DEVELOPMENT OF A RANGE OF HIGH PEAK POWER SOLID-STATE AMPLIFIERS FOR USE IN THE HEAVY ION LINAC AT JINR, DUBNA

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Abstract

A range of LDMOS based amplifiers rated for up to 340 kW peak power and operating at 100.625 MHz were developed for use as RF sources for driving cavities in the Heavy Ion Linac (HILac) at JINR, Dubna. The final solution had to be compact and competitive while addressing technical challenges such as phase and amplitude stability, long term reliability, reflected power handling and serviceability. Design considerations and performance results are presented.

INTRODUCTION

As part of the Nuclotron-based Ion Collider Facility (NICA) under construction at JINR, Dubna, a new Heavy Ion Linear Accelerator (HILac) has been developed by Bevatech GmbH. HILac comprises a 4-Rod-RFP and two 1H-drift tube cavities. These cavities are driven by all solid-state high power RF amplifiers designed and manufactured by Tomco Technologies: one at 140 kW and two at 340 kW.

TECHNICAL OVERVIEW

The key technical specifications of the amplifiers are listed in Table 1.

Table 1: Key Amplifier Specifications

Frequency	100.625 MHz ± 1.5 MHz
Peak Output Power	140 kW and 340 kW pulsed
Pulse Width	200 µs
Maximum Duty Cycle	0.2%
Gain and Phase Stability within the pulse	<0.1 dB and <1° over the last 40 µs of the pulse
Gain stability long term	<0.2 dB change over 5 hours
Load Transients	Withstands 100% reflection at full rated power for at least 100 µs

The design of these systems incorporates several levels of modularity which allow for operation in partial failure mode, simple servicing, and optional built-in redundancy.

The required power levels are achieved by combining multiple amplifier sub-systems in parallel via custom designed high power Wilkinson combiners. The base amplifier sub-system is rated for 36 kW PEP and is the same across all the systems thus simplifying spares holding. The 140 kW system consists of five amplifier subsystems; the 340 kW system consists of eleven.

Each 36 kW amplifier unit comprises six 8-channel LDMOS power amplifier modules rated for 6 kW PEP, a driver, a 6:1 combiner and logic/control circuits. Fig. 1 shows an internal view of a 36 kW amplifier chassis.

In addition to the amplifier sub-units, each system includes a central interface/control unit, switched mode power supply units and a final output combiner and dual directional coupler.

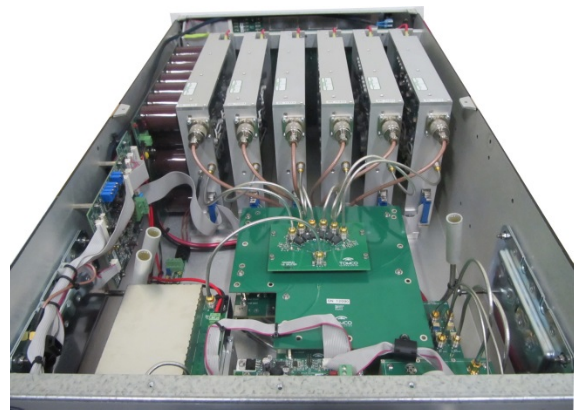

Figure 1: Internal View of 36 kW Amplifier Unit.

DESIGN CONSIDERATIONS

Reflected Power Handling

A key design requirement is that the amplifiers must be capable of operating at full output power during events of high reflection (up to 100%). Such events occur repeatedly in normal operation when the cavity is filled at the start of each pulse, and also during any anomalous events such as cavity arcs. Although circulators are an option at 100 MHz, they are physically large, expensive and thermally unstable. The design effort, therefore, aimed to produce an amplifier intrinsically rugged enough to remain stable and well behaved under all load conditions at full power.

Power Amplifier Design

Although the latest LDMOS transistors are electrically extremely rugged, they can still be damaged if the die temperature is permitted to exceed its specified limits. In this application, the pulse width and duty cycle were so low that thermal considerations were minimal, and there was no risk of overheating the silicon die despite the very large peak heat dissipation that could occur during full-power mismatch events. This made it possible to fully exploit the electrical ruggedness of the LDMOS devices and design the amplifiers to withstand high reflection events without the use of circulators.

A carefully designed negative feedback circuit, along with approximately 1 dB of resistive attenuation in the

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output path of each transistor, ensured minimal gain variation and complete stability under all load conditions.

The low duty cycle permitted a very high power density to be achieved. Eight 1.25 kW transistors were combined on each PA module via an on-board L-C Wilkinson network to comfortably produce a nominal output of around 6 kW.

