Nuclear Propulsion through Direct Conversion of Fusion Energy:

The Fusion Driven Rocket

John Slough
David Kirtley, Anthony Pancotti, Michael Pfaff,
Christopher Pihl, George Votroubek

MSNW LLC
8551 154th Avenue NE, Redmond WA 98052
sloughj@msnwllc.com

NIAC SPRING SYMPOSIUM
March 27-29, 2012 - Pasadena, CA

Talk Outline

I. **Description and Motivation for the Fusion Driven Rocket (FDR)**
   i. Dramatic reduction in time and cost for manned space travel
   ii. Mitigation of space radiation risk (GCR exposure)
   iii. Large payload mass fraction (> 50%) for Mars Direct

II. **Basic physics of the FDR**
   i. Magneto-Inertial Fusion
   ii. FDR approach and fusion gain scaling
   iii. Application to space propulsion

III. **Mission studies**
   i. Analytical Calculations
   ii. Rapid Mars Transits - 30d and 90d
   iii. Mission Trade Study
   iv. Initial results from Copernicus modeling

IV. **Plans for future FDR development to TRL 5**
   i. Design of the FDR breakeven proof of concept experiment
   ii. Mission analysis refinements
   iii. Technology development and spin-offs (fusion electric power plant!?)

Criteria for Propulsion System To Enable Rapid Planetary Missions

(1) Must provide for the reaction energy (chemical, fission, fusion) to be converted efficiently into propulsive (directed) energy.

FDR NTR NEP Chemical

(2) Propellant must achieve sufficiently high Isp (~ 2000s) for reasonable payload mass fractions.

FDR NTR NEP Chemical

(3) It cannot be so massive to require in space assembly, and/or mission complex as to require several ETO launches.

FDR NTR NEP Chemical

(4) It should be based on currently accepted principles of physics and reasonable technology extrapolation (no cold fusion, matter/anti-matter, $P\text{-}^{11}B$, worm holes etc.)

FDR NTR NEP Chemical

Trip Time and the Specific Power (Mass) for Direct Mission to Mars

Accelerating the space ship mass M_{ss} over a time τ implies a power P where:

$$P_j \approx \frac{M_{ss} v_c^2}{2\tau}$$

One defines a characteristic velocity v_c:

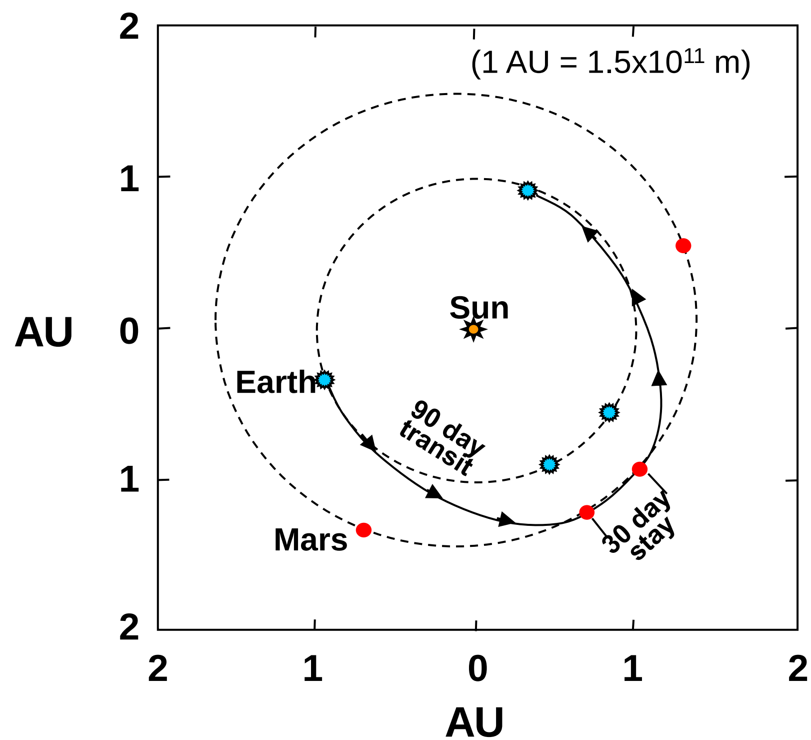
$$v_c = (2\alpha\tau)^{1/2}$$

where α_P is the specific power:

$$\alpha_P = \frac{P_j}{M_{ss}} = \alpha_M^{-1}$$

with α_M the specific mass.

The the trip time, τ_{trip}, to go a distance L is



$$\tau_{trip} \approx 2 \frac{L}{v_c} \quad \text{or} \quad \tau_{trip}(\text{days}) \cong 51.6 \left[\alpha_M (\text{kg/kW}) L^2 (\text{AU})\right]^{1/3}$$

For the 90 day Mars transit (L ~ 1.5 AU) requires α >~ 2.5

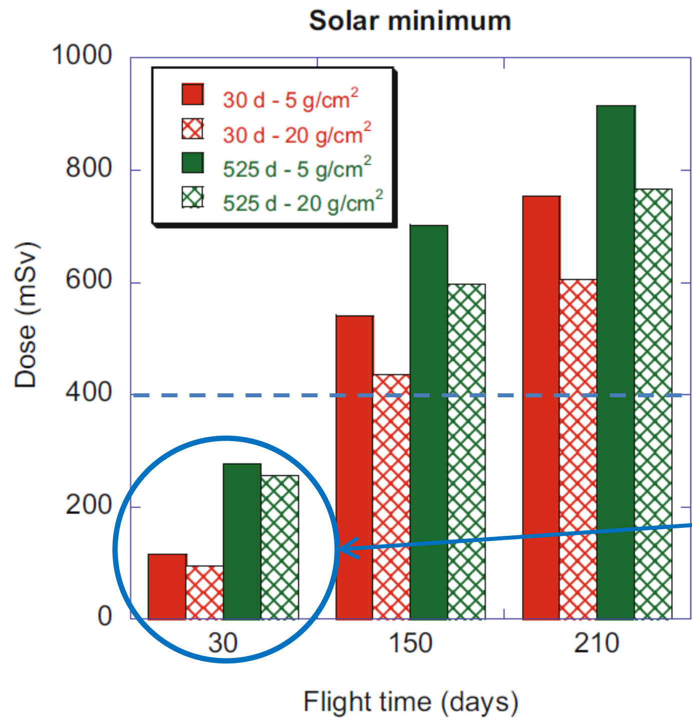
For the 30 day Mars transit (L ~ 0.7 AU) requires α_M >~ 0.4

FDR: $4 < \alpha_M < 0.3$

Estimated Total Equivalent Doses for a Mars mission

Mars sortie mission (30 days stay)

Long stay at Mars base (525 days)



Current technology (210 days)

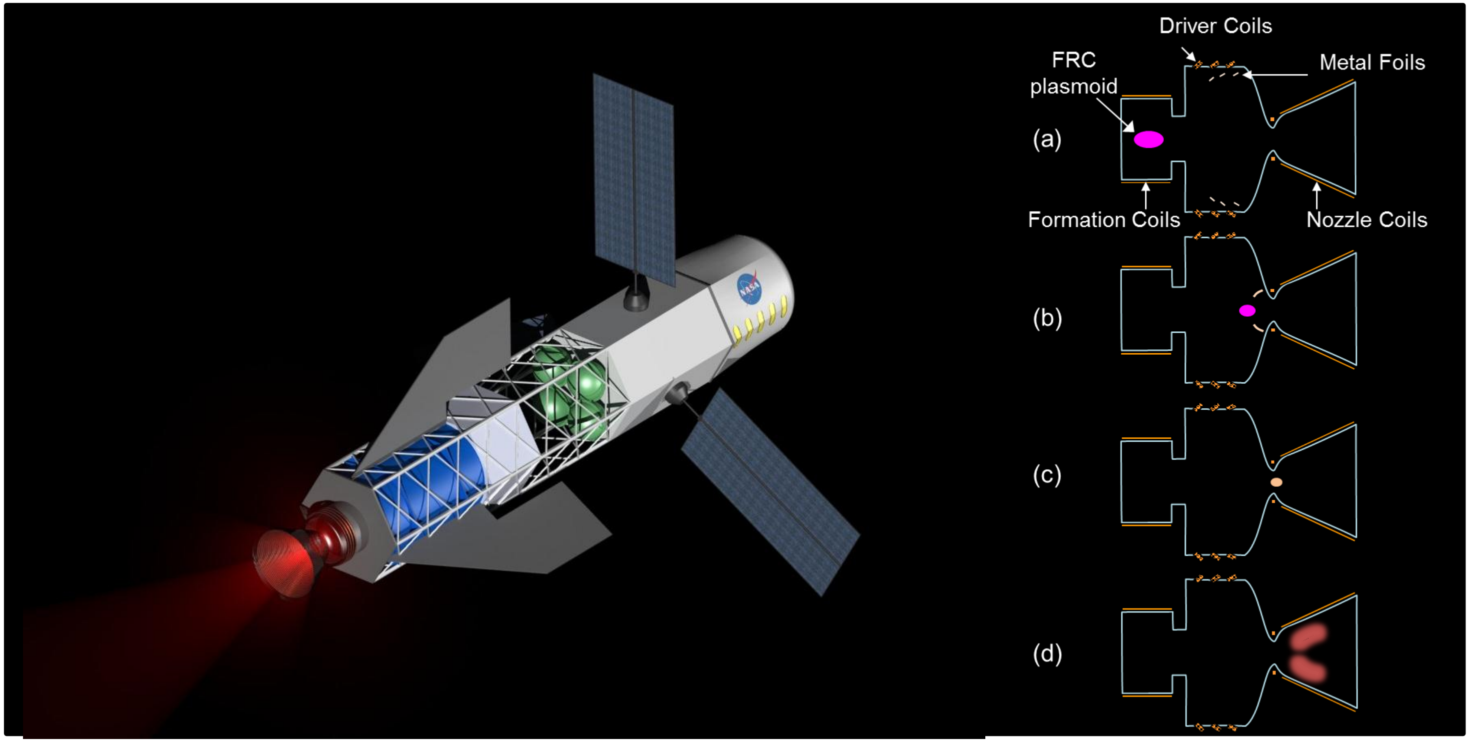
Nuclear thermal/electric reactor (150 days)

