BEAM TUNING FOR LONGITUDINAL PROFILE AT J-PARC LINAC

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Abstract

Using bunch shape monitors (BSMs), we measured the longitudinal bunch lengths of negative hydrogen ion beams in the J-PARC linac. A BSM was installed between two linacs, separate-type drift tube linac (SDTL) and an annular-ring-coupled structure linac (ACS), having acceleration frequencies of 324 and 972 MHz, respectively. We used radio-frequency amplitude modulation of bunches in the beam transport between the SDTL and ACS to minimize emittance growth and beam loss. We conducted amplitude scanning and compared the results with the twiss-parameters obtained from the transverse profiles. In this paper, we discuss the results of amplitude tuning of the buncher cavity at the point of beam loss and emittance. We also discuss the measurement results for various equipartitioning settings of quadrupole magnets.

INTRODUCTION

At the energy upgrade project in the J-PARC linac, we installed an annular-ring-coupled structure linac (ACS) whose acceleration frequency of 972 MHz can be used to obtain beam energies ranging from 191 to 400 MeV downstream of the separate-type drift tube linac (SDTL). The acceleration frequency of the ACS is three times that of the SDTL; as this frequency jump may lead to beam loss owing to longitudinal (phase spread) mismatch, conducting phase-width matching between the SDTL and ACS sections is critical. To implement this matching strategy, we developed bunch shape monitors (BSMs) to follow the beam behavior in the two ACS-type buncher cavities. A tuning method involving phase-width matching of the three BSMs along with transverse profile matching was proposed. To establish equipartitioning conditions that would meet the beam dynamics design of the J-PARC linac, we use both the transverse profile and the phase width. In this paper, we explain and discuss the measurement results for the various equipartitioning settings.

BUNCH SHAPE MONITOR IN J-PARC LINAC

Bunch Shape Measurement

In collaboration with the Institute for Nuclear Research of the Russian Academy of Sciences (INR/RAS), a device for the beam phase width measurement was designed based on the observation of secondary electrons from a single wire intersecting a beam. After a series of beam bunches under measurement intersect a target wire having a diameter of 0.1 mm, low-energy secondary electrons are emitted owing to the beam–wire interaction [1, 2]. The wire is held at a negative potential of typically −10 kV. The secondary electrons move almost radially and enter a radio frequency (RF) deflector through collimators. An RF field with the same frequency as the accelerating RF (324 MHz) is applied to deflect the excess secondary electrons by an angle that depends on the phase of the deflecting field. By adjusting the deflecting field phase with respect to the accelerator RF reference, the phase widths of the bunches can be obtained.

Installation Layout

Three BSMs were installed upstream of the ACS section and two ACS-type bunchers were installed between the SDTL and ACS sections, as shown in Fig. 1. We implemented a tuning method involving phase-width matching using the three BSMs along with transverse profile matching. During the BSM measurements, the two 972-MHz ACS-type buncher cavities served as control knobs for phase-width matching [3]. Later, all three BSMs were removed and disassembled for out-gas conditioning. Currently, only one BSM has been reinstalled in front of the ACS01 cavity using additional vacuum pumps [4]. In this study, we used all three BSMs for amplitude scanning of the two ACS type-bunchers, while the single reinstalled BSM in front of the ACS01 was primarily used for an equipartitioning study. We set the longitudinal direction as the direction for phase spreading.

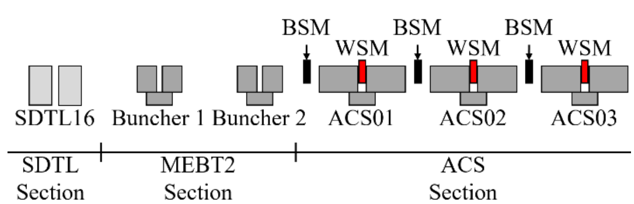

Figure 1: BSM and WSM layout around the upstream ACS section. Positions of WSMs and BSMs are indicated with arrows.

BUNCH SHAPE MEASUREMENT

During BSM calibration, a full scan was performed wherein the RMS beam width was measured as a function of SDTL15 cavity amplitude and compared with simulations performed using IMPACT and TraceWin. The results for the most upstream BSM (BMS#1) in Fig. 1, which was used further to measure emittance, can be seen in Fig. 2, wherein a close agreement between simulation and measurement is observed.

With the synchronous phase of SDTL15 set to bunching mode (−90°), the root-mean-square (RMS) phase width was measured at the BSMs as a function of the cavity

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amplitude. The resulting beam profiles measured for the J-PARC linac can be seen in Fig. 2, which shows the phase width for the entire pulse duration. The phase-width emittance measurement was performed at the SDTL–ACS transition using one BSM. The emittance and twiss-parameters at SDTL15 were then calculated by performing a three-parameter scan to fit the measured beam widths. The fitting was performed by particle tracking using IMPACT simulation assuming a Gaussian distribution at SDTL15 [5].

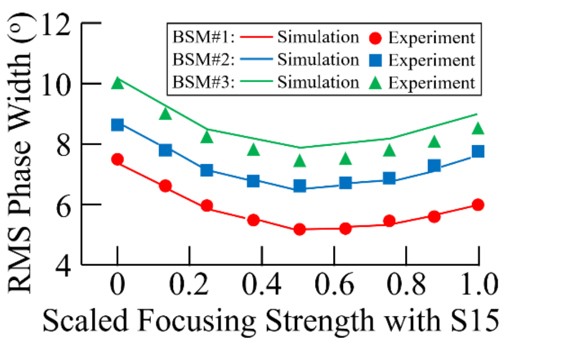

Figure 2: Measured RMS beam phase width versus focusing strength of last SDTL cavity (SDTL15) and corresponding simulation results.

BEAM STUDY FOR EQUIPARTITIONING

To study the space-charge-driven transverse–longitudinal (phase spread) coupling resonance, we used the BSMs to measure the emittance of phase width. The results are expected to contribute to the design of the beam operational parameters for the energy-upgraded linac. The high-intensity linac design follows the equipartitioning (EP) condition, namely, that strict control of the transverse and longitudinal tune ratios throughout the linac is considered to be important. To ensure space-charge-driven resonance, emittance exchange between the longitudinal and transverse planes should be minimized, as indicated in the tune ratio diagram (Hofmann's stability charts). Using BSMs, experimentally measuring this resonance phenomenon was possible [6] by simultaneously monitoring the transverse and longitudinal emittances for the first time.

When the J-PARC project was being designed, there was sufficient evidence from the pioneering works of I. Hofmann, R. A. Jameson et al, [7] and data based on experience from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory in the United States that EP-conditioned lattices offer a natural solution for emittance conservation in such high-intensity hadron accelerators. Fortunately, the J-PARC linac could find its EP solution as a baseline design without sacrificing hardware efficiency. The J-PARC linac can also be used in a wide range of off-EP conditions. As such, there is an opportunity not only for investigating basic beam physics principles but also for further optimizations of machine operation.

Normally, it can be assumed that $T_x = T_y$, where T_x, T_y, and T_z represent the horizontal, vertical, and longitudinal temperatures, respectively. As shown in Fig. 3, it is within the existing hardware capability to set the DTL, SDTL, and ACS to operate at a wide range the horizontal-to-longitudinal-temperature ratio (T_x/T_z). It is also equivalent to the ratio of oscillation energies in the transverse and longitudinal planes, as given as follows:

$$T_x/T_z = r_x^2k_x^2/r_z^2k_z^2 = \varepsilon_x k_x/\varepsilon_z k_z \quad , \qquad (1)$$

where r is the radius of the beam RMS envelope, ε is the RMS emittance, and the degree of focusing is proportional to the wave number k (with current) and k_0 (zero current). For instance, the settings to the left in Fig. 3 represent reduced transverse focusing or increased longitudinal focusing. The EP condition generates the largest stable area for beam propagation.

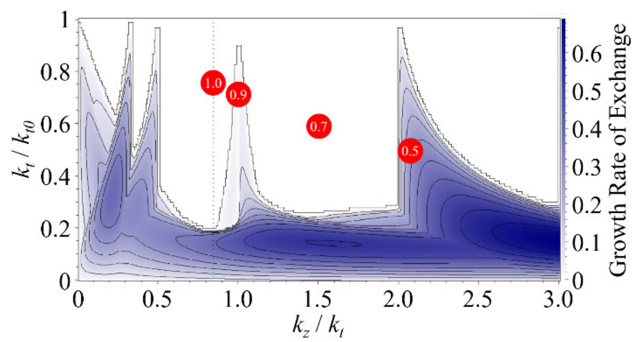

Figure 3: Hoffman's stability chart for J-PARC linac with emittance ratio $\varepsilon_z/\varepsilon_t = 1.2$ [9].

Four working points at temperature ratios of 1.0, 0.9, 0.7, and 0.5 were assessed, as shown in Fig. 3. To avoid any uncertainty from matching into the DTL, only the SDTL section was modified for each test case; this was done by adjusting the quadrupole gradients so that the beam stayed on the resonance, thus, enhancing the effect. The front-end and DTL settings were kept constant for all measurements. The beam current was set at 15 mA, which is the operating value.

The experimental procedure followed several steps. First, the quadrupole settings in the SDTL section were changed to bring the working point to the desired value. Transverse matching was then achieved at the DTL–SDTL transition with an array of wire scanner monitors (WSMs) and quadrupoles. Next, the WSMs were used to measure the transverse emittance at the ACS entrance. Finally, the BSMs at the ACS entrance were used to evaluate the longitudinal emittance (details of the SDTL–ACS section are shown in Fig. 1). This procedure was repeated for each of the working points. The gradients of four quadrupoles in DTL–SDTL transition were varied, and the beam size was measured using four periodically placed wire WSMs. Matching involved the use of an envelope over several quadrupole tuning iterations until the RMS beam widths became equal.

By determining the phase advance between the wire scanners, the emittance and twiss-parameters could be obtained by applying a parameter fitting routine to the measured RMS beam widths. For this, a three-dimensional

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envelope model of the machine used during the operation was developed using Open XAL [5, 8].

The phase width measurement results are shown in Fig. 4, and the emittance evolution throughout the linac for the four cases is summarized in Fig. 5 and Table 1, which shows some emittance exchange for the case $T = 0.9$ ($k_z/k_t = 1$) and a much stronger exchange for $T = 0.5$ ($k_z/k_t = 2$), but no exchange for the cases T = 1.0 or 0.7. It is also interesting to note that there is a strong longitudinal emittance growth between the end of the SDTL and BSM locations, which is caused by the absence of longitudinal focusing in this section and is the reason that multiparticle tracking is required to estimate the emittance.

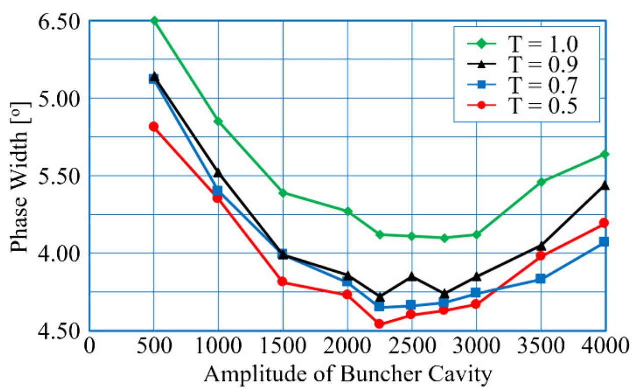

Figure 4: Measured phase-width in the linac for the four tested working points.

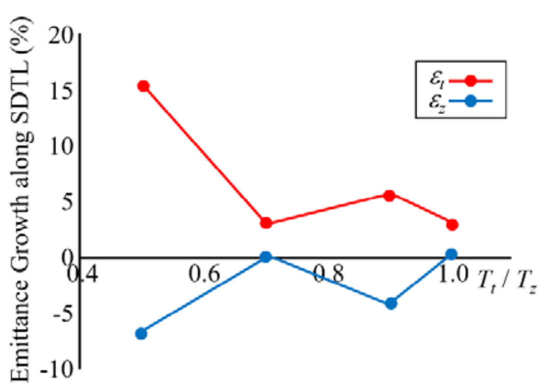

Figure 5: Simulated emittance growth in the linac for the four tested working points.

Table 1: Measured J-PARC Linac Emittance Values for the Four Working Points Tested [9].

T_t/T_z	DTL output [π.mm.mrad]	
	ε_t	ε_z
1.0	0.216	0.269
0.9	0.229	0.233
0.7	0.253	0.223
0.5	0.293	0.160

As explained above, the transverse emittance was measured at the SDTL output using a set of WSMs at the beginning of the ACS section. The longitudinal emittance was estimated using the RMS beam phase lengths measured by BSM1.

A clear increase in transverse emittance coupled with a decrease of longitudinal one was observed for the case $T = 0.5$. This is the first experimental observation of emittance exchange in a linac driven by the $k_z/k_t = 2$ resonance; it is also the first emittance exchange measurement in a proton linac with emittance ratios close to 1. Additionally, an unexpected halo was transversely measured, as indicated by the long tails in Fig. 6. Some exchanges were also measured for the case T = 0.7, which, as it has neither been numerically predicted nor by theory, was unexpected.

Although the first experimental evidence for emittance exchange at $k_z/k_t = 2$ in a proton linac with emittance ratios close to 1 is certainly encouraging in terms of the prospects for EP tuning, questions still remain. Efforts are being made to quantify our measurement limitations and fully understand the results. The unexpected emittance exchange seen at $T = 0.7$ should also be studied further.

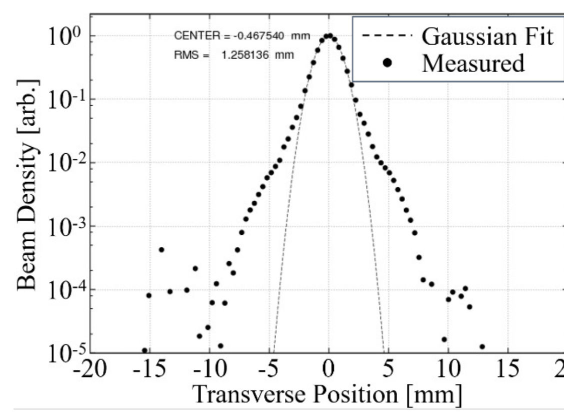

Figure 6: Measured transverse beam profiles in the ACS section at $T_t / T_z = 0.5$.

CONCLUSION

Experiments to determine the beam dynamics of the J-PARC linac design, which follows the EP condition, were conducted by measuring the longitudinal bunch length to produce Hofmann's stability charts indicating a region of space-charge driven transverse–longitudinal coupling resonance. The results supported this chart and the condition for avoiding the resonant region was estimated using the operational settings.

BSM measurements have the advantage of being able to measure longitudinal emittance; in this study, the accuracy of both transverse and longitudinal emittance measurements was verified. This method brings the discussion back to the choice of working point (i.e., using the EP set-point or not) and the use of stability charts in linac design.

The implications of these results for future linac designs are clear. Based on this experiment, there is now sufficient experimental and theoretical evidence to support the avoidance of the $k_z/k_t = 1$ and $k_z/k_t = 2$ stopbands. From our analysis, it is clear that a design procedure based on the EP criterion does not necessarily equate to the absence of emittance growth and halo development. It is also clear that safe working points do exist outside of EP; to avoid the

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growth of intra-beam-stripping, setting a larger T point as a safe working position outside of the EP region is possible.

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