352.2 MHz – 150 KW SOLID STATE AMPLIFIERS AT THE ESRF

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Abstract

The ESRF has ordered seven 352.2 MHz – 150 kW Solid State Amplifiers (SSA) from the French company ELTA, with a design derived from the existing SSA developed by SOLEIL. The first four SSA will be commissioned by the end of 2011 and will be connected to the two booster cavities in winter 2012 providing in total 600 kW in 10 Hz cycles. Thanks to anti-flicker capacitor banks with a total of 3.2 F in the 280 V DC power supply, up to only 400 kW will be drawn from the mains as compared to 1200 kW for the former klystron transmitter. The three remaining SSA will be received in 2012 and will feed three new single cell HOM damped cavities on the storage ring. The analysis of the market had shown that an alternative to klystrons needed to be investigated to guarantee the long term operation of the ESRF. SSA can be operated with a number of RF modules lost and are therefore intrinsically highly redundant. In parallel to the production by industry of this first batch of SSA, the ESRF is developing its own amplifier modules and proposing an alternative way to combine typically one hundred RF modules using a single cavity combiner.

INTRODUCTION

In the frame of a large upgrade programme of the ESRF, major developments are under way on the 352.2 MHz RF system [1]. In preparation of a 300 mA option, an increase of the ESRF current from 200 to 300 mA was tested successfully with the existing RF system. At 300 mA the HOM tuning of the five-cell copper cavities becomes delicate, and in view of a reliable operation in user mode, the development of HOM damped copper cavities was launched in 2005. Three operational prototypes are now being delivered by three manufacturers [2]. Note that the 300 mA option was finally not retained for phase 1 of the ESRF upgrade.

Phase 1 of the upgrade includes the implementation of a first batch of seven 150 kW solid state amplifiers (SSA): four SSA will replace the klystron transmitter of the booster and three SSA will power the new HOM damped cavities on the storage ring [2]. The objectives are:

- Qualifying SSA as alternative to high power klystrons to guarantee the long term operation of the ESRF, thereby preparing a possible replacement of other klystron transmitters in further upgrade phases.
- Saving electrical power on the booster thanks to the anti flicker system needed for the cycling at 10 Hz.
- Qualifying with beam a new storage ring RF unit comprising 3 HOM damped cavities powered by 3 SSA, which could replace one klystron powered five-cell copper cavity.

When ordering SSA with a total of more than 1 MW output power, it was decided to develop the required competence and contribute to the improvement of this technology by launching in parallel an in house R&D program.

PROCUREMENT OF SEVEN 15O KW SSA

ELTA Design Based on SOLEIL SSA

Following an international call for tender, seven 150 kW SSA were ordered from ELTA/AREVA, who benefits from a transfer of technology from SOLEIL [3]. For this project, SOLEIL developed a new RF module using the latest 6^{th} generation LDMOS-FET (BLF578 from NXP), which allowed doubling the nominal power of the basic RF module in Figure 1 from 330 W to 650 W. By combining 128 such modules the single tower shown in Figure 2 delivers more than 75 kW. The RF modules are mounted on water cooled plates together with individual 280 VDC to 50 VDC converter boards, which also monitor the total DC current and temperature of each transistor as well as the temperature of each circulator load. Only two such towers are needed to build the 150 kW amplifier shown in Figure 3.

Status of the Contract with ELTA

The first milestone related to the RF module was successfully passed in February 2010: the efficiency at 650W was over 68% and measured temperatures of both the transistor and the circuit were surprisingly low (<60°C). In summer 2010 a 500 hours fatigue test was performed with 16 RF modules that were switched ON and OFF 7500 times without any detected degradation.

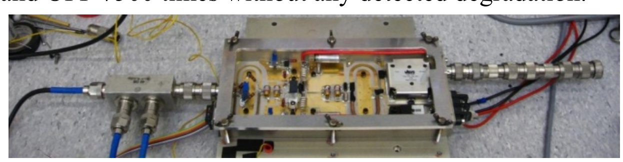

Figure 1: ELTA/SOLEIL 650 W RF module under test.

