AMPLIFIER TEST STAND FOR THE CRM CYCLOTRON

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Abstract

The final stage amplifier stability has proved to be an important issue in the commissioning of CRM cyclotron at CIAE. An air cooled 4CX15,000 tube final amplifier was designed to evaluate the anode circuit and neutralization, both of which are weak points of the CRM cyclotron amplifier. Instead of strip line, the new designed anode structure adopts coaxial form, resulting less chance of parasitic resonance in the circuits. A tuneable neutralization circuits was also included in the design, giving an opportunity to fine tune in high power operations. First, the instability in CRM RF system will be analyzed in this paper, followed with the new amplifier designs including the tube operating line calculations, input/output circuits designs and finite integral simulations. The mechanical design for tube socket and anode tank were successfully carried out using the data provided in this paper. The final stage amplifier was then manufactured, assembled and commissioned. In the power test with dummy load, more than 9.2kW RF fundamental power was provided at the frequency of 44.5MHz.

Key Words: RF Amplifier; neutralization; coaxial resonator

INTRODUCTION

In the commissioning of CRM cyclotron at CIAE[1], a parasitic resonance mode was found having significant influence to the RF system stability[2], showing an unreasonable screen current incensement of 200% once the amplifier output exceeds 6kW when driving cavity load. The reason of this parasitic mode concerns the interaction of the transmission line and cavity and will be analyzed in the following section. To solve the instability, the transmission line length was adjusted to multiple of half wave length, and the neutralization of the amplifier was tuned accordingly to have more stable gain margin considering the final stage taking ground cathode configuration[2]. As the plan of upgrading beam current to 1mA put forward, the amplifier anode transformer was changed to a bigger one giving more anode potential, from 7.5kV to 9.2kV, yielding extra 4.5kW output power. In such a case, the stability of the final stage once again is challenged. It was then decided to make an amplifier test stand to evaluate feasibility of high power tuneable neutralization circuits. In the same time, the test stand can be used to test new tubes before it is mounted on the CRM RF amplifier. The frequency of the test stand was decided as 44.5 MHz, in case the 1:1 scale cooper cavity return earlier, it can be used in the cavity power test for 100MeV cyclotron.

The original amplifier of CRM cyclotron was designed and manufactured by a local Chinese company, having 3 parallel strip lines in anode circuits. To have a different choice and expecting less parasitic in anode circuits, the coaxial structure was selected in the amplifier test stand design. Also, the design of the test stand amplifier takes advantage of modern 3D finite integral simulations. While calculation for the active components (e.g. the final stage tube) follows the traditional analytical way, as will be reported in Section 3 of this paper.

INSATBILITY IN THE RF SYSTEM OF CRM CYCLOTRON

The differences between amplifiers used in broadcasting and cyclotron is that for the latter, the amplifier was operated with a narrow band high Q load through a certain length of transmission line[3,4].

The instability showing up in CRM cyclotron RF system is that when the amplifier operated with a dummy load, there was no evidence of instability even at full power level, which is around 10kW[5]. Once connected through about 6 meters rigid 3-inch line to the cavity, it can be stable in low power level. However, if we try to increase power e.g. to 6kW, the screen current will increase rapidly. When continuing to increase the power, the tuning loop in LLRF control starts to tune the cavity in a wrong direction, which will eventually kill the resonance of the cavity.

To evaluate the situation, a set of differential equation model is developed. Specially, in electrical designs, the equation model is often represented as SPICE models.

SPICE Model of CRM RF System

Though modern 3D finite computation tools has offered an integral environment to interactive with electrical design tools, for simplicity, a cavity model was put forward using parameters identified in real operations. In general, the fundamental resonance of a cyclotron cavity can be represented as parallel RLC circuits. Another approach is to split the cavity into two parts: the Dee plate and the coaxial part.

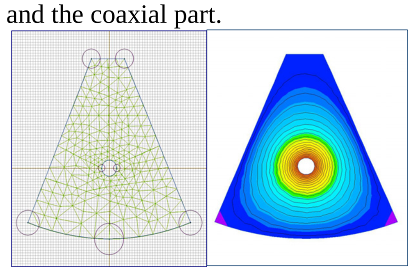


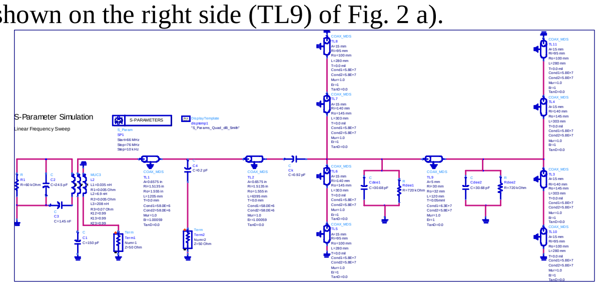
Figure 1: stem impedance calculation

According to the geometry of the cavity[6], in the cavity model, the impedance of two coaxial parts is calculated using analytical equations and 2D Laplace's solver respectively. Then the equivalent components for the Dee plate are calibrated using measurements results, by means of checking Q value and resonance frequency.

