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AN APPROACH TO SPACE POWER

G. H. Miley, J. H. Nadler, T. Hochberg,
O. Barnouin, and Y. B. Gu
Fusion Studies Laboratory
Department of Nuclear Engineering
University of Illinois
Urbana, IL 61801

ABSTRACT

Fusion offers the potential for a very high specific power, providing a large specific impulse that can be traded-off with thrust for mission optimization. Thus fusion is a leading candidate for missions beyond the moon. Here we discuss a new approach for space fusion power, namely Inertial Electrostatic Confinement (IEC). This method offers a high power density in a relatively small, simple device. It appears capable of burning aneutronic fuels which are most desirable for space applications and is well suited for direct conversion. An experimental device to test the concept is described.

INTRODUCTION

The potential advantages of using a fusion device for space power, both station and propulsion, are well known (See Refs. 1-2 and Fig. 1). These include a very high power density and a relatively "clean" power source. However several concerns have been voiced. The first is the feasibility of developing a suitable fusion device in a near term time frame. The second is the need for a device capable of burning advanced fuels, providing a very low neutron and radioactivity involvement. The work presented here describes an experiment designed as a first step towards answering both issues: namely, an IEC device that can, in principle, be developed rapidly and which can burn fuels like D-^{3}He and p-^{11}B.

Recent conceptual studies have concentrated on D-^{3}He fueled devices using magnetic or inertial concepts as candidates for future missions such as Mars or deep space travel. Based upon our review of issues involved, however, IEC emerges as one of the most attractive fusion concepts. This approach offers several significant advantages, including a highly non-Maxwellian plasma which is capable of burning advanced fuels, a relatively simple structure capable of high power density in a relatively small device, and a "natural" coupling to direct energy conversion.

The IEC concept was originally proposed by Farnsworth [3]. Several years after that Hirsch proposed a variation of that design [4]. It is this design of Hirsch's that we base our experiment upon. Figure 2 illustrates our experimental set-up. Electrons are emitted into the vessel from two thoriated tungsten hoops. These electrons then travel about the anode, ionizing the background gas. The created ions will be accelerated towards the cathode where they will form a radial ion current. This current creates a positive space charge in the very center of the IEC device which draws electrons in, creating a very high density central reaction "core" region (Fig. 3). However, energetic charged particle fusion products (MeV protons, alphas) will have sufficient energy to escape the well, allowing coupling to a direct-collector type energy conversion device. This approach, in principle, can lead to stable inner particle reaction rates which are significantly greater than those possible in magnetic confinement and avoid the need for pulsed operation used in inertial confinement.

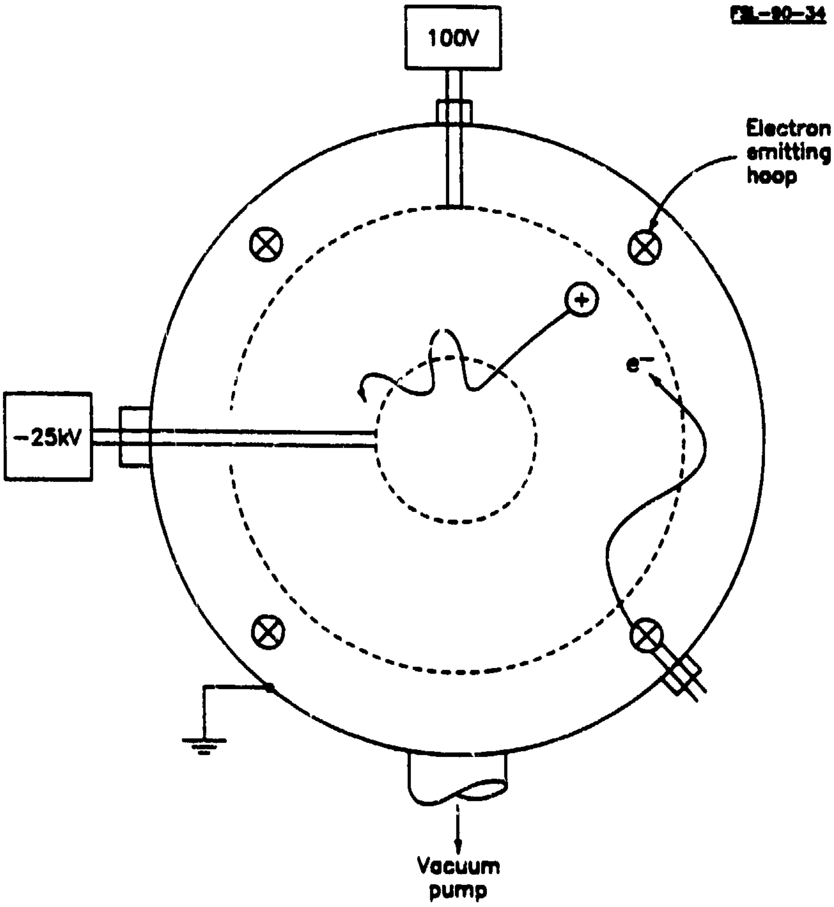
- **VERY HIGH SPECIFIC POWER**
- **VERY HIGH SPECIFIC IMPULSE THAT CAN BE VARIED FOR MISSION OPTIMIZATIONS**
- **HIGHER THRUST THAN ION ENGINES**
- **DEUTERIUM - HELIUM 3: OFFERS BASIC INHERENT SAFETY**
  - **NON TOXIC**
  - **NON HYPERGOLIC/EXPLOSIVE MIXTURE UNDER NORMAL PHYSICAL ENVIRONMENTS**
  - **NON RADIOACTIVE ISOTOPES**
  - **LOWEST NEUTRON FLUX OF REACTIVE ADVANCED FUELS**
- **MISSION ADVANTAGES**
  - **POTENTIAL FOR LONG LIFE**
  - **RESERVICABLE**
  - **ALLOWS CONSIDERATION OF DUAL MODE OPERATION, PROPULSION AND POWER.**

