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CONCEPT AND DEVELOPMENT OF 65 kW SOLID-STATE RF AMPLIFIERS FOR SIRIUS

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Abstract

Sirius is a 4th generation synchrotron light source currently operating with 100 mA stored beam and one room temperature RF cavity driven by two 65 kW solid-state amplifiers (SSAs). After installation of the cryogenic plant, two superconducting (SC) RF cavities are planned to replace the room temperature cavity. Each SC cavity is going to be driven by a 250 kW RF signal at 500 MHz, resulting from the combination of four 65 kW RF SSAs. Due to the recent development of 900 W solid-state power amplifier modules, a new topology was proposed for the four amplifiers that still need to be constructed. For the amplifier's combining stage, a cavity combiner with 80 input ports was simulated. For the dividing stage, 8-way and 10-way power splitters were designed. The general scheme of the amplifier is presented, as well as simulation and measurement results.

INTRODUCTION

Sirius is a 4th generation synchrotron light source located in the city of Campinas, Brazil. It comprises a 350 MeV, 3 GHz linac, a 2 Hz booster and a 3 GeV, 500 MHz storage ring. It is currently able to store a stable 100 mA electron beam, accelerated by a room temperature 7-cell PETRA cavity. This cavity is driven by two solid state amplifiers, each one able to deliver up to 65 kW RF power. After the cryogenic plant installation, the PETRA cavity is expected to be superseded by two superconducting (SC) CESR B-cell cavities to enable the storage of higher beam currents. To achieve 350 mA, each cavity will require up to 250 kW at 500 MHz, so more RF amplifiers are necessary.

The Brazilian Synchrotron Light Laboratory (LNLS) was one of the first facilities of its kind to employ solid state technology on RF amplifiers, along with SOLEIL. LNLS' late 2nd generation synchrotron light source operated for 10 years with solid state amplifiers (SSAs) on its storage ring with positive results. Its benefits, like modularity, high MTBF and efficiency, absence of high DC voltages, among others, are well known. Therefore, solid state technology continues to be the choice for RF amplification at Sirius' storage ring.

The two 65 kW SSAs currently operating will also be employed for one of the SC cavities, along with other two amplifiers of the same topology that are being assembled and will be tested on the second semester of 2022. For the other SC cavity, a new solid-state power amplifier module has been developed in 2021 and has shown better efficiency, as well as higher gain and output power level. For several reasons, these amplifier modules would be incompatible with the current SSA topology, so an effort has been made to devise a new topology, which includes a different RF power splitting and combining scheme.

The following sections are dedicated to briefly present RF devices of the proposed RF amplifier, as well as studies to evaluate key parameters for future operation.

AMPLIFIER MODULE

The desgined amplifier module has been already mentioned in a previous conference, along with the performance of some prototypes [1]. It was able to output 900 W in the workbench reliably, but could not handle full reflected output power at the isolator due to poor thermal management of the RF termination, which was only rated for 800 W.

Therefore, an aluminum case with embedded copper tube was designed to assure better thermal dissipation. Thermal simulations were carried out to optimize the copper tube path and location. Minor changes on the RF and bias circuit were also made. Moreover, some room inside the case was left to house an eventual control board dedicated to gate bias control and data acquisition. Finally, a 1200 W RF termination was selected for the new version.

The modified aluminum cases will arrive soon and fine tuning of the RF parameters will be done on the workbench. After that, the production of a test batch will be launched. Fig. 1 presents a detailed 3D drawing of the assembled amplifier module.

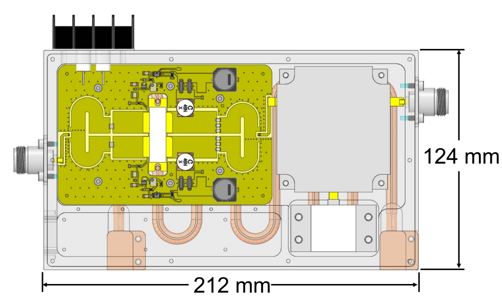

Figure 1: Top view of the amplifier module mechanical assembly CAD.

POWER DIVIDERS

8-Way Divider

Each amplifier module will be driven by one of the output ports of an 8-way RF power divider. It is built by cascading 2-way Wilkinson power dividers three times. It isolates output ports and prevents failing modules from impacting other modules' input power. This device was simulated in HFSS and a prototype was assembled and soldered in-house and is presented in Fig. 2. Main RF parameters are presented

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in Table 1. Difference between measured amplitude and phase of the output ports was not greater than 0.3 dB and 1.5°, respectively.

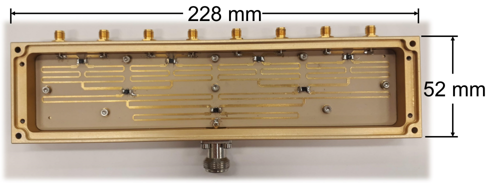

Figure 2: Top view of the 8-way divider prototype.

