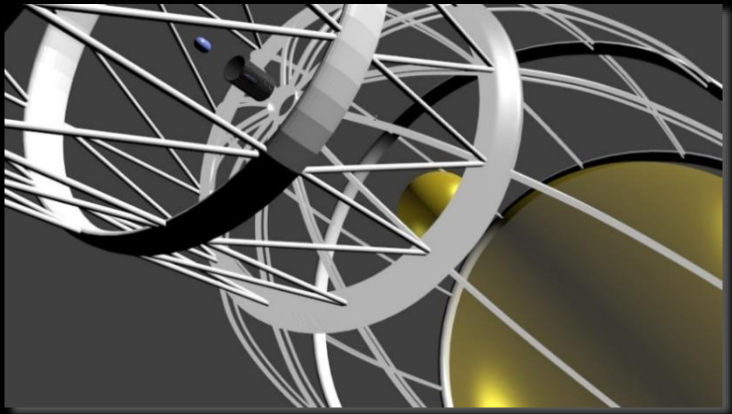
Gradient Field Imploding Liner Fusion Propulsion System

Phase I Study



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Denver, CO

Why the interest in fusion propulsion?

Go Far ● Get There Fast ● Carry Lots of Stuff

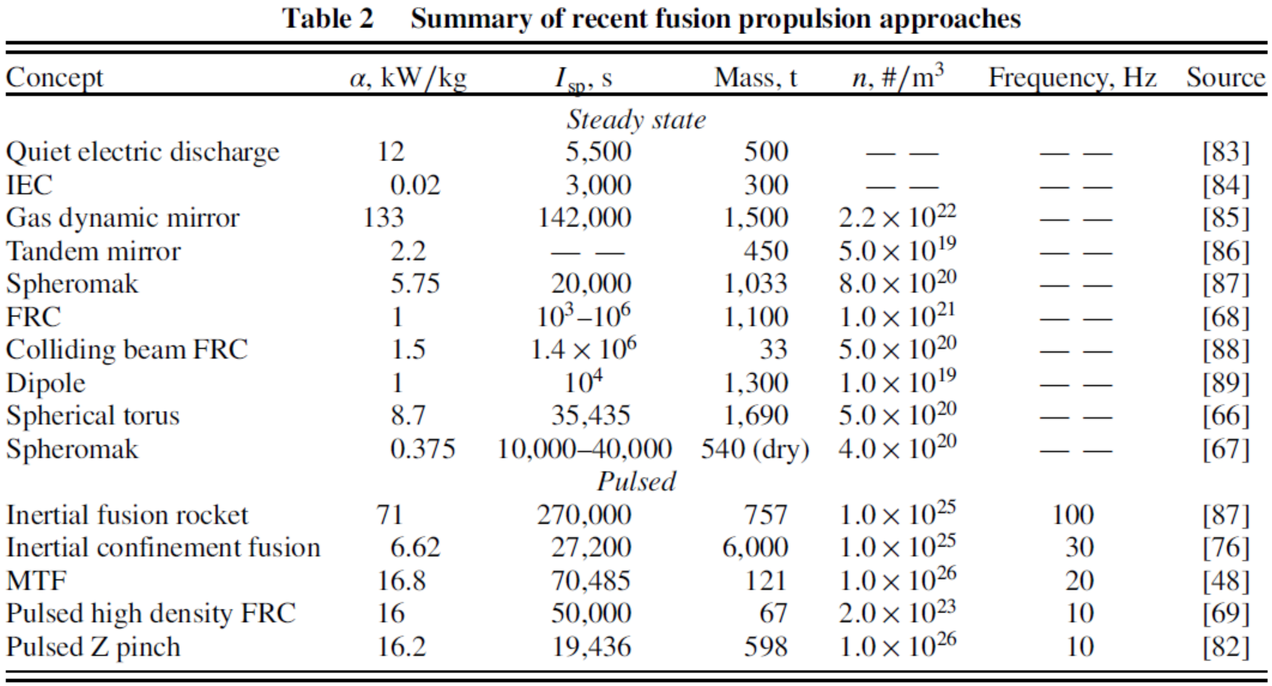


Table 2 Summary of recent fusion propulsion approaches

Concept	α, kW/kg	I_{sp}, s	Mass, t	n, #/m^3	Frequency, Hz	Source
		Steady state				
Quiet electric discharge	12	5,500	500	— —	— —	[83]
IEC	0.02	3,000	300	— —	— —	[84]
Gas dynamic mirror	133	142,000	1,500	2.2×10^{22}	— —	[85]
Tandem mirror	2.2	— —	450	5.0×10^{19}	— —	[86]
Spheromak	5.75	20,000	1,033	8.0×10^{20}	— —	[87]
FRC	1	10^3–10^6	1,100	1.0×10^{21}	— —	[68]
Colliding beam FRC	1.5	1.4×10^6	33	5.0×10^{20}	— —	[88]
Dipole	1	10^4	1,300	1.0×10^{19}	— —	[89]
Spherical torus	8.7	35,435	1,690	5.0×10^{20}	— —	[66]
Spheromak	0.375	10,000–40,000	540 (dry)	4.0×10^{20}	— —	[67]
		Pulsed				
Inertial fusion rocket	71	270,000	757	1.0×10^{25}	100	[87]
Inertial confinement fusion	6.62	27,200	6,000	1.0×10^{25}	30	[76]
MTF	16.8	70,485	121	1.0×10^{26}	20	[48]
Pulsed high density FRC	16	50,000	67	2.0×10^{23}	10	[69]
Pulsed Z pinch	16.2	19,436	598	1.0×10^{26}	10	[82]

Cassibry et al., "Case and Development Path for Fusion Propulsion," *Journal of Spacecraft and Rockets*, 52 (2), pp. 595-612, March-April 2015 *(and references therein)*

$$\frac{m_f}{m_0} = e^{-\Delta v/v_e}$$

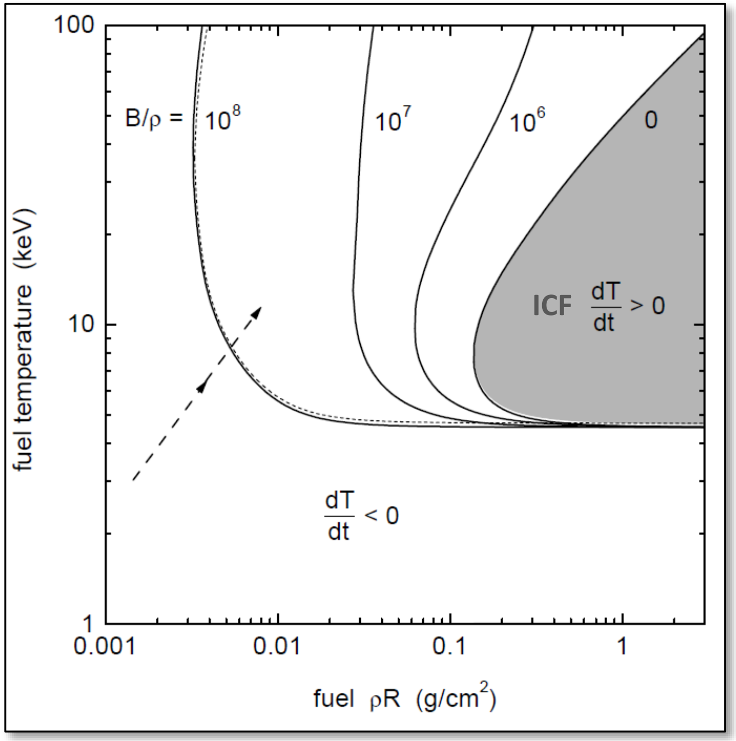
- Solar system destinations require $\Delta v \approx 10^4 - 10^5$ m/s
- High I_{sp} (= v_e/g) required for reasonable payload mass fractions
- Fusion offers high specific power (kW/kg) to reduce trip times

Several studies have defined the benefits of fusion propulsion for rapid trip times to Mars and the outer solar system

Magnetoinertial Fusion (MIF)

- A high current pulse generates an intense magnetic field that implodes an annular liner, heating and confining a plasma on axis
- A strong internal magnetic field reduces electron thermal losses and enhances alpha particle self-heating of the fusion fuel
- Reduces the areal density (*ρr)* threshold for ignition to well below conventional Inertial Confinement Fusion values
- Currently used in liner-driven FRC and Z-pinch experiments

*Lindl-Widner Diagram (DT cylinder at stagnation)**



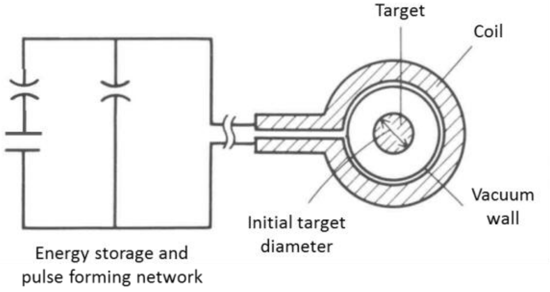
**Basko, M. et al., "Ignition conditions for magnetized target fusion in cylindrical geometry," Nuclear Fusion, Vol. 40, No. 1 (2000)*

Paths to MIF Compression

- **Z-pinch:** Pulsed axial current through liner generates azimuthal magnetic field; radial $j_z X B_\Theta$ Lorentz force implodes the liner
- **Θ-pinch:** Induced azimuthal liner current generates axial magnetic field; radial $j_\Theta X B_z$ Lorentz force implodes the liner
- **Liner material** serves to:
  - Conserve magnetic flux
  - Compress the target to ignition
  - Inertially confine the target long enough so the fusion yield exceeds energy losses (driver efficiency, radiative losses, etc.)
- **Equivalent view:** Magnetic flux excluded by the conducting liner generates external magnetic field pressure, imploding the target

