ANOMALOUS TRANSPORT DUE TO MAGNETIC TURBULENCE
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ABSTRACT

In this paper we consider transport in a toroidal system with broken flux surfaces. Flux surfaces with rational field line winding number can degenerate and form magnetic islands. Where neighbouring chains of islands overlap, a region of chaotic field forms. Thus, the generic topology of the magnetic field in a toroidal device consists of an alternation of shells with 'good' surfaces and shells with islands or chaotic field.

In a chaotic field, a field line fills up a region of space and thus makes significant radial excursions. Particles following a chaotic field line may experience rapid radial transport. Recent experimental evidence for the existence of alternating layers with high and low thermal transport is presented. The implication for the determination of transport coefficients is discussed. It is shown that a transport analysis that does not resolve the fine structure of the transport coefficient yields results that are almost meaningless.

I. INTRODUCTION

A much-used paradigm in tokamak physics is that field lines lie on nested toroidal surfaces: the flux surfaces. On these surfaces the pressure is assumed constant, and because of the extremely good thermal conductivity along field lines, the temperature is constant, too.

In the neo-classical theory transport from surface to surface occurs through collisions of particles, taking into account the particle drifts across the field (due to the curvature and gradient of the magnetic field). Neo-classical transport constitutes the irreducible background transport. Additional to this, still maintaining the concept of perfect flux surfaces, fluctuating E×B drifts can enhance the transport level. This has been discussed in the lecture on 'Electrostatic Fluctuations'.

A conceptually different possibility is that field lines, instead of lying on flux surfaces, wander through the torus. In this case radial transport can occur even when the particles follow the field lines obediently. Clearly, this concept breaks with the paradigm of nested flux surfaces.

Thus, we often distinguish, as is done in this summer school, 'electrostatic' and 'magnetic' turbulence. However, it is important to realise that electrostatic fluctuations are accompanied by perturbations of the magnetic field, and vice versa. The distinction is somewhat artificial.

But let us, for the sake of clarity, pursue the line of thought: the magnetic field is perturbed in such a way that the field lines do not lie on neat, nested surfaces anymore. In the limiting case of a fully chaotic field, a single field line fills up the whole torus. Between the limiting cases of the perfect nested surfaces at the one end and the fully chaotic field on the other, one finds systems in which the surfaces with rational q-value are degenerated and have formed layers of stochastic field, which are separated by regions of 'good' flux surfaces. Transport of particles and energy in such a system is governed by the topology of the field.

While it is clear that magnetic turbulence can contribute significantly to anomalous transport, it has turned out to be very hard to produce quantitative results, either theoretically or experimentally.

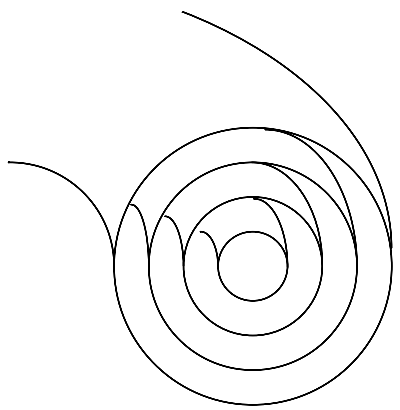
Experimentally, the problem is that magnetic fluctuations of the order $(\tilde{B}/B)=10^{-4}$ are sufficient to explain the observed transport. Such small fluctuations are extremely difficult to measure, especially since a measurement of the B-field - inside a plasma at a temperature of several keV - is difficult anyway.

The theory of transport in a partly chaotic magnetic field is an area of active research. Both the fundamental questions: 'why and how do the flux surfaces break up? , and 'can we give a self-consistent description of the plasma in a chaotic field?’ and the practical question: 'supposing we know the equations that describe the chaotic field, can we work out the transport?' are still open.

The remainder of these lecture notes is meant as a summary rather than a syllabus. The structure is as follows:
Introduction; Topology of the magnetic field: flux surfaces, islands, stochastic field; General considerations about the effect of chaotic fields on plasma transport; Examples of experimental evidence for the existence of small magnetic structures in tokamak plasmas; Experimental evidence for a layered topology; and its importance for the interpretation of transport measurements; Experimental estimation of the radial correlation length of magnetic turbulence in tokamaks; Discussion.

