DEGRADATION OF THE BEAM PASSING THROUGH IDLE COUPLED CAVITIES

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Abstract

Effects of wake fields on a high intensity proton beam are studied, when it passes through idle coupled cavities (The same number of modes as that of gaps that compose of the cavities build up.). Since the cavities are designed for an accelerated beam, the shunt impedance for the respective mode is different from the designed value, when the beam is not accelerated. This change of shunt impedances reduces the detuning effects in the sense of the reduction of the beam degradation.

INTRODUCTION

J-PARC (Japan Proton Accelerator Research Complex) is composed of linac, 3GeV RCS (Rapid Cycling Synchrotron) and Main ring [1]. In the first stage, 181[MeV], 30[mA] proton beam will be injected into RCS. In the upgraded J-PARC, it is planned that 400[MeV], 50[mA] proton beam will be injected into RCS through ACS (Annular Coupled Structure linac).

Before we inject the beam into RCS in case of the upgraded J-PARC, it is necessary to investigate the beam degradation due to the idle ACS, because RCS in J-PARC requests the momentum spread should be below 0.1%[1] before injection. It is not clear that we can reduce the beam degradation, especially when the chopped beam is injected into the cavity, by selecting the most appropriate frequency of the cavity, because the coupling effects between gaps (the shunt impedance for the non-accelerated beam is different from the designed value, because the ACS is designed for the accelerated beam.) is not negligible for the proton beam.

Further, as our commissioning, it is necessary to let beam pass through idle cavities, in order to adjust parameters of the accelerator. Tuning phase and amplitude of the powered cavity is one of the important processes at the commissioning of linac. The scheme of measurements of TOF (time of flight) is sometimes used for this purpose. Since many cavities exist between monitors for the measurements, it is severer the measurement of TOF as the intensity of beam becomes higher. Under this situation, it is important to investigate wake field effects on the beam quality [2].

In section 2, we consider the situation that the 181[MeV], 30[mA] chopped beam passes through the idle ACS. In section 3, we discuss the possibility of the correction scheme of TOF. Conclusions follow in section 4.

THE BEAM DEGRADATION

In the upgraded J-PARC, it is planned that 400[MeV], 50[mA] proton beam will be injected into RCS through ACS. The ACS is composed of 42 cavities. One cavity is composed of N_g=17 gaps [3]. Parameters for the ACS were already calculated by M. Ikegami: the shunt impedance ZT^2=41.223[MΩ/m], the quality factor Q=20300 and the frequency of the cavity $f_{\pi/2}$=972[MHz] [3].

Let us consider the situation that 181[MeV], 30[mA] chopped beam described in Fig.1 passes through the idle ACS. J-PARC RCS condition requires the momentum spread should be below 0.1%[1] before injection. It is not clear that we can reduce the momentum (energy) spread by selecting the most appropriate frequency of the idle cavities, because the coupling effects between gaps are not negligible for proton beam. Further, the chopped beam has many intrinsic frequencies.

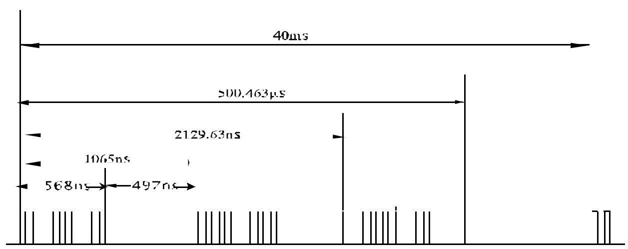

Figure 1: The chopped beam at J-PARC is described. Time period of the smallest pulse is 324[MHz]. The time period of the bunch (1065[ns]) corresponds to 0.93[MHz]. The interval of bunches is fluctuating around 1065[ns] (typically ~3[ns]). The repetition rate of the beam is 25[Hz].

Let us explain how to calculate frequencies and the shunt impedance of the coupled cavity when beam is not accelerated. When ACS has only one tuner, Brillouin curve for the detuned cavity is obtained by solving

$$D_{N_g}=\begin{vmatrix} i\left(\frac{\omega}{2\pi f_{\pi/2}}-\frac{2\pi f_{\pi/2}}{\omega}\right) & i\frac{\kappa}{2} & \cdots & 0 \\ i\frac{\kappa}{2} & i\left(\frac{\omega}{2\pi f_{\pi/2}}-\frac{2\pi f_{\pi/2}}{\omega}\right) & \cdots & \vdots \\ \vdots & \vdots & \ddots & i\frac{\kappa}{2} \\ 0 & \cdots & i\frac{\kappa}{2} & i\left(\frac{\omega}{2\pi f_{\pi/2}}-\frac{2\pi f_{\pi/2}}{\omega}\right) \end{vmatrix}=0, \quad (1)$$

