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THE MESA 15kW CW 1.3 GHz SOLID STATE POWER AMPLIFIER PROTOTYPE*

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Abstract

The Mainz Energy recovering Superconducting Accelerator MESA is a multi-turn energy recovery linac with beam energies in the 100 MeV regime currently designed and build at the Institut für Kernphysik (KPH) of Johannes Gutenberg-Universität Mainz. The main accelerator consists of two superconducting Rossendorf type modules, while the injector MAMBO (MilliAMpere BOoster) relies on normal conducting technology. The high power RF system is planned completely in solid state technology. With the high power demands of the normal conducting RF cavities up-to-date transistor technology with increased power density has to be used.

A 15 kW CW power amplifier prototype with the new technology has been developed by Sigma Phi Electronics and delivered to KPH. In this paper we will present the results of the performance measurements of the amplifier.

INTRODUCTION

The multi-turn energy recovery linac (ERL) MESA (Mainz Energy recovering Superconducting Accelerator) is going to be dedicated to particle physics experiments in the low energy regime of some 100 MeV. There will be two main experimental setups at MESA: MAGIX (MESA Gas Internal target eXperiment) [1] and the external target experiment P2 [2].

The P2 experiment measures the weak mixing angle from parity violation of polarised electrons scattered on a fixed target. While MAGIX measures the proton radius and searches for dark photons by scattering electrons on an internal gas jet target.

For MAGIX, MESA will be operated in energy recovery (ER) mode at beam energies of up to 105 MeV with beam currents of up to 1 mA. For P2, in external beam (EB) mode, at maximum 155 MeV with up to 150 µA will be supplied. In a later project stage, the ER mode beam current shall be upgraded to 10 mA.

The MESA lattice uses a double sided design, where the two superconducting radio frequency (SRF) modules of the main linac are placed in both long straight sections [3,4]. The design of the SRF modules follows the design of HZDR [5], but with some specific modifications [6, 7].

The injector MAMBO is a 1.3 GHz normal conducting, room temperature (RT) linac in bi-periodic on-axis configuration [8–10]. It accelerates the beam to an energy of 5 MeV and will be able to provide up to 10 mA. The first RT RF-section is a graded-β section, the following three sections have a constant β.

MESA RF SYSTEMS

The MESA RF systems have to fulfil quite different power needs. While the superconducting SRF cavities in principle need to be powered with just 5.6 kW of beam loading per cavity in EB mode and provide some power during ramp up of the beam current in ER mode, the injector has to be fed with the beam power and the ohmic losses of the copper. This adds up to roughly 50 kW to 70 kW per RF-section.

Following an in-depth review of the available technologies [11], solid state power amplifiers (SSPA) have been chosen for powering both SRF as well as RT RF cavities.

In an SSPA several transistors are used in parallel to amplify the input signal. Therefore the signal is split and distributed to the transistors and recombined after amplification. In order to keep a reasonable signal-to-noise ratio the input signal is amplified in a pre-amplifier stage before splitting. It is clear that for an optimum power combining the length of all signal paths have to be the same. For a block diagram of a typical SSPA see Fig. 1.

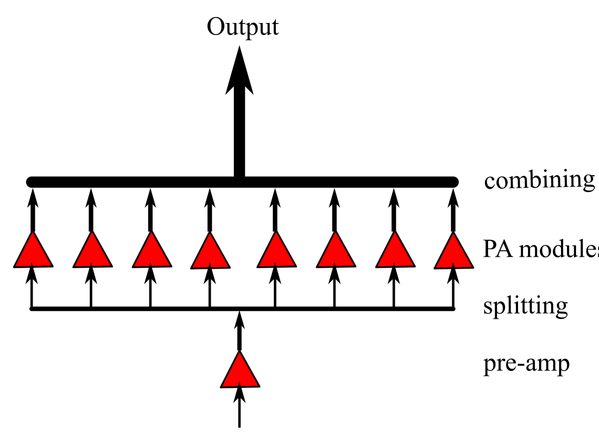

Figure 1: Block diagram of a solid-state power amplifier.

