SLOTTED LINE POWER TESTING OF THE DIRECTLY COUPLED RF AMPLIFIERS

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Abstract

The direct coupling of radiofrequency (RF) power amplifiers to their cavities has many advantages compared to the 50 Ohm feeder line coupling. The main disadvantage of the direct coupling is the fact that its power testing needs to be done with the amplifier coupled to the cavity because a 50 Ohm water cooled resistor can not be used for that purpose due to a lack of the appropriate impedance matching. We found a solution to this problem in using a longitudinally slotted coaxial line short-circuiting the amplifier cabinet. The slotted line accommodates a 50 Ohm water cooled resistor in parallel to the short-circuiting plate, enabling one to vary the quality factor of the amplifier cabinet by moving the resistor connection along the line. The solution was used to test the (50 kW) power amplifiers of the RF system of the VINCY Cyclotron long before the assembling of its cavities.

INTRODUCTION

The TESLA Accelerator Installation, in the Vinča Institute of Nuclear Sciences, consists of three machines: a compact isochronous cyclotron, the VINCY Cyclotron, an electron cyclotron resonance heavy ion source, the mVINIS Ion Source, a volume positive or negative light ion source, the pVINIS Ion Source, and a number of low energy and high energy experimental channels [1].

The VINCY Cyclotron is designed as a multipurpose machine. With the mentioned ion sources, the installation programs for use will be the basic and applied research in physics, chemistry and biology, development of materials and nuclear technologies, production of radioisotopes and radiopharmaceuticals, and proton therapy.

The VINCY Cyclotron has two poles with the diameter of 2000 mm and four sectors per pole. The bending constant is 145 MeV and focusing constant is 75 MeV. The magnetic structure of the cyclotron consists of ferromagnetic elements, main coils and correction coils. All sides of the sector i.e. radial, azimuthal and axial sides are shimmed. The distance between the magnet valleys is 190 mm and the minimal distance between magnet hills is 31 mm. The maximal value of the magnetic induction at the center of the cyclotron is 2.016 T. The extraction radius is 860 mm.

RADIOFREQUENCY SYSTEM

Radiofrequency system consists of two resonators, each one powered by its own amplifier chain, control and safety subsystem [2]. Resonators are of $\lambda/4$ type with the resonant frequency in the range from 17 MHz to 31 MHz. The coarse changes of the eigenfrequency are performed via a sliding short while fine tuning is performed by a trimming loop. Both amplifier chains begin with frequency synthesizer and consist of tree amplifiers. The first stage, a predriver amplifier is a commercial wideband amplifier MARCONI H1000, modified to have an operating range up to 31 MHz, and to be driven by a frequency synthesizer. The second and third stages are custom made driver and power amplifiers in cascode configuration. The driver amplifiers are realized with a 20 kW tetrodes in the grounded cathode configuration and the power amplifiers are realized with 75 kW tetrodes in the grounded grid configuration [3]. The power amplifier is directly coupled to the resonator via coupling line and coupling loop (Fig. 1a). Actually, a completely new approach of direct coupling is applied - the detuned primary coupling [4].

DETUNED PRIMARY COUPLING

The power amplifier cabinet and coupling line with coupling loop forms a $\lambda/2$ resonant structure (primary) inductively coupled to the RF resonator which is a $\lambda/4$ resonant structure (secondary). The position of the coupling loop is fixed, and the desired dee-to-anode voltage ratio is acheived by detuning the eigenfrequency of the primary relative to the eigenfrequency of the secondary, without changing the coupling factor (Figure 1a).

The detuned primary coupling have several crucial advantages over conventional coupling method and direct coupling. First, there is no impedance matching on both sides of the 50 Ω feeder line, and there is no motion in vacuum close to the vacuum window of the coupling line. In the case of the arc sparking between the dee and anti-dee, the load impedance of the power tube does not undergo a large jump. Namely, in standard direct coupling, load impedance of the power tube in the case of arc sparking undergoes a large jump of few tens of dB because the secondary is short-circuited. In the case of detuned primary, this impedance jump is not too large i.e. it is in the range of tens of % of the magnitude in normal operation [4,5].

The main disadvantage of the concept of direct coupling, and detuned primary coupling as well, is that comercial amplifiers are not available, and one is forced to fabricate custom made amplifiers. The main reason for the lack of comecially available amplifiers for direct coupling is the impossibility of testing the amplifer without an RF cavity. In this paper we present a solution to this problem, i.e. the method of testing direct coupled amplifiers without accompanied RF cavity (Figure 1b).