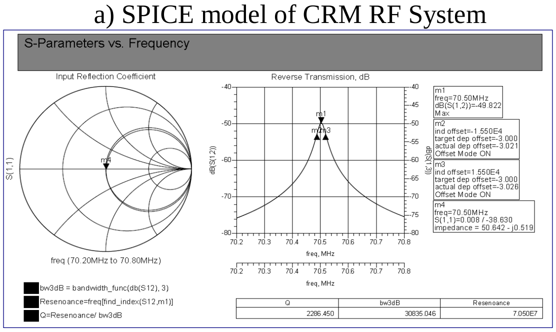
In CRM cavity, the upper part of stem has a triangular shaped outer conductor. The impedance of this part can be evaluated using equ. 1.

$$Z_0 = \frac{1}{cC_{tri}} \qquad (1)$$

Where c is the speed of the light travelling in vacuum, and C_{tri} is the capacitance per unit length of the object, which can be calculated using electrostatic code, as shown in Fig. 1. The impedance for this part is calculated as 133.8ohm, and a cylindrical with outer diameter of 280mm is substituted for this triangular section (e.g. TL3, 4, 6, 7 in Fig. 2a). The other parameters included in the cavity model is taken from measurements and adjusted to have an identical resonance curve shown in Fig. 2 b), e.g. the coupling capacitor is set to 0.92pF, the Dee capacitance and dissipation is set to 30.68pF and 720ohm respectively. The connection bar that connects the two hot arms, was model as a section of transmission line as shown on the right side (TL9) of Fig. 2 a).



a) SPICE model of CRM RF System



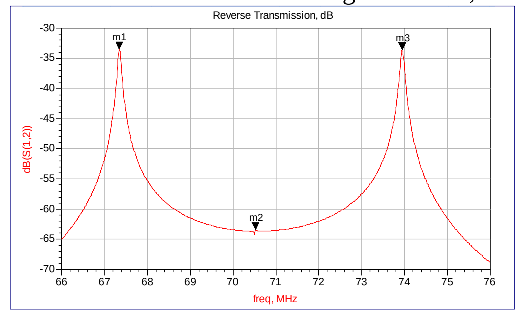
b) S parameter of the cavity model

Figure 2: CRM cyclotron RF system Model

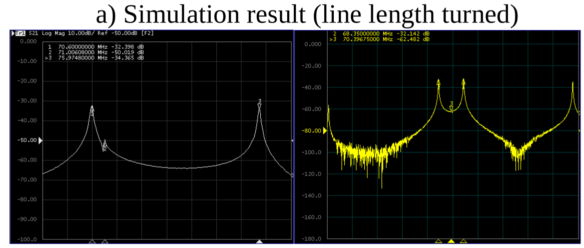
The transmission line modelling takes advantage of TX-Line model in the SPICE software, in which an inner diameter of 1.315 inch and outer diameter of 3.027 inch is specified for 3 inch rigid line. In the middle of the transmission line, a capacitive pickup was connected to the inner conductor, together with a 50 ohm port, as to facilitate the extraction of S parameters.

The equivalent circuits for final stage tube amplifier in cold state includes the dissipation of the anode tank, tube output capacitor, shunt inductor, compensation capacitor etc. as shown on the left side of Fig.2 a). It should be noted that in the model an inductive loop with 50 ohm port was added to give stimulations.

The measurement using network analyser for CRM cyclotron RF system is shown in Fig. 3 b), as predicted using the above SPICE model. On the left hand of Fig. 3 b), about 0.4MHz lower than working resonance,



a) Simulation result (line length turned)



b) before adjusting c) after adjusting

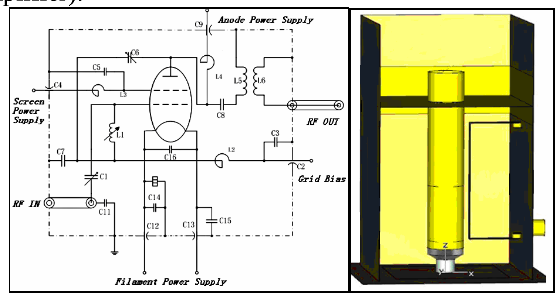
Figure 3: Transmission line length effects on parasitic resonance mode, simulations and measurements

there is a parasitic resonance mode generated by incorrect transmission line length w.r.t. multiple of half wave length. This resonance is determined as the primary source of the CRM RF system instability. Using the SPICE model, the correct transmission line length was easily determined, as shown in Fig.3 a) and the two harmful resonances were turned to be symmetrical w.r.t. the cavity resonance, which in turn is a proof of having right line length.

