**Plasma physics**

# Fusion in magnetized plasmas

*from A.C. Riviere*

FUSION of light nuclei under controlled conditions promises to be a source of energy for electricity generation in the future. The latest acheivements in plasma physics and controlled nuclear fusion, many of which were reported at a recent conference*, make it clear that considerable progress has been made towards the conditions needed for 'ignition', when energy lost from the plasma is matched by energy gained from alpha particles produced by fusion reactions. In a plasma that is half deuterium and half tritium, this requires the product of nuclear density ($N$) and energy confinement time $\tau_E$ to exceed about $2 \times 10^{20}\ \mathrm{m}^{-3}\mathrm{s}$ with the temperature above 10 KeV ($10^8$ K).

The main approach to fusion has been to use a magnetic field to isolate the hot plasma from the vacuum vessel wall, and the most successful magnetic field geometry is that of the 'tokamak' which combines a strong toroidal field with the field due to a toroidal current flowing in the plasma. A record value of $0.8 \times 10^{20}\ \mathrm{m}^{-3}\mathrm{s}$ for $N\tau_E$ at 1.5 KeV has been achieved in the Alcator C tokamak at MIT (M. Greenwald) by injecting solid hydrogen pellets into the ohmically heated plasma. This method of refuelling raises $N$ without causing a reduction in $\tau_E$. In a much larger tokamak, Doublet III at San Diego, a value of $0.14 \times 10^{20}\ \mathrm{m}^{-3}\mathrm{s}$ for $N\tau_E$ at 6 KeV has been achieved by combined neutral-beam heating and hydrogen-pellet refuelling in a divertor configuration. In the latter variant of the tokamak, magnetic field lines are arranged to connect the plasma edge to a remote collector rather than have the plasma edge defined by a local solid surface. This allows some control over the flow of impurity ions into the plasma and thereby a reduction in radiation losses. Experiments at ASDEX, Max Planck Institut, Garching and PDX, Princeton, also show improved performance with a divertor, particularly in allowing the maintenance of a second plasma state, called the H-mode, the $\tau_E$ of which is about a factor of 2 better than that of the more usual state. In the H-mode a steep rise in temperature occurs at the plasma edge but whether the divertor configuration is essential for this to be formed is not yet clear.

Although plasma densities and temperatures close to those required for ignition have been achieved separately at various times, it remains difficult to reach the necessary energy confinement time. Energy is lost from the plasmas in fusion experiments at an anomalously high rate compared with that expected from the effect of electron-ion collisions. Until recently the scaling of $\tau_E$ with size for tokamaks was though to vary as the square of the scale size — in particular, $\tau_E \propto a^2$, where $a$ is the minor radius of the plasma — so larger and larger machines have been built. With results now available from a wide range of machines it is, instead, found that $\tau_E$ increases as the cube of the scale size, probably as $\tau_E \propto aR^2$, where $R$ is the major radius of the torus (P.C. Efthimion, TFTR, Princeton). The Joint European Torus (JET), the largest tokamak built so far with $R = 2.96$ m and $a = 1.25$ m, started operating about a year ago and its performance is at least as good as was originally hoped — with $\tau_E$ about 0.8 s — and confirms the scaling with $aR^2$ (P. Rebut and J.G. Cordey). Plasma currents approaching 4 MA have been achieved in JET and 25 MW of additional plasma heating power is soon to be installed. This is expected to drive the plasma density and temperature up to the conditions where the power deposited by the $\alpha$-particles from thermonuclear reactions will play a major role (P. Rebut).

Many new experiments have been successful in improving energy confinement. For example, injection of deuterium instead of hydrogen beams into deuterium plasmas at Doublet III and ASDEX, refuelling with pellets rather than feeding gas at the plasma boundary at Alcator C and Doublet III, addition of low Z impurity ions at ISX-B, Oak Ridge, and the use of magnetic divertors at ASDEX, Doublet III and PDX. An explanation for all these effects did not emerge at the meeting, although careful construction of the relative shape of temperature and density profiles may be one factor in minimizing the cross-field energy flow to the walls.

A clear answer is, however, emerging on the maximum value of the ratio ($\beta$) of plasma to magnetic-field pressure that can be supported by tokamaks with present techniques. Many experiments have found a $\beta$ limit, independent of the form of heating, given by $\beta = \mathrm{const} \times I/(aB)\%$, where $I$ is the plasma current and $B$ the value of the toroidal field at the plasma centre. The maximum value of the constant achieved in experiments at Doublet III, ASDEX, PDX, and both CLEO and TOSCA (Culham), is about 3.5, which is in quite good agreement with theoretical calculations by several groups. Beyond this value of $\beta$, the $\tau_E$ decreases rapidly or the plasma completely breaks up ('disrupts') and the plasma energy is lost. The currently observed limit to $\beta$ is rather restrictive for present thermonuclear reactor designs based on the tokamak, because their values of $I/aB$ are too small. Some re-thinking of typical reactor parameters is now needed. It should be recalled that there is a limit (the Kruskal/Shafranov limit) above which the plasma current of a tokamak cannot be increased; at higher currents the plasma usually disrupts and terminates the discharge.

The ability to contain a higher value of $\beta$ is expected for the reversed field pinch (RFP) — a toroidal magnetic system in which the toroidal field is reduced relative to that of a tokamak and is comparable with the poloidal field. An RFP achieves gross stability by reversing the toroidal field in the outer plasma layers, thereby providing a region where the field-line pitch changes rapidly with radius (high shear). Although the development of RFPs is somewhat behind that of the tokamak, D.A. Baker (Los Alamos National Laboratory) reported that an electron temperature of 0.5 KeV has been achieved in the ZT-40M experiment with a plasma current of 0.4 MA; the discharge duration had been improved from a few ms to 27 ms at lower currents. Similar progress was described by P.G. Carolan (Culham) from the performance of the HBTX1A experiment. These parameters move the RFP performance towards that of tokamaks of the

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## 100 years ago

*THE PEABODY MUSEUM AT NEW HAVEN, U.S.*

THE Peabody Museum, Mr. Ingersoll informs us, stands on the corner of Elm and High Street, just without the *campus* of Yale College. The building is due to the liberality of George Peabody, who gave a sum of money, in 1866, to erect a house for the collections. Thanks to the financial prosperity of Massachusetts, the bonds for a hundred and fifty thousand dollars had greatly increased, and those set aside for the first wing of the building had become worth a hundred and seventy-five thousands dollars when the trustees began to build. With that sum they have erected one of the finest buildings, for its purpose, in the United States—a lofty and ornamental structure of red brick and cream-coloured stone, whose broad and numerous windows expresss the desire of the investigators within for all the light they can get.

The glory of the Yale Museum is its palæontological treasures, brought together wholly by Prof. O. C. Marsh. The few representatives of this collection visible in the second-floor and in the hall-ways are alone sufficient to stamp the museum as pre-eminent of this line; but they are merely an advertisement of what cellar and attic contain. It is not too much to say that, in respect to vertebrate palæontology (outside of fishes), this museum is not surpassed in the world. Where other collections own fragments or single skeletons, Prof. Marsh boasts scores or hundreds of individuals.

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