Print - ISSN : 2319–9814
Online - ISSN : 2319–9822

Journal of
Space Exploration

WWW.MEHTAPRESS.COM

Full Paper

A fusion space probe - Viper, an ultra high Isp pulsed fusion rocket

Akshata Krishnamurthy*, Paul Keutelian, George Chen, Benjamin Ulmen, John Orcutt, George H.Miley

University of Illinois at Urbana-Champaign, Urbana, IL 61801, (USA)
E-mail : akrshnm2@illinois.edu; ghmiley@illinois.edu

Received: January 05, 2013
Accepted: March 15, 2013
Published: March 30, 2013

***Corresponding author's Name & Add.**

Akshata Krishnamurthy
University of Illinois at Urbana-Champaign, Urbana, IL 61801, (USA)
E-mail : akrshnm2@illinois.edu

Abstract

The Viper Pulsed Fusion Rocket (PFR) is an ultra-high specific impulse, variable thrust, space probe concept recently proposed for unmanned interstellar exploration. The design is based on an aneutronic Inertial Electrostatic Confinement (IEC) fusion power unit producing an Isp in the range of $10^4 – 10^6$ seconds with advanced proton - Boron-11 (p-^{11}B) fuel and a neutral propellant. The IEC is fed highly ionized p-^{11}B by an RF permanent magnet helicon array. Anisotropic alpha particle products produced in the fusion reaction are magnetically collimated and are quasi-equilibrated with a neutral gas and exhausted through a magnetic nozzle. Through the coupling of a pulsed helicon array, Viper accomplishes a power gain of greater than seven by achieving very high plasma densities in the Helicon. The probe has a launch mass of approximately 30 metric tons and a total power production of 360 MW.

Keywords

Unmanned probe; Fusion propulsion; Space probe; Helicon; IEC; Interstellar exploration.

INTRODUCTION

Viper is an unmanned fusion space probe proposed for next generation interstellar missions and scientific exploration[1]. With the present economy and limited budget, stress has shifted from manned missions to unmanned interstellar exploration. Hence, there is a growing need to explore and develop new designs to support such demanding missions. This is one of the few fusion space probe studies. Prior studies, Project Daedelus[2] and Project Icarus[3], were proposed by the British Interplanetary Sciences. In contract a number of conceptual manned space ships using fusion have been published, e.g. see[4] and references contained therein. A key difference is that the probe can operate with much lower power, but scaling down the fusion reactor requires use of a concept capability of compact lightweight operation. The unique helicon injected IEC system proposed here uniquely meets these requirements.

Viper is a high specific impulse, variable thrust fusion probe design proposed to tackle the challenges of a deep space mission and overcome the limitations of these previous designs. Utilizing an aneutronic fusion reaction, the IEC produces negligibly low levels of neutron radiation. A plentiful propellant (Boron-11) is used, and the system operates at moderate thrust (10 - 2000 N) and extremely high specific impulse ($10^4 – 10^6$ s). An advanced scientific exploration mission demands high efficiency and optimal usage of the fusion energy to produce thrust. The Viper probe satisfies this need and the concept represents an ideal candidate for the next generation of interstellar propulsion. The Viper is also the first step towards building a manned probe for deep space missions in the future. The extreme distance of extra-solar transit requires a near-term propulsion solution that can provide high thrust and high specific impulse based on known laws of physics. Many presently operating electrical propulsion technologies provide the high specific impulse, but not the thrust, necessary to make a subluminal interstellar voyage realizable in the near future. Similarly, even the most advanced hybrid rockets in use today are not nearly efficient enough to provide thrust on a trans-Plutonian or interstellar mission. The Viper concept describes a propulsion solution that provides the necessary long term thrust, efficiency, propellant simplicity and scalability for an outer-solar mission while also achieving heavy lift cargo functionality. The concept engine is the culmination of recent advances in plasma generation technology mated with a high-performance approach to generating thrust from nuclear fusion energy. The Inertial Electrostatic Confinement (IEC) device, pioneered by P.T. Farnsworth[5] in the 1960's and championed by R. W. Bussard[6] and G.H. Miley[7] in the 1990's, has the potential under pulsed operation to provide a favorable ignition environment for p-^{11}B fuel based on recent advances in helicon plasma generation and pulsed power technology. In addition to allowing efficient direct conversion of the fusion reaction products to thrust, Viper achieves a low shielding mass due to the aneutronic nature of the p-^{11}B fusion reactions involved. Boron is an abundant fuel and obtained mostly from mineral deposits.. The anisotropic behavior of the alpha particles is favorable for magnetic collimation, and hence efficient thrust production. In addition, the thrust efficiency is further enhanced by the more nearly monoenergetic energy of the alphas compared to the three-body random energy distribution previously predicted.

KEY REACTION

Viper utilizes an advanced category of fuels considered 'aneutronic'. These fusion cycles are those which produce very little neutron radiation (< 1% of fusion energy) via primary reactions or significant side reactions. Chief among these of particular note are the ^{3}He-^{3}He, ^{3}He-^{6}Li, and p-^{11}B reactions. Dual helium reactions are impractical for any near term study and deployment due to helium-3's low availability and ^{3}He-^{6}Li requires a substantially higher ignition temperature. p-^{11}B is therefore an attractive fuel due to its natural abundance, negligible neutron radiation emission producing three energetic alpha particles of 2-4 MeV per reaction. Among the aforesaid fuels, p-^{11}B has the most promising attributes as an advanced fuel and the reaction involved in this design is:

$$p + {}^{11}B \rightarrow 3\ {}^{4}He + 8.7\ MeV \qquad (1)$$

The reaction predominately goes to the kinetic energy of charged reaction products - three doubly ionized Helium nuclei (α particles). The fuel itself is non-radioactive and produces exhaust (α, p^{+}, e^{-}).

