PT-1 Plasmoid Thruster capable of multi-mode operation

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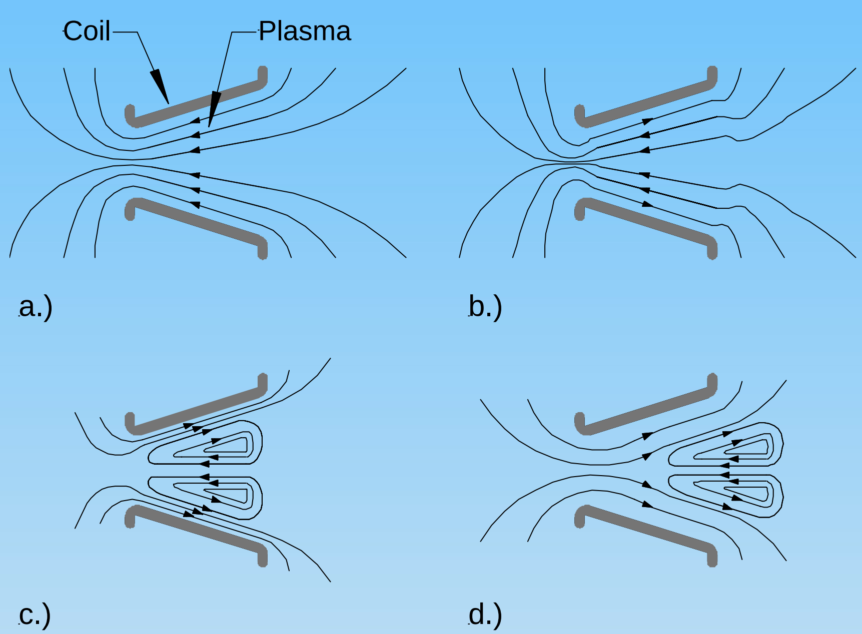
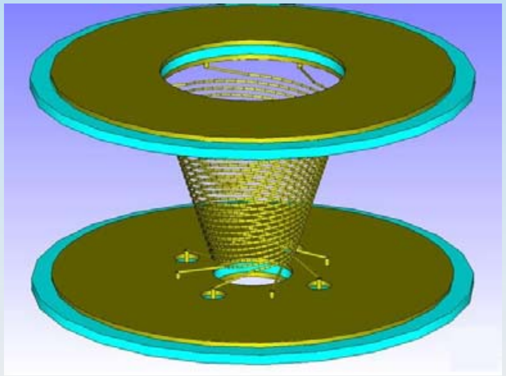
Review - What is a “plasmoid” thruster



Left: formation sequence of a plasmoid.

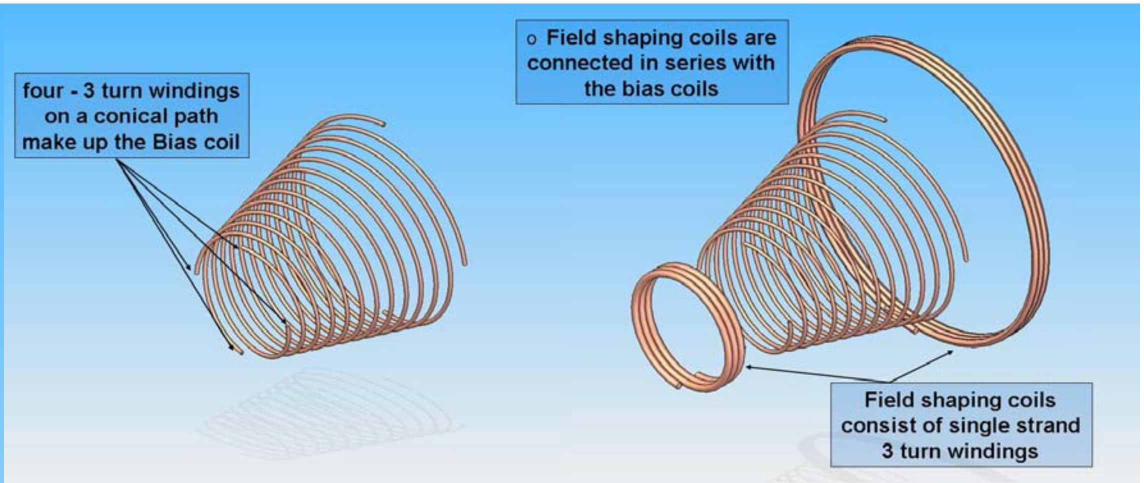
(a) “BIAS” field is embedded in a pre-ionized plasma
(b) “DRIVE” coil fires and imposes a stronger and reversed field
(c) The reversed “DRIVE” field intensifies, causing the “BIAS” field lines to break and reconnect ,forming a plasmoid
(d) “DRIVE” field expels the plasmoid from the coil at high velocities

