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RF System of ICR Proton Linac

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At the ICR Kyoto University, a 7 MeV proton linac has been operated. Two klystrons are main amplifiers and driver-amplifiers are solid state amplifiers for the linac. It can feed the RF power of 800 kW at the frequency of 433.3 MHz ±1 MHz. The pulse width is 65 μS and the repetition is 180 Hz. An RF control circuit regulates the phase and the amplitude of the RF field in the accelerator cavity. It consists of an RF interlock, a phase locked loop (PLL) and an auto level controller (ALC). The error of the RF phase is within ±3° with PLL and the error of the amplitude is ±0.2 % with ALC.

KEY WORDS: Linac / Klystron / RF control / PLL / ALC

1. Introduction

The ICR proton linac is an accelerator consisting of a 2 MeV radio frequency quadrupole (RFQ) and a 7 MeV Alvarez linac. The RF system is required to feed the high power RF to the accelerator cavities. The phase and the amplitude of the RF pulse must be stable. The schematic diagram of the RF system is shown in Fig. 1 [1], [2].

The required RF power is 600 kW for the RFQ and 490 kW for the Alvarez cavity at the beam current of 30 mA. The pulse width is 65 μS and the maximum repetition is 180 Hz. A

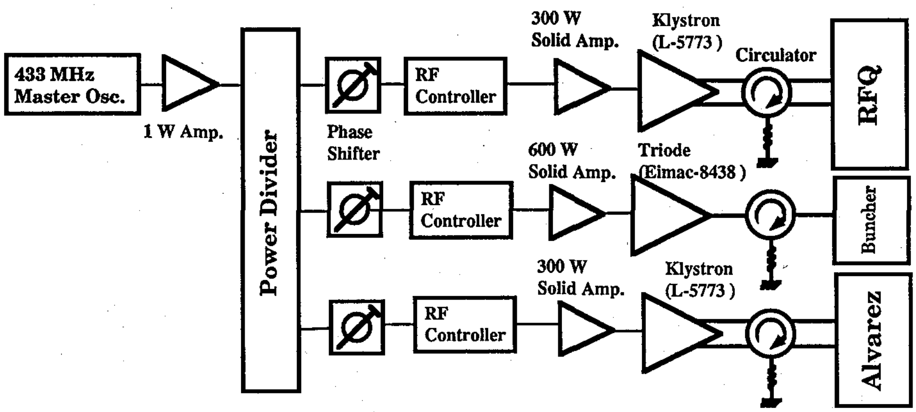

Figure 1 The schematic block diagram of the RF system for the ICR proton linac.

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klystron was chosen as a main RF amplifier. The RF frequency is 433 MHz that is higher than that of the conventional ion linacs. The choice of the high RF frequency makes the use of the klystron possible. The driver-amplifiers are solid state amplifiers. The required power is only 100 W because of the high gain of the klystron. This RF system has following merits. The operation and the maintenance are easy and the reliability is improved compared with the conventional tetrode system.

The RF amplifiers for the buncher are different from that of other cavities [3]. A triode (Eimac 8938) is a main RF amplifier because the required power is only 3.7 kW for the buncher cavity. The maximum output power of the triode is 5.6 kW at the pulse width of 120 μS and the repetition of 180 Hz. The driver-amplifier is a 600 W solid state amplifier.

There are many disturbances to the RF field. The RF field error makes the beam quality worse and may cause the beam loss. The RF control circuit is needed to regulate the RF field. It consists of some units as shown in Fig. 2. They are,

- an RF interlock circuit,
- a resonant frequency control circuit,
- an auto level control (ALC),
- a phase locked loop (PLL),
- an RF boost circuit.

2. RF amplifiers

The major RF amplifiers are 300 W solid state amplifiers and the klystron. The 300 W amplifier is a driver-amplifier for the klystron. It is a class A type FET amplifier. The errors of the amplitude and the phase of the output RF are within ±0.3% and ±1°, respectively. The phase error is much smaller than that of the klystron.