The primary systems of the Viper unmanned probe, as shown in Figure 1, are the Helicon and the IEC, each of them discussed separately in this section. The IEC is fed highly ionized p-^{11}B by an RF permanent magnet helicon array. Anisotropic alpha particle products produced in the fusion reaction are magnetically collimated. About 10% of their energy is directly converted to electrical power for recycle and station keeping while the remainder continues with the alphas going to the magnetic nozzle. These

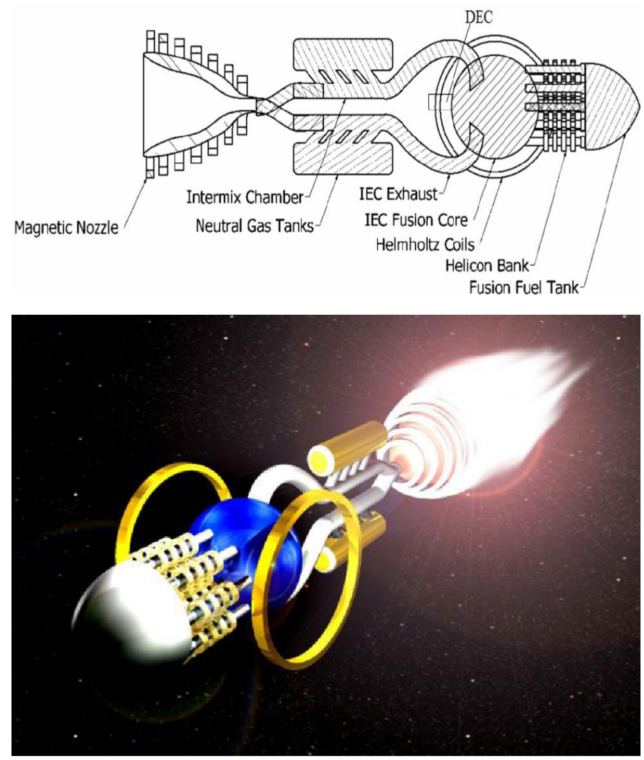


Figure 1 : (Above) Schematic diagram showing the primary systems of the Viper unmanned fusion probe and (Below) Artist's conception of the Viper probe

energetic alpha products are quasi-equilibrated with a neutral gas such as hydrogen and exhausted through the magnetic nozzle.

Through the coupling of a pulsed mode helicon array and the IEC confinement, high density non-Maxwellian plasma beam is produced in the pulsed mode. The following processes already mentioned involve the alpha particle extraction and collimation for direct conversion into electrical power and into the energetic magnetic nozzle for propulsion. The collimator consists of a pair of Helmholtz coils anti-parallel to the magnetic channel. This configuration creates a central region with no magnetic field, thus providing a channel for the flow of ions into the magnetic expanded region. This expander is used to convert the perpendicular component of kinetic energy of the charged particles into parallel component. Direct energy converters (DEC) are placed ahead of the expanders to convert the kinetic energy of the alpha particles into electrical energy. Momota et. al.[8] experimentally (using an electron source simulation technique) and numerically evaluated the use of hexapolar direct energy converters (HPDEC) to collimate charged fusion products with positive results. Miley[9] and others have reported similar results but acknowledged complications and efficiency reduction introduced by an isotropic source of charge carriers. However, recent work by Stave[10] has shown p-^{11}B alpha particles are generated at two anisotropic energies. Two 4-MeV alphas open at an average angle of 155°, with a third alpha being produced semi-isotropically at approximately 1 MeV, leading to predictable paths along the coil field lines. Collimation and direct energy conversion efficiency can be maximized by a guided optimization of the coil position and magnetic expander orientation. The second important part of the process involves the electrostatic conversion process. Power drawn from the DEC plates may be as high as 4 MeV, requiring a bank of step-down transformers to convert the power to readily accessible voltages for onboard electronics. Power for the pulsed equipment is pumped into Marx capacitor supplies for recirculation. The remaining alpha particles are magnetically directed to the intermix chamber where they are passively circulated by a rotating magnetic field with injected neutral gas. This propulsive efficiency, or the percentage of net power reserved for propulsion generation is a key factor in designing a high-thrust configuration. The high energy alphas will quickly ionize the injected gas, transferring much of their energy and semi-equilibrating with it to create a high velocity exhaust mass flow. Reaction rates are predicted at 10^{19} per cubic centimeter. Viper is an interstellar-capable probe with launch mass of approximately 30 MT, the calculations of which are discussed in detail in the later part of this paper. Extrapolation of present laboratory-scaled helicon and IEC experiments to desired conditions is theoretically achievable, but requires the resolution of physics complications regarding stability and propellant/fuel mixing. Future developmental efforts should also focus on experimental power scaling of the helicon in pulsed mode, numerical simulation of potential p-^{11}B confinement geometries and a theoretical investigation of the plasma thermochemistry.

Helicon

The helicon is a plasma source that ionizes gas through radio frequency heating. The helicon mode produces a low frequency electromagnetic whistler wave that achieves energy deposition by stripping the electrons from the gas in the source tube, and accelerating the ions through a constant B field supplied by permanent magnets. Various antenna designs can be employed in the generation of a helicon wave, such as the right-handed helical antenna.

Then Helicon produces plasma by driving an antenna at a frequency between the ion and electron cyclotron frequencies. Helicon waves are cylindrically bounded low-frequency whistler waves and propagate between the ion and electron cyclotron frequencies. The antenna is generally wrapped around an insulating cylindrical tube. The antenna current induces a magnetic field as power is increased. This drives an electric field within the tube. The power input to the antenna is increased until breakdown of the neutral gas occurs. Hence, helicon plasma is classified as inductively coupled plasma. A DC magnetic field surrounding the cylindrical tube drives the helicon waves. Typical laboratory parameters for the operation of helicon plasma source for injection into the IEC device are: pressure in the mTorr range, driving frequency of the order of MHz, input power of hundreds of watts, DC magnetic field of several hundred Gauss, a cylindrical tube with a length of tens of centimeters and diameter of a few centimeters. Taking into account the physical configuration of the helicon plasma: bound, cylindrical, collisionless and uniform density, the dispersion relationship for this system can be derived.

The helicon is widely recognized as one of the best sources of highly ionized, high-density low energy plasma. In Viper, this capability is coupled with the IEC where ion acceleration to the high energies required for fusion is achieved. While steady state operation of helicons is normally studied, there are advantages to pulsed power helicons that are only just being realized. Marx generators with 250 Hz resolution over a 400 picosecond pulse up to 200 mA have recently been commercialized, paving the way for high power delivery for plasma applications. The timed evolution of helicon wave-heated plasma was first studied by Chen[11]; and more recently described in detail by Boswell[12] at the Australian National University. Research has focused primarily on the study of transient neutral depletion, unstable electron temperature fluctuations in the helicon double layer thruster, and the character of the decay from breakdown, to steady state, to relaxation. Boswell first observed that pulsed operation in the 10 microsecond regime demonstrates a burst in ion density and correspondingly high plasma current with respect to steady-state values. This is believed to be a result of a burst of "hot" secondary electrons generated by a transient resonance. An increase in plasma current and ion density are both advantageous design parameters for a helicon-fed IEC reactor. Steady-state ion density values have been reported as high as 10^{14} cm^{-3} in the low power range with B -fields varying from 100 to 1000 Gauss. Very recently Takahashi[13] observed that ion density scales linearly with RF power lesser than 1000 W, and a greater-than-linearity relation has been suggested for higher power regimes. Chen[14] also reported favorable scaling of ion density and plasma confinement with B-field strength for a range of values, noting however, the existence of instabilities in the density/B-field space indicative of a complex resonance mechanism. Further study is required to better quantify how this phenomenon could be used to enhance the density profile of a helicon. While the physical processes underlying these high-density transients are not fully understood in a theoretical context, densities approaching 10^{17} cm^{-3} are realizable in a pulsed helicon with high B-field and an optimized high power regime.