After a call for tenders for a 15 kW prototype, the contract was awarded to Sigma Phi Electronics (SPE) beginning of 2016. The amplifier has been delivered to Mainz last October. The RF specification of the prototype as given by KPH in the tender documents can be found in table 1. Additionally the specification asked for a variable drain voltage to optimise efficiency in part load operation by adjusting the working point of the transistors and thus the 1 dB-compression point (P1). Further the specification defines a maximum footprint area of the high power amplifiers for MAMBO. Since

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Table 1: Specification of the MESA 1.3 GHz Solid State Power Amplifier Prototype as given by KPH in the tender documents.

Frequency	1300 MHz
Bandwidth	±5 MHz
P1 output power	15 kW CW
Gain flatness:	
- over power (@ f_0)	$< \pm 1$ dB
- in bandwidth (P_{out} = const)	$< \pm 0.3$ dB
Phase flatness:	
- over power (@ f_0)	$< 10°$
- in bandwidth (P_{out} = const)	$< 10°$
Phase noise	$< \pm 0.01°$
Amplitude noise	$< 10^{-4}$
Harmonics (@ P1)	< -45 dBc
Spurious (@ P1)	< -60 dBc
S/N within bandwidth	< -70 dBc
VSWR (input)	1.5 (max.)
VSWR (output)	1.5 (max.)
Pulse operation:	
Rise/fall time	< 100 ns
Pulse droop (100 µs, 50% d.c.)	<10%

all SSPA at MESA shall use the same RF-modules, a new transistor type with higher power density made by Infinion (PTVA127002EV) had to be employed.

The prototype consists of eight amplifier modules with 2 kW each. A module is build up from four RF-pallets each populated with a single 500 W transistor. Limiting the power per module to 2 kW has two advantages: the modules are relatively small, light weight and easy to handle and SPE was able to reuse the design of wave guide combiners used for projects of HZDR [12] and HZB. The modules are constructed for a fast exchange in case of failure, water and electrical connections are self-locking, only RF connectors (SMA and 7/16) need tools.

PERFORMANCE OF THE PROTOTYPE

During the factory acceptance the performance of the SSPA prototype was tested. The output power as a function of input power was measured at different drain voltages U_d. Additionally, the electrical power produced by the DC power supply was noted. Thereof transmission, gain, compression and efficiency were determined. A phase detector was used to measure phase behaviour as a function of power and frequency.

At the nominal drain voltage (U_d = 50 V) of this transistor type P1 is at ($P_{\text{in}} = -3.6$ dBm, $P_{\text{out}} = 71.6$ dBm), or ($P_{\text{in}} = 0.437$ mW, $P_{\text{out}} = 14.5$ kW) respectively. The gain at P1 is 75.2 dB. It does not differ more than ±1 dB with input power which is well within specification (see Fig. 2). The effciency is 46.7% at P1 (see Fig. 3).

In Fig. 3 the efficiency as function of output power at different working points of the transistors is shown. As one

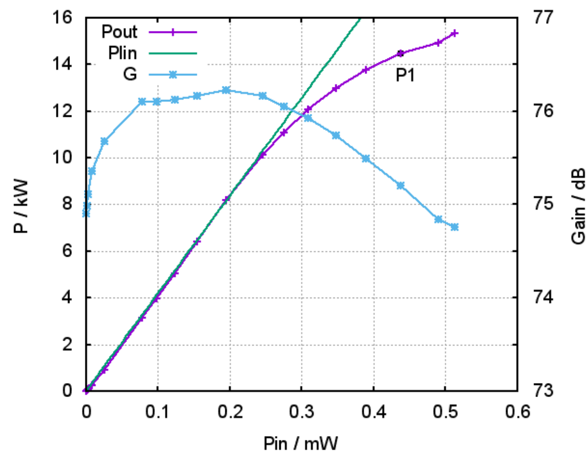

Figure 2: Output power P_{out} and gain G at U_d = 50 V and f_0 = 1.3 GHz as function of input power. The 1 dB compression point is marked in the transmission curve. A straight (P_{lin}) was fitted to P_{out} to guide the eye.

