

## 2 kW BALANCED RF POWER MODULE FOR A 30 kW SOLID-STATE PULSED RF POWER AMPLIFIER AT 352 MHz

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### Abstract

Design and development of a 30 kW, 352 MHz pulsed RF solid-state power amplifier to be utilized for feeding re-bunching cavities in proton linac, is in progress at ESS-Bilbao. This modular transmitter is based on in-phase combination of compact, water-cooled 2 kW RF power modules, each one consists of two combined LDMOS transistors in balanced configuration. The modules include individual bias control, measurement and supply circuits. Gate modulation is foreseen to increase efficiency in pulsed regime that is up to 3ms RF pulse width and 10% duty cycle. The 2 kW RF power module has been developed and the test results are discussed.

### INTRUCTION

In linear accelerators, RF structures often require power levels in the order of MW peak power that practically limits the available options for RF sources to vacuum tube amplifiers with current transistor technology and realistic space limitations. However, due to the advantages of Solid-State Power Amplifiers (SSPAs), they are preferred wherever the required power permits. One of such applications is to feed buncher cavities in Medium Energy Beam Transport (MEBT) section in a proton LINAC, where the RF power needed is 20 to 40 kW peak power and is well justified to use SSPAs instead of RF tubes.

In CW regime, high power solid-state amplifiers have demonstrated reliable operation in synchrotron light sources [1, 2], but employing SSPAs in heavy particle accelerators where long RF pulses and low repetition rates are applied is still to be examined in practice since some considerations due to temperature and power cycling in LDMOS RF power transistors and its effect on transistor life time might be of concern [3].

### 2 KW BALANCED AMPLIFIER

A 2kW High Power Amplifier (HPA) as building block for construction of 30 kW amplifier has been designed and fabricated. This amplifier is based on balanced combination of 2 single ended 1 kW amplifier by means of 90° compact coaxial hybrid couplers. This design provides the advantages of balanced configuration such as better stability and wider bandwidth in a compact structure. Also due to its good input/output matching impedance and good stability, the output circulator for each unit amplifier can be omitted. Since many unit amplifiers are usually used to construct a high power SSPA, eliminating circulators and their mating 50 ohm loads will reduce cost, complexity and power loss in the system.

The unit amplifier design is based on NXP LDMOS transistor BLF578 that can deliver more than 1kW peak RF power with high reliability in pulsed applications. It can also be substituted by BLF578XR to ensure the ruggedness of amplifier against unwanted power reflections in absence of output isolator.

Figure 1 shows the prototype of 2 kW HPA module. The space between two unit amplifiers is reserved for DC power distribution, current sensors and temperature compensation circuit.

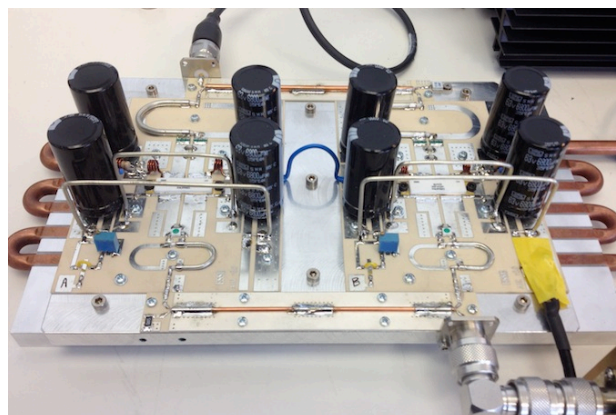


Figure 1: 2kW balanced HPA prototype.

Final dimensions of the 2kW module including DC and local control circuits will be 260x200x70mm. Table 1 shows specifications and measurement results of the HPA.

Table 1: 2kW HPA Specifications

Frequency	352 MHz	
Output Power	2000 W	No compression
Efficiency	58%	Continued gate bias
Bandwidth	40 MHz	±0.25dB
Gain	21.3 dB	
Input Return Loss	29.7 dB	@ 352 MHz
RF Pulse Width	≤ 3 ms	
Repetition Rate	≤ 30 Hz	
RF Pulse Droop	0.23 dB	In 1.5ms pulse
	0.41 dB	In 3 ms pulse

### Gate Modulation

In pulsed RF applications, duty cycle is typically low, so during large percentage of the time, drain quiescent current just turns to heat dissipation thus lowering the

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efficiency. Especially when linearity in wide dynamic range is needed, as a solution the quiescent current should be set high (moving towards class A operation), this can significantly reduce the amplifier efficiency. In this case, gate modulation will be inevitable.

Measurement results on 1kW unit amplifier show with 300mA total drain quiescent current ( $I_{DQ}$ ) and 4.5% duty cycle, gate modulation can increase efficiency by 10% while with 40mA  $I_{DQ}$  efficiency improves by only 1%.

### DC Distribution and Local Control

A single 50V DC voltage is distributed for all HPAs. Inside modules, low power linear regulators provide low voltages to supply current sensor ICs and other circuits.

