STABILITY EVALUATION FOR LONG FB LOOP DELAY IN THE ACS CAVITY FIELD CONTROL FOR THE J-PARC LINAC 400-MEV UPGRADE

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Abstract

For 400-MeV upgrade of the J-PARC Linac. ACS (Annular Coupled Structure) cavities, which are driven by 972-MHz RF, will be installed.

The ACS cavity has complicated structure. Its Q-value is very low and the operation frequency is tree times high in comparison with that of the SDTL cavity. So the stabilizing control of the ACS accelerating field will be more difficult than present RF system. Further more the chopped beam loading compensation is required. Especially, a debuncher, which has ACS structure, will be located very far from the klystron, consequently the feedback loop delay will be about 1.5 μs. This paper will show the simulation results of the feedback control of the ACS cavity field including long loop delay. As the result, it was found that the required stability could be satisfied.

INTRODUCTION

J-PARC will be one of the highest intensity proton accelerators, which consists of a 400-MeV Linac, a 3-GeV, 1-MW rapid-cycling synchrotron (RCS) and a main ring (MR) [1]. The beam is applied to several experimental facilities, for example, the Materials and Life Science Facility (MLF), the Hadron Physics Facility and the Neutrino Facility.

The linac has the RFQ, 3 DTL cavities and 32 SDTL cavities to accelerate the beams up to 191 MeV. They are driven by 324-MHz RF systems. And, 21 ACS cavities will be install to accelerate the beams from 191 MeV up to 400 MeV [2]. The RF frequency of the ACS is 972 MHz. ACS structure will be also applied to bunchers and debunchers in the high β section. The maximum peak current of the linac will be 50 mA for the RCS injection.

In the present phase, the ACS cavities are not installed yet, and the linac provides 181-MeV beam to the RCS. In this case, the last 2 cavities of the SDTL are applied as debunchers. The 400-MeV upgrade of the linac is in progress now.

The field stabilization control of the ACS cavity will be more difficult than that of the present 324-MHz RF systems because the RF frequency is three times higher and its loaded-Q value (Q_L) is about 8000; it is very low in comparison with the DTL and SDTL cavities of which Q_L is about 20000. Especially, the second debuncher (Debuncher2, DB2) will be located very far from the klystron as shown Fig. 1: the distance between two of them will be longer than 110 m. Its feedback loop delay is estimated to be about 1.5 μs. This delay is about twice of usual case. Therefore, the FB control performance including the long loop delay should be evaluated absolutely for the DB2. This paper will show the simulation results of the feedback control of the ACS cavity field including long loop delay.

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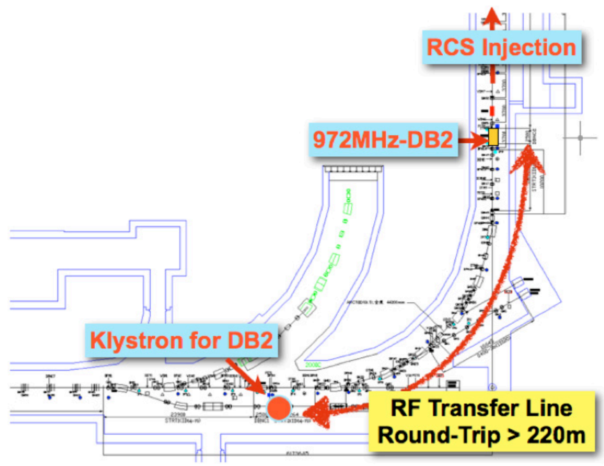

Figure 1: Location of the Debuncer2 and the klystron before the RCS injection.

BEAM STRUCTURE AND RF SYSTEM

Maximum peak current of the linac will be 50 mA. Macro-pulses of 500-μs widths are accelerated in 25-Hz repetition. An RF-chopper, which is located in the medium energy beam transport line (MEBT), chops the macro-pulse into medium pulses as synchronized with the RCS RF frequency of about 1 MHz.

