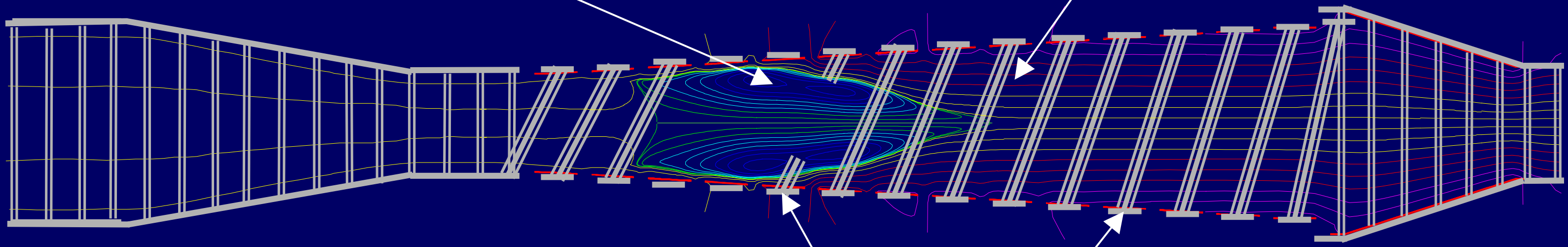
Propagating Magnetic Wave Accelerator (PMWAC) for Manned Deep Space Missions



Magnetized Plasma Toroid

Propagating Magnetic Field
(from 2D MHD calculation)

Helical Transmission Coil

Parameter	First Stage	Final
System length	5 m	25 m
Plasma mass m_p :	0.2 mg D_2	(same)
Final plasma velocity:	3×10^5 m/sec (I_{sp} = 30,000 s)	1×10^6 m/s
Acceleration (Force):	2×10^{10} m/s (4 kN)	(same)
Thrust Power (0.2 kHz rep)	2 MW	20 MW

Propulsion Requirements for Deep Space Missions

- High Specific Power - α ($kW_{thrust}/kg_{spaceship}$)

  $\alpha > 1$ kW/kg

- High (and variable) exhaust velocities v_{ex}

  max $v_{ex} \sim 10^4$ km/s   ($I_{sp} = v_{ex}/g \sim 10^6$ s)

- Continuous power with near zero maintenance for months

Trip Time and the Specific Power Requirement

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

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

One defines a characteristic velocity v_c:

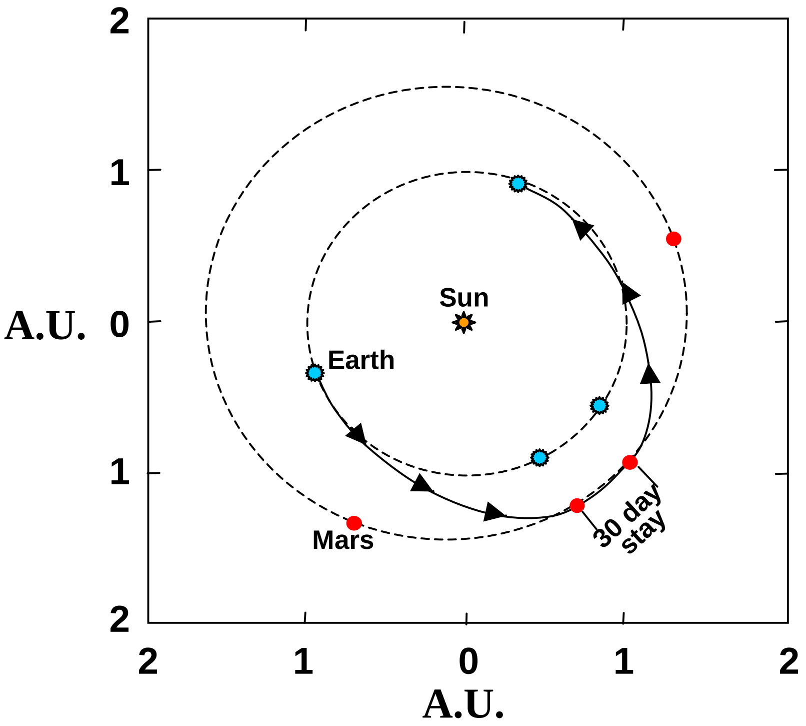
$$v_c = (2\,\alpha\,\tau)^{1/2}$$

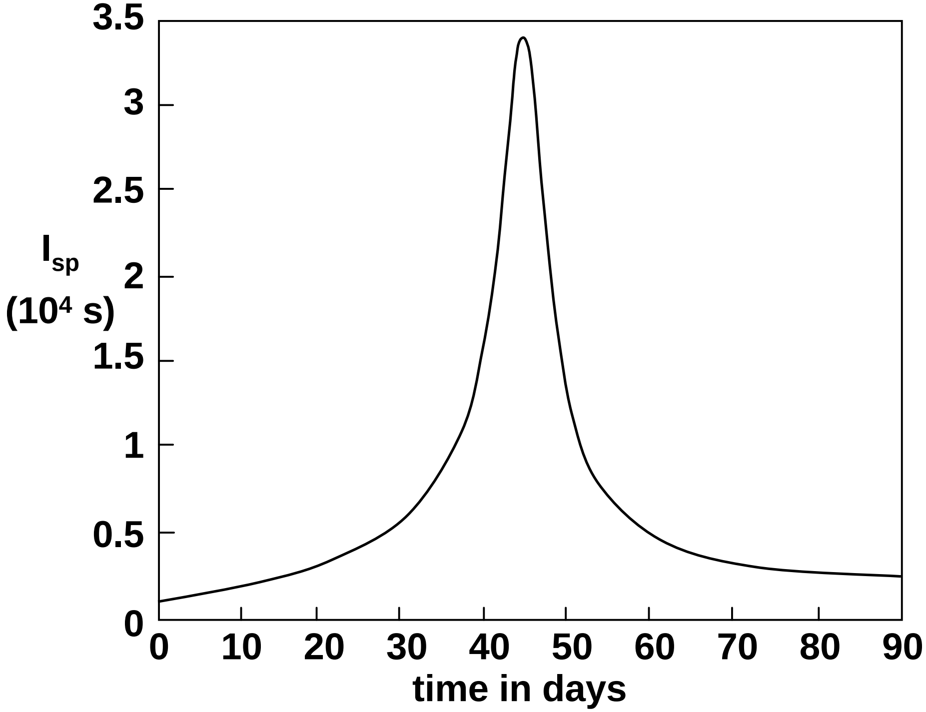
where α is the specific power.

