# PROJECT ICARUS: ANALYSIS OF PLASMA JET DRIVEN MAGNETO-INERTIAL FUSION AS POTENTIAL PRIMARY PROPULSION DRIVER FOR PROJECT ICARUS

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*Keywords: Icarus, Interstellar propulsion, magneto-inertial fusion, plasma, HEDP*

Human hopes of reaching stars other than the Sun are currently limited by the maturity of advanced propulsion technologies. One of the few candidate propulsion systems for providing interstellar flight capabilities is nuclear fusion. In the past many fusion propulsion concepts have been proposed and some of them even explored in high detail (Project Daedalus), however, as scientific progress in this field has advanced, new fusion concepts have emerged that merit evaluation as potential drivers for interstellar missions. Plasma jet driven Magneto-Inertial Fusion (PJMIF) is one of those concepts. PJMIF involves a salvo of converging plasma jets that form a uniform liner, which compresses a magnetized target to fusion conditions. It is an Inertial Confinement Fusion (ICF)-Magnetic Confinement Fusion (MCF) hybrid approach that has the potential for many benefits over both ICF and MCF, such as lower system mass and significantly lower cost. This paper concentrates on a thermodynamic assessment of basic performance parameters necessary for utilization of PJMIF as a candidate propulsion system for the Project Icarus mission. These parameters include: specific impulse, thrust, exhaust velocity, mass of the engine system, mass of the fuel required etc. This is a submission of the Project Icarus Study Group.

## 1. INTRODUCTION

Interstellar endeavors have been a part of scientific and engineering fantasy long before man set foot on the moon. Reaching of the “shiny things” in the night sky was probably one of the first wishes of the early astronomers, although they did not know that those were actually massive balls of thermonuclear reactions that we today call stars. After two and a half millennia, human intellect took man to the sky, then to Earth orbit, then to the Moon and today, we certainly posses the technology necessary to have manned missions to Mars. However, let us not forget that some of the most prominent astronomical discoveries during the 20$^{th}$ and 21$^{st}$ century, were and are still made by remarkable satellites and probes, some of which are already beyond the borders of our Solar system. The insights that those human-built devices gave us are by all standards groundbreaking. The incredible amounts of detailed information that are extracted from countless photos, videos and other forms of analysis, going from our Solar neighborhood to most remote areas of the Universe, are scientifically invaluable and, whether we are willing to admit or not, very relevant to our existence. Satellites and probes are, in a way, the extension of human physical presence and therefore represent an important factor in paving the path for many technological innovations, scientific endeavors and ultimately space colonization.

Reaching stars other than our Sun remained an unsolvable puzzle for science and engineering throughout most of history, purely because most of technology required has not been demonstrated or has not even been theoretically developed. However, during the seventies, a group of members of the British Interplanetary Society (Bond, Martin, et.al.) conducted a study that is now known as the Daedalus project. Daedalus was a feasibility study, meant to provide an insight to what would it take to reach another star within human lifetime. The project was never meant to develop detailed blueprints for an interstellar mission, as most of the necessary technological advancements had to be *reasonably extrapolated* based on the current state-of-the-art technology. The final result of the study was a detailed report [1] on 190 meters tall, two-stage, fusion-propulsion based, unmanned probe that needed to carry about 50000 tons of fuel, travelling on average around 0.12*c*, so it would reach Barnard’s star within 46 years. The project remained the most detailed study of interstellar mission to day.

Thirty years later, science and technology made significant progress in all relevant fields for interstellar travel: propulsion (nuclear fusion), materials, communications, computing power, general physics etc. and with relatively recent discoveries of potential earth-like, nearby, extra-solar planetary systems, the old dream of going beyond the Solar system became ever more meaningful.

## 2. OVERVIEW OF THE ICARUS PROJECT

Project Icarus is the unofficial heir of project Daedalus, with almost identical goals, but with an idea of re-evaluating Daedalus solutions, based on today's knowledge and technology. Icarus was started under the initiative of Tau Zero Foundation (TZF) and in collaboration with British Interplanetary Society (BIS), in September 2009. It is purely volunteer based effort, with the team structure being nationally and geographically diverse. The project purpose statement, as defined in the Icarus Project Program Document [2], is:

1. *To design a credible interstellar probe that is a concept design for a potential mission in the coming centuries.*
2. *To allow a direct technology comparison with Daedalus and provide an assessment of the maturity of fusion based space propulsion for future precursor missions.*
3. *To generate greater interest in the real term prospects for interstellar precursor missions that are based on credible science.*
4. *To motivate a new generation of scientists to be interested in designing space missions that go beyond our solar system.*

Terms of reference, that are also defined by [2] and which set up necessary requirements for the mission are quoted as follows:

1. *To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium.*
2. *The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.*
3. *The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner.*
4. *The spacecraft must be designed to allow for a variety of target stars.*
5. *The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).*
6. *The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.*

Project Icarus is divided into 20 research modules, which represent important aspects and areas of mission development. Some of the modules are: primary propulsion, secondary propulsion, fuel and fuel acquisition, science, computing and data management, communications and telemetry etc. (for full list of modules see [2]).

This paper concentrates on the conceptual design and thermodynamic analysis of the primary propulsion of the Icarus mission, based on Plasma-Jet driven Magneto-Inertial Fusion (PJMIF) concept [3, 4]. Conceptual design and thermodynamic analysis involve assessment of propulsion parameters such as specific impulse, power to mass ratio, thrust, as well as basic structural issues of arrangement of the plasma-guns, nozzle structure, radiators and estimation of mass concerned with the mentioned spacecraft elements. The paper also provides a review of necessary assumptions about the desired mission parameters, short insight to some historical milestones in fusion propulsion and a brief discussion on needed technological extrapolations.

## 3. PREVIOUS WORK

The main problem of dealing with advanced propulsion, especially nuclear fusion, is the fact that fusion with gain has not yet been achieved even for terrestrial purposes. Because of that, significant theoretical effort has been put in development of appropriate models and viable estimates about such propulsion systems. The first ideas about fusion propulsion showed up during late fifties (Maslen, [5]) and early sixties, where notable works come from Englert [6] and Hilton et.al. [7, 8]. Englert and Hilton primarily talked about a primitive magnetic mirror type approach, for which was later shown that it cannot obtain net power, but the authors recognized some of the important obstacles that need to be overcome and demonstrated innovative thinking. Hilton in his 1964 paper points out that fusion propulsion provides a revolution in space propulsion as high specific impulse and high power to mass ratio are potentially available. Gradecak [9] provides a nice overview of the unconventional propulsion systems of the time and also, though briefly, compares fusion to electric propulsion, claiming that fusion propulsion system similar to ones described by Hilton and Englert can achieve specific impulse up to $5\text{x}10^5$ s. In 1971, Reinmann [10] discussed another magnetic mirror concept, claiming specific impulses of $2\text{x}10^5$ s and power to mass ratio of 2.5 kW/kg. Next significant concept was already mentioned Daedalus project [1], which remains one of the (only) detailed fusion concepts which was specifically designed for an interstellar mission. Borowski [11] in 1987 provides a good comparison between compact toroid tokamaks, spherical torus tokamaks and ICF approach fusion propulsion systems. Borowski's ICF approach showed possible access to 53 GW of total power, with specific impulse as high as $2.7\text{x}10^5$ s and power to mass ratio of 110 kW/kg. Santarius [12] in his 1989 paper provides another overview of fusion propulsion concepts, claiming specific impulses up to $10^6$ s, while also stating that it is feasible to achieve power to mass ratios of 10 kW/kg. At the end of the paper the author points out the potential benefits of field reversed configuration (FRC) approach, which as will be shown hereby, represents an important part of PJMIF. In the second half of the nineties Kammash and Lee [13] argue that their gasdynamic mirror approach can reach specific impulse values of $4.07\ \text{x}10^5$ s, with incredible 670 GW of total power, but on the other hand quite "low" power to mass ratio of only 6.35 kW/kg, which of course means that the total mass of the system is incredible 105 kt. In 1999, Thio et.al. present their paper [14], where they describe the magnetic target fusion (MTF) approach, which is in this case essentially PJMIF. Authors give a very good mathematical description of the physics and well explained principles of the system, while providing values for specific impulse of $7.7 \times 10^4$ s, stunning power to mass ratio of up to 1.14 MW/kg at repetition rate $\omega$ = 100 Hz and with thrust of 340 kN. For given repetition rate jet power is found at 128 GW and so the total mass of the system would be mere 112 t. Basic theoretical reasoning for these numbers will be presented in the next section, however for more details please see the reference. Next important reference is the work of Adams et.al. [15] in which the group from NASA Marshall Space Flight Centre provides a 140-page analysis of interplanetary mission with human-crew, with PJMIF as primary propulsion. The study provides detailed analysis of different technical components i.e. magnetic nozzle construction, plasma gun distribution, detailed power and energy flows, precise mass estimates and material considerations, while providing a large variety of useful figures, few of which are used in this paper. In 2004, Williams [16] made a good summary of AIAA's "*Recommended Design Practices For Conceptual Nuclear Fusion Space Propulsion Systems*" [17], providing a simplified form of the report and bringing out some good examples of technological extrapolations. Adams and Cassibry [18] in 2005 did a motivational paper revising some of the previous fusion concepts, followed by a similar paper by Romanelli and Brunno [19] in 2006, where the latter authors have a table clearly showing significantly higher power to mass ratios of the PJMIF concept.

