HIGH POWER SOLID-STATE AMPLIFIERS. NEW DEVELOPMENTS AND TECHNOLOGY COMPARISON *

G. B. Sharkov[1], A. I. Botyachkova[1,2], E.V. Ivanov[1], N. G. Kalugin[1], A.A. Krasnov[1], K. K. Naraianamurtkhi[1], K.I. Nikolskiy[1], S. A. Polikhov[1], I.N. Rezanov[1], A.Y. Smirnov[1], P.M. Yazev[1]

[1] Siemens Research Center, Moscow, Russia

[2] National Research Nuclear University (MEPhI) Chemical Physics Department

Abstract

We present a newly developed compact and cost effective SSPA with megawatt range output power and scalable architecture. System components test results are discussed. A comparison of the state-of-the-art vacuum tube and solid-state technologies of RF power amplifiers for scientific accelerators is given.

INTRODUCTION

The last year's developments in the field of high power high frequency solid-state transistors lead to the expansion of solid-state technology on the RF amplifiers market. Developing Si, SiC, GaN, GaAs LDMOS, FET transistors [1] allow building not only the drivers for vacuum tubes, but to substitute the entire RF systems [2]. The general trend on the market is to reduce the Total Cost of Ownership (TCO) which brings in system, operating, and construction costs. The typical TCO breakdown for 10 years operation of thirty amplifiers at 50% wall plug efficiency is shown in Table 1. The operation costs have so large impact on TCO that the increase of the efficiency by ~10% can compensate the whole procurement cost.

Table 1: Total Cost of Ownership. Breakdown for Thirty 800 kW Amplifiers Working for 10 Years

Cost	Role in TCO
Procurement cost	14%
Construction cost	14%
Operation costs	69%
Service costs, spare parts, % from procurement	1%
Costs of downtime	1%
R&D and labour	1%

Particular market segments demand different ways to reduce these costs. While PET cyclotrons, lasers and plasma sources require high persistence against reflected waves, the broadcast market needs high signal purity and linearity. The construction costs driven by the footprint of PA's is a significant share of the cost books of such projects as large light and neutron sources, HEP Linacs. The reduction of TCO can be achieved using following approaches:

1. Reduction of procurement price using novel high power cost effective solid-state technologies;
2. Reduction of construction costs using more compact devices;
3. Reduction of service costs by icreasing MTBF and reduction of spares costs;
4. Increase of system availability (downtime costs) by reduction of MTTR;
5. Reduction of energy costs by increase of PA's efficiency;
6. Reduction of R&D, labor costs for high qualified RF specialists providing turnkey solutions.

For us this lead to the following responses on abovementioned market demands:

1. Standardization of amplifier architecture and subsystems for different applications;
2. Modular structure;
3. Usage of fast connectors for fast module maintenance;
4. Ability to work at full power and nominal efficiency with several broken RF power modules;
5. Efficient and compact RF power combination from numerous transistors in few (one/two) steps;
6. All-in-one solution with power supply, LLRF, control system, cooling etc. onboard.

SYSTEM ARCHITECTURE

Driven by these tasks the system concept has been developed and being validated through building a solid-state microwave generator prototype with technical requirements according ESS low-β section specification. The system structure is presented on Fig. 1. It consists of a 19-inch cabinets with a docking station for several RF generating modules, the power combiner with RF switches for failed RFM disconnection, power supply and capacitor blocks to feed the RF modules with electrical energy required for the pulse, the control system and cooling system.

The system has versatile modular structure allowing fast module change. The idea behind it is to reduce the efforts needed to build the generator for a new specification. To do so the system should be easy scalable in output power. It can be done by using mechanical standard with RF modules/cabinets which can be easily added to the system, e.g. 19'' cabinets with standard racks. The redesign for a new frequency should affect the redesign of the RF module and the power combiner only.

*Work supported by:
Skolkovo Foundation, Russia. www.sk.ru

ISBN 978-3-95450-142-7

All other subsystems should be kept the same for wide range of frequencies (from tens of MHz up to 1.3 GHz) and powers (from tens of kilowatts up to megawatt range) and hence can be produced in series.

