

ANTIMATTER-INITIATED MICROFISSION/ FUSION: CONCEPT, MISSIONS, AND SYSTEMS STUDIES FOR EXPLORATION OF DEEP SPACE

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Abstract

The energy released by antimatter annihilation is 180 MJ/ μg , greater than that of fusion, fission, and chemical combustion. From a space mission point-of-view, this is exceptional because it implies a propellant source that may have little appreciable mass. Nevertheless, the antiproton (\bar{p}) mass required for beamed-core annihilation engines for deep space missions may be several kilograms, which exceeds current production capabilities (14 ng/yr) by over ten orders of magnitude. Here, we present two concepts, which are a hybrid of antimatter and fusion technologies. The inclusion of the fusion aspect can reduce \bar{p} requirements to 1-100 μg , which may be obtainable in the near future. Also discussed is a propulsion experiment using only 5×10^9 antiprotons, which will validate several antimatter-initiated microfission/fusion objectives.

1. Introduction

Throughout the latter half of the 20th century, the world has obtained access to the majority of planets within the Solar System. The lifetimes of five to ten years for such unmanned missions (e.g. Viking, Mariner, Voyager, Galileo, Cassini) were comfortably met through the use of chemical propellants, due to a combination of short mission ranges and payload masses below ten metric tons. However, manned investigations to other planets and scientific inquiries to the Heliopause at 200 AU and beyond have not been established. Short-duration manned interplanetary missions required exceptional thrust and moderate $I_{sp} > 1000$ sec., and exceptional specific impulses beyond 10,000 seconds were necessary for unmanned, precursor-interstellar missions. These were beyond the capabilities of chemical propellants, which is currently limited to about 450 sec.¹

The energy density yielded from various chemical and nuclear reactions is a key of measuring its performance. Indeed, the energy released from chemical combustion is seven orders of magnitude below that of nuclear fission or fusion, and ten orders of magnitude below that of antimatter annihilation.² Antimatter annihilation presents the highest energy density known in existence, which is 180 MJ/ μg . In fact, antiproton-proton annihilation can provide an $I_{sp} = 10^7$ sec, which is sufficient enough for pure, interstellar missions. However, the quantity of antimatter required for such an interstellar spacecraft range from 1 to 1000 kilograms, exceeding current antiproton production capabilities of 14 ng/year by at least ten orders of magnitude.

For the scope of the missions presented above, the required I_{sp} ranges from 10^3 to 10^5 seconds. Extra I_{sp} can be sacrificed in favor of greater thrust and reduced onboard antimatter. Methods of tailoring desired thrust and I_{sp} from antimatter annihilation have been developed. One important concept, Antimatter-Catalyzed Microfission/fusion (ACMF), can reduce mass estimates to ten micrograms.³ ACMF-based concepts are suitable for interplanetary missions. Another concept, Antimatter-Initiated Microfusion (AIM), is better suited for the precursor-interstellar regime, between 200-10,000 AU.⁴ Missions utilizing AIM may reach the Oort Cloud at 10,000 AU within fifty years.

2. Antimatter-Catalyzed Microfission/fusion (ACMF)

The concept of using antimatter to initiate nuclear fission is well understood. In 1992 members of the Laboratory for Elementary Particle Science at Penn State University observed large fission and neutron yields from antiproton annihilation at rest in a natural

uranium target.⁵ Calculations indicate that short bursts of antiprotons could induce temperatures of several keV in a small compressed pellet.⁶ These conditions are appropriate for ignition of a hydrogen fusion burn within the microsphere. Targets with yields up to 302 GJ are considered, with compression provided by light ion beams or lasers. Baseline parameters for ignition are: antiproton energy, 1.2 MeV; number, 10^{11} ; pulse length, 2 ns; and deposition volume, 1 mm^3 .

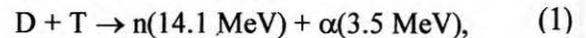
Most of the energy from the microfission/fusion process is in the form of radiation and hot (35 keV average temperature) plasma. Energy is produced in a target consisting of about 3.0 g of nuclear fuel. The nuclear fuel is in a molar ratio of 9:1 of DT:U(235). Initially, the proportions of energy produced in the target are 83% radiation, 15% neutron kinetic energy, and 2% random ion and electron kinetic energy.

