FUEL ENCAPSULATION FOR INERTIAL ELECTROSTATIC CONFINEMENT NUCLEAR FUSION REACTORS

CHRISTOPHER MACLEOD[1], NICCOLO F. CAPANNI[2] AND KENNETH S. GOW[1]
1. *The School of Engineering, The Robert Gordon University, Schoolhill, Aberdeen, AB10 1FR, UK.*
2. *The School of Computing, The Robert Gordon University, St Andrews St, Aberdeen, AB25 1HG, UK.*

Inertial Electrostatic Confinement (IEC) is an approach to nuclear fusion which utilises the properties of electrostatically accelerated ion-beams instead of hot plasmas. The best known device which uses the principle is the Farnsworth-Hirsch fusor. It has been argued that such devices have some potential advantages in spaceflight and in-particular as power-supplies for trans-atmospheric propulsion. This paper builds on previous work in the field and focuses on how the fixing of the fuel for such reactors in a solid, liquid or encapsulated form may provide a high enough energy-density to make such devices practical power sources. Several methods of fixing the fuel are discussed; theoretical calculations are presented and applicable literature is reviewed. Finally, there is a discussion of practical issues and feasibility, together with suggestions for further work.

Keywords: Nuclear fusion, fusors, fuseotron, Inertial Electrostatic Confinement, propulsion, power

1. INTRODUCTION

Inertial Electrostatic Confinement (IEC) fusion is an idea originated by Philo T. Farnsworth (1906 - 1971) and further developed by a number of other researchers and experimenters. 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 still not achieved useful power output.

IEC fusion has received less interest of late 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. These have been described in detail in other papers [1-3] and so it is not proposed to discuss them further here. The potential advantages make IEC fusion a candidate as a power source for future trans-atmospheric vehicles, and the development of such a lightweight but powerful energy source means that a number of hitherto under-researched propulsion schemes for such vehicles may be feasible [1]; this, in turn, may facilitate mass-access to space. Such considerations make IEC an important target for further research.

This current paper follows on from our previous publication in *JBIS*, “A Reconsideration of Electrostatically Accelerated and Confined Nuclear Fusion for Space Applications” [1]. The first paper contains a reappraisal and redesign of IEC fusion and, in particular, presents several new systems for energy reclaim which change the energy balance of the machine and make it much more feasible as a practical power source. This material culminated in the presentation of a new design of device - the *Fuseotron*. However, the paper also highlighted a problem with all IEC techniques – that of *achieving a high enough fuel-density in the target area*. Without achieving a sufficiently high fuel-density, the machine cannot produce enough power for practical purposes.

This paper looks at the topic of target-density in more detail and, in particular, at the possibilities of fixing the target in a high-density solid, liquid or encapsulated (gaseous) form. It begins by briefly reviewing the basic technology and principles of IEC, then goes on to present the fuel density problem and explains some possible solutions. A literature review and supporting data are then given. Finally, the practicalities of the system are reviewed and conclusions presented.

2. TECHNOLOGY

It is not the intention of this paper to present a comprehensive overview of IEC principles and literature - this has already been done in the first paper [1]. However, a brief review of the system is important in order to understand the ideas presented later.

Consider first, the governing equation of nuclear fusion:

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

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. 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 [4-6]. Note that, in these discussions, the number of particles (which is dimensionless) is denoted by the hash symbol - #. If both species are the same, then N_aN_b can be replaced by a single number:

$$R = \frac{1}{4}\sigma N^2 v \qquad (2)$$

An extremely important observation may be made about equations 1 and 2, which is: *They do 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 [1, 2].

However, there is another approach. 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*. This is the basis of IEC fusion systems discussed in this paper.

The three most commonly proposed reactions for use in IEC systems are: Deuterium-Tritium (notated as D-T), Deuterium-Deuterium (D-D) or Deuterium-Helium 3 (D-He^3). The D-T reaction is the most favourable, having a reaction cross-section (σ_f) of about 5×10^{-28} m^2 at a beam-energy of around 100 keV. All three of these reactions produce neutrons as one of their fusion products.

Because the presence of neutrons causes extra complexity and they have inherent safety issues, some researchers consider *aneutronic* reactions to be a better solution [7]. The two most important of these involve the collision of protons with Boron-11 and Lithium-7.

Consider now the Farnsworth Fusor reactor mentioned in the introduction. The device is based on the idea of accelerating a beam of ions of species *a* onto a target of species *b*. The target was an ion-cloud held in a simple ion-trap grid structure (labelled "containment grid" in the diagram). The topology of the machine is shown in Fig. 1.

This machine and others developed from it (by various groups of researchers, including Willard H. Bennett, William C. Elmore and his co-workers [8], Robert L. Hirsch [9] and Robert W. Bussard [7]), represent half a century of research and development into IEC. However, none of these devices, nor those made by more modern experimenters, produced the substantial amounts of power hoped for.

One of the main reasons for this may be seen in the following example: Taking the D-T reaction, it is obviously necessary to supply around 100 keV of energy to accelerate each ion towards the target. A successful fusion reaction releases 17.6 MeV. This means that, to break-even (and assuming no losses in the system), one in every 117 accelerated particles must result in a fusion event. However, this is unlikely because the particles are much more likely (between 10 and 100 times) to scatter, due to Coulombic forces in the ion cloud, than fuse (this scattering is denoted by the scattering cross-section figure σ_s).

This was the problem which our initial paper [1] set out to solve. It showed that, if both the used-beam and fusion particles could be captured and their energy reused, then the energy-balance of the whole system changed completely. To be specific, a machine using the D-T reaction, reclaiming 70% of its particle energy is capable of generating around twice the energy originally supplied. One reclaiming 80% of its energy, could generate up to five times its supply energy, and finally a machine capable of reclaiming 90% could generate approximately ten times its input energy [1].

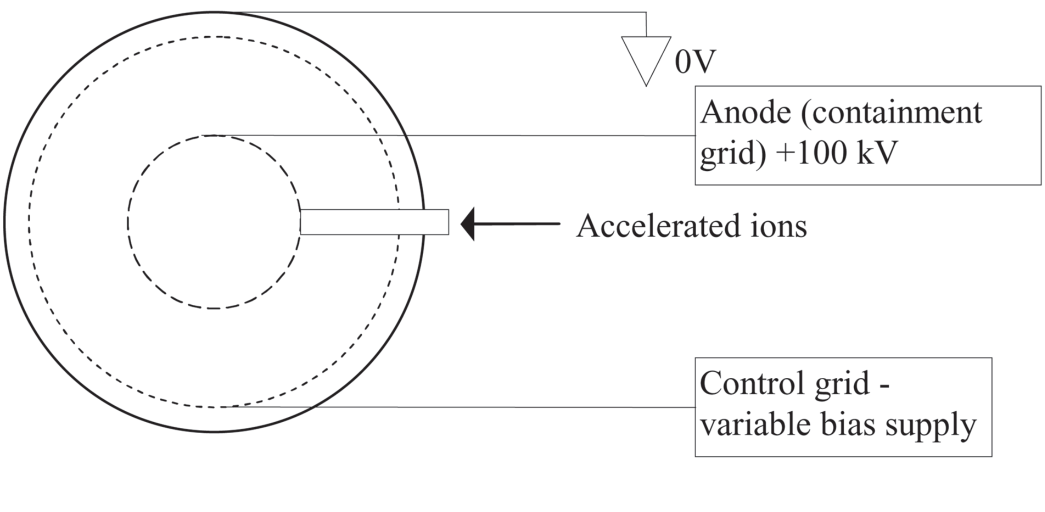
The paper then went on to present methods of reclaiming this energy using several techniques with a theoretical maximum reclaim of over 90%. The two main methods explored were a DC reclaim, originally developed by Richard Post [10], and a new AC method, using radio-frequency cavities [11]. As a result of this, the paper suggested a new type of machine based on these ideas and christened the *fuseotron*. This device is shown schematically in Fig. 2. Note that, although for clarity, the diagram shows the energy reclaim device as an arc in front of the target, in reality it would completely enclose it in a spherical structure.

