OPERATION OF 432-MHz RF SOURCE FOR THE JHP PROTON LINAC

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Abstract

A test linac of the Japanese Hadron Project (JHP) has been constructed at KEK. High power and high duty rf-source (432 MHz) are supplied for the RFQ and drift-tube (DTL) accelerating cavities by two klystrons. Each klystron can produce maximum 2-MW peak power with ~3% duty (650 μsec pulse-duration and 50 Hz repetition-rate). At the higher duty operation of the klystron, fairly large phase-shift of the klystron output were observed as we expected, because the cathode voltage's sag in the long pulse-duration. In the actual linac operation, a beam loading effect is another reason to require a low-level control for maintaining the cavity rf-field at the proper level and for the phase-lock to the beam. The low-level control of the rf-power is designed to control the power level as well as the phase of the cavity rf-field with controlling the klystron drive-power by the feedback signals. This requires that the klystron must be operated below the saturation. The operation of the rf-system including the accelerating cavities will be reported.

Introduction

The constructions of main components of the JHP-test linac were almost done, and the initial stage high-power conditioning of the accelerating cavity such as RFQ has been completed and accelerated the proton beam successfully even at limited intensities [1]. The high-power processing of the DTL-cavity has just begun. After finishing the high-power aging, the DTL will be linked to the RFQ and be tested for accelerating [2]. The UHF rf-source for these cavities were supplied by the two klystrons; the klystrons are connected to common cathode high-voltage but each anode voltage are controlled individually. From the point of view of the amount of rf-power for these cavities, only one klystron can produce the required power. However, the possibility to control the rf-sources; power-level as well as phasing control, for each type cavity is great advantage with using two klystrons. The power-level for each cavity might be different and be changing depending on the operating condition of the linac. The phase adjustment between the cavities will also be controlled easily in this scheme. The another possibility of the two klystron scheme is the stabilizeation of the cavity field-level and the phase relative to the beam within one pulse-duration by using feedback and feedforward technique. The two type cavities have different Q-value, therefore, individual rf-signal processing might be needed for each cavity system. The JHP-linac is designed to accelerate very intense proton beam [3], this means that heavy beam-loading can be expected at the very long pulse duration (~600 μsec). The fluctuation of the klystron-output caused by the fluctuation of the high-voltage (cathode voltage), and no-constant rf-power and phase within the pulse-duration caused by the cathode-voltage's sag will also require such low-level rf-signal processing. The automatic-level control (ALC) and phase-lock loop (PLL) has been tried in the RFQ cavity system without beam-acceleration. The feasibility of such low-level control may be exhibited even though the parameters for the feedback circuit are not fully optimized yet.

High-Power System

The power supply can feed klystron-beam-power to two klystrons for generating maximum 2MW rf-power with 600 μsec pulse duration at 50 Hz repetition-rate for each klystrons [4]. The anode voltage for modulating the beam current of the klystron is supplied by dividing the cathode voltage with switching by the hard-tube as discussed in reference 4. Therefore the pulse-duration and the beam current of each klystron can be changed separately with applying the common cathode voltage. The high power rf-sources (432 MHz) generated at each klystron are directed to the RFQ and DTL cavities through each WR-1800 waveguide and Y-junction circulator system. During the ALC and PLL test of the RFQ system, both klystrons were simultaneously operated at almost same beam-power and pulse-duration at cathode voltage ~80 kV irrelevant to the output rf-power. Therefore the sag of the cathode voltage didn't depend on the output power but on pulse-duration of each klystron. Actually in the above test, the rf-output of the klystron for RFQ were ≤480 kW and rf for DTL was switched off. The beam current of both klystron was fixed to lowest beam modulation of our system; beam perveance ~ 1.3 x 10^{-6}.

