JBIS, Vol. 63, pp.192-205, 2010

A RECONSIDERATION OF ELECTROSTATICALLY ACCELERATED AND CONFINED NUCLEAR FUSION FOR SPACE APPLICATIONS

CHRISTOPHER MACLEOD AND KENNETH S. GOW
The School of Engineering, The Robert Gordon University, Schoolhill, Aberdeen AB10 1FR

Most present-day research into Nuclear Fusion concentrates on high-temperature plasmas combined with Inertial or Magnetic Confinement. However, there exists another body of less well-known work based on Electrostatic Acceleration and Confinement. The most thoroughly researched of these devices is known as the Farnsworth Fusor. This paper reviews the technique and then argues that, with development, similar technologies would be particularly suited to space-borne applications, due to their safety, simplicity and light weight. The paper then goes on to suggest several possible directions for new research into such devices which might result in a working machine.

Keywords: Nuclear fusion, fusors, fuseotron, scram, electromagnetic activation, inertial electrostatic confinement, propulsion, power, electrostatic acceleration

1. INTRODUCTION

The provision of a suitable energy supply is obviously critical to any manned exploration of space. On permanent bases, space-stations or colonies, large or heavy power-plants may be acceptable. On spacecraft, however, small and light systems are typically needed. In particular, there is a specific requirement for power sources suitable for use in vehicles designed to reach orbit using innovative propulsion concepts.

Such concepts are required, in the view of many commentators, because of the expense, infrastructure, logistical and safety issues associated with conventional rocketry. These limitations mean that such technology may never offer cheap mass-access to space. Aside from this, any such rocket will have to carry its oxidiser on-board, limiting the smallest size of effective vehicle.

The traditional alternatives to rocketry are air-breathing engines like Scramjets. However, these too have failed to live up to their initial promise. This is despite forty years of development and recent investment in tests like HyShot, HyCause, X-43A and X-51A. Their failure is easy to understand - to achieve 100 MW of power (comparable to a large turbojet), around 20 m^3 of air-hydrogen mixture at sea-level pressure needs to be burnt each second. To release all of its energy, the hydrogen and air must be mixed stoichiometrically at the molecular level [1]. However, even good turbulent mixing is not enough to achieve the required results - only molecular diffusion can mix to this degree. Given that diffusion is governed by Fick's law and that the maximum diffusion coefficient of hydrogen into air is around 2.6 $cm^2\ s^{-1}$ [2] (just below its auto-ignition temperature with air, at a typical Scramjet combustor pressure [3]), then the air and hydrogen must be turbulently mixed over the entire volume to a contact dimension of only a few millimetres if diffusion is going to act within the time available for complete mixing at high Mach [4]. This analysis makes it seem very unlikely indeed that a viable Scramjet can be achieved practically.

Should a low-weight and powerful source of energy become available, however, many other options for trans-atmospheric propulsion are then feasible. These include laser driven systems [5, 6]; heating by electromagnetic activation [7, 8] (or other electrical methods of heating); using plasmas and MHD [9, 10]; forced non-equilibrium reactions (for example involving nitrogen [11]), coupling to natural or induced electrostatic, magnetic or electromagnetic fields and others involving various combinations of these. Many of these possibilities have yet to be fully explored theoretically.

Any detailed study of the energy-density of possible power-sources immediately presents three options. These are: firstly, the direct conversion of matter into energy by annihilation; secondly, nuclear-fission and finally, nuclear fusion. The first of these is presently beyond our technical capabilities; and whilst the second is currently feasible, it has obvious and well-known major drawbacks – for example, the production of dangerous, long half-life heavy isotopes and fission products which need extensive shielding and cumbersome moderation systems. This leaves the option of fusion.

Most current fusion research concentrates on inertially or magnetically confined hot plasmas. The new ITER reactor at Cadarache in France is a good example of the latter approach. However, it is being built at a cost of around £4 billion and will weigh approximately 23,000 tons. Typical inertial systems are similar - the well-known NIF facility cost around £2.5 billion and its reaction-chamber alone weighs 130 tonnes (a figure for the weight of the huge optical system is not available, but it certainly weighs many thousands of tons). So, although there are suggestions for the development of such technology, it will have to improve dramatically for use in a trans-atmospheric craft [12, 13].

There is though, another approach to building a fusion reactor. This relies on accelerating and confining the fusion components by electrostatic means, and has the potential to deliver a light-weight and powerful energy source, suitable for use in spacecraft. In recent years it has been rather neglected, as attention was focused on the alternatives. However, the time is now ripe for a reappraisal, due to new developments in several areas of science which may make it much more feasible.

This paper reviews the existing science on electrostatic acceleration and confinement at the conceptual level and makes suggestions for new approaches based on recent developments in other fields and on the authors' own ideas. It is not meant to outline a working system but to act as a resource for researchers that can point the way to further experiments and simulations which might result in an operational machine. These results could be considered in a future systems-analysis that might lead to a practical spacecraft design.

2. BASIC PRINCIPLES

The governing equation of nuclear fusion is:

$$R = \sigma N_a N_b v \tag{1}$$

Where R is the number of fusions in a given volume of space, per unit time (sometimes referred to as the Reaction-Rate Density), 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, that 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 [15].

If the two species are moving at different velocities - for example in the case of a beam of Deuterium impinging on a beam of Tritium, then v is given by the modulus of the relative velocity:

$$v = |\mathbf{v}_a - \mathbf{v}_b| \tag{2}$$

Similarly, if both species are the same (for example two beams of Deuterium), then $N_a N_b$ can be replaced by a single number. For example, if $N_a = N_b$ each contributing to half of the total number-density, N (that is $N_a = N_b = 0.5N$):

$$R = \frac{1}{4}\sigma N^2 v \tag{3}$$

An extremely important observation may be made about equation 1, which is: *It does not contain any temperature term*. Yet both inertial and magnetic confinement schemes depend on heating plasmas to temperatures in excess of 100 million Kelvin. This is because the average particle velocity in a gas depends on its temperature. So high temperature is used to obtain the necessary particle velocities. The average velocity of a particle in a Maxwell-distributed system, at temperature T, is given by:

$$\bar{v} = \sqrt{\frac{8kT}{m\pi}}$$

Where m is the particle mass (kg) and k is Boltzmann's constant. Note that this formula only holds true for some plasmas, depending on the nature of collisions between the constituent particles.

Heating the plasma like this has many disadvantages. The amount of energy required is enormous and the resulting heat-loss is also huge and difficult to reclaim [14-16]. Also, keeping the plasma concentrated in one place is difficult and requires large magnetic or other force-fields - exactly because it is highly energised and therefore has high particle velocities. The containment problem may be equated to trying to squeeze a balloon to a small size by excerpting pressure on the outside - the balloon will try and escape by herniating through any small gap available (in the case of practical systems, through gaps in the magnetic field, immediately dissipating its energy) [16]. In the gravitational-confinement system of a star, this problem is avoided because the force is much higher and because gravity acts from the centre of mass, effectively "sucking" the plasma into the middle, rather then "squeezing" it from the outside. Heating the plasma sufficiently, and effectively containing it, are some of the more serious problems with hot-plasma systems, but by no-means the only ones.

However, there is another approach - which is the topic of this discussion. Looking back at equation 1, a beam of ions of species a could be electrostatically accelerated, to the required velocity v, and then allowed to collide with stationary particles of species b. Alternatively, a beam of species a can be made to collide with a beam of species b. These two ideas form the basis of the systems discussed in this paper.

Three possible fusion reactions [15], which might be used in such a system are: Deuterium-Tritium (notated as D-T), Deuterium-Deuterium (D-D) or Deuterium-Helium 3 (D-He^3):

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

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

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

Where p is a hydrogen nucleus (a proton), α is an alpha particle (a helium nucleus) and n is a neutron. As will be discussed later, the presence of the neutron makes the D-D and D-T reactions (which are termed *neutronic*) more problematic to extract energy from. Figure 1, shows the fusion cross-section for these three reactions (for more accurate versions of the graphs, see references [14-16]).

The energies involved are quoted in electron-volts (eV) - because 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 the most favourable, having a cross-section (σ) of around 5×10^{-28} m^2 at just over 100 keV. Electrostatically accelerating deuterium ions through 100,000 volts is straight-forward using a simple linear accelerator - a similar idea to the electron-gun in a cathode-ray tube. The velocity of the accelerated particle is given by:

$$v = \sqrt{\frac{2eV}{m}} \tag{4}$$

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

The problem with the system outlined above is that only a small proportion of the accelerated particles fuse with the

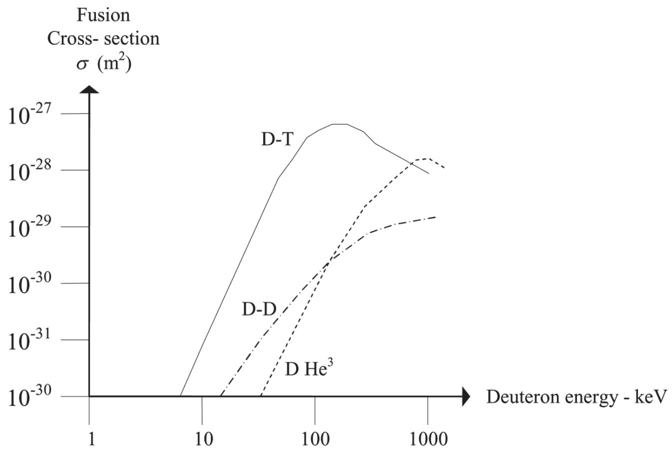

Fig. 1 The fusion cross-sections of three important fusion reactions at different energies.

target; most of them either pass straight through, are scattered (effectively losing energy to heat) or lose energy in other ways (for example by ionising the target).