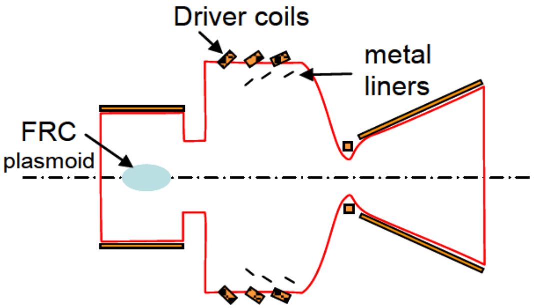
Θ-Pinch Basics

Θ-pinch coil and circuit



Adapted from Miyamoto, K. Plasma Physics for Nuclear Fusion, MIT Press, Cambridge, MA (1987)

Fusion Driven Rocket



Shimazu, A., Slough, J., Pancotti, A., "Parametric Optimization of the Fusion Driven Rocket Liner Compression Driver," AIAA-2016-4538, 52nd AIAA/SAE/ASEE Joint Propulsion Conf, July 25-27, 2016, Salt Lake City, UT

- Pulsed, high current discharge generates a rapidly increasing axial B-field between the drive coil and conducting liner
- Lorentz force/increasing radial pressure implodes a material liner and compresses fuel target (typically an FRC plasma)
  - e.g. approach used by Slough et al. in the Fusion Driven Rocket (2012-15 NIAC I, II)
- At maximum compression, pressure is balanced between the stagnating liner material, external magnetic field, trapped internal magnetic field, and fuel pressure

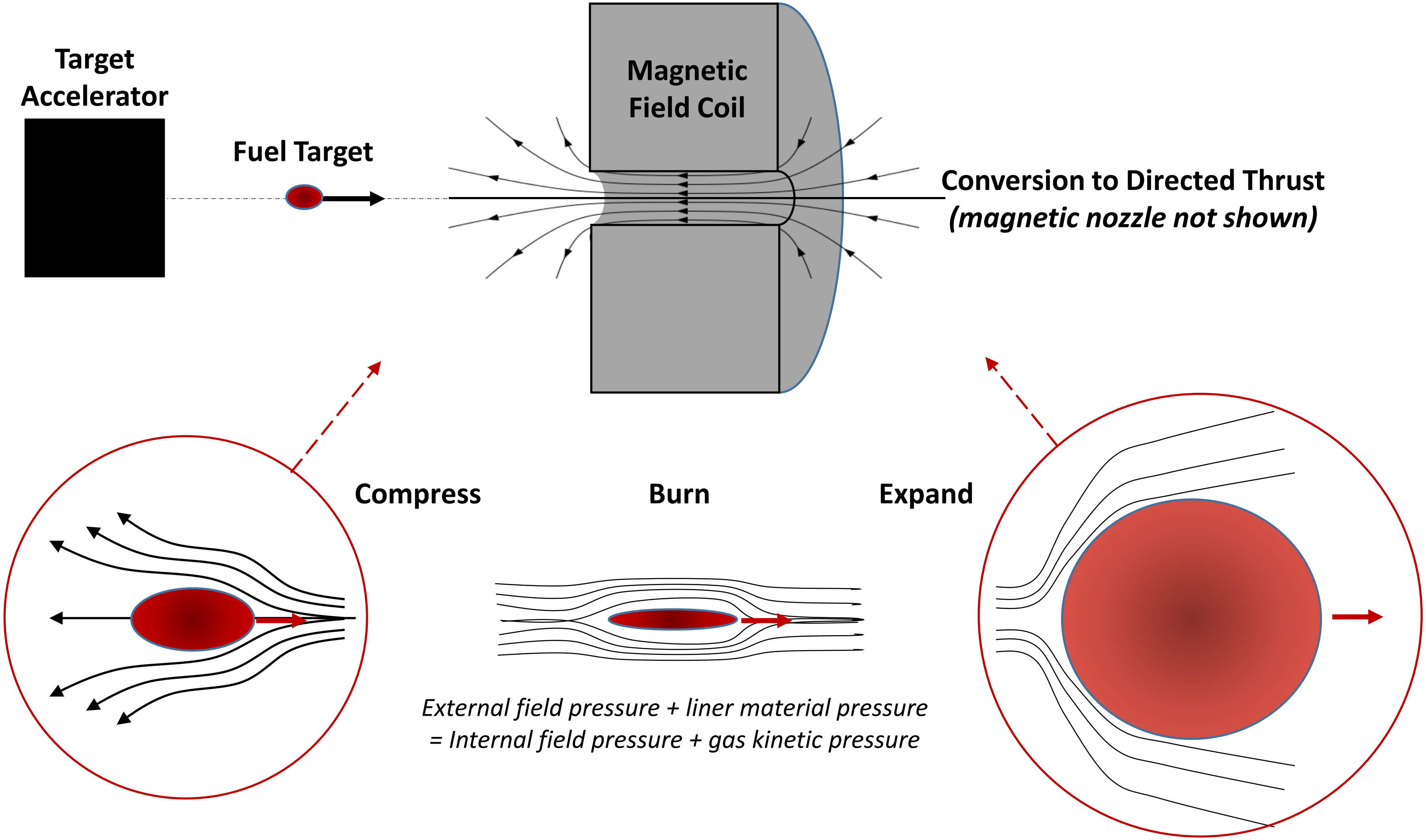
New Approach to Liner Compression

- Replace the time changing magnetic field generated by the pulsed current coil with a target moving rapidly into a steady-state magnetic field gradient
- Equivalent to time changing magnetic field observed in the target frame of reference:

$$\dot{I} \propto \dot{B}_z = v_z \frac{\partial B}{\partial z}$$

- Magnetic flux is excluded by/internally trapped by the liner
- Unbalanced radial pressure rapidly implodes the fuel target
- Requires implosion time < diffusion time of B-field into liner
  - Typical compression times ≈ several µsec, diffusion times ≈ msec

Preliminary Concept



Target Accelerator

Fuel Target

Magnetic Field Coil

Conversion to Directed Thrust
(magnetic nozzle not shown)

Compress

Burn

Expand

External field pressure + liner material pressure
= Internal field pressure + gas kinetic pressure

How This Helps

- Replaces pulsed drive coil with steady state superconducting magnet, mitigating issues with repetitive, high current pulse generation
  - Reduces resistive losses, energy storage requirements
  - Reduces demands on switches, power components, etc.
  - Target can be accelerated to required velocity over longer time period
- Fairly compact linear geometry for in-space applications
  - Strong gradient field produced by small bore magnet
  - Length dictated by target velocity and magnetic field diffusion time
  - Readily incorporates magnetic nozzle for directed plasma thrust
  - Amenable to ground based testing
- Provides options for axial magnetic field trapping in the target and laser preheating to improve target gain

Challenges and Goals

Phase I

- Understand the dynamics between the rapidly moving target and the gradient field
  - Sufficient pressure generated to provide rapid liner implosion/fusion
  - Growth of liner instabilities (RT, other interchange instabilities; mitigation)
- Initial fuel target design (geometry, liner material, fuel type)
- Accelerator trades to achieve high target velocities (km's/s)
- Methods to reduce the required amount of compression
  - Target preheating, embedded magnetic field to reduce thermal transport
- Initial coil design to generate strong magnetic field gradient
- Evaluate magnetic nozzle to direct the hot expanding plasma

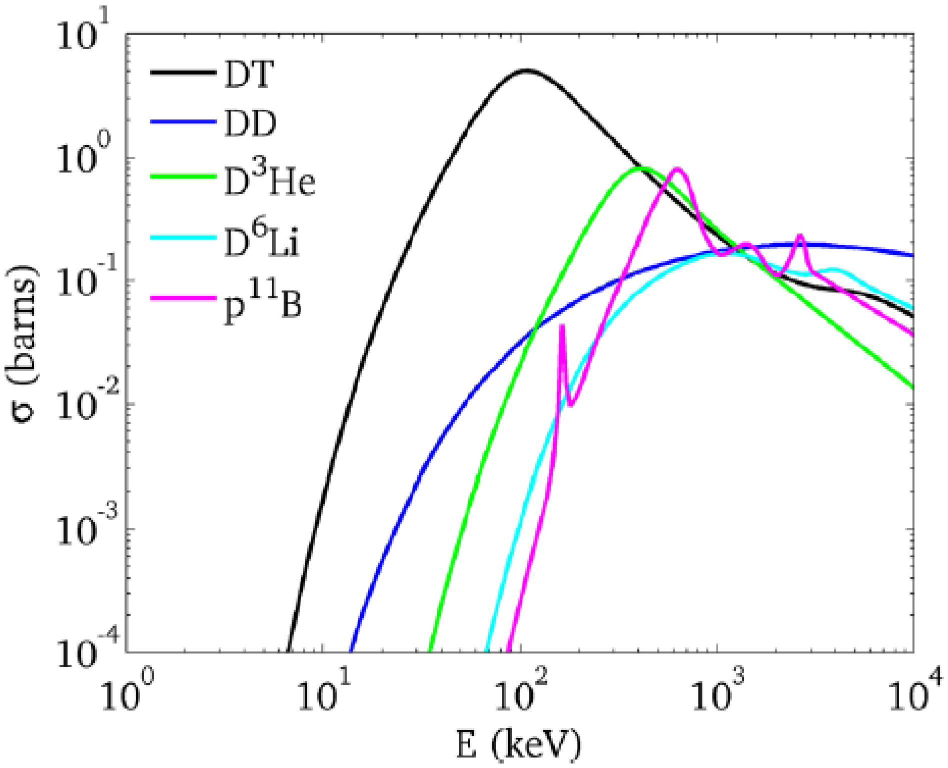
Pull together into an initial vehicle design and comparative mission analysis

