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Published in:
Journal of the British Interplanetary Society (JBIS)

Publication date:
2015

An Alternative Design for Electrostatically Accelerated Ion Beam Fusion

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Inertial Electrostatic Confinement (IEC) is an alternative approach to nuclear fusion which uses electrostatically accelerated ions instead of hot plasmas. The best known device that utilises the principle is the Farnsworth-Hirsch Fusor. It has been argued that such devices have potential applications in spaceflight because of weight and other advantages. However, like other fusion reactors, practical machines have not yet been forthcoming. This paper builds on previous work to suggest an alternative topology for IEC-like reactors. This topology inverts the normal machine structure, potentially has significant advantages standard designs and may achieve the reaction-rates necessary for practical power generation.

Keywords: Nuclear Fusion, Fusor, Inertial Electrostatic Confinement, Power.

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1. Introduction

Inertial Electrostatic Confinement (IEC) fusion is an idea originated by Philo T Farnsworth (1906 - 1971) and was subsequently developed further by other researchers. Unlike Magnetic Confinement fusion and Inertial Confinement fusion, it does not rely on heating fuel plasmas up to hundreds of millions of Kelvin to work, but instead achieves fusion by using an electrostatic field to accelerate fuel ions into a target, with which they fuse. Like other fusion techniques, although demonstrator machines have been built, these have yet to achieve useful power output.

IEC fusion has, of late, received less interest than Magnetic or Inertially Confined fusion; however, it has several potential advantages over these - particularly in space-borne applications. The possible advantages include, weight, safety, size, simplicity and cost.

This paper builds on previous work by our group published in JBIS [1, 2] and suggests a new topology and mode of operation for IEC-like reactors.

2. Basic principles of fusion

Many different fusion reactions have been proposed as suitable for energy generation [3]. Four candidates that might prove useable are: Deuterium-Tritium (notated as D-T), Deuterium-Deuterium (D-D) or Deuterium-Helium 3 (D-He^3). The reactions are:

$$D + T \rightarrow n + \alpha + 17.6 \text{ MeV}$$

$$D + D \rightarrow p + T + 4.1 \text{ MeV}$$
$$D + D \rightarrow n + He^3 + 3.2 \text{ MeV}$$

$$D + He^3 \rightarrow p + \alpha + 18.3 \text{ MeV}$$

Where p is a hydrogen nucleus (a proton), α is an alpha particle (a helium nucleus) and n is a neutron. The presence of the neutron makes the D-D and D-T reactions (which are termed *neutronic*) more problematic to extract energy from.

The governing equation of fusion reactions is:

$$R = \sigma N_a N_b v \qquad (1)$$

Where R is the number of reactions in a given volume of space, per unit time and is usually quoted in units of fusions per cubic metre per second ($\#m^{-3}s^{-1}$). N_a and N_b are the number-densities ($\#m^{-3}$) of the two reacting species - for example Tritium and Deuterium (note: in these equations, the # symbol is used to denote particle numbers). The relative speed of the two species is v (ms^{-1}). Finally, σ is the fusion cross-section (m^2), this variable varies with velocity [3].

If the two species are moving at different velocities, v is given by the modulus of the relative velocity:

$$v = \left|\mathbf{v}_a - \mathbf{v}_b\right| \qquad (2)$$

Other types of fusion reactor heat a plasma to hundreds of millions of Kelvin to produce the particle velocities suitable for fusion, but instead IEC fusion uses electrostatic acceleration to produce the necessary speed.

Electrostatically accelerating Deuterium ions through 100,000 volts is straight-forward using a simple linear accelerator - similar to the electron-gun in a cathode-ray tube. The velocity of the accelerated particle is given by:

$$v = \sqrt{\frac{2eV}{m}} \qquad (3)$$

Where V is the accelerating voltage, e is the particle charge (C) and m is its mass (kg). For Deuterium accelerated through 150 keV, $v \approx 3.8 \times 10^6$ ms^{-1}.