The trip time τ_{trip} to go a distance L is given roughly as:

$$\tau_{trip} \approx 2\frac{L}{v_c} \qquad \tau_{trip}(\text{months}) = \frac{2L(\text{astronomical units})^{2/3}}{\alpha(\text{kW/kg})^{1/3}}$$

Rapid Manned Mars Mission Power Requirement





$$\alpha(\text{kW/kg}) = 8\,\frac{[S(\text{astronomical units})]^2}{\tau(\text{months})^3} \approx 1$$

for M_{ss} ~ 20 MT, $P_{thrust} = 20$ MW

Velocity and Energy Requirements for Deep Space Missions

(α =1 kW/kg)

Destination	$x_{trip} \sim 2$ A.U. (Mars)	$t_{trip} \sim 3$ months
	$x_{trip} \sim 10$ A.U. (Jupiter)	$t_{trip} \sim 12$ months
Characteristic Velocity	$v_{Mars} \sim 125$ km/sec	
	$v_{Jupiter} \sim 250$ km/sec	
Specific Energy	$\varepsilon_{Mars} \sim 8\text{x}10^9$ J/kg	
	$\varepsilon_{Jupiter} \sim 3\text{x}10^{10}$ J/kg	

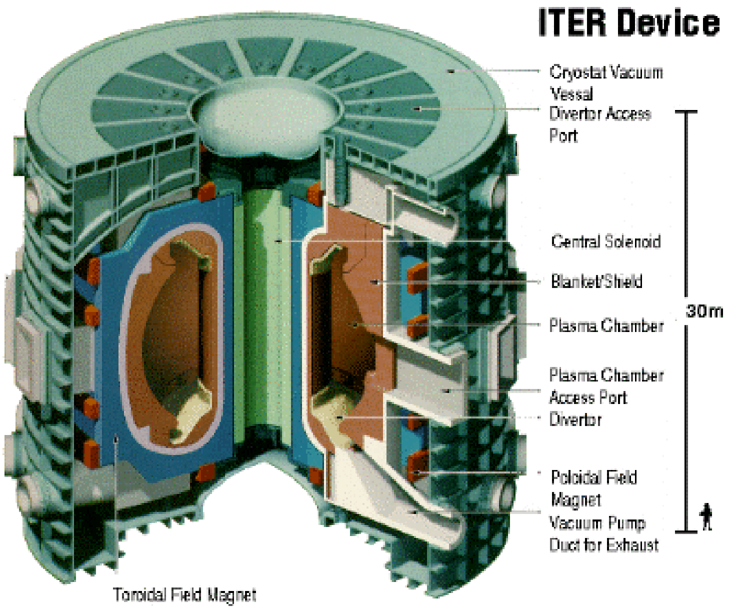
$$\boxed{\begin{array}{l}\alpha = v_{char}^2/2t_{trip} \\ \varepsilon = v_{char}^2/2 = \alpha\, t_{trip}\end{array}}$$

Propulsion System	Exhaust (km/sec)
Chemical	5
Electric	30
FRC at RPPL	250
Thermal Fusion	2000

Fuel	Specific Energy
Chemical	$1\text{x}10^7$ J/kg
Fission	$5\text{x}10^{13}$ J/kg
Fusion	$1\text{x}10^{15}$ J/kg