II. TOPOLOGY OF THE MAGNETIC FIELD

A. The paradigm system: nested toroidal flux surfaces.

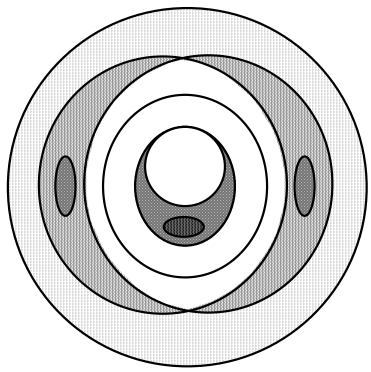


- Flux surfaces are isobars and isothermals
- Transport is one-dimensional: from surface to surface.
- Classical transport:
  through collisions only, step size = gyro radius
- Neo-classical transport: step size enhanced by particle trapping and drifts due to the curvature and gradient of the B-field
- Anomalous transport: transport through E×B drifts caused by a fluctuating E-field (Electrostatic turbulence).

Elaborations of this paradigm system form a substantial fraction of the cultural heritage of the fusion research community. However, while the picture is nice, it is not necessarily true: flux surfaces can break up to form magnetic islands. On flux surfaces with a simple rational winding number (q=number of toroidal turns a field line needs to make one poloidal turn) these islands can reach macroscopic proportions. They can be observed with e.g. Soft X-ray tomography, Electron Cyclotron Emission spectroscopy, interferometry or Thomson scattering.

B. Large magnetic islands

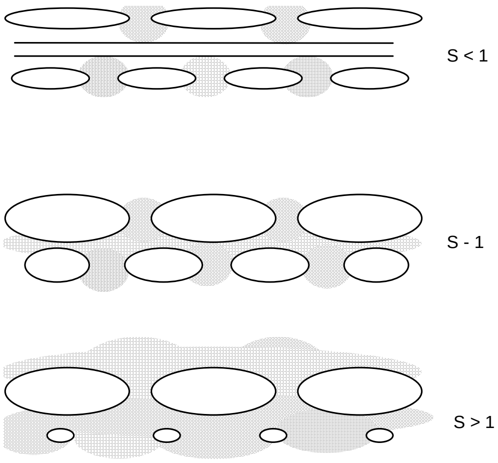
Large magnetic islands are often observed in tokamaks. Usually they are associated with gross MHD instability: the sawtooth instability (at q=1), or the major disruption (large islands at q=2). The observations of large islands demonstrates that the degeneration of flux surfaces can really occur. How about small islands?



C. Chains of Small Magnetic Islands

On surfaces with less simple rationality, smaller islands could develop, which are more difficult to detect. Neighbouring surfaces may form chains of islands that are separated by intact surfaces. At the tips of the islands (in the X-points) some stochastisation of the field may occur. If the islands grow, they may overlap and destroy the surfaces between the island chains. This region then becomes chaotic. For larger overlap, the field may become chaotic over a larger range, encompassing two or more island chains. Only remnants of islands are left in a chaotic sea. In principle, a fully chaotic field can be obtained: a single field line that fills the entire space. The overlap is parameterised by the Chirikov overlap parameter S, defined as the width of the islands divided by their separation

The field line equations in a torus form a Hamiltonian system. The nest of perfect toroidal surfaces is described by an unperturbed, integrable Hamiltonian H_0, the perturbation by a small, non-integrable Hamiltonian H_1. Surfaces with rational winding number are topologically unstable: even a small perturbation leads to degeneration. This type of system is the subject of active research in mathematics. The behaviour of field lines in a partly chaotic field (overlap parameter S>1, but not S>>1) is a far from trivial problem, and not at all understood. (See e.g. [1])



Note that these studies consider the 'motion' of a field line, i.e. the movement of its position in the poloidal plane under travel along the field line, for a *static* magnetic perturbation. In other words, the toroidal angle acts as a 'time'. In a plasma, it should be expected that chains of islands continuously grow, saturate and decay: a real time dependence. This introduces a decorrelation time into the problem, the importance of which will be discussed below.

III. SMALL ISLANDS ARE LARGE ENOUGH TO BE IMPORTANT

Significant contributions to transport can be expected if the width of the small islands is comparable to the electron gyro-radius or banana width. This is very small (typically 10^{-4} m), and is achieved with radial field components of order $\tilde{B}/B = 10^{-5} - 10^{-4}$. This small size implies that:

- Transport-relevant islands will be difficult to measure
- In a theoretical treatment: finite Larmor radius effects and electron inertia can be important.
- In a numerical treatment: numerical errors can easily be of the size of the field fluctuations.

IV. RESEARCH APPROACHES

Accepting that flux surfaces can break up and that this is a potential source of anomalous transport, the question is what we can undertake to learn more about the phenomenon. A few approaches are distinguished:

A. Theory

1. Try to answer the question: why would flux surfaces break up? I.e. try to identify suitable instabilities. Many instabilities have been proposed that could lead to formation of small islands. To mention a few:
- Thermal instability [2,3]
- Finite Larmor radius effects[4]
- Bootstrap current/neoclassical tearing mode e.g.[5]

It is still unclear if there is a single instability that could be held responsible for the universal transport in tokamaks, or if one should look for an interaction of different instabilities.