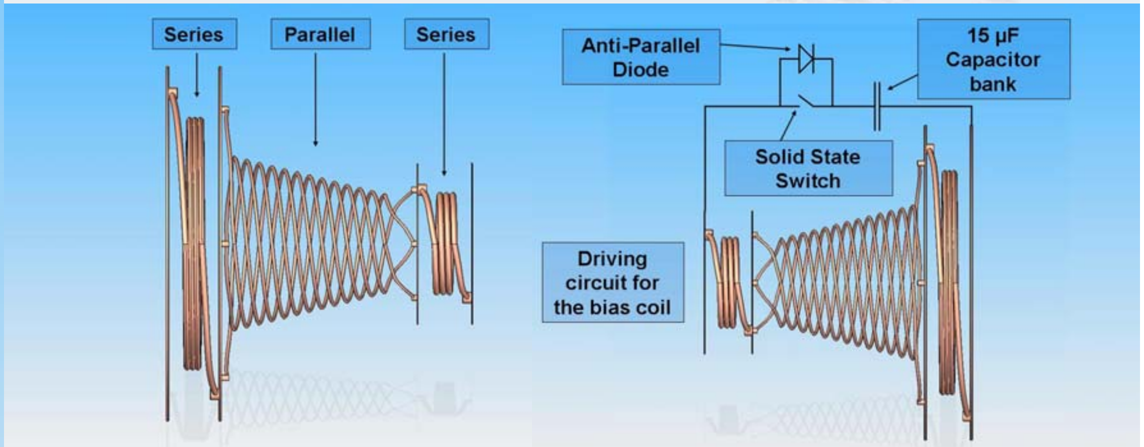


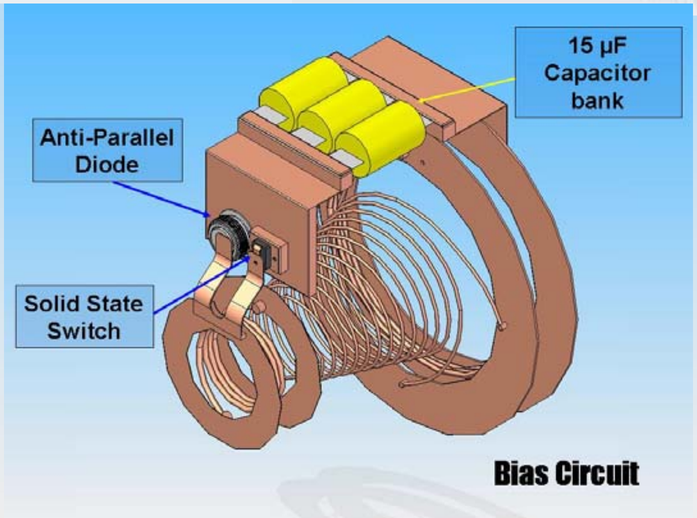
In the PT-1, the “DRIVE” and “BIAS” coils are helically inter-wound, 4 lead, 3 turn coils, with a 16.6° half-angle conical form.

Bias Circuit

- **Bias coil :**
  - **4 lead, 3 turn coils, on a 16.6° half-angle conical form**
- **Field shaping coils:**
  - **single lead, 3 turn coils with no conical angle**
  - **fore & aft of the bias coil**
- **Inductance of bias circuit: 4.1 +/- 0.1 μH**
  - **includes the bias coil & field shaping coils**
- **Bias circuit resistance: 44 +/- 1 mΩ**
- **Bias circuit unloaded frequency: 20 kHz**
  - **25 μsec half cycle time**
- **Bias circuit capacitor charging bank: 15 μF**
  - **charged from an floating battery source**
- **Solid State switched**
  - **Applied pulsed power, model S 38**
- **Maximum voltage : 4 kV**
  - **Typical operational voltage: 1.5 to 2.0 kV**
- **Peak Current (approx.): 7.65 kAmps for an initial charge of 4 kV**







Drive Circuit

- Drive coil :
  - 4 lead, 3 turn coils, on a 15° half-angle conical form
  - Drive & bias coils are wound together on a common mandrel

- Inductance drive circuit: 633 +/- 10 nH

- Drive circuit resistance: 13 +/- 1 mΩ

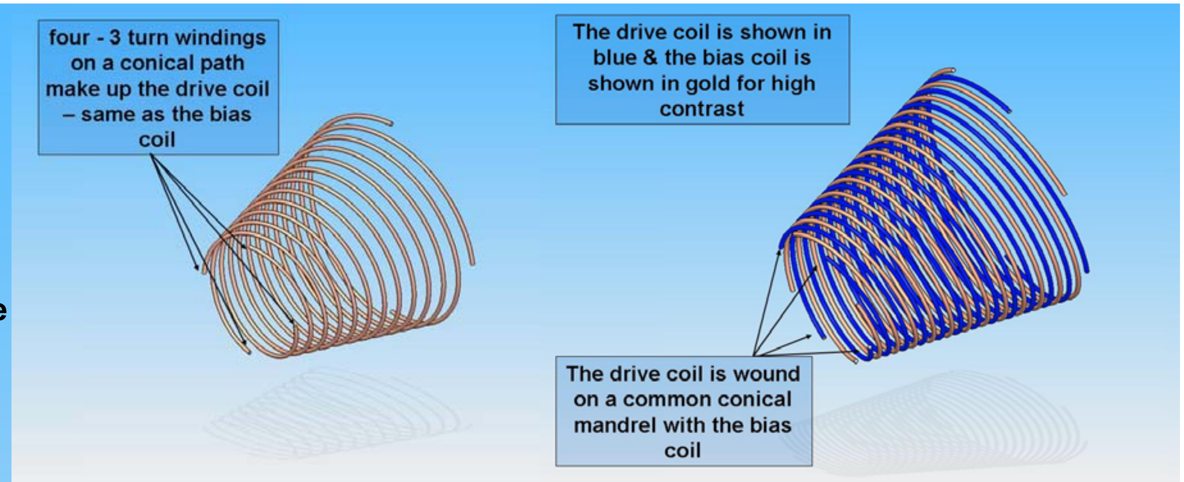
- Drive circuit unloaded frequency: 52 kHz
  - 9.5 μsec half cycle time

