

High power 352 MHz solid state amplifiers developed at the Synchrotron SOLEIL

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In SOLEIL, 5 solid state amplifiers provide the required rf power at 352 MHz: 1×35 kW in the booster and 4×190 kW in the storage ring. They consist in a combination of a large number of 330 W elementary modules (1×147 in the booster and 4×724 in the storage ring), based on a design developed in-house, with MOSFETs (metal-oxide-semiconductor field-effect transistors), integrated circulators, and individual power supplies. Although quite innovative and challenging for the required power range, this technology is very attractive and presents significant advantages as compared to the more conventional vacuum tubes, klystrons, or inductive output tubes (IOTs). The booster and two of the storage ring power plants have been successfully commissioned and the first operational experience is quite satisfactory. The amplifiers proved to be very reliable as well as easy and flexible in operation; they have not been responsible for any beam time loss.

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I. INTRODUCTION

A. Brief history

At LURE-Orsay, a program of research and development on solid state amplifiers started about 15 years ago. Solid state amplifiers for 1.8 kW at 100 MHz and 1.2 kW at 500 MHz were realized and operated on the SUPER-ACO ring. From their commissioning in 1997 until the LURE shutdown in December 2003, they have run without a single failure while the tetrodes, which were used previously, had to be replaced periodically [1].

When the SOLEIL project studies started in the mid-1990s, it was naturally proposed to benefit from the experience acquired in that domain. The development of a 352 MHz–2.5 kW prototype was launched with the goal to validate both the 330 W amplifier module design and the power combination scheme. The successful results led to the decision of applying this technology for SOLEIL, at first to the 35 kW booster amplifier (147 modules) and then adapting it to the four 190 kW amplifiers of the storage ring (4×724 modules).

In synergy with these projects, two other 2.5 kW amplifiers were built, following the same approach, one at 352 MHz for LNL (Laboratori Nazionali di Legnaro) [2] and another one at 476 MHz for LNLS, the Brazilian light source, where it is reliably operated since several years [3].

In March 2004, the booster amplifier could deliver up to 35 kW cw into a dummy load, a world record for a solid state amplifier. This record was then superseded, in May 2006, with the successful tests of two of the storage ring amplifiers up to 190 kW. The complete booster rf plant as well as one-half of the storage ring rf system (cryomodule No. 1, two amplifiers, the associated cryogenic plant, control, and LLRF systems) have been commissioned and they are now operational at the expected performance. They proved to be quite reliable, in particular, the ampli-

fiers which have not yet caused any beam time loss. The second part of the storage ring rf system is presently under fabrication and it should be implemented in the middle of 2008, in order to increase the stored beam current from 300 mA up to 500 mA.

B. General technological context

Different possible alternatives for the rf power sources were considered in terms of modularity and technology, with vacuum tubes (Klystron, IOT, Diacrode) and the solid state version.

Most of the vacuum tubes production is intended to the market of the television (TV) broadcast transmitters (~ 50 kW in ultrahigh frequency band), an area where the IOT is progressively replacing the klystron. This tendency is even accelerated by the arrival of digital TV, which requires lower power (< 10 kW), better suited for the IOT or solid state technology. For accelerator applications, which require higher average power (several 100 kW), klystrons were generally used. However, this area represents a small part of market, not large enough to assure the survival of the klystron production. Moreover, the accelerator community, in order to fit the market actualities, start being converted to use IOTs, which results in rushing the disappearance of the high average power klystrons. Two to four IOTs are generally combined in order to achieve the power plant requirement (a few 100 kW). For instance, DIAMOND, ALBA, and ELETTRA (upgrading) have opted for this solution [4–6].

The solid state amplifier is another alternative, applied so far only for much lower power (a few kW). The application of this technology to the SOLEIL high power 352 MHz amplifiers (1×35 kW and 4×190 kW) is quite innovative; it is the outcome of several years of in-house development.

