

## STATUS OF THE 476 MHz 50 kW SOLID STATE AMPLIFIER FOR THE LNLS STORAGE RING

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### Abstract

In November 2010, LNLS plans to replace the two 50 kW UHF klystron system which currently provides power to the RF cavities installed in the storage ring. To replace this system, two 50 kW solid state amplifiers have been built and are now under commissioning. Thanks to a close collaboration with the Synchrotron SOLEIL started in 1999, LNLS adapted the characteristics of the French project to 476 MHz. A short description of the amplifiers is presented, as well as the power tests performed with one of them using a resistive load.

### INTRODUCTION

LNLS started to work with solid state amplifiers in 1999, in the wake of developments that were underway at LURE, in France. At that time LURE was designing the new top level synchrotron light source SOLEIL, boldly planning to have its RF system totally based on solid state amplifiers. In close collaboration with LURE's RF group, LNLS built a 900 W solid state amplifier operating at 476 MHz to drive the booster RF cavity. The SOLEIL RF system operates at 352 MHz, meaning that a great deal of development had to be done in house. Since it started routine operations in 2001 the booster amplifier has been working very well. In 2007 it was successfully upgraded to 2 kW as part of a program to reduce injection time in the storage ring [1].

Solid state amplifiers are an effective alternative to commercial UHF electron tubes like klystrons and IOTs, which are becoming increasingly more expensive to purchase and operate. Maintainability and higher electrical efficiency are the main features of the new technology. The substitution will have a great impact on the operational costs of the RF system. At the LNLS storage ring the current klystron based RF system has a very low efficiency since its power consumption is constant regardless of the instantaneous power needs of the accelerator. In turn, the expenditure of energy of the solid state devices will follow the RF power demand and that represents a considerable reduction in operation costs compared to the current system. Moreover, the intrinsic modularity of its topology makes the solid state amplifier more reliable since it continues to operate even if a few amplifier modules fail. Replacing failed modules is straightforward and keeping spare modules much cheaper. Besides, the maintenance of a failed amplifier module can be done in house at very low cost.

The LNLS Synchrotron Light Source is based on a 1.37 GeV electron storage ring operating with initial beam current of 250 mA. The storage ring has 3 IDs installed in its straight sections: a 2 T multipolar wiggler,

a 4 T SC wiggler and an EPU undulator. In 2009, its 14 beam lines were used by approximately 1300 researchers from Brazil and other countries. Two other beam lines are under construction and are scheduled to open for users in 2011.

The Storage Ring RF system is equipped with two 476 MHz single cell cavities powered by two 50 kW UHF CW klystrons. Each cavity is driven by an independent system, each one comprising a klystron tube and its support subsystems (HV, filament and focusing solenoids power supplies), high power circulator, low level RF and control. During each one of the 11.5 hours shifts for users the beam current in the storage ring decreases from 250 to 170 mA. During this period the total RF power required from the RF cavities varies from 48 kW to 36 kW, and that represents an average power of about 40 kW demanded from the whole system. Considering the power consumption of the HV power supply and other subsystems that feed the klystrons, the average efficiency of klystrons is only 15%.

The high operation cost of the klystron system, related both to the electric power consumption and to the necessity to keep a set of expensive spare klystron tubes, motivated LNLS to take more decisive steps towards the solid state technology. In 2007, the federal funding agency FINEP approved a project to design and build two solid state amplifiers capable of delivering the 100 kW of RF power at 476 MHz necessary to drive the current storage ring RF system. In this paper we present the results of the first high power tests of the amplifiers, that are currently under commissioning at LNLS.



Figure 1: 476 MHz Solid State Amplifier tower being commissioned at the RF test area at the LNLS.

## THE AMPLIFIER

In 2008, in 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 a MOSFET amplifier module with integrated circulator and individual power supply, capable of delivering more than 330 W of power at 476 MHz. High output power can be obtained by adequately combining the output power of a large number of such modules. 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, the monitoring and the interlock systems of the amplifiers have been developed in house and have already been carefully tested. Limitations in the available infrastructure allow testing just one amplifier at a time. Although both amplifiers are completely assembled just one of them is undergoing exhaustive performance tests.