Since each particle takes approximately 150 keV to accelerate (ignoring other losses) and the yield from the D-T reaction is 17.6 MeV, then for break-even, one in every 117 particles must fuse. Of course there are other large losses involved in a practical system - particularly in retrieving the energy from the fusion products. Taking a typical heat-engine efficiency of 30% for this, then one in every 35 particles would need to fuse for break-even. Table 1 shows the number of fusions per second required in order to achieve various gross power-outputs - that is the raw power-output before losses are considered (as previously noted, 100 MW is similar to the output of a large turbojet, 5 MW is representative of a small aircraft engine).

Many of the loss mechanisms alluded to above are quite small - for example the ionisation energy of Deuterium is only around 15eV and issues like Bremsstrahlung radiation, which are important in magnetic confinement, are generally secondary in the type of reactors discussed here. However, scattering is a larger and more complex problem.

There are several different modes of scattering; however, at the energies of interest here, the most important is Coulomb or Rutherford Scattering [15]. This occurs because of electrostatic repulsion between two particles (in these examples, two positive ions). Figure 2a shows the effect for a single particle, Fig. 2b shows the typical paths taken by many incident particles.

In Fig. 2a, only the path of the incoming particle is shown, obviously the second particle will also be scattered. The incoming particle is deflected through an angle θ by the (like) electrostatic charge on the second particle. The variable r is the distance between the incoming particle's initial trajectory and a line through the system's centre of mass. The scattering angle [15] is related to the system parameters by the equation:

$$\tan\left(\frac{\theta}{2}\right) = \frac{q_1 q_2}{4\pi\varepsilon_0 m_r v^2 r} \tag{5}$$

Where q_1 and q_2 are the charges of the two particles, ε_0 is permittivity of free space and v is the relative speed, given in equation 2. The variable m_r is the relative mass of the system, given by:

TABLE 1: *The Rate of Fusion Reactions Required to Produce Particular Gross Power Outputs.*

Power released (MW)	Number of reactions per second (#s^{-1})
1000	3.6×10^{20}
500	1.8×10^{20}
200	7.1×10^{19}
100	3.6×10^{19}
50	1.8×10^{19}
10	3.6×10^{18}
5	1.8×10^{18}
1	3.6×10^{17}

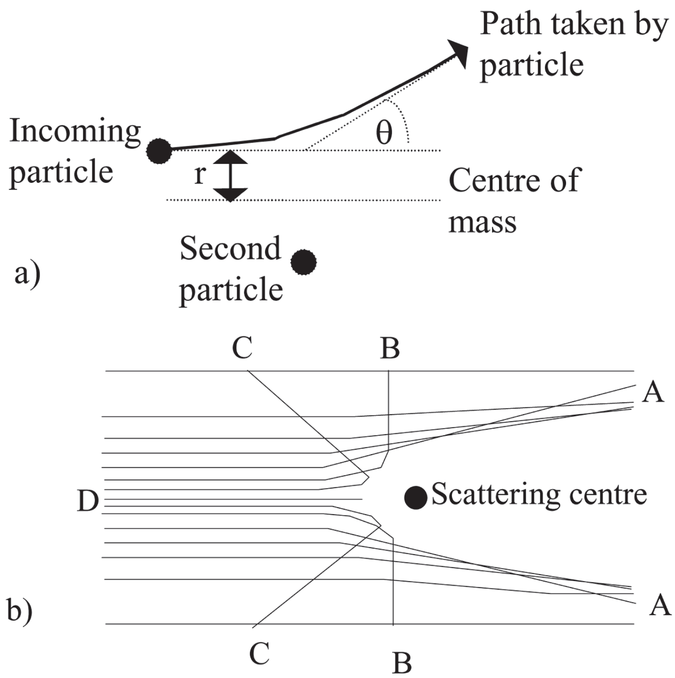

Fig. 2 Coulomb scattering of two particles.

$$m_r = \frac{m_1 m_2}{m_1 + m_2}$$

The typical paths taken by particles at different initial distances from the centre line is shown qualitatively in Fig. 2b. From this it can be seen that most particles end up at points near A, having only been deflected slightly. A few end up at B, and fewer still at C. A direct hit, which doesn't fuse (a rare occurrence) will be reflected straight back to D.

The exact formulation of this process for a particular system is complex because it depends on the density of particles in the target and also on their state - as a plasma (in which case, some of their charge is "masked" by the electrons surrounding them), neutral atoms or an ion-gas without electrons. This will be discussed in later sections.

It is possible to write down a formula like that of equation 1 for scattering and define a "scattering cross-section" in a similar way to the fusion cross-section already discussed. Figure 3 shows a graph of this for the D-T reaction, plotted on the same scale as the fusion cross-section.

One can immediately see that a particle has one or two

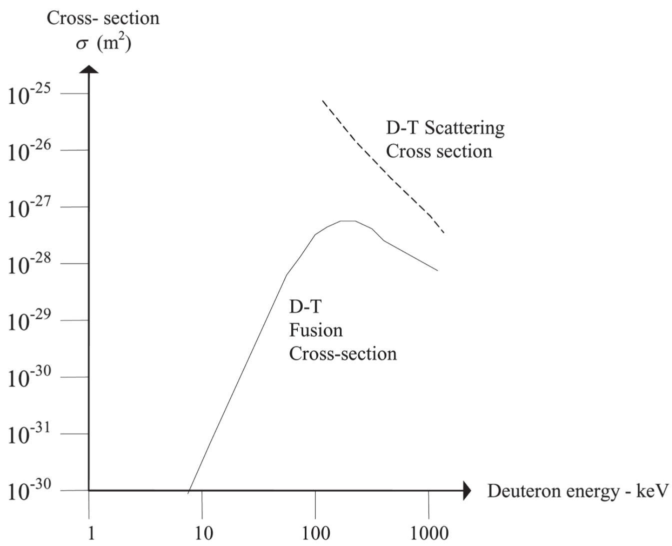

Fig. 3 Fusion cross-section and scattering cross-section plotted on the same scale.

magnitudes more chance of been scattered then fusing. So, as a crude first approximation, it can be said that what is not fused or passes straight through, is scattered [15].

The energy resulting from the fusion reactions described above is the kinetic energy of the product particles. In most designs this is converted into useful thermal energy by a Lithium casing surrounding the reaction chamber [14]. Radiation and charged particles are absorbed by this (or the chamber walls with which it is in contact), heat results, and this is retrieved using a conventional heat-exchanger in the Lithium. In neutronic reactions, much of the energy is often carried by the neutrons themselves. These are absorbed by the lithium to produce useful tritium and helium. The kinetic energy of the products is also absorbed by the casing to again produce heat. This reaction [16] is:

$$Li^6 + n \rightarrow T + He^4 + 4.8 \text{ MeV}$$

The extra complexity introduced by the presence of neutrons along with their inherent safety issues and the inefficiency of traditional heat exchange has led some to consider *aneutronic* reactions. There are several of these - however, the front runners are:

$$B^{11} + p \rightarrow 3He^4 + 8.7 \text{ MeV}$$

and

$$Li^7 + p \rightarrow 2He^4 + 17.2 \text{ MeV}$$

The Boron reaction was particularly favoured by Bussard [12, 13] and the availability of charged particles allows other methods of energy collection which will be discussed later. Some of these reactions (including the Boron one) are not technically fusion, but should strictly be classed as fission. This raises the possibility that any exothermic particle reaction should be considered a candidate [16].

The ideas and problems highlighted in this section will form the basis for discussion in the later sections, and practical solutions will subsequently be suggested. However, firstly, the basic machine originally proposed to exploit this type of reaction will be discussed in section 3.

3. A SHORT HISTORY OF INERTIAL ELECTROSTATIC CONFINEMENT

Philo T Farnsworth (1906 - 1971) 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, as described in the previous section. He developed this idea experimentally and filed several patents describing it (US patents, numbers: 3,258,402; 3,386,883 and 3,664,920). During this early period, a related patent was also filed by pioneering plasma physicist Willard H Bennett (US patent 3,120,475), and William C Elmore, James L Tuck and Kenneth M Watson of Los-Alamos Laboratory published the first scientific paper describing the theory of a similar machine [17]. The operating principle of these devices became known as *Inertial-Electrostatic Confinement* or IEC. Farnsworth's original idea is shown in Fig. 4.

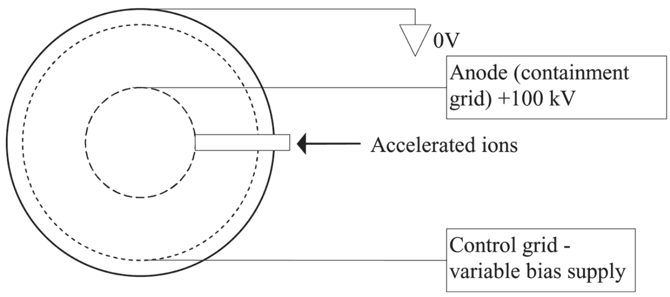

Fig. 4 Structure originally proposed by Farnsworth.

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 high particle density. The control grid (which is not present in the Elmore design) was used to "fine tune" the shape of the main field. The detailed mathematics of the electric fields required had been worked out in earlier papers on valves with spherical geometries [18].

