# DEVELOPMENT OF 20 kW RF AMPLIFIER FOR COMPACT CYCLOTRON*

Seung Hyun Lee, H.S. Song, J.H. Kim, T.V. Cong, H.S. Kim,
Lee Y. S., Y. H. Yeon, Jong Seo Chai,#
WCU Department of Energy Science / School of Information & Communication Engineering,
Sungkyunkwan University, Suwon 440-746, Korea

*Abstract*

Compact cyclotron for PET RI production accelerates H- ions using electric field. For accelerating ions in cyclotron, RF amplifier is developed to transmit RF power to RF resonating cavity.

RF amplifier generates high-power RF signal up to 20 kW with narrow band frequency. The amplifier device was used of triode vacuum tube operated in cathode-driven. Impedance matching systems were composed of bridge-network system. Components of impedance matching system had rigid structure to endure high-power RF signal. Variable inductors of matching components have been used of short-bar movement system for changing reactance of characteristic impedance. The experiment results were measured by VSWR meter and network analyzer.

## INTRODUCTION

Compact cyclotron for PET RI production has a role to accelerate H- ions to 9 MeV energy level. For accelerating ions from PIG ion-source, electric field (E-field) is needed up to 40 kV in this cyclotron. In RF cavity, acceleration gap is about 3 mm and loaded Q-factor is about 1500. It means that RF amplifier would transmit 8 kW RF signal [1]. Also RF amplifier could satisfy stability in operation, because cyclotron emits continuous beam in continuous wave (CW) RF operation mode [2].

This paper describes the development of power amplifier stage of RF amplifier from design to manufacture. The operation is accomplished in CW mode for cyclotron operation and pulse wave modulation (PWM) for RF cavity conditioning. The result of experiments to transmit RF signal has been measured by VSWR meter. And network analyzer is confirmed frequency response.

## AMPLIFIER REVIEW

Figure 1 shows the scheme of RF amplifier system. It consists of power supply stage and RF amplification stage. Operation sequence was controlled by PLC unit. Filament source is consisted of AVR transformer.

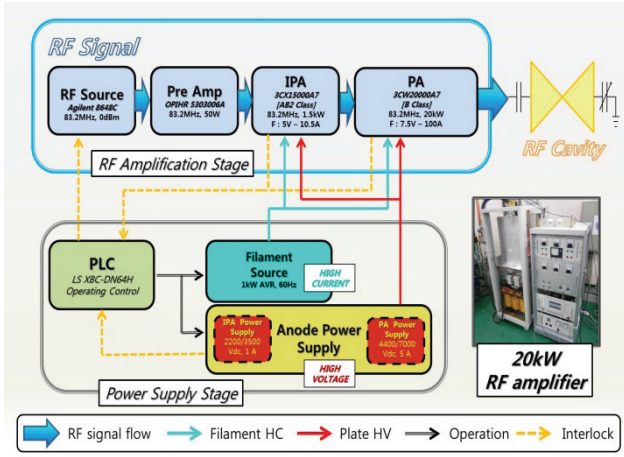


Figure 1: Scheme of RF amplifier system.

Anode Power Supply (APS) in power supply stage could generate DC voltage with two values. It makes the difference gain of amplification. Power amplifier (PA) stage is a main stage for 20 kW RF amplification. It consists impedance matching circuits to match the characteristic impedance as 50 Ω, and filter circuits to block RF leakage signal for filament and plate stage. Table 1 is summarised of RF amplifier operating parameters.

Table 1: Operating Parameters

| Parameter | Value |
|---|---|
| Resonating frequency | 83.2 MHz |
| Maximum Driving RF Power | 1.5 kW |
| Maximum Output RF Power | 10/20 kW |
| Maximum DC anode voltage | 4000/7000 V |
| Maximum DC anode current | 5 A |
| Idling DC anode current | 180 mA |
| Characteristic Impedance | 50 Ω |
| Main Power source | 380 V / 92 A - 3rd Phase |
| Maximum Gain of amplifier | 15 dB |
| Operating Efficiency | 65 % |

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# jschai@skku.edu

## CIRCUIT DESIGN

The circuits consisted of 3 parts – vacuum tube, filament/anode low-pass filter, and impedance matching circuit. For design circuits, all of circuits were simplified using passive elements.

### *Triode Tube Operating Parameters*

EIMAC 3CW20000A7 was used as amplification device. It is high-mu power triode vacuum tube. Triode is more stable in operation than pentode and tetrode because of RF power consumption [3]. To using this, 20 kW RF amplifier was designed in cathode-driven of Class-B mode at grid-grounded for high stability [4]. It satisfies the cyclotron operation feature. Vacuum tube characteristics were shown in Table 2.

