Preliminary study of differential effects in fast magnetic compression experiments

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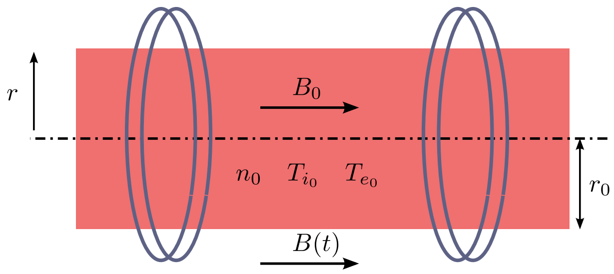
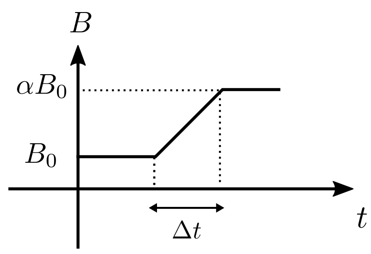
Fast magnetic plasma compression has been suggested for time resolved plasma wave properties control [1]. In such concepts, an axial magnetic field $\mathbf{B} = B(t)\hat{\mathbf{z}}$ changes with time, in order to compress a pre-magnetized plasma, and hence control the plasma density under the assumption that $n \propto |B|$.



(a) Geometry considered



(b) Time evolution of the control magnetic field

Figure 1: Fast magnetic compression of a pre-magnetized plasma. A background magnetic field $\mathbf{B} = B_0\hat{\mathbf{z}}$ is embedded in the plasma. The axial magnetic field outside the plasma $B(t)$ is ramped up over a time Δt. For fast compression, $\Delta t < 2\pi/\omega_{ci}$.

Simple picture

When the compression time Δt is large compared to the ion gyro-period $\tau_{ci} = 2\pi/\omega_{ci}$, with $\omega_{ci} = q_i B_0/m_i$, both ions and electrons are magnetized. The charged particles motion then consists essentially in the radial cross field drift $E_\phi \times B_z$, with $E_\phi(r) = -r\dot{B}/2$ the induced azimuthal electric field.

On the other hand, when the compression time is shorter than the ion gyro-period, but larger than the electron gyro-period, electrons and ions motion differ. Magnetized electrons drift radially inward, similarly to what is observed for slower compression. Contrarily, ions are essentially unmagnetized on this time-scale, and ions motion is primarily dictated by the induced electric field $E_\phi(r) = -r\dot{B}/2$. Since the ions motion is largely azimuthal, radial charge separation occurs, which is the source of a radial electric field E_r. When this radial electric field becomes comparable or larger than the azimuthal field, ions move radially inward. Another consequence of this radial electric field is the azimuthal electron drift $-E_r \times B_z$, which can momentarily lead to large azimuthal currents.

Interestingly, experimental evidence of ion separation has been reported in the case of magnetic field penetration in a non-magnetized plasma on similar time-scales [2]. In light of the very simplified fast compression picture depicted above, one can ask whether the ion separation could be the result of differential rotation effects [4, 5]. To better address these questions, a numerical modeling effort has been initiated.

Preliminary results from numerical modeling

In order to avoid additional complications associated with cylindrical geometry, the model considered here is 1D planar. As illustrated in Fig. 4, we consider the interaction of an electromagnetic pulse propagating in vacuum and a magnetized plasma slab of finite width using a fully electromagnetic relativistic PIC code. A background field $\mathbf{B} = B_0\hat{\mathbf{z}}$ is present everywhere in the domain. The pulse amplitude is δB, with $\delta B/B_0$ typically equal to 1%, and the pulse width is $\pi c/\omega$, with $\omega = 2.5\omega_{ci}$. The plasma compositions considered are either an electron-proton mixture, or an electron-proton-He$^+$ mixture, in which case $n_{0_{\mathrm{He}^+}} = n_{0_{\mathrm{H}^+}} = n_0/2$. Real mass ratios are used, with $m_{\mathrm{H}^+}/m_e = 1836$ and $m_{\mathrm{He}^+}/m_{\mathrm{H}^+} = 4$. In all cases, the ion cyclotron frequency of reference ω_{ci} is the proton cyclotron frequency.

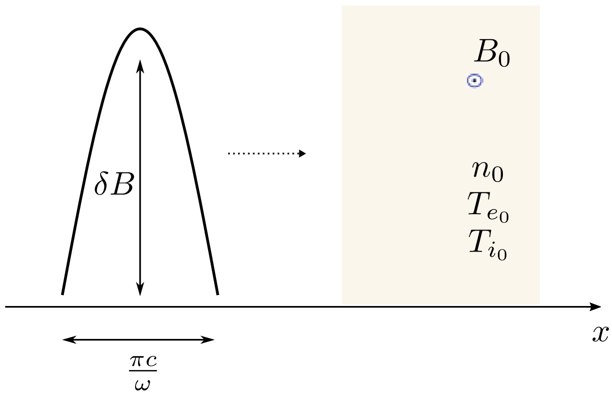


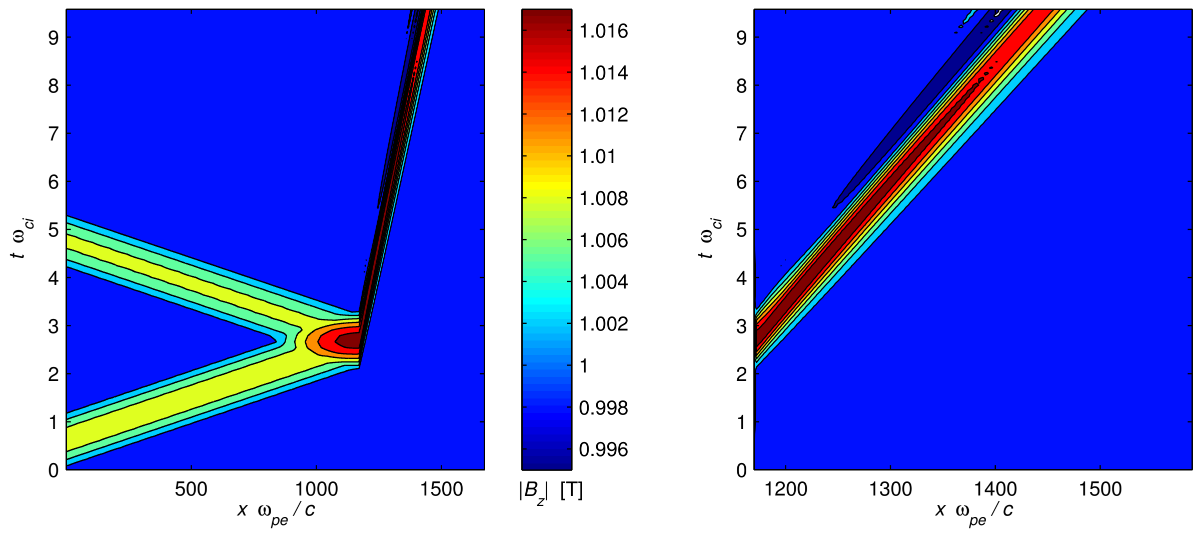
Figure 2: Geometry modeled with a fully electromagnetic relativistic PIC code. $\delta B/B_0$ is typically 1%, and $\omega = 2.5\omega_{ci}$. Background field $B_0 = 1$ T, $n_0 \sim 10^{12}$ cm^{-3}, $T_{e_0} = 3$ eV, $T_{i_0} = 0.1$ eV.

Upon interaction with the plasma slab, the incident pulse energy,

$$\varepsilon_p = \frac{\pi c}{5\mu_0\omega_{ci}}\delta B^2,$$

is divided into three components. First, a large fraction of the incident energy is reflected in the form of a reflected pulse. Second, part of the energy is transferred to plasma kinetic energy.

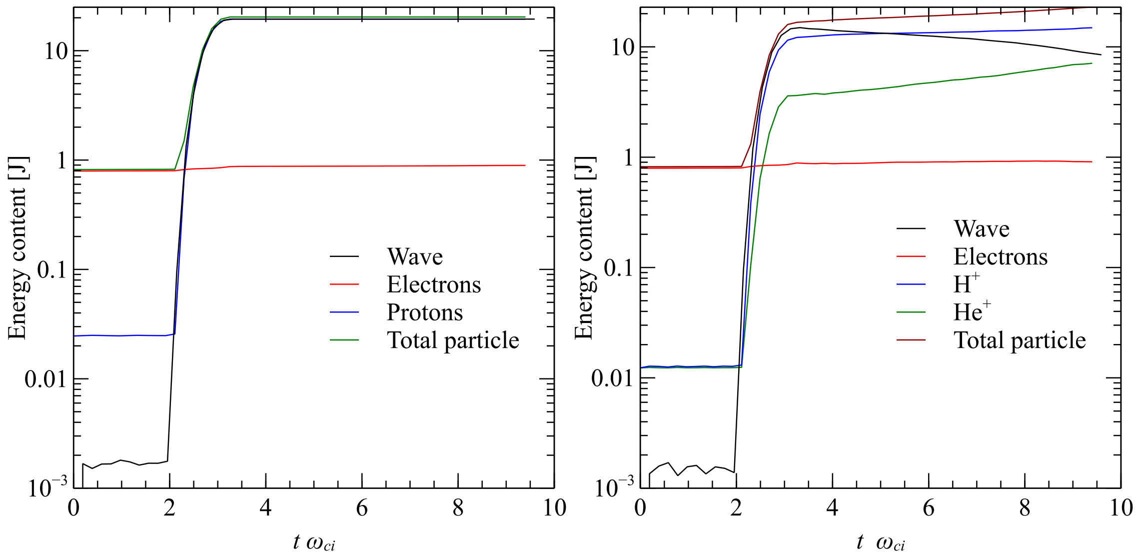
Third, some of the incident energy is transferred to plasma waves. The existence of incident, reflected and transmitted pulses is illustrated through the magnetic field spatial and temporal evolution given in Fig. 3, and obtained for an electron-proton plasma. For the plasma parameters and pulse shape considered here, the energy transmitted to the plasma wave is about 12%. From Fig. 3(b), the phase velocity can be estimated to be about $2.1 \pm 0.2\ 10^7$ m.s^{-1}. This is consistent with the phase velocity of a compressional Alfven wave, which for the small temperatures considered here propagates at the Alfven speed $v_A = B/\sqrt{\mu_0 n_0 m_i} \sim 2.2\ 10^7$ m.s^{-1}.



(a) Whole simulation domain (b) Zoom on the initial plasma region

Figure 3: Z component of the magnetic field in the simulation domain for an electron-proton plasma. The plasma initially extends from 1170 c/ω_{pe} to 1588 c/ω_{pe}. The incident pulse amplitude is $\delta B/B_0 = 1\%$, and the initial density is $n_0 = 10^{12}$ cm^{-3}.

Comparison of the time evolution of the energy content obtained for an electron-proton plasma and a multi-ions species plasma indicates evidence of differential heating effects. For the electron-proton case, Fig. 4(a) shows that after an initial particle acceleration phase, the wave propagates with no dissipation. The wave energy is conserved, and particles do not acquire energy from the wave. On the other hand, for a multi-ions species plasma, wave damping is observed as illustrated in Fig. 4(b). This result is consistent with previous results obtained for magnetosonic pulses [3], *i. e.* larger compression times. The initial phase is similar to the electron-proton plasma case, with most of the energy transferred to the ions axial motion. For the $\mathrm{H}^+ - \mathrm{He}^+$ mixture considered, the energy initially transferred to the light and heavy species is of the order of $m_{\mathrm{H}^+}/(m_{\mathrm{H}^+} + m_{\mathrm{He}^+})$ and $m_{\mathrm{He}^+}/(m_{\mathrm{H}^+} + m_{\mathrm{He}^+})$, respectively. After this initial phase, the propagating plasma wave transfers energy to the particles, leading to wave damping. Interestingly, the initial energy transfer is preferentially towards the light ions (protons), while the wave damping seems to preferentially heat heavy ions (He^+).



(a) $e^- - H^+$

(b) $e^- - H^+ - He^+$

Figure 4: Time evolution of plasma wave and particle kinetic energy content for two different plasma compositions. Wave damping is observed for multi-ions species plasma, but not for the electron-proton plasma. In both cases, the incident pulse energy $\varepsilon_p \sim 156$ J.

Discussion and Caveat

The results presented here offer only a preliminary understanding of the physical mechanisms through which differential effects might be observed in fast magnetic compression experiments. To fully understand this effect, it remains to extend the simulations here to different relative abundances of different ions, as well as to consider a variety of different plasma parameters. To compare to experiments, it would be necessary as well to consider cylindrical geometry.

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