Confining plasma in a spherically-convergent electrostatic potential well: the Farnsworth-Hirsch fusor

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Abstract

A device to confine a plasma in an electrostatic potential well was constructed with the objective of demonstrating nuclear fusion. A plasma of rarefied air was successfully confined, resulting in a discharge glow.

Contents

1 Introduction

1.1 Preamble

Nuclear fusion has a particular fascination both for scientists and the general public. This may be explained by the elegance of the theory that explains the phenomenon, its unfamiliarity in everyday life, and of course the promise it holds for providing our society with energy in the future.

Obtaining useful energy from fusion has proven to be among the most difficult scientific and engineering projects so far undertaken, far more difficult than that of landing a human on the moon and returning them to Earth. When that feat was accomplished in 1969, the progress of technology seemed to be swift, and any task within our means to accomplish. It was thought likely that fusion reactors would be generating electricity before the turn of the century.

Four decades on, it is clear that fusion power will not be realised on a large scale for many more decades still. It is seldom noted, however, that nuclear fusion reactions are not difficult to obtain in themselves. Two deuterons colliding with energies in the order of 10s of keV will have a chance of fusing, and it is not difficult to accelerate particles to these energies. The easiest way to do so is using electric fields.

An apparatus was assembled which could create fusion reactions in this way, although in practice the limitations of the vacuum equipment available prevented actual fusion from being observed. The device constructed was a Farnsworth-Hirsch fusor, named for the inventors Philo T. Farnsworth and Robert L. Hirsch who developed the design in the 1960s. This device is conceptually very simple.

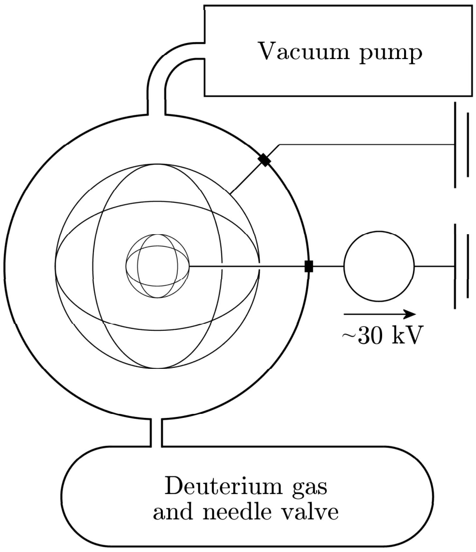

Figure 1: A basic fusor setup.

1.2 Concept

A Farnsworth-Hirsch fusor consists of two spherical wire grids, one larger than the other, mounted concentrically inside an evacuated vacuum vessel. A high voltage is placed across the grids - conventionally, the inner grid becomes a cathode while the outer grid remains earthed. The vessel is then back-filled with deuterium gas.

The intense electric field near the cathode causes breakdown in the deuterium gas, and positive deuterons begin to oscillate in simple harmonic motion about the centre of the potential well formed by the two grids. When two deuterons collide near the centre, there is a chance of fusion taking place.

A voltage of $\sim$30 kV is required before significant fusion begins to occur, and a vacuum of $\sim 10^{-6}$ mbar will be required before deuterium is introduced. An operating pressure of $\sim 10^{-4}$ mbar is typical. [1]

1.3 History

The fusor concept originated when Philo Farnsworth was experimenting with multipacting vacuum tubes in the early 1950s. He noticed that at high voltages, many of his tubes produced brightly glowing plasmoids. These were generally an impediment to the functioning of the vacuum tubes, but Farnsworth realised that they could be used in other ways.

Farnsworth's early fusor designs involved multiple ion guns aligned so that their beam axes intersected at the centre of the device. These designs never achieved significant fusion, but later work by other scientists showed that a simple arrangement of wire grids actually worked much better. Robert Hirsch was the first to propose the specific design described above, in a 1967 paper where he described observing 'copious neutron emission' from the device. [1]

1.4 Applications

There are two equally likely fusion reactions [2] possible when two deuterons collide.

