USING A 1.3 GHz 20 kW SOLID STATE AMPLIFIER AS RF POWER SUPPLY FOR DC-SRF PHOTO-INJECTOR*

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Abstract

R&D of a 1.3 GHz 20 kW CW solid state amplifier, which consists of 88 elementary modules with individual power supplies, has been carried out under the cooperation between BBEF (Beijing) and Peking University for the DC-SRF photo-injector. It has been installed and applied to the experiments of the DC-SRF photo-injector at Peking University since 2012. The structure, test with full power and full reflection, improvements and performance for long-term operation of this 20 kW solid state RF amplifier will be described in this presentation.

INTRODUCTION

The DC-SRF photo-injector which combines a DC Pierce structure and a superconducting cavity was firstly proposed by Peking University in 2001 [1]. The prototype of the DC-SRF photo-injector with a 1.3 GHz 1.5-cell superconducting cavity was constructed and preliminary experiments at 4.2 K demonstrated its feasibility in 2004 with the electron beam energy gain of about 1 MeV [2]. In the beam experiments of the prototype injector, a 4.5 kW solid state amplifier (SSA) was used. It was combined by eight unit modules and a dummy load cooled by water. Each module was supposed to deliver up to 600 W, which included four 150 W transistors. The designed output power was 4.5 kW but only 3.5 kW had been achieved finally.

After demonstrating the feasibility of prototype, we designed and constructed an upgraded DC-SRF injector with a 3.5-cell cavity. The designed beam power is 13 kW with beam current of 2.6 mA and energy gain of 5 MeV [3]. Taking into account the regulation reserve of 20% for phase and amplitude control and 6% for losses in the waveguide distribution, an amplifier with the output up to 18 kW is required. So a 20 kW CW amplifier at 1.3 GHz is needed. Table 1 shows the technical specification of the power amplifier.

There are three kinds of possible RF amplifiers, which are klystrons, IOTs and SSAs, can provide CW 20 kW RF power at 1.3GHz. The ELBE CW-LINAC employs four pairs of 10 kW SSAs to replace the 10 kW klystrons for the four superconducting 9-cell TESLA cavities in January 2012 [4]. The Cornell Energy-Recovery Linac (ERL) injector has two high power 1300 MHz RF systems, the first system is based on a 16 kW IOT transmitter to drive a normal conducting buncher cavity, and the second system employs five 120 kW klystron to feed 2-cell superconducting cavities [5]. ALICE at Daresbury Laboratory uses 5 IOTs from three different commercial suppliers [6].

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Table 1: Technical Specification of the Power Amplifier

Parameter	Required
Frequency Range	1300±0.05MHz
CW & Pulsed Output Power (1dB Compression)	⩾ 20 kW
Linear Gain	⩾73dB
Output Harmonics 2nd Order	⩽-30 dBc
Output Harmonics 3rd Order	⩽-30 dBc
RF Phase Shift vs. Output	⩽10°
Gain Change vs. Output	⩽2.0 dB
Efficiency at 20kW output	⩾40%

From the experience gained from our 1.3 GHz 3.5 kW SSA, we realized the advantages of SSA for small facilities such as high modularity with the associated redundancy and flexibility, elimination of high voltage and high power circulator, and simple start-up procedures and low maintenance cost. Especially at that time transistors with CW output power more than 200 W at 1.3 GHz were available from industry and the amplifier could be made in China. So we decided to manufacture a SSA under the collaboration with BBEF by the end of 2009.

STRUCTURE OF THE 1.3 GHz 20 kW SSA

Benefitted from the transistors with output power more than 200 W, the unit module which contains two transistors, a circulator and a terminal can deliver output power up to CW 350 W after its construction. The transistors (MRF6V13250H) are from freescale, and it is claimed each one can deliver up to CW 230 W at 1.3 GHz, and a little bit higher to 250 W in pulsed mode with length of 200 μs and duty factor of 10%. The custom made circulator (VBM1387) is from VALVO in Germany, its isolation is more than 25 dB, and full reflection with the CW power of 400 W is allowed. The terminal (Series 32-1209) is from Florida RF Labs and its power capability is up to 500 W. Each unit module is powered by its own power supply with the output voltage of 50 V and the current up to 14 A. The designed efficiency of AC to DC convertor is 92%.

