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A4_4 Magnetic field alignments for nuclear fusion

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Abstract
This article considers two different configurations of magnetic field that could be used for magnetically confined nuclear fusion and considers whether using magnetic pressure to confine the plasma would allow a magnetic field of reasonable strength to be used. It was found that a feasible magnetic field strength (0.18 T) would be required to constrain the particles with an average energy, but it leaves the calculation regarding more energetic particles for further work.

Introduction
One of the aims of modern physical science is to create solutions to the problem of the so-called energy crisis, while also attempting to address the issue of climate change and greenhouse gases. Nuclear fusion is one of the potential sources of energy that could be used and that is 'clean' (i.e. does not emit greenhouse gases). The most common form of fusion device is a tokamak, in which a gas is heated to very high temperatures (10^8 K [1]) and is ionised. The resultant plasma is confined using a magnetic field. One of the related devices to the tokamak is the pinch device (of various types) however it suffers from some of the plasma inevitably escaping and damaging the device meaning that it can only run for very short periods of time and hence does not run long enough to generate enough energy to be of use. If the loss of plasma from the pinch could be reduced simply by using a different magnetic field alignment then it would obviously be beneficial and so this article shall consider using magnetic pressure to confine the plasma and will see if such a system would require a feasible magnetic field strength.

Magnetic mirror
What follows is a brief description of the type of magnetic field configuration used in a basic pinch device. Consider a region of magnetic field of varying field strength, as shown in Fig. 1. The magnetic moment (μ) of a charged particle in a magnetic field is given by Eq. (1), with m the mass of the particle, B the magnetic field strength and $v_\perp$ the velocity of a particle perpendicular to the magnetic field. Introducing the mirror ratio (R_m), which is a constant for any given configuration, it is possible to obtain an expression relating the ratio of the magnetic field strength at its weakest point (B_0) to that at its strongest point (B_r) with the inverse of the mirror ratio as given by (2) [4]. The magnetic moment is a constant regardless of the magnetic field strength, so it can be seen from Eq. (1), as B increases, $v_\perp$ must increase. Due to conservation of energy, $v_\parallel$ must decrease if $v_\perp$ increases, eventually

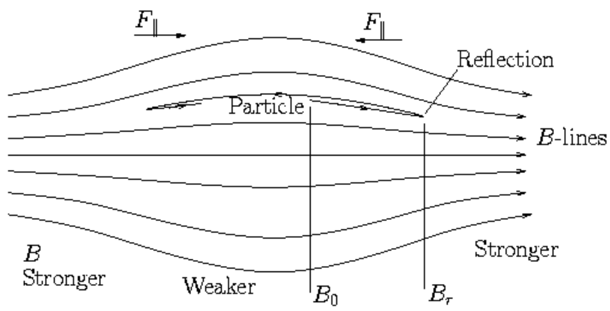

Fig. 1: The magnetic field alignment that gives rise to a magnetic bottle. [3]

causing the charged particle to be reflected and change direction. If another similar region of magnetic field is present at some other point in the particle's motion, then the particle will once again be reflected and will now be trapped between these two points in what is known as a magnetic bottle.

$$\mu = \frac{1}{2}\frac{mv_\perp^2}{B}. \tag{1}$$

$$\frac{B_0}{B_r} = \frac{1}{R_m}. \tag{2}$$

Magnetic pressure
Consider a uniform region of magnetic field with a charged particle entering the area. It will experience a Larmor force which makes it move in a circle segment of radius r_L, the Larmor radius. This force will act on the particle until it is no longer in the area of magnetic field (the particle will have travelled through a semi-circle) and thus the particle will be effectively reflected (it will also have drifted and hence there will be a resultant current, but this shall not be considered here). This results in what is known as magnetic pressure, which follows the relation given in Eq. (3) [5], with μ_0 being the permeability of free space.

$$P_{\mathrm{mag}} = \frac{B^2}{2\mu_0}. \quad (3)$$

Discussion

Taking Eq. (3),then combining it with the pressure exerted by a plasma (Eq.(4) [4]) and rearranging for B, one arrives at (5), with n the particle density, k_B the Boltzmann constant and T the temperature of the plasma.

$$P = nk_BT. \quad (4)$$

$$B = \sqrt{2\mu_0 nk_BT}. \quad (5)$$

Of the values in Eq. (5), some are known and some must be estimated. The constants k_B and μ_0 are known, the temperature will be assumed to be that within the JET tokamak (10^8 K [1]) and the plasma number density shall be 9×10^{13} cm^{-3} [6]. Putting all of these values into Eq. (5) along with the known value for the constants leads to a magnetic field strength of approximately 0.18 T.

At first glance, the magnetic field apparently required to confine this high temperature plasma seems perfectly achievable. One fifth of a Tesla is not a small magnetic field (planetary magnetic fields are often hundreds of nT) but it is quite possible to generate a field of this strength on Earth. This calculation does of course ignore a single, very important factor. Equating pressures in this manner takes account of average energies only. The particles making up the plasma will have a Maxwellian temperature distribution and so while a magnetic field of strength of 0.18 T might well be sufficient to confine the particles with an average energy, it will not confine those of more extreme energies. It would be an interesting further extension to look at confining those particles with much higher energies and taking an acceptable fraction of leaked plasma, to again work out the required magnetic field in this situation.

Conclusion

It proved possible to calculate the magnetic field strength required to allow the magnetic pressure from the magnetic field alignment to equal the pressure exerted by the plasma and this value turned out to be 0.18 T. This does not of course stop any particles of higher energies than the average and so it has been left to further investigations to ascertain if the magnetic field strength is of plausible strength to confine more energetic particles.

REFERENCES

[1] www.jet.efda.org (06/02/2011)
[2] www.jet.efda.org (09/02/2011)
[3] silas.psfc.mit.edu (06/02/2011)
[4] F. F. Chen, *Introduction to plasma physics and controlled fusion, Volume 1: Plasma physics* (Springer, 2006), Sec. 2.3.3.
[5] S. Milan, *Space plasmas* Lecture course, October - December 2010
[6] V. G. Petrov et. al., *Measurements of the Plasma Density in the FTU Tokamak by a Pulsed Time-of-Flight X-Wave Refractometer*, (Pleiades Publishing Ltd., 2008) Plasma Physics Reports, Vol 34, pp24 - 30