COMMISSIONING OF FIRST 352.2 MHz - 150 kW SOLID STATE AMPLIFIERS AT THE ESRF AND STATUS OF R&D*

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Abstract

Four 352.2 MHz - 150 kW Solid State Amplifiers (SSA), based on the SOLEIL design and supplied by ELTA/AREVA, are in operation on the ESRF booster since March 2012. An interesting effect was observed during commissioning that is inherent to the combination of many RF amplifier modules at high power. While it has only little impact on the booster SSA operated in pulsed regime, some modifications were necessary for the three SSAs that will be delivered by ELTA for an operation in CW on the storage ring. In parallel, the ESRF is developing a more compact SSA using cavity combiners* instead of the widely adopted coaxial combiner trees. The status of this R&D project is also reported.

INTRODUCTION

Major developments are in good progress on the 352.2 MHz RF system in the frame of a large upgrade programme of the ESRF [1, 2, 3]. Phase 1 of this upgrade includes the implementation of a first batch of seven 150 kW solid state amplifiers (SSA). Four SSAs are in operation since March 2012 on the booster where they replace the former klystron transmitter. Three SSAs are being delivered this year to power three new single cell Higher Order Mode (HOM) damped cavities on the storage ring, which will be installed this summer between two undulators on the new 7 meter long straight section in cell 23 [3].

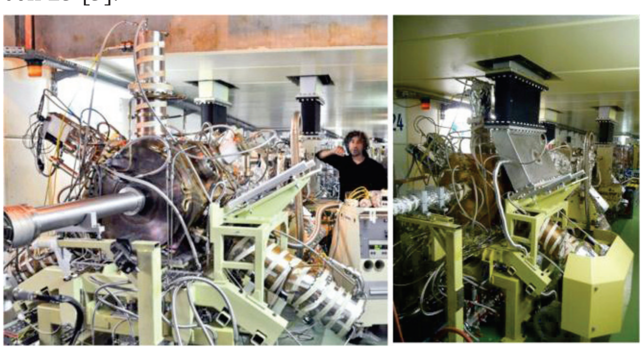

Figure 1: RI and SDMS cavities individually tested on cell 25 with up to 200 mA of beam, all fillings, 800 kV accelerating voltage and up to 150 kW total RF power.

The HOM damped cavities were designed at the ESRF and manufactured by three companies: RI, SDMS and CINEL [1]. As shown in Figure 1, the cavities from RI and SDMS have been validated with beam on the existing RF section in cell 25, using RF power from klystron transmitter TRA3. After RF conditioning in the RF power teststand, the third cavity from CINEL will be directly installed with the others on cell 23. Although the 300 mA option has not been retained for phase 1 of the ESRF upgrade, this development will be of prime importance for phase 2: as compared to the existing machine, the new low emittance ring will be twice as sensitive to HOM driven instabilities and require HOM damping [4].

This paper focuses on the experience gained after more than one year of operation of the four booster SSAs and on subsequent improvements implemented on the three remaining SSAs for the storage ring. The status of SSA development at the ESRF using planar RF modules and cavity combiners is also reported.

ONE YEAR OF BOOSTER OPERATION WITH THE NEW SSA'S

Figure 2 shows the booster RF room with the four 150 kW SSAs delivered by ELTA/AREVA following a transfer of technology from SOLEIL [2]. The power from 128 RF modules delivering up to 650 W is combined by means of a coaxial combiner tree with quarter wavelength transformers as depicted in figure 3. The combination of two such 75 kW "towers" constitutes a 150 kW SSA.

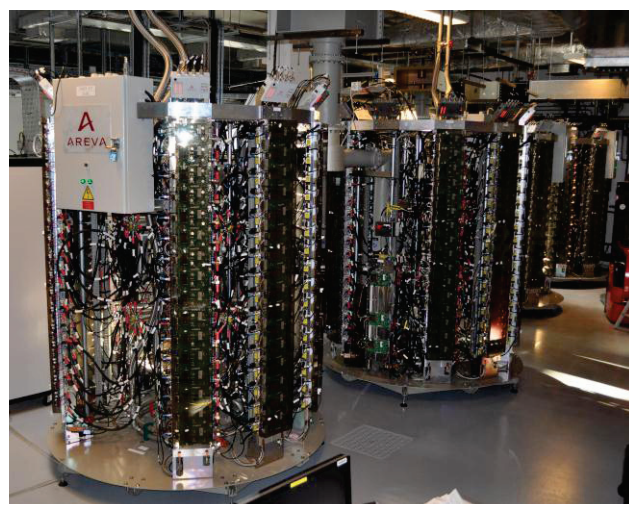

Figure 2: Four 150 kW SSAs on the ESRF booster.