For high quality and high intensity beam acceleration, the stability of the accelerating field is one of the most important issues. Since the momentum spread (Δp/p) of the RCS injection beam is required to be within 0.1%, the accelerating field error of the linac must maintained within ±1% in amplitude and ±1 degree in phase. To realize this stability, a digital feedback (FB) control is used in the low level RF (LLRF) control system, and a feed-forward (FF) technique is combined with the FB control for the beam loading compensation [3]. Furthermore, for the ACS cavity an additional function, which suppresses the field vibration caused by the chopped beam loading, is needed [4][5].

In the 181-MeV acceleration of the linac, the 24 LLRF systems are operated in a frequency of 324 MHz and the stability of ±0.2% in amplitude and ±0.2 degree in phase is achieved including the beam loading. This RF stability makes high reproducibility of the injection beam and then contributes to the steady commissioning progress of the J-PARC.

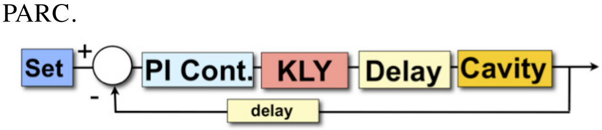

Figure 2: Simplified Block model of the FB control.

FEATURING FB COTNROL PROPERTY BY TRANSFER FUNCTION

Basically, the simple block model of the FB control as shown in Fig. 2 is considered for the evaluation. Because most of the RF components have wide-band relative to the cavity, It is contemplated that the simple block model of Fig. 2 is sufficiently valid. Since require input power for the DB2 is maximum 500 kW, the saturation and non-linearity of the klystron can be ignored; the maximum klystron out power is 3 MW. In this case, the transfer matrices of the open loop ($\mathbf{H}_{open}$) and closed loop ($\mathbf{H}_{close}$) are

$$\mathbf{H}_{close} = \left[\mathbf{E} + H_{delayR}\cdot\mathbf{G}\right]^{-1}\cdot\mathbf{G}, \quad \mathbf{H}_{open} = H_{delayR}\cdot\mathbf{G}$$
$$\mathbf{G} = \mathbf{H}_{cav}\cdot H_{delayF}\cdot H_{kly}\cdot H_{PI}, \qquad (1)$$
$$\mathbf{H}_{PI} = P_{gain} + \frac{I_{gain}}{s},\ \mathbf{H}_{dalayF} = e^{-sT_{dF}},\ \mathbf{H}_{delayR} = e^{-sT_{dR}}$$

where $\mathbf{H}_{cav}$ and $\mathbf{H}_{kly}$ are the transfer function of cavity and klystron, respectively, and P_{gain} and I_{gain} are the proportional gain and integral gain of the proportional-integral (PI) FB control, respectively, and T_{dF} and T_{dR} are delay time in the forwarding and returning transfer line, respectively. H_{cav} and H_{kly} are given by

$$\mathbf{H}_{cav} = \frac{\omega_{1/2}}{\Delta\omega^2 + \left(s+\omega_{1/2}\right)^2}\begin{pmatrix} s+\omega_{1/2} & -\Delta\omega \\ \Delta\omega & s+\omega_{1/2}\end{pmatrix} \qquad (2)$$
$$\Delta\omega = \omega_0 - \omega,\ \omega_{1/2} = \frac{\omega_0}{2Q_L},$$
$$\mathbf{H}_{kly} = \frac{\omega_{kly}}{\omega_{kly} + s}, \qquad (3)$$

respectively, where ω_0 is resonace frequency of the cavity, QL is loaded Q-value of the cavity and the ω_{kly} is

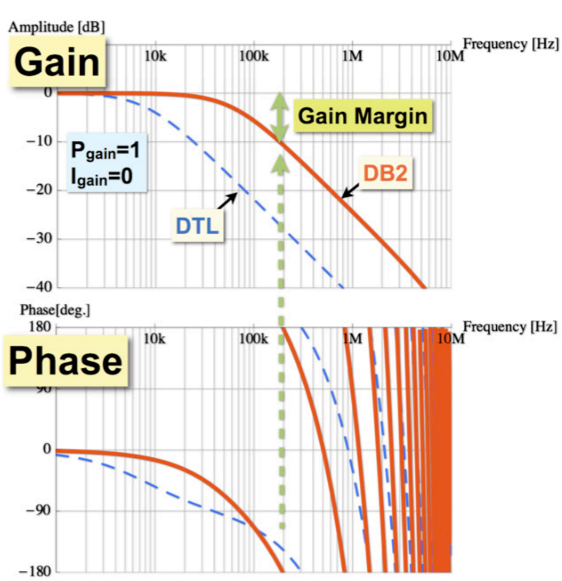

Figure 3: Bode polot of the open loop in Fig. 2 for DB2 and DTL control system.

