COMMISSIONING AND ONE YEAR OPERATION OF THE 50 kW SOLID STATE AMPLIFIERS OF THE LNLS STORAGE RING RF SYSTEM *

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Abstract

In December 2010 a pair of high power solid state amplifiers was installed in the RF system of the LNLS electron storage ring. The new amplifiers replaced the UHF klystron system that had been in operation since the machine started to operate in 1996. Each one of the two storage ring solid state amplifiers can deliver up to 50 kW at the operating frequency of 476 MHz. The conversion to the solid state technology was motivated by the greater efficiency of the new amplifiers for the operational conditions of the LNLS light source, and by the cost of keeping spare klystron tubes. Before installation the amplifiers were commissioned and fully characterized in the RF test area. This paper summarizes the results of these tests and presents an overview of one year of operation of the amplifiers in the storage ring.

INTRODUCTION

LNLS started to work with high power RF solid state amplifiers (SSA) in 1999, in the wake of developments that were under way at LURE, in France, which was at that time designing the future third generation synchrotron light source SOLEIL[1]. In close collaboration with LURE's RF group, LNLS built a four module 900 W SSA operating at 476 MHz to drive the booster RF cavity. The booster amplifier has been a success since it started operating in 2001. The booster system has been upgraded twice, the first time in 2007 to increase the output power to 2 kW, which led to a better efficiency of the whole injector system. The last upgrade aimed at the standardization of the amplifier modules, which now use the same family of transistors as the storage ring system.

The positive experience with the booster RF system, allied to the high operation costs of the klystron system, either related to the electric power consumption or to the need to keep a set of expensive spare tubes, motivated LNLS to move towards the solid state technology even for the storage ring RF system.

In 2007, the Brazilian federal funding agency FINEP approved a project to design and build two SSA capable of delivering the total 100 kW of power at 476 MHz necessary to drive the current storage ring RF system (Figure 1). In 2008, in close collaboration with the SOLEIL RF group, the amplifiers were designed and the main components were prototyped, specified and ordered. The heart of the system is the MOSFET based amplifier module, with an integrated circulator and individual power supply, each one capable to deliver more than 330 W of power at 476 MHz.

Figure 1: The two towers of the 50 kW solid state RF amplifiers operating in 476 MHz installed in the storage ring. From left to right the two 150 kVA DC power supplies, the racks of the low level RF and the two solid state amplifiers.

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Two amplifiers have been assembled, each one built from the combination of 162 such modules and 50 kW nominal maximum output power. Modules, cables, combiners, dividers, power supplies, in short all the components of the amplifier were extensively characterised at the RF laboratory before assembly. The control, monitoring and interlock systems of the amplifiers were carefully tested. In the beginning of 2010 both amplifiers were fully assembled and ready for commissioning in a test area [2]. The amplifiers passed a series of tests and measurements in order to be approved for installation in the storage ring.

The following is an overview of the main tests performed on the set of amplifiers and an evaluation of one year operation of the SSA in the storage ring.

THE RF SYSTEM

Up to the installation of the new amplifiers, the RF system of the storage ring comprised a set of two room temperature RF cavities (ELETTRA cavities), each one driven by a 40 kW UHF klystron operating at 476 MHz protected by a high power circulator, a low level RF system (LLRF) with tune, phase and amplitude loops, and a cooling water control unit to keep the temperature of the cavities stable within ±0.05ºC. The operation of a klystron tube requires a series of peripheral equipments: a high voltage power supply, electron gun filament and focusing solenoids power supplies, a high power circulator is mandatory to protect the tube from reflected power and high SWR.

Operating Conditions of the RF System

The operating conditions of the LNLS storage ring during user shifts do not require full output power from the klystron tubes. In fact, in a regular user shift the power demand for each cavity is typically of the order of 25 kW in the beginning of the shift dropping to 17 kW in the end, corresponding to a current variation from 250 to 140 mA during a typical beam period. In normal operation conditions the gap voltage in each storage ring RF cavity is set to 250 kV. For this working condition the electrical efficiency of the klystron system is quite small, close to 17% on the average.

Main Characteristics of the Solid State Devices

Differently from the klystron tube, the power consumption of the SSA depends on the output power of the amplifier. Each SSA requires a 150 kVA DC power supply capable of delivering the necessary power to drive the 162 amplifier modules. At full power the efficiency of the SSA is close to 55% and that of the DC power supply is close to 90%. The lower the output power the lower the efficiency but, in the worst operating condition of the storage ring the solid state system has at least twice the efficiency of the klystron system in the same conditions. In normal operation conditions the efficiency of the amplifiers is about 40% and the overall electric power consumption of the RF system is approximately half with the new amplifiers.

Table 1 lists the main parameters of the SSA. The modules are based on the BLF574 NXP power LDMOS transistor and can safely operate at output powers as high as 370 W under controlled test conditions. Each module has a built in narrow band circulator (474–478 MHz) and is unconditionally stable. BBEF (China) produced and performed the fine tuning of the modules.