Phase I Study Approach

Target Fuel

Reaction	*Energy Release*
$\boxed{D + T \rightarrow \alpha + n}$	17.59 MeV
$D + D \rightarrow T + p$	4.04 MeV
$D + D \rightarrow {}^3\mathrm{He} + n$	3.27 MeV
$D + {}^3\mathrm{He} \rightarrow \alpha + p$	18.35 MeV
$D + {}^6\mathrm{Li} \rightarrow 2\alpha$	22.374 MeV
$D + {}^6\mathrm{Li} \rightarrow p + {}^7\mathrm{Li}$	5.026 MeV
$D + {}^6\mathrm{Li} \rightarrow n + {}^7\mathrm{Be}$	3.38 MeV
$p + {}^{11}B \rightarrow 3\alpha$	8.68 MeV
$n + {}^6\mathrm{Li} \rightarrow T + \alpha$	4.86 MeV
$n + {}^7\mathrm{Li} \rightarrow T + \alpha + n$	– 2.87 MeV

Cross section vs. center of mass energy



Start with D-T as the “easiest” to ignite for this feasibility study

Cassibry et al., “Case and Development Path for Fusion Propulsion,” *Journal of Spacecraft and Rockets*, 52 (2), pp. 595-612, Mar-April 2015

Accelerator Trades

- Light Gas/Rail Guns
  - Experimentally demonstrated to several km/s
  - Potential erosion of rails/component
  - May be useful for initial ground tests
- Electrothermal Accelerators
  - Investigated to refuel tokomak reactors
  - Ablative plasma arc drives electromagnetic acceleration
  - Experimentally demonstrated to a few km/s with 1-g pellets
- Electromagnetic Accelerators
  - e.g. pulsed inductive macron accelerator ≈ 1-gram at 5-10 km/s
- Laser Acceleration
  - Rapid ablative acceleration of target material
  - Experimentally demonstrated to several 10’s of km/s

Approach, cont.

Reduce Compression Requirements

- Fuel preheating reduces amount of adiabatic compression required to reach fusion temperature conditions:

$$T_f = T_o \left(\frac{r_0}{r_f}\right)^{4/3}$$

r_0 = *initial fuel radius*
r_f = *final fuel radius*

  - Option: Laser provides both ablative target acceleration and fuel heating prior to compression in magnetic field gradient

- Initial magnetic flux trapped within fuel provides strong axial field when compressed:

$$B_f = B_o \left(\frac{r_0}{r_f}\right)^{2}$$

  - Reduces radial ion and electron thermal transport losses
  - Enhances compressed fuel heating by α-particle energy deposition

Analytic Models

- MATLAB modeling for preliminary field calculations, adiabatic liner compression, target sizing estimates; using to guide initial inputs to comprehensive 3D numerical model (SPFMax)
- Adapting semi-analytic MIF model* to assist with rapid trade space evaluations and target performance estimates
  - Liner dynamics and compression, fuel ionization and adiabatic heating, optional fuel preheating (laser) absorption), α-particle energy deposition, radiative losses, ion and electron thermal conduction losses, end losses, magnetic flux losses, fusion reaction rates, energy balance and gain calculations
  - Reasonable published comparisons with LASNEX numerical models
  - Modifying equations to incorporate high speed target interactions with gradient magnetic field and corresponding liner compression dynamics

McBride, R. and Slutz, S., "A semi-analytic model of magnetized liner inertial fusion," Physics of Plasmas* ***22**, 052708 (2015)*

Numerical Model: SPFMax

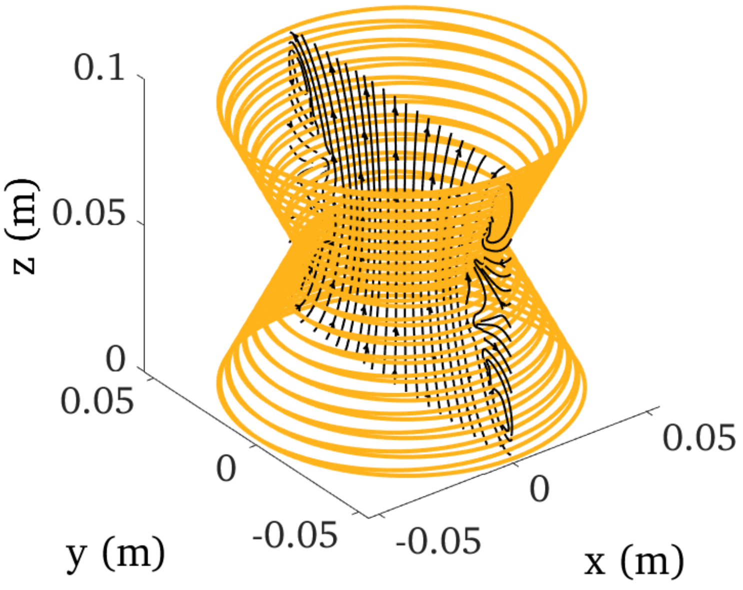
*Smooth Particle Hydrodynamics with Maxwell equation solver**

- 3D multiphysics code, vectorized and GPU-enabled in Matlab; developed by UAH for MIF and fission/fusion hybrid research
- Includes tabular equations of state to model variable levels of ionization, thermal conduction, radiation emission and absorption, shock capturing, real viscosity, electromagnetic field propagation and forces in the plasma, a self-consistent circuit model, and nonlocal absorption of fusion ion product energy
- Resolves vacuum/plasma interface and nonlocal transport of charged particle deposition
- Currently completing the integration and testing of the SPFMax electromagnetic equation solver

**Additional details in backup slides*

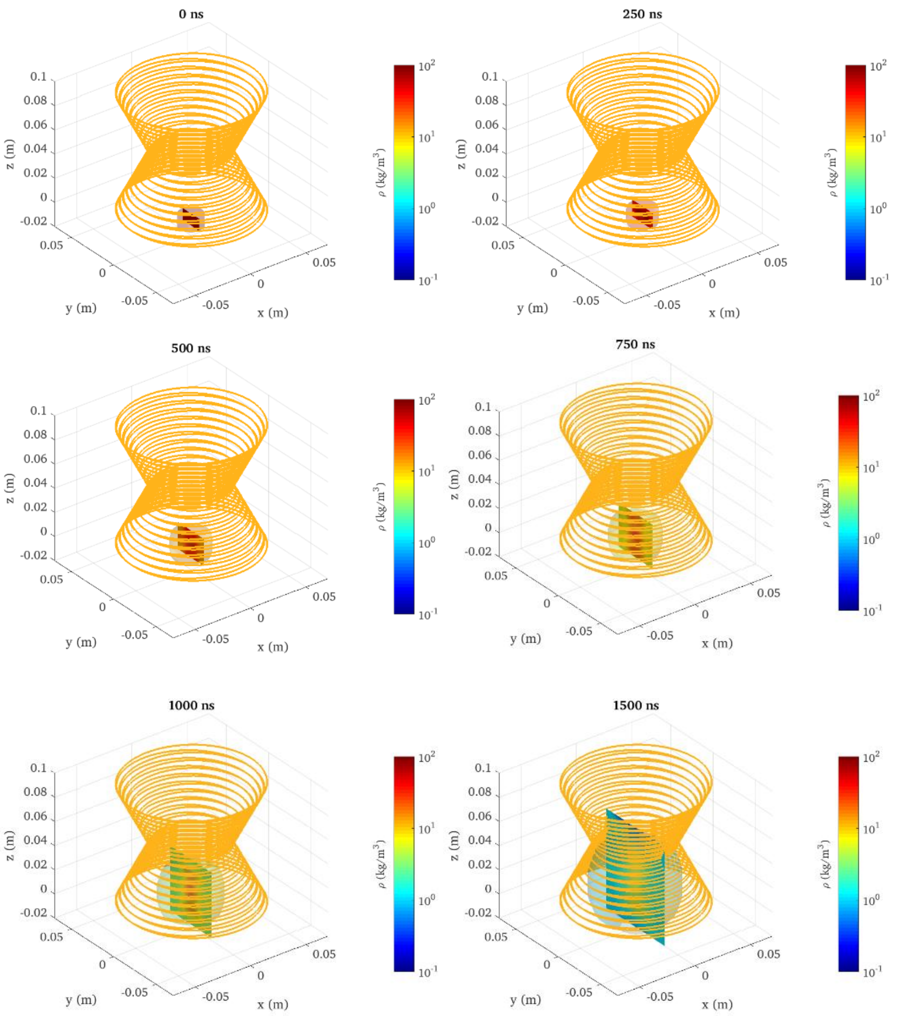
Approach, cont.

Preliminary SPFMax Results



Initial Magnetic Field Topology in Converging/Diverging Nozzle

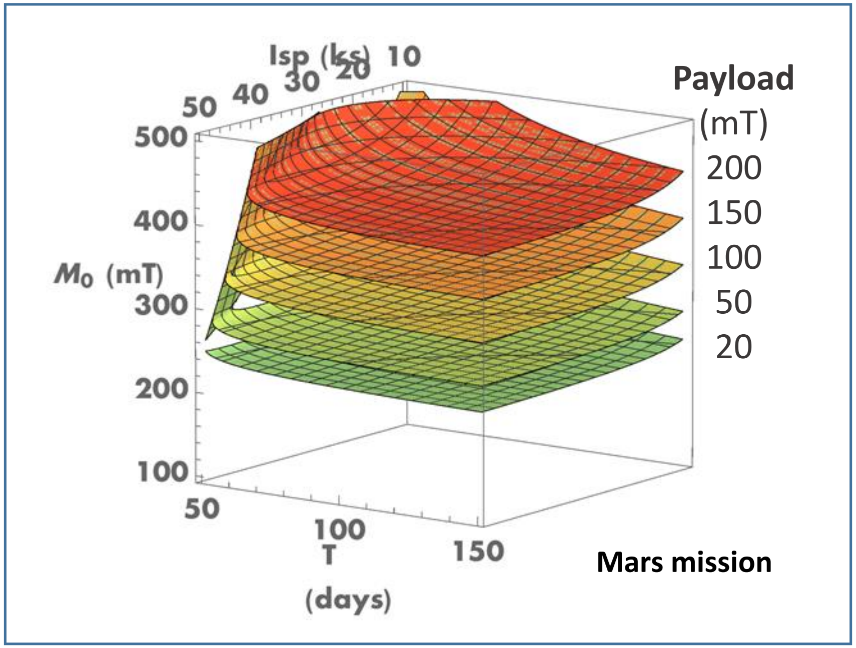
Density slice and surface plot during initial motion of target through entrance of coil. Azimuthal current induced on target by **vxB** back EMF



Mission Modeling

- Initial parametric assessments using approximation techniques to optimize performance requirements
  - e.g. Gilland, J. H., "Mission and System Optimization of Nuclear Electric Propulsion Vehicles for Lunar and Mars Missions," NASA CR 189058
- Model inputs: power, specific impulse (Isp), thrust or efficiency vs. Isp, system mass, desired payload mass, propellant
- Initial cases being evaluated include round-trip Earth-Mars and round-trip Earth-Saturn
- Detailed mission analysis using Copernicus code once engine performance and vehicle design are more refined
  - *Copernicus Trajectory Design and Optimization System software (https://software.nasa.gov/software/MSC-25863-1; available for use by federal employees and contractors to the federal government ; installed at MSFC and OAI)*

Initial Mission Modeling Results



Test case: Payload mass delivered to Mars with NIAC PUFF concept (2013/Adams et al.)

- 16 kW/kg, 1 GW pulsed system, evaluated over a range of Isp from 10,000 s to 50,000 s
- Baseline the approximation method
- Adapt for gradient-field concept performance parameters

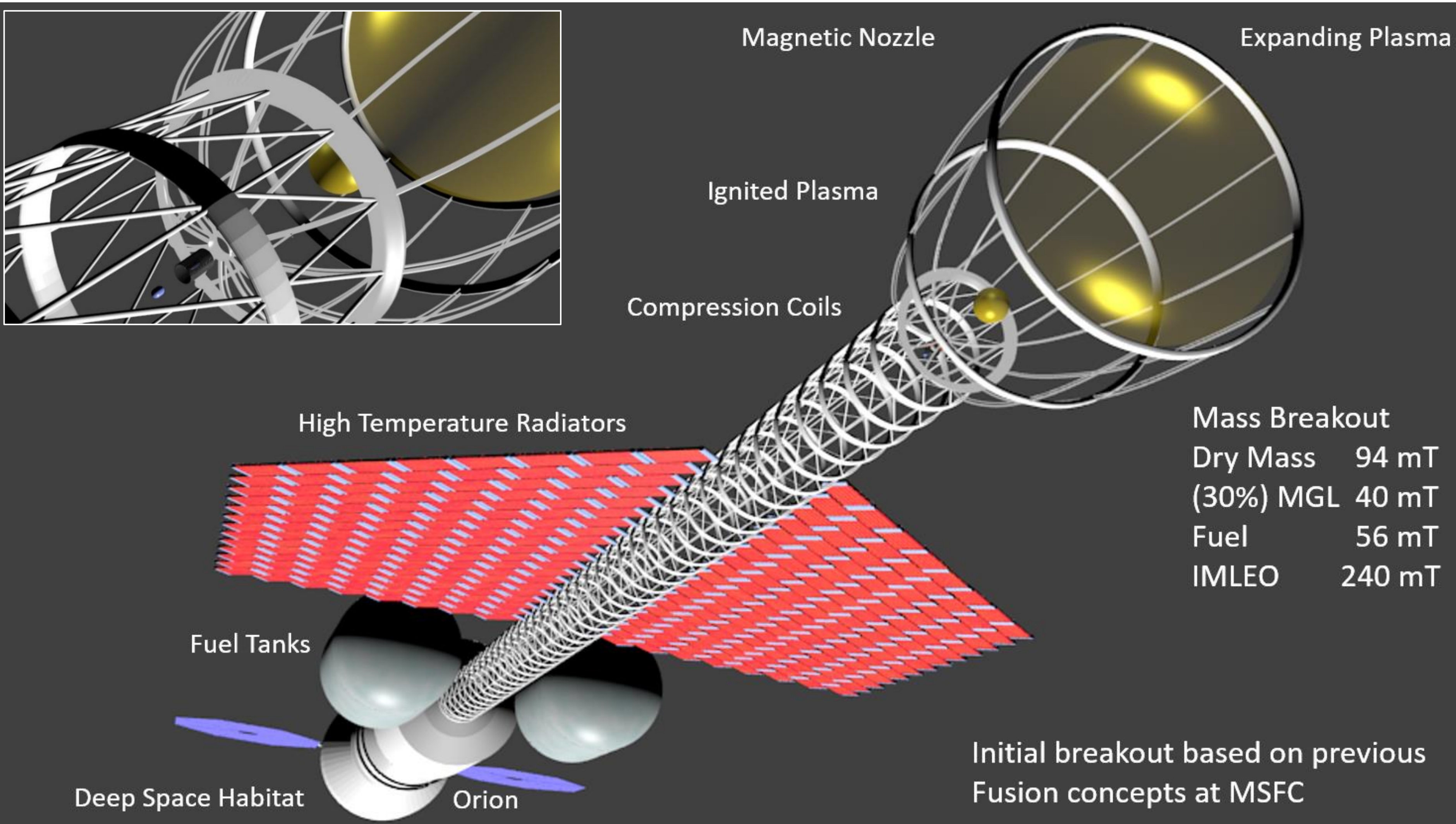
Gradient field concept: Preliminary modeling estimates indicate one-way trip times of less than 1-year for both Mars and Saturn:

- Mars: 60-90 days, 100-150 mT payload from LEO, 2 SLS-Block 2 launches
- Saturn: 200 days, 50-100 mT payload from LEO, 2 SLS-Block 2 launches*
- Initial results indicate Isp > 20,000 s provides greatest benefit

Jackman, A., "Space Launch System" (2016) https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_171779.pdf

Approach, cont.

Initial Vehicle Concept



Mass Breakout	
Dry Mass	94 mT
(30%) MGL	40 mT
Fuel	56 mT
IMLEO	240 mT

Initial breakout based on previous Fusion concepts at MSFC

Summary

- **Developing the tools needed to evaluate concept performance in a mission context:**
    - Analytic models to provide initial performance estimates
    - SPFMax code for detailed understanding of target implosion physics, energy gain, and directed plasma exhaust
    - Trajectory approximation methods to bound mission parameters
    - NASA Copernicus trajectory code for more detailed mission analysis
    - Updating prior MSFC and UAH fusion vehicle analysis with new engine design and performance parameters
- **Incorporates steady advancements in larger DOE terrestrial magnetoinertial fusion experiments**
    - Guides the target designs, implosion conditions, and magnetic field strengths that need to be reproduced in the gradient-field concept
    - Innovative MIF approach adapted for in-space propulsion applications
    - Allows continued progress toward mission-enabling fusion vehicle design

Acknowledgements

We gratefully acknowledge the support provided by the NASA Innovative and Advanced Concepts Program for this NIAC Phase I concept study

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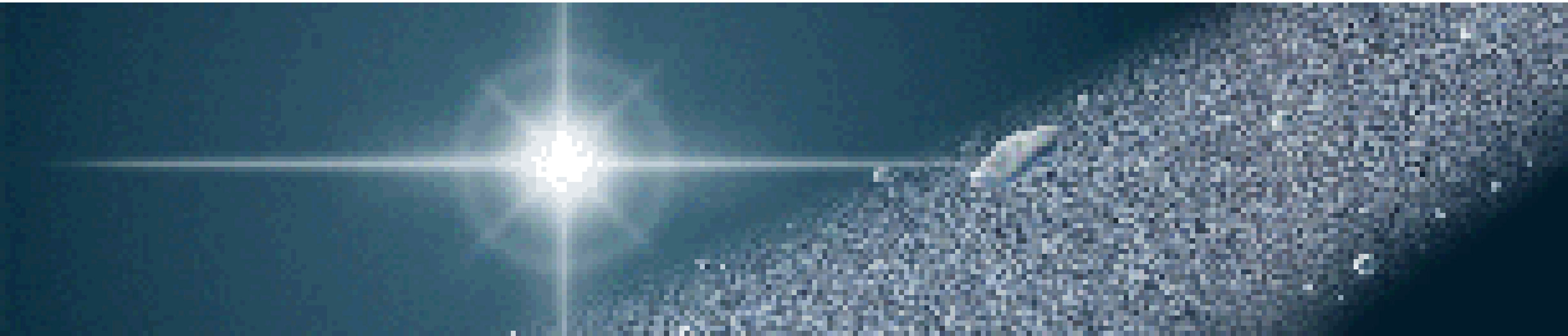