### Amplifier Modules

The amplifier modules are the heart of the solid state amplifier. High power amplification can be achieved by the parallel combination of the output power of several individual modules. The amplifier modules are based on the BLF 574 NXP power LDMOS transistor. The modules were tested and can safely operate at output powers as high as 370 W at the frequency of 476 MHz. The module has a built in narrow band circulator (474–478 MHz) and is unconditionally stable.

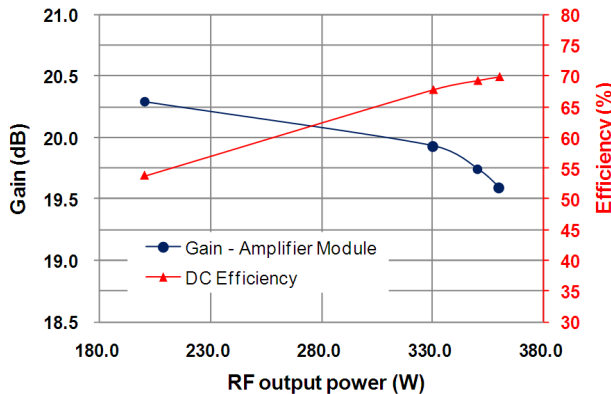


Figure 2: Gain and efficiency characteristics of a 476 MHz solid state amplifier module.

When the amplifier is at maximum nominal output power each module contribute with about 330 W to the total power. At that power the measured characteristics of the modules show an average gain of  $19.91 \pm 0.18$  dB, phase dispersion smaller than  $10^\circ$ , the efficiency is about 68% and K stability factor larger than 15 dB. The typical variation of gain and efficiency with the output power of the module is shown in Figure 2.

The manufacturing, tests and characterization of the amplifier modules, as well as the power combiners and splitters, were contracted to BBEF Electronics (Beijing, China) and arrived at the LNSL in 2009. Each module has its own DC power supply. The BLF574 transistors require

a supply voltage of 50 V. The power supply board is based on the TDK-Lambda PAF600F280-48 600 W DC-DC (280 V–48 V) converter. Each module require no more than 10 A from the power supply at maximum output power.

### Final Amplifier Layout

Progresses in transistor technology in recent years have enabled a significant simplification of the original design of the amplifier. One amplification layer could be removed from the original topology. The final design uses a single module as preamp for the parallel combination of 80 modules that form one of the two branches of the amplifier. The amplifier layout follows the topology of SOLEIL's amplifier towers. Figure 3 shows a schematic drawing of the device.

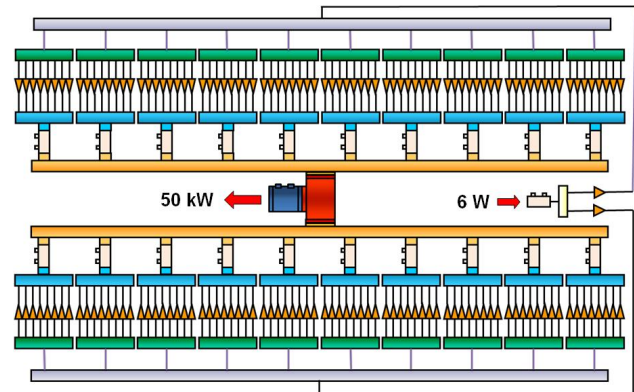


Figure 3: 50 kW 476 MHz LNLS Solid State Amplifier Power combination scheme.

Two amplifiers have been assembled, each one built from the combination of 162 amplifier modules carefully assembled over water cooled plates. Each amplifier module and its power supply are assembled at opposite sides of the cooled plate. The water cooling system has a maximum flow of 1000 l/h in operation and is equipped with temperature sensors and flow meters for each individual plate. The cooling hoses are all connected at a lower level than the electrical wiring in order to avoid the risk of electrical breakdown in the case of water leaks.

A high power DC power supply delivers the electric power for the modules converters. The monitoring system is attached to the same structure that holds the cooling plates. Both are described below.

### DC Power Supply

The supply voltage for the DC-DC converters connected to each amplifier module has to be in the range from 200VDC to 400VDC. A power supply was designed to feed all 162 DC-DC converters used in one tower amplifier. The power supply is connected to the 380VAC three-phase system. A delta-star transformer lowers the voltage to 220VAC, which is then rectified by a diode bridge and filtered by a 4050uF/500V capacitor bank, providing an output voltage of 300VDC at 400A maximum load current. The output of this source is

divided into ten sets of copper bar tracks, one for each cooling plate, connecting to the power DC-DC converters in parallel.