One can immediately see that this basic topology would be unlikely to work well, given the losses from scattering described in the last section. Elmore, Tuck and Watson had also pointed out, in their paper, that it was very difficult to achieve the necessary stable ion-density in the middle of such a structure.

The next major development was the arrival, at the Farnsworth laboratory (then part of ITT), of Robert L Hirsch (who would later direct the whole US fusion energy program). Hirsch proposed several improvements to the Farnsworth machine (US patents, numbers: 3,530,036; 3,530,497; 3,533,910 and 3,655,508) and published a paper describing his work [19]. This paper is also a good source of reference for some of the earlier theoretical work on electrode configurations.

Hirsch experimented with several different configurations. In his main design, the machine is initially filled with gas. This is ionised at the edge of the structure by corona discharge. In the centre, instead of a positive spherical grid (the anode), there was a negatively charged one. The positive ions from the edge are accelerated towards this grid, passing though it (because of its open structure) and into the middle of the machine, here they may fuse with other ions - so dispensing with the need for ion accelerators. If they should pass through the middle, they will be slowed down on exit from the grid structure and re-accelerated back for a further pass - this continues until they have fused.

Such machines produced plenty of neutrons, but the losses were always much greater than the energy generated. At the same time, the grid was seen to glow due to ion collisions. This led to the supposition that the main loss mechanism was this collision with the grid. While, this might be significant, it is more likely that the constant deceleration and then re-acceleration of the ions by the grid uses up supply energy. It will be shown in the following sections how methods can be introduced to recover energy from the “used” ions, and thus markedly improve the efficiency of the process.

The next important scientist to take an interest in the technique was Robert W Bussard, who was most famous for the “Bussard Ramjet” conception of an interstellar drive. Bussard immediately saw the possible space-borne applications of IEC and set about trying to tackle the loss problem. His solution was to stop the ions colliding with the grid by using a magnetic field to guide them past it. This field was generated by coils integrated into the grid structure. This idea is known as the *Polywell* concept. Bussard received funding from US naval research for the project and produced several patents (US patents, numbers 4,826,646 and 5,160,695) and papers [20-23].

Unfortunately, Bussard died in 2007 before he finished his research. Two articles published in *Analog Magazine* by Tom Ligon describe his work [12, 13]. These papers (which are also available on-line) also give a excellent non-technical overview of the whole IEC enterprise and its relationship to space-travel, as well as an interesting critique of main-stream research into fusion.

Several major universities have also had long-standing involvement with IEC research and development. These include Brigham-Young, Pennsylvania-State and Illinois. The work at Illinois is led by George Miley, has received several grants, and is considered particularly important [24]. It has resulted in the production of a commercial neutron source based on the IEC concept and is still on-going [25]. Another important contribution to the technology is a series of publications by Todd H Rider at MIT [26-28]. These establish the limitations of IEC and, in particular, point out that a fundamental constraint on a system of this type is imposed by target ions heating up through collision and gaining enough energy to escape the ion-trap. This aspect will be discussed in later sections of the paper.

Finally, it should be mentioned that there are many independent experimenters and inventors working on machines based on Farnsworth, Elmore, Hirsch and Bussard topologies. Enthusiasts call these designs *Fusors*. Discussion groups and individuals abound on internet sites (a good example of this is the site fusor.net). Also, several independent companies have been formed to try and implement similar technologies (for example, Crossfire fusor). Some papers of interest by other authors are given in the references [29-32].

It should be noted that since interest started in the late 1950s, technology has moved on in several related disciplines. The next sections reappraise the method and suggest ways in which it might be improved and how new ideas or techniques from other fields can be incorporated into it and perhaps make a working machine.

4. REAPPRAISAL AND REDESIGN

To begin a reappraisal of the machines described above, two main cases are discussed below. The first of these is based on the original Farnsworth idea of using an accelerated beam which is focused onto a static target. The other interesting case is that of two colliding beams. A third case is that of the Hirsch-type machine, which uses grids to symmetrically accelerate ions from all sides onto the target. This is described in detail in the literature [19]. There are some doubts as to the accuracy of the predictions about this design, as explained in the next section.

To start the discussion, consider what equation 1 suggests about the optimum conditions for fusion in a Farnsworth-like device. Firstly, in order to optimise the chance of fusion in a single pass, the target ion-cloud should be dense, and the path-length through it long. Since scattering at large angles results in too much loss of kinetic energy for subsequent fusion, particles scattered at such angles should leave the active area quickly before they interact further (and increase the heat in the target). All this suggests a sausage-shaped device as shown in Fig. 5, with the cross-section of the target slightly greater than that of the beam.

Because such a device uses an accelerated beam to impinge on a cold cloud of particles, it might be generally termed an *Accelerated Beam, Cold Target* or ABCT approach.

The important components of this type of architecture can be considered one by one. Ion sources consist of a supply of atoms which are ionised by heat, electromagnetic radiation or radioactive means [33]. These are then accelerated by an electrostatic potential (in the case of D-T reaction, by around 150 kV). There may also be other elements to focus and control the beam. This is shown diagramatically in Fig. 6.

Such ion guns are available in a range of scales, from devices which supply tiny ion-currents, to the Deuterium ion-source at the heart of the ITER neutral beam heating arrangement [34]; this supplies a 40A ion current at a particle energy of 1MeV.

The ion-trap which contains the target particles might be of the spherical grid type proposed by Farnsworth; however, more recent work has produced more efficient designs which can contain higher ion densities - the Paul and Penning type traps [36]. These, however, have the disadvantage of not having an open structure in their basic form. The capacity of such traps is discussed in the next section. One area which has not yet been fully researched is the use of Metamaterials [35] in the design of traps. These are structures designed using sandwiches of materials with different relative permittivities or permeabilities, which allow electric or magnetic fields to be manipulated into predetermined shapes.

The particles in the target do not have to be ions, they could be in the form of a plasma contained by a magnetic field - the most common linear magnetic device of a similar shape to that shown in Fig. 5 is called a mirror machine [40]. The particles could also be atoms. However, these are difficult to contain in a restricted area - and this is necessary to allow fusion products

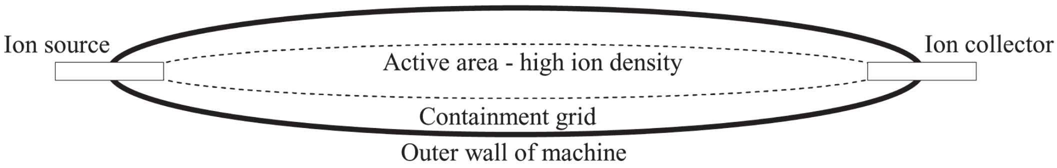

Fig. 5 A generalised Farnsworth-like reactor.

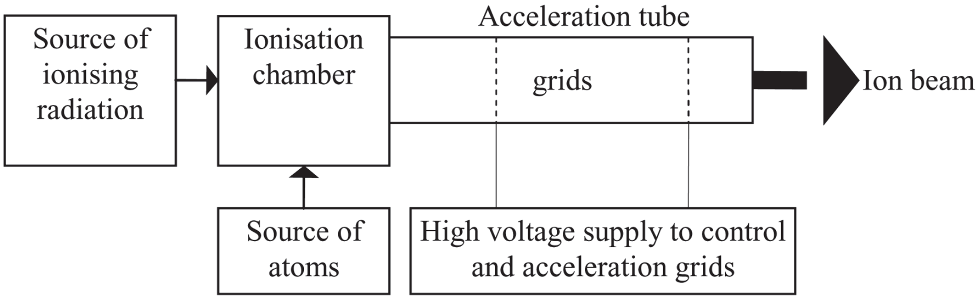

Fig. 6 An source of accelerated ions, sometimes termed an ion "gun."

and redundant beam particles to escape without heating the target cloud. For reasons which will become apparent in the next section, this is an interesting and important issue.

Using ions does have several advantages. For example, energy is not lost in ionisation (as it would be in atoms) and there is no electron scattering of the incident beam (as there is in a plasma). Although these mechanisms introduce fairly small losses (as stated earlier, the ionisation energy of Deuterium is only 13 eV), they mean that the energy balance between the various approaches is slightly different.

Consider now the other system of interest - two (or more) colliding beams [15] as shown in Fig. 7.

This system might be termed *Accelerated Beam, Accelerated Beam* or ABAB. The components used are the same as described above without the ion trap. An expression for the particle density in an ion beam is derived in the next section. The previous comments on the optimum shape of the reaction-site also apply here. The volume of this can be found simply (this derivation may also be applied to the ABCT system). Consider the situation shown in Fig. 8.

Here there are two beams, a smaller one of diameter D_1 intersecting a larger one of diameter D_2 at an angle of θ. The length over which they intersect is labelled *L*. Now, from basic trigonometry:

$$\sin(180-\theta)=\frac{D_2}{L}$$

This can be rearranged for *L*, and since sin (180 - θ) = sin θ, then:

$$L=\frac{D_2}{\sin\theta}$$

The volume of the intersection is this multiplied by the cross-sectional area of the smaller beam. If the latter beam is circular, then, the volume *Vol* is:

$$Vol=\frac{\pi D_1^2 D_2}{4\sin\theta} \qquad (6)$$

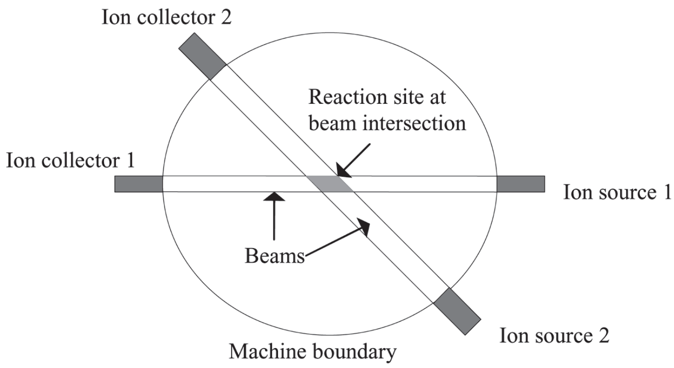

Fig. 7 Two colliding beams in a machine.

