100 kW VERY COMPACT PULSED SOLID-STATE RF AMPLIFIER: DEVELOPMENT AND TESTS

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Abstract

Solid-state RF power amplifier (SSPA) technology has developed significantly over recent years [1]. Powers of hundreds of kilowatts are being achieved, driven by the developments of LDMOS and other transistor technologies [2]. The price and size of SSPA still correlate with the output power (due to the number and cost of transistors), which is not the case for vacuum tube based devices. In order to be competitive with tetrodes, klystrons, IOT's and other tubes at higher levels of power and frequency, SSPA's should be designed to be more compact and cheaper than current offerings, using the high efficiency and reliability of modern transistors to produce highly available amplifier systems. The scalability of SSPA output power is achieved by a modular architecture based on several ~1kW transistors; this gives an important advantage over vacuum tubes.

In order to meet challenging demands for high power, efficient, reliable, compact and cost effective RF amplifiers, a novel architecture of SSPA is employed and a 100 kW prototype has been developed (Fig. 1). The complete system fits into one 19'' cabinet. It is developed according to the requirements of the ESS project's "low-beta" part of the Linac: 400 kW, 352 MHz, 3.5 msec pulse at 14 Hz repetition rate, <5 m^2 footprint [3].

ARCHITECTURE

The main idea of the proposed architecture is to reduce the manufacturing cost, especially removing hand assembly and tuning and the need for highly skilled personnel. Since the materials costs are mainly driven by the costs of transistors and matching elements, which are hard to reduce, the labour costs is the main manageable cost driver. To achieve this goal one needs to standardise all subsystems for any frequency within roughly 20 – 1300 MHz and any output power from 10 to 1500 kW, such that each new specification will not cause significant redesign and R&D. The system should be modular, so that changes to the working frequency will lead to the redesign of a minimum set of subsystems. Ideally this would be limited to the PCB's with RF transistors and the power combiners. All subsystems should fit into one 19'' cabinet, so that one cabinet can serve as a standalone RF amplifier comprising individual PA modules and power combiner and respective ancillary systems*. Increasing the required output power will then be implemented by providing complete cabinet amplifiers with a final stage power combiner mounted above the cabinets. This approach provides a fully scalable system. The low level modularity of the system together with the ability to work without all of the PA modules functional and the ability to "hot swap" units allows very high availability (potentially 99.9%) to be achieved which is unachievable by single vacuum tube systems.

Commercial-off-the-shelf (COTS) components are used as much as possible to reduce the R&D scope to the core technology only. Sub-Systems such as high reliability DC power sources, cooling water distribution and the 19'' cabinet can be bought freely. The main modules of the control system (CS) can be developed once for all specifications, so that only frequency specific modules will be changed for each application.

Transistor evaluation boards, which are usually taken as building blocks for SSPA development [4], become quite bulky for high power systems, where hundreds of transistors are needed. Consequently the power amplifier building block should contain at least two transistors (four might be an option for pulsed systems to minimize the cost of connectors, PCB's, etc.). One should avoid designing the matching circuits using coaxial wires since they require laborious hand work. A flat transformer on a PCB is a good choice to reach the needed precision and repeatability (taking into account the possible overheating issues).

Figure 1: 100 kW 352 MHz pulsed SSPA prototype.

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* For systems with high average power or for CW operation the DC power supplies may be placed in separate cabinet

Components of PA modules are usually quite sensitive to temperature, impedances, etc. Hence the imbalances between modules will cause additional losses. The precise tuning of dozens of PA modules over several output parameters, such as: output power, phase, gain and phase linearity, etc.: again requires costly and laborious hand work. Alternatively an active splitter can be used to compensate for the phase and amplitude differences between the modules. A slow feedback loop can be used to compensate for temperature related drift.

Modern high power LDMOS transistors can survive up to 100% reflected wave. This gives the possibility to avoid using circulators in the system, which are usually installed to protect from imbalances in the system with conventional splitters. The circulators are bulky, expensive, decrease overall efficiency and need their own voltage control and cooling. Using modern RF transistors and splitters with phase and amplitude control one can avoid not only the circulators inside the SSPA, but also at the output and this improves efficiency in comparison with vacuum tubes.

PROTOTYPE OVERVIEW

The architecture principles described above have been used to design a 400 kW prototype according to the ESS “low-beta” specification and to build a prototype 100 kW section of the complete amplifier. The system consists of a 38U high 19” cabinet with cooling system and wiring at the rear. Two racks with six 8.7 kW PA modules in each are placed below and above the 12:1 power combiner, which is configured as a rectangular shape and fits into the 19” standard rack. Prior to assembly into the system each PA module has been tested for output power, phase and performance at full reflection under any phase angle. The PA modules are fed with 50 V DC power from a COTS power supply through capacitor boxes which store the pulse energy. The control system consists of: 1) the main board with central microprocessor to control system behaviour and communicate with the master control system; 2) a 12-channel active splitter with amplitude and phase shifters for each channel and RS485 channel for data transfer between the PA modules and the main board; 3) peripheral board to provide control and monitoring of supplementary components like water flow meters.