As shown above, many fusion propulsion concepts have been proposed over the course of history, with numerous variants and innovations, ranging from different steady state concepts, like magnetic mirrors, tokamaks and spheromaks to nowadays more popular inertial confinement fusion (ICF), PJMIF and other field reversed configuration (FRC) systems. Logically, in such variety of solutions a vast number of performance parameters have been claimed, based on the assumptions, models used and last, but not least, level of author's optimism. This paper tries to combine the most rational assumptions and extrapolations, based on the fairly numerous cited works.

## 4. INTRODUCTION TO PJMIF PROPULSION CONCEPT

In spite of the fact that PJMIF is a relatively new concept, presented in its current form by Thio et.al. in [3, 4], a fair amount of studies on PJMIF as propulsion system have been done and especially on general PJMIF theory that involves confinement times [20], scaling laws [21], hydrodynamic efficiencies [22], rail-gun parameters [23] etc. PJMIF involves converging plasma jets that are launched from symmetrically distributed plasma rail-guns, so as jets come in, they merge and form a plasma *liner* that compresses the plasmoid target (spheromak or FRC), which reaches fusion conditions at peak compression. The simplified process is shown in Figure 1.

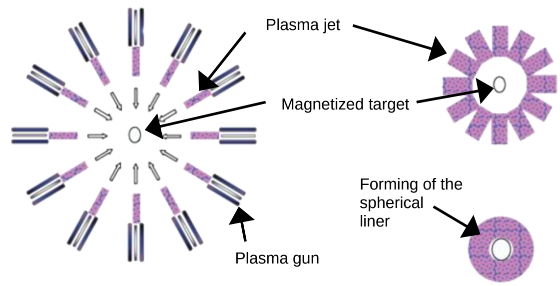


Figure 1: PJMIF concept drawing, [24]

The main advantage of PJMIF over classical ICF and MCF is that it does well in combining the best of both concepts, namely inertial compression and strong magnetic fields. Magnetic field is embedded in the target plasmoid as shown in Figure 2, so when the target compresses, the magnetic flux increases inversely proportional to the radius of the target, taking magnetic field strength to MG levels [14].

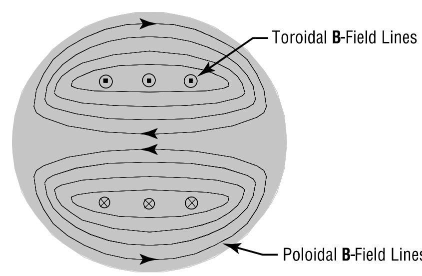


Figure 2: Spheromak target configuration, [15].

The benefit of this mechanism is more efficiency, allowing PJMIF to operate at an intermediate *parameter space* [25], theoretically allowing fusion with gain at low input energies of 50 to 75 MJ.

For terrestrial purposes PJMIF the rail-guns would be distributed across a full sphere, however for propulsion purposes a parabolic nozzle has to be used in order to allow the exhaust jet to exit. The principle of such a fusion propulsion magnetic nozzle concept has been well described by several previous studies [1, 14, 15, 26], so here we will only present the basic concepts. The nozzle consists several superconducting coils which create a specific magnetic field configuration inside the nozzle chamber (Figure 3).

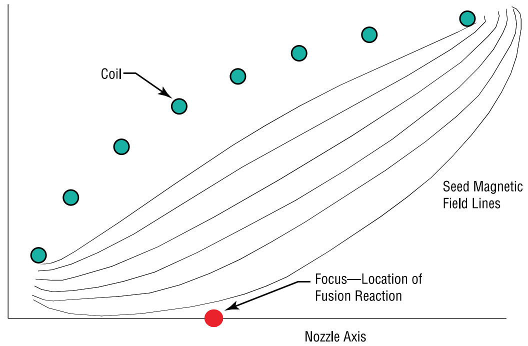


Figure 3: Initial magnetic field configuration, [15].

