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MULTIPLE BEAM INDUCTION LINAC RESEARCH AT LBL*

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Abstract. We present results of progress on the LBL multiple beam induction linac experiment (MBE-4). This machine models the accelerator physics of the electric-focused portion of a driver for heavy ion inertial confinement fusion. Four beams of cesium ions are accelerated in common through twenty four induction gaps while being separately focussed in individual electrostatic AG focussing channels. Early experiments have demonstrated current amplification in the linac, from 10 mA to 90 mA per beam. This is achieved both by acceleration (from 200 keV to 1 MeV) and by carefully controlled bunch compression. Recent experiments have concentrated on studies of beams extracted from an ion source which produces 5 mA cesium beams at emittances near 0.03 π mm-mrad (normalized). Experiments and theory show a growth of emittance (by about a factor of 2) as these beams are accelerated through the linac. Results of recent measurements of the transverse emittance behavior of these strongly space-charge-dominated ion beams are reviewed and compared with theory.

INTRODUCTION

The multiple beam experiment (MBE-4) was constructed at LBL as part of the laboratory's program of accelerator research towards a heavy ion induction linac driver for inertial confinement fusion (ICF). The induction linac approach to heavy ion driven ICF and the unique features required of such an accelerator have been discussed extensively in the literature[1]. MBE-4 was designed to model some of the accelerator physics issues of a portion of such a driver in which the transverse focusing is achieved by electrostatic quadrupoles. A detailed description of the accelerator and the parameters of the experiment can be found in references 2 and 3. Briefly it comprises four beams of singly charged cesium ions, extracted from thermionic alumino-silicate sources, which are accelerated across a single diode gap to a nominal energy of 200 keV, the voltage being supplied by a Marx generator . After passing through the diode gap the beams enter an electrostatic quadrupole matching section which adjusts their envelopes for suitable injection into the induction linac. Once in the induction linac the beams are transported in individual electrostatic-quadrupole-focussing channnels consisting of 30 periods, while being accelerated through 24 common induction pulsers. The unit cell length is 45.72 cm resulting in an overall linac length of approximately 13.7 metres. Each doublet is followed by a gap for acceleration with the exception of every fifth gap which is reserved for diagnostic access and vacuum pumping. A schematic of the overall experimental arrangement is shown in figure 1.

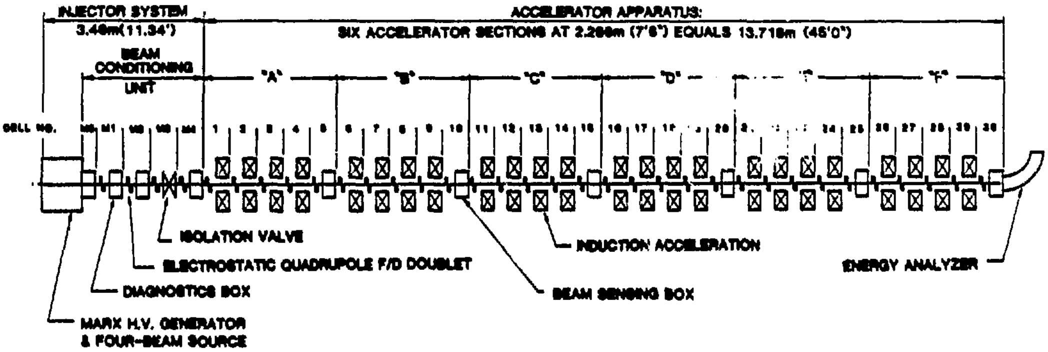

Figure 1. Schematic diagram of MBE-4

The diagnostic instruments used on MBE-4 consist of biased Faraday cups for total current measurement and the familiar "double-slit" scanner arrangement for measuring emittance. The slits, which are coupled to Faraday cups and which can be inserted in both principal transverse planes, also provide data on the transverse beam profile, the beam envelope and the angular and positional deviations of the bunch center from the linac axis. In addition to the scanners, which essentially yield information on the transverse properties of the beams, we employ an electrostatic spectrometer to determine the distribution of longitudinal energy within the ion bunch. A brief discussion of the MBE-4 diagnostics and the evaluation routines used for reducing the raw data can be found in reference[4].