It is important to keep in mind that in a plasma with 'normal' magnetic shear, i.e. a monotonically increasing q-profile, the O-points of magnetic islands correspond to a depression of the current density. Knowing that higher temperature translates into lower electrical resistivity, a thermally stable situation can be realised in very low or reversed shear regions. Here, an O-point can be formed which thanks to its superior confinement has a higher temperature than the ambient plasma, which leads to a local enhancement of current density, which in turn gives rise to island growth [6].

2. Assuming a chaotic field, compute i) the field line trajectories and ii) the ensuing plasma transport. The two steps should be considered as separate problems. The study of chaotic field line trajectories is mathematical subject of remarkable intricacy, which we shall not further consider here. Particles may follow field lines until they are decorrelated by collisions, drifts, or because the field line loses its identity after one auto-correlation length, or due to temporal fluctuations of the B-field.

The seminal paper in this field is due to Rechester and Rosenbluth [7]. With heuristic arguments, they derive a formula for 'collisionless diffusion' of test particles in a stochastic magnetic field:

$$D \sim v_{//} D_M \quad (1)$$

where the 'diffusion of field lines' is described by the coefficient $D_M = L_{//} (\tilde{B}/B)^2$, and the parallel correlation length of the perturbation is estimated by $L_{//} \sim \pi qR$.

This formula brings out the essential division of the field line 'transport' (characterised by D_M) and the movement of particles along the field ($v_{//}$). The formula is widely used, even if the conditions for its applicability are difficult to meet in a tokamak. These conditions are:

- Fully developed chaotic field (overlap parameter S>>1);
- Parallel correlation length much shorter than the mean free path of electrons.
- Stationary magnetic field, i.e. the typical time scale on which the perturbing fields vary is much longer than the collision time.

Moreover, the derivation assumes that a field line in a chaotic field region makes a random walk, which can be described as a diffusion process (hence 'field line diffusion')

In [8] these assumptions are analysed and in most cases found invalid. Based on numerical simulations test particle transport coefficients are given for more realistic conditions. These are in general smaller than those estimated with eqn (1), and scale differently with $v_{//}$. The basic characteristic that faster particles are more sensitive to magnetic turbulence is retained, though.

B. Experiment

For the experimentalist, there are two approaches to magnetic turbulence. First, he can try to directly measure the perturbed B-field, or equivalent perturbations of e.g. the current density j, or strongly related quantities such as T_e. If these can be measured, their fluctuating behaviour should be characterised. A more indirect way of investigating magnetic turbulence is to look for characteristic effects on transport, e.g. of the fast particles that are much more sensitive to it than thermal particles. Thus:

1. Try to characterise the chaotic field:

- Measure fluctuations of B_r, j, T_e
- Determine the radial, poloidal and toroidal (//B) correlation lengths of measured fluctuations (i.e. k-spectra)
- Determine the correlation times (i.e. frequency spectra)
- Apply methods from chaos theory, e.g. time series analysis, to characterise the underlying instability. (There have been several attempts to apply such methods, with very limited success).

2. Look for other clues typical of magnetic turbulence:

- Ratio of thermal to mass transport (individual particles, and therefore heat, travel fast along field lines; mass transport is limited to ion velocity by the ambipolar fields)
- Confinement of suprathermal electrons (naively, one expects a quick loss of fast electrons in a stochastic field. This expectation has turned out to be too simple, but the velocity does influence the confinement of a particle)

We shall give examples of such measurements below.

V. EXPERIMENTAL EVIDENCE

Although magnetic turbulence is difficult to access, there is an extensive literature of relevant measurements. We give a representative selection:

In the edge of the plasma:

Filamentation of H_α emission in TFTR [9]:

Measurements with a CCD-camera showed a regular structure of parallel, narrow bands of high emissivity. These were aligned with the field lines. The poloidal extension was short (3-5 cm) while parallel wavelength was much longer (≈100 cm)

Magnetic fluctuations in JET [10]:

Broadband (10 - 60 kHz range) magnetic fluctuations measured with Mirnov coils just outside the plasma showed:

- Correlation length along the field lines: 2πR or longer (i.e. very long)

- Poloidal extension: mode number m = 10 to 100. The magnetic turbulence corresponds to fluctuations in the visible light. The level of the B-fluctuations scaled with the inverse energy confinement time.

