A feasibility and design study of utilizing high-powered lasers for MPD thrusters

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Abstract: A feasibility and design study of utilizing high-powered lasers to produce highly-ionized plasma for magnetoplasmadynamic (MPD) thrusters (MPDTs). Laser-induced ionization for MPDTs may improve the performance of MPDTs over conventional methods of generating plasma and may be one of the key technologies to assist in the evolution of laser-induced fusion rocket propulsion. Some conceptual engineering designs of how such a laser-induced MPD thruster system could be developed are presented.

Nomenclature

CO_2	= Carbon dioxide
CW	= Continuous Wave
EM	= Electromagnetic
MPD	= Magnetoplasmadynamic
MPDT	= Magnetoplasmadynamic Thruster
Nd:YAG	= Neodymium: Yttrium Aluminum Garnet

I. Introduction

A Feasibility and design study of utilizing high-powered lasers to produce highly-ionized plasma for magnetoplasmadynamic thrusters (MPDTs) was conducted. This study was to fulfill the thesis requirement for the Master of Science in Space Studies, Aerospace Sciences concentration, at the Department of Space Studies of the American Military University. Laser-induced ionization for MPDTs may improve performance of MPDTs over conventional methods of generating plasma and could assist in the evolution of laser-induced fusion spacecraft propulsion. This paper will examine three questions. (1) Can a laser be used to ionize gas? (2) Can laser-induced plasma be utilized in MPDTs? (3) What are some conceptual engineering designs of how such a laser-induced MPDT thruster be developed? This work briefly reviews the field of MPD propulsion that uses plasma as its working fluid. It reviews some fundamental of lasers as well as some research work that has already been made in laser-electric propulsion. From these fundamental concepts of MPDTs and lasers, some conceptual design configurations on how such a laser-induced MPDT are presented.

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II. Review of MPDTs, Lasers and Laser-Plasma Interaction

A. Magnetoplasmadynamic (MPD) Thrusters

The magnetoplasmadynamic thruster (MPDT) utilizes the Lorentz force to accelerate plasma from a spacecraft. The Lorentz force within the MPDT can be generated either internally by the electrical flow itself or by an external magnetic field.[1, 2] Refer to Figure 1.

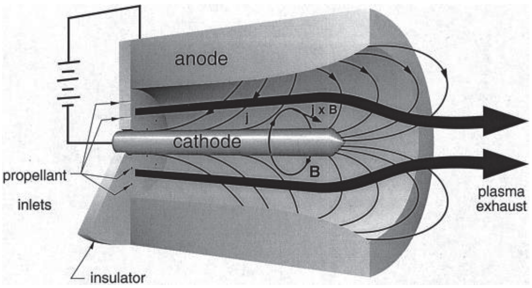

Figure 1 Simplified magnetoplasmadynamic thruster schematic[3]

1. Self-Field MPD Thruster

Self-field MPDTs utilize a magnetic field that is generated by an electric arc discharge across an anode (+) and a cathode (-). The configuration of a self-field MPD is the same as an arcjet where a central cathode is coaxially located within a cylindrical anode. The propellant gas flows in between the void of the anode and cathode. A high electrical voltage potential is established between this void.[4, 5] Refer to Figure 2 on the left.

2. Applied-Field MPD Thruster

Applied-field MPDTs utilize an external magnetic field to provide the Lorentz force. This thruster has a centrally located cathode inside within the anode. The arc across the space between the anode and cathode would ionize the propellant gas into a plasma. See Figure 2.

The difference is that an external magnet would be energized to develop the **E X B** condition to produce the Lorentz force on the plasma that would accelerate the conductive plasma from the MPDT.[6, 7] Researchers have developed a steady-state, applied-field, rectangular MPD thruster. The researchers demonstrated a higher thrust efficiency by lowering the mass flow rate.[8] Refer to Figure 2 on the right.

