DEVELOPMENT OF HIGH RF POWER SOLID STATE AMPLIFIERS AT SOLEIL

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Abstract

At SOLEIL, 5 solid state amplifiers (SSA) provide the required 352 MHz CW power : 1 x 35 kW for the Booster (BO) cavity and 4 x 180 kW for the 4 superconducting cavities of the Storage Ring (SR). Based on a design fully developed in house, they consist in a combination of a large number of 330 W elementary modules (1 x 147 in the BO and 4 x 724 in the SR) with MOSFET transistors, integrated circulators and individual power supplies.

After 5 years of operation, this innovative design has proved itself and demonstrated that it is an attractive alternative to the vacuum tube amplifiers, featuring an outstanding reliability and a MTBF > 1 year.

In the meantime, thanks to the acquired expertise and the arrival of the 6th generation transistors, SOLEIL has carried out developments which led to doubling the power of the elementary module (700 W @ 352 MHz & 500 MHz) while improving the performance in terms of gain, linearity, efficiency and thermal stress. This approach was also extended to frequencies from the FM to L band.

The increasing interest in this technology has led SOLEIL to collaborate with several other laboratories and conclude a transfer of know-how to the French company, ELTA-AREVA.

SOLEIL 352 MHZ CW POWER SOLID STATE AMPLIFIERS (SSA)

The decision of using solid state amplifiers (SSA), instead of the usual vacuum tube (klystron or IOT) amplifiers, for providing the high CW RF power required at 352 MHz for SOLEIL, 1 x 35 kW in the Booster (BO) and 4 x 180 kW in the Storage Ring (SR), was quite innovative and challenging. These SSA consist in a combination of a large number of 330 W elementary modules (1 x 147 in the BO and 4 x 724 in the SR), based on a design developed in house and manufactured in the industry, with MOSFET transistors, integrated circulators and individual power supplies. A detailed description of their design and performance can be found in ref. [1].

Booster Solid State Amplifier

The 35 kW CW BO amplifier (fig. 1) consists in a single tower comprising 147 amplifier modules (with VDMOS D1029UK05 from SEMELAB) and their power supply boards (with 600 W - 280 Vdc / 28 Vdc converters from TDK-Lambda), bolded on both sides of water cooled dissipaters. In the centre of the tower stand the components for the power splitting and recombination.

The BO amplifier was commissioned on SOLEIL site in July 2005 and since then it has run for about 30 000 hours with only a single trip in operation, due to a human mistake. Only 5 (out of the 147) modules had minor problems, which did not impact at all the operating conditions and they could be quickly repaired during scheduled machine shutdowns. That is a great advantage of this design with high modularity and redundancy.

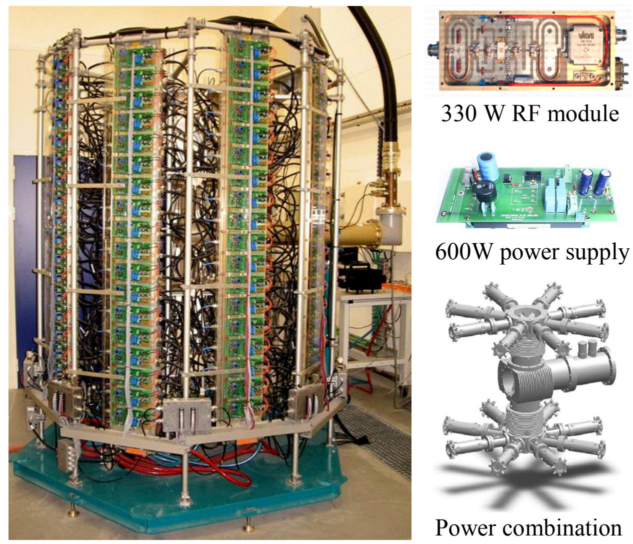

Figure 1: 35 kW SSA of the SOLEIL Booster.

Storage Ring Solid State Amplifiers

In the SR, four 180 kW CW SSA are powering the four superconducting cavities, which are accommodated inside two cryomodules (CM) [2, 3, 4]. They are based on the same principle as the BO one, extended to four towers of 45 kW (fig. 2). The use of another MOSFET device (LDMOS LR301 from POLYFET) with higher gain and better linearity is the main difference.

Figure 2: 180 kW SSA of the SOLEIL Storage Ring.