Table 1: Performance of 8-way Divider

Parameter	Value
Input Return Loss	> 23 dB
Output Return Loss	> 28 dB
Insertion Loss - 9.03 dB	< 0.37 dB
Isolation	> 40 dB

The 8-way divider was tested with up to 2 adjacent ports open and 50 W input power. The resistors' measured temperatures were at least 40 °C lower than the maximum temperature provided by the manufacturer. The device was deemed able for operation and a pilot batch is under procurement.

10-Way Divider

A 10-way divider was designed to feed each of the amplifier's 8-way dividers. It consists of quarter-wavelength microstrip lines of approximately $50\sqrt{10}\,\Omega$. Because the 8-way divider can keep an input return loss (RL) greater than 13 dB for two open output ports, impedance modulation of the outputs of the 10-way divider are kept at a safe level to suppress meaningful deviations of nominal amplitude and phase values between ports.

This device was simulated in HFSS and showed an input RL greater than 30 dB at 500 MHz, and insertion loss (IL) on its output ports only 0.1 dB away from the ideal value. The assembly of the 10-way divider is underway and should be completed in a couple of months. Figure 3 presents a view of the detailed 3D CAD of the device.

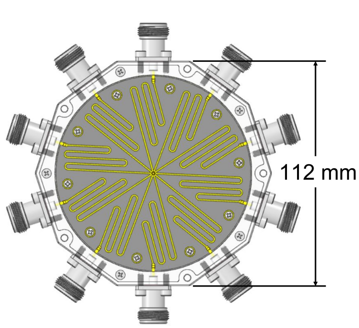

Figure 3: View of the 10-way divider mechanical CAD.

CAVITY COMBINER

A cavity combiner (CaCo) was chosen as the method to combine the output of 80 amplifier modules. Historically, amplifiers employed at LNLS' machines were combined with cascaded coaxial combiners, which were called "combiner trees". This topology usually shows an overall lower combining efficiency than a combiner cavity, which translates to more modules being employed just to generate heat instead of useful RF power. Moreover, cabling becomes troublesome as the power level of modules increase, so direct assembly into the cavity wall is planned for future amplifiers. This also helps to improve the combining scheme's efficiency.

The CaCo working principles' are similar to other structures already presented in the literature [2]. Input magnetic loops have the same size and, to achieve the same transmission coefficient to the output port, some of them need to be rotated depending on its relative height on the structure due to the assymetry of the magnetic field strength. This parametric study was done in HFSS, and the maximum phase shift difference from input ports to output was found to be as high as 10°.

CaCo's Efficiency Study

A study was carried out to assess the cavity combiner's ruggedness to amplitude and phase deviations due to imperfect manufacturing processes of preceding input devices. For a given set of amplitude and phase standar deviations, 1.10^7 samples of 80 input waves were generated. Then, they were sorted in regard to phase in an ascending order as to counterbalance the cavity magnetic field's assymetry. Finally, the input waves were operated in the scattering matrix of the CaCo, and the structure's efficiency was gathered from the scattered waves and the mean efficiency value for each case was calculated. The mean efficiency and its standard deviation can be found in Fig. 4. It is seen that the combining efficiency of the structure can reach over 98 % for some sets of amplitude and phase deviations.

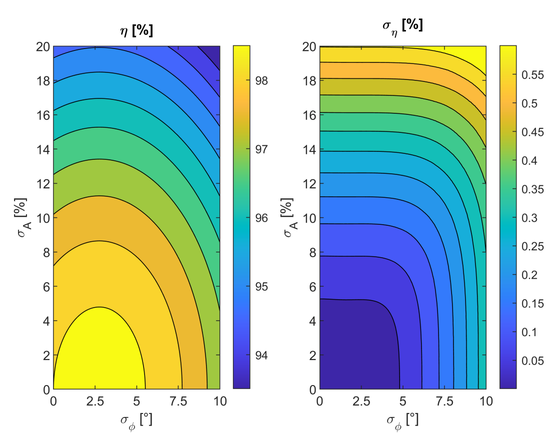

Figure 4: CaCo mean efficiency (left) and its standard deviation (right) for sets of sampled input waves.

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Faulty Modules' Operation

It was also analyzed how amplifier module's faults can impact the necessary input power levels to achieve 65 kW on the CaCo's output. A faulty module is represented by zero input power on an input port that was randomly selected. The input power of the operational ports are considered to be the same and the maximum incident power for each case was extracted. This procedure was iterated 5.10^7 times for faults ranging from 1 to 4 modules. Figure 5 presents the probability for values of maximum incident power in any input port of the strucutre, along its mean value and standard deviation.

