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PREPRINTSTUDY OF HEAVY ION BEAMS DURING LONGITUDINAL
COMPRESSION USING PARTICLE SIMULATION*Darwin D.-M. Ho and Scott T. Brandon
Lawrence Livermore National Laboratory
University of California
Livermore, California 94550This paper was prepared for submittal to
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STUDY OF HEAVY ION BEAMS DURING LONGITUDINAL
COMPRESSION USING PARTICLE SIMULATION*

Darwin D.-M. Ho and Scott T. Brandon
Lawrence Livermore National Laboratory
University of California
Livermore, California 94550

ABSTRACT

Particle simulations show that during longitudinal compression, there is little growth in beam longitudinal and transverse emittance. Both longitudinal and transverse temperatures follow adiabatic laws. The compressed beam has negligible longitudinal momentum spread and therefore can satisfy stringent requirements for final focusing.

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Introduction

It is necessary to compress longitudinally a heavy ion beam, emerging from an induction linac, in order to generate enough power for high gain implosions. To relieve the constraints in the final focusing lens design, it may be advantageous for the compressed beam to have uniform line charge density and uniform longitudinal momentum. The basic principle of the compression scenario for achieving this final beam configuration and the longitudinal dynamics have been described in our previous report.[1] With the newly expanded capabilities of the Condor 2-1/2D particle code, we are now able to make a much more detailed study of beam dynamics during compression. In this paper, we will show that in order to simulate the compression self-consistently, it is necessary to vary the longitudinal temperature, transverse temperature, beam density, and beam radius along the beam. The result of the particle simulations, the emittance growth, and the effect of longitudinal temperature on compression will be discussed.

Self-Consistent Particle Simulations and Emittance Growth of Heavy Ion Beams During Compression

We start with a 3 m long beam and let it go through self compression until the length reaches 1 m. This is because, as mentioned in Ref. [1], there is an analytical approximation that describes the line-charge density λ along the beam longitudinal coordinate z if the beam is less than 3 m long and if the compressed configuration is 1 m long. Thus, the easiest way to calculate the beam initial parameters is to start with a 3 m long beam. The initial λ of the 3 m long beam is shown in Fig. 1(a). In the first part of this section, we will describe the method for obtaining the initial parameters for a 3 m long beam in radial

equilibrium and the initialization of the particle simulation. In the second part of this section, results from the particle simulation will be discussed.

Obtaining the initial parameters for a beam in radial equilibrium

Since λ varies along z , the beam radius also varies along z . Near the two ends of the beam, λ decreases to low values and thus the beam radius is predominantly determined by the transverse temperature, i.e. the beam is no longer dominated by space charge. Thus, it is necessary to employ the envelope equation with the emittance term in order to determine the equilibrium beam radius as one of the initial conditions for particle simulation.

The envelope equation that follows the trajectory of a slice of the beam has the form [2]

$$\frac{\partial^2 \tilde{a}}{\partial t^2} = \beta^2 c^2 \left(-k\tilde{a} + \frac{\tilde{\epsilon}^2}{\tilde{a}^3} + \frac{Q}{4\tilde{a}} \right), \quad (1)$$

where

$$\tilde{a}^2 \equiv (1/N) \sum_{i=1}^N x_i^2.$$

Here x_i is the distance from beam center on coordinate x , which is perpendicular to the beam longitudinal axis, of particle i . The total number of particle in a thin slice of the beam is denoted by N . For a uniform radial density profile, $\tilde{a} = (1/2)a$ where a is the beam radius. Note that it is accurate to assume that the beam has a uniform radial density profile, except near the two ends, if the initial equilibrium profile is uniform. The rms emittance is $\bar{\epsilon}$ where the bar denotes rms value; the averaged applied force per unit mass from the FODO system is

$-\beta^2 c^2 \tilde{k} a$; the generalized perveance [2] is Q and is proportional to the line charge density λ , the speed of light is c ; and the relativistic parameter is B .

The normalized emittance $\epsilon_n = (B\gamma)\epsilon$ is constant along the beam but $B\gamma$ is a function of z because of the initial longitudinal velocity v_z tilt. However, the velocity tilt is of order 10^{-2} times the beam center velocity. Thus, we will treat $B\gamma$ as a constant. For a sample calculation, we choose a heavy-ion beam at the final compressed configuration having $a = 3$ cm, $\lambda = 6.9 \times 10^{-5}$ C/m, the edge emittance $\epsilon = 3 \times 10^{-5}$ m-rad (Ref. [3]), and a corresponding transverse temperature of about 6.2 keV. To solve for radius, we set the right-hand side of Eq. (1) equal to zero. The calculated particle distribution within the beam envelope as a function of z is shown in Fig. 1(b). Near the two ends of the beam, the radius expands to about twice the calculated value (with constant density profile) after approximately 10^{-8} seconds. This is due to the fact that the density profile is nonuniform near the ends because the beam is no longer space-charge dominated. The velocity tilt v_z required to compress the beam is shown in Fig. 1(c). The peak velocity at the two ends of the beam equals to $|2.7 \times 10^6|$ m/sec.

The transverse temperature $T_{\perp}$ and longitudinal temperature $T_{\parallel}$ also vary along the beam. The transverse temperature follows the adiabatic 2-D compression law $(\gamma=2)^{1/2}$, i.e.

$$T_{\perp} = T_0 \left(\frac{a_0}{a(z)} \right)^2 \quad (2)$$

Here, the subscript 0 refers to quantities at beam center. Since we have calculated the beam radius, $T_{\perp}$ can be obtained and is shown in Fig. 1(d) as a function of z .

To estimate the maximum allowable $T_{\parallel}$, note that for proper focusing of the beam onto the target, the longitudinal momentum variation of the beam $\Delta p_z/p_z$ at the final focusing lens should typically be less than 10^{-3} to 10^{-4} (Ref. [4]). Thus the maximum allowable $T_{\parallel}$ at the compressed configuration is about 0(10 keV). Since pressure force is much less than the electrostatic force along the longitudinal direction, mixing due to thermal spread is not important. Thus, $T_{\parallel}$ follows the 1-D adiabatic compression law ($\gamma=3$), i.e.

$$T_{\parallel} = T_0 \left(\frac{\lambda(z)}{\lambda_0} \right)^2 \quad (3)$$

Using this relation, and taking $T_{\parallel}$ to be 10 keV, $T_{\parallel}$ versus z is plotted in Fig. 1(e). The existence of $T_{\parallel}$ is also evidenced on the v_z versus z plot as shown in Fig. 1(c). In the absence of $T_{\parallel}$, v_z versus z would be just a zero-width straight line.

Incorporating the initial parameters of the beam as specified above, the Condor particle code is used to simulate the self-compression. Forty-six-thousand (46000) particles are employed in the model. The initial transverse velocity v_x is plotted versus x on Fig. 1(f); this plot is essentially identical to the plot for v_y versus y , because of axial symmetry. Note that on this plot, there are particles with relatively high v_x around $x=0$. This is because particles at the two ends have higher transverse temperature and are contained in areas with small radius. However, the normalized x emittance is constant along the beam as shown in Fig. 1(g); this plot is essentially identical to the plot for y emittance versus z .

To observe whether there is emittance growth, it is necessary to use normalized emittance ϵ_n since particles are decelerated along the beam

due to the space-charge gradient. The normalized rms emittance in the x direction, measured on the coordinate of any slice along the beam, is [2]

$$\overline{\epsilon_n^x} = \frac{1}{c} [\overline{\dot{x}^2} - \overline{(\dot{x})^2}]^{1/2}, \quad (4)$$

where dots indicate time derivatives. Although Condor measures emittance on the coordinate moving with the beam center, the normalized emittance obtained from Condor for each slice of the beam equals that given by Eq. (4) because the velocity difference between the beam head and beam tail is non-relativistic.

Particle simulations

We found that when the beam completes the self-compression and becomes 1 m long, no particles have been lost. The line charge density and radius become uniform along z, as expected, as shown in Figs. 1(h) and 1(i). The slope of v_z versus z becomes flat [Fig. 1(j)] and the distribution of v_z is equivalent of having a $T_{||}$ of 12 keV except at the two ends as shown in Fig. 1(l). The final $T_{||}$ is 2 keV higher than what we would have expected but the $\Delta p_z/p_z$ is still well within the constraint of the final focusing lens. The transverse temperature along the beam also decreases, due to radial expansion, to the value at the beam center and becomes uniform except at the two ends as shown in Fig. 1(k). Figure 1(m) shows that there are no longer particles scattered along the p_x axis around $x=0$ as in Fig. 1(f). The particles near the two ends of the beam undergo rotation in v_x -x phase space which is caused by radial expansion during the longitudinal compression. The $\overline{\epsilon_n^x}$ shown in Fig. 1(n) has approximately the same value, along most of the beam, at the end of the compression as it had at the start. The emittance growth, which

mainly occurs at the two ends, is estimated to be less than ten percent. The radial electric field at the beam ends is not linear in radius since at this location the beam is not space-charge dominated. Nonlinear fields give rise to effective emittance growth.

The projected radial density distribution of the entire beam is uniform as shown in Fig. 2. This, in addition to the fact that the radial electric field along the beam is almost zero except near the two ends, confirms the assumption -- the radial density profile is uniform -- that we made earlier.

Finally, we have carried out a simulation otherwise identical to the one discussed above but with initial $T_{||}=0$. Figure 3 shows that there is essentially no longitudinal emittance growth, except at the two ends, in this case.

Conclusion

Condor particle simulations of beam compression confirm the predictions of simple 1-D theory provided that the initial beam parameters are carefully chosen for the simulation. The compressed beam satisfies the current and $\Delta p_z/p_z$ constraints of the final focusing requirements. Longitudinal and transverse emittance growths are very small and are well within the tolerable limits.

References

- [1] D. D.-M. Ho, R. O. Bangerter, E. P. Lee, and S. T. Brandon, Laser Program Annual Report 1986, Lawrence Livermore National Laboratory. In addition, a detailed description of the beam dynamics during longitudinal compression will be published in Particle Accelerators. Also D. D.-M. Ho, et al., AIP Conference Proceedings 152: Heavy Ion Inertial Fusion, 1986, pp. 243-252.
- [2] E. P. Lee, "Model Equation for High Current Transport," LBL-19798, 1985.
- [3] KIBALL-II: An Improved Ion Beam Driven Fusion Reactor Study, Kernforschungszentrum Karlsruhe, 1985.
- [4] D. L. Judd, "Phase-Space Constraints on Induction-Linac Heavy-Ion Inertial-Fusion Igniters," LBL-14038, 1982.

Figure Captions

Fig. 1. Beam initial parameters.

- (a) Line-charge density vs. z .
 - (b) Radial distribution of beam particles vs. z .
 - (c) Longitudinal velocity vs. z .
 - (d) Transverse temperature vs. z .
 - (e) Longitudinal temperature vs. z .
 - (f) Velocity in x direction vs. x .
 - (g) Normalized emittance in x direction vs. z .
- Beam parameters at the end of compression
- (h) Line-charge density vs. z .
 - (i) Radial distribution of beam particles vs. z .
 - (j) Longitudinal velocity vs. z .
 - (k) Transverse temperature vs. z .
 - (l) Longitudinal temperature vs. z .

(m) Velocity in x direction vs. x.

(n) Normalized emittance in x direction vs. z.

Fig. 2. Projection of the radial density distribution along the entire beam.

Fig. 3. Longitudinal momentum versus z at the end of the compression with initial $T_{||}=0$.

Fig. 1. (Continued next page.)

Fig. 1.

Fig. 2.

Fig. 3.