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Development of an Automatic Frequency Control (AFC) System for RF Electron Linear Accelerators

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1. Introduction

The Radiation Equipment Research Division of the Korea Atomic Energy Research Institute has been developing and upgrading a medical/industrial X-band RF electron linear accelerators. The medical compact RF electron linear accelerator consists of an electron gun, an acceleration tube (accelerating structure), two solenoid magnets, two steering magnets, a magnetron, modulator, an automatic frequency control (AFC) system, and an X-ray generating target. [1-6]. The accelerating structure of the component is composed of oxygen-free high-conductivity copper (OFHC). Therefore, the volume of the structure, hence, its resonance frequency can easily be changeable if the ambient temperature and pressure are changed. If the RF frequency of the 9300 MHz magnetron and the resonance frequency of accelerating structure are not matched, performance of the structure can be degraded. [7]. An AFC system is automatically matched with the RF frequency of the magnetron and resonance frequency of the accelerating structure, which obtained a high output power and reliable accelerator operation. In this paper, the design, fabrication, and RF power test of the AFC system for the X-band linac are presented.

2. Design and Specifications

2.1 Pillbox Cavity Model

The relationship between the radius and the frequency of the accelerating structure is as following. The general dispersion relation of the cylindrical resonator in transverse magnetic (TM) mode is given by Eq. (2.1).

$$\omega^2 / c^2 = k^2\mathrm{mn} + k^2\mathrm{z} \qquad (2.1)$$

where $k_{\mathrm{mn}} = x_{\mathrm{mn}} / R$ and $k_{\mathrm{z}} = 2\pi / \lambda = p\pi / l$, p = 0,1,2… Some values of the zeros of the Bessel functions, x_{mn}, are given in Table 2.1.

Table 2.1. Zeros of $J_{\mathrm{m}}(x)$ or x_{mn}.

m	x_{m1}	x_{m2}	x_{m3}
0	2.405	5.520	8.654
1	3.832	7.016	10.173
2	5.136	8.417	11.620

Although the accelerating structure is fabricated in accordance with the designed value of the resonance frequency and tuned, the volume is changed depending on environmental factors, such as ambient temperature and pressure. As in Eq. (2.2), when the volume (radial direction, R) of the accelerating structure of transverse magnetic (TM_{010}) mode is changed, the resonance frequency is also changed accordingly. x_{mn} is the nth root of the equation, $J_{\mathrm{m}}(x_{\mathrm{mm}}) = 0$. The integers m and n take the values m = 0, 1, 2…, and n = 1, 2, 3… The resonance frequencies are given by

$$\omega_{mnp} = \frac{1}{\sqrt{\varepsilon\mu}}\sqrt{\frac{x_{mn}{}^2}{R^2} + \frac{p^2\pi^2}{l^2}} \,. \qquad (2.2)$$

2.2 Phase-locked loop (PLL) Model

AFC system is configured based on the PLL model, which includes an RF section, intermediate frequency (IF) section, and local oscillator (LO) section. Some resonance frequency controllers use a DC motor, chain, and potentiometer to store the position and to tune frequency. However, we use a step motor to remove the additional components and the concept of the super-heterodyne method is used for frequency downconversion to minimize the phase delay.

Figure 2.1 is a basic schematic diagram of the PLL; in general, it is composed of four key elements:

1. Phase Detector (PD)
2. Loop Filter (LP)
3. Voltage-Controlled Oscillator (VCO)

The PLL is a non-linear analog device that uses a negative feedback loop to reduce or zero the phase difference between the input signal and the output signal. Since the phase difference decreases, the two signals of frequency become equal.

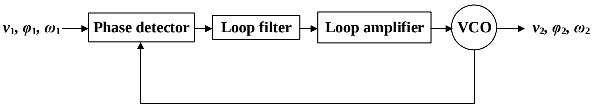

Fig. 2.1. Concept of the PLL.

2.3 Design Specifications

An overall block diagram of the AFC system is shown in Fig. 2.2. The frequency tuning range is equal to the tuning frequency of the magnetron with a maximum of 9300 ± 25 MHz. The forward power and reflected power were set to be less than 20 dBm. The AFC system can also support TCP/IP remote data communication. Additionally, to consider the radiation shielding during operation, it was designed to have small openings. The RF power is generated from the magnetron and the forward power and the reflected power are coupled by the directional couplers. When the output pulse is transmitted through the internal process, the motor rotates the frequency tuning shaft of the magnetron in accordance with the AFC input pulse.

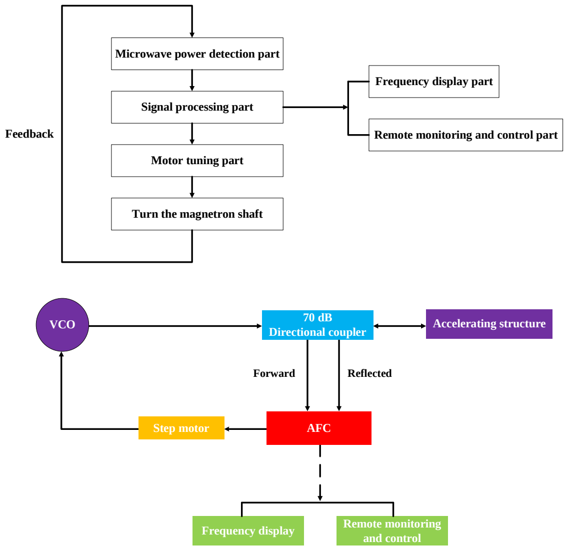

Fig. 2.2. Overall system block diagram of the AFC system.

3. Test Result

As shown in Fig. 3.1, the AFC system could lock into the operating frequency within about 10 minutes due to the warm-up time of the accelerator. The locked frequency was 9312.3066 MHz, and the frequency deviation was about 0.01%. As soon as the frequency was locked to around 9312.3066 MHz, the reflected RF power was also decreased simultaneously as shown in Fig. 3.1.

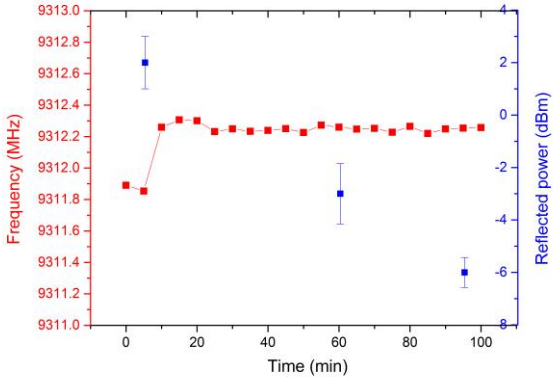

Fig. 3.1. Trends of RF frequency and the reflected power for two hours AFC system operation.

4. Conclusions

The main function of the AFC system is automatically matching of the resonance frequency of the accelerating structure and the RF frequency of the magnetron. For the frequency tuning, a fine tuning of 10 kHz is possible by rotating the tuning shaft with a rotation of 0.72 degree per pulse. Therefore, the frequency deviation is about 0.01%, and almost full RF power (2.1 MW) transmission was obtained because the reflected power is minimized.

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