Fusion Driven Rocket (30 days)

Solid bars – calculation for spacecraft with a minimum shield (5 g/cm^2 Al)
Dashed bars – calculations for a thick shield (20 g/cm^2 Al)

- The career limit is 400 mSv for a 25 year old with a 3% risk of fatal cancer
- There is actually great uncertainty as to what the actual risk is for long term low level exposure

Fusion Propulsion Based on the Inductively-Driven, Metal Propellant Compression of an FRC Plasmoid

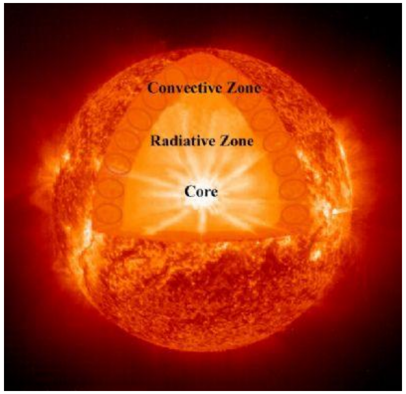


- **Lowest mass fusion system is realized with FRC compressed by convergent array of magnetically driven metal foils - steps (a), (b)**
- **Fusion neutron and particle energy is directly transferred to the encapsulating, thick metal blanket - step (c)**
  - Provides spacecraft isolation from fusion process
  - Eliminates need for large radiator mass
- **Expansion of hot, ionized propellant in magnetic nozzle - step (d)**
  - Produces high thrust at optimal Isp

II. Basic physics of the FDR

Fusion Ignition Successes

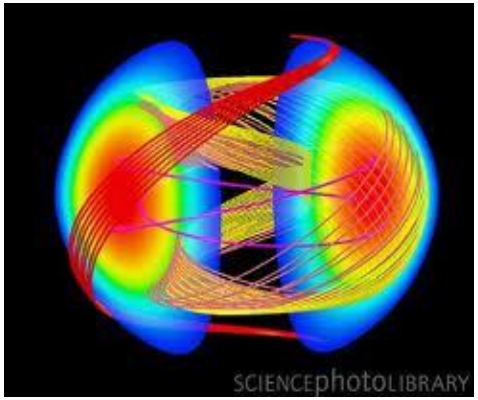
Steady State Burn with Gravitational Compression and Confinement



Transient Burn from Explosive Material Compression and Inertial Confinement

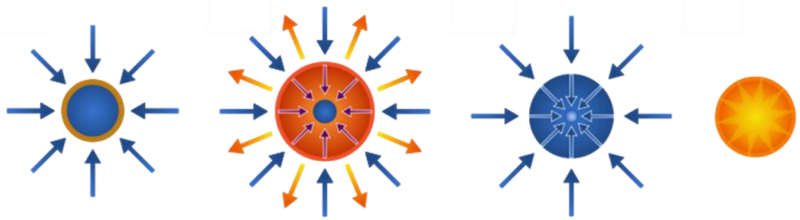
Have lead to the Two Main Approaches for Controlled Fusion

Steady State Burn with Fusion α Heating and Magnetic Confinement



spherical tokamak pressure contours and field line topology

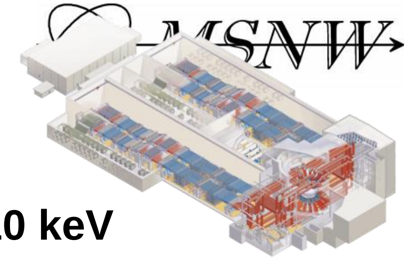
Micro-scale Version without Chemical/Nuclear Driver



1. radiation (x-rays, laser, or ion) energy deposition rapidly heats shell (liner) surrounding D-T fuel
2 - fuel is compressed by the rocket-like blow-off of the hot surface material
3 - fuel core reaches density and temperature for fusion ignition yielding ~ 200 times the compressional energy

