Longitudinal Beam Dynamics For Heavy Ion Fusion*

Debra A. Callahan, A. Bruce Langdon, Alex Friedman
Lawrence Livermore National Laboratory, Livermore, CA 94550
Irving Haber
Naval Research Laboratory, Washington, DC 20375

Abstract

The longitudinal wall impedance instability is of potential importance for a heavy ion fusion (HIF) driver because complete stabilization of this mode via momentum spread is impractical due to the requirement of focusing the beam onto the inertial confinement fusion target. This instability is being studied with the WARPrz particle-in-cell code. The impedance of the induction linac modules is modeled as a wall impedance corresponding to a continuum of resistors and capacitors in parallel. We discuss simulations of the this instability, including reflection of perturbations off the beam end, the effect of finite temperature on the growth rate, and errors in intermittently-applied axial confining fields as a seed for this instability. We also present very long simulations in which we study the approach to equilibrium.

I. Introduction

Because of the large cost involved in building a full scale heavy ion fusion (HIF) accelerator, much effort has gone into simulating the physics of space-charge-dominated beams needed for HIF. These simulations have been successfully compared with existing experiments. The WARP family of codes [1] has been developed to study driver issues. The code is made up of five major physics packages: a 3d particle-in-cell code in Cartesian geometry, a 3d electrostatic field solver, a cylindrically symmetric (r, z) particle-in-cell code, an r, z electrostatic field solver, and an envelope code. This family of codes is being used to study a variety of heavy ion fusion issues.[2, 3, 4, 5]

To model the longitudinal dynamics of these beams, the r, z portion of the WARP code was developed. This code is a 2.5 dimensional, cylindrically symmetric particle-in-cell code. Calculation of the field solution is done in a window that moves with the beam. In this window, the fields are very close to purely electrostatic, since the force due to magnetic fields is down by $(u/c)^2$ compared with the force due to the electric fields where u is the velocity in the beam frame. The beam frame velocity for a heavy ion fusion driver is much less than 1% of the speed of light.

II. Longitudinal Instability

This instability is of concern for a HIF driver because it amplifies small perturbations launched from the beam head. These perturbations may be caused by errors in the accelerating fields, or errors in applying axial confining fields ("ear" fields). The instability has the same mechanism used in "resistive wall" amplifiers with the impedance coming from the accelerating modules. This mode can be stabilized by a sufficiently large longitudinal momentum spread; however, chromatic aberration in the focusing lens system restricts the amount of momentum spread allowed. Since HIF driver beams travel at a fraction of the speed of light ($\leq c/3$), growth from this instability can be reduced by using "feed-forward" techniques in which perturbations are detected at one point along the accelerator, a signal is sent ahead, and a correcting field is applied downstream. One dimensional feed-forward simulations by K. Hahn [6] were successful in reducing growth due to this instability. Although these techniques enable suppression of the instability, the low growth rate makes the instability difficult to study experimentally. Experiments are underway at the University of Maryland [7, 8] to study longitudinal beam dynamics including the longitudinal instability in a small scale experiment by using space-charge-dominated electron beams. We are using simulations to understand such issues as the reflection of waves off the beam ends, the effects of finite temperature on this instability and errors which can result in finite amplitude seeds for the instability.

The longitudinal instability can be seen via a simple fluid model. If we consider an incompressible beam with radius a traveling down a pipe of radius r_{wall}, 1-d linear cold fluid theory shows that two waves will develop in the beam frame–a forward traveling wave and a backward traveling wave. These waves propagate with a phase velocity in the

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beam frame given by

$$v_{\text{phase}} = \sqrt{\frac{Ze\lambda g}{4\pi\epsilon_0 m}} \tag{1}$$

where Z is the charge, λ is the line charge density (with units of charge/length), m is the mass, $g = \ln(r_{\text{wall}}^2/a^2)$. Adding a wall composed of a continuum of resistors and capacitors in parallel to this model results in decay of the forward traveling wave while the backward traveling wave grows. This growth is largest when the perturbation wavelength is large compared with the pipe radius. In a heavy ion fusion driver, the impedance that drives this instability comes from the induction acceleration modules.

To study this instability, we added a model for a wall with a continuum of resistors and capacitors in parallel to WARPrz.[9] This approximation for the induction modules contains the relevant physics, and also corresponds well with much of the analytic work being done. We calculate the resistive wall contribution to the electric field using the Poisson solve at the boundary. This is smoother and more physical than using the explicit beam current.

Simulations including a purely resistive wall in which a perturbation is launched from the beam head have shown growth of the backward traveling wave. The measured growth rate is down from the cold beam theory by about 15%. We believe this is due to the effects of finite transverse temperature. This is an area of current research.

The perturbation reflects off the beam tail. During reflection we see a steepening of the perturbation. This appears to be a non-linear effect as it is greater in larger perturbations than in small ones. The narrowing of the perturbation puts it in a dispersive regime, so that as the perturbation travels from beam tail to head, it decays and slower wavelengths begin to lag behind the main perturbation.

Cold beam fluid theory predicts that a capacitive component of the impedance will reduce the growth rate as well as lengthen the wavelength of the most unstable mode. This has been seen in WARPrz simulations. Very long wavelength ($\sim$ beam length) perturbations are excited, but little growth is seen. These perturbations slosh back and forth from beam head to tail with little change in size.

III. Intermittently-Applied "Ear" Fields

To get a realistic look at the effects of the longitudinal instability, sources of finite amplitude perturbations on the beam need to be considered. One source of such perturbations is the intermittency of applied axial confining electric fields ("ear" fields). In most of our simulations, ear fields are applied at each time step and are designed to keep the beam from expanding or contracting. In an experiment, these fields will be applied at fixed locations along the accelerator and the beam will expand and contract between applications. The application of these fields can cause a train of perturbations to be launched from the beam head and these perturbations will be amplified by the longitudinal instability.

In our simulations, each application of the ears was made up of the following steps:

1. Let the beam expand for .48 μs (48 m at $c/3$)

2. Apply ears fields to both ends of the beam for .0875 μs and reverse expansion velocities.

3. Let the beam expand for .48 μs. At the end of this expansion, the beam should be back to its original length.

The perturbations on the beam were minimized when we applyed an electric ear field which was proportional to the average particle velocity in the beam frame as a function of z after the first expansion. The proportionality constant was varied until the beam was close to its original state after one application. The same ear field was used for each application. We found that we were able to apply these ear fields more than 20 times without significant perturbations developing on the beam, even in the presence of a 100 ohms/meter resistive wall.[9]

We then added an error to the ear fields. In the first case, the error added was a "bump" which had the algebraic form of one half the period of a sine wave with magnitude 5% of the local ear field. The same error was added at each application and this error made the ear fields too large. We believed that by applying an error in the same direction each time, we would see a worst case since there was no way for the errors to cancel one another out. We found this was not the case. We ran the simulation for 25 applications of the intermittent ears and saw that the first few applications excited a perturbation on the beam. Later in time, however, we saw that the beam adjusted itself to the error in the ear fields.

This phenomenon has also been seen in experiments done by A. Faltens. [10] These experiments were designed to test longitudinal bunch control in the beam tail on the SBTE at LBL. In this experiments, no attempt was made to match the waveform of the applied ear fields to the beam profile. Instead, fields of the form $[1 - \exp(-at)]$ were applied. In the experiment, mismatches in the ear fields caused waves to be launched from the beam tail in the early pulsers, but at later times the beam reached a new steady state configuration.

After seeing the beam adjust to a systematic error in the ears, we applied errors to the ears of random size and sign. The shape of the error was the same as in the last case, but the size of the errors varied randomly from 5% too large to 5% too small ($+5\% \geq$ error $\geq -5\%$). In this case, we see the expected train of perturbations launched from the beam head, growing as they approach the beam tail. The width of these perturbations is measured to be approximately the wavelength of the most unstable mode of the longitudinal instability. Figure 1 shows the electrostatic potential on axis vs z after 15 applications of the ear fields with 100 ohms/meter wall resistance.

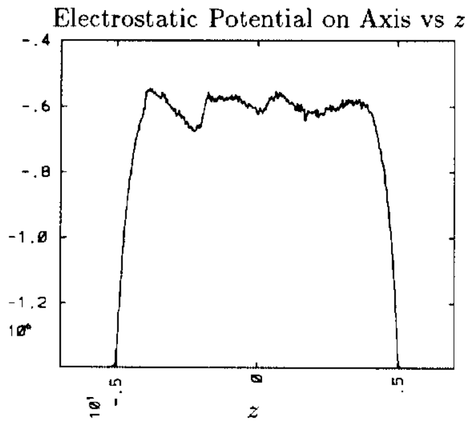

Figure 1: Random size errors in ears fields produce perturbations at the most unstable wavelength

IV. Beam Equilibria

The initial loading of the particles assumes a beam current profile as a function of z which is constant in the center and a parabolic falloff in the beam ends. The transverse emittance is scaled such that it is proportional to the beam current. This leads to constant phase advance along the beam. Simulations done with WARP3d[11] showed little emittance growth in the flat, center section of the beam, but emittance growth in the parabolic beam ends. This suggested that our assumed profile is not an equilibrium and lead us to undertake longer simulations with WARPrz in search of an equilibrium state.

Simulations were done on HIF driver scale beams (3000 Amps current, $c/3$ beam velocity). A 5 meter beam length was chosen for computational convenience with 50% of the beam length in the flat center section and 50% in the parabolic ends (25% in each end). Ear fields composed of an electric field to offset the space charge force plus an electric field component to offset the pressure were calculated based on the initial loading and applied at every time step.

The simulation was run for 96 μs in which time the beam traveled 9.6 km. Over the long run, the transverse thermal velocity in the beam center grows by about 10% and a corresponding increase in emittance is seen in the beam center. The transverse thermal velocity in the beam ends increases considerably and by the end of the run is constant over most of the beam.

V. Conclusions and Future Work

The WARPrz code has been used to model three aspects of the longitudinal dynamics of space-charge-dominated beams needed for heavy ion fusion. By modeling the impedance of the accelerating modules, we have simulated the longitudinal instability and seen growth of the backward traveling wave, reflection of perturbations off the beam end, and the partially stabilizing effects of the capacitive component of the module impedance. We have modeled intermittently-applied axial confining fields including errors and have seen the beam adjust to systematic errors in these fields, while randomly sized errors excite the most unstable mode of the longitudinal instability. We have run very long simulations in search of an equilibrium state and found that the beam tends toward a constant transverse temperature over most of the beam, even in the beam ends.

In the future, we will study the effects of finite transverse temperature on the growth rate of the longitudinal instability. We believe the transverse temperature is responsible for the decrease in growth rate that we see in warm beam simulations. We will also simulate feed-forward stabilization as a mechanism for correcting errors on the beam and reducing the growth rate of the instability. We also hope to couple our observations about beam equilibria with a more complete theory.

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