

HIGH POWER CAVITY COMBINER FOR RF AMPLIFIERS

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Abstract

A new approach of RF power combination has been developed for the ALBA Storage Ring RF system: a three port high power Cavity Combiner (CaCo). A prototype has been successfully built and tested in Thales Electron Devices, Thonon, France. The final goal is to combine the power of two 80 kW IOTs at 500 MHz, in order to provide a total output power of more than 150 kW. In this paper, a summary of the analytical and simulation analysis of the expected behaviour is given. In basis of that, the decided geometric constrains and the final design configuration chosen for the prototype production are explained. Low power test results and matching, and finally the high power test performances are shown. As a conclusion, the RF system of the ALBA Storage Ring will incorporate the CaCo concept to obtain the needed power per cavity from the combination of two IOTs.

INTRODUCTION

The energy lost by the beam in the ALBA Storage Ring will be replaced by six RF cavities, each one of them supplied with 150 kW cw at 499.654 MHz. This power level will be obtained by adding up two 80 kW IOTs in a CaCo. Then, the CaCo insertion losses (reflection and dissipation) are limited to a maximum of 0.3 dB.

CaCo should meet the IOT requirements in terms of Voltage Standing Wave Ratio (VSWR), which optimum is <1.1 and maximum is 1.5 [1]. Moreover, CaCo must have a minimum 3 dB bandwidth of 6 MHz centred on the working frequency.

The two CaCo's input ports are coaxial type, 4 1/16", matching the IOT's output, and the CaCo output is coupled to a WR1800, suitable for the transmission of 150 kW signal.

CaCo presents another capability in terms of higher frequencies filtering. This could be very useful to avoid High Order Modes (HOM) excitation in the accelerating cavity. Finally, CaCo is also requested to work safely and efficiently in case of an IOT failure.

ANALYTICAL CONSIDERATIONS

Pillbox Cavity

As shown in Figure 1, CaCo is realized using a coupled pillbox cavity. For transmitting power from the input couplers to the output coupler, the TM₀₁₀ pillbox cavity mode will be used, which resonant frequency is:

$$f_0 \cong \frac{1}{2\pi\sqrt{\mu\epsilon}} \frac{2.40483}{a}$$

where *a* is the CaCo's radius.

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So, to tune the TM₀₁₀ on the ALBA RF frequency we should choose *a*=229.6 mm.

There is another free variable: the cavity length *l*. From the unloaded quality factor relation

$$Q_0 = \frac{\eta}{2\sqrt{\frac{\omega\mu}{2\sigma}}} \frac{1}{1 + \frac{a}{l}}$$

The longer the CaCo, the higher its unloaded quality factor, and therefore, for the same energy stored there are lower losses. However, the longer the CaCo, the more HOM in the same frequency range. The best trade-off between harmonics filtering capabilities and maximum unloaded quality factor for the TM₀₁₀ mode has to be found.

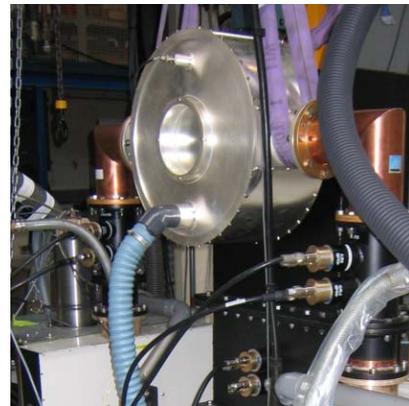


Figure 1 : Cavity Combiner (CaCo).

Scattering Matrix

The scattering matrix characterizes completely the behaviour of a microwave network in terms of power exchanged between ports by the considered modes, describing the phase and amplitude relationship between forward and reflected waves. The scattering matrix for our reciprocal, symmetric, loss free device that does not reflect power if symmetrically supplied is given by

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

where φ_1 and φ_3 take arbitrary values (see [2] for more details).

SIMULATION ANALYSIS

Electromagnetic Simulations

CST MICROWAVE STUDIO® has been used for the CaCo electromagnetic simulation. The couplers' dimension and position have been designed for total transmission of the fundamental TM_{010} mode and also for filtering out the HOM. The estimated values obtained by CELLS, for copper material, and for 150 kW output power, are: VSWR of 1.034; efficiency up to 98 % (wall losses are negligible); bandwidth at -3 dB is 15 MHz; and maximum dissipated power around 225 W.