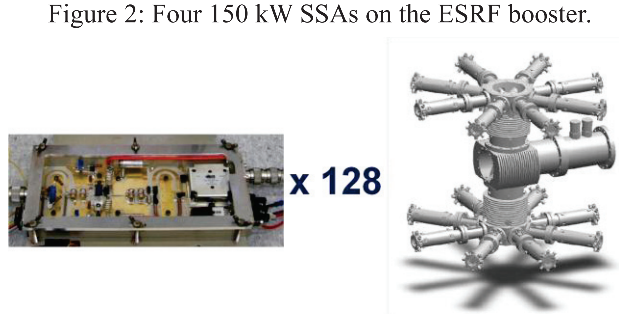

Figure 3: SOLEIL/ELTA 650 W RF module and 75 kW coaxial combiner tree with $\lambda/4$ transformers.

*The development of cavity combiners receives funding from the EU as work package WP7 in the framework of the FP7/ESFRI/CRISP program.

400 kW – 280 V DC Power Supply

The four SSAs were connected to the booster cavities in March 2012, which they normally feed with 10 Hz pulses. A 3.2 F capacitor bank, installed on the 280 V DC power supply, to smooth out the power drawn from the mains, limits the flicker at 10 Hz. This system also brings substantial power savings: in order to obtain typically 485 kW of RF power at the crest of the booster pulse, only 366 kW AC are continuously drawn from the mains. Under similar operation conditions, this is about one third of the power demand of the former klystron transmitter.

Excellent Operation Reliability

After some early debugging an excellent reliability of the SSA technology was confirmed. Within one year and a total of 1100 hours of operation, the filling of the storage ring was only postponed three times due to some early control hardware failures. Only one out of about one thousand RF modules and one DC/DC converter feeding an RF module failed, without disturbing the operation thanks to the intrinsic redundancy of the SSAs. Some smaller bugs mainly on the amplifier control were progressively corrected. Another six modules where damaged during the last March shutdown due to a leak in the ESRF water supply above one SSA.

Performance

The 280 V DC to RF power conversion efficiency is between 57 % and 58 % at the nominal 150 kW output power and therefore exceeds the specified 55 %. After one year of operation, the measured efficiency evolves within the 1 % measurement uncertainty: so far no significant evolution is thus observed.

IMPROVED SSA'S FOR THE STORAGE RING

Unforeseen Problem at SAT of Booster SSAs

At the site acceptance test (SAT) of the SSAs for the booster, the compliance with the ESRF specification was checked for pulsed booster operation as well as for continuous wave (CW) operation foreseen on the storage ring. The SSAs satisfied the most demanding constraint:

(1) 150 kW output power and 50 kW reverse power at any phase (reflection coefficient $|r| = 1/\sqrt{3}$).

They also complied with another important requirement concerning the built-in redundancy:

(2) 150 kW output with 6 unpowered RF modules.

This guarantees that the operation is not interrupted if a limited number of RF modules fail and it constitutes one of the key advantages of modular Solid State Amplifiers.

However, when setting up the combined conditions (1) and (2), i.e. when switching off some RF modules with the SSA operated at full power on a mismatched load, **arcing** occurred in the output circuits of the **unpowered modules.** The 800 W circulator loads that absorb the reverse power and thereby protect the transistors were burnt, as well as the circulator connections and the output power cables. Later measurements showed that depending on the phase of the mismatch, up to 1700 W are returned to the module, which are well above the load rating. This effect can be explained as follows:

- For an individual RF module, the combiner tree constitutes a strong mismatch with close to 100 % reflection.
- When operated at the same power and phase, the output waves from all the modules interfere constructively at the outputs of the combiners. Each active module receives transmitted waves from all the other modules which interfere destructively with the own reflection. Under these nominal operating conditions, all active modules are "virtually" matched.
- If one or several RF modules are switched off, they only see the reverse power transmitted from the other modules, which is of the order of the power of one module, about 615 W at nominal 150 kW operation.
- If the SSA feeds a mismatched load, the corresponding reverse power is equally distributed to the circulator loads of all RF modules. According to the specification, it can reach 205 W. For the **unpowered modules** this interferes with the 615 W transmitted from the active modules. For the worst phase of the mismatch, the total power can amount to:

$$P_{reverse} = [\sqrt{615} + \sqrt{205}]^2 = 1530\ W,$$

which is close to the measured 1700 W, i.e. much too high for the 800 W circulator loads.

The following technical remedies were implemented.

Booster SSAs

The output circuit of the RF modules was tested with variable reverse power. In CW operation, overheating of the circulator loads indeed occurred slightly above the respective nominal power levels for 800 W loads and alternative 1200 W loads. However, when powered with ESRF booster pulses, no degradation of 800 W loads was observed up to 3 kW at the crest. This allowed accepting the booster SSAs as delivered by ELTA.

Remaining Three SSAs for the Storage Ring

Inserting a high power circulator at the output of the SSAs would completely solve the problem, since the SSA would always "see" a perfectly matched load. However, ELTA did not retain this solution. Instead, ELTA implemented the following measures:

a) Replace the 800 W by 1200 W loads on all future RF modules.

b) Following a suggestion from SOLEIL, insert a 90° phase shift between the first 6 kW-x8-combiners and the subsequent 50 kW-x8-combiners (20 cm longer radial arms in figure 3). For any passive module, the reverse waves coming from the neighbouring active modules of the same 6 kW combiners then interferes destructively with those from all other active modules of the SSA, keeping the maximum load power below 1200 W.

c) Additional 3.5 kW interlocks for the reverse power at the 6 kW level (output of 1st x8-combiner).

d) Use of flame retardant coaxial RF power cables.

The modified RF modules are compatible with the booster SSAs and will be used as spares for all the SSAs.

ESRF SSA USING A CAVITY COMBINER

The ESRF is developing a more compact SSA using a cavity to combine the power from 132 RF modules providing 600 to 800 W each [2]. This work receives funding from the EU within the FP7/ESFRI/CRISP project, in which the ESRF is building a 352.2 MHz - 75 kW prototype preceded by a 10 kW demonstrator. It also includes feasibility studies for the partner labs CERN, GSI and ESS at various frequencies.

10 kW Prototype

Figure 4 shows the 10 kW demonstrator with only three active water cooled "wings", each of which supports six 700 W RF modules, which use the same BLF 578 6th generation LDMOSFET as the SSAs supplied by ELTA. The coupling loops are integrated in the end faces of the wings, which constitute the side walls of the cavity. This results in a substantially reduced footprint and avoids the use of coaxial RF power cables. In the 10 kW version, the 19 missing wings of the future 75 kW prototype are replaced with blind flanges. Planar Wilkinson splitters on the rear sides of the wings distribute the RF drive power.

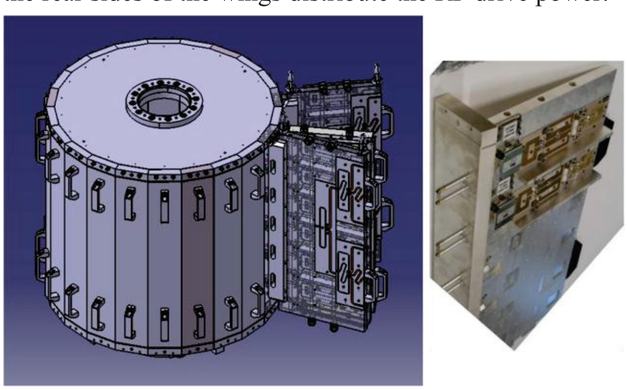

Figure 4: 10 kW demonstrator.

All three wings are now equipped with a total of 6 RF modules each, as shown in Figure 5. The innovative ESRF design features:

- Printed circuit input and output baluns,
- Planar quarter wavelength transmission lines replacing the drain chokes,
- Use of very few components, all Surface Mounted Devices and prone to automated manufacturing.

The measured performances of the 18 modules in Table 1 fully meet the needs for the prototype. However, there is still room for improvements. For the ongoing R&D a collaboration contract has been set up with the Uppsala University to further optimize the circuit board.

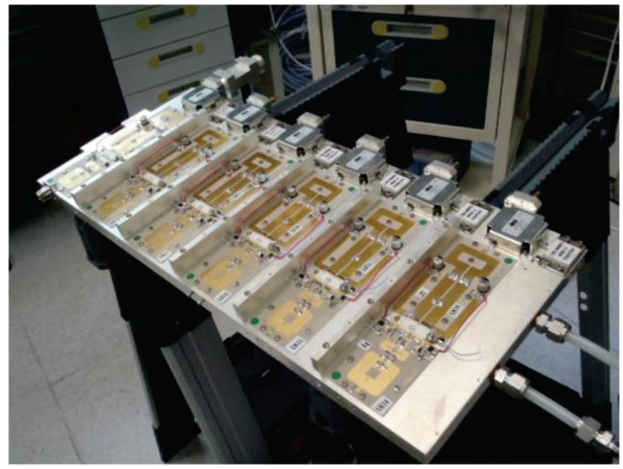

Figure 5: One of three wings supporting 6 innovative, fully planar RF modules developed at the ESRF.

The combiner cavity has already been tested and qualified at low power [2]. All auxiliaries including the 50 V power supplies and the controller are in house. Assembly is under way and the power tests at 10 to 12 kW are foreseen in June 2013.

Table 1: Average Performance of 18 ESRF RF Modules, including Output Circulators

RF output power	Average gain	Average efficiency
400 W	20.6 dB	50.8 %
700 W	20.0 dB	64.1 %

CONCLUSION

One year of operation with 600 kW SSAs on the ESRF booster have confirmed the expected high reliability of this technology. In the coming year the additional three slightly improved 150 kW SSAs will be commissioned on the storage ring. The ESRF is also contributing to the further development of this promising technology with the implementation of more compact cavity combiners and innovative fully planar high power RF modules.

ACKNOWLEGMENT

The design and implementation of the 280 V DC power supplies for the SSAs by the ESRF Power Supply Group is greatly acknowledged.

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