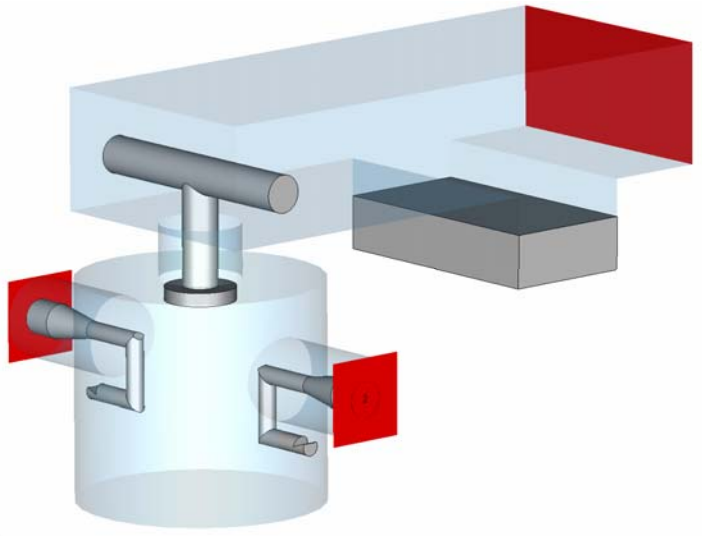
Design of a 150 kW Cavity Combiner (CaCo) for RF power sources of the ALBA synchrotron



Borut Baricevic

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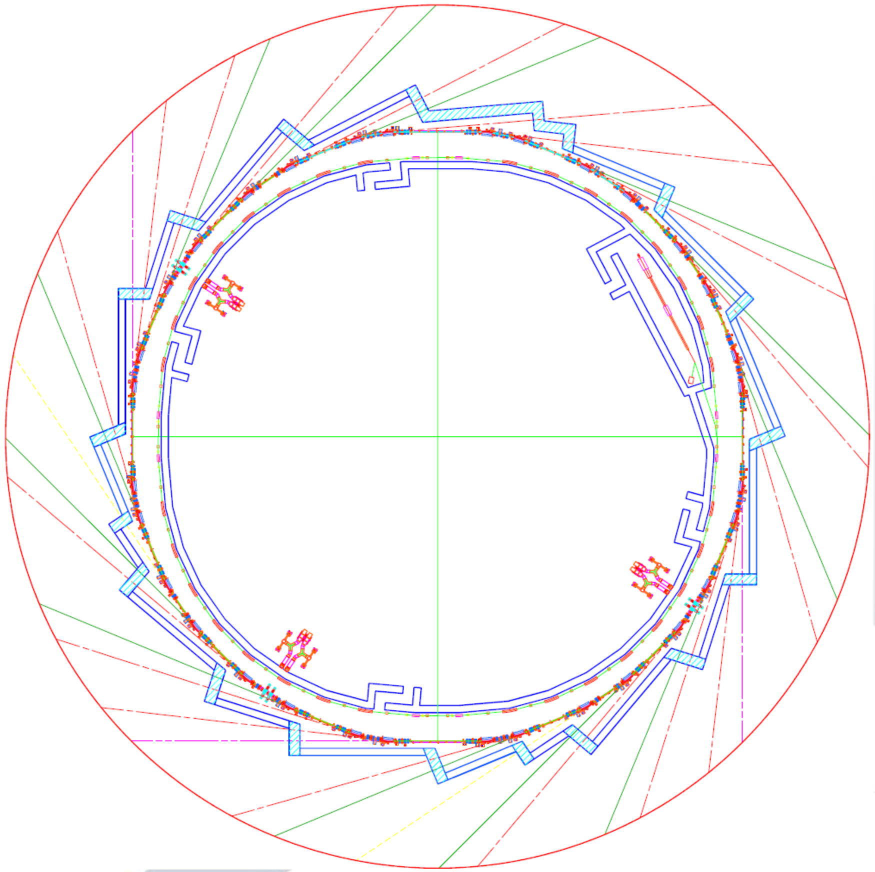
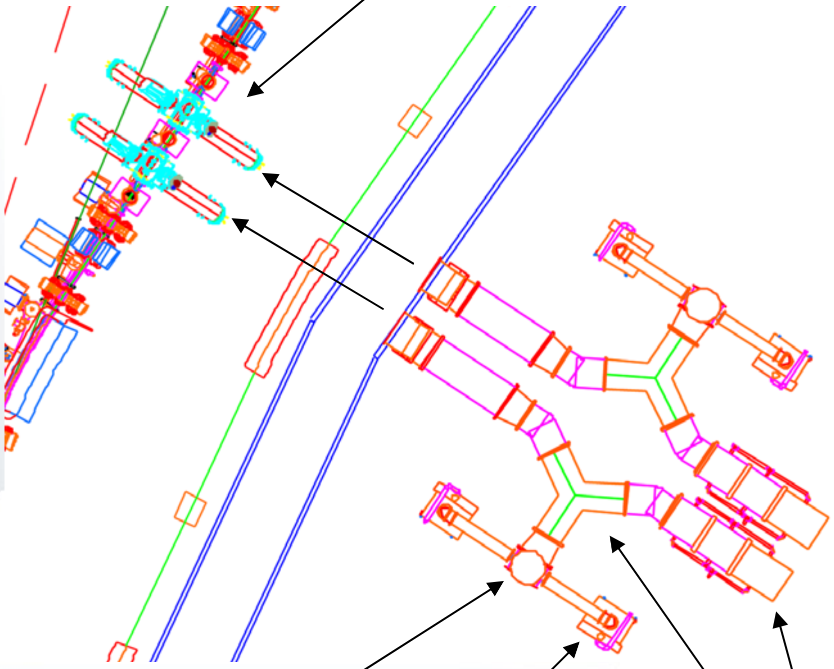
- Combiner's requirements
- Analytical design approach
- Combiner's analytical limits
- Numerical design (CST Microwave Studio)
- Power lost, reflections and efficiency
- Improvements
- Thales proposal

