SPACE PROBE APPLICATION OF IEC THRUSTERS

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Earlier studies have described Inertial Electrostatic Confinement (IEC) fusion power concepts using either D-He^3 or p-B^{11} fuels to provide a high-power density fusion propulsion system capable of aggressive deep space missions. However, this requires a large multi-GW thruster forcing a long term development program. As a first step, we examine here a progression of near-term IEC thrusters, stating with a 1-10 kWe electrically-driven IEC jet thruster for satellites followed by a small 50-100 kW IEC fusion thruster module for next generation large deep space spacecraft. The initial electrically-powered unit is a novel multi-jet plasma thruster based on spherical IEC technology using electrical input power from a solar panel. This type of unit is discussed and its advantages for next step electrically driven units are identified.

I. THE ELECTRICALLY-DRIVEN IEC JET THRUSTER

A novel plasma jet thruster, based on Inertial Electrostatic Confinement (IEC) technology, is under development for an ultra maneuverable-space thruster for satellite and small probe thrust operations. The IEC Jet design potential offers a unique capability to cover a wide range of powers (few Watts to Kilowatts). It offers good efficiency while providing a plasma jet that can start with a large diameter but be narrowed directionally to focus on targets. The IEC thruster uses a spherical configuration, wherein ions are generated and accelerated towards the center of a spherical vacuum chamber. A virtual cathode forms in the high-density central core region, combined with a locally distorted cathode grid potential field, extracts accelerated ions into an intense quasi-neutral ion jet. This configuration gives low gas leakage and good heat removal making it possible to scale the design to either low power or high power, covering requirements for present small satellites on to future medium and large satellites. In addition to maneuverable thrusting, the jet channel extraction technique enables directing and focusing the plasma stream onto an asteroid or other object for its interrogation. Analysis of the plasma emission provides an identification of the materials and surface features of the object. The IEC system also offers an attractive fusion power source for other applications. The IEC jet thruster provides a step towards a future p-B^{11} IEC power source and/or thruster for satellite operations. This possibility is briefly discussed here.

I.A. Current Electric Thruster and Future Needs

Present space thrusters typically use hydrazine propellant for orbit insertion and station keeping on large GEO satellites, Arc Jet Thrusters have also been used to electrostatically enhance performance for these operations. Also, high power Hall current thrusters that electrostatically accelerate Xe ions have been developed by NASA with discharge power levels ranging from 6.4 to 72.5 kilowatts. (Ref.1). These devices produce thrust ranging from 0.3 to 2.5 newtons, and specific impulses up to 4500 sec at 1 kV. Recently, AeroJet together and Lockheed Martin Space Systems Company[2] have qualified a 4.5-kW Hall Thruster Propulsion System (HTPS) which will be used on military communication satellites and has demonstrated 240 mN of thrust with specific impulse of 1980 s at 400V acceleration. The total thruster mass including power processor unit is 25.90 kg and life testing has demonstrated in excess of 4500 hrs of operation. While such thrusters serve current needs well, future broadband commercial and military communication satellites of 20-50 kW broadcast power will require much more efficient thruster performance. This challenge provides the motivation for IEC jet application discussed here, starting with the electrically driven version and continuing to a future high power p-B^{11} fusion unit.

I.B. Relation to Other Prior Thrusters

NASA and other laboratories have worked toward developing advanced HTPSs[3] for future satellite applications. Such thrusters, however, do not scale well to lower powers for small satellites, nor are exhaust plasma modifications possible to provide fast mauverability. The IEC-jet thruster appears uniquely able to address both issues.

Conventional plasma thrusters such as the Hall thruster have undergone much more experimental study than the IEC-jet thruster. However, the simplicity of the IEC-Jet thruster design and its thermal scalability makes it feasible to quickly develop and test.