It can be shown [1] that a beam, produced like this, made up of particles of unitary change, has an equivalent particle-density of:

$$N_b = \frac{I 6.24 \times 10^{18}}{av} \qquad (4)$$

Where a is the cross-sectional area of the beam, v is the particle velocity and I is the beam current.

Figure 1 shows the fusion cross-section of the three candidate reactions mentioned earlier (for more accurate versions of the graphs, see references [3]).

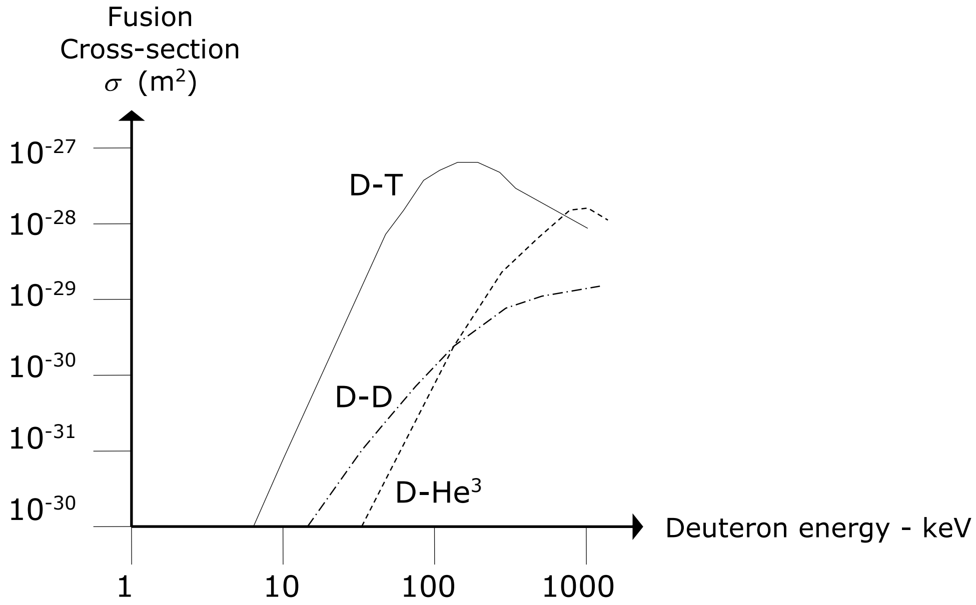

Fig. 1 The fusion cross-sections of three important fusion reactions at different energies.

The energies involved are quoted in electron-volts (eV) - this is a convenient unit to work with, when dealing with nuclear particles. An electron-volt is the energy gained by an electron as it is accelerated through a potential difference of 1 volt. It may be seen from the graph, that the D-T reaction is particularly favourable, having a cross-section (σ) of around 5×10^{-28} m^2 at just over 100 keV.

3. The basic IEC reactor

The basic IEC design was introduced by Philo Farnsworth. He was an American inventor who made several important contributions to the development of practical electronic television. Farnsworth had a great deal of experience with thermionic valves (electron-tubes in the USA). In the late 1950s he realised that it might be possible to use valve-originated technology to produce a fusion reactor, based on the idea of allowing electrostatically accelerated ions to collide with a target. He developed this idea experimentally and filed several patents describing it. Farnsworth's original idea is shown in figure 2.

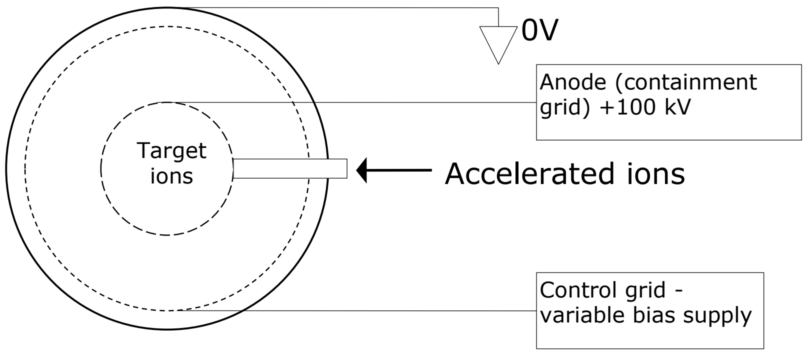

Fig. 2 Structure originally proposed by Farnsworth.