Inertial electrostatic confinement (IEC)

The Inertial Electrostatic Confinement (IEC) concept was originally conceived by P. T. Farnsworth for thermonuclear fusion in 1953[5]. In 1959, R. Hirsch working with Farnsworth built and demonstrated an IEC device, which he called the Fusor. The principle of operation was to establish electric potential fields so that ions and electrons are confined solely by the electrostatic fields and by their own inertia. Nuclear fusion could be achieved if the ions were maintained at a high temperature.

Most of the experiments in the 1960s and 1970s focused on measuring the electrostatic potential profile inside the IEC device. When ions converge at the center, a positive space charge is created at the center that repels the ions and attracts electrons toward the center. The electrons can also attract the ions toward the very center of the IEC. This structure sets up a "double" potential well. This potential well ultimately serves as a potential trap for ions, giving a high density of energetic ions, thus providing a high fusion rate from beam-beam collisions between the recirculating ions.

IEC research began at the University of Illinois Fusion Studies Laboratory under the directorship of Dr. George H. Miley in the early 1990s[7]. This research was focused on the development of IEC devices for fusion to eventually develop commercial neutron generator. In this work, the unique Star mode was discovered, which was instrumental in commercializing the IEC technology as it enabled high rates of neutron production with minimal collisional erosion of the grid wires.. The three characteristic modes of operation in an IEC device are the star mode, central spot mode and jet (halo) mode. These modes have different potential structures, operating parameters and are stable as well as easily reproducible[7].

The IEC employs a electrostatic potential trap to collide and fuse ionized hydrogen and Boron-11. This trap configuration relies on multiple deep potential wells and a specialized grid design to establish and maintain ion confinement as well as mitigate thermal losses and Bremsstrahlung emission. Sedwick[15] has attempted improving confinement times by experimenting with multiple concentric grids to improve the well structure without inadvertently causing electron-ion interaction. Doing this while minimizing Bremsstrahlung is an ongoing challenge. In addition, ultimately a deep potential well isolating the grids from the fusing plasma would seem necessary for a fusion device.

A viable confinement scheme must significantly reduce electron-ion scattering and thermal contact. Previous studies have focused on reflection scattering and reabsorption to increase energy confinement, but these methods will only go so far. Non-Maxwellian fusion plasma in the IEC can accomplish breakeven without excessive recirculation energy if the beam-beam temperature ratios remain suitably high, $T_i/T_e >> 10$ and the electrons remain cold. Space charge limitations should allow for this at operational densities. Certain instabilities will be observed but can be mitigated with successful energy confinement and beam control. Two-mode and Weibel magnetostatic instabilities have been studied closely and should be avoidable for plasma densities under 10^{20} per cubic centimeter for the time scales under consideration here. In addition to virtual grid development, confinement can be enhanced by brute force increase in well depth that appears possible with pulsed operation since it allows significant increase in delivered cathode current.

PROBE CHARACTERISTICS

Viper weighs an estimated 30 metric tons, with the individual component weights estimated in TABLE 1. As seen, the IEC structure, power supplies, shielding and cooling are the major mass components. Had a magnetic or laser fusion system been used, the fusion reactor part would be much more massive compared to the simple structure of the IEC.

A viable space-based fusion propulsion system must resolve many of the core problems that have rendered systems based on conventional fusion cycles impractical to deploy in space. Besides breakeven, spacecraft-specific challenges such as compactness and fuel economy have proven to be difficult to achieve for other fusion cycles. Previously proposed D-T, D-D and D-He fusion devices, whether electrostatically, magnetically or inertially confined; have all been saddled with unrealistic requirements for radiation shielding. Since this design is for application in unmanned missions, most of the shielding mass is to protect the electronic components on-board. While the ITER concept has demonstrated the highest level of technological readiness and development, the materiel bulk and complexity renders it an impractical path to nuclear propulsion. Viper experiences very low gamma ray or neutron producing side reactions, minimizing the shielding mass necessary for the electronic components on the probe and the reduction of Bremsstrahlung losses drastically reduces necessary thermal radiator mass over previous fusion designs.

Mode of operation

The system parameters are listed in TABLE 2 and discussed in detail in the following sections. The Viper fuses reactants in a 1-millisecond pulse. After the helicon pulse, the helicon is shut off to reduce power consumption while the IEC remains under power until confinement is lost or all of the fuel is burned. This is the confinement time,

TABLE 1 : Breakdown of masses of individual components of the Viper system

Primary Systems	Mass (metric tons)
Helicon Array	2
IEC	8
Magnetic nozzle	1.5
Power supplies (Marx, HPDEC, transformers)	5
Structure and Shielding	7
Cooling System	4
Injectors, tanks, lines, etc.	0.75
Guidance and electronics	0.15
Scientific Payload	1.5
Total	29.9

τ_{conf} = 62.5 ms. As charged products are generated from the reaction, they are magnetically collimated by a pair of Helmholtz coils in an axial direction and funneled through a magnetic expander to a direct energy conversion (DEC) plate to draw off electrical power. The DEC plate is biased to a desired voltage, causing an incident particle to be electrostatically decelerated and its potential picked up and converted to current. Previous efforts reported by Burton and Miley[4] acknowledged technological limitations to efficiently drawing all of an incident charged particle's energy, but Viper only requires ~12% of the net alpha-carried energy to remain in self-powered operation.