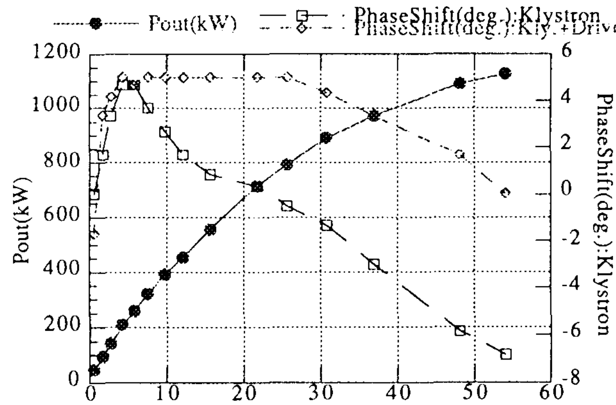

Figure 1: Klystron Output vs. Drive Power

The characteristic performances of the klystron are shown in figure 1. The power levels of ≤480 kW were below enough the saturation and output power is almost linearly controlled by the drive power. On the other hand, the drive-power dependence of the phase shift shows the steep dependence at small drive-power (≤ 5 W) whereas week dependence at higher drive-power. Two phase shift data were taken; klystron itself and klystron + driver amp. This peculiarity can explain the relatively strong phase-shift caused by the ALC at small output region, as discussed later.

Low-Level Control

The block diagram of the low-level control is shown in figure 2. Both of the ALC and PLL were processed by the feedback-controller with adjusting the time constant of the filter. The feedback module was originally developed for TRISTAN accelerator at KEK [5] and was modified for these applications as shown in figure 3. The delay of the both loop is ~1.2 μsec (including the klystron delay of ~200 nsec) without counting the RFQ cavity. The delay was estimated as signal propagation time between the phase-shifter to phase-detector or between the rf-modulator to the rf-detector without the cavity, respectively. The filling time of the RFQ is ~5.2 μsec corresponding to the Q-value of 28000. The band-width of the klystron is more than 2MHz for -1 dB output down [4]. The band-widths of the other components are much wider than the klystron (≥ 10 MHz).

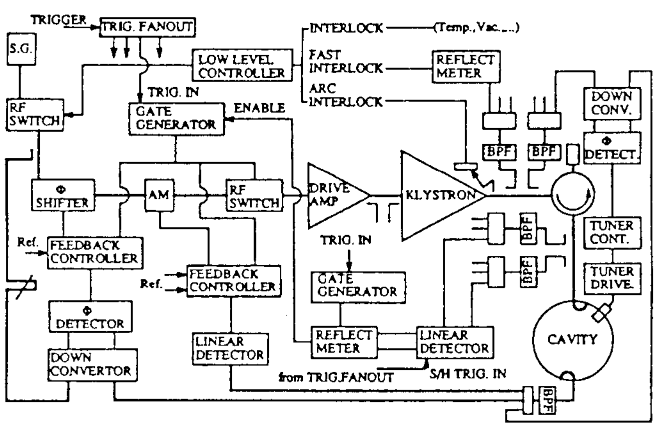

Figure 2: The block diagram of low-level control.

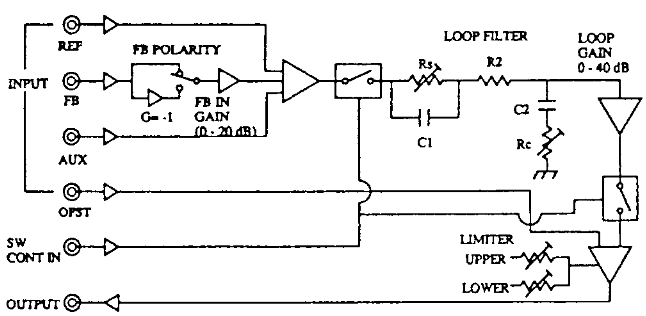

Figure 3: The block diagram of feedback module.
C1=0, C2=0.47μF, R2=1kΩ, Rs=0-10kΩ, Rc=0-1kΩ.