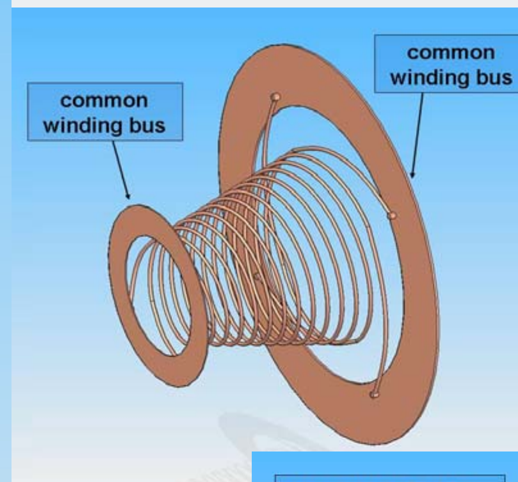
- Drive circuit capacitor charging bank 15 μF
  - charged from an floating battery source

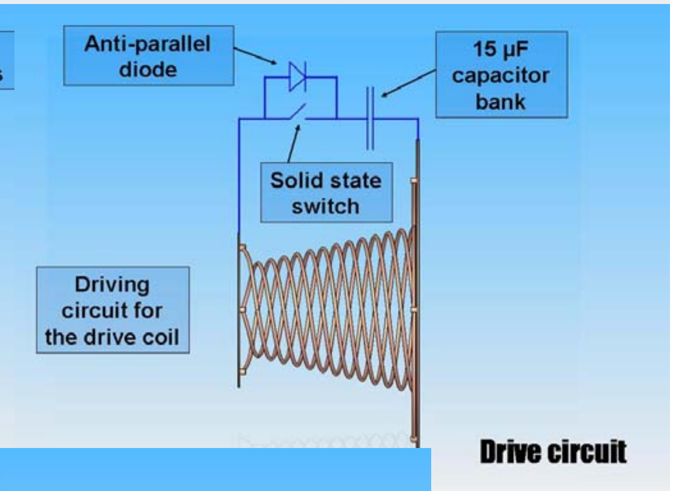
- Solid State switched
  - Applied pulsed power model S 29-6-2

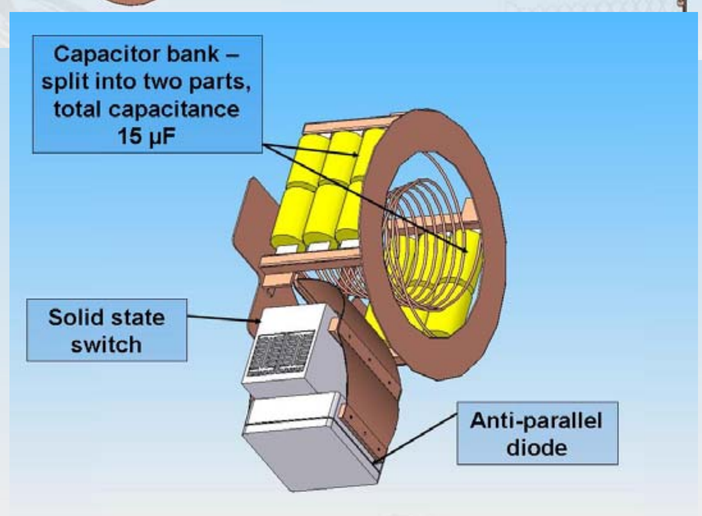
- Maximum voltage : 8 kV
- Typical operational voltage: 3.0 to 4.0 kV