After the target has been formed in the focus of the nozzle, the plasma jets are launched. Jets come in with velocities in range of hundreds km/s, merging and hitting the target. Upon impact of the liner on the target, an inward shock is launched from the target-liner interface, heating up the target, while the liner simultaneously continues to compress it further. At maximum compression, the fuel ignites causing fusion burn. The plasma afterwards rapidly expands compressing the pre-existing magnetic field of the nozzle. Part of expanding plasma's kinetic energy is generating a current in the coils which is used to regenerate the energy in the capacitor banks. Maximum field compression moment is shown in Figure 4.

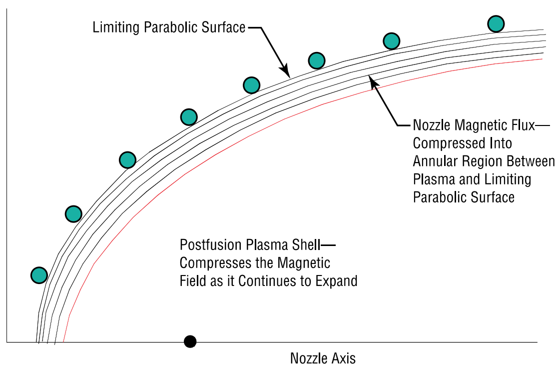


Figure 4: Maximum compression of the nozzle field, [15].

Nozzle's compressed magnetic field acts as a "spring", converting back the stagnated plasma energy into a directed thrust. As the magnetic field relaxes to the initial condition, capacitors are already charged and the process is ready to be repeated. In the next section we will go through the physical and mathematical description of the process, providing equations for propulsion figures of merit.

## 5. MATHEMATICAL MODEL

Most of theory behind the analysis has been taken from Thio [14], with modifications being applied as original work used D-T fuel and liner had a specific role of converting the fast neutrons back to charged particles via ionization (acting as a partial neutron shield). Scheme of the modified model is given in Figure 5.

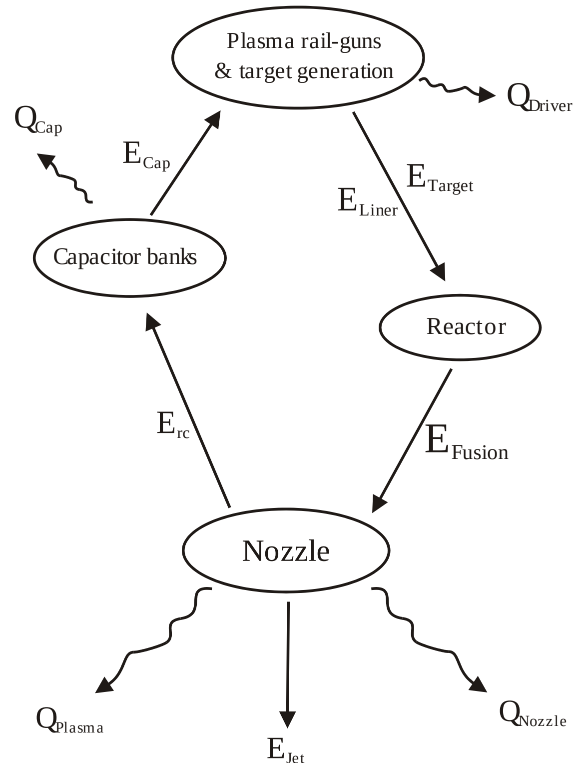


Figure 5: Main paths of energy in the system.

