

# A NEW DESIGN OF CYCIAE230 SUPERCONDUCTING CYCLOTRON RF-DRIVEN SYSTEM\*

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## Abstract

A superconducting cyclotron with a beam energy of 246.2 MeV has been developed and commissioned by the China Institute of Atomic Energy. The RF system of the first CYCIAE-230 cyclotron adopts two tetrode amplifiers to drive the cavities simultaneously. The driven power is 180 degrees out of phase, and each amplifier was designed to deliver 75 kW RF power to the resonators. In practice, it was found that the driven power is beyond necessary, and only 80 kW RF power is required for the beam. Hence, an upgrade of the existing RF-driven system to the state-of-art of solid-state technology is put forward by the CIAE cyclotron team. Furthermore, this alternative design also includes an optimization of the coupling between amplifiers and the cavities since the old coupler shows nonidealities under long-term high-power operations. A driven schema utilizing multiple low-power capacitive couplers is designed to address this issue, taking advantage of the cavity as a power combiner. In this paper, a review of the existing RF-driven system will be given first. It will be followed by an analysis of the limitation of such a system in practice. A new design of the solid amplifier, the new driven method, and a capacitive window will also be reported.

## INTRODUCTION

Proton cancer therapy has been increasingly adopted in China's domestic medical activities. To address cancer, a growing threat to Chinese public health, a superconducting cyclotron, namely CYCIAE-230, has been developed and commissioned by the China Institute of Atomic Energy in the last several years [1] under the support of the program of proton therapy and space science launched by China National Nuclear Corporation (CNNC).

This superconducting cyclotron uses Ni-Ti alloy in liquid helium temperature to generate about 3 Tesla magnet fields [2] to constrain the proton and uses second harmonics RF field to accelerate it from several electron voltages to 242.6 MeV. In total, before extraction, the particle is accelerated about 5,300 times, eight times per turn. The diameter of the magnet pole is ~890 mm, while the weight is about 90 tons.

The RF system of CYCIAE230 consists of a set of resonators, two independent 75 kW amplifiers, and one set of LLRF control [3]. The resonators are two capacitive coupled similar coaxial cavities.

Each cavity shares the same resonance parameters, such as identical capacitance, inductance, and shunt impedance. Two identically designed cavities are electromagnetically joined together by the distributed capacitance in the central region. The system resonance frequency can be determined as formula below.

$$\begin{cases} Y_{AB} = \frac{1}{R_1} + j \left( \omega C_{11} - \frac{1}{\omega C L_1} \right) + \frac{\omega^2 C_{12}^2}{\frac{1}{R_2} + j \left( \omega C_{22} - \frac{1}{\omega C L_2} \right)} \\ C_{11} = C_{12} + C_1 \\ C_{22} = C_{12} + C_2 \end{cases}$$

$R_1$ ,  $L_1$ ,  $C_1$ ,  $R_2$ ,  $L_2$ , and  $C_2$  are parallel impedance, distributed inductance, and capacitance of the two Dees, respectively.  $C_{12}$  is the coupling capacitance between the two groups. In an ideal condition, let the two cavities be the same, e.g.,  $R_1 = R_2$ ,  $C_1 = C_2$ , and  $L_1 = L_2$ ; the resonators have the same resonance frequency,  $\omega_0$ . And, let the coupling coefficient be defined as  $K = \frac{C_{12}}{\sqrt{C_{11}C_{22}}}$ . The resonant frequency can be solved as,

$$\omega^2 = \frac{(1 \pm K)}{(1 + K)(1 - K)} \omega_0^2$$

this gives two resonance frequencies:

$$\begin{cases} \omega_l = \frac{1}{\sqrt{1 + K}} \omega_0 \\ \omega_u = \frac{1}{\sqrt{1 - K}} \omega_0 \end{cases}$$

The  $\pi$  resonance mode,  $\omega_l$ , is selected as the operation mode for beam acceleration for cyclotron CYCIAE230, which is the 2<sup>nd</sup> harmonic particle cyclotron frequency. A push-pull driven method is chosen to roll out the resonance at  $\omega_u$ .

## CHARACTER OF EXISTING RF SYSTEM

Two groups of resonators are involved in the  $\pi$  mode beam acceleration, each of which has an independent power coupler. These two couplers are used simultaneously and are driven by two separated 75 kW tetrode amplifiers in a push-pull configuration. By applying RF power with 180 degrees out-of-phase, the simulated mode of the cavities group can be simplified, as shown in Fig. 1.

The measurement setup is shown in Fig. 1a. The drive RF is taken from network analyzer port-1 and is divided using a push-pull power divider to drive through the identical-length rigid transmission to the two couplers. A cavity

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pickup is connected with network analyzer port 2. In this way, the cavities response is measured at low power; the result is shown in Fig. 1b. It can be easily found that no extra resonance mode can be stimulated with this driven method other than the  $\pi$  resonance mode. Compared to the single coupler/one amplifier-driven approach, parasitics [3] can be greatly limited.

