Exploring Paradigms for Energy Conversion under Compression

N. J. Fisch, S. Davidovits, V. I. Geyko

Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA

Very large facilities compress plasma to incredible pressures for inertial confinement fusion. As plasma is compressed, it reaches higher temperatures, just like an ideal gas. If the plasma is hotter to begin with, then more energy will need to be expended to accomplish the same reduction in volume, with this energy going into achieving yet higher temperatures. However, when plasma is compressed, so might be compressed other structures within the plasma, not necessarily associated with random motion of particles. These other structures include embedded plasma waves [1–6], motion with finite total angular momentum [7–9], nonlinear waves [5, 6], and turbulent energy [10, 11]. Just as the temperature increases with compression, so do these other forms of energy, although with different laws relating energy to volume.

Using the energy of compression to increase these other forms of energy creates the possibility of arranging for a sudden transformation of this energy to heat. For example, in increasing wave energy under plasma compression, there may come a point where the wave no longer exists or is heavily damped. Then there will be the sudden release of this wave energy into ions or electrons. One application of the sudden transformation of another form of energy into temperature might be igniting a fusion plasma, particularly if the temperature of fuel ions is increased. Another transformation of interest is to transform this energy into energy in the magnetic field. This might happen if the energy flowed to electrons traveling in one direction, so as to produce currents through a current drive effect. Yet another useful possibility is to transform this energy into electron temperature so as to produce a sudden burst of x-rays. In each of these cases, the energy of compression is utilized to increase the energy in another form, and then eventually this energy might be suddenly released into a very useful form of energy.

Because plasma supports such a variety of plasma waves, a large effort has gone into identifying how waves in plasma can be amplified under compression, and then how this wave energy can be suddenly released [1–6]. Here we will focus on recent developments in two other possibilities: The first possibility is the increase under compression in the turbulent motion of plasma, where electrons and ions move together in a turbulent fashion. The plasma energy can then be separated into random motion of particles, where electrons and ions can have large relative velocities upon collision, and the turbulent kinetic energy (TKE) where the motion is random but correlated so colliding particles have less relative motion. The second possibility is when the plasma rotates, such that, as opposed to the first case, there is net angular momentum.

Experiments on the Z-pinch facility at at Weizmann suggested that the TKE might in fact be larger than the thermal kinetic energy [12–14]. In these gas-pinch experiments, the majority of the plasma kinetic energy resides in the directed energy of the imploding ions. However, even in the frame of reference moving with the compression, it is inferred that most of the kinetic energy resides in the ions. Of particular interest is the inference that most of the ion energy resides not in ion temperature but in TKE. This was inferred from line broadening measurements as well as from energy balance arguments. This experiment stimulates the question of how the increase in energy due to compression is partitioned between thermal and turbulent components.

Turbulence undergoing compression depends on the ratio, S, of two timescales, $S = \tau_t/\tau_c$. The first timescale is the turbulent decay (turnover) time, $\tau_t = k/\varepsilon$, where k is the TKE and ε is the decay rate (through viscosity) of the TKE. The second is the compression timescale, $\tau_c = L/V_c$, where L is the length scale (side length) of the region of compressing turbulence and V_c is the compression velocity. For slow compressions, the compression time is much larger than the turbulent decay time, $S \ll 1$, and the TKE simply decays during the compression, albeit at a rate that is slower than with no compression. When the two timescales are comparable, $S \sim 1$, the turbulence is sustained during the compression. Fast compressions, with $S \gg 1$, lead to substantial growth of the TKE.

The growth and evolution of the TKE in plasma is very different from in neutral gas; in plasma undergoing rapid compression there is a sudden dissipation effect not present in neutral gas, due to the sensitivity in plasma of the viscosity to temperature [10]. The TKE, which initially grows due to the rapid compression, suddenly dissipates (into temperature) at a well defined moment, since the viscosity in plasma rises so fast with temperature ($\mu \sim T^{5/2}$). Once the dissipation begins, it escalates, since the dissipation increases the temperature further, which in turn increases the viscosity further.

This sudden viscous dissipation effect may be exploitable for a new fast-ignition fusion concept [10], and may be controllable through the manipulation of plasma charge state [11], which also has a strong impact on the plasma viscosity. Because energy stored in the plasma TKE does not cause radiation or fusion, one may imagine initially storing most of the plasma energy in TKE, which is then amplified during compression. This keeps the plasma comparatively cool versus the case where the initial energy is stored in plasma temperature, reducing losses to radiation and preventing any premature fusion. After the compression has amplified the plasma TKE and density, the sudden viscous dissipation effect rapidly converts the TKE into temperature, causing the plasma to ignite.

A numerical simulation of the sudden viscous dissipation effect is shown in Fig. 1 [10]. An initially turbulent flow field, with TKE normalized to 1, is compressed on times ($\tau_c = 1/2V_b$) slower than ($V_b = S = 0.1$), comparable to ($V_b = S = 1$) and faster than ($V_b = S = 10, 100$) the initial turbulence timescale $\tau_0 = (k/\varepsilon)_0 \sim 1/2$. The initial domain is a box of size 1^3, time progresses right to left ($t = (1-L)/(2V_b)$) as the compression shrinks the domain. When the compression is slow, the TKE damps, albeit at a slower rate than it would with no compression. When it is comparable, the energy stays relatively constant before damping. When it is faster, the TKE grows substantially, before being suddenly dissipated over a small range of L. Also shown is the theoretical rapid distortion theory (RDT) solution, which is exact while the compression is extremely fast. As time increases the flow is increasingly contained in the largest structures as the smaller structures run into the viscous scales. All plots are normalized to side length 1, in the lab frame the absolute size of all structures decreases in time.

