

Project Icarus M4: Primary Propulsion

Evaluation of Antiproton Catalyzed Fusion for Interstellar propulsion

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Abstract

Due to the ability of antiprotons to annihilate with ordinary matter with 100% efficiency, antiprotons serve as an exceptionally high-energy density storage mechanism. Upon annihilation, sufficient energy can be generated to trigger fusion reactions. In this paper we study a variety of ways that antiprotons can be utilized as drivers for fusion ignition. In addition, we explore a number of specific anti-proton driven fusion propulsion concepts. The technological maturity of such concepts is examined, and recommendations given for future Project Icarus research pertaining to this study.

This is a submission of the Project Icarus Study Group.

Keywords: antiproton catalyzed fusion, interstellar propulsion, fusion propulsion, Project Icarus.

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1 Introduction

Since the 1980's antiprotons have been studied for their potential applications for spacecraft propulsion[1-4]. It has also been demonstrated that, to heat a propellant directly, quantities on the order of a milligram are required [5] for missions of value. Indeed, tens of nanograms would be sufficient for interplanetary missions. However, this is currently far beyond our present technological capabilities. This has not prevented ideas being explored involving the utilization of antiprotons, in much lower quantities, to initiate nuclear reactions. These ideas fall broadly into three cases.

- Case 1: The utilization of antiprotons to fission heavy nuclei.
- Case 2: The direct heating of fusion fuels leading to ignition.
- Case 3: Using antiprotons to create muons, which are then used for muon catalyzed fusion.

For the first case, antiprotons are annihilated within a heavy nucleus such as uranium. This leads to almost 100% fissioning of the nucleus [6]. The fission fragments account for about 20% of the energy, with about 14 neutrons emitted, with some of the neutrons producing additional, lower yield, fissions. The fusion fuel readily absorbs the energy contained within the fission fragments, however, absorption of the neutron energy is more challenging, and absorption of the gamma ray energy is extremely difficult. The critical factor here, is the ability of the antiproton annihilations to sustain fission reactions without the need for a critical mass of fissionable material. This fission energy then generates the energy necessary to ignite the fusion reactions.

For Case 2, antiprotons can be used to directly initiate fusion reactions [7]. The reaction products of antiproton annihilation with matter are mostly pions and kaons. Of the pions which are created, approximately 60% are charged. The pions are extremely rapid, and move at about 95%c, and fusion reactions can be initiated within a plasma which absorbs this kinetic energy. A Pion will decay into a muon and a neutrino in about 20 ns. The charged muons can also deposit energy into the plasma. The muon itself also decays into an electron, a positron and two neutrinos, and they too can also deposit energy into a plasma. Antiproton annihilation serves as a lightweight solution to heating plasma to fusion ignition temperatures.

Case 3, antiproton-nucleon annihilations, results in muon generation, which can be used to sustain muon catalyzed fusion(μ CF) of a mixture of deuterium-tritium [8]. μ CF allows for fusion to take place at temperatures significantly lower than those required for thermonuclear fusion. Muons are 207 times more massive than electrons, and shields the Coulombic repulsion between two nuclei which draws them far closer together in a covalent bond than electrons. Because of this closer proximity, the strong nuclear force is able to fuse the nuclei together.

Because of their potential to initiate fusion reactions, and their exceptionally high-energy density storage, antiprotons are of interest to Project Icarus for use in the Module 4.0, Primary Propulsion module. Rocket propulsion driven by antiproton annihilation is also attractive because the charged reaction products can be manipulated by magnetic nozzles for the creation of thrust. Propulsion energy derived from these fuels can potentially demonstrate both high jet power levels and high exhaust velocities. However, these systems will be complex, and should be designed to be compact, portable, and self-contained. Because of these criteria, the following would necessarily need to be developed [9]:

- Lightweight reactor and drivers systems.
- Radiation Shields.
- High current density superconductors
- Cryoplants for magnet/propellant maintenance.
- Power conversion systems for reactor startup and operational support.
- Heat rejection system for dealing with waste heat.
- Magnetic nozzle designs for thrust.
- Antiproton storage, extraction and injection systems.

