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Most people know that matter in the world can exist in three phases: solid, liquid, and gas. Our thick atmosphere keeps common temperatures and pressures in ranges that naturally only admit these phases; however, the extreme conditions of the universe drives more than 99% of existing normal matter into a highly energetic fourth phase: plasma. Thus, understanding the physics of extreme phases of matter is both cosmologically and, as we shall see, economically beneficial to society. Plasma phase transitions are very endothermic, supplying not only enough energy to overcome attractive intermolecular forces between particles, but also enough to completely ionize (overcome the electrical attraction between the electron and nucleus) the electrons. Because plasmas are essentially a "soup" of electrons and nuclei, they are extremely responsive to electric and magnetic fields and scientists can achieve impressive accelerations in controlled chambers. This exploitation of plasmas' susceptibility to electromagnetic oscillations is at the heart of plasma energetics research.

Before we can understand the applications of plasma, we must understand how to generate plasma. Typically, researchers use an inert gas such as argon or helium and supply the ionization energy using laser pulses or capacitor discharges. We can only create sufficient temperatures in short impulses, such as the energy released in laser pulses or capacitor discharge. We define a plasma's degree of ionization as the percent of atoms that lost electrons. Common laboratory plasmas are termed "non-thermal" (not in thermal equilibrium) because the electrons are at a much higher temperature than the nuclei due to the ionizing energy impulse; hence, highly ionized plasmas are called "hot," and vice-versa. Currently, scientists can create ultra-dense hot plasma using laser pulse durations of 10^{-12} seconds with peak power of 5 MeV (Kodoma, 2001). Colder plasmas are typically created by filling a capacitor with the working gas (acting similar to a dielectric in this case) and performing a high-power discharge. Discharge-generated plasmas have the advantage that they are cheaper and tend to ignite via a kinetic chain reaction. Both types of plasma generation have viable implementations in

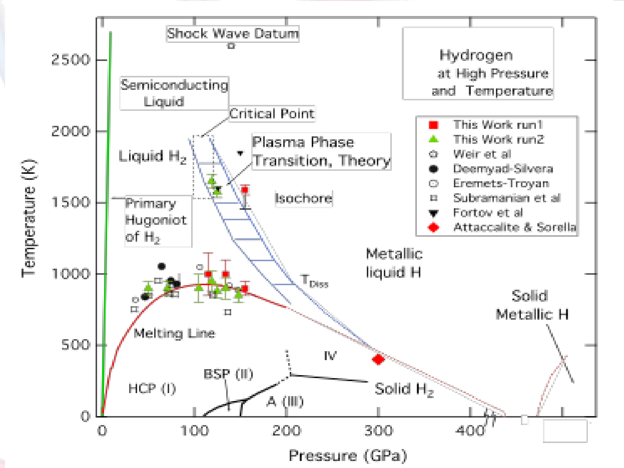

Figure 1. Experimentally determined phase diagram of hydrogen showing the plasma transition line.

extraction energetics.

Energy considerations aside, it appears rather simple to generate a plasma: simply point an energy source and shoot. The main struggle scientists face with studying plasma is being able to reliably create a plasma that we know how to mathematically model so that we may give detailed physical descriptions of interesting plasma properties. What makes a plasma hard to study? First and foremost, plasma is a collection of moving charged particles. We know from Maxwell's equations that moving charges create magnetic fields and changing magnetic fields create charge – and we know that charged particles are dynamically affected by both. This means that each plasma particle is not only moving under the influence of its initial ionization energy but is also constantly driven by *its own and other* electric and magnetic oscillations (Schmidt, 2012). Due to this property, we say a plasma is a magnetized substance. The dynamics of a particle moving under the influence of other particles (in the case of gravitation, we could imagine a solar system) is a well-known problem called an "N-body problem." The classic N-body

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problem actually differs from plasma mechanics in that plasmas are magnetized, meaning that its trajectory has another convoluting factor (the fields caused from its own movement) (Schmidt, 2012). In general, the magnetized N-body problem is computationally too intensive to perform in whole, but scientists apply an important assumption called the plasma approximation: that each particle has an effective magnetizing