The dynamics of this device are completely different to those in thermal systems. Whereas thermal fusion depends on high confinement times – as defined by measures like the Lawson Criterion; an IEC system with reclaim uses exactly the opposite effect – free elastic scattering of beam and fusion products out of the active area. It is fairly easy to see that, for a long thin target, where particles are either scattered out of the active area or fuse, the beam energy per fusion is:

$$\frac{\sigma_s}{\sigma_f} E_b$$

Beak-even occurs when the returned energy from the fusion products is equal to the lost energy in the beam:

Fig. 1 Structure originally proposed by Farnsworth.



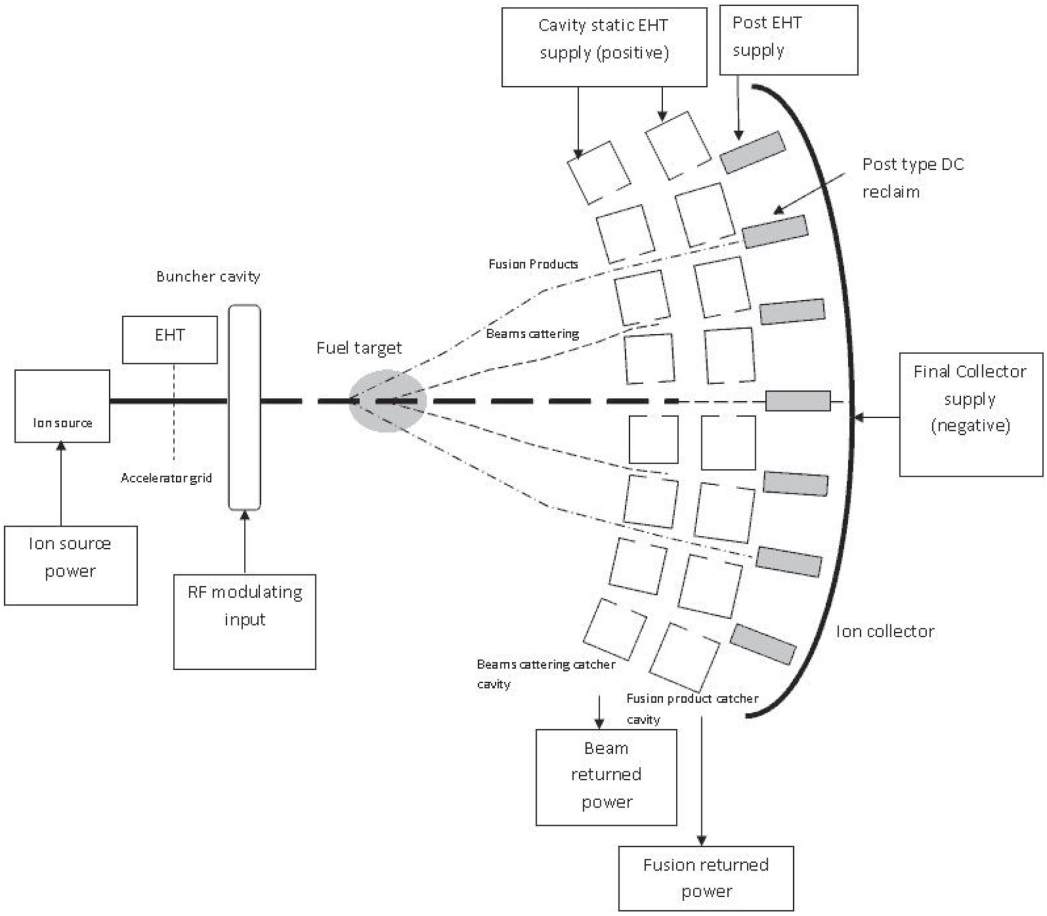


Fig. 2 Structure of a Fuseotron type machine.

$$\eta_f E_f = \frac{\sigma_s}{\sigma_f} E_b (1-\eta_b)$$

And therefore the reclaimed energy is:

$$E_t = \eta_f E_f - \frac{(1-\eta_b)\sigma_s E_b}{\sigma_f} \tag{9}$$

Where E_t is the total reclaimed energy returned to the device per fused particle, η_f is the fusion-product reclaim efficiency, η_b is the scattered-beam reclaim efficiency, E_f is the produced fusion energy per particle and E_b is the energy per beam particle. The scattering symbols have the meaning explained in section 2. If particles are not scattered immediately out of the target area (because, for example, it is too thick) then σ_s/σ_f can be replaced by a new ratio *r*, representing the actual measured ratio of particles scattered out of the active area to fused particles. The total net energy returned can be calculated by multiplying E_t by the number of fusions taking place given by equations 1 and 2. The total efficiency η_t is given by the energy released per unit beam energy:

$$\eta_t = \frac{\eta_f E_f - \frac{(1-\eta_b)\sigma_s E_b}{\sigma_f}}{\frac{\sigma_s}{\sigma_f} E_b}$$

However, there is a problem which stops this type of machine being immediately practical. Although the fuseotron structure can in-theory recover a large percentage of the energy from the used beam, scattered particles and fusion products, this is of little consequence if the initial energy being generated is too small to be useful. After all, there is no point in generating 10 times more energy than is consumed, if all that is being produced is a millijoule.

The main factor controlling the gross energy produced is the particle density of the fuel. However, if the target is fixed as an ion-cloud in a trap (or as a plasma contained in a magnetic bottle), there are serious practical limits to its maximum density. It is this problem, and its possible solutions, which has led to the creation of the current paper.

3. HIGH DENSITY FUELS

Since each D-T reaction releases 17.6 MeV, it takes 3.6×10^{11} reactions to release 1 joule of energy and that number of reactions per second to supply 1 W of power. Using this information and equation 1, it is possible to draw up a table of target/beam particle-densities necessary to achieve various power densities; this is shown in Table 1. The target particle density is shown as *N* and the combined beam-target density as N^2, as in equation 2. This assumes equal beam-target densities - a point which will be considered later. To find an approximate power-density if the target and beam densities are different, multiply the target-density N_a by the beam-density N_b and then look up this value in the N^2 column and read the corresponding power-density (for example, if the target-density is 10^{22} #m^{-3} and the beam-density is 10^{18} #m^{-3}, then the product is 10^{40} (#m^{-3})^2

TABLE 1: *Particle Densities Required for Produced Reaction Power Densities*.

