

## HIGH POWER (35 KW AND 190 KW) 352 MHZ SOLID STATE AMPLIFIERS FOR THE SOLEIL SYNCHROTRON

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### Abstract

In the SOLEIL storage ring (SR), two cryomodules, each containing a pair of superconducting cavities will provide the maximum power of 600 kW, required at the nominal energy of 2.75 GeV with the full beam current of 500 mA and all the insertion devices. Each of the four cavities will be powered with a 190 kW solid state amplifier consisting in a combination of 315 W elementary modules (about 700 modules per amplifier). The amplifier modules, based on a technology developed in house, with MOSFET transistor, integrated circulator and individual power supply, are being fabricated in the industry. In the Booster (BO), a 35 kW solid state amplifier (147 modules) will power a 5-cell copper cavity of the LEP type. The first operational results and the status of the RF power plants are reported in this paper. Although quite innovative for the required power range, the solid state technology proved to be very attractive with significant advantages as compared to vacuum tubes.

### INTRODUCTION

At LURE-Orsay, a program of R&D on solid state amplifiers started ~ 12 years ago. After the success of a couple of applications in the few kW range [1,2,3,4], it was decided to use this technology for the 352 MHz 35 kW amplifier of the SOLEIL BO. It shall power a 5-cell copper cavity of the CERN LEP type that will provide up to 0.8 MV of accelerating RF voltage with 20 kW of power (~ 15 kW dissipated into the cavity walls and 5 kW delivered to the beam) [5].

For the SR, different possible alternatives, with either vacuum tubes (Klystron, IOT, Diacode) or the solid state version, were considered in terms of modularity and technology. The absence of commercially available vacuum tubes at 352 MHz in the 180 - 400 kW power range, led us to select the solid state technology with 4 power plants capable of providing up to 190 kW CW [6]. They will power two cryomodules, each housing a pair of 352 MHz superconducting cavities that shall transfer up to 575 kW of RF power to the electron beam [7,8].

Although it is quite innovative in this power range, the solid state technology presents significant advantages: high modularity with the associated redundancy and flexibility, elimination of HV and high power circulator, simpler start-up procedures and operation control, no need for periodical replacement, low operational costs (no costly spare parts). For the SOLEIL case, the total investment cost is lower than the solutions with vacuum tubes and one can profit of the existing in house expertise.

In the following sections, the design of the SOLEIL solid state amplifiers for the BO and SR are described; their status and schedule are reported.

### BO 35 KW SOLID STATE AMPLIFIER

#### Design of the 330 W amplifier module [9]

The amplifier module (Fig. 1) includes one push-pull VDMOS, D1029UK05 from SEMELAB that is protected by means of a drop-in circulator from VALVO with a 50 W – 50 Ω RF load. This integrated circulator is essential for ensuring unconditionally stable conditions. The input and output circuits are matched thanks to two pairs of trimmer capacitors.

Each module has its own power supply board, based on a 600 W - 300 VDC / 30 VDC converter (Fig. 2) from INVENSYS LAMBDA.

The complete modules, manufactured and tested by RFPA, according to the SOLEIL specifications, reached the expected performance : 10 dB < Gain < 11.5 dB, phase dispersion < 15°, input matching > 30 dB at 330 W and K (stability factor) > 8 dB at 1.4 A.

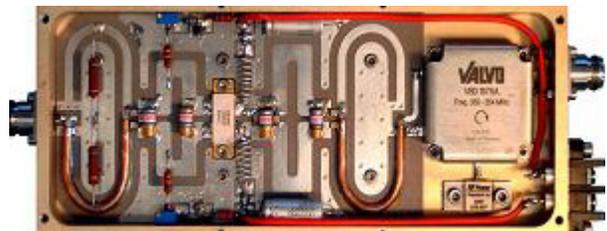


Figure 1: 330 W amplifier module



Figure 2: DC/DC converter board

#### Amplifier power combination and assembly

The power combination scheme for one half of the BO amplifier is described in figure 3; the complete plant is made of two such 20 kW units. The 40 W input power is amplified by the 1<sup>st</sup> stage module, the output of which is split into 8 and re-amplified, twice, leading to 64 times 330 W which are re-combined per 8 in two stages, 2.5 kW and 20 kW. That leads to a total of 146 modules (+ 1 “stand-by”) for the complete amplifier.

Each 2.5 kW branch as well as the 40 kW output are equipped with monitoring bi-directional couplers. All splitters, combiners and couplers were designed in house with HFSS computations and tests on prototypes. The

final fabrication of the mechanical parts was contracted to LNLS while the assembling and testing were performed in house. Amplifier components and complete assembly are shown in Fig. 4.

