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Tuning of RF amplitude and phase for the drift tube linac in J-PARC

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Abstract The J-PARC linac has three DTL tanks to accelerate the negative hydrogen ions from 3 MeV to 50 MeV. The RF phase and amplitude are adjusted for each cavity with a phase scan method within the accuracy of 1° in phase and 1% in amplitude. The experimental results show a remarkable agreement with the numerical model within a sufficient margin in the tuning of the last two DTL tanks. However, a notable discrepancy between the experiment and the numerical model is seen in the tuning of the first DTL tank. After studying with a three-dimensional multi-particle simulation, the generation of the low energy component and the pronounced filamentation are identified as the main causes of the discrepancy. The optimization of the tuning scheme is also discussed to attain the tuning goal accuracy for the first DTL tank.

Key words high-intensity beam, drift tube linac, signature matching, J-PARC

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1 Introduction

J-PARC (Japan Particle Accelerator Research Complex) is one of the latest high-intensity proton accelerator facilities built jointly by JAEA and KEK[1, 2]. The design output energy, the peak current, and the beam power for its linac are respectively 181 MeV, 30 mA, and 36 kW. A primary concern for a high intensity proton accelerator such as J-PARC linac is to mitigate the beam losses to avoid excess radiation activation. A correct RF set-point is widely accepted as essential in avoiding excess beam quality deterioration. The correct RF set-point can minimize the beam loss due to the longitudinal mismatch, which is considered to be one of the possible driving mechanisms for the halo formation[3]. An accurate tuning is crucial for J-PARC linac. Especially, finer tuning of the RF set-point is particularly important for the DTL (Drift Tube Linac), which locates at the upstream section of the linac. It is required that each RF station is tuned within an accuracy of 1 degree in phase and 1% in amplitude. Within this error tolerance, it has been confirmed in a multi-particle simulation that the beam loss arising from the RF set-point error is negligibly small[4].

In this paper, the tuning procedure for J-PARC DTL is presented together with the experimental results obtained in the beam commissioning. A three-dimensional multi-particle simulation is also performed to reproduce the experimental results.

2 Tuning scheme

The DTL section consists of three DTL tanks, which we refer to as DTL1, DTL2, and DTL3 from the upstream side, respectively. The basic idea of the RF tuning is based on the phase scan method[5]. The beam phase is measured with an FCT (Fast Current Transformers). Each DTL tank has an FCT at its exit as shown in Fig. 1. The output energy from each tank is measured with two downstream FCT's based on the TOF (Time Of Flight) method.

The phase scan provides us with a dependence of the output energy on the tank phase, which we refer to as a “phase scan curve”. The phase scan measurement is repeated with different tank levels to be compared with the PARMILA[6] numerical model.

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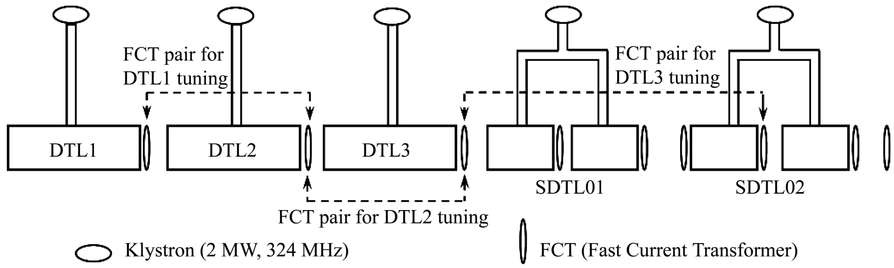

Fig. 1. Scheme of the FCT layout for the DTL tuning.

A tuning strategy called "phase signature matching"[5] is also introduced for numerical analysis. In this method, we try to reproduce the overall shape of the measured phase scan curve with a numerical model. To enable effective signature matching, a typical scanning range adopted is ±30°.

