UEDGE Simulations of a Direct Fusion Drive FRC Rocket

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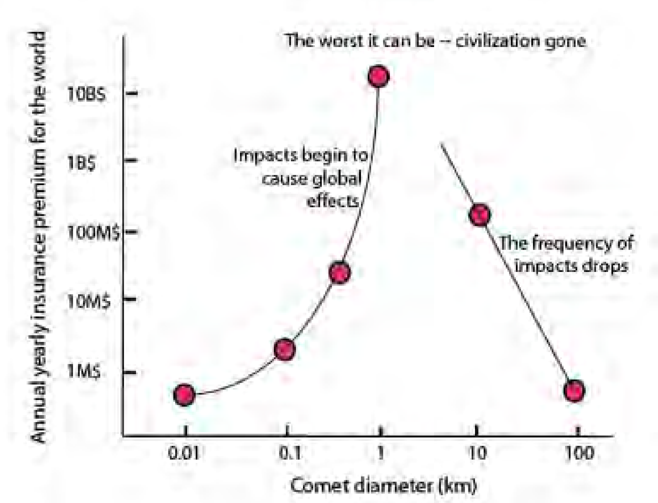
OBJECTIVES

- **Evaluate the field-reversed configuration (FRC) for use as a direct fusion drive rocket engine. Determine the expected values for thrust, specific impulse, and propulsion efficiency as a function of gas and power inputs.**
- **Develop an understanding of plasma parameters and determine what value of gas input will maximize thrust for a given power input.**

BACKGROUND: FRC AS A ROCKET

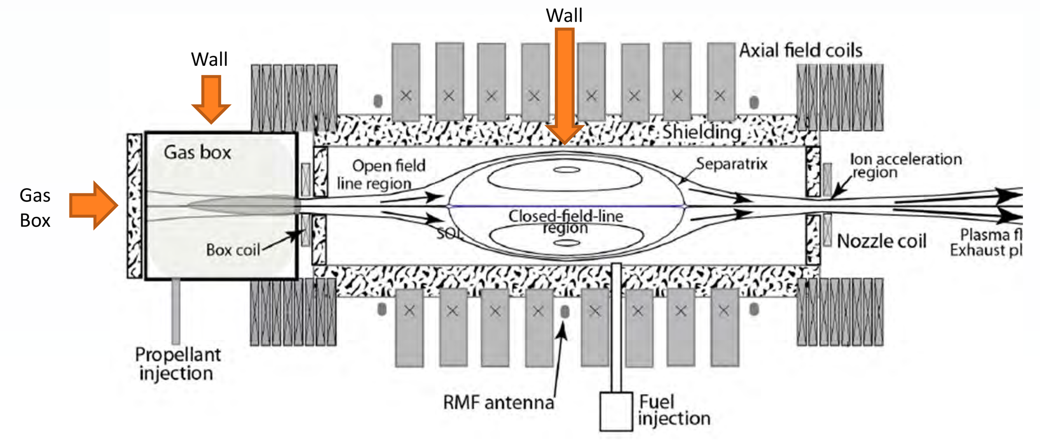
- An FRC rocket could be used for manned or unmanned space exploration within the solar system, beyond the range of chemical rockets.
- **Chemical rockets are not fast enough** to reach a comet and change its trajectory. An FRC used as a rocket could do so.



- Comets are low-frequency, high expected cost events. Their expected cost to society per year is approximately **$10 billion**.
- Investment in a comet defense system would have a high expected return.

