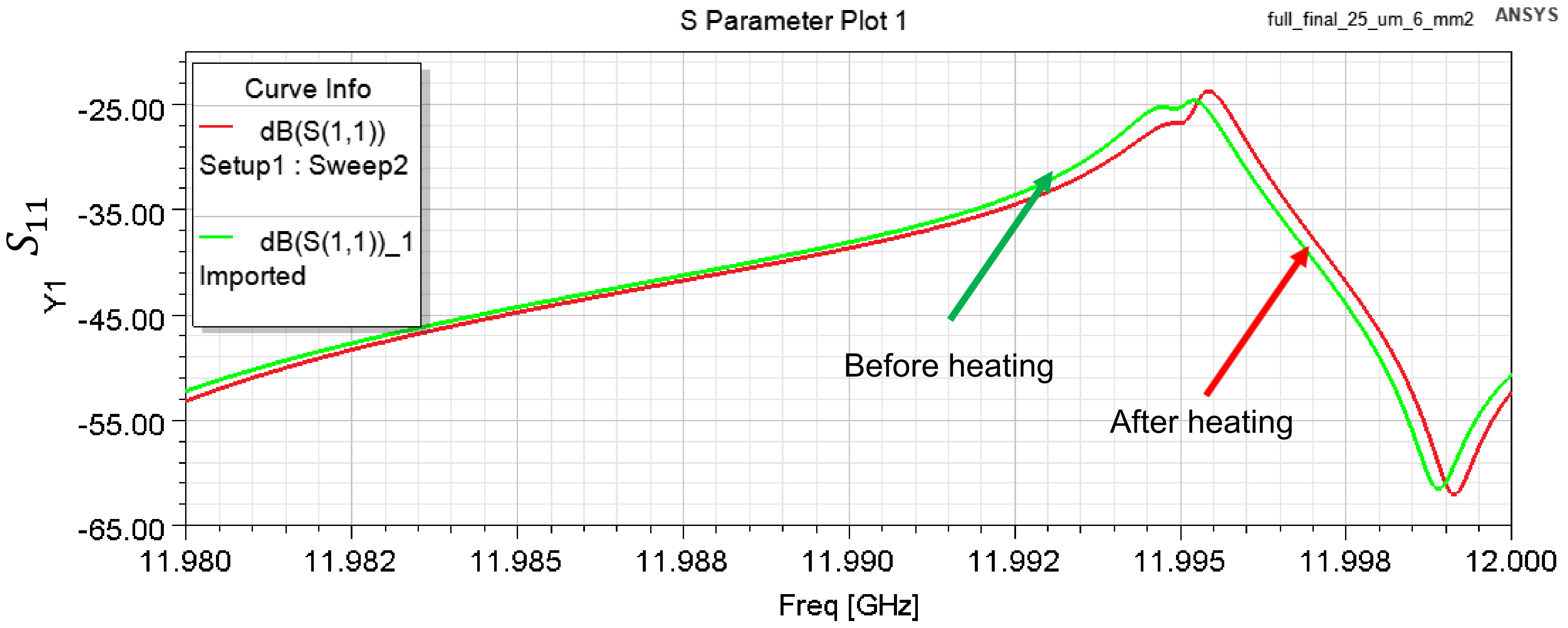
Due to thermal expansion geometry of device changes, so the scattering parameters which depents on the Geometry.
Below graphs we can see before and after heating values.



Name	X	Y
m1	11.9951	0.7686
m2	11.9953	0.7726

Before heating

After heating



Before heating

After heating

Heating shifts resonant frequency and detunes waveguide/cavity matching.

Thank you for your attention!

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