CONF-860510--L

RECEIVED BY OSTI JUN 23 1986

UCRL- 94347
PREPRINT

Longitudinal Compression of Heavy-Ion Beams
With Minimum Requirements on Final Focus

D. D.-M. Ho, R. O. Bangerter, J. W.-K. Mark,
and S. T. Brandon
Lawrence Livermore National Laboratory, Livermore, CA 94550

E. P. Lee
Lawrence Berkeley Laboratory, Berkeley, CA 94720

This paper was prepared for submittal
to International Symposium on Heavy Ion Fusion
Washington, D.C., May 27-29, 1986

May 27, 1986

The logo of the Lawrence Livermore National Laboratory is a large, stylized, black and white graphic. It features a large, bold, black 'L' shape that curves around the bottom right corner of the page. Inside the curve of the 'L', the words 'Lawrence Livermore National Laboratory' are written in a white, sans-serif font, arranged diagonally from the top left to the bottom right.

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

MASTERLONGITUDINAL COMPRESSION OF HEAVY-ION BEAMS
WITH MINIMUM REQUIREMENTS ON FINAL FOCUSD. D.-M. Ho, R. O. Bengerter, J. W.-K. Mark,
and S. T. Brandon

Lawrence Livermore National Laboratory, Livermore, CA 94550

E. P. Lee

Lawrence Berkeley Laboratory, Berkeley, CA 94720

ABSTRACT

A method is developed to compress a heavy-ion beam longitudinally in such a way that the compressed pulse has a constant line-charge density profile and uniform longitudinal momentum. These conditions may be important from the standpoint of final focusing. By realizing the similarity of the equations that describe the 1-D charged-particle motion to the equations that describe 1-D ideal gas flow, the evolution of λ and the velocity tilt can be calculated using the method of characteristics developed for unsteady supersonic gasdynamics. Particle simulations confirm the theory. Various schemes for pulse shaping have been investigated.

INTRODUCTION

In induction linac for heavy-ion fusion, the heavy-ion beam must be compressed longitudinally in order to provide the required power for target implosion. Various authors have attempted to investigate this problem previously. Harber¹ studied the compression of a rectangularly-shaped pulse with a linear velocity tilt (variation of longitudinal particle velocity from beam-head to beam-tail). Bisogano, Lee, and Mark² investigated the compression of a parabolic-shaped pulse again using a linear velocity tilt. These studies showed that the compressed beam does not have constant line-charge density λ and/or uniform particle longitudinal momentum. However, the requirements for the compressed beam to have uniform λ and velocity may be important from the standpoint of final focusing. The purpose of this paper is to show 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 traveling in the accelerator before the compression starts.

The first part of this paper describes the compression scenario and the theoretical basis behind it. Fluid equations and the method of characteristics developed for unsteady supersonic gasdynamics are applied to this problem. The second part presents the particle simulation which confirms the theory. Possible schemes for pulse shaping and other considerations are discussed in the final part of this paper.

EEXB

COMPRESSION SCENARIO

The procedure for beam compression consists of the following steps.

(1) When the beam is still in the accelerator, the space-charge effect (the longitudinal electrostatic force resulting from the gradient of λ) is relatively low since the beam is still long (~ 10 - 15 m). The line-charge density can be assumed to be constant along the beam. Under these circumstances, it is possible to change the constant λ profile to any reasonably shaped λ profile by giving the beam a proper velocity tilt. This can be understood by first writing the continuity equation (fluid equations can be used if the longitudinal temperature is negligible) in the Lagrangian coordinate, i.e.

$$\frac{\partial \Gamma}{\partial t} = \frac{\partial v_z}{\partial m}, \quad (1)$$

where $\Gamma = 1/\lambda$, v_z is the longitudinal fluid velocity in the center of mass frame, and $dm = \lambda dz$. If space charge is not important, then v_z for each particle is almost a constant after the required velocity tilt is imposed on the beam at the beginning of the process. If the desired pulse shape is achieved in time T , then after integrating Eq. (1) trivially in time and converting the equation back to the Eulerian coordinate gives

$$\left. \frac{\partial v_z(z)}{\partial z} \right|_T = \left(1 - \frac{\lambda(T,z)}{\lambda(0,z)} \right) \frac{1}{T}. \quad (2)$$

Since $\lambda(0,z)$ is independent of z and $\lambda(T,z)$ is given, the profile of the velocity tilt can be obtained from Eq. (2).

Figure 1(a) shows that the beam in the accelerator does not have a velocity tilt initially. A velocity tilt is gradually imposed on the beam. This tilt reaches a maximum in Fig. 1(b) and is removed gradually afterwards. The removal is complete when the desired λ profile is achieved in Fig. 1(c).

(2) A linear velocity tilt is now gradually given to the beam until the peaks of the tilt reach $\pm 2 C_s$ (see Fig. 1(d)). Here, the ion sound velocity is

$$C_s \approx \sqrt{(Ze/m)g\lambda},$$

where Ze and m are ion charge and mass, and g is a constant. Due to the compression resulting from the linear velocity tilt, the

beam length (as shown in Fig. 1(d)) is now shorter than it was in Fig. 1(c). However, compressing the beam by a linear velocity tilt has preserved the functional form of λ .

(3) At this point, a "mid-course" correction is given to the beam in order to change the linear velocity profile to the shape given in Fig. 1(e). Since the maximum difference in velocity between this velocity profile and the linear profile is small, the "mid-course" correction can be carried out in a time scale so short that the functional form of λ in Fig. 1(e) remains essentially the same as that shown in Fig. 1(d).

(4) No more external manipulation of the beam is required beyond Fig. 1(e). (The λ and velocity profiles of the beam at the instant when the beam leaves the accelerator are shown in Fig. 1(f).) The velocity tilt shown in Fig. 1(e) compresses the beam in such a way that the electrostatic force generated by the gradient of λ removes all the velocity tilt at end of the compression process (see Fig. 1(h)).

In order to determine the λ and velocity-tilt profiles in Fig. 1(e), one realizes that the equations for 1-D charged-particle motion (with negligible longitudinal temperature) 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 $(Ze/m)g\partial\lambda/\partial Z$. Therefore, the longitudinal compression process (between Figs. 1(e) and 1(h)) 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^{3,4}. The time-reversibility of this problem was first suggested by Faltens and Lee⁵. Thus, the λ and velocity profiles in Fig. 1(e) can be obtained by using the method of characteristics developed for unsteady supersonic gasdynamics⁴. The discussion of this method is involved and hence is deferred to a forthcoming paper.

PARTICLE SIMULATION

A beam with parameters listed in Table I is used for the simulation using the 2-1/2-D Condor particle code.

50 00 0586:2053

Fig. 1 Compression scenario

Compression scenario continues

(e)

(f)

(g)

(h)

TABLE I
BEAM PARAMETERS

Beam Length (at the end of acceleration)	10 m
Beam Radius	3 cm
Total Beam Current	715 amp/beam
Total Charge/Beam	69.4 micro coulomb
Ion Energy (at the end of acceleration)	11.5 GeV
Ion Mass	210 amu
Charge State of Individual Ion	+ 3
Ion Sound Velocity	4×10^5 m/sec
λ	6.9×10^{-6} coulomb/m
<u>After Compression</u>	
Final Beam Length	1 m
λ	6.9×10^{-5} coulomb/m

In the simulation, the beam particles are represented by 9×10^4 test particles. The radial boundary condition in the simulation represents a cylindrical perfect conductor at a radius of 6 cm. The quadrupole magnetic field is represented by an azimuthally symmetric radial electric field which is constant in the longitudinal direction and the field strength is proportional to the radius.

The simulation starts when the beam is 5m long. The λ and velocity-tilt profiles shown in Fig. 2(a) are obtained using the method of characteristics. Initially, the beam has a radial temperature of 200 eV and has no longitudinal temperature. After a time of 4.2×10^{-7} sec, the beam is compressed to a length of approximately 3 m as shown in Fig. 2(b). Figure 2(c) is the λ and velocity-tilt profiles obtained from analytical calculations corresponding to the same instant of time as that of Fig. 2(b). Comparison of Fig. 2(b) and 2(c) shows that the particle simulation agrees very well with the theoretical calculations.

Since the radial electric field used in the simulation is constant in time, the simulation is restarted when the beam length reaches 3m. The input data used are those shown in Fig. 2(c). Also, a new equilibrium radial electric field is used. After a time of 4.2×10^{-7} sec, the compression process is completed and the compressed beam now has a length of 1m. As shown in Fig. 2(d), the final λ profile is almost flat and the velocity tilt is essentially removed. Thus, particle simulation again confirms the theory. In addition, no substantial growth in longitudinal or radial emittance is observed in the simulation.

Fig. 2 Line - charge density and velocity - tilt profiles from particle simulation

50 00 0586 2054

Line - charge density and velocity - tilt profiles from particle simulation continues

PULSE SHAPING AND OTHER CONSIDERATIONS

Pulse shaping can be obtained easily by delaying the relative arrival time of different pulses on the target. The delaying of some pulses can be obtained by making the beam lines for some of the pulses a few meters longer than those for the other pulses. Another possible way of achieving pulse shaping is to give each pulse a non-symmetrical (observed from center of the beam) λ and velocity-tilt profiles. The profiles for the non-symmetric case are shown in Fig. 3(a). Figure 3(b) shows the λ and velocity-tilt profiles at the end of compression. This method may not require delaying beams; however, the focusing system would have to accommodate the variation in current and momentum.

Fig. 3. Non-symmetric λ and Velocity-tilt Profiles

Using the beam parameters given in Table I and taking engineering restrictions into account, calculations indicate that the initial manipulation of λ and velocity-tilt profiles (between Figs. 1(a) and 1(e)) can be carried out rapidly enough so that the space-charge effect does not cause appreciable pulse shape deterioration.

CONCLUSIONS

A method is developed to compress a heavy-ion beam longitudinally in such a way that the compressed pulse has a uniform λ profile and uniform longitudinal momentum. These conditions may be important from the standpoint of final focusing. The initial λ and velocity-tilt profiles for the pulse is calculated by invoking the method of characteristics developed for unsteady supersonic gasdynamics. Particle simulations confirm the theory. Various schemes are available for achieving the desired pulse shape. No substantial growth in either longitudinal or transverse emittance is observed. Estimates show that the initial manipulation of λ and velocity-tilt profiles can be carried out rapidly enough so that space-charge effect does not cause serious pulse shape deterioration.

REFERENCES

1. I. Harber, Proceedings of the Symposium on Accelerator Aspects of Heavy Ion Fusion, GSI-82-8, (Gesellschaft für Schwerionenforschung, Darmstadt, West Germany, 1982), p. 372.
2. J. Bisogano, E. P. Lee, and J. W.-K. Mark, Laser Program Annual Report 84 (Lawrence Livermore National Laboratory, Livermore, CA., 1985), p. 3-28.
3. L. D. Landau and E. M. Lifshitz, Fluid Mechanics (Pergamon Press, Oxford, 1959), Ch. X.
4. A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow, (The Ronald Press Co., New York, 1953), Ch. 24.
5. A. Faltens, E. P. Lee, and S. S. Rosenblum, submitted to Journal of Applied Physics.

Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.