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SRF (synchrotron radiation fusion) drive for interplanetary spaceships

Abstract

A concept first proposed by the author in 1991 in presentation on advanced propulsion before the NASA Synthesis Group is that of using the synchrotron radiation from D-He3 fusion plasmas to heat a magnetically confined hydrogen plasma for propulsion. This concept was explored by in detail in 1993 in NASA funded research and found to be successful. In this concept a fusion temperature Tokomak plasma burning d-He3 can transport unlimited megawatts of power to heat a propulsion plasma without any energy conversion hardware and with both the fusion and propulsion plasmas separately optimized for their respective roles. Separation of plasma from the magnetic nozzle, a serious problem in all plasma propulsion schemes, is also solved by using high-order multi-pole fields.

INTRODUCTION: THE POWER AND PROPULSION OF AN ULTIMATE SPACE SHIP

Let us consider the conceptual design of an ultimate spaceship for travel within the solar system, something which has heretofore only existed in science fiction, but now can be considered based the latest science and technology. (Figure 1) We would consider that such an ultimate spaceship would be powered by fusion energy and use hydrogen propellant in the form of high temperature plasma for propulsion since both the fuel and propellant for such systems are abundant. We would imagine such an ultimate space ship would be compact, like the space ships of science fiction or a modern nuclear powered submarine, and thus possess systems of great efficiency, so that large radiators to get rid of excess heat and large fuel tanks for propulsion are absent from the design. That is, we imagine a design that is compact and functional with cargo, crew, passengers, being most of the structure, and space for propulsion and power being a lesser fraction, as in modern ship or airliner.

The rocket exhaust thermal speed rises with rocket thrust chamber temperature and largely determines the propellant mass fraction of any rocket. Therefore, plasma, the 4th state of matter following solid, liquid and gaseous states in progressively higher temperature must be considered the ultimate rocket exhaust. This leads to the concept of an ultimate rocket engine whose thrust chamber consists of magnetic lines of force and within which a plasma is heated by intense EM (Electro-Magnetic) radiation. (Figure 2.) The magnetism prevents the plasma from touching any material parts of

Figure 1 : Space ship of classic science fiction

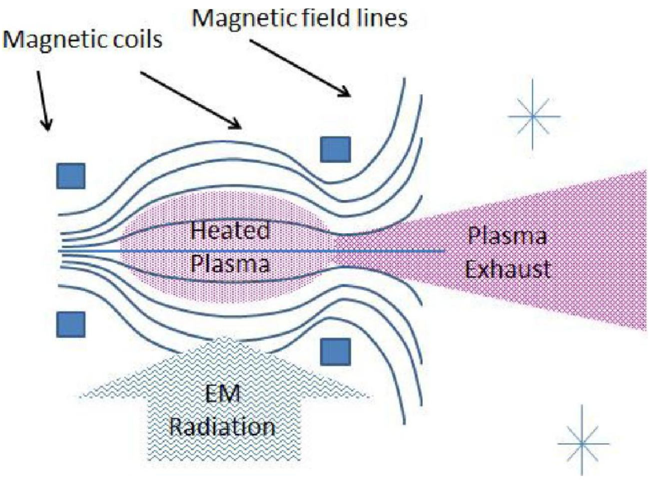

Figure 2 : The ultimate rocket engine, where plasma is confined in a thrust chamber of magnetism and heated by intense EM radiation before exhausting into space, However, many details must addressed in such a scheme