TABLE 2 : System Parameters of the Viper probe

System parameters	Constants
τ_p (s)	0.001
f_{pps}	12
τ_{imp} , τ_{conf} (s)	0.063
f_{pps}	12
R (s^{-1})	10^{19}
E_α (MeV)	8.7
(kg/s)	10^{-5} – 10^{-2}
n_{i1},n_{i2} (cm^{-3})	$1.6\text{x}10^{18}$

Power

Despite its advantages over other fuels, there are significant technological challenges to obtaining ignition in a break-even candidate reactor on the p-^{11}B cycle. Previous attempts to develop p-^{11}B reactors have been derailed by its comparatively high ignition temperature, low cross section and parasitic losses due to Bremsstrahlung when compared to D-T and D-D. Viper can overcome these losses with reasonable assumptions of plasma density and Bremsstrahlung losses. Supposing an equal-or-favorable scaling between source and fusion plasma density, $n_{fusion} \geq n_{source}$, power can be computed in watts per unit volume as:

$$P = n_{i1} n_{i2} E_\alpha e \sigma_v \quad (2)$$

Nadler's study[16] of the 500μs pulsed operation of a D-D IEC revealed a production of 10^9 n/s and a Q factor of 10^{-5}. From their data, extrapolations made based on the cross section and plasma density can yield reasonable estimates of the necessary pulsed cathode current. Their results can be seen below with respect to current scaling. Under I^3-reaction rate scaling assumptions, a comparison between the D-D and p-^{11}B cross sections at their respective ideal ignition temperatures provides an estimate of the necessary cathode power to achieve break-even for p-^{11}B:

$$\left(I_{p-{}^{11}B} \approx I_{DD}\sqrt{\frac{\sigma_{v,p-{}^{11}B}}{\sigma_{v,DD}}}\right) \quad (3)$$

As a conservative estimate, the cathode power can be increased by as much as a factor of 30% to justify assumptions of I^3-scaling confinement strength and well formation. With a pulsed individual helicon density of 10^{17} cm^{-3} and theoretical array density $1.6\text{x}10^{18}$ cm^{-3}, required τ_{conf} approaches a reasonable 10^{-1}. A design condition of τ_{conf} = 62.5ms is theoretically achievable under the described parameters.

$$\frac{10^{16}}{n_i} = \tau_{conf} \approx .063\ s \quad (4)$$

Performance

Pulsed operation requires an instantaneous and average treatment of thrust and specific impulse. We must quantify how many energetic particles and how much cold gas will mix for each pulse. The simplest way to handle the cold gas propellant is to assume it is exhausted from a pressure vessel at a constant flow rate, $\mathbf{m}_{prop}$. The number of alpha particles per pulse is determined by the reaction rate and the pulse length.

$$v_e \approx \sqrt{\frac{2E_\alpha eR\gamma_{fp}\tau_p\eta_{sys}}{3RM_\alpha\tau_p + \dot{m}_{prop}\tau_p}} \quad (5)$$

$$\eta_{sys} = \eta_{cap}\eta_{mag}\eta_{mix}\eta_{prop} \quad (6)$$

$$\dot{m}_{tot} \equiv \dot{m}_\alpha + \dot{m}_{prop} = \tau_p(3RM_\alpha + \dot{m}_{prop}) \approx \dot{m}_{prop} \quad (7)$$

$$\gamma_{fg} \equiv focus\ gain\ parameter = \frac{(n_{core})^2}{(n_{helicon})^2} \quad (8)$$

where $R \equiv reaction\ rate\ [\frac{\#}{s}]$, $M_\alpha \equiv$ mass of 1 alpha particle.

$E_\alpha \eta_{sys}$ is the kinetic energy available to mixing. η_{sys} is the total efficiency with which the system converts the inertial energy of the alpha particles into propulsive force. It is a product of the alpha capture efficiency, the magnetic nozzle efficiency, mixing efficiency, and propulsive efficiency. Each efficiency parameter represents an inertial loss mechanism between fusion reactions and propulsive jet exhaust. γ_{fg} enables a consideration of confinement schemes in which core density can be improved over helicon-delivered plasma density.

It's important to note that this energy formulation makes a significant assumption. By characterizing the total kinetic energy in the exhaust jet as the energy of the alpha particles divided by the total exhaust mass, it is assumed that the kinetic energy of the alpha particles can be elastically and ideally spread between all available cold gas particles in each pulse. This assumption is supported by allowing η_{mix} to arbitrarily represent all related losses. A deeper numerical simulation of this mixing environment may yield a physical understanding of these losses – including dependencies on thermodynamic conditions and system variables. For a first approximation, we may consider $(1 - \eta_{mix})\, E_\alpha \eta_{cap} \eta_{prop}$ to be the energy lost to propulsion under non-ideal mixing conditions.

Even in a power gain device there are bound to be losses incurred in energy conversion, power transmission and transformation and working fluid contact. An attempt has been made to compute, or estimate where there is insufficient available literature, the inefficiencies present throughout the system, as shown in TABLE 3, in order to present a viable engine concept. While the individual values are generally high, the losses become very important when their product occurs. These efficiencies are used to obtain the exit velocity and the resulting values plotted in Figure 2.

TABLE 3 : List of efficiencies of various processes involved in the design of the Viper system

Efficiency Parameter	Approximation	Function of
η_{cap}	0.90	Helmholtz orientation
η_{mag}	0.80	Detachment, divergence, viscosity
η_{dep}	0.60	$\dot{m}$, Bremsstrahlung, mixing
η_{prop}	0.86	System Power
$\eta_{helicon}$	0.75	RF power, B-field
η_{el}	0.80	Heat and conversion
η_{util}	TBD	Unburned Boron fuel
η_{brem}	0.50	T_i/T_e, Bremsstrahlung re-absorption

The variations of thrust and specific impulse with mass flow rate have been plotted in Figure 2. The optimum configuration for outer-solar explorations would be the intersection point in the above graph with a thrust of 275 N and Isp of 200,000 s at a mass flow rate of 0.25 g/s. Other configurations like very high thrust with relatively low specific impulse (thrust of 2300 N and Isp of 24,000 s at a mass flow rate of 9.95 g/s) or very high specific impulse and relatively low thrust (thrust of 70 N and Isp of 710,000 s at a mass flow rate of 0.01 g/s) can be used depending upon the mission needs.