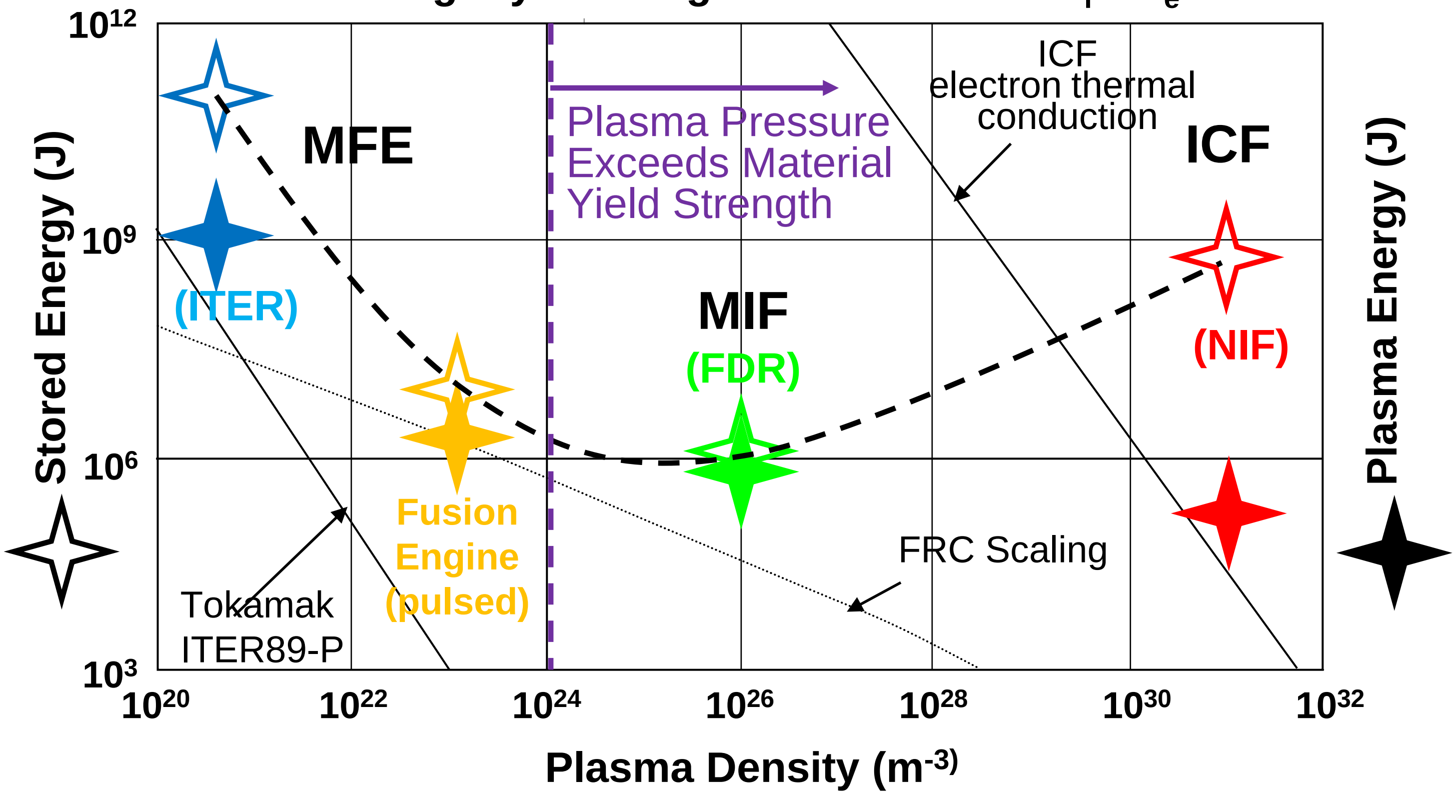
ITER

Magneto-Inertial Fusion
Best of Both Worlds



NIF

Solid stars signify fusion gain conditions w $T_i = T_e = 10$ keV



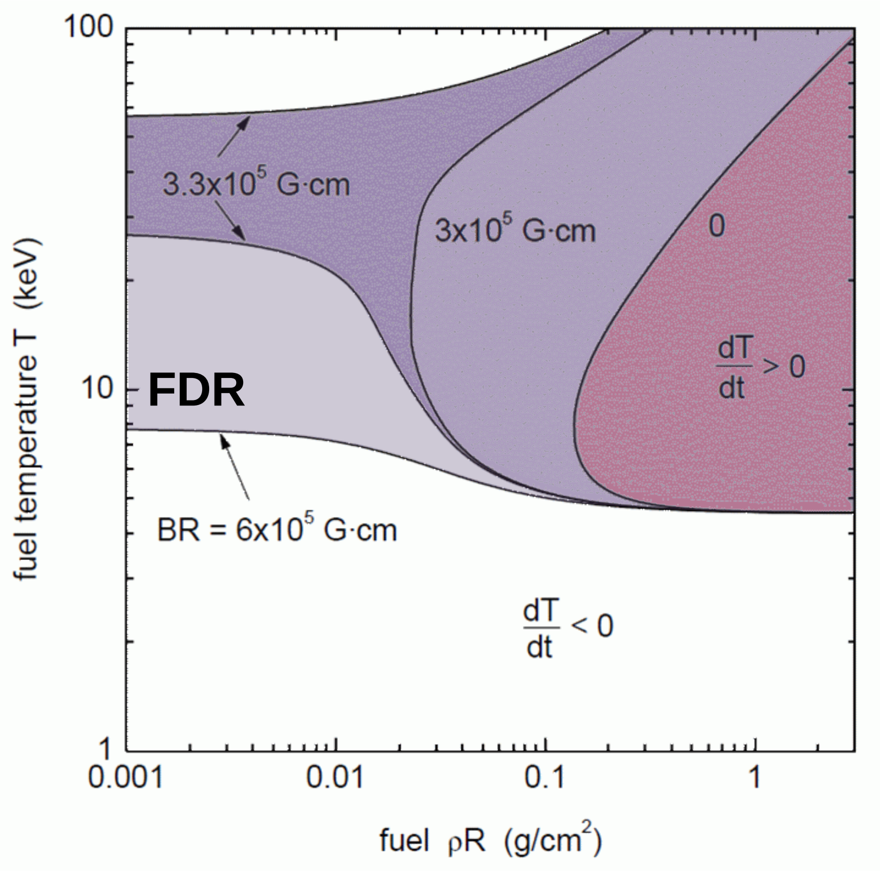
ITER MFE Issues:

- Enormous magnetic energy requires SS Magnets
- Due to topological complexity must operate continuously for > 30 yrs
- Devastating transient instabilities defy solution

NIF ICF Issues:

- Enormous storage energy (~400 MJ) due to very low driver (laser) efficiency
- Even with stand-off , reactor wall and first optics “see” primary fusion products
- Intricate and minute target with sub-nsec timing make for challenging technologies

Lindl-Widner Diagram with Magnetic Field Confinement Of the Fusion Alphas



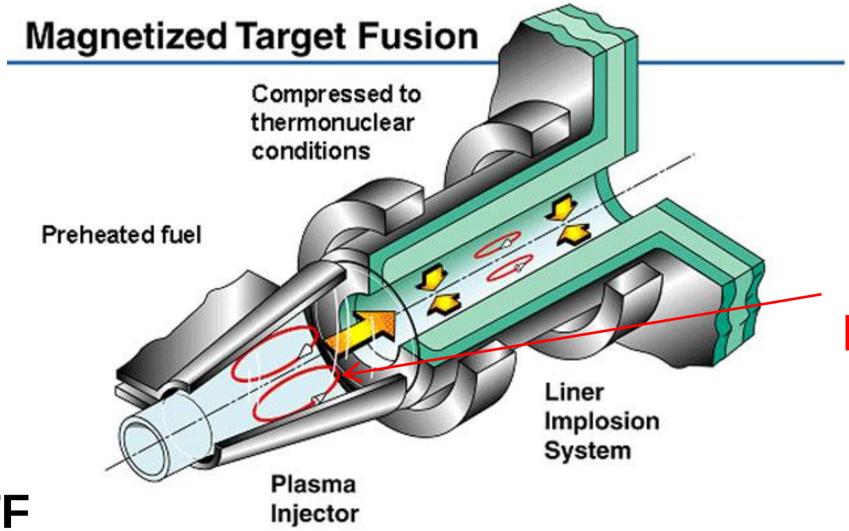
The BR form of the L-W diagram. Ignition curves for different product BR.

When the BR parameter exceeds the threshold value, the dT/dt > 0 region extends to infinitely small ρR and ignition becomes possible at any ρR.

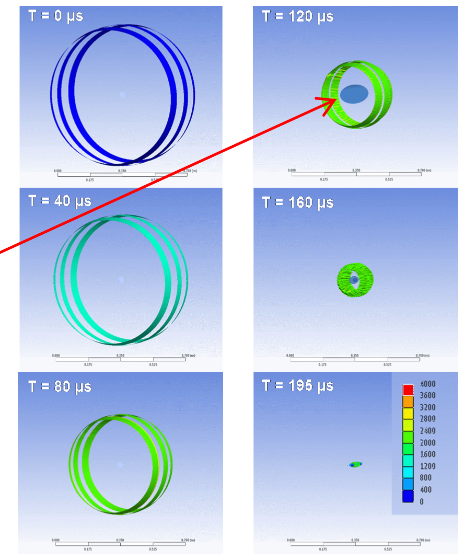
Magneto-Inertial Fusion
Two Approaches

Shell (liner) implosion driven by B_θ from large axial currents in shell.

Liner implosion from **j×B** force between external coil and induced liner currents



FRC plasmoid



MTF Issues:

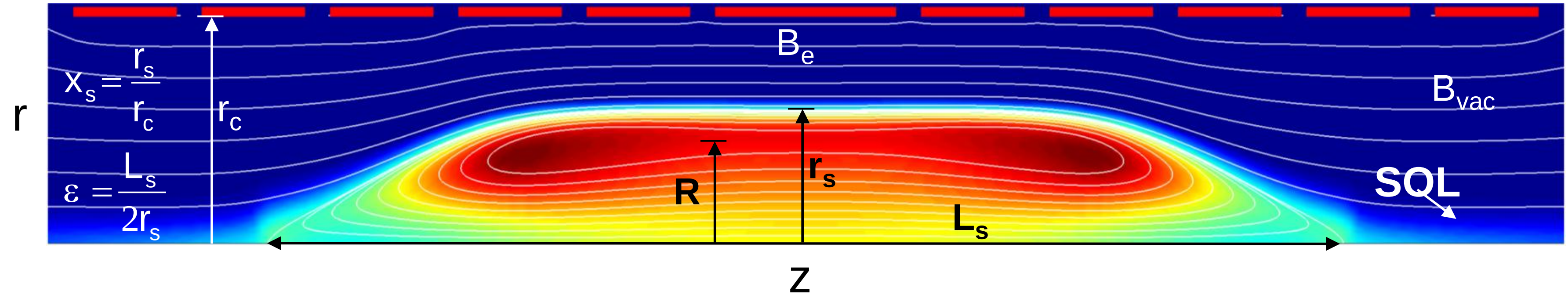
- Extremely low inductance load difficult to drive (massively parallel HV caps and switches)
- Close proximity and electrical contact ⇒ major collateral damage with each pulse
- Small FRC must be formed close to implosion ⇒ marginal B for ignition w injector destruction
- Only inefficient 2D compression possible ⇒ requires much larger driver energy

FDR Advantages:

- Large driver coil easy to power with ample standoff
- Driver electrically isolated from liner and magnetically from fusion process
- Large FRC can be formed external to implosion with abundant B for ignition
- Full 3D compression can be realized for efficient compression and translation

Field Reversed Configuration (FRC)

Magnetic Field lines and Pressure Contours



Key Equilibrium Relations:

$$B_{ext} = \frac{B_{vac}}{1 - x_s^2}$$

$$P_0 = n_0 kT = \frac{B_{ext}^2}{2\mu_0}$$

$$\langle \beta \rangle = 1 - \frac{1}{2} x_s^2$$

Flux Conservation

External measurements of B yield
FRC separatrix radius $r_s(z)$, FRC length L_s
$\Rightarrow$ volume, position, velocity

Radial Pressure Balance

Simple cross-tube interferometric measurement with r_s from yields $\langle n \rangle$ and T

Axial Pressure Balance

With above obtain plasma energy, Inventory, confinement times

FRC equilibrium constraints and the diagnostic measurements that together with the equilibrium relations that are employed to determine the basic parameters of the FRC equilibrium

Fusion Based on Inductively Driven Liner Compression of the FRC

The energy within the FRC separatrix at peak compression is dominated by plasma energy that is in pressure balance with the edge magnetic field B_0, so that one can write:

$$E_L = \frac{1}{2} M_L v_L^2 \quad = \quad 3 n_0 k T_0 \cdot \frac{4}{3} \pi r_0^3 \varepsilon \quad = \quad \frac{B_0^2}{\mu_0} \pi r_0^3 \varepsilon \qquad (1)$$

The zero subscript indicates values at peak compression where $r_s \sim r_0$ and magnetic pressure balance ($2n_0kT_0 = B_0^2/2\mu_0$).

Fusion energy produced in the FRC during the liner's dwell time τ_D at peak compression:

$$E_{fus} \cong \quad 1.2 \times 10^{-12} n_0^2 \langle \sigma v \rangle \frac{4}{3} \pi r_0^3 \varepsilon \tau_D \quad = \quad 1.1 \times 10^{-42} n_0^2 T_0^2 \frac{r_0^4}{v_L} \varepsilon \qquad (2)$$

where n_0 and T_0 are the peak density and temperature, and where the liner shell dwell time at peak compression, τ_D, ~ $2r_0/v_L$

Fusion Based on Inductively Driven Liner Compression of the FRC (cont.)