Fig. 1 Advantages of Fusion Energy for Space (From Ref. 1)

The plasma exhaust from the IEC could be used in a direct propulsion concept. However, a very attractive alternative is to couple the IEC to an electrically driven ion propulsion unit. The latter represents a well developed propulsion concept [5,6]. The high specific power offered by the IEC plus the use of direct conversion make its use with an ion thruster unit most attractive.

PHYSICS OF INERTIAL-ELECTROSTATIC CONFINEMENT

The confinement of plasma in an IEC device has been demonstrated in two different geometries, spherical and cylindrical [7,8]. Spherical geometry offers stronger "convergence", i.e. a higher power density. Thus we are focusing on this geometry. The potential wells, that are needed to confine the plasma, are created by the formation of "virtual" anodes and cathodes, which are in turn created by the accumulation of space charge at the center of the vacuum vessel. This is brought about by injecting ions into a vessel which contains a highly transparent cathode placed concentric with the outer vessel wall. The ion current will travel about the cathode creating a virtual anode, which will then attract electrons. The electrons will travel about this anode in the same manner as the ions, and hence another virtual cathode will be created. In this manner, multiple virtual wells can be created.



- Electrons are emitted from hoop
- 100V biased grid accelerates the electrons
- Ions are created by e⁻ collisions with background gas
- Inner HV cathode accelerates ions
- SFID A vessel diameter 30cm
- SFID B vessel diameter 61cm

Fig. 2 Hoop Arrangement for Electron Injection

The wells created in this fashion confine the plasma where the fusion occurs. But there are several ways in which to bring all this about. Mentioned above is ion injection; other methods would include electron injection, with a real anode in addition to the cathode. In this manner, the electrons would travel about the anode ionizing background gas, creating the ions that will then fall into the cathode.

A variety of fusion fuels can be used: D-D, D-T, D-^{3}He, p-^{7}Li and p-^{11}B to name a few. The first two involve the use of radioactive tritium and the creation of high energy neutrons. The last three are virtually aneutronic and create minimal problems with radioactivity. Their products are high energy charged particles which are ideal for a direct energy conversion system.