Nuclear Power is Necessary for Deep Space Travel

Current and Planned “Breakeven” Fusion Experiments

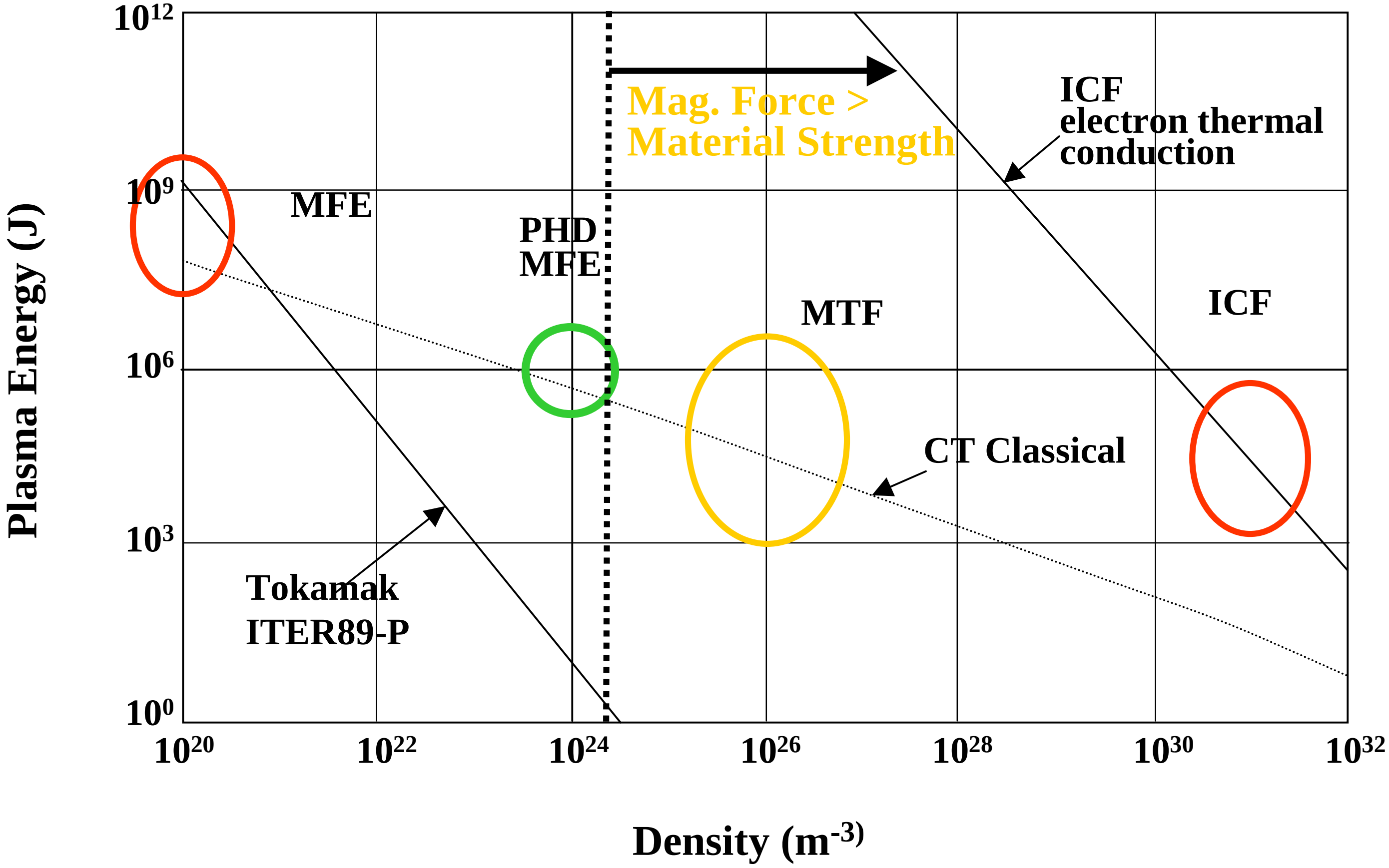


ITER (MFE)

PHD

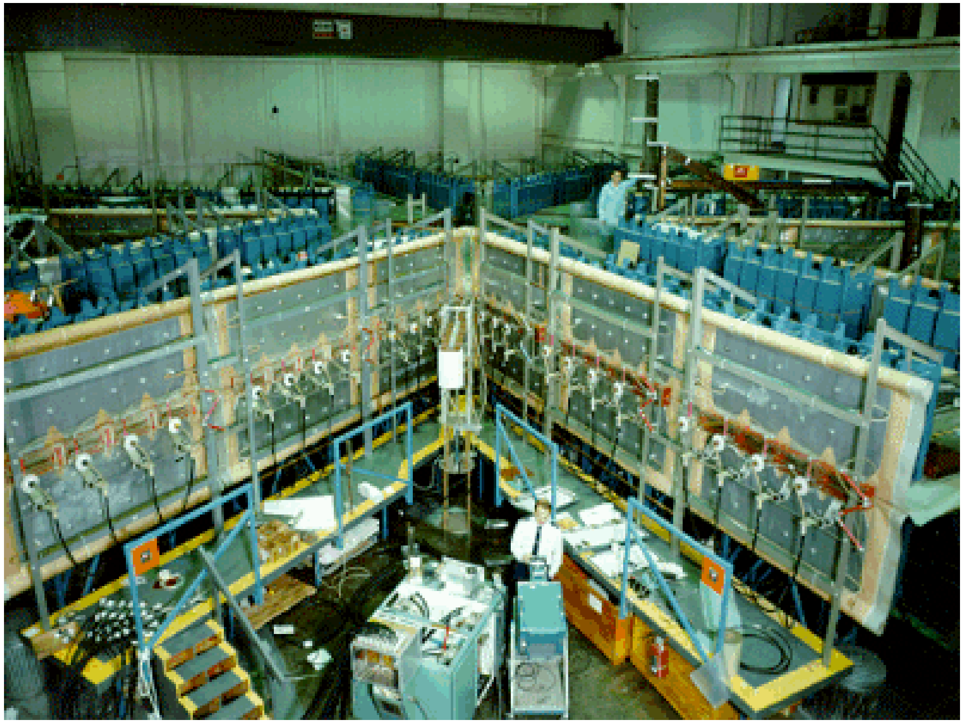
NIF (ICF)

Plasma Density and Energy Regimes for Different Fusion Concepts



High Voltage Energy Storage

V~ 120 kV



Shiva Star Facility for MTF
~ 10 MJ

⇔

Low Voltage Storage

V~ 12 V

2 Auto Batteries
~10 MJ

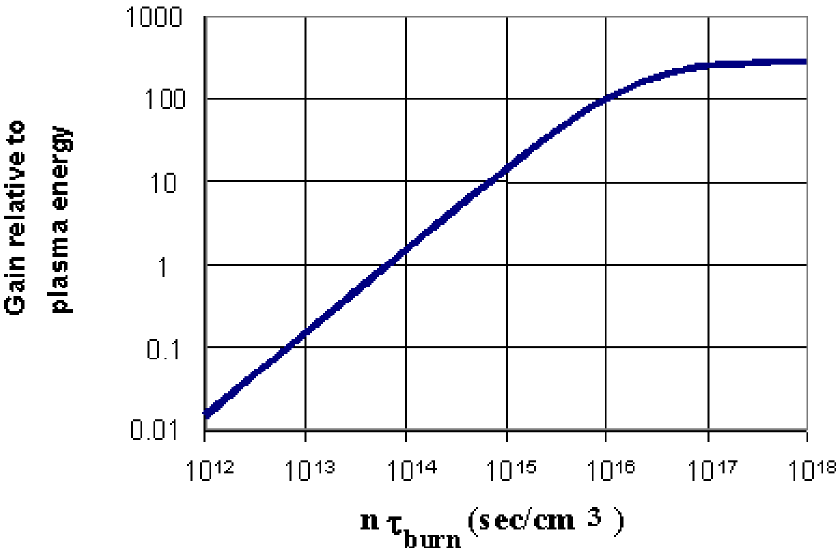
Pulsed High Density (PHD) Fusion Basics

- Fusion reaction rate R:

$R = n_D n_T \langle \sigma_{DT} v \rangle$

At T_p = 10 keV,

$\langle \sigma_{DT} v \rangle \cong 10^{-22}$ m^3/sec



- For space-based fusion:

G ~ 3 (thermal electrical)

$n\tau_{burn} \sim 1\text{x}10^{20}$ m^{-3} sec

To maintain burn: $\tau_E \sim \tau_{burn}$

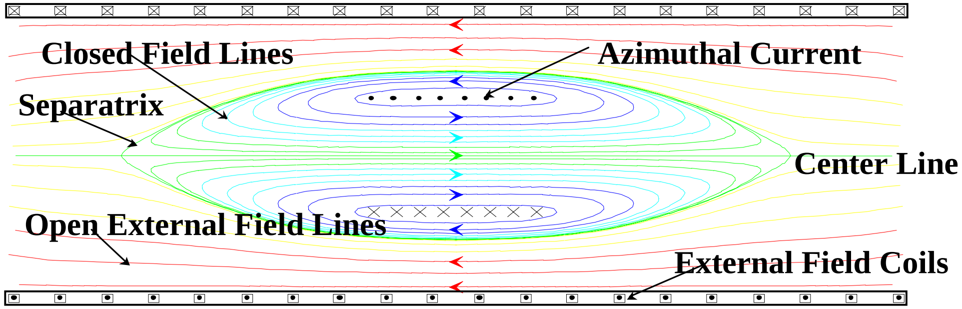
- Lawson Criterion: ~ $n\tau_E \sim 1\text{x}10^{20}$ m^{-3} sec