Primer on Smooth Particle Hydrodynamic Method

- Gridless Lagrangian technique wit approximations
  1. Integral approximation

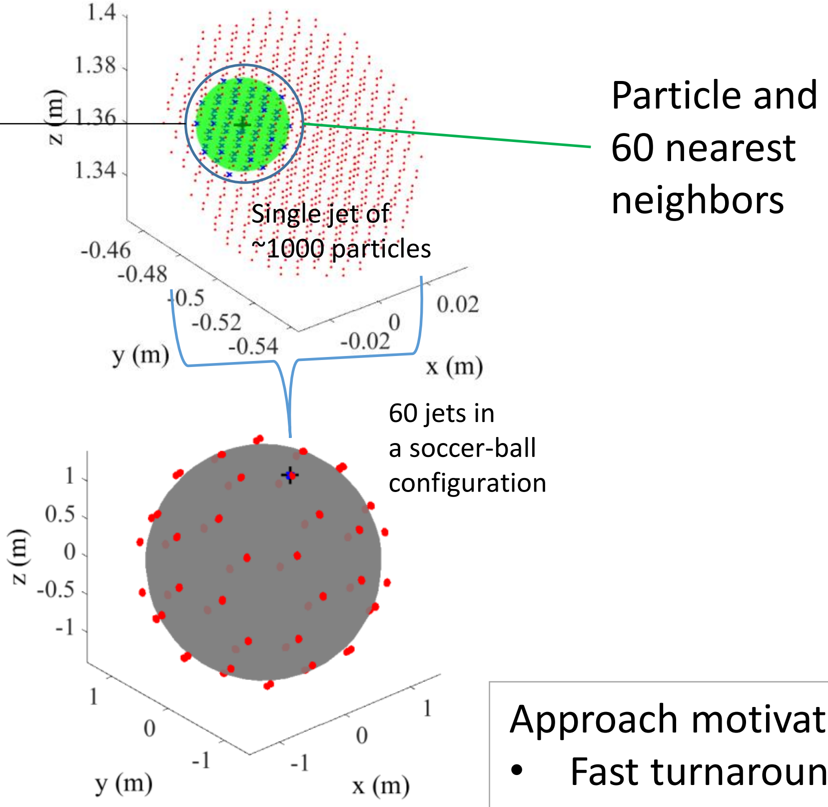
     $$A_a(r)=\int A(r')W(r-r',h)\,dr'$$

  2. Integral approximated by summation interpolant:

     $$A_a=\sum_{\boxed{b}} A_b V_b W_{ab}(r-r',h)$$

- Derivatives are obtained by:

  $$\nabla A_a=\sum_{b} A_b V_b \nabla W_{ab}(r-r',h)$$



Particle and 60 nearest neighbors

Single jet of ~1000 particles

60 jets in a soccer-ball configuration

Approach motivated by
- Fast turnaround on 3D simulations
- Mixing of particles

SPFMax, cont.

Governing plasma equations in SPFMax:

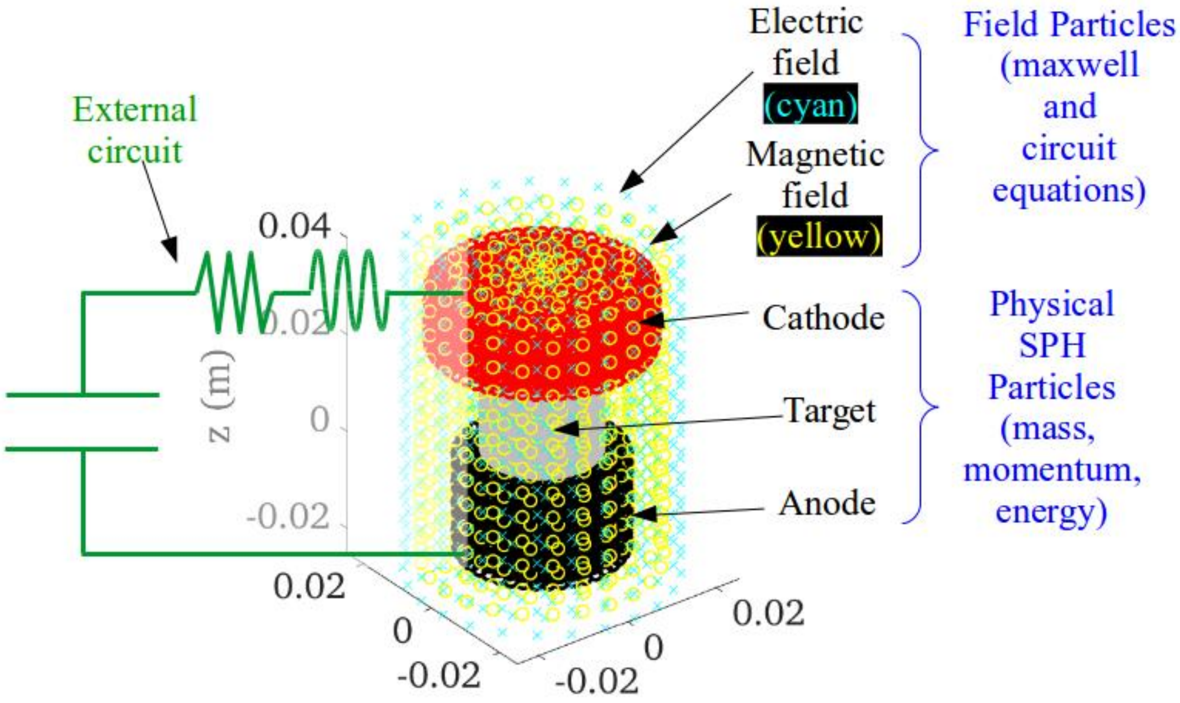
$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho}\nabla p + \nabla\cdot\boldsymbol{\tau} + \frac{1}{\rho}\mathbf{j}\times\mathbf{B}$$

$$\frac{\partial e_i}{\partial t} = -\frac{p_i}{\rho}\nabla\cdot\mathbf{u} + \frac{\boldsymbol{\tau}}{\rho}\nabla\cdot\mathbf{u} - \nabla\cdot\left(k_i\nabla T_i\right) + Q_{ei}$$

$$\frac{\partial e_e}{\partial t} = -\frac{p_e}{\rho}\nabla\cdot\mathbf{u} - \nabla\cdot\left(k_e\nabla T\right) - 4\sigma T_e^4\chi_{Planck} - Q_{ei} + \frac{\eta}{\rho}j^2$$

SPFMax, cont.

Implementation of the Electromagnetic solver uses an external lumped element circuit model, transmission line network for the SPH particles, and scalar and magnetic vector potential for the electromagnetic fields



$$\dot{V}_1 = -\frac{I_1}{C_1}$$

$$\dot{I}_1 = \frac{1}{L_1}\left(V_1 - R_1 I_1 - V_{T,1}\right)$$

$$\dot{V}_{T,1} = \frac{l_T}{C_T}\left(\frac{I_1 - I_{T,1}}{\Delta z}\right)$$

$$\dot{V}_{T,i} = \frac{l_T}{C_T}\left(\frac{I_{T,i-1} - I_{T,i}}{\Delta z}\right) \quad \text{i = 2 to N}$$

$$\dot{I}_{T,i} = \frac{l_{T,i}}{L_{T,i}}\left(\frac{V_{T,i} - V_{T,i+1}}{\Delta z}\right) - \frac{I_{T,i} R_{T,i}}{L_{T,i}} \quad \text{i = 1 to N-1}$$

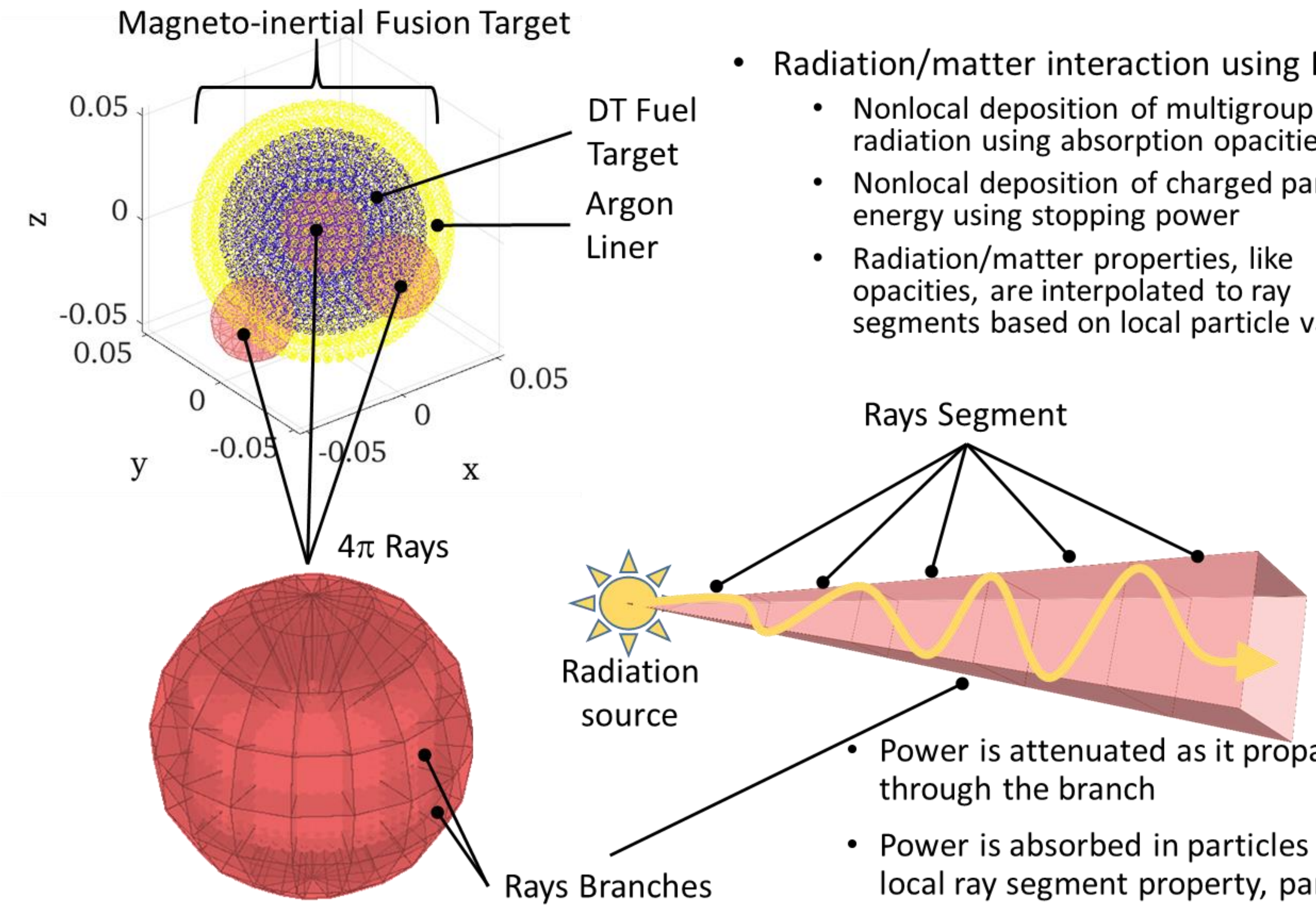
$$\dot{I}_{T,N} = \frac{1}{L_{SPH}}\left(\phi_{SPH,pos} - \phi_{SPH,neg}\right) - \frac{I_{T,N} R_{T,N}}{L_{T,N}}$$

$$\frac{\partial \phi}{\partial t} = c^2\left(\nabla^2 \phi + \frac{\rho_c}{\varepsilon_0}\right) \qquad \frac{\partial \mathbf{A}}{\partial t} = c^2\left(\nabla^2 \mathbf{A} + \mu_0 \mathbf{j}\right)$$

$$\mathbf{E} = -\nabla \phi - \frac{\partial \mathbf{A}}{\partial t} \qquad \mathbf{B} = \nabla \times \mathbf{A}$$

SPFMax, cont.