The klystron is L-5773 (Litton). The RF power from the klystron is fed to the accelerator cavity through the waveguide (WR-2100). Figure 3 shows the schematic block diagram of

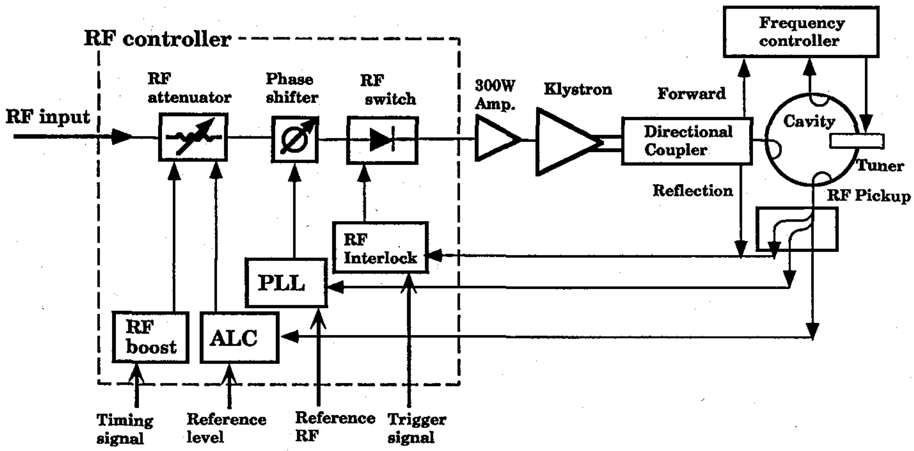

Figure 2 The schematic block diagram of the RF control system.

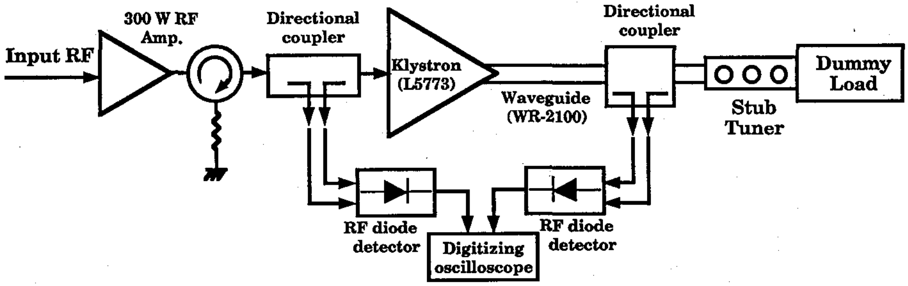

Figure 3 The schematic block diagram of the measurement setup of the output power from the klystron.

the measurement setup of the output power from the klystron. The dummy-load can absorb the RF peak power of 1 MW at the 1% duty factor [4]. The forward and reflected RF power are picked up by the directional coupler. The signals are detected by the RF diode detectors and monitored by a digitizing oscilloscope.

Figure 4 (a) shows the dependence of the output power on the input power at the various frequency. The cathode voltage is 90 kV and the return loss of the dummy-load is -27 dB. The pulse width is 65 μS and the repetition is 18 Hz. The maximum power is over the 900 kW at any frequency. But the available power is 800 kW to maintain the stable operation by the feedback control because the linearity of the RF power is important for the feedback control. Figure 4 (b) shows the gain and the efficiency of the klystron. It was measured at the same condition as the results of the Figure 4 (a). The RF frequency is 433.3 MHz. The efficiency and the gain are 41% and 42 dB, respectively when the output power is 800 kW.

The output power of the klystron is affected by the RF reflection from the accelerator cavity because the load impedance for the klystron varies with the reflection. It happens in the rising time of the RF pulse and by the beam loading or by the discharging in the cavity.