R (#m^{-3}s^{-1})	N (#m^{-3})	N^2 (#m^{-3})^2	Power Density (1)	Power Density (2)	Comments
10^{11}	10^{16}	10^{32}	0.3 W/m^3	300 nW/cm^3	
10^{13}	10^{17}	10^{34}	30 W/m^3	30 mW/cm^3	Ion Traps
10^{15}	10^{18}	10^{36}	3 kW/m^3	3 mW/cm^3	Small mirror machine
10^{17}	10^{19}	10^{38}	0.3 MW/m^3	300 mW/cm^3	100 A/cm^2 Ion beam
10^{19}	10^{20}	10^{40}	30 MW/m^3	30 W/cm^3	1 kA/cm^2 Ion beam
10^{21}	10^{21}	10^{42}	3 GW/m^3	3 kW/cm^3	Max mag confinement
10^{23}	10^{22}	10^{44}	300 GW/m^3	300 kW/cm^3	
10^{25}	10^{23}	10^{46}	30 TW/m^3	30 MW/cm^3	
10^{27}	10^{24}	10^{48}	3 PW/m^3	3 GW/cm^3	
10^{29}	10^{25}	10^{50}	300 PW/m^3	300 GW/cm^3	1 atm T_2 at STP
10^{31}	10^{26}	10^{52}	30 EW/m^3	3 TW/cm^3	4 atm T_2 at ST
10^{33}	10^{27}	10^{54}	3000 EW/m^3	3 PW/cm^3	
10^{34}	10^{28}	10^{58}	300,000 EW/m^3	300 PW/cm^3	Liquid/Solid T_2

which, if found in the N^2 column, corresponds to a power density of about 30 MWm^{-3}).

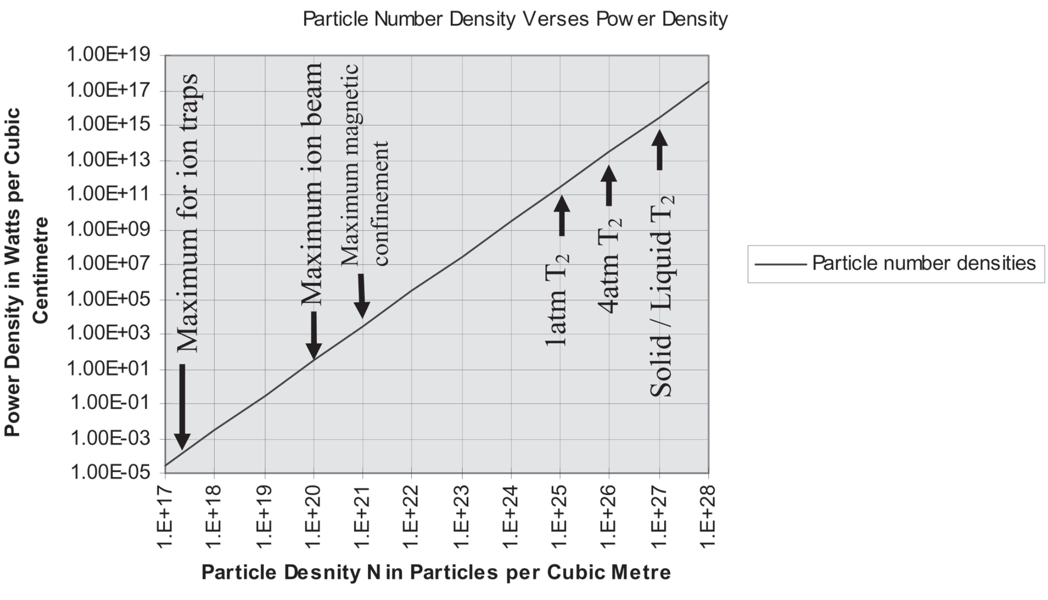
The two columns of power densities are power-density per cubic metre, which is useful for comparison with other systems; and power-density per cubic centimetre, which is useful because the actual target size is likely to be of this order of magnitude. The comments in the last column will be discussed in later sections; note however, that T_2 is a tritium molecule and STP is Standard Temperature and Pressure (293 K and 101 kPa). Figure 3 shows the power-density per cubic centimetre plotted against target particle density.

One can immediately see that target densities in the order of 10^{19} - 10^{20} #m^{-3} are required to achieve a power-density of around 1 W per cm^3 (1 MW per m^3), which is a useful figure-of-merit, since it is comparable with a jet engine. However, a great deal of work has been done on the maximum capacity of modern ion traps [12, 13] and this is only around 10^{16} - 10^{17} #m^{-3} which is several orders of magnitude below what is required in a practical machine. Magnetically confined plasmas in small mirror devices are slightly denser, but still well below useful densities [14]. Interestingly, the neutron and power generation values of experimental devices reported in literature [9, 15], from commercial IEC neutron sources, correspond almost exactly to the figures shown in Table 1 - an indication that the theory presented here is correct.

This analysis leads to one conclusion - that in order to achieve the required power from the reactor, the target must be fixed in a much denser form. It is proposed that this is either as a solid pellet (either frozen, or as a compound), in liquid form (encapsulated, as free drops or as a free stream of liquid) or in a gaseous form (as an encapsulated or injected gas). All of these options involve neutral rather than ionised species and the effect of this will be discussed in later sections. There is insufficient space in this paper to explore all the possibilities in detail; however, the general principles outlined in the next section apply to several of the most important.

Maintaining Tritium or Deuterium in a frozen or liquid form in storage is challenging (although it is done regularly for other

Fig. 3 The relationship between particle density and resulting power density.



purposes [16]). The melting point of Deuterium is around 18K at atmospheric pressure and Tritium is 21K. Deuterium's boiling point is 23K and that of Tritium is 25K. Of course these can be relaxed under pressure; however, this leaves the practical difficulty of introduction into the reaction chamber. The situation for other fuels like Boron-11 and Lithium-7 is much easier - since these are both solids under atmospheric conditions. In all these cases, for reasons which will be outlined later, the substance will probably need to be boiled and ionised using a focused laser beam or the inherent energy of the ion-beam itself. The practicalities of this will be discussed in section 5.

The potential difficulties of handling and using cryogenic solid pellets or liquids in the system leads to another option - that of encapsulating the target in a gaseous state in a shell, capsule or some similar bubble-like structure (all these structures will be referred to generically, as a bubble, in subsequent discussion). In this case, the bubble could be burst using either the power of the ion-beam or a laser as described above. In the case of laser heating, this could either burst the bubble by melting its envelope material (for example, if it were made from a suitable polymer), or by heating the gas inside, expanding it, and forcing the bubble to explode (this could also be done in other ways - for example, by using microwave heating). If required, the effusion rate of gas from the bubble could be controlled by having "windows" or holes in the bubble envelope structure, which would preferentially melt when exposed to the laser.

One final possibility is a device in the reaction-chamber which could inject the target molecules in solid, liquid or gaseous form into the path of the beam.

4. EXPANSION THEORY

In all the cases mentioned above, once the gas is released, no further heat is added until the beam impinges on it. This state of affairs is known as *Free Expansion*. Although in some cases the release is not symmetrical, the general formulae obtained by expansion from a bubble-like structure can be applied as a first approximation in most cases. Because of its applicability, this section of the paper is delegated to that case.

There are several papers which treat the expansion of gas into a vacuum from a bubble-like structure. One of the most important is that by Greenspan and Butler [17]. This paper specifically considers gas escape from the type of structure described in the previous section. It builds on earlier work by Stanyukovich on the equations of motion of a gas in these situations [18]. The treatment is a classical thermo-fluids one, and is based on formulating and solving fluid-flux equations. A similar approach was taken by Molmud [19] for lower pressure gases, and this was built on by Narasimha [20]. Other papers of interest, based on these approaches, are listed in the references [21-23].

