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Progress in Modeling of Pre-ionization and Geometric Effects on a Field-Reversed Configuration Plasma Thruster

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In recent years, compact toroid (CT) plasma (e.g., field-reversed configurations, plasmoids, or spheromaks) has been considered for propulsion applications. A limited number of studies have been conducted thus far with each investigating different aspects of CT plasma. The current investigation into CT plasma documented here focuses on developing a thruster concept to assess the efficiencies of CT plasma formation and acceleration. The assessment consists of developing MHD simulations that model a typical CT test article. The pre-ionization geometry and device geometry parameters are varied in these simulations to determine the efficiencies.

I. Introduction

THERE has been specific interest in using spacecraft with the ability to perform rapid maneuvers between various orbits or inclinations for high-powered propulsion missions. Such ability permits a capacity to establish and maintain an operationally responsive space (ORS) environment. The goal for ORS is to provide an affordable capability to place and operate assets, whether national or military, in and through space and near-space. An electric thruster that forms and accelerates compact plasma toroids has the potential to meet the challenges associated with this capability. The physical operation of thrusters of this type is divided into three main stages: 1) ionization/plasma creation; 2) compact toroidal-plasma formation; and 3) compact toroidal-plasma acceleration. The CT plasma investigated here is the field-reversed configuration (FRC) plasma where the axial magnetic field dominates over the azimuthal magnetic field.

The development of an optimum FRC plasma thruster design would be beneficial in the field of advanced space propulsion by dramatically increasing thrust and specific-impulse of spacecraft propulsion. The result of such development would reduce launch costs and facilitate rapid repositioning of space assets in the near-Earth environment. In the case of a propulsion application for an ORS environment, a high efficiency (>70%) propulsion system with the capability of high thrust levels (1N-1kN) and a specific impulse that is at least 5000 sec is advantageous. The current state-of-the-art electric propulsion systems such as Hall thrusters or ion thrusters, have higher specific impulse, but significantly lower thrust compared to chemical systems. In a FRC device, a compressed, high-density plasma is formed efficiently. The compressed plasma is translated and ejected from the thruster by magnetic field pressure. Developing a device that utilizes heavier atomic gases (allowing for greater kinetic energy input) would enable a system to achieve the desired performance on conventional space assets.

II. FRC Formation

Conventional CT formation given by Goldenbaum[1]and Bellan[2] consists of four main steps as illustrated in Fig. 1[1,2] and is described as follows: 1) pre-ionization; 2) implosion; 3) reconnection; and 4) equilibrium. The start of the sequence begins with a gas-filled volume and a straight bias magnetic field which is produced by a slow external coil thus effectively pre-ionizing the gas and producing plasma.

After pre-ionization, implosion occurs (refer to Fig. 1) where a fast capacitor bank is used to discharge through the theta coil thus creating a reversed magnetic field (reversion occurs on a time-scale that is less than the magnetic diffusion time). Radial compression of the initial bias field is caused by the implosion field. Following the implosion, reconnection of the field lines at the ends of the device occurs and a toroidal plasma current is established. At equilibrium, the CT consists of a toroidal plasma current with a poloidal magnetic field and is enveloped in the outer poloidal field. Following formations, the CT translates out of the device.

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A variety of methods can be implemented to accomplish pre-ionization which includes theta-ringing[3], ringing-multi poles[4], microwaves[5], and pulsed laser ionization[6]. The pre-ionization stage is the most critical phase in FRC formation. If the pre-ionization is not sufficient or uniform the discharge current does not couple with the plasma, resulting in either a poor or no FRC formation.[3] A combination of two main heating modes, snowplow and Ohmic-resistive modes, occur in typical FRC devices. An initial shock heating first occurs which then transitions into Ohmic heating. The Ohmic heating is slower and continues to heat and compress the plasma.[7]