Since most of the energy is in the form of high energy radiation, a high Z material (WLS) is desired to absorb and reradiate at lower frequencies (temperatures). The purpose of this is to optimize ablation of a thruster shell exposed to this radiation. The WLS (wavelength shifter) is a spherical shell of 200 g of lead, which has a K-shell absorption edge near the peak of 115 keV for a spectrum with an average temperature of 35 keV. Of the 302 GJ of energy generated in the target, 247 GJ is absorbed by the WLS. This energy is distributed over the WLS volume according to a stellar photosphere model,⁷ initially 5.6 keV at the center and 2.3 keV at the surface. Since only a thin skin on the surface of the shell radiates, most of the lead is near the 5.6 KeV temperature, which corresponds to an ionization level of $Z^*=75$. This temperature is not high enough to remove inner shell electrons, thus enabling continuing K-shell absorption of radiation. Energy distributions of photons radiated from the photosphere around the WLS show a very significant shift of radiation down to a mean value of about 1 keV energy (204 GJ).

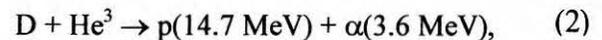
3. Antimatter-Initiated Microfusion (AIM)

Physicists have been working for fifty years in an attempt to "spark" fusion fuel into a significant burn. ICF experiments use short pulses of intense laser or particle beams to compress and heat targets by ablation of surrounding materials. Using intense magnetic fields, MCF experiments attempt to continuously compress and heat fusion fuel into a burn. In general, results to date have been measurable, but incomplete, burns of the target material. Inefficient coupling of beams to the target, and plasma instabilities have been largely responsible for the failure for full ignition.

These experiments have generally attempted fusion of hydrogen isotopes deuterium (D) and tritium (T), which has a low ignition temperature. The fusion reaction:



presents serious problems for space applications: (1) large amounts of radioactive tritium are required. From space transportation safety considerations, this requires special shielding; (2) the neutrons require absorbers if their energy is to be used to heat propellant, and (3) if not fully shielded, the neutrons will cause severe radiation damage to the engine and payload. In all, the additional weight required may be at least 1 Tonne, which would be intolerable for a small, fast interstellar probe. The DHe^3 reaction,



is aneutronic, provided the fuel is burned at a sufficiently high temperature so that the competing $D + D \rightarrow n + He^3$ fusion rate is insignificant. Future AIM illustrations use DHe^3 as the fusion fuel.

One can inject small fusion fuel droplets into a cloud of antiprotons confined in a very small volume within a reaction Penning trap. The reaction trap (Figure 1) is roughly the size of a shoebox, weighing roughly 10 kg. It is fed 10^{11} antiprotons on a periodic basis from a portable trap (not shown) positioned about 1 meter away on axis, safe from fusion debris. Radial confinement within a 0.8 cm maximum diameter orbit is provided by a 20T axial magnetic field. Axial trapping of the 2 cm long cloud of antiprotons within a 10 keV space charge electric potential on the electrodes is shown in Figure 2a.