HIGH POWER TESTS

The schematic diagram of the assembled cabinets for test and measurement is shown in Fig. 2. Minor connections are not shown. The amplifier cabinet was assembled as intended for the 400 kW amplifier. Auxiliary (test) cabinet was used to place the AC power distribution and safety module (PDM), RF generator, and measurement equipment. Under normal conditions (not as a test set up) all of the 100 kW amplifier components would be contained within a single 19” cabinet.

Two directional couplers (DC1, DC2) were used for measurement of output power after the RF power combiner. The third directional coupler (DC3) was used to independently monitor output RF power from the RFM #1.

Measurement Results

The 100 kW pulse shape is shown on Fig.2. The flat top droop during the pulse is about 5%.

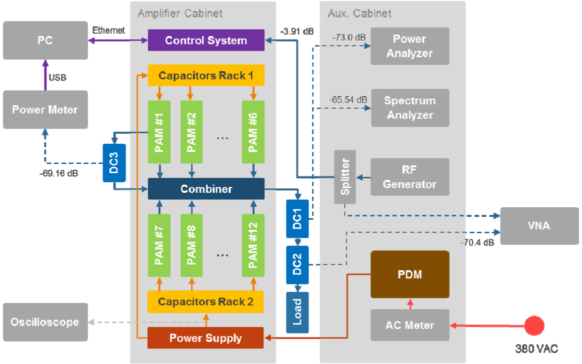
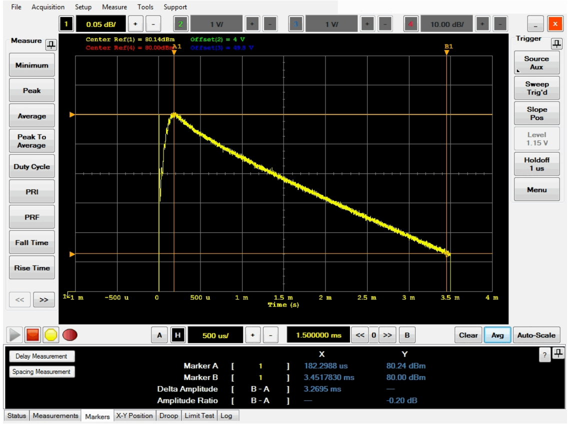


Figure 2: 100 kW SSPA test stand connection diagram.

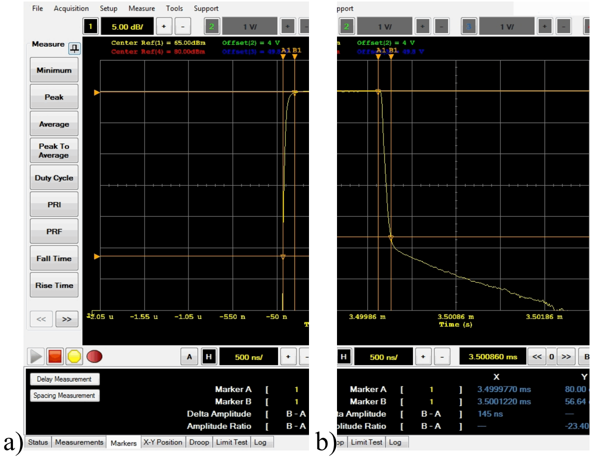
Close up views of the pulse leading and falling edges are shown in Fig. 3. Measured between 10-90 percentage points rise time is 100 ns and fall time is 36 ns (Fig. 4). The falling edge trailing tail is caused by RF generator behaviour.



```
Center Ref(1) = 80.14dBm     Offset(2) = 4 V
Center Ref(4) = 80.00dBm     Offset(3) = 49.8 V
```

```
                                  X                Y
Marker A         [   1   ]   182.2988 us       80.24 dBm
Marker B         [   1   ]   3.4517830 ms      80.00 dBm
Delta Amplitude  [ B - A ]   3.2695 ms         —
Amplitude Ratio  [ B - A ]   —                 -0.20 dB
```

Figure 3: 100 kW close up view of pulse top.



a)

```
Center Ref(1) = 65.00dBm     Offset(2) = 4 V
Center Ref(4) = 80.00dBm     Offset(3) = 49.8 V

Marker A         [   1
Marker B         [   1
Delta Amplitude  [ B - A
Amplitude Ratio  [ B - A
```

b)

```
Offset(2) = 4 V
Offset(3) = 49.8 V

                                X                 Y
Marker A         [   1   ]   3.4999770 ms      80.00
Marker B         [   1   ]   3.5001220 ms      56.64
ta Amplitude     [ B - A ]   145 ns            —
plitude Ratio    [ B - A ]   —                 -23.40
```

Figure 4: Pulse leading (a) and falling (b) edges.