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Figure 1 shows the overall structure of the SSA. It consists of 8 transistor banks. Each bank generates 3 kW and is decoupled by a coaxial-waveguide transition from 1 5/8 inch rigid line to WR650 waveguide, and in which, there are 11 elementary modules with individual power supplies and one module is used as a preamplifier to drive the other ten. Figure 2 is the photograph of the SSA, the big plates cooled by water with flow rate of 4.9 m^3/h at 4 bar are the transistor banks, the 350 W unit modules are mounted on the upper side and the 700 W AC to DC convertors are on the reverse side.

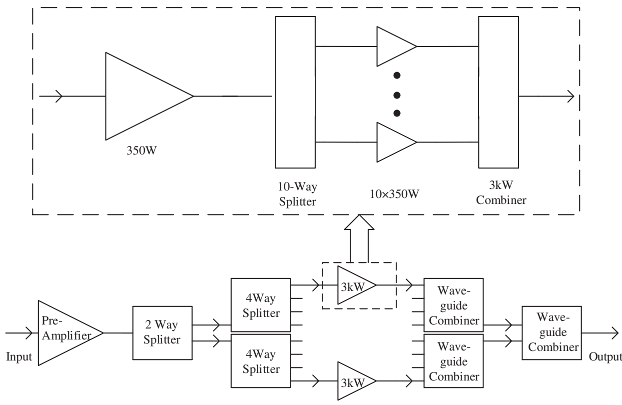

Figure 1: Structure of 20kW SSA.

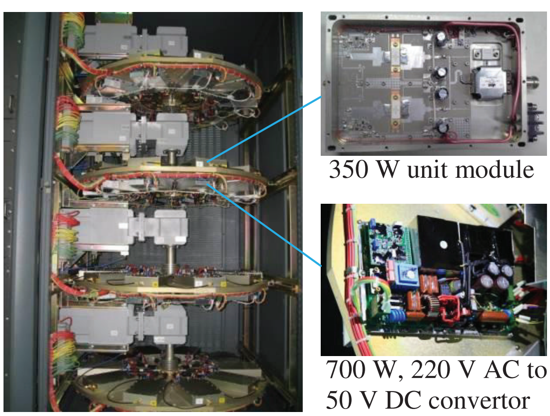

Figure 2: 1.3 GHz 20 kW SSA.

TEST AND RESULTS

After the accomplishment of the manufactory and factory test in BBEF, the SSA had been delivered to Peking University in the January of 2012. After installation, the tests of the amplifier including whether the basic parameters reach the designed values, long term performance with dummy load, full CW reflection, and the performance in pulse mode.

The results in detail are brought out in the following. The gain and output of the power amplifier is illustrated in Fig. 3, it can be seen the gain is larger than 85 dB and changes 1.6 dB from 1kW to 20kW. The phase shift changes 9.5° when the output power increased as shown in Fig. 4. The 3 dB bandwidth of the amplifier is more than 30 MHz, and it is much larger than typical 3 dB bandwidth of klystron and IOT. The drain efficiency of the SSA is 38% at 20 kW output and 25% at half power output. The efficiency of RF power, which is 34% at 20 kW output and 20% at half output, is a little lower. The second and third harmonics of the output RF signal are suppressed which are -68.9 dBc and -57.1 dBc respectively, while those of the input RF signal are -41.7 dBc and -49.7 dBc respectively. The long term stability of the amplifier was measured with the low level control system and the results of 5kW output and 17kW output are illustrated in Fig. 5 and Fig. 6 respectively. The temperature gradient of the power is ±0.8%/ °C, and we did not get the temperature gradient of the phase as the temperature of the coolant and the output power are both fluctuating during the measurements. We also measured the parameters of the amplifier in pulsed mode. The rising time of the input RF signal is about 54 ns, and the output is 64 ns. In delay measurement, the output signal is 386 ns later than the input signal, which includes the propagation time of 230 ns through coaxial cable with length of 45 m, the propagation time of 81 ns through the waveguide with the length of 17.5 m, so the delay of the amplifier is about 75 ns. The power consumed by the amplifier in pulsed mode was measured and there is a wall-plug power consuming of about 9 kW when the amplifier is only turned on but without RF output. This 9 kW is the quiescent power drain and it varies when the transistor works at different quiescent points. In our case, in order to maintain small gain fluctuation, the quiescent power drain is quite large and then limits the efficiency.