This solution presents significant advantages as compared to the vacuum tubes: (i) high modularity with associated redundancy and flexibility, (ii) elimination of the high voltage handling and of the high power circulator, (iii) simpler start-up procedures and operation control, (iv) no need for periodical replacement, (v) lower operational costs (no costly spare parts) and easier maintenance, (vi) for the SOLEIL case (352 MHz), lower investment cost with profit of the existing in-house expertise.

The above-mentioned advantages, as well as the absence of commercially available vacuum tubes at 352 MHz in the desired power range and therefore the need for expensive development, led us to select the solid state technology for SOLEIL with one 35 kW amplifier for the booster cavity and four 190 kW amplifiers, one for each cavity of the storage ring.

II. BOOSTER 35 kW SOLID STATE AMPLIFIER

The booster amplifier is powering a 5-cell copper cavity of the CERN LEP type which provides up to 0.8 MV of accelerating rf voltage with 20 kW of power (~ 15 kW dissipated in the cavity walls and 5 kW delivered to the beam) [7].

A. Design of the 330 W amplifier module

The elementary amplifier module, shown in Fig. 1, includes one push-pull VDMOS—D1029UK05 from SEMELAB. Tests on many samples pointed out that this device, selected from the standard D1029UK with guaranteed gain of 13 dB, for 350 W at 175 MHz and 28 Vdc,



FIG. 1. (Color) 330 W amplifier module.

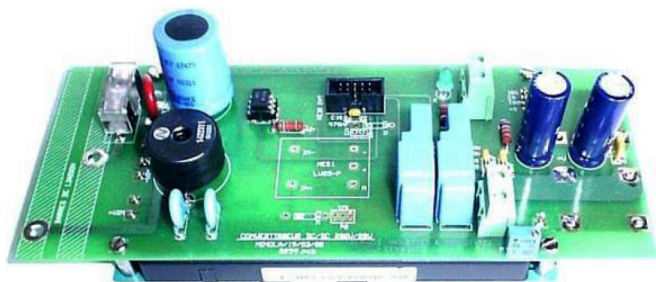


FIG. 2. (Color) 600 W-300 Vdc/30 Vdc converter board.

TABLE I. Main performance of the booster amplifier modules.

Operating frequency	352 MHz
Output power	330 W
Dc supply voltage	30 V
Gain	10 dB $< G <$ 11.5 dB
Gain compression	< 1.5 dB
Efficiency	$> 62\%$
Phase dispersion	$< 15^\circ$
Input matching, S_{11}	< -30 dB
Stability margin factor, K	> 8 dB at low level (2×0.7 A)

could reliably operate with a gain of about 11 dB, for 330 W at 352 MHz and 30 Vdc. A circulator from VALVO with a 500 W – 50 Ω rf termination is integrated in each module in order to protect the transistors from excess of reflected power; moreover, this component is essential for ensuring unconditionally stable conditions. The input and output circuits are matched thanks to two pairs of adjustable capacitors.

The complete modules were manufactured and tested, according to the SOLEIL specifications, by RFPA, a French company located near Bordeaux. Finally, they all reached the expected performance, as listed in Table I.

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

B. Amplifier power combination and assembly

The power combination scheme for one-half of the booster amplifier is described in Fig. 3; the complete plant is made of two such units. The 40 W input power is amplified by the first stage module, the output of which is split into 8 and reamplified, twice, leading to 64 times 330 W, which are recombined 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 bidirectional couplers. All split-

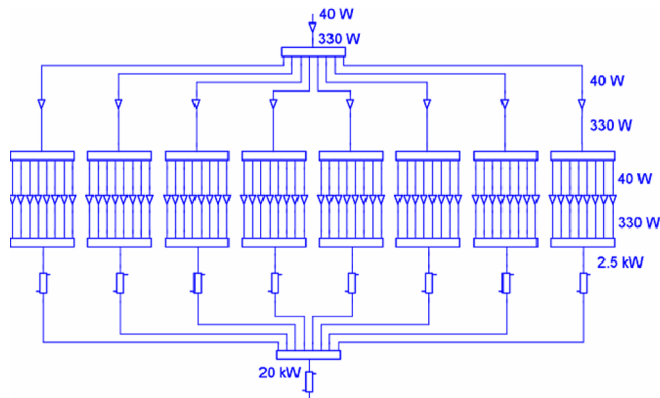


FIG. 3. (Color) Power combination scheme (1/2 booster amplifier).