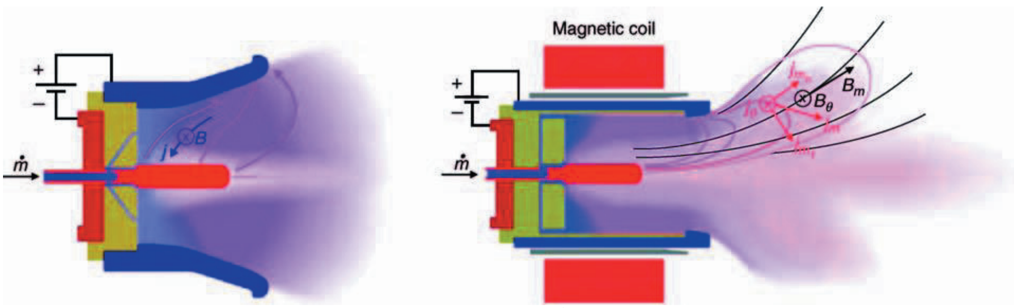

Figure 2 Self-Field and Applied-Field MPD thrusters[9]

B. Components of a Laser

Four components are required to produce laser light. Those components are the active medium, excitation mechanism, feedback mechanism, and the output coupler.[10, 11] Refer to Figure 3 and Figure 4.

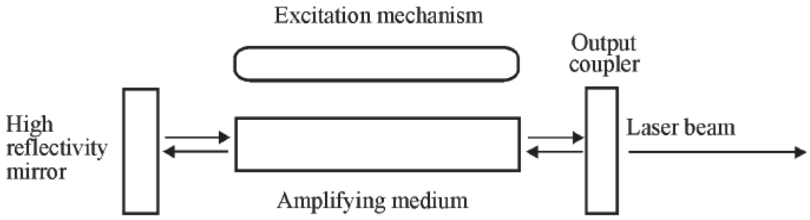

Figure 3 Schematic diagram showing the basic structure of a laser[12]

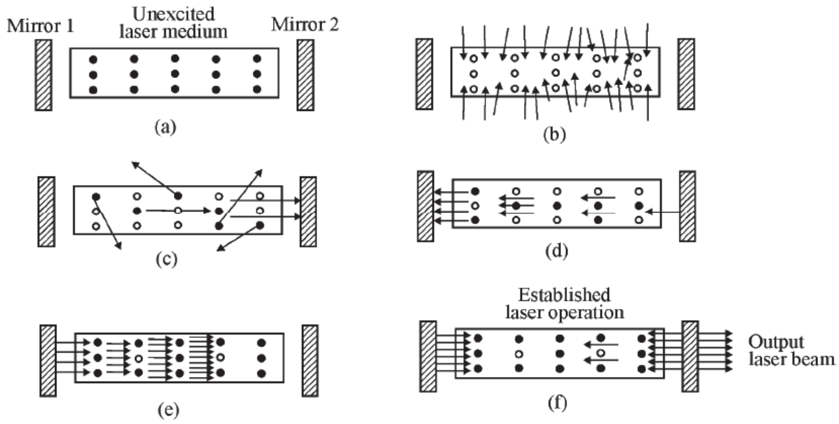

Figure 4 Sequence of "pumping" the laser: Step-by-step development of laser oscillation in a typical laser cavity: (a) unexcited laser medium; (b) pumping of laser medium; (c) spontaneous and stimulated emission; (d) light amplification begins; (e) light amplification continues; (f) established laser operation[13]

C. Laser-Plasma Interaction

A super-intense laser pulse is considered to be when the field amplitude of the laser is large enough to drive the electrons within the plasma to accelerate towards relativistic speeds, that is, close to the speed of light.[14] The most powerful continuous-wave laser is the CO_2 laser that can deliver over 10kW of power.[15]