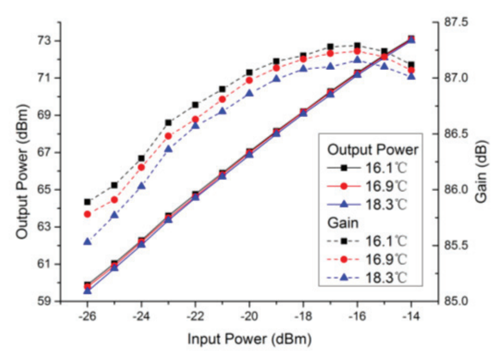

Figure 3: Output power and gain of the 20kW SSA.

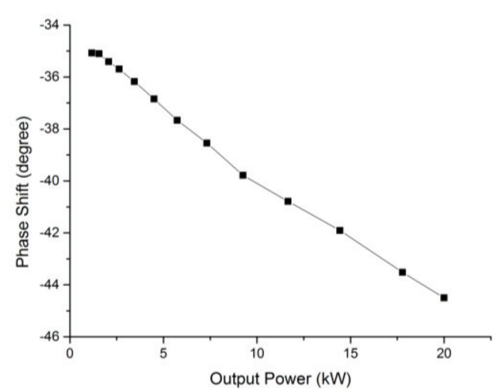

Figure 4: Phase shift of the 20kW SSA.

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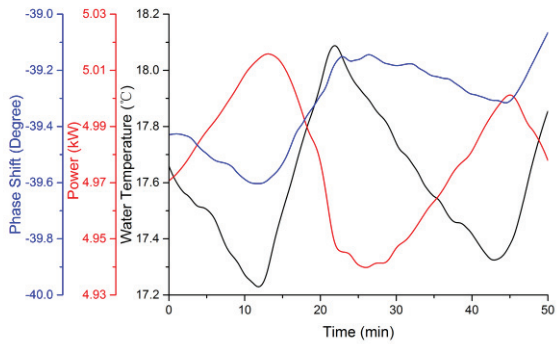

Figure 5: Stability measurements with 5 kW output.

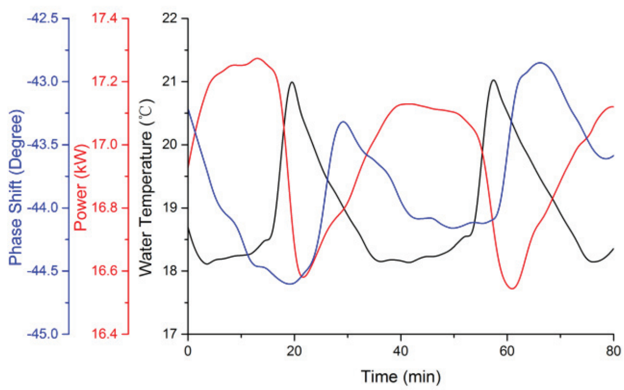

Figure 6: Stability measurements with 17 kW output.

IMPROVEMENTS AND PERFORMANCE

Because there is no large power circulator for the SSA but the full reflection may exist during the commissioning and even the operation of the DC-SRF photo-injector, we tested the SSA in full reflection with forward power of 20 kW. There were two problems during the full reflection test, one was a PTFE-support of a 1 5/8 inch rigid line was burnt and the other was one 3 kW transistor bank failed because the printed circuits near the output of the unit modules had cracked. Therefore, we realized the temperature monitoring of other components besides the unit modules is also important for the amplifier safety interlock to avoid breakdown of the SSA. And then we added temperature sensors on the eight coaxial-waveguide transitions. Stable operation of the SSA was then resumed and the amplifier sustained a test for ten minutes full reflection with CW forward power of 16 kW.

For the commissioning and operation of the DC-SRF photo-injector, a digital low level RF control system was constructed based on the FPGA and the results of the control system show the field instability is less than 0.1% (rms) for amplitude and 0.1° (rms) for phase. During the commissioning and routine operation of the DC-SRF photo-injector, the amplifier works well and has run for about 2000 hours without any big problem. Failures of a few transistors occurred (3 over 88) and the SSA was still delivering RF power. The eight spare unit modules made the replacement very easy.

CONCLUSIONS

A 1.3 GHz 20 kW CW SSA has been installed at Peking University. The efficiency of RF power is 34% with full output of 20 kW, the phase and gain various 9.5°and 1.6 dB respectively when output power changed from 1 to 20 kW and the temperature gradient of amplitude is ±0.8% / °C. Full reflection test was carried out with a short waveguide terminal, and the result is 16 kW over 16 kW in CW for ten minutes without problem. It has been used for routine operation of the DC-SRF photo-injector successfully since 2013.

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