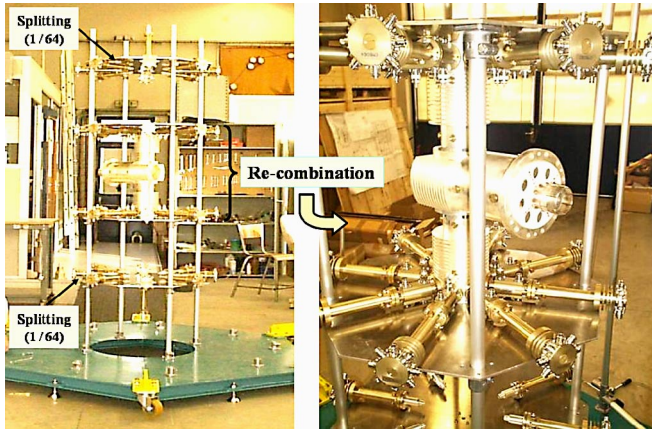


FIG. 4. (Color) Booster amplifier spine (power splitting and recombination).

ters, combiners, and couplers were designed in-house, using the HFSS computer code from ANSOFT and tests on prototypes. The final fabrication of the mechanical parts was contracted to the Brazilian light source, LNLS, while the assembling and tests were also performed in-house. The amplifier “spine,” formed by the components for the power splitting and recombination, is shown in Fig. 4 and the complete assembly in Fig. 5. The amplifier modules and their associated DC/DC converter boards are mounted on each side of thermal dissipaters, made of water-cooled aluminum plates. The complete amplifier consists in 8 long dissipaters (2 m) with 18 modules and a short one (0.5 m) with 3 modules, of which one is in stand-by.

The electrical power from the mains is dc converted with a rudimentary 300 V – 330 A diode rectifier (Fig. 6) and distributed in the amplifier by means of a pair of copper rods per dissipater, on which are bolted the DC/DC converter boards (Fig. 7).

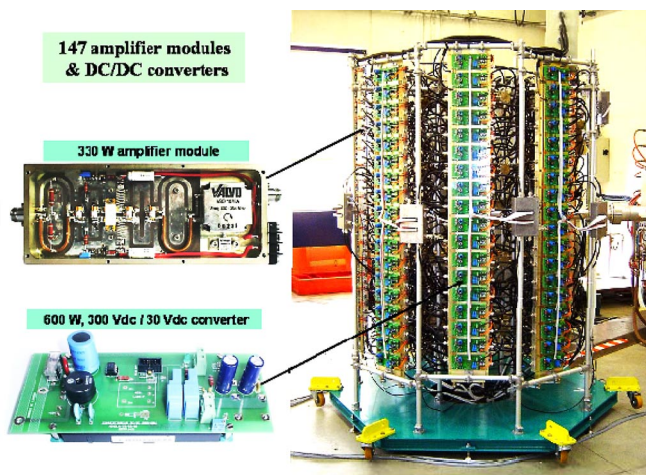


FIG. 5. (Color) 35 kW booster amplifier.