The ABAB topology has some possible advantages over ABCT, which will be discussed later.

4.1 Particle Density Issues

Given the size and available power from a typical gas-turbine, it would seem reasonable to expect a power-density of around 1 MW (or greater) per cubic-metre of space from a practical fusion reactor designed for a trans-atmospheric spaceplane. Taking equation 3 as a starting point, the terms *v* and σ are constant for the maximum reaction rate of a fusion reaction. In the case of the D-T reaction, *v* is approximately 3.8×10^6 ms^{-1} and σ is 5×10^{-28} m^2 and so *v*σ is 1.9×10^{-21} m^3 s^{-1}.

The data from Table 1 shows the number of fusion reactions required per second for 1MW is 3.6×10^{17} consequently, using equation 3:

$$3.6\times10^{17}=\frac{1}{4}1.9\times10^{-21}N^2$$

and

$$\therefore N^2\approx 7.5\times10^{38}$$

or

$$N\approx 2.7\times10^{19}\ \#\text{m}^{-3}$$

So, the number-density of both reaction components multi-

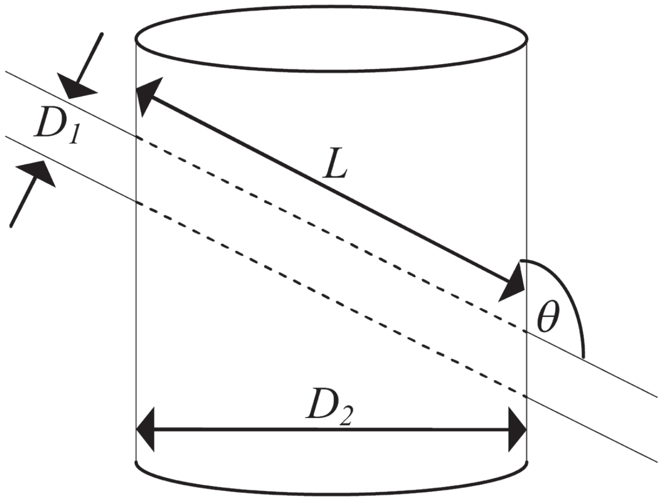

Fig. 8 A small beam passing through a larger one.

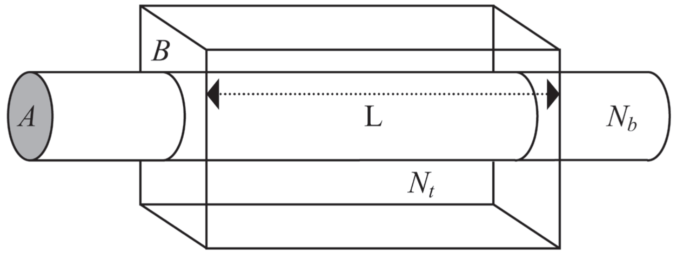

Fig. 9 An ion beam of cross sectional area *A* and length *L*.

plied together would have to be at least 7.5 × 10^{38} #m^{-3} and if the components had equal number-densities, these would have to be at least 2.7 × 10^{19} #m^{-3}.

A problem arises when considering how these densities might be obtained. It has already been noted [17] that Elmore and his colleagues calculated theoretically that the central ion trap could not attain the necessary ion-densities in a stable configuration. This problem can be elucidated clearly by considering more sophisticated traps.

As mentioned in the previous section, modern ion-traps are generally based on either the Penning or Paul designs [36]. These are available in a variety of different novel configurations [37]. Such traps are more efficient than Farnsworth's spherical grid system. A substantial amount of work has been done on their maximum practical capacity [38, 39], and this can be shown to be around 10^{16} #m^{-3} to 10^{17} #m^{-3}. Magnetic confinement systems of a similar size are limited to around 10^{18} #m^{-3} [40]. This information, rounded to the nearest order of magnitude, is summarised in Table 2.

To extend the discussion to ion beams, an expression for the particle density in a ion beam can be simply derived. First consider a beam of cross-sectional area *A* as shown in Fig. 9.

Typically, this beam will pass through the ion-cloud in the trap *B*. The length of the ion-cloud is *L*, the particle number-density of the ion-cloud is N_t and that of the beam is N_b.

Assuming that the beam enters the ion cloud at time $t = 0$ and passes out at time $t = \Delta t$, then the volume swept by the beam in this time is:

$$vol = AV\Delta t$$

where *V* is the particle velocity (given by equation 4). The number of particles in the swept volume is:

$$\# = AV\Delta t N_b$$

Since one coulomb of ions of unity charge is 6.24 × 10^{18} particles, then the number of coulombs of charge in the volume is:

$$C = \frac{AV\Delta t N_b}{6.24\times 10^{18}}$$

Finally, since the current *I* is charge per unit time:

$$N_b = \frac{I 6.24\times 10^{18}}{AV}$$

This is a useful form of the equation, because the beam-current is usually fairly easy to measure or calculate.

Maximum equilibrium beam-currents can be calculated from Child-Langmuir relationships or measured directly. In current practical systems, these are in the order of 100 A per cm^2 [41]. Using the relationship developed above, this corresponds to a

TABLE 2: *Table of Available Densities (Rounded to Nearest Order of Magnitude) and Resulting Fusion Power Densities.*

R (#$m^{-3}s^{-1}$)	N (#m^{-3})	N (#cm^{-3})	N^2 (#m^{-3})^2	Power density	Comments
10^{7}	10^{14}	10^{8}	10^{28}	30 mW/m^3	
10^{9}	10^{15}	10^{9}	10^{30}	3 mW/m^3	100mA deuterium beam
10^{11}	10^{16}	10^{10}	10^{32}	0.3 W/m^3	
10^{13}	10^{17}	10^{11}	10^{34}	30 W/m^3	Ion traps
10^{15}	10^{18}	10^{12}	10^{36}	3 kW/m^3	Small mirror machine
10^{17}	10^{19}	10^{13}	10^{38}	0.3 MW/m^3	
10^{19}	10^{20}	10^{14}	10^{40}	30 MW/m^3	
10^{21}	10^{21}	10^{15}	10^{42}	3 GW/m^3	Maximum magnetically confined density
10^{23}	10^{22}	10^{16}	10^{44}	300 GW/m^3	
10^{29}	10^{25}	10^{19}	10^{50}	300000 TW/m^3	Density of air at sea level

particle density of approximately 1.5×10^{18} #m^{-3}, which is similar to the typical density available in a small magnetic-confinement device.

It should be noted at this stage that several authors from Hirsch onwards [19] have argued that much higher reaction rates are achievable using their spherical grided acceleration systems - this is because the ion current is impinging on the reaction area symmetrically from all sides and therefore the initial surrounding ion-density is lower than the theoretical maximum limits. However, measured reaction rates do not bear this out - the claimed neutron generation rates of one billion per second [19] only correspond to a developed power of about 3mW!

At first sight, this would appear to restrict the available power density to a few kilowatts per cubic metre, and fall an order of magnitude short of the densities required to achieve the previously stated goal of a megawatt per cubic metre. However, although the figures quoted above are for beams of pulsed systems, the figures for traps are for systems in *equilibrium* (note the Elmore statement quoted above: that the required ion density is probably not attainable in a *stable* system). If systems are allowed to operate for short durations, then the equilibrium densities may be exceeded by orders of magnitude [42]. It might seem at first sight that pulsed operation would be a disadvantage - however, as shown in the next section it might be exactly what is required for efficient energy reclamation.

The attainment of a sufficient particle density might also be achieved by other means - one of the most important of which is the use of neutral beams. These can be added together to achieve much higher densities than ionised beams. They are generated by accelerating an ion beam in the normal way, and then adding electrons (or other particles of opposite charge) to produce neutral atoms [41], as shown in Fig. 10. It might also be possible to produce stationary neutral clouds in a similar way. One topology for a machine using neutral beams in this way is shown in Fig. 11.

In this scheme, the neutral beams must have enough energy to maintain their integrity without excessive divergence, until they enter the reaction area. The beams would probably be pulsed by electrical or mechanical means for reasons explained in the next section. One can also envisage a neutral particle version of the Hirsch machine, where the accelerated ions pass through a neutralising region (for example, an electrostatically retained electron-cloud), before converging in the centre of the machine. Other options like fixing the target in solid, liquid or encapsulated form (for example, as frozen Deuterium pellets or as a suitable compound) have not yet been examined theoretically.