- Peak Current (approx.): 39 kAmps for an initial charge of 8 kV





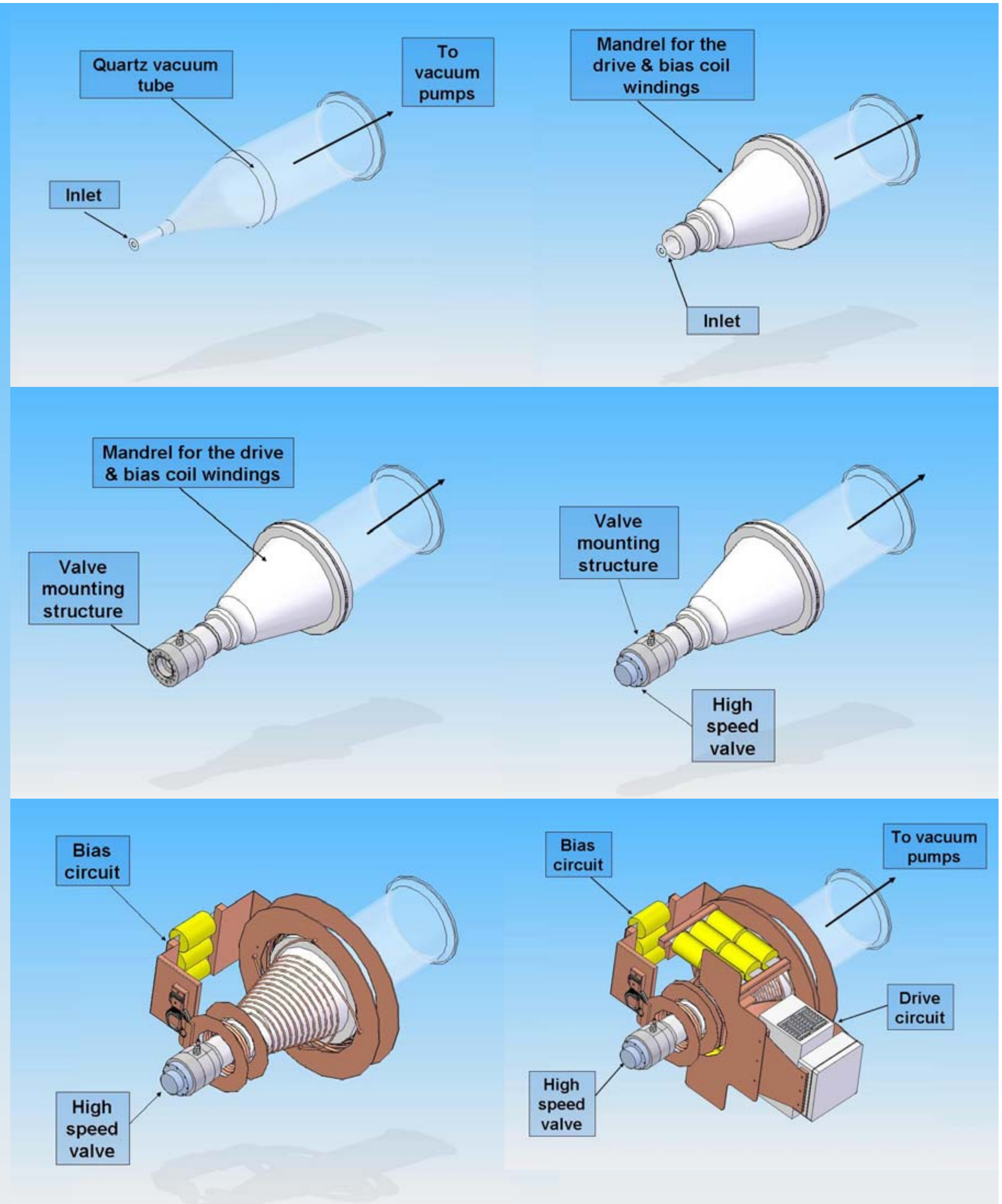




Gas Distribution

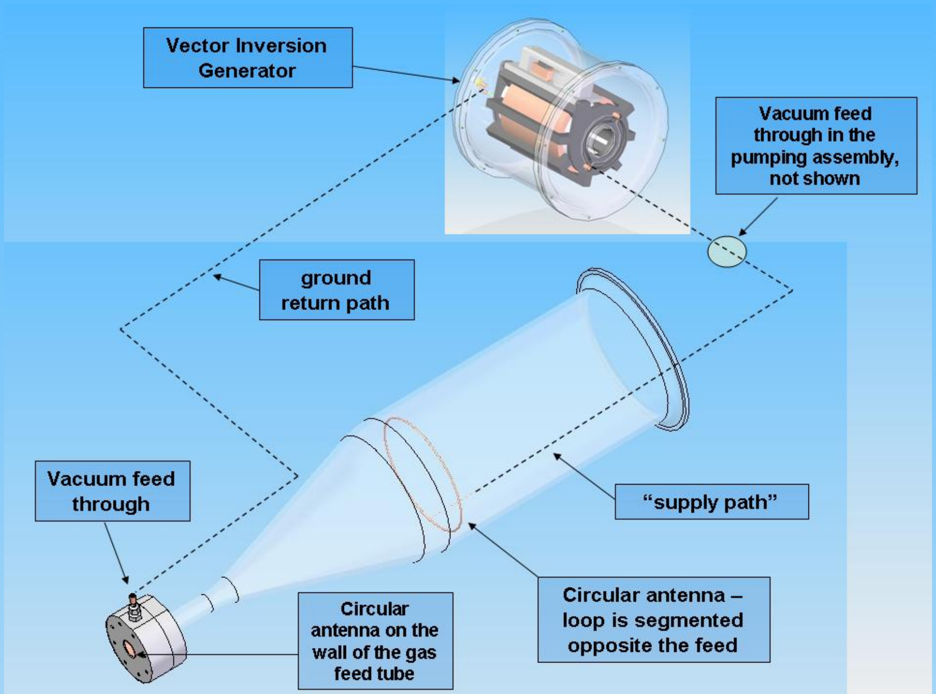
The gas is pulsed into an enclosed vacuum space constructed of pyrex glass. Vacuum is provided by a turbo pump & scroll pump combination