In the jet thruster concept the plasma target at the center of the chamber where the multiple ion beams intersect, serves to deflect ions into the escaping jet plasma. The resulting virtual anode, in combination with curved potential lines due to the cathode grid, diverts ions, forming a strong plasma jet. This jet is channeled out through an enlarged grid hole and guide structure attached to the grid. This design promises a good efficiency and thrust while providing a low weight.

In addition, the IEC jet offers two added features that increase its potential effectiveness for probing various space objects. The fact that the IEC jet can be controlled to multiple areas over the sphere would allow the platform to use its propulsive jet to maneuver itself close to a target and then simply open a second jet offset 180 degrees from the propulsive one. The second jet would serve to integrate the platform, saving time and fuel when reorienting the plume at the target. Other current systems such as Hall thrusters would first have to position themselves close to the target, then reorient such that the exhaust plume is directed at the target.

An additionally relevant aspect to the IEC jet thruster is the option to operate as a pulsed device. This becomes especially important when considering how long it may take to disable a defensive target (the platform's impulse time to disable). The use of an intense pulsed jet could disable the target before it has time to maneuver or apply defensive layers. The basic IEC has been operated experimentally in a pulsed mode using a capacitive power unit. However, formation of the jet has only been studied under steady-state operation to date.

An added long-term potential advantage of developing the IEC-jet thruster is that the concept can eventually be extended to an ultra high impulse fusion power/propulsion unit. Indeed, the thruster concept arose from work on a fusion based IEC used for fusion neutron production.[4,5] In that case, however, the ratio of fusion power out to the electrical power input (Q) is too low to be used for power production. Still this provides an extensive database for moving rapidly to the higher Q units needed for a fusion thruster.

I.C. Description of the IEC

The IEC device is basically a spherical plasma diode. It has a ground potential on an outer sphere, and a negative potential on a transparent inner spherical grid (see Fig. 1). Ions are generated in a discharge region between the vacuum chamber wall and the grid.[5] Adding electron emitters at the boundary and another additional electrical grid near the grounded outer sphere better localizes the source profile for ions in the device. This technique is employed for the thruster design, allowing operation at lower gas pressures and insuring a neutralized jet.[6,7] For a given grid design and dimensions, an operational "window" exits where high density ion beams will form in the IEC device, initiating the "star mode" of operation (Fig. 2.). Care in the grid design, especially use of relatively large grid openings, is required for this mode. The resulting high-density space-charge-neutralized ion beams, termed "Microchannels," are created that pass through the open spaces between the grid wires. This unique operational mode, originally discovered by UI researchers,[5] increases the effective grid transparency from the geometric value (on the order of 90%) to a much higher value (98-99%) (Ref. 8). In effect, the microchannels guide ions through the center of the grid openings, greatly reducing the rate of ion collisions with the grid. The creation of these microchannels significantly reduces ion bombardment and erosion of the grid and increases the power efficiency.

Fig. 1. Schematic diagram of an IEC Device.

I.D. IEC Jet Thruster Configuration

For conventional star mode operation, such as that shown in Fig. 2, the IEC grid is designed to be highly symmetric so that the microchannel beams are also symmetric, providing good convergences at the central core. However, experiments have demonstrated that enlarging one of the grid openings distorts the local potential surfaces. The potential surface formed by the enlarged opening then extends deeper into the interior grid volume than do the small "standard" openings. Thus ions recirculating in the grid volume eventually "find" the exit surface at this opening and are guided out. The exit opening is surrounded by a cylindrical grid guide which has a slightly lower potential than the main grid, thus providing a potential trough that guides the escaping ions out, forming the exit "jet"[9] (see Fig. 3). The ions electrostactically drag electrons, providing a space charge neutral flow. This results in the creation of a very intense, tightly coupled space-charge neutralized jet plasma directed outward from the central core. It is this mode of operation (star with jet) that is employed for the IEC thruster. The jet formation has been explained theoretically[4,5] in terms of the distortion of the potential surface at the enlarged grid opening described above. Such operation has been routinely obtained in laboratory IEC devices under steady-state operation, with the plasma jet being maintained for hours. The power carried by the jet has been demonstrated by a calorimetric measurement using the temperature rise of a target plate placed in its path. Over half of the 2 kW energy imparted to the ions by the accelerating grid in the Fig. 2 experiment is effectively funneled into the jet, and no major bombardment of ions to the vacuum chamber wall or grid are observed. It was confirmed that the major portion of the energy was carried by the ions as desired for successful thrusting by varying the potential of the calorimetric plate. In summary, this configuration provides a way to efficiently convert the energy stored by accelerated ions in the symmetric microchannels in the spherical IEC into a directed beam or “jet”.