The Naval Research Laboratory's NRL Plasma Formulary reports that the highest-power CW laser is the CO_2 providing more than 100kW (10^5 W) of power. When pulsed, the CO_2 can provide more than 20 terawatts (20 X 10^{12} W) of power. The Nd:YAG laser operated in CW mode can provide more than 10kW (10^4 W) of power. When operated in pulsed-mode, Nd:YAG lasers can provide 1 gigawatt (10^9 W) of power.[16] The Brookhaven National Laboratory is already developing a one terawatt powered carbon dioxide laser for their Accelerator Test Facility.[17]

Laser radiation can be used to ionize hydrogen gas into hydrogen plasma. Laser radiation can heat a propellant to much higher temperatures than can be achieved with chemical reaction or with a nuclear reaction.[18] Laser sustained plasma in pure hydrogen has been achieved in 1979.[19]

D. Plasma Generation via Laser for Electric Propulsion

Coherent laser light can ionize a gas into plasma. Laser-generated plasmas are very dense.[20] The laser is a large amplitude of electromagnetic energy and the momentum that is carry by the EM wave is transferred directly to the plasma. This transfer is termed the 'ponderomotive force.'[21] Kruer defines the yardstick for high-energy density as exceeding 10^{11} J/m^3. This corresponds to a pressure of 1 Mbar.[22]

Toyoda, Komurasaki and Arakawa presented a paper on an experimental research into a CW CO_2 Laser Thruster. They termed it, LSP (Laser Sustained Plasma). They were able to sustain laser power at 700W for several seconds during their experiments. They fired the CW CO_2 through a beam expander, through some lens and into a thruster chamber into inert gas, both argon and nitrogen. They were able to obtain an efficiency of 37% of the laser power going into thrust.[23]

Berkery and Choueiri of the Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL) presented how a laser discharge could initiate ionization for gases-fed pulsed plasma thruster (PPT). They used a laser to initiate a laser-induced pulse into a gas-fed propellant system. This pulse would be used to produce a uniform current ‘sheet’ within a PPT that led to a current that produces breakdown at an undervoltage. They found that they did not have success with using ultraviolet light but they did have success with using infrared laser light.[24]

Horisawa, Sasaki, Igari and Kimura presented the concept of a laser-electric ‘hybrid’ thruster at the 2005 IEPC. Their laser-electric hybrid thruster uses a laser to ablate a solid fuel propellant into a plasma for the use of electromagnetic acceleration instead of using a direct acceleration using only a beam of laser energy. They performed a feasibility study on both electrostatic and electromagnetic acceleration modes and demonstrated that their hybrid thruster would improve thrust and efficiency.[25]

Sasaki, Horisawa, Funaki and Kimura followed up two years later with thrust performance data of the Laser-Electric Hybrid Thruster by analyzing the thrust performance of the electromagnetic acceleration mode for the Laser-Electric Hybrid Thruster. They used an Nd:YAG laser to ablate the solid propellant. They found that electric discharges can be achieved around 500V and observed plasma emission behavior with a camera. They observed high specific impulses and thrust efficiencies at low energies.[26]

Ayabe, Hideyuki, Funaki and Kimura also performed an experiment of using a rectangular laser-electromagnetic hybrid pulsed plasma thruster. The researchers conducted experiments that used a rectangular discharge channel along with laser-induced plasma and then accelerated this plasma by way of electromagnetic forces as opposed to accelerating with just laser ablation. What they discovered was that higher performance was obtained when they used higher laser energy.[27]

Four years later, Horisawa, Mashima, Yamada and Funaki obtained high specific impulse for an experiment that used the Rectangular Laser-Electromagnetic Hybrid Acceleration Thruster. They concentrated on trying to obtain improved specific impulse (decreased propellant consumption rate) by changing the geometry of the thruster acceleration channel. They confirmed that they could obtain higher electromagnetic acceleration effects by increasing the volume of the acceleration chamber.[28] Oigawa, Hosisaa and Funaki extended the research into improvements of the Laser Electromagnetic Hybrid Thruster. The goal of this study was to observe the plasma acceleration processes and to understand the physics behind high-speed plasma generation within a rectangular laser EM Hybrid PPT.[29]