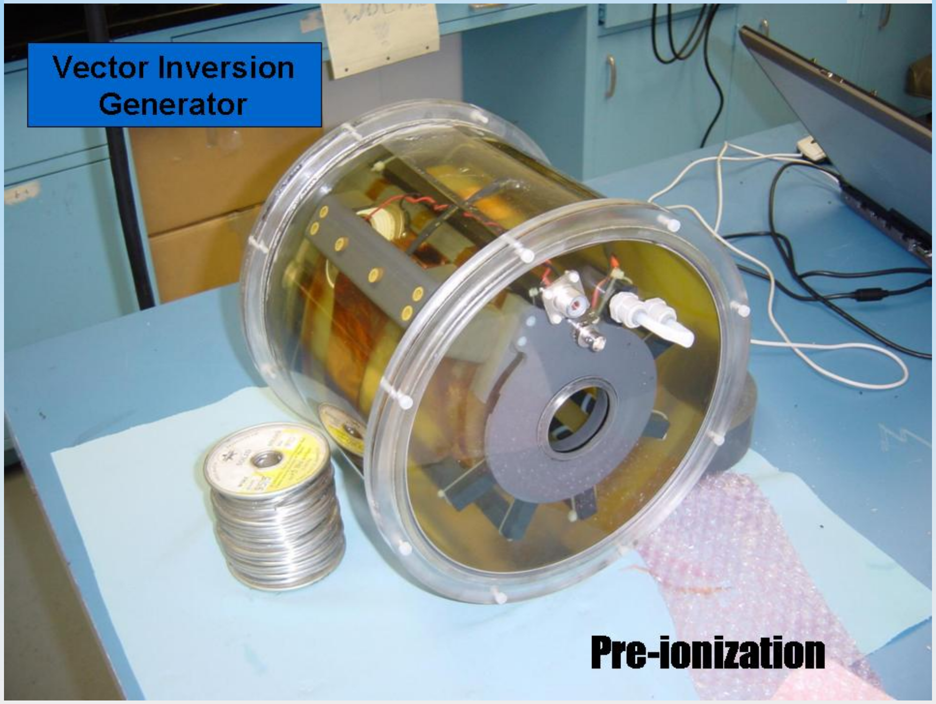
- **The vacuum enclosure sits inside the conical windings of the drive & bias coils**
- **Test gas is Argon**
- **A High speed valve is used to pulse the Argon into the vacuum space**
  - **The valve can cycle open & shut in under 70 µsec**
- **Mass bit delivered by the valve is calibrated by supply pressure**
  - **Capable of delivering from 50 µg to ≥ 350 µg per pulse based on current calibration data**
  - **Target mass bit per pulse is 140 µg**
- **The gas distribution has not yet been measured & distribution timing is based on gas dynamic estimates**



Pre-ionization

- Pre-ionization increases coupling efficiency
- This method was chosen to provide pre-ionization at a minimum energy cost per pulse
- Pre-ionization is accomplished through capacitive coupling to the Argon shortly after it is pulsed into the vacuum chamber
- A Vector Inversion Generator (VIG) is used as the voltage source
    - The VIG is a spiral wound capacitor that provides pulse compression and voltage multiplication
    - 30 to 50 kV, 1 Mhz oscillating pulsed source (approx. 3 cycles)
    - Each discharge is < 0.2 Joules
- The voltage potential is erected axially across the pulsed Argon gas between two circular antenna arrays at the fore and aft ends of the coil structure