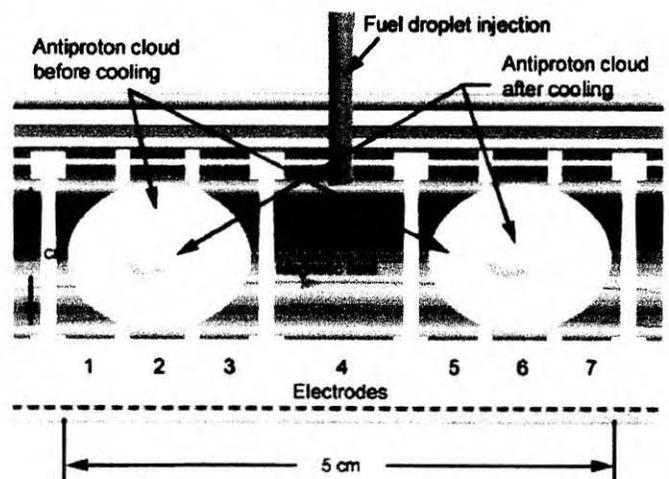


Fig. 1 Side view illustration of the AIMStar reaction trap

The key ingredient for heating of the 42 ng DHe^3 or DT liquid droplet is antiproton-induced fission fragments, which have a range of 45 μm in the droplet. In order to spark the microfusion process, 5×10^8 antiprotons are annihilated in a 2% molar admixture of an actinide or pre-actinide metal, such as Pb^{208} or U^{238} , with the DHe^3 or DT. Annihilation takes place on the surface of the antiproton cloud, peeling back 0.5% of the cloud. The power density released by the fission fragments into the core is about $5 \times 10^{13} \text{ W/cm}^3$, fully ionizing the D and He^3 or T atoms. This is roughly comparable to a 1 kJ, 1 ns laser depositing its energy over a 200 μm ICF target, a system much too massive for driving a small space probe.

It has been shown that the fission fragments from antiproton-induced fission are not radioactive,⁸ so there is no concern of accumulative radioactive contamination of the engine and spacecraft as the engine burns.

The heating of the plasma takes place in 1 ns, and is confined in the center of the trap by application of a weak nested well potential (Figure 2b, 2c). To compress the fully ionized fuel droplet to high density

and temperature sufficient to start a fusion burn, a strong nested well potential is applied, as shown in Figure 2d. The application of a 600 kV potential, which introduces an important challenge to Penning trap operation, results in a 100 keV ion plasma with density $n = 6 \times 10^{17} \text{ ions/cm}^3$, which when combined with a $\tau = 20 \text{ ms}$ lifetime satisfies Lawson's criterion ($n\tau > 5 \times 10^{15} \text{ s/cm}^3$) for a full fusion burn. Because the kinetic pressure of the plasma under these conditions exceeds the magnetic pressure, a question that must be best answered experimentally arises as to the lifetime of the plasma against this instability.

Antiprotons not consumed in the original ionization of the droplet await later use, trapped in the wings of the potential well. Upon completion of the burn, the potential is returned to its original configuration (Figure 2a), minus 0.5% of the original load of 10^{11} antiprotons. The four-cycle process is repeated 200 times, followed by one cycle used to load another 10^{11} antiprotons from the storage trap into the reaction trap. The duty factor of the reaction trap is 99.5%, and delivers 0.75 MW (15 kJ/20 ms cycle) of continuous power in the form of protons and alpha particles (33 MW in the case of DT).