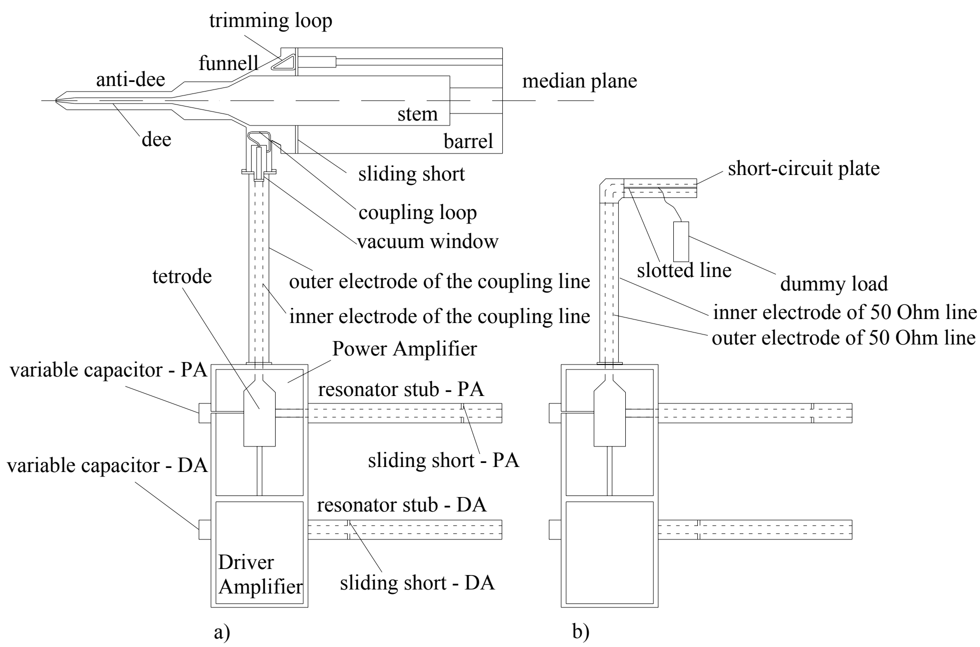

Figure 1: a) A schematic diagram of one of the resonators with the coupling line and the coupling loop of the RF system of the VINCY Cyclotron. It includes one of the drivers and power amplifiers of the RF system. b) A schematic diagram of a test setup of the power and driver amplifiers of the RF system of the VINCY Cyclotron.

SLOTTED LINE POWER TESTING

A solution to the problem was found by using a longitudinally slotted coaxial line short-circuiting the amplifier cabinet (Fig. 1b). The slotted line accommodates a 50 Ohm water cooled resistor in parallel to the short-circuiting plate enabling one to vary the quality factor (i.e. power consumption) of the amplifier cabinet by moving the resistor connection along the line.

RF amplifier has two adjusting elements (Fig. 1a): a lateral coaxial stub with sliding short and a vacuum capacitor which ensures that a λ/2 resonant structure can be achieved. Two adjusting elements were needed to avoid high order modes in the RF amplifier [6]. Load impedance of the power tetrode has to be real or very close to a real value and around 2 kΩ (amplifier class C, anode RF voltage is 10 kV and output power is 50 kW). Resonance condition (when the tetrode can "see" a real impedance) in the λ/2 structure is achieved by mentioned adjusting elements. The quality factor of the cabinet structure alone (not coupled to the resonator) is about 1000 (depending on the working frequency, 17 MHz to 31 MHz), which gives a power consumption of only about 0.3 kW. To increase the power consumption of the tetrode, one can add a 50 Ohm water cooled resistor in parallel to the short-circuiting plate of the coaxial line (Fig. 1b). The quality factor (i.e. power consumption) of the amplifier cabinet can be adjusted by moving the resistor connection along the line, since the cosine-like voltage distribution along the line changes from zero to nominal 10 kV close to the tetrode, corresponding to power consumptions for various positions of the resistor connections along the line between zero and very high values.

Figure 2: A photo of the 40 kW dummy load coupled to the slotted line, as a test setup arrangement for the power test of the power and driver amplifiers.

The adjustable resistor connection along the line is achieved by fabricating a slotted segment of the resonant coaxial line (Figs. 2 and 3), accommodating a sliding dummy load connection. In power tests, a 40 kW dummy load was used while amplifier class was AB.

A parameter which was unknown was the length of the slotted part of the line that can accommodate the resistor connection for the needed power consumption at working frequencies of the cabinet. Let us assume that the voltage distribution along the line is not perturbed by connecting the resistor. For getting a 40 kW power consumption of the load, the line voltage at the connection should be around U=1400 V, since the power dissipated in the resistor will be

$$P = U^2/R, \text{ while } R = 50\ \Omega$$

Calculation based on the transmission line theory gives the slotted part length of about 400 mm, measured from short-circuit of the slotted line, which covers the necessary range of positions of the resistor (Table 1). We decided to fabricate a longer slotted line, of about 800 mm, to have a more convenient situation for adjusting and fabrication.

Table 1: The results of calculations for the resistor position measured from the short-circuited end of the slotted line. The voltage (U) and current (I) amplitudes are given.

Freq. [MHz]	Resistor position [mm]	U at res. position [kV]	I at res. position [A]	U at 800 mm [kV]
17	390	1.406	198	2.855
31	220	1.405	196	4872

Working points of the RF amplifier, i.e. positions of the adjusting elements, were determined for different frequencies by low level measurements with the model of the resonator coupled to RF amplifier [4, 5, 6]. These measurements also showed that the assumption of the voltage distribution along the line not being perturbed by connecting the dummy load to the resonant structure was a good approximation.

The fabricated slotted line allowed us to test the power amplifiers of the RF system of the VINCY Cyclotron long before assembling of its cavities [7].

Figure 3: Photo of the detail of the connection of the dummy load cable to the slotted line.

POWER TEST OF THE AMPLIFIERS

Using the described solution, the power and driver amplifiers of the VINCY Cyclotron were successfully tested. Unfortunately, the commercial dummy load of only 40 kW was available for testing, and this was the only reason why the amplifiers were not tested at full output power (50 kW). Output power was measured with three different methods: calorimetric measurements that were performed on cooling water, direct measurements of the output RF voltage at the anode of the power amplifier and directional coupler is used for voltage measurements near the dummy load connection. Values for the output power obtained with these different methods differs less than 10 %.

CONCLUSION

The RF system of the VINCY Cyclotron uses completely new type of direct coupling – the detuned primary coupling between the power amplifier and the resonator. The power and driver amplifiers were fabricated long before the resonators. The described solution using the slotted line accompanied with adequate dummy load allowed us to perform power tests of the power and driver amplifiers of the RF system. Nevertheless, the solution allows testing of any type of directly coupled amplifier before the resonator (load) is constructed.

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