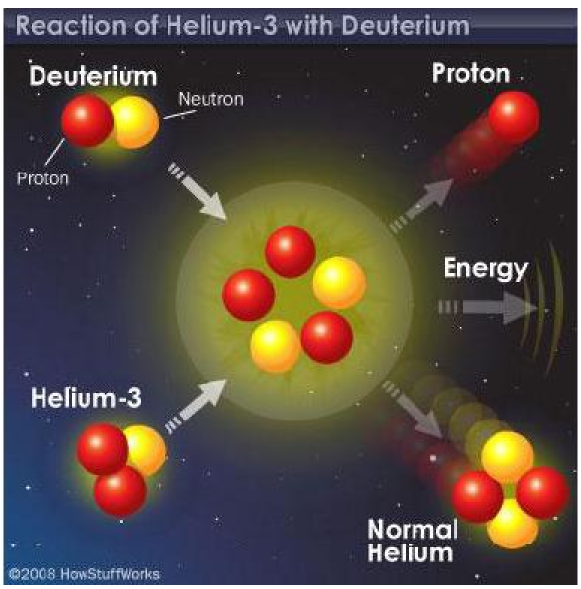

Figure 4 : The D-He3 reaction that liberates a high energy proton and a He4 nucleus or alpha particle

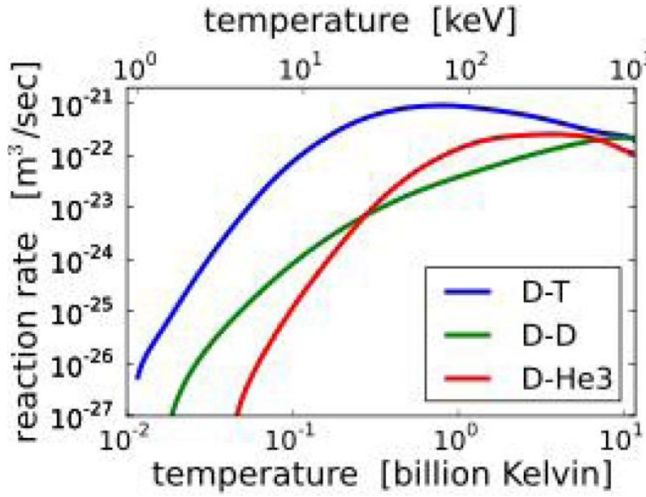

Figure 3 : The reactivity per unit volume of various fusion cycles as a function of temperature, Note that the D-He3 reaction is the second most reactive after D-T

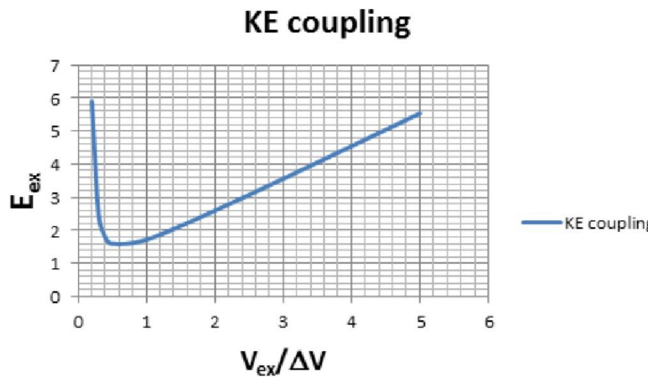

Figure 5 : The ratio of exhaust energy expended over space ship kinetic energy produced. E_{ex} is thus a measure of wasted exhaust energy. Note that a broad minimum in wasted energy occurs near the ΔV of the mission

the spaceship before it exhausts into space and also freely passes the EM radiation that heats the plasma. This basic concept is sound, but many details in such a scheme are important.

The ultimate power source for a spaceship propelled by plasma would be helium-3 deuterium fusion, which releases all its energy in the form of charged particle motion and releases no neutrons. This would allow generation of vast amounts of electric power at high efficiency in a compact power plant with little or no radiation shielding being required for the crew. Both helium 3 and deuterium are space resources and so would allow the spaceship to travel anywhere in the solar system.

The details of the transfer of power from this ultimate power source and the ultimate rocket engine are important, however, if high efficiency is to be achieved. One must imagine systems capable of capturing large amounts of power from the D-He3 reactor and converting this into EM radiation suitable for heating the magnetically confined propulsion plasma and these systems must be very efficient. Direct use of the fusion plasma for propulsion appears problematical from the first glance because the plasma conditions for creating maximum fusion power require strong confinement of the plasma, the antithesis of a rocket engine. Therefore, the key problem an ultimate spaceship appears to be the problem of power conversion and transfer between two plasmas. One plasma must be in a strongly closed magnetic geometry that generates fusion power and the other with an open magnetic geometry that generates rocket thrust by letting the heated plasma escape. Between these plasmas must be a “power-train” of energy conversion and transfer. For the ultimate spaceship such a power-train must be of maximum efficiency and simplicity.

It appears that nature itself has provided the means for efficient and simple power-coupling between the

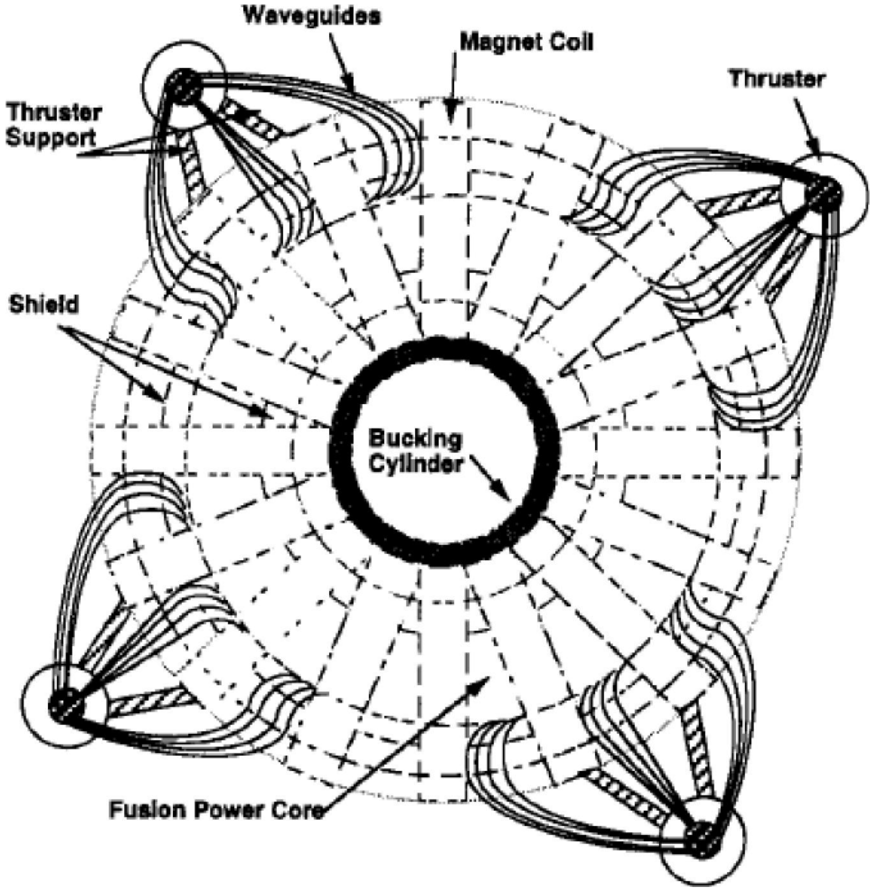

Figure 6 : A figure taken from the reference 2 intial study of SRF showing the arrangement of small thrust chambers around a D-He3 burning Tokamak, Losses occurred in the walls of the many small waveguides

two plasmas of such a space ship's power-propulsion system. Since both plasmas are in magnetic fields and consist of masses of charged particles spiraling around magnetic field lines, they can be connected via electromagnetic fields that are resonant between them. Both plasmas, being magnetized, are strong radiators and absorbers of radiation. This concept was first grasped by the author in 1991 and included in a briefing on "Advanced Propulsion" delivered to the NASA Synthesis group (1).

Basically, it will be shown, that in a hot fusion plasma suitable for burning D-He3, electrons radiate synchrotron radiation in large amounts in the millimeter wavelength range and thus radiation can be ducted to the plasma in a thrust chamber and used to heat the propulsion plasma. The system is called SRF (Synchrotron Radiation Fusion) propulsion (2). In the remainder of this article, the basic architecture of a SRF drive will be described and numerical studies of its efficiency summarized. Concepts for improvement of the basic scheme will be discussed, as a basis for further research.

Specific impulse and thrust versus power in space mission profiles

EP (Electric Propulsion) using plasmas has now become a reality for both commercial and scientific missions in space. This was inevitable because electric propulsion allows much higher I_{sp} (see Eq. 1) than is possible from chemical propellants, and this allows lower propellant mass to be used for similar missions, thereby lowering launch weight, and thus costs, for satellite and other systems. Hence the driving force for the acceptance of EP on satellites was initially economic, and was driven by I_{sp}. These relations were previously considered for the MET (Microwave Electro-Thermal Thruster) (3). That plasma propuslion gave access to I_{sp} values higher than chemical, explains its rapid acceptance. However, it is also obvious that I_{sp} is only one parameter of several that must be examined when considering EP in the context of real space missions.

Thrust kinetic power, *KP*, is defined in Eq. 2. Efficiency, η, defined here as the ratio between kinetic power in the exhaust plume, *KP* and input electromagnetic power, *P*, from the spacecraft power plant, is also an essential quantity (Eq. 3). Finally T/P, the thrust per unit input power (see Equation 4.) is another important parameter, related to both efficiency and I_{sp} that must be considered when choosing a plasma thruster for a space mission. Power on spacecraft is a limited and carefully apportioned quantity in real space missions, be they near Earth or interplanetary. This means power and thrust level for any given EP technology on a mission is effectively fixed. Thrust level is important for executing maneuvers within a timely manner. If only specific impulse was important, the ultimate EP device would simply be a flash-light; it would consume no propellant, but it would give no useful thrust either, except perhaps for an interstellar voyage where flight mission time scales were centuries. Since I_{sp} and *T/P* are nearly reciprocal, the two quantities must be traded.

$$I_{sp} = \frac{T}{gM_{,t}} = \frac{A\rho V^2}{gA\rho V} = \frac{V_{ex}}{g} \qquad (1)$$

$$T = M_{,t} V_{ex} \qquad (2)$$

$$KP = \frac{1}{2} M_{,t} V_{ex}^2 = \eta P \qquad (3)$$

$$\frac{T}{P} = \frac{2\eta M_{,t} V_{ex}}{M_{,t} V_{ex}^2} = \frac{2\eta}{V_{ex}} = \frac{2\eta}{g I_{sp}} \qquad (4)$$

Propulsion systems achieve both high specific impulse and high thrust per unit power if they are very efficient. Therefore, the key both high thrust per unit power and high I_{sp} is to reduce power transfer losses between the power source and the rocket engine.

More than just system efficiency on the space craft is required for an efficient space transportation system, we must also ensure that the exhaust kinetic energy is comparable to the kinetic energy of the space ship flying its mission. In the ideal mission the exhaust of the rocket will become nearly stationary as the rocket moves through space, the forward velocity of the rocket being exactly balanced by the backward motion of the exhaust out its back. For this reason, the fanjet, or bypass jet engine, is very popular for commercial airliners that fly at high but below-sonic speeds because it moves mostly air at subsonic speeds by a large ducted fan, likewise the turboprop, where a gas turbine turns a propeller, is popular for low speed air travel. In both cases the working fluid used for propulsion is mostly air pushed backwards at roughly the cruising speed of the aircraft, resulting good coupling of the propulsion to produce kinetic energy in the aircraft. Likewise, a supersonic jet fighter has an afterburner, producing supersonic exhaust, for cruising a supersonic speeds. In each case the exhaust speed is comparable to the vehicle cruising speed. Thus for a spaceship on a mission it is desirable for its flight speed for the mission to be roughly its exhaust velocity. This means that in the frame of the Solar system, only the spaceship itself has much motion, the exhaust will simply orbit the Sun, while the spaceship moves between orbits.