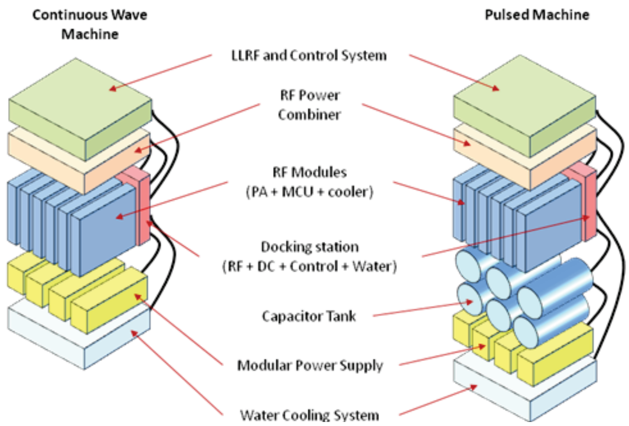

Figure 1: The general architecture of Siemens' solid-state amplifier.

The special technique is used to build RF modules with several (2-8) transistors onboard and to combine the RF power with minimum power combination iterations. The high power per module reduces the number of inputs of power combiner and makes system compact (~200kW/m^2) while power combination with high isolation between inputs and good combination/division equality makes system tolerant to the reflected waves. The efficient power combination and use of state-of-the-art transistors ensures high overall efficiency of the generator which is more than 55% from the wall plug (up to 65% at ~50-100 MHz).

The RF modules and capacitors are placed in different blocks allowing to change the duty cycle up to CW operation easily. The PIN-diodes based RF switches allow to disconnect the broken RF module from power combiner with strongly defined impedance leading to very low efficiency drop at the nominal output power. They also allow to perform amplitude and phase calibration of each RF module which avoids the necessity for precise cutting of RF cables between LLRF, RF modules and power combiner. The docking station for RF modules with fast connectors gives the possibility to change the modules in case of maintenance in the fastest way, reducing the MTTR. Since the RF modules and capacitor blocks are equipped with own sensors the control system has the information of their degradation. This allows to predict when the spare parts should be placed, which increases the MTBF of the whole generator to almost infinity.

SSMG PROTOTYPE

The described above concept of solid-state amplifier formed the base for the 400kW pulsed amplifier being developed for ESS specification. The technical requirements are listed in Table 2. The design and test results of main components of the system are described below.

Table 2: ESS Low-β Technical Requirements

Frequency of operation	**352.21 MHz**
Output power	≥ 400 kW
3 dB bandwidth	≥ 200 kHz
Pulse width	3.5 ms
Frequency of pulses	14 Hz
Harmonics	< -35 dBc
Spurious	< -60 dBc
Linearity	± 0.5 dB between 40 kW and 400 kW
Gain amplitude stability for slow time scale (time >5 µs)	± 1 dB
Gain phase stability (time >5 µs)	± 5°

8 kW RF Module

The module consists of four 2kW pallets with high power LDMOS transistors. The pallets are placed at one side of water cooled radiator together with the output matching circuit and power sensors. The input and output RF circuits are made on the PCB to avoid the manual tuning and hence decrease the production costs. On the other side of the radiator the Wilkinson power final combiner and DC distribution circuits are placed. In addition the microcontroller for the module control and telemetry is placed. The module has a stack of quick connectors for input RF signal, digital signals, DC power, cooling water, RF output connector. The capacitors block is connected to the docking station using wide low-inductance bus bar.

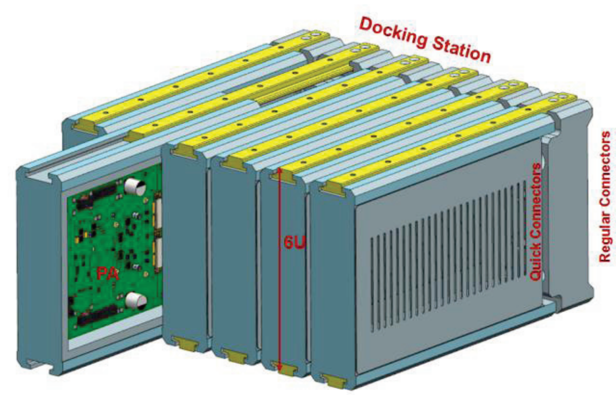

Figure 2: The general view of RF modules block with six modules and the docking station.

