The Plasmoid Thruster Experiment (PTX)

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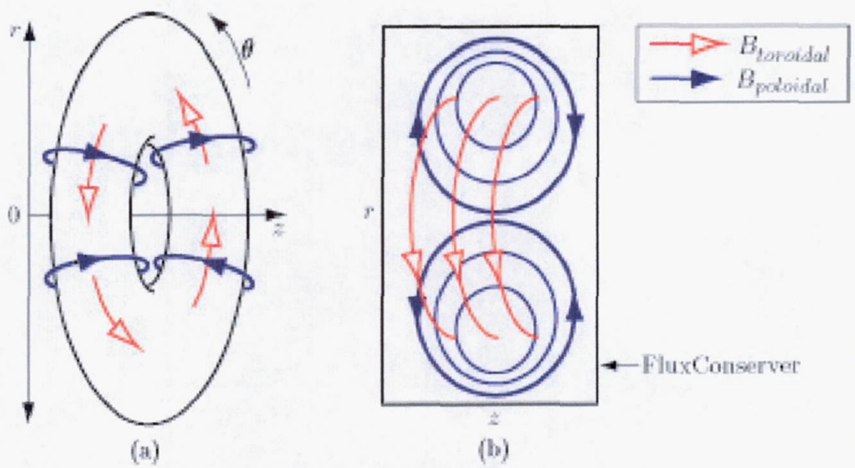
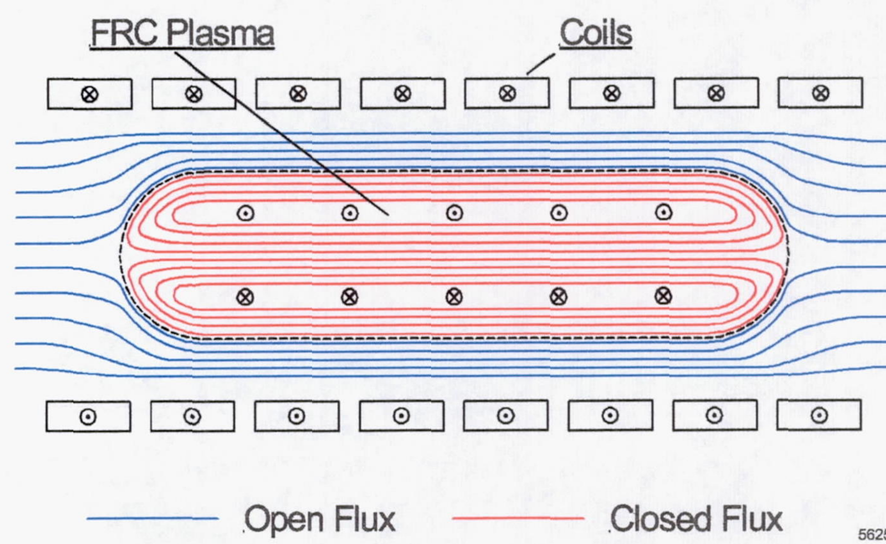
The Plasmoid Thruster Experiment (PTX)

- **The purpose of the Plasma Thruster Experiment (PTX) is to investigate the use of inductively formed, magnetized plasmas for space propulsion**
- **These plasmas have internal currents and embedded magnetic fields which contain the plasma and allow for inductive acceleration of the reaction mass.**
- **Both "Field Reversed Configuration" and "Spheromak" plasmas are being investigated**



Spheromak

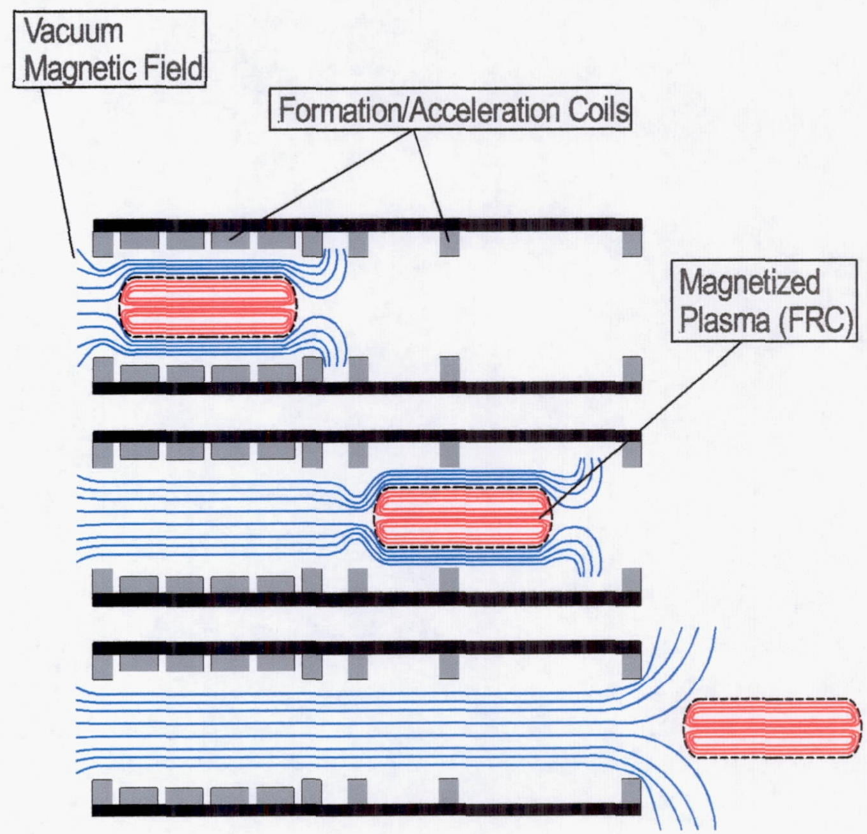
Field Reversed Configuration (FRC)



The Plasma Thruster Experiment (PTX)

Compact Toroid Propulsion

- Compact Toroids are repetitively formed (inductively) and magnetically accelerated
- This process is electrode-less
- Potential performance:
  - Jet Power: 10 kW – MW's
  - Specific Impulse: 5,000 – 15,000 s
  - Efficiency: 50 – 80 %
- Potential Applications:
  - Low power (P_{JET} < 100 kW), high specific impulse (I_{SP} > 5,000 s) missions
  - High power (P_{JET} ~ MW's), high specific impulse missions



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Advantages / Requirements of a Plasmoid Thruster

Advantages

- High I_{sp}: 5,000 s – 15,000 s
- High thrust density: $P_{chamber} = 10^5 - 10^6$ Pa
- Inductively formed – no electrodes
- Plasma exhaust is contained by integral magnetic field; this should aid in detachment, compared to nozzled thrusters
- FRC's are empirically well understood – the technology draws on results routinely obtained in FRC fusion research
- FRC's have already been accelerated to 250 km/s – yielding an "I_{sp}" equivalent of 25,000 s
- Potentially scalable to high powers (up to MW's) as the Jet Power is proportional to the rep-rate

Technological Requirements

- As this is a pulsed device, it requires:
- Rep-rates > 10 hz
- Recapture of inductive energy
- Either:

  Low-voltage (< 20 kV) formation and acceleration technology: Solid-state switches
- Or:

  High-voltage (10-40 kV) switches, and high energy-density capacitors
- **Much improvement required over existing technology**