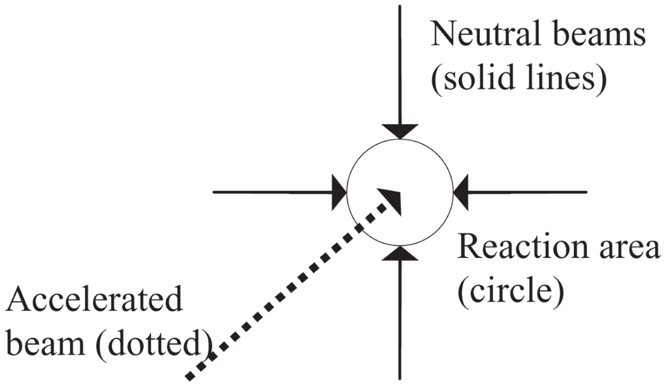

Fig. 11 A machine adding neutral beams together to produce a large target particle density.

So, although achieving the necessary ion density in the device to return a reasonable power output is a practical challenge, there are several promising lines of enquiry which look likely to lead to the attainment of the aim.

4.2 Energy Recovery

Up until this point it has been assumed (with the exception of the Hirsch device, which will be discussed later) that the remaining energy of the accelerated beam is lost after it has passed through the target (or is only collected by a low-efficiency heat-exchanger). However, the principle argument of this paper is that this need not be the case - there are ways to efficiently collect this energy. These result in novel machine topologies, that have not been addressed in other work, and which are discussed below. First, however, the energy balance of the system will be considered, assuming that such beam-energy can be reclaimed.

Near the beginning of the paper it was stated that, assuming no losses, one in every 117 D-T accelerated particles had to result in a successful fusion reaction in order for the system to break-even. However, what if energy could be reclaimed from the used beam with an efficiency of (say) 90%? If this were the case, and it is assumed that the fusion products are also collected at 90% efficiency, then only one in around 1070 particles needs to be successful for break-even. Table 3 shows how different energy reclaim efficiencies would effect the number of required fusions, assuming both beam-energy and fusion product-energy are reclaimed with the same efficiency in a D-T reaction. From the table, it is fairly easy to see that energy reclaim is an improvement over Farnsworth's basic device as long as its efficiency is greater than 50%.

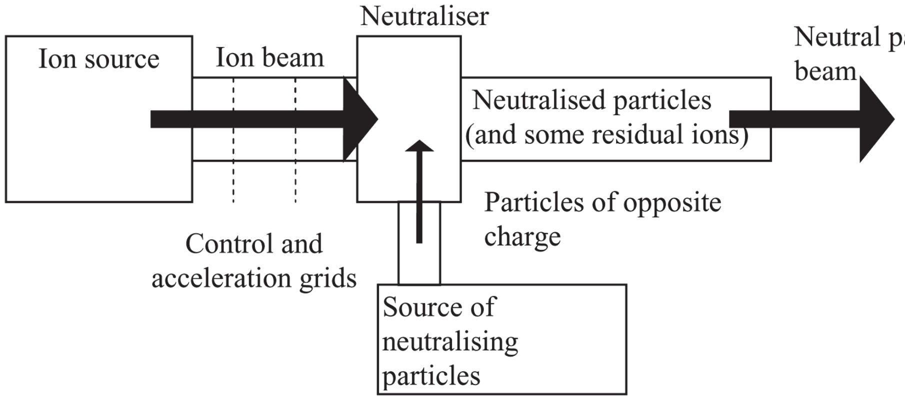

Fig. 10 A neutral beam generator.

TABLE 3: *Number of Beam-Particles Required per Fusion for Break-Even With Energy Reclaim.*

Energy reclaim efficency (%)	Reclaimed fusion-product energy per particle (MeV)	Reclaimed beam-energy per particle (keV)	Number of accelerated particles per fusion required for break-even
90	16.0	15	1068
80	14.2	30	473
70	12.5	45	278
60	10.7	60	178
50	8.9	75	119
40	7.1	90	79
30	5.3	105	50

There are two ways to reclaim this energy - a DC approach and an AC approach. For maximum effect, both of these assume that all or a substantial amount of the reaction energy is carried by charged particles. In other words, the reaction is or is approaching aneutronic. It is possible to use these techniques simply to capture beam energies and rely on the lithium blanket approach to capture product energy; however, this seems rather wasteful and inelegant.

Taking the DC approach first, this was first outlined in detail by Richard Post in 1969 as a method of reclaiming energy from mirror machines [43]. His approach has since been proposed by many other researchers [44] and is even used in some high-power microwave valves to improve efficiency [45]. The idea is shown in Fig. 12.

Each pair of plates is held at a static potential, where $V_1 < V_2 < V_3 < V_4$. As the ion travels along the tube it gets slowed by the field between the plates until it is finally collected by the plate at the corresponding potential to its kinetic energy. It there appears as a unit of current flowing at this potential. For example, if a deuterium ion accelerated to 100 kV is collected by the plate of the same potential it would appear as a tiny current flowing at that potential.

The energy converters, illustrated in the figure, are rectifiers and inverters which convert the collected energy into a common voltage which can then be fed into a load, the return of which is the electrons originally liberated from the beam atoms.

Post demonstrated this system practically with a 96% energy conversion efficiency. He also showed [43] that the efficiency was approximately:

$$\eta \approx 1 - \frac{1}{N}$$

Where N is the number of collector electrodes.

This discussion helps to shed light on the dynamics of the Hirsch device. Here, it was assumed that when an ion missed its target it gave up its energy to the grid on its outwards journey from the active area. However, the discussion above shows that this would only be efficient if all the ions retained their initial energy, were collected by a grid of a corresponding potential, which then re-emitted them. The original Hirsch configuration was too primitive to achieve this efficiently.

Obviously the system shown in Fig. 12 is also rather unsuitable as a collection device as it does not collect ions scattered at large angles, or the fusion products, which can be scattered at any angle. One might imagine a ABCT configuration similar to the one shown in Fig. 13, where the collector surrounds the active area and collects all the resultant particles. However, this has several obvious drawbacks (for example the need for a megavolt grid to collect the fusion products).

For a system like that shown in Fig. 13 to work, it is likely that the ion beam would be pulsed, and that once the reaction in the centre of the device took place, the collector grids would

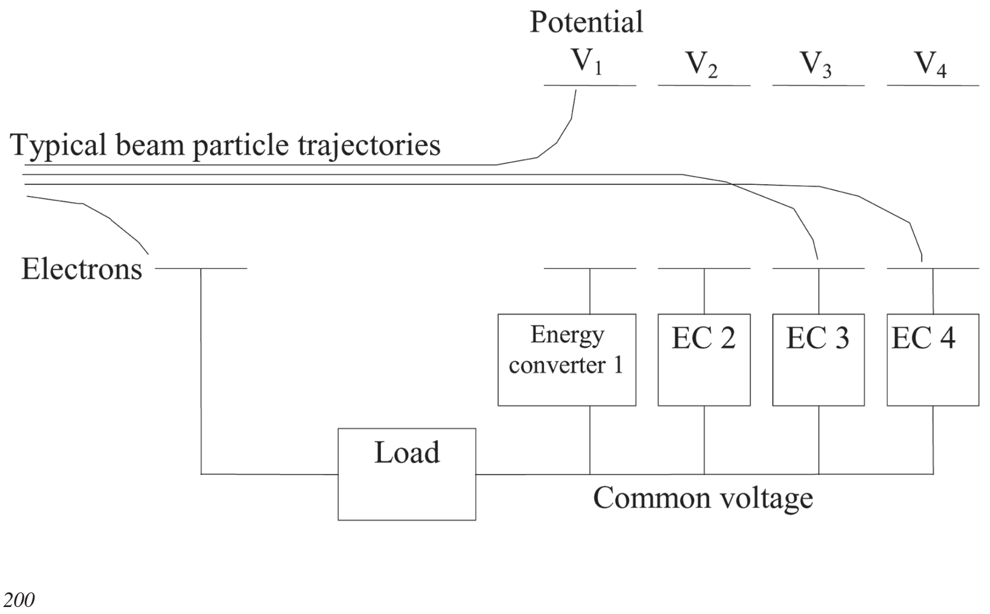

Fig. 12 DC energy reclaim from a ion beam.

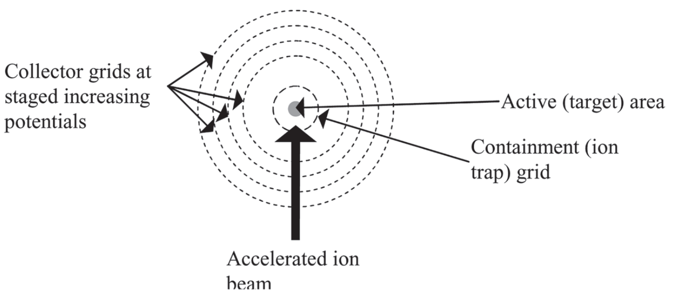

Fig. 13 A particle collector configured in a spherical geometry.

retrieve energy from the scattered and fused particles. Indeed, as discussed in the last section, a pulsed system is probably necessary anyway to achieve the required particle densities for useful power outputs. However, using pulsed or modulated beams opens up another, arguably more interesting, possibility for energy recovery, outlined below.

This second system for energy reclaim assumes that the system is modulated or pulsed and might therefore be termed an AC approach. The operation of this idea can be illustrated using its inspiration - the Klystron valve; this is shown in Fig. 14.

In the Klystron, an electron beam is passed through a cavity (known as the buncher) which impresses a signal on it. The signal is retrieved by another cavity known as the catcher. Any remaining electrons are collected by a positive collector electrode [46].

A cavity is basically a conductive box with a coupling aperture, the dimensions of which are chosen so that it is resonant at the frequency of interest. The theory of resonant electromagnetic cavities is beyond the scope of this paper, but is covered extensively elsewhere [46].