Output Combiners

The 140 kW and 340 kW systems required output combiners of 5:1 and 11:1 respectively. Both Wilkinson and Gysel topologies were considered, with the Wilkinson being favoured due to its greatly reduced complexity and low parts count. However, in contrast to the Gysel, the balancing resistors in a Wilkinson are "live" and float at the full potential of the RF inputs. This presents a challenge since any stray capacitance between the resistors and ground results in increased insertion loss and poor isolation between combiner inputs. This problem was exacerbated by the fact that due to the very high power levels involved, the balancing resistors needed to be physically quite large.

To meet the basic requirements of high voltage and power handling, the combiner resistor network was constructed using large tubular carborundum resistors suspended inside a tank filled with silicone oil. However, the effects of stray capacitance between the live resistors and the metal walls of the oil tank resulted in very poor performance.

Several schemes aimed at reducing this stray capacitance were modelled and prototyped. Acceptable results were finally achieved using an arrangement of "active shielding" around the resistors. This consisted of a conductive plate placed adjacent to each resistor body, connected to the "live" common node end of the resistor array (see Fig. 2)

Figure 2: Combiner Balance Resistors with Shielding.

Since the plates were at the same potential as the resistors, no capacitive current flowed through the resistors to ground. The now lossless stray capacitance between the active shield plates and the metal wall of the tank was easily tuned out using an inductor. The performance of the combiner was greatly improved, as shown in Fig. 3

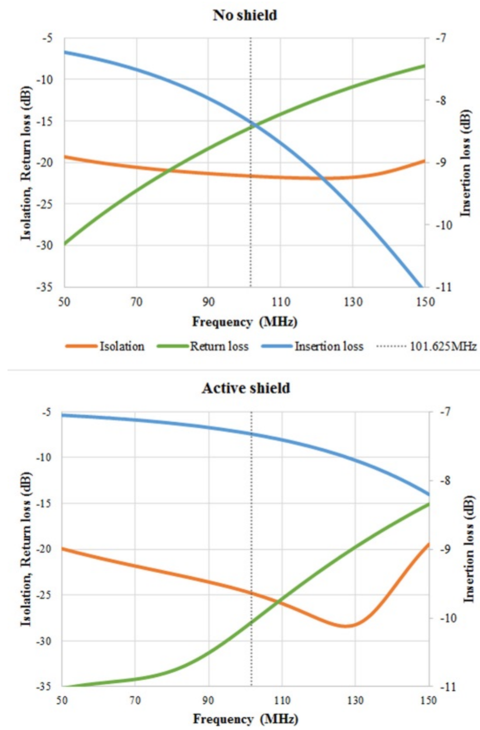

Figure 3: Return Loss and Insertion Loss of Final Output Combiner using Shielded and Unshielded Resistors.

The combiner output impedance match, 5:1 for the 140 kW and 11:1 for the 340 kW, was implemented as a transmission line impedance transformer constructed using standard EIA rigid line outer, with a stepped diameter inner conductor carefully designed to maintain a safe voltage gradient at all points along its length. An oil reservoir and expansion tank (with safety valve) keep the high voltage sections of the combiner filled with oil while avoiding any pressure build-up. A photograph of the complete 340 kW combiner is shown in Fig. 4.

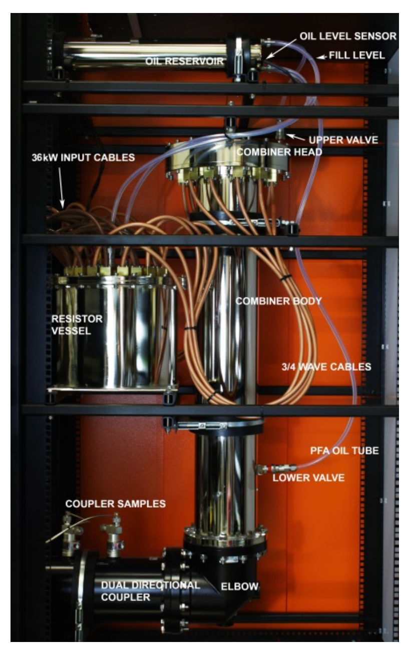

Figure 4: 340 kW Output Combiner.

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RESULTS

System Performance Results

Fig. 5 shows the gain and phase variation over a 30 dB power range for the 340 kW system. Gain flatness from 10% to 90% of full rated power is within the specified linearity requirement of <3 dB.