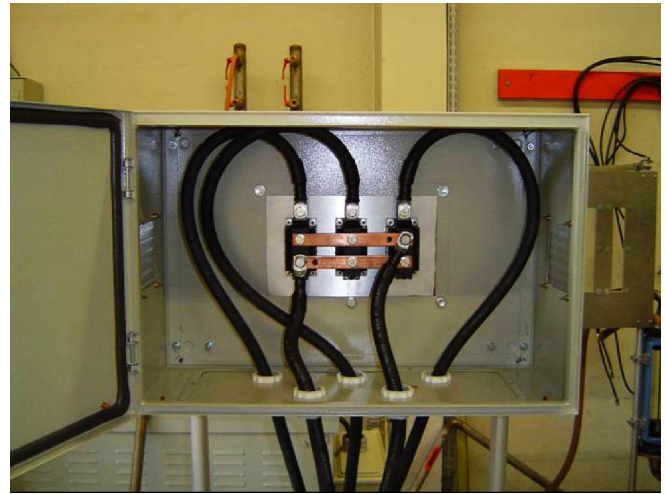


FIG. 6. (Color) 300 V–330 A diode rectifier for the booster rf amplifier.

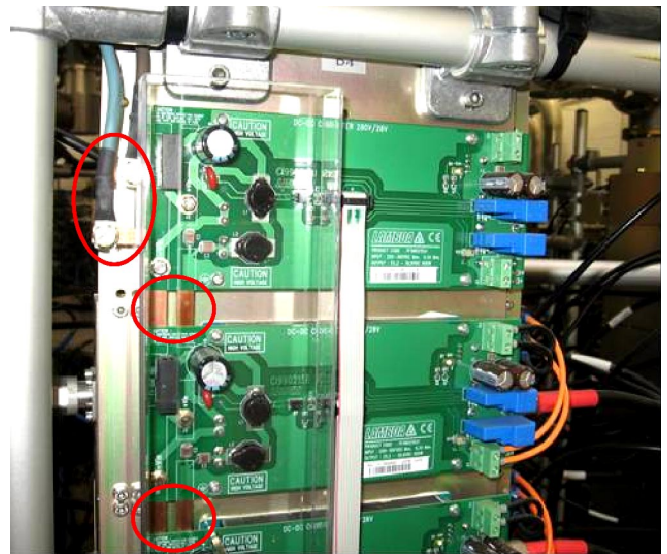


FIG. 7. (Color) 300 V distribution on the dc/dc converters.

C. Control system

Figure 8 shows a schematic diagram of the booster rf control system. The 292 transistor currents and 32 rf powers (incident and reflected at the 2.5 kW stage) are permanently monitored by a microcontroller through a multiplexing system. The reflected power at the output of the amplifier, the cavity vacuum, the personnel safety, and machine safety are interlocked by a fast hardwired system. All the other “slow interlocks” from the amplifier, cavity, and LLRF (low level rf system comprising the frequency, phase, and amplitude control loops) are monitored by a programmable logic controller, linked to the microcontroller via a RS232 bus and to the SOLEIL control system (TANGO) via Ethernet, through a CPCI board. In case of

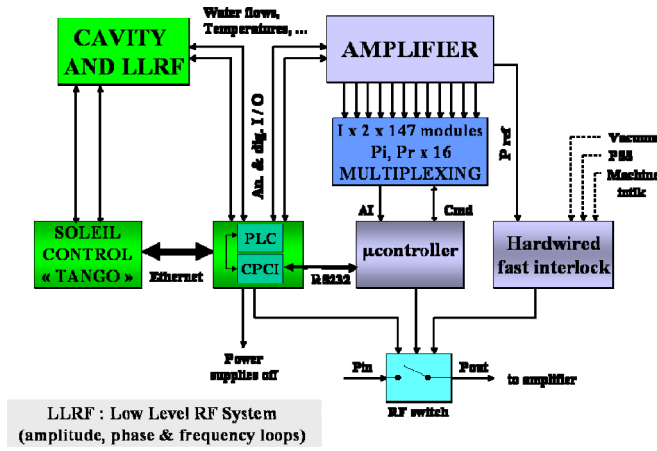


FIG. 8. (Color) Diagram of the booster rf control system.

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.