The idea behind Farnsworth's machine was that target ions would be contained in the middle of the spherical grid-anode by its strong positive potential (often considered a form of simple *ion-trap*). The anode acted as a "potential well" - in effect, the ions were repelled by the anode grid-structure on all sides and clustered in the centre of the machine. Accelerated ions would then be fired into this region of higher particle density. The control grid (not present in later designs) was used to "fine tune" the shape of the main field.

This machine and others developed from it (by various groups of researchers, including Willard H Bennett, William C Elmore, Robert L Hirsch and Robert W Bussard), represent half a century of research and development into IEC [4 - 6]. However, none of these devices, nor those made by more modern experimenters, have produced the substantial amounts of power hoped for.

4. Reconsideration of the topology – a new reactor design

In the following description of the new machine topology, some basic detail on operation has been omitted because this has been extensively covered in the previous JBIS papers [1, 2]. A stylised diagram of the reactor is shown in figure 3.

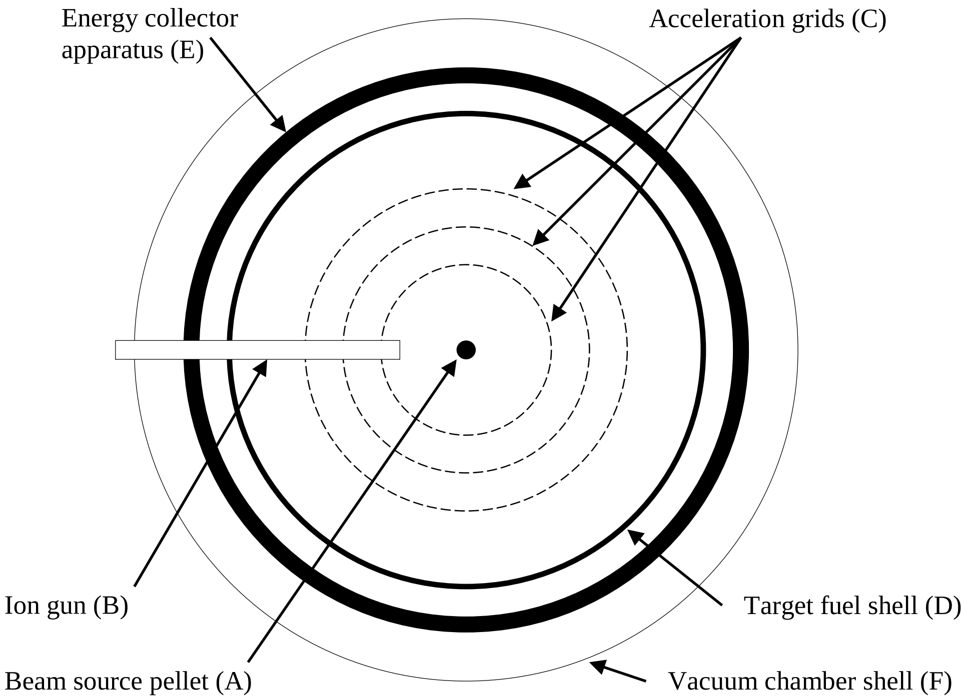

Fig. 3 A stylised cross-section of the new reactor, showing the arrangement of its internal parts.

The operation of the reactor is as follows: The accelerated particles originate in the centre of the machine as a solid pellet, a liquid drop or a gas capsule (labelled A in the figure, and referred to as the “pellet” in the following discussion). This pellet is vaporised and ionised (in this case, by an ion-beam from the ion-gun, B). The resultant ionised particles from the pellet are then accelerated outwards by a series of concentric high-voltage grids (C). These accelerated particles collide with the fuel, which is arranged as a spherical shell around the periphery of the machine (D), causing fusion and the release of energy. The energy, both waste and fusion (contained within the energetic particles, produced by the fusion reaction) is retrieved by the collector apparatus (E) surrounding the fuel. This energy-retrieval apparatus has already been outlined in detail in our previous papers [1, 2]. The whole thing is contained in an evacuated vacuum-vessel (F).