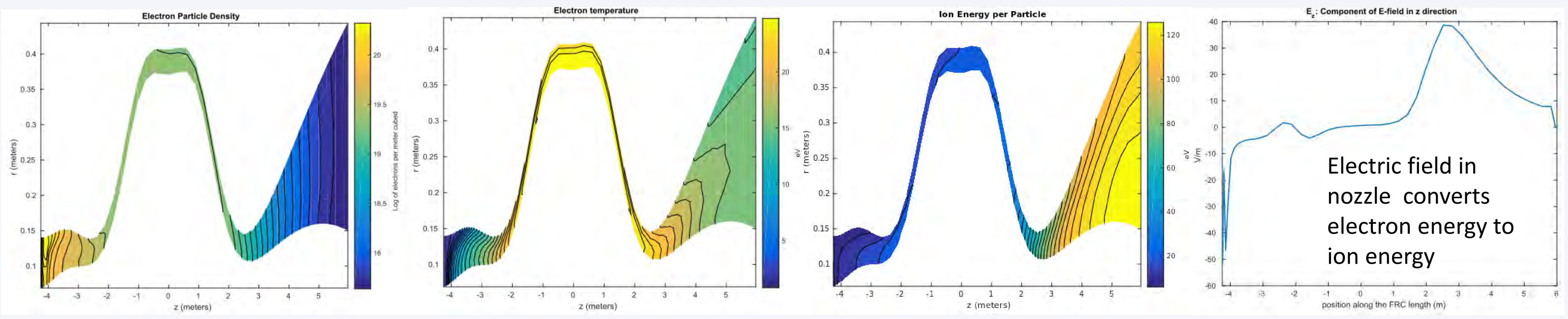
BACKGROUND: SCRAPE-OFF LAYER (SOL)

- Pictured below is a schematic of an FRC with an asymmetric SOL used for direct-fusion drive.
- Propellant gas (Deuterium) is injected into a gas box, as shown on the left. Plasma formed in the gas box is heated by fusion products from the FRC core as it flows along the SOL. The heated plasma is then ejected out a magnetic nozzle at the opposite end, generating thrust.



SCRAPE OFF LAYER PARAMETERS

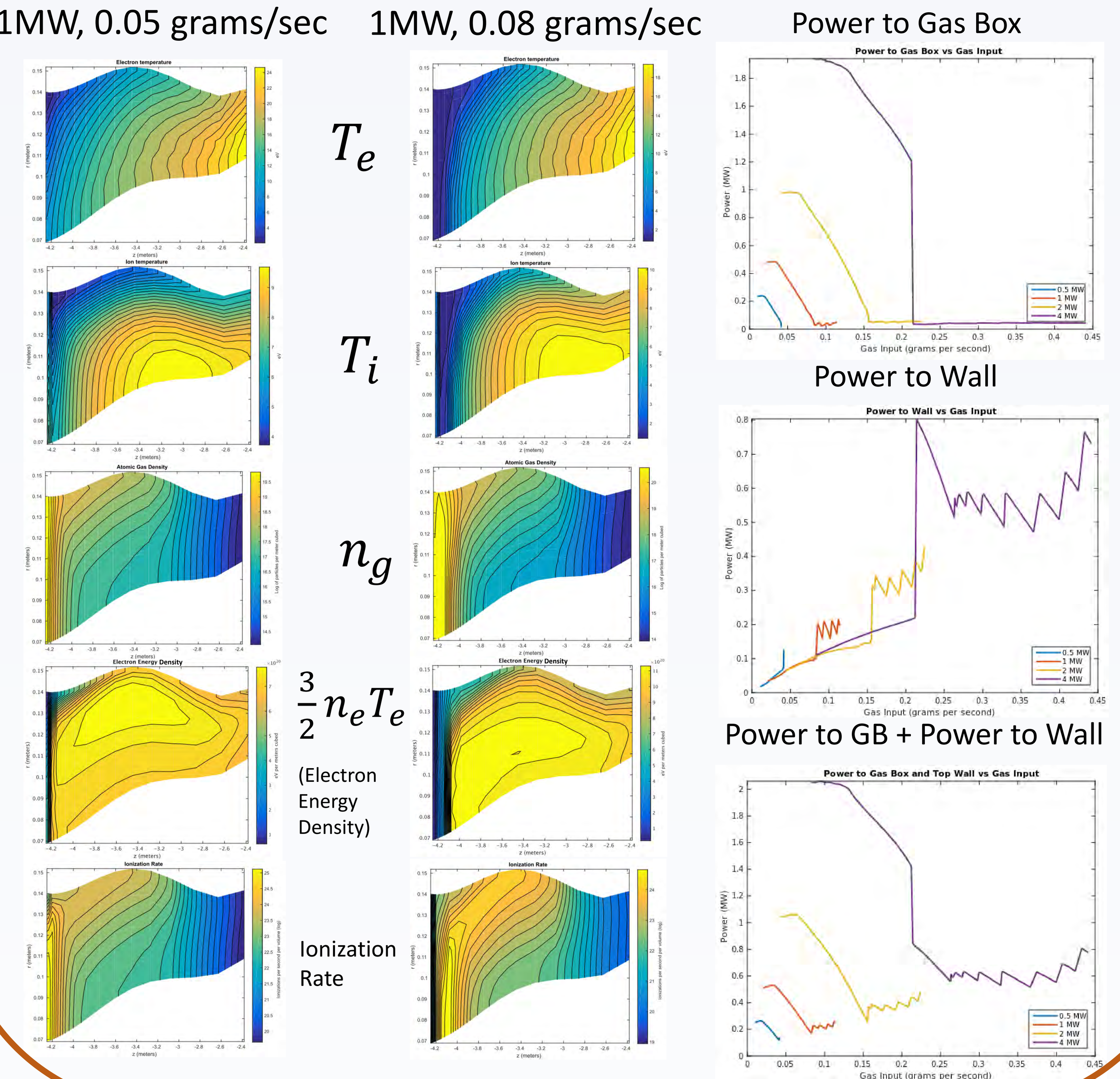
- 1MW input power and 0.08 grams per second of gas input is shown