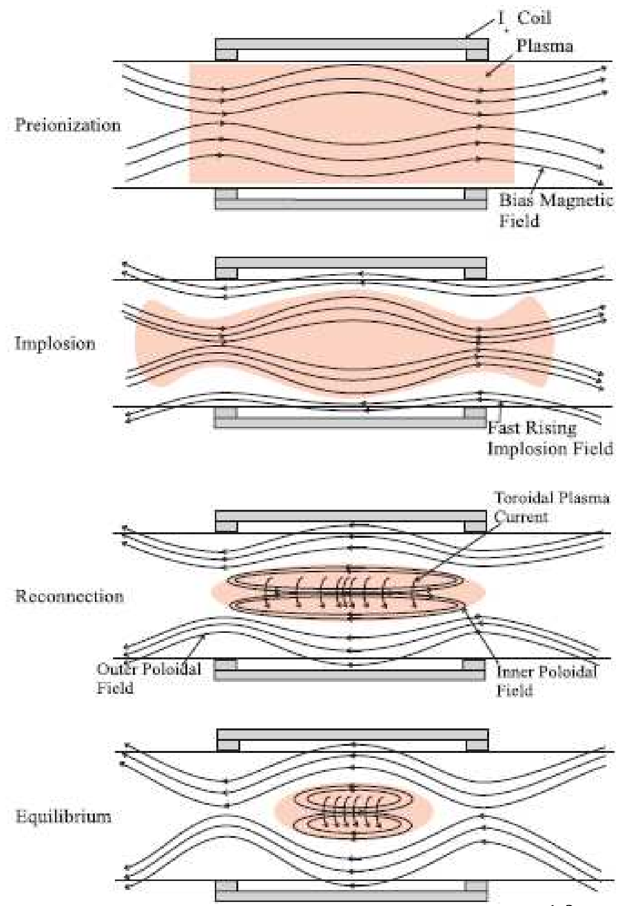


Figure 1. Schematics of the CT formation process.[1, 2]

III. Applications to Space Propulsion

Kirtley compiled a list of experiments that studied FRC plasma over nearly the past 50 years. This list, illustrating the operational parameters of the experiments, is featured in Fig. 2.[7] From the listing, the studies into FRC plasma propulsion were not of much interest until the late 1990's and early 2000's. The list also shows the parameters and size of each experiment. The parameters vary significantly between each experiment. The latest experiments for propulsion include XOCOT, MAP, and PTX. The remainder of this section will discuss each of these test articles in terms of results and relation to the simulated FRC device to be investigated here. Also, these experiments are introduced to illustrate the variation in the design of a CT plasma device. By establishing what configurations are commonly used, the configuration of the simulation model being developed can be varied similarly.

The most recent interest in propulsion applications of FRC plasma comes from the Air Force Research Laboratory (AFRL) in the form of an annular CT accelerator called XOCOT.[8, 9] This annular device was developed in an effort to study efficient pre-ionization mechanisms and the formation and acceleration of a CT. XOCOT was operated using argon and xenon (only used after the efficient pre-ionization mechanism was determined) for 185 μs, 250 μs and 450 μs discharge times over a discharge voltage of 500-1000 V and pressure of 3-20 mTorr.[7] Using a 250 J discharge the peak argon and xenon densities and temperatures were found to be, respectively, $5x10^{19}$ m^{-3}, 11 eV, and $2x10^{20}$ m^{-3} , 8 eV.[7] The experiment device was sized with a diameter of 40 cm and length of 30 cm. The results of the AFRL study thus far show successful CT formation at a discharge time of 185 μs for xenon. The compressed discharges of xenon did not exhibit the instabilities found in the argon case at the same discharge time. The device does utilize a low-power glow seed discharge and high-voltage, low-energy azimuthal ringing. XOCOT is the most current FRC device and closely relates to the planned device for this investigation. Investigation by an outside contractor working with the AFRL team has qualitatively shown that the annular geometry is superior to previous cylindrical designs.[10] The AFRL annular FRC device will serve as an initial benchmark for the annular case in the simulation work.