To evaluate the results quantitatively, a deviation error of the signature matching is calculated. The measured phase scan curves under various RF amplitude settings are compared with a reference curve. The phase scan curve obtained with a numerical model for the design RF set-point is adopted as the reference curve. The reference curve is expanded with a polynomial function as

$$f_0(\Delta\Phi) = a_0 + \sum_{i=1}^{12} a_i \cdot (\Delta\Phi)^i \,, \tag{1}$$

where $f_0(\Delta\Phi)$ is a function representing the dependence of the output energy on the phase set-point shift $\Delta\Phi$. The coefficients a_i are determined to reproduce the modeled phase scan curve. Then, the modeled phase scan curve is shifted to fit the measured phase scan curve as

$$f(\Delta\Phi) = f_0(\Delta\Phi + \Delta\Phi_0) + c_0 \,, \tag{2}$$

where $\Delta\Phi_0$ and c_0 are determined to obtain the optimum fitting. The variance, or the sum of squared residuals, χ^2 is calculated as

$$\chi^2 = \frac{\sum_{j=1}^{n} (f_j - W_j)^2}{n} \,, \tag{3}$$

where $f_j = f(\Delta\Phi_j)$ with $\Delta\Phi_j$ being $\Delta\Phi$ for a specific measurement. The corresponding beam energy obtained in the experiment is denoted as W_j. The variance χ^2 is normalized by the number of measurements in the phase scan curve n. We calculate χ^2 for each phase scan curve with different amplitude setting, and the obtained χ^2 is fitted using a 2nd-order polynomial function with respect to the tank amplitude so as to find the optimum tank level. Namely, the tank amplitude is determined in the way that the scanned curve gives the minimum χ^2 value. The obtained $\Delta\Phi_0$ for the amplitude is translated into the shift between the phase set-value and the phase experienced by the beam.

3 Experimental result

The first DTL tuning was conducted in December 2006. Since then, several series of tunings have been performed for the DTL RF set-point, and the tuning procedure has mostly been established. In the tuning, the peak current is reduced to 5 mA from the design value of 30 mA. The pulse length was reduced to 30 μs from the design value of 500 μs in the first series, and 50 μs thereafter.

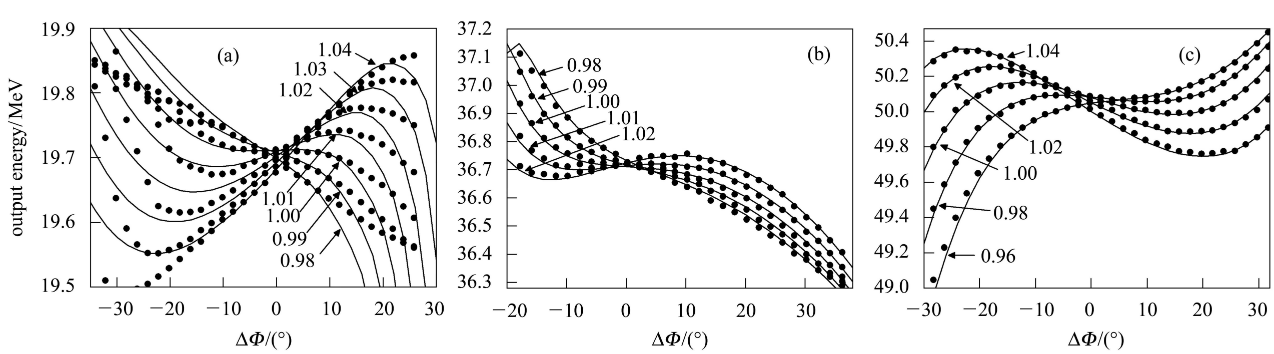

Fig. 2. Measured and simulated phase scan curves for DTL1 (a), DTL2 (b), and DTL3 (c). The phase scan curves with several different tank levels are shown for each tank with the RF amplitude annotated in the value of A. The measured results are shown with circle markers, and the curves from PARMILA modeling are shown with solid lines.

The phase scan curves measured in June 2007 are shown in Fig. 2. The injection energy to DTL1 is corrected by accelerating the beam with a buncher cavity by 34 keV. The phase is scanned with different amplitudes as indicated in the figure. In this figure, the phase scan curves obtained with the PARMILA model are also shown for comparison. It is readily seen in Fig. 2 that the measured phase scan curves are thoroughly reproduced by the numerical model for DTL2 and DTL3. However, it shows notable deviations in DTL1 especially for the case with an RF set-point away from its design value.

In performing the χ^2-based tuning for DTL2 and DTL3, the optimum amplitude set-point is determined from the 2nd-order polynomial fitting to the corresponding χ^2 values as shown in Fig. 3, where five phase scan curves with the amplitude step width of 0.2% are analyzed. It is clearly seen in this figure that the value of χ^2 shows a sharp sensitivity for the RF set-point. Then, the scheme is expected to have a resolution of better than 0.2% in the amplitude tuning.

After finding the optimum tank level (that corresponds to the minimum point in Fig. 3), we perform another phase scan with the determined amplitude to find the optimum phase setting.