Perhaps more importantly, antiprotons offer a welcome alternative to conventional fusion ignition systems, in the sense that antimatter have the highest specific energy for any physical entity. An antiproton beam offers 90MJ/ μ g upon annihilating its matter counterpart. As an energy package and delivery system, antiprotons hold a major advantage over laser and particle beam equipment, specifically in the context of space propulsion, where the total mass of the spacecraft is of critical importance.

As a comparison, the National Ignition Facility (NIF), as an example of a conventional ICF driver, delivers 1.3MJ of laser energy to a deuterium-tritium (DT) pellet. The total mass of the facility is on the order of 100,000 tonnes, and has cost over \$2B (US). This total mass does not even include the external electricity supply system that is required to charge the capacitor banks for each firing.

In this paper we first summarize three antiproton driver schemes that have been studied in the literature for providing the spark necessary to ignite traditional Inertial Confinement Fusion (ICF) systems. Namely, volumetric ignition, hotspot ignition and fast ignition. Next, we explore a hybrid of the ICF scheme known as Magnetic Inertial Confinement Fusion (MICF) in the context of using antimatter drivers. Following this, we examine an antiproton-driven fusion scheme using unconventional aneutronic fuels. The latter parts of the paper are left to study specific antiproton-driven fusion rocket propulsion systems, and an assessment of the relative technological maturity of the ideas presented in this paper. Finally we provide recommendations for Phase 4 of Project Icarus.

This study is relevant to the following ToR project requirements: (ToR#2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (ToR#3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner (ToR#5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus) (ToR#6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

2 Fundamental Concepts

In this section we explore some of the ideas and concepts relating to antiproton catalyzed fusion propulsion.

2.1 Summary of Antiproton Driven Inertial Confinement Fusion Schemes

In this subsection, some of the salient features of a antiproton (sometimes expressed \overline{p}), driven ICF technology will be examined.

As mentioned above, antiproton annihilation offers a specific energy of 90 MJ/ μ g and is therefore an exceptional type of energy package and delivery system. The specific advantages of using \overline{p} as drivers, as detailed in [10] include:

• Massive reduction in driver mass, power hardware recirculation and waste heat radiators.

• Low injection energies since the energy does not originate in the beam energy, but the annihilation energy of the particles.

• The ability to adjust the driver delivery kinetic energy.

Based on the results of a paper by Perkins et al [10] we summarize the physics underlying the utility of \overline{p} driven ICF for a variety of classes of high-yield schemes. The ignition schemes examined in this research are:

- Volumetric Ignition
- Hotspot Ignition
- Fast Ignition

Of interest is the fraction of annihilation energy that is useful for ablative compression and fast ignition.

2.1.1 Volumetric Ignition

For volumetric ignition, most of the compressed fuel is heated to the ignition temperature. Such conditions can come about in a typical ICF target if, for example, a high intensity laser generates electrons on a $\sim \mu m$ metallic or glass shell which would enclose a solid or liquid DT core. This rapidly heated shell would explode with gigabars of pressure and, via momentum conservation, would create a converging shockwave heating the DT core.

In principle, \overline{p} can annihilate the bulk of the DT fuel, to drive this process. One issue with this scheme is the low energy deposition efficiency due to the fact that pions created in the annihilation event would be long range, and so would escape the reaction without energetically contributing to it. One way to reduce this effect is to seed the DT with a heavy element such as uranium. The heavy element would undergo antiproton-fission and the fission fragments would augment the energy deposition in the fuel. This antiproton-driven fission-fusion scheme was the proposed propulsion system for the ICAN spacecraft concept.

2.1.2 Hotspot Ignition

Hotspot ignition involves a target being isentropically compressed and ignited from a central high temperature core. This scheme gives significantly higher gains than for volumetric ignition. In such a fuel pellet, the assembly consists of a central low density, high temperature core region, contain a small fraction of the fuel in pressure equilibrium with the surrounding cool high density fuel.

With this setup, \overline{p} could be used to drive a hotspot ignition replacing conventional schemes. As with volumetric ignition a heavy metal could be seeded throughout the fuel pellet to enhance the energy deposition. As well as the advantage of the low specific mass, high specific energy of the antiproton-driver, antiprotons would produce higher rocket efficiencies [10].