Williams produced two papers on the utilization of laser-driven ponderomotive forces to produce spacecraft propulsion. Ponderomotive force is the momentum that is carried by the electromagnetic wave that is generated by a laser-beam.[30] In particular, Williams was focusing on using the ponderomotive forces that are developed by laser “wake-fields” within the plasma to produce near-relativistic velocities. The focus of this research was to use nuclear fusion energy to energize a laser to produce a plasma wake-field to improve electric propulsion.[31, 32] C. Joshi, reports on the ‘Wakefield Accelerator’ as a way to produce the driving force to accelerate particles that will ride on a wave of plasma towards relativistic velocities. This Wakefield accelerator would require a high-intensity laser beam to generate and accelerate plasma.[33] Marcchi dedicates a section within his textbook to Laser Wakefield Accelerators.[34]

Laser pulses can provide a compressive action such as is done via inertial confinement fusion.[35] The use of nuclear (fission or fusion) energy to develop plasma and using the wake-field effect to drive plasmas towards relativistic velocities are beyond the scope of this paper but serves to illustrate the importance of the role and the ability of the laser to both produce and accelerate a plasma for spacecraft propulsion.

III. Some Conceptual Designs of Laser-Induced MPDTs

Since it has been established that a laser can ionize a gas into a plasma, the first step is to efficiently ionize a propellant gas with a laser. The author conceived of using one or several lasers to generate plasma by passing the laser beam back and forth multiple times through the propellant gas by the use of reflection. One method to reflect laser light is to use a series of prisms. Refer to Figure 5 and Figure 6. A prism can be used as a “retro-reflector”.[36] Retro-reflectors utilize ‘total internal reflection’ where the beam will reflect internally within the prism.[37] This reflection can be directed back toward but offset to, the source of light.[38]

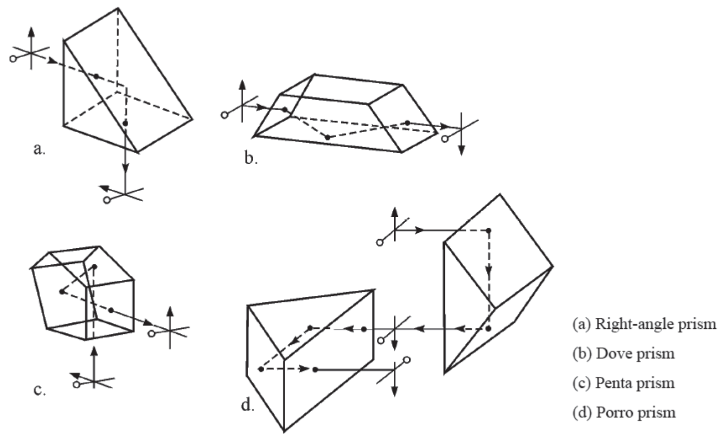

Figure 5 Varieties of translucent prisms can be used as retro-reflectors[39]

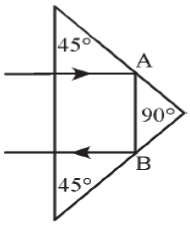

Figure 6 Simple retro-reflector[40]

1. <u>Retro-Reflector Laser-Induced Plasma</u>

The proposed thruster would make use of one or more high-powered CO_2 or Nd:YAG lasers along with a series of “retro-reflectors” within the plasma generation chamber. Refer to Figure 7. If a series of prisms are aligned along the lateral side of the plasma generation chamber, a single laser beam can be used to retro-reflect the beam across a single plane multiple times. This MPDT arrangement would be used to minimize the number of lasers onboard the spacecraft by utilizing retro-reflectors to bounce the laser back and forth through a gas propellant in a radial fashion. If a second plane (Figure 7) is established, perpendicularly, another laser could be used with its own set of retro-reflectors that are also aligned perpendicular to the first plane of retro-reflectors. Additional planes could be used to add yet another set of laser beams through the propellant gas before it enters the MPDT for Lorentz force acceleration.