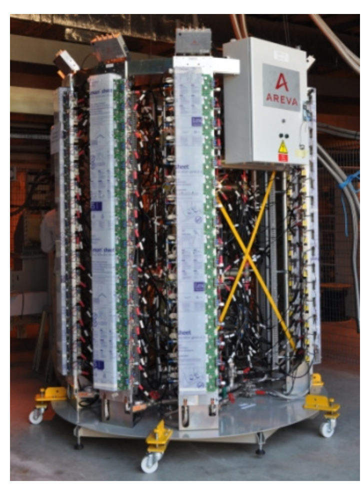

Figure 2: First 75 kW amplifier tower combining 128 RF modules.

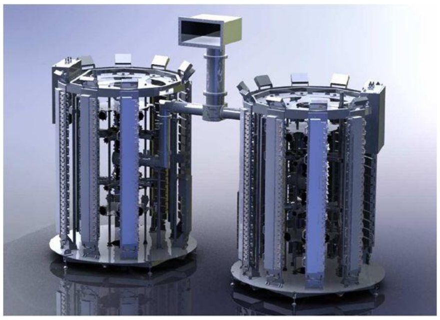

Figure 3: 150 kW SSA built of two 75 kW towers.

The 2nd milestone passed with honour when the first 75 kW tower delivered its full power into a dummy load in April 2011. The efficiency of the tower was an amazing 59%. The 3rd milestone was reached after running a full power operation of this tower during 1000 hours. During this test, an interesting phenomenon occurred: the efficiency dropped from 59% to 57%, still above the specified 55 %. The gain fell accordingly.

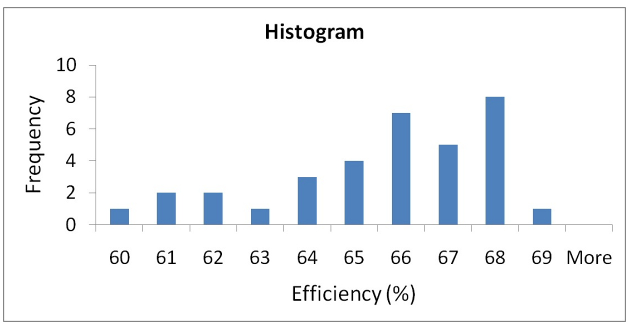

Figure 4: Distribution of measured efficiency for 34 RF modules after 1000 h run test.

The histogram of the efficiency after the 1000 h test, measured at ESRF, is shown above. Nearly all modules were in the 68% bin before the test (70% when measured at the manufacturer's). We think this slight efficiency and gain decrease is due to electron trapping in the LDMOS channel. To support this hypothesis, we could partly regenerate a module equipped with a coverless transistor by exposing it to the sunshine for 1 h without voltage applied. The UV radiation empties the electron traps. Trap density is linked to the manufacturing process of the transistor. NXP checked that the transistors were still in the specification and ELTA is currently further investigating this phenomenon.

IMPLEMENTATION AT THE ESRF

Replacement of Booster Klystron with 4 SSA

Figures 5 and 6 show how the first 4 SSA will be installed in the now emptied booster RF room (during the works, since January 2011, the booster cavities have been fed with a spare klystron transmitter located elsewhere). The 4 SSA will be operated in 10 Hz or 1 Hz cycles with a maximum RF peak power of 600 kW and powered with a common 400 kW - 280 VDC power supply*. Four 0.8 F anti-flicker capacitor banks filter the DC power demand, so that up to only 400 kW will be drawn from the mains. This is to be compared to 1200 kW needed by the former klystron transmitter, where the RF pulse was obtained by modulating the RF drive at constant klystron DC beam.