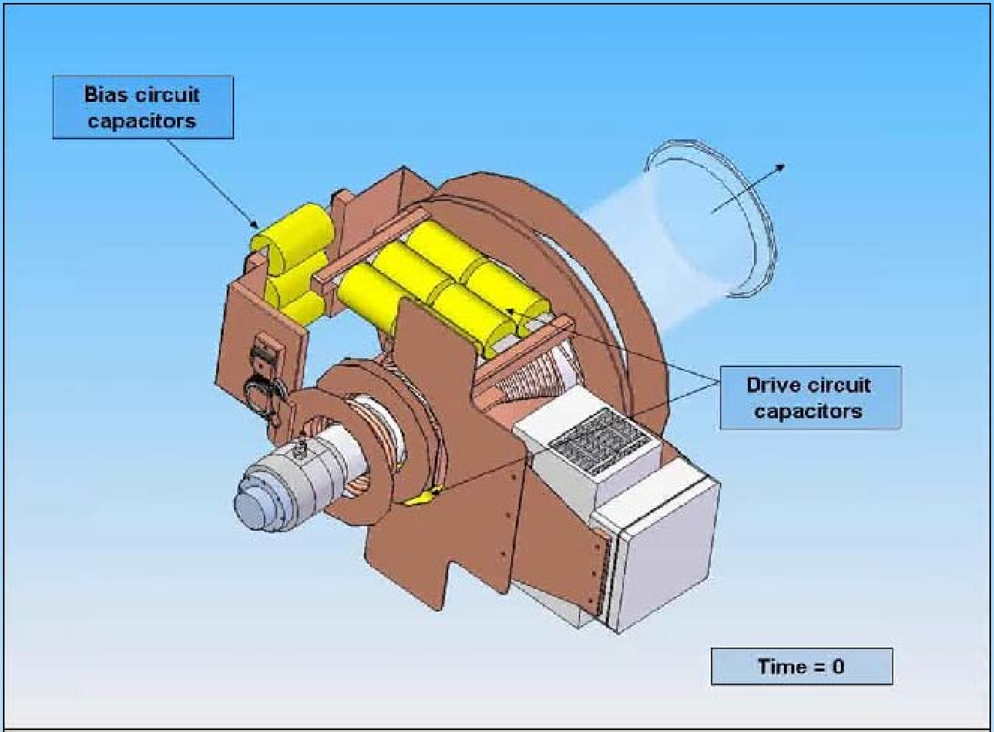


PT – 1
Plasmoid Thruster

Operation sequence

- The thruster components are triggered individually via fiber optic line. The controls & instrumentation are contained inside a RF shielded room.
- Time = 0
  - Capacitor banks for the Drive & Bias circuits are charged
  - Firing sequence begins by triggering the high speed valve,
    - ✓ injects the Argon mass bit
- Time = 0.750 ms
  - Bias field is initiated

    (For field reverse current (FRC) operation)
- Time = 0.784 ms
  - VIG is triggered, ionizing the gas
    - ✓ this is 2 μsec prior to the drive pulse
- Time = 0.786 ms
  - Drive circuit is pulsed
    - ✓ this is 36 μsec after initiation of the bias circuit



operation sequence

For field reverse current (FRC) mode:

drive circuit timing is set to have the bias current in the reverse direction to the drive current

Advantages

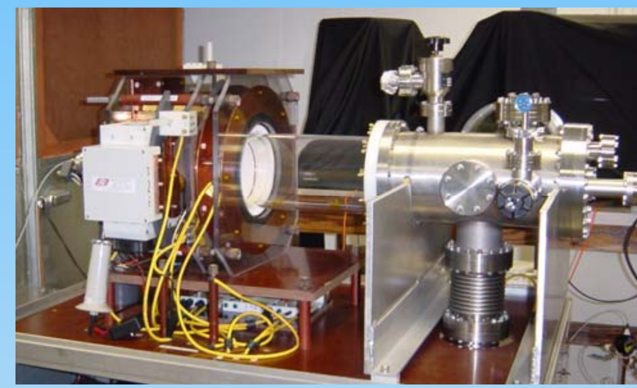
The Plasmoid Thruster operates by repetitively forming and accelerating plasmoids (compact toroids) to high velocity

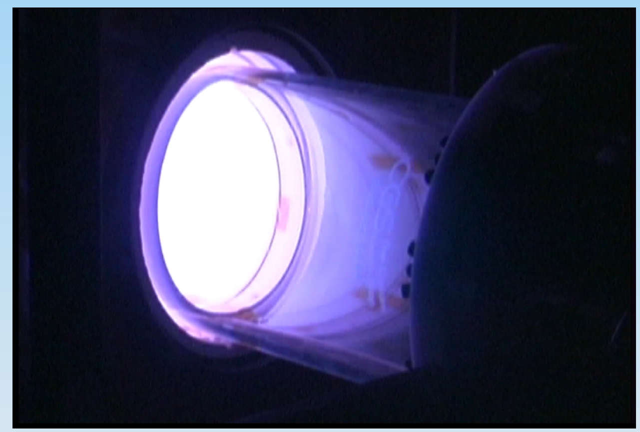
- **The plasma is accelerated inductively**

  1. **electrode erosion eliminated by eliminating the electrode, providing long system life-time.**

  2. **No thermionic emission required, which leads to a simpler system design – less heating problems with valves, controls, sensors, capacitors, etc.**

  3. **Not as dependent on propellant used, allowing wider choice of propellants, including ISRU derived propellants.**
     <u>Thruster is not limited to use with Xenon</u>





- **The propellant is confined on closed magnetic field lines that are not connected to the thruster – i.e. the plasma is formed pre-detached.**

  - This may increase the thruster efficiency over other pulsed inductive thruster designs

Advantages

- **The thruster is a pulsed device**

  - Thruster efficiency is dependent upon the characteristics of the pulse sequence – not the repetition rate. The Thruster can be throttled over a wide range without changing thruster efficiency.

- **Solid State Switched! – No spark gaps!**

- **Expected performance range**

  - Isp: 1,500 – 10,000 seconds: adjustable by varying the Ar mass bit/energy per pulse ratio – upper Isp limit not experimentally verified yet

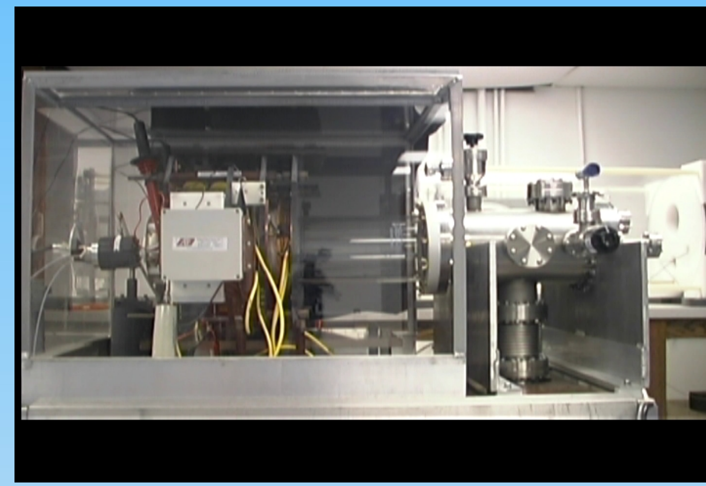
  - Expected thrust bit per pulse: tuneable, based on the mass bit/energy bit ratio per pulse