Gated measurements with an external trigger were used for amplifier output spectrum curve acquisition. To obtain real values of harmonic amplitudes the traces from the spectrum analyser were stored in numerical format. Then the directional coupler dependency of coupling coefficient on frequency was applied to the stored spectrum. The result is shown on Fig. 5. The harmonic values are better than -49 dBc and the spurious measured are better than -65 dBc.

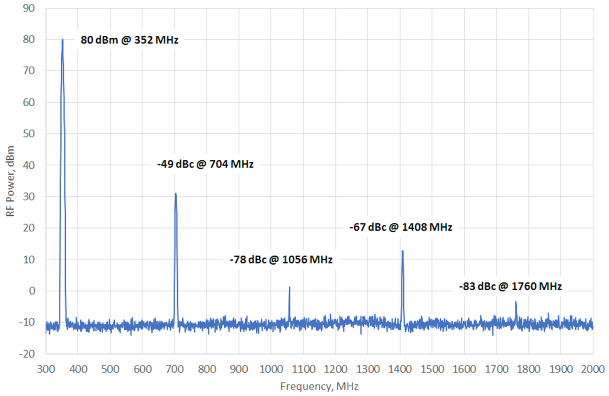


Figure 5: Amplifier output spectrum at 100 kW from 300 MHz to 2 GHz.

Dependencies of the amplifier behaviour are presented in Fig. 6. Achieved RF amplifier gain is better than 75 dB for 10-100 kW output RF power range. Extrapolating this value to four cabinets, the expected value of gain for a 400 kW amplifier will be higher than 81 dB. This value is 4 dB lower than that required in the ESS specification. Therefore, some modification of the amplifying scheme inside the CS or RFM is required to meet the specification.

The amplifier -3dB bandwidth is ±15.5 MHz.

The DC efficiency of the amplifier was derived from the average DC power consumption at the output of the 50 V power supply and the average output RF power (see Fig. 2). At 100 kW output RF power, the measured DC efficiency is 55% (see Fig. 6).

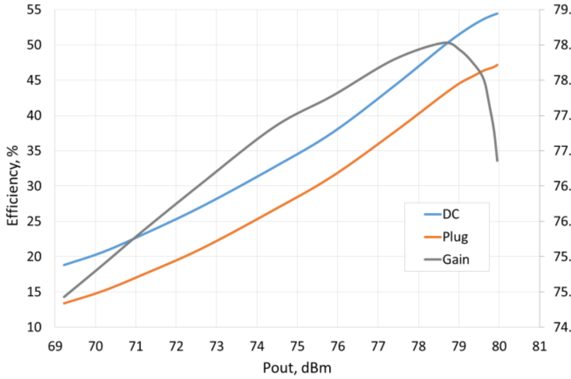


Figure 6: RF amplifier dependencies of Gain, plug and DC efficiency vs. Pout.

The wall plug efficiency of the amplifier was calculated based on the measurements of the AC power meter which includes the consumption of all the SSPA subsystems, including power supplies, control system, valves, detectors, etc. The plug efficiency (average AC power consumption over average RF power output) measured for 100 kW peak power is 47% (see Fig. 6). The lower value compared to DC efficiency is caused by the efficiency of the 50 V PSU (about 93%) and several sources of continuous power consumption, like control system, water valve, main contactor, PSU internal controllers, etc.

CONCLUSION

The novel architecture of SSPA has been developed and validated on a high power pulsed prototype. The system is very compact: 100 kW obtained from one 19” cabinet (0.6x0.6 m^2). The efficiency measured from the wall plug is competitive with vacuum tube based devices. High modularity and redundancy of the system gives the ability to operate with broken modules without any stops or power degradation giving excellent overall availability. During testing the system has operated without circulators. No significant imbalances between PA modules have been seen.

The following results were achieved:

- Output power up to 104 kW for 3.5 ms pulses at 5% duty cycle
- Plug efficiency of 47% at 100 kW of RF power
- Gain of > 75 dB
- Harmonics are less than -49 dBc (< -35 dBc required)
- Spurious are less than -65 dBc (< -60 dBc required)
- -3dB bandwidth is ±15.5 MHz (> 250 kHz required)
- Pulse rise time is 100 ns, fall time is 36 ns (< 2 µs rise time required)
- Pulse droop during 3.5 ms pulse is about 5% (±1 dB required)
- Phase stability during 3.5 ms pulse is ±1° (±5° required)
- Operation without circulators

To meet the specification for all points the following activity will be performed:

- Efficiency increased with optimization of continuous power consumption is possible.
- Some modification of the amplifying scheme inside the Control System or RF Modules can increase the gain value.
- Gain linearity can be improved with improved schematic.

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