We can write an equation for the wasted exhaust energy based on the mission ΔV, such for a mission to Mars from Earth, and the Tsilokovsky Equation for rocket propulsion. We begin first with the Tsilokovsky relation for payload mass fraction : m_f/m_o as a function of the ratio of ΔV to the exhaust velocity V_{ex} :

$$\frac{m_o}{m_f} = \exp(\Delta V / V_{ex}) = 1 + \Delta V / V_{ex} \cdots \qquad (5)$$

We then combine this result with an expression for the fuel kinetic energy and find a function that gives the ratio of the total kinetic energy of the fuel expended, in the spaceship frame, to the mission payload kinetic energy after it has achieved the mission ΔV.

$$E_{excess} = \frac{\frac{1}{2}(m_o - m_f)V_{ex}^{\ 2}}{\frac{1}{2} m_f \Delta V^2} = \left(\exp(\Delta V / V_{ex}) - 1\right)\frac{V_{ex}^{\ 2}}{\Delta V^2} \qquad (6)$$

The function of this ratio with the ratio Vex/ ΔV is seen in Figure 5. It can be seen easily that a broad optimum exists for the most efficient use of kinetic energy of the exhaust when it is approximately equal to the mission ΔV.

This calculation immediately shows why direct use of the reaction products of D-He3 fusion as rocket exhaust is not appropriate for a mission within the Solar system. With an energy yield of of 18MeV and a mass of the reaction products of 5 amu = 940MeV, we find the approximate value of the exhaust velocity of the fusion products is:

$$V_{ex} = c\sqrt{2\frac{1.8MeV}{4.7GeV}} = 26{,}256\text{km/sec}$$

This is much higher than the typical mission ΔV of 20km/sec, or less, to reach the most interesting planets of the Solar system, and thus most of the fusion energy would be wasted in the form of helium and hydrogen flying around the Solar system at high speed while the spaceship moves at modest velocity. Therefore, part of the function of a power transfer system on a spaceship is to "impedance match" the fusion power system energy output, in the form of moving charged particles, to the mission ΔV. In the cause of SRF this means transferring power form the hot fusion plasma to the cooler thrust chamber plasma

The feasibility and important technical issues of SRF drive

Basically, the burning of D-He3 in a magnetically confined plasma requires temperatures so high,approximately 30keV, that the gyrating electrons become semi-relativistic and radiate synchrotron radiation in large amounts. This radiation is radiation is reabsorbed and reradiated many times in the magnetized plasma before leaving the plasma surface. The high energy ions, the proton and alpha particles produced by the D-He3 reaction transfer energy to the electrons in the plasma via Coulomb collisions and thus this fusion energy is then radiated out of the plasma. By the same processes, a cooler magnetized plasma can absorb this energy, so that energy is transported from the reactor plasma to the propulsion plasma with no other mechanisms than a microwave waveguide connecting the plasma chambers. Electromagnetic radiation transfers more power than any other known process in the universe. Because the thermonuclear plasma can radiate power at high rates and the propulsion plasma can absorb it at equally high rates such an SRF system of plasma power and propulsion can be scaled even to enormous sizes and powers. In the 1997 study funded by NASA (2), the basic feasibility of SRF drive was demonstrated by studying the transfer of power between a realistic model of a Tokomak Plasma burning D-He3 and four equally spaced thruster plasmas as shown in Figure 6. Power was transferred from the Tokomak chamber via several waveguides to each thrust chamber, which contained a magnetized plasma. Using hydrogen as a basic propellant, full ionization can be achieved at approximately 15eV temperatures and above giving a basic exhaust velocity of 12km/sec. Such a basic exhaust velocity would be highly appropriate for interplanetary missions.

The preliminary study attempted no optimization of the overall system but did achieved a power transfer efficiency of fusion power to thrust kinetic power of 40% and thus showed its basic feasibility. However, its projected thrust to mass ratio was poor. The SRF system was too heavy. Several reasons for this were evident, in particular the problem of the great weight of Tokomak design used. The problem of absorption of synchrotron power in the waveguides, which used a high surface field design leading to heating of the waveguide was also present. These problems might be addressed by moving to high field compact Tokomaks to reduce their mass, mounting the Tokomak in a large holrahm which would shaped to focus the synchrotron radiation onto a single target plasma, as shown in Figure 7. The large holrahm design would lower synchrotron radiation field intensities on the metal surfaces, decreasing losses due to resistive heating.