The S parameter after tuning is shown in Fig. 3 c), from the figures it can be concluded that in frequency 68.35MHz and 72.35MHz, the parasitic resonances still has much higher impedance seen by the anode. Therefore, a hot tuneable neutralization or dumping method should be considered to get the final stage unconditional stable. As the nature of dumping method is to remove part of the output power to a dummy load, considering the CRM cyclotron is still short of power for its 1mA project, the better choice is to have a better neutralization, taking the fact that the amplifier is designed in ground cathode configuration.

AMPLIFER TEST STAND DESIGN

Ground cathode circuits have been adopted to minimize the driven power and to provide a higher gain in the final stage. The tube operating parameters was identified from the 4CX15,000A tube characteristic curves using EMAIC graphic method "Tube Performance Computer". A set of input and output RF circuits were designed according to the impedance determined from the working line, in which, a coaxial structure was selected as output due to the reduced chance of producing parasitic resonance for the anode. In order to give an accurate direction of the mechanical design, the finite integral method was selected to calculate the cavity. It is worth noting that, however, in the application of cyclotron RF systems, the tube amplifier may suffer from the side resonance effect caused by the transmission taped with the high Q load. To achieve higher stability in this case, a high power tuneable neutralization circuit was included, as can be found as C_6 in Fig. 4(the DC equivalent circuits of the amplifier).



a) DC equivalent circuits b) CST model

Figure 4: DC equivalent circuits and anode circuits

Tube Operating Parameters

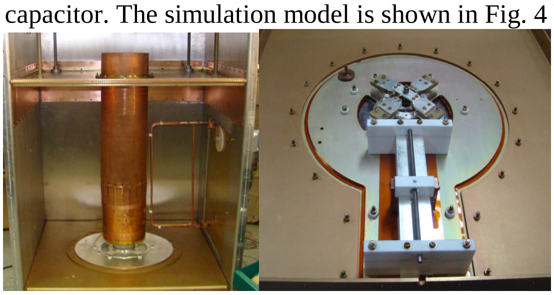
The anode DC power supply is designed to give 7.9kV potential, while the grid bias is set to -230V, letting a small DC current flowing through the tube, as a compromise of efficiency and linearity. The residual anode voltage was estimated as 1kV, giving a voltage swing about 6.9kV. These parameters are used to determine the load line in EMAIC tools, yielding the operating parameters, as listed in Tab.1.

Table 1. Calculated parameters for the amplifier

Anode potential	7.9KV
Screen potential	765V
Grid potential	-230V
Anode DC Current	1.7A
Anode RF Current	3.1A
Anode RF resistance	2.13kohm
Output power	10kW
Anode dissipation	3.8kW
Anode efficiency	63%
Gain	33dB

Input, Output and Neutralization Circuits

The output circuit was simulated using CST MWS, in which the output stage of the tube is treated as a vacuum capacitor. Load impedance of 2.13kohm is represented as a discrete component through the geometrical center of the capacitor. The simulation model is shown in Fig. 4 b).



a) Anode tank b) Input and neutralization

Figure 5: Pictures of the amplifier test stand

The input circuits consist of a vacuum coupling capacitor and a strip line inductor. The strip line and the input capacitance of the tube form the resonance, and the coupling capacitor adapts it to 50omh. The neutralization circuits pick up small amount of output power, feedback to the ground side of the strip line. In such a case, the nature of the tube current conduction will ensure the feedback to be a negative one. These two sections are shown in Fig.5.

TEST OF THE AMPLIFIER

Low Level RF Measurements

The low level RF measurements are performed using vector network analyzer. Note that difference still exists between tube cold and hot parameters, the major task for low level measurements is to adjust the input, output and the feedback loop not far from its optimal status. The result of the cold tests with VNA is that, input S11=-52 db@44.5MHz; output S22=-41db@44.5MHz; input output transfer S21=-34.5db @44.5MHz.

High Power Tests

The high power test for the moment is only done with a 20kW dummy load. The 7 hours endurance test shows that the amplifier itself is stable for output 9.2kW fundamental RF power at 44.5MHz. Afterwards, when the driven power increases, it reaches a salutation state as the anode current increase slowly and screen current increases linearly with input power. It is believed the test stand amplifier can give more power once the anode potential is increased.

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