Performances of Feedback

Without any feedback, the klystron output suffered the effect of the cathode voltage's sag (~3.6 kV / 80kV); the droop of output power was ~30 kW at 480 kW output and the phase shift was ~-26° in the 600 μsec pulse duration; the typical pulse shapes of the phase fluctuations of the klystron output are shown in figure 8 for no feedback case. These larger values compared to the values reported in ref.4 are due to the parallel klystron operation. Following tests were carried out in these conditions. The adjustments of the filter's parameters of ALC and PLL are carried out to make flat outputs for dc-reference signals (REF input) in the pulse duration. The obtained flatness (the signal of FB input) for power levels (level of RFQ pickup signal) and for phases are ≤1% (noise level of the detect signal) and ≤±0.3°, respectively.

Results of ALC/PLL

The frequency responses of the closed loop gain were measured by adding the synchronized sine-waves (AUX input) to a dc-reference signal of the feedback module. When the frequency of the sine-wave was greater than 2 kHz more than one-cycle of sine-wave could be observed in the 600 μsec pulse duration and the amplitude of the modulated output could be detected. On the other hand, when the frequency was less than 2 kHz the maximum and minimum of the modulated output were measured by shifting the synchronized phase of the sine-wave relative to the gate-pulse. The results are shown in figure 4, 5 for ALC and PLL, respectively.

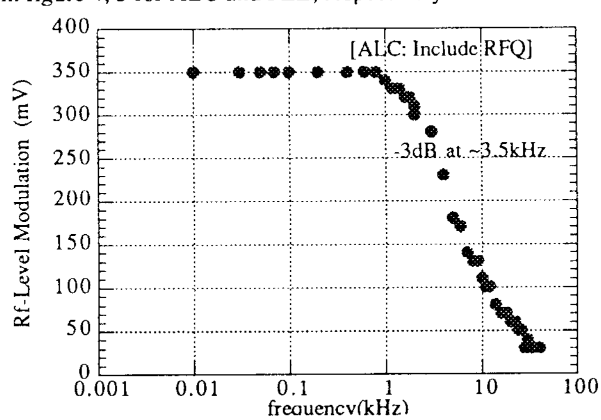

Figure 4: Frequency dependence of the ALC.

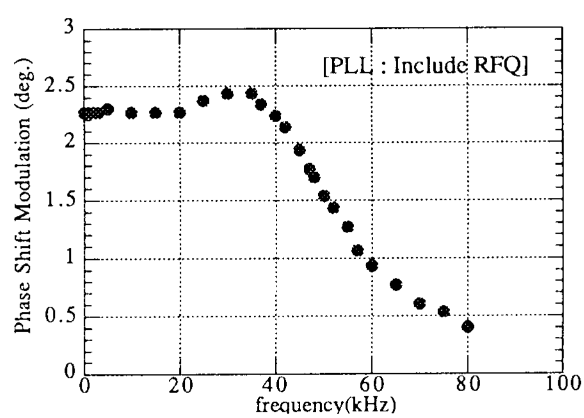

Figure 5: Frequency dependence of the PLL.

Figure 6 shows the step response of the ALC where the square-wave was added to the dc-reference signal instead of the sine-wave in the above test. Typical frequency responses are shown in figure 7. The obtained frequency response of the ALC is rather poor compared to the PLL; -3dB down at 3.5 kHz for ALC, on the other hand 49 kHz for PLL. This is partially because the poor step response of the rf-detector output (~1.8 μsec rise time); almost factor 2 is better for phase-detector output. As discussed in the loop delay, these rise times of rf-detector output or phase-detector output were measured by the step-responses that applied to the rf-modulator or phase-shifter, respectively, therefor these outputs included the every contribution from the whole components (except RFQ cavity) which form the loops such as klystron , driver, circulator, etc. The slower rise-time of the ALC is mainly due to the rf-detector. The difference between the ALC and PLL frequency response can't be attributed to the RFQ, because almost same difference had been observed in the tests where the RFQ was not included in the loop; only klystron's outputs were stabilized. Can the ~1 μsec difference of the rise time between the ALC and PLL explain these frequency dependencies? We didn't fully understand this at this moment.