The usual approximation for the D-T fusion cross section in this temperature range: $\langle\sigma v\rangle \cong 1.1\text{x}10^{-31}\ T^2(\text{eV})$ was also assumed. Pressure balance, together with expressions (1) and (2) yields for the fusion gain:

$$G = \frac{E_{fus}}{E_L} = 1.73\times10^{-3}\sqrt{\frac{M_L}{l_0}}B_0 = 4.3\text{x}10^{-8}M_L^{1/2}E_L^{11/8} \qquad (3)$$

where l_0 (= $2r_0 \cdot \varepsilon$) is the length of the FRC at peak compression. The last expression is obtained from adiabatic scaling laws $\Rightarrow$

$$E_L \sim B_0^2 r_0^2 l_0 \sim B_0^{4/5} \quad \text{and} \quad l_0 \sim r_0^{2/5} \sim B_0^{-1/5} \qquad (4)$$

to express G in terms of the liner kinetic energy E_L and mass M_L only.

Fusion Ignition will amplify gain by large factor. It is estimated that the total fusion gain $G_F \sim 5\text{-}10 \cdot G$. For a large margin of safety, it is assumed that: $G_F = 2.5G$ or,

$$\mathbf{G_F = 1.1\times10^{-7}\ M_L^{1/2}\ E_L^{11/8}}$$

Material Constraints with Inductively Accelerated Liners

- The material properties relating to this resistive heating (electrical conductivity, melting point, heat capacity, etc.) can be characterized by a parameter g_M defined by the "current integral":

$$\int_0^{t_m} I^2\, dt = g_M\, A^2$$

I - current flowing through the material cross-sectional area
A = w×δ, where w is the liner width and δ is the liner thickness.

- The driving force is simply the magnetic pressure ($B^2/2\mu_0$) applied over the surface area of the metal facing the coil when in close proximity to the driving coil.
- The current can be related to the force through Ampere's law which can be reasonably approximated as $B = \mu_0 I/w$.

One finds for the maximum velocity for a given shell thickness δ:

$$v_m(m/s) = 2.5\text{x}10^4\ \delta_{Al}\ (mm) - \text{Aluminum 6061}$$
$$v_m(m/s) = 1.6\text{x}10^4\ \delta_{Li}\ (mm) - \text{Lithium}$$

III. Mission Studies

Mission Parameters with The Fusion Driven Rocket (FDR)

From the initial analysis of the FDR mass, Isp and power generation, two missions were selected for further study

90-Day Mission to Mars

Objective: High Mass Fraction

Advantages:

- **No precursor cargo missions needed**
- **Long or short stay time**

30-Day Mission to Mars

Objective: Fastest possible mission

Advantages:

- **Lowest cost, risk**
- **Minimum radiation exposure**

Parameter*	90 day	30 day
Jet Power (MW)	2.6	33
Solar Power (kW)	27	350
Isp (sec)	5,140	5,140
Specific Mass (kg/kW)	4.3	0.38
Initial Mass (mT)	90	153
Payload Mass Fraction	65%	36%

Both missions have ability for direct abort and return

*Assumes FDR operation with fusion ignition gain of 200

Analytical Model
(Fusion Side)

$$E_{out} \equiv G_F E_{in}$$

$$G_F = 1.1 \times 10^{-7} M_L^{1/2} E_L^{11/8}$$

$$E_{in} = E_L = \tfrac{1}{2} M_L v_L^2$$

$$v_L = 2.0 \times 10^4 M_L$$

$$E_{out} = 5.7 \times 10^{12} M^{7.63}$$

$$E_k = \eta_T \left(E_{out} - e_{ion} M_L \right)$$

$$I_{sp} = \frac{\left(2 E_k / M_L\right)^{1/2}}{g_0}$$

From action Integral constraint where R_L= 1.2 m, w = 0.15m

Energy loss in ionization of liner (~75 MJ/kg)

E_{out} = fusion energy + E_{in}

E_L = liner kinetic energy

$E_{in} = E_L + E_{FRC} \cong E_L$

M_L = mass of liner

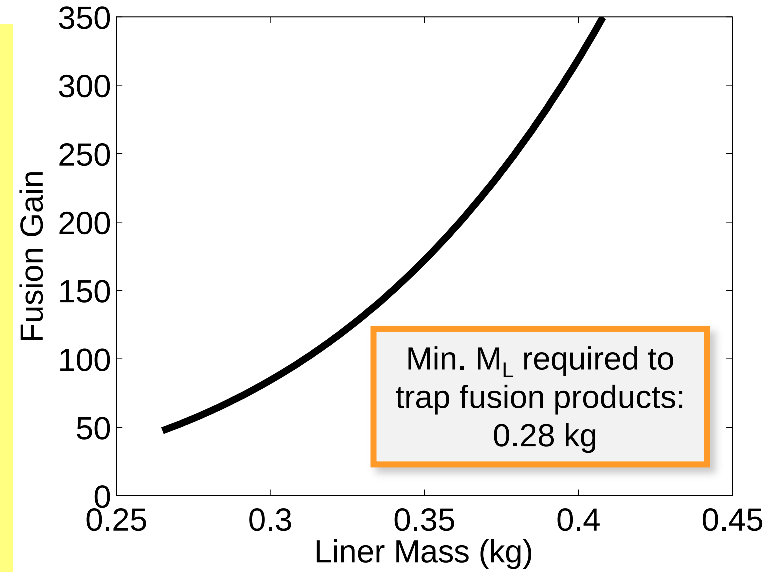
v_L = velocity of Liner

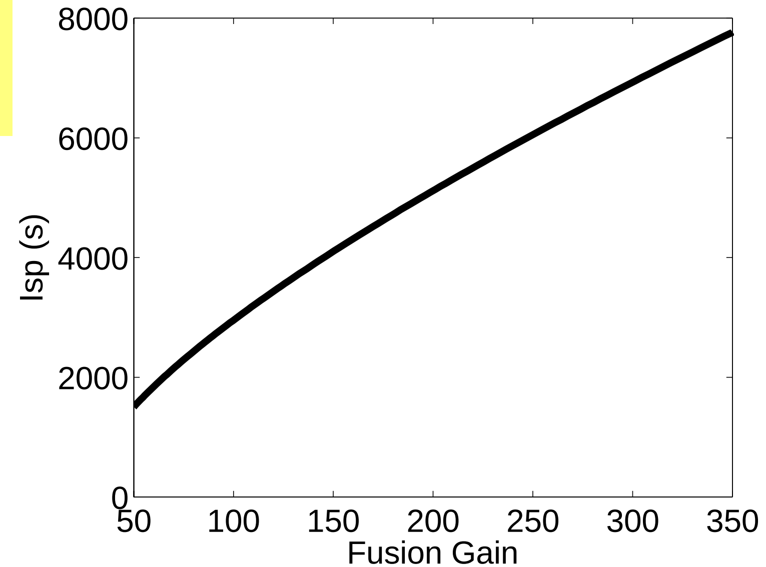
$\eta_C = E_L / E_{cap} = 0.5$

η_T = thrust efficiency = 0.9

E_k = kinetic (Jet) energy

I_{sp} = specific impulse





For known Liner Mass a Specific Impulse is determined

Isp links fusion conditions with mission equations

Analytical Model
(Mission side)

Rocket Equations

$$MR = e^{\left(\frac{\Delta V}{I_{sp} g_0}\right)}$$

$$MR = \frac{M_i}{M_f}$$

$$M_f = M_{PL} + M_S$$

$$M_i = M_{PL} + M_S + M_P$$

$$M_P = M_L \, f \, \Delta T$$

$$M_s = \frac{E_{in}}{\alpha_{cap}} + \frac{P_{SEP}}{\alpha_{SEP}} + 0.1\,MPL$$

$$E_{in} = \frac{P_{SEP}}{f}$$

7 Equations

7 Unknowns

MR = Mass Ratio
M_f = Final mass
M_i = Initial mass
M_P = Propellant mass
M_s = Structural mass
f = Frequency
α_{cap} = Specific mass of capacitors
α_{SEP} = Specific mass of solar panels
P_{SEP} = Solar panel power

I_{sp} from fusion conditions

Delta V requirement as a function of trip time: Solution to Lambert Problem

- It is assumed that initially FDR employs solar panels for house keeping power
- Eventually it would be derived directly from nozzle flux compression

Effect of FDR Fusion Gain On Key Mission Parameters

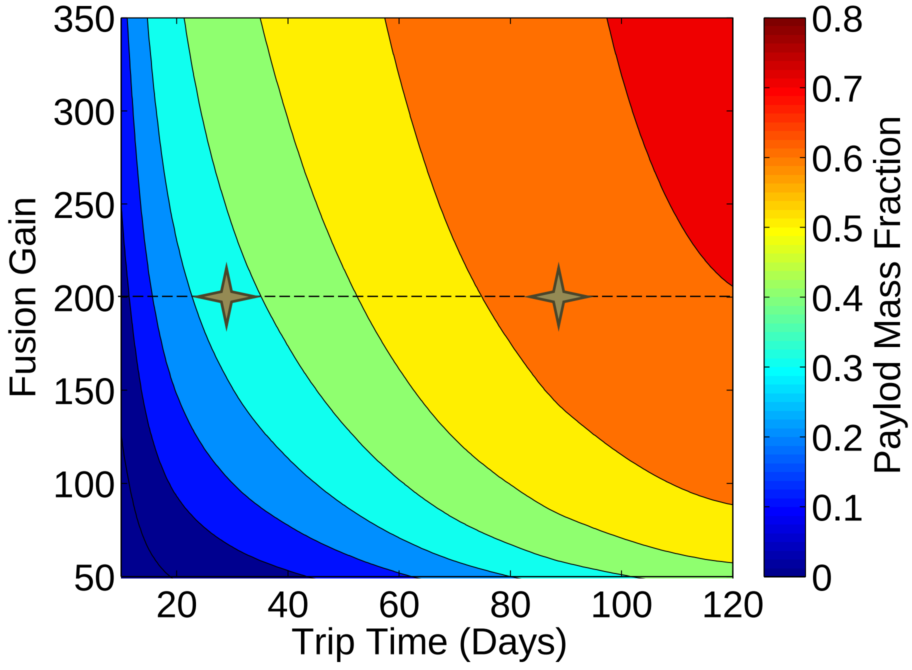
Fusions Assumption:

- Ionization cost is 75 MJ/kg
- Coupling Efficiency to liner is 50%
- Thrust conversation η_t ~ 90%
- Realistic liner mass are 0.28 kg to 0.41 kg
  - Corresponds to a Gain of 50 to 500
- Ignition Factor of 5
- Safety margin of 2: $G_F = G_F$(calc.)/2

Mission Assumptions:

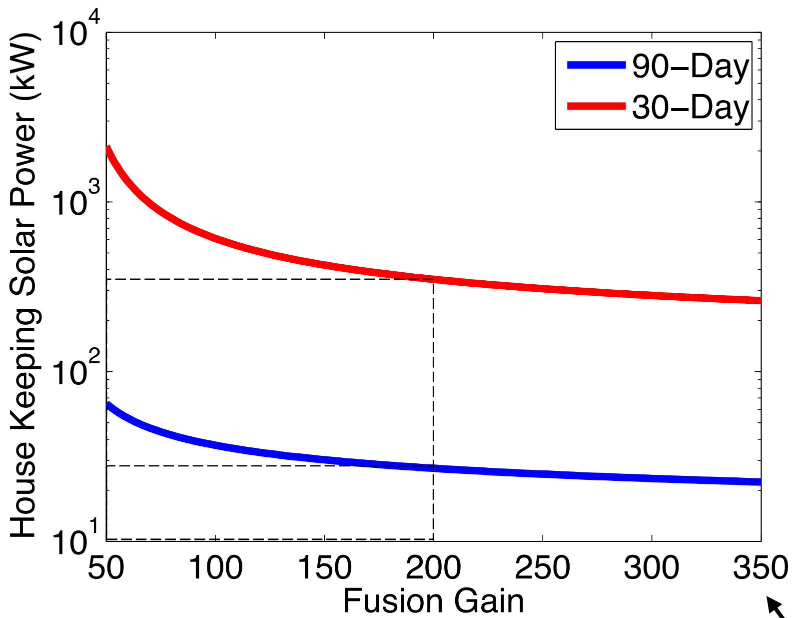
- Mass of Payload= 61 mT
  - Habitat 31 mT
  - Aeroshell 16 mT
  - Descent System 14 mT

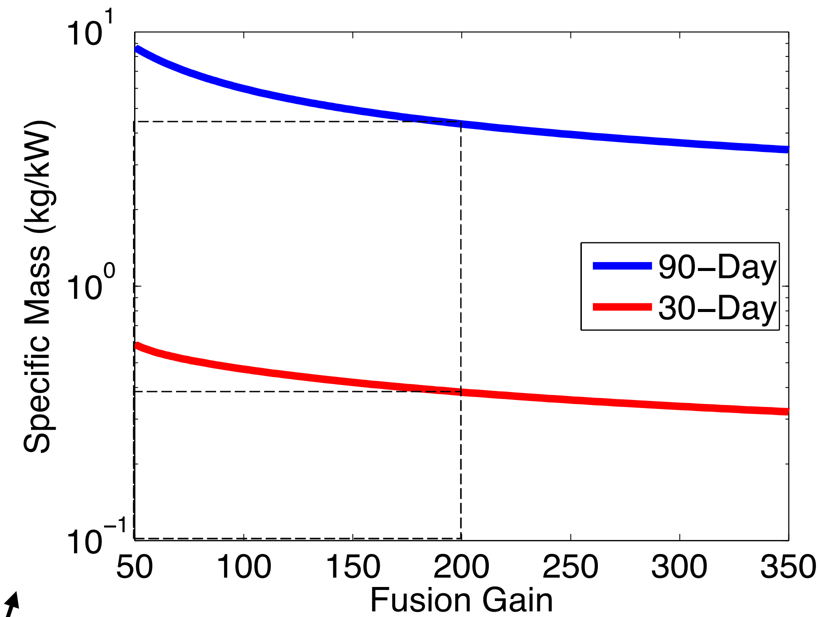
  DRM 3.0
- Specific Mass of capacitors ~ 1 J/kg
- Specific Mass of Solar Electric Panels 200 W/kg
- Tankage fraction of 10% (tanks, structure, radiator, etc.)
- Payload mass fraction =Play load Mass
- System Specific Mass = Dry Mass/SEP (kg/kW)
- Analysis for single transit optimal transit to Mars
- Full propulsive braking for Mar Capture - no aerobraking

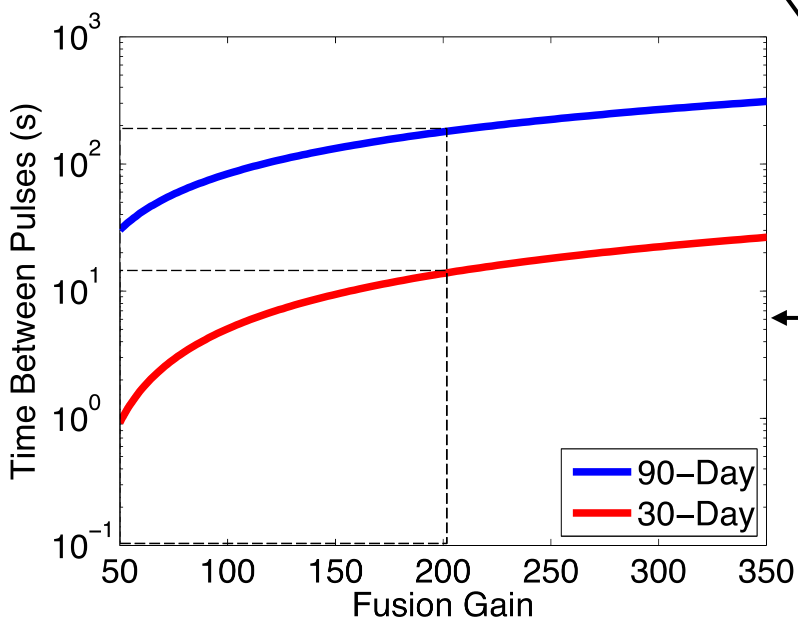


- Longer Trip times allow for higher payload mass fraction
- Larger Fusion Gains result in higher payload mass fraction

FDR Mission Parameters







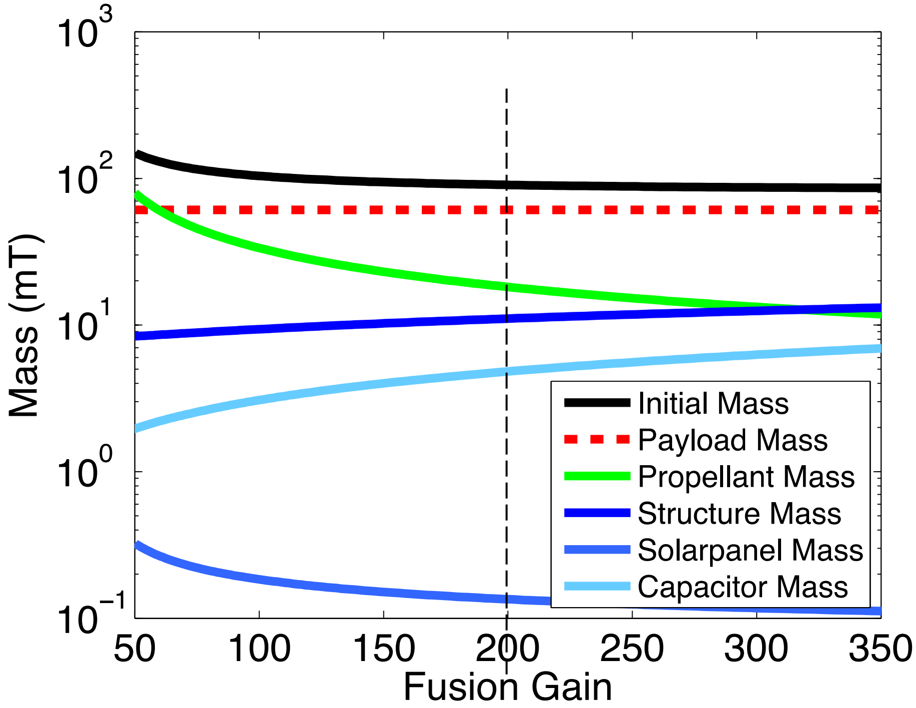
Solar Power requirement runs from modest - 25 kW (90 day) to moderate - 320 kW (30 day).

Specific mass is appropriate for each mission at G_F = 200.

