Characterizing Thrust Performance of a Stabilized Z-Pinch Using a Ballistic Pendulum

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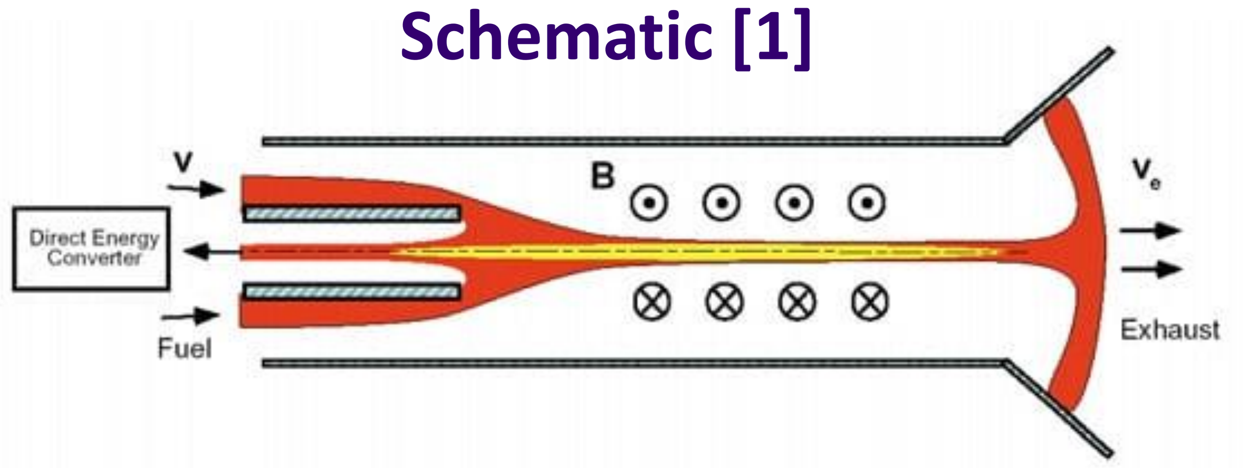
Deep Space Travel with Fusion

>Interstellar flight is not feasible with current rocket technology, which produce too low exhaust speeds and require enormous amounts of propellant.

> The Z-pinch configuration could fulfill the requirements of both high thrust and high propellant utilization efficiency for operation into deep space

Z-Pinch Plasma Thruster Schematic [1]



>Thermonuclear fusion occurring in the plasma creates the high energy density needed for deep space missions

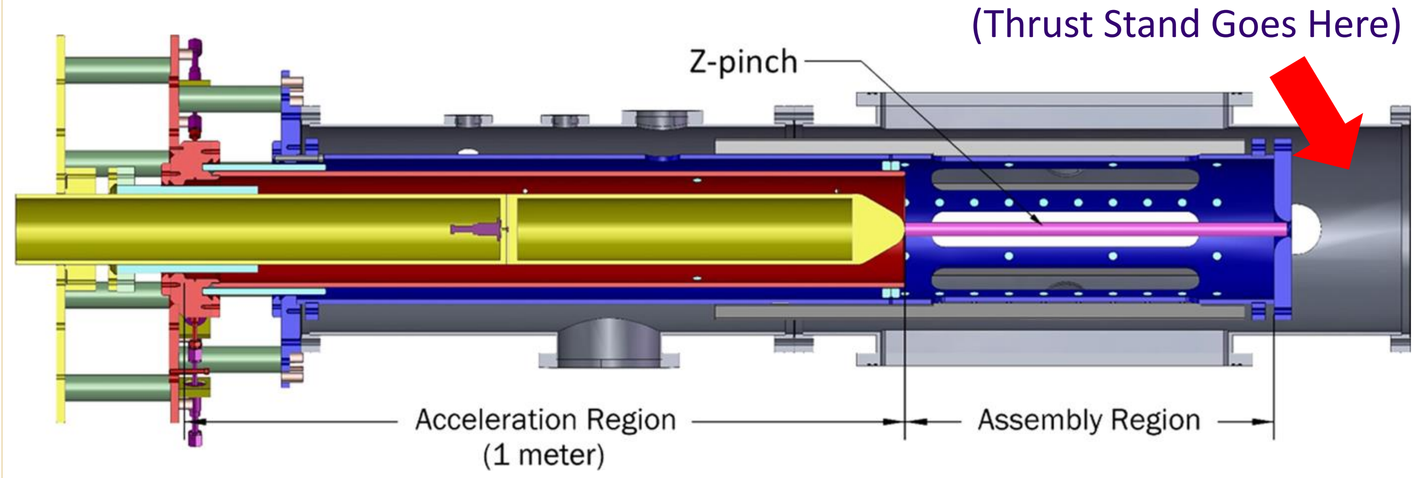
> The Z-pinch thruster would be lighter and smaller than other fusion approaches, which require complex applied magnetic fields

What is a Z-Pinch?