- Plasma pressure < Magnet Yield Limit (2x10^4 Atm):

(T_p = 10 keV) $n_{fus} = 1\text{x}10^{24}$ m^{-3}

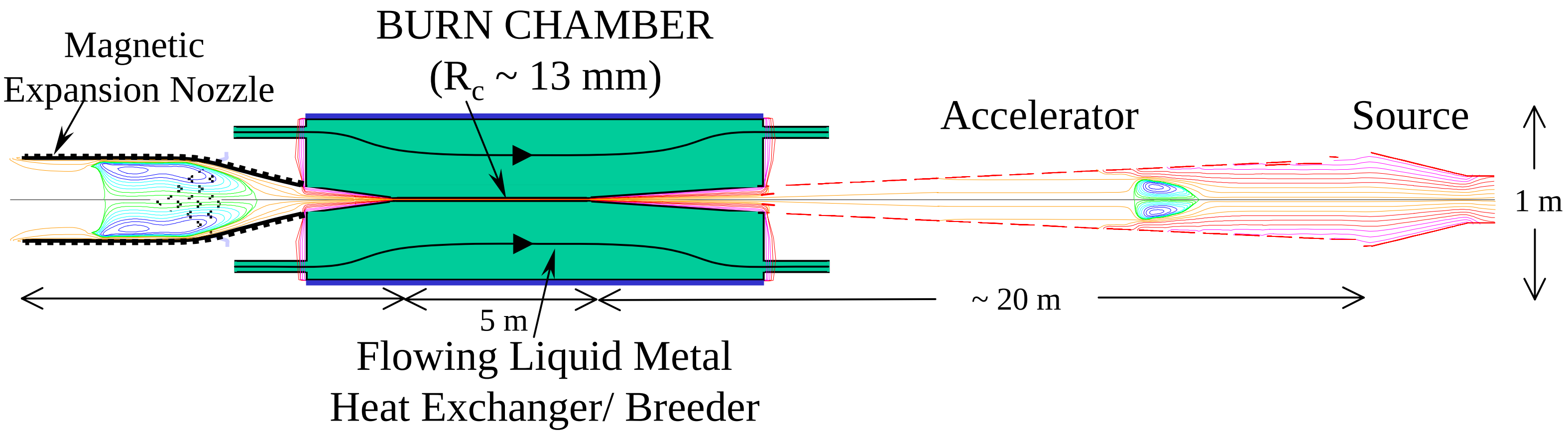
and τ_E = 100 μsec

Field Reversed Configuration (FRC) Propulsion



- Propellant (plasma) is magnetically insulated from thruster wall
- No plasma detachment problem
  - -plasma (FRC) contained separate a magnetic envelope
- Plasma is thermally isolated from thruster walls
  - -fully ionized plasma is vacuum isolated
- Both thrust and Isp can be varied easily over a wide range
  - -change of gas fill pressure is all that is required
- Thrust and Isp are decoupled from plasma thermal energy
  - -with $v_{dir} >> v_{th}$ theoretical efficiency can approach unity
- **Enables a direct, simple method to achieve fusion propulsion with minimum investment**

PHD Fusion Rocket



From past FRC experiments: $\tau_E \sim \tau_N = 1.3\text{x}10^{-12}\, x_s\, r_p^{\,2}\, n^{1/2}$ $(x_s = r_p/R_c)$
with $n = n_{fus}$, r_p =1 cm (R_c = 1.3 cm)
with l_p/r_p= 5 E_p= 50 kJ
rep rate = 200 Hz 17 MW directed thrust power

- FRC formed at low energy (~5 kJ) and relatively low density (~10^{21} m^{-3})
- FRC accelerated and compressed by low energy propagating magnetic field (< 0.4 T).
- FRC is decelerated, compressed, and heated as it enters high field burn chamber
- FRC expands and cools converting thermal and magnetic energy into directed thrust

FRC Acceleration and Heating Expts. at UW

FRC mass:
0.4 mg Deuterium

FRC terminal velocity:

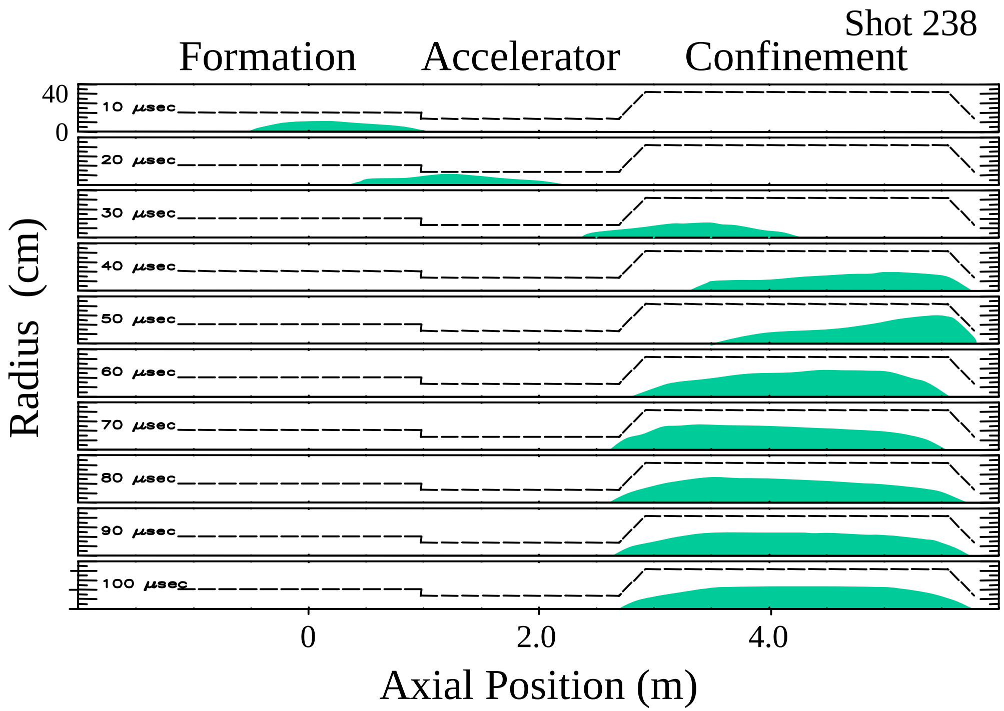
$v_d = 2.5\text{x}10^5$ m/s

Average FRC acceleration:
(5 - 30 µsec)

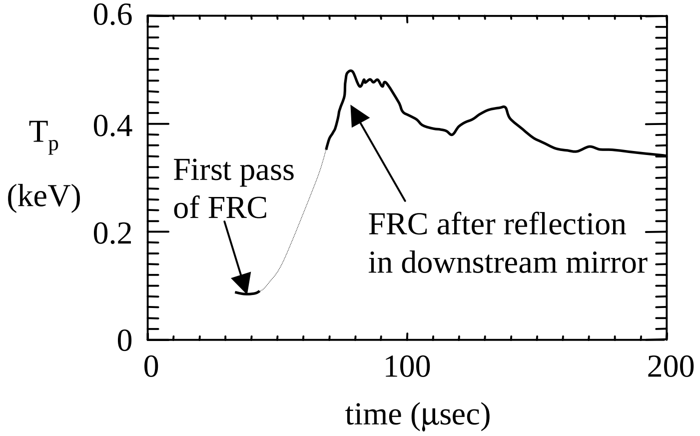
$a_{avg} = 9\text{x}10^9$ m/s^2

FRC Energy (final)

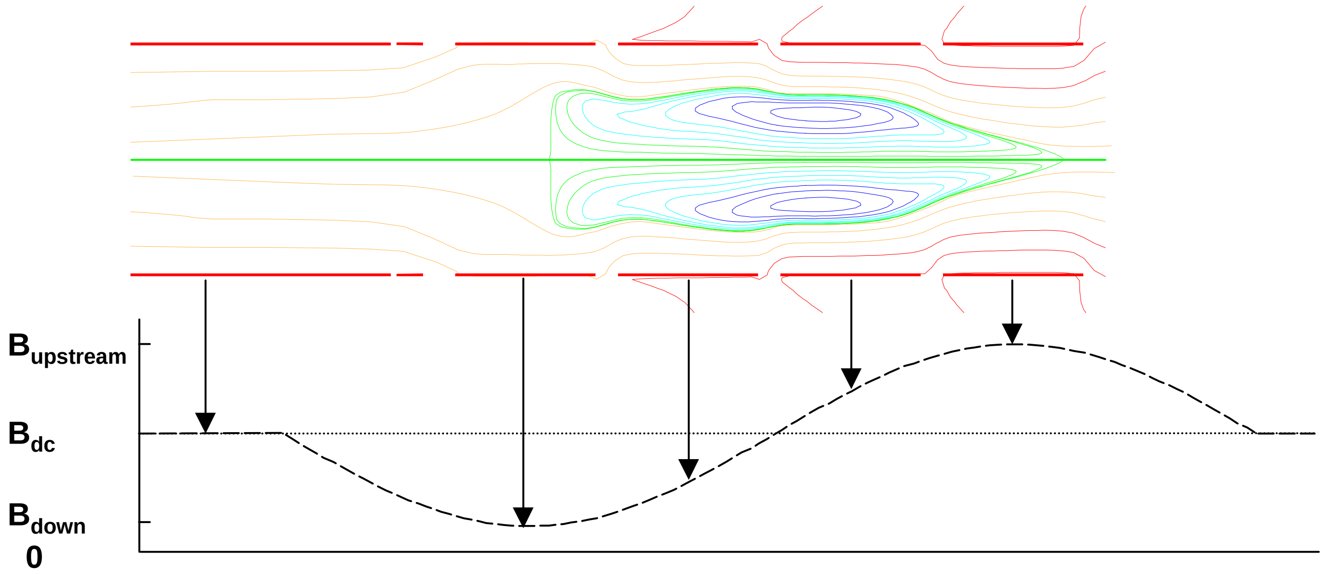
15 kJ



Thermal Conversion of
FRC directed Energy



FRC Acceleration Method Employed in UW Expts.



- Upper plot of flux contours taken from numerical calculations for discharge 1647 during the acceleration of an FRC at UW.

- Bottom plot illustrates phasing of the accelerator coils
  Each coil in turn is switched on for one complete cycle.
  Phase of each coil at time of calculation is indicated by arrow

Propagating Magnetic Wave Accelerator

For transmission line:

$$v_p^2 = \frac{1}{LC} \qquad Z^2 = \frac{L}{C}$$

For shell capacitor (per unit length):

$$C = \frac{2\pi R_c \varepsilon_0 \kappa \varepsilon_S}{V}$$

Inductance (per unit length):

$$L = \mu_0 \pi R_c^2 n^2$$

From these eqs. Solving for R_c

$$R_c = \frac{2 V \kappa \varepsilon_S}{c^2 B^2}$$

and finally for the phase velocity:

$$v_P = \left[\frac{2V}{R_c^3 \kappa \varepsilon_S}\right]^{1/2} \frac{c}{2\pi n}$$

