pitch of the magnetic field lines is equal to m/n and $(m \pm 1) / n)$ produces elongated eddies in the direction perpendicular to S. A rigorous analysis of the problem shows that the typical radial width of the eigenmode is of the order of $(a\rho_i)^{1/2}$. Thus, if the linear coupling dominates the radial correlation length can be estimated to be $L_r \approx (a\rho_i)^{1/2}$. Nonlinear decorrelation mechanisms tend to break up this structure in such a way that each poloidal harmonic behaves independently from the others. If such a mechanism dominates we can estimate $L_r \approx \rho_i$. Therefore, the rough estimate of the local thermal conductivity given above can be reduced to two different limits: $\chi_{turb} \approx D_B$ and $\chi_{turb} \approx (\rho_i/a)\, D_B$, with $D_B = cT/e\mathbf{B}$ the Bohm coefficient. The two different limits are called Bohm and Gyro-Bohm, respectively.

Historically, the first example of mechanism leading to the reduction of L_r, and therefore to a reduction of the turbulent flux, was proposed for the explanation of the transition to the High confinement mode (H-mode) which is obtained routinely in tokamaks with a magnetic separatrix at the plasma edge and corresponds to the formation of a local transport barrier. The improvement mechanism can be explained as the formation of a sheared $\mathbf{E} \times \mathbf{B}$ flow. If an electric field is produced in the direction perpendicular to the magnetic surface, the plasma starts to rotate with an $\mathbf{E} \times \mathbf{B}$ velocity which lies on the magnetic surface and is directed in the direction perpendicular to the equilibrium magnetic field. If the radial electric field is spatially nonhomogeneous, plasma volumes on neighbouring magnetic surfaces rotate with different velocities. Such a shear in the rotation velocity tears apart turbulent eddies elongated in the radial direction and reduces the transport level. Experimental support for this idea has been obtained in many magnetic confinement devices (*ie* tokamaks, stellarators and reversed field pinches) either by the analysis of spontaneous transitions or by using polarization probe techniques for the radial electric field generation. During the transition, the experimental measurements show the formation of an inhomogeneous radial electric field and the reduction of the turbulence level. But, how can such a field can be maintained? The radial electric field can be generated by the pressure gradient and poloidal and toroidal rotation. In the absence of substantial plasma rotation the radial electric field must be proportional to the local ion pressure gradient. Thus, a simple bifurcation paradigm can be constructed. A steepening of the pressure gradient produces a radial electric field which decreases the turbulence level and allows the maintaining of a steep pressure gradient. The closeness to turbulence thresholds, the type of instability driving the turbulence and the presence of sheared flows are considered critical elements in determining the transition between different transport regimes (*ie* Bohm versus Gyro-Bohm).

In the last five years a second mechanism for reducing the turbulent transport has been experimentally found in tokamaks which involves the production of nonmonotonic current density profiles (the current density is needed to produce the poloidal component of the equilibrium magnetic field). If such a condition is achieved, a transport barrier is formed with no turbulent transport. The understanding of this phenomenology is still in progress. A possible explanation might be that in these plasma regimes the magnetic configuration reduces the level of turbulence and/or the coupling between neighbouring poloidal harmonics. As a consequence, the power threshold for the transition to enhanced confinement regimes via sheared radial electric field effects is reduced. Thus, sheared radial electric fields could provide a universal mechanism to control plasma turbulence in fusion plasmas.

With an eye on the future, the understanding and development of methods for controlling plasma turbulence have opened a new path in plasma physics research and contributed to the design of a nuclear fusion plant.

Further reading

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The Understanding of Operational Limits

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Given the high cost of experimental devices in magnetic fusion research it is important to have reliable and predictive tools for their operation. This, together with the complexity of the geometry, has prompted a major effort in the development of numerical techniques.

From single particles...

The particular magnetic geometry stems from the requirement that the particles should be confined by the magnetic field. The particle motion is a fast race along the field lines added to a slower drift across the magnetic surfaces. Therefore the topology is toroidal, with field lines helically twisting about the magnetic axis.

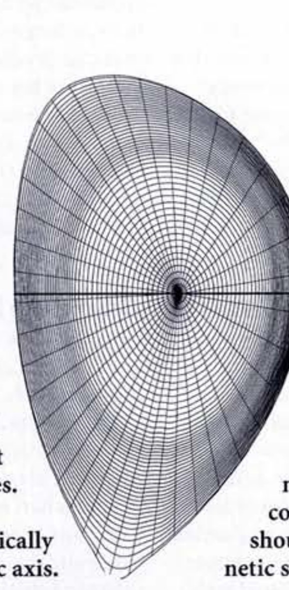

Fig 1 Mesh used in the computation of plasma equilibrium and stability, showing a cross-section of an ITER tokamak plasma with nested magnetic surfaces

This 'twisting' can be created by a plasma current (tokamak) or by currents in shaped coils (stellarator). The field lines should wind round nested magnetic surfaces (*figure* 1).