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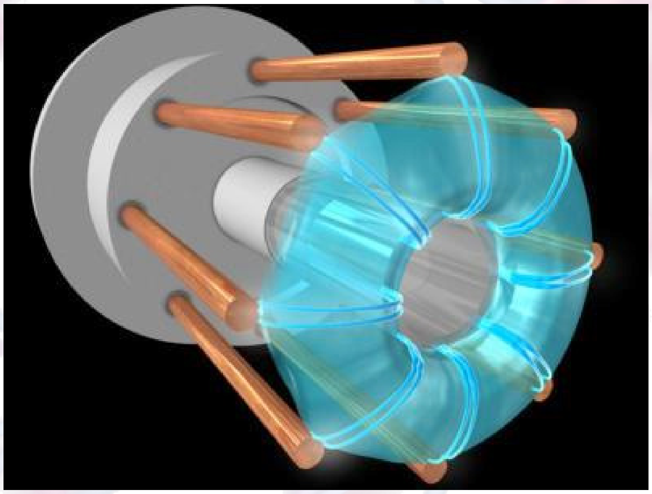

Figure 2. Computer diagram of DPF plasmoid under magnetic piston.

radius over which we can average external forces from nearby particles. These simplifications have proven sufficient to give us simulations of plasma. In particular, we have found that plasmas interact as a whole using long-range electrodynamic wave interactions called the plasma oscillation (Schmidt, 2012). By probing further and finding information about the plasma particle velocity distribution, scientists were able to provide full simulations of a plasma, including both electrodynamic (long-range) and kinetic (short-range, collisions) effects. This is important because, plasma energetics is a balance of electrical and mechanical equilibrium.

While there are many novel ideas for plasma fusion energy, two of the most common (and intriguing) are Tokamak magnetically confined plasmas and dense-plasma focus (DPF) Z-Pinch devices. DPF devices have garnered so much interest for their simplicity and theoretical effectiveness. These devices are built in the shape of a cylindrical capacitor with an outer diameter of up to 7-8 inches. The gas dielectric is ignited

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using DC discharge and the jolt of electricity travels radially outward, ionizing the gas and creating a strong magnetic that pinches the plasma into a small ball with a diameter of about a thousandth of an inch (Schmidt, 2013). As we have discussed, the plasma is so susceptible to magnetic forces that the ions can literally adhere to magnetic field lines and form mechanically stable (usually spherical/elliptical objects) called plasmoids.

In the literature, this compelling magnetic force is often called the magnetic pressure or a magnetic piston (just as a gas would move according to a piston, the plasma moves according to a magnetic field). The plasmoid moves up this small chamber at breakneck speed, releasing X-rays along the way until it pinches at the top of the cylinder (the Z-pinch) (Schmidt, 2013). Here, the magnetic field curls inward much like the field of earth at its poles. This causes the plasmoid to literally implode on itself at the end of the chamber, releasing huge amounts of collision (high-energy) and decelerating (Bremsstrahlung, low-energy) radiation. On the other hand, Tokamak devices are large laboratory chambers constructed in the shape of a torus. Unlike DPF devices, Tokamaks use lasers to ignite the plasma; thus, these machines usually work with hot plasmas (Messaiaen, 1996). Tokamaks were originally developed to study plasmas in their entirety, but their powerful magnetic fields can allow for even larger-energy plasmoid implosions. Such chambers are known as Tokamak fusion reactors (Messaiaen, 1996).

The main difference between how Tokamaks and DPF devices work is that Tokamaks electrodynamically stabilize the plasma into a plasmoid and allow it to accelerate through the torus until they implode it into energy. The synergy between these techniques is that Tokamaks allow us to study magnetically confined plasmas; that is, we learn what kinds of electric or magnetic fields work to strengthen a plasma against instabilities (Messaiaen, 1996). Together, these two techniques have unlocked new avenues in low-energy fusion and electromagnetic power generation.

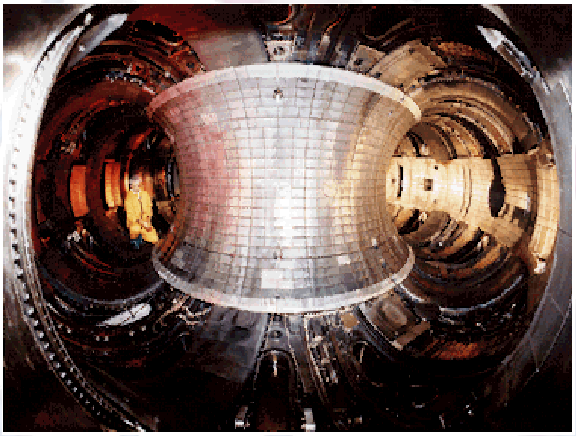

Figure 3. Inside of Tokamak Fusion Reactor chamber

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