Figure 3 shows the amplitude stability of the 2.3 kW pallet pulse within 0.13dB.

Figure 4 shows the fast rise and fall performance which is less than 250 ns.

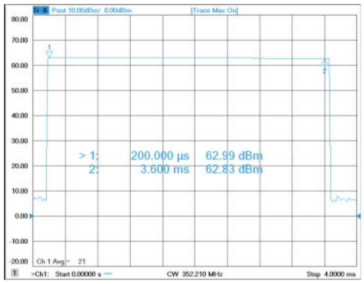

Figure 3: RF power stability. Power droop through pulse 0.13 dB.

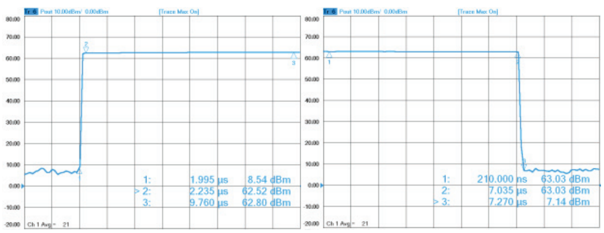

Figure 4: Rising and falling edges of 3.5 ms pulse, .10-90% rise time – 0.24 us, fall time – 0.235 us.

To ensure the resistance of the system (which has no circulators) to the full reflection, the tests with a short at the output of the pallet have been performed. The test was performed with the trombone phase shifter. It showed that the pallet can withstand full reflection at any phase during 3.5 ms pulse (duty cycle 5%) without transistor heating more than 70°C.

Power Combiner

The 12:1 (Fig. 5b) power combiner is a 2U-high box shaped coaxial structure with the inductive RF power summation. It consists of summation part with 12 7-16 connectors and matching part to match the impedance to the output 1 5/8'' connector. This 100 kW power combiner is used to combine 12 RF modules of one 19'' cabinet. The power division equality measured is <1% while the inputs isolation is -20dB which is close to the theoretical limit of such structure. The losses in the 12:1 power combiners measured are within 0.75%. The final 4:1 combiner (Fig. 5a) with a directional coupler (Fig. 5c) is placed at the top of the cabinets.

Figure 5: a: 4:1 final power combiner; b: 12:1 100 kW power combiner; c: bi-directional coupler.

Comparison of S11 parameter measured and simulated is shown on Figure 6.

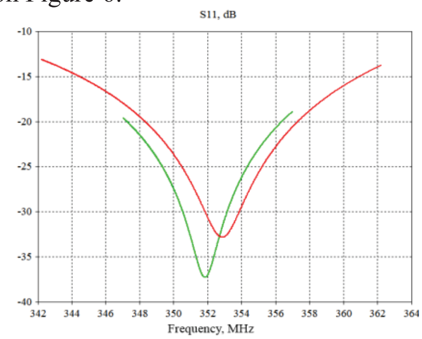

Figure 6: S11 parameters of 12:1 power combiner: green – calculated; red – measured.

Control System

The control system is realized in 3U 19'' standard crate. It consists of following units. The central processing unit (CPU) provides the basic functionality of the system: control over all RF modules parameters, interconnection with external control, frequency generation (in the generator regime), distribution of frequency to active splitters, processing of interlock signals. The active splitter modules utilizing variable attenuators and phase shifters distribute for each RF module individual signals with given amplitude and phase shift, they also provide data and interlocks transfer with RF modules.

CONCLUSION

Recent development of high power RF transistors and SSPA's based on them show that their efficiency, sizes and robustness provide competitive TOC values compared to vacuum tubes. The direction to compete with vacuum tubes at higher RF powers is supported by our ongoing development of 400 kW prototype for ESS specification. The results of RF module and power combiners tests are presented. Further assembling and high power tests are to be done in the nearest future.

ACKNOWLEDGMENT

The authors would like to thank Marcus Zerb, Alexey Tribendis and Ulrich Ratzinger for fruitful discussions and their permanent support.

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ISBN 978-3-95450-142-7