The energy capture efficiency of such cavities is high - they are able to retrieve a maximum of around 90% of the energy from a modulated beam (and 80% typically in practice) in a single stage. A two practical two-stage cavity system can retrieve around 95% of the energy [47], and this could even be followed by a Post-type DC system to "mop up" any remaining particles.

A device employing cavity energy-retrieval might look similar to that shown in Fig. 15. Here the beam is modulated by a buncher (although the ion source itself might be designed for pulsed operation from the outset). The catcher cavities are shown in a semicircle in the diagram, for clarity - but they could completely enclose the trap in a circular structure. They are arranged so that the scattered particles reach them all at the

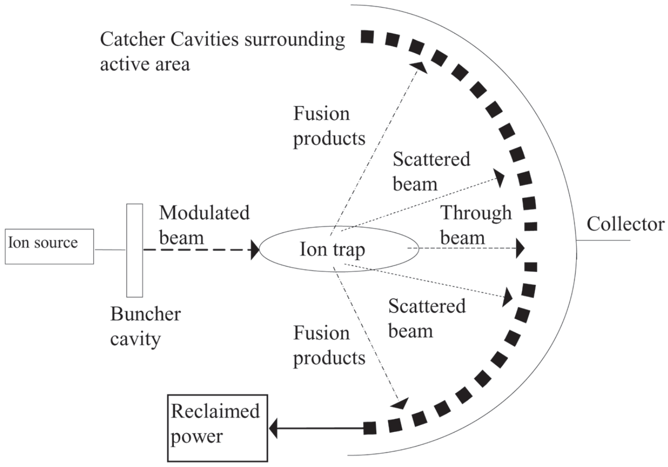

Fig. 15 Structure of a Fuseotron type machine.

same time. Such a device might be termed a *Fuseotron* (from *Fuso*-r + Klys-*tron*).

The cavity structure can be connected to a high-voltage DC power-supply and shaped so that a positive electrostatic field is used to guide the ions through the cavities. The detail of a single section of a basic set-up is shown in Fig. 16. The electrical connections are routed behind cavities in the beam shadow.

A practical structure would probably be more complex, with two (or more) stages of cavity and separate structures for both the beam and product ions, as shown in Fig. 17. There is also a predictable energy-loss inherent in such a system; this is equal to the Kinetic-energy change of the ions as they are diverted into the beam channel by the electrostatic field.

An alternative option to the simple cavities discussed above would be to use the type of cavities employed in Gyrotron valves [48, 49]. These have the advantage that they have a broader bandwidth. This means that less attention needs to be focused on the particle bunching - which is necessary for good efficiency of simple cavities. However, Gyrotron cavities need a strong magnetic field to operate, which is a disadvantage. This approach is shown in Fig. 18. Other possibilities for further work include slow-wave and transformer structures and, of course, hybrid approaches may also be used. The whole structure could also potentially be bent around into an endless circular magnetron-like device, with particles circulating under the influence of a magnetic field.

Another area for consideration is whether neutron and other

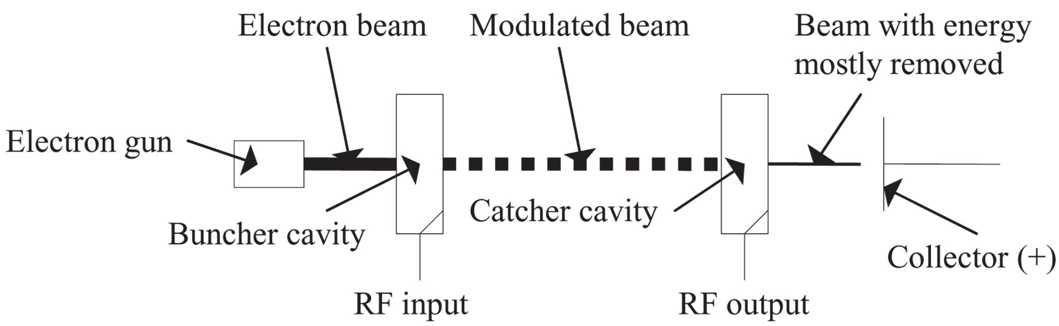

Fig. 14 Diagram illustrating the operation of a Klystron.

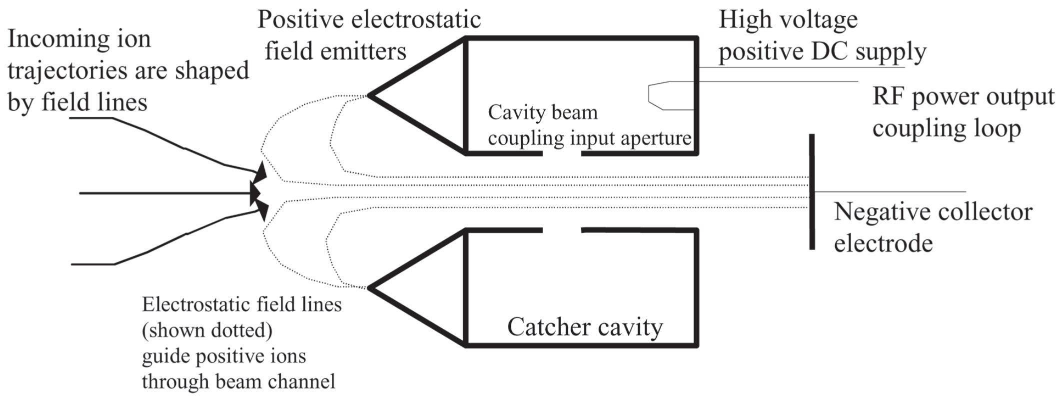

Fig. 16 A basic cavity structure showing connections and electrostatic beam guidance.

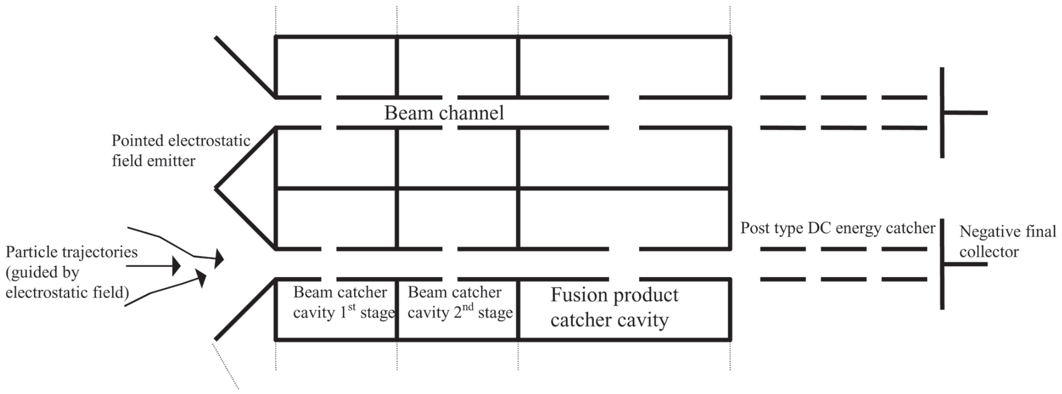

Fig. 17 A more realistic structure for a section of the surrounding cavities.

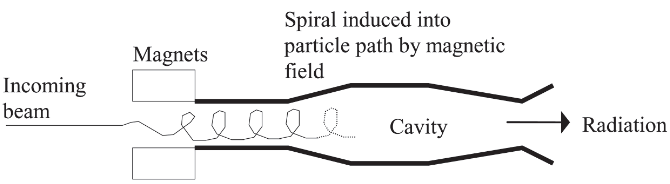

Fig. 18 A Gyrotron type cavity.

fusion products could be converted directly into electricity (or into an electron stream for another purpose, or energy recovery) by allowing them to heat the back-plate of an electron generator device as shown in Fig. 19.

4.3 Practical Issues

As alluded to in the sections above, there are several practical problems which need to be overcome before these devices can become viable. Although these issues appear present technical obstacles to a working system, none of them seems to be insoluble in the light of current knowledge. This section outlines two particular areas which need further work in order to make IEC systems an engineering reality. The first of these is the achievement of high density in the active area and the second is good energy reclamation. These two areas are now considered in turn.

The importance of a high particle density has already been described in some detail in the preceding sections. There are also some related issues which need some further consideration. One is the isolation of high and low densities in the machine. For the ion source and acceleration system to work effectively they need to operate in a good vacuum. Stray particles cause unwanted collisions, scattering the beam and result-

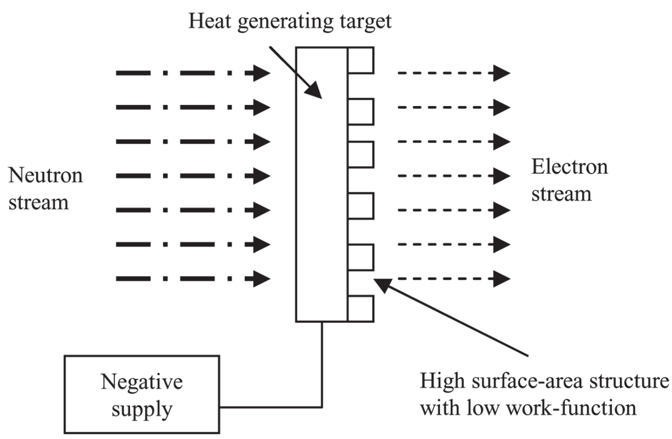

Fig 19 Direct conversion into an electron stream.

ing in an increase of waste heat. This means that good containment of the target particles is important, and this is the principle reason why ions and plasmas are the main focus of research - both can be effectively contained. As well as being difficult to physically separate from the beam, neutral atoms also contain bound electrons and some of the incident beam energy is used up ionising these. A plasma can be contained, but although the electrons are now separate from their parent nuclei, they are still present and are scattering sites for the beam; they can spill easily into the main vacuum with the deleterious effects already described, and can also carry away heat energy (although some of the reclaim systems mentioned in the section above may ameliorate the problem by recovering these). Ionic systems therefore have several advantages over neutral ones.

The target particle cloud needs to be dense and well contained for the reasons already mentioned. It also needs to be shaped appropriately. If the target is too large or the wrong shape, then scattered and fused products will undergo further secondary scattering in the cloud with several undesirable consequences. These include the transfer of heat to the cloud, raising its entropy and removing recoverable energy from the system and the spillage of scattered particles out of the trap and into the main chamber with the results already discussed. This is why the long, thin, sausage-shaped topology described in the sections above is useful.

Although a system based on ionic entrapment is in some respects ideal, there are two problems associated with it. The first of these is overcoming the natural coulombic repulsion of the ions in order to gain a dense enough target. This issue has already been discussed. The second is the form of the ion trap necessary to contain a high enough density. Paul and Penning traps tend to enclose the ions in metal structures and this stops the scattered and fusion products escaping freely as required by the energy capture systems. However, as previously discussed, novel trap topologies are available and there is still research to be done, ideally to produce a trap with the field topology shown in Fig. 20.

Such a structure should ideally have no physical protrusions into its active region. Although this might not be possible as a static system, dynamic approaches such as standing waves and collapsing field profiles have still to be explored. Other non-linear field phenomena – for example field arrangements similar to those which cause charge bunching in Gunn diodes might also be explored.

The use of neutral beams was discussed in a previous section as a possible solution to the density issue. However, as already noted, neutral particles are difficult to contain and also use energy in ionisation (although this is small, only 13 eV for a Deuterium atom). Any neutral beam system would probably therefore be pulsed. The individual pulses being sent to reach the reaction area at exactly the same time as the accelerated beam. Scattered and fused components would then be expelled from the centre quickly, due to their inherent velocity, and captured by the retrieval system. The remaining neutral particles would need to be evacuated before a new pulse was initiated. In such a system, timing would be critical.

Consider now the practical problems associated with the accelerated ion beam. The technology of ion acceleration is fairly simple; however, if the device is to operate in a pulsed mode there are some added complications. These mostly involve ensuring that the ion pulses arrive at the target with optimal timing - this is critical for cavity efficiency. Ideally the density profile of the beam should be a sinusoidal variation. However, in practice this may be difficult to achieve due to different initial ion velocities. Reducing the variability of ion velocity is a significant way of improving the beam profile, and this can be achieved by sorting the ions before acceleration into a narrow velocity band. This is often done in Ion Scattering Spectroscopy [50] for the same reason. The ions are injected into a curved duct or tube under the influence of a constant magnetic field, only those with exactly the energy required to emerge from the other end without hitting the tube walls are accelerated. The idea is shown in Fig. 21. This is one of several useful techniques which can be adapted from this field.

Another practical issue concerns power-management in the system. The energy inputs and outputs can be divided up into

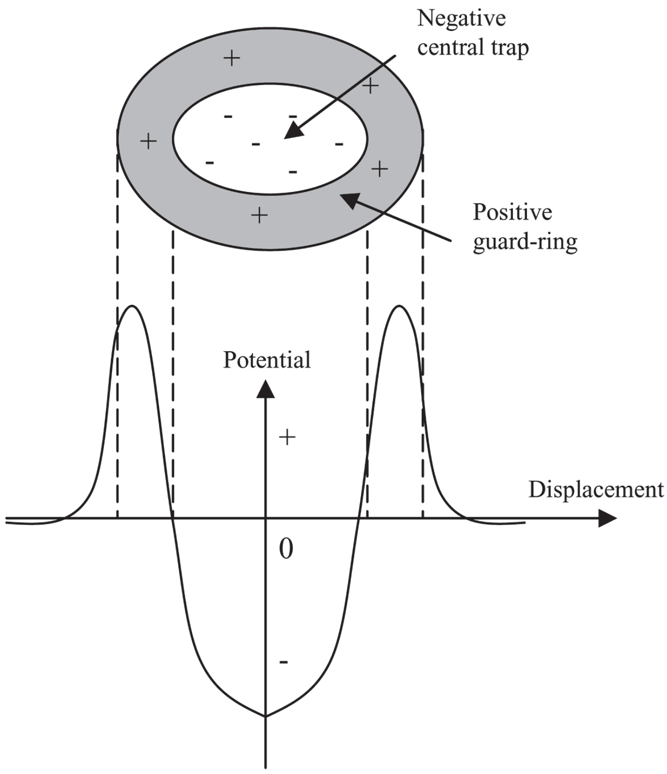

Fig. 20 Ideal theoretical ion-trap structure.

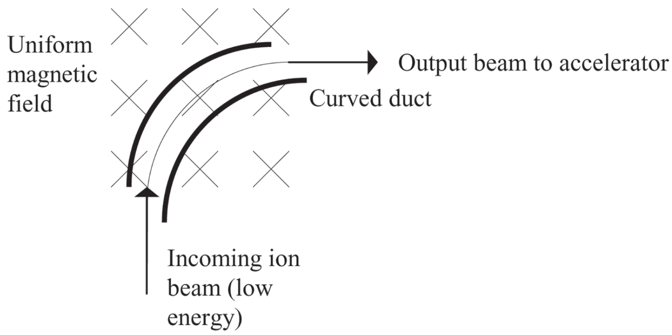

Fig. 21 Ion velocity sorting.

two classes - "internal" and "external." This classification differentiates the power produced and consumed within the device from the power delivered-to or drawn-from external sources. In the steady-state the system is a net source of power; however, in the start-up phase, external power is probably required. Figure 22 illustrates the broad input and output groupings and details some of the internal sources and loads. The key to running the system efficiently will be the intelligent handling of these by the management system.

5. DISCUSSION AND CONCLUSIONS

In order to truly revolutionise access to space and its subsequent development, a new approach to energy supply is needed. There are two options for this - one is a new source of power, of which the ideas outlined in this paper are an example; the other is a more efficient way of storing power, of which there are several in development [8] and others suggested theoretically [51]. Of course, in the current environmental climate, there are also many Earth-bound applications of such technologies.

Even although electrostatically-controlled fusion is to some degree a speculative endeavour, the idea has so many potential

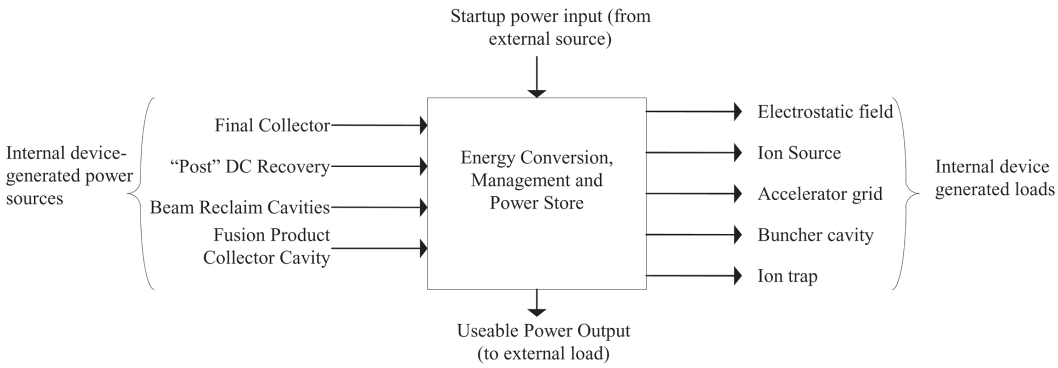

Fig. 22 Typical inputs and outputs to an intelligent power-handling system.

advantages that it simply cannot be ignored; these include weight, power-density, safety and simplicity. The nature of the system also means that there are also good possibilities for direct integration with some of propulsion ideas mentioned earlier, such a system for the EMA concept [7] is shown below in Fig. 23 (the converter shown in Fig. 19 could potentially also be intermediate in this process).

It is the assertion of this paper that the fundamental science of IEC fusion can be advanced substantially if an interdisciplinary approach is taken and current advances are incorporated into the existing designs. In particular, the fields of high-power valves, particle accelerators, magnetically-confined fusion and ion spectroscopy need to join forces with traditional IEC technology if such advances are to be made - this synthesis also needs to include expertise and experience from these areas as well as "hard" technology. In turn, magnetically-confined fusion has something to learn from these disciplines.

This paper contains two main technical points. The first is that research needs to be done in order to find a practical way to obtain the necessary particle densities in the reaction area of the machine. Although this may seem a difficult task, there are definite lines of enquiry which can be pursued and more experimental work needs to be done in the area in order to explore the best way to proceed. The second (and more important) point is that there are methods of energy reclaim which have not yet been considered and which fundamentally change the power-dynamics of the system. These offer a complete and elegant system-level integration, which solves several of problems hitherto associated with IEC. The most important of these recovery techniques is the modulated-beam system outlined above - and this appears not to have been suggested in previous work.