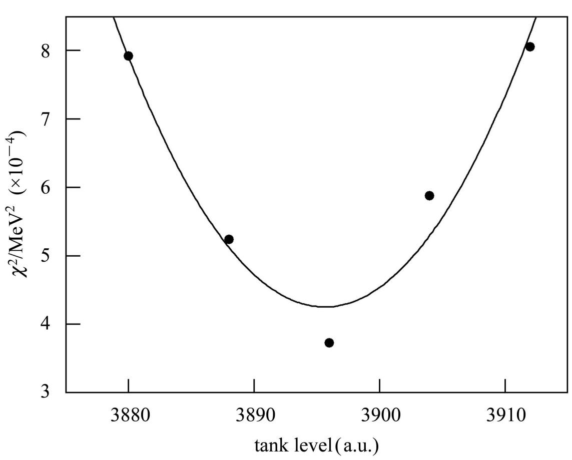

Fig. 3. The variance of the measured phase scan curve from the reference curve for DTL2. The variance is shown in terms of χ^2 as a function of the RF amplitude setting. The χ^2 value is shown with a dot, and the 2nd-order polynomial fit to it is shown with a solid line. The horizontal axis of this figure is taken as the tank amplitude in the raw setting value for the RF control system.

The sensitivity of the procedure to obtain the optimum phase set-point is illustrated in Fig. 4, which shows the dependence of χ^2 on the choice of the phase setting. It is clearly seen in this figure that the value of χ^2 shows a distinct sensitivity for the RF phase set-point, and the scheme is expected to have a resolution of better than 0.4 degree in the phase tuning.

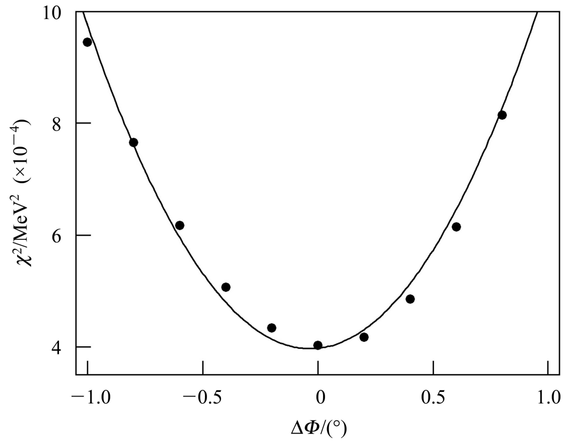

Fig. 4. The variance of the phase scan curve with the optimized amplitude setting from the reference curve for DTL2. The variance is evaluated in terms of χ^2 for a varied phase set-point with a step width of 0.2°. The χ^2 value is shown with a dot, and the 2nd-order polynomial fit to it is shown with a solid line.

The analogous result is obtained in the DTL3 tuning, while the result is not shown. Therefore, we conclude that the tuning accuracy is sufficiently better than 1° in phase and 1% in amplitude for DTL2 and DTL3.

However, we have found it difficult to apply the χ^2-based method to DTL1. As shown in Fig. 2(a), the trend of the phase scan curve is totally different when the amplitude setting is lower than the design value. Even with higher amplitude, the experimental curve shows a large deviation from the modeling for a large phase shift from the design value. This disagreement has motivated us to establish a more rigorous numerical model employing a fully three-dimensional multi-particle tracking.

4 Detailed comparison with multi-particle simulation

To investigate the disagreement between the PARMILA model and the measurement for DTL1, a parallel PIC (Particle-In-Cell) simulation has been performed with the IMPACT[7] code. The tracking is performed from the exit of the RFQ with the same initial distribution with the PARMILA[8]. The non-linear Lorentz map integrator is utilized to deal with the highly nonlinear RF force which arises from unusually large RF set-point deviations involved in the phase scan tuning. To attain a reasonable accuracy, the integration step width is set to about $\beta\lambda/100$.

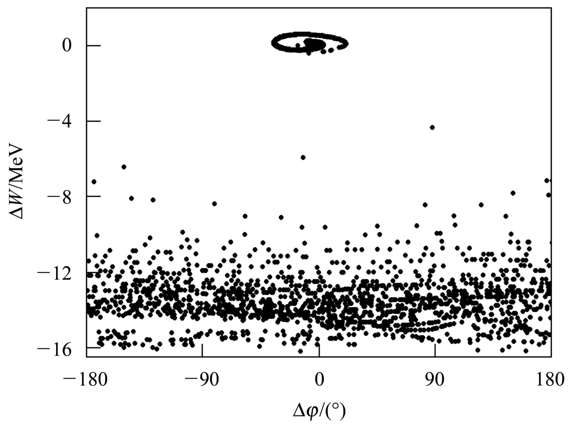

Fig. 5. The longitudinal phase space distribution at the DTL1 exit simulated with IMPACT (A=1.00, $\Delta\Phi$=25°).