Another method of addressing the problem is to develop a model based on Kinetic Theory, and this is the technique adopted by Keller [24]. The results are in good agreement with the classical approach [16], and they possibly offer more insight into the physical particle-dynamics of the situation.

All the treatments listed above generally provide an exact, analytical, three-dimensional set of solutions to the expansion problem. They are generally rather cumbersome and much too complex for the purposes of quick and simple repeated calculations to ascertain whether a particular topology is likely to work. For this reason, a simpler, but approximate, one-dimensional approach is presented below. The aim is not to give exact particle distributions, but to allow ball-park figures to be calculated quickly.

At the pressures and temperatures under consideration in this discussion, it is reasonable to make an ideal gas approximation [25]. This being the case, particles in the gas have a probabilistic speed distribution approximated by the Maxwell Speed Distribution (MSD), given by:

$$D(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\left(\frac{mv^2}{2kT}\right)} \tag{3}$$

Where $D(v)$ is the probability of a particle having a given velocity v, the particle mass is m, the absolute temperature is T and k is the Boltzmann constant [26, 27]. This produces a distribution like that shown in Fig. 4. The meaning of the various velocities indicated on the diagram will become clear as the discussion progresses.

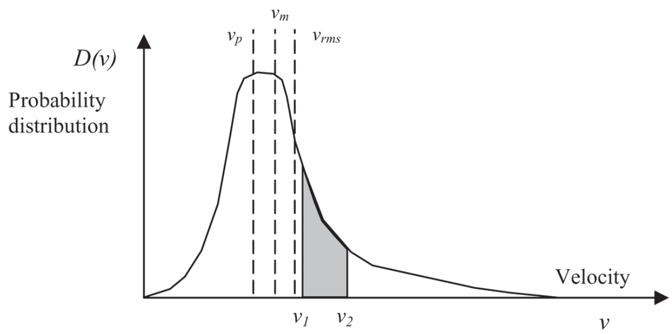


Fig. 4 The Maxwell Speed Distribution.

Figure 4 therefore shows the speed distribution of gas particles inside a bubble or capsule of gas at a given temperature. Consider now what happens if the boundary of the bubble disappears and the gas is free to expand into a vacuum. Since the expansion is adiabatic and the gas is ideal, the velocity distribution shown in the figure continues to hold [28].

Assuming that the bubble is small compared with the surrounding space, then at time t, each particle will have travelled a distance x according to its position in the velocity distribution where $x = vt$. This will mean that, in one dimension, with the bubble located at zero on the x axis, the probability of finding particle at a location along that direction will look as shown in Fig. 5. Notice however, that statistically, half the particles will go in the negative direction, and therefore the graph will be symmetrical about zero.

Turning back to the initial velocity distribution, the probability of finding a particle between two velocities v_1 and v_2 (see Fig. 4) is:

$$P = \int_{v_1}^{v_2} D(v)dv = c_1 \int_{v_1}^{v_2} v^2 e^{c_2 v^2} dv \tag{4}$$

Where:

$$c_1 = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2}$$

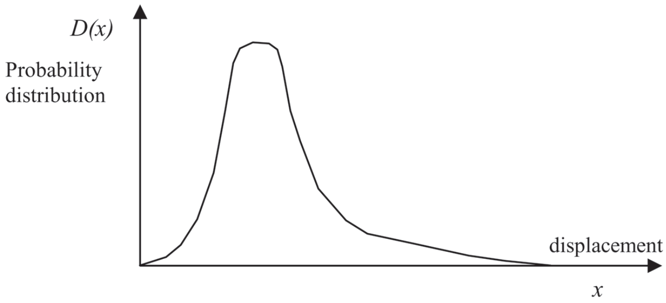


Fig. 5 The spatial distribution of particles after an arbitrary time.

And

$$c_2 = -\frac{m}{2kT}$$

Solutions to this type of integral do exist, however they are complicated by the inclusion of an error function (erf) and an exact solution will not be pursued here. Equation 4 also gives the probability of finding a particle (which has travelled in the positive direction) between two points on the x axis, x_1 and x_2 given that:

$$v_1 = \frac{x_1}{t} \text{ and } v_2 = \frac{x_2}{t} \quad (5)$$

Where t is the time after the bubble has burst.

This one-dimensional reasoning can be extended further to give the particle density between two surfaces in three-dimensional space, assuming that the gas expands outwards symmetrically. This is because the probability function, over all space, must sum to 1. If the bubble originally contained n particles, then these too must be distributed over this space. Now, assuming that we wish to find the particle density between two radii of the expanding gas r_1 and r_2 in the vacuum, we can replace x_1 and x_2 by r_1 and r_2 in equation 5 and by symmetry, since the gas quickly forms a spherical shell:

$$N = \frac{\left[\int_{v_1}^{v_2} D(v)dv\right]n}{\frac{4\pi}{3}(r_2^3 - r_1^3)}$$

Where N is the number density of particles between r_1 and r_2 in $\#m^{-3}$.

Fortunately, rather than performing these complex integrations, there is a straightforward way to make simple calculations on gas expansion from the bubble. Integrating equation 3 to find the average (mean) velocity, v_m of the gas is easy. This, together with the rms velocity, v_{rms} and the most probable velocity v_p is shown below. See Fig. 4 for a graphical representation of these:

$$v_m = \sqrt{\frac{8kT}{\pi m}} \quad (6)$$

$$v_{rms} = \sqrt{\frac{3kT}{m}} \quad (7)$$

$$v_p = \sqrt{\frac{2kT}{m}} \quad (8)$$

Since $x = vt$, estimating the mean velocity allows us to have a good picture of where most of the gas is after time t and the difference between the mean and rms distances calculated like this is a good indication of the region of maximum gas density.

As can be seen from equation 3, the temperature of the gas has a strong effect on its velocity probability distribution – not only in terms of the values shown above, but also in terms of the shape of the velocity distributions. At lower temperatures these are much more compact, having a narrower range of velocities, as shown in Fig. 6. This means that altering the temperature of the gas is an important way of controlling its expansion.

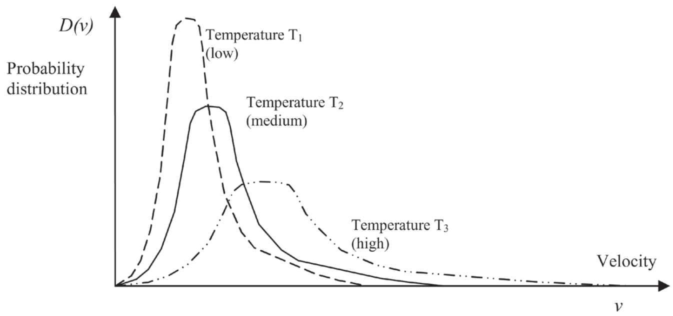


Fig. 6 Controlling expansion using temperature.

Consider now a likely target – Tritium. Table 2 shows the mean particle-velocities for Tritium at various temperatures and Fig. 7 shows its expansion into a vacuum at 273 K. It may be seen from this that an average molecule has moved 1 cm in about 7.2 μS; this interval makes beam timing using modern electronic control a fairly straightforward task.