Plasmoid Thruster Experiment

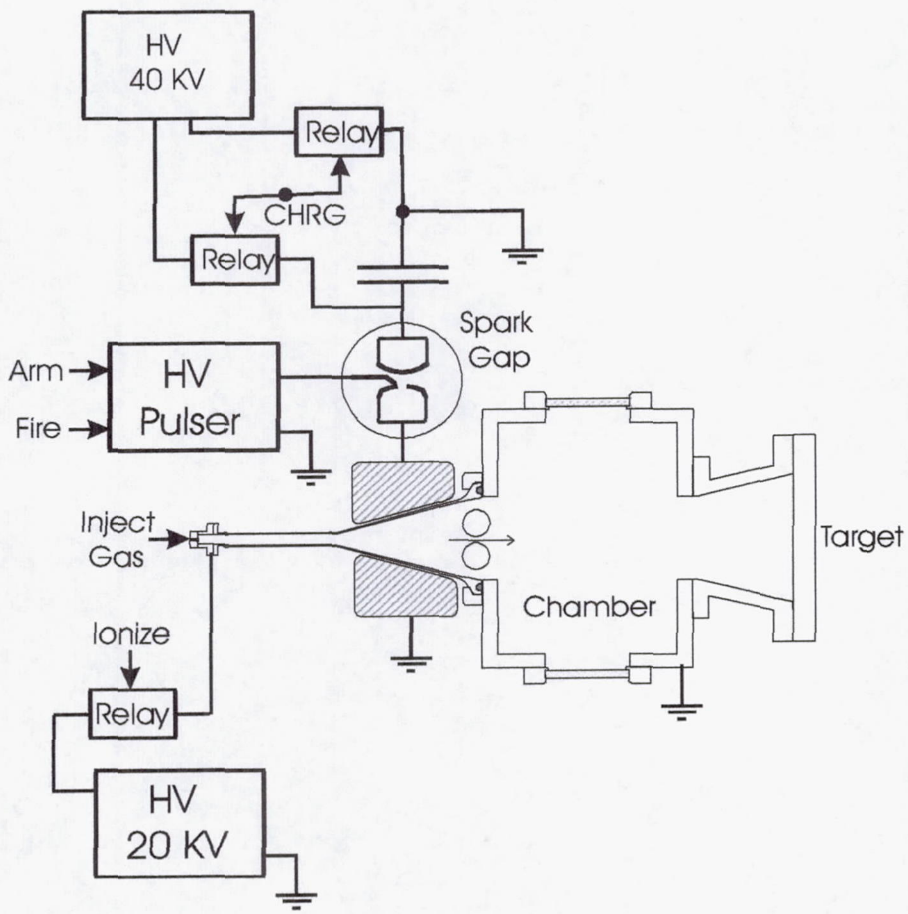
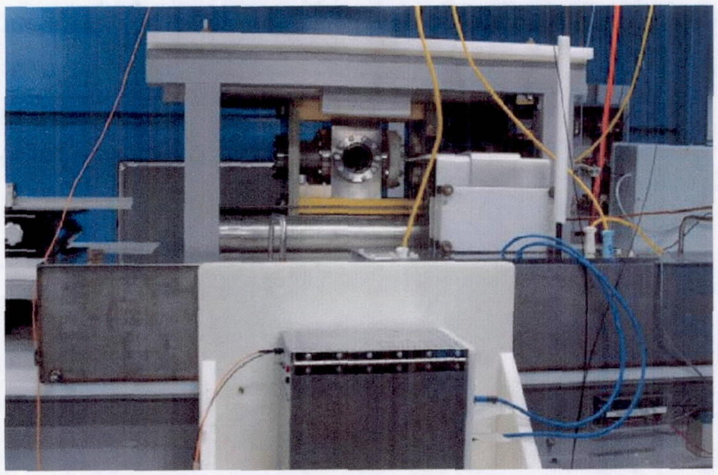
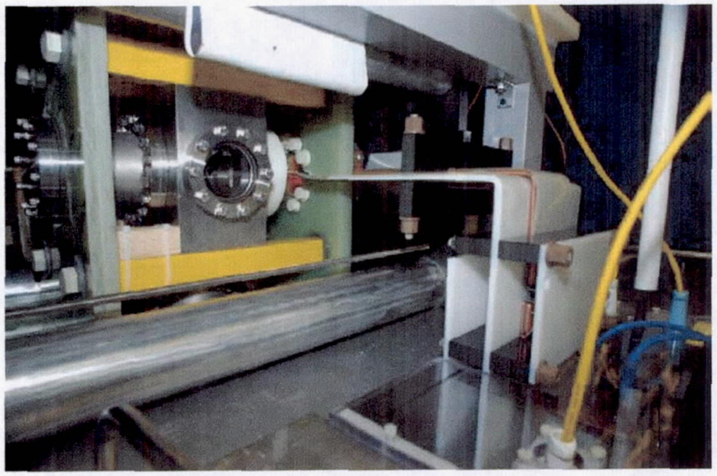


Diagram of Plasmoid Thruster Experiment



Plasmoid Thruster Experiment - Side View



Plasmoid Thruster Experiment - Oblique View

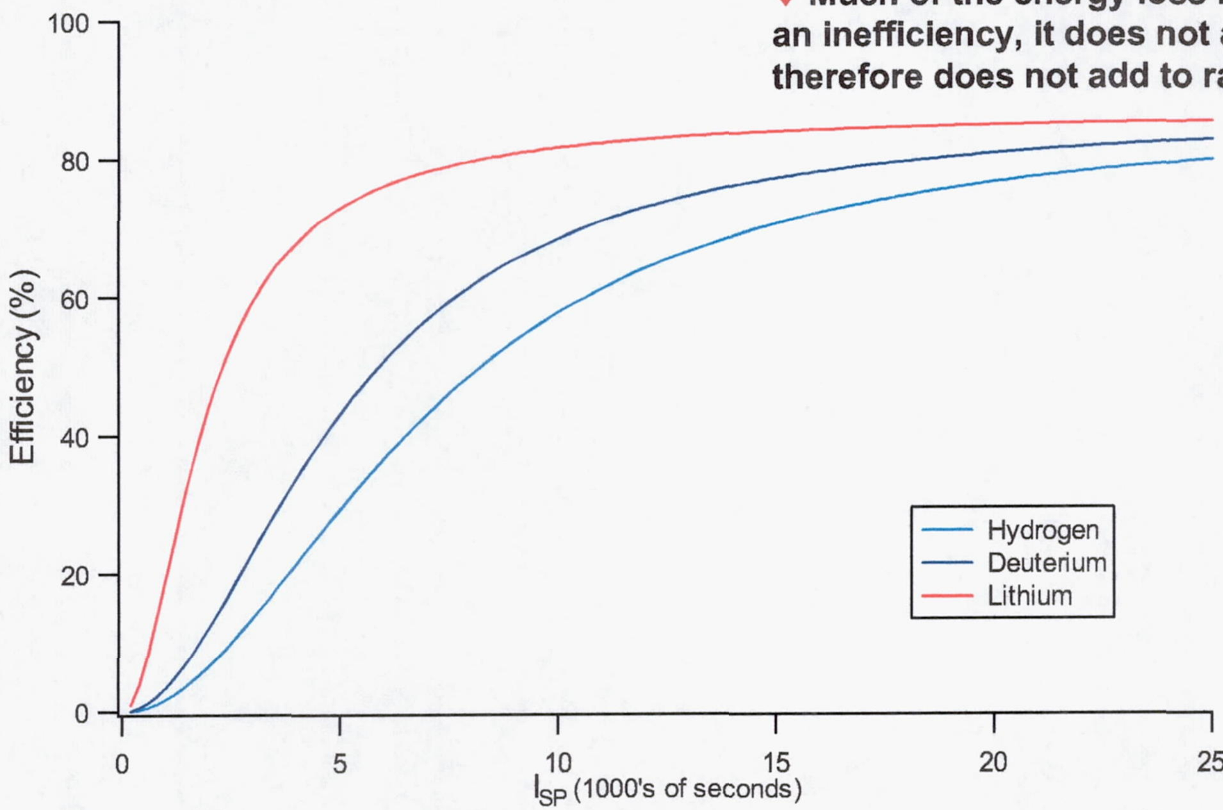
PTX- Projected Efficiency

Assumptions:

- Empirical FRC scaling laws
- Complete inductive recapture
- Resistive coils
- Impurity line-radiation losses included

Conclusions:

- Lower performance limit is likely around 5,000s I_{SP}
- Resistive losses are not catastrophic
- Internal energy of FRC is not a prohibitive frozen-flow loss; some of this may be recaptured when the plasma exits the nozzle
- Much of the energy loss is in the flow. Although it is an inefficiency, it does not appear as waste-heat (and therefore does not add to radiator mass).