where the only $((N_g+1)/2, (N_g+1)/2)$ component of D_{Ng} is replaced by $i(\omega/2\pi(f_{\pi/2}+df)-2\pi(f_{\pi/2}+df)/\omega)$ and df is the amount of detuned frequency (D_{Ng} is the determinant of N_g*N_g.)[4]. Here κ=0.055 [5] is the coupling constant. One of detuned cases is represented in Fig.2. The frequency f_k is changed only when the mode index (k) is odd. We approximately reproduce the well-known Brillouin curve formula:

$$f_k = f_{\frac{\pi}{2}}\left(1-\frac{\kappa}{2}\cos\left[k\frac{\pi}{N_g+1}\right]\right), \quad (2)$$

if κ is negligibly small and df=0, where k runs from 1 to N_g (k=9 is the accelerating mode.).

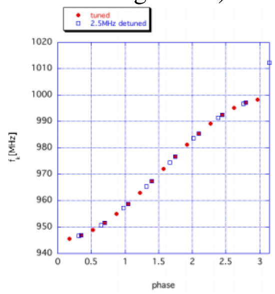

Figure 2: Brillouin curve of the detuned cavity. Blue square represents the case that the π/2 mode is 2.5[MHz] detuned. Detuning effects change the frequency f_k, only when k is odd. Horizontal axis is the argument of cos in Eq.(2). Vertical axis is the frequency for the respective mode.

We calculate the shunt impedance for the non-accelerated beam, using the designed shunt impedance R^m[3](which means that for the accelerated beam), where m is the cavity index. Here we assume that the voltage of i-th gap in the m-th cavity for mode k is represented as

$$V_i^m = V_0^m \cos\left[2\pi f_k t - i\frac{\pi k}{(N_g+1)/2}\right], \quad (3)$$

where m runs from 1 to 42, i runs from 0 to N_g-1. Thus, we obtain the shunt impedance for the non-accelerated beam:

$$\sum_{i=0}^{N_g-1}\frac{R_m}{N_g}\cos\left[i\pi\left(\frac{\beta_m}{\beta}\frac{f_k}{f_{\pi/2}}-\frac{k}{(N_g+1)/2}\right)\right], \quad (4)$$

where β is the actual velocity of the beam and β_m is the designed β. When the particle were accelerated in π/2 mode, the argument of cos in Eq.(4) would be 0. Therefore, this shunt impedance reproduces the designed shunt impedance (R^m). According to Eq.(4), the shunt impedances for k=9,10,11 behave like those in Fig.3. The shunt impedance for the respective mode equally contributes on the effective shunt impedance of the linac. The shunt impedance for k=9 contributes on the first part, that for k=10 does on the middle part, and that for k=11 does on the final part of the linac.

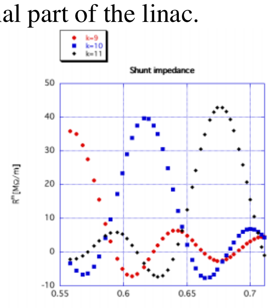

Figure 3: The shunt impedances for k=9,10,11 along the linac. The shunt impedance for the respective mode equally contributes on the effective shunt impedance of the linac.

The effective shunt impedance ($ZT^2(\beta)$) for the linac is given by taking an average of Eq.(4), then,

$$ZT^2(\beta) = \frac{\sum_{m=1}^{42}\frac{N_g\beta_m c}{2f_{\pi/2}}\sum_{i=0}^{16}\frac{R_m}{N_g}\cos\left[i\pi\left(\frac{\beta_m}{\beta}\frac{f_k}{f_{\pi/2}}-\frac{k}{(N_g+1)/2}\right)\right]}{\sum_{m=1}^{42}\frac{N_g\beta_m c}{2f_{\pi/2}}}. \quad (5)$$

$ZT^2(\beta)$ is 4.29[MΩ/m] for k=9, that 8.84[MΩ/m] for k=10 and that 12.87[MΩ/m] for k=11. Since the designed effective shunt impedance for the accelerating mode was 41.223[MΩ/m], $ZT^2(\beta)$ for this mode becomes 1/10 times smaller, while $ZT^2(\beta)$ for k=10, k=11 are increasing.

The energy loss and energy spread of the beam are expressed in Fig.4 when the beam passes through the idle ACS. The energy loss is reduced by detuning effects indeed, while the effect on the energy spread is not so drastic. There are peaks in both figures in Fig.4. These peaks correspond to intrinsic frequencies of the beam. The beam profile for df=1.94[MHz], which is the most appropriate frequency, is represented in Fig.5. Transient effects are significant. It is found that the beam has an onion structure due to multi-wake effects.