TABLE 2: *Mean Particle Velocity of Tritium at Various Temperatures.*

Temperature (K)	Mean Velocity (ms^{-1})	Time for molecule at mean velocity to travel 1 mm
73	716	1.4 μS
123	930	1.1 μS
173	1103	907 nS
223	1252	799 nS
273	1385	722 nS
323	1507	664 nS
373	1619	618 nS
473	1823	549 nS
772	2331	429 nS
1273	2991	334 nS

In the analysis above, it was assumed that the bubble is small in comparison with the expanding shell. However, this is a rather poor assumption since the ion beam will be hitting the shell of expanding gas very soon after its release. The effect of a finite bubble can be seen qualitatively by considering Fig. 8.

Points A, B and C are three locations within the homogeneous gas. At each of these points, the particle velocity distribution is as shown in Fig. 4. Therefore, the effect of the finite size

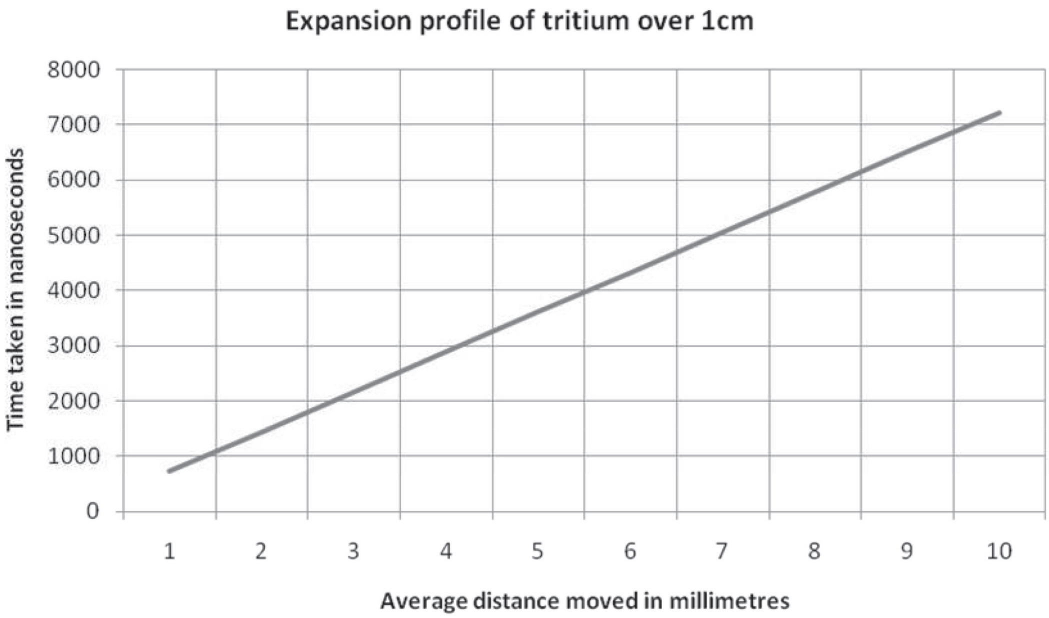


Fig. 7 The expansion of Tritium into a vacuum at 273 K

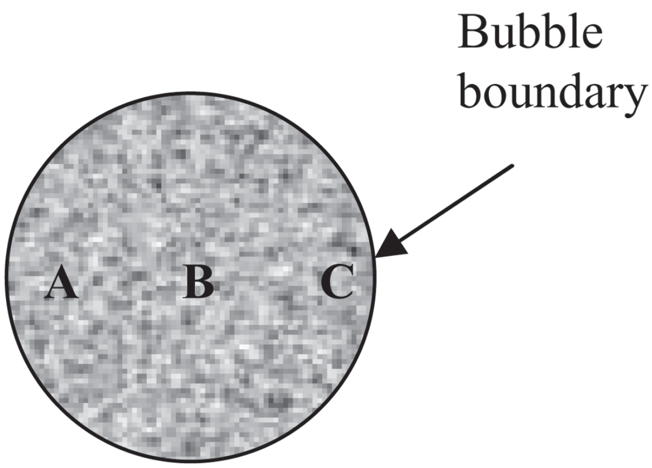


Fig. 8 The effect of a finite bubble.

of the capsule is to broaden the curve shown in that figure by the diameter of the bubble. In particular, for the rough calculations given above, the width over which equations 6, 7, and 8 apply is roughly the diameter of the bubble.

Now consider the case of a hole or window in the side of the bubble. The effect of this depends on the size of the hole. If it is small compared with the mean free path of the gas molecules and the size of the bubble, then they exit by *effusion*. The mean free path is given by:

$$\ell = \frac{kT}{\sqrt{2}\pi d^2 p}$$

Where d is the diameter of the gas molecules and p is the pressure inside the bubble. Effusive flow holds when a molecule can exit the window without collisions with other molecules being likely. In this case, subject to some simple assumptions, by integrating the velocity distribution of the molecules (equation 3), it is simple to find the number of molecules hitting the wall of the bubble per unit time [29], this turns out to be:

$$n_w = \frac{Nv_m}{4}$$

Therefore, the number escaping per unit time through a round window of radius a is:

$$n_r = \pi a^2 \frac{Nv_m}{4}$$

So the case of a completely "burst" bubble and that of a small window or hole in the bubble turn out to be reasonably straightforward. The case between the two is intermediate and more difficult to calculate as it requires a treatment of viscous flow through an orifice [29]; this is considered in some of the papers in the references [21-23].

Finally, consider the case of a liquid being boiled by an impinging beam or a solid sublimating. The situation from a gas dynamics point of view is more complex (because of the added heat). The liberated target particles will react almost immediately with the incoming beam particles, without the opportunity for expansion (and probably not conform to the ideal gas assumption). This is a difficult case to treat theoretically and there appears to be no directly applicable results available in the literature. It is also subject to the limitations on solid or liquid targets explained in the next section. Experiments and simulations are therefore required to shed light on the resultant dynamics and also to confirm the particle densities thereby generated.

5. PRACTICAL REALISATION OF TARGET

A substantial body of work has been done on solid injectors for use in magnetically confined systems. These include the tritium compatible injector developed for the tokamak reactor at Oak Ridge National Laboratory. This pneumatic system, which fires 4 mm diameter pellets into the machine, is reported by Baylor and his colleagues [30]. Another similar system for use in the ITER reactor is described by Viniar and his co-workers [31]. Both these papers contain references to other work of interest.

When considering the use of targets in solid or liquid form, it should be noted that, generally, such targets must be vaporised and perhaps ionised before they are subjected to bombardment by the accelerated beam. This is because it has been shown [6] that such targets absorb the beam energy through a number of mechanisms. These include absorption by intermolecular forces in the solid or liquid matrix, simple heating, ionisation and the activation of electrons to higher quantum energy levels (if the electrons are still bound within atoms). Thus, particles are not always elastically scattered out of the target area – which is an obvious and vital requirement for all the proposed energy recovery strategies.

A solid or liquid target could be vaporised and ionised using the inherent energy of the beam itself - though this may be inefficient - or by laser, RF heating or electrical means. The assumption is that if the solid or liquid is struck quickly by the beam, it will have a higher density than for a normal gas under stable conditions, as shown in Fig. 9. However, the extra complexity, and the practical problems associated with ensuring that the beam is not obstructed and can scatter properly are strong reasons for favouring an encapsulated gas approach over one using solids or liquids.

