DESIGN, CONSTRUCTION AND COMMISSIONING OF THE 100KW RF AMPLIFIER FOR CYCIAE-100

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Abstract

As a major part of the BRIF project, CYCIAE-100, the 100MeV high intensity cyclotron being constructed at CIAE, will provide 200μA-500μA proton beam ranging from 75MeV to 100MeV for RIB production. Two identical 100kW RF amplifiers will be used to drive two cavities independently to accelerate H- beam up to 100 MeV. The detail technical specification has been investigated, fixed, and initial design has been finished by CIAE. Then, the construction design and manufacture is done by China Academy of Aero and Space. The on site test is successful by mutual efforts. The final commissioning is under way with a full scale prototype cavity at CIAE. A general description of the CYCIAE-100 RF system design will be given, as well as the review of 100kW amplifier design. In the commissioning of the amplifier with dummy load, different high order resonances are found when operated at different frequencies between 42MHz to 46MHz. An equivalent circuit model is carried out to hunt down the problems. The model and related analysis will be reported together with the process and results of high power test with the cavity load through about 35-meter 6-1/8" rigid coaxial line.

INTRODUCTION

For the RF system of CYCIAE-100, two 100kW amplifiers will be connected though about 35 meters 6 inch transmission line to power the two cavities individually. A set of digital low level controls will be used to ensure the amplitude of the each cavity, tuning of each cavity and regulation of the phase difference between the two cavities [1][2].

As planned years ago, a full scale OFHC test cavity was fabricated in year 2009, polished and assembled in early 2010. In the mean time, the two amplifiers were designed in year 2008, approved by CIAE, and manufactured by the 23th research institute of CASIC (Changfeng Broadcasting Co. Ltd.). In early 2010, the two amplifiers finished various kinds of factory tests, and one of them is shipped to CIAE cyclotron laboratory. With the full scale cavity and the amplifier on site, the cyclotron laboratory prepared the vacuum system, the water cooling system and the 150kW mains system for the amplifier test with the real cavity load. The amplifier design will be reviewed in Section 2, while the factory test and the on site test with cavity load will be reported in Section 3 and Section 4 respectively. To dump the

transmission line high order mode at a frequency of 311.5MHz, a harmonic absorber will be promoted in Section 5 as next step.

AMPLIFIER DESIGN REVIEW

The amplifier chain consists of a 6kW solid driving stage, a 100kW final stage and necessary low level protection circuits.

The driving stage utilizes BLF287 MOSFET as core amplification unit. There are in total 32 these units in the driving stage. The combination of RF power is divided into three stages. Firstly, four 200W units was combined together making an amplification unit capable of delivering 800W power, taking 4U space in a 19 inch cabinet; Secondly, four 800W units combine their power together to get ~3kW RF power; eventually, the two 3kW units were combined together as the driving stage solid amplifier with a capability of delivering more than 6kW power.

The final stage uses a EMAIC 4CW150,000 power tube, a ground grid configuration is selected. To be more specific, both the grid and the screen are RF grounded to the tank wall. Though in ground grid configuration, certain amount of driven power will be directed to output, which in turn means more driven power. Yet, from stability point of view, still it is a good choice for high power amplifiers, especially in the case to power a high Q load, e.g. the cyclotron cavity.
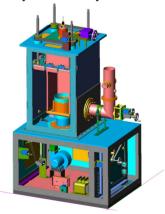

Figure 1: The final stage amplifier

As shown in Fig. 1, the anode tank uses a quarter-wave cavity with a movable short driven by four synchronized worm wheels. The inner conductor is made of copper while the outer is of copper clad aluminium. The output power of the amplifier is channelled out though a

COMET variable vacuum capacitor, connected at the voltage terminal of the resonator.

Tube Operating Parameters

Considering the efficiency, the tube is designed to operate in class C. Once the conductive angle is selected, the residual anode potential can be determined using formula 1.

$$E_{a(\min)} = 0.5 \cdot \left(1 - \sqrt{1 - \frac{8P}{0.5 \cdot S \cdot E_a^2 \cdot \alpha_1(\theta)}} \right) E_a \qquad (1)$$

Where E_a is the DC anode potential, P is the design output RF power, S is the transconductance of tube and θ is the conductive angle. In a similar way, one may find out the maximum current by

$$I_{a(\max)} = \frac{2P}{\left(E_a - E_{a(\min)} \right) \cdot \alpha_1(\theta)} \qquad (2)$$

Then the operating line can be fixed on tube constant-current curves, using point $A\left(E_{a(\min)}, I_{a(\max)} \right)$, and $P\left(E_a, I_{a(\min)} \right)$, as shown in Fig.2. It should be noted that $I_{a(\min)}$ is chosen by experience.
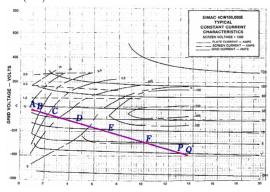
Figure 2: Tube operating line for 4CW150,000

The output power, DC meter readings as well as the fundamental RF peak current and tube anode impedance can be calculated out by applying Runge-Kutta method to the operating line. The result is tabulated as follows.