The topology of this reactor is fundamentally different to other “fusor” (IEC) type devices. In standard fusor designs (as shown in figure 2), the source particles start on the periphery of the machine and are accelerated in towards the centre by grids or an ion gun. The target fuel is located at the middle (usually in the form of ions, trapped by an electrostatic field). The reaction happens in the centre and it is here that the fusion products originate. It can be seen from the previous description that the new reactor design is the opposite of this (the beam originates in the middle and accelerates outwards) - effectively an inversion of the normal fusor design (it is turned inside-out). As will be discussed in the following sections, this potentially affords huge advantages in the operation of the machine - advantages which may make it a practical proposition for generating usable power.

5. Disadvantages of previous designs

The principle disadvantage of standard fusor designs lies in the particle density of the target and beam (the incoming accelerated particles). In most designs, the target is in the form of an ionised gas contained in an ion-trap. This means that the maximum ion density in the target is around 10^{16} to 10^{17} $\#m^{-3}$; giving, from equation 1, an achievable generated power-density of only around 30 Wm^{-3}. In a previous JBIS paper [2], it was shown that much higher particle densities (up to 10^{27} $\#m^{-3}$) could be achieved by using neutral gas, liquid or solid targets and this potentially opened the door to practical power-densities. However, this situation still leaves the issue of the beam to be addressed. The equivalent particle-density of the beam is given by equation 4. However, due to the electrostatic repulsion forces within it, most references [7] agree that only beam-densities of up to around 100 Acm^{-2}, for a constant beam (giving an equivalent particle density of around 2.01×10^{18} $\#m^{-3}$) and perhaps 10 times this for pulsed or space-charge neutralised beams are stable. Again, these low particle-densities result in low fusion power-densities which are unlikely to provide practical machines.

6. Advantages and disadvantages of the proposed design

The major advantage of the new topology, explored in this paper, is that the machine provides much higher particle densities than previous devices - particle densities which are capable of producing useful power. The most important principle of the machine's operation is that instead of beam instability due to electrostatic repulsion being a problem, the machine actually exploits it to produce much higher ion densities. This is achieved in the following way.

Because the particles to be accelerated start as a solid, liquid or neutral gas in the centre of the machine, they are already at very high density (around 10^{27} $\#m^{-3}$ in the case of a solid); this source is vaporised and ionised by a suitable means - in the case of the example above by an ion-gun. The ion-density at this point is much too high for stability - but this is advantageous because this instability causes the particles to be thrown outwards - in the direction of the target (as opposed to trying to squash them inwards into the middle, as in previous designs). The high-density ions are then accelerated *outwards* towards the target at the correct speed by the acceleration grids.

Further advantages of the new design will become clear by considering more carefully the process above, stage by stage. Firstly, the pellet is ionised. This can be done using photoionisation, strong electric fields, ion beams or by other means. The ion-gun method, shown in the previous figure, has several advantages. Firstly, if the beam is of the correct energy (several hundred keV, as shown in figure 1), then any ions missing or passing through the pellet will themselves be capable of causing fusion in the target. Secondly, even if this is not desired, any remaining energy in the beam can be reclaimed using the AC and DC systems already described (at above 80% efficiency and perhaps above 90% [1]). Hence, energy is either used in ionisation, in fusion, as kinetic energy transferred to the fuel (which will, in-turn, be reclaimed) or directly reclaimed. The approximate amount of energy required to ionise a gaseous capsule of Deuterium of volume 1 cm^3 at 1 atm of internal pressure is 23 J, for a capsule at 4 atm is 225 J and for a solid or liquid pellet of the same volume is 2240 J. This means that, with an ionising beam-density of 100 Acm^{-2}, even a solid target will be ionised in a few microseconds [8, 9] (and, of course, use several ion guns may be used).