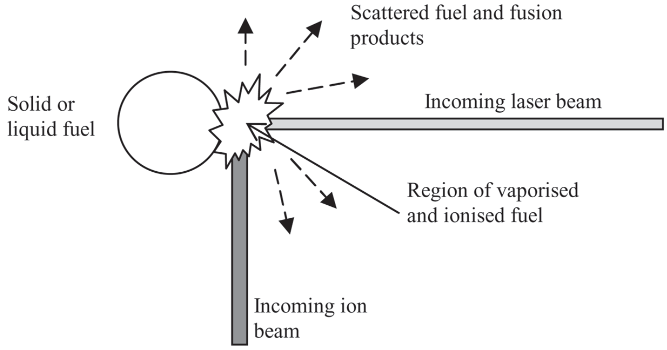


Fig. 9 Probable mode of use of a solid or liquid target.

As can be seen from the arguments above, there are some important potential disadvantages to using a solid or liquid target. For this reason, encapsulated gaseous targets would currently seem to have some advantages. Looking back to Table 1 and Fig. 3, a combined target-beam particle-density of between 10^{44} and 10^{48} $(\#m^{-3})^2$ would give a power density in the range of hundreds of kilowatts to hundreds of megawatts of power in a realistically sized target. Given that a reasonable estimate of achievable beam density (to be discussed later) is around 10^{19} $\#m^{-3}$ then this makes the required target density in the region of 10^{25} to 10^{29} $\#m^{-3}$ in terms of a gaseous shell and a lower limit of density for the tritium target of around 10^{25} $\#m^{-3}$ - which corresponds to a capsule pressure of around 1 atm at room temperature.

As described above, the interaction of capsules with lasers is potentially important. There are many different references which outline the interaction dynamics of different lasers with materials. CO_2 and Nd-YAG lasers are probably the two most widely used types described. Basic information can be found in Steen [32]; this book also specifically covers the interaction of lasers with Deuterium pellets. Other references include Luxton and Parker [33] and Webb and Jones [34].

The ionisation of the target is an interesting issue. The ionisation energy of tritium is around 14 eV, so to fully ionise 1 cm^3 of the gas at STP requires about 21 J of energy (but around 1000 times more at solid densities). In theory, this could be provided easily by the incident beam. Given that a beam particle statistically undergoes between 10 and 100 scattering events before fusion, even if each of these resulted in an ionisation event, the beam would lose only around 1.5 keV – or about 1.5% of its energy. The issue mentioned in some references [6] of major amounts of energy disappearing into the electronic activation of the target, refers to targets compounded with other elements which have much higher ionisation energies than simple hydrogen isotopes. Nevertheless, it may be beneficial for reasons of target control and efficiency to ionise the target by one of the other methods mentioned.

The discussion in the paragraphs above also highlights the issue of free electrons in the target. These make the consideration of the system more complex due to their interactions with the beam [5]. The absence of electrons from ion traps is one of their advantages but also causes their main disadvantage - because the neutralising effect of the electrons (Debye shielding) allows a higher particle density to be achieved. The quantitative effect of the free electrons does not seem to affect the predicted results in Hirsch type machines [8, 9] (these use electrons to form a potential-well in the centre of the device). However, Braams and Stott [6] indicate that, at least in thermal systems, their effect depends on temperature and that higher temperatures have an advantage in this regard. More practical research work needs to be done on this aspect of the system, as the existing information is based on research into high temperature fusion systems which have different dynamics to IEC fusion. The situation for an IEC system with energy reclaim would seem to solve or negate the problems mentioned - due to the elastic nature of the particle collisions involved, which conserves product kinetic energy. There are also several possible ways of removing electrons or at least reducing their local density for short periods as shown in Fig. 10.

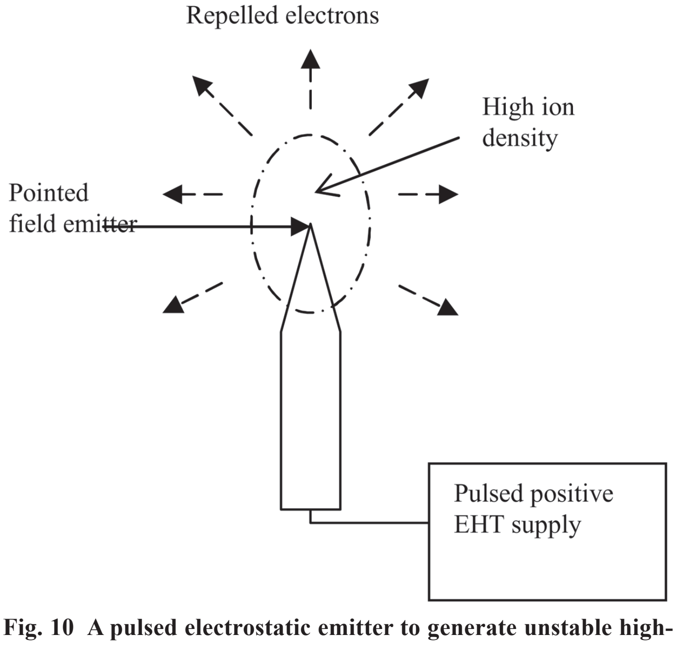


Fig. 10 A pulsed electrostatic emitter to generate unstable high-density ion concentrations.

Here an insulated metallic spike (or an array of them) is introduced into the plasma. If the spike is subject to a high pulsed potential, it will attract either ions or electrons towards it. This will form a temporary unstable region of high density – particularly since, due to their mass, electrons have a much higher mobility than ions. This may then be timed so that beam impinges on the region at the point of maximum density. This strategy could also be used to generate temporary regions of high density within more conventional ion traps or beams (and a similar effect could alternatively be engineered using metamaterials [35]).

As explained in the first paper, the optimum shape for the target is long and thin. However, as will be described shortly, it is likely that multiple impinging beams will be necessary in a practical system. If these beams enter from different directions, then a star shaped capsule might be used as shown in Fig. 11.

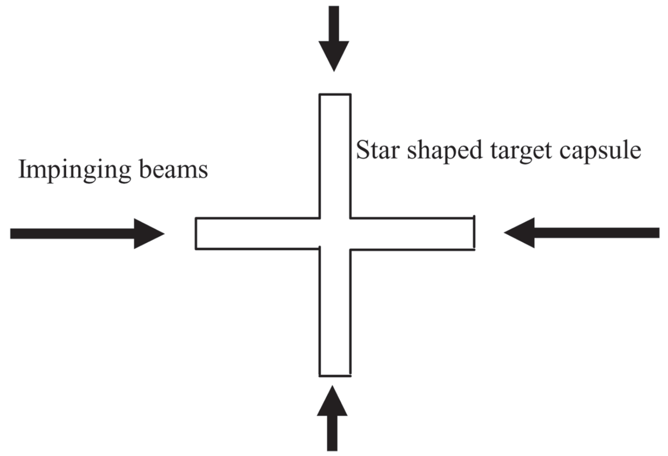


Fig. 11 A capsule suitable for use with beams impinging from different angles onto the target.

6. BEAM CONSIDERATIONS

There is another important constraint on system performance which needs to be addressed before a final system can be designed – that of beam limitation. Although the target density means that, according to equations 1 and 9, a certain energy output can be expected, this is not actually the case. In reality, particles can only fuse if their relative velocities are suitable – and this is limited by the achievable beam densities.