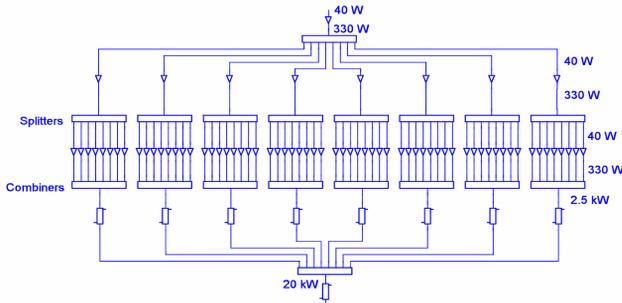


Figure 3 : Power combination (1/2 BO amplifier)

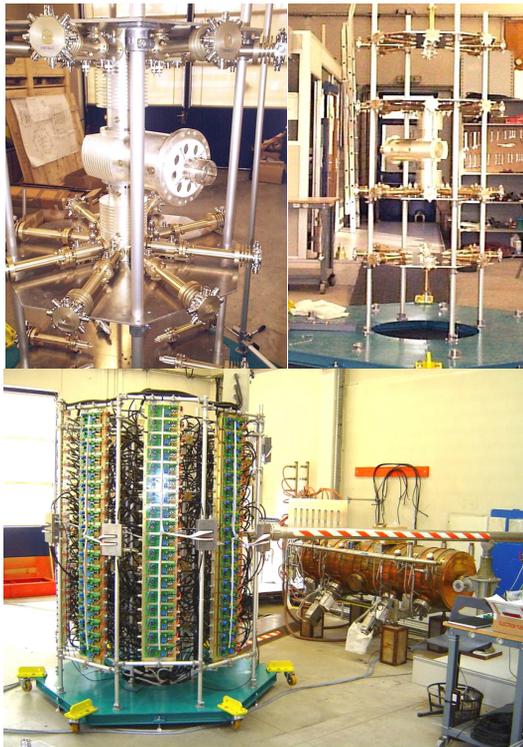


Figure 4 : BO amplifier assembly

### Control system

Fig. 5 shows a schema of the BO RF control system. The 292 transistor currents and 32 RF powers (incident & reflected at the 2.5 kW stage) are permanently monitored by a  $\mu$ controller through a multiplexing system.

The reflected power at the output of the amplifier, the cavity vacuum, the personal and machine safety are interlocked by a fast hardwired system. All the other “slow signals” from the amplifier, cavity and LLES (Low Level Electronic System comprising the frequency, phase and amplitude control loops) are monitored by a PLC, linked to the  $\mu$ controller via a RS232 bus and to the SOLEIL control system via Ethernet. In case of fault the RF power can be stopped by acting on the RF switch located in the amplifier drive chain and/or switching off the power supplies.

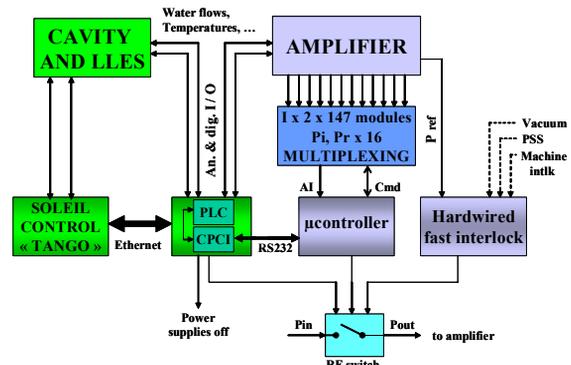


Figure 5 : Booster RF control system

The characteristics of the LLES are summarised below.

	Amplitude	Phase	Frequency
Accuracy	$\pm 0.25 \%$	$\pm 0.4^\circ$	$\pm 30 \text{ Hz}$
3dB bandwidth	10 kHz	7 kHz	5 Hz

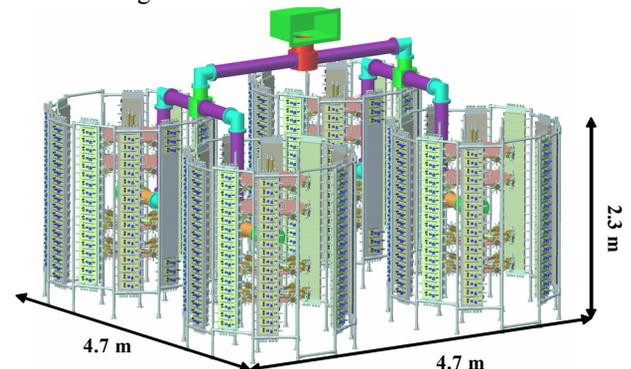
### Power tests

The 2.5 kW units were first tested individually and amongst the 147 modules, only 3 showed minor problems that could be fixed rapidly. After all units have been tested up to 2.5 kW they were combined together. The first day of operation, 35 kW was delivered into a dummy load, with transistor DC currents below 8.6 A (one side), that is far from their limit. The measured global efficiency of 50% (including circulators and DC/DC converters) is comparable to other types of amplifier. Over the useful range, 1 - 25 kW, the phase and gain changes vs power are  $10^\circ$  and 2.5 dB. Following the successful results of the first day operation, a long test run was launched; after about 500 hours of continuous operation at 30 kW CW into a dummy load, without the least fault interlock, no performance degradation was noticed. The amplifier was then connected to the BO cavity for RF conditioning up to 30 kW and for testing the control and LLES. The complete RF power plant (amplifier, cavity, control & LLES) has run for more than 1500 hours in the test area, without problem. It is being installed on site and should be operational for the BO commissioning in June 2005.