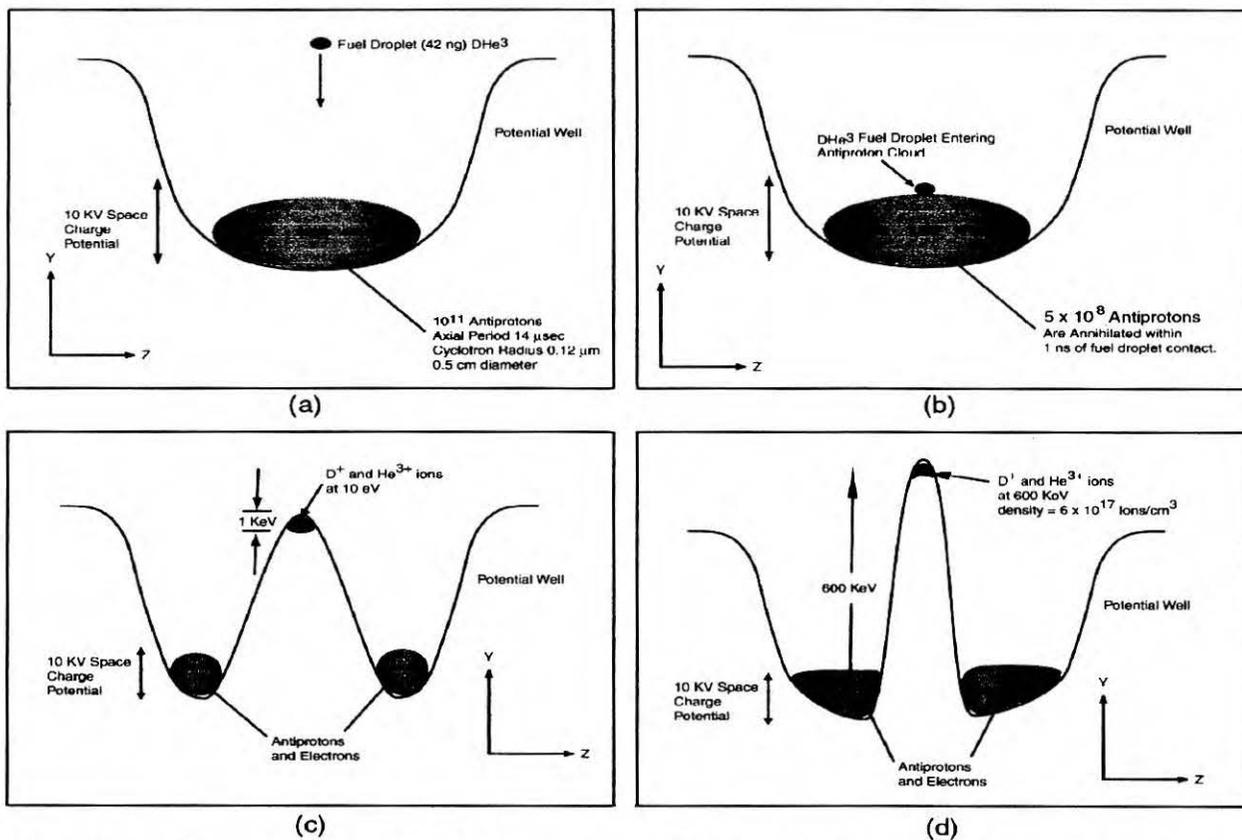


Fig.2 Chronological illustrations of the AIM process. Fuel is injected in Figure (a) and enters the cloud and annihilates with 5×10^8 antiprotons in (b). A weak-nested potential well is used to separate the charged species as shown in (c), and a 600 keV potential is applied to spark microfusion, as shown in (d).

4. Mission Examples

4.1 ICAN-II (Interplanetary Spacecraft)

ICAN-II implements the ACMF concept. The spacecraft is equipped with an adequate shock absorbing apparatus and a means of safely intercepting debris from a nuclear explosion to use the explosion energy derived from ACMF to propel the craft at both high thrust and high Isp. Historically, the first serious effort at this type of propulsion was the ORION pusher-plate system. Other sophisticated systems employ a polyethylene canopy tethered to a winch (MEDUSA), as proposed by J. Solem.⁹

In the current version of the ICAN-II, a sector of a spherical silicon carbide (SiC) shell of 4 m radius is used to intercept radiation from the explosion. This radiation heats the inner surface of the shell to keV temperatures, and the resultant expanding plasma produces thrust. An older, schematic version of the ICAN-II spacecraft, including the engine at the aft end, is shown in Figure 3. A more recent design is shown in Figure 4. Estimates of component masses for a 120 day, $\Delta V = 100$ km/s Mars mission (RT) are given in Table 1.

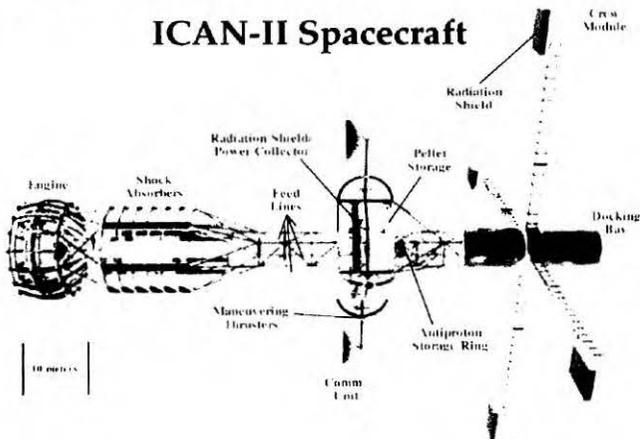


Fig.3 Original configuration of the ICAN-II Spacecraft

For a ΔV of 100 km/sec and an Isp of 13,500 seconds (200 g WLS), 362 metric tons of propellant are required for a 347 metric ton ICAN II dry mass (see Table 1). With a 200 g WLS, the thrust is about 100 kN, which accelerates the outbound craft to a 25 km/sec ΔV in 3 days. For 800 g of ejected mass, about 30 ng of antiprotons are required. Hence, ICAN-II could be fueled with one year's production of antiprotons at Fermilab in the very near future.