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.02\ \mathrm{MeV}) \quad (1)$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}\ (2.45\ \mathrm{MeV}) \quad (2)$$

The tritons produced in (1) can then undergo further fusion [2] with another deuteron.

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}\ (3.5\ \mathrm{MeV}) + \mathrm{n}\ (14.1\ \mathrm{MeV}) \quad (3)$$

These equations explain the significant neutron flux observed by Hirsch.

The fusor is not a practical means of generating energy, owing to limits in grid transparency, unavoidable thermalisation, and bremmstrahlung radiation losses [3]. However, versions of the fusor are being used commercially as neutron sources.

2 Theory

2.1 Reaction Cross-Sections

The probability that a fusion reaction will occur when two nuclei collide is called the 'reaction cross-section', and it has units of area. It is not a basic theoretical property, merely a useful practical number, and can be roughly understood as follows.

If there is a flux of particles travelling through a 'tunnel' of cross-sectional area A, and at some point that tunnel is obstructed by another particle of area a in the direction of flux, then the probability for some travelling particle of colliding with the obstructing particle is a/A. It follows that the 'cross-section' of the obstructing particle may be calculated by multiplying the probability of collision by the area of the tunnel.

In the case of nuclear fusion reactions, the respective cross-sections depend on numerous variables including the charge, mass, and energy of the colliding nuclei. The usual unit for these quantities is the *barn*, 10^{-28} m^2, so named because it is 'as big as a barn' in comparison to typical nuclear cross-sections.

Figure 2 demonstrates that particle energies of only 10s of keV are sufficient to obtain significant D-D fusion.

2.2 Neutron Flux

Demonstrating fusion requires the measurement of a significant neutron flux. The expected neutron flux can be predicted from the reaction rate, which can in turn be predicted using the reaction cross-section, grid voltage and measured current.

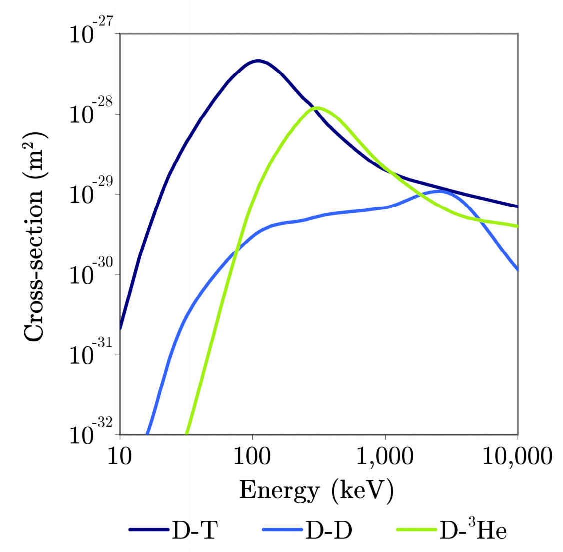

Figure 2: Reaction cross-sections for important fusion reactions (adapted from figure in [4]).

The following theory is adapted from the supplement to [1].

Gauss's Flux Law determines that in the case where the inner electrode is a spherical hollow ball, the electric field inside it will be zero. Of course the real electrode is a wire grid and will not be perfectly spherical, but to a reasonable approximation there will be no electric field within the inner electrode. It follows that the kinetic energy of the deuterons within the reaction volume will be largely constant.

$$E = qV, \tag{4}$$

where q is the charge of the ions accelerated and V is the voltage between the electrodes. The charge of a deuteron is $+e$, so E will be one keV per kV of voltage.

By simple relation with the kinetic energy equation (the ions will not be relativistic), we determine that

$$v = \sqrt{\frac{2eV}{m_D}}. \tag{5}$$

Dividing the velocity by the grid diameter $2r$ gives the approximate time τ that each ion is inside the grid.

If we assume that the current from our power supply is entirely due to the flow of ions within the fusor, we can calculate the rate at which deuterons are entering the inner grid by dividing the current in Amps by e. This must then be multiplied by a 'recirculation factor' f to account for the fact that the ions will pass through the inner grid more than once, owing to its relative transparency.

