RF AMPLITUDE AND PHASE TUNING OF J-PARC SDTL

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Abstract

A fine tuning has been performed for RF phase and amplitude of SDTL (Separate-type Drift Tube Linac) station in the beam commissioning of J-PARC LINAC. A phase-scan method is adopted to carry out the tuning. An adequate set-point is determined by matching measured absolute beam energy with those from a modeling. The tuning goal is satisfied using this method, which required within 1° for phase and 1 % for amplitude. This paper presents detail procedures of RF tuning of SDTL.

INTRODUCTION

The H^- beam is accelerated from 50-MeV to 181-MeV using 15 SDTL stations in the J-PARC LINAC. Each SDTL station includes 2 RF cavities, and is driven by one klystron, which operates at 324MHz.

In the beam commissioning of J-PARC LINAC, the RF tuning is performed with a phase-scan method [1~3], which has been used widely in many accelerator facilities. It involves varying phase over 360° and amplitude over ±4% to measure absolute beam energy. A detail tuning strategy was described in [4].

The tuning accuracy is required within 1° for phase and 1% for amplitude. To achieve the tuning goal, a signature matching method is proposed and implemented, which compares measured beam energy with those from a modeling to find an adequate set-point. The set-point is determined from the best matching between measurement and modeling. The modeling data is generated using the PARMILA [5] software.

During tuning a SDTL station, all upstream tanks are turned on, and downstream tanks are turned off.

DATA ACQUISITION

FCT Layout

The absolute beam energy is measured with the aid of FCT (Fast Current Transformer) based on the TOF (Time-Of-Flight) method. For each SDTL station, 2 TOF pairs, called long pair and short pair respectively, are prepared to measure the time of flight to calculate the beam energy as Fig. 1 illustrated. The distance between FCT's is measured with a laser-tracker with an accuracy of ~0.2mm.

Each TOF pair consists of 2 FCT's. In typical case, one FCT is shared by long pair and short pair.

The short pair locates near the exit of SDTL station under tuning. Usually the distance between 2 FCT's is around 2 $\beta\lambda$. It is advantageous for rough energy measurement because there is no possibility of miscounting the wave number. A problem is that it is difficult to measure the beam energy accurately because the measurement error has a large effect to the result.

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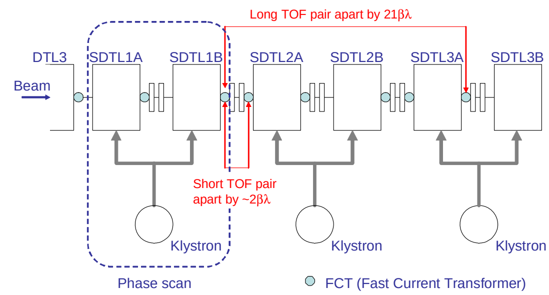

Figure 1: Schematic of TOF Pair of SDTL01.

A high precise energy is measured utilizing a long TOF pair. The long pair is apart over several tanks, and the distance is around a few ten $\beta\lambda$ or even over hundred $\beta\lambda$. For example, the long TOF pair of SDTL01 is over 3 tanks in-between, and the distance is about 21-$\beta\lambda$ as Fig. 1 illustrated.

The error caused by measurement can be reduced very much for long pair because the distance is long enough. A problem is that the possibility is high to miscount the wave number. A strategy is utilized to avoid this problem, which will be described later.

Data Acquisition

An automated application is developed under the XAL [6] framework for data acquisition and analysis. It varies the amplitude and the phase of RF klystron in a specified range. For each scan point, the measured quantities consist of 4 types described as bellow:

- FCT voltages. It is essential for beam energy measurement. It presents the time of flight of beam directly.
- Read-back of tank setting value. The value is monitored to ensure a corrected data setting.
- Monitor value of tank levels and phases. The read-back value from RF feed-back system presents current status of RF cavities. It is measured to ensure the cavities behaved as expected. Each SDTL station consists of 2 tanks, and the read-back values of amplitude and phase from 2 tanks are measured.
- Beam current. The beam current is used to detect a beam fault and validate a measurement. The range can be specified from the application.

Also, a flag signal from machine protection system is used to validate the measured FCT voltages.

BEAM ENERGY

Fig. 2 shows the obtained phase-scan curves for SDTL01 station, which plots 3 energy curves on right side. (1) The dot-marked line is measured beam energy using short TOF pair. (2) The square-marked line is measured energy using long TOF pair. (3) The line without marker is beam energy from modeling. The set-point is assumed to be 0º when generating energy data from the modeling. On Fig. 2, the modeling curve is shifted 180º to get a good display.

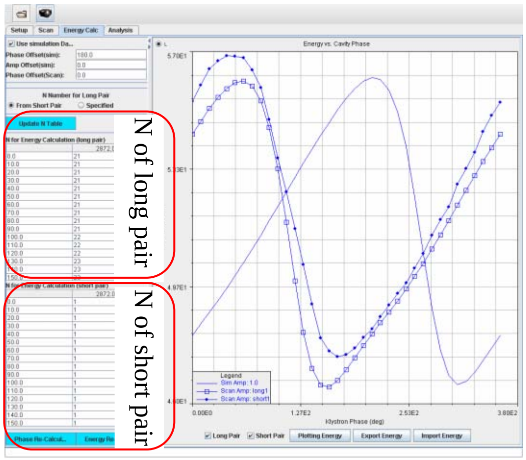

Figure 2: Beam Energy at SDTL01.

A good agreement is showed on Fig. 2 between modeling curve and measurement using long TOF pair. The set-point is determined by matching the curve of long pair with those from modeling. The energy obtained from short pair is rough, and the maximum energy deviation at a same scan point is over 2MeV from that using long pair. The short pair is utilized to avoid miscounting wave number of long pair.

It is important to count the $\beta\lambda$ period correctly during energy calculation. The distance of short pair is short, and there is no possibility of miscounting. For long pair, it is difficult because the distance is long. As Fig. 2 showed, for SDTL01, the integer part (N) is around 21, and varies between 21 and 23 during scan. To avoid miscounting, the N value of long pair is determined by the integer part of Equation 1.

$$N_{long} = (N_{short} \cdot 360 + \Delta\varphi_{short}) \cdot (L_{long} / L_{short}) / 360 \quad (1)$$

The left part is the phase difference measured by FCT pair. It is calculated by subtracting the beam phase at downstream FCT from the phase at upstream FCT because the system is calibrated in that way.

In principle, it is enough to get a right N value using Equation 1. Still it is possible to miscount the N value due to the measurement error. To avoid it, the energies are calculated around selected N. The N is decided from which provides an energy closest to that from short pair.

Above policy assumes that the measured energy using short pair is correct. Practically, there are some noise even wrong points. In this case, a “Specified” mode is provided to specify the N value manually.

SET-POINT

To seek an adequate set-point, a signature matching method is implemented for the SDTL tuning. It matches the measured energy curve with those from modeling in whole scan range (360º). The set-point is determined from the best matching point between the measurement and the modeling.

The modeling data is fitted using Equation 2. A nonlinear Least-Squares algorithm (Levenberg-Marquardt method [7]) is used for the fitting.

$$f_0(x) = a_0 + \sum_{i=1}^{5} a_i \cdot \cos(i \cdot (x+\theta)) + \sum_{i=1}^{5} b_i \cdot \sin(i \cdot (x+\theta)) \quad (2)$$

All scan curves obtained at each scanned tank level are shifted using Equation 3 to find a best matching with the modeling curve.

$$f(x) = f_0(x+\varphi_0) + c_0 \quad (3)$$

A matching error χ^2 is defined in Equation 4.

$$\chi^2 = \sum_{i=1}^{m} (f_i - E_i)^2 \Big/ M \quad (4)$$

Here f_i is energy fitted by Equation 3, E_i is measured beam energy, and M is number of scan points.

The matching errors for all scanned tank levels are fitting with a 2-order polynomial function. Fig. 3 shows a result of matching error of SDTL01. The best set-point is found at the minimum position as Fig. 3 illustrated.

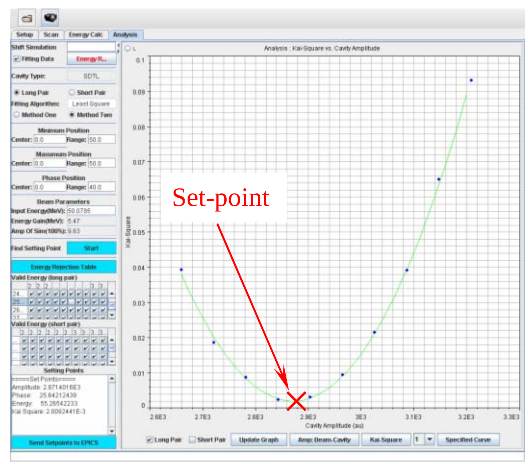

Figure 3: Plotting of χ^2 vs. Tank level for SDTL01.

In principle, the phase set-point can be determined at the same time. To satisfy the tuning requirement, a rescan is performed at determined amplitude. The accurate phase set-point is decided from phase shift φ_0 in Equation 3.

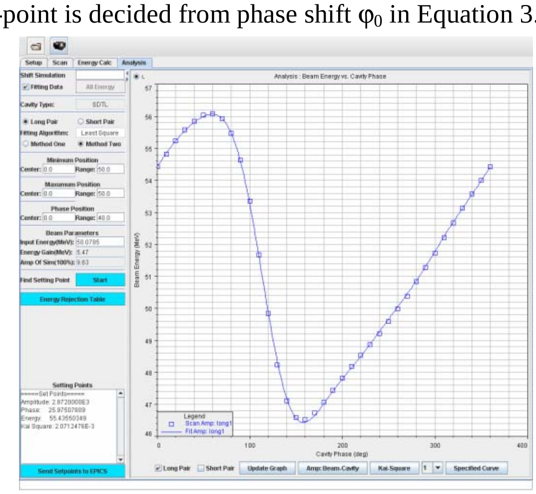

Figure 4: Rescan at amplitude set-point of SDTL01.

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Fig. 4 demonstrates the rescan result of SDTL01. The matching result is plotted on the right side. The square marker is measured beam energy, and the line is modeling data fitted with Equation 2 and shifted using Equation 3. The matching error is 0.21%.

The agreement between measurement and modeling is excellent for all SDTL stations as Fig. 5 illustrated. All curves are plotted by aligning the phase set-point on the left side for a good display. The dot marker is measured energy, and the line is modeling data fitted with Equation 2 and shifted using Equation 3.

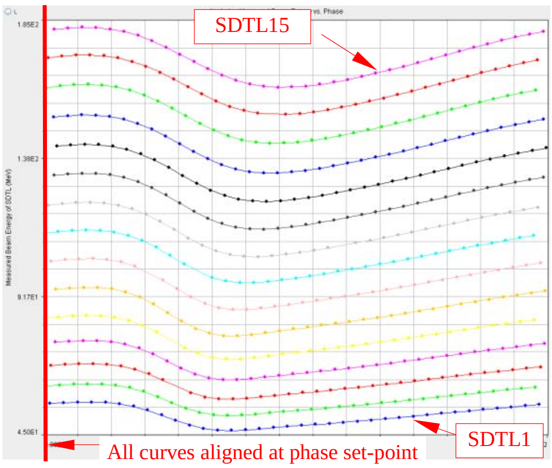

Figure 5: Signature matching for all SDTL stations.

A worst mismatch was observed at SDTL06 during the beam study of Apr. 2007, which was 0.83%. The set-points of amplitude and phase of all SDTL are listed in Table 1.

Table 1: Tuning result for all SDTL stations

	χ^2	A	Φ	Design (MeV)	Measure (MeV)	Energy Error
S01	0.0021	2872	25.9	55.55	55.43	-0.22%
S02	0.0020	2788	78.7	61.66	61.50	-0.26%
S03	0.0053	3781	115.7	68.44	68.27	-0.25%
S04	0.0041	3549	292.3	76.00	75.99	-0.01%
S05	0.0070	3611	259.7	84.35	84.36	0.01%
S06	0.0083	3553	252.0	93.64	93.73	0.10%
S07	0.0030	3625	215.2	103.10	103.38	0.27%
S08	0.0009	3374	350.0	112.66	112.99	0.29%
S09	0.0009	3452	296.9	122.32	122.38	0.04%
S10	0.0012	3351	182.8	132.07	132.18	0.08%
S11	0.0018	3436	260.9	141.84	141.90	0.04%
S12	0.0006	3138	213.0	151.65	151.79	0.09%
S13	0.0012	3443	168.6	161.45	162.11	0.41%
S14	0.0009	3302	97.1	171.26	172.06	0.45%
S15	0.0002	3353	192.9	181.04	181.39	0.14%

The measured beam energies were taken from rescan curve at the decided set-point. The maximum energy deviation from design energy was 0.45% observed at SDTL14 as Table 1 illustrated. The beam of J-PARC LINAC was accelerated to 181.39MeV, which was measured at exit of SDTL15 using long TOF pair. The output energy was 0.14% higher than the design value. The beam profile at SDTL section illustrates in Fig. 6.

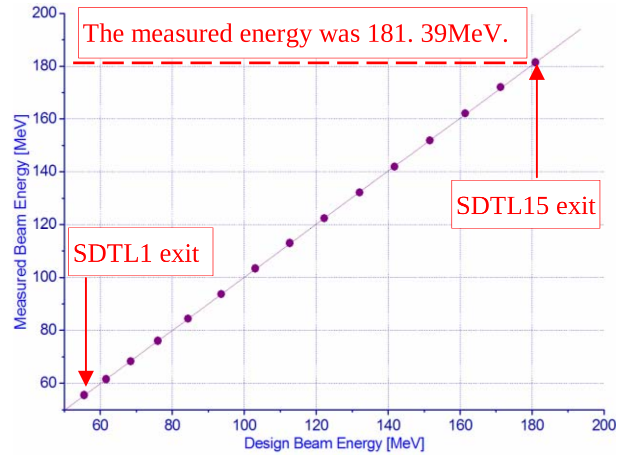

Figure 6: Beam energy profile at SDTL section.

CONCLUSION

An accurate tuning for RF amplitude and phase has been performed for all SDTL stations using the phase-scan method. The beam absolute energy has been measured based on the TOF method as originally planned.

All set-points for SDTL have been determined using the signature matching method. The tuning accuracy of 1° in phase and 1% in amplitude has achieved, and the beam has been accelerated at each SDTL as expected.

The final output energy of J-PARC LINAC was about 181.39MeV measured at the exit of SDTL15. It was about 0.14% higher than the design energy.

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