TED simulation uses MAXWELL 3D, a proprietary code similar to ANSOFT's HFSS. It is based on cavity walls made of copper or silver plated brass ensuring a low surface resistivity. The losses have been evaluated for each subassembly and found very small, similarly to CELLS results, as seen in Table 1.

Table 1: CaCo power losses estimated by TED.

Subassembly	Losses [W]
Coaxial conductors and loops	67,3
CaCo Body	283.7
Output WR1800 transition	45.3
TOTAL Losses	396.3

With such low values, a pressurized air cooling system is enough to reduce the structure's temperature. If experience shows otherwise, the implementation of water pipes around the CaCo walls is possible.

Thermo-Mechanical Simulations

The frequency drift when submitted to the aforementioned losses and to air cooling has also been computed by TED with analytical approximation. The temperature in the CaCo walls reaches 49.7 °C, producing a frequency drift of 0.24 MHz. This very small frequency drift does not call for further investigation. No tuning system is required since the bandwidth is wide enough to cope with such a minor drift.

FINAL DESIGN CONFIGURATION

Some parameters have been adjusted by TED with the aim to reduce the CaCo dimensions (producing a very compact model), and to ease the construction. Among them the diameter and height of the resonator, the input coupling loops size, the size and height of the post in the output waveguide, the distance between this post and the WR1800 short circuit termination and the capacitance attached to the aforesaid post. Moreover, in order to correct manufacturing errors, a tuning element has been added in the CaCo floor.

According to CELLS dissipated power estimation [3], the coaxial 4 1/16" presents bigger power density than a coaxial 6 1/8". Nevertheless, coaxial 4 1/16" seems to be suitable for transmitting the 80 kW if an appropriate air cooling system is designed.

Therefore, the final design is shown in Figure 2.

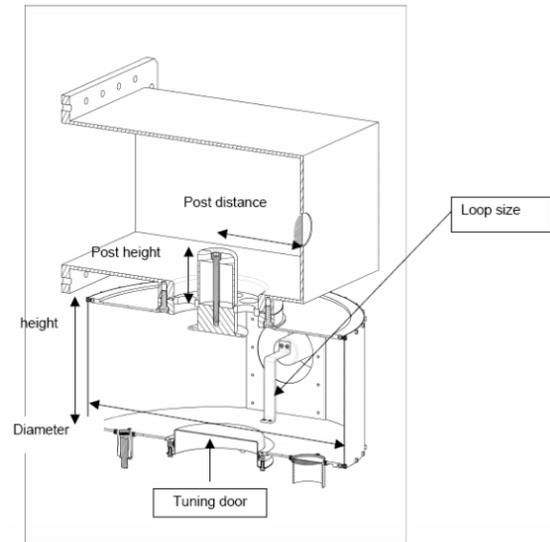


Figure 2: CaCo (TED manufactured prototype).

LOW POWER TESTS

The low power tests have been performed at the TED premises in Thonon. Initially, the reflected power at the resonance frequency was higher than expected and the bandwidth lower than expected, as seen in Figure 3. After some try and error, the height of the output coupler post was increased by 12 mm; improving the low power results at the fundamental TM_{010} mode.

The measured S parameters are very similar to the expected by theoretical analysis. Transmission was also investigated for the HOM and no peculiarities were discovered. We can conclude that the CaCo is filtering out the HOM.

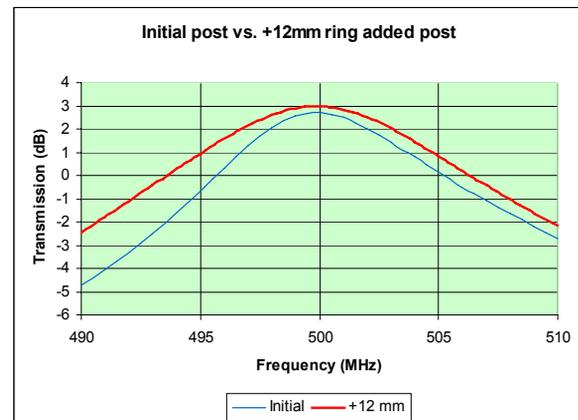


Figure 3: Low power test results.

HIGH POWER TESTS

Power Measurements

The high power tests have been also performed at the TED premises in Thonon. Power was measured by two methods: first with directional couplers, second with the voltage and current from the high voltage supplies and the calorimetric data of the tube boilers.