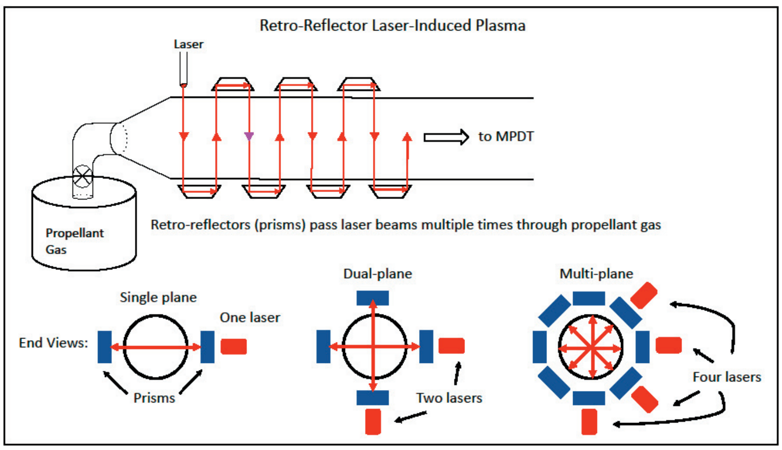

Figure 7 Retro-reflector laser-induced MPDT (Millen 2014)

2. Laser-Induced Plasma by a Single Elliptical Reflector

Refer to Figure 8. The concept is to place multiple lasers, aimed radially, along one of the foci-points within the reflective, elliptical chamber. The other foci-point would be a transparent tube, running longitudinally, containing the propellant gas. This concept is to direct multiple laser beams into a single tube containing the propellant gas.

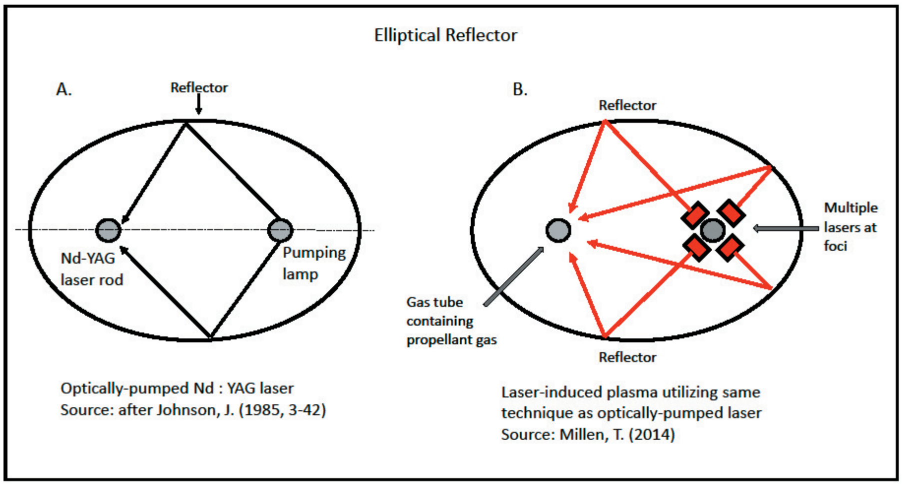

Figure 8 Elliptical reflector (Diagram A. Johnson, J. 1985 and Diagram B. Millen, T. 2014)

3. Laser-Induced Plasma by a Double-Elliptical Reflector

The concept of using a double-elliptical reflector to laser-induce plasma was also inspired by how an optically-pumped solid (crystal) laser can be configured. The single elliptical chamber has a disadvantage of being offset and not symmetrical. An improvement to the single chamber concept is to use a double-elliptical reflector chamber where two separate reflective-elliptical chambers share a single common foci. Refer to Figure 9 and Figure 10. Again, the concept is to place multiple lasers, aimed radially, along each of the two outer foci-points within two reflective, elliptical chambers. The shared foci-point would be a transparent tube, running longitudinally, containing the propellant gas. This concept is to also direct multiple laser beams into a single tube containing the propellant gas but is symmetric along axis of the MPDT chamber.