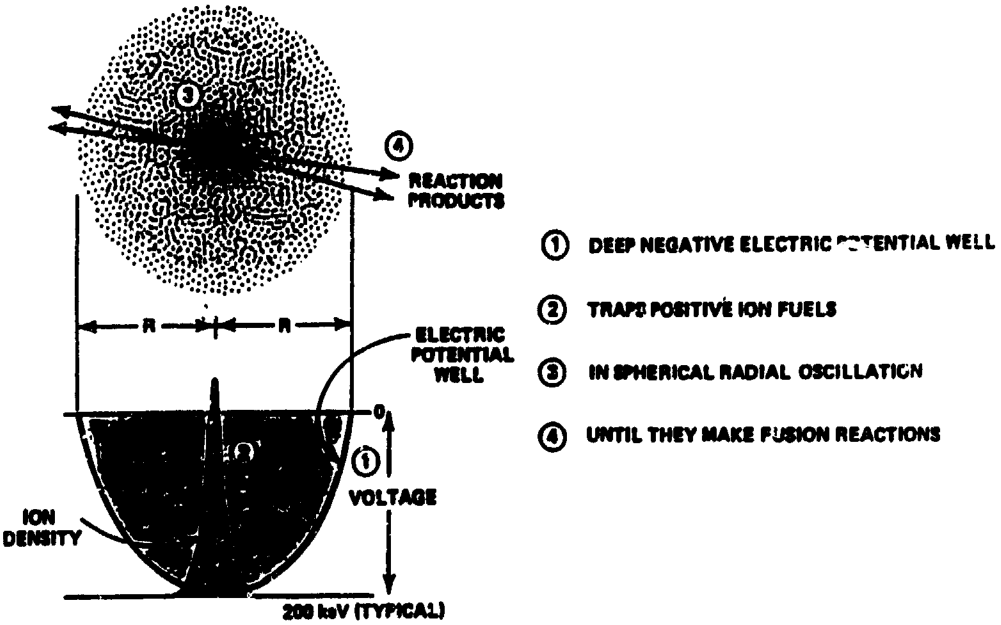


Fig. 3 Principles of Operation-1

U OF I EXPERIMENT

The experiment ongoing at the University of Illinois incorporates two different approaches: electron injection to cause ionization with background gas, and direct ion injection. The former method was outlined earlier; the electrons oscillate about an anode, creating ions which are accelerated by the inner cathode. This set-up is depicted in Fig. 2. Later experiments will employ ion guns and will do away with the electron injection and the outer anode. Two ion guns will be mounted at right angles to each other, with just the cathode remaining in the center of the vessel. The injected ions will start travel about the cathode, trapping negative space charge inside the cathode, and forming a virtual anode. This in turn can lead to the formation of multiple wells, analogous to the skins on an onion.

Two different sized devices will be used (Fig. 4). The smaller device, SFID-A (Spherical Fusion Illinois Device) employs a vessel 29.5 cm in diameter, the larger device, SFID-B, is 61.0 cm in diameter. The cathode and anode in SFID-A will be 7.5 cm and 22.5 cm, respectively. The cathode and anode in SFID-B is 15.2 cm and 45.7 cm, respectively. Both cathodes will be powered by a 100 kV, 25 mA(max) power supply.

A variety of diagnostics will be used. The first to be employed will be a BF_3 proportional counter placed inside a neutron moderator outside the vacuum vessels. The expected neutron count with these parameters is expected to be in the 10^7 neutrons/second region for SFID-B. Additional instrumentation which is presently under development includes a biased probe and an ion beam probe. The biased probe will provide measurements of the plasma density profile during operation of the device with only the anode present. The ion beam probe will be used for potential well measurements. It will be similar to the electron probe employed on an earlier IEC device [9]. However, that device used an anode in the vessel instead of the cathode. Thus, in the present case it is necessary to substitute an ion beam to carry out potential well mapping.

SFID-A (30 cm):

1) Demonstrate operation of a small Hirsch device.
2) Demonstrate scaling parameters.
3) Test the Illinois diagnostics.
4) Measure electrostatic wells.

SFID-B (61 cm):

1) Demonstrate scaling to a large device.
2) Refine diagnostic analysis of center core physics.
3) Study of center core physics.
4) Preliminary study of ion gun injection.
5) Study effects of asymmetries of ion source.

Fig. 4 Physics Objectives

POWER GENERATION

An IEC fusion device can, in principle, be operated using advanced fuels [10] that produce little or no neutrons during the fusion process. The basic advantage that IEC offers in this respect is that the interacting ions are not thermalized, i.e., remain highly non-maxwellian (Fig. 5). This results in a more beam-beam type reaction which is most favorable for burning advanced fuels with their higher temperature requirements. Three reactions of this type that appear most appropriate for this device are D-^{3}He, p-^{7}Li, and p-^{11}B. These reactions proceed as:

$$\begin{aligned}
&D + {}^{3}He \; \text{-->} \; {}^{4}He\ (3.6\ MeV) + p\ (14.7 MeV)\\
&p + {}^{11}B \; \text{-->} \; 3\ {}^{4}He\ (8.7\ MeV)\\
&p + {}^{7}Li \; \text{-->} \; 2\ {}^{4}He\ (17.5\ MeV)
\end{aligned}$$

