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Short communication

Confinement of fusion plasmas with electric fields

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Abstract

Most fusion reactor designs involve the confinement of plasmas by magnetic fields. We show that electric fields may also be useful in fusion energy devices.

Key words: Fusion energy, plasma confinement.

1. Introduction

Most fusion reactor designs have involved either magnetic or inertial confinement forces[1]. It has often been assumed that electric fields could only contain one component of a plasma: ions or electrons[2]. Lavrentyev[3] and Farnsworth[4] have shown, however, that a spherical system of alternating electric fields makes possible the simultaneous confinement of both ions and electrons (fig. 1a).

In the absence of loss to electrodes the confinement time of such a device would be[5,6]

$$\tau \approx \tau_e \frac{e\Delta V}{T} \exp \frac{e\Delta V}{T} \tag{1}$$

where τ_e is the electron scattering time, e the electronic charge, and ΔV the height of the potential barrier confining a plasma of temperature $T_i = T_e = T$.

Since for Coulomb collisions

$$\tau_e \approx 2 \times 10^4 \frac{T^{3/2}}{n} \tag{2}$$

we can write:

$$n\tau \approx 2 \times 10^4 T^{3/2} \frac{e\Delta V}{T} \exp \frac{e\Delta V}{T} \tag{3}$$

noting the absence of dependence on device size. For a fusion reactor we require $n\tau \geqslant 10^{14}\,\mathrm{cm^{-3}\,s}$ and $T \geqslant 10^4\,\mathrm{eV}$ and find that $e\Delta V/T \sim 7$. As originally envisioned an

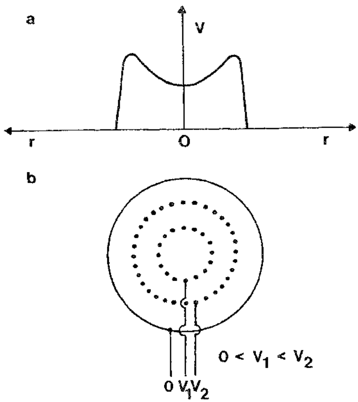

FIG. 1. (a) Plasma potential as a function of plasma radius. (b) Electrostatic confinement device with electrode bias voltages V_1 and V_2.

'electrostatic confinement device' might consist of a set of three concentric spherical electrodes (grids)[3] (fig. 1b).

Such a device suffers from grid bombardment heating as well as plasma loss to the electrodes[7]. To reduce these losses, Lavrentyev suggested that the grids be fabricated from numerous current-carrying wires surrounding themselves with insulating magnetic field layers[8]. These new machines were variously called 'electromagnetic' or 'Lavrentyev' traps.

On the other hand, Farnsworth stuck with a magnetic field-free system but suggested that one or more of the metal grids be replaced by space-charge layers[4]. This is not expressly prohibited by Earnshaw's theorem (which only applies in regions containing zero charge density[9]) but neither has the resulting 'inertial-electrostatic confinement' system proven especially effective in actual experiments.

By constraining the potential structure from three down to one dimensional (by use of an axial magnetic field) this system has evolved into the 'Tandem mirror' concept as proposed by Dimov[10]. The magnetic mirroring forces can then anchor the space charge so as to enforce the potential profile required in fig. 1a.

More recently, Jones[11] has proposed 'magnetoelectrostatic confinement', a system in which the Lavrentyev electrodes are replaced by swarms of charged particles ('space charge' again) guided by, and anchored on to, magnetic flux tubes. One might imagine, for instance, that the grids of fig. 1b had been replaced by azimuthal magnetic field lines loaded with ions or electrons. In practice, toroidal systems are envisioned[12] containing good magnetic surfaces flooded with non-neutral plasma. The magnetically insulated toroidal space-charge layers then establish a radial potential profile like that of fig. 1a. This profile, in turn, confines a hot (roughly charge neutral) fusioning toroidal plasma core.

It is actually quite easy to establish such non-monotonically varying radial potential profiles even in closed magnetic geometries (at least transiently). Neutral plasma can be formed as the toroidal field is ramping up. This can be followed by the injection of a non-neutral plasma near the periphery and a further increase in the toroidal field. After additional magnetic compression, a neutral plasma layer can be added near the wall.