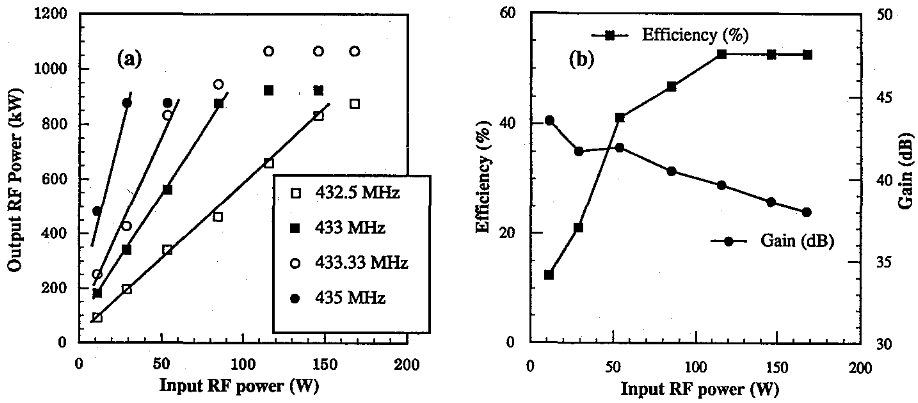

Figure 4 (a) The dependence of the output power on the input power at the various frequency.
(b) The gain and the efficiency of the klystron at 433.3 MHz.
The cathode voltage of the klystron is 90 kV. The pulse width is 65 μS and the repetition is 18 Hz.

The effect depends on not only the reflected power, but the phase in the reflection. Figure 5 shows the relation between the output power and the phase of the reflected power with the various reflected power. The frequency is 433.3 MHz. The amplitude and the phase of the reflected power are changed by the stub tuner. The results show the difficulty of the RF control under the reflection. The output power does not depend on the reflection power when the reflection phase is set to be 40° or −80°. But it is not practical because the length of the waveguide between the cavity and the klystron must be adjusted to change the reflection phase. And the reflection phase is a function of beam current for the beam loading. We installed a high power isolator between the accelerator cavity and the klystron to eliminate such effects at the high current beam acceleration [5]. It consists of a circulator and a dummy-load. It absorbs the reflected power from the cavity. No effect of the reflection is observed after the installation of the isolator.

3. RF control circuit

3-1 RF Interlock

When the RF level in the cavity or the reflected power from the cavity exceeds the critical value, the RF interlock works to protect the system. It stops the RF pulse immediately by an RF switch. The Schottky diode is used in the switch. It works within 10 nS but it takes more time for the RF level in the cavity to go down because of the high Q-value.

3-2 Resonant frequency control

The dependence of the resonant frequency of the accelerator cavity on the temperature is 8 kHz/°C. The temperature of the cooling water is controlled at 35.0°C ±0.1°C. But the resonant frequency of the Alvarez cavity at the high duty operation is 10 kHz lower than that at the low duty operation. There is the local temperature rise in the cavity and it results in the resonant frequency shift. To compensate the shift, the resonant frequency is tuned by the 3

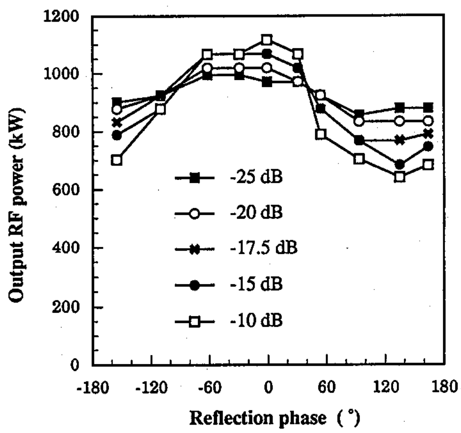

Figure 5 The relation between the output power of the klystron and the phase of the reflected power with various reflected power. The RF frequency is 433.3 MHz.

tuners in the Alvarez cavity. The tuner is a cylindrical block and has the resonant frequency shift of 6.5 kHz/1 mm. In the RFQ cavity, there are 25 tuners that are used for the control of the field distribution. The resonant frequency compensation in the RFQ is not made by the tuners but by the RF frequency tuning of the master oscillator. It means that the resonant frequency of the Alvarez cavity follows that of the RFQ.