The number n of ions inside the grid at any time is given by

$$n = \frac{I}{e} f \tau = \frac{I}{e} f \frac{2r}{v}. \tag{6}$$

The reaction rate equals the square of the ion density multiplied by the product of reaction cross-section σ and ion velocity v.

$$R = \rho^2 \sigma v = \sigma \left(\frac{3If}{2\pi e r^2} \right)^2 \left(\frac{m_D}{2eV} \right)^{\frac{1}{2}} \tag{7}$$

This result is an approximation owing to the numerous assumptions made and the neglect of possible reactions outside the inner grid.

The values of I and f are difficult to predict but will depend greatly on the quality of the vacuum, the geometry of the grids and other variables that are difficult to quantify. Nevertheless, by assuming that $\sigma \approx 10^{-30}$ m^2, that I is on the order of 10^{-3} A and that f is on the order of 10, and supposing a voltage of 30 kV, a reaction rate on the order of 10^3 s^{-1} would be expected. Since 50% of reactions will release neutrons (ignoring D-T reactions which will be negligible in number), we would expect neutron production to be on the same order of magnitude.

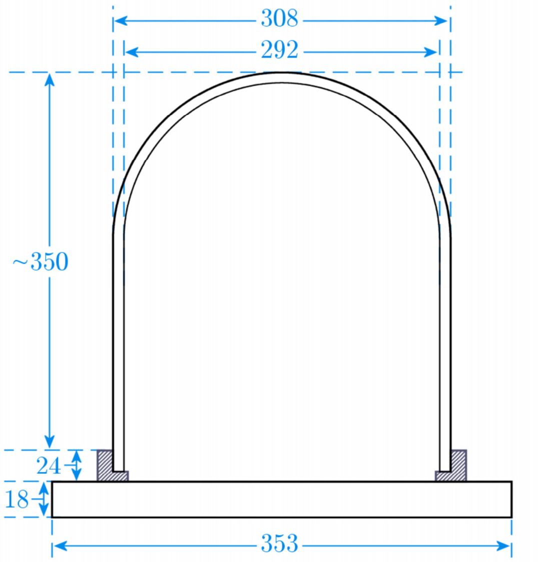

Figure 3: Diagram indicating the dimensions of the vacuum chamber equipment. All values in mm, diagram not to scale.

3 Implementation

3.1 Equipment

Throughout the project, Richard Hull's notes on fusor construction [5] were of great help, and they informed most of the design and construction decisions made.

The vacuum equipment used was taken from an evaporation plating apparatus, and included a rotary pump, stainless steel base plate, and a pyrex bell jar. A pressure gauge, steel vacuum hose, and numerous vacuum fittings were also obtained.

The electrical equipment included a power supply rated for up to 100 kV at up to 10 mA, and fittings to transfer that power to the vacuum chamber. The required spherical wire grids were manufactured from stainless steel wire by welding lengths of wire into hoops and silver-soldering them together. The large outer grid required brass pieces to hold the hoops together during the silver soldering process.

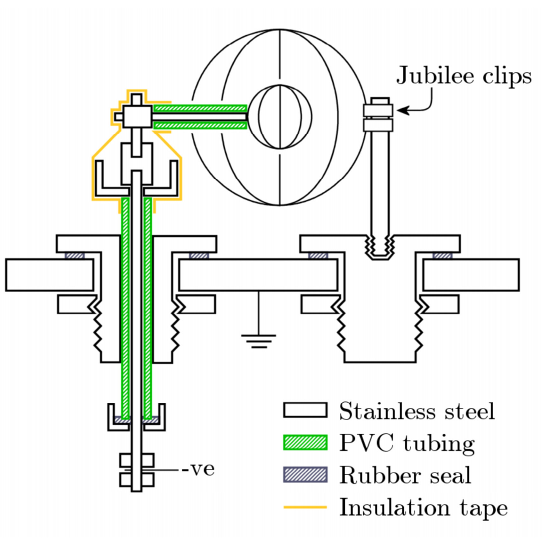

Figure 4: Diagram illustrating the design of the electrical feed-throughs. Diagram not to scale.