A temperature compensated gate bias is foreseen to set the amplifiers at class AB with adjustable drain quiescent current. This bias circuit can provide either CW or pulsed modulated bias voltage by means of external trigger/command signal coming from global control and timing system.

Total 68mF storage capacitors with low equivalent series resistor (ESR) are used for each HPA module to maintain DC voltage during the pulse width, ensuring reasonable RF pulse droop (0.4dB in 3ms pulse).

### Performance

Two different 1kW unit amplifiers have been designed and developed, one based on 50 ohm input/output baluns and the other using 25 ohm semi-rigid coaxial cables as balun. The latter showed better performances and was chosen for assembling 2 kW HPA module.

Gain and efficiency have been measured with  $I_{DQ}=50\text{mA}$  for each transistor with continues DC bias and without gate modulation. RF pulse width was 1.5ms with 4.5% duty cycle. Results are shown in Fig. 2.

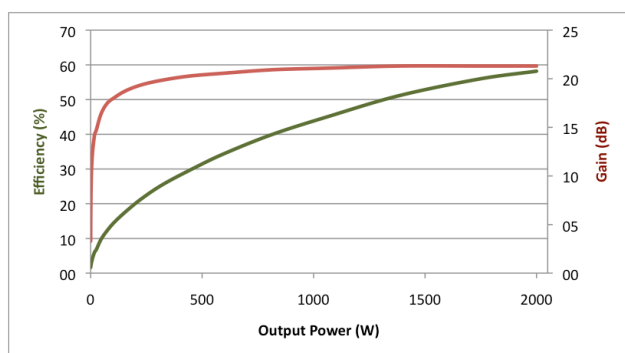


Figure 2: Measured gain and efficiency of the 2kW balanced amplifier,  $I_{DQ}=100\text{mA}$  total, no gate modulation.

As it was expected from balanced amplifier architecture, test results show good performances in terms of bandwidth, input/output matching impedance and stability. Also the combination is less sensitive to transistor parameters tolerances. Gain variation in 40MHz bandwidth has been measured as low as 0.5 dB ( $\pm 0.25\text{dB}$ ) and input return loss in the centre frequency is 29.7dB while the measured value for each single-ended unit amplifier was 19dB.

Having a low quiescent current as 100mA for the 2kW module, without gate modulation the efficiency is acceptable but linearity may not be satisfied within large dynamic range of input power. In this case, for 20dB change in input power, the gain will vary 14dB, which is not suitable for some applications especially when there is no compensation loop in system. In the same dynamic range, the input/output phase changes by  $\pm 3^\circ$  (Fig. 3)

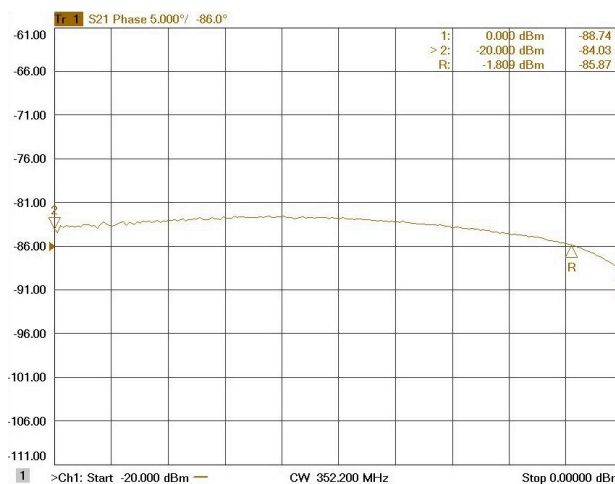


Figure 3: Phase variations within 20dB input dynamic range for 2kW amplifier ( $5^\circ/\text{div}$ ).

To reduce variations of gain and phase within the dynamic range, the most convenient way would be to increase drain quiescent current, nevertheless there will be a compromise between linearity and efficiency.

The rise time of RF pulse was also measured (Fig. 4). RF reaches to 2kW peak power in 50ns. If the amplifier is in gate modulation mode, DC should be on 50 $\mu\text{s}$  before RF pulse to ensure flatness and stability of the bias voltage in the presence of RF signal.

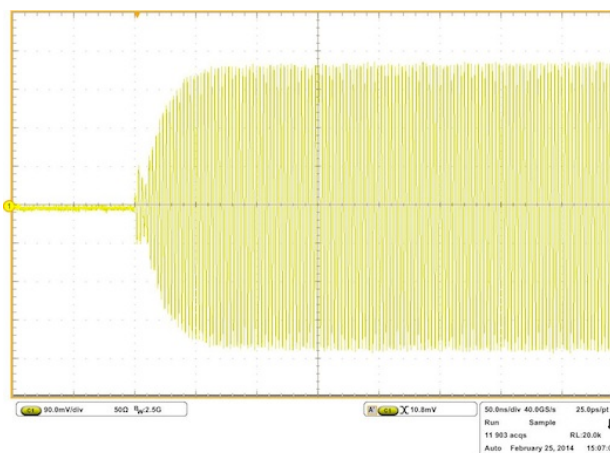


Figure 4: RF pulse rise time for 2kW amplifier ( $50\text{ns}/\text{div}$ ).