Thrust chambers in the preliminary study were considered to be asymmetric simple mirrors with RF stabilization and the loss cone plasma as considered to provide the thrust. This system would probably be effective at low powers and low levels of thrust. However to increase its thrust per unit mass, for high power, compact versions of the SRF, problems will occur in the simple mirror thrusters.

In a system driven by intense radiation with dense plasmas in the thrust chamber, plasma will be trapped on closed field lines and have difficulty leaving them. This means plasma leaving a magnetic nozzle could easily tear the magnetic field lines and produce, rather than a simple uniform exhaust, a series of plasmoids. This entrainment of plasma of the field lines will cause loss of thrust and efficiency as field lines between the ejected plasmoid and ship stretch and break. (see Figure 8) Even worse, plasma that remains trapped on magnetic field lines can easily circulate around them and bombard the spaceship structure, further reducing thrust.

A way to solve this problem with the magnetic thrust chamber is to redesign the thrust chambers so they used magnetic multi-pole fields where the magnetic field lines arch into the plasma and thus the plasma is kept away from the walls but not entrained on magnetic lines of force to as great a degree. Such magnetically insulated plasma chambers are already success-

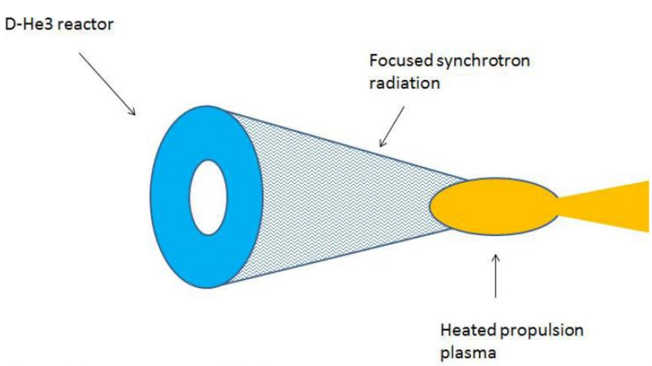

Figure 7 : A concept for SRF where the power plant plasma and propulsion plasma are part of a holrahm structure that ducts and focuses the synchrotron radiation from the power plant onto the propulsion plasma, This would reduce synchrotron field intensities on most metal surfaces and increase efficiency

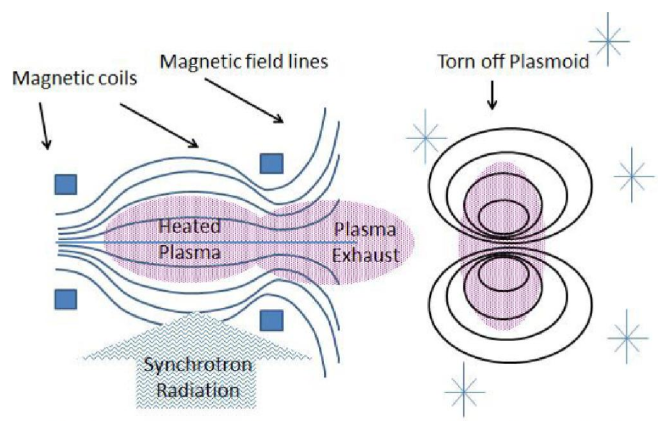

Figure 8 : A magnetic tearing mode operating in an intensely driven propulsion plasma. Heated plasma in an intensely driven thruster exits by tearing loose magnetic flux and forming a series of plasmoids