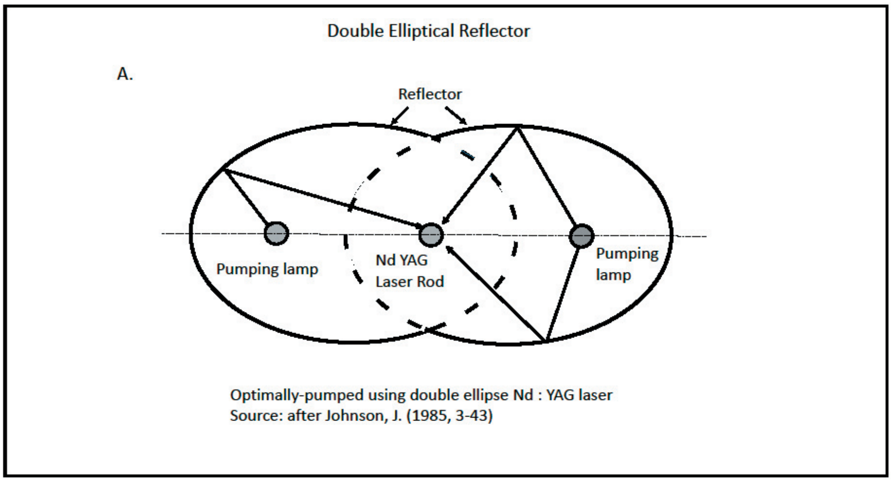

Figure 9 Double Elliptical Reflector MPDT[41]

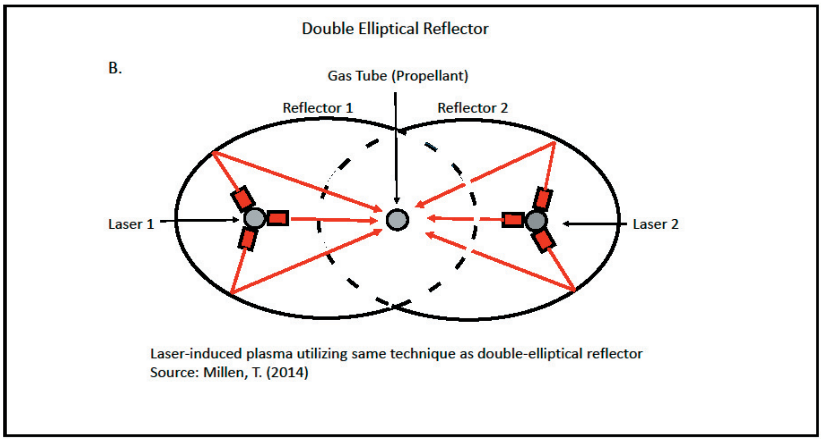

Figure 10 Double Elliptical Reflector MPDT (Millen, T. 2014)

4. Laser-Induced Self-Field MPDT

Refer to Figure 11. To simplify the conceptual drawing, the laser is shown as an 'array' of lasers. This array of lasers could consist of one, two, or several lasers that are arranged laterally with one plane of retro-reflectors or in one of the reflective-elliptical chambers. This drawing illustrates how a laser or lasers can be used upstream of a 'traditional' self-field MPDT.

After the propellant gas is ionized into a plasma, the plasma is then passed downstream into the coaxial chamber of a self-field MPDT. An electric field is established through the plasma which produces the electric-arc. As with the traditional configuration, a self-induced magnetic field is generated around the central cathode. The combination of the electric current density, **j**, crossing the magnetic **B**-field produces the plasma thrust due to the Lorentz force.