2.1.3 Fast Ignition

Target gain could be increased, and compression energy for ignition reduced, when compared to hotspot ignition, if the fuel is compressed initially to a density higher than in the hotspot case, but less than the cold bulk fuel density, and then ignited separately over a small region. In essence, the compression of the target, and the actual ignition are decoupled.

Initially a slow driver (\sim 100ns) compresses the fuel to intermediate densities, next the ignition energy is delivered by a fast (\sim 10ps) separate system. Antiprotons could be used as either the ablative drive system to compress the fuel, or as the source to ignite the burn.

The conclusion of [10] is that antiproton-driven fast ignition offers the highest gains, however, with the added complexity of two separate \overline{p} injections, adding significantly to the complexity of the system. It is recommended that anti-proton driven ICF be studied further in Phase 4, with a deeper focus on quantitative results.

2.2 Antiproton Driven Magnetically Insulated Inertial Confinement Fusion Propulsion

Kammash [11], as part of a NIAC study, has explore the concept of Magnetically Insulated Inertial Confinement Fusion (MICF), with antiprotons used as drivers to initiate the fusion reaction.

Arguably the main distinguishing feature of MICF is a *self-generated* magnetic field which insulates the plasma from the metallic shell that contains it during the burn. MICF couples the positive aspects of both magnetic and inertial fusion in that containment of the plasma is provided by a metallic shell such as tungsten or gold, while its thermal energy is insulated from that shell by a self-generated magnetic field. This field is known to scale directly with the square root of the plasma temperature and inversely with the spot diameter at the point of beam incidence.

The confinement time for an MICF system is much larger than a traditional inertial confinement system since the speed of sound varies directly with the square root of the temperature of the medium and inversely with the square root of its density. This means that the shock wave which begins at the *inner* surface of the shell travels much more rapidly, and therefore the confinement time is lower.

The fusion reactions can be triggered by a driver (lasers or particles) that enter the target pellet through a hole. The driver delivers sufficient energy to ablate the fuel-coated *inner* wall and to form the hot plasma. The lifetime of the plasma can be found by examining the time it takes the shock wave to traverse the shell thickness. Estimates by Kammash suggest times of 100 nanoseconds. This is two orders of magnitude greater than implosion inertial fusion, which corresponds to a longer burn time, and hence, greater gain. If sufficient energy is delivered by the driver, a hot plasma is generated at pellet the core. This plasma will undergo fusion reactions and create energy.



Fig. 3. Illustration of Magnetically Insulated Inertial Confinement Fusion. The top image shows the driver entering the gap in the hollow pellet. The driver ignites the inner shell of the pellet to create a plasma, which is self confined by its own magnetic field.

This system has a number of attractive features that make it suitable for an advanced propulsion system. Because large energy magnifications are possible through the fusion reactions, large particle escape velocities generate large specific impulses. This leads to the conclusion of [11] that MICF would make an effective propulsion system. Kammash estimates $I_{sp} \sim 10^6$ s, arguably making MICF propulsion suitable for an interstellar mission. It also capitalizes on current research technology in the manufacture of fusion fuel coated targets. In addition, the flexibility in the pellet design mean that a variable specific impulse, variable thrust device could be easily engineered.

Kammash [11] suggest that a nanogram of antiprotons is sufficient to ignite a MICF target, able to deliver 10,000N of thrust at a pulse repetition rate of 10 Hz. In his propulsion concept, MICF pellets would be injected into a reaction chamber, and subsequently, a beam of antiprotons would initiate the fusion reaction. The reaction products would then exhaust through a magnetic nozzle to produce thrust.

The use of antiprotons, thus, clearly has the potential of allowing for a low mass driver, as opposed to massive and complex laser or particle drivers that require huge accelerators. It is recommended that antiproton-driven MICF be studied further in Phase 4, since it has many properties that would be attractive for primary propulsion.

2.3 Antimatter Driven P-B¹¹ Rocket System

Of interest to the propulsion community are the so called aneutronic fusion reactions. In such a reaction neutrons carry less than 1% of the total released energy, and would mitigate neutron radiation problems associated with commonly studied fusion reactions. Some aneutronic reactions, for example P-B¹¹, create only charged particles, which are ideal for propulsion purposes since these particles can be directed for thrust using magnetic nozzles. Although these fusion reactions sound ideal, the conditions required to create them are more extreme than those required for the DT cycle. P-B¹¹ fusion requires temperatures 10 times higher than for DT fusion.