Introduction



ALBA storage ring



RF plants

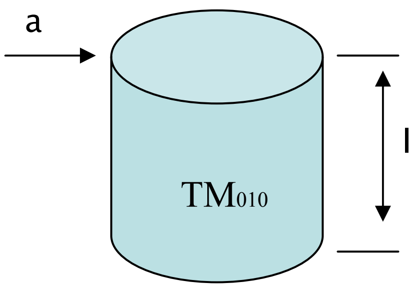
Combiners requirements

➢ Working frequency:	500 MHz
➢ Output power:	150 kW
➢ Input power:	2 x 80 kW
➢ IOT VSWR limit:	1.5
➢ Suggested IOT VSWR limit:	1.1
➢ Insertion loss:	< 0.3 dB (7 % of losses)
➢ Bandwidth:	> 6 MHz

- IOT harmonics filtering capabilities
- High efficiency in single IOT operation (fail working condition)

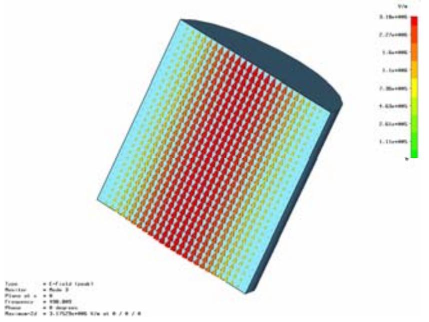
Analytical design approach

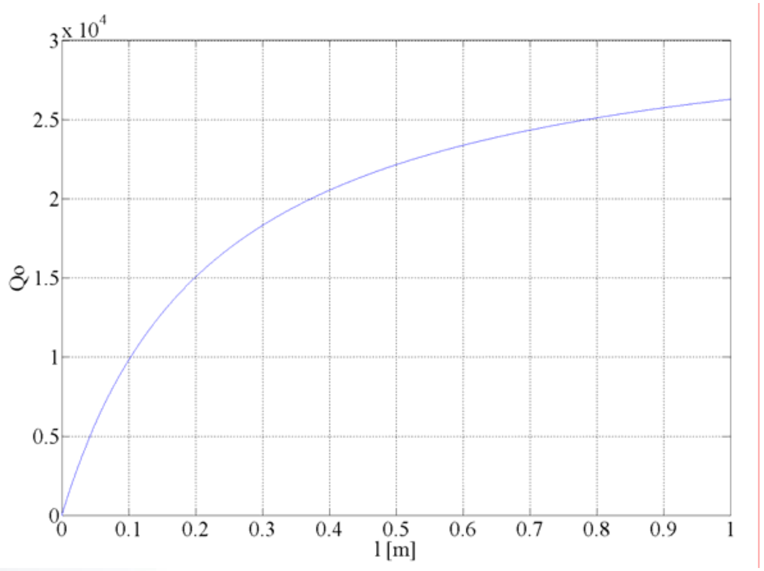
Pillbox cavity:



$$f_0 \cong \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}} \frac{2.40483}{a} \Rightarrow a = 229.6\ mm$$

$$Q_0 \cong \frac{\eta}{2\sqrt{\frac{\omega\mu_0}{2\sigma}}} \frac{2.40483}{1+\frac{a}{l}}$$





$$l = 511.5\ mm$$

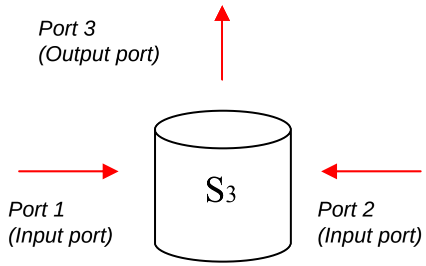
Pillbox HOMs:

$$f_{HOM\,(TM_{mnk})} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}} \sqrt{\left(\frac{u_{m,n}}{a}\right)^2 + \left(\frac{k\pi}{l}\right)^2}$$

$$f_{HOM\,(TE_{mnk})} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}} \sqrt{\left(\frac{v_{m,n}}{a}\right)^2 + \left(\frac{k\pi}{l}\right)^2}$$

The best trade-off between harmonics filtering capabilities and maximum unloaded quality factor.

Analytical design approach



Scattering matrix: How combiner's scattering matrix should look like?

Combiner's properties:

1) 3 ports device
2) Symmetry respect input ports
3) Made with reciprocal materials
4) When *symmetrically supplied*: zero reflections at the input ports
5) Loss free device

Scattering matrix's properties:

1) 3x3 Scattering matrix
2) Invariance respect input ports' row permutation
3) Symmetric scattering matrix

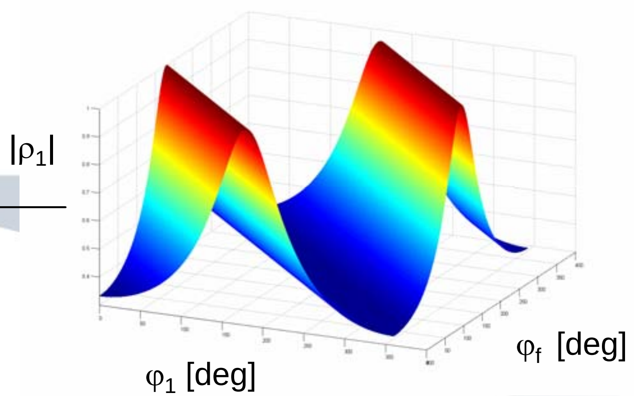
$$S_3 = \begin{bmatrix} -\frac{1}{2}e^{j\varphi_1} & \frac{1}{2}e^{j\varphi_1} & \frac{\sqrt{2}}{2}e^{j\varphi_3} \\ \frac{1}{2}e^{j\varphi_1} & -\frac{1}{2}e^{j\varphi_1} & \frac{\sqrt{2}}{2}e^{j\varphi_3} \\ \frac{\sqrt{2}}{2}e^{j\varphi_3} & \frac{\sqrt{2}}{2}e^{j\varphi_3} & 0 \end{bmatrix}$$

Single IOT operation: The turned off IOT output cavity is detuned in order to reflect all the power coming from the combiner.

The reflection coefficient seen by the combiner if one of the input ports reflects all the power results: $e^{j\varphi_f}$

This load produces reflections on the still operating input port.

The **minimum** reflection coefficient magnitude seen by the still operating IOT is 0.33 which corresponds to a VSWR=2 > 1.5.



It doesn't matter how we made the combiner: we cannot operate the system in single IOT mode.

We have to look for another solution.

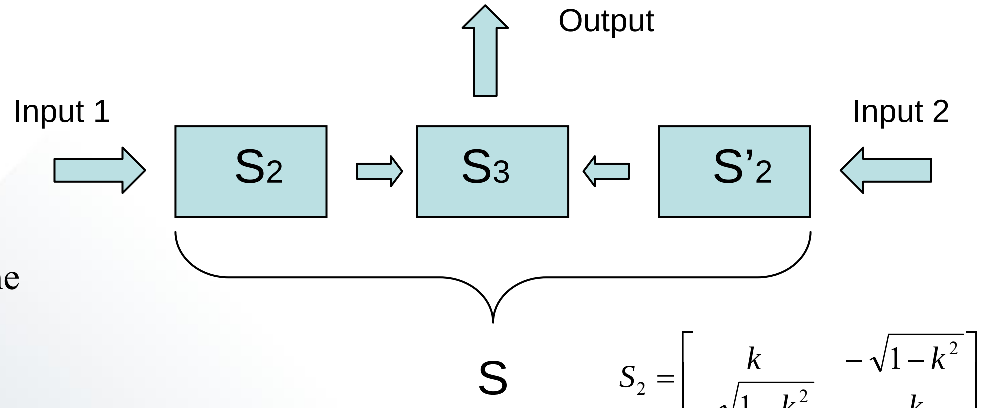
Analytical design approach

1. Proposal:

Symmetrical and fail operation trade-off

Combiner's properties:

1) 3 ports device
2) Symmetry respect input ports
3) Made with reciprocal materials
4) ~~When *symmetrically supplied*: zero reflections at the input ports~~
5) Loss free device

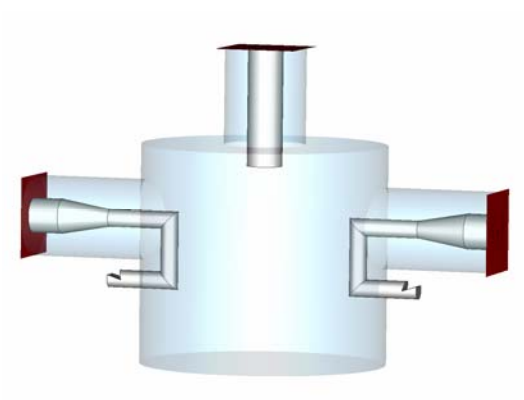


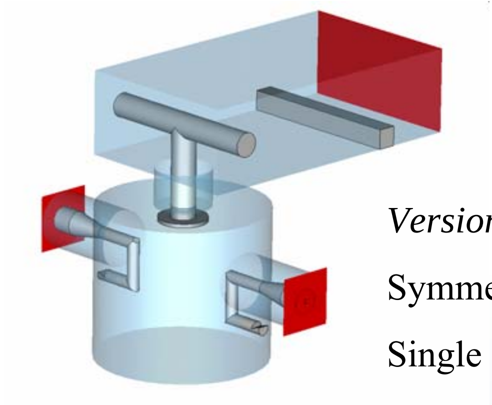
$$S_2 = \begin{bmatrix} k & -\sqrt{1-k^2} \\ -\sqrt{1-k^2} & -k \end{bmatrix}$$

Design parameter *k*	INPUT VSWR (Symmetrical condition)	INPUT SWR (Fail condition)	EFFICIENCY (Symmetrical condition)	EFFICIENCY (Fail Condition)
0.00	1.00	2.00	100%	89%
0.05	1.11	1.81	100%	92%
0.06	1.13	1.77	100%	92%
0.09	1.20	1.67	99%	94%
0.12	1.27	1.57	99%	95%
0.13	1.30	1.54	98%	95%
0.14	1.33	1.51	98%	96%
0.15	1.35	1.48	98%	96%
0.20	1.50	1.33	96%	98%
0.22	1.56	1.28	95%	99%
0.23	1.60	1.25	95%	99%
0.24	1.63	1.23	94%	99%

Numerical design

The analytical results were used as start point for the CST Microwave Studio numerical design.



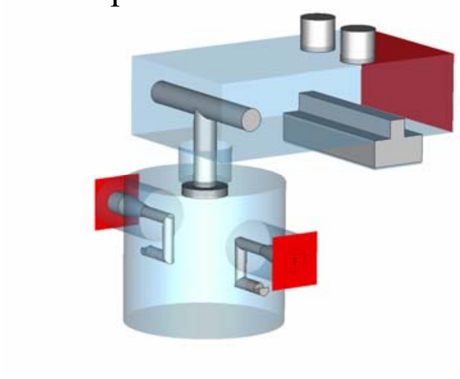


Version 1:

Symmetrical operation: VSWR=1.34 Efficiency: 98%

Single IOT operation : VSWR=1.52 Efficiency: 96%

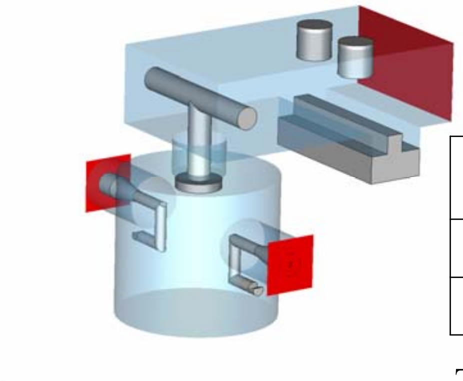
2. Proposal:



Symmetrical operation

VSWR=1.096

Efficiency: 99.79%



Fail operation

VSWR=1.125

Efficiency: 99.65%

Version 2: Double effect plunger

Version 2	VSWR	Reflection efficiency	Power dissipated
Symm. Operation	1.069	99.79%	225.3 W (2x80 kW)
Fail Operation	1.125	99.65%	151.1 W (80 kW)

The losses are negligible respect the power transferred to the output port. Due to the power dissipated the efficiency is reduced only of 0.1 %.