D. Power tests and first operational experience

The 2.5 kW units were first tested individually and, amongst the 147 modules, only 3 showed minor problems that could be quickly repaired. After all units have been tested up to 2.5 kW they were combined together. The first day of operation, 35 kW cw was delivered into a dummy load: a world record for a solid state amplifier. All transistor currents are below 8.6 A, that is far from their limit. The measured global efficiency of 50% (including circulators and power supplies) is comparable to other types of amplifiers. Over the useful range, 1–25 kW, the phase and gain changes versus power are only 10° and 2.5 dB.

Following the successful results of the first day of operation, the good functionality was confirmed with long duration runs at 30 kW cw, at first connected to the dummy load (~ 500 h) and then to the booster cavity (~ 1000 h): neither major problem nor performance degradation were encountered; only a few minor faults were experienced, essentially due to cabling mistakes that could be rapidly repaired. It is worth mentioning that these fault events did not stop nor perturb the amplifier operation. Note also that, during the cavity rf conditioning process, full reflection events occurred several times; they normally switched off the system without any trouble for the amplifier. Finally, we performed a test with high average reflected power, artificially created by detuning of the cavity, 10 over 30 kW, in cw for a few days without problem.

The complete booster rf plant (amplifier, cavity, control, and LLRF system) was installed in the machine in the spring of 2005 and commissioned in the following summer. The system, which has run about 4000 hours to date, has proved to be quite reliable (zero beam time loss caused by the amplifier) as well as very easy and flexible in operation. Only a single module failure occurred, due to a bad solder,

which did not affect at all the operating conditions and could be quickly repaired during a scheduled machine shutdown.

III. STORAGE RING 190 kW AMPLIFIERS

In the storage ring, two cryomodules, each containing a pair of superconducting cavities, will provide the rf voltage of 4 MV and 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 amplifier [7].

A. Design evolution

A schematic view of the storage ring 190 kW amplifier is shown in Fig. 9. It is based on the same principle as the booster one, extended to 4 units of 50 kW. One of the main changes as compared to the booster is the use of a new type of MOSFET, the LDMOS LR301 from POLYFET, which can achieve better performance than the VDMOS D1029UK05. The new LDMOS based amplifier module has been optimized in the frame of a SOLEIL-POLYFET

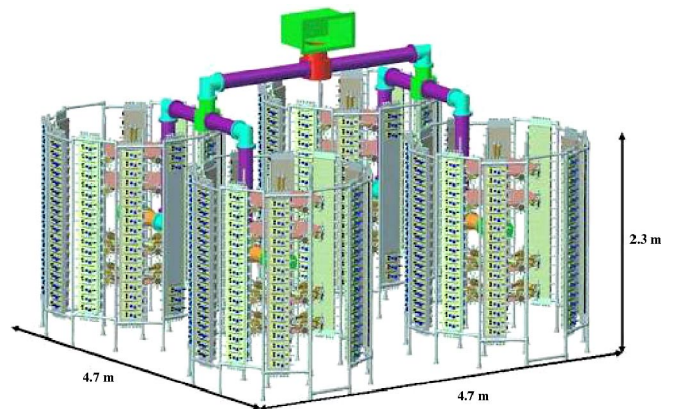


FIG. 9. (Color) Storage ring 190 kW amplifier.

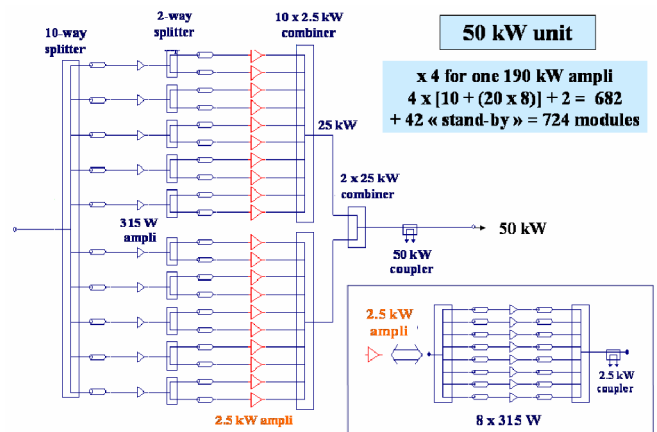


FIG. 10. (Color) Power combination scheme for a 50 kW tower (1/4 of the storage ring amplifier).

