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THE 648 MHz KLYSTRON POWER SOURCE SYSTEM OF CSNS-II LINAC SUPERCONDUCTING ELLIPSOID CAVITY

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Abstract

The CSNS-II superconducting Linac accelerator includes 20 sets of 324 MHz superconducting spoke cavities and 24 sets of 648 MHz superconducting ellipsoidal cavities. The beam energy at the end of the superconducting Linac accelerator reaches 300 MeV. The 324 MHz solid-state power source supplies RF power to superconducting spoke cavity, while the 648 MHz klystron power source supplies RF power to superconducting ellipsoid cavity. The RF pulse width of the 648 MHz klystron is 1.2 ms, the repetition rate is 5 0Hz, and the peak power is 1.2 MW. The 1.5 ms long pulse solid-state modulator provides high voltage pulse for the klystron, and each modulator is equipped with four klystrons.

INTRODUCTION

At the end of March 2024, the phase II of China Spallation Neutron Source (CSNS-II) project began, 20 sets of 324 MHz spoke cavities are connected behind the DTL accelerators, the spoke cavities increase the energy of the H^- ions from 80 MeV to 173 MeV. Then, 24 sets of 648 MHz medium β ellipsoidal cavities further increase the energy of the H^- ions to 300 MeV.

THE RF POWER SOURCE SYSTEMS

The RF power source systems provide RF power required for 50 mA of peak beam current over a pulse length of 700 µs at a repetition rate of 50 Hz. The beam cutting rate is 40%. The fill and fall time of the ellipsoidal cavities will be on the order of 300µs, the RF pulse length of the RF power source is set 1.2ms, the duty factor of the RF power is 6%. The RF peak power demands of the CSNS Linac superconducting cavities are shown in Fig. 1. According to the RF peak power demand, the 324 MHz spoke cavities are powered by solid state amplifiers, and the 648 MHz klystron power sources are adopted to supply RF power for superconducting ellipsoidal cavities.

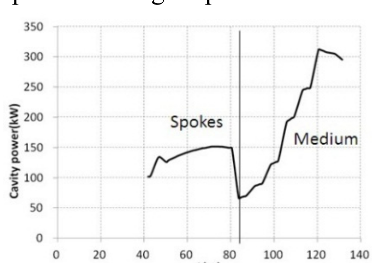

Figure 1: RF power demands of spoke cavities and ellipsoidal cavities.

THE 648 MHz KLYSTRON POWER SOURCE OF ELLIPSOID CAVITY

Each 648 MHz klystron power source of ellipsoidal cavities consists of a modulator, a 648 MHz klystron, a circulator and dummy load, WR1500 waveguides to deliver the RF power to cavities. One modulator provides the high voltage pulse to four klystrons.

Klystron

The klystrons operates at a frequency of 648 MHz and the saturation peak power is 1.2 MW. With the 6% duty cycle for CSNS-II Linac RF system, this means that the average power level at saturation is about 72kW, the specifications of the 648 MHz klystron are shown in Table 1 [1].

Table 1: The Specifications of 648 MHz Klystron

Parameter	Value	Unit
Center Frequency	648	MHz
Bandwidth	±0.5	MHz
RF Peak Power	⩾1.2	MW
RF Pulse Width	1.2	ms
Repetition rate	50	Hz
Gain	≥45	dB
Efficiency	50	%
Cathode Voltage	-105	kV

The 648 MHz klystron is designed with mod-anode configuration, and the modulator outputs high voltage pulse to the klystron cathode, the high voltage pulse applied to the mod-anode can be adjusted through resistive divider. The electron gun part of the klystron includes two section ceramics, this part is placed in an oil tank to protect the ceramics from high voltage breakdown. After receiving the prototype of the 648 MHz klystron, we aged the klystron with a hi-potter, and the withstand voltage between the mod-anode and the cathode was aged to 90 kV, the withstand voltage between the mod-anode and the ground was aged to 70 kV. The prototype passed the site acceptance test in October 2023, the test results have met all the specification requirements. The 648 MHz klystron operates in horizontal orientation, it has a separate magnet, and the photograph of the klystron installed at CSNS site is shown is Fig. 2.

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Figure 2: The 648 MHz klystron of CSNS-II Linac superconducting ellipsoidal cavity.

Modulator

The modulator is responsible for converting the grid power into high voltage pulses. Based on the 648 MHz klystron design requirements, the modulator is long-pulsed, the pulse width of the high voltage should be larger than 1.2 ms. After evaluating several topologies, the stacked multi-level (SML) modulator topology similar to ESS design scheme is adopted [2]. The SML modulator operates in series with multiple modules, the power conversion process of each module is described below. The first conversion stage is active Front-End, the converter connects modulator with the AC line, the active Front-End technology can shape the line currents to be sinusoidal and in phase with the line voltage, and minimize the line current harmonics and reactive power. The next stage is a buck charger which connects the dc-link capacitor to the main capacitor bank, the buck charger keeps the charging power constant, flick-free operation of the modulator is attained. The voltage of the capacitor is less than 1 kV.