Table 2: Vacuum Tube Characteristics

| Parameter | Value |
|---|---|
| Filament Voltage/Current | 7.5V/100A |
| Grid dissipation | 500W |
| Input impedance | 59pF ∥ 33Ω |
| Output Impedance | 36pF ∥ 980Ω |
| Cooling | Forced Air (250cfm)<br>Water cooling (18 l/min) |

### *Filament/Plate Low-Pass Filter*

Filament of vacuum tube emits electrons to the plate when high voltage derived. If amplifier is in operation, the output power could affect electrons flow. It makes not only the distortion of output RF signal, but high-voltage surge on plate that could make the APS breakdown [3]. To prevent these problems, low-pass filter circuit was designed using lumped elements. Inductors were used as elliptical type air coil designed by

$$L = \frac{d^2 * n^2}{18d + 40l}$$

L is inductance in mH, d is coil diameter in inches, l is coil length in inches, n is number of turns [5]. Capacitors were selected of ceramic capacitor to endure high currents.

### *Impedance Matching Circuit Design*

Vacuum tube is divided as cathode and anode. When input signal flows to cathode, output signal is amplified in anode. Each stage would be matched at 50 Ω to decrease the reflect power. Elements of matching circuit consisted of L-C passive elements. These elements could minimize the RF power loss [6].

Characteristic impedance of vacuum tube was derived by

$$Z = \left(R_{parallel} \parallel C_{parallel}\right) = 1 \div (1/R_p + 1/jwC_p)$$

Matching circuits were composed of bridge-network system. This carried out both impedance matching and RF signal filtering. It passes only specific operating frequency. Inductors of matching circuit were made of rigid plane strip-line structure. Between the planes, movable short-bar was attached to change the value of inductance. In variable inductor, all of planes were used of copper plate covered with high-purity silver. It decreases the resistivity and surface roughness. Capacitors were used of NPO ceramic capacitors which has low temperature coefficient. It could endure high power RF signal. Coupling capacitors which have high capacitance value were used to block DC signal and to transmit RF signal with no reflection. Designed power amplifier equivalent circuit was shown in Fig. 2.

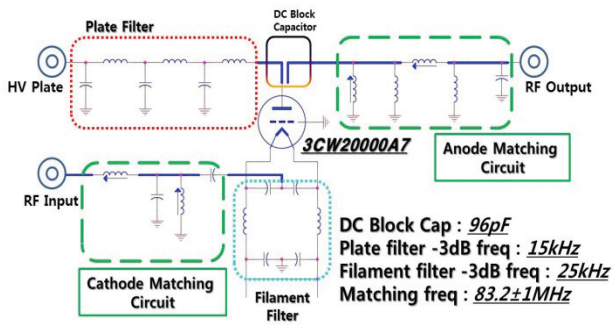


Figure 2: Equivalent circuit of power amplifier design.

## MANUFACTURING

RF amplifier was fabricated in a single case. The size of PA stage is 490 * 685 * 650 $mm^3$. Material of case is alumina. Planes of case were attached with finger stocks to maximize the contact surface. Voltage signals from power supply were connected with feed-through capacitors that block the RF leakage.

Variable inductors were designed by CATIA 3D [7]. It concerned electric fields data to find overheat position. After design, they were confirmed the value by using HP 85047A network analyzer. Anode DC block capacitor was used of 5-layer Kapton® film. Transmission line was consisted of a 36 m (10λ) – 3 1/8" rigid cable. In transmission line, CONNECTICUT MICROWAVE 270026 directional coupler was connected to measure the forward and reflect power. If high-reflect power was generated, surge-short bar could bypass RF signal for preventing vacuum tube breakdown. More 4 kW reflect power generates unexpectedly, PLC control unit orders to automatically turn off APS. Figure 3 was summarised of RF amplifier manufacture.




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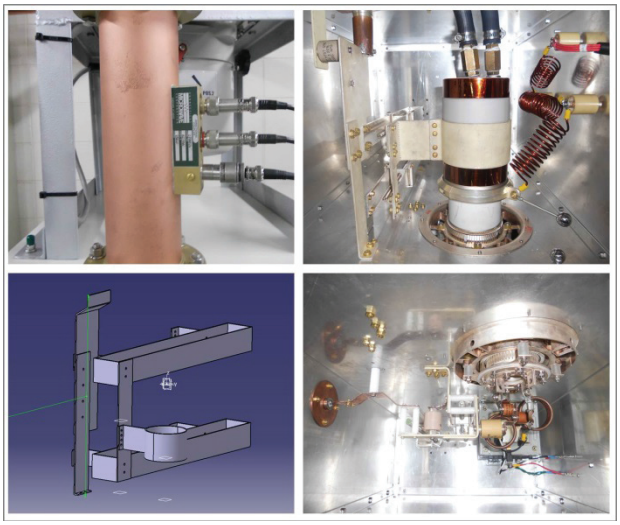

Figure 3: Power amplifier manufacture.