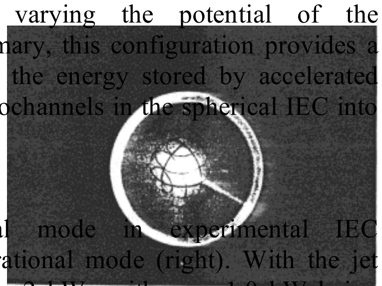

Fig. 2. Star operational mode in experimental IEC device.(right) and Jet operational mode (right). With the jet case, the input power was ~2 kWe with over 1.0 kW being carried out by the jet flow.

I.E. Comparison to a “Planar” Plasma Thruster

The IEC thruster can be viewed as transforming a conventional ion thruster into a spherical form. In the case of a planar thruster, ions are also formed in a discharge region. However, instead of recirculation within a spherical region, a magnetic field is frequently used in the planar case to contain electrons, providing a long path to maximize ionization collisions. Thus ion source regions are basically for both IEC and planar ion thrusters, and the recirculation provided by the grids or the magnetic fields play equivalent roles in both devices. The challenge for the IEC jet thruster concept is how to extract a net thrust from the spherical configuration. That is where the two concepts (planar vs. IEC) diverge. In the IEC, the star formation acts to maintain or store the accelerated ions until they are diverted directionally and escape out through the plasma jet opening. In contrast, the ions from the interior of the planar thruster are accelerated and extracted out through a large area grid structure.

Overall, the IEC configuration offers distinct advantages. First, the grid structures used in the IEC thruster are much more open than those used in the planar designs. When combined with microchannel ion focusing, this prevents ion-grid collisions, greatly reducing grid erosion and significantly increasing the thruster lifetime. Second, transforming the device into a sphere makes the overall unit more compact per unit-ion-source volume, implying a weight reduction advantage. Third, unwanted neutral propellant gas leakage would be reduced, due to the smaller net opening required by the high-density jet, vs. a conventional planar thruster having multiple grid openings. This advantage becomes especially important for thruster applications. Assuming that the IEC thruster efficiency is comparable to that of the planar ion thruster design, the IEC thruster then offers significant advantages based on these operational improvements.

II. JET EXTRACTOR DESIGN

As already described, to obtain thrust from an IEC device, a valley or trough must be created in the electrostatic potential, and a hole must be physically cut into the grounded spherical chamber (Fig. 3).

Fig. 3. Design of the~~an~~ IEC jet thruster. Experimental Device (Top) and Design drawing (Bottom).

The channel grid must be well insulated from the chamber to prevent short-circuiting or arc over. A separate insulated feed-through cable maintains the negative potential on the inner spherical and channel grids. Makeup propellant gas is fed into the ionization region through needle valve controlled tubing located around the chamber wall. To control neutralization of the plasma jet, additional electron emitters are attached close to the jet discharge hole. Control of the jet diameter and focus is obtained in two ways: first, the channel grid is separately hinged with a small servo motor such that its axis can be moved over a volume defined by a 10% cone angle; second, the grid bias can be varied over a range up to the chamber potential to provide focus control over the jet flow. A large negative grid bias creates a tight focus while reduction of this potential allows the plasma to expand, giving interactive control over the beam cross section.