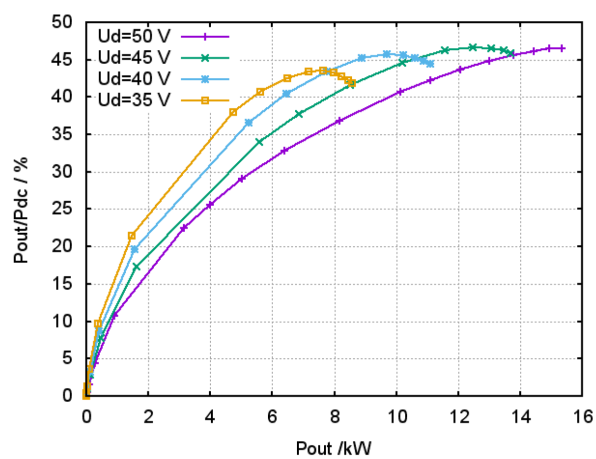

Figure 3: Efficiency of the SSPA at different drain voltages U_d. One can see that for low output power it can be sensible to reduce U_d to optimise the efficiency.

can easily see, in part load lowering U_d by 10 V to 15 V can increase the efficiency by about 10 %. Since beam loading per section in MAMBO may vary between some 100 W and some 10 kW, depending on the particular experiment, it can be quite sensible to reduce the power consumption of the RF system.

The phase transformation of the SSPA in dependence of output power as well as the slope of the phase transformation is shown in Fig. 4. From 4 kW to 15 kW the change of phase is within specification. This is acceptable, because 5 kW are needed to build up the nominal field gradient in the SRF modules due to the chosen Q_E. So beam operation at less power is not expected. And since there are no jumps in phase within the low power region operating the PA should be possible with regulation.

Gain and phase were measured over frequency (see Fig. 5) at $P_{\text{in}} = -3$ dBm, i.e. in saturation. The gain flatness is

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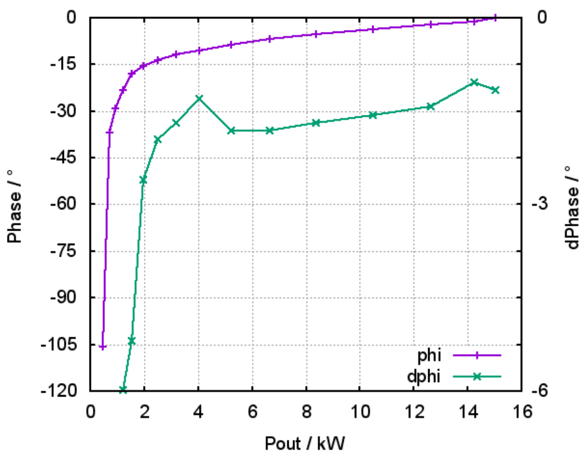

Figure 4: Relative phase (ϕ) and change of phase ($d\phi$) as function of P_{out} at 1.3 GHz and $U_d = 50$ V. The phase at maximum power was chosen as reference phase.

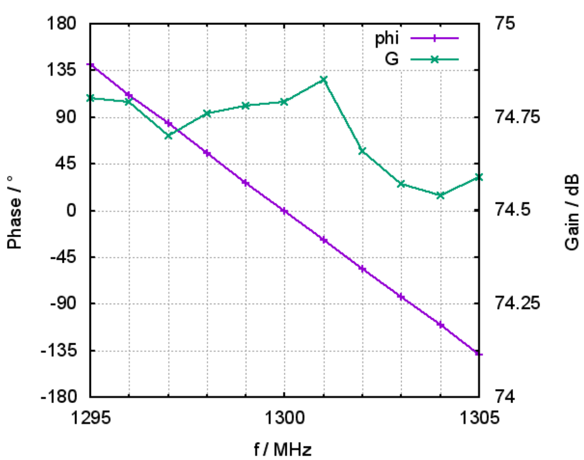

Figure 5: Gain G and relative phase ϕ at $P_{in} = -3$ dBm and $U_d = 50$ V with frequency. The phase was referenced to the phase at 1300 MHz.