This situation is best illustrated by example. Consider a beam current density of 100 A cm^{-2} and a cross sectional area of 1 cm, this quite is an achievable density practically. It was shown in the first paper [1] that, a beam, made up of particles of unitary change, has an equivalent particle density of:

$$N_b = \frac{I6.24\times10^{18}}{aV}$$

Where a is the cross sectional area of the beam, V is the particle velocity and I is the beam current. Thus, the beam in this example only has an equivalent particle density of 2.01×10^{18} # m^{-3}. Given that only between 1 in 10 and 1 in 100 of these particles fuse, this corresponds to 2.01×10^{16} fusions per second in the worst case or a power density of 30 kW m^{-3}. This is not good news given that target sizes are likely to be in the size range of centimetres rather than metres.

Fortunately, these are several ways around this restriction. Firstly, the science of modern ion sources has been rapidly developing - in particular with regard to Space-Charge Neutralised beams. These are capable of pulsed current densities in excess of 1 kA cm^{-2} (equivalent to $N_b = 2.01 \times 10^{19}$ # m^{-3}). The important review paper by Humphries on this technique is required reading [36]. Even higher densities may be obtained through unstable short-term magnetic or electrostatic confinement or pinch technologies [6] - for example as shown in Fig. 12.

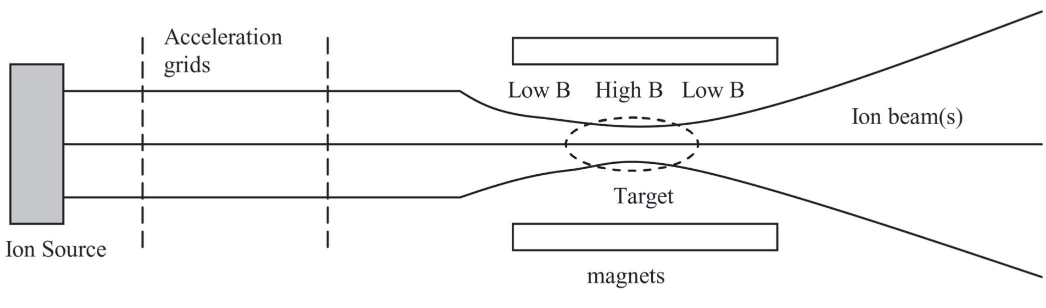
Secondly, as suggested by our previous paper, neutral beams [37] may be utilized. These are used extensively in magnetically confined fusion for heating and other purposes. Because they do not experience coulomb scattering, they may be added together to produce much more intense beams than conventional ion sources. Other similar strategies might include a directional neutralising or shielding beam as shown in Fig. 13. Such systems, in combination with the short term confinement described above, should theoretically lead to single-beam densities of at least 10^{21} #m^{-3}.

Finally, a little thought into the design of the system topology indicates that there are a large number of ways around the particle beam density limitation based on using several beams, beams of different profiles and multiple targets. As an example, one such system is illustrated below in Fig. 14.

In this design, three annular beams (labelled A, B and C in the diagram) are injected along the axis of a cylindrical machine. Target pellets are injected sequentially in a similar annual fashion to form a cylindrical configuration in the longitudinal plane of the beams, using, for example, target injectors like those already discussed [30] (note that, for clarity, in the diagram above, the cylindrical nature of the target configuration is only shown in cross-section). The beams could then be fired into the targets starting with A and progressing outwards to B and then C, such that the products from A would arrive at the B targets just as they are activated. This would result in the products arriving at the energy reclaim system at the correct time.

Because such a system contains several untested concepts, it is difficult to calculate the potential power developed precisely. However, an approximate, but soundly-based estimate may be given by way of illustration: Assuming that there is a battery of such machines, taking up a volume similar to a medium sized turbofan engine (approximately 10 m^3). Each machine 3 m long and using 10 annular beams, of 1 cm across and separated from the adjacent ring by 1 cm. If the pellets are spaced so that they took up half length of the machine (for example each 1 cm long, separated by 1 cm from the next), equations 1 and 9 give a developed power in excess of 20 MW.

Fig. 12 Short term confinement using a magnetic field.



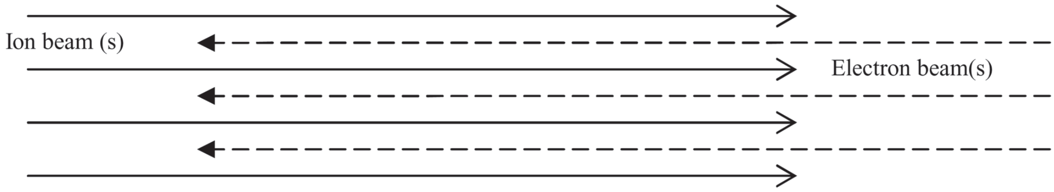


Fig. 13 Directional ion-electron charge neutralisation.

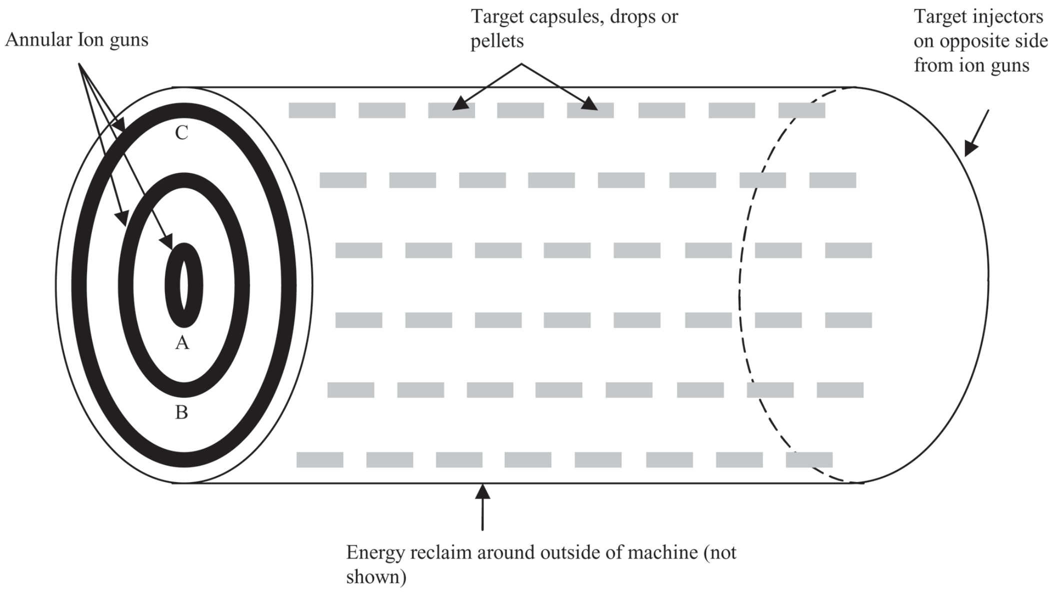


Fig. 14 Using machine topology to overcome beam density limitations.

7. CONCLUSIONS

Although fusion by IEC technology is a speculative endeavour, its potential advantages mean that it is much too important to be ignored. This is particularly true in the field of space-based development and space-travel, where a new, powerful but lightweight power-source, may open up innovative avenues for trans-atmospheric propulsion and facilitate mass-access to space.