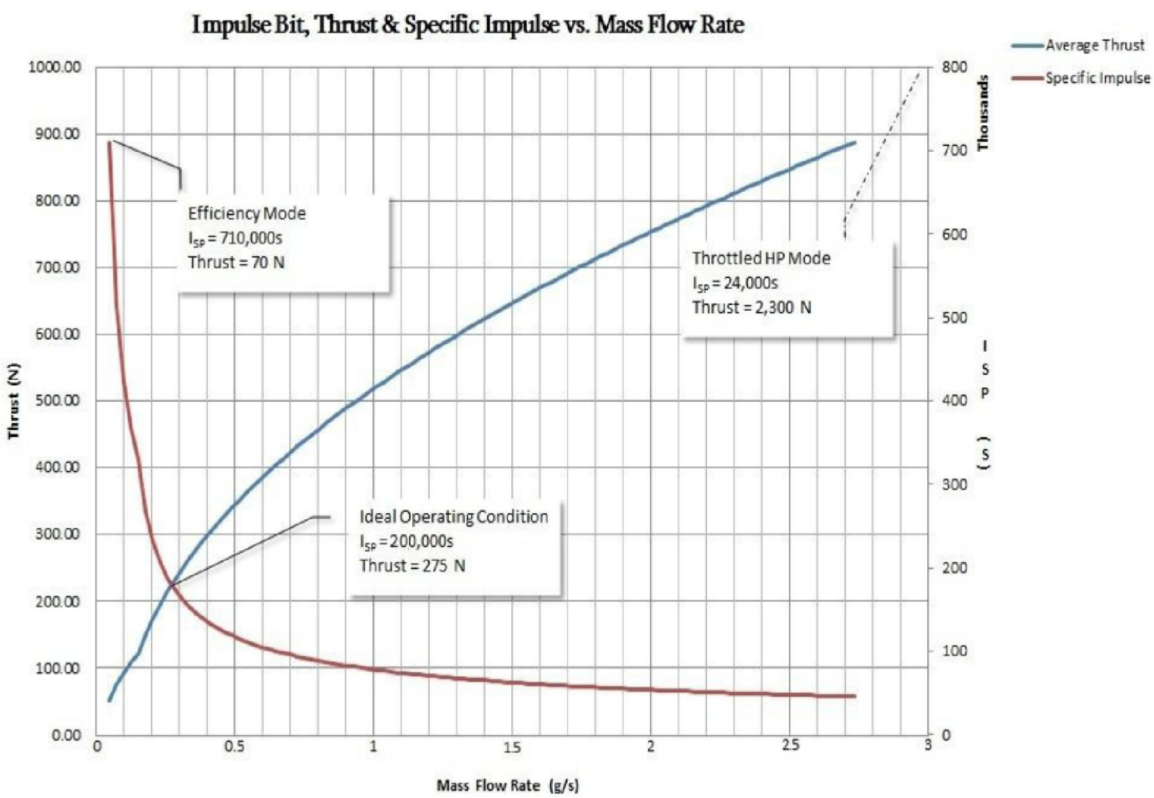


Figure 2 : Variation of thrust and specific impulse with mass flow rate

At $\tau_{conf} = \tau_{imp} = .063$ s, it is possible to increase the pulse rate from 12 per second to as high as 16 to achieve more thrust without sacrificing specific impulse. A plot of the average thrust versus pulse rate in high thrust mode can be studied as in Figure 3. A nominal pulse rate of 12 per second was chosen to assure adequate time for the helicon array to vacate excess plasma, but could theoretically be increased to vary thrust for mission objectives or reduced to conserve propellant.

Delta-v budget

The delta-v budget is an important factor in planning any space mission. The net delta v denotes the effort required to carry out all the propulsive tasks and orbital maneuvers during the entire mission. The delta-v range and its variation with propellant mass for the three primary operating modes have been calculated and plotted in Figure 4.

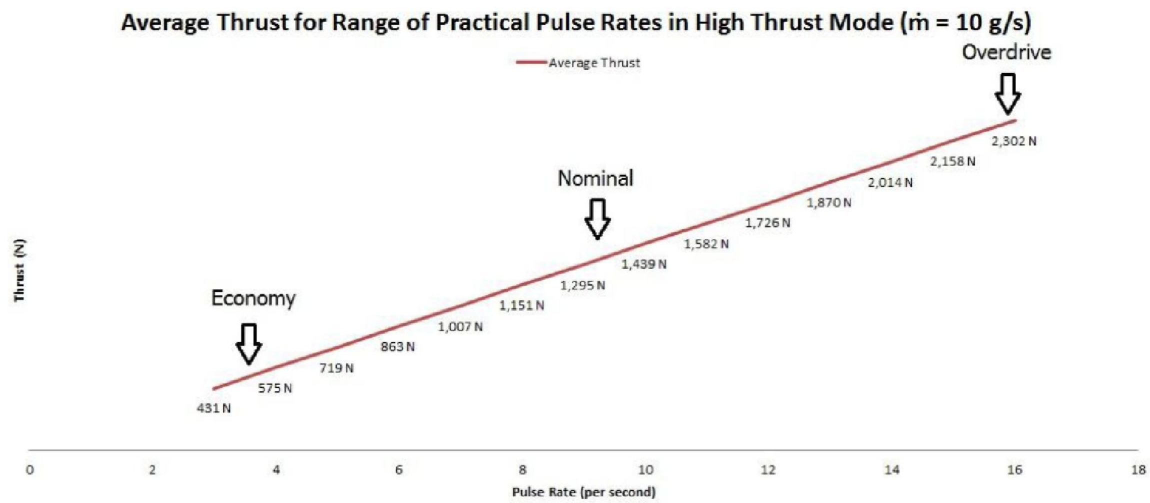


Figure 3 : Variation of average thrust with pulse rate in high thrust mode

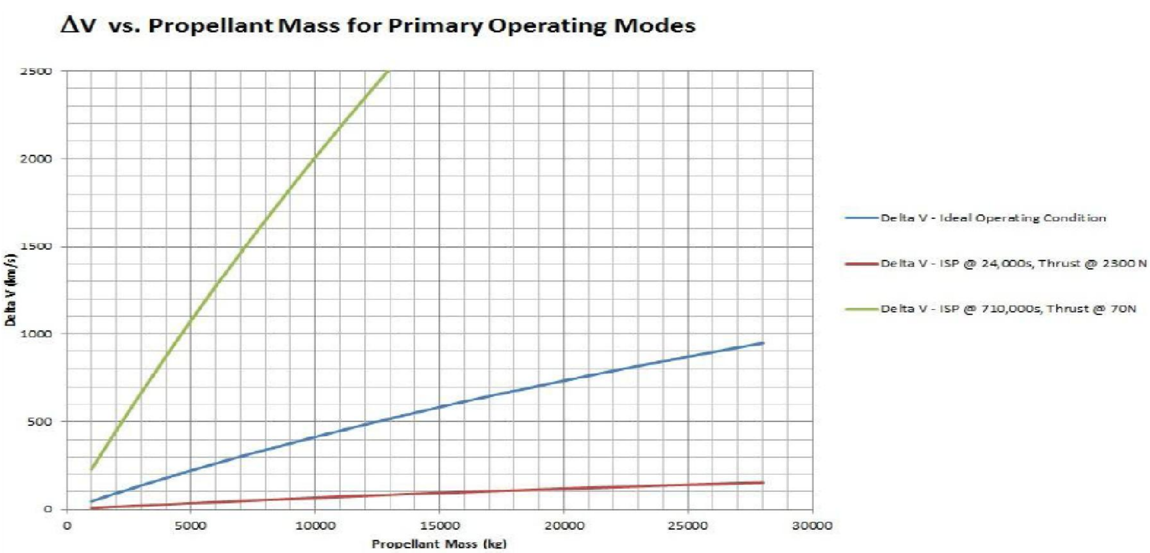


Figure 4 : Variation of delta-v with propellant mass for primary operating modes

Comparison of viper with previous deep space probes

A comparison of Viper PFR with two well-known deep space probes namely Voyager 1[17] and Pioneer 10[18] is presented in Figure 5. The Viper space probe weighs 30000 kg with a thrust power of 180 MW and reactor power of 360 MW. It produces a variable thrust in the range of 75-2,300 N and a specific impulse of 25,000-700,000 s. At a thrust of 275 N and mass flow rate of 0.25 g/s, the Viper would travel at 2,460,630 miles per hour, taking approximately 1156 years to reach Proxima Centauri which is 4.24 light years away.