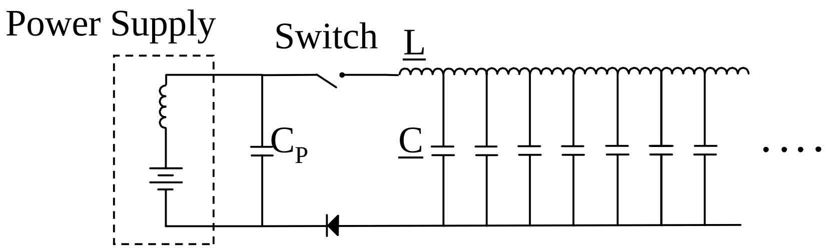
$BaTiO_3$

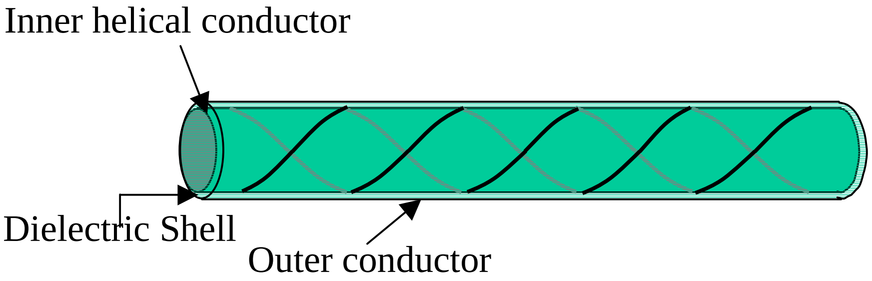
1 cm

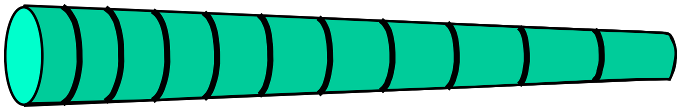
$\varepsilon_S = 5 \times 10^6$ V/m

$\kappa = 2500 * \varepsilon_0$

$V = \pm 25$ kV





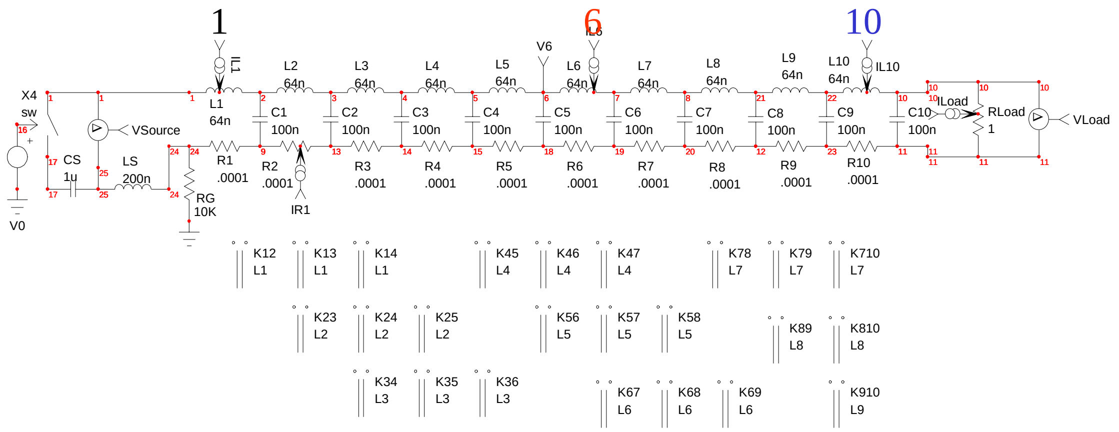


$$v_P = \frac{1.35 \times 10^5}{R_c^{1.5}\, n}\ \mathrm{m/s}$$

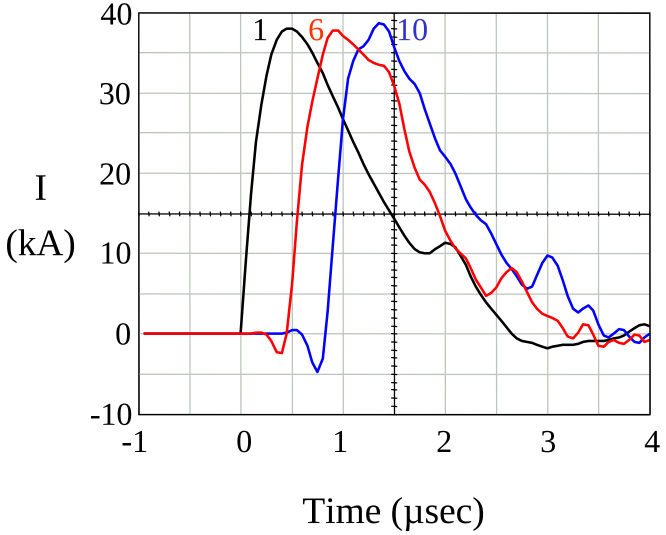