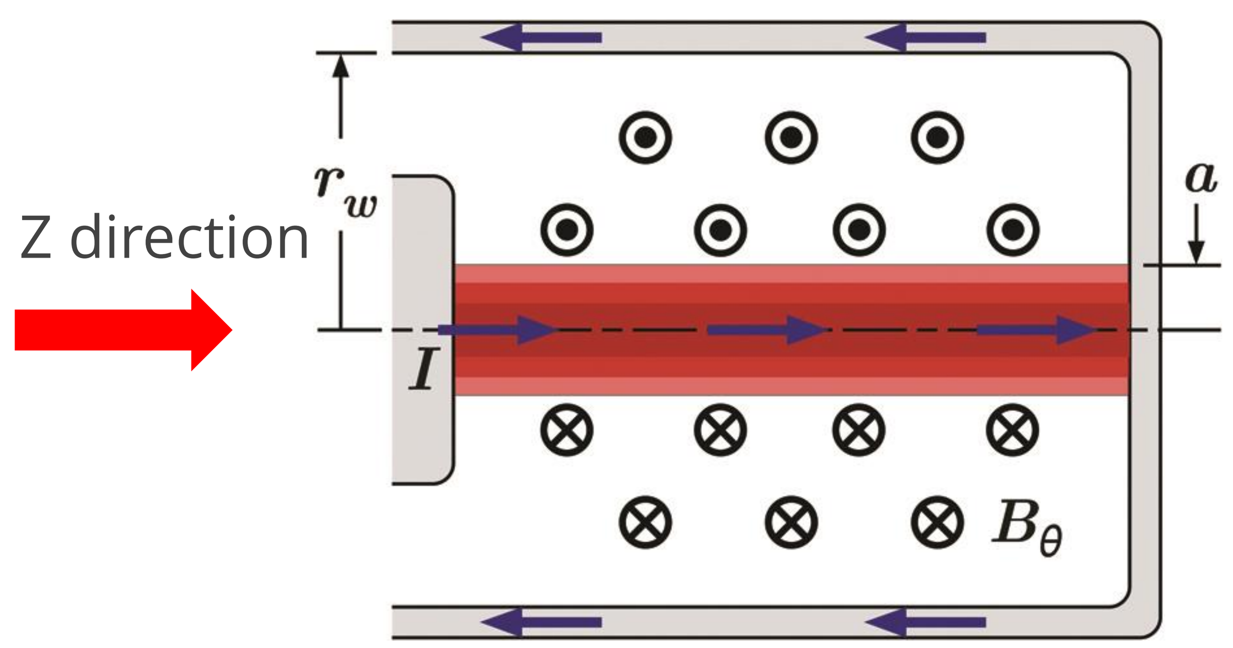
>A Z-pinch is a configuration that magnetically confines high-temperature and high-density plasma to attain the conditions necessary for fusion

>The Z-pinch is advantageous for achieving fusion as it does not require an applied magnetic field, and is a simple, linear configuration

The ZaP-HD Experiment [2]



Z-Pinch Equilibrium [3]



>As the plasma is made up of moving charges with a current in the 'Z' direction, an azimuthal magnetic field radially 'pinches' the plasma via the Lorentz force.

Measuring Thrust on ZaP-HD

>The Z-pinch in the device generates thrust by exhausting plasma from one end of the assembly region. The exhaust plasma then impacts a ballistic pendulum, thereby imparting momentum.

> Measuring the pendulum's time-dependent oscillation amplitude and phase using a laser sensor allows for calculation of the plasma's impulse.

