STUDIES ON WAKE FIELD IN ANNULAR COUPLED STRUCTURE

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Abstract

LINAC injector of J-PARC (Japan Proton Accelerator Research Complex) was recently successfully upgraded from 181 MeV to 400 MeV, applying a type of coupled cavity linac (CCL) structure ACS (Annular Coupled Structure). It was warmly discussed since very beginning on the wake field in the ACS cavities, where there are CCL modes with the same number as that of cells within ~50 MHz, possibly resonating with high intensity proton/H- beams. One of the most important effects from the wake field is the influence on the ACS phase scan. Analytical and simulation studies, as well as the countermeasures were prepared before the energy upgrade. Fortunately we found that detuning of the ACS was unnecessary, which helped to save much work in the commissioning. In addition we got chance to make experiment studies. It was also discussed why the wake field is not so serious as we expected at the very beginning.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high-intensity proton accelerator, which consists of a linac[1], as shown in Fig.1, a 3GeV synchrotron (rapid cycling synchrotron, RCS), and a main ring synchrotron (MR).

The J-PARC linac consisted of a 3 MeV RFQ, 50 MeV DTL (Drift Tube Linac) and 181/190 MeV SDTL (Separate-type DTL) before 2013. It was upgraded to 400 MeV in Jan., 2014, with 42 (21 coupled pairs) new annular-ring coupled structure (ACS) [2] installed during the summer shutdown in 2013.

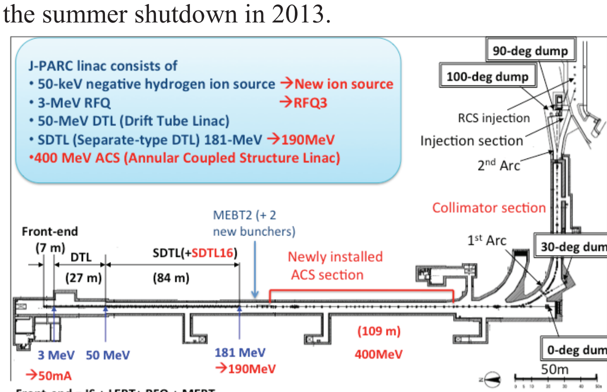

Figure 1: Layout of J-PARC linac.

The present nominal operation current is 15mA, with designed peak current of 30 mA applied for beam studies. A new RF ion source and a new RFQ (RFQ3) are being installed in the summer shutdown this year with designed current of 50mA. The commissioning is scheduled in this October.

ACS is a type of normal conducting coupled cavity linac (CCL) structure, optimized for efficient acceleration for mid-beta high-power pulsed hadron beams. ACS cavities used for acceleration at J-PARC have $N_g = 17$ gaps. Every two ACS cavities are coupled by a bridge coupler and fed by one Klystron, as shown in Fig. 2.

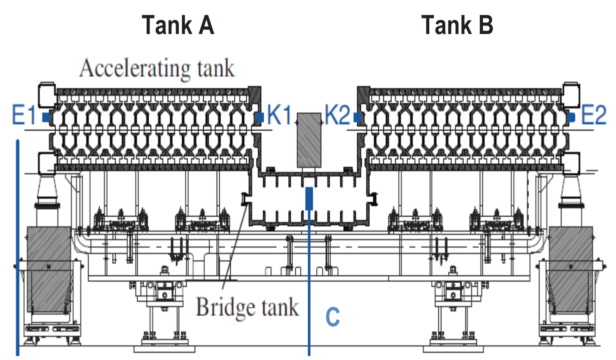

Figure 2: Sketch of J-PARC ACS cavity for acceleration.

