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D. D.-M. Ho, R. O. Bangerter, E. P. Lee,
S. Brandon, and J. W.-K. Mark

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DYNAMICS OF HEAVY ION BEAMS DURING LONGITUDINAL COMPRESSION[*]

D. D.-M. Ho,[†] R. O. Bangerter,[†] E. P. Lee,[††] S. Brandon,[†] and J. W.-K. Mark[†]

Abstract

Heavy ion beam with initially uniform line charge density can be compressed longitudinally by an order of magnitude in such a way that the compressed beam has uniform line charge density and velocity-tilt profiles. There are no envelope mismatch oscillations during compression. Although the transverse temperature varies along the beam and also varies with time, no substantial longitudinal and transverse emittance growth has been observed. Scaling laws for beam radius and transport system parameters are given.

Introduction

After acceleration in an induction linac, a heavy ion beam which is to drive an ICF pellet must be compressed longitudinally to meet the power requirement for high gain. From the standpoint of final focusing, it may be advantageous for the compressed beam to have uniform line-charge density λ and uniform particle longitudinal momentum. This paper shows that it is possible for the beam to satisfy these requirements at the end of the compression process if the beam is given proper λ and velocity-tilt profiles while the beam is still traveling in the accelerator before compression starts. This paper also shows that there are no significant envelope mismatch oscillations and although the transverse temperature varies along the beam and varies with time, there is no substantial longitudinal and transverse emittance growth during compression. Scaling laws for the beam radius and transport system parameters are given for various regions along the drift-compression section.

Compression Scenario

When the beam is still in the accelerator, the longitudinal space-charge force is relatively small since the pulse is still long. Thus, it is possible to change the λ profile, from an initially uniform profile, to any reasonably shaped profile by giving the beam a proper velocity tilt. When the desired λ profile is achieved, the tilt is removed through appropriate wave forms on the accelerating gaps. Now, another velocity tilt is gradually given to the beam until the peaks of the tilt reach $\pm 2C_s$ (see Figure 1(a)) where $C_s \equiv \sqrt{(ze/\pi)g\lambda}$ and g is a dimensionless constant of order unity.[1] No more external manipulation of the beam is required beyond this point. The velocity tilt compresses the beam in such a way that the electrostatic force generated by the gradient of λ removes all the velocity tilt at the end of the compression process while the λ profile becomes uniform. The 1-D theory is confirmed by 2-1/2-D particle-in-all simulation as shown in Figure 1(c). Figure 1(b) is a intermediate step of the beam evolution between Figures 1(a) and 1(c). The beam envelope corresponds to conditions at Figure 1(b) is shown in Figure 2(a) and that corresponds to Figure 1(c) is shown in Figure 2(b).

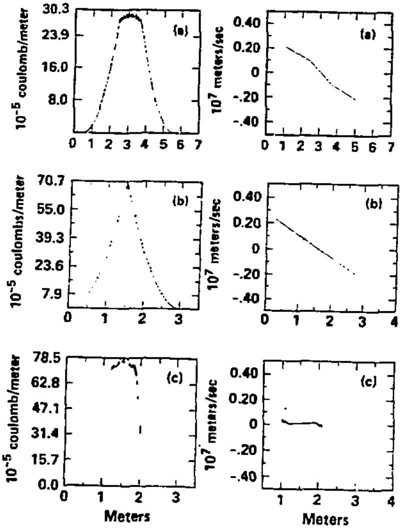

Figure 1. Line-charge and velocity-tilt profiles at various stages during longitudinal compression.

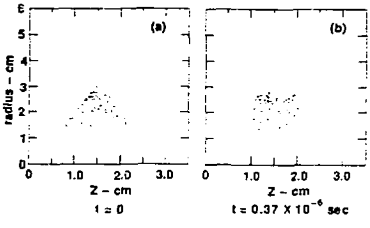

Figure 2. Radial particle distribution during beam compression.