Pulse rate is low for both missions. times raging from 14 s (30 day) to 3 min. (90 day). Provides adequate time for recovery and reload.

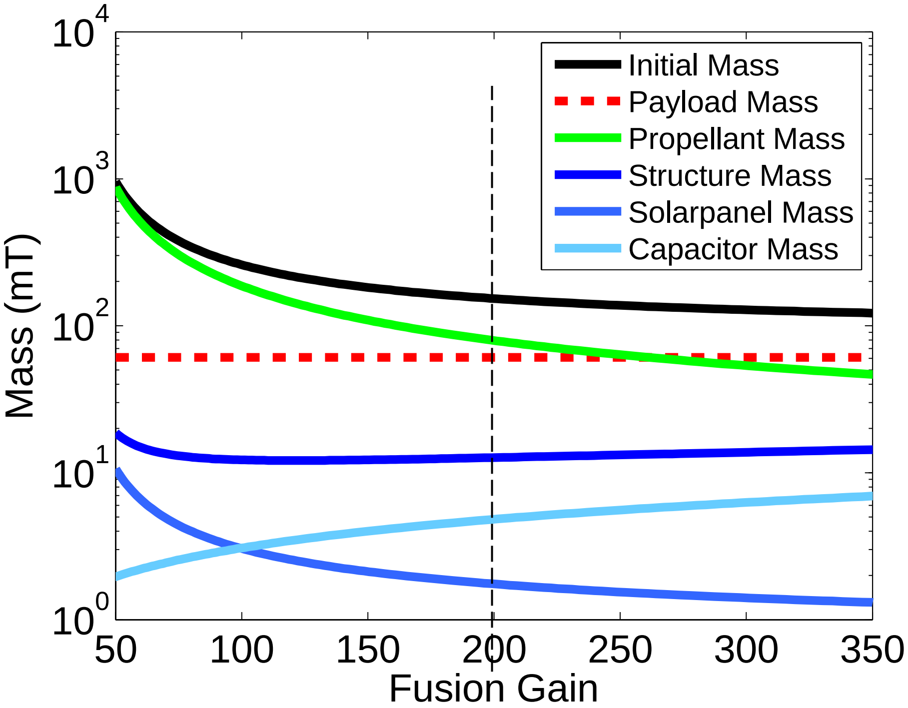
Mission Mass Parameters

90-Day Mission to Mars (ΔV = 13.5 km/s)



- Take all supplies in one trip
- Simplified mission architectures
- No precursor cargo missions needed
- Vastly reduced mission cost
- Single launch possibilities

30-Day Mission to Mars (ΔV = 40.9 km/s)



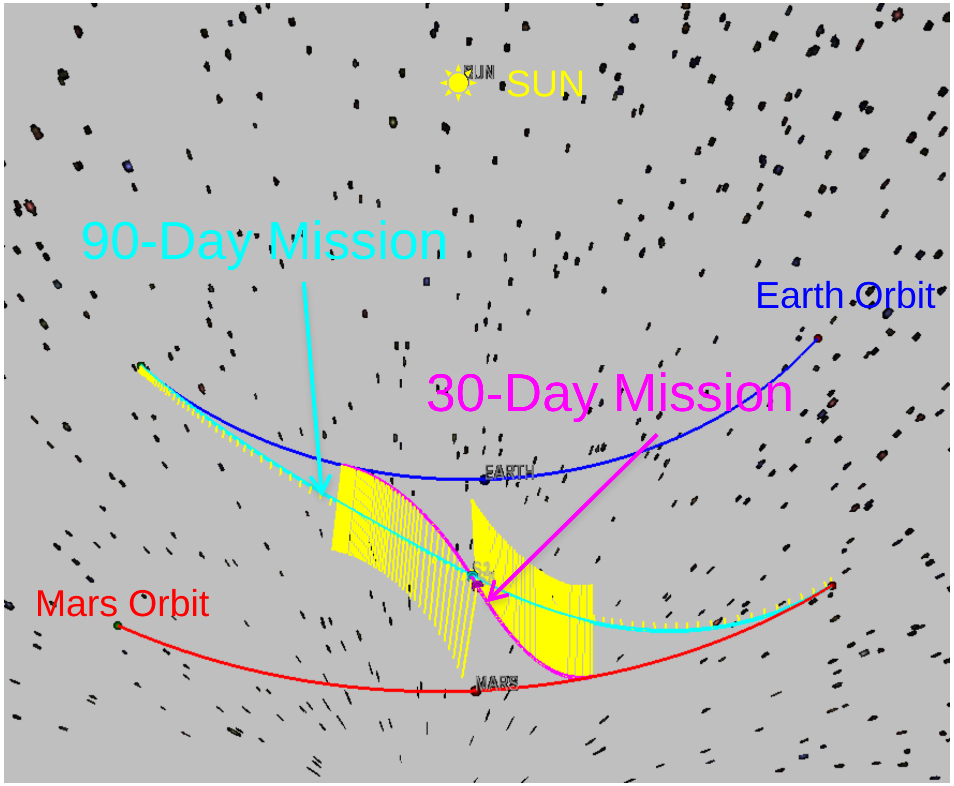
- Lower risk
- Minimum radiation exposure
- Apollo type mission architecture
- Key to routine Martian visitation
- Develops propulsion technology needed for Outer

COPERNICUS

Finite Burn with Sub Optimal Control

Impulse Burn			
Trip Time (Days)	Delta V (km/s)		
	Segment 1	Segment 2	Total
90	13.7	15.2	28.9
30	47.3	50.5	97.9

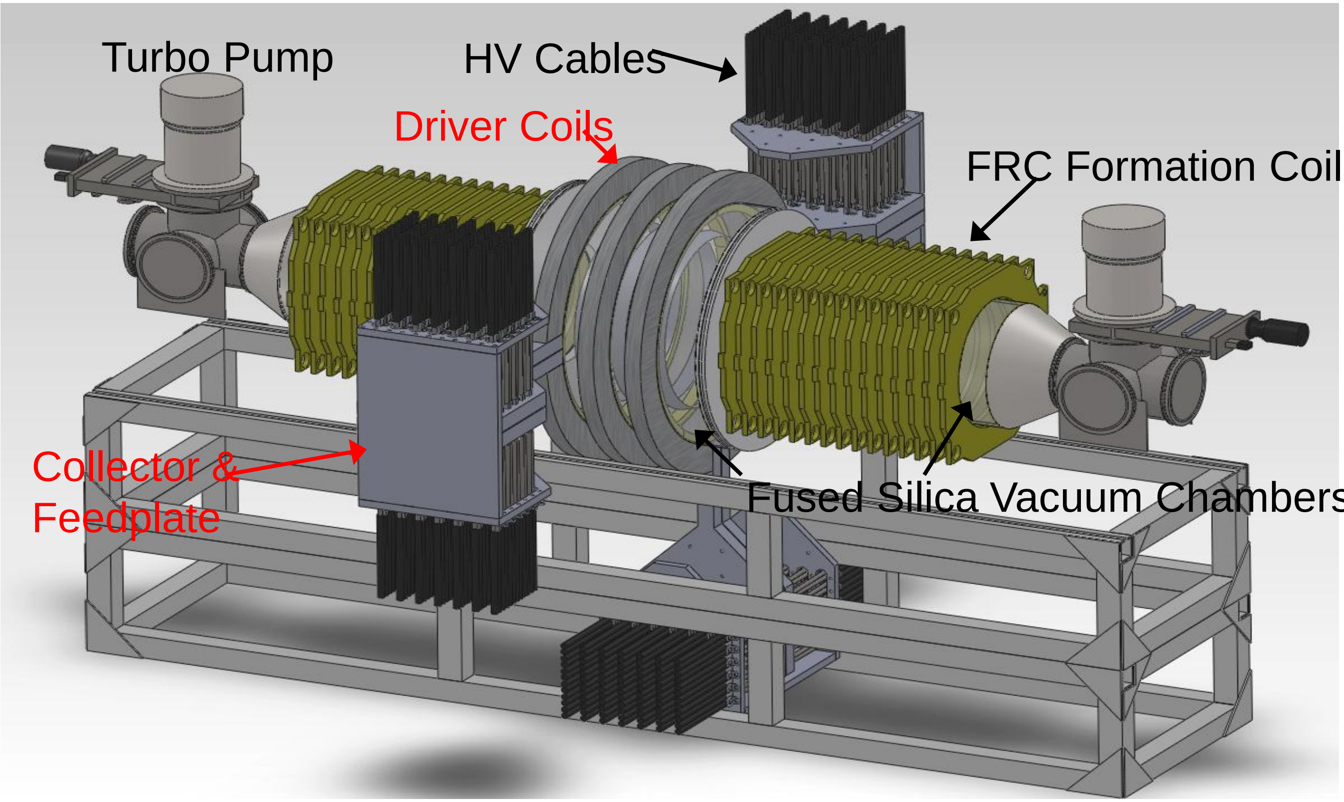
Finite continuous burn			
Trip Time (Days)	Delta V (km/s)		
	Segment 1	Segment 2	Total
90	13.7	15.2	28.9
30	47.3	50.5	97.9



Copernicus will be now be employed for full mission architecture, OCT analysis, and parametric trade studies