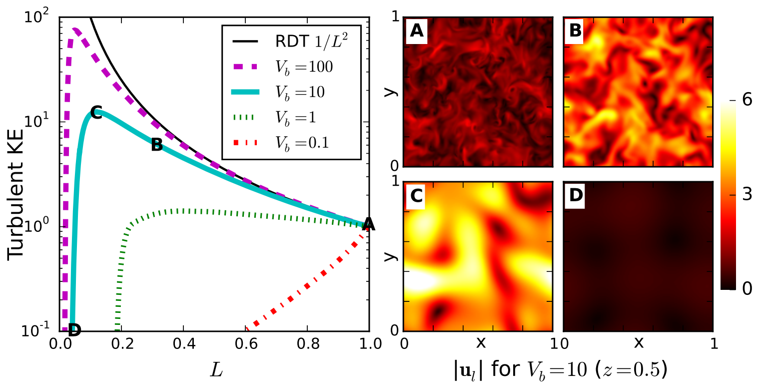

Figure 1: Left: TKE during compression at various rates. Right: Flowfield slices showing the magnitude of the turbulent flow velocity in the lab frame for $V_b = 10$. The fields progress in time from A→B→C→D, and are marked on the left graph. Figure from Davidovits and Fisch [10].

A second hydrodynamic energy storage effect occurs when the gas undergoing compression has finite angular momentum. Consider a gas spinning in a cylinder while it is undergoing axial compression. As the gas rotates about its axis, it will become hotter, but not as hot absent the rotation. To see this, consider that as the gas becomes hotter under compression, gas molecules originally flung by centrifugal forces to the periphery become more homogeneously distributed. Since the heating changes the moment of

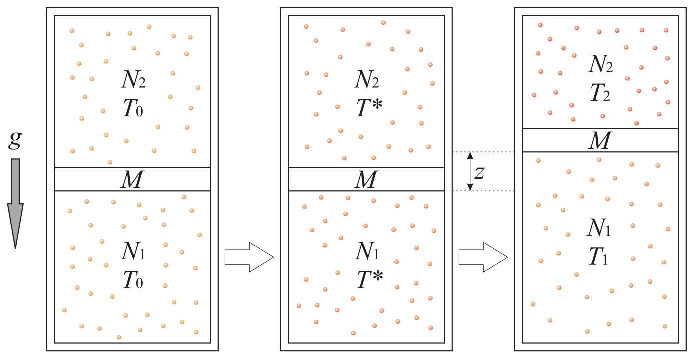

Figure 2: Lateral compression of two chambers in a vertical gravitational field. Figure is from Geyko and Fisch [9].

inertia, the gas must spin faster to conserve angular momentum. Thus, some of the energy expended in compressing the gas goes into to making the gas rotate faster, rather than into heating it, making it softer to compress axially. This is the rotation-dependent heat capacity [7]. This rotation-dependent heat capacity effect may be exploited to increase the the efficiency of low-temperature Otto cycle engines [8]. In a compressing plasma, such as a Z-pinch with substantial rotation, the effect might lead to a means of storing energy for later use.

Interestingly, radial temperature differentials arise under axial compression in a piezo-thermal effect [9]. That effect can be seen more easily for gravity in a slab geometry. where the force is constant (rather than coupled to the temperature and density as the centrifugal force is) as in Fig. 2, where a partition of mass M is imagined to separate the top and bottom regions. Under lateral compression, the gas becomes hotter, so that temperature increases vertically uniformly from T_0 to T^*. Since the gas in a gravitational field is densest on bottom, the pressure on bottom increases more than on top, so the partition rises. The gas in the lower part performs mechanical work, hence cools; the gas in the upper part is compressed and heats. This piezo-thermal effect clearly persists even without the partition. The formation of a temperature gradient, perpendicular both to the force and to the direction of compression is quite general, and the temperature differential can be of the order of the temperature change [9]. In the case of axial compression of spinning gas, the gas reaches the highest on axis, where the density is lowest, and it coolest on the periphery. For reacting gases, which could be very sensitive to temperature, whether for combustion, fusion, or radiation, this effect might be significant.

Work supported by DTRA, NNSA, DOE, and NSF.

References

[1] I. Y. Dodin, V. I. Geyko, and N. J. Fisch, Phys. Plasmas **16**, 112101 (2009).
[2] P. F. Schmit, I. Y. Dodin, and N. J. Fisch, Phys. Rev. Lett. **105**, 175003 (2010).
[3] P. F. Schmit, I. Y. Dodin, and N. J. Fisch, Phys. Plasmas **18**, 042103 (2011).
[4] P. F. Schmit and N. J. Fisch, Phys. Rev. Lett. **108**, 215003 (2012).
[5] P. F. Schmit, I. Y. Dodin, J. Rocks, and N. J. Fisch, Phys. Rev. Lett. **110**, 055001 (2013).
[6] I. Y. Dodin, P. F. Schmit, J. Rocks, and N. J. Fisch, Physical Review Letters **110**, 215006 (2013).
[7] V. I. Geyko and N. J. Fisch, Phys. Rev. Lett. **110**, 150604 (2013).
[8] V. I. Geyko and N. J. Fisch, Phys. Rev. E **90**, 022139 (2014).
[9] V. I. Geyko and N. J. Fisch, arXiv:1604.00063 (2016).
[10] S. Davidovits and N. J. Fisch, Physical Review Letters **116**, 105004 (2016).
[11] S. Davidovits and N. J. Fisch, arXiv:1605.03164 (2016).
[12] V. Kroupp et al., Physical Review Letters **107**, 115001 (2007).
[13] V. Kroupp et al., Physical Review Letters **98**, 105001 (2011).
[14] Y. Maron et al., Physical Review Letters **111**, 035001 (2013).