In order to determine the λ and velocity-tilt profiles in Figure 1(a), one realizes

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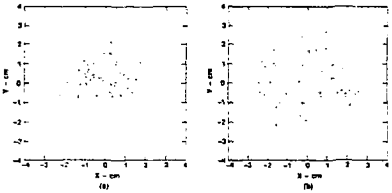
[†] Lawrence Livermore National Laboratory, Livermore, CA 94550

[††] Lawrence Berkeley Laboratory, Berkeley, CA 94720

that the equations for 1-D charged-particle motion are identical to those for 1-D ideal gas motion except that the pressure force ∇P in the fluid equation is now replaced by the electrostatic force (i.e. $E_z = -g\partial\lambda/\partial z$). Therefore, the longitudinal compression process can be treated exactly as the time-reversal process for the free expansion of a slab of gas with initial constant pressure and density profiles.[2] A more detailed description of the longitudinal compression scenario is given in a forthcoming report.[3]

Transverse Dynamics During Longitudinal Compression

The change in λ, after the beam travels a typical lattice period of length 2L is small, i.e. $\Delta\lambda/\lambda \ll 1$. Therefore $\partial^2 a/\partial t^2 \to 0$ in the beam frame if $\partial^2 a/\partial t^2 = 0$ initially. Here, a is the rms envelope radius. Since there is no mismatch oscillation, the density profile stays essentially uniform if it is uniform initially. This is confirmed by simulation as shown in Figure 3. Figure 3(a) is the projection of all the beam particles on the transverse plane at the time corresponding to the beam in the configuration shown in Figure 1(b) and Figure 2(a) while Figure 3(b) corresponds to beam configuration at Figure 1(c) and Figure 2(b). Thus, all forces in the transverse direction are linear and no emittance growth is observed in both the longitudinal and transverse directions.



(a)

(b)

Figure 3. Projection of beam particles on the transverse plane.

Note that the normalized emittance ϵ_N is constant everywhere along the beam and is also constant in time. Therefore, the transverse temperature is approximatly proportional to $1/a^2$ which varies along the beam. It is necessary to take this fact into account in the particle particle-in-cell simulation. Also not that the absence of mismatch oscillations is important for final focusing lens design considerations.

Scaling Laws for the Beam Radius and for Transport System Parameters During Compression

For constant external focusing strength without mismatch oscillations, the rms radius for a space-charge dominated beam varies as

$$a \propto \sqrt{Q} \quad ,$$

and at the beam center (1)

$$\frac{\sigma}{\sigma_0} \propto \frac{1}{Q_0} \quad .$$

where

$$Q \equiv \frac{2ze\lambda}{4\pi\epsilon_0 B^2 \gamma^3 Mc^2}$$

is the generalized perveance, Q_0 is Q at the beam center, and $\sigma(\sigma^0)$ is the single particle phase advance with (without) space-charge effect.

If the pole-tip magnetic field B^0 is fixed; σ^0 is fixed at 90°; but the fractional occupancy of quadrupoles η and the half period L are allowed to vary, then

$$\sqrt{\eta}\,[3-2\eta]^{1/4} \propto \sqrt{Q_0} \quad ,$$

$$L = \frac{\text{conts.}}{\sqrt{\eta}\,[3-2\eta]^{1/4}} \quad , \qquad (2)$$

$$\frac{\sigma}{\sigma_0} \propto \frac{1}{\sqrt{Q_0}} \quad .$$

If η is fixed but B_0 is increasing, then

$$\sqrt{B_0} \propto \sqrt{Q_0}$$

$$L = \frac{\text{const.}}{\sqrt{B_0}} \qquad (3)$$

and

$$\frac{\sigma}{\sigma_0} \propto \frac{1}{\sqrt{Q_0}} \quad .$$

Finally, if η and B_0 are fixed but the aperture radius is allowed to increase and if the ratio of the aperture radius to the beam radius is fixed, then

$$a \propto Q,$$

$$L/\sqrt{a} = \text{const.}, \qquad (4)$$

and

$$\frac{\sigma}{\sigma_0} \propto \frac{1}{Q_0^{3/2}} \quad .$$

A more detailed description of the material presented in this section is given in Ref. [3].

Pulse Shaping and Related Considerations

Pulse shaping can be easily obtained by delaying the relative arrival time of different pulses on the target. Finally note that the radius of the beam is greatly expanded, e.g. greater than 10 cm, inside the final focusing lens system. Thus, the rectangularly-shaped pulse may be able to pass through the lens system, which normally exceeds 20m in length,[4,5] without too much erosion at both ends due to the re-expansion of the rarefaction waves.

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