In the interior of the plasma:

Direct measurements of the B-fluctuations in Tore Supra [11]

By making use of the cross-polarisation scattering of microwaves it was possible to measure the level of magnetic fluctuations in the interior of the Tore Supra plasma. Typical values were in the range $\tilde{B}/B = 10^{-5}$ to 10^{-4}. Calculations based on the Rechester-Rosenbluth formula showed that these fluctuations could be the cause of the measured anomalous electron heat transport.

The 'Snake' in JET [12]

In JET an m=n=1 structure of high density and pressure - but normal temperature - can form. It is observed frequently after pellet injection. This high-pressure tube is long-lived and very stable: it survives sawtooth crashes and appears to move along with the position of the q=1 surface. It is thought that the snake is a closed flux tube, and the excellent confinement properties confirm the hypothesis that inside magnetic islands transport is strongly reduced. Snakes have been found in many other tokamaks since their discovery in JET. This is result is confirmed by the observation of :

The Runaway Snake in TEXTOR [13]

In TEXTOR, snakes of 30 MeV runaway electrons were observed by diagnosing the synchrotron radiation they emit. These narrow beams of runaway electrons are confined in an m=n=1 island structure (even if they are significantly displaced with respect to the magnetic island!) and have excellent confinement, while the runaway population outside the island is lost during the island formation.

High-resolution T_e profiles

Measurements of the electron temperature profile in JET with the LIDAR diagnostic [14], have shown flat spots in the profile associated with q-surfaces of simple rationality (q=1, 3/2, 2,..). These measurements can be interpreted as evidence for small magnetic islands. Similar observations with a Thomson scattering diagnostic are reported from TFTR. However, attempts to measure these T_e-structures with an ECE diagnostic did not support their existence [15]. High-resolution Thomson scattering measurements also revealed structures that were identified as magnetic islands in RTP [16] and TEXTOR [17].

Striations of H_α-light from the ablation cloud of a pellet in Tore Supra. [18]

The intensity of the light emitted by the neutral cloud of a pellet that travels through the plasma is a measure of the ablation rate. In Tore Supra, this intensity was found to show dips when the pellet crossed q-surfaces with simple rationality. The hypothesis is that on such a surface the pellet is in contact with only a small fraction of the surface (because the field lines close back on themselves) which cools rapidly, leading to a falling ablation rate.

Correlation reflectometry in JET [19]

Measurements with 4 reflectometer channels that were tuned to slightly different radial positions in the plasma, showed that the radial coherence length of density fluctuations was very short (<1cm) in Ohmic and H-mode plasmas, while in L-mode it was much longer (up to 5 cm or more) and increasing with the input power. Studies with toroidally separated channels showed that the observed density fluctuations are due to unsmooth surfaces of constant density that rotate toroidally. This could be interpreted as evidence for the existence of small magnetic structures.

One might interpret measurements of density fluctuations as being measurements of moving spatial density structures, in which case the results may be regarded, as relevant for magnetic turbulence. Typical results for the correlation lengths $L_{C//}$ and $L_{C\perp}$ (parallel and perpendicular to the field lines) and the correlation time τ_C:

- $L_{C//} >> R$ (major radius)
- $L_{C\perp} \approx$ 3% of the minor radius, i.e. scaling with machine size!
- τ_C = 10 - 100 μs

VI. SUMMARY OF PART I

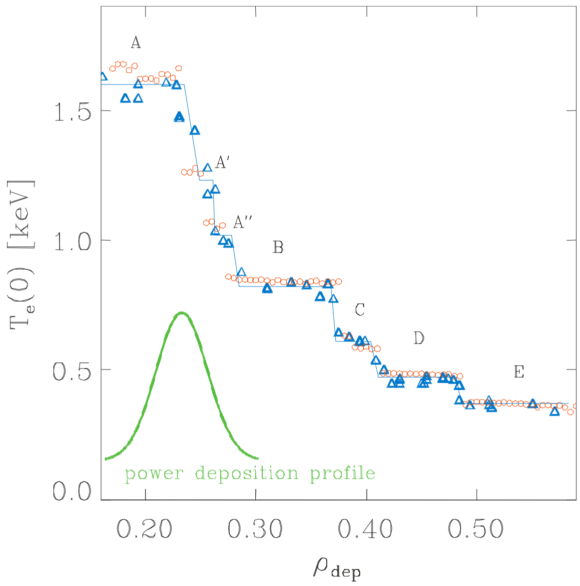
- The nest of ideal toroidal flux surfaces can break up into a mix of 'magnetic islands, regions of stochastic field, and 'good' surfaces.
- Even very small magnetic structures can be important for macroscopic plasma behaviour such as transport.
- There is plenty experimental evidence that tokamak plasmas exhibit some degree of magnetic turbulence, BUT

- Precise measurements of magnetic turbulence are not yet available, and the need for good magnetic diagnostics in the plasma interior is great.
- Common observations for magnetic structures:
  - Extension along field lines is long (more than a toroidal turn)
  - Sizes in poloidal plane of the order of percents of the minor radius.
- There are many different mechanisms that could break up the flux surfaces.