The next stage is high frequency inverter, the IGBT H-bridge inverter is used inside each module to generate high frequency pulse, the frequency range is from 15kHz to 20 kHz. Then, the high frequency transformer steps up the 1kV primary voltage to 20 kV, the transformer magnetic core uses nanocrystalline material to reduce losses. The passive diodes rectify the voltage from the transformer secondary, the passive high voltage filter outputs a smooth DC high voltage pulse. The design scheme was simulated with Matlab/Simulink, the simulation schematic diagram is shown in Fig. 3. The simulation results verify that the power conversion process is consistent with the design scheme. The simulation results are shown in Fig. 4.

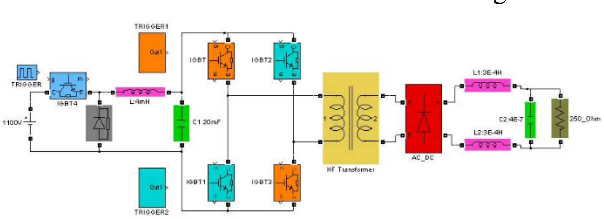

Figure 3: The simulation schematic diagram of modulator.

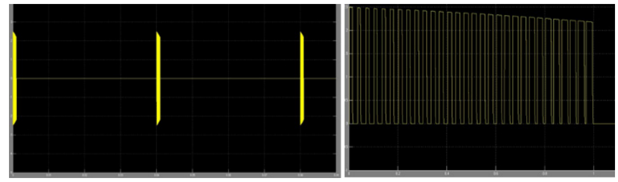

Figure 4: The simulation results of the modulator.

In order to evaluate the SML modulator design scheme, a prototype development started in October 2020. To balance the universality of the modulator, the maximum pulse voltage and current of the modulator can reach 120 kV and 120 A, respectively. The prototype contains six HV modules, each module can deliver 20 kV during the pulse, and six modules are connected in series on the output stage. The specifications of the prototype are shown in Table 2.

Table 2: The Specifications of Modulator Prototype

Parameter	Value	Unit
Pulse Voltage	120	kV
Pulse Current	120	A
Pulse Length	1.5	ms
Pulse Drop	<1	%
Rising time	150	μs
Repetition Rate	25	Hz
Ripple	<0.3	%
Efficiency	>90	%
THD	<5	%

The main body of the modulator is shown in Fig. 5. The commissioning of the modulator prototype is still ongoing, once the primary current of the high-frequency transformer is too high, the distribution parameters of the leads from the H-bridge to the high-frequency transformer cause a voltage drop, resulting in a decrease in secondary voltage. This issue has been significantly improved by reducing the lead length and isolating the copper sheets from each other. Until now, the load-bearing capacity of the improved module is enhanced, the secondary voltage of the transformer can reach 20 kV under the condition of the load current 120 A.

Figure 5: The main body of the modulator.

High Voltage Pulse Divider

Because the 648 MHz klystron with mod-anode configuration, a high voltage pulse divider is designed to supply proportional pulse voltage to mod-anode through resistor division. This part is placed in a separate oil tank, and the isolation transformer of the klystron filament power supply

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is also placed inside. The photograph and schematic diagram are shown in the Fig. 6.

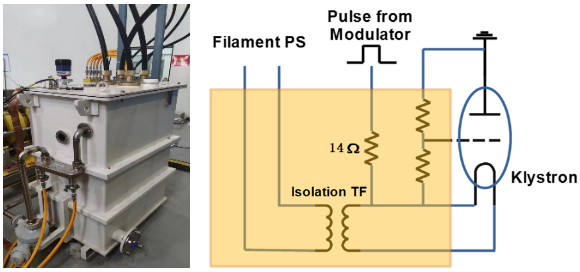

Figure 6: The photograph and schematic diagram of the pulse divider.

HIGH POWER TESTING

The 648 MHz klystron power source system completed site acceptance test in October 2023. The RF peak pulse power was 1.2 MW, the peak power was measured in RS power meter, the result is shown in the Fig. 7. The RF pulse width 1.2 ms, the repetition rate 25 Hz, and after 24 hours of continuous operation, no faults occurred. The 648 MHz circulator, dummy load and waveguide transmission system also passed the high power test.

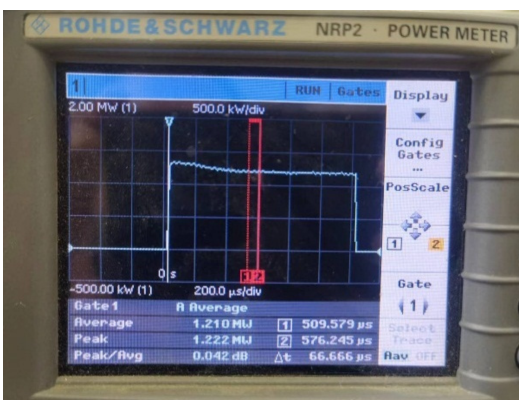

Figure 7: 1.2MW peak power of the 648 MHz klystron.

CONCLUSION

The prototype of the 648 MHz klystron power source system has completed the high power test, the long pulse solid-state modulators are still being improved. The next step is to increase the system repetition rate to 50Hz for the purpose of isotope production. The initial test results of the system have verified that this 648MHz klystron power source can meet the RF power requirements of the CSNS-II Linac superconducting ellipsoidal cavities.

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