As initially scheduled, for about two years, SOLEIL has been operated with a beam current limited below 300 mA, using a single CM, powered by two SSA. The 2nd CM and the other two SSA were commissioned in summer 2008 allowing the delivery of 400 mA in routine operation for the users. The capability of storing up to 500 mA under stable conditions has been already demonstrated. So far, after about 25 000 running hours on CM1 and 15 000 on CM2, the 4 SSA of the SR, as the BO one, have proved themselves, featuring an outstanding reliability with a MTBF > 1 year, which has largely contributed in the achievement of a high beam availability for the users (~ 98%) [5]. The module failure rate is about 3.5 % a year of which 1/4 due to transistor breakdowns and 3/4 to soldering degradations. It is worthwhile mentioning that it is only a matter of maintenance, typically a few days of manpower and 5 k€ of repairing cost per year for the four SR SSA, again without impact on the operation. Although that remains quite acceptable, a significant improvement is still expected from the new generation of modules, which were recently developed, with more robust transistors and relaxed thermal stress.

SSA TRANSFER OF KNOW-HOW AND NEW DEVELOPMENTS

Following the success of the SOLEIL SSA, several laboratories have expressed their intention of using this technology for powering their accelerators: the CEA/DIF at 352 MHz (DEINOS project [6]), the Swiss (SLS) and Brazilian (LNLS) light sources at 500 MHz and 476 MHz, respectively. In 2006, a prototype of 2.5 kW (8 modules) at 352 MHz was delivered to the CEA in anticipation of a series of four 20 kW SSA; however it was not followed up as DEINOS remained unfunded. The SLS is building on its own a 500 MHz prototype, based on the SOLEIL technology [7]. In 2007, a collaboration agreement was concluded between SOLEIL and LNLS for the production of two SSA of 50 kW at 476 MHz, relying on components designed by SOLEIL. The two amplifiers were successfully tested on a dummy load in April 2010 and commissioned end of 2010 on the LNLS SR (fig. 3) where they are operating quite satisfactorily [8].

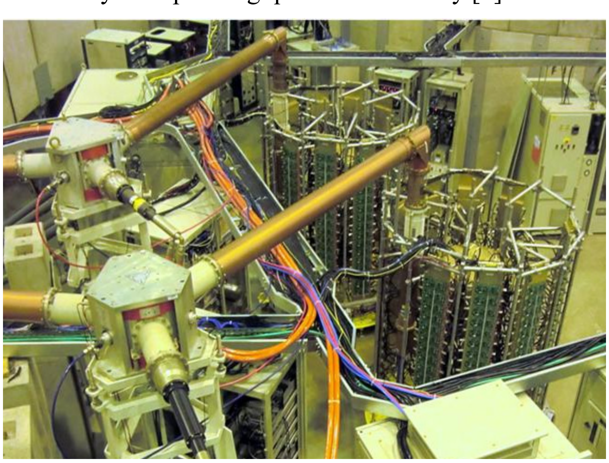

Figure 3: The two 50 kW SSA of the LNLS Storage Ring.

Transfer of Know-How

The growing interest in the SOLEIL SSA technology and in particular the ESRF upgrade project of replacing all its klystron amplifiers by SSA (22 SSA of 150 kW at 352 MHz), led SOLEIL to conclude an agreement of transfer of know-how with the French company ELTA, a subsidiary of AREVA TA. On one hand ELTA already had some expertise in the fields of high frequencies and power converters and wanted to extend its involvement in the world of large scientific instruments. As, on the other hand, it is not in the mission of SOLEIL to produce or make business, this was a profitable partnership for both parties. With the support from SOLEIL, ELTA could thus tender and win the ESRF contract for seven SOLEIL type SSA of 150 kW, first phase of the ESRF RF upgrade.

New Generation of SSA

After the commissioning of its SSA, SOLEIL has carried on with R & D in this domain. The acquired experience together with the arrival on the market of the so called 6th generation transistors – with 50 V instead of 30 V dc voltage – has led to fast progress. A module of 400 W at 476 MHz (with LDMOS BLF574 from NXP) was first worked out in the frame of the collaboration with LNLS and then 700 W at 352 MHz (with LDMOS BLF578 from NXP) in anticipation of the ESRF project. That represents a huge improvement as compared to the SOLEIL original LR301 modules: more than twice the power, with better performance in terms of gain (~ 20 dB instead of 13 dB), of efficiency (> 70 % instead of 60 %), of linearity and moreover much less thermal stress (ΔT_{max} of 50 °C instead of 105 °C), which should result in longer life time and lower failure rate. Similar performances were also achieved with prototypes of 500 MHz modules, based on the same transistor, BLF578 (see below).