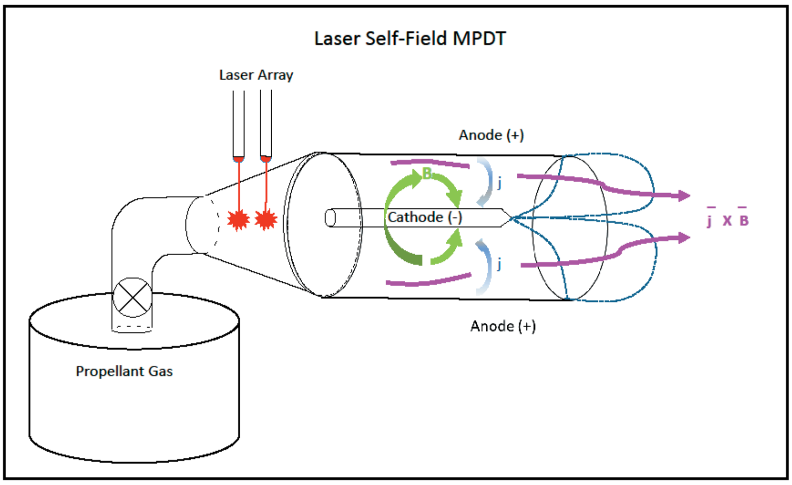

Figure 11 Laser-induced self-field MPDT (Millen 2014)

5. Laser-Induced Applied-Field MPDT

Refer to Figure 12. Again, to simplify the conceptual drawing, the laser is shown as an 'array' of lasers. This array of lasers could consist of one, two, or more lasers that are arranged laterally with one plane of retro-reflectors or in one of the reflective-elliptical chambers. The drawing illustrates how a laser or lasers can be used upstream of a 'traditional' applied-field MPDT.

After the propellant gas is ionized into a plasma, the plasma is then passed downstream into the cylindrical (or elliptical) chamber of an applied-field MPDT. An electric field is established through the plasma which produces the electric current density, **j**. The drawing was made for visual simplicity by showing just the 'ends' (N and S) of the applied magnetic field of a permanent magnet. Since no isolated magnetic poles (no 'monopoles') have been discovered[42], this drawing would appear to be impossible. Practically, it would be more likely that an electromagnet solenoid would surround the plasma acceleration chamber to provide the **B**-field. The combination of the electric current density, **j**, crossing the magnetic **B**-field produces the plasma thrust due to the Lorentz force.

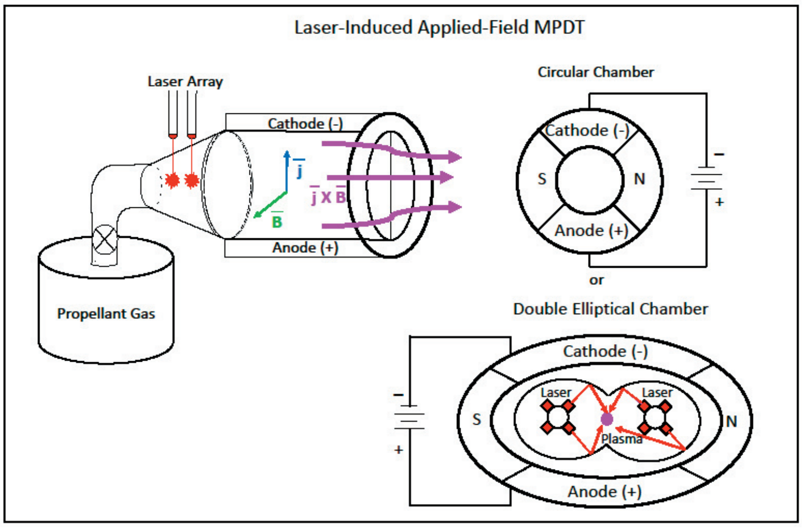

Figure 12 Laser-induced applied-field MPDT (Millen 2014)