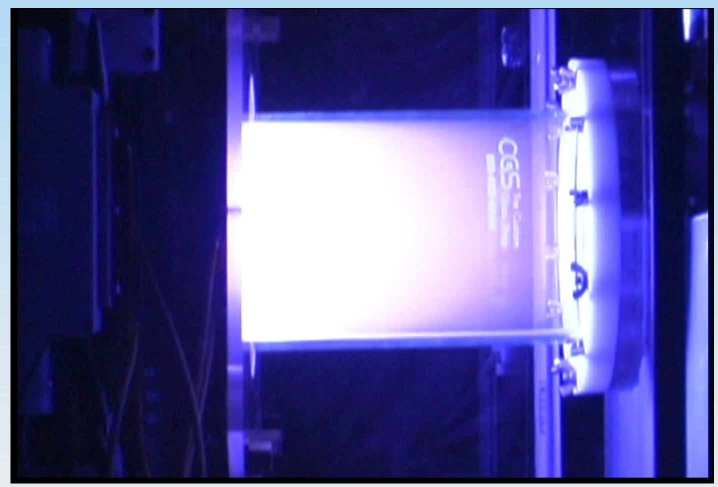
  ❖ Thrust measurements have not been made to date

  - Jet Power: based on rep-rate – same thruster could provide a wide range of power demands

  - Specific Power: on the order of 1-3 kW/kg based on lab thruster weight – this would improve with an optimized flight ready design. Specific power is also rep-rate dependent

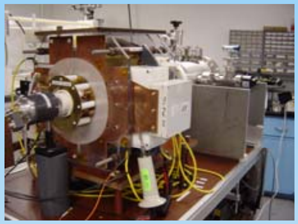
  - Efficiency: expected to be between 30% to 45%

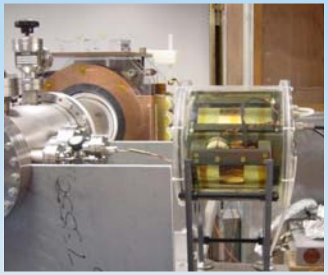




Experimental advantage of the current laboratory thruster design

- Modular construction
  - The components of the thruster operate independently
    - By changing the timing & operation sequence, the thruster can be tested in several modes. For example:
      - **Field reverse current mode:**
        - » **Drive & Bias currents in opposite directions**
      - **Theta pinch mode:**
        - » **Drive & Bias currents in the same direction**
      - **Pre-ionized PIT mode:**
        - » **Drive current only**
    - Individual components can be modified or changed out without rebuilding the whole thruster

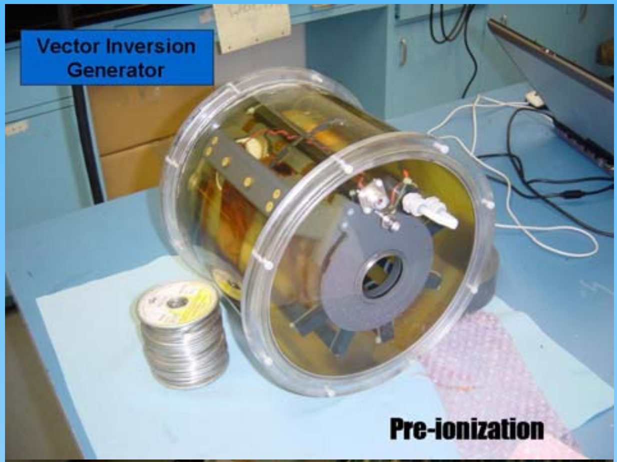


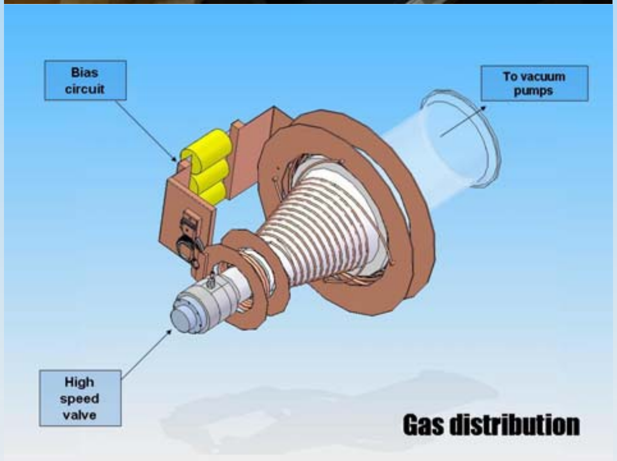


Lessons learned from the current design iteration

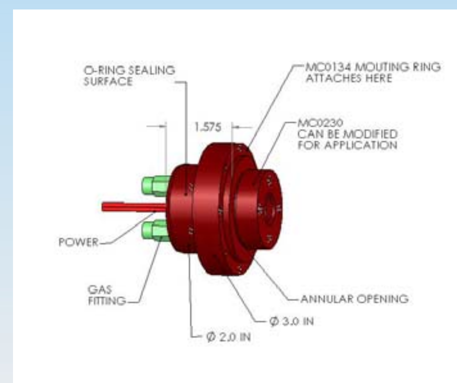
- **Insufficient pre-ionization**
  - **A higher energy VIG should be used**
    - **2 - 3 Joules per pulse should be adequate**