This paper and our previous publication present a number of hitherto unreported new ideas for experimentation. The most important of these are the suggested methods of energy recovery, techniques to obtain dense targets and beams, and new machine topologies. Calculations based on models of these systems show good agreement with measured results from experiments published in older papers, and indicate that IEC fusion using this approach has different dynamics to the confinement-time based criteria used to assess thermal systems. The technology required to make the system work appears to almost within our reach or at least achievable with further development work.

As can be seen from this paper, although the detailed theory of the system is complex, simplified calculations yield useful results which can indicate whether a system is feasible or not. At the moment, the encapsulated neutral gas concept, with a roughly atmospheric-pressure capsule, appears to the front runner in terms of providing a controllable but dense target. The ion beams used in the system also need to be carefully considered and require some further development; however, suitable technologies for experimentation exist.

Any further theoretical work must now wait until some of these ideas and principles are confirmed by experiment. In particular, more work must be done on scattering from dense neutral or unstable dynamic targets and on suitable neutral, multiple, unstable and profiled ion beams. If these results confirm that elastic scattering out of the target area is the dominant mechanism and that an appropriate power-density can be achieved, then the whole IEC project will receive a major boost.

Assuming that the experiments outlined above show positive results, there are several other practical aspects of the system which need to be addressed. These include how to maintain a good vacuum and keep the active area clear and how long each capsule can be held in the path of the beam. However, these issues would certainly be addressable should the larger questions mentioned in the paragraph above be answered in the affirmative.

Apart from the obvious work required to get the system operational, some other possibilities for more speculative future work are worth consideration. These include: The use of IEC fusion as a direct drive in interplanetary craft in a similar way to that suggested for laser activated inertial systems; Combinations of both IEC encapsulated and laser-inertial systems; the delayed entrapment and confinement of the fuel inside the capsule to aid fusion and the profiling of target spatial density to facilitate a well modulated product beam.

Finally, the authors hope that this paper, read along with our previous publication, will demonstrate that there is still a great deal of potential in the field of IEC fusion and give ideas for further experimentation. Given that billions of pounds [3, 4] have been spent on other forms of fusion, it seems only reasonable that the quite modest sums required to investigate such devices should be invested.

REFERENCES

1. C. MacLeod and K.S. Gow, "A Reconsideration of Electrostatically Accelerated and Confined Nuclear Fusion for Space Applications", *JBIS*, **63**, pp.192-205, 2010.
2. T. Ligon, "The World's Simplest Fusion Reactor, and How to Make it Work", *Analog Science Fiction and Fact*, **118**, pp.40-54, 1998.
3. T. Ligon, "The World's Simplest Fusion Reactor Revisited", *Analog Science Fiction and Fact*, **128**, pp.60-80, 2008.
4. G. McCracken and P. Stott, "*Fusion: The Energy of the Universe*", Elsevier (Complementary Science Series), Amsterdam, 2005.
5. A.A. Harms *et al*, "*Principles of Fusion Energy*", World Scientific, Singapore, 2000.
6. C.M. Braams and P.E. Stott, "*Nuclear Fusion*", Institute of Physics Publishing, Bristol, 2002.
7. R.W. Bussard, "System technical and economic features of QED-engine-driven space transportation", *33rd AIAA joint propulsion conference*, 1997. Paper AIAA 97-3071.
8. 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.
9. R.L Hirsch, "On the inertial-electrostatic confinement of ionised fusion gases", *Journal of applied physics*, **38**, pp.4522-4534, 1967.
10. 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.
11. J. Welch, "The maximum efficiency of a conventional klystron output cavity", *Stanford Linear Accelerator Conference*, 1989. SLAC paper reference SLAC-PUB-3976.
12. 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
13. D.J. Wineland, "Ion traps for large storage capacity", *Proceedings of the cooling, condensation, and storage of Hydrogen cluster ions workshop*, Menlo Park California, pp.168-181, 1987.
14. 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.
15. T.A. Hochberg, "Characterisation and modelling of the gas discharge in a SFID neuron generator", PhD Thesis, University of Illinois, 1992.
16. D.L. Demin *et al*, "Liquid tritium target", *Hyperfine Interactions*, **119**, pp.349-351, 1999.
17. H.P. Greenspan and D.S. Butler, "On the expansion of a gas into vacuum", *Journal of fluid mechanics*, **13**, pp.101-119, 1962.
18. K.P. Stanyukovich, "*Unsteady motion of continuous media*", Pergamon Press, New York, 1960.
19. P. Molmud, "The expansion of a rarefied gas into a vacuum", Space Technologies Laboratories, Los Angeles, 1958.
20. R. Narasimha, "Collisionless expansion of gases into vacuum", *Journal of fluid mechanics*, **12**, pp.294-308, 1961.
21. L.E. Levine, "The expansion of a wedge of gas into a vacuum", *The mathematical proceedings of the Cambridge Philosophical Society*, **64**, pp.1151-1163, 1968.
22. D.M. Moody, "Unsteady expansion of an ideal gas into a vacuum", *Journal of fluid mechanics*, **214**, pp.455-468, 1990.
23. D.C. Pack, "The expansion of a jet of gas into a vacuum or near vacuum", *Fluid Dynamic Transactions*, **7**, pp.57-79, 1974.
24. J.B. Keller, "On the solution of the Boltzmann Equation for rarefied gases", *Communications on pure and applied mathematics*, **1**, pp.275-285, 1948.
25. T. Guenault, "*Statistical Physics*", Routledge, London, pp.76-82, 1988.
26. H.D. Young and R. A. Freedman, "*University Physics (9th ed)*", Addision-Wesley, Reading MA, pp.517-520, 1996.
27. W.P. Crummett and A.B. Western, "*University Physics*", Wm C Brown Pub, Dubuque, IA, pp.564–579, 1994.
28. G. Rogers and Y. Mayhew, "*Engineering Thermodynamics (4th Ed)*", Longman Scientific and Technical, Harlow, pp.160-161, 1992,
29. R.D. Present, "*Kinetic theory of gases*", McGraw-Hill, Newyork, pp.21-32, 1958.
30. L.R. Baylor *et al*, "Pellet Injector Development and Experiments at ORNL", *The 15th IEEE/NPSS symposium on Fusion Engineering*, Hyannis MA, Vol. 2, pp.583-588, 1993.
31. I.V. Viniar *et al*, "A large-scale Prototype of a Tritium Pellet Injector for the ITER International Tokamak", *Instruments and Experimental Techniques*, **45**, pp.127-131, 2002.
32. W.M. Steen, "*Laser Material Processing (3rd ed)*", Springer, London, 2003.
33. J.T. Luxton and D.E. Parker, "*Industrial Lasers and their Applications*", Prentice-Hall, Englewood cliffs, 1985.
34. C. Webb and J. Jones (eds), "*Handbook of Laser Technology and Applications: Volume III – Applications*", IOP Publishing, London, 2004.
35. J.B. Pendry, D. Schurig and D.R. Smith, "Controlling Electromagnetic Fields", *Science*, **312**, pp.1780-1782, 2006.
36. S. Humphries, "Intense pulsed ion beams for fusion applications", *Nuclear Fusion*, **20**, pp.1549-1612, 1980.
37. J. Park and G.A. Wurden, "Intense diagnostic neural beam for ITER", *ITER forum*, University of Maryland, 2003.

(Received 23 June 2011; 17 August 2011)

* * *