The principal aim of the MBE-4 experiments is to study multiple beam handling and to demonstrate current amplification during acceleration of the beams, both of these features being crucial to the induction linac driver concept. Induction linacs can exhibit current amplification by differentially accelerating the tail of the bunch with respect to the head so compressing the bunch in time as it is accelerated through the machine. This is in contrast to the natural tendency of the bunch to lengthen as a result of the strong longitudinal space charge forces present at its ends where there is a gradient in the line charge density. Once again the success of the MBE-4 program in achieving its principal aims has been documented[4,5,6] with controlled bunch compression having allowed initial beam currents of 4x10 mA to be amplified to 4x90 mA at a final kinetic energy of 900 keV. In addition improved control of the compressed current waveform was achieved with a more gentle schedule of acceleration which yielded 4x35 mA at a final energy of 620 keV.

Despite the successful achievement of longitudinal compression in MBE-4 an unexpected and undesirable surprise was the appearance of a growth in the normalised r.m.s. transverse emittance of the beam by a factor of approximately two during acceleration whereas the un-accelerated or drifting beam emittance appeared to be constant during its transport to the end of the linac[4]. Following this discovery more recent studies on MBE-4 have been concerned almost exclusively with the investigation of emittance growth. The results of recent experiments and theoretical work in this area are the subject of this paper.

SOURCE MODIFICATIONS

As the principal issues of handling multiple beams, in so far as they can be studied with MBE-4, are believed to have been settled with the early MBE-4 experiments, more recent work has been performed with only one beam. This allows our investigation of the emittance behaviour to proceed more rapidly. The r.m.s. emittance of space charge dominated beams in linacs can grow if there is a change in the electrostatic field energy of the beam. A change in the beam density distribution can reduce this field energy at the expense of transverse beam heating which is essentially emittance growth. It has been observed in previous MBE-4 experiments that following extraction of the ion beam from the diode gap the beam is found to have a hollow current density distribution.This is undesirable in terms of its potential for emittance growth via a re-distribution of its density profile. In an attempt to produce a beam with a more uniform current density distribution we have modified the post extraction diode geometry to allow only the central uniform part of the beam to be transmitted. This has been achieved by using a positively biased aperture to scrape off the outermost rays, albeit at the expense of reducing the transmitted beam current from its previous value of 10 mA to a nominal value of 5 mA. Ultimately a re-designed source geometry will be employed to allow the generation of a uniform beam with the full 10 mA current.

A number of aperture diameters were tried with 11 mm appearing to be an optimum with regard to the uniformity of the transmitted current density. In addition to lowering the transmitted beam current the source modifications produce a beam of lower emittance, 0.03 π mm-mrad as opposed to the original value of 0.07 π mm-mrad,at the input of the linac.

As this emittance reduction occurs in both transverse planes the net result is a brighter beam.

BEAM EXPERIMENTS

Having established that the new source configuration behaved largely as expected our attention turned to investigations of the emittance behavior in the linac. Firstly we looked at the variation of the r.m.s. emittance of the drifting beam with diagnostic station. In general we find that the emittance shows a gradual, but not monotonic, increase as it travels from the beginning to the end of the machine, figure 2(a).

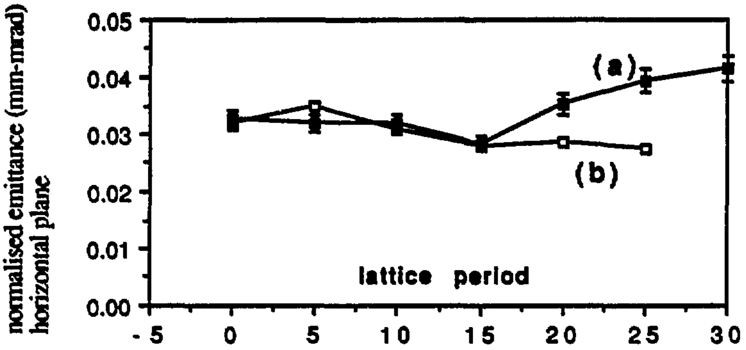

Figure 2. Dependence of emittance on lattice point for of-axis and on-axis beams.

The increase observed is in marked contrast to the 10 mA drifting beam case where the emittance was found to be constant. Our initial efforts to understand this behaviour included experiments to improve the beam matching from the injector and extensive efforts to provide beam steering at injection in order to minimise positional and angular offsets at the linac input. The result of these efforts was to show that different initial conditions would provide different dependences of emittance variation with diagnostic station (of which fig.2(a) is typical), but that all would display variations of up to 30%. For rigidly fixed initial conditions, however, we have been able to establish that the measured beam emittance at a given station is highly reproducible (<5% change). From this we conclude that different emittances measured on different occasions are firmly due to changes in initial conditions and not due to lack of measurement repeatability.

Following the work of Celata[7] we have been aware for some time that the emittance of space-charge-dominated beams propagating in electrostatic focused channels might vary in a complicated oscillatory manner. More recently we have been running simulations which indicate that the displacement in amplitude and direction of the beam from the linac axis determines the extent to which the emittance might grow. In addition, the growth is found to be more severe for smaller initial emittances. Figure 3 shows the results of computations for a beam on axis and for a beam displaced from the axis in both transverse directions by 3 mm. These runs are performed for the case of the MBE-4 geometry (the clear aperture in the quadrupoles is 27 mm and the nominal beam diameter is 10 mm).

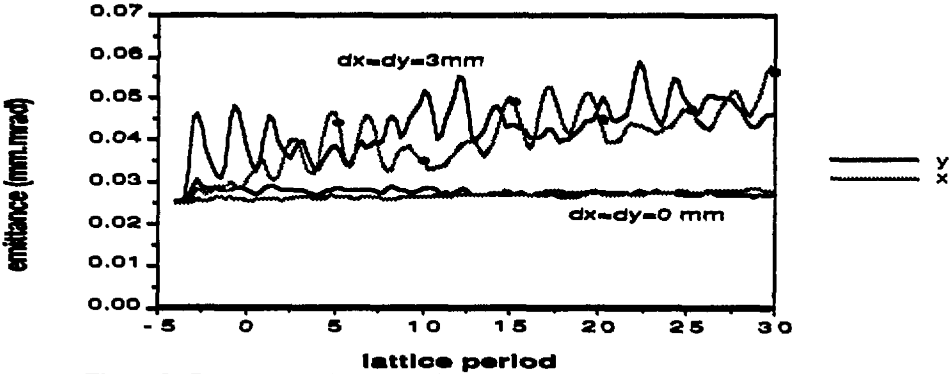

Figure 3. Computed emittance variations in both transverse (x and y) planes for of-axis and on axis beams. The dots indicate possible measured values at the MBE-4 diagnostic stations.

It should be clear from this curve that the increase and decrease of emittance shown in figure 2(a) could be explained by the sparse sampling of this variation at discrete points. To test this hypothesis we have improved our steering capability to reduce the input offsets in the horizontal position and angle of the beam centroid close to zero. This means that the betatron oscillation amplitude of the propagating beam is determined mainly by residual kicks received by the beam as a result of small alignment errors in the positioning of the quadrupoles. As a result, and after removing a section of the linac which was responsible for kicking the beam from the linac axis, we have been able to reduce the coherent betatron oscillation amplitude from 5 mm to 1.5 mm. The resulting variation of measured emittance with diagnostic station is shown in figure 2(b). One should note that relative to the "off-axis" beam the "on-axis" beam shows a greatly reduced variation in emittance.

DISCUSSION

We suspect that the observed emittance variations for the 5 mA drifting beam could be due to its large oscillation amplitude as is predicted by our theory[8,9]. The fact that such oscillations were not seen on the 10 mA drifting beam may have been due to its smaller tune depression, again in agreement with our simulation results. Indeed by employing a technique whereby we can effectively measure the beam emittance at points intermediate to our diagnostic stations we have recently seen evidence of the oscillatory nature of the emittance variations and of a dramatic reduction in these variations for well centered beams. Future work on MBE-4 will be devoted to exploring the possibility that the observed emittance growth for the accelerating beam is also explained by our theory and that the apparent irreproducibility in measurements of the accelerated beam emittance was merely due to changing initial conditions.

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