Starting premise of PJMIF is that the majority of the initial input energy is kinetic energy of the liner ($E_{\text{liner}}$), while much lesser portion of the input energy is associated with the target and jets thermal energy ($E_{\text{target}}$). The total available energy of the fusion process ($E_{\text{fusion}}$) is the input energy times gain ($G$), which for plasma liners is around 50 [20, 27].

$$E_{fusion} = G\big(E_{target} + E_{liner}\big) = E_{cp} + E_n \quad (1)$$

Total fusion energy includes energy of the charged particles ($E_{\text{cp}}$) and energy of neutrons that might occur during the reaction ($E_{\text{n}}$). Since D-He$^3$ reaction was chosen as primary fuel for this analysis, the neutron portion of the energy is virtually inexistent, thus we can conclude that total energy available for propulsion and regeneration is effectively energy of the charged particles: $E_{\text{cp}} = E_{\text{fusion}}$. Portion of this energy that is available to the nozzle for creating thrust is:

$$E_{cpnozzle} = E_{cp} - Q_{plasma} - Q_{nozzle} - E_{rc} \quad (2)$$

where $Q_{\text{plasma}}$ is the amount of heat that stays trapped inside the exhaust plasma:

$$Q_{plasma} = (1 - \eta_{MHD})\Delta E_B \quad (3)$$

with $\eta_{\text{MHD}}$ being constant of proportionality which has similar values to the efficiency of a direct MHD generator ($\approx 0.8$) [14]. $\eta_{\text{MHD}}$ is proportional to the magnetic Reynolds number, which is very high for the case of expanding fusion plasma. $\Delta E_B$ is the amount of work that is being done by the expanding plasma when it compresses the initial magnetic field of the nozzle (Figures 1 and 2). The assumption is that all charged particle kinetic energy is converted into this work, so $\Delta E_B = E_{cp}$ [15]. $Q_{nozzle}$ is the heat that gets trapped in the nozzle coils and is given by:

$$Q_{nozzle} = (1 - \eta_{cryo})\Delta E_B \qquad (4)$$

with $\eta_{cryo}$ being the electrical efficiency of the coils, which is for superconducting coils on the order of 0.98. $E_{rc}$ is the energy used for regeneration and can be represented as:

$$E_{rc} = (E_{target} + E_{liner})(3 - \eta_{cap} - \eta_{driver}) \qquad (5)$$

where $\eta_{cap}$ is the efficiency of capacitor charging and is assumed to be very high ($\approx 0.98$) and $\eta_{driver}$ is the efficiency of the rail guns and target-generating theta-pinch guns ($\approx 0.3$). Other heat losses associated with the system are the amount of heat that gets generated in the capacitor banks ($Q_{cap}$) and heat generated in the plasma rail-guns ($Q_{driver}$), which are incorporated within $E_{rc}$ by Eq. (5). Equations (1) through (5) close the energy balance of the system.

In order to calculate the relevant propulsion parameters like exhaust velocity, specific impulse, jet power etc., one must be familiar with the basic magnetic nozzle theory. Detailed derivations will be skipped for sake of discussion length, but thorough overview can be found in [15, 26] and [14]. The analysis begins with the calculation of the average macroscopic velocity of the expanding plasma after fusion occurs. This is fairly straightforward as we already made the assumption that $\Delta E_B = E_{cp}$, so we have:

$$V = \sqrt{\frac{2E_{cp}}{m_p}} \qquad (6)$$

where $m_p$ is the total mass of the plasma. Two important angles that influence nozzle performance are the mean angular deviation $\delta\theta_D$ and orifice angle $\theta_\alpha$. The nozzle has a parabolic-shaped side cross-section and so the angular deviation angle is formed by a ray reflected from a surface and a line perpendicular to the surface at the point of reflection. According to [26], for a parabolic nozzle this angle should be around $\pi/12$. The orifice angle is the angle covering the length of the nozzle that extends beyond the reaction point (focus) and is taken to be $5\pi/12$.

Axial impulse has two components, one coming from the spherically expanding plasma and the other from reflected plasma. Expressions for both are given by equations (7) and (8), respectively:

$$p_{zexp} = \frac{1}{4} m_p V sin^2(\theta_\alpha) \qquad (7)$$

$$p_{zref} = m_p V cos^2\left(\frac{\theta_\alpha}{2}\right)\cos(\delta\theta_D) \qquad (8)$$

Net axial forward impulse is the sum of the previous two:

$$p_z = m_p V\left[\cos(\delta\theta_D) + \sin^2\left(\frac{\theta_\alpha}{2}\right)\right] cos^2\left(\frac{\theta_\alpha}{2}\right) \qquad (9)$$

Nozzle efficiency is further given by:

$$\eta_j = \frac{p_z}{m_p V} \qquad (10)$$

or if one would expand the previous expression:

$$\eta_j = \sqrt{\varepsilon_k(1 - \varepsilon_c)}$$
$$\left[\cos(\delta\theta_D) + \sin^2\left(\frac{\theta_\alpha}{2}\right)\right] cos^2\left(\frac{\theta_\alpha}{2}\right) \qquad (11)$$

According to [14, 26] maximum theoretical efficiency of the nozzle is around 86%. Equations (6) through (11) provide us with enough information that we can calculate the relevant figures of merit. Net momentum of the jet is:

$$M_{jet} = \eta_j\sqrt{2m_p E_{cpnozzle}} \qquad (12)$$

Exhaust velocity is then:

$$V_{ex} = \frac{M_{jet}}{m_p} \qquad (13)$$

Energy of the jet (single pulse):

$$E_{jet} = \frac{M_{jet}^2}{2m_p} = \eta_j^2 E_{cpnozzle} \qquad (14)$$

If we have a firing frequency of ω, then power of the jet is:

$$P_{jet} = \omega E_{jet} \qquad (15)$$

Thrust can be calculated by:

$$T = \omega M_{jet} \qquad (16)$$

and finally specific impulse is given by:

$$I_{sp} = \frac{V_{ex}}{g_0} \qquad (17)$$

where $g_0$ is gravitational constant. Since significant portion of the propulsion system's mass is waste-heat disposal, we hereby investigate this aspect as well. In order to begin we first need to evaluate the exact amount of heat that is being released in the capacitors and the rail-guns. This is easily done by manipulating Eq. (5), so that we get:

$$Q_{driver} = (E_{liner} + E_{driver})(1 - \eta_{driver}) \qquad (18)$$

$$Q_{cap} = (E_{liner} + E_{driver})(1 - \eta_{cap}) \qquad (19)$$

Total waste heat is then:

$$Q_{waste} = Q_{nozzle} + Q_{cap} + Q_{driver} \quad (20)$$

Total heat power that needs to be disposed is simply:

$$H_{reject} = \omega Q_{waste}(1 - \eta_{sec}) \quad (21)$$

where $\eta_{sec}$ is the fraction of the total rejected heat that is being used for secondary power needs of the spacecraft. Once we have the total heat power value, it is easy to calculate needed radiator mass if we have the value of specific heat radiation of the radiator given in kW/kg. Value of this constant has been taken to be 50 kW/kg which may sound optimistic, but if care would be taken during design, it might be within the reach of near term technology [14].

As obvious from Eqs. (1) through (21), used model heavily relies on efficiency factor estimates. This is not considered a problem as this paper concentrates only on preliminary propulsion analysis and rough estimation of performance parameters.

## 6. RESULTS & DISCUSSION

Two distinct analyses have been carried out. The first one concentrates on evaluating most influential input parameters for the PJMIF propulsion system and their impact on specific impulse and power to mass ratio. Second analysis presents calculations of all important propulsion figures of merit for three different technological extrapolation scenarios: conservative, medium and optimistic.

Previous studies of PJMIF as a propulsion system [14, 15], although very thorough in calculating mission or maximum performance parameters, did not really analyze the influence of different input parameters, such as initial jet velocity, total mass of the plasma and gain. During calculations for the three technological extrapolation scenarios it has been noticed that values of gain and initial jet velocity can significantly improve performance. This is expected as both parameters have a major influence on the fusion energy term $E_{fusion}$ (Eq. (1)), which is the primary source of energy for the whole system. Gain directly multiplies the input energy, while initial velocity has a major impact through the value of plasma liner kinetic energy, which increases with the square of jet velocity. On the other hand, total mass of the plasma has proved to be a minor factor for the specific impulse. If gain and velocity are kept constant and mass is changed from 1 μg to 2 g, the total value of specific impulse changes only by a factor of 2. Of course, power to mass ratio varies significantly with mass, as expected. Figures 6 and 7 present ranges of specific impulse and power to mass ratio as functions of initial jet velocity and gain, therefore providing a rough overview of PJMIF capabilities as a propulsion system. As a note, power to mass ratio in this work is calculated as jet power over calculated fuel mass, since fuel mass for interstellar missions is dominant.

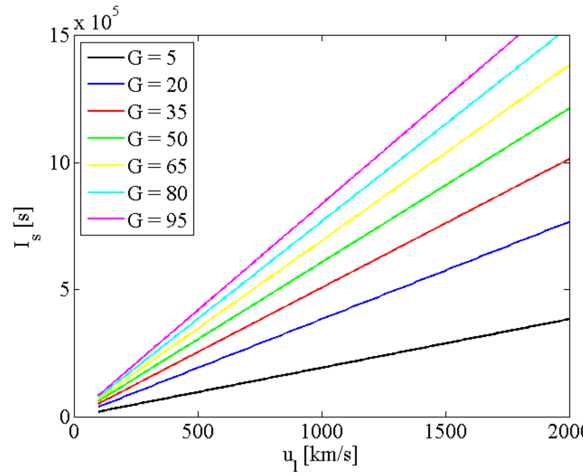


Figure 6: Specific impulse as a function of initial jet velocity and gain.

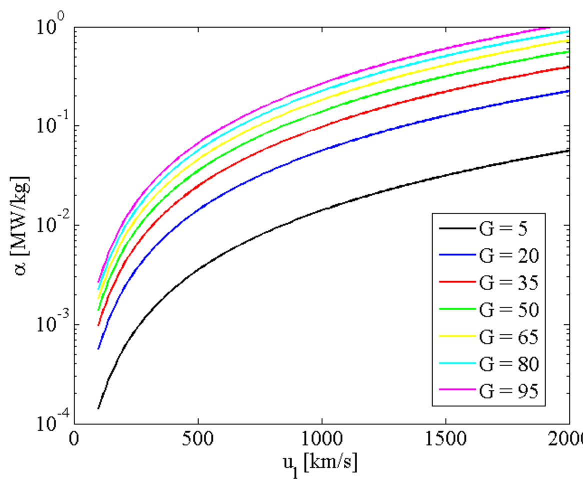


Figure 7: Power to mass ratio as a function of initial jet velocity and gain.

What can be seen in Figures 6 and 7 is that very high specific impulses and specific jet powers can be achieved with fairly low jet velocities of a few hundred km/s. These regimes of PJMIF propulsion represent a very minor technological extrapolation, while the performance would be sufficient for manned Solar system or precursor interstellar missions. However, if one needs extreme performance for interstellar flight, two options are available: increase in jet velocity to over 1000 km/s or significant improvement of fusion gain.

In the second part of PJMIF propulsion analysis, three technological extrapolation scenarios have been studied. Input parameters that have been varied for the three cases are given in Table 1. Gain is assumed to be 50, which is in accordance with current theoretical knowledge of PJMIF

[14, 21, 27]. This value can be increased if the liner would be of sufficient density or if strong magnetic field duration could be prolonged, so that the ion scattering and electron-thermal conduction could be further suppressed. Every increase in gain could significantly benefit the performance, but it has been decided to pursue the calculations based on current theoretical gain estimates. Frequency of firing has also been kept constant at $\omega$ = 200 Hz, which is 50 Hz less than what Daedalus propulsion system assumed. As shown by Long et.al. [28], firing frequency has a low impact on total mission duration time after 200 Hz and decrease in firing frequency can provide significant mass reduction and lower technical requirements on the drivers. Initial jet velocities have been chosen based on current knowledge of plasma gun and plasma thruster technologies. Within the Plasma Liner Experiment (PLX), 200 µg plasma jets have been accelerated to 100 km/s [23], with 200 km/s being within reach of present day technology. An important milestone for plasma jet acceleration has been achieved in 1988 when Hammer et.al. [29] successfully accelerated 20 µg plasma rings up to 2500 km/s by a coaxial plasma gun. Optimistic scenario calculation is accounting for this achievement when assuming plasma jet velocity of 1500 km/s. Other important parameters that are necessary for mission evaluation are burn time and $\Delta V$. The estimated values that Icarus would like to achieve with the first stage are around $\Delta V$ = 0.08$c$ and $\Delta t$ = 4 years. These parameters were chosen partially because the two-stage vehicle configuration estimates of Long et.al. [28] and partially to keep the mission requirements and calculations conservative. Results are shown in Table 2.

Table 1: Input parameters that have been varied

| | Conservative | Medium | Optimistic |
|---|---|---|---|
| $m_p$ [g] | 2.2 | 1.5 | 1.0 |
| $u_l$ [km/s] | 200 | 750 | 1500 |
| $\eta_{sec}$ | 0.01 | 0.001 | 0.001 |

Table 2: Resulting parameters ($m_f$ – total fuel mass, $u_{ex}$ – exhaust velocity, $T$ –thrust, $I_{sp}$ – specific impulse, $P_{jet}$ – jet power, $\alpha$ – power to mass ratio, $m_{rad}$ – radiator mass)

| | Conservative | Medium | Optimistic |
|---|---|---|---|
| $m_f$ [t] | 55503.36 | 37843.20 | 25228.80 |
| $u_{ex}$ [km/s] | 1189.79 | 4461.27 | 8922.48 |
| $T$ [MN] | 0.52 | 1.34 | 1.78 |
| $I_{sp}$ [s] | 121284 | 454768 | 909529 |
| $P_{jet}$ [GW] | 311.43 | 2985.45 | 7961.07 |
| $\alpha$ [MW/kg] | 0.0056 | 0.0789 | 0.3156 |
| $H_{waste}$ [GW] | 15.14 | 145.13 | 387 |
| $m_{rad}$ [t] | 299.76 | 2899.67 | 7732.33 |

For assumed initial mass of 39000 t and given $\Delta t$ and $\Delta V$, rough estimates for design parameters are $u_{ex} \approx$ 5500 km/s, $T \approx$ 1.7 MN, $I_{sp} \approx$ 560000 s, $P_{jet} \approx$ 9328 GW and $\alpha \approx$ 0.29 MW/kg. As can be seen from Table 2, the conservative option for PJMIF does not meet the required performance for interstellar missions, especially when it comes to power demand. This is caused by insufficient velocities, as input kinetic energy is low, and due to relatively low gain value. As mentioned earlier, conservative calculations prove not to be sufficient for interstellar distances, but the numbers do show potential for Solar system missions. The medium extrapolated scenario with significantly increased jet velocity is already stepping into the interstellar mission parameter range. With specific impulse of roughly 455000 s, thrust of 1.34 MN and total jet power of close to 3 TW, such a propulsion system would be more than enough for a precursor mission to Oort cloud or even a full interstellar mission with reduced $\Delta V$. Certainly the most interesting of the three calculations is the optimistic extrapolation. It is assumed that by the time Icarus mission would mature, we would be able to launch total plasma mass of 1 g with speeds up to 1500 km/s. Although small amounts of plasma have been accelerated to speeds of 2500 km/s [29], it is not unreasonable to think that same can be done with more significant amounts of plasma. In addition, even if one would argue that such high velocities are impossible for plasma masses on the order of 0.01 g, it is good to keep in mind that plasma guns are significantly less complex than i.e. lasers and that we can keep the total mass of the fuel simply by increasing the number of the guns. Liner kinetic energy scales with square of the velocity and so the optimistic scenario easily reaches and surpasses the required performance demands.

There are several very important highlights that need to be pointed out. First, the overall estimated fuel mass for the optimistic scenario is only 25000 t, which is more than 40% less fuel than what was estimated for Daedalus mission first stage. Second, PJMIF propulsion system would completely overcome some of the most complex engineering problems that ICF has embedded, involving fuel storage, complex pellet production and pellet injection. Third, vast amounts of heat will be generated in the coils during operation and in order to avoid excessive radiator mass, more efficient heat exchangers need to be developed with specific heat output larger than 50 kW/kg. Fourth, presented optimistic scenario still involves gain of only 50 and if this number would increase even slightly by further advances in driver technology, hybridization with ICF or utilization of outside magnetic fields [27], it would provide an additional boost to the whole concept, potentially driving initial mass even lower or lowering demands for initial jet velocity.

## 7. CONCLUSIONS

PJMIF was explored as a candidate fusion approach for the Icarus mission primary propulsion system. PJMIF's advantage over ICF and MCF lies in its utilization of strong magnetic fields that get generated inside the target plasmoid as it gets compressed by the plasma liner. This allows better confinement of the high-energy ions and suppression of electron-thermal conduction losses, therefore theoretically providing an easier, more efficient path toward nuclear fusion with gain. Furthermore, several important issues concerning ICF fuel storage and pellet production are solved by the PJMIF approach. For an interstellar mission fuel mass is one of the driving design factors. From conservative PJMIF theory, secondary burn of the plasma liner will be negligible. The result is a tradeoff where less energy is invested to ignite the fusion fuel, but a significant portion of the plasma mass remains unused. However, with assumptions of high initial plasma jet velocity, even with the conservative gain estimates, used PJMIF model provides sufficient or better performance results with possibility of over 40% fuel mass savings in comparison to the Daedalus mission. Further optimistic scenarios can be extrapolated and discussed which would deliver even higher performance and would involve combination of innovations in the drivers for plasma acceleration and improving secondary burn of the plasma liner.

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