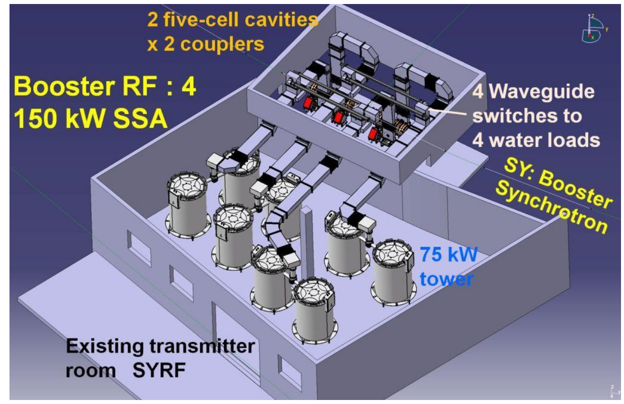

Figure 5: Four SSA replacing the klystron on the booster.

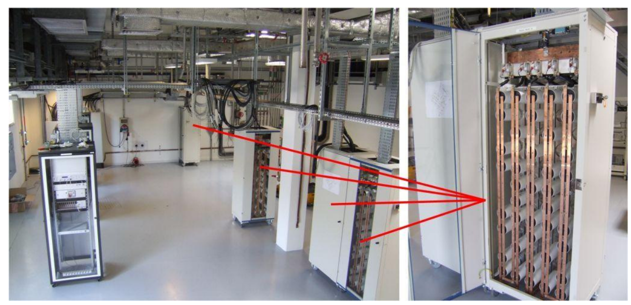

Figure 6: Booster transmitter room SYRF ready to receive 4 SSA (*right: one 0.8 F capacitor bank for each SSA).*

Each SSA will have a control rack with the following crates:

- Low Level RF and Driver crate with RS232 com.
- Hardwired Fast Interlock crate with RS232 com.
- Programmable Logical Controller (slow interlocks) crate with TCP/IP com.
- RF amplitude & phase measurement / RS232 com.

An additional common rack will house the transmitter control computer (PCI Express) and a further LLRF crate with the FPGA based IQ regulation loop for the 50 ms booster acceleration pulse.

The 4 SSA for the booster will be installed and tested individually on a dummy load by mid December 2011, starting mid September with the 1st SSA. An EH tuner is used to provide a variable mismatch at any phase. Commissioning on the booster cavities will take place in the first quarter of 2012.

Powering of 3 HOM Damped Cavities with SSA on the Storage Ring Cell 23

The three remaining SSA for the storage ring will be delivered and tested in 2012. They will feed the 3 HOM damped cavities in cell 23 of the storage ring in CW mode and therefore be powered by one 350 kW – 280 VDC

*The power supply was developed by K. Bulstra, S. Lagarde, P. Falaise and J.-F. Bouteille from the ESRF Power Supply Group.

power supply each (without anti-flicker system). Note that the Insertion Device (ID) straight section of cell 23 will be the first to be lengthened from 5 to 7 m. This will allow installing the 3 HOM damped cavities in-between the two canted undulators of ID23 [1, 2].

ESRF DEVELOPMENT OF SSA USING CAVITY COMBINERS

A research program was launched to further develop high power solid state amplifiers for particle accelerators. It will receive funding from the EU as working package WP 3E in the framework of the FP7/ESFRI/CRISP program, involving CERN-SLHC, ESS, GSI-FAIR as partners.

Cavity Combiner

A cavity combiner was developed at ESRF, a collaboration of the RF and Mechanical Engineering Groups. In its ultimate version shown in Figure 7, it couples 132 modules into one 352.2MHz cylindrical cavity in E010 mode. A prototype with only 18 inputs has been built and tested at low level (see Figure 8). The input coupling is provided by loops protruding in the cavity. The output coupling is just a capacitive post linking the top of the cavity with a waveguide.