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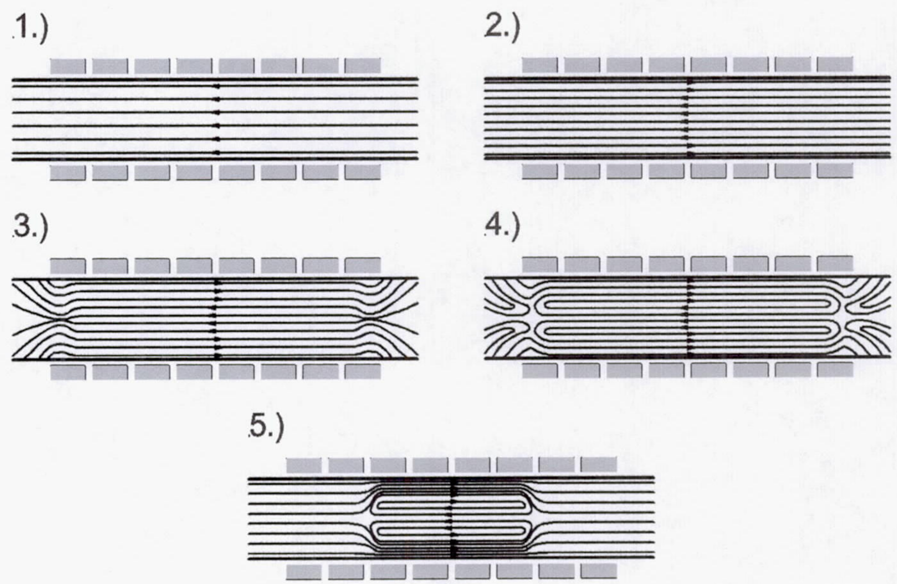
Compact Toroid Theta-pinch Formation

- The FRC is made in a formation stage (theta-pinch compression, shown at right)
- It is then propelled to high velocity in an acceleration stage by compressing the magnetic field behind it: v = 20 – 100 km/s
- Thrust is determined by the plasma density and the rep-rate (subject to power constraints)
- Initially, we will begin by making a single FRC and accelerating it
- Later, if the concept proves out, the system will be upgraded for burst mode operation (5-10 cycles)
- Other formation techniques, such as RMF (Rotating Magnetic Field) may be tried

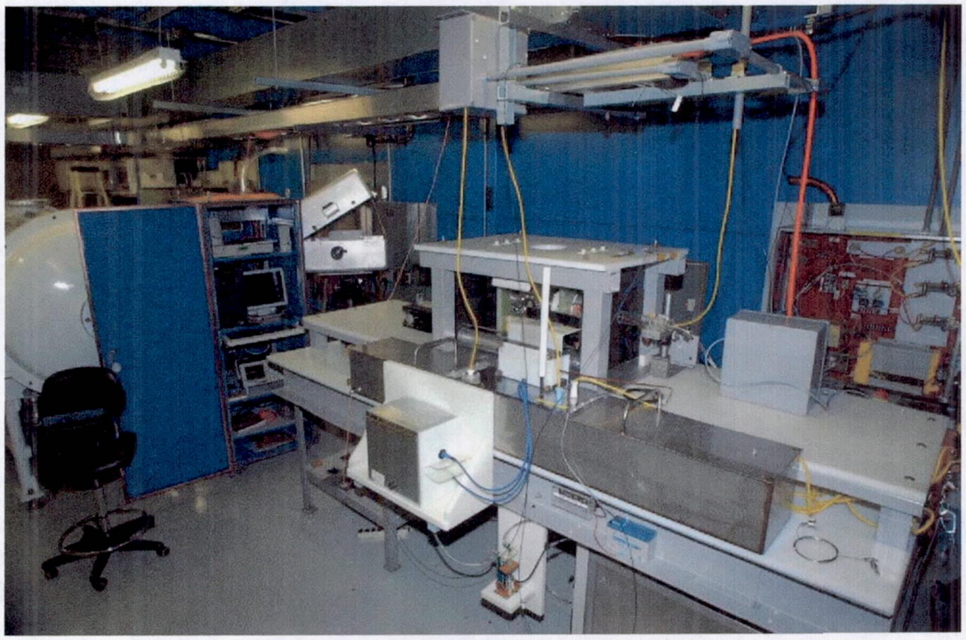


<u>Of key importance is to determine limits to</u>:

- Efficiency (plasma purity, resistive losses, inductive losses, etc.)
- Rep-rated operation/ mass injection
- Inductive recovery of “ringing” field energy

Plasmoid Thruster Experiment (PTX)

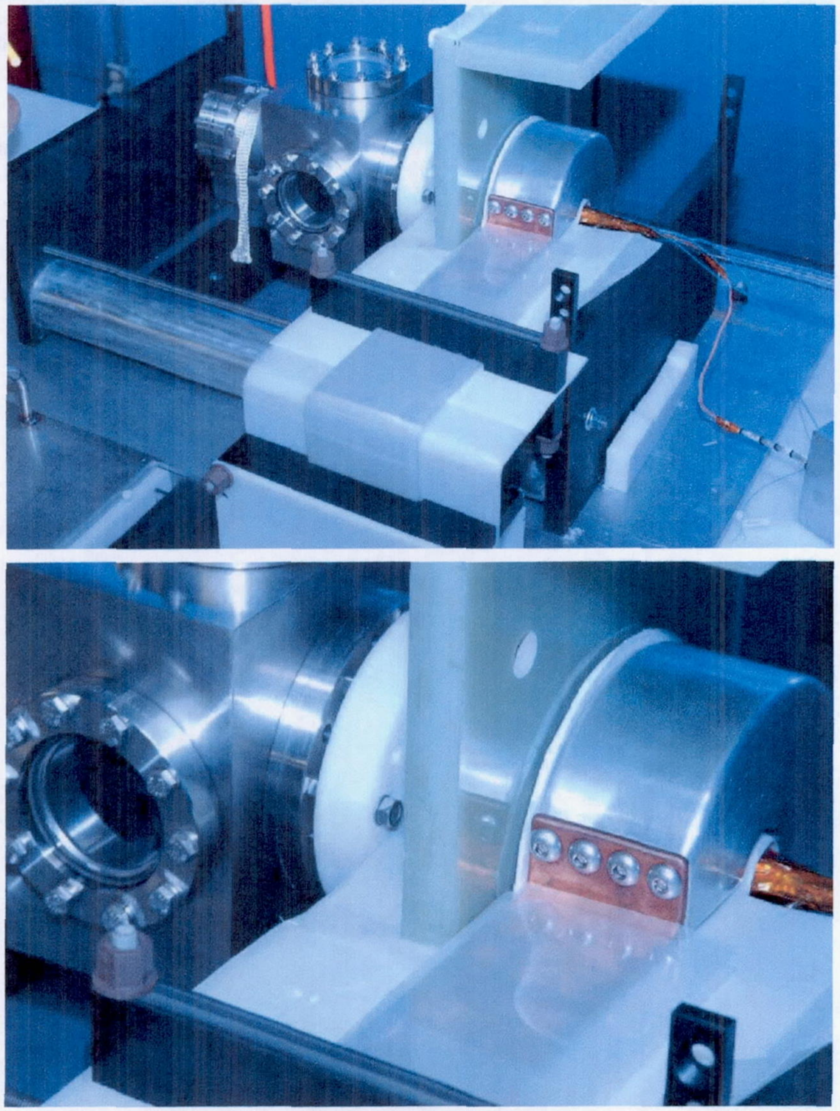
- Plasmoid Thruster inductively forms and magnetically accelerates plasmoids (compact toroids) using a conical theta-pinch coil
- Conical theta pinches were previously investigated for fusion applications by Wells, Pietrzyk, Kawai, etc. Their work did not address propulsion relevant questions
- This experiment makes use of existing hardware
- Uses same control and trigger system as proposed larger FRC machine (FAST)
- Serves as a precursor experiment to the FRC
- Earliest path to allow system development and integration



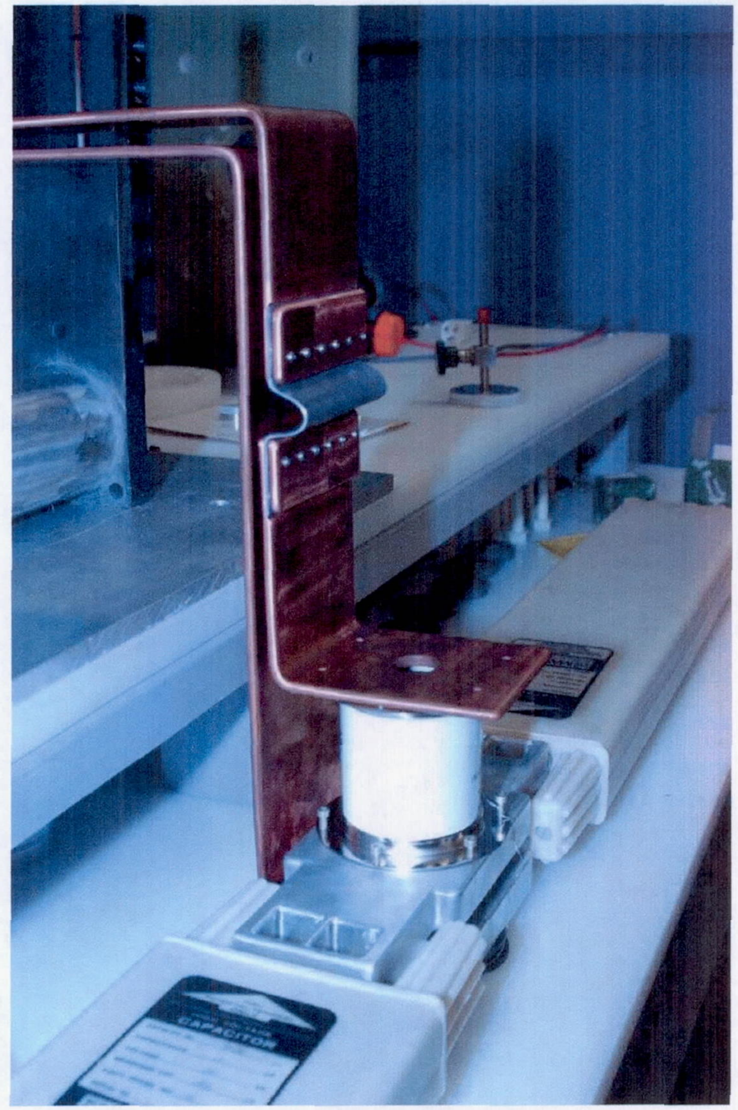
Plasmoid Thruster Experiment - Laboratory