IV. Plans for FDR development to TRL 5

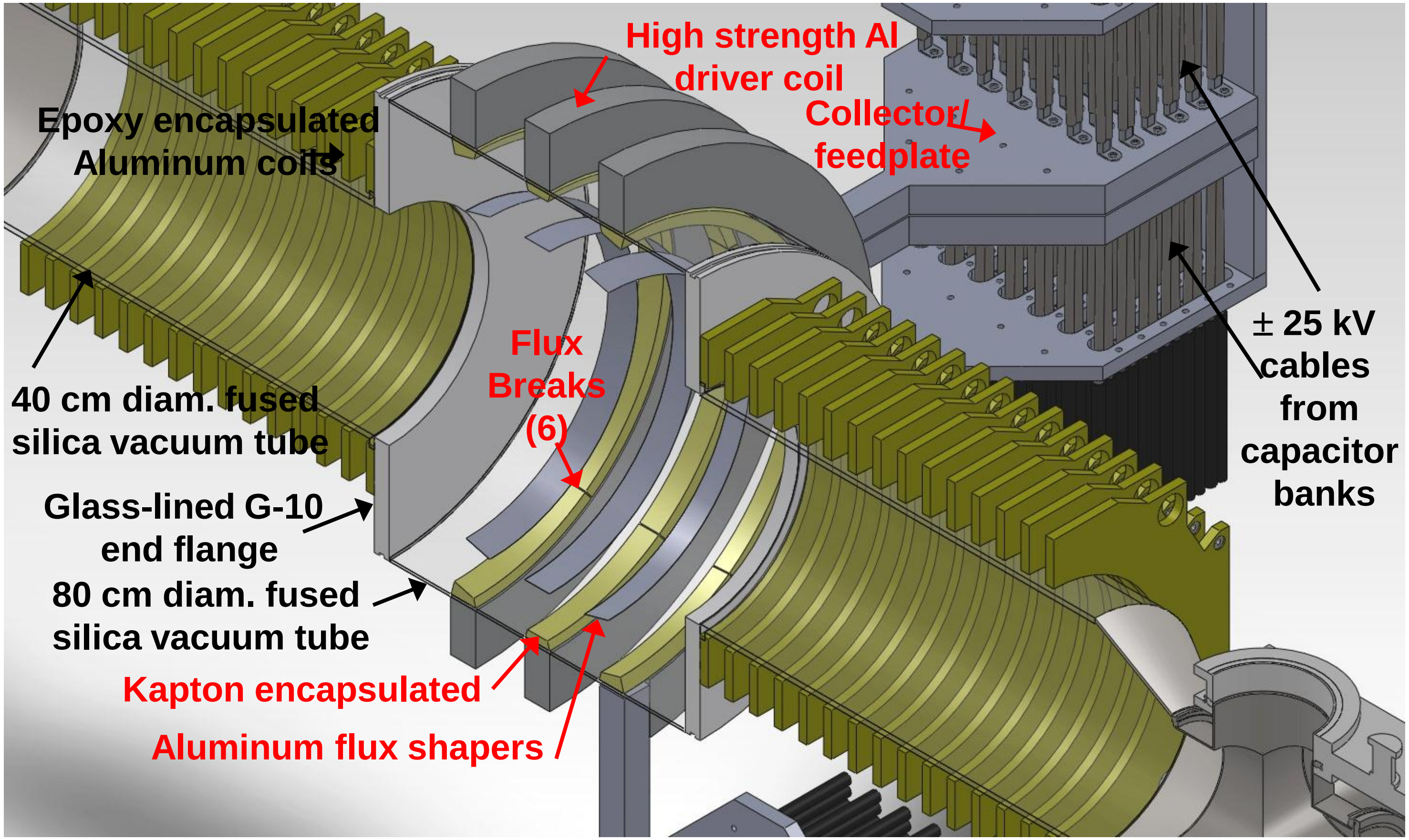
Design of the FDR Breakeven Proof of Concept Experiment



CAD drawing of the proposed 3D liner compression experiment.

- The elements labeled in black are part of the existing equipment at MSNW and the UW.
- All power supplies and capacitors required are also available (FRC formation – MSNW, liner compression – UW).
- Parts labeled in red will need to be fabricated.

Cutaway of FDR Validation Liner Compression Experiment



Black labels indicate existing equipment with red indicating equipment to be fabricated.

PHD Experiment at the UW Plasma Dynamics Laboratory

PHD experiment with some of the 1.75 MJ, ±25 kV capacitor modules shown in the foreground.

- More than sufficient bank energy for G~1 experiment
- Equipment becomes available in July 2012

Anticipated Parameters from FDR Validation Experiment

MSNW

FRC adiabatic scaling laws

Adiabatic Law:	$P \sim V^{-5/3}$	$T \sim B_e^{4/5}$
Rad. P Balance:	$P \sim nkT \sim B_e^{2}$	$n \sim B_e^{6/5}$
Particle Cons:	$nV = const.$	$r_s^2\, l_s \sim B_e^{-6/5}$
FRC φ Cons:	$\varphi \sim r_c^2\, B_e\ (const\ x_s)$	$l_s \sim r_s^{2/5}$

$\Rightarrow$

In experiment, FRC radial and axial compressions would occur simultaneously

Parameter	Merged FRC ($t = \tau_{1/4}$)	Radial FRC Compression	Axial FRC Compression
v_L (km/s)	2.5	~ 0	0
r_L (cm)	22.5	0.9	0.9
r_s (cm)	20	0.8	0.88
l_s (cm)	80	22	3.5
B_{ext} (T)	0.16	100	410
T_e+T_i (keV)	0.06	5	15
n (m^{-3})	1.1×10^{21}	2.5×10^{24}	1.4×10^{25}
E_p (kJ)	2.2	180	560
E (Pa)	1.5×10^{4}	6×10^{9}	10^{11}
τ_N (μs)	600	175	270

Initial FRC size, temp density and energy same as past FRC's

FRC lifetime $>> \tau_{dwell} \sim 4$

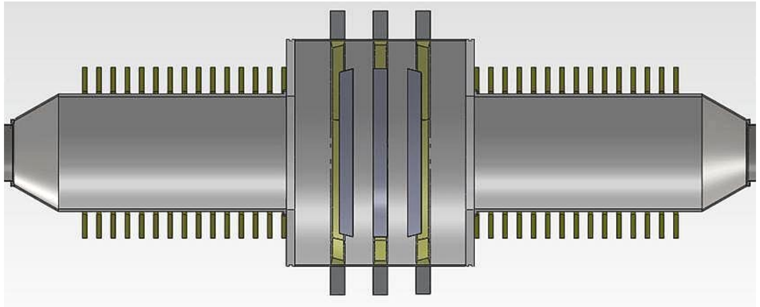
Final field similar to that achieved in several flux compression expts.

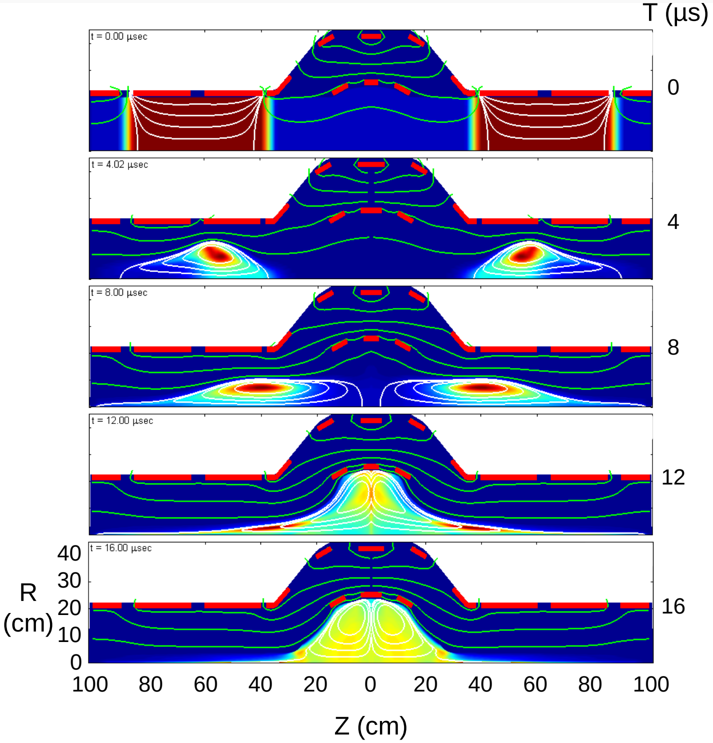
Sub MJ FRC Requires only 33% bank eff.