In the case of a 1 meter long rectangular waveguide the efficiency, due to the dissipations, is reduced of 0.0257%.

Numerical design - Improvements

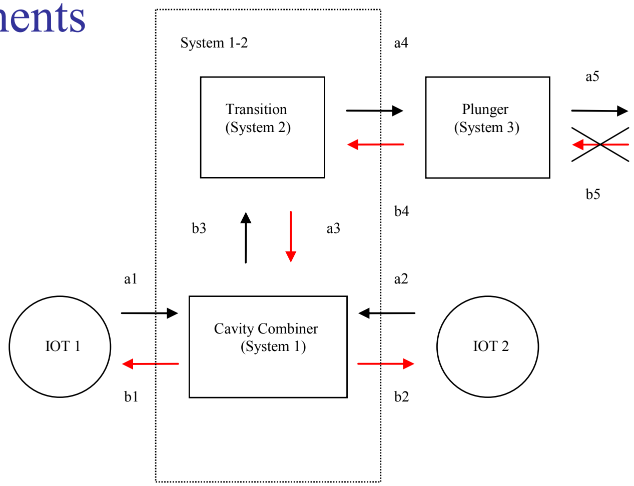
Version 3: To reduce the reflections a new design strategy is followed.

For version 1 & 2 the transition to rectangular waveguide was optimized for the trade-off between the symmetrical and fail operation.

Now the transition is optimized only for the symmetrical operation.

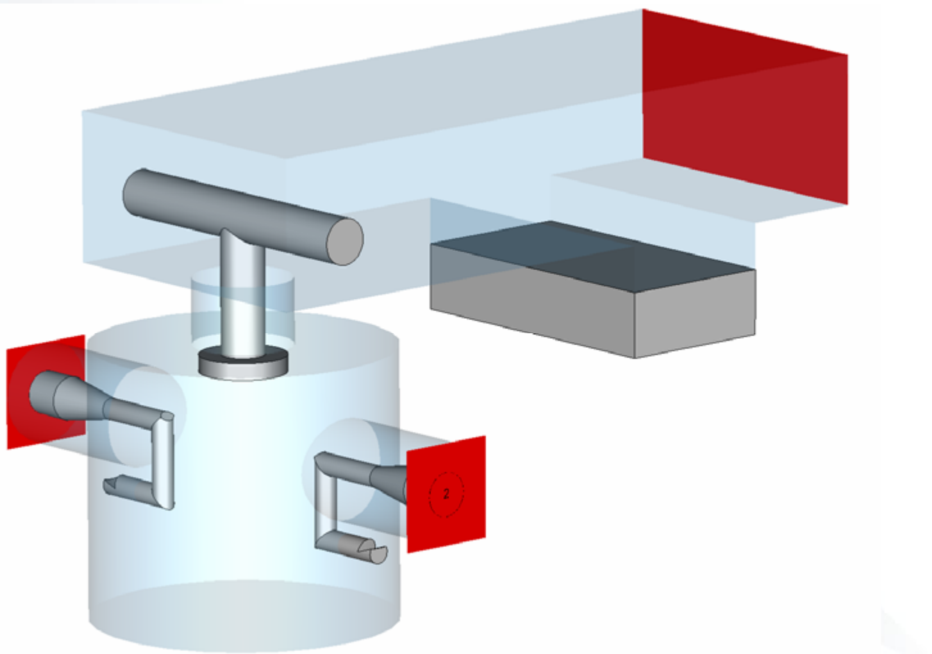
Then a plunger for the fail working condition was developed. This plunger was developed to:

- Reject the reflected waves on the IOT port
- Minimize the stresses of failed IOT coaxial line
- Minimize the stresses on the cavity coaxial output port



Performances:

Version 3	VSWR	Reflection efficiency	Power dissipated
Symm. Operation	1.0083	(99.9983%)	210.4 W (2x80 kW)
Fail Operation	1.0290	(99.9796%)	120.5 W (80 kW)



The total efficiency considering the losses and also the really negligible reflections is higher than 99.8% in both the operations.