Ballistic Pendulum Design

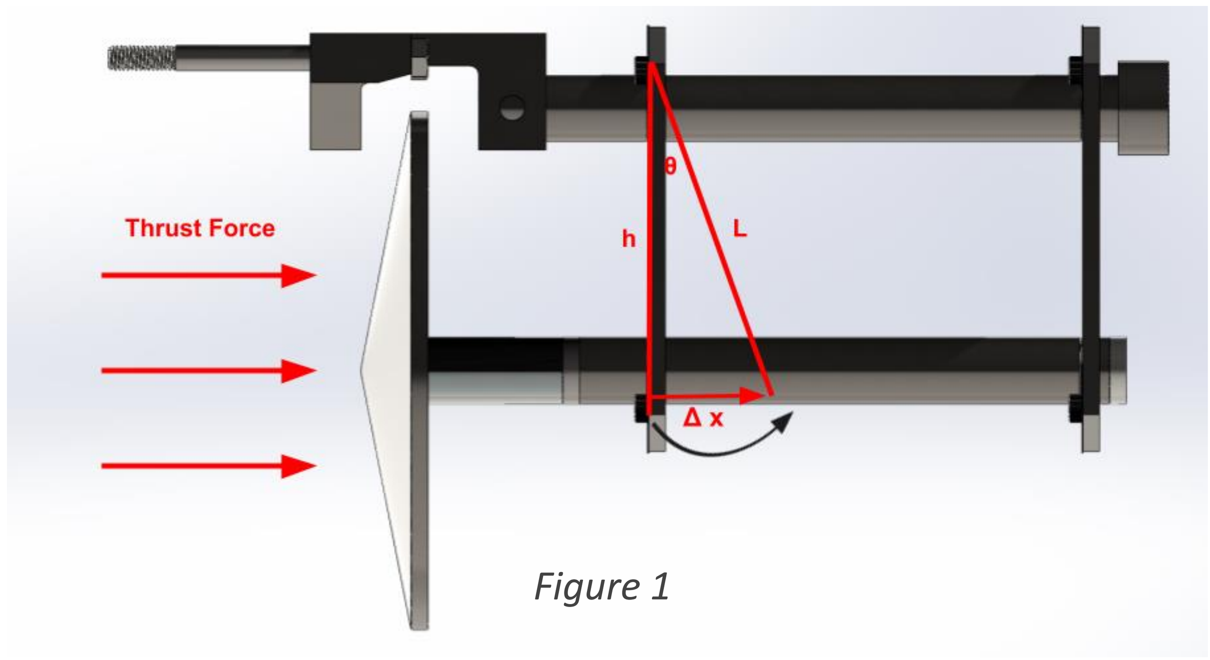


Figure 1

Methods

>The plasma-facing surface is conical to convert axial flow to radial flow in order to assume an inelastic collision.

>The position of the pendulum is recorded for 10 seconds before and after each shot of plasma. Maximum displacement is calculated by subtracting displacement before the shot. Using the conservation of energy calculate the impulse imparted on the pendulum.

$$\frac{1}{2}mv^2 = mgh \rightarrow v = \sqrt{2gh}$$

>We conserve linear momentum, J as:

$$M_p v_p = J = (m + M_p) v_{all}$$

>To compute impulse, we use trigonometric identities to obtain the maximum height of the pendulum using the geometry shown in Figure 1.

$$\begin{aligned} h &= L(1 - cos\theta) \\ &= L(1 - \sqrt{1 - sin^2\theta}) \\ &= L\left(1 - \sqrt{1 - \left(\frac{\Delta x}{L}\right)^2}\right) \end{aligned}$$

>All together, we can compute impulse as a function of horizontal displacement.

$$J = M_p \sqrt{2gL\left(1 - \sqrt{1 - \left(\frac{\Delta x}{L}\right)^2}\right)}$$

>To derive thrust, we must divide the computed total impulse by the pinch lifetime

> To determine the propellant utilization efficiency, we can compute specific impulse by dividing the total impulse by the weight of the propellant with:

$$I_{sp} = \frac{I_{tot}}{m g_0}$$

I_{sp} = specific impulse
M_p = mass of plasma
L = length of pendulum arm
Δx = change in distance
Θ = angle
v_p = velocity of plasma
h = height
m = mass
J = impulse
v = velocity
g = gravity

Expected Results

> Once the thrust stand is installed, we can process deflection measurements into values of thrust and specific impulse of ZaP-HD.

> We expect to record more than 1000 newtons of thrust and 7000 seconds of specific impulse as our new configuration is more potent than previously tested ones.

Thruster Comparisons [4]

Device Name	Thrust (N)	Specific Impulse (s)
Aerojet Hall Thruster	0.254	2020
Aerojet AEPS	0.6	2800
VASIMR VX-200	6	5000
ZaP-HD	1000	7000
Theoretical Z-Pinch Thruster	$3.3 * 10^5$	$3.5 * 10^5$

Acknowledgements

[1] U. Shumlak et al. "Advanced Space Propulsion Based on the Flow-Stabilized Z-Pinch Fusion Concept," AIAA 2006-4805. *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. July 2006.
[2] M. P. Ross, U. Shumlak; Digital holographic interferometry employing Fresnel transform reconstruction for the study of flow shear stabilized Z-pinch plasmas. *Rev Sci Instrum* 1 October 2016; 87 (10): 103502.
[3] U. Shumlak; Z-pinch fusion. Journal of Applied Physics 29 May 2020; 127 (20): 200901.
[4] Smythe, J. (2023). *Electrode Geometry Effects on Plume Characteristics and Thruster Performance of ZaP-HD* (Master's Thesis). University of Washington.

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