Since the products of these reactions consist entirely of charged particles, the energy from the reaction can be extracted by making the fusion products climb a potential barrier [10,11]. If the core of the fusion device is surrounded by a spherical ion collector at high potential, the energy of the radially escaping ions will be converted directly to electrical current at the high voltage. For example, for the p-^{11}B reaction, each reaction product carries ~2.9 MeV of energy and the particles are doubly charged. This implies that an ion collector maintained at ~2.9 MV would convert nearly all of the energy of the escaping ions into electricity.

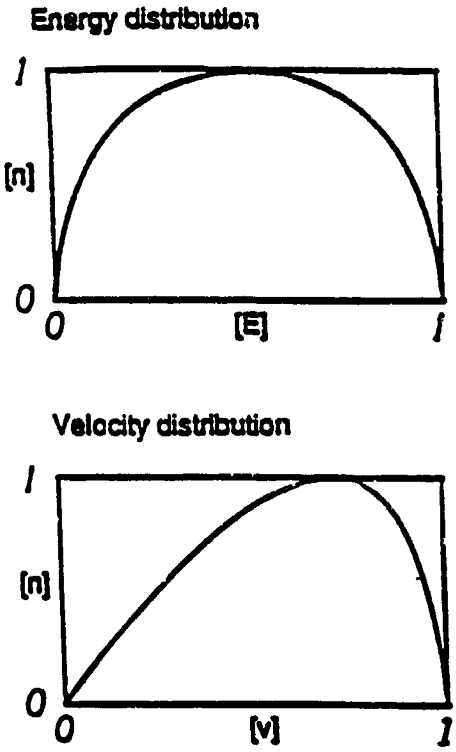


Fig. 5. Energy and velocity distributions for central collisions in radially-nonenergetic, converging ion flow. Center-of-mass and center-of-geometry are coincident in the system.

To illustrate the potential for such operation, results from preliminary calculations are presented in Tables I and II. In Table I we see that a well depth as large as -200 kV can be obtained in a 200-cm sphere with only a modest imbalance in the electron density (δn^-) in the plasma core. The well depth should be set to match the energy at the peak in the cross section (in the c-m system) for the fusion fuel employed. This means a well of only 40 kV is required for DT, 160 kV for D-^{3}He, and 560 kV for p-^{11}B (Table II). Thus, in principle, the 200-cm sphere in the earlier example could burn D-^{3}He with, as shown in Table II, an attractive effective energy gain of over 100.

Such a power generation system has several advantages for space power. It is relatively lightweight, compact, and creates virtually no radioactivity or radiation. It requires only small quantities of fuel, and since it has no moving parts it would be vibration free and durable.

PROPULSION

Two space propulsion systems based on the inertial-electrostatic fusion systems will be mentioned here. The first is very straightforward: the electric power produced by the direct energy convertor described above would be used to power ion thrusters. Such a system would be simple, rugged, and would have a very high specific impulse. The ion thruster that this would be connected to "has evolved to the point of flight readiness..." [6].

Table I

NEGATIVE ELECTRIC POTENTIAL WELLS WITH UNIFORM CHARGE DENSITY

Well Depth Ew (keV)	Sphere Radius R (cm)	Charge Density δn^- (1/cm+3)	Charge Neutrality Deviation, for no-1E15/cm^3
200	200	1.66E7	1.66E-8
100	100	3.32E7	3.32E-8
100	31.6	3.32E*	3.32E-7
10	3.16	3.32E9	3.32E-6

δn^-: differential electron density required to create well
no: central ion density

Table II

REACTION ENERGY AND EFFECTIVE ENERGY GAIN AT PEAK CROSS-SECTION FOR FUSION FUELS

Fusion Fuels	Fusion Energy, Released (MeV)	Peak Cross Section σ (b)	Energy at Peak	Gain at Peak
DT	17.6	5	40	440
D-^{3}He	18.3	0.7	160	114
p-^{6}Li	4.0	0.2	1250	3.2
p-^{11}B	8.7	0.8	560	15.5

The second system is one that was proposed by R. W. Bussard [12]. This concept is a high thrust, high specific impulse system referred to as QED. Here, high voltages from the IEC accelerate a relativistic electron beam (REB) which would be directed into a magnetically confined plasma. The REB couples strongly with the plasma, heating it to high temperatures. The plasma is allowed to exhaust through a magnetically insulated nozzle providing thrust while fresh propellant is continuously injected into the system radially. R. W. Bussard [12] calculates that such a system could provide a specific impulse as high as 3000 seconds, with accelerations as high as 0.5 g.