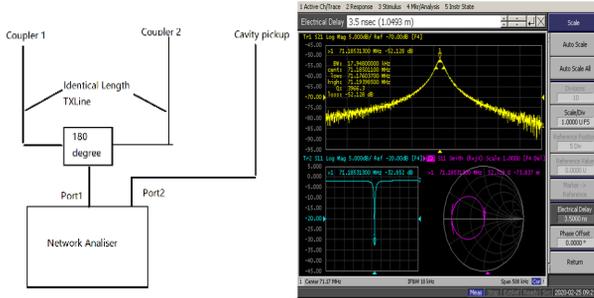


Figure 1: Resonator transfer function measurement, a) test setup, b) network analyser results.

The driven amplifiers in the beam tuning phase are two tetrode-based designed systems. It was designed to provide 150 kW RF-driven power to the cavities in total. However, in practice, the cavities only need 80 kW to establish the required acceleration voltage. The power reservation, in this case, is too much. The polarization and the typical runtime parameters of the final stage amplifier tube 4CW100,000E are tabulated in Table 1. It's easy to find out that, for the amplifier system, the drawback of this scenario is that the power efficiency is lower than expected. This is one reason to design a new RF-driven system for the RF of the CYCIAE230 cyclotron.

Table 1: Parameters of the Tetrode FPA

Item	Value	Unit
Anode Potential	13.5	kV
Screen Potential	900	V
Grid Potential	-280	V
Anode DC Current	5.5	A
Driven Power	1.5	kW
Output power	40	kW
Power efficiency	70	%
Anode dissipation	13	kW

The driven stage amplifier is a solid-state design capable of delivering 4 kW RF in CW mode. The RF window and the FPA transmission line are two  $4\frac{1}{2}$  rigid lines about 30 m long. An amplitude and phase adjusting device is included at a low power level to drive the two amplifiers simultaneously. The FPA and the power supply are shown in Fig. 2.

The existing RF windows broke several times during the beam commissioning phase. The couplings of the two resonators are independent of two loops. Both of them are located at the bottom of magnet valley. The ceramic vacuum sealing is about  $\frac{1}{4}$  lambda away from the loop, outside the return yoke beneath the cyclotron. The stationary leaking magnet field is in orders of several kilo gauss.

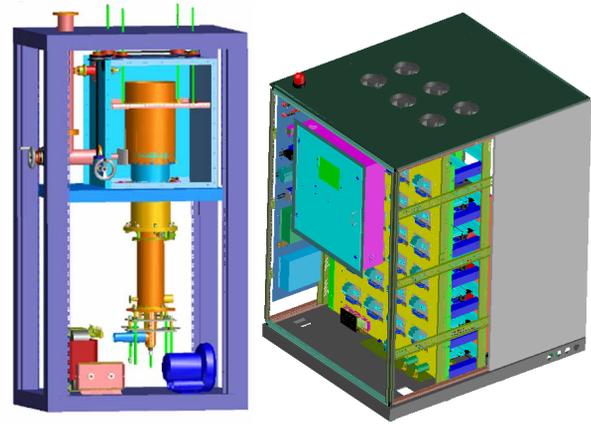


Figure 2: 75 kW Tetrode Amplifier, a) FPA, b) power supply.

In the beginning, the vacuum at the ceramic window is not ideal, which leads to a material sputtering on the ceramic. According to the analysis, the discharge on the ceramic is a two-stage process. In the beginning, it was the electron bombardment, the discoloring on the ceramic is gray. Without interference, it will develop into the second stage, the plasma discharge, which is fatal for the ceramic, as shown in Fig. 3a. The issue is solved by increasing the vacuum level around the ceramic and removing the outgassing item (when exposed to the electron cloud).

However, the ceramic window still breaks sometimes. This time, instead of sputtering copper on the ceramic, which creates a short circuit in the insulator, the vacuum seal fails, as shown in Figs. 3b and 3c. As analyzed previously, in stage one, the field-emitted electrons' trajectory is controlled by the RF e-field and the leaking magnet field. It is believed that is the reason for uneven burn marks on the ceramics. To address this issue, we added a magnetic field near the ceramic insulator to manipulate the movement of the electrons. Fig. 3b was an unsuccessful trial to modulate the geometry of the ceramic insulator. With the magnet field corrector, it still brokes. The TiN coating on the surface of this unsuccessful trial also indicates that the electrons are not initially from the ceramic itself.