well within specification. The phase flatness exceeds the specified change, but shows a linear behaviour which should therefore not be a crucial problem. Phase noise was 0.2° with spikes to 1° a 5 kHz rate, thus exceeding specification. The phase noise was tracked down to the DC power supply (PS) purchased from MAGNA-Power. The specified ripple is not kept by the PS. SPE will replace the PS to allow operation of the SSPA in MESA. Due to the PS problems, short-term amplitude noise was not yet checked.

The unregulated long-term stability of P_{out} in thermal equilibrium was roughly ±100 W.

Harmonics of 1.3 GHz were found at $f_2 = -54$ dBc, $f_3 = -61.9$ dBc and $f_4 = -78.6$ dBc. The side-bands to the fundamental from rectification are below −43 dBc.

Pulse operation has not yet been tested.

SUMMARY & OUTLOOK

The SSPA has been tested with a dummy load. The performance in general is well within specification. Some flaws were found during factory acceptance that have been already corrected by SPE. The DC power supply, which spoils the short-term stability of the SSPA, will be exchanged by SPE. Tests with real RF-sections, both SRF and RT RF, will take place in the second half of this year, then involving also pulse operation to commission the sections. So further operational experiences will be gained.

REFERENCES

[1] S. Baunack "Low energy accelerators for high precision measurements", *Electromagnetic Interactions with nucleons and nuclei conference (EINN20017)*, Paphos, Cyprus, Oct. 2017

[2] N. Berger, *et al.* "Measuring the weak mixing angle with the P2 experiment at MESA", J. Univ. Sci. Tech. China 46 (2016) 6, 481-487, arXiv:1511.03934

[3] R. Heine, *et al.* "Lattice and start to end simulation of the Mainz energy-recovering superconducting accelerator MESA", *IPAC'14*, Dresden, Germany, June 2014, MOPRO108, p. 346.

[4] D. Simon, *et al.* "Lattice and beam dynamics of the energy recovery mode of the Mainz energy-recovering superconducting accelerator MESA", *IPAC'15*, Richmond, VA, USA, May 2015, MOPWA046, p. 220.

[5] J. Teichert, *et al.* "RF status of superconducting module development suitable for CW operation: ELBE cryostats", NIM A **557** (2006) 239.

[6] T. Stengler, *et al.* "Modified ELBE type cryomodules for the Mainz energy-recovering superconducting accelerator MESA", *SRF'15*, Whistler, BC, Canada, Sept. 2015, THPB116, p. 1413.

[7] T. Stengler, *et al.* "Status of the superconducting cryomodules and cryogenic system for the Mainz Energy-recovering Superconducting Accelerator MESA", *IPAC'16*, Busan, Korea, May 2016, WEPMB009, p. 2134.

[8] R. Heine, K. Aulenbacher, "Injector linac for the MESA facility", *IPAC'13*, Shanghai, China, May 2013, WEPWA001, p. 2150.

[9] R. Heine, *et al.* "Further investigations on the MESA injector", *IPAC'15*, Richmond, VA, USA, May 2015, TUPWA045, p. 1515.

[10] R. Heine, *et al.* "Current status of the Milliampere Booster for the Mainz energy-recovering superconducting accelerator", *IPAC'16*, Busan, Korea, May 2016, TUPOW002, p. 1741.

[11] R. Heine, F. Fichtner "Concept of the high power RF systems for MESA", *IPAC'17*, Copenhagen, Danmark, May 2017, THPIK023, p. 4147.

[12] H.Büttig, *et al.* "16 kW upgrade of the 1.3 GHz ELBE RF-system with solid state amplifiers", *IPAC'11*, San Sebastian, Spain, Sept. 2011, MOPC128, p. 379