- Scale of this experiment readily permits upgrade to repetitive operation (smaller power supply)
- Platform for diagnostics development

Plasmoid Thruster Experiment

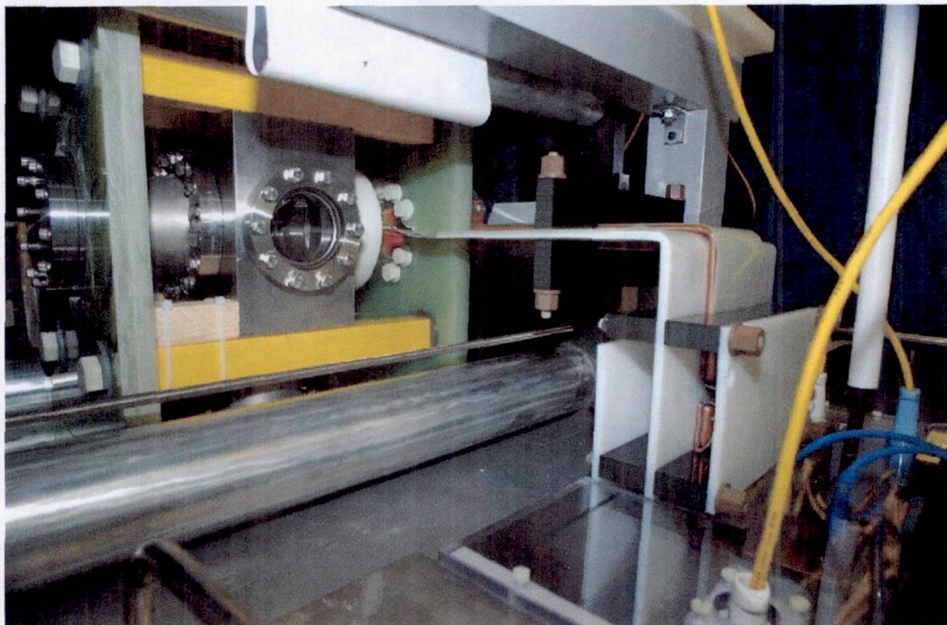


Plasmoid Chamber, Theta-Pinch Coil, and Bus

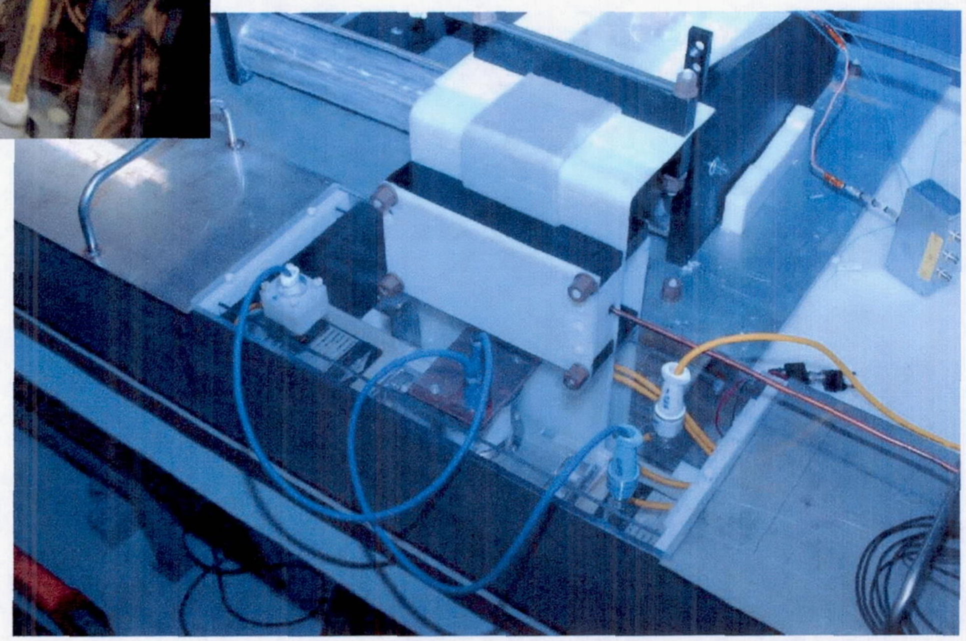


Capacitors, Switch and Bus

Plasmoid Thruster Experiment



Plasmoid chamber and Bus structure



Capacitor bank (in oil tank) with spark gap switch

Plasmoid Thruster Experiment

Simulation of PTX Coil/Bank Circuit using SPICE:

Assumed Circuit Component Values

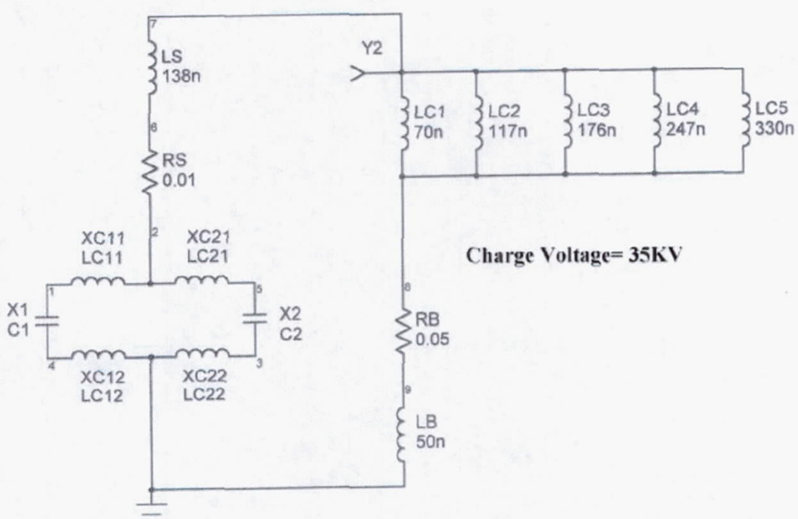
$C = 640$ nF
$L_{ext} = 194$ nH
$L_{coil} = 28$ nH
$V_{charge} = 35$ kV
$\Delta t = 10$ ns