Radiation damage to the ICAN-II vehicle can result from neutrons, which pose a threat to the stored targets, antiprotons, and the crew of the vehicle. In order to remedy this, 1.2 meters of lithium hydride shielding

(Power Shield) is required. In addition, 2.2 meters of shielding (Crew Shield) is needed to limit crew exposure to ~ 30 rems over the duration of a mission.

Table 1. Estimate of ICAN-II Vehicle Masses for 120 day, $\Delta V = 100$ km/s Mars Mission (RT)

Component	Mass (metric tons)
Ion Driver	100
Engine Structure	27
Spacecraft Structure	30
Antiproton Traps	5
Neutron Shielding	45
Power Processing	58
Payload on ICAN	20
Mars Lander/Surface Payload	53
<u>Mars Mission Ascent Vehicle</u>	<u>9</u>
Total Dry Mass	347
<u>Mass of Silicon Carbide Thrust Shell</u>	<u>362</u>
Total Mass of ICAN	709

Finally, part of the intense blast of neutrons from the pellet ignition is absorbed by the Power Shield to drive a 10 MW electric generator, which provides power for the ion drivers and other systems on the spacecraft. A liquid droplet radiator (see Figure 4) has been designed for expelling the excess 60 MW of heat from the Power Shield into space.

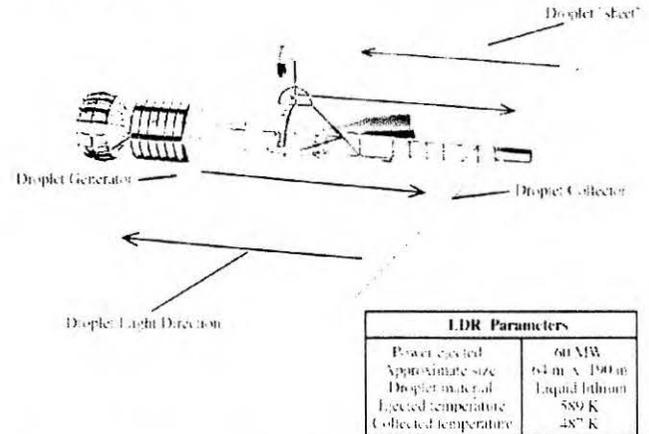


Fig.4 ICAN-II with Liquid Droplet Radiator Deployed

4.2 AIMStar (Precursor-Interstellar Spacecraft)

A preliminary design of the AIMStar spacecraft, which utilizes the AIM concept, is shown in Figure 5. Reaction traps, antiproton storage, and remaining engine components are located to the aft of a special "booster rocket" used only to accelerate the payload to a velocity of $\sim 0.003c$. So that communication with Earth becomes unobstructed, the booster engine separates at burnout, leaving only the payload, which then fully deploys its antenna and scientific instruments. A magnetometer, found farthest from the

central hub, is used to examine magnetic fields of the interstellar medium and determine the location of the termination shock discussed previously. A near-infrared spectrometer is used to examine Brown Dwarves in the Oort Cloud, and the optical imager serves a dual-purpose to detect large clumps of cold matter and to tell the spectrometer where to point. An astrophysics package, containing an ion-mass spectrometer, investigates high-energy matter and plasma contained within the interstellar medium. The payload mass is 216 kg, and the entire gross mass is 1805 kg.

Assuming that Ka-band will be employed on the Deep Space Network by 2030,¹⁰ a 100 bps data rate at 10,000 AU can be achieved by use of an 8m parabolic antenna. This requires 780W of power, which can be acquired through the use of RTG's envisioned for the future (AMTEC's).

A 50 year, pre-cursor mission to 10,000 AU, using the design above, is shown in Table 2. For comparison, parameters for both DHe³ and DT fusion-driven systems are shown. The DT system has lower ignition temperatures, but presents problems associated with containment of 14 MeV neutrons and tritium. The numbers in Table 2 assume 100% energy transfer efficiency, which is of course not realistic. The fusion energy must be converted to thrust through an energy conversion system.

Studies of the energy conversion system are underway. Initial design and analysis suggests that efficiencies as high as 80% can be obtained. We are proposing to use the high-energy proton/alpha beam as an ion source for an electrostatic thruster. The current design is being investigated using Particle-in-Cell techniques to obtain performance characteristics and system efficiencies. Preliminary results suggest that high efficiencies can be obtained utilizing moderate electromagnetic fields for confinement and acceleration

of the propellant plasma.

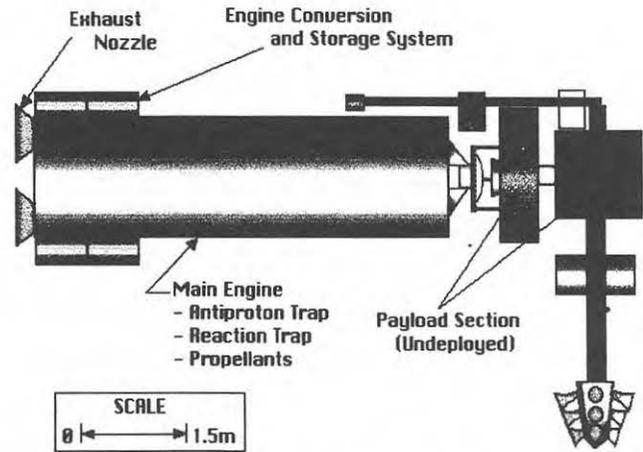


Fig.5 Profile of the AIMStar spacecraft

5. First Stage Propulsion Experiment with Antiprotons

Because only 5×10^8 antiprotons are required per shot of fusion fuel, smaller-scale experiments may be conducted. A proposed first-generation antimatter thruster serves as a predecessor to AIM. The thruster uses a combination of the NASA Marshall Space Flight Center's High Performance Antimatter Trap HiPAT¹¹ and a scaled version of the AIM reaction trap. This reaction trap uses U²³⁸ coated lithium hydride fuel, and it allows quick storage of 5×10^9 antiprotons, which is required to elevate the temperature of the heavier lithium component to 10 eV. Similarities to the AIM paradigm include a double-nested potential well and antiproton microfission with a U²³⁸ shell. The fission fragments ionize the LiH target, which expands and propels through a magnetic configuration. We consider HiPAT an optimum choice for a LiH plasma experiment due to its proficiency in storage quantities and lifetimes. The MHD program MACH2 is therefore used to confirm the plasma confinement and propulsion at varying magnetic field strengths.¹²

Table 2. AIMStar 50-year Mission to 10,000 A.U.

Parameters	DT	DHe ³
ΔV	956 km/s	956 km/s
V_e	5.98×10^5 m/s	5.98×10^5 m/s
I_{sp}	61,000 s	61,000 s
Power	33 MW	0.75 MW
Thrust	55.2 N	1.25 N
dm/dt	9.22×10^{-5} kg/s	2.09×10^{-6} kg/s
t_b	0.50 yr = 6 mo.	22 yr
Distance @ burnout	37 AU	1635 AU
α_{ave}	30.5 kW/kg	0.69 kW/kg
N_{pbar}	130 μ g	28.5 μ g

Approximately 10^{12} antiprotons are loaded into the HiPAT Penning trap at a national particle accelerator/decelerator lab (e.g. Fermi National Laboratory, Brookhaven National Laboratory). These antiprotons sympathetically cool to 100 eV with electrons already residing in the trap. The portable trap mates with a reaction trap at another research site. By electrostatic means the antiprotons are transferred in order to guarantee that 5×10^9 antiprotons reside in the LiH reaction trap.

Smaller confinement quantities and shorter time scales relax the conditions for the reaction trap. To allow proper expansion of the LiH plasma, the control region is presumably similar to HiPAT, which is similar to that shown in Figure 1, but with 30 cm length and 6 cm diameter. A 0.2 T axial magnetic field can be provided using permanent, rare earth magnets, or with a superconducting coil. The reaction trap consists of approximately eleven electrodes, two of which are not shown in Figure 1, used for detection. These electrodes would provide a double-nested potential well, which splits the initial packet of antiprotons into two clouds of approximate equal density. The reaction trap also contains a portal, which introduces the LiH fuel droplet into the control region.

The 100 ng fuel droplet consists of a $22.5 \mu\text{m}$ LiH core (40 ng), surrounded by a U^{238} shell of $\sim 0.5 \mu\text{m}$ thickness. When the antiproton cloud is collapsed upon the fuel pellet, the antiprotons immediately annihilate with the uranium shell. Pions and gamma rays spark microfission with the U^{238} nucleus. This produces two fission fragments of approximate mass 111 a.u. of 100 MeV each. Over the span of $23 \mu\text{m}$, the energy is deposited into the remaining uranium shell of the LiH:U(238) pellet and/or the LiH core.

In reality, ablation of the uranium shell before all 5×10^9 antiprotons annihilate is a distinct issue, and it suggests increasing the uranium shell thickness. For simulation purposes, however, the uranium shell is neglected.

Dealing with a neutral, collisional plasma, MACH2 can provide a robust numerical solution to the 2-D axis-symmetric problem.¹² However, there are certain limitations with this code, particularly for an unsteady expansion. Also, certain parameters of the MHD equations can be neglected due to the initial temperature and density of the LiH gas. Parameters and uncertainties such as bremsstrahlung radiation are resolved in other works,^{13,14} which are not reproduced here for sake of simplicity.

Simulations have shown that, in the absence of a magnetic field, the Li fluid diffuses throughout the entire control volume prior to its ejection downstream at an axial velocity of $\sim 40000 \text{ m/s}$.¹³ This produces an undesired effect of heat transfer to the titanium or copper electrodes, which reduces the specific impulse and therefore thrust of the system. Figure 6 illustrates results from a MACH2 simulation that is nearly similar, but with three discrepancies: 1) An axial magnetic field with $B = 0.2 \text{ T}$ is applied; 2) thermal diffusion is neglected; and 3) the density of the background is increased only to sufficiently accommodate for magnetic diffusion throughout the control volume. As expected, the plasma remains confined to the z-axis (axis of symmetry) and propagates downstream at a higher density of $3 \times 10^{-6} \text{ kg/m}^3$, approximately a factor of 100 greater than without a magnetic field. Moreover, the axial velocity increases marginally to $\sim 55000 \text{ m/s}$ (local Mach number = 4), presumably due to the plasma's preferential expansion in the axial

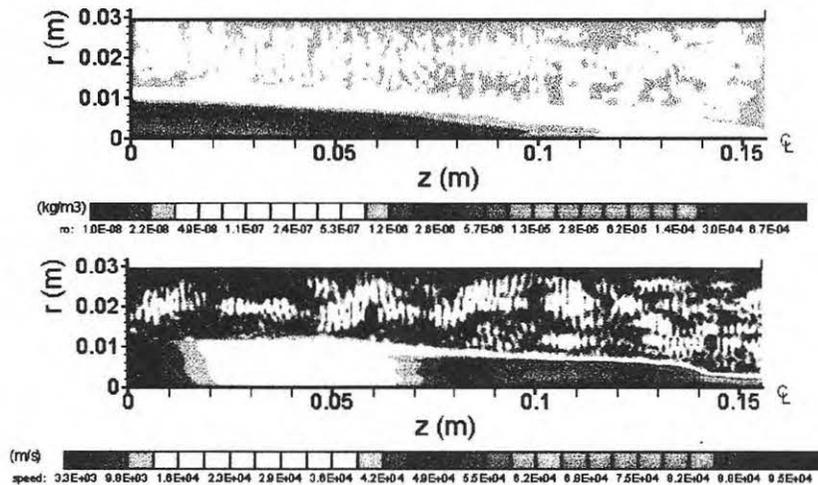


Fig.6 Density and speed contours of Li^+ expansion at $2 \mu\text{sec}$ with $B = 0.2 \text{ T}$, $\rho_0 \sim 1 \times 10^{-4} \text{ kg m}^{-3}$, and $T_0 = 10 \text{ eV}$

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