Instability and Target Design in a Z-Pinch Driven Pulsed Fission / Fusion Engine

Abstract

Advanced forms of propulsion are required to drastically improve upon the limits of existing technology and enable deep space exploration. Nuclear reactors, both fission and fusion, have great potential as systems with high energy density for spacecraft propulsion. There are a variety of nuclear propulsion concepts that have been proposed over the last several decades. Some of these rely on the confinement of plasmas by both magnetic and inertial means. When discussing the plasma confinement one must consider the stability of the system. The conditions of the plasma dictate the burn rate of the nuclear fuel; therefore, the plasma must maintain a minimum set of conditions in order to achieve an adequate burn. Instabilities limit plasma confinement through growing fluctuations in density and pressure. This results in turbulent mixing and loss of confinement. Thus it is desirable to find ways of managing the impact of instabilities that arise in order for a sufficient burn of the fuel such that surplus energy can be converted into a propulsive force. Note that the same instabilities plague the confinement of plasmas for terrestrial power generation.

Over the last several years there has been research relating to the development of a Pulsed Fission-Fusion Engine (PuFF) conducted by the authors and others at their respective institutions. The propulsion system concept centers on the use of a z-pinch to compress a plasma in order to induce nuclear reactions. The plasma along with the additional energy released by the fission and fusion processes is expanded with a magnetic nozzle to produce thrust. The concept, if developed, is expected to have an improvement in specific impulse of several orders of magnitude in comparison with chemical propulsion systems. The z-pinch has been explored in the past as a method to confine a plasma via magnetic confinement fusion (MCF) for power generation. It suffers; however, from instabilities that so far have prevented break even conditions.

The propulsion system provides thrust through pulsed operation. This system attempts to find an advantageous point in the operational space of density and energy that lies between the regimes of magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). It is thought that some of the restrictions inherent to these two processes can be relaxed by operating in the regime of Magnetic Inertial Fusion (MIF) which combine an implosion with a magnetized target. The PuFF concept engine operates as a MIF system with the addition of fission fuel to further relax the requirements of the drivers.

The z-pinch can be described as a cylindrical or annular plasma through which a current is applied along the axis over a short (ns) period of time at high power. The current induces an azimuthal magnetic field. This process produces the Lorentz force the compresses the plasma. A diagram of this can be seen in the figure below.

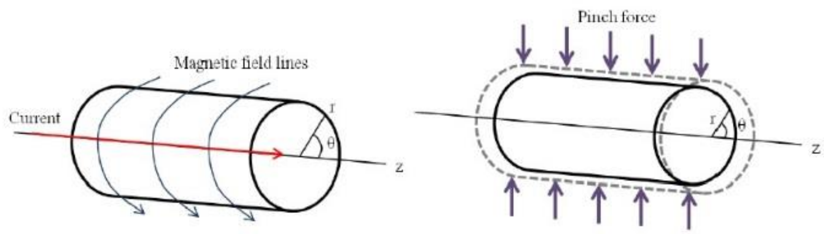

Figure 1 Diagram of a Z-Pinch

In order for this concept to be successful the target must be designed to mitigate or manage the instabilities in the process, of which the Magneto-Rayleigh-Taylor Instability is the most destructive, in order to reach required plasma conditions. The target must also meet system and nuclear requirements. As one would imagine, the design of a target is a complex problem. This paper presents the results of modeling and analysis into the instabilities that develop in the PuFF target. Verification of the code is also presented through comparison with published experimental results. There are various processes that have been shown or theorized to reduce or modify the growth rate of the instability. This knowledge will be used to model and analyze targets with specific features designed to capitalize on these processes. The goal of the target instability modeling is to integrate features into the design of the target to obtain conditions adequate to initiate a burn wave and reach a useable burn fraction.

The results developed and presented in this paper are obtained using a smooth particle hydrodynamic code. Smooth particle hydrodynamics is a mesh-free lagrangian method that divides the fluid (or in this case plasma) into discrete points. Each point has a certain distance over which the properties of the point is smoothed. The code captures physics of interest to plasma compression, nuclear reactions and electromagnetism. The resolution and speed of computation can be easily adjusted by controlling the number of points or particles the model uses to represent the objects. The smooth particle hydrodynamic code was verified through comparison with relevant experimental data available in literature. In the case of the verification models, the code was used to build a model that was representative of the experiment of interest. Boundary conditions, initial conditions, materials, geometry, etc. were all defined to match as closely as possible that in the actual experiment. The model was then run to produce an output file tracking properties over time. The results were then examined to determine how well the model reproduced the evolution of the experiment over time. Multiple verification models were examined in order to adequately gauge the effectiveness of the code. The first verification model was a simple tungsten wire z-pinch. The second verification model replicated a recent Magnetic Liner Inertial Fusion (MagLIF) experiment.

The compression of a plasma in a z-pinch via a magnetic field is an unstable process that is dominated by the Rayleigh-Taylor Instability. This instability occurs when a fluid of lower density accelerates or supports a fluid of higher density. In the case of a z-pinch the magnetic field acts as the low density fluid and the plasma as the high density fluid. Small perturbations quickly grow, typically with a dominate wavelength, and become nonlinear. This turns the compression into a turbulent mixing process and is counterproductive to fusion power generation. The interest in modeling this process stems from the need to manage the instability development in the compression of the PuFF fuel. Operating in regimes outside of ideal MHD introduces many processes, whose significance varies greatly with initial conditions, that reduce or mitigate the growth rate of the instability. It may be possible to design a fuel pellet for the PuFF propulsion system that reaches adequate fuel burn ratios through managing the instability development by introducing specific physical processes. Processes of interest include resistivity, viscosity, and shear forces. For instance, MagLIF experiments have shown suppression of instability development through the application of a dielectric (highly resistive) layer to the liner. Also, frozen deuterium wire z-pinch experiments showed greater than anticipated levels of stability. It is thought this might be due to resistivity. Also, the University of Washington has shown that shear forces along the edge of a z-pinch can provide stability. Interesting processes such as these could potentially be incorporated into the fuel and pinch system design in order to reach conditions in the fuel to induce a burn wave and reach burn ratios that provide large amounts of energy.

The ongoing research into a z-pinch driven pulsed fission fusion engine has the potential to result in an in space propulsion system with 2 orders of magnitude greater specific impulse than chemical engines if successful. It may be possible to design the fuel and compression system to manage the instabilities and achieve adequate burn fractions. The work presented in this paper includes code verification and modeling of z-pinch targets designed to employ processes to modify the instability growth rate. These results are used to drive and suggest a fuel pellet and compression system design. An analysis of the expected achievable burn fraction and resulting propulsive capability is presented.