3-3 PLL and ALC

The beam loading is one of the disturbances to the RF field. The variation of the amplitude and the phase are,

$$\delta E = -\frac{P_b t}{2W_{cavity}} E,$$

$$\delta \theta = -\frac{P_b t}{2W_{cavity}} \tan \varphi_s,$$

where P_b is a beam power, W_{cavity} is a stored power in the cavity, t is a pulse width of the beam and φ_s is a synchronous phase of the beam. In the Alvarez linac, even if the pulse width of the beam is 10 μS, the field variation is 15% and the phase variation is 5° by the beam loading of the 30 mA.

The fluctuation of the klystron cathode voltage also disturbs the RF field, especially the RF phase. The relation between the fluctuation of the cathode voltage and the phase shift is,

$$\delta \theta = -\frac{2\pi f L}{c} \cdot \frac{\frac{eV_{cath}}{m_0 c^2}}{\left\{\left(1+\frac{eV_{cath}}{m_0 c^2}\right)^2 - 1\right\}^{3/2}} \cdot \frac{\delta V_{cath}}{V_{cath}} \approx 8 \cdot \frac{\delta V_{cath} \times 100}{V_{cath}} \ (°),$$

where f is the RF frequency, L is the distance from the cathode to the collector of the klystron, c is the light speed, m_0 is the rest mass of the electron, V_{cath} is the cathode voltage and δV_{cath} is the fluctuation of the cathode voltage. There are two components in the fluctuation. One is a slow component that is come from the fluctuation of the commercial power supply. The slow fluctuation of the cathode voltage is 0.5% and it corresponds to the phase error of 4°. The other is a fast component that is a droop within the pulse. In our case, the residual droop of the cathode voltage is 1.5%, which is achieved by adjusting compensation capacitor in the divider for the modulating anode. The droop corresponds to the phase error of 12°.

The field error is regulated by the feedback control circuits of the ALC and PLL in Fig. 2. The fast response is desirable to control the various frequency components of the field errors. In the RF system, the cavity has the slowest response because of the high Q-value and the total response is limited by the second slowest element. The physical length of the RF control system also limits the response. The total length is about 75 m and the cutoff frequency is 1 MHz.

The schematic block diagram of the PLL is shown in Fig. 6 (a). The critical element is the phase detector in the PLL. In the phase detector, the pickup and the reference RF signals of 433 MHz are converted down to 5 MHz signals by 50 MHz and 5 MHz offset generators. The time difference of the leading edge between them is measured by the flip-flops. It can detect the phase from 0° to 360° with a good linearity. Figure 7 (a) shows the response of the phase

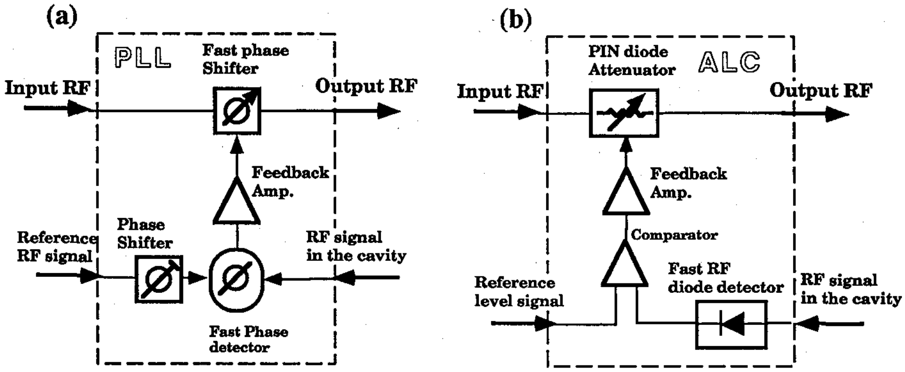

Figure 6 The schematic block diagram of the PLL (a) and of the ALC (b).

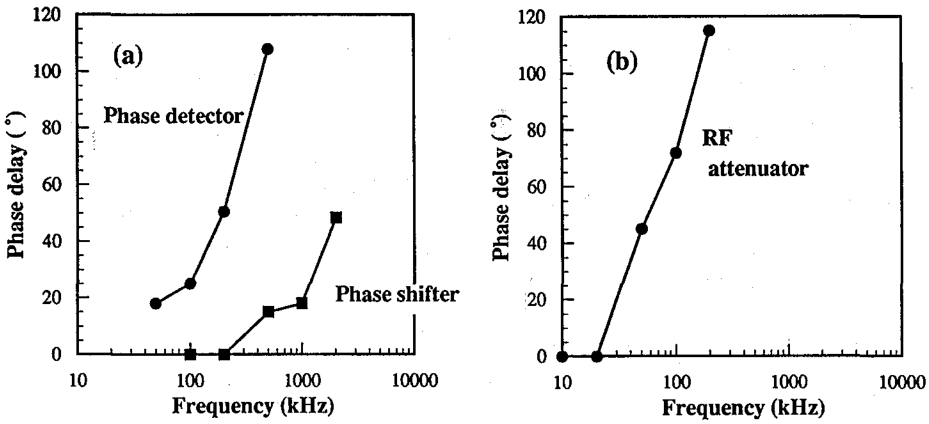

Figure 7 (a) The frequency response of the phase shifter and the phase detector in the PLL.
(b) The frequency response of the RF attenuator in the ALC.
The phase delay is a response delay between the modulation of the input and output signal of the element.

detector. The cutoff frequency is 200 kHz. The feedback amplifier is a series of fast OP amplifiers. The bandwidth is 2 MHz and the gain is more than 20 dB. The phase shifter consists of 90° hybrids, variable capacitors and diodes. The cutoff frequency of the phase shifter is about 2 MHz as shown in Fig. 7 (a).

The schematic block diagram of the ALC is shown in Fig. 6 (b). In the ALC, the critical element is the RF attenuator. It is a PIN diode mixer. Although it has the low distortion of the signal, the response is slow as shown in Fig. 7 (b). The cutoff frequency is 100 kHz. It is close to the response of the cavity. The RF detector is consist of fast amplifiers and diodes. The rise time is 0.1 μS. The feedback amplifier is the same as that of the PLL.

Figure 8 shows the RF signals in the RFQ cavity, which are picked up by the loop on the RFQ cavity. The RF frequency is 433 MHz and the pulse width is 60 μS. The beam current is 0.3 mA and the beam loading is negligible. The field error is mainly caused by the droop of the cathode voltage. The signals are monitored by the fast RF diode detector and by the phase detector. Figure 8 (a) shows the RF amplitude with ALC and without ALC. Figure 8 (b) shows the RF phase with PLL and without PLL. The upper TTL pulses in the figures show the timing when the PLL or ALC is working. The amplitude error of ±0.6% is reduced to ±0.2% with the ALC. The phase error is reduced from ±8° to ±3° with the PLL.

3-4 RF boost

The filling time in the accelerator cavity is

$$\tau = \frac{Q}{\omega},$$

where Q is a Q-value and ω is an angular frequency and τ is a filling time. In the Alvarez linac, the Q-value is 40000 and the filling time is 15 μS. It takes more time for the power level in the tank to reach the final value. The short rise time is desirable to obtain the long beam pulse width. We increase the RF power at the leading 20 μS of the RF pulse, which is called "RF-boost". Figure 9 shows the RF pulse with the RF-boost and without the RF-boost.

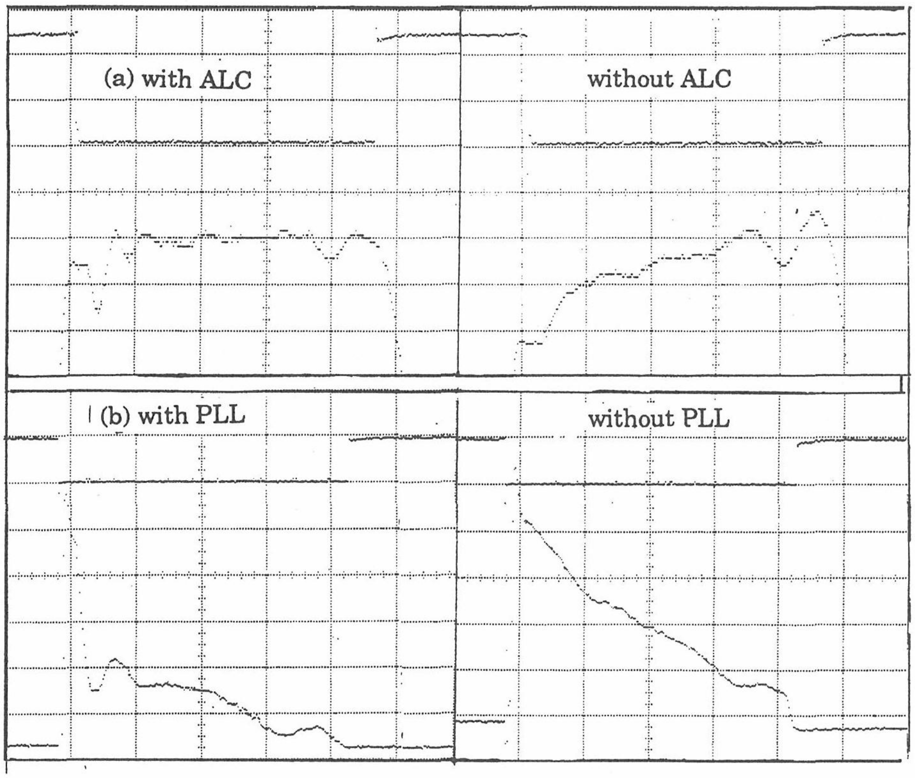

Figure 8 (a) The RF amplitude error with ALC and without ALC in the RFQ cavity (0.5%/div).
(b) The RF phase error with PLL and without PLL in the RFQ cavity (4°/div).
The upper TTL pulse shows the timing when the PLL or ALC is working.
The RF frequency is 433 MHz and the RF power is 540 kW.

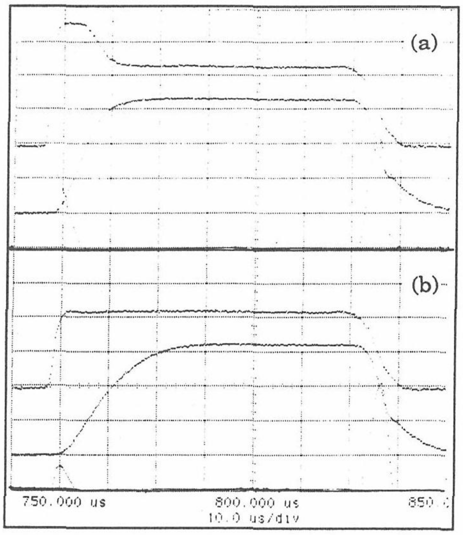

Figure 9 The RF pulse with the RF-boost (a) and without the RF-boost (b) in the Alvarez cavity. The upper pulse shows an input RF power to the cavity and the lower pulse shows an RF field in the cavity.

The flat top of 50 μS is achieved with the RF boost and the ALC. It is supposed that the same circuit is effective for the beam loading compensation.

4. Summary

The RF amplifier system consisting of the solid state amplifiers and the klystrons, can feed the RF power of 800 kW for the ICR proton linac. It has been operated stable. The problem about the reflected power is settled by the high power isolator.

The phase and the amplitude error in the RF field are regulated within $\pm 3^\circ$ and $\pm 0.2\%$ with the PLL and ALC, respectively. It is desirable that the RF phase is regulated within 1° for the high current beam acceleration. The response of each element, especially the phase detector and the RF attenuator must be improved for the purpose.

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