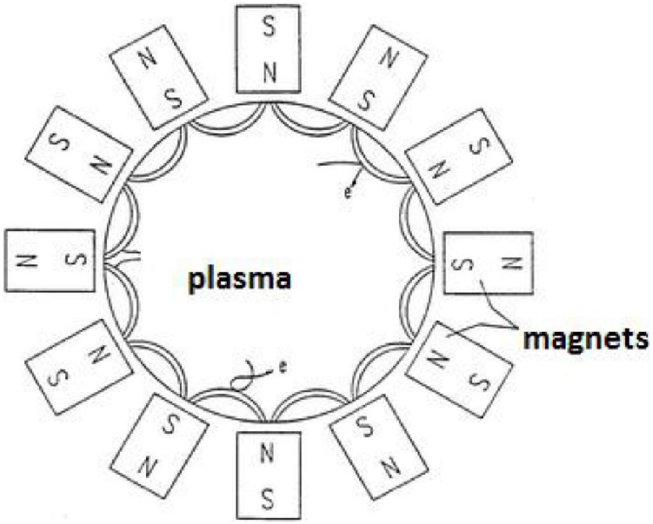

Figure 9 : The magnetic configuration of a plasma generating chamber for an ion thruster, Here, a "picket fence" of magnetic fields confines the plasma

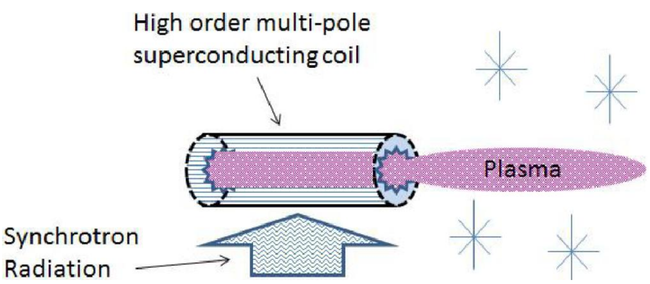

Figure 11 : A multi-pole magnetically confined plasma as the propulsion plasma for an SRF system

fully employed in ion thrusters (see Figure 9)

Such magnetic multipole confined plasmas are often employed as plasma sources (Figure 10). They could be modified to serve as plasma thrust chambers for the SRF, as shown in Figure 11.

SUMMARY AND DISCUSSION

Therefore the problems identified in the preliminary SRF study: the high mass of the Tokomak power plant, the losses in the microwave ducting for the synchrotron radiation, and the problem of magnetic reconnection in the intense driving of a magnetically confined thruster plasmas, can each be solved with the SRF giving much high thrust to mass ratio. It must be also remembered that the SRF system can be scaled to large size for large spaceships with fusion power going as plasma volume whereas structural mass goes approximately as surface area, so that for large enough systems SRF will become the most attractive basis for large spaceship propulsion. As one Department of Energy official, on seeing a briefing on the SRF drive for spaceships, exclaimed : ***"this system is inevitable"***

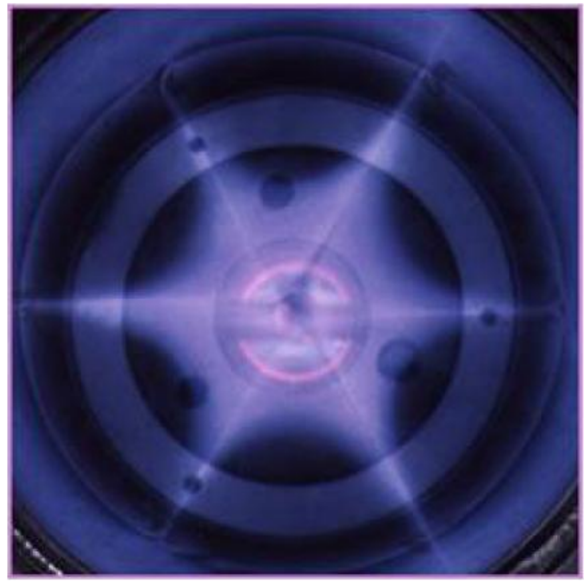

Figure 10 : An end-view of a hexa-pole magnetically confined linear plasma

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