TABLE I. Estimated Performance Parameters for the IEC Ion Thruster

III. EXPERIMENT DESIGN AND PERFORMANCE

Fig. 3 shows the thruster components. Present experimental studies use an existing spherical IEC chamber of ~30-cm with a 1-cm diameter port on one side of it for beam extraction (this unit is somewhat larger than needed for -micro-satellites). An 8-cm diameter spherical electrical tungsten or tantalum wire grid, having a geometric transparency of ~90%, will be mounted inside the chamber. A ~1-cm diameter hole will cut into the side of the wire grid. This hole is aligned with it in the chamber wall and connected to it by a 2-cm diameter cylindrical guide grid. An insulator covering the grounded wall prevents arc-over from the ground to the cylindrical grid. The inner electrical grids are connected to a 500-kV dc power supply through the insulated feed-through cable. A positively charged outer grid with a variable voltage of ~ 10-100 V is mounted on a swivel connector at the outside of the beam extraction port of the chamber, in combination with four electron emitters.. Xenon, is bled into the chamber through holes at appropriate locations around the wall of the vessel. The choice for the voltages on the outer grids is flexible, so long as a sufficient ion generation rate is achieved. The net accelerating voltage is kept at ~ 1 kV to achieve an exhaust velocity in the range of 30,000 m/s (ISP <3000 seconds). The mission for a communications satellite is optimized with a specific impulse in this range. A higher specific impulse reduces propellant requirements, but the power requirements and the mass associated with power source components increase correspondingly.

Parameter	**IEC Ion Thruster**
Propellant	**Xenon**
Molecular Weight (amu)	**131.3**
Specific Impulse (s)	**3000**
Thrust (mN)	**34**
Jet Power (W)	**500**
Net accelerating Potential (V)	**600**
Beam Current (mA)	**832**
Power Loss to Grid (W)	**≤50**
Power Loss to Bresstrahlung Radiation (W)	**< 1**
Power loss to Ionization of Propellant (W)	**200-250**
Input Power (W)	**750-800**
Thruster Efficiency (%)	**62-68**

III.A. Estimated Performance Parameters

Table I lists the estimated performance parameters for an IEC jet thruster based on experimental data available to date plus extrapolation of other ion thruster data.[10-12] Despite higher densities and temperatures in the central core plasma, energy losses due to bremsstrahlung radiation are still negligible.[12] Thermal radiation losses should be comparable to conventional thrusters. Overall, the energy expenditure per ion turns out to be comparable to that for conventional ion thrusters, and is <300 eV per ion.

In summary, the power efficiency of the IEC thruster appears to be competitive to existing ion thrusters. Thus, the major advantages outlined earlier, include a more compact design, large heat rejection area, an exhaust jet closer to quasi-neutrality, reduced neutral propellant leakage, and reduced grid erosion. Consequently, the mass of the IEC jet thruster system can be reduced compared to a high power Hall-type thruster while its lifetime can be significantly increased. In this overall context, then, the IEC jet thruster potentially offers an important improvement in performance for high power thruster applications.

IV. SCALE-UP TO p-B^{11} IEC SPACE POWER UNIT/THRUSTER

The electrically driven IEC jet thruster provides an important database for a next step p-B^{11} IEC jet thruster. Neutronless fusion seems essential in a small space thruster to avoid excessive weight from shielding of electronics. Considerable experience with fusing plasmas in IECs has been gained through development of IEC DD neutron sources. These devices operate with ~80 keV D ion beams using the non-Maxwellian character of the IEC. This important characteristic makes use of p-B^{11} a realistic goal. In fact, operation with circulating ion energies at the desired 150 kV energy for p-B^{11} has already been achieved at the University of Illinois and several other laboratories working on IECs. The issue then is how to achieve adequate confinement times. The approach being pursued at Illinois is the formation of deep potential wells with angular ion injection using a differentially pumped RF ion gun. The basic potential well structure developed in the IEC is illustrated in Fig. 4.