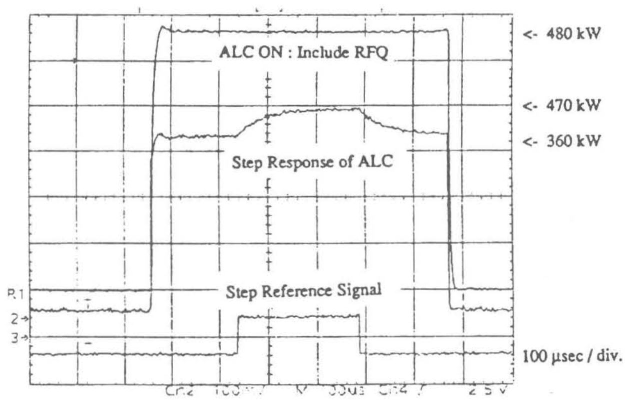

Figure 6: Step response of the ALC.

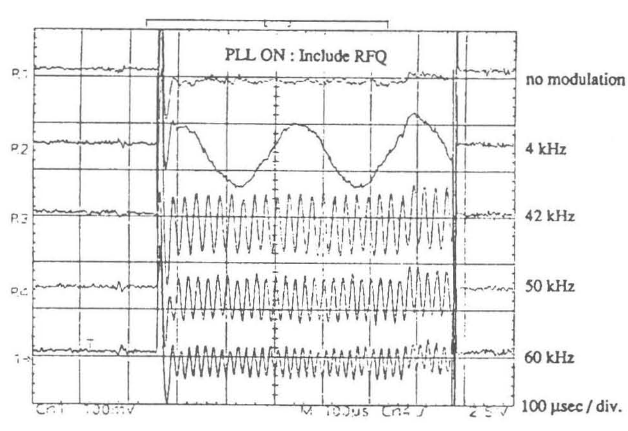

Figure 7: Frequency Response of the PLL. (vertical : 1.7° / div.).

Interference between Amplitude and Phase -Modulation

Even in the absence of the RFQ cavity, the interference between the amplitude and the phase modulation were observed in some operating points. The amplitude modulations of ~9 kW (at Pout~500kW) were observed for the ~13° step phase modulation. No ALC nor PLL was processed here. This is due to the rf-level changing at the phase shifter as a function of the control voltage for phase shift. The reduction of this change will be tried for avoiding possible extra complexity in ALC/PLL simultaneous operation. Figure 8 shows phase modulation due to step amplitude modulation at several output levels; ALC of the klystron is processed and step signal was applied for reference signal whereas PLL was off. This is due to the steep drive-power dependence of the klystron phase at smaller power as shown in figure 1. Typical ALC and PLL tests were done at the proper drive power region. So, no effects of the interference were observed and both feedback loops were works stable in the ALC/PLL simultaneous operation at this moment.

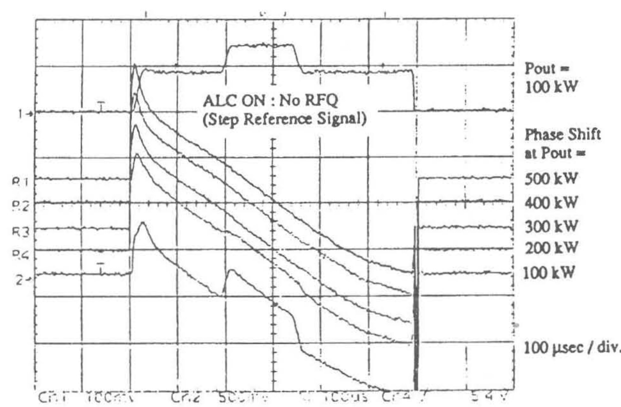

Figure 8: Phase modulation due to step ALC modulation at several output powers. (8° /div. for phase shift).

Summary

The feedback control for the RFQ cavity system has been tried at long pulse operation. The feasibility to compensate the heavy beam loading as well as the stabilization of the cavity field were shown, even though more delicate tuning may be required for actual beam acceleration. The understanding of the reason why the response of the ALC is so slow compared to the PLL is crucial for improving the response time if it is possible. To avoid the unnecessary complication in the future applications, it should be minimized the interference between the amplitude-phase modulation.

References

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