The pyrex bell jar was placed on the steel base plate, with a rubber gasket to ensure a good vacuum seal (see figure 3). The base plate included nine inlets within the circumference of the bell jar. Two were used to house the voltage feed-throughs, the other seven were plugged with three blanks and four rubber bungs.

3.2 Electrical fittings

The electrical feed-throughs were largely assembled from vacuum fittings that had been used in the previous plating setup, with the addition of PVC tubing and plastic tape to provide insulation to the negative electrode and prevent arcing within the chamber (see figure 4). The inner grid was silver-soldered onto a threaded metal rod, which was insulated with PVC tubing, and mounted using a boss. The outer grid was attached using a pair of jubilee clips.

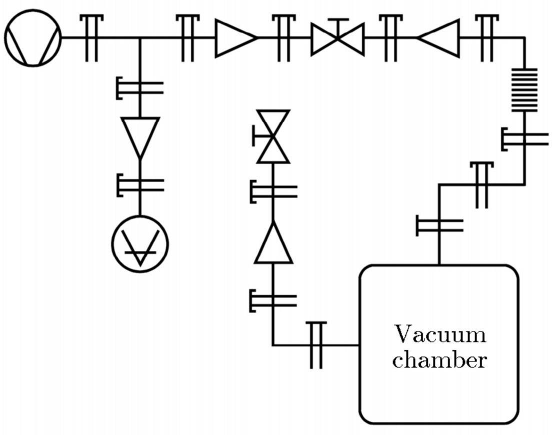

Figure 5: Schematic illustrating the layout of the vacuum system, using symbols from [6].

3.3 Vacuum equipment

The vacuum pump was tested and found to be capable of producing a vacuum of 4.8×10^{-3} mbar. The vacuum equipment was assembled as illustrated in figure 5. On completion, the best vacuum obtained tended to $\sim 1.0 \times 10^{-2}$ mbar.

This was sufficient for the initial testing of the apparatus, in which a plasma of rarefied air was confined. Higher vacuums would have been necessary for the fusion application of the apparatus, however, there was insufficient time to proceed to that stage.

3.4 Risks

The main risk in this project stems from the use of very high voltages [5]. High voltage safety precautions were taken at every stage. No operator worked in close proximity to uninsulated electrical connections, and all connections were insulated carefully after assembly. An earthed conducting rod was used to ensure that all components were fully discharged after testing, before any operator approached them again.

The use of vacuum equipment posed some risks, the greatest of which was the risk that the bell jar might implode. A metal shield was placed over the bell jar whenever it was to be evacuated, and it was not removed until the pressure had been restored.

There were radiological risks, including x-rays resulting from the high voltages, as well as fast neutrons in the full fusing configuration. As events transpired, very high voltages were never used and the experiment never reached the point of fusion. A safe distance was kept from the operating device until it had been established using an x-ray dosimeter that no x-rays were penetrating the bell jar at the voltages used.

4 Outcomes

4.1 Successes and Failures

The completed apparatus produced an impressive discharge glow confined within the inner grid. The glow was generally blue in colour, consistent with the expected emission spectrum for nitrogen.

Confinement seemed reasonably good at 5 kV, with one very noticeable jet directed towards the 'south pole' of the outer grid. As the voltage was increased, fluctuations in the plasma also increased.

The project was successful in demonstrating that a plasma could be confined in an electric field. It was unsuccessful in demonstrating nuclear fusion.

4.2 Conclusion

The project was quite challenging, somewhat successful, and very enjoyable. It is regrettable that more time was not available in which to try and attain the vacuum required for fusion, but there is no reason why the same apparatus could not be used with a superior pump to demonstrate that phenomenon.

References

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[4] *Magnetic Fusion: Introduction*, accessible at http://www-fusion-magnetique.cea.fr/gb/fusion/fusion.htm/

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[6] Huntington Mechanical Laboratories, Inc: *Graphic Symbols for Important Components Used in Vacuum Technology*, accessible at http://vacuumfeedthru.com/tech_libr/symbols/default.htm