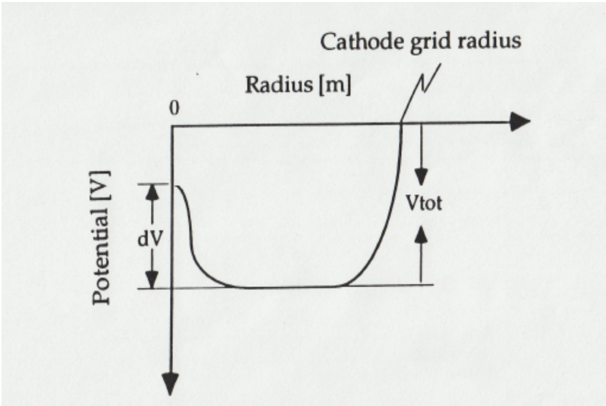

Fig. 4. Schematic of IEC potential well. Here V_{tot} is equivalent to the applied voltage while dV is the well depth. For efficient p-B^{11} fusion a depth of about 150 keV is desired.

Experiments using a collimated proton detector confirm the creation of potential well of this type, but more work with differentially pumped angular injection ion guns is required to fully demonstrate the wide, deep potential well ultimately required. Extensive simulations of ion injection with controlled angular momentum have defined conditions of potential well structures needed for p-B^{11} operation. As found in Ref. 13, "the ballistic core radius (the radius for straight line ion trajectories) is 2.5-5 times larger than the dense ion core radius and double the well radius. This fact demonstrates that the "poissor" type electric potential structure controls the ion density distribution profile. It is a "focusing" type structure which makes a dense fusion plasma core possible at high ion angular momentum. With this formation, a fusion rate scaling of I^5 was achieved in simulations where I is the IEC cathode current. This current scaling is higher than traditional beam-beam I^2 scaling due to the fact that the double well depth also increases with the cathode current. With this increase of double well depth and width, the particle trapping time increases and consequently the fusion probability goes up. This nonlinear well scaling has been used in a very preliminary p-B^{11} power unit study discussed next.

Earlier design studies for p-B^{11} space power have focused on large propulsion units with 1000s of MW for deep space missions. While the present study is focused on much smaller power units, these early propulsion studies illustrate an important point; namely the very high power to weight ration offered by IEC power units. An assessment of thirteen previously published fusion space propulsion concepts for fast solar system travel is given in Ref. 14. This study reviews compared operational performance for various missions. An IEC concept by R.W. Bussard[15,16] using a reactor fueled with p-B^{11} was found most attractive. Performance data was provided for a Mars transfer, and the Bussard IEC concept resulted in a total system thrust-to-weight ratio of some 20 milli-g's and a 68 metric ton dry weight. This vividly illustrates the capability of p-B^{11} IEC fusion to achieve high power-to-weight ratios. This design concept did not use p-B^{11} alpha particles directly for thrust. Instead, they were used to generate electricity by direct conversion, which in turn powered electron beams to heat high pressure plasma for expansion and acceleration. In that sense, the Bussard power unit was more like the electrical power source envisioned here, but operating at a much higher power level.

A preliminary conceptual design for a 100 kWe p-B^{11} IEC space power unit closely follows data from an earlier MWeD-He^3 space power design by Miley.[17] A block diagram of 100 kWe p-B^{11} IEC unit is shown in Figure 5. Details about the components and their operation can be found in the earlier design study.[17] This unit has four main components: the IEC itself, a direct energy converter, step-down electronics, and an energy storage/pulse-forming unit. In addition, cooling systems and waste heat radiation play a major role. The reactors uses an ion current cubed (I^3) scaling for the physics design and achieves a Q~ 0.95. For simplicity only a two grid electrostatic energy convertor is employed giving a conversion efficiency of ~ 55% for processing recirculating and station power. These conservative values are considered representative of first generation units. Further improvements would be anticipated for later generation units as experience with operational units is obtained.