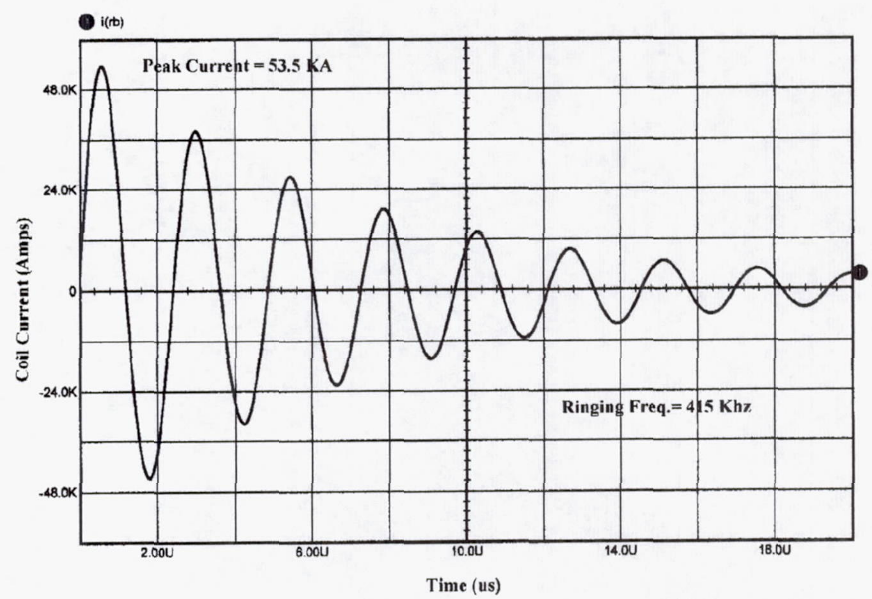
SPICE Simulation Results

$I_{PEAK} = 53.5$ kA

$t_{1/4} = 0.602$ ms

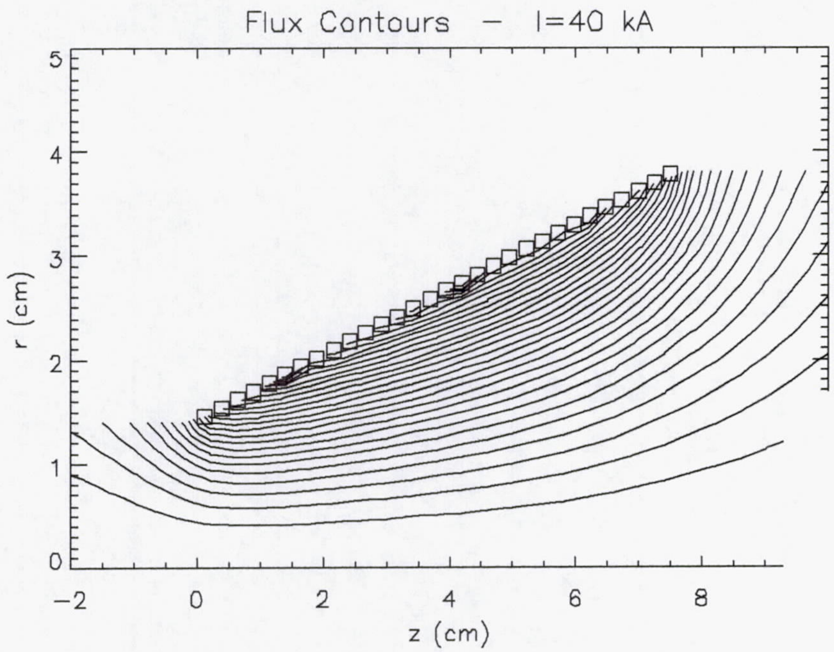
Five Zone Conical Theta Pinch Model

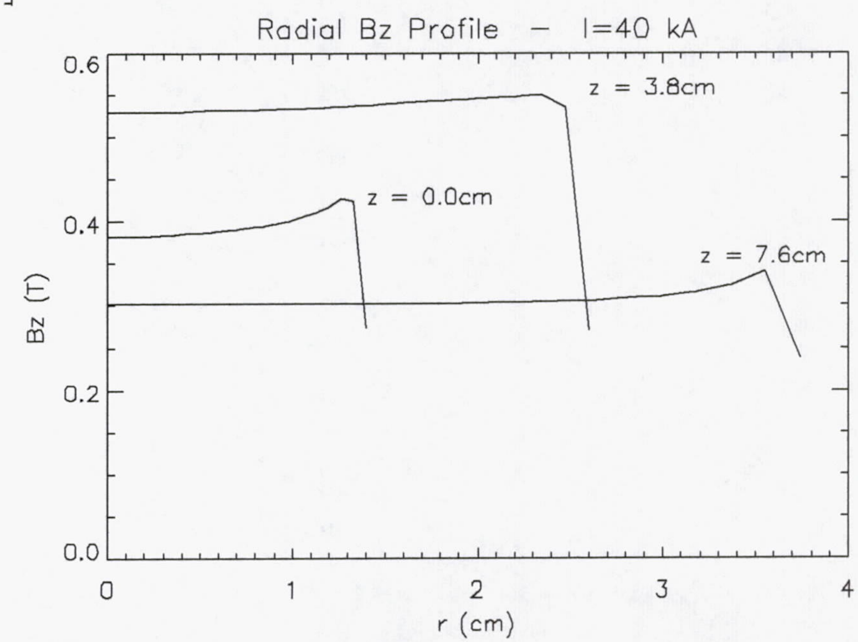




Plasmoid Thruster Experiment

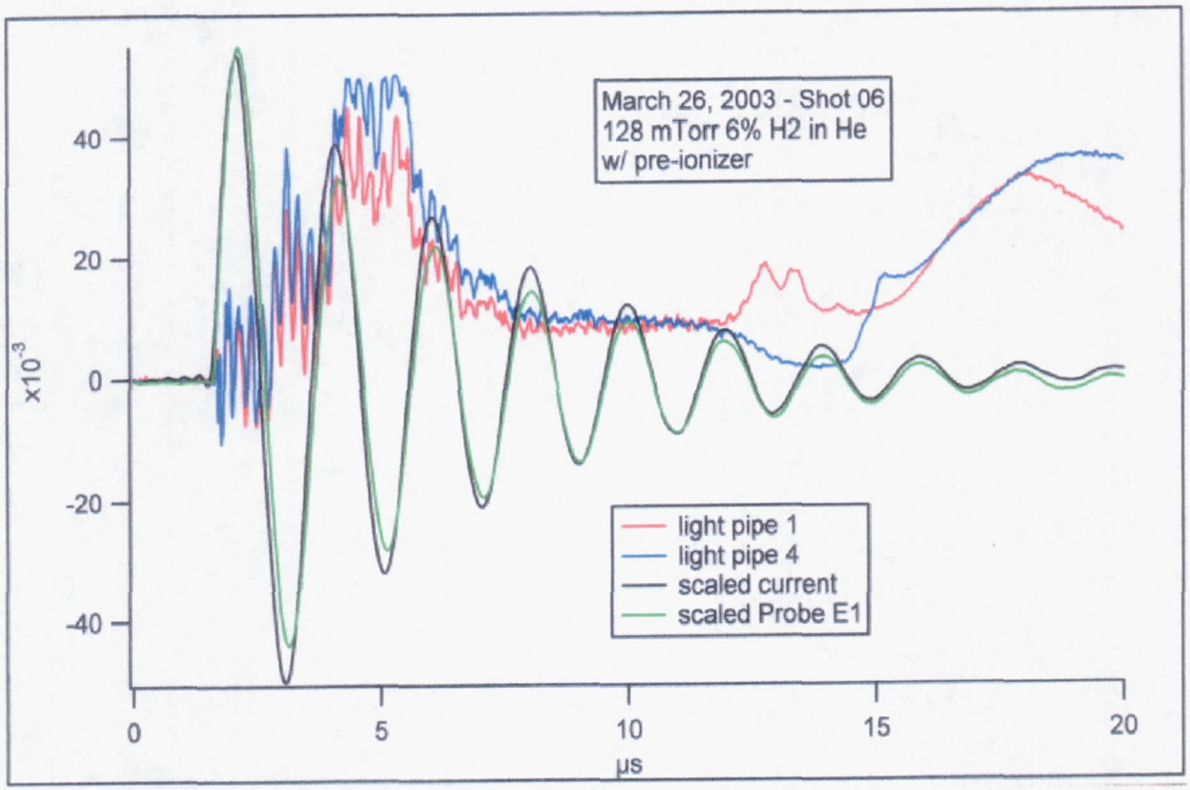
Theta-pinch Coil produces a magnetic field of up to 5 kgauss:



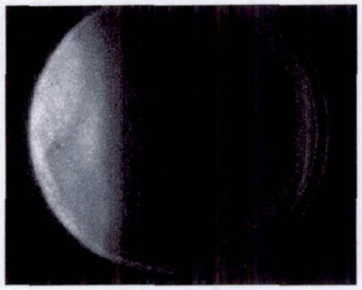


Plasmoid Thruster Experiment

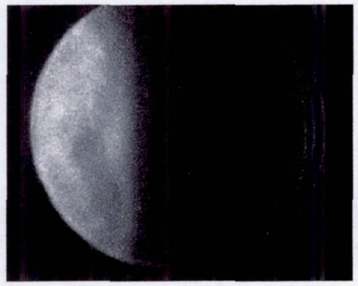
Test Firing of PTX Capacitor Bank:
•Charge voltage = 35 kV, Peak current = 52 kA - predicted by SPICE
• Photomultiplier Measurements give “Time of Flight” velocity measurements
•Velocity of 20 km/sec at light pipe position (propagating into backfill gas)
•Implosion velocity > 100 km/sec