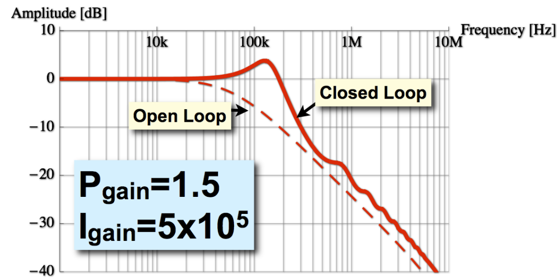

Figure 4: Bode plot of the closed loop for DB2.

bandwidth of the klystron. In our case, ω_{kly} is about 5 MHz.

Figure 3 shows Bode plot of the open loop transfer function (the diagonal element of $\mathbf{H}_{open}$). In this case, $\Delta\omega$=0, Q_L=8000, and the total delay time (T_{dF}+T_{dR}) is 1.5 μs. In the figure, solid line corresponds to the DB2 and dashed line corresponds to the DTL case of Q_L=20000 and T_{dF}+T_{dR}=0.7μ for the comparison. From Fig. 3, the gain margin for the DB2 control is about 10 dB (P_{gain} ~ 3). Since maximum of P_{gain} is generally restricted to be about half of gain margin in practical use, P_{gain} will be 1.5 in the actual operation; it is very low FB gain. The Bode plot of the closed loop is shown in Fig. 4, where P_{gain}=1.5 and I_{gain}=5x10^5. Bare bandwidth of the control is obtained by giving higher integral gain (I_{gain}).

Now, for the cause of instability, we assume that 1%-external noise (modulation) intermixes on klystron input as shown in Fig. 5. The cavity response against the noise of f_N-frequency under the FB control is shown in Fig. 6 for the DB2. From this figure, it is found that about 100-kHz noise cannot be suppressed. The noise of lower frequency than 100 kHz is suppressed by integral FB control and that of higher frequency is restricted by the cavity bandwidth.

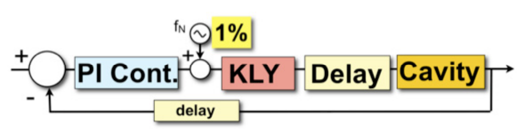

Figure 5: Assumption of 1%-modulation mixing on the klystron input.

TIME DOMAIN SIMULATON

In order to estimate stability of the amplitude and phase more specifically, calculation of the time evolution is needed. The calculation code was programmed to simulate the RF pulse control process of the system shown in Fig. 2 or Fig. 5. To simulate the time evolution, the transfer functions of the each component are converted to the difference formulas. For the PI-control, the same process as the FPGA in the digital FB system is simulated. For the cavity response, the difference formula is obtained from the state equation given by

$$\dot{V}_r(t) + \omega_{1/2}V_r(t) + \Delta\omega V_j(t) = R_L\omega_{1/2}I_r(t)$$
$$\dot{V}_j(t) + \omega_{1/2}V_j(t) - \Delta\omega V_r(t) = R_L\omega_{1/2}I_j(t), \qquad (4)$$

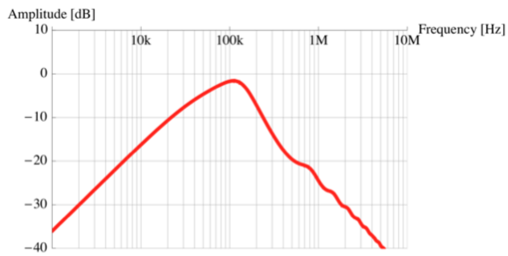

Figure 6: DB2 cavity response of the 1%-modulatin mixing on klystron input.