With these improvements above, the mean time between coupling windows significantly increased. However, the ceramic still breaks from time to time occasionally. Most of them happen when there is significant sparking inside the cyclotron dee system, e.g., when finger contact of the rear part of the Dee is burned. It is believed that two issues can not be further improved with the current loop antenna design. One of them is that the loop cannot shield electrons from the dee plate, which traveled along the magnet line, from the Dee plate to heat the inner conductor. This will lead to secondary electrons moving along the leaking magnet field, eventually heating the ceramic insulator. The second is that the leaking magnet field greatly influences the ceramic outside the magnet field. The local magnet field line needs to be better defined. Based on these considerations, a new capacitive window is designed, as will be described in the following section.

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Figure 3: Ceramic insulator failure, a) material sputtering, b) geometry changed, c) without magnet field, with disk-type ceramic.

### DESIGN OF NEW DRIVEN SYSTEM

As pretty standard in RF combiner design, the coupling coefficient of each port to the combined port follows:

$$C_{1N} = 10 \log \frac{1}{|S_{21}|^2} = 10 \log N \dots (N \neq 1)$$

where, N is the port number of the combiner. In the CYCIAE230 cavity case, each resonator is either capacitive coupled inside the cyclotron or is directly connected. Therefore, it can be easily seen that this coupling is acting like a port in the combiner's case. So, the coupling coefficient of multiple coupling windows for the CYCIAE230 cavity is:

$$C_{1N} = 10 \log(2N) \dots (N \neq 1)$$

where, N is the number of coupling windows. N is equal to two in the existing RF system of the CYCIAE230 cyclotron. Hence, if measured directly using a network analyzer, the  $S_{11}$  is -6 db. Later, if desired, four coupling windows are used in the new system. The  $S_{11}$  is expected to be -9 db.

A new solid-state RF amplifier was built to replace existing tetrode amplifiers with higher configuration flexibility. The configuration of the solid-state amplifier is four identical cabinets, each of which can provide 30 kW of RF driven with a 4½ line output. This can be used directly in the case of four resonator couplers. If only two couplers exist, two power combiners will be added to adapt to the existing RF-driven method.

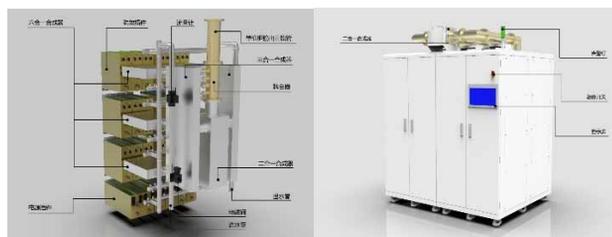


Figure 4: 60 kW Solid-state Amplifier Module, a) 30 kW SSA module, b) 60 kW SSA.

Each 60 kW solid-state amplifier consists of two 30 kW modules. The internal view of each 30 kW module is shown in Fig. 4a. And the output power is combined at the top of the cabinet, as shown in Fig. 4b. The amplification unit is made of Ampleon power LDMOS transistor ART2K0FE, and each unit can provide 1500 kW RF output and is protected with a 2 kW circulator module. The output RF power is combined using a 1 to 6 combiner, then combined with a 1 to 3 combiner, followed by a 1 to 2 combiner. Therefore, 36 modules are integrated to get 30 kW output with a comfortable redundancy.

Multiple new disc-type ceramic windows and capacitive couplers are planned to be manufactured in early 2023. These new couplers will be installed inside several valleys of the cyclotron, where well-defined magnetic lines are expected to constrain field-emitted electrons, preventing the spark from developing into the second stage. Since this installation location is near the main cyclotron chamber, a better vacuum level is expected too. One capacitive coupler, two capacitive couplers, or four capacitive couplers configurations will be tested with the new solid-state RF amplifiers to determine which is the best choice for the driven method of the CYCIAE230 cyclotron RF system. The stretch of the new coupler is shown in Fig. 5.

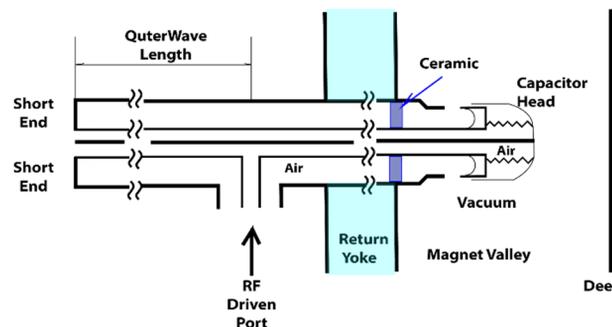


Figure 5: A sketch of the capacitive coupler with disk ceramic insulator.

### CONCLUSION

An analysis toward improving the CYCIAE230 RF driven system has been put forward. The new amplifier as well as the new coupling window are planned to be built in year 2023. A test will be carried on to verify the new driven method of this cyclotron RF system.

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