Space propulsion applications have been explored by groups at the University of Washington and the University of Alabama-Huntsville. Each of the universities has had a different design for the FRC device. The University of Washington group used a cylindrical device with uniform pre-ionization plasma, while the University of Alabama-Huntsville used a conical device with uniform pre-ionized plasma.

Slough, *et.al*, at University of Washington have developed two experimental test articles for space propulsion applications. The Propagating Magnetic Wave Plasma Accelerator (PMWAC) device was developed with the intent to provide an efficient method for converting plasma energy into thrust and specific impulse required for the high power of fast missions.[11] The Magnetically Accelerated Plasmoid (MAP) experiment continues the objective of achieving high-thrust and high performance, but also investigates optimal performance in a device with a 20 cm diameter.[11,12] From the studies of these two devices, the results have shown an ejection velocity of at least $1.8x10^5$ m/s for each plasmoid which gives a total impulse bit of 0.3 N-s.

Year	Experiment	Lab	Length (cm)	Diameter (cm)	B_{Peak} (kG)	Po (mTorr)	τ (μs)	Main studies
1959	-	NRL	10	6	100	100	2	Annihilation
1962	Scylla I	LASL	11	5	55	85	3	Annihilation
1962	Scylla II	LASL	19	8	125	85	4	Rotation
1964	0-P	Garching	30	5	53	100	1	Tearing
1965	Pharos	NRL	180	17	30	60	30	Confinement
1967	Centaur	Culham	50	19	21	20	15	Confinement
1967	Julietta	Jülich	128	11	27	50	15	Tearing
1971	E-G	Garching	70	11	28	50	25	Tearing
1979	TOR	Kurchatov	150	30	10	5	100	Formation
1979	FRX-A	LASL	100	25	6	5	30	Confinement
1981	FRX-B	LANL	100	25	13	25	60	Confinement
1982	STP-L	Nagoya	150	12	10	9	30	Rotation
1983	FRX-c	LANL	200	50	8	15	300	Confinement
1984	TRX-I	MSNW	100	25	10	10	150	Formation
1985	HBQM	U Wash	300	22	5	5	30	Formation
1986	TRX-2	STI	100	24	13	10	100	Confinement
1987	CSS	U Wash	100	45	3	40	60	Slow-formation
1988	FRXC	LANL	200	70	6	5	450	Formation
1990	LSX	STI	500	90	8	3		Stability
1998	TRAP	U Wash	200	27	1	20		Translation
1999	STX	U Wash	300	40	0.1*	0.4	400	Propulsion
2003	TCS**	U Wash	260	80	5			RMF Formation
2004	PHD	U Wash		18	7			Translation
2005	PTX	NASA	7	8.3	1.0	40		Propulsion
2006	MAP**	MSNW		20				Propulsion
2007	XOCOT**	AFRL	30	40	1.5	14	100	Propulsion
*	RMF							
**	On-Going							

Figure 2. Summary of FRC experiments.[7]

The group at the University of Alabama-Huntsville has developed the Plasmoid Thruster Experiment (PTX) to evaluate the use of plasmoids for propulsion.[13-15] PTX produces plasmoids with a conical geometry instead of cylindrical. The results from this experiment have shown exit velocities up to $2x10^4$ m/s. This geometry allows for the benefit of plasmoid creation and acceleration to occur within the same step.