To start with, we have performed an IMPACT simulation for the case with the amplitude setting of A=1.00 and the phase setting of $\Delta\Phi$=25°, where the discrepancy between the measurement and the model is particularly large. In this case, a substantial portion of the beam is spilt out of the RF bucket as shown in Fig. 5. In this figure, the horizontal and longitudinal axes are taken as the particle energy, ΔW, and phase, $\Delta\varphi$, relative to the design particle.

To be noted here is that ΔW=0 corresponds to the design output beam energy of 19.7 MeV for DTL1. Most of the spilt out portion of the beam stays with the energy of several MeV, and it lowers the average output energy of the numerical model. Because the phase of the low energy component is spread to cover the whole phase range after a long drift space between the FCT pair, the low energy component is not properly detected with the downstream FCT. As readily seen in Fig. 2(a), the phase scan curve has an obvious discrepancy in its trend in the case with $\Delta\Phi > 15°$. This discrepancy is mainly explained by the generation of the low energy component. After eliminating the low energy component, the disagreement between the measured beam energy and that from the numerical model is reduced to several tens of keV. This residual discrepancy is comparable with those in another region of the distinctive discrepancy in Fig. 2(a), namely, $\Delta\Phi < -15°$.

Figure 6 shows the longitudinal phase space distribution for the case with the amplitude setting of A=1.02 and the phase setting of $\Delta\Phi = -29.5°$. As seen in Fig. 2(a), the measured beam energy is 53 keV higher than that predicted by the numerical model. It is readily seen in Fig. 6 that the beam distribution is significantly distorted due to pronounced filamentation. To be also noted is that the shapes of the developed arms are dependent on the initial distribution. To illustrate the dependence, we show the longitudinal phase space distribution with the same RF set-point but different initial distribution, namely, the six-dimensional Gaussian distribution in Fig. 6(b). The centroid beam energy of Fig. 6(b) is 71 keV lower than that in Fig. 6(a). Because the centroid energy is dependent on the detailed shape of the filamentation, the ambiguity of several tens of keV is easily caused

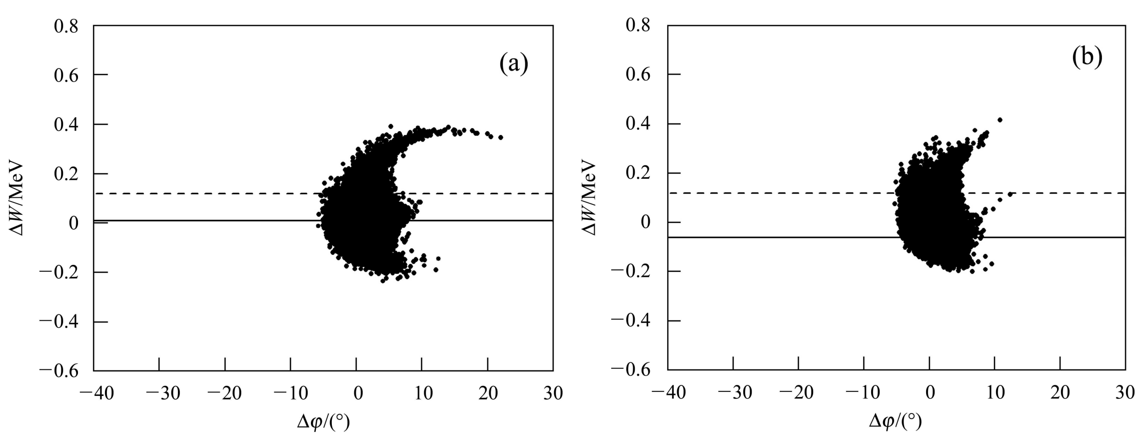

Fig. 6. The longitudinal phase space distribution at the DTL1 exit simulated with IMPACT (A=1.02, $\Delta\Phi = -29.5°$). The PARMTEQM distribution is adopted in (a) at the RFQ exit, whereas an idealized six-dimensional Gaussian distribution is employed in (b). The measured beam energy is shown with a broken line, and the centroid of the simulated distribution with a solid line.

by the uncertainty in the assumed initial distribution. Due to the lack of longitudinal diagnostics in the beam transport line between RFQ and DTL, we are unable to confirm the credibility of the initial longitudinal distribution at the RFQ exit.