- Final FRC parameters yield a fusion gain **G = 1.6** (M_L=0.18 kg Al)

2D Resistive MHD Calculation of the Formation and Merging of FRCs Inside the Converging Liners

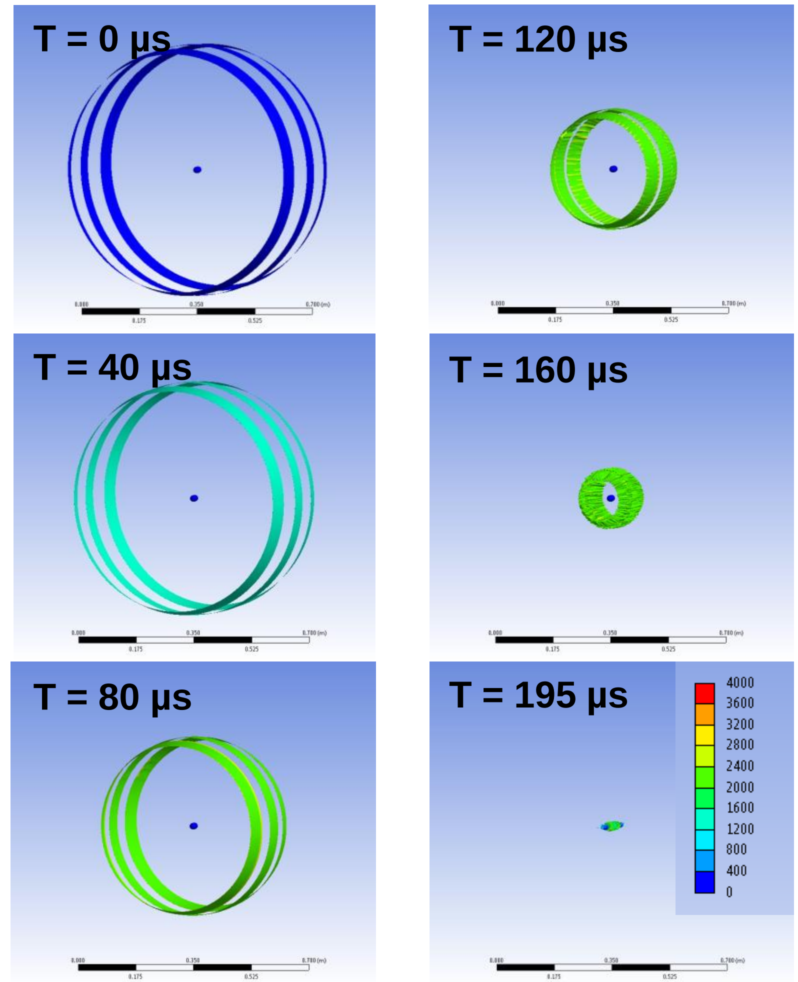
- Code geometry and fields are identical to that employed in the experimental design.
- Target FRC parameters that are realized match closely those desired for liner compression
- Formation time is short (< 20 µsec) justifiying FRC injection late in the liner implosion
- FRC lifetime scaling more than sufficient for expected 80-100 µsec left to peak implosion





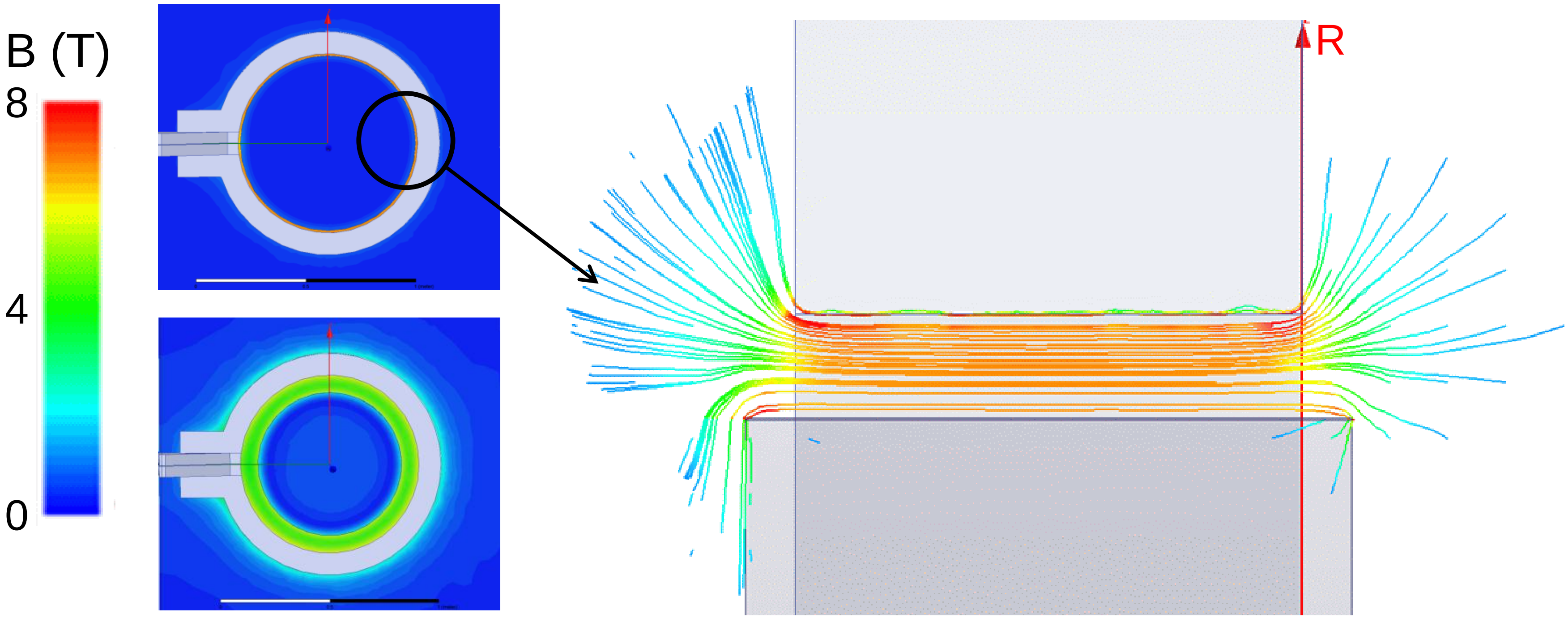
ANSYS Multiphysics® 3D Calculations of the Convergent Implosion of three Al Liners

- Three 0.4 m radius, 5 cm wide, 0.2 mm thick Aluminum liners converging onto a stationary test target.
- The scale of the ellipsoid target (1×3.5 cm) is that anticipated for the final FRC compressed to over 1 megabar (10^{11} Pa) energy density
- Aluminum rings quickly yield to the pressure equivalent of a 7 T magnetic field (~ 6 Mpa).
- A high order buckling is observed later during implosion but does not inhibit convergence where **v_L ~ 2.4 km/sec**



Liner behavior very close to ideal 1D approx. assumed in analysis

ANSYS Maxwell® Calculations of the 3D Electromagnetic Fields



- Solution for a 0.4 m radius coil driving a 6 cm wide, 0.2 mm thick Al liner.
- The circuit was based on the capacitor bank currently available at the UW Plasma Dynamics Laboratory.
- The spatial forces on the liner at various times and radii are calculated and used as input into the dynamic calculation similar to the one shown above.
- Mutual interaction between coils and liners will also be investigated.

Theoretical Validation of Key FDR Elements (peer reviewed papers)

SUBMEGAJOULE LINER IMPLOSION OF A CLOSED FIELD LINE CONFIGURATION

PLASMA ENGINEERING

KEYWORDS: *fusion, high-density plasma, pinches*

R. PAUL DRAKE, JAMES H. HAMMER, CHARLES W. HARTMAN, L. JOHN PERKINS, and DIMITRI D. RYUTOV*
Lawrence Livermore National Laboratory, Livermore, California 94550

Received April 28, 1995
Accepted for Publication March 4, 1996

- Importance of 3D compression
- Superiority of high β FRC target
- Magnetic field limits thermal and particle loss - **even with (cold) wall confinement and β > 1**

Ignition conditions for magnetized target fusion in cylindrical geometry

M.M. Basko[a]*, A.J. Kemp[b], J. Meyer-ter-Vehn[b]

[a] Département de Recherches sur la Fusion Controlée, CEA Cadarache, St. Paul-lez-Durance, France

[b] Max-Planck-Institut für Quantenoptik, Garching, Germany

Nuclear Fusion, Vol. 40, No. 1

- Ignition possible with magnetized plasma **where ρR <<1** but BR > 60 T-cm.
- Magnetic field well within range of larger FRCs.

Fusion Based on the Inductively-Driven Lithium Liner Compression of an FRC Plasmoid

John Slough, David Kirtley, Anthony Pancotti, Christopher Pihl, George Votroubek
(Submitted to *Journal of Fusion Energy* 2012)

- Method for producing 3D liner implosions with stand-off
- Generation of FRC plasma target with sufficient magnetization and confinement for ignition
- Method for efficient conversion of plasma, radiation, and fusion energy in a manner that protects and magnetically isolates reactor

Experimental Validation of Key FDR Elements (peer reviewed papers)

MSNW

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 12 DECEMBER 2002

Generation of 600 T by electromagnetic flux compression with improved implosion symmetry

Y. H. Matsuda,[a] F. Herlach,[b] S. Ikeda, and N. Miura[c]
Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

(Received 23 April 2002; accepted 22 September 2002)

- Demonstrated inductively driven liner compression of B_z fields > 1 Mbar

IOP Publishing and International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion 51 (2011) 053008 (10pp) doi:10.1088/0029-5515/51/5/053008

Creation of a high-temperature plasma through merging and compression of supersonic field reversed configuration plasmoids

John Slough, George Votroubek and Chris Pihl
MSNW LLC, 8551 154th Avenue NE, Redmond, WA 98052, USA

- Demonstrated the stable formation, merging and magnetic compression of the FRC
- FRC lifetime better than previous scaling

J Fusion Energ
DOI 10.1007/s10894-010-9335-6

ORIGINAL RESEARCH

The Plasma Liner Compression Experiment

George Votroubek · John Slough

- Demonstrated successful FRC liner compression with a xenon plasma liner

Experimental demonstration of fusion gain with inductively driven metal liners

Hope to publish in the near future!