For more than half an hour, a combined power of more than 150 kW was maintained in the CaCo. During this time no arcs were detected. The surface temperature of the CaCo was evaluated with thermal stickers, and they indicated a fairly even temperature of 46 °C, in very good agreement with the analytical approximation.

Tuning

Above 50 kW of RF power per IOT, the primary output cavity and the drift tube of the IOT itself expands due to losses. This expansion was compensated by tuning again the primary output cavity of the IOT.

Results

The results of the directional couplers measurements are presented in Table 2. They confirm the good efficiency of the CaCo at full power (96%). For comparison, the calorimetric measurements show a maximum output power of 154 kW.

Table 2: Directional coupler measurements of the high power test (maximums).

IOT 1 [kW]		IOT 2 [kW]		WR1800 output [kW]
P _{forward}	P _{reflected}	P _{forward}	P _{reflected}	
86.9	3.5	76.6	3.1	156.9

CASE OF AN IOT FAILURE

In the case of an IOT failure, it should look like a reflective load and therefore should have imaginary impedance. All the power is reflected back by the failed IOT and the reflection coefficient seen by the working IOT is

$$\rho_1 = -\frac{1}{2} e^{j\varphi_1} + \frac{1}{4} e^{j2\varphi_1} \frac{1}{e^{-j\varphi_F} + \frac{1}{2} e^{j\varphi_1}}$$

where φ_F is function of the distance between the CaCo and the failed IOT. The magnitude of this reflection coefficient is plotted in the range $[0, 2\pi]$ in Figure 4.

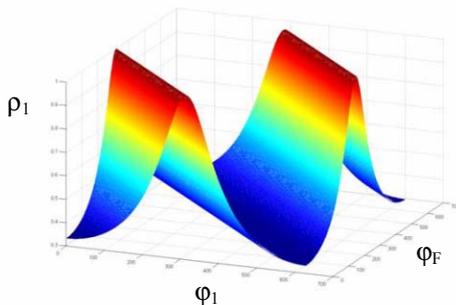


Figure 4: Reflection vs. phases in case of an IOT failure.

The minimum value of the reflection coefficient is 0.33, i.e. a VSWR of 2. This means that the operating IOT will be working against a high VSWR, so losing efficiency.

This can be observed in Table 3, where the experimental results for the case of the failure of the

IOT_2 are shown. The tests were done at TED premises by removing suddenly the drive to the IOT_2.

Comparing with Table 2, the forward power of IOT_1 decreased by almost 25 kW, i.e. its efficiency decreased by almost 30%. On the other hand, the transmission efficiency of the CaCo is still over 84%.

Table 3: High power results (case of an IOT failure).

IOT 1 [kW]		IOT 2 [kW]		WR1800 output [kW]
P _{forward}	P _{reflected}	P _{forward}	P _{reflected}	
62.0	5.6	7.9	10.0	52.3

If one wants to improve the efficiency of the system for the case of an IOT failure, a tuning system to match the active IOT output has to be foreseen. This can be achieved by adding a plunger structure at the CaCo's WR1800 output, as shown in Figure 5.

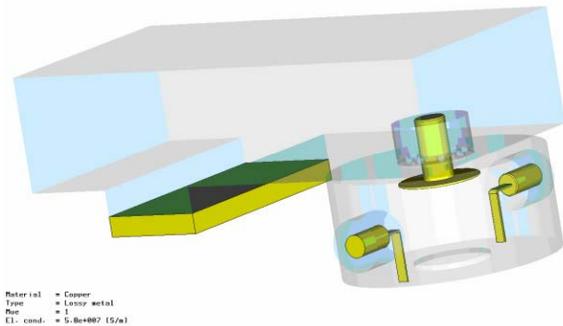


Figure 5: CaCo model with tuning system.

CST MICROWAVE STUDIO® simulations show that in this case a transmission efficiency of more than 95% can be achieved.

CONCLUSIONS

The CaCo prototype, manufactured and tested by TED, works properly and it will be used in the ALBA Storage Ring combining two 80 kW IOTs.

The power losses in the CaCo walls are quite low and a pressurised air cooling is enough to reduce the CaCo's wall temperature.

Coaxial 4 1/16" lines, coupling the IOT's outputs, can be used as they are also air cooled.

In the case of an IOT failure, and as future evolution, a plunger can be added in the WR1800 transition.

REFERENCES

- [1] Thales Electron Devices, Technical specification of TH 793 – Pyrobloc Grid IOT. March 2004.
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