Numerical design – Bandwidth and Tuning capabilities

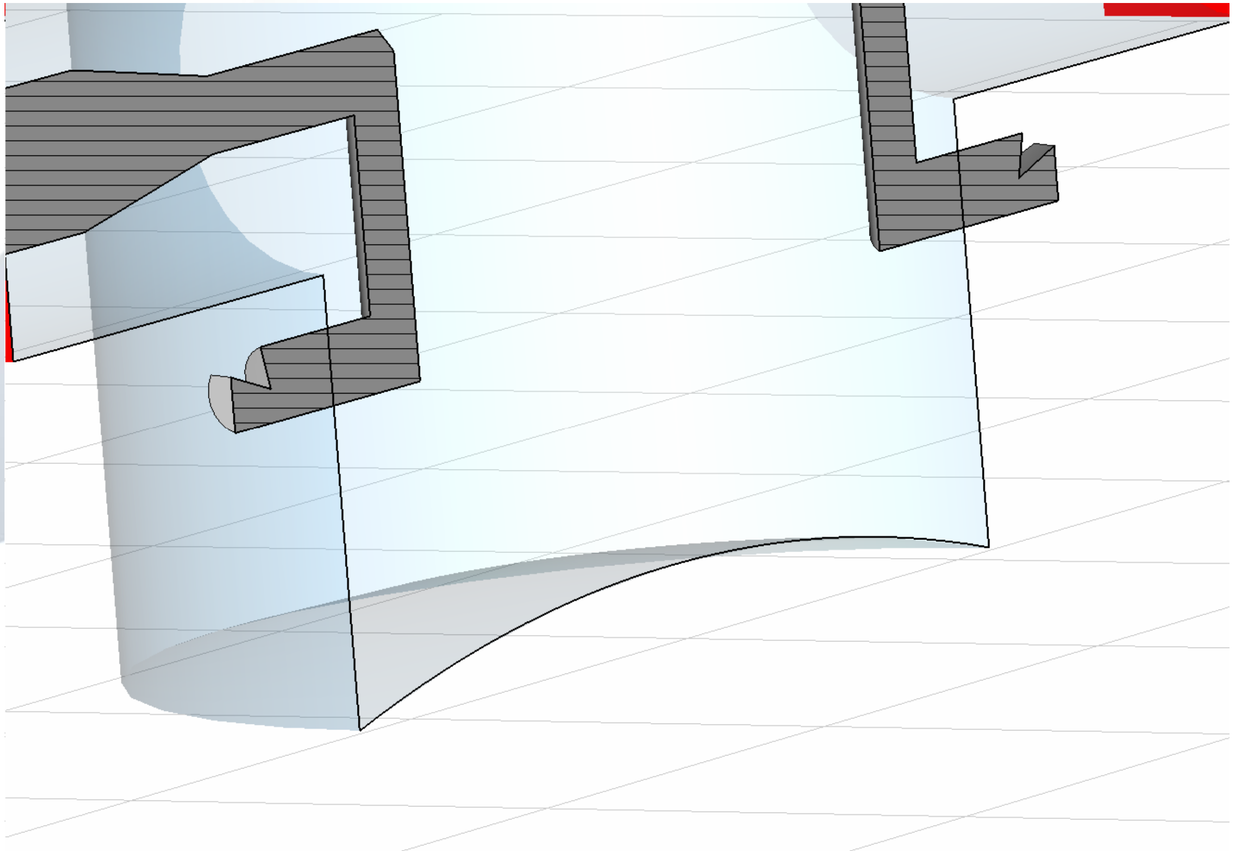
However a resonant mode is used to combine power, the cavity combiner is a broadband system.

The -3dB bandwidth is 30 MHz for the symmetrical operation and 44 MHz for the fail operation.

Whatever a tuning system has been foreseen to correct small manufacturing errors inside tolerances.

The sensitivity on the TM_{010} resonant frequency respect cavity bottom deformation is 225 kHz/mm.

With a deformation of ±10 mm the frequency shift obtained enables the correction of ∓1mm in the cavity radius.



Thales proposal

Thales Electron Devices is developing a cavity combiner prototype for Alba.

Thales optimized the combiner only for the symmetrical operation.