SPFMax Radiation Matter Interactions



- Radiation/matter interaction using Rays
  - Nonlocal deposition of multigroup radiation using absorption opacities
  - Nonlocal deposition of charged particle energy using stopping power
  - Radiation/matter properties, like opacities, are interpolated to ray segments based on local particle values

- Power is attenuated as it propagates through the branch
- Power is absorbed in particles based on local ray segment property, particle size, and distance from radiation source

GRADIENT FIELD IMPLODING LINER FUSION PROPULSION SYSTEM

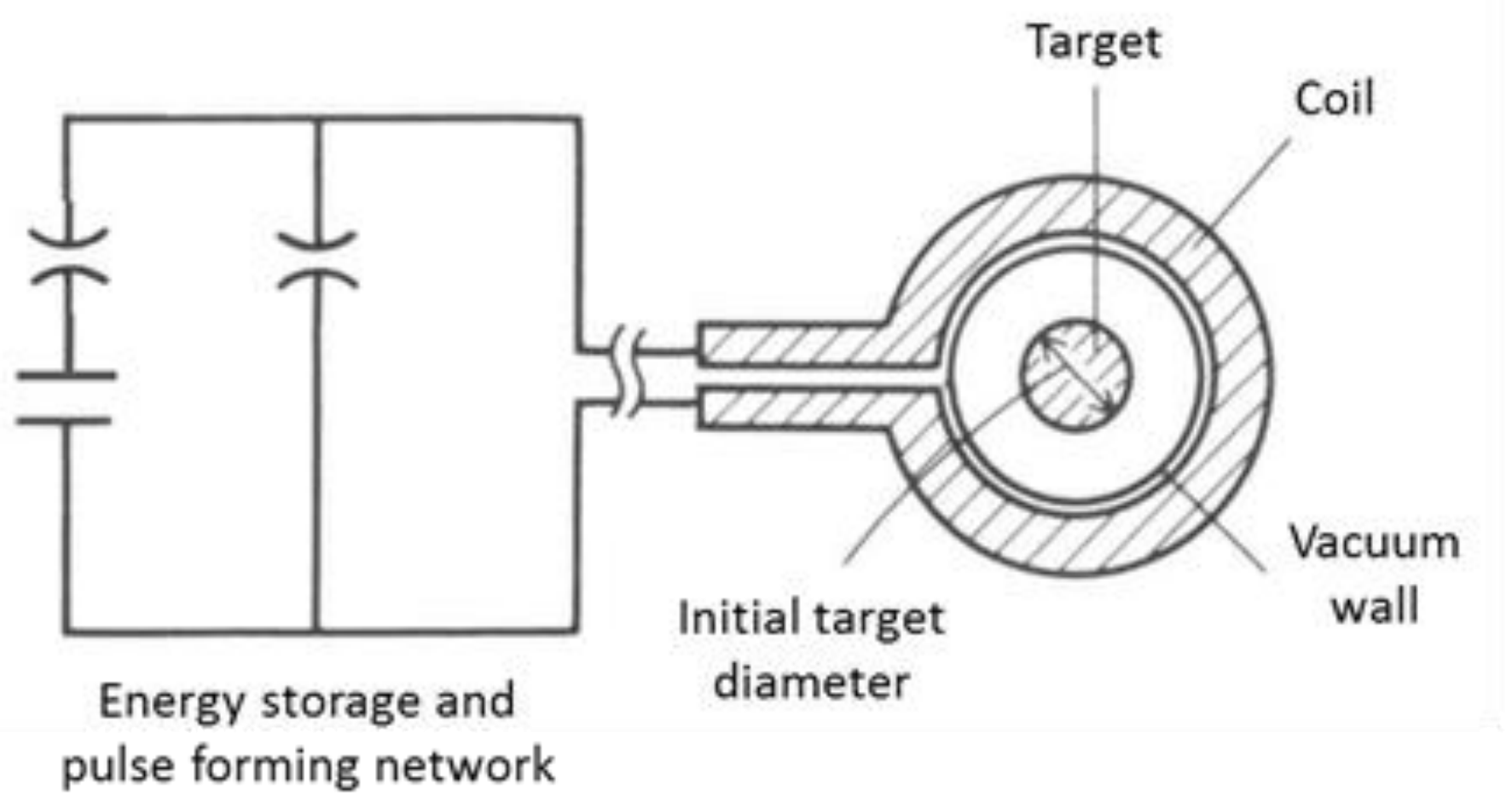
A NEW APPROACH TO MAGNETOINERTIAL FUSION FOR IN-SPACE PROPULSION

Michael LaPointe[a], Robert Adams[a], Jason Cassibry[b], Ross Cortez[b], James Gilland[c]
[a]Marshall Space Flight Center; [b]University of Alabama, Huntsville; [c]Ohio Aerospace Institute

BACKGROUND: Magnetoinertial fusion (MIF) employs a high, rapidly pulsed current in a target liner to generate an intense magnetic field, creating an unbalanced pressure that radially implodes the target to achieve fusion conditions. Compressed magnetic fields internal to the fuel target reduce electron thermal diffusion losses and confine fusion generated α-particles to improve fuel heating.

INNOVATION: We replace the pulsed current coil and stationary target used in MIF Θ-pinch concepts with a fast moving target fired axially into a static, high gradient magnetic field. This is equivalent to generating an intense time changing magnetic field in the target frame of reference, resulting in an unbalanced radial pressure that rapidly implodes the fuel target.

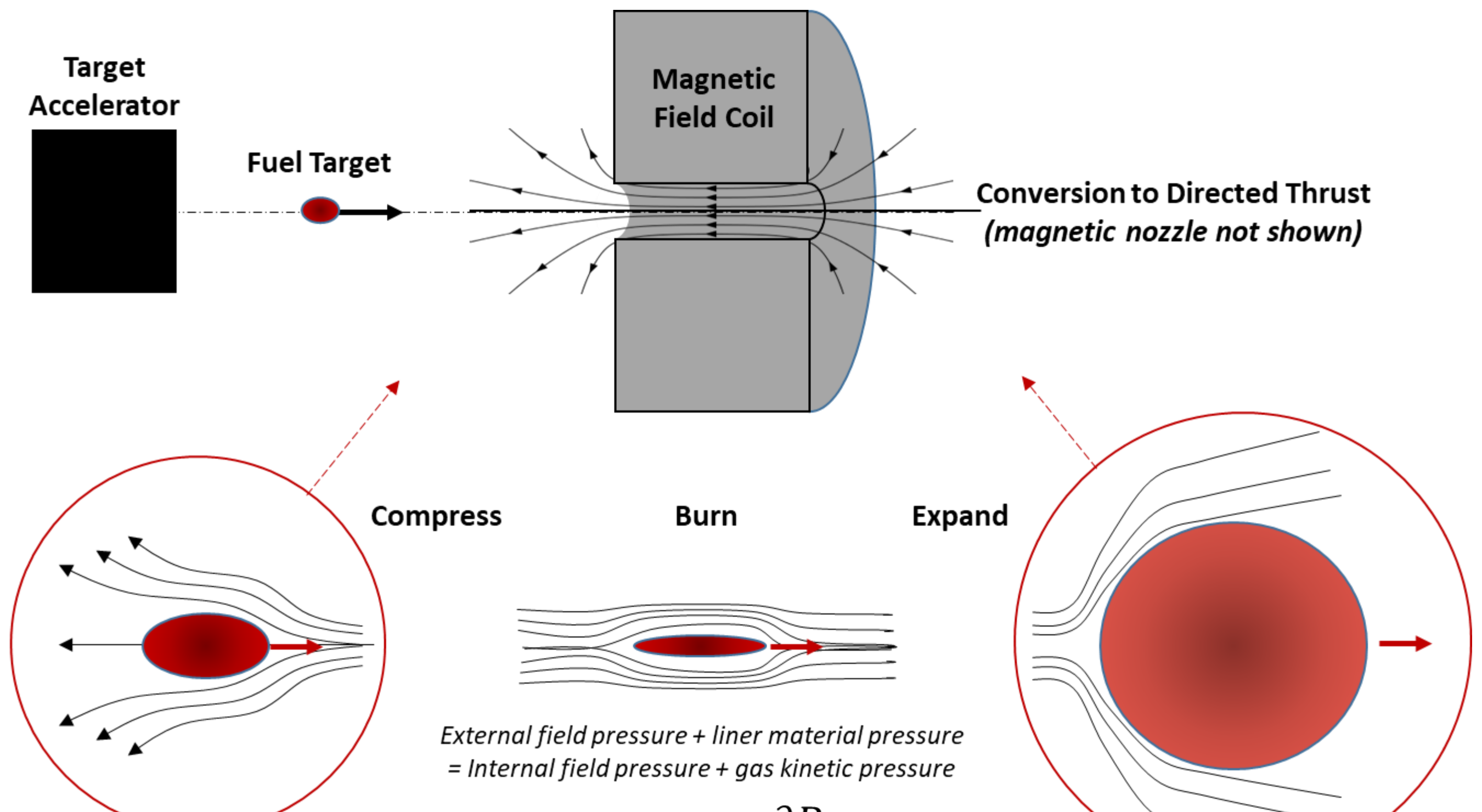
Θ-pinch coil and circuit for Compression