$n_{e,i} \approx 3e19/m^3$ $T_e \approx 25eV$ Ion Energy $\approx 20 - 100eV$

GAS BOX PARAMETERS

1MW, 0.05 grams/sec — 1MW, 0.08 grams/sec — Power to Gas Box



ROCKET EQUATIONS

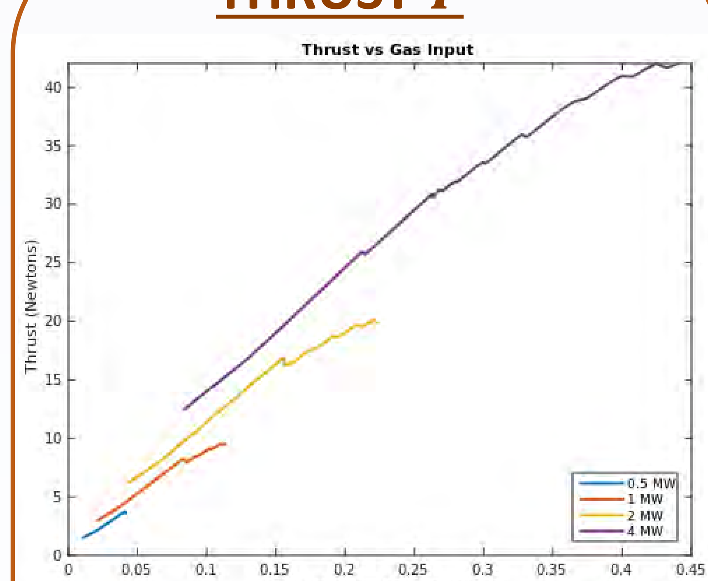
- Thrust is computed at the open end of the rocket with the following equation:

$$T = \sum_{\sigma} \int dA m_{\sigma} n_{\sigma} (v_{\parallel\sigma} cos(\theta))^2$$

- This is a generalized version of the rocket equation $T = \dot{m}v$
- Propulsion efficiency η is the proportion of power input going to the KE of the particles
- I_{sp} is the specific impulse or exhaust velocity
- G is the gas input
- $T \propto G^{1/2}$ and $I_{sp} \propto G^{-1/2}$ assuming $\frac{\partial \eta}{\partial G} = 0$