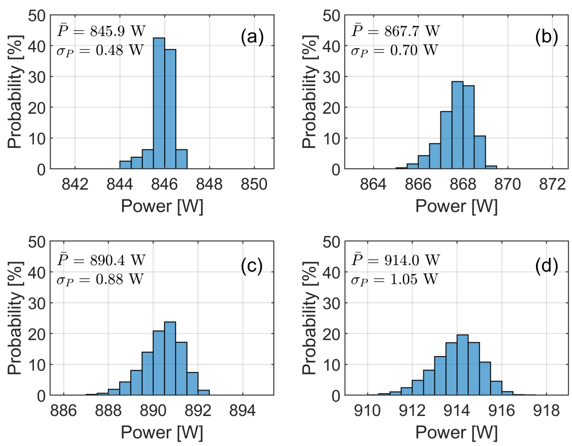

Figure 5: Maximum incident power for (a) 1, (b) 2, (c) 3 and (d) 4 faulty modules on random input ports.

It can be seen that, based on power levels already achieved on the workbench, the structure may operate with up to 3 faulty amplifier modules without impacting overall operation of the storage ring's RF plant. It is important to note that mean values may be higher if amplitude and phase deviations of the input waves are considered. These deviations will be evaluated after the production takes place.

The incident and scattered (total) power flow on the input ports did not exceed 1 kW for any case considered, which is the maximum power rating of the module's circulator. Also, the mean phase of the output power signal did not seem to change considerably with respect to faulty modules.

Manufacturing Process

A calendering process of an aluminum sheet, followed by soldering of both ends and fine machining of the inner surface will be attempted to build the lateral wall of the CaCo. With this procedure, it is expected to significantly reduce manufacturing costs in comparison to machining an aluminum block. Two walls with roughly half the CaCo's height will be produced and assembled together with flanges. The outer side of the cylinder will be machined to produce flat surfaces to install magnetic loop's flanges.

Figure 6 presents a detailed 3D drawing of the CaCo and some of its key components. Detailing of all the mechanical pieces is underway and a prototype will be manufactured in the following months. The structure will be tuned by varying the input couplers' rotation and key parameters, like the cavity unloaded and loaded quality factor, will be extracted.

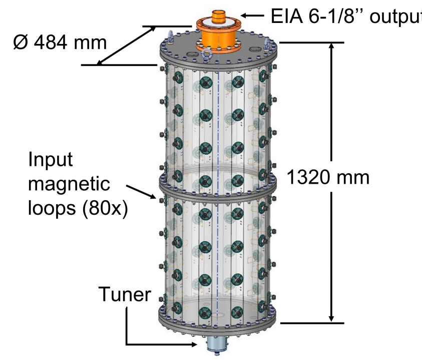

Figure 6: View of the proposed cavity combiner 3D CAD.

AMPLIFIER'S SUBSYSTEMS

Besides the RF devices already mentioned, the amplifier will house a pre-amplifier crate to amplify the signal coming from the low-level RF system and feed the 10-way divider input. Several off-the-shelf DC converter solutions are being analyzed to comprise the amplifier. Critical parameters are AC/DC conversion efficiency and the possibility to tune the drain bias voltage to operate the amplifier module's on high efficiency indepedently of the amplifier's output power level.

A control and interlock system will also be integrated to the amplifier to allow for safe operation and communication with Sirius's EPICS-based control system. The company PiTec, which designed some of Sirius beamlines' photon detectors, is collaborating with CNPEM to provide solutions regarding all aspects of the amplifier design, and will assist in the production and testing of the structures [3]. A schematic of the amplifier is presented in Fig. 7.

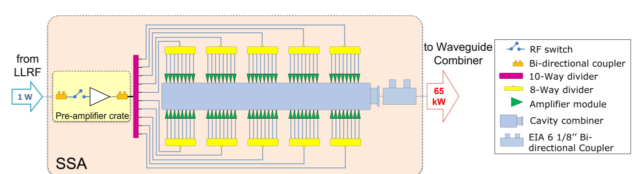

Figure 7: Schematic of the SSA's RF system.

CONCLUSION

A new topology of solid-state amplifiers was proposed to accomodate new power amplifier modules that were developed for Sirius's storage ring RF system. Several RF devices were simulated and fabricated to assess future amplifiers' operation. Simulation results have shown that the devised configuration is able to provide a 65 kW output RF signal at 500 MHz, even considering non-ideal cases. A prototype of the amplifier is expected to be assembled and operated in the second semester of 2022, and production of the 4 units will start in 2023.

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REFERENCES

[1] M. H. Wallner, R. H. A. Farias, A. P. B. Lima, and F. S. de Oliveira, ”Novel 500 MHz solid state power amplifier module development at Sirius”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 2349-2351, doi:10.18429/JACoW-IPAC2021-TUPAB358

[2] C. de la Morena *et al.*, “Single-step port-reconfigurable cavity combiner with high efficiency”, *Nuclear Instruments and Methods in Physics Research A*, vol. 972, Aug. 2020, doi:10.1016/j.nima.2020.164108

[3] PiTec, https://www.pitec.co/.