Adapted from Miyamoto, K. Plasma Physics for Nuclear Fusion, MIT Press, Cambridge, MA (1987)

- Pulsed, high current discharge generates a rapidly increasing axial B-field between the drive coil and conducting liner
- Increasing radial pressure due to time changing magnetic field implodes a material liner and compresses the fuel target

Steady-State Gradient Magnetic Field for Compression



External field pressure + liner material pressure = Internal field pressure + gas kinetic pressure

$$\dot{I} \propto \dot{B}_z = v_z \frac{\partial B}{\partial z}$$

- Magnetic flux is excluded by/internally trapped by the liner
- Unbalanced radial pressure rapidly implodes the fuel target

BENEFITS:

- Replaces the pulsed current coil and PFN with a steady state superconducting magnet
  - Mitigates associated issues with rapid, repetitive, high current pulse generation in the drive coil
  - Target acceleration over a longer time period reduces demands on switches, power components, etc.
- Preliminary analysis indicates a fairly compact engine geometry
  - Strong gradient magnetic field is produced by a constant current, small bore coil
  - Maximum system length is dictated by target velocity and magnetic field diffusion time
- Linear geometry provides options for generating/trapping an initial axial magnetic field in the target and for pulsed laser preheating to improve fuel ignition and compression temperatures

Why Fusion?

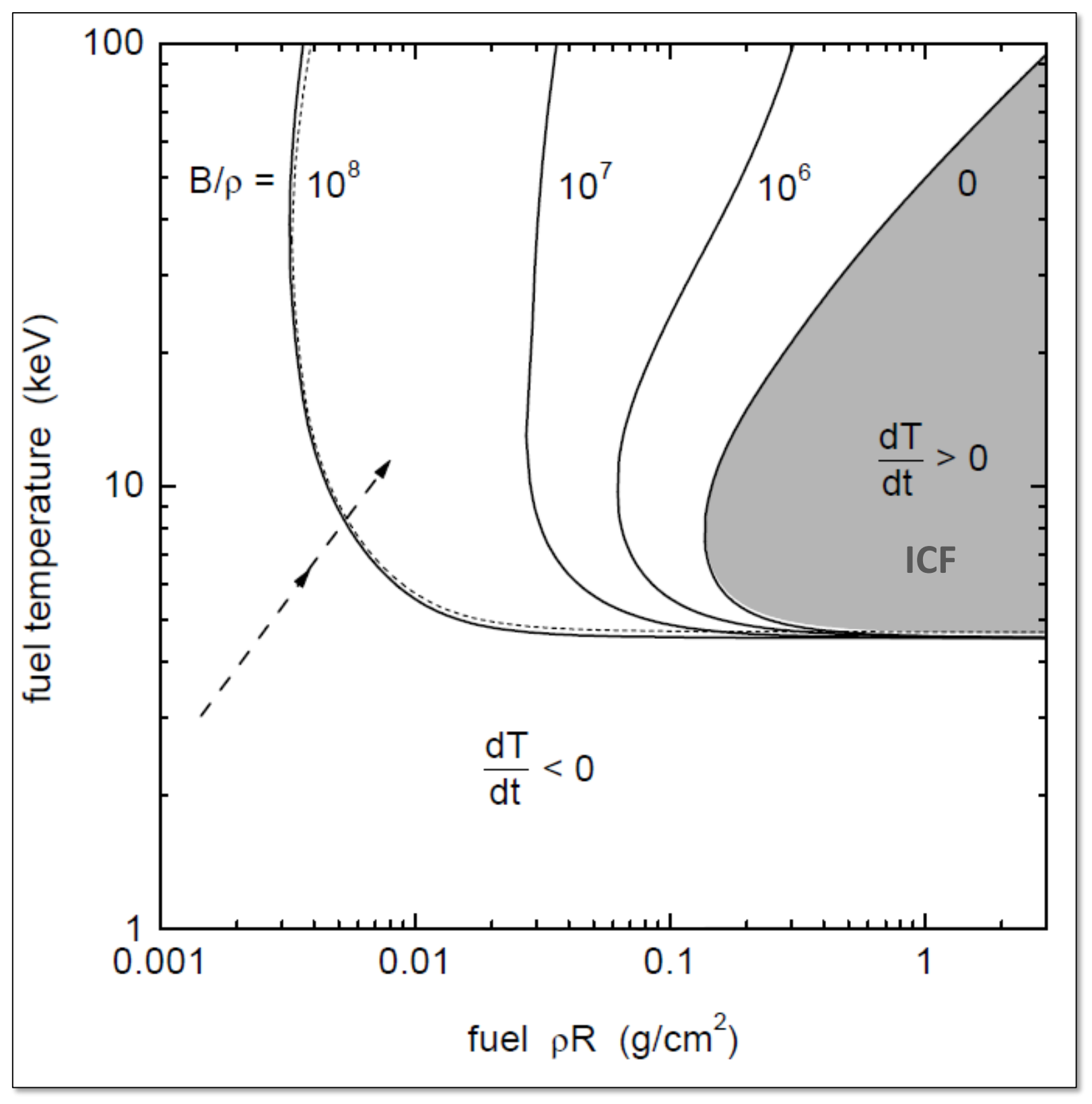
Rocket Equation

$$\frac{m_f}{m_0} = e^{-\Delta v / v_e}$$

m_o = initial mass
m_f = final mass
Δv = velocity change
v_e = exhaust velocity

- Solar system destinations require $\Delta v \approx 10^4 - 10^5$ m/s
- Reasonable payload mass fractions require propellant exhaust velocities comparable to mission Δv
- Fusion offers high specific power (kW/kg) to reduce trip times

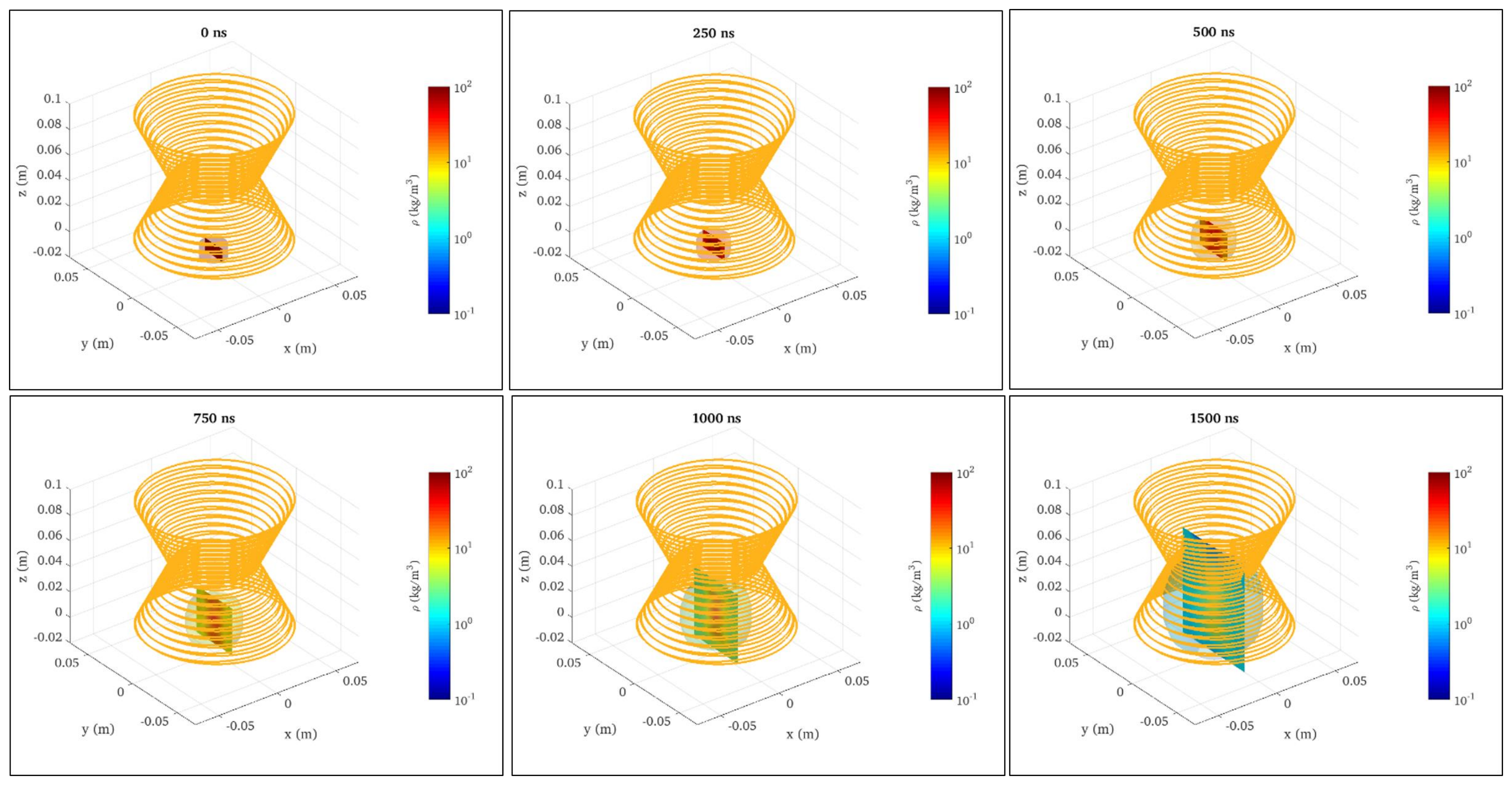
*MIF Lindl-Widner Diagram (DT cylinder at stagnation)**