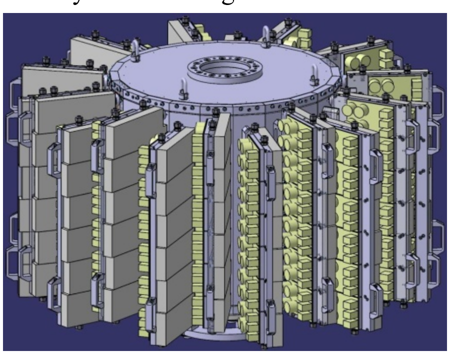

Figure 7: Cavity combiner with 22 pallets, each integrating 6 RF modules and their power supplies.

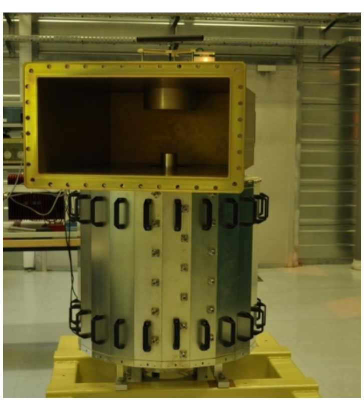

Figure 8: Lab prototype with the output coupler.

The S parameters have been (tediously) measured and the power transfer was 96% with high confidence interval as it is the sum of many measurements. The expected advantages are the (comparatively) small footprint, the possibility of easily adapting the number of modules and good power transfer efficiency.

RF Modules With Planar Balun

The existing RF modules developed at SOLEIL are using LDMOS transistors in class AB push-pull operation. They require balun transformers at the input and the output. These baluns are made with coaxial lines accurately cut to dimension, bended and welded on the printed circuit board. These operations are time consuming and prone to manufacturing variations. We tried to alleviate this tedious process by using printed circuit suspended baluns. The principle was patented long ago by Motorola [4] and a version of it recently described by NXP [5]. It is shown in Figure 9. Both sides of the transformer are printed on the PCB.

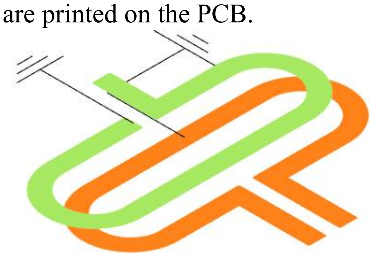

Figure 9: Printed balun transformer.

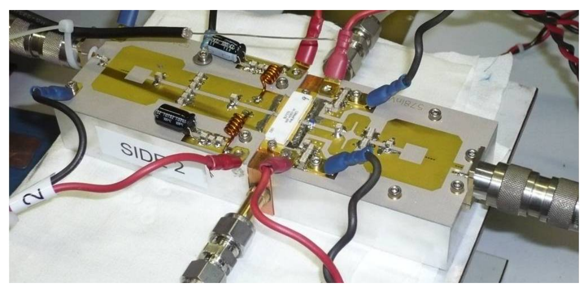

Figure 10: RF module using printed balun transformers.

A version of this was implemented at ESRF as shown in Figure 10. The power was limited to some 400 W due to the high temperature of output matching capacitors. Those went over 100°C, which is not suitable for lifetime. This was somehow expected as a suspended balun is difficult to cool. A second version of the output circuit is currently being manufactured, featuring high thermal conductivity substrate and no capacitor on the balun.

REFERENCES

[1] J.-L. Revol et al., "Performance and Upgrade of the ESRF Light Source", IPAC'11, San Sebastian, September 2011, THPC009 (2011).
[2] V. Serrière et al., "352.2 MHz HOM Damped Normal Conducting ESRF Cavity: Design and Fabrication", IPAC'11, San Sebastian, September 2011, MOPC004 (2011).
[3] P. Marchand et al., "Developments of High Power Solid State Amplifiers at SOLEIL", IPAC'11, San Sebastian, September 2011, MOPC127 (2011).
[4] Motorola patent EP0418538. Inventor J. J. BOUNY.
[5] Application note 10858 published by NXP.