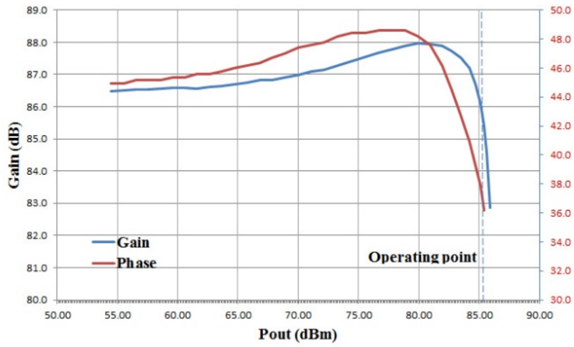

Figure 5: Gain and Phase as a function of Output Power.

A key specification is the amplitude tilt over the last 40 µs which must be <0.1 dB. Fig. 6 shows an RF pulse captured while operating the 340 kW system into a 1H cavity. The yellow trace shows the amplifier forward voltage, the blue trace shows the cavity reflected voltage and the red trace shows the cavity forward voltage.

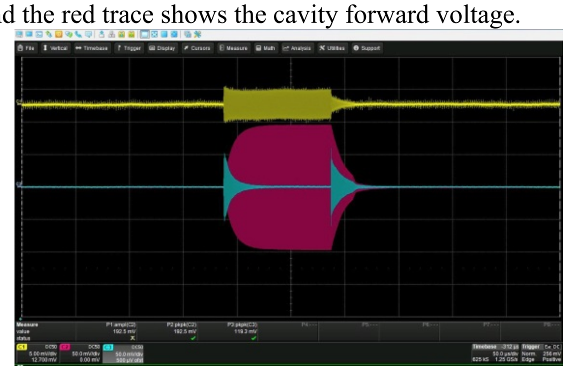

Figure 6: Amplifier and Cavity Voltage Waveforms.

Fig. 7 shows the long term gain stability measured over 15 hours.

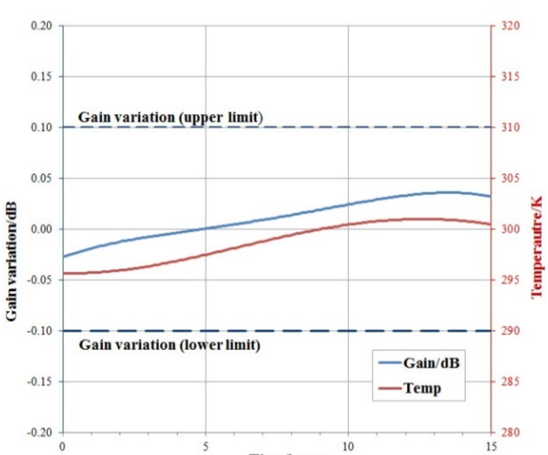

Figure 7: Gain and Ambient Temperature over Time.

Contemporaneous measurement of ambient temperature indicated that the very small gain change observed was most likely due to variation in ambient temperature. The gain variation is still comfortably within required limits.

RF Testing and Commissioning

The amplifiers were pre-tested in the Factory Acceptance Tests with full power into a water load and a calibrated bi-directional coupler. Power consumption for each amplifier versus output power was validated. In addition, a cavity with a Q factor of around 7000 was used as a load to test sensitivity and behaviour in the matched and unmatched case. In a stress test, all three amplifiers were driven with 5-10% excess power. Long term stability tests at 90% full power were performed over 2 days.

At JINR the three amplifiers were positioned one floor above the Linac as a gallery (see Fig. 8).

Figure 8: Front and Rear Views of Amplifiers.

The connections to the cavities were made with 6-1/8" rigid lines having significant headroom for higher power levels. After installation of all amplifiers, connections to LLRF system, rigid lines and HILac cavities at JINR, the pre-conditioned cavities were fully conditioned. During this process RF power was gradually increased whilst maintaining minimum reflected power. After multipacting barriers had been eliminated and outgassing decreased, more RF power was fed into the cavity. These processes took about 1-2 days per cavity.

The rugged mismatch performance of the solid-state amplifiers was clearly demonstrated in tests involving turning the amplifiers on and off at different power levels instantaneously. Even in test cases with enforced mismatch producing higher reflection, all RF amplifiers operated continuously at full performance. During the HILac commissioning in October [1], all amplifiers ran without failure or downtime.

REFERENCES

[1] A. M. Bazanov et.al, "Commissioning of the New Heavy Ion Linac at the NICA Project", Proceedings of RuPAC2016, St. Petersburg, Russia