where V(t) and I(t) are the RF envelop of the cavity voltage and driving current, respectively, and subscripts r and j indicate the real and imaginary, respectively [6]. R_L is cavity input impedance. Moreover, effects of the non-linearity (saturation) of the klystron and the voltage sag of the DC power supply (HVDCPS) are including into the calculation. The amplitude and phase sag of the klystron due to the HVDCPS is about 10% and 30 degrees, respectively. Since the FPGA of our digital FB system is working at 48 MHz, the time step of the simulation is 20 ns (50 MHz).

For the operation parameters of DB2 for 30-mA average beam current, assuming the accelerating phase (ϕ_s) to be maximum -60 degrees, the optimum tuning parameters of the cavity are given by

$$\beta = 1 + b = 1.3, \quad Q_L = Q_o/(1+\beta) \approx 8000$$
$$\Psi_{opt} = \arctan\left(\frac{b}{1+\beta}\tan(\phi_s)\right) = -12.7\,\text{deg}. \tag{5}$$
$$\Delta f_{opt} = f_0 - f = \frac{f_{rf}}{2Q_L}\tan(\Psi_{opt}) = -13.7kHz$$

where b is the loading factor (P_c/P_b), β is the coupling of the cavity and, $\Delta\Psi_{opt}$ and Δf_{opt} are detuning angle and detuning frequency, respectively, for the optimum-tuning of the cavity.

Figure 7 shows the simulation results of the RF pulse control. In this case, the macro pulse beam of 300-μs width is loaded. It is not chopped. In the figure, solid line shows the cavity field, and dashed line corresponds to the cavity feeding. P_{gain} and I_{gain} are the same values as Fig. 4. In the calculation the beam current (I_{beam}) given by Eq. 6 is added to I(t) in the driving term of Eq. 5.

$$I_{beam} = \frac{b}{1+\beta}\cdot\frac{I_{cav}}{\cos(\phi_s)}. \tag{6}$$

In the simulation result shown in Fig.7, the klystron sag and the beam loading are completely compensated, and the stability of ±0.1% in amplitude and ±0.1 deg. in phase is obtained except the start and end of the macro pulse beam. The beam loading at the start/end of beam can be compensated by FF control in practical operation. Present simulation does not include the FF control. The chopped beam loading is discussed in Reference [5].

Incidentally, it is found that the cavity input phase agrees well with the cavity phase during the beam pulse shown in Fig. 7; it shows exactly the optimum tuning effect of the cavity. In this simulation, when P_{gain} is greater than 3, the calculation diverges; this result agrees with analysis of the transfer function as shown in Fig 3. Besides, the frequency characteristics for the case of Fig 5 and Fig 6 can be recognized in the time-domain simulation.

In addition, since ACS cavity has periodic structure, the FB instability due to the pass band modes [7] has to be studied.

SUMMARY

The performance of the stabilizing control of the ACS cavity field was estimated including long loop delay of about 1.5 μs. As the simulation result, the required stability is satisfied by giving high integral gain in FB control. However, about 100-kHz noise is not expected to be suppressed by the FB control.

Study of the FB instability due to the pass band modes of the ACS cavity is planned in the future.

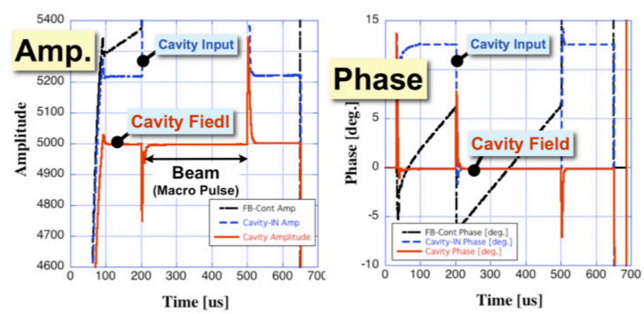

Figure 7: Simulation results of the amplitude and phase in the RF pulse control for the DB2.

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