As a property of CCL, J-PARC ACS has $N_{mode} = 2N_g - 1$ resonant modes in the cavity within frequency range of ~ ± 2.5 % near the acceleration mode (π/2-mode), which can be resonant to the beam with MW-level of peak power. Shunt impedance of J-PARC ACS is ranged in 36~45 MΩ/m. In the very beginning of J-PARC wake field of ACS aroused discussions. One major worry is the effect by the wake field on ACS phase scan, which is used to set each cavity voltage and phase as design. Beam needs to pass through several downstream idle cavities to get enough flight distance for energy measurement. Wake field decelerates the beam, and could affect the measurement.

In the previous studies it was proposed to detune the downstream idle ACS cavities in the phase scan measurement [3]. It will be enormously time-consuming for the commissioning and hardware preparation.

In our recent studies it is found that the ACS wake field is not sensitive to the incoming beam energy within the phase scan range, although it is ineligible. The phase scan curves are mainly moved conformably, so that the ACS detuning could be fortunately avoided. This conclusion has been verified in the commissioning.

Another motivation for further wake field studies came from the observation of free oscillation of ACS after power off. The properties of ACS modes except for the main one were not interesting during ACS preparation. The wake field is the only way to learn these features.

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QUALITATIVE CALCULATION OF ACS WAKE

Resonant modes of CCL are obtained by solving the eigenvalue for the coupling matrix L from the coupling equation set, whose rank equals to the cell number N_c

$$L = \begin{pmatrix} 1 & \kappa & \cdots & 0 & \cdots & 0 \\ \kappa/2 & 1 & \kappa/2 & 0 & \cdots & 0 \\ 0 & \kappa/2 & 1 & \kappa/2 & \cdots & 0 \\ \vdots & 0 & \cdots & \ddots & \cdots & \vdots \\ 0 & 0 & \cdots & \kappa/2 & 1 & \kappa/2 \\ 0 & 0 & \cdots & \cdots & \kappa & 1 \end{pmatrix}$$

The eigenvalue is $\left(f_{\pi/2}/f\right)^2$, where $f_{\pi/2}$ is the resonant frequency of a single cell and also the frequency of the $\pi/2$ mode, f has $N_{mode} \equiv N_c = 2N_g - 1$ solutions. There are N_g acceleration cells (gaps) and $N_g - 1$ coupling cells. κ is the coupling constant. For J-PARC ACS, κ is designed to be 5~6% between coupling cells and acceleration cells, ~12% between intermediate cells and bridge coupler cells. Solutions of f follow the Brillouin curve, also as shown in Fig.3,

$$\frac{f_k}{f_{\pi/2}} = 1 - \frac{\kappa}{2}\cos\left(\frac{2\pi k}{N_{mode}-1}\right),\ k=0, \ldots, N_{mode} - 1$$

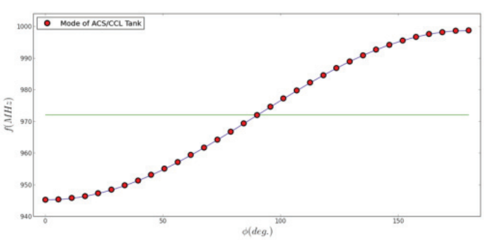

Figure 3: ACS modes shown in the Brillouin curve of the CCL cavity.

It is noticeable that κ is also the frequency range of the modes, which can be measured directly.

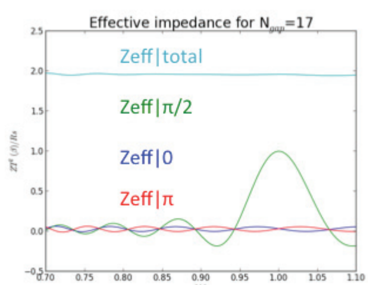

Figure 4: ACS effective impedance is insensitive to the incoming beam velocity.