Advantages of MIF

- Adiabatic radial compression generated by unbalanced magnetic field external to target
- Compresses a magnetic field internal to the target, reduces electron thermal losses and enhances alpha particle self-heating of the fusion fuel
- Reduces the areal density (*ρr)* threshold for ignition to well below conventional Inertial Confinement Fusion (ICF) values

**Basko, M. et al., "Ignition conditions for magnetized target fusion in cylindrical geometry," Nuclear Fusion, Vol. 40, No. 1 (2000)*

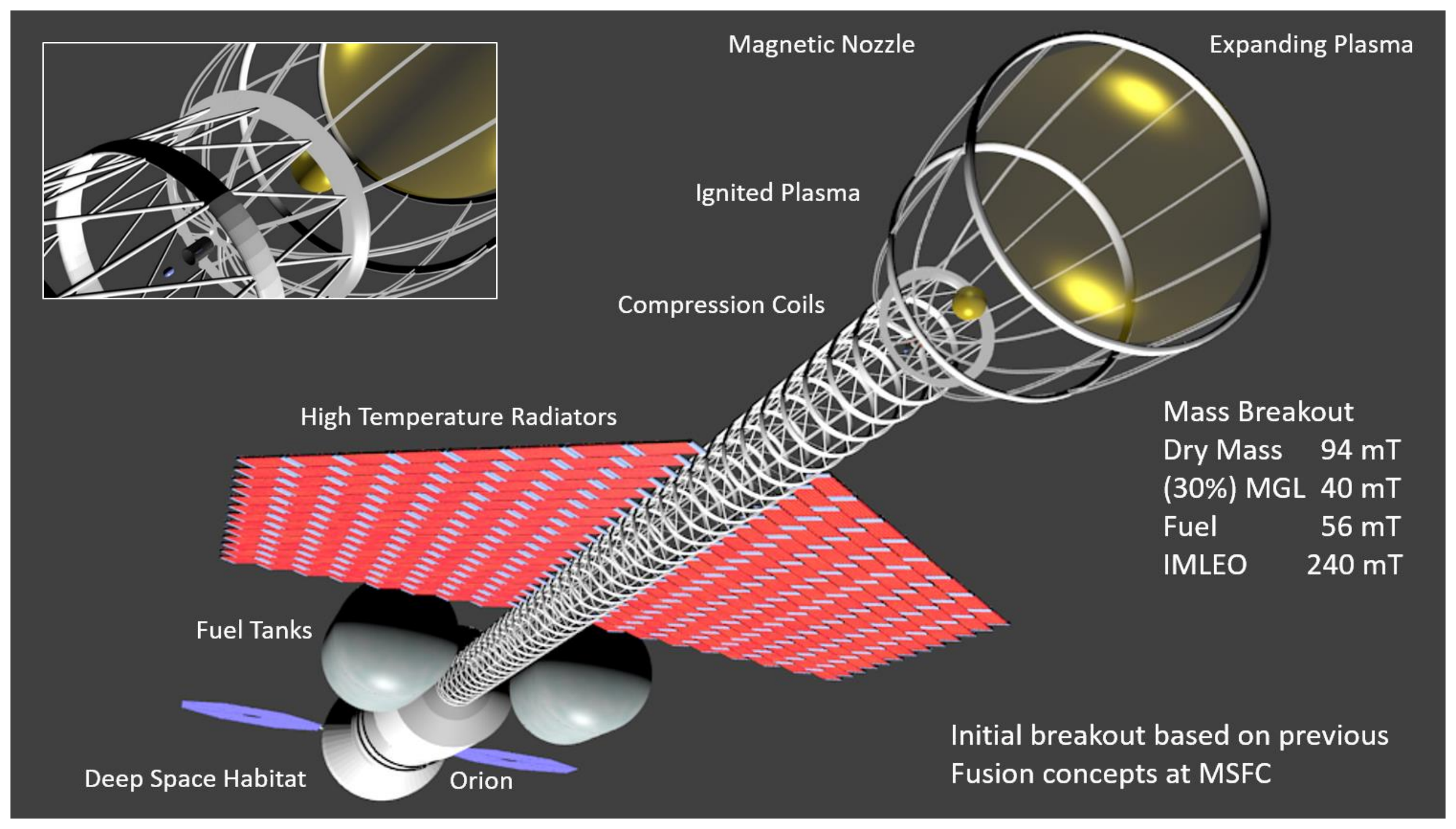


SPFMax: Density slice and surface plot during initial motion of target through entrance of coil. Azimuthal current is induced on target by vxB back EMF

KEY PHASE I GOALS:

- Establish requirements for magnetic field coil, target accelerator, and encapsulated fuel target, leading to an initial system concept design
- Perform analysis and detailed SPFMax modeling to understand the dynamics between the rapidly moving target and the gradient field
  - Sufficient radial force to provide rapid liner implosion and fuel ignition
  - Growth of liner instabilities (interchange instabilities and mitigation)
- Develop integrated vehicle concept based on prior MSFC/UAH designs
- Model representative Earth-Mars and Earth-Saturn round-trip missions using NASA Copernicus trajectory code to establish concept benefits

Preliminary Vehicle Design



Mass Breakout	
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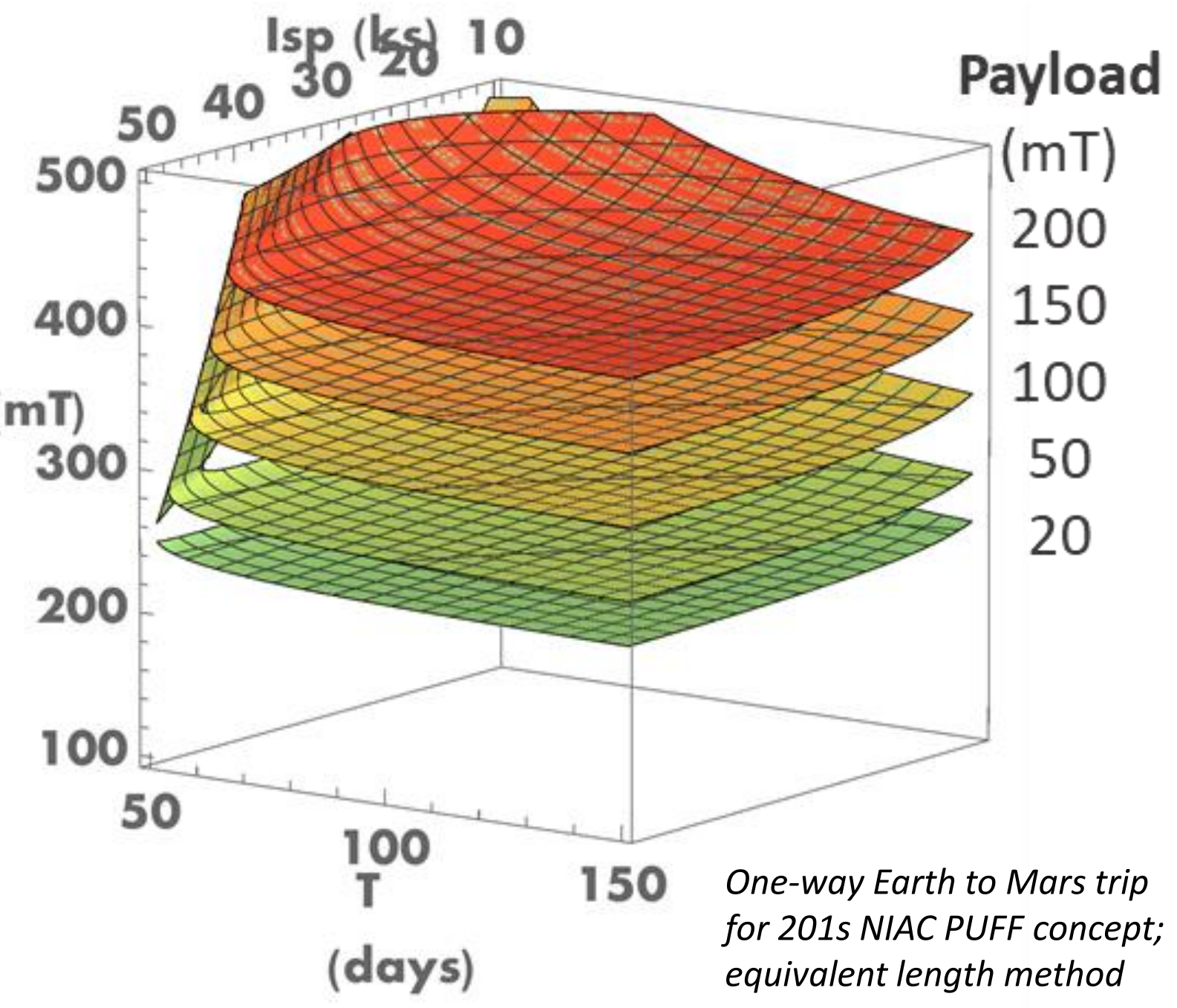
Fuel	56 mT
IMLEO	240 mT

Initial breakout based on previous Fusion concepts at MSFC

Preliminary Mars Mission Analysis



One-way Earth to Mars trip for 201s NIAC PUFF concept; equivalent length method

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