### *Dividers, Combiners and Other Components*

The set of dividers, combiners and couplers necessary to mount the amplifier was prototyped at the LNLS. The 2-way 50 kW and the 10-way 25 kW power combiners were built at the LNLS workshops. The final production and characterization of all low power combiners, dividers and couplers was ordered to BBEF. The cables were ordered from an external supplier and have all of them been characterized at LNLS and grouped based on phase advance similarity.

### *Control and Monitoring System*

A signal acquisition system continuously monitors and records various parameters of the amplifier. The current consumed by the pair of transistors of the push-pull circuit of the BLF574, the incident and reflected power in each input branch of the 10-way 25 kW combiners, and the amplifier incident and reflected input and output power are all monitored. A multiplexed electronics controlled by a PIC microcontroller collects, process the data and provides communication via serial RS-232. A standalone supervisory program updates all 368 parameters every second, allowing them to be recorded for future analysis. The amplifiers are controlled from the control room by the storage ring control programs.

## COMMISSIONING

The first amplifier is under commissioning and has been tested up to 50 kW output power for several hours. The amplifiers must pass a series of tests and are expected to be installed in the storage ring at the end of 2010. The amplifiers have been assembled in a test area in one of the laboratory buildings on campus. The local infrastructure allows testing just one amplifier at a time. Moreover, the site has no temperature control and that can vary by several degrees during a typical day. The amplifier is being tested using a matched 80 kW RF water cooled load. The supervisory and the interlock systems were tested in advance. The directional couplers were characterized in the RF lab as well as the detector diode circuits. A RF generator coupled to a preamp circuit was used to drive the amplifier.

### *High Power Tests*

The start up of the amplifier was surprisingly smooth. The output power reached 20 kW in the very first day. Measurements of the incident and reflected power at the various stages of the amplifier were consistent with the current delivered by the DC-DC converters and with temperature measurements taken at the cooling water inlet and outlet. Eight hours long stability tests have been performed but the results are not conclusive. For a fixed reference output power from the main RF generator, with no control loop, the amplifier output power and the gain

vary slightly during the day. The measurements show a profile that resembles the temperature variation of the test area, decreasing with the temperature. The tests must be repeated under more controlled conditions.

Measurements of output power, gain and efficiency have been performed. Maximum gain is at 32 kW output power and at the maximum power the amplifier still not reached the 1-dB gain compression point (Figure 4).

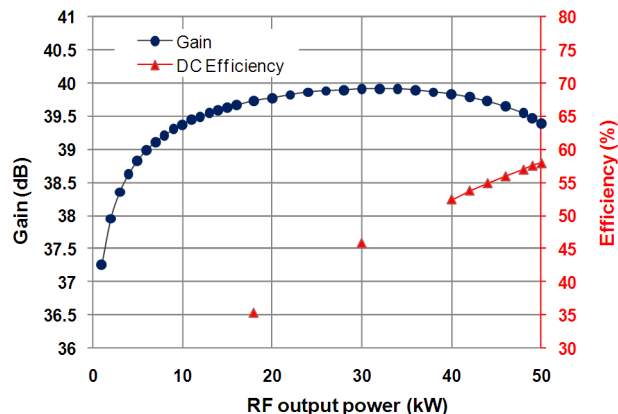


Figure 4: Gain and efficiency of the 476 MHz Solid State Amplifier tower under commissioning at the LNLS.

Measurements of the harmonic contamination show very low sidebands that decrease with power. For the typical operation power, 25 kW, the sideband at 380 kHz is at -66 dBc. Thermographic check up of the modules and power supplies show that at maximum power temperatures in the modules can reach 85°C.

## FINAL REMARKS

One of the two solid state amplifiers assembled at LNLS is under commissioning and has undergone several performance tests. The results are quite promising. Long duration stability tests are still necessary to simulate the actual operation conditions in the storage ring. That is mandatory for the decision to install the new system in the storage ring by the end of 2010. Once implemented, the installation of the new system is expected to be transparent for the operation of the storage ring but there will be significant energy consumption savings.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] C. Pardine et al., "Commissioning of the 2,2 kW, 476 MHz Solid State RF Power Source for the LNLS Booster Synchrotron", EPAC'08, Genoa, June 2008, MOPD029, p. 511 (2008); <http://www.JACoW.org>.