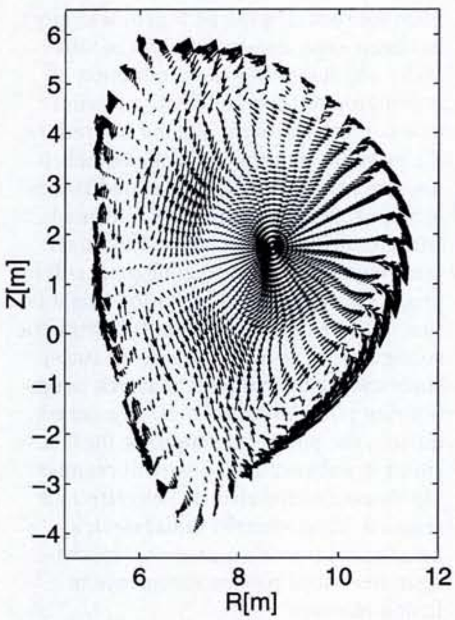

Fig 2 Unstable plasma motion in ITER when the pressure is above the ideal limit

...to collective effects

Designing a magnetic configuration that confines particles is not enough. For fusion to be efficient there must be enough particles at a high enough temperature, in other words a high enough pressure. But the motion of particles in a many-body system can be quite different from single-particle motion, in the same way the behaviour of a crowd can be different from that of a lone pedestrian. These phenomena are called 'collective effects'. Many types of instabilities can occur: when the pressure or the plasma current exceeds certain values the plasma sets spontaneously in motion, and within microseconds the plasma can touch the walls and be lost.

So it is necessary to avoid the fastest instabilities. The relevant timescale is that of the time for a perturbation to propagate along the configuration. These fast instabilities are described by the 'ideal Magnetohydrodynamic (MHD)' model, that considers the plasma to be a perfectly conducting fluid.

How can you compute?

The aim of the computation is to determine the pressure and current limits in a given configuration, and possibly to devise ways of increasing them. The toroidal curvature and the shear of magnetic field lines play an important role in these instabilities. Therefore the actual geometry of the configuration must be correctly described. The system of partial differential equations is then too complex to be solved without computational techniques. Moreover, these equations have singularities, and the solution methods need to be adapted accordingly.

The basic idea is to discretize the equations, that is to approximate the various functions on a finite number of grid points. An example of such a mesh is shown in *figure* 1. The differential equations then reduce to a system of linear algebraic equations. The number of grid points necessary to obtain a reasonable accuracy implies that the number of equations is typically of the order of 10^5-10^6.

And the result is ...

The exploitation of ideal MHD codes has yielded an extremely useful scaling law for the maximum achievable pressure in a tokamak. After analysing the stability of several configurations, assuming various plasma current and pressure profiles, the conclusion is extremely simple: the pressure limit in a tokamak is proportional to the plasma current and to the magnetic field strength, and inversely proportional to the minor radius of the plasma. The proportionality constant has been obtained from computations and has been shown to be almost the same in all existing tokamaks. An example of unstable plasma motion when the pressure exceeds the ideal MHD limit is shown in *figure* 2. The scaling law was instrumental in favouring elongated plasma cross-sections, which for the same minor radius can carry more current than circular plasmas. Nowadays, no one in the world dares even to propose the construction of a circular cross-section tokamak. The advantage of elongated plasmas has nevertheless a price: the plasma position must be carefully controlled to avoid vertical instabilities that can lead to violent disruptions (*figure* 3). Therefore there have been substantial efforts to develop codes that can predict the plasma behaviour including the feedback control system. These are now routinely used for machine design. The scaling law implies also that the pressure limit should be higher in small aspect ratio devices, which has been brilliantly confirmed in experiments recently.

Beyond the limits

Since this law was postulated, there has been several attempts to increase the limit, in other words to refine this semi-empirical law. For example, it has been shown by computations, and verified in experiments, that MHD instabilities can be quenched when the plasma rotates at a sufficient speed in the presence of a resistive wall. The pressure can exceed by some 50% the limiting value without rotation.

For stellarators a simple scaling law for the maximum pressure does not exist. The intrinsic three-dimensionality and the wide variety of configurations implies that the search for the pressure limit relies heavily on efficient computations. Optimization of a stellarator must be viewed globally (*see Nührenberg, chapter 3.4*). For example, the W-7X stellarator now in construction is predicted to have a maximum achievable beta (ratio of pressure to magnetic pressure) of about 5%, which would be good enough for a fusion device. The TJ-II device now in operation in Madrid (*see Alejaldre, chapter 5.1*) is expected to have similar optimum beta values; moreover, the flexibility of TJ-II will allow checking of the predicted beta limit dependence on the various types of configurations that can be achieved.

Towards longer timescales

The result of the above computation is a map in the operational space of the limits that by no means should be hit. The experiments can run for long periods. Unfortunately, other slower types of instabilities can set in. They are due to the finite collisionality—hence resistivity—of the plasma. They can tear certain magnetic surfaces into chains of magnetic islands that slowly grow in size and lead to a collapse of the pressure and sometimes even to disruptions. The numerical analysis of this phenomenon is rather recent. The pressure limit set by these modes can be twice as low as that set by ideal modes.

This is not yet the end of the story. The quality of the magnetic bottle is measured not only by the pressure it can hold but also by the energy confinement time. This is determined by the transport properties of the configuration. Increased transport is a consequence of yet other types of instabilities that are driven by ion temperature gradients; the resulting turbulence does not destroy the magnetic configuration but convects the energy away. The understanding of this phenomenon and its numerical modelling (*see chapters 3.1 and 3.5*) does not yet translate into operational limits in terms of global quantities, but that is certainly the way to go in the future.

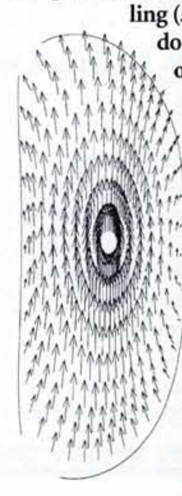

Fig 3 Unstable vertical motion in an elongated tokamak plasma

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