DEVELOPMENT OF 12KW RF POWER SUPPLY FOR CYCHU-10 CYCLOTRON

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Abstract

A 12kW RF power supply has been developed for CYCHU-10 cyclotron. The signal synthesizer based on AD9859 can track cavity resonant frequency rapidly with monitoring the ratio of reflected and forward power in real time, and stabilize constant Dee voltage amplitude with the auto Shaped On/Off Keying function. The designed centre frequency is 101MHz, and bandwidth is 1MHz. The intermediate power amplifier can provide up to 600W driving power. The final stage amplifier based on triode 3CW20,000H7 operates in grounded grid configuration, which is stable and reliable. The performance test has been completed with 50Ω resistor load, and major results are shown in this paper.

INTRODUCTION

CYCHU-10 is a 10MeV compact cyclotron developed in Huazhong University of Science and Technology (HUST). The average magnetic field is about 1.65T, and the cyclotron adopts fourth harmonic acceleration. The designed resonant frequency of cavity is 101 MHz during start up. No automatic tuning capacitor to compensate the shift of cavity resonant frequency, the RF synthesizer will track the resonant frequency according to ratio of reflected and forward power of final amplifier. The numerical analysis of the cavity shows resonant frequency shift is within ±0.5MHz, so the designed centre frequency of RF power supply is 101MHz with 1MHz bandwidth [1]. Main specifications of RF power supply are listed in Table 1.

Table 1: Main Specifications of RF Power Amplifier

Parameter	Value
Rated Power Output	12 kW
Frequency Range	100.5~101.5 MHz
Frequency Resolution	$<1\text{x}10^{-5}$
Stability	+/- 20ppm
Output Impedance	50 ohms

The RF power supply mainly comprises of a signal synthesizer with +3dBm maximum output, intermediate power amplifier (IPA), final stage power amplifier (PA). The signal synthesizer utilizes DDS chip AD9859 to generate variable frequency and amplitude sinusoidal signal. IPA contains three stage solid-state amplifiers, and can provide PA with up to 600W driving power. PA based on triode needs more driving power compared with tetrode, but the cost of whole RF power supply is lower than tetrode's. In addition, the triode amplifier needs no grid bias power supply when it operates in grounded grid configuration. The grid of triode connects to RF ground directly, to prevent capacitive feedback between anode and cathode.

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SIGNAL SYNTHESIZER

Direct Digital Synthesis (DDS) is an advanced frequency synthesis technology around the world, which has advantages such as short frequency conversion time, high frequency resolution, and wide frequency band and so on. Considering the requirements of rapid frequency response and high frequency resolution, DDS is the best choice to fulfil flexible output frequency tuning.

AD9859 is designed to provide fine tuning resolution with 32-bit frequency tuning word (FTW), and its maximum system clock frequency (f_s) can reach 400MHz. The output frequency (f_o) of this chip is a function of f_s and FTW. The exact relationship is given as[2]:

$$\begin{cases} f_0 = (FTW)(f_s)/2^{32} & \text{with } 0 \le \text{FTW} \le 2^{31} \\ f_0 = f_s \times \left(1 - (FTW/2^{32})\right) & \text{with } 2^{31} \le \text{FTW} \le 2^{31}-1 \end{cases} \quad (1)$$

The RF power supply adopts AD9859 to synthesize sine wave around 101MHz directly. In addition to synthesize fine sine signal, it can also achieve amplitude modulation with the Shaped On/Off Keying (OSK) function. In auto OSK operation, the signal amplitude increases or deceases step by step automatically between 0 and 100% depending on the logic level applied on external OSK pin. In manual OSK operation, the RF controller can control output amplitude directly by writing the scale factor value into the dedicated register. This function is used in burst transmissions of digital data to reduce the adverse spectral impact of short, abrupt bursts of data [2]. An integrated ramp counter enables a smooth transition with a programmed linear amplitude slope [2].