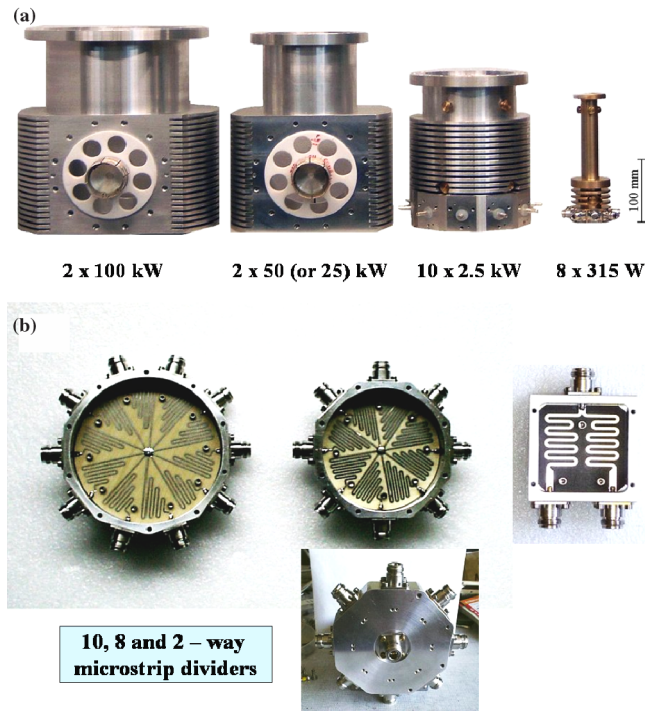


FIG. 11. (Color) Storage ring amplifier power combiners (a) and dividers (b).

collaboration work, after several iterations for matching the characteristics of the transistor itself and the associated circuit. The higher gain of the LR301 transistors (> 13 dB at 315 W and 28 Vdc) led us to optimize the power combination scheme in a different way, using a total of 682 modules for the 190 kW amplifier (Fig. 10). However, in order to improve the reliability, 42 modules were added, which will stay on stand-by.

The complete family of power combiners is shown in Fig. 11(a). The 10-way, 8-way, and 2-way power splitters

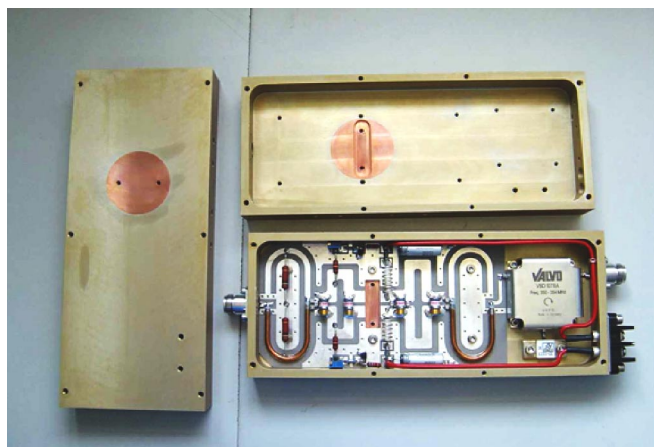


FIG. 12. (Color) Storage ring amplifier module with copper slug through the aluminum case.