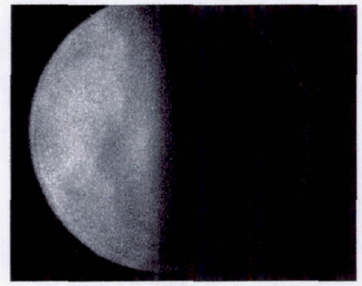
Plasmoid Thruster Experiment



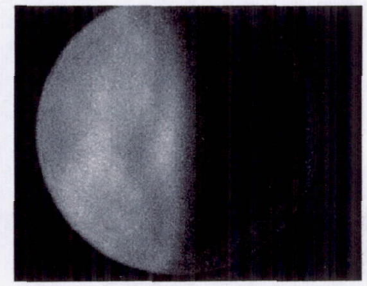
21 us



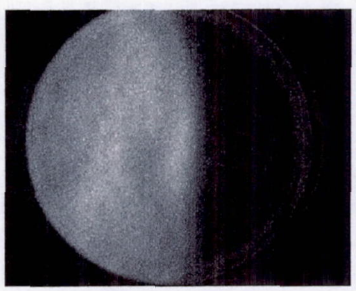
22 us



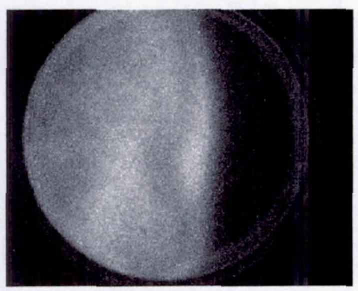
23 us



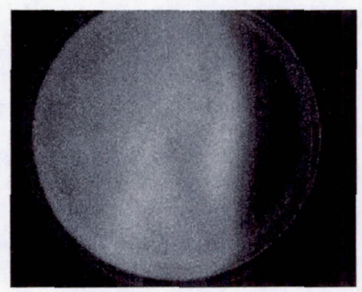
24 us



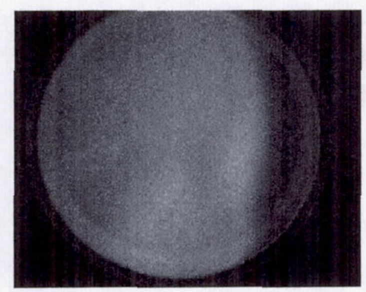
25 us



26 us



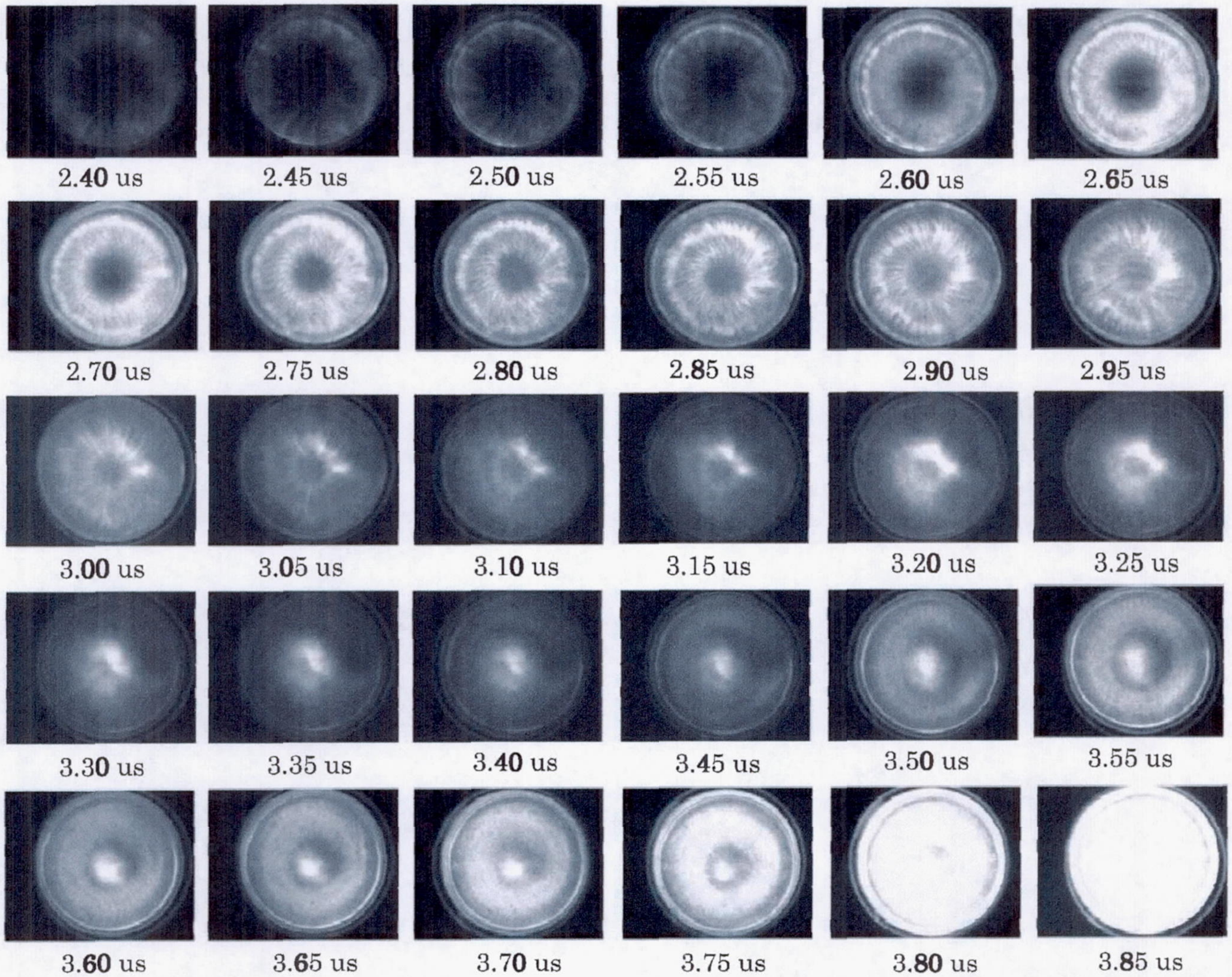
27 us



28 us

Propagating Plasmoid in Air at 43 mTorr backfill pressure (Side View)
Velocity for this test was 5.3 kilometers/sec.

The Plasmoid Thruster Experiment (PTX)



Time development of Plasmoid (view into throat of pinch coil). The coil current was 53.5 KA.
Exposure time: 20 ns, time between frames- 50 ns. Pressure: 125 mTorr, Gas- 6% H_2, Bal He

PTX Diagnostics

Diagnostics planned for use in the next year (on PTX):

- **Excluded Flux Array**:
  An axial array of flux loops and B-dot probes measures r_s along the FRC through the relation:
  $$F = B p(r_l^2 - r_s^2)$$
  From r_s, b may be found from:
  $$<b> = 1 - r_s^2 / (2\, r_c^2)$$

- **High-speed Photography**:
  For imaging plasmoids in the exhaust chamber
  - PI-Max gated CCD cameras
  - Hamamatsu streak camera
  - Cordin 100 Mframe/s framing camera

- **Internal Magnetic Field Probes**:
  Measure shape and magnetic structure of translating plasmoid

- **Langmuir Probes**:
  Makes local measurement of n_e and T_e

- **Interferometry** :
  Heterodyne, quadrature He-Ne interferometer: line-averaged n_e for plasma inventory measurement

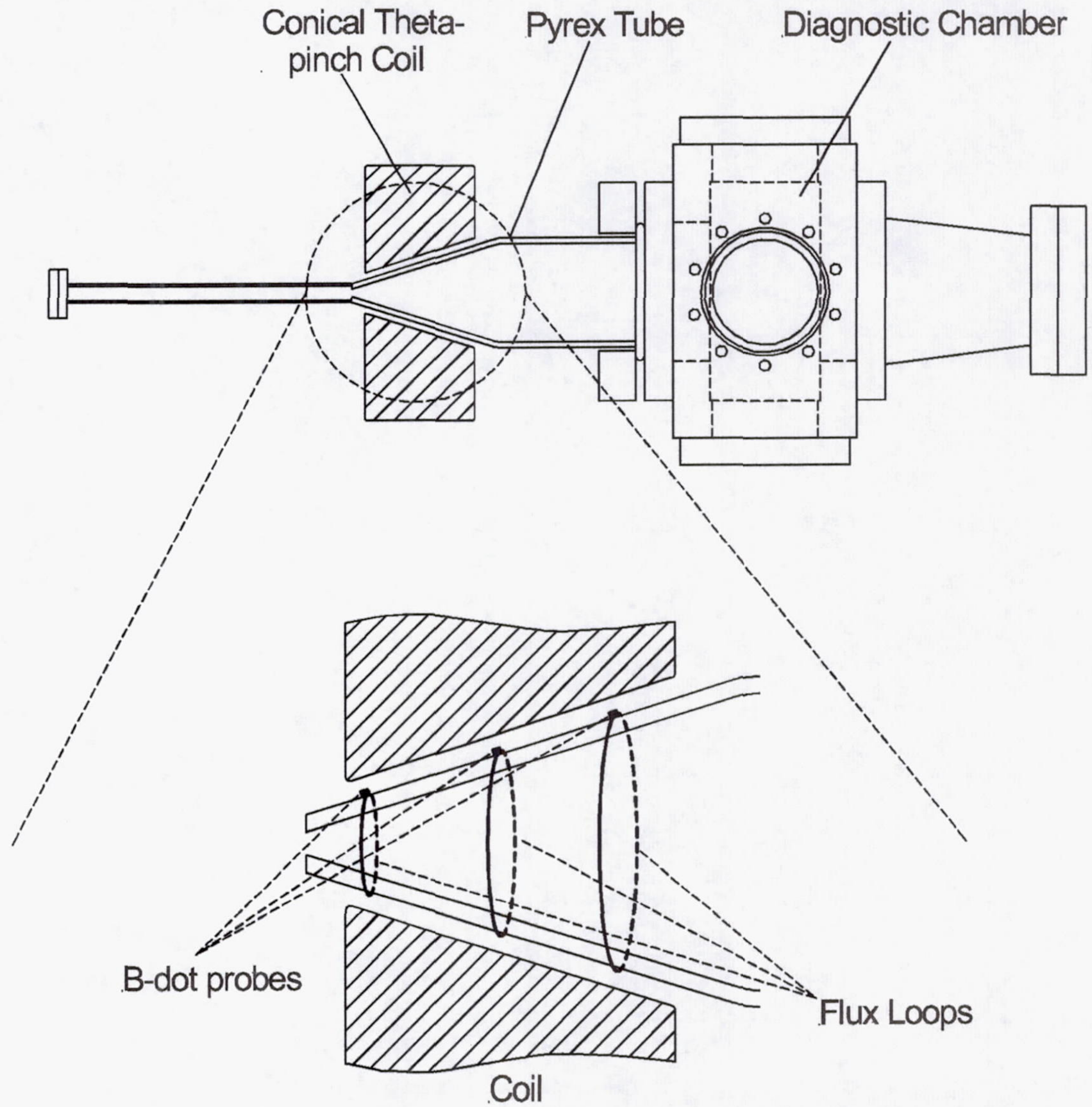
Additional Diagnostics:

(as needed)

- Thomson scattering: local T_e
- Ion Doppler Broadening: local T_i
- Bolometry: Radiated Power
- Faraday Rotation Probe: local magnetic field
- X-ray Spectrum Analyzer†
- X-ray Camera†

† For Fusion

Excluded Flux Array (shown on the PTX chamber)



An axial array of flux loops and B-dot probes measures r_s (separatrix radius) along the FRC through the relation:

$$F = B\,\mathrm{p}(r_l^2 - r_s^2)$$

From r_s, β may be found from:

$$\langle b \rangle = 1 - r_s^2 / (2\, r_c^2)$$

Simulations using MOQUI

- MOQUI is a 2-D, single fluid code that solves the resistive MHD equations of motion
- It's related to MACH, but has been specialized for use with Theta-pinches
- Electron inertia is neglected
- Has the following Ohm's Law:

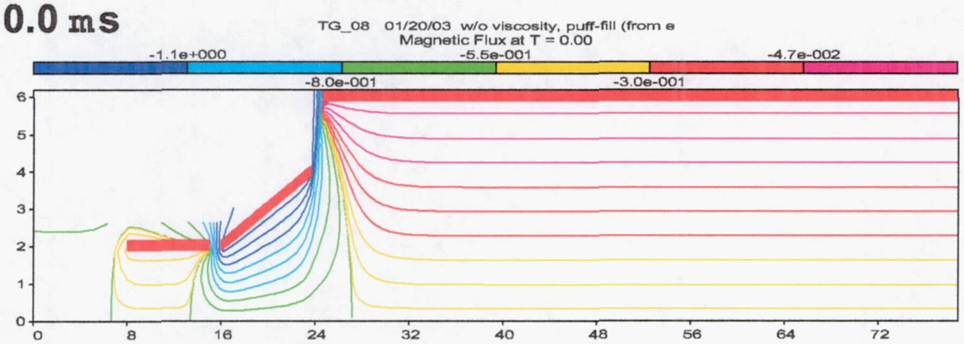
$$\vec{E} = -\vec{v}_i \times \vec{B} + \left[\eta_{\parallel}\vec{J}_{\parallel} + \eta_{\perp}\vec{J}_{\perp} - \eta_{\wedge}(\vec{b}\times\vec{J})\right] + \frac{1}{en_e}(\vec{J}\times\vec{B}) - \frac{1}{en_e}\nabla P_e + \frac{1}{en_e}\vec{R}_T$$

which includes parallel, perpendicular, and transverse resistivities, Hall term, electron pressure, and Braginskii term

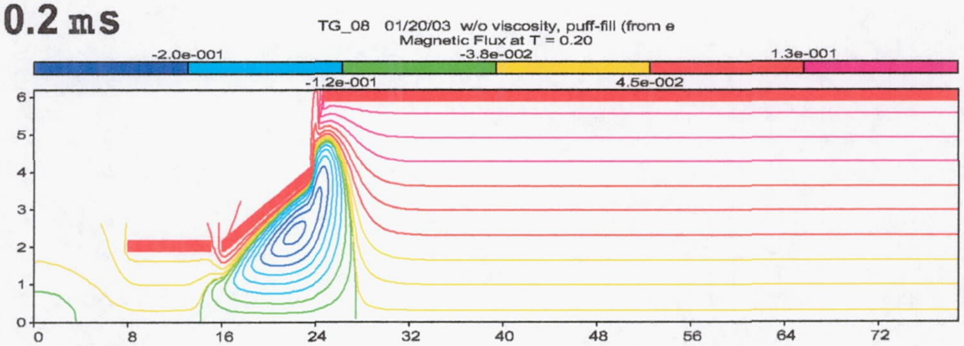
- Includes three resistivity models:
  - Classical (Spitzer)
  - Chodura (empirical)
  - LHD (Lower Hybrid Drift Instability)
- MOQUI and Post-Processor furnished by R. Milroy at RPPL, University of Washington