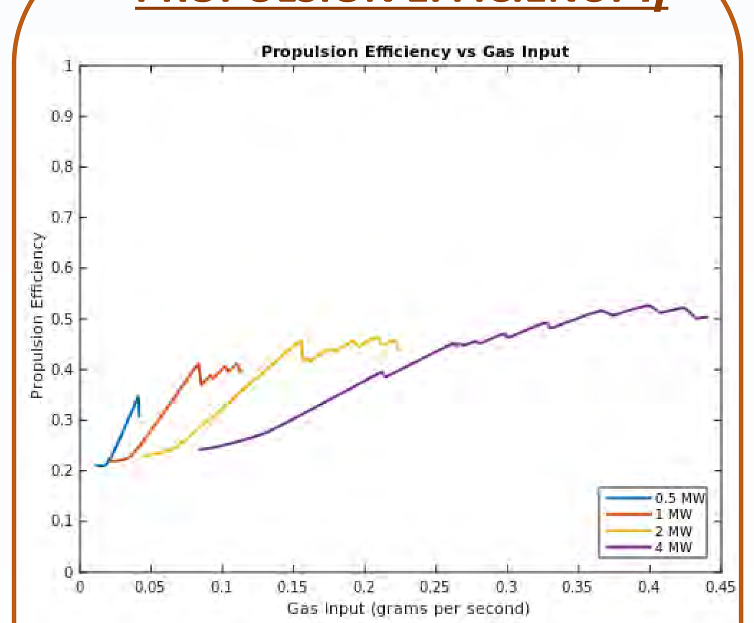
ROCKET PERFORMANCE

THRUST T



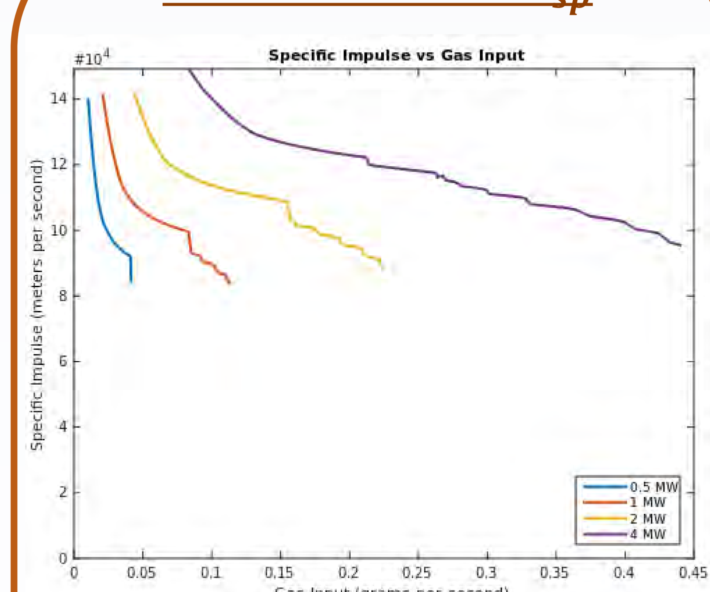
- **$T \sim 5$ - $10N$ for 1MW reactor**
- Thrust increases with gas input
- T is approximately proportional to G, not $G^{1/2}$, because η depends on I

PROPULSION EFFICIENCY η



- **$\eta \sim 0.2$ - 0.5**
- η increases with G

SPECIFIC IMPULSE I_{sp}



- $I_{sp} \sim 10^5 m/s$
- Specific Impulse decreases with G

SIMULATION METHOD

- This work was done using UEDGE, a 2-dimensional plasma transport code. The code was written by Tom Rognlien et al. at LLNL. A magnetic field geometry created by Bruce Cohen was used to simulate an FRC SOL.
- The code solves multi-fluid equations for plasma variables, as well as the Braginskii transport equations. The code produces steady state solutions.

ANALYSIS

- As the gas input G increases, the plasma in the gas box transitions from an attached state to an detached state.
- Power flow to the material surfaces (gas box and wall) of the FRC is lower in a detached state.
- If less power flows to material surfaces, more power must flow out of the open end of the FRC. Thus, detachment and the associated decrease in power to the gas box is the mechanism for increasing η.

HIGHER GAS INPUT TO THE GAS BOX IMPROVES PERFORMANCE

- Higher gas input is associated with higher thrust, higher efficiency, and less power to material surfaces.
- There is a tradeoff between thrust and specific impulse.
- A direct fusion drive FRC rocket could expect 5-10N of thrust per MW of SOL heating power.

REFERENCES AND ACKNOWLEDGEMENTS

Wurden, G. A., Weber, T. E., Turchi, P. J., Parks, P. B., Evans, T. E., Cohen, S. A., . . . Campbell, E. M. (2015). A New Vision for Fusion Energy Research: Fusion Rocket Engines for Planetary Defense. Journal of Fusion Energy J Fusion Energ, 35(1), 123-133.

Cohen, S. A., et al.

G.S. Chu and S.A. Cohen, PRL 76, 1248 (1995)

B. Cohen, T. Rognlien, LLNL, UEDGE Simulations of a 2D Nozzle

Matthew Chu Cheong, et al. Energetic Particle Slowing in FRC Edge

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