In the operation, only the $\pi/2$ mode is excited and dominating. While if the cavity is idle, all the modes are equally seen by the beam. So it is useful to calculate the effective impedance of ACS cavity which sums up voltage of all modes resonating to an incoming beam with relative velocity β. As a first approximation in case of no tuning for some certain modes, same shunt impedance R_s are assumed to all the modes. The effective impedance for an ACS cavity could be obtained as,

$$ZT^2(\beta) = \sum_{k=0}^{N_{mode}} \sum_{i=0}^{N_g} \frac{R_s}{N_g} \cos\left[i\pi\left(\frac{\beta_m}{\beta}\frac{f_k}{f_{\frac{\pi}{2}}} - \frac{k}{(N_{mode}-1)/2}\right)\right]$$

where β_g is the cavity geometry beta, R_s the shunt impedance, index i and k sum up the gap and modes respectively. If the gap number is big enough (>10) effective impedance becomes insensitive to β, as shown in Fig.4 for the $N_g = 17$ case.

This leads to important conclusions. First, even by some means the cavity is detuned, that simply means another mode is domination instead of the previous one. The strength of wake can be hardly reduced. Second, the flat effective impedance is good news if it is true. When the upstream cavities are in phase scan, the output beam with energy differing by several percent get same deceleration by the wake in the downstream idle ACS cavities. The phase scan curve just translation without deformation, so that they can still be used to determine the voltage and phase by fitting with simulation. By the way, the absolution value of the energy measurement is not as important as absolution difference, considering the measurement errors.

Therefore the detuning might not be necessary and also not effective, due to the broadband characteristics of the effective impedance.

However these conclusions have conditions. In reality the amplitude of the wake depends on many effects. The bunch has finite length and it is getting longer without longitudinal focusing due to divergence and space charge. Tuning and configuration of the cavity may restrain some of the modes and the main mode could be optimized.

The beam with curtain velocity resonates with a curtain mode. But the beam is always coming by roughly 324 MHz. The inconsistency of resonance and driven frequency will also restrain the wake of some modes.

Moreover the wake field should not be too strong to blow up the beam at once. In the experiment with 30mA it is not observed. 5 mA was proposed for the phase scan. It proved to be satisfying. 5 mA is the minimum for stable operation of ion source and relevant monitor resolution.

According to the formula of effective impedance and given shunt impedance 40 MΩ/m, beam peak current of 30 mA, one can estimate the maximum wake voltage to be in 1 MV per cavity level.

The procedure of building up the wake is also interesting. If it is slow compared with typical measurement pulse of 100 μs, it will cause some uncertainties. The building up factor $\lambda = \frac{\omega_{rf}}{2Q}$, where ω_{rf} is the rf angular frequency, here it is $2\pi \cdot 972$ MHz, Q the cavity quality factor, here it is ~20300, λ^{-1}~6.65 μs.

Transient calculations can give more details of the wake field. There will be another paper to present the further studies.

MEASUREMENT

With the calculation of effective impedance, the biggest question of the effects of ACS wake on phase scan was answered and no-detune/5mA scheme proved to be satisfying in the commissioning. But there are still motivations for experimental studies on wake field, such as wake amplitude and pattern, equilibrium and so on.

Moreover, there were some interesting phenomena observed in the free oscillation in ACS, as shown in Fig.5.

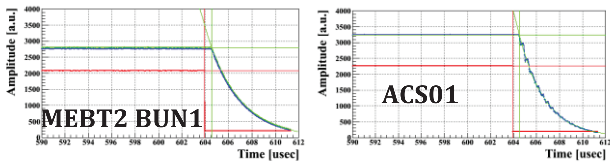

Figure 5: Free oscillation observed in ACS. MEBT2 buncher-1: 10-gap ACS, ACS01: 17-gap.

The “free oscillation” is in the decay part after the amplifier power-off. The measurements were obtained from the ACS pickup, shown in Fig.2. Zigzags were found for ACS01, and it should not be noise compared with MEBT2 buncher-1. It was wave beat by modes with close frequencies. Two pairs of neighboring modes, $\frac{\pi}{2} \pm 1$, $\frac{\pi}{2} \pm 2$ were found by the frequency analysis.