6. Longitudinal laser-induced, applied-field MPDT

Refer to Figure 13. Possibly the simplest method of producing laser-induced plasma is to direct the laser beam longitudinally downstream into the MPDT chamber. This MPDT arrangement would use a single high-powered laser by placing it at the central radius of the MPDT. The laser would fire through the gas propellant downstream along the applied-field MPDT where the Lorentz force would accelerate the plasma. This arrangement could use either a high-powered CO_2 laser for larger spacecraft while the diode-pumped Nd:YAG could be used for small spacecraft such as a nanosatellite.

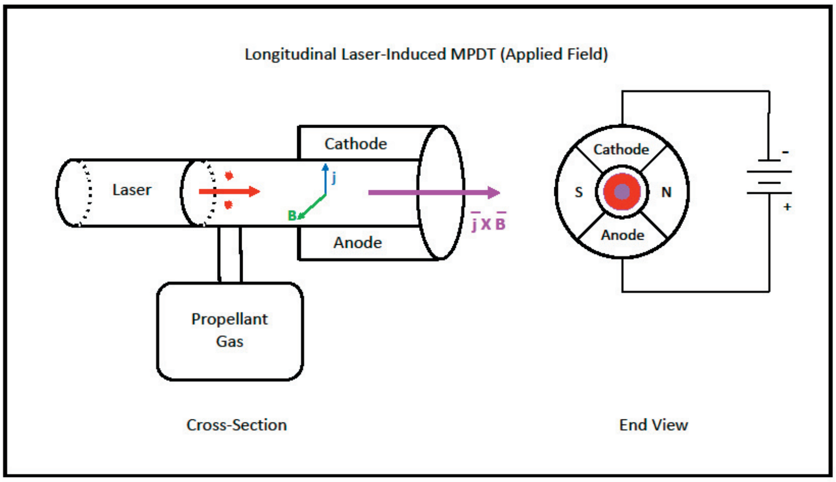

Figure13 Longitudinal laser-induced applied-field MPDT (Millen 2014)

IV. Conclusion

Electric propulsion and laser technology provide a new variation of an electromagnetic thruster. Research into various IEPC and NASA documents indicate that lasers can ionize gas into a plasma much better than other methods, such as thermal, electric arc or microwave. The major drawbacks at this time are the efficiency of the laser itself and the onboard electrical power system to support such a laser-induced MPDT propulsion system.

Lasers have been used to improve the performance of pulsed-plasma thrusters (PPTs). Evolving experiments by Japanese researchers has moved into the field of laser-electric hybrid PPT. The PPT and the MPD are both electromagnetic rockets that use plasma as their working fluid. At this time, it appears that no one has made any research effort into the development of a laser-induced MPDT. Conceptual illustrations show how such a laser-induced MPDT could be designed. The next step, developing such a propulsion system would require additional work as well as funding to mature this technology.

A number of problems need to be overcome to produce high-powered, laser-induced plasma propulsion systems, including: Hardening existing high-powered lasers for the space environment; Increasing the power efficiency of lasers; Developing or improving onboard electrical power supplies to operate both the laser and the MPDT; Generating enough energy by the laser to convert a propellant gas into a highly-ionized plasma; and Generating a strong enough magnetic field to channel and drive the plasma.

Several promising technologies are already being developed that will aid in the potential production of a laser-induced MPDT, including: production of higher-powered lasers; production of higher-efficiency lasers; production of superconducting, low-loss magnets; production of electrical power sources to energize lasers and electromagnets; and production of magnetic nozzles to thermally accelerate the plasma as well as electromagnetic accelerating it via the Lorentz force.

Laser-induced magnetoplasmadynamic thrusters can play an important role in providing electric rocket propulsion for both manned and unmanned spacecraft in the future.

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