## 30 kW AMPLIFIER PLAN

Development of a 30kW amplifier is under way at ESS-Bilbao for feeding re-bunching cavities in the MEBT section of proton linear accelerator. Three of such RF cavities working at 352.2 MHz will be accommodated in

this section and their main task is to maintain longitudinal focussing on the 3MeV particle bunches coming from Radio Frequency Quadruple (RFQ) and to match the beam between RFQ, MEBT and Drift Tube Linac (DTL). RF peak power needed for each cavity is between 15 to 20kW with maximum 3ms pulse width and 5% duty cycle. To be on the safe side and considering RF distribution loss and regulation overhead, the developed amplifier will be capable of delivering 30kW peak RF power at 1dB compression point. This amplifier can also be utilized as driver for tetrodes and the 2kW HPA modules are good options to be used as predriver for IOTs.

The amplifier is made up of two 17kW sub-amplifiers, each one consists of 10 HPA (2kW balanced modules) and 10-way divider and combiner (Fig. 5)

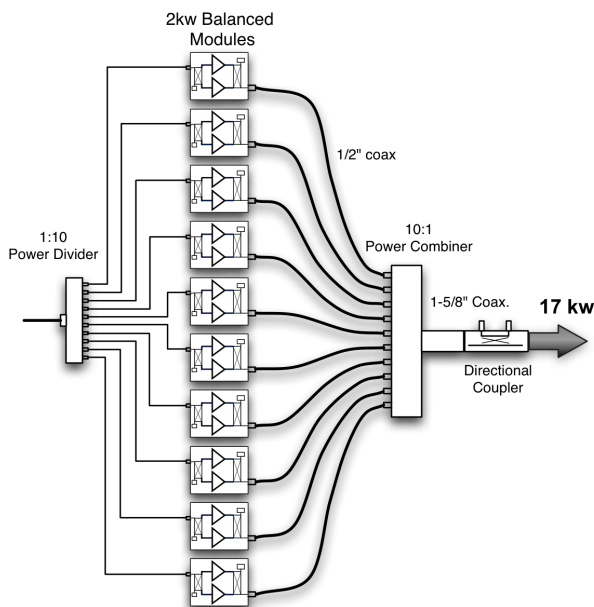


Figure 5: 17 kW sub-amplifier block diagram.

The design of 10:1 in-phase power combiner is based on Gysel combiner in order to have good isolation between HPA modules.

30 kW RF power will be obtained by combining two 17 kW amplifiers by a 2:1 radial power combiner with matching section. (Fig. 6). Since any fault in the 600W driver can shut down the whole transmitter, to increase reliability, a backup amplifier is foreseen in the 600W driver unit. The same HPA module will be used as driver but hybrid couplers will be replaced by high-speed RF switches that can change the driver amplifier through a hard wire interlock control within microseconds in case of transistor failure.

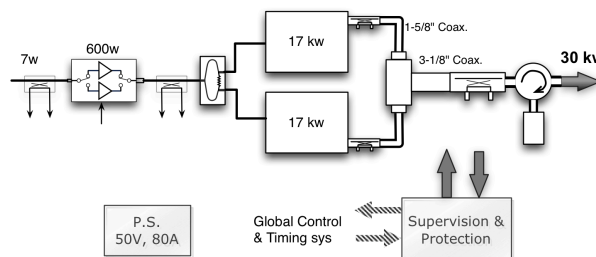


Figure 6: 30 kW Amplifier block diagram.

## Cooling

The amplifier is water-cooled and each two HPA modules are mounted on a water heat sink, back to back. In normal operation with 5% duty cycle, the total amount of heat dissipation to be removed by cooling system will be some 1500W. By using water-cooling instead of forced-air, the amplifier will be compact and can be implemented in a 19" rack as well as having more stable gain and output power and improving the transistors life time by decreasing junction temperature.

## CONTROL SYSTEM

The 30 kW amplifier control and interlock system comprises of DC current and voltage measurements (inside HPAs), RF power and pulse width measurement, fast electronic interlock circuits and timing system. These signals will be connected to a NI cRIO with four 16 channel analog input modules and two 4 channel high speed digital I/O, for monitoring and control both locally and remotely.

## CONCLUSION

Utilizing 2 kW balanced amplifiers shows to be a good trade-off between size and modularity for construction of high power solid-state amplifiers. It also improves the amplifier performance in terms of bandwidth, output power degradation (in case of transistor failure), efficiency and stability.

A 30 kW pulsed RF power amplifier utilizing such HPA modules is discussed. This amplifier will be implemented in a 19" rack including its power combiner, power supply and control/interlock system. It can be utilized for feeding buncher cavities in a proton linac as well as predriver for some RF vacuum tube amplifiers.

## REFERENCES

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