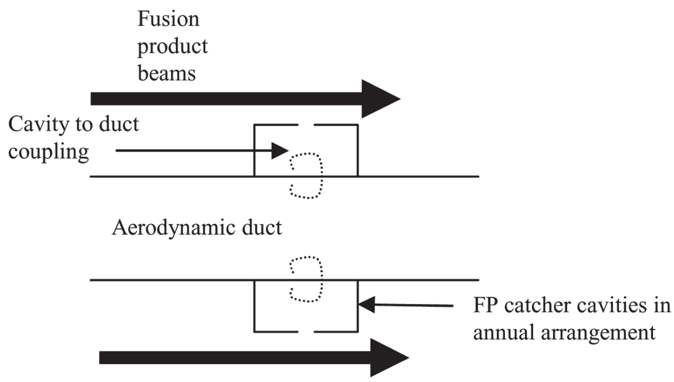

Fig 23 Integration of fusion system with EMA.

Research into the system outlined here presents some risk - as previously mentioned, some of the ideas are speculative. However, as also mentioned, the potential rewards are immense. The financial costs of trying out these ideas are but a drop in the ocean compared with the vast sums currently being spent on magnetically confined fusion. Many large universities already have suitable vacuum vessels which may be used to experiment with these ideas and the device can be built up and researched in a modular fashion, from the central trap-system outwards. Given this, the cost of experimentation is in the order of hundreds of thousands to a few million pounds - only a moderately sized research program.

REFERENCES

1. W.H. Heiser *et al.*, "*Hypersonic Airbreathing Propulsion*", AIAA Education Series, Washington, pp 277 - 313, 1994.
2. R.B. Bird, W.E. Stewart and E.N. Lightfoot, "*Transport Phenomena*", Wiley, New York, pp 518 - 525, 2002.
3. F.S. Billig, "Design and development of single stage to orbit vehicles", *John-Hopkins Applied Physics Laboratory Technical Digest*, **11**, pp.336–352, 1990.
4. Anon (Compressed Gas Association), "*Handbook of Compressed Gases (4th ed)*", Kluwer Academic Publishers, Norwell, pp.60-62, 1999.
5. L.N. Myrabo and D.G. Messitt, "Ground and Flight Tests of a Laser Propelled Vehicle," The *34th AIAA Joint Propulsion Conference*, 1998. Paper AIAA-98-3735.
6. Y. Minami and S. Uchida, "Water Vapour Propulsion Powered by a High-Powered Laser Diode", *JBIS*, **62**, pp.332-339, 2009.
7. C. MacLeod, "Electromagnetically Activated Hypersonic Ducts", *JBIS*, **62**, pp.99-109, 2009.
8. C. MacLeod, K.S. Gow and N.F. Capanni, "Some Practical Aspects of Electromagnetic Activation", *JBIS*, **62**, pp.320-331, 2009.
9. E.P. Gurijanov and P.T. Harsha, "AJAX: New Dimensions in Hypersonic Technology", *AIAA*, 1996. Paper AIAA-96-5211.
10. R.S. Fry, "A Century of Ramjet Propulsion Technology Evolution", *Journal of Propulsion and Power*, **20**, pp.27-58, 2004.
11. R. Clark, "Using both Atmospheric Oxygen and Nitrogen for Hypersonic Propulsion", available from: http://sci.tech-archive.net/Archive/sci.astro/2008-02/msg00176.html. (Date Accessed 27 January 2011)
12. T. Ligon, "The World's Simplest Fusion Reactor, and How to Make it Work", *Analog Science Fiction and Fact*, **118**, pp.40-54, 1998.
13. T. Ligon, "The World's Simplest Fusion Reactor Revisited", *Analog Science Fiction and Fact*, **128**, pp.60-80, 2008.
14. G. McCracken and P. Stott, "*Fusion: The Energy of the Universe*", Elsevier (Complementary Science Series), Amsterdam, 2005.
15. A.A. Harms *et al.*, "*Principles of Fusion Energy*", World Scientific, Singapore, 2000.
16. C.M. Braams and P.E. Stott, "*Nuclear Fusion*", Institute of Physics Publishing, Bristol, 2002.
17. W.C. Elmore, J.L. Tuck and K.W. Watson, "On the inertial-Electrostatic

Confinement of a Plasma", *The Physics of Fluids*, **2**, pp.239-247, 1959.
18. I. Langmuir and K.B. Blodgett, "Currents limited by space charge between concentric spheres", *Physics Review*, **23**, pp.49-59, 1924.
19. R.L Hirsch, "On the inertial-electrostatic confinement of ionised fusion gases", *Journal of applied physics*, **38**, pp.4522-4534, 1967.
20. R.W. Bussard and L.W. Jameson, "From SSTO to Saturn's moons: Super-performance fusion propulsion for practical spaceflight", *30th AIAA joint propulsion conference*, 1994. Paper AIAA 94-3269.
21. R.W. Bussard, "Fusion as electric propulsion", *Journal of Propulsion and Power*, 6, pp 567 - 574, 1990.
22. R.W. Bussard and L.W. Jameson, "Inertial-electrostatic-fusion propulsion spectrum: Air-breathing to interstellar flight", *Journal of Propulsion and Power*, **11**, pp.365-372, 1995.
23. R.W. Bussard, "System technical and economic features of QED-engine-driven space transportation", *33rd AIAA joint propulsion conference*, 1997. Paper AIAA 97-3071.
24. B.E. Edwards, "Ion dynamics in spherical reflex diode," PhD Thesis, University of Illinois, 1979.
25. T.A. Hochberg, "Characterisation and modelling of the gas discharge in a SFID neutron generator," PhD Thesis, University of Illinois, 1992.
26. T.D. Rider, "A general critique of inertial-electrostatic confinement fusion systems," MSc thesis, MIT, 1994.
27. T.D. Rider, "Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium," PhD thesis, MIT, 1995.
28. T.D. Rider, "Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium", *Physics of Plasmas*, **4**, pp.1039-1046, 1997.
29. E. Bakhoum, "Very small scale electrostatic-confinement fusion apparatus", *IEEE Transactions on plasma science*, **37**, pp.2090-2097, 2009.
30. C. Dietruch, "Improving particle confinement in inertial-electrostatic fusion for spacecraft power and propulsion", MIT, 2007.
31. G.D. Porter, "Some considerations on the Electrostatic confinement of fusion gases", Pennsylvania-State university, 1968.
32. G.A. Imel, "A theoretical model of a spherical electrostatic confinement device", Pennsylvania-State university, 1968.
33. B. Wolf, "*Handbook of ion sources*", CRC Press, Bara Raton, 1995.
34. R. Hemsworth, "Status of the ITER heating neutral beam system", *Nuclear Fusion*, **49**, Paper 045006, 2009
35. J.B. Pendry, D. Schurig and D. R. Smith, "Controlling Electromagnetic Fields", *Science*, **312**, pp.1780-1782, 2006.
36. P.K. Ghosh, "*Ion traps*", Clarendon Press, Oxford, 1995.
37. J.R. Castrejon-Pita, "*Design, development and operation of novel ion trap geometries*", VDM-Verlag, Saarbucken, 2009.
38. G. Li, S Guan and A.G. Marshall, "Comparison of equilibrium ion density distribution and trapping force in Penning, Paul and combined ion traps", *Journal of the American Society of Mass Spectrometry*, **9**, pp.473-481, 1998.
39. D.J. Wineland, "Ion traps for large storage capacity", *Proceedings of the cooling, condensation, and storage of Hydrogen cluster ions workshop*, Menlo Park California, 1987, pp.168-181.
40. J.L. Ferreira, S.F. de Silva and I da Rego, "A multi magnetic mirror machine for plasma production with electron cyclotron resonance", *Revista de Fisica aplicada e instrumentacao*, **17**, pp.54-59, 2004.
41. J. Park and G.A. Wurden, "Intense diagnostic neutral beam for ITER," ITER forum, University of Maryland, 2003.
42. J.M. Neri *et al*., "An intense pulsed barium ion source", *IEEE Transactions on Nuclear Science*, **28**, pp.3378-3379, 1981.
43. R.F. Post, "Mirror Systems: Fuel Cycles, Loss Reduction and Energy Recovery", *British Nuclear Energy Society, Nuclear Fusion Reactor Conference at Culham laboratory*, pp.87-111, 1969.
44. R.W. Moir, "Direct energy conversion in fusion reactors", in *Energy technology handbook*, ed. D.M. Considine, McGraw-Hill, New York, pp.5-150-5-154, 1977.
45. H.G. Kosmahl, B.D, McNary and O. Sauseny, "High Efficiency, 200-Watt, 12-Gigahertz Travelling Wave Tube", *NASA Report TN D-7709*.
46. R.E. Collins, "*Foundations for Micowave Engineering (2nd ed)*", McGraw-Hill, New York, 1992.
47. J. Welch, "The maximum efficiency of a conventional klystron output cavity", *Stanford Linear Accelerator Conference*, 1989. SLAC paper reference: SLAC-PUB-3976.
48. G.S. Nusinovich, "*Introduction to the Physics of Gyrotrons*", The John Hopkins University Press, Baltimore, 2004.
49. M.V. Kartikeyan, E. Borie and M Thumm, "*Gyrotrons: High-power Microwave and Millimeter Wave Technology*", Springer, New York, 2003.
50. H. Helbig, "Introduction to Low Energy Ion Scattering Spectroscopy," The Solar Energy Research Institute, Golden Co, 1979.
51. C. MacLeod, "*A Match Made in Heaven*", Electronics World, **111**, pp 20-22.

(Received 1 September 2010; 6 December 2010)

*   *   *