Assisting ion-beam collision ionisation with other methods may be advantageous - especially with electrostatic fields as shown in figure 4. Here, a source of high static field (in this case, a needle-like structure) is placed in the middle of the pellet; this not only helps with ionisation by electron stripping, but also to accelerate the ions outwards, towards the target.

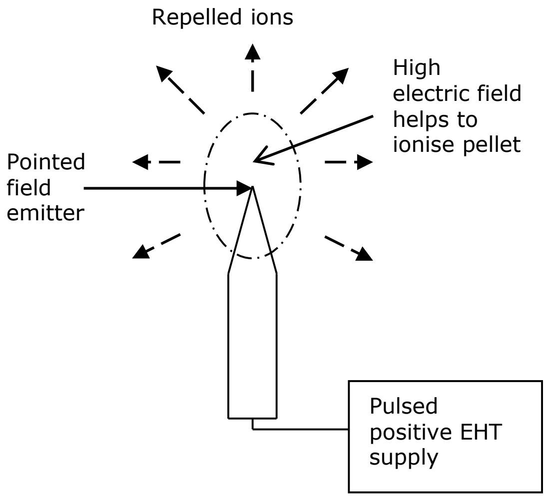

Fig. 4 A switchable source of high electrostatic field in the centre of the machine may be beneficial.

There are numerous other advantages to the topology. For example, since the particles are accelerated out of the centre of the machine, it is essentially self-cleaning and by reversing the polarity of the grids after each beam pulse, electrons and negative-ions can also be cleared from the central region (or left-over energy reclaimed via the grids). This illustrates how, by varying and switching the electrode-voltages, the machine is also more controllable than those with centrally located targets - these voltages potentially allow the exact parameters of the machine to be finely adjusted for maximum efficiency.

There may also be advantages in using a faster ionisation beam (one with a higher particle energy). This is because such a beam (at a fixed current-density) carries more energy - such energy can be transferred to several of the pellet particles to be ionised in the form of a collision cascade involving multiple atoms - meaning that the initial ionising beam can maintain its stability while transferring more energy to the pellet.

Notice also that, if the reaction products were directed through an appropriate nozzle (mechanical or electromagnetic), the basic principle works equally well as a direct propulsion unit. Likewise, the machine might be integrated into other suitable systems to power them directly without the intermediate conversion to electrical power.

Turning again to the example of a solid pellet and a 100 Acm^{-2} ionising beam. Assuming that the ions are accelerated to 150 keV (roughly optimum for the D-T reaction), by equation 3 they will be travelling at around 3.8×10^6 ms^{-1}, this means that, by the time the pellet is fully ionised, they would have formed a sphere of radius roughly 19m and a volume of 29000 m^3 - which corresponds to an accelerated particle density of 3.5×10^{22} #m^{-3}. If this collides with a solid target-shell of the type already discussed, the generated energy by equation 1 is around 2.8×10^9 J per pellet. This figure is subject to some hefty losses in terms of energy reclaim, heating and other issues [1] - nevertheless, one can see that the power available is orders of magnitude more than in other designs.

The main disadvantage of the topology lies in the practical design of the fuel shell. Making this gaseous or liquid would present interesting challenges from a purely mechanical point of view - gas would have to be contained in some sort of bubble-like structure and might be released, for example by laser action. The gas-dynamics of this process is covered in detail in a previous paper [2]. A liquid might, similarly, have to be contained in some way and both this and a solid might be vaporised (for example by laser) before the fusion reaction takes place - again, see reference [2] for further mathematical discussion of this. It might also prove necessary to ionise the target before collision - however, the nature of the machine means that this would be possible in several ways - including embedding compounds to facilitate it in the fuel and then activating these with microwave heating (as well as the other methods, already described, with regard to the pellet). If the target were liquid or solid, then the fusion products would be generated mostly on the inside of the shell and its thickness might cause inefficiency due to absorption. These issues are mostly straightforward engineering ones and should be overcome with further practical experiments and modelling.