Simulation of PTX using MOQUI

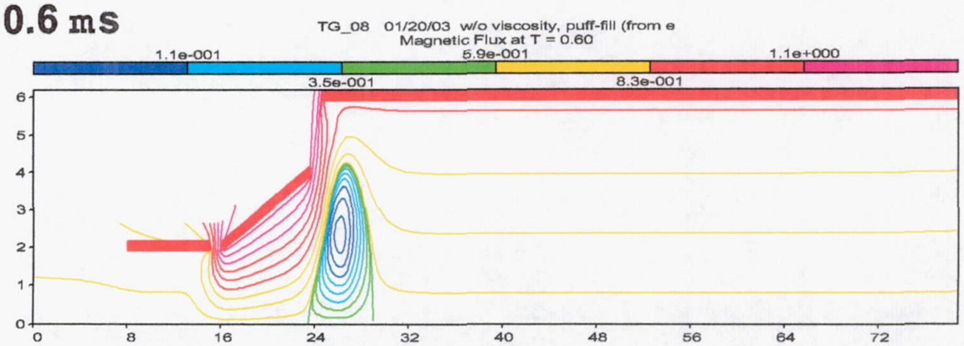
t = 0.0 ms



t = 0.2 ms



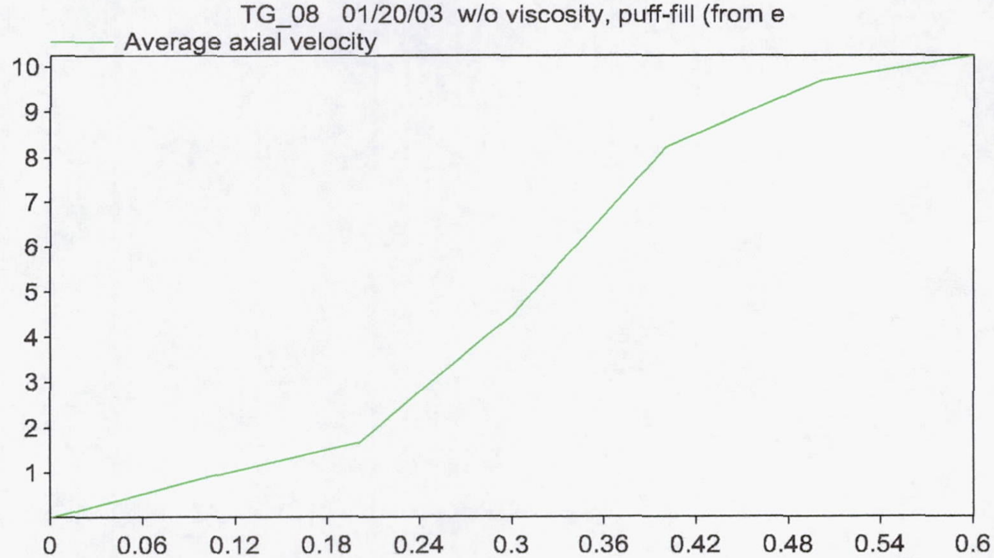
t = 0.6 ms



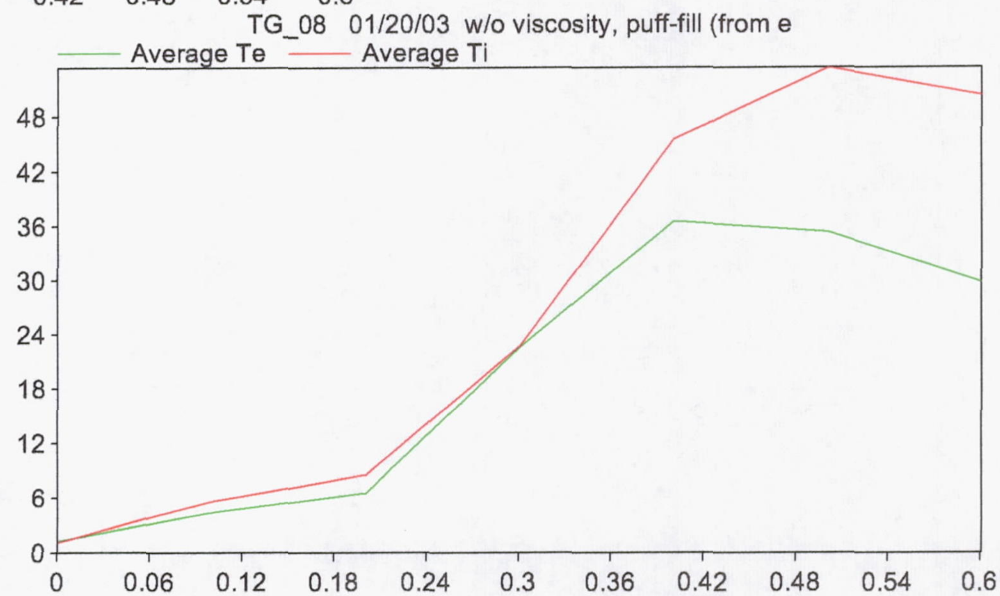
Conditions:

- B_{bias} = 200 gauss
- I_{coil} = 40 kA
- Gas: Hydrogen
- Puff-fill at 20 mTorr

Simulation of PTX using MOQUI



Axial Velocity (cm/ms) of plasmoid. Peak velocity of 100 km/s reached after 0.6 ms



Electron and Ion Temperature

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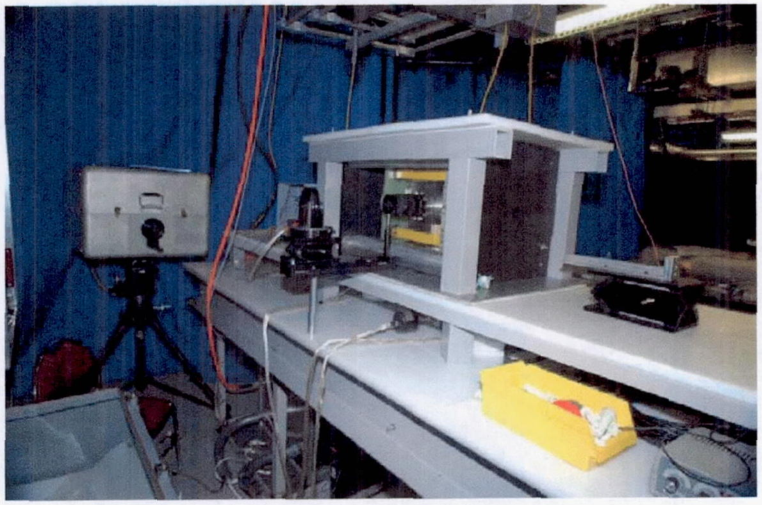
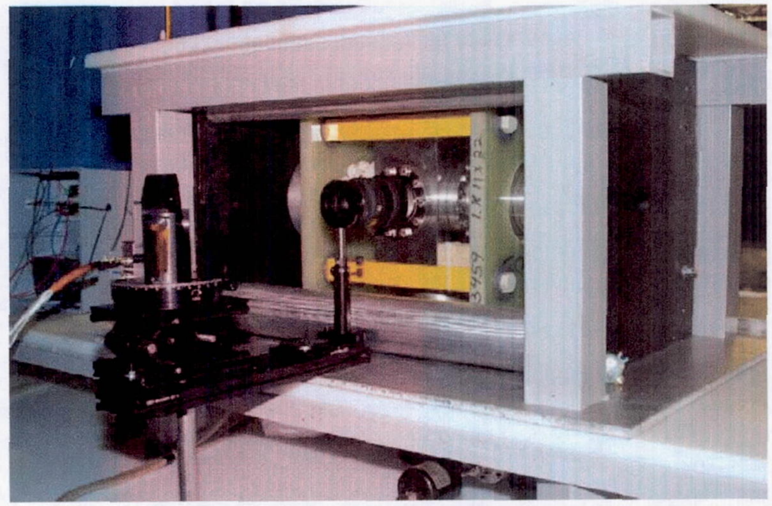
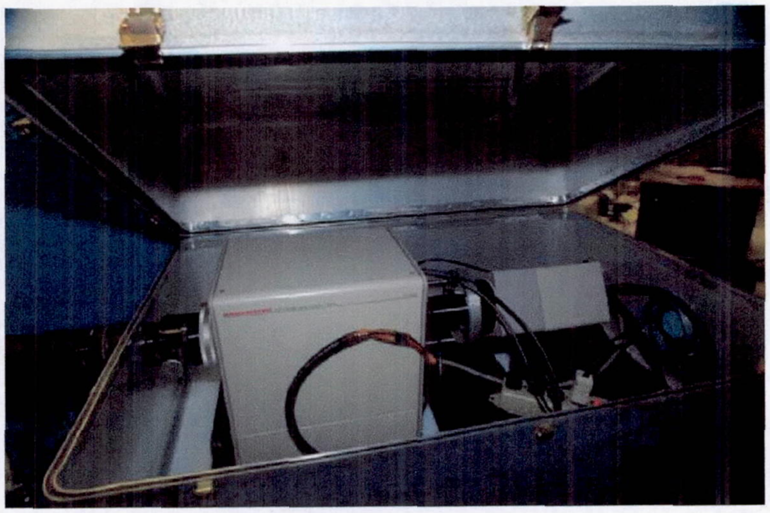
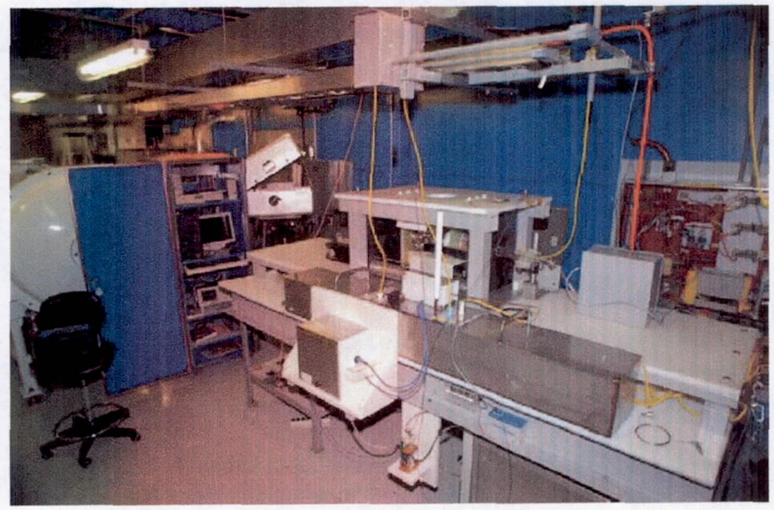
The Plasmoid Thruster Experiment (PTX)









The Plasmoid Thruster Experiment (PTX)

Future Work

Near Term (4-6 months)

Development of fast preionizer
- Installation of Gas Injection system
- Rep-rated operation (2-3 second bursts)
- Determination of mass loading, momentum
- Diagnostics- Excluded Flux Array, Langmuir Probes and He-Ne Interferometer

Far Term

- Phase II design- higher power
- Acceleration Stages
- Power recovery to boost efficiency

References

Kawai, K., Z.A. Pietrzyk, and H.T. Hunter, "Generation of poloidally rotating spheromaks by the conical theta pinch, Phys. Fluids, 30 (8), August 1987.

Wells, D.R., E. Nolting, F. Cooke, Jr., J. Tunstall, P. Jindra, and J. Hirschberg, ", "Adiabatic Compression of Plasma Vortex StructuresPhysical Review Letters, 33, No. 20., Nov. 1974.

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