The 150 kW - 352 MHz amplifiers for the ESRF will consist in two 75 kW towers, relying on these new generation modules. All the RF components (amplifier modules, bi-directional couplers, power dividers and combiners), were designed by SOLEIL and then their production was contracted by ELTA to the Chinese company, Beijing BBEF Science & Technology Co., Ltd.

A 10 kW unit comprising one dissipater with 16 modules and their power supply boards was successfully tested on a dummy load at SOLEIL in June 2010. The first tower delivered by ELTA is under tests at the ESRF and the following ones are being assembled [9].

SOLEIL is also evaluating lower power (~ 330 W) 6th generation transistors, from NXP and Freescale, which could advantageously replace the LR301 actually used in the 180 kW SSA of the SR, with only minor modifications. Samples are presently under long term run test and, although the evaluation is not yet completed, we can already anticipate much better performance and reliability from any of these new devices.

In view of storing 500 mA, using a single CM, the combination of two SR SSA for powering one cavity is being investigated. For this purpose, input power couplers, capable of handling more than 300 kW are being developed in the frame work of a collaboration agreement with CERN and ESRF [10].

Other SSA Projects and Further Upgrades

As mentioned above, rather good performance could be achieved with BLF578-modules, re-tuned for operating at 500 MHz (18 dB gain and 67 % efficiency at 650 W). It is planned to build SSA amplifiers, based on this module design, 1 x 50 kW for ThomX [11] and 4 x 150 kW for SESAME [12], two light source projects in which SOLEIL is involved. Recently, ELETTRA [13] and HZB [14] have also got in touch with SOLEIL showing great interest in 75 kW - 500 MHz SSA.

In the frame of the above mentioned projects, we are investigating new features which could make our design still more flexible, like the use of modular high efficiency 220 V ac - 50 V dc power converters with easy voltage monitoring and a last stage combiner with adjustable coupling. The latter would allow preserving a matched condition for variable configurations with different numbers of modules per dissipater or different numbers of dissipaters per tower. For instance, a 55 kW tower consisting in 6 dissipaters could be easily upgraded up to 73 kW by inserting two additional dissipaters. A special waveguide-to-coaxial combiner (WaCCo) with a movable short circuit is being studied for this purpose (fig. 4).

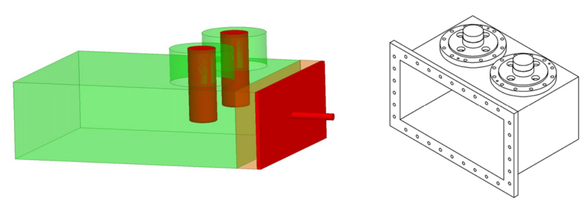

Figure 4: Sketch of the WaCCo with adjustable coupling.

Housing the whole SSA inside a cabinet is an alternative to the actual open tower arrangement.

R&Ds were also carried out with the aim at extending our SSA technology to frequencies ranging from the FM up to the L band. In that frame, we are working with the German company, Valvo Bauelemente GmbH, in order to validate a set of circulators which could cover the whole frequency range. At the lower side, we have built a prototype of 88 MHz module, which has delivered up to 900 W with a gain of 25 dB and an efficiency of ~ 80 %. At the upper side, BBEF, has built a SSA of 20 kW CW at 1.3 GHz with 400 W modules, for the Beijing University.

A collaboration agreement with CERN for producing a 10 kW - 200 MHz prototype should be soon finalized.

CONCLUSIONS

The experience acquired at SOLEIL with high CW 352 MHz power SSA has demonstrated that this technology can advantageously replace the vacuum tubes (tetrodes, klystrons or IOTs) in such an application. The extreme modularity of this technology and the elimination of HV equipment bring significant advantages while the cost remains comparable.

More generally, in synchrotron accelerators or storage rings, in order to improve the performance one usually chooses to power each cavity individually, which leads to the need for RF power sources of ~ 300 kW CW (typical input coupler limitation) at frequency ranging from ~ 100 up to 700 MHz and that fits the capabilities of the SSA.

The Energy Recovery Linac (ERL), based on superconducting CW RF, is regarded as a promising way of achieving high average current (~ 100 mA) and very small electron beam emittance as required for future light sources or high energy physics applications [15, 16]. In the ERL configuration, the required power per cavity is typically a few 10 kW CW over a frequency range from 0.7 up to 1.5 GHz. This is another field of application well suited to the SSA.

On the other hand the SSA cannot oust the klystron as far as very high peak power (tens of MW) is concerned.

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