The scheme of signal synthesizer is presented in Figure 1. AD8324 is a low cost amplifier to provide IPA with enough driving power. When the reflected power exceeds the configured crowbar threshold, it will shut down AD8324 firstly, and then RF controller will attempt to restart at the lasting operating frequency. Dee Voltage Feedback is proportional to the resonant voltage between Dee and dummy Dee electrode of cavity. During continuous wave (CW) operation mode, AD9859 works on auto OSK operation mode, and logic level of OSK pin

based on comparison between Dee Voltage Feedback and Dee Voltage reference will determine the direction of amplitude adjustment. When OSK pin is logic '1', the value of amplitude scale factor increases at a configured rate, or deceases with logic '0'.

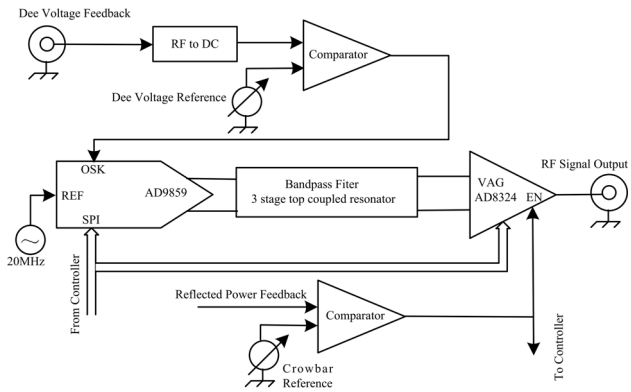

Figure 1: Scheme of the signal synthesizer.

INTERMEDIATE POWER AMPLIFIER

To get enough driving power for PA, IPA comprises of three-stage amplifiers to output up to 600W. Figure 2 shows the scheme of IPA. Both preamplifier and second amplifier use a single solid-state transmitter. The third amplifier contains four same units based on BLF177 MOS transistor, and the characteristics of power divider at input port and combiner at output port are important for stable running with high performance.

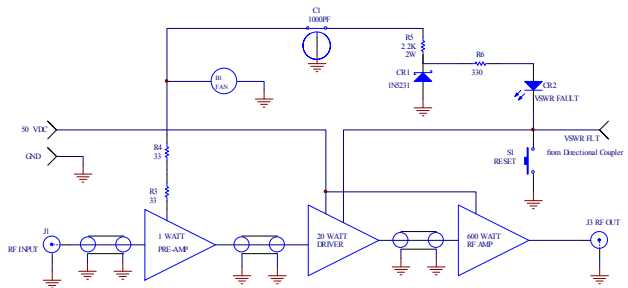

Figure 2: Scheme of intermediate power amplifier.

A directional coupler after the third amplifier monitors the reflected and forward power of IPA. When VSWR exceeds the threshold, the signal VSWR FLT will be clamped at low level and output power of second amplifier will drop to 20% of rated value suddenly in order to avoid damage. Once it occurs, we need to press the 'RESET' button manually in order to recover normal operation.

TRIODE AMPLIFIER

To withstand high reflected power, a vacuum tube is better choice for the final stage amplifier relative to solid-state transistors. Considering low cost and rich design experience for triode, we chooses a 3CW20,000H7 tube to operate in grounded grid configuration in final stage amplifier. It's capable to deliver up to 12 kW CW power to the resonance cavity around 101 MHz [3]. Figure 3 shows the schematic of triode circuit.

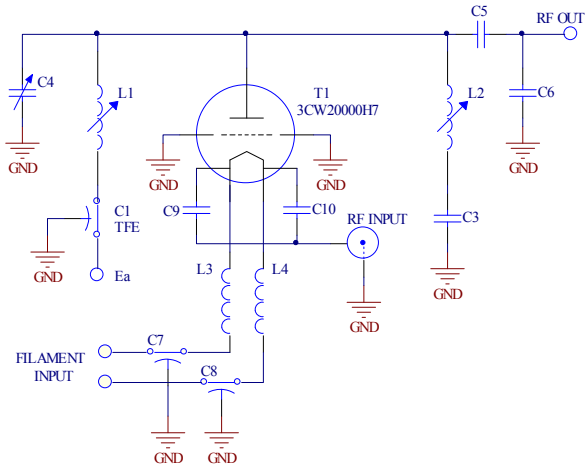

Figure 3: Schematic of triode circuit.