$v_P = 10^6$ m/s   B = 0.5 T

for $R_c = 5.5$ cm   n = 10 turns/m

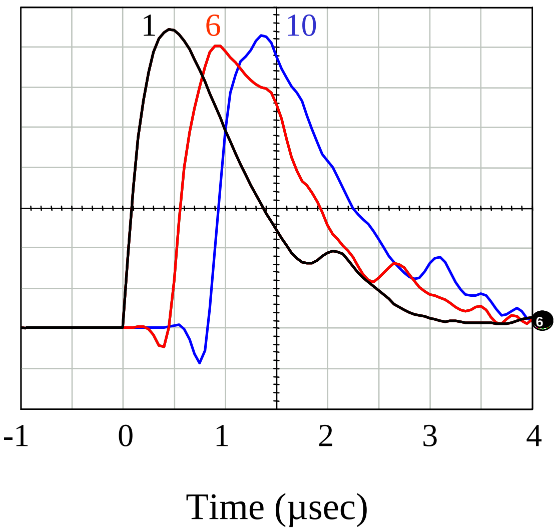
PMWAC SPICE Calculation for Constant Z



Vacuum load

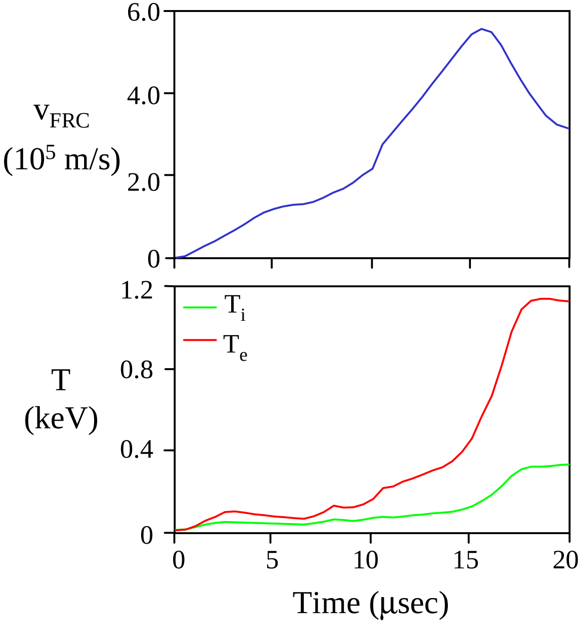


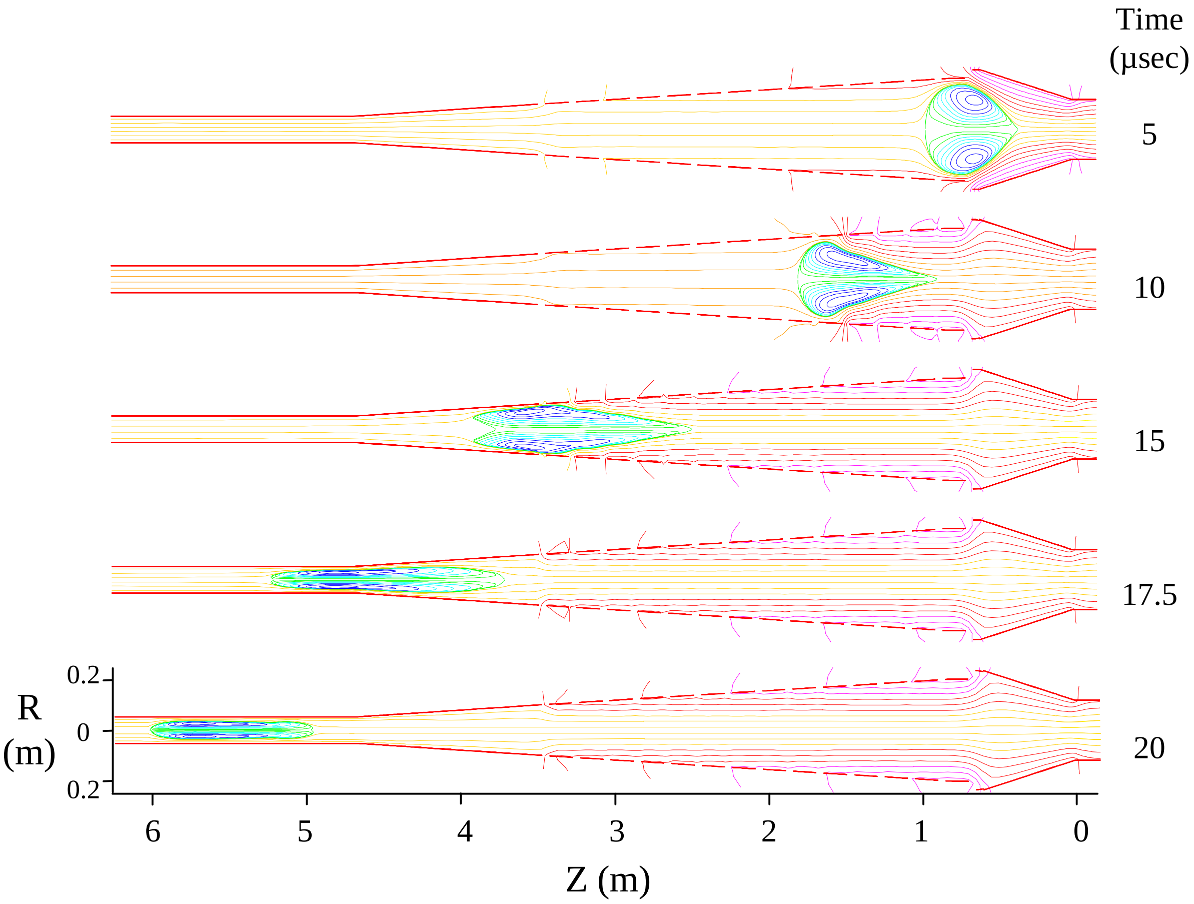
Dissipative load (plasma)



Resistive 2D MHD Calculation of FRC with Propagating Magnetic Field (0.4 T)