The cavity proposed by Thales is shorter than the one designed at CELLS. (l_{Thales}=214 mm l_{CELLS}=409 mm)

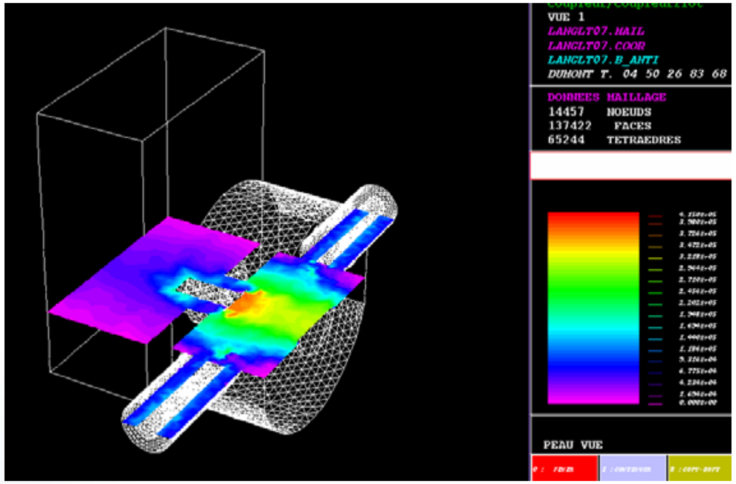
The power dissipated by the combiner developed by Thales is 396.2 W. The combiner designed at CELLS dissipates only 210.4 W.

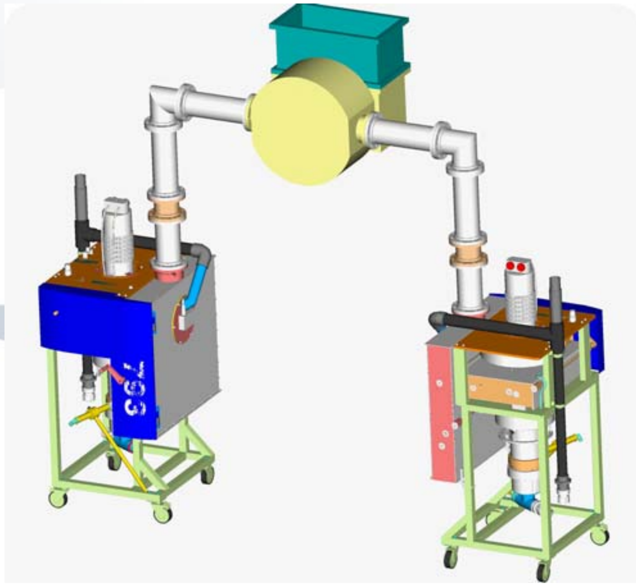
Thales will use for the combiner 4 1/16” air cooled coaxial lines.

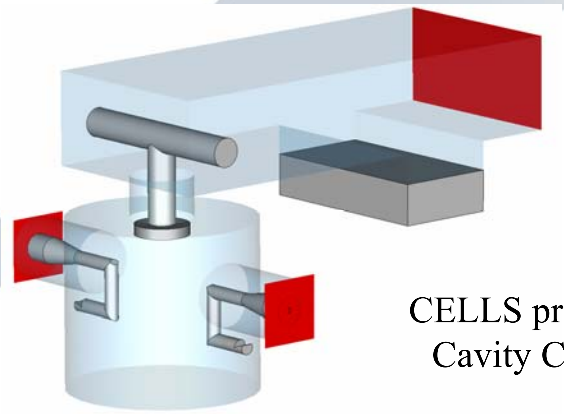
CELLS proposed a 6 1/8” air cooled solution.

The Thales output coupler is held by a teflon disk.

The CELLS output coupler is fixed on the rectangular waveguide body.