The most prominent of recent NASA deep space probes, Voyager 1, weighed 721.9 kg with input power of 420 W. The speed of Voyager 1 is 35000 miles per hour, which would take it 80,000 years to reach Proxima Centauri. Pioneer 10 which became the first space probe to achieve escape velocity from the solar system had a launch mass of 258 kg and input power of 155 W. The speed of travel of Pioneer 10 is 28000 miles per hour that would take it approximately 101,600 years to reach Proxima

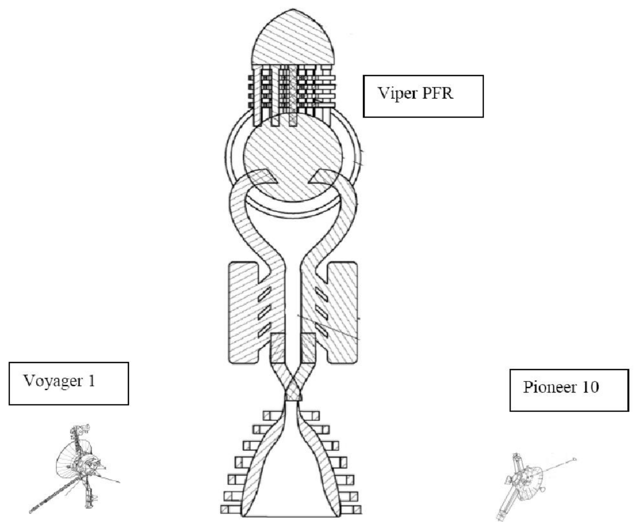


Figure 5 : Size comparison of Voyager 1, Pioneer 10 and Viper probes

Centauri. It can be observed that these previous space probes have a low launch mass and operate at lower speeds and hence, are not suitable for interstellar travel. Thus Viper would be the first step towards realizing the goal of interstellar explorations.

Furthermore, a comparison of Viper with previous fusion propulsion confinement concepts has been elucidated by Krishnamurthy[19].

Plan for development of the viper space probe

The first step towards bringing this design into reality is to carry out intensive research in the following directions:

Breakeven IEC fusion confinement

Stability of virtual grid formation and corresponding potential well confinement in the IEC is still unverified and needs to be demonstrated and further explored experimentally. Estimates of the pulsed cathode current required to achieve the breakeven condition in the IEC need to be experimentally verified.

Impulse chamber

Multi-physics modeling will be necessary to capture both continuum fluid mechanics and discrete momentum transfer in a charged particle environment.

Magnetic nozzle

More insight is required into recombination rates, magnetic instability and divergence losses, in addition to determining magnetic nozzle geometries.

Helicon power scaling

Prior research has explored the helicon power regime above 10 kW, but the underlying temporal evolution of the helicon wave in pulsed operation is still not well understood. Helicon-IEC coupling requires an equal-or-favorable density scaling between the source plasma density and fusion plasma density. Empirical study of helicon-IEC coupling with regard to ion trajectories, energies and electron pressure are underway by the authors at the University of Illinois – Urbana/Champaign HIIPER Space Propulsion Lab.

Pulsed power IEC

Indications are favorable that pulsing is the ideal path to reaching breakeven in any IEC configuration because it allows higher cathode currents with more compact power mass; however, more research into the pulse/plasma interaction is involved.

Possible next step breakeven experiment and use of p-B^{11}

Various publications have presented information about the existing data and theory for IEC operation. The potential for use in applications such as a neutron source and related radiation sources are well established. However, the ultimate goal is to develop a power producing IEC. The unique ability of the IEC to use non-Maxwellian plasma to burn advanced fuels to minimize radioactive and radiation emission involvement is an advantage. However the best current device results are 5 or 6 orders of magnitude down in energy gain or Q (energy out/ in) = 1 corresponding to breakeven. The IEC can be scaled up in energy gain while keeping a small size since the losses are in velocity space (i.e. via ion upscattering out of the potential well trap). To provide the reader with some insight into the possible IEC power device, a conceptual proposal for a near term IEC breakeven experiment is provided to prove the physics of operation with aneutronic p-B^{11} fuel.

Demonstration of net energy gain using IEC aneutronic fusion

The IEC is one of the few approaches to fusion that has the potential of burning aneutronic fuels such as D-He^3 and p-B^{11} (Boron-11 Isotope) in a reasonable scale device. This fuel results in charged-particle reaction products which allow efficient use of direct energy conversion technology with no direct greenhouse emissions and minimal radioactivity or radioactive wastes. The experiment proposed here would provide verifiable and reproducible proof of break-even conditions necessary to burn p-B^{11} as a practical aneutronic fuel in an IEC fusion power-generating device.

The goal is to burn relatively inexpensive aneutronic p-B^{11} fuel, avoiding issues of tritium breeding and radioactivity that the D-T burning devices face. The IEC creates a deep potential electrostatic 'well' for improved confinement in an ion injected IEC. This will be done with specially designed ion guns to inject ions into the IEC with strong focus and controlled angular momentum. Confinement scaling in the IEC is in velocity space (vs. physical space which brings in reducing the surface to volume ratio), allowing breakeven and power production in small volume plasmas. Thus in principle, energy breakeven could be demonstrated in the IEC in a very dense plasma "core" occupying only a few cc volume with only a few 100s of watts in and out.

The use of the new gun injected technology to obtain breakeven in a dense plasma core in the IEC of 100s of cc volume and with 20-25 kW input power seems practical. This proof-of-principle device would demonstrate the physics of energy production and provide the basis for going rapidly to practical IEC power plants. This route could lead to power reactors for distributed power applications in the range of a MW.

Vision of a future p-B^{11} fusion plant

In the ultimate power plant, the preferred fusion reaction would employ aneutronic p-B^{11} fuel, which fuses to produce energetic alpha particles with no neutrons and minimal radioactivity. p-B^{11} reactors in the central IEC core result in MeV energy alpha particles according to the reaction: $p+B^{11} \rightarrow 3\alpha$. Due to its inherent non-Maxwellian (beam-like) plasma, the IEC is especially well suited for burning a fuel such as p-B^{11} which requires high energies (~150 keV). In operation, a bulk of the IEC driving energy is given to ions so an applied voltage of ~180 kV provides ion energies near the peak of the p-B^{11} cross section. The key physics challenge then for the IEC is to achieve good ion confinement via strong ion trapping (i.e. large number of recirculations) in the potential well. This trapped plasma must meet the Lawson criterion for energy to break-even with p-B^{11}, $n\tau \sim 10^{16}$ cm^{-3}- sec (two orders of magnitude above the requirement for D-T fusion). Here n is the ion density and τ is the ion confinement time. Assuming the converged core density in the potential well of ~10^{16} cm^{-3}, ion trap times of ~ 1 sec are required. Plasma simulations show that carefully controlled injection can provide the potential well trap required to achieve this goal.

Proposed breakeven experiment

Present IEC experiments at UIUC are designed to baseline Q impact of ion injection conditions combined with supplemental electron sources to maintain the desired quasi–neutrality. One of the current experiments, shown in Figure 7, consists of a 16-inch diam. spherical vacuum system with a spherical grid held at a high potential. This system produces about 10^8 reactions/sec based on neutron counting experiments. A specially designed radio frequency (RF) ion gun is installed on the potential well formation for ion trapping.

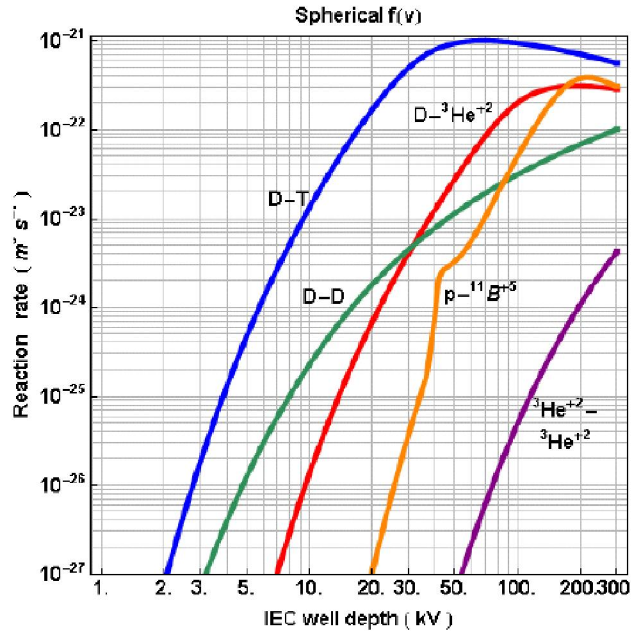


Figure 6 : p-B^{11} Fusion Cross Section Energy Requirements. The p-B^{11} reaction rate approaches that of D-T at very high energies, i.e. deep potential wells.

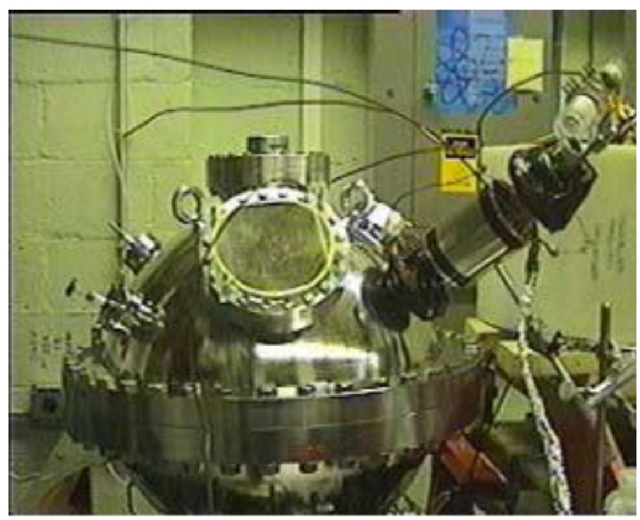
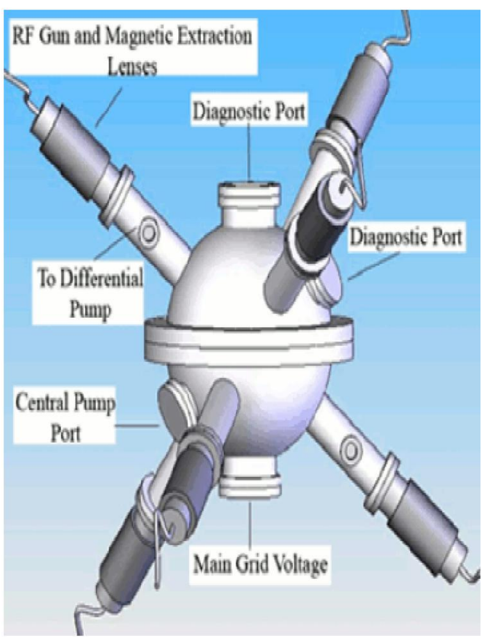


Figure 7 : IEC system with radio frequency ion gun

side of the chamber to study controlled ion injection and corresponding The injected ion current, *I*, with one gun was only ~ 50 mA. Still, based on measurements of neutrons emitted using deuterium fuel, the Q (fusion energy gain/energy in) was order of 10^{-6} which is remarkable for such a small device. These results, plus supporting computer simulation studies, show that the scale-up of this device to 12 injector guns plus adding strong differential pumping, could potentially achieve breakeven. The proposed ion injected IEC device with 12 guns is shown schematically in Figure 8. The key to achieving breakeven conditions in this device is to inject ions with good focus and the desired angular momentum. The RF ion gun has a unique magnetic nozzle to achieve that. Electrons are simulateously introduced and this eliminates the need for a grid by formation of a deep potential well (ion trap). This configuration is highly non-Maxwellian due to the beam dominated nature of the trapped ions. Precise control is maintained over the energy and angular momentum of injected ions and a balanced supply of electrons is provided. An RF ion injector capable of such operation has been demonstrated at UIUC as discussed earlier. A schematic sketch of the gun design is shown here in Figure 8. A key component is the magnetic focusing lens at the gun extraction port. This allows very efficient differential pumping between the high pressure gun chamber and the low pressure IEC chamber and provides focus control. This experiment will involve very high power inputs (about a MW). To avoid excessive power supply and thermal controls, a Marx bank pulsed power input with peak powers of ~ 1 MW over 1 msec at 0.01 Hz will be used. Pulsed experiments with equivalent power inputs on one gun have already been performed successfully. The pulse length is set long enough to provide quasi equilibrium physics conditions in the trapped plasma during the “flat top” region of the pulse”. Thus the data obtained is relevant to eventful steady-state reactors where the internal fusion power production alleviates the input power supply requirement.

CONCLUSION

Viper is an unmanned fusion-powered space probe designed based on the coupling of a helicon source and IEC that uses p-^{11}B as the fuel. Purposed for outer-solar system exploration, the probe is capable of Plutonian transit years shorter than modern electrical propulsion probes with comparable scientific payloads. The feasibility of the Viper concept has been established through conservative estimates of developable technologies to enable future up scaling to interstellar mission profiles. The engine concept’s ability to be multi-purposed as a heavy lift cargo vessel servicing future deep space outposts also appears promising. The coupling of pulsed operation and the high density Helicon plasma source has been described to the advantage of specific breakeven figures of merit. Viper’s advanced capabilities stem from this unique coupling. Utilizing the aneutronic p-^{11}B reaction, the problems involving shielding mass, safety concerns and neutron radiation is virtually eliminated. Future improvements and modifications to this design study may develop specific



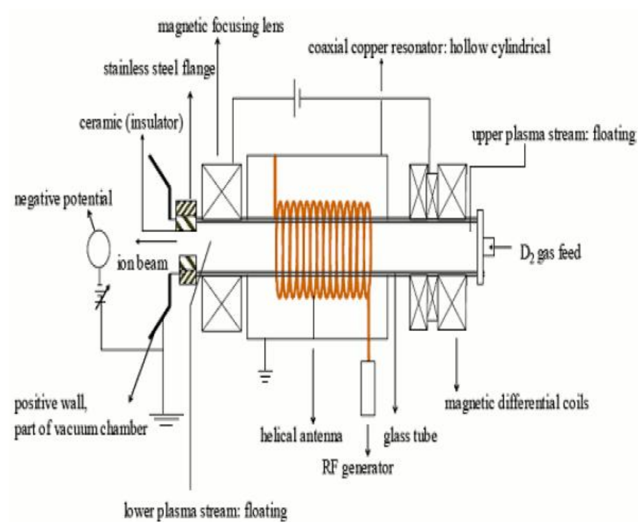


Figure 8 : (Left) Multiple ion gun concept - Six guns shown for simplicity, but twelve are proposed for the breakeven study, and (right) Differentially pumped RF- driven ion gun

virtualized grid geometries or explore differential pulsing of the Helicon/IEC coupling for even further advances in source density. Developmental issues have been identified to allow an experimental development program. Fortunately, due to the small, relatively simple structure of the Viper engine, development should be possible with a comparatively low budget (compared to the financial expenditure on the complex Tokamak, ITER, designed for terrestrial land electrical power).

NOMENCLATURE

p-^{11}B : proton Boron-11
T_e : electron temperature
T_i : ion temperature
$\dot{m}_{prop}$: mass flow rate

τ_{conf} : confinement time
E_α : Energy of alpha particle
σ : cross section of p-^{11}B
η_{sys} : system efficiency
η_{util} : utilization efficiency
η_{mag} : magnetic nozzle efficiency
η_{prop} : propellent efficiency
$\eta_{helicon}$: helicon efficiency
η_{brem} : Bremsstrahlung efficiency
η_{prop} : Propulsive efficiency
R : reaction rate
M_α : mass of 1 alpha particle

REFERENCES

[1] J.Orcutt, A.Krishnamurthy, G.H.Miley, P.Keutelian, B.Ulmen; Journal of British Interplanetary Sciences, Accepted, **(2012)**.

[2] A.Bond, A.R.Martin; Journal of British Interplanetary Sciences Supplement, S5-S7 **(1978)**.

[3] K.F.Long, R.K.Obousy, A.C.Tziolas, A.Mann, R.Osborne, A.Presby, M.Fogg; Journal of British Interplanetary Sciences, **62(11/12)** **(2009)**.

[4] R.L.Burton, H.Momota, N.Richardson, Y.Shaban, G.H.Miley; Fusion ship II: A fast manned interplanetary space vehicle using inertial electrostatic fusion, Space Technology and Applications International Forum-STAIF Proceedings, 553-562 **(2003)**.

[5] P.Farnsworth; US Patent, **3**, 386 883 **(1968)**.

[6] R.W.Bussard; Fusion Technology, **19**, 273 **(1991)**.

[7] G.H.Miley, John Sved; Applied Radiation and Isotopes, **48**, 1557-1561 **(1997)**.

[8] H.Momota, G.H.Miley, J.Nadler; National Inst.Fusion Sci., **641**, 11 **(2000)**.

[9] G.H.Miley, Fusion energy conversion, American Nuclear Society, Hinsdale, Illinois **(1976)**.

[10] S.Stave, M.W.Ahmed, R.H.France III, S.S.Henshaw, B.Muller, B.A.Perdue; Physics Letters B, 26-29 **(2011)**.

[11] F.F.Chen; Plasma Phys.Control Fusion, **33**, 4 339-364 **(1991)**.

[12] R.W.Boswell, D.Vender; Plasma Sources Sci.Technol., **4**, 534 **(1995)**.

[13] K.Takahashi, T.Lafleur, C.Charles, P.Alexander, R.W.Boswell, M.Perren; Applied Physics Letters **(2011)**.

[14] F.F.Chen; Introduction to plasma physics and controlled fusion, ISBN 13:987-0-306-41332-2, **1**, 2nd edition, New York: Springer, **(2006)**.

[15] R.J.Sedwick, T.J.McGuire, C.C.Dietrich, N.Z.Warner, D.A.Zayas; Multi-grid IEC fusion for space power and propulsion, AIAA/ASMA/SAE/ASEE Joint Propulsion Conference and Exhibit, 1-18 **(2006)**.

[16] J.H.Nadler, G.H.Miley, M.Coventry, M.Williams, B.Jurczyk, R.Stubbers; Fusion Engineering, 209-212 **(1999)**.

[17] Voyager 1; http://en.wikipedia.org/wiki/File: Voyager_Program_-_spacecraft_diagram.png, Accessed June 17th **(2012)**.

[18] Pioneer 10; http://www.physics.uiowa.edu/newsletter/2003/pa03-alumni.html, Accessed June 17th **(2012)**.

[19] A.Krishnamurthy, B.A.Ulmen, P.Keutelian, G.Chen, G.H.Miley, Comparison of the viper pulsed fusion rocket to prior space propulsion design studies, AIAA SPACE 2012 Conference & Exposition and AIAA Complex Aerospace System Exchange, Pasadena, California, September **(2012)**.