## EXPERIMENTS AND RESULTS

Characteristic impedance value was calculated by HP 85047A network analyzer. Parameter of S11 in cathode is -29.3 dB, anode value is -30.3 dB in 83.2 MHz. The unloaded Q value of amplifier output was about 420. Result of impedance matching was same as Fig. 4.

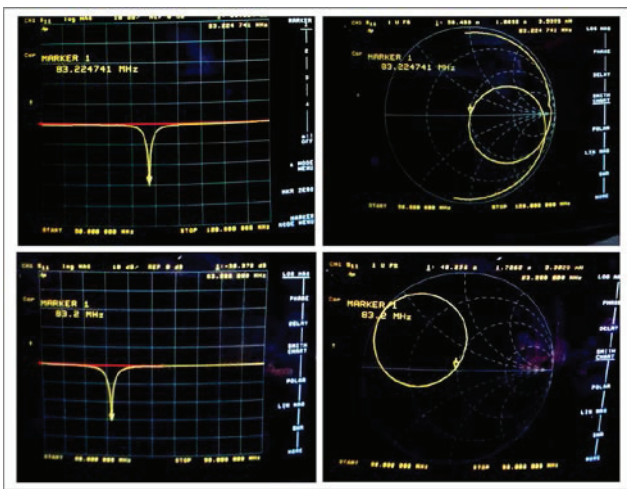

Figure 4: Results of impedance matching cathode (upper) and anode (lower).

RF power experiment was performed with dummy-load in CW mode to dummy load. Every experiment, 30 minutes for cathode heating time, then 90 minutes for RF transmitting test were allowed. Experimental condition was written as below:

- Operating frequency is 83.2 MHz fixed.
- Driving power is restricted maximum 500 W.
- Operation mode is separated as 4000/7000 $V_{dc}$.
- RF power is measure by DAIWA CN-801 HP.
- HP 8595E spectrum analyzer and Agilent Infinium oscilloscope are used.

RF output transmit result was shown in Fig. 5.

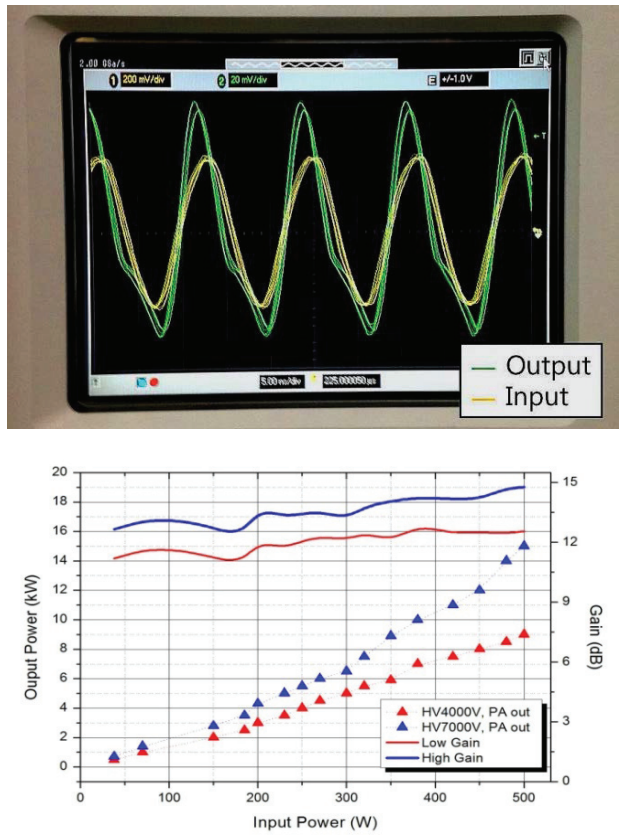


Figure 5: RF transmit measurement waveform (upper) and power transmit (lower).

## CONCLUSION

In experiment, maximum amplification gain is about 15 dB. It shows that output RF power is 15 kW when driving power is 0.5 kW. Phase shift of RF signal from input to output is 43 °. When high-power RF output is generated in anode part, the temperature of connection point in variable inductor is about 80-90 ℃. It would be modified to change the structure of inductors.

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