7. Conclusions

That a new compact source of high-density power (or a way of storing and releasing such power) would revolutionise space travel is in little doubt. Such a source would enable both propulsion systems [2] and self-contained living environments. Of the possible sources of power shown in figure 5, The first and second have been explored fairly thoroughly (although there do remain areas of interest - for example, energy stored within the structure of materials - like crystal dislocations). The fourth and fifth levels remain only a theoretical possibility (level five may not exist at all) and level six is out-with our present scientific capability. This leaves the third option as the best with current technology - and especially fusion, because of the well documented issues with traditional fission (10).

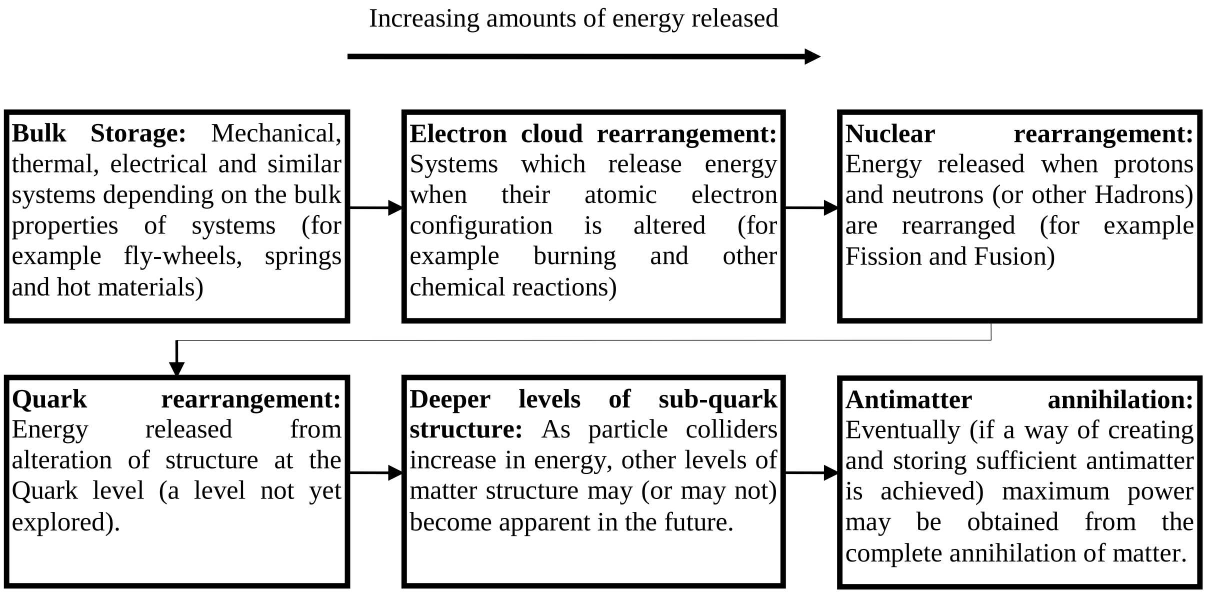

Fig. 5 A hierarchy of practical and theoretical power sources for space applications.

The reactor outlined here has several advantages over previous designs and it is hoped moves towards a practical implementation for this type of machine. These advantages all stem from the origin of the beam as a pellet *in the centre of the machine,* from which the accelerated particles originate. The electrostatic repulsion of the generated particles, which causes instability and low particle density in other devices, is exactly what makes this design work and gives it inherent superiority. In addition, there are several other possible advantages**:**

- All energy inputs, not used up in ionisation or fusion processes directly, are potentially reclaimable by our previously discussed methods [1, 2] – even waste heat caused by scattering.
- Since the particles are accelerated outwards, the centre of the machine is self-cleaning.
- The main acceleration grid can be switched to differing potentials at different times in the cycle, giving the machine inherent controllability.
- Both the accelerated particles and the fusion products are travelling towards the energy collectors, making efficiency high.
- It has possible direct propulsion applications.

This new design demonstrates that there is still plenty of room for the innovative re-imagining of this type of reactor. This re-imagining may be in its topology as in this paper or perhaps by combining it with other methods like other types of fusion or fission. Either way, this is a topic worthy of further study and more resource than is currently being afforded to it.

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