TRANSVERSE BEAM DYNAMICS STUDIES OF A HEAVY ION INDUCTION LINAC

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Abstract

The multiple beam induction linac experiment (MBE-4) was built to study the accelerator physics of the low energy, electrostatically focussed end of a driver for heavy ion inertial confinement fusion. In this machine four beams of Cs^+ ions are accelerated through 24 common induction gaps while being focussed in separate AG focussing channels. Each channel consists of a syncopated FODO lattice of 30 periods.

We report results of the most recent studies of the transverse beam dynamics of a single drifting (180 keV) beam in this machine. The dependence of the emittance on the zero-current phase advance shows systematic variations which may be understood in the light of previous theoretical work on this topic. This result, unique to the beam parameters of a linac for heavy ion fusion, will be discussed in the context of its implications for a driver design. In addition we will discuss recent measurements of the motion of the beam centroid through the linac. These measurements, coupled with simulations, have proven to be a powerful tool in determining the presence of misalignment errors in the lattice of the accelerator.

Introduction

MBE-4 is an experimental induction linac in which four beams of Cs^+ propagate through 24 common induction gaps while being focussed by individual electrostatic quadrupole channels, each consisting of 30 FODO periods[1,2]. The linac is constructed from six sections (denoted A through to F) each comprising 5 "lattice periods (l.p.)". Each l.p. is followed by a gap the first four of which are accelerating gaps while the fifth is reserved for diagnostic access. The diagnostic ports allow measurements of the beam size, emittance, and position and angular offsets of the beam centroid with respect to the linac axis. These measurements can be made in both planes transverse to the direction of propagation. This paper describes recent studies of the transverse emittance of one of these beams as it drifts through the linac at its injection energy of 180 keV. This beam has a nominal current of 5 mA and enters the linac with a normalized r.m.s emittance, ε_n, of 0.03 π mm-mrad where the normalized emittance is defined as

$$\varepsilon_n = 4\beta\pi\left(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right)^{1/2}$$

with β equal to the ratio of the ion speed to the speed of light and x and x' are the usual phase space variables.

Theory

For the parameters of MBE-4 one can calculate that the ratio of the space-charge depressed tune, σ, to the zero-current tune, σ_0 is give by $\sigma/\sigma_0 = 0.1$. Simulations have shown that such strongly space charge depressed beams propagating in electrostatic focussing systems might exhibit oscillations and growth in emittance[3]. As part of this work it was found that a small dodecapole component in the quadrupoles is beneficial, and the MBE-4 quadrupoles are so constructed. More recent simulations pertinent to the MBE-4 lattice configuration and quadrupole geometry have confirmed this behavior and have shown the evolution of the emittance to be strongly dependent on the amplitude of the coherent betatron oscillation of the beam[4]. Emittance variations are due to the excitation of coherent beam modes driven by external non-linear fields and image forces, amplitude modulated by the beam's coherent oscillation[4].

Experiments

Measurements made at the discretely available diagnostic stations on MBE-4 have indeed shown that the emittance is not constant but decreases and increases while the beam drifts through the linac. As MBE-4 is configured to allow diagnostic access at the end of each section only, however, a method is required whereby one could effectively measure the emittance at points both up and downstream of a given diagnostic station. The total distance travelled by a beam drifting in a linac can be expressed equally well in terms of accumulated betatron phase advance (for any given phase advance per unit cell). The technique then was to measure the emittance at a given diagnostic station for varying values of the lattice focussing strength, i.e. varying σ_0. This is achieved by simply varying the voltages on the quadrupoles. That this method allows one to observe the oscillation over all phases can be seen by inspection of figure 1(b). This figure shows the variation of the beam centroid, $\langle x\rangle$, with changes in zero-current tune measured in the horizontal plane at l.p. 20 (end of section D). The finite amplitude of this betatron oscillation is due primarily to injection offsets. One can see that to obtain a phase excursion of 2π

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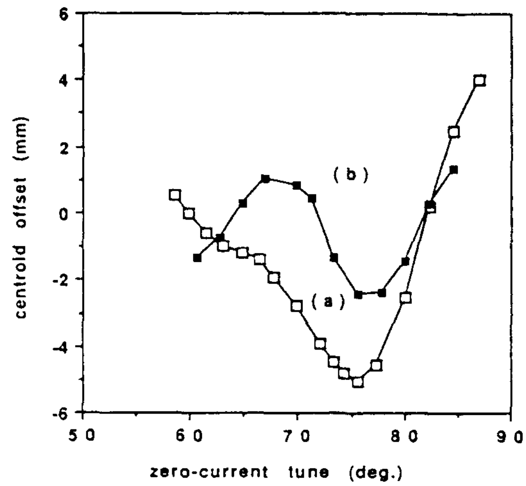

Fig. 1. Beam centroid position for kicked (a) and un-kicked (b) beam vs. zero-current tune.

one requires a change in σ_0 of 18^0/cell for the 20 cells as expected. Similar variations in the offset of the angle of the beam centroid, <x'>, are also observed.

Emittance measurements

Initial emittance measurements were made in the horizontal plane at l.p. 25. As in the simulation, large variations were observed, up to 50%, in the emittance about the matched tune value of $\sigma_0 = 70^0$, figure 2(a). The range of quadrupole voltage employed was restricted by the requirement not to lose beam due to radial expansion (low voltage end) or instability (high voltage end). Although we did not re-match the injector for each linac quadrupole setting we do not believe mis-match errors to be responsible for the large variations in emittance. Indeed many measured emittances are below the value measured for the matched beam.Similar variations in emittance were observed in the vertical plane at l.p. 25 and in the horizontal plane at l.p. 20, fig.3(a).

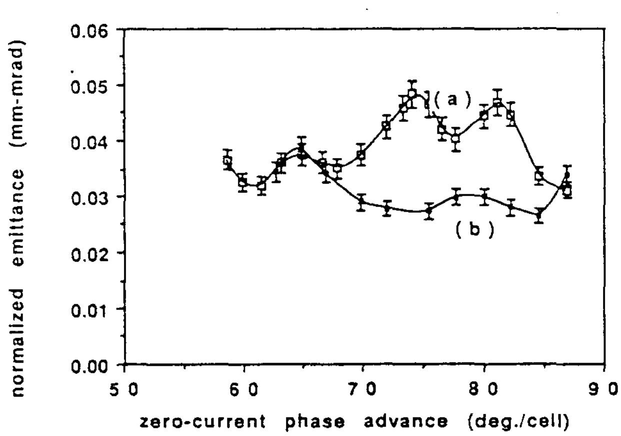

Fig. 2. Emittance measured at l.p. 25 for coherent amplitudes of (a) 4.5 mm and (b) 1.2 mm.

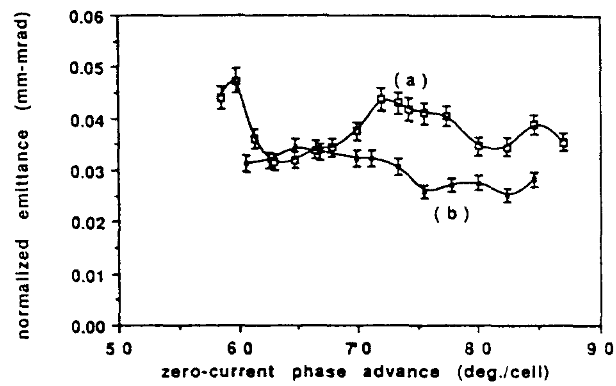

Fig. 3. Emittance measurements at l.p. 20 for coherent amplitudes of (a) 4.5 mm and (b) 1.9 mm.

The corresponding coherent amplitude in the horizontal plane was +/- 4.5mm (i.e. 9 mm peak to peak). One should bear in mind that the beam envelope has a maximum radius of 10 mm (nom.) and travels through a channel of 27 mm bore radius. Although this amplitude is good for driving the emittance changes it was too large to be accounted for in terms of injection offsets. In addition the variation of observed betatron phase was much less than expected on the basis of tune excursion. It was concluded that the horizontal motion of the beam was subject to a disturbance, perhaps due to a mechanical misalignment in one of the lattice quadrupoles. This subject is discussed further below.

To test the hypothesis that the emittance variations are the result of the large coherent amplitude we removed the offending disturbance to the beam and repeated the measurements at l.p. 20. This resulted in a coherent amplitude of +/- 1.9 mm determined by injection conditions and residual alignment errors. The variation in emittance also fell rather dramatically to 25%. A greater reduction in the coherent amplitude (1.2 mm) was achieved by using a steering array to reduce the initial offsets in the horizontal plane at the input to the linac. Subsequent measurements at l.p. 25 show little variation of emittance for tune values between 70^0/cell and 85^0/cell, fig. 2(b). This is in stark contrast to the variation found over the same tune range for the 4.5 mm coherent amplitude, fig. 2(a). The theory predicts that emittance growth in one plane may result from offsets in either plane. Therefore, some variation in the emittance may be accounted for as a result of offsets in the vertical plane which we have not attempted to correct.

Beam Centroid Measurements

As stated previously the amplitudes of the coherent oscillation measured at l.p. 20 and l.p. 25 were too large to be explained by the initial offsets of the position and angle of the beam centroid. Nevertheless the data for <x> and <x'> at l.p. 20, when mapped through 5 lattice periods, were found to be in good agreement with the data at l.p. 25. To investigate the possibility that the beam was suffering a kick in the linac we measured the variation of <x> for the beam as a function of σ_0 at each diagnostic station. The amplitude observed at l.p. 10, 1.4 mm, was consistent with the initial injection conditions and the Twiss parameters appropriate to the lattice optics. However at l.p. 15 it was found that the coherent amplitude was no longer consistent with a well aligned linac. We conclude that the data taken at l.p. 20 is due to the superposition of two oscillations, one due to the initial offsets and a second due to the kick in section C[5]. In fact we were able to locate the position of the kick close to l.p. 11 by fitting the measured data to transport computations in which the beam was given a single kick at different locations in turn. In order to remove the disturbance to the beam (the cause of which is still unknown) we replaced section C of the machine with section F, having already established the integrity of section F by successfully mapping data from l.p. 25 onto data taken at l.p. 30. The variation of <x> with σ_0, measured at l.p. 20, before and after the exchange of section C for section F is shown in figures 1(a) and 1(b). The data clearly confirm that the disturbance was located in section C. The amplitude and period of the oscillation for figure 1(b) is consistent with injection offsets.

Discussion and Conclusions

As the preservation of alignment and beam emittance are both crucial to the HIF driver concept it is clear that emittance growth in the low energy electrostatic focussed section of the linac is highly undesirable. The experiments discussed above therefore may impact choices in the design of this part of a driver. It is clear that, if one wishes to keep emittance growth to a minimum, one must strive to keep the beam on axis. This may be achieved by specifying sufficient machining and alignment tolerances on the lattice elements and it is necessary to determine how stringent the alignment tolerances must be. Alternatively, the detection and subsequent correction of errors in the motion of the beam may be possible. Both of these alternatives will have their respective financial consequences. A third possibility, that might obviate strict alignment or frequent correction, would be to run the linac with less tune depression[6]. This however may require a more expensive focussing channel for a given beam current.

In conclusion we have obtained experimental evidence in support of the simulation work of references 3 and 4, i.e. that the transverse emittance of strongly space-charge dominated ion beams propagating in electrostatic focussing structures will be subject to oscillation if the beam is off-axis as it travels through the structure. In contrast, when the beam is on, or close to the axis, the degree of variation in the emittance is considerably smaller. In addition our measurements of the coherent betatron oscillation amplitude have revealed the presence of alignment errors in the linac. Our technique of measuring the position of the beam centroid while changing the total accumulated phase advance at a given diagnostic station has since proven to be a valuable means of determining whether or not misalignments are present in the linac.

Acknowledgements

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References

1. A.I. Warwick et al, "Performance of MBE-4, an Experimental Induction Linear Accelerator for Heavy Ions", in Proceedings of the Linear Accelerator Conference, (Williamsburg) 1988.
2. T. Garvey et al, "Multiple Beam Induction Linac Research at LBL", to appear in the Proceedings of the 8th International Conference on High Power Beams,(Novosibirsk) 1990. Also LBL-28167.
3. C.M. Celata, "The Effect of Nonlinear Forces on Coherently Oscillating Space-Charge-Dominated Beams", Proceedings of the Particle Accelerator Conference, pp 996-1000, (Washington), 1987.
4. K. Hahn and L. Smith, "MBE-4 Simulations", in HIFAR Half-Year Report, LBL-29094, 1990.
5. A. Faltens, priv. comm.
6. At the time of writing we are performing experiments which appear to indicate that beams of higher initial emittance do not exhibit the emittance oscillations discussed above.