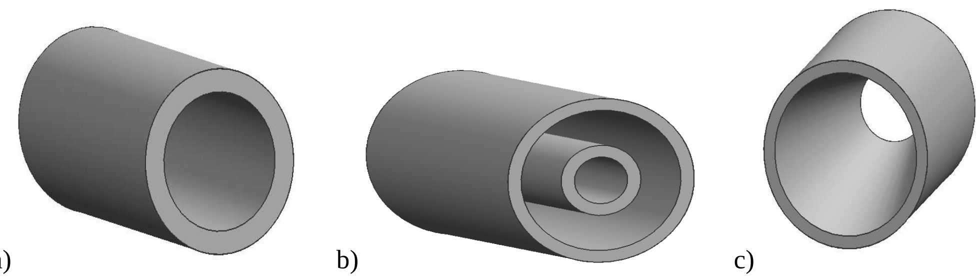
IV. FRC Thruster Model Design

The objective in the development of the FRC plasma thruster is to obtain the best design configuration based on the assessment of the efficiencies in FRC formation and acceleration. This design is sought by simulating various configurations and conditions of FRC formation and acceleration using the MHD code NIMROD. The simulations specifically examine the 1) pre-ionization geometry effect using annular, centerline-peaked, and uniform-fill initial plasma distributions; and 2) device geometry effects by varying shape (annular, conical, and cylindrical), length, and diameter. Ultimately based on the results of the simulation, the goal is to develop at a future date an experimental test article to validate the simulated predictions.

The initial step in simulating the FRC device in NIMROD will be to establish that the simulations are providing consistent, realistic results. This will be done by trying to duplicate the results of published data of related experiments. Once this initial step is finished, two investigations will begin which will examine the effects of varying specific characteristics of the FRC thruster on CT formation and acceleration. Based on the investigation results, a model of a FRC thruster can be assembled. Further simulations will be conducted using this efficient FRC thruster design to produce a data package. The data package will be for comparison purposes with the results taken from a future FRC experiment test article.

In the first investigation, the effect of the pre-ionization geometry will be studied. In the pre-ionization phase, adjustment will only be made to the initial plasma distribution and each simulation will use a cylindrical device geometry, identical pulse-compression waveform, and same formation sequence. The initial plasma distributions of annular, centerlined-peaked, and uniform-fill will be utilized. The cylindrical geometry will be used since this geometry allows for all three of the initial distributions. A CT figure of merit is employed to evaluate the efficiency of the plasma distribution in each simulation. A comparison between the merits of each distribution will occur to determine which distribution most efficiently formed the CT.

For the second investigation, two separate sets of simulations are performed to establish the effect of device geometry on CTs. The first set of simulations (using the initial plasma distribution with the best efficiency) will study the three typical geometries (see Fig. 3) found in FRC devices; cylindrical, conical, and annular. Again, a CT formation figure of merit along with a propulsion figure of merit is used to evaluate these three geometries. In the second set of simulations, the dimensions of the simulated FRC device is adjusted. The length will range from 20 cm to 75 cm and the diameter will range from 20 cm to 40 cm which is consistent with current FRC devices. These simulations will utilize the best initial plasma distribution along with the most efficient geometry.



a) b) c)

Figure 3. Example Device Geometries: a)Cylindrical, b) Annular, c) Conical

V. Simulation Progress

Simulation work was originally slated to be completed using the MHD code MACH2. Due to operational challenges, the NIMROD code was selected to replace MACH2. Initial simulations utilizing NIMROD are in development at this time. Table 1 lists the initial parameter ranges that are being utilized in the FRC simulations. These ranges are consistent with the ranges established in the related CT devices that have been or are currently being studied. These ranges allow for a continued study of specific parameters (e.g., discharge time) in effort to expand understanding the effects of these parameters. The aim of these simulations is to delineate which pre-ionization distribution and device geometry provides the best efficiencies and ultimately the best propulsive results. The simulations will model the heavier atomic gases of argon and xenon while utilizing lower energy methods for plasma production.

Table 1. Initial Parameter Ranges for FRC Simulations

Parameter	Range
Device Length	20-75 cm
Device Diameter	20-40 cm
Discharge Time	100-500 s
Pressure	3-20 mTorr
Discharge Voltages	500-1000 V

VI. Conclusion

The prospect of utilizing FRC plasma in a propulsion application that meets the demands of ORS has made it advantageous for further development. Related FRC test articles have limitedly studied the effects of the configuration parameters on CT formation, acceleration, and expansion into a vacuum environment. The initial investigation into the FRC thruster must begin with simulations that vary the parameters of pre-ionization geometry, device geometry, and the expansion of the plasma into a vacuum to establish which parameters produce the most efficient results. By ascertaining the best parameters, a configuration can be simulated and then constructed which would generate the best propulsion performance.

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