PART II: EXPERIMENTAL EVIDENCE IN RTP AND TEXTOR

I. Alternating shells of good and bad thermal transport, demonstrated in RTP [20].

In the Rijnhuizen tokamak RTP an experiment was carried out showing that the plasma consists of alternating shells with good and bad electron thermal conductivity. In this experiment a highly localised power source (ECH, see lecture E. Westerhof) was scanned through the plasma, either dynamically (during a single discharge) or on a shot-to-shot basis. The power of this source dominated the power balance, i.e. all other power terms (Ohmic heating, losses due to energy transfer to the ions or through radiation) were an order of magnitude or more smaller. The central $T_e(0)$ was measured using Thomson scattering.

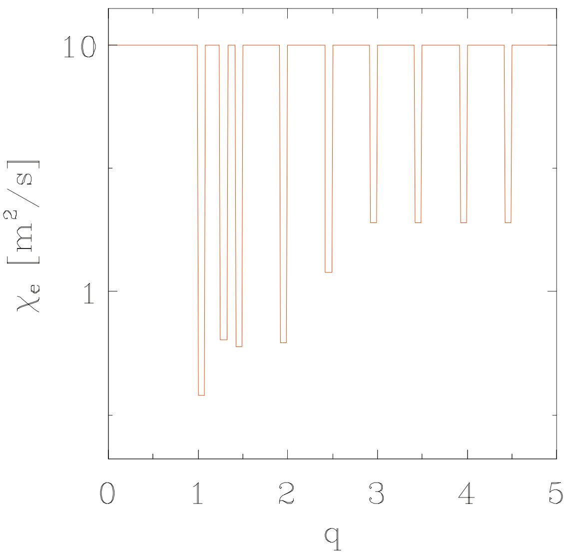


The basic result of this experiment is the behaviour of $T_e(0)$ as a function of the radius of power deposition r_{dep}. Clearly, when the electron thermal diffusivity is a smooth function of r, $T_e(0)$ must be a smooth, monotonic function of r. The experiment shows a different picture.

It is observed that instead of changing smoothly as a function of r_{dep} the $T_e(0)$ makes discrete steps. Clearly, such behaviour can be expected when the thermal diffusivity is not a smooth function of r, but shows narrow transport barriers, separated by regions of high thermal conductivity. The steps occur when the heating spot moves over a transport barrier.

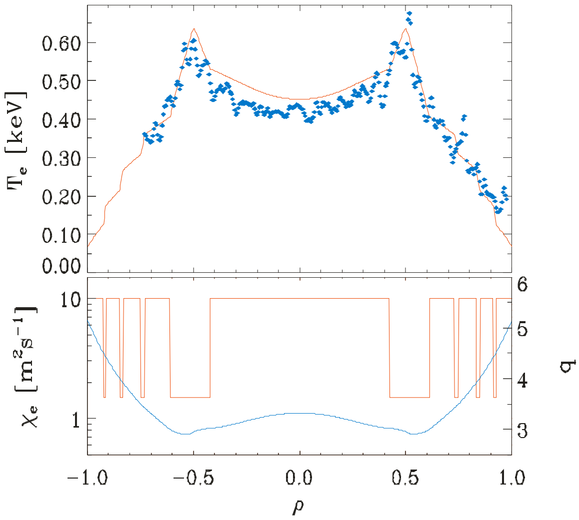
Careful analysis showed that the position of the barriers is closely linked to the q-profile: the barriers are found close to the rational values q = 1, 4/3, 3/2, 2, 5/2, 3,...

A transport model featuring transport barriers near rational q values was shown able to provide a very good description of the data, shown in the figure as small circles. In this model, the thermal diffusivity is a function of q only, as shown in the picture below.



Thus, in this model, the width of the barriers depends on the local magnetic shear. This results in a non-linear coupling between the T_e profile, the current density profile and corresponding q-profile, the resulting χ_e profile, which in turn determines the T_e profile. It is this non-linear coupling that causes the sharp transitions in the power deposition scan shown above.

In the figure below, an illustration is given of how the generic χ_e as a function of q translates into an actual spatial χ_e profile, in which a particular barrier can become pronounced if the shear is low around a rational q value. The figure also shows that in such conