MEASUREMENT OF RESONANT SPACE CHARGE EFFECTS IN THE J-PARC LINAC

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Abstract

Traditionally, high intensity linac designs follow the “equipartitioning condition”, a strict control of the transverse and longitudinal tune ratios throughout the linac that ensures space-charge driven emittance exchange between the longitudinal and transverse planes is minimised. However, equipartitioning imposes strict rules on the linac design, thus limiting the design options and increasing the overall construction cost. More recently, practical tools have been developed that offer guidelines in designing non-equipartitioned linacs, by charting the stable regions in a tune ratio diagram (Hofmann’s Charts). While these stability diagrams have been backed by extensive multiparticle simulations and some experimental evidence, questions still remain regarding the practical consequences of crossing the resonances. In this paper preliminary results are presented from an experimental study conducted in the J-PARC linac, where for the first time we measured both the transverse and longitudinal emittance for different linac working points. A detailed analysis will be presented as well as a discussion on the wider implications of this experiment.

INTRODUCTION

Space-charge coupling resonances have long been recognised as possible sources of emittance growth or exchange with potentially severe consequences for beam quality and transmission rates. Historically, resonances have been avoided by designing “equipartitioned” (EQP) linacs, by keeping the beam temperatures equal in the transverse and longitudinal planes: $T_t/T_z \sim k_t\varepsilon_t/k_z\varepsilon_z = 1$, where k is the tune and ε the emittance. Analytical work done over the last two decades has shown that high current non-equipartioned beams do not necessarily evolve towards equilibrium and the resulting emittance redistribution. Provided the tunes are chosen such that coupling resonances are avoided, linacs that break the EQP rule can be safely designed and operated [1], [2].

Stability diagrams have been developed that chart the unstable areas where coupling resonances can be excited. These charts show analytically calculated growth rates for different emittance ratios as a function of tune depression and longitudinal to transverse focussing ratio and are now a practical design tool for linac beam dynamics [3].

Confirmation of this work has been made possible by means of multiparticle simulations. However, experimental verification remains limited. The most notable evidence comes from a 2009 experiment at UNILAC in GSI in which the linac lattice has been modified to cross the $k_z/k_t = 1$ resonance. The resulting transverse emittance growth has been measured thus giving an indication of a resonance space charge effect. It has to be noted that an emittance ratio $\varepsilon_z/\varepsilon_t$ of 10 has been used which is much larger than those usually found in proton/H^- linacs where the ratio is closer to 1 [4].

THE EXPERIMENT

At the moment, the J-PARC linac consists of an H^- ion source, a Low Energy Beam Transport Line (LEBT), a 324 MHz, 3 MeV RFQ and a Medium Energy Beam Transport Line (MEBT1). After the front end, a Drift Tube Linac (DTL) accelerates the beam to ~50 MeV followed by a Separated-type DTL (SDTL) up to ~181 MeV. A major upgrade envisaged for the summer of 2013 will see the beam energy taken to 400 MeV by a series of annular coupled structures (ACS) operating at 972 MHz. A transport line (L3BT) injects the beam to the RCS (Figure 1) [5]. As the reference design is EQP and uses wide-ranging electromagnetic quadrupoles throughout, the linac offers unique experimental opportunities to test different operating lattices.

Four working points have been tried with temperature ratios of 1.0, 0.9, 0.7 and 0.5 as can be seen in Figure 2. To avoid any uncertainty from matching into the DTL, only the SDTL section has been modified for each test case, by adjusting the quadrupole gradients such that the beam stays on the resonance, thus enhancing the effect.

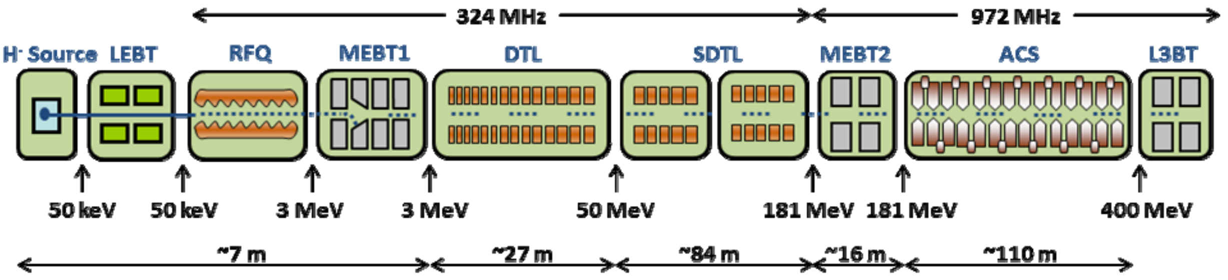

Figure 1: Schematic layout of the J-PARC linac.

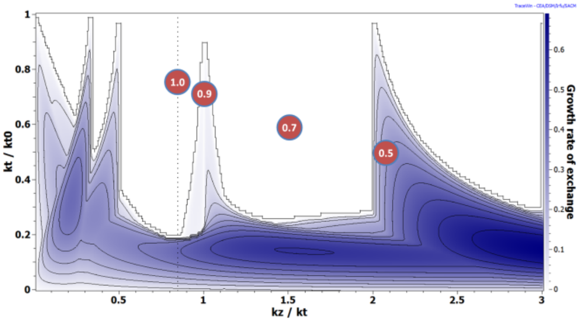

Figure 2: J-PARC linac stability chart for an emittance ratio $\varepsilon_z/\varepsilon_t = 1.2$. Dotted is the EQP line.

The front end and the DTL settings are kept constant for all measurements. The beam current was set at 15 mA.

Transverse matching is achieved at the DTL – SDTL transition with four wire scanners and four quadrupoles. This step requires the use of an envelope code and several iterations until the beam widths measured with the wire scanners are equal.

Simulations

In preparation for the experiment extensive multiparticle simulations have been performed with Impact [6] and Tracewin [7]. The results reported here refer to Tracewin only. Figure 3 shows the emittance evolution throughout the linac for the four cases. Some emittance exchange can be seen for case 0.9 and much stronger for 0.5, while cases 1.0 and 0.7 show no exchange. It is interesting to note a strong emittance growth longitudinally between the end of the SDTL (tank SDTL15) and the location of the bunch shape monitors. This is caused by the absence of longitudinal focussing in this section (~20 m). A summary of the emittance values at the end of the linac can be seen in Table 1.

Measurements

Transverse emittance is measured at the beginning of the ACS section using another set of wire scanners. By knowing the phase advance between the scanners, emittance and Twiss parameters can be obtained by a fitting routine. Typical horizontal and vertical beam profiles measured with one of the ACS wire scanners can be seen in Figure 4.

Longitudinal emittance is measured using the recently installed Bunch Shape Monitors (BSM) at the beginning of the ACS section. For this, the synchronous phase of tank SDTL15 is set to bunching mode and the RMS phase width is measured at BSM1 as a function of the tank amplitude. Details of this measurement are given in a separate paper [8].

The emittance at SDTL15 is calculated by doing a 3 parameter scan to fit the measured beam widths. As the envelope model cannot be used in this case, the fitting is done by particle tracking using Impact and assuming a Gaussian distribution at SDTL15. The measured longitudinal RMS phase widths for all the cases as well as the Impact fit can be seen in Figure 5.

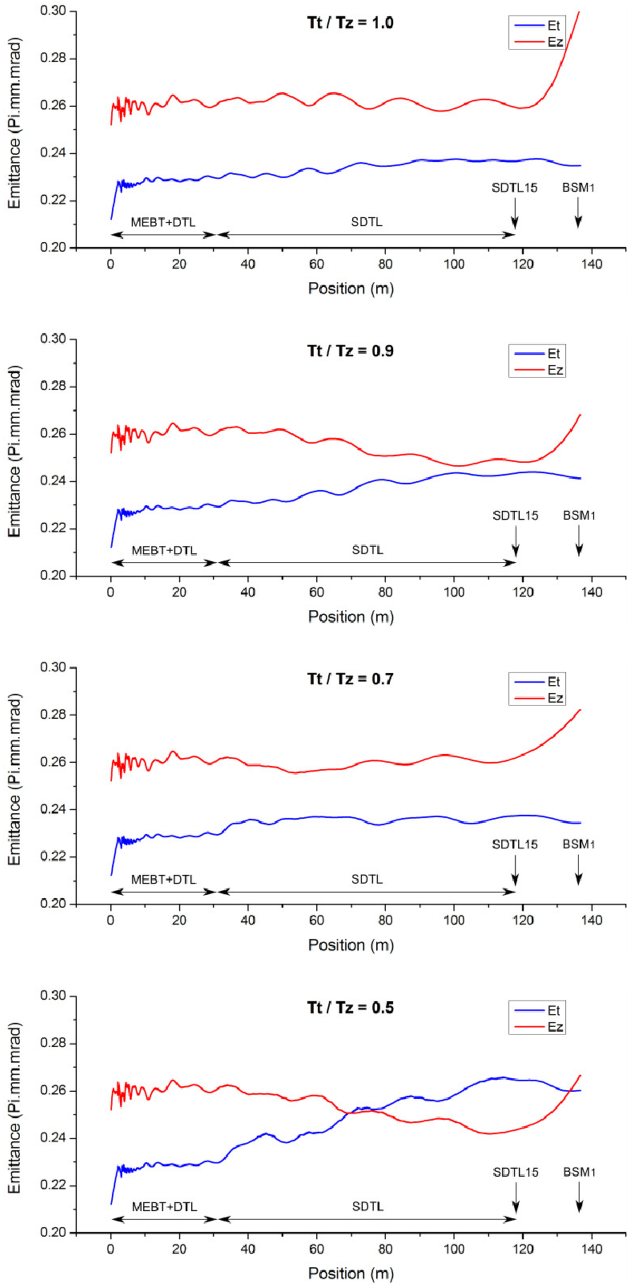

Figure 3: Simulated emittance evolution for the four test cases (RMS Normalised).

Table 1: Simulated linac output emittance at SDTL15 and BSM1 locations (RMS Normalised)

T_t/T_z	ε_t (π.mm.mrad)		ε_z (π.mm.mrad)	
	SDTL15	BSM1	SDTL15	BSM1
1.0	0.237	0.234	0.261	0.275
0.9	0.243	0.247	0.249	0.280
0.7	0.237	0.239	0.260	0.297
0.5	0.266	0.261	0.243	0.269

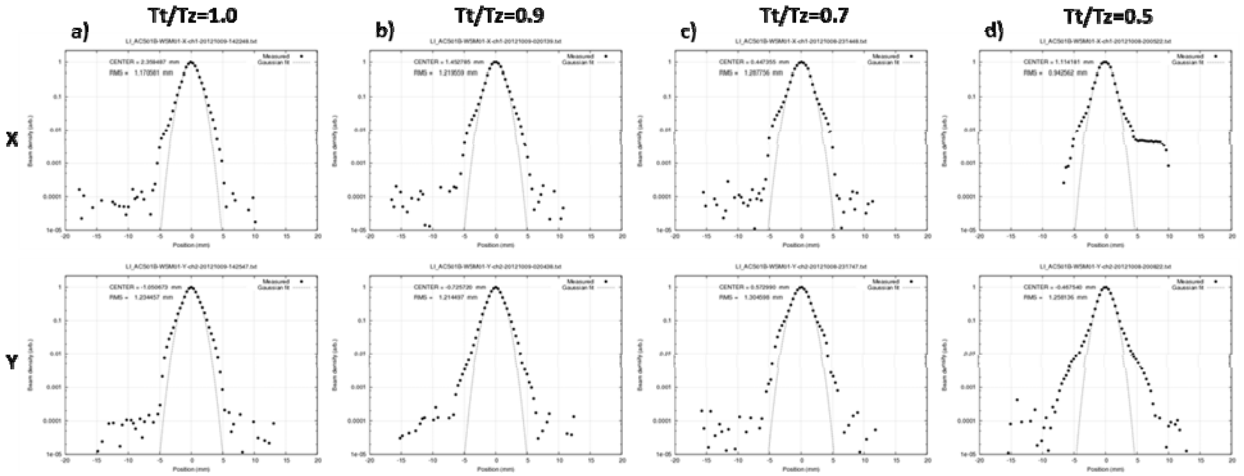

Figure 4: Measured transverse beam profiles in the ACS section. The horizontal axis is the measured width (mm) while the vertical is the logarithmic beam density (a.u.). Clear halo can be seen for case T=0.5.

DISCUSSION

The transverse and longitudinal emittance values can be seen in Table 2. A clear increase in transverse emittance coupled with a decrease longitudinally has been observed for case 0.5. The result is encouraging as it is the first experimental observation of emittance exchange driven by the $k_z/k_t = 2$ resonance in a linac with emittance ratios close to 1. Nevertheless, the level of exchange is much higher than predicted by simulation. Additionally, unexpected halo has been measured transversally as indicated by the long tails in Figure 4d.

The measurements for case 1.0 and 0.9 are both consistent with our simulations with some weak exchange observed for 0.9. However, a small level of exchange has also been measured for case 0.7, which hasn't been predicted numerically. While this could be explained by the larger transverse mismatch at SDTL input than for the other cases, questions still remain.

While efforts are still being made to quantify the measurement limitations and the effect of errors, these preliminary measurements could indicate that an unrecognised mechanism might be contributing to the stronger emittance exchange. It is hoped that some of these initial observations will be explained by repeating the experiment after the energy upgrade. This will have the obvious advantage of measuring longitudinal emittance without the significant SDTL15 to BSM1 emittance growth.

Table 2: Measured emittance values at SDTL15.

T_t/T_z	ε_t (π.mm.mrad)	ε_z (π.mm.mrad)
1.0	0.216	0.269
0.9	0.229	0.233
0.7	0.253	0.223
0.5	0.293	0.161

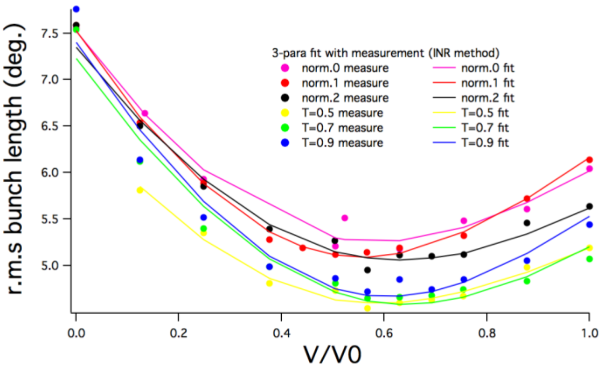

Figure 5: Measured RMS bunch length (experiment and Impact fit).

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