Table 1. Calculated parameters for the amplifier

Anode potential	13.5 kV
Screen potential	0.95 kV
Grid potential	-360V
Anode DC Current	10.55A
Anode RF Current	16.82A
Anode RF resistance	751 ohm
Output power	106 kW
Anode dissipation	36 kW
Gain	15dB

Input and Output Circuits Design

As the amplifier is designed to be driven from cathode, the input circuits need to adapt very low impedance (e.g. 6.2-9.5j ohm) to normal 50 ohm driving port. The circuit

consists of 3 components, i.e. a shunt variable vacuum capacitor, a serial inductor and a parallel strip line inductor. The matching procedures are relatively easy can be well understood using smith chart.
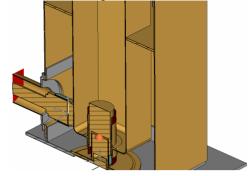
Figure 3: Amplifier Output circuits design

The output circuits design concerns modelling the anode tank structures in 3D electromagnetic software. As shown in Fig. 3, the model consists of a tube anode structure, a lumped element representing anode resistance, an anode Kapton® DC block capacitor, upper part of the tube socket including screen DC block capacitor, a rectangular coaxial resonator, a vacuum capacitor structure and the output port. The simulation is performed with the lumped resistor set to 751ohm. Several iterations with different output capacitance and short plate position had been done by time domain solver, for the evaluation of the tuning and matching of the anode tank. The results shows the S_{11} of output port could reach -35.82db when the output capacitance is set to 18.8pF, which is right in the middle of the COMET variable capacitor tuning range. In the mean time, the short plate travelling range is also determined to cover the whole amplifier frequency range.

HIGH POWER TEST

Test with Dummy Load

The power test with dummy load was done at the CASIC. During the seven hour endurance test, the amplifier worked in a reliable manner. Though there was small gain difference in the solid stage comparing the data acquired in noon and evening, it was believed to be caused by room temperature variation, and concluded as acceptable.
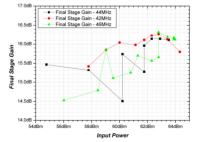
Figure 4: Final stage gain versus input power

Also, gain linearity with respect to different output power level has been checked during the factory test, the

final stage trends to have 1 db higher gain in high power, as shown in Fig.4. Note the gain jumping in the chart is for test purpose, cause by deliberately turning up or down the anode potential (700V each time) during the test.

For higher harmonics measurements, the amplifier has -28db for 2nd and -27db for 3rd. A reflective high power filter was promoted by 23th institute of CASIC and fabricated, installed in the transmission line during the power test with dummy load. After the installation, the 2nd and 3rd harmonic are well below -50db.

Test with Cavity Load

Though the waveform and the spectrum look clean and nice after the filter, the filter was not installed during the test with cavity after one of the amplifiers was shipped to CIAE site. To clarify this issue, a similar SPICE model including the filter and the cavity has been developed and studied, following the CRM cyclotron RF system model (reported in another paper of this conference). Afterward, the parasitic resonance has been confirmed by network analyzer measurements, thus both sides agreed to remove the filter from the transmission line.

After the vacuum, cooling and the AC mains input satisfied the hot test requirement, the real load test for the amplifier was carried on in summer of 2010. The major purpose of the high power test with the cavity is to check if instability exists in high power operation, meanwhile verification of Dee accelerating voltage is also important.

At the begin of the high power experiment, the conditioning progress takes longer time than expected, due to the fact that the vacuum is not so good and frequently the vacuum tank need to be opened for various reasons, e.g. changing water pipe sealing, installing new temperature sensor etc. As the carbon compounds are slowly but steadily built up on certain surface of the cavity, feed power to the cavity is easier time by time. After three weeks, continuous wave can be applied to the cavity after 2 to 3 hours of pulse conditioning.
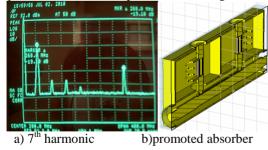

a) 7th harmonic   b)promoted absorber

Figure 5: DC equivalent circuits and anode circuits

The amplifier has proved to be reliable in high power test. Even at the beginning, to feed power into the cavity, with low duty cycle in several microseconds, the amplifier was driven to its limit with reflect almost equal to forward power in level of 100kW, and no big issues emerged except that several small isolation transformer was broken down due to isolation material imperfection.

One issue to be confirmed and handled later is that the 7th harmonic is abnormally higher compare to the power

test with dummy load. The spectrum taken from the transmission line is shown in Fig.5 a). A promotion of high harmonic absorber has been put forward by RF group, as shown in Fig.5 b). The centre frequency of the 3db coupler in the absorber is set to 318.5MHz, in the hope of lowering the transmission line Q at the 7th. The absorber is to be fabricated after the installation of trombone, in case the 7th harmonic resonance cannot be weakened or moved to other frequency by fine turning of the transmission line length.
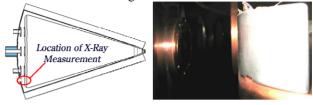

Figure 6: One of the X-ray measurement positions

Another major task is to verify the shunt impedance in high power, with the present of field emission electrons load and possible dark current load. It is planned to use X-Ray to calibrate the Dee voltage [3]. The difficulty of this task is related with finding a position with higher x-ray yields and good alignment [3] [4], considering the fact that the cavity for CYCIAE-100 has an unique voltage distribution [5]. To be more accurate in the measurement, the electron motion as well as photons yields curve has been calculated for this case, using the method in [3][6]. After these works done, considering the accessibility of the vacuum tank, around the middle plane, four different locations were selected to install AMPTEK XR-100SDD detector, one of which is shown in Fig.6. The experiment will be performed soon after the detector is available.

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