Table 1: Solid State Amplifiers Main Parameters

Operation frequency	476 MHz
Nominal maximum output power	50 kW
Maximum gain (@30kW)	40 dB
Efficiency (@50kW)	58%
Harmonic contamination (±380kHz)	-66 dBc
1-dB compression point	>50 kW
Number of modules	162
Maximum output power per module	330 W

COMMISSIONING IN THE TEST AREA

In order to be cleared for installation in the storage ring the SSA were tested in the RF test area for nine months. Due to limitations in the water cooling system they had to be commissioned one at a time and a water load was used for power tests. During the test period several voltage sags and short power outages occurred without any damage to the amplifier modules. During that period six amplifier modules failed (out of 324 in use in both amplifiers) and had to be replaced. In all these events the SSA continued to work normally and the damaged module did not have to be replaced right away. It is noteworthy that all these modules could be repaired in house. This modularity and easiness of maintenance, added to the fact that keeping a safe number of spare modules is extremely cheaper than keeping a spare klystron tube, are other attractive features of these amplifiers.

Tests were performed to check the robustness of the SSA to sudden variations of the output power. At 50 kW the amplifier has not achieved the 1-dB compression point and can potentially deliver a fairly higher output power at the cost of pushing the modules to their limits. An interlock for maximum output power was introduced to prevent the amplifiers from working in such conditions. In fact, in an accidental event the output power was once suddenly raised beyond the nominal maximum and resulted in the failure of one of the modules. In that case the excess output power led to overheating and burnout of a trimming capacitor of the impedance matching output line, but resulted in no damage to the power transistor.

Failures in the DC-DC converters were also a problem in the beginning of the commissioning. At high output power several capacitors on the converters input line failed and were removed after a revaluation of the design. Temperature maps of the converters circuit cards showed that the replacement was successful.

The amplifiers were tested for short time stability and for long time stability and endurance. Temperature

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variations affect the gain and the phase advance of the RF signal. This dependence was observed in the test area. A 10ºC temperature variation in the modules cooling bars results in about 10º phase variation of the RF output signal. In the storage ring the water cooling system has a good temperature control (±0.1 ºC) and in the worst operational conditions the temperature of the hall can vary by ±1ºC. Small phase variations and slow gain variations are smoothly compensated by the control loops of the LLRF.

OPERATION IN THE STORAGE RING

The installation of the amplifiers and rearrangement of the RF system took place in the last two weeks of November, 2010 (Figure 1). The klystron system was removed and the low level RF racks were remodelled to adapt to the new system. The high power circulators were kept for extra protection of the SSA, even though the internal circulators of the modules have been dimensioned to stand full reflected power in any condition.

The protection of the RF system had to be remodelled and a PLC is used for the interlock system. In addition to the existing protections against reflected and maximum output power, an extra interlock for maximum input power was added to prevent excess incident power on the modules. They have been effective in protecting the amplifiers against possible failures in the control system. In the operational aspect, despite the many changes in the high level control system, the transition to the new operation routine was quite smooth for the machine operators.

After more than a year of continuous operation in the storage ring the performance of the SSA have been remarkably good. In 16 months only four modules had to be replaced (1.3% of the total), all of them repaired in house. So far none of the 324 DC-DC converters had to be replaced and this is also the case for cables, combiners and dividers of the SSA. In fact, most of the problems with the SSA were not related to RF. In the first weeks of operation many trips occurred due to interlock related problems. After one year several flow meters of the modules water cooling start to show signs of deterioration and to signal false alarms. Rotameters will be used in a new version of the cooling system.

In the klystron system the ripple of high voltage power supplies induced a large phase variation in the RF delivered to the cavities but that was largely neutralized by the phase loops in the LLRF. The actuation signals in these loops are now very stable compared to the noisy behaviour observed in the former klystron system (Figure 2).

There is no clear evidence of degradation in the efficiency and gain of the amplifier modules up to this moment. In the user shifts the SSA operate mostly at half power in a very slack condition and that certainly helps to maintain the performance of the modules.

The effectiveness of the in house repairs is attested by the fact that the current SSA of the booster RF system uses modules of the high power amplifiers that failed and were fixed in house. The booster SSA has been in operation since December 2011 and is also performing extremely well and with great reliability.

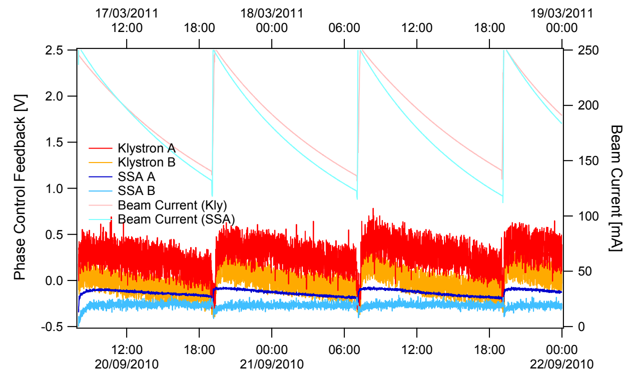

Figure 2: Actuation signal of the phase control feedback loop of the RF system before and after the SSA.

FINAL REMARKS

The LNLS synchrotron light source is operating since December 2010 with a pair of 50 kW solid state amplifiers to drive its RF cavities. The replacement of the old system by the new one was smooth and the failures observed until now have been mostly related to fine tuning of the protection interlock system. Since the operations started there have been very few failures directly connected to the amplifiers. The system is very robust, reliable and easy to maintain. SSA are planned to be used in the RF system of SIRIUS, the new Brazilian synchrotron light source.

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