## SR 190 kW SOLID STATE AMPLIFIERS

### 190 kW amplifier design

The SR 190 kW amplifier is based on the same principle as the BO one, extended to four “towers” of  $\sim 50 \text{ kW}$ , as shown in Fig. 6 below.



One of the main changes as compared to the BO is the use of a new type of MOSFET, the LDMOS LR301 from POLYFET which can achieve better performance than the VDMOS D1029UK. Its higher gain (> 13 dB) led us to optimise the power combination scheme in a different way, using a total of 682 modules for the 190 kW amplifier (Fig. 7). Finally, 42 modules were added in “stand-by” for more redundancy.

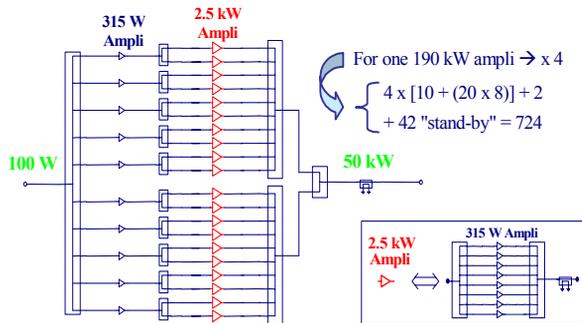


Figure 7 : Power combination scheme (50 kW “tower”)

The complete families of power combiners and splitters are shown in Fig. 8; the splitters are built from micro-strip circuits making them more compact and cheaper than with coaxial lines. As another upgrade, the insertion of a Cu slug through the Al case of the modules, at the transistor location, significantly improves the heat transfer (computer simulations show a 15° temperature drop).



Figure 8 : Power combiners (a) and splitters (b)

### 190 kW amplifiers status

The achievement of a suitable LDMOS based amplifier module, in accordance with the SOLEIL specifications, required several iterations for matching the characteristics of the transistor itself and its associated circuit. This development was realised in the frame of a POLYFET-SOLEIL collaboration work. The manufacturing and tests of the amplifier modules, as well as the power combiners and splitters were then contracted to BBEF Electronics (Beijing). In June 04, after the successful tests of a 2.5 kW unit, built from a pre-series of 8 modules with LR301-V3 transistors, the design was validated and the series production was launched. In a second stage, a first 50 kW tower was assembled and tested up to 48 kW CW on December 23<sup>rd</sup>, as a Christmas gift (Fig. 9).

Beginning of 2005, a long test run was started at 40 kW CW during which several module failures occurred. After ~ 1000 hours of operation, 14 over 180 modules had

failed; they all show the same default : a high gate leakage current at one side of the push pull pair. It is worth mentioning that the transistor failures didn't stop the amplifier, which was still delivering its power.

The fabrication of LR301-V4, was launched by POLYFET with the aim of improving the toughness, at the expense of a slightly lower gain (- 1dB) than LR301-V3. A 50 kW tower with the new version of transistors is under tests.



Figure 9 : First SR 50 kW tower

## CONCLUSION

The required RF power for the SOLEIL BO and SR will be provided using solid state amplifiers (1 x 35 kW & 4 x 190 kW). They consist in a combination of a large number of 330 W amplifier modules (1 x 147 & 4 x 724), based on a design developed in house, with MOSFET transistors, integrated circulator and individual power supply. The BO RF plant (VDMOS amplifier, cavity, control & LLES) has run for ~ 1500 hours in the test area, without trouble. It is being installed on site and shall be operational for the BO commissioning in June 05.

For the SR 190 kW amplifiers, LDMOS (instead of VDMOS) transistors have been selected. During the tests of the first 50 kW tower (1/4 amplifier), failures of a few transistors occurred (14 over 180, after 1000 h of operation). A new version of them, designed to be tougher, is being tested. In spite of the encountered troubles, we still plan to achieve two 190 kW amplifiers for powering the 1<sup>st</sup> cryomodule at the start of the SR commissioning in March 2006. The two next ones will be implemented to power the 2<sup>nd</sup> cryomodule, one year later.

## ACKNOWLEDGEMENTS

The authors would like to thank, in particular the RF members who actively participate to the assembling and tests of the amplifiers and more generally the SOLEIL and LURE staff for their contribution.

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