In conclusion, the discrepancy between the measured phase scan curve and that from a numerical model observed in the DTL1 tuning seems to be mainly attributable to the generation of the low energy component and severe filamentation. Because the filamentation depends on the initial distribution, the discrepancy of several tens of keV is unavoidable with the RF set-point far from the design value. Then, the phase signature matching is valid only in the narrow region around the design set-point where the filamentation is sufficiently modest. As the phase scan curve is rather flat in the vicinity of the design set-point, it is difficult to find an adequate phase set-point adopting the above mentioned χ^2-based method with a narrow phase range. A possible way to circumvent this difficulty is to adopt two or more reference phase scan curves in the χ^2 analysis as in SNS[9, 10]. The range of the phase and amplitude subjected to the χ^2 analysis is to be determined to avoid the ambiguity from the substantial filamentation. As a guideline, we discard the RF set-points where IMPACT results with the PARMTEQM distribution and the idealized six-dimensional Gaussian distribution show the discrepancy of larger than 2 keV in the centroid energy. While this choice of the threshold is rather arbitrary, it is comparable with the expected resolution of the TOF measurement. This guideline leads us to adopt two phase scan curves of A=0.99 and 1.00 as the reference with the limited phase scanning range from $-10°$ to $10°$.

The phase scan curves for DTL1 are shown again in Fig. 7, where the parameter range is limited with the above mentioned criterion. It is readily seen in this figure that the experiment and the numerical model show a reasonable agreement. As clearly seen in this figure, the tuning accuracy of 1° in phase and 1% in amplitude is attainable for DTL1 with the narrow range analysis with two reference curves.

The notable discrepancy between the experiment and the numerical model has been observed only in the DTL1 tuning. This is explained by the fact that the significant filamentation is induced only for DTL1 within the assumed parameter range in the phase scan tuning. However, we need further investigation on the reason why DTL1 is so prone to develop significant filamentation. While the underlying mechanism is still open, it seems reasonable to assume that the following two factors play some role in the filamentation development. One is the phase spread which is the largest at the DTL1 entrance (about 5.2° in rms), and gradually reduced toward the end of DTL3 (about 2.0° in rms). The other is the number of cells which is also the largest in DTL1 (76) and reduced in DTL2 (43) and DTL3 (27).

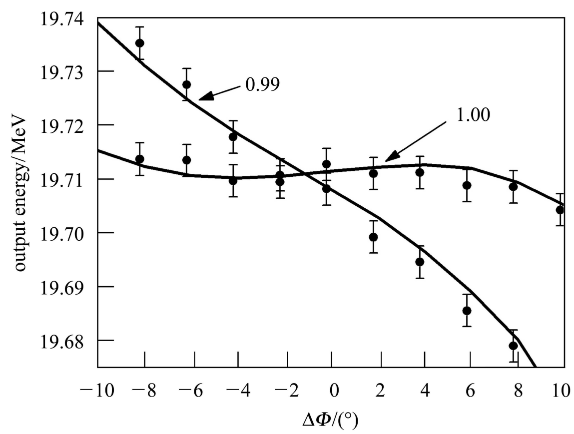

Fig. 7. Measured and simulated phase scan curves for DTL1 with a restricted parameter range. Two phase scan curves are shown for A=0.99 and 1.00 as annotated in the figure. The measured results are shown as circle markers, and the curves from PARMILA modeling are shown as solid lines. The error bar is set to ±3 keV estimated from the expected measurement resolution and the statistical uncertainty due to the limited number of macro-particles.

5 Summary

In the beam commissioning of J-PARC linac, the RF set-point tuning has been performed based on the phase scan method. A χ^2-based analysis is successfully adopted to realize the tuning accuracy of 1° in phase and 1% in amplitude with a sufficient margin for DTL2 and DTL3.

In the DTL1 tuning, however, the phase scan curves show a notable discrepancy from the numerical model especially with the RF set-points far from its design value. A three-dimensional particle simulation has been conducted with IMPACT, and the generation of the low energy component and the severe filamentation are identified as the main sources of the observed discrepancy. We found that it is essential to adopt two or more phase scan curves as the reference restricting the parameter range for the phase scan to determine the optimum phase set-point with sufficient accuracy. After that, we have confirmed that the tuning goal of 1% in amplitude and 1° in phase is satisfied.

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