- **There should be less separation between the coils and the propellant gas**
  - **currently the coils are separated from the propellant by the mandrel and the glass vacuum tube**
  - **The coils should be potted such that the gas is within a few thousandth's of an inch from the coil surface to take full advantage of the plasma decoupling length**





Some of the missing pieces needed for Plasmoid thrusters



- **The inert gas distribution has not been characterized**
  - **Measurements of the gas pulse should be made with a Fast Ionization Gauge**
- **A valve capable of surviving billions of pulses is needed**
  - **The current high speed valve in use is low mass beryllium copper Belleville spring diaphragm**
  - **Limited in pulse rate by I^2R heating & not likely to survive a billion + pulses**
  - **A piezoelectric valve needs to be developed for this application**
- **A flight ready thruster would require intensive study into shielding and minimization of the RF noise created from the thruster operation**

Recommendations for developing an operational plasmoid thruster

- **Insufficient experimental data to date**
  - **Bdot & Triple probe measurements should be made with several species of test gas**
  - **Performance should be characterized with respect to thruster charge voltages & relative timing values**
  - **High speed photography of the plasma ignition is required to determine the MHD for the plasma ignition**

Thrust stand measurements are also needed on a upgraded thruster design

- **thruster testing in all three modes:**
  - **FRC, theta-pinch, & Pre-ionized PIT should be made with a device that can perform all three modes of operation for an “apples to apples comparison”**
  - **A “long view” answer as to which design will work best has not been validated by experiment**
- **Optimum cone angle is not known – bell nozzle/curved nozzle shape?**
- **Energy recovery should be incorporated into the drive & bias circuits which may increase the efficiency to > 50%**
- **To date, rep-rate testing has not been performed**

Practical application advantages of a plasmoid thruster

- **Workhorse for an orbit changing satellite**
  - **Highly throttle-able**
  - **When the mentioned engineering challenges are overcome, long thruster lifetime is possible**
  - **Inexpensive propellant (not Xenon) – likely ammonia**
    - **Xenon: > $5000 per kg**
    - **Ammonia: < $1 per kg**
  - **Could also be considered for a dual use monopropellant since any gas that can be ionized is a potential propellant**

- **Advantages to science missions:**
  - **ISRU propellant use is made possible since multiple forms of gas propellant can be used: return trip fuel does not need to be carried on the leg out**
    - **This translates directly into a lower payload mass ratio (Rp). A lower Rp can be used to achieve:**
      - **a higher payload mass or**
      - **an overall lower launch mass weight or**
      - **a faster trip time or**
      - **some combination of these three**

$$R_p = \frac{m_{fuel} + m_{payload}}{m_{payload}}$$

one leg

$$R_p^{n\ legs} = \frac{m_{total\ \ for\ n\ legs}}{m_{payload}}$$

More payload or lower launch weight

$$\Delta v = u_e \ln\left(R_p\right)$$

Higher Δ*v* =

Faster trip time

Practical application advantages of a Plasmoid thruster

- **Advantages to science missions:**
  - **For solar powered missions with variable solar power availability :**
    - **Highly throttle-able via change in rep-rate <u>and</u>**
    - **Thruster efficiency is based on individual pulse characteristics – not cw characteristics.**
      - ➢ **Constant optimum thruster efficiency – the pulsed thruster efficiency can be optimized for the entire trip – maximizing use of the propellant for the entire trip**

  - **By varying the mass bit/energy bit per pulse ratio the thruster's Isp can be varied**

    - **Isp can be selectively changed over a mission, to optimize propulsion for the mission parameters**
      - **Higher power availability & a premium on propellant availability:**
        - » **Higher Isp & a smaller mass bit per pulse**
      - **Power at a premium & abundant propellant availability (INSITU):**
        - » **Lower Isp, larger mass bit per pulse**

    - **Variable mass bit/energy bit per pulse makes the thruster "tuneable" to a given propellant species for maximum thruster efficiency**

Conclusion

- Pulsed EP thrusters provide advantages that could become mission enabling for future projects
  - Pulsed inductive thruster technology is still in its infancy
  - To reach TRL parity with continuous throughput EP significant research is required
  - For pulsed power EP to be ready to fit near term (10 to 20 year mission planning) research & development needs to be funded & worked today

- New propulsion is on the horizon – pulsed EP such as the Plasmoid Thruster is a viable solution:
  - Current flight ready EP uses costly propellant
  - The number of in-flight missions for science & defense is likely to increase with time and to require significantly more propellant to meet mission requirements
    - **Multiple orbital transfers**
    - **Multiple objective missions and/or higher longevity on-station requirements**
  - Without a thruster capable of using a more cost effective propellant, an increasing amount of mission budget will need to go to propellant costs

Thank you for your time!