Despite the challenges associated with P-B¹¹ fusion, one obvious benefit of utilizing such a reaction is the abundance of the elements involved. Project Daedalus used helium 3 as a component of its fuel due to the large amount of charged particles created in the deuterium helium-3 fusion cycle. One issue regarding this fuel choice, however, is the rarity of helium-3 on Earth, and the need for a mining operation, possibly around one of the Jovian moons.

One idea, proposed by Kammash [12], is to utilize antiprotons \overline{p} , to ignite the P-B¹¹ reactions in an MICF scheme as discussed in the previous section. In [12], Kammash determines that excessive radiation losses are a major obstacle to ignition, and calculates a gain of only 0.17% for a P-B¹¹ MICF system. Kammash proposes modifying the particle density, and plasma temperature to increase this and the main conclusion of [12] is that a proof of concept demonstrator could be built in the near future. Another conclusion is that it is entirely feasible that a propulsion system utilizing an \overline{p} -driven MICF system could achieve $I_{sp} \sim 10^5$ s.

Given these early predictions, it is recommended that P-B¹¹ fusion be explored in more detail for Phase 4. One issue with the MICF system is clearly the fabrication of complex pellets with a hole, and also the timing issues associated with firing an antiproton stream into such a hole, and such issues are clearly not trivial. Clearly the greatest advantages of a P-B¹¹ fusion propulsion system is the abundance of fuel on Earth, and the fact that the reaction is aneutronic, which is ideal for propulsion.

2.4 Antiproton-driven Inertial Confinement Fusion Rocket

In this section we review the basic functionality of an antimatter-driven ICF rocket. According to the Lawson criterion, the conditions required for a fusion ignition to occur can be summarized in the following equation:

$$n\tau T > 10^{21} \, keV \, s/m^3$$
 (1)

where *n* is the ion density, τ is the confinement time, and T is the temperature. The above value on the right-hand side is specific for the DT reaction. For the case of ICF, one typically requires a high density of fuel, confined for a short period of time. Typically megajoule pulses of lasers or ions from a driver, lasting a few tens to hundreds of nanoseconds, ablate the outer surfaces of a fuel pellet which implode the fuel to high densities and heat the central core. As the fuel burns, the energy that is created is used to heat and ignite more of the fuel. An alpha particle driven thermonuclear burn wave propagates radially outward through the pellet.

Because an ICF system does not require heavy superconducting coils for fusion, as in the case of Magnetic Confinement Fusion (MCF), it offers a more compact and lower weight propulsion system, and is thus a more attractive option when compared to MCF. By having sufficiently high pulse repetition rates, and ICF rocket could, in principle, operate at extremely high power levels. Of course, the Daedalus utilized superconducting coils however, this was for bootstrapping energy from the magnetic field generated from the pulse for the next fusion reaction, and were also used in the magnetic nozzles.



Fig 1. Illustration of imploding fusion pellet. High energy electron or ion beams radiate the target pellet, causing the out surface to ablate. The resulting high pressure density wave set up in the pellet converges to the center of the target, initiating fusion.

Cassenti [13] has considered a pellet design consisting of several materials (Fig. 2). The pellet consists of a hemisphere of fissionable material such as U²³⁵. This is surrounded by a hemisphere of fusion fuel, for example deuterium-tritium, or lithium deuteride. A heavy metal shell surrounds the fuel, with the outer layer consisting of a dense and high melting point material such as tungsten. The pellet also contains a hole through which a pulse of antiprotons and positrons is injected. Antiproton annihilation occurs at the surface of the hemisphere, which ionizes the fuel.



Fig 2. A fission/fusion hybrid ICF pellet design. A beam of antiprotons catalyzes the reaction.

The ionized fuel ions fill the empty core with a plasma, and electrons created in the annihilation create a current flow which also generates a magnetic field. This magnetic field has the effect of trapping the charged particles which include fission fragments, electrons, muons and pions. These

particles heat the core of the pellet to fusion temperatures. The purpose of the Uranium on the inside layer is to reflect neutrons back into the fuel.

The exhaust velocity can be determined from

$$\frac{1}{2}m_T v_e^2 = \frac{m_f E_a}{2A m_{amu}} \tag{2}$$

where m_T is the total pellet mass, m_f is the final pellet mass, E_a is the energy of the alpha particle emitted, A is the atomic weight of the fissionable material, and m_{amu} is the atomic mass unit 1.66×10^{-27} kg. Cassenti's model [13] explores the case of a fuel pellet consisting of deuteriumtritium fuel, with an alpha-particle energy of 3.5 MeV. Table 1 contains the pellet geometry.

Description	Dimension, cm
Core radius, R _f	0.01
Fuel radius, R _c	1.0
Uranium shell thickness, hu	0.0
Tungsten shell thickness, h_u	0.01
Antiproton beam radius, d	0.0003
Uranium hemisphere radius, a	0.03
Hemisphere distance from core surface, δ	0.0075

Table 1. Pellet geometry.

For an antimatter pulse consisting of 3×10^9 antiprotons, lasting 30ns, an exhaust velocity of $6\times10^7 m/s$ is obtained for 100% burn-up, using Eqn. 2 . The specific impulse can be approximated from

$$I_{\rm sp} = \frac{v_e}{g} \tag{3}$$

and so the specific impulse for 10% burn-up is about 200,000s. Improved burn up leads to higher specific impulses.

Improvements in the model would consist of performing simulations of the antiproton annihilation, fission reactions, plasma ignition, electromagnetic fields and the fusion of the fuel. In addition, simulations of the outer shell is also necessary. This would assist in obtaining improved values for the specific impulse of the system.

2.5 Gas Core Antimatter Rocket

Although not a fusion rocket catalyzed by antimatter, it's interesting to explore an alternative propulsion scheme that utilized antihydrogen annihilation.

Nuclear rockets have been studied for several decades, notably the NERVA program lead to the actual building and testing of a nuclear rocket, although none have actually flown. In this scheme, a working fluid, typically Hydrogen, is heated to a high temperature by a nuclear reactor, and is then ejected through a nozzle at high speed to create thrust.



Fig. 3. Schematic of a nuclear rocket.

In theory, a nuclear rocket has virtually limitless performance, however, the limiting aspect of the system is related to the materials, which limits the performance of the engine. A summary of nuclear rocket technology can be found by French [14].

In the NERVA engine, criticality requirements implied that only materials with a low neutron capture cross-section be used. Identical characteristics also control the engine core size and mass. If the nuclear reactor is replaced with a proton-antiproton annihilation, the criticality requirements no longer dictate the materials used. Borowski [9] estimates that, using antihydrogen as a fuel source, the tungsten core heat exchanger could run at temperatures of about 3000 K, resulting in an $I_{\rm sp} \sim 1,000$ s, for a solid core rocket. This is a vast improvements on chemical rockets for interplanetary mission scenario's, but far too low to be of interest as a primary propulsion source for an interstellar mission.

The limitations that are imposed on the solid core rocket can be overcome by allowing the core material to exist in a plasma state, a so called 'gas core' rocket. In the case of a gas core fission rocket, a sphere of fissioning plasma is held at a temperature of 25,000 - 100,000 K and the energy is dissipated in the form of black-body radiation. This subsequently heats the propellant which generates thrust. With the inclusion of a radiator cooled system, an $I_{sp} \sim 6,000$ s, is estimated.

A gas-core system is also a possible design configuration for an antimatter rocket. In this design, the reaction chamber contains a high pressure tungsten gas/plasma which absorbs the fragments of the antihydrogen annihilation after it has interacted with the tungsten debris. Transfer of the energy to the hydrogen working fluid would be via radiative transfer.



Fig. 4. An antimatter gas-core rocket with a high pressure tungsten gas/plasma to absorb the antihydrogen annihilation debris.

One of the major operational challenges for the antimatter gas-core rocket is the radiation of heat. For $I_{\rm sp} \sim 5,000$ s, an external radiator must dissipate $I_{\rm sp} \sim 1,332$ MW originating as gamma rays. Cassenti [15] estimates a radiator mass of 193 tonnes to accomplish this. Typically, the generative cooling overwhelms the high specific impulse for the antimatter gas-core rocket.

Although not strictly antimatter catalyzed fusion, this concept is worth mentioning for completeness. However, due to the low specific impulse from this system, and mass penalties based on the external radiator requirements it is recommended that gas-core antimatter rockets not be studied further as a primary propulsion system for Project Icarus. However, there may be some interest for secondary propulsion.

3 Technological Maturity

Issues relating to the technological maturity for utilizing antimatter, specifically antiprotons, to initiate fusion reactions, boils down to two main problems.

- 1. Creation of antiprotons in sufficient quantities so as to be useful.
- 2. Storage of antiprotons.
- 3. Consideration of how to utilize/shield gamma rays which are produced in \sim 5% of the reactions due to meson decay.

Both of these issues will be tackled in more detail in a separate trade study planned by the author [16]. Antiproton-driven fusion is currently at an extremely low TRL, and is considered to be somewhat speculative. However, based on the Project Icarus Terms of Reference, detailed in [17], which state 'The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.' This is certainly a scheme which could conceivably be evolved over the coming decades without an excessive stretch of the imagination.

The primary direction for ICF being studied today is the indirect drive hot spot ignition and fast ignition schemes. NIF has plans to achieve ignition during 2011/2012, and so ICF is at a reasonably developed stage theoretically, and is approaching practical demonstration. As a way of generating propulsion for spacecraft, however, the TRL is very low (~ TRL1-2).

4 Future Advances

The use of either antimatter and or fusion power for propulsion is clearly at a very low Technology Readiness Level (TRL). Key advances that would assist in improving the TRL's and moving toward any kind of propulsion prototype will involve:

- Demonstration of ICF fusion ignition
- Demonstration of ICF Gain
- Demonstration of possibility of pellet mass production
- Demonstration of MICF concept
- Mass reduction of fusion driver technology
- Demonstration of large scale production and storage of antimatter
- Demonstration of magnetic nozzle technology
- Progress with antimatter generation, storage, and manipulation
- Demonstration of antiproton-driven ICF

5 Conclusions

Antiprotons are an exceptional energy package and delivery system, however their application to antiproton-driven ICF is speculative. Particularly, the handling of antiprotons and their requisite injection precision will raise major technical challenges. Both the storage and the manipulation of antiprotons, particularly in the form of antihydrogen, is at present only at a very basic stage.

In this paper we have summarized the utility of antiprotons specifically as an ICF driver, and also explored some novel propulsion systems. It is the conclusion of this paper that antiprotons hold terrific potential for igniting the fusion burn necessary for ICF pulse propulsion. Their utilization could dramatically reduce the mass of any spacecraft by reducing the need for massive laser/particle beam drivers. Should no breakthroughs in laser/particle beam drivers present itself, it appears that antiprotons would be the ideal replacement.

However, due to the infancy of the research on practical applications of antimatter technology for space propulsion and ICF ignition, it is recommended that such technology be approached tentatively, for risk of appearing to stretch the limits of the ToR, namely credible extrapolations of existing technology. Further research is needed, specifically relating to the generation of, storage, and handling of antiprotons.

6 Recommendations

Based on the research performed in this paper, the following recommendations are made for future study.

- Determine whether ICF laser/particle driver masses can be reduced and how will the massed compare with any AM storage and delivery system? For example, what's the potential for positronic lasers or other drivers?
- Explore the challenges associated with fabricating, in large quantities, pellets with the necessary hole for MICF or fast ignition.
- Perform further research on the potential of μ CF, since this was not studied in detail in this paper.
- Study antiproton-driven MICF further in Phase 4, since it has many properties that would be attractive for primary propulsion.
- Study P-B¹¹ fusion further, especially in the context of antiproton drivers.
- Determine for the case of MICF, what mass of antiprotons would be necessary for an interstellar mission, and can storage technology be sufficiently extrapolated so as to remain 'credible'?
- Recommend that gas-core antimatter rockets *not* be studied further for primary propulsion but not to rule this out for secondary propulsion.
- Study the possible fusion pellet size reductions for an AMCF system when compared to conventional ICF.
- Examine the potential gains from AMCF when compared to other drivers.
- Explore current research already performed spacecraft with some element of propulsion derived from antimatter systems namely Aimstar and ICAN-II.
- Examine phenomenology of self-generated magnetic fields within targets of the type created in Field Reversed Configurations.

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