Equation 1 was derived on the basis of electrostatic confinement alone. Various authors have considered the more complicated problem of plasma transport across a magnetic field in the presence of an electric field. Stix predicts[13] that the crossfield drift velocity will be

$$V_{\perp} = \frac{nT_e}{B^2}\eta_{\perp} \exp\left(\frac{-e\Delta V}{T_i}\right)\nabla\left(\frac{e\Delta V}{T_e}\right) \tag{4}$$

so the confinement time will scale as

$$\tau \approx \frac{r^2}{4D_{\perp}\dfrac{e\Delta V}{T}\exp\left(\dfrac{-e\Delta V}{T}\right)} \tag{5}$$

where $D_{\perp}$ is the crossfield diffusion coefficient for ordinary magnetic confinement, r the plasma radius, and we have assumed $T_i = T_e = T$.

On the other hand, Hershkowitz *et al*[14], and Zhilinskii and Tsendin[15] have employed equations which amount to the scaling law:

$$\tau = \frac{r^2}{4D_{\perp}\exp\left(\dfrac{-e\Delta V}{T}\right)}. \tag{6}$$

In either case, reasonable values of $e\Delta V/T$ result in orders of magnitude improvement in confinement.

Clark *et al*[16] have considered the use of an electrostatic field to contain energetic alpha particles in a Tokamak. They calculate the line density of excess charge needed to generate an electric field

$$E \approx \frac{2N_b e}{r}. \tag{7}$$

For our value $e\Delta V/T \sim 5$–10, $E =$ a few $\Delta V/r$ and $N_b \sim 10^{12}\,\mathrm{cm}^{-1}$. The excess charge density is only $= 10^8\,\mathrm{cm}^{-3}$ which is very small compared with typical core plasma densities $n \sim 10^{14}\,\mathrm{cm}^{-3}$. Such magnetised (space charge) virtual electrodes will disperse due to diffusion and electrostatic repulsion according to

$$\Gamma = D_{\perp}\nabla n + D_{\perp}\frac{ne}{T}\nabla V \approx D_{\perp}\frac{ne}{r}\frac{\Delta V}{T}. \tag{8}$$

The layer will thus diffuse $\sim e\Delta V/T$ times faster than a magnetically confined plasma. The particle and energy investment are small, however, and injection might be used to sustain the layers.

Various means for injecting net charge into a magnetised plasma have been discussed by Jones[17] and Miley *et al*[18]. Successful preliminary experiments have been conducted by Jones[12]. It might also be possible to reduce $D_\perp$ for the virtual electrodes by assembling the non-neutral space charge from superthermal (energetic) particle streams. Classically, the coulomb collision frequency of such superthermal particles would be much reduced, leading to a decrease in $D_\perp$.

References

1. Heppenheimer, T. A. *The man-made Sun*, Little Brown, 1984.
2. Roth, J. R *Introduction to fusion energy*, Ibis Publishing, 1986, p. 436.
3. Lavrentyev, O. O. *Ukr. Fiz. Zh.*, 1963, **8**, 440–445.
4. Hirsch, R. L. *J. Appl. Phys.*, 1967, **38**, 4522–4534.
5. Pastukhov, V. P. *Nucl. Fusion*, 1974, **14**, 3–6.
6. Dolan, T. J *Electrostatic confinement*, LLL report UCID-17576, Aug. 1977.
7. Elmore, W. C., Tuck, J. L and Watson, K M. *Phys. Fluids*, 1959, **2**, 239–246.
8. Lavrentyev, O. O. *Ukr. Fiz. Zh.*, 1963, **8**, 446–451.
9. Barger, V D. and Olsson, M. G. *Classical electricity and magnetism*, Allyn and Bacon, 1987, p. 68.
10. Dimov, G. I., Zakaidakov, V V. and Kishinevskii, M. E. *Fiz. Plazmy*, 1976, **2**, 597–610.
11. Jones, R *Lett. Nuovo Cimento*, 1983, **37**, 330–332.
12. Jones, R. *Lett. Nuovo Cimento*, 1985, **42**, 117–122.
13. Stix, T. H. *Phys. Fluids*, 1971, **14**, 692–701.
14. Hershkowitz, N., Hendricks, K. and Carpenter, R. T. *J. Appl. Phys.*, 1982, **53**, 4105–4112.
15. Zhilinskii, A. P. and Tsendin, L. D. *Sov. Phys. Usp.*, 1980, **23**, 331–355.
16. Clark, W., Korn, P., Mondelli, A. and Rostoker, N. *6th Sym. Eng. Prob. of Fusion Res.*, 1975, pp. 178–183.
17. Jones, R. *Bull. Am. Phys. Soc.*, 1989, **34**, 121.
18. Miley, G. H., Downum, W. B., Hively, L. M. and Choi, C. K. *J. Nucl. Mater.*, 1980, **93**, 197.