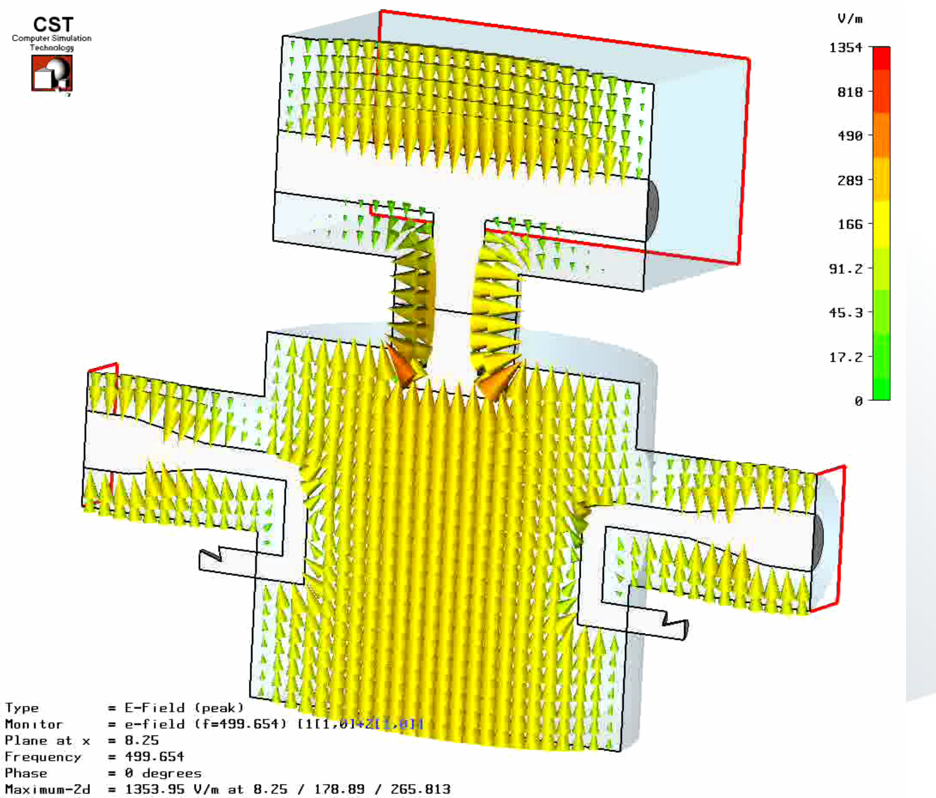




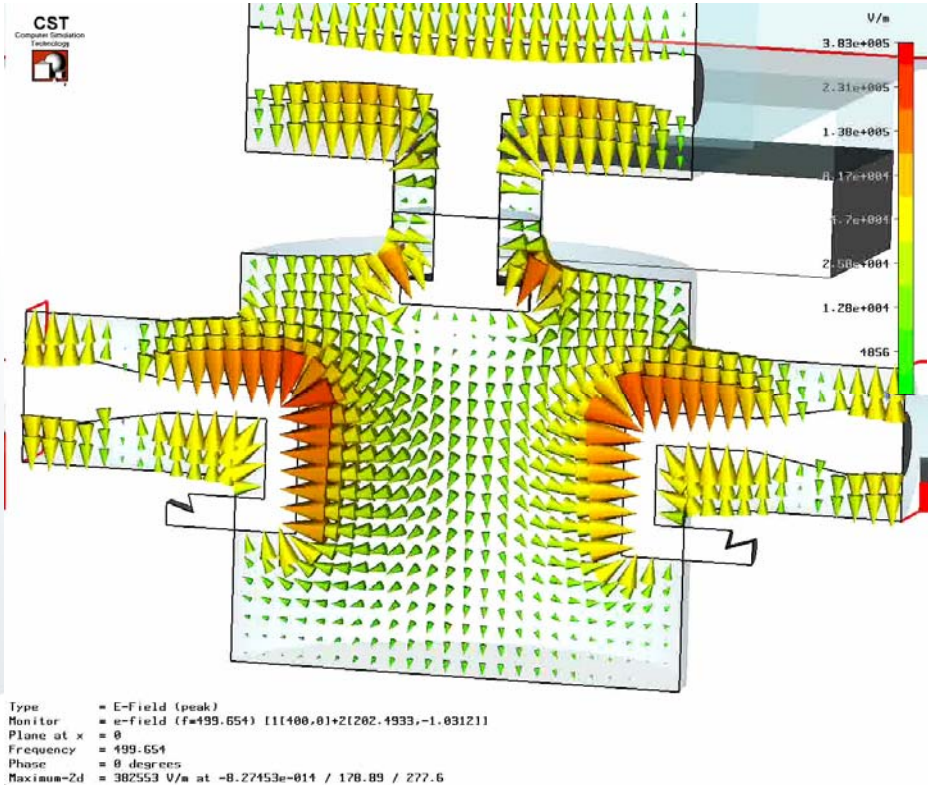
CELLS proposal for Cavity Combiner

Conclusions

Symmetrical operation (Ver. 3)



Fail operation (Ver. 3)



The most important problem of the cavity combiner design are the *waves reflected* upstream.

A *static cavity* combiner cannot be used if the single IOT operation is foreseen.

The *trade-off* between the symmetrical and fail operation is feasible if IOT performances are not degraded for VSWR > 1.1.

The structure dissipates a very *small power*. A compressed air cooling system should be enough to ensure a safe operation. The *efficiency* reduction due to the losses and the power dissipated is 0.2%.