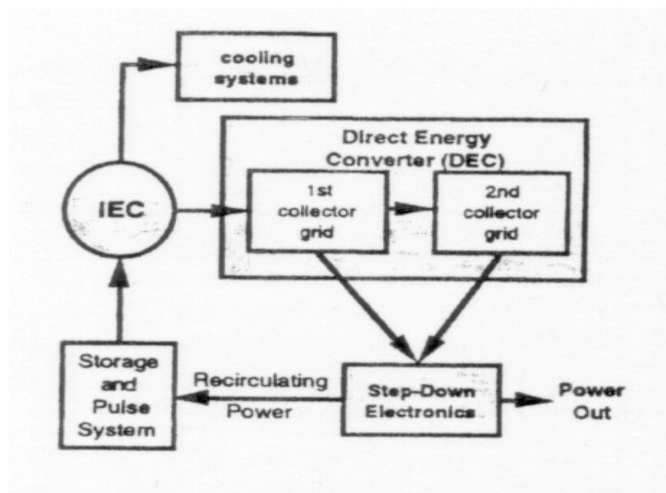

Fig. 5. Power flow diagram for a conceptual p-B^{11} IEC power plant.

Based on component data from the prior study in Ref. 17, a 100-kWe p-B^{11} IEC power plant is estimated to weigh about 100 kg, exclusive of cooling radiators. This result is very encouraging for use with future commercial space power applications.

As noted earlier, the scaling of the fusion reaction rate with I^3 is predicted from simulations studies.[13] There are, however, several theories that support even steeper scaling rates with current due to greater compression associated with standing wave formation.[14, 18] If this scaling is verified, pulsed operation would become particularly attractive as a way to achieve high peak currents, thus taking advantage of the strong current scaling.

The physics issues that must be resolved for achievement of a successful p-B^{11} IEC power unit largely involve handling power drains, including: 1) electron confinement, 2) ion losses to the grid, 3) charge exchange, 4) control of ion source profile, and 5) angular momentum.[19] Experiments with DD IEC neutron sources have shown steady progress. Numerous studies worldwide have reported exceedingly high neutron yields from DD IECs and direct measurements of potential well formation are continuing in several labs.[20] This progress gives encouragement that these physics issues can be successfully resolved.

The design considered here is for an electrical power unit. However, a propulsion version using the jet thruster concept could also be envisioned. An important aspect of such a unit would be the need to develop a magnetic grid system to redirect the nearly isotopic velocity distribution of the MeV alpha particles for the p-B^{11} into a direct thrust (Note that in the eclectically driven jet the situation is much simpler since the ion energies involved are only in the keV range and thus can be directed easily by electrostatic potentials). Such a collimator configuration has been studied both theoretically and experimentally by Momota, et al.[21] While this system adds some weight, the simple construction of the required Helmholtz and Cusp coils is not excessively weight intensive. More study of this version is needed to understand issues for development of such small p-B^{11} propulsion units.

A series of IEC fusion experiments are needed to resolve the relevant technical issues, so that private industry can aggressively pursue the engineering and manufacturing development of Q~1 IEC reactor systems.

V. CONCLUSIONS

This paper identifies an orderly progression of IEC applications in commercial space power, starting with an electrically driven IEC thruster. The attractive characteristics of the electrically driven device, namely light weight, low maintenance, low fuel leakage and extreme maneuverability make it a near-term competitor with other devices such as Hall thrusters. The subsequent extension to a p-B^{11} self powered unit would address the demanding requirements for future high power space units. Much more research and development is required to ensure that steps occur in a timely fashion,. However, due to the relatively small physical scale of the IEC, an aggressive experimental program can be undertaken at a reasonable cost.

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