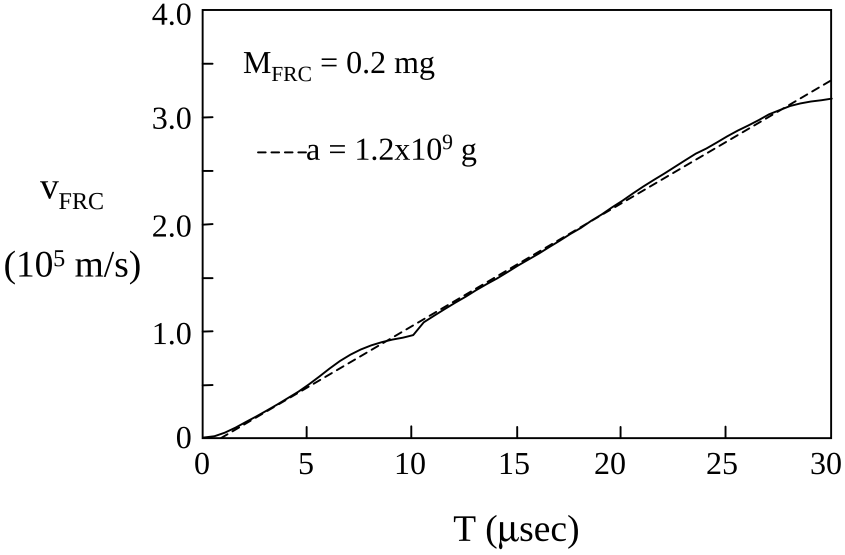
V_{accel} = 30 kV, M_{FRC} =

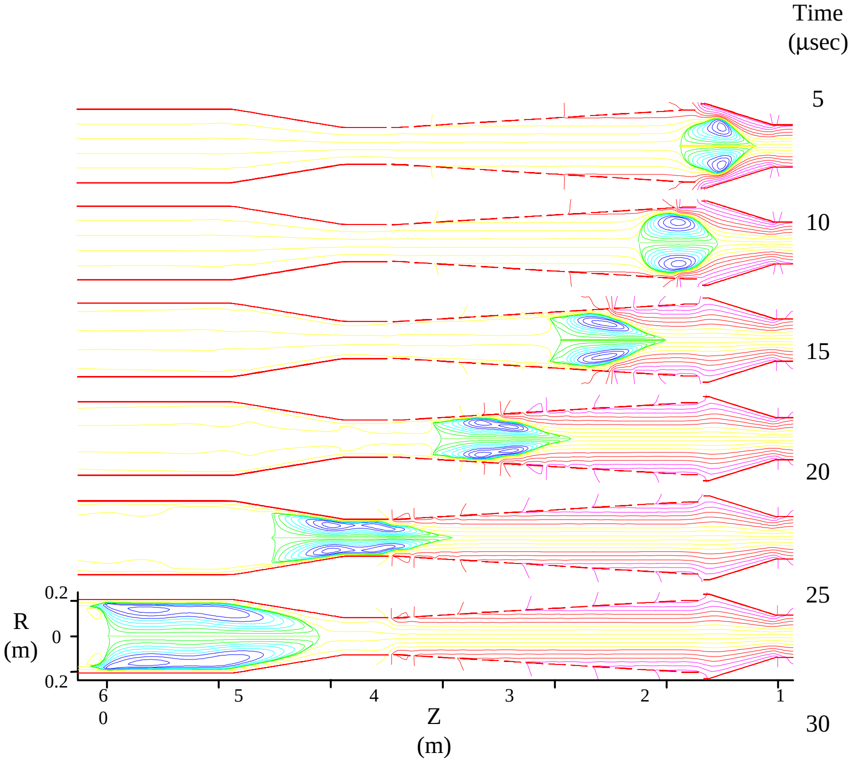




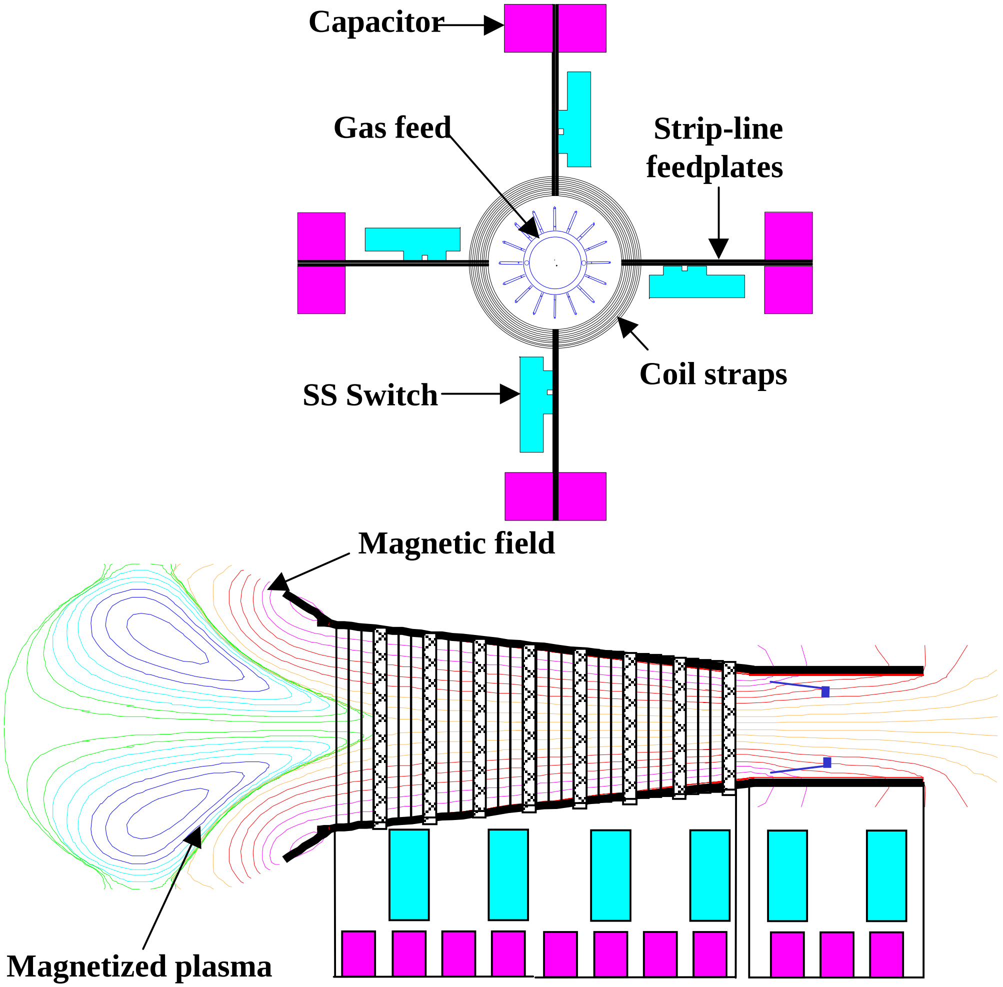
PMWAC Can Also Be Employed to Provide High I_{sp}, High Thrust Electrical propulsion

V = ± 3.5 kV ⇔ B_{acc} = 0.2 T





Inductive Magnetized Plasma Accelerator Source Developed with NASA STTR funding at MSNW



Capacitor

Gas feed

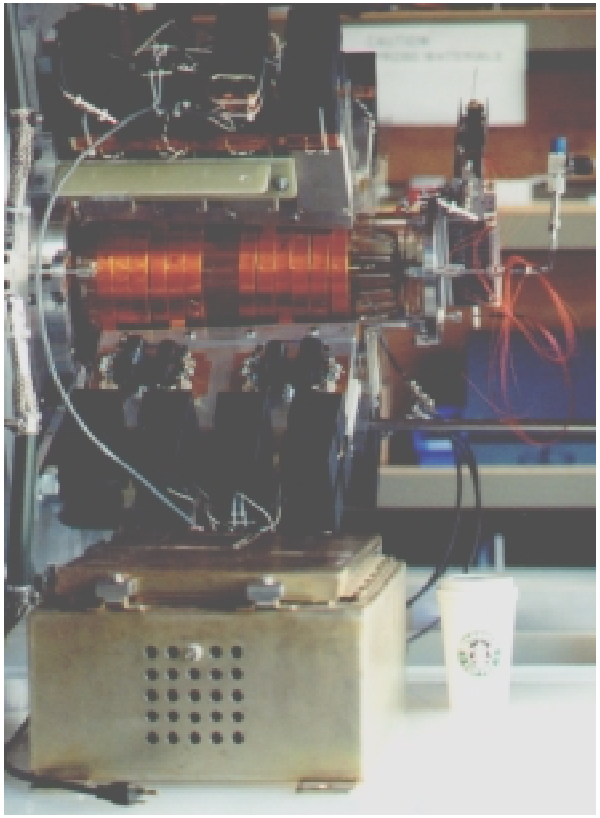
Strip-line feedplates

Coil straps

SS Switch

Magnetic field

Magnetized plasma



PMWAC Development Program

Phase 1:

- Determine Accelerator Requirements and Parameters
- Design Proto-Accelerator for Electrical Validation
- Construct Accelerator and Measure Electrical Performance
- Develop Full Electrical Model with Plasma Interaction

Phase II:

- Design and Construct Full-scale Accelerator
- Install Accelerator and Demonstrate FRC Acceleration to Fusion Velocities (~10^6 m/s).