The designed anode DC voltage (E_a) is 7000V, and designed voltage utilization (η_a) is 90%. The equivalent output impedance (Z_o) of triode can be obtained by [4]

$$Z_o = \frac{(E_a \times \eta_a)^2}{2P_o} \quad (2)$$

where P_o is the output power of triode amplifier. Substituting P_o=12kW, E_a =7000V, and η_a=90% into Eq.2, we get $Z_o \approx 1654\Omega$. By means of the iterative computations, a fairly accurate simulation result of triode output network has been obtained (see Fig. 4).

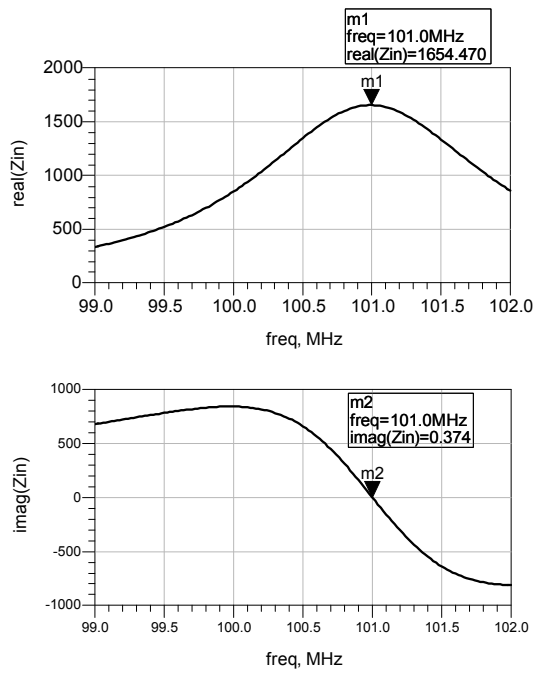

Figure 4: Simulation result of triode output network.

In output network, the structure of capacitors C5 and C6 likes a transformer, and we can simply assume the

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ratio of these two capacitors mainly determines equivalent impedance of load with other parameters unchanged. During performance testing, it's necessary to adjust capacitor C4 again for minimizing the reflected power, once this ratio is changed.

The performance testing has been finished with 50Ω resistor load in factory (see Fig. 5). The major parameters of triode amplifier at operating frequency 101MHz are shown in Table 2. Where I_a is anode DC current, and I_g is grid DC current of triode.

Table 2: Testing Result of Triode Amplifier

P_o(kW)	E_a(V)	I_a(A)	I_g(A)
12	6800	2.95	0.24
10	6800	2.65	0.14
8	6800	2.35	0.12

Figure 5: Photo of the whole RF power supply during performance testing.

CONCLUSIONS

Based on monitoring the ratio of reflected and forward power in real time, the signal synthesizer can find and track cavity resonant frequency. With the function of auto Shaped On/Off Keying, AD9859 can realize amplitude stabilizing easily. It can achieve rapid crowbar protection to disable the AD8324 based on comparison between reflected power feedback and configured crowbar threshold. The final stage amplifier based on triode 3CW20,000H7 is capable to deliver up to 12 kW CW power around 101 MHz, and the grounded grid configuration is stable and reliable. The further test and experiment will be carried out.

ACKNOWLEDGMENT

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REFERENCES

[1] D. Li, T. Hu, K. Liu, et al. "Design and research of RF system for 10MeV compact cyclotron", Sci China Phys Mech Astron, 2011, 54(suppl.2): s225-s230.

[2] Analog Devices, Inc., "AD9859 Datasheet", 2009; http://www.analog.com.

[3] Svetlana Electron Devices, "3CW20,000H7 Technical Data". http://www.svetlana.com.

[4] R. Singh, A. Mukharjee, D.S. Bhattacharya, et al. "Design and Testing of 200 kW/91.2MHz RF Amplifier", Fusion Engineering and Design. 82(2007) 854-857.