FUEL REQUIREMENTS AND LUNAR HELIUM-3

The D-^{3}He reaction represents a very attractive approach to fusion for space applications by combining relative ease of operation (e.g., relatively modest plasma temperature and confinement time requirements) with nearly aneutronic operation (neutrons from D-D reactions are reduced in the present beam-beam approach compared to a Maxwellian D-^{3}He plasma). The main difficulty with this approach is the lack of natural sources of ^{3}He on the earth. While ^{3}He can be bred using accelerator-like techniques [13], the other route which is well suited to space applications is lunar mining [13,14]. Apollo lunar samples indicate that ~10^9 kg could be obtained from the lunar surface which has been impregnated with ^{3}He and other gases by long bombardment of the solar wind [14]. This amount of ^{3}He could fuel fusion plants yielding over 10^7 Gw-yr, representing a sufficient resource for both terrestrial applications and an active space program. Subsequent needs could eventually move on to extract ^{3}He from other sources (such as the 10^{23} kg estimated on Jupiter).

In conclusion, it should be stressed that lunar ^{3}He is not absolutely essential for the development of advanced fuel fusion power sources. Indeed ^{3}He can be bred; or p-^{11}B, though more difficult to burn, could be developed. Still, in terms of a power source for space, lunar ^{3}He appears to fit in so well that this approach deserves serious study.

SUMMARY

Fusion offers a most attractive way to power deep space travel. IEC offers a different approach to fusion confinement which combines a high power density with the ability to burn aneutronic fuels and employ direct energy conversion. An experiment to explore this approach has been described. While considerable R & D would be required to scale this experiment up to the power levels required for space applications, the small size and relative simplicity of IEC imply that such development could be done rapidly compared to other fusion devices.

ACKNOWLEDGEMENTS

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REFERENCES

1. Slides and Notes from Minicourse on Fusion Applications in Space, Salt Lake City, Utah, 9 Oct. 1988, G. H. Miley editor, Fusion Studies Laboratory, University of Illinois, Urbana, IL.

2. Haloulakos, V. E., and Bourque, R. F., "Fusion Propulsion Study," AL-TR-89-005, Astronautics Laboratory, Edwards AFB, CA (1989).

3. Farnsworth, P. T., US Patent #3,258,402, issued June 28, 1966.

4. Hirsch, R. L., Meeks, G. A., US Patent #3,530,497, issued September 22, 1970.

5. Langmuir, D. B., Stuhlinger, E., and Sellen, J. M., *Electrostatic Propulsion*, Academic Press, New York (1961).

6. NASA Lewis Research Center, *Ion Propulsion For Spacecraft*, Cleveland, OH (1977).

7. Hirsch, R. L., "Inertial-Electrostatic Confinement of Ionized Fusion Gases," *J. Appl. Physics*, 38, #4, p. 4522 (1967).

8. Dolan, T. J., Verdeyen, J. T., Meeker, D. J., and Cherrington, B. E., "Electrostatic-Inertial Plasma Confinement," *J. Appl. Physics*, 43, #4, p. 1590 (1972).

9. Swanson, D., Cherrington, B. E., Verdeyen, J. T., "Potential Well Structure in an Inertial Electrostatic Plasma Confinement Device", *Phys. Fluids*, 16, #11, p. 1939 (1975).

10. Miley, G. H., *Fusion Energy Conversion*, American Nuclear Society, LaGrange, IL, (1976).

11. Hsiao, M.-Y., Ohnishi, M., "Summary of the U.S. Japan Workshop on D-^{3}He/Field-Reversed Configurations," *Fusion Technology*, *16*, 276 (1989).

12. Bussard, R. W., "Fusion as Electric Propulsion," *J. Propulsion and Power*, to be published May/June 1990.

13. Miley, G. H., "^{3}He Sources for D-^{3}He Fusion Power," *Nuclear Instruments and Methods in Physics Research*, *A271*, 197 (1988).

14. Wittenberg, L. J., Santarius, J. F., and Kulcinski, G. L., "Lunar Source of ^{3}He For Commercial Fusion Power," *Fusion Technol. 10*, 167 (1986).