The observations of free oscillation show the existence and possibility of excitation of the nearby modes in the ACS. This additionally motivates the wake field experiments not only for the beam-cavity interactions but also for the ACS properties.

Wake field experiments were proposed with 25mA and 15mA with two measurement schemes:

1. Accelerate up to SDTL15 (181 MeV), measuring wake field at SDTL16, Buncher3-4, ACS01-21
2. Accelerate up to ACS03 (217 MeV), measuring wake field at ACS04-21

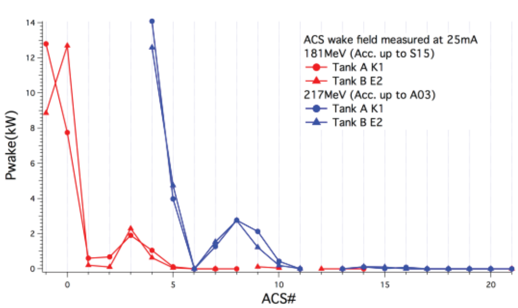

Figure 6: Measured wake power in the ACS cavities.

Wake field were measured with oscilloscope from 4 pickups, E1, E2, K1, K2 as shown in Fig.2. Measurement from directional coupler was also done for calibration. The results were double checked by the measurement with power meter. The results are shown in Fig.6-8.

Maximum peak wake field found at ACS04 for 217 MeV: ~12 kW or 0.5 MeV energy loss at 25 mA, for each tank A/B.

Wake amplitude decreases and oscillates with difference between beta of beam and geometry β-β_g. This can be qualitatively explained by the impedance pattern. Simulation of transient process is needed for more satisfying explanation.

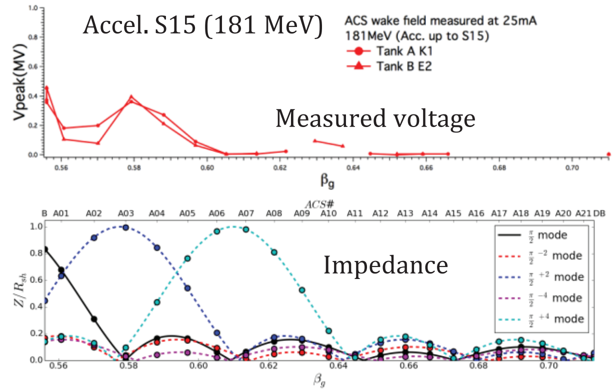

Figure 7: Measured wake field amplitude compared with effective impedance, measurement scheme 1.

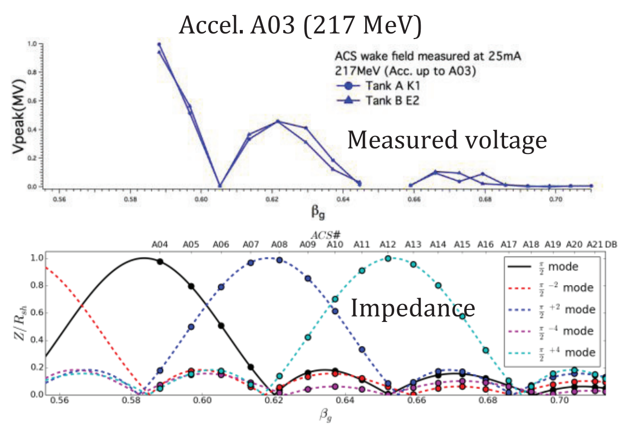

Figure 8: Measured wake field amplitude compared with effective impedance, measurement scheme 2.

CONCLUSION

Wake field effect in ACS is not negligible, which could cause 1MeV deceleration of beam for 30mA, found both from theoretical and experimental studies.

In reality all or some of wake modes could be suppressed by many effects, such as bunch lengthening, cavity configuration and so on.

No-detuning and 5mA scheme proved to be satisfying for ACS phase scan in the commissioning.

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