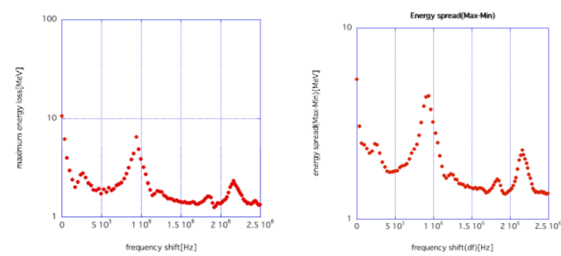

Figure 4: The energy loss and energy spread of the beam for the detuned frequency of cavity. The energy loss can be 1.27[MeV] and the energy spread can 1.34[MeV] at df=1.94[MHz].

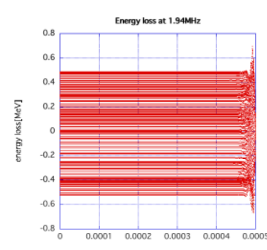

Figure 5: The beam profile at df=1.94[MHz]. The right hand side is earlier along the time axis. It is found that the beam has an onion structure due to multi-wake effects.

THE CORRECTION SCHEME OF TOF

Let us consider the situation that the 30[mA], β=0.532007, 324[MHz] beam passes through idle cavities (the beam has no multi-intrinsic frequencies in this case.) in order to tune the phase and amplitude of another powered cavity. Here we assume that the idle cavities exist between monitors.

In this situation, we measure the TOF and evaluate the beam energy. Since the wake field effect is so serious that the TOF is modulated when the beam passes through the idle cavities. We take into account the modulation of pulse interval due to wake field effects. The energy loss of the beam ΔE due to wake field effects can be calculated, and the results are described in the right figure of Fig.6 where df=2[MHz]. The TOF under the influence of the wake field is described in the left figure of Fig.6. Since the TOF for the final particle is 442.73[ns], we can calculate β=L/t/c=0.531941 where L=70.65[m]. In this calculation the detuned cavity space is assumed to be the drift space. This value is -0.012% different from the original β(=0.532007) due to wake field effects.

In order to do fine tuning, we had better correct this TOF. When the following relation is satisfied:

$$\frac{mc^2}{\sqrt{1-L^2/\left(c^2(t-\Delta t)^2\right)}} - \Delta E \approx \frac{mc^2}{\sqrt{1-L^2/\left(c^2 t^2\right)}}, \qquad (6)$$

Δt can be approximately written as,

$$\Delta t \approx \frac{t^3 c^2}{L^2 mc^2}\left(1-\frac{L^2}{c^2 t^2}\right)\Delta E, \qquad (7)$$

where t-Δt is the corrected TOF, while t is the measured TOF. We can correct the TOF, when we know the ΔE in advance. According to the right figure of Fig.6, we find that the asymptotic value of ΔE=0.06526[MeV]. Then, we obtain Δt =73.2[ps] by Eq.(7). Using this Δt, β=L/(t-Δt)/c=0.532029. This value coincides with the original β with 0.004% accuracy. Thus, this correction scheme is useful to reproduce the original β.

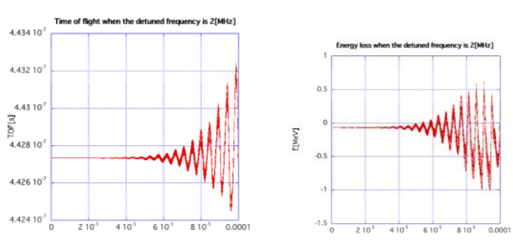

Figure 6: The left figure describes the TOF when the beam passes through the idle cavities. The right figure does the energy loss due to wake effects. The passing length L=70.65[m].

CONCLUSIONS

We investigate the influence of the wake field on the high intensity proton beam passing through detuned cavities. In particular, we have to notice the limitation of the reduction of the beam degradation due to the detuning effects, when the chopped beam passes through the cavity. The energy spread cannot be drastically reduced by the detuning effect, especially when the beam has multi intrinsic frequencies, because there are many resonance points along the detuned frequency axis. There are multi-peaks in the figure of the energy spread along the detuned frequency, which means that the allowed region is restricted.

We should notice coupling effects of the cavities, when we detune the frequency of them. There build up the same number of frequencies as the number of gaps in the coupled cavity. When the beam passes through detuned coupled cavities, the shunt impedance for this case is different from the designed shunt impedance. The coupling effects can reduce the shunt impedance for the accelerating mode, while shunt impedances for the other modes may become larger. This is because the behavior of the shunt impedance for the designed β_m is different for respective mode. Thus, we should beware of the limitation of the reduction of the beam degradation due to these coupling effects.

We also study the correction scheme of the TOF by subtracting the wake field effect from the beam, for tuning the phase and amplitude of another powered cavities. By knowing the deceleration energy of the beam due to the wake field effects, we can obtain the corrected TOF and evaluate the original energy of the beam.

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