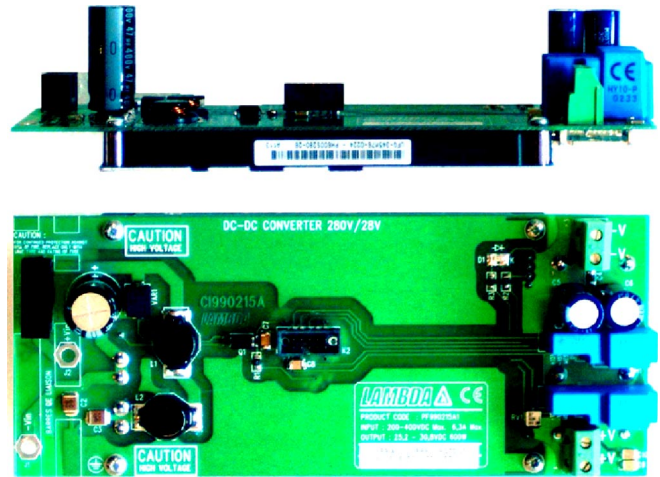


FIG. 13. (Color) 600 W-280 Vdc/28 Vdc converters (storage ring version in SMD).

are built with microstrip circuits [Fig. 11(b)], making them more compact and cheaper than with coaxial lines.

As other upgrades, the insertion of a copper slug through the aluminum case of the amplifier modules, at the transistor location (Fig. 12), significantly improves the heat transfer (computer simulations show a 15° temperature drop) and the DC/DC converter boards were realized in surface-mount technology (SMD) by INVENSYS LAMBDA (Fig. 13).

The control system is very similar to the booster one, but the multiplexing system is extended to the larger number of modules. Figure 14 shows a typical display of the amplifier parameters monitored by the microcontroller: transistor currents, incident and reflected power for one 50 kW tower.

The manufacturing and tests of the amplifier modules, as well as the power combiners and splitters, were contracted to BBEF Electronics (Beijing). While testing the first 50 kW tower (1/4 amplifier) with LR301-V3 transistors, we observed an unexpected high transistor failure rate (15 over 180, after 1000 hours of operation); they all showed



FIG. 14. (Color) 50 kW tower control display (transistor currents, P_i and P_r).

the same anomaly: a high gate leakage current at one side of the push-pull pair. That led us to launch the fabrication of another version, LR301-V4, with the aim of improving the toughness at the expense of a slight reduction in gain (-1 dB). As this reduced the failure rate by a factor of 3, we decided to go on with the LR301-V4 and settled the following module specifications: $13 < \text{gain} < 14.5$ dB at 315 W and 28 Vdc, the other parameters remaining identical to those of the booster.

The electrical power from the 20 kV mains is distributed on 4 units, comprising a 3-phase 20 kV/230 V transformer and a 270 V – 1600 A rectifier, each connected to its amplifier by means of 4 cable pairs (one per 50 kW tower).

B. Commissioning and first operational experience

Between May 2005 and March 2006, eight towers were assembled and individually tested up to 48 kW. In April 2006, a new world record: two amplifiers (combination of four towers) were successfully tested up to 190 kW cw into a dummy load (Fig. 15). The measured performance was quite good: a change of 7° in phase and 2 dB in gain over the power range, 10–190 kW, all transistor currents below 9.6 A and a global efficiency of about 50% at full power. Then the amplifiers were connected to the cryomodule No. 1 for the rf conditioning of its two cavities up to 1.7 MV with 80 kW cw, fully reflected under the mismatched condition at zero current.

During the summer of 2006, one-half of the storage ring rf system (cryomodule No. 1, two amplifiers, the associated cryogenic plant, control, and LLRF systems) was commissioned, as scheduled for the first year of SOLEIL operation with $I_{\text{beam}} < 300$ mA. The operational experience (~ 2000 running hours) is up to date fully satisfactory. The goal of storing 300 mA of stable beam, using a single cryomodule with about 150 kW into each cavity, was quickly achieved and the amplifiers have not yet caused any loss of beam time. Nevertheless, although it is not perturbing for the operation, a significant number of

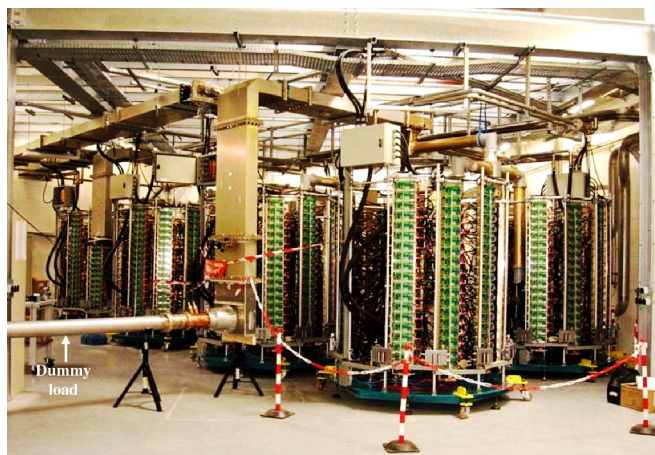


FIG. 15. (Color) Storage ring amplifiers 1 and 2.

transistor failures have occurred, distributed as follows: (i) individual tower test on T1: 5 failures/180 modules, after 1500 running hours; on T2–T8: 13 failures/1250 modules, for run durations from few hours to few days, depending on the tower; in addition on T2, 52 modules were damaged, all at once, by an overdriving mistake; interlock protections have been added in order to prevent from reproducing such an occurrence; (ii) 14 failures/1450 modules during the tests of the amplifiers 1 and 2 and the cavity conditioning (~ 500 h); (iii) 20 failures/1450 modules, after 2000 hours of machine operation.

Amongst these failures we can distinguish between two types: 80% of them correspond to direct transistor damages, characterized by a high gate leakage current at one side of the push-pull pair, and 20% of them result from the burning out of the circulator load, which finally leads to damaging the transistor (on both sides of the push-pull).

The above results show that the rate of failures tends to decrease with time, however the statistics is not yet sufficient to find out what comes from the “infant mortality” and what is the actual mean time between failures (MTBF); longer running periods are required for that. With the 100 spare modules which have been contracted, we will be able to make a turn over with 50 usable in-house while 50 are in repair. A contract of maintenance, including the transistor supply, is under negotiation with BBEF.

The second part of the storage ring rf system, which is under fabrication, should be made operational in the middle of 2008, in order to increase the stored beam current from 300 mA up to 500 mA; 6 of the 8 required towers for the amplifiers 3 and 4 are already assembled.

IV. CONCLUSION

The decision of using solid state amplifiers for providing the high average 352 MHz rf power required for SOLEIL, 1×35 kW in the booster and 4×190 kW in the storage ring was quite innovative and challenging. These amplifiers consist in a combination of a large number of 330 W elementary modules (1×147 in the booster and 4×724 in the storage ring), based on a design developed in-house and manufactured in the industry. The extreme modularity of this technology and the elimination of high voltage equipment bring significant advantages as compared to the more conventional vacuum tube amplifiers, while the cost remains comparable.

Up to date, the booster and two of the storage ring power plants have been commissioned and the first operational experience is quite satisfactory. They proved to be very reliable as well as easy and flexible in operation. After 4000 running hours in the booster (2000 in the storage ring, respectively), the amplifiers have not been responsible for any loss of beam time. Although not perturbing for the operation and decreasing with time, the transistor failure

rate on the storage ring amplifiers cannot yet be assessed. Statistics over longer running time are required in order to distinguish between “infant mortality” and actual MTBF.

Several laboratories have expressed their intention of adopting the solid state technology “à la SOLEIL”: the Swiss (SLS) and Brazilian (LNLS) light sources for 60 kW amplifiers at 500 MHz; ESRF for 200 kW amplifiers and CEA for one 20 kW at 352 MHz. In 2006, a 352 MHz–2.5 kW unit was built and delivered to CEA. Collaboration agreements for transfer of technology are under elaboration.

Investigations of other suitable transistors are going on for frequency between 352 MHz up to 1.3 GHz.

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group, who have actively contributed to the success of this challenging task of applying the solid state technology to high power rf amplifiers for particle accelerators.

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