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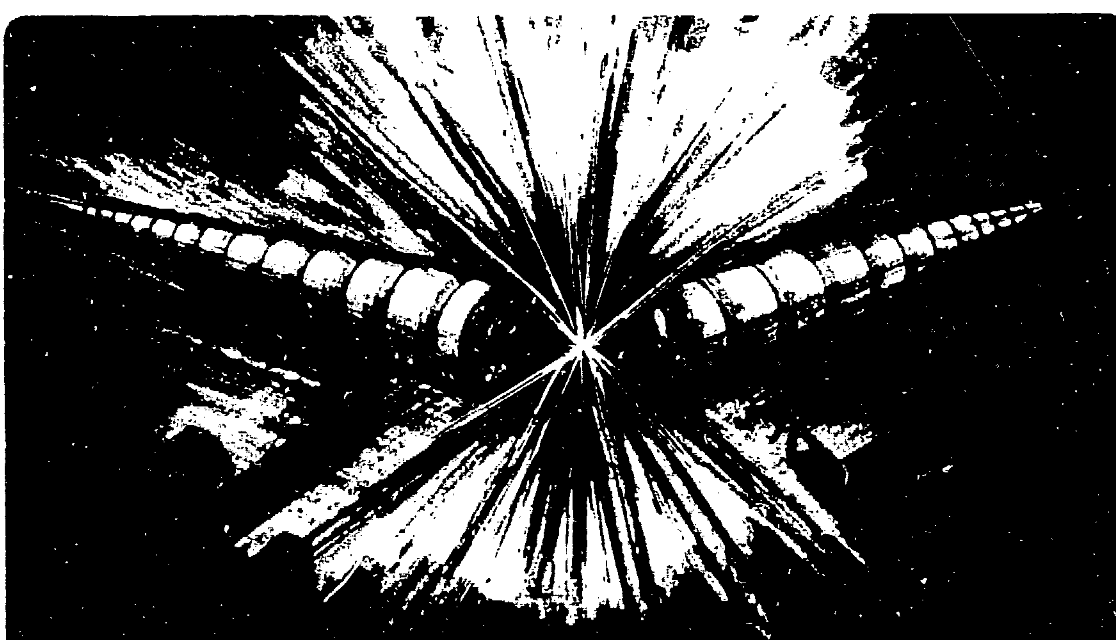

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ACCELERATION, CURRENT AMPLIFICATION AND EMITTANCE IN MBE-4, AN EXPERIMENTAL BEAM INDUCTION LINEAR ACCELERATOR FOR HEAVY IONS*

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ACCELERATION, CURRENT AMPLIFICATION AND EMITTANCE IN MBE-4, AN EXPERIMENTAL MULTIPLE BEAM INDUCTION LINEAR ACCELERATOR FOR HEAVY IONS*

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Abstract

We report on the implementation of a second schedule of acceleration and current amplification in MBE-4. Control of the beam current within the bunch is improved over that in the first schedule by the addition of several small amplitude induction pulsers to compensate for acceleration errors and to control the ends of the bunch. Measurements of the longitudinal and transverse emittance are presented.

Introduction

An experimental induction linac, called MBE 4, has been constructed to demonstrate acceleration and current amplification of multiple heavy ion beams. This work is part of a program to study the use of such an accelerator, on a much larger scale, as a driver for heavy ion inertial fusion. MBE-4 is 16m long and accelerates four space-charge-dominated beams of singly-charged cesium ions from an initial energy of 200 keV, amplifying the current in each beam from the initial value of 10mA. Construction of the apparatus was completed late in 1987. The four beamlets are focussed transversely by electrostatic quadrupoles. Acceleration is achieved at the gaps between quadrupole doublets by induction modules, in which a shaped voltage pulse of about 20kV is induced by discharging a capacitor into a shaping circuit which loops the induction core.

The acceleration schedule

A recent report[1] describes the apparatus and the first schedule of acceleration and current amplification to be implemented. In this first schedule the current of each of the four beams was amplified vigorously from 10mA to 90mA while the kinetic energy was increased from 200keV to 700keV. We report here on a second schedule of acceleration and current amplification, gentler than the first. The beams are accelerated to 620keV and the beamlet current is amplified to 35mA.

In the first schedule most of the induction cores were devoted to acceleration. Control of the bunch ends and the correction of acceleration errors was accomplished by modifying the shapes of the accelerating pulses. We found that more flexibility was required for good control of the beam current waveforms. In the second, more gentle schedule, reported here, we have devoted six of the 24 accelerating gaps exclusively to produce small correcting voltage pulses. These correcting stations are spaced down the linac so as to be able to modify the velocity profile of the bunch before errors have time to oscillate into current fluctuations[1]. They can also serve to hold the bunch ends together against the longitudinal space charge forces. The current amplification factor is reduced from 9 to 3.5, giving a bunch length compression more comparable to that in a fusion driver. Table 1 compares this second 'gentle' acceleration schedule with that of a representative driver[2].

Tuning the longitudinal dynamics

We again employed our simple one-dimensional simulation code SLID[3] to design the gentle schedule. This computation uses experimentally measured accelerating voltage waveforms on the accelerating gaps (those not devoted to correction) and generates ideal accelerating waveforms for use on the correction gaps. This means that in the computation the velocity profile of the bunch is perfectly corrected at each correction gap, to perpetuate the shape of the beam current waveform down the linac[3].

We first implement the schedule with the correcting gaps turned off. Our actual correcting pulses can only approximately match the ideal correction waveforms. We have three or four trim pulses that can be added at each correcting gap. Each pulse is up to 5kV in amplitude and rises and falls in about 400ns with a 20% undershoot. The amplitude, polarity and timing can easily be adjusted, and the beam bunch is accelerated through the linac without loss, regardless of these correctors. This situation lends itself to empirical tuning of the correctors, monitoring the beam current waveform at each of the monitoring stations along the linac and tuning for uniform current waveforms with controlled bunch ends. Figure 1 shows the results. Control of the current bunch is better than in the first vigorous schedule and much easier to implement.

Table 1 - Comparison of the parameters of MBE-4 with a driver design.

	MBE-4	MBE-4 (gentle schedule)	DRIVER	DRIVER	DRIVER
longitudinal position (z)	z=0m	z=14m	z=0m	z=400m	z=4km
charge number	1	1	3	3	3
mass number	133	133	200	200	200
kinetic energy	0.2MeV	0.62MeV	10MeV	100MeV	10GeV
ß	$1.8.10^{-3}$	$3.2.10^{-3}$	10-2	$3.2.10^{-2}$	$3.2.10^{-1}$
number of beams	4	4	64	*16	16
current per beam	10mA	†35mA	0.7A	14A	562A
line charge Cm^{-1}	$1.9.10^{-8}$	†$3.6.10^{-8}$	$2.3.10^{-7}$	$1.4.10^{-6}$	$5.9.10^{-6}$
overall bunch length	1.3m	0.86m	60m	38.4m	9.6m
overall bunch duration	2.5μs	900ns	20μs	4μs	100ns

†Peak value
*Beams merge transversely, so that the current per beam increases by a factor of four at this point.

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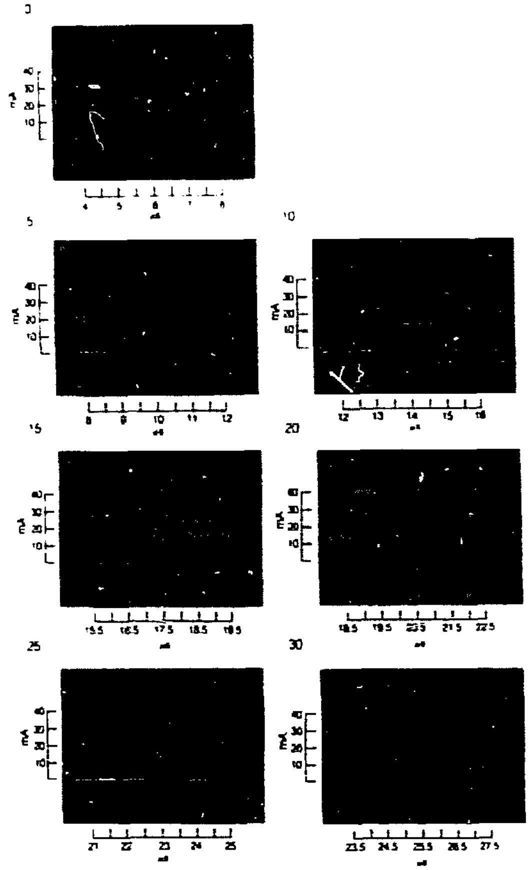

Figure 1. Current waveforms at each diagnostic gap through the linac under the gentle schedule.

Transverse Emittance

Figure 2 shows time resolved measurements of the un-normalized transverse emittance at the end of MBE-4, a) for a drifting beam at 200 keV with no acceleration and b) for a beam accelerated through the gentle schedule to 620keV. These data are for a slice of about 100ns duration at the detector, midway between head and tail of the bunch. Because of the increase in velocity, the un-normalized emittance in b) should be reduced by a factor of 1.75. Instead we observe that the un-normalized emittance is little changed, implying emittance growth of approximately this magnitude. At this point in the experimental program we have not yet been able to accelerate the beam bunch through MBE-4 at full current (10mA amplified to 35mA in this case) without observing some emittance growth. We have previously reported acceleration through the first half of the linac[3] (amplifying the current from 13 mA to 36 mA) without any observed emittance increase. Work is continuing to locate the source of the measured growth and to improve the performance of the linac in this respect. We are considering several potential sources of growth in the transverse emittance during acceleration.

i) The accelerating fields have some non-linear transverse components although the contribution to the emittance growth from this source is expected to be small.

ii) Since the beam has acquired a velocity difference varying from head to tail, variations in either the kinetic energy or in the beam centroid position during the 100ns sampling time of the emittance measurements could make the measured value appear larger. These effects, however, are estimated to be small.

iii) We have experimentally determined that the angular resolution of the emittance apparatus does not contribute to the observed growth.

iv) We are presently checking for envelope mismatch oscillations and coherent betatron oscillations which may cause the beam to sample the non-linear fields at large aperture radius. Since the beam occupies only about 50% of the aperture, this effect is absent unless there is an unsuspected accelerator malfunction.

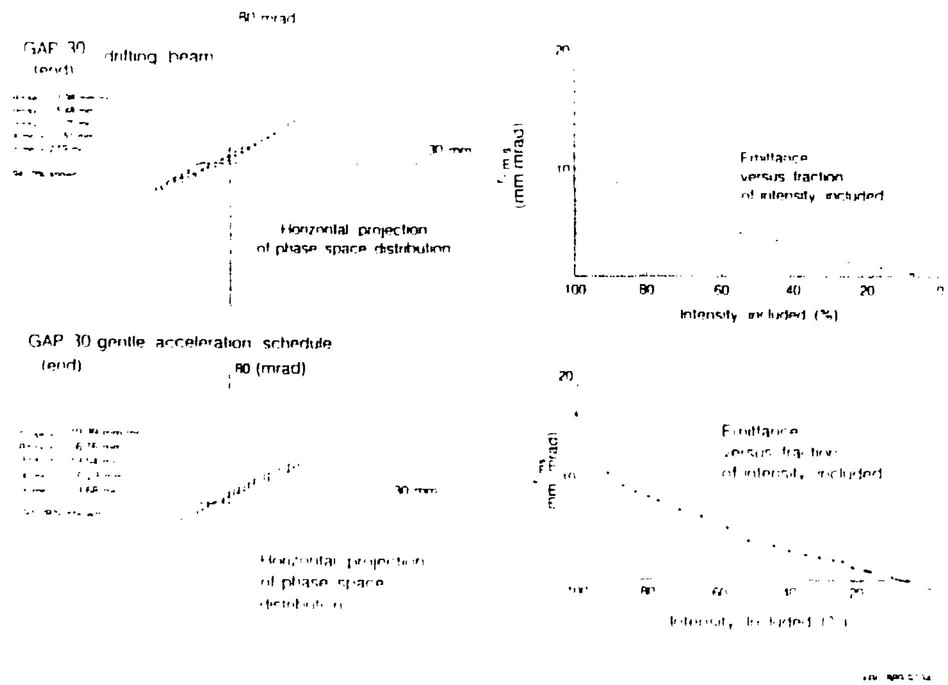

Figure 2. Measured transverse un-normalized emittance at the end of the accelerator in the longitudinal centre of the bunch for a drifting and an accelerated beam. Phase space plots are shown on the left. On the right the emittance is plotted against the fraction of the intensity included as a varying threshold is applied to the phase space density.

We are also currently scrutinizing data which suggests that the transverse emittance decreases at the head and tail of the bunch as they are eroded by the longitudinal space charge forces. This is contrary to our expectations and to results from a $2\frac{1}{2}$ dimensional PIC code.

There is still some work required to clarify the measurements of transverse emittance on MBE-4.

Longitudinal Emittance

The longitudinal emittance is essentially zero at first and increases along the accelerator as acceleration errors are accumulated. It is measured with an electrostatic analyzer and is shown in figure 3. The contours are logarithmic in intensity. The measurement is made over about 100 shots and includes the shot-to-shot variations in kinetic energy and arrival time. These shot-to-shot variations arise from small variations of the voltage pulses from the accelerating modules and give rise to the finite width of the distribution over and above the resolution (1/2% kinetic energy, 10 ns in time) of the measurement in figure 3. Some systematic perturbations are observable at the bunch ends. There the kinetic energy is not a single-valued function of the arrival time, even in a single shot, due to the effects of the correcting pulsers which are used to control the bunch ends against the longitudinal space charge force. The area of an ellipse surrounding this distribution is set by the systematic acceleration errors and is estimated to be:

$$\pi\varepsilon_{longitudinal} = 3.0 \cdot 10^{-3} \pi \text{ eV s}$$

which is 75% of the value previously obtained in the first vigorous acceleration schedule. (If the systematic errors were to be removed the value would drop by half).

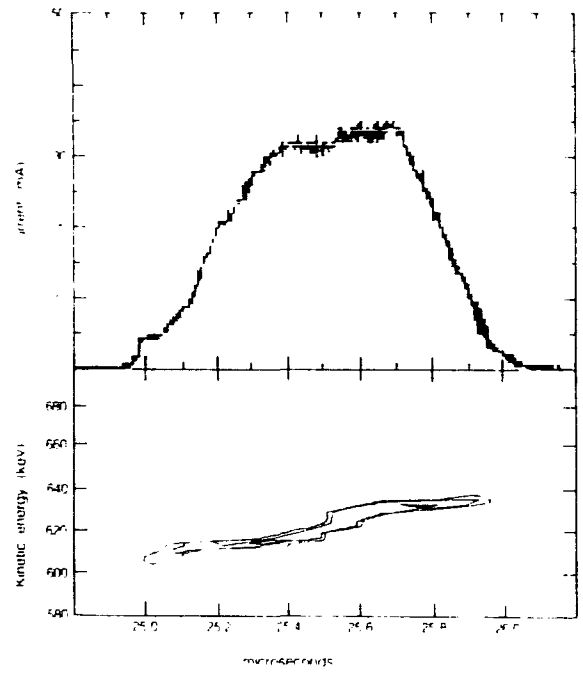

Figure 3. Measured longitudinal emittance at the end of the accelerator.

We now address the relationship between the longitudinal emittance achieved in MBE-4 and that required in a fusion driver.

The uncorrelated acceleration errors acting, at each gap, on a particular slice of the bunch length, contribute to the final momentum spread like a one dimensional random walk with a step size decreasing down the linac. The contribution is largest from the beginning of the accelerator because of subsequent acceleration and subsequent bunch shortening.

In order to derive a simple expression for the final momentum spread we assume that the voltage (ΔV) applied to the beam is the same at each gap, with uncorrelated errors having the same root mean square magnitude ($\sqrt{<\eta^2>} \cdot \Delta V$) where η is the fractional voltage error. Then the final r.m.s. momentum spread is given by

$$\Delta p_{r.m.s.}/p = \left[\left(<\eta^2> V_f^{1/2} \right) / \left(2 N V_i^{1/2} \right) \right]^{1/2}$$

where N is the number of accelerating gaps, V_f is the beam kinetic energy at the end of the linac and V_i is the kinetic energy at injection.

In MBE-4, V_i=200keV, V_f=620keV, N = 21 and the maximum accelerating voltage error is about 2.5% giving $<\eta^2> = 2 \cdot 10^{-4}$ for a uniform distribution of random error amplitude with zero mean. Using these parameters in the formula above and the bunch duration from figure 3 gives

$$\pi\varepsilon_{longitudinal} = 3.6 \cdot 10^{-3} \pi \text{ eV s}$$

which is close to the measured value. These errors are also consistent with the amplitude of the fluctuations in the current waveforms (Fig. 1).

Using the same accelerating voltage and accelerating errors in a fusion driver with V_i=10MeV and V_f=10GeV (table 1) gives $N = 1.5 \cdot 10^5$ and

$$\Delta p_{r.m.s.}/p = 1.5 \cdot 10^{-4}$$

This is close to the value of 1 to 2 x 10^{-4} that would be allowed under the constraints of the final focus onto the fusion target, which would allow little margin for other sources of growth, such as from the interaction between the high-current beams and the structure impedances. Accordingly, the control of incoherent errors in voltage must be better than the ± 2.5% at present obtained in MBE-4. In an analysis of the longitudinal emittance requirements for a reference driver, Faltens and Keefe[5] assumed, first that a contingency factor of 10 be included to allow for emittance growth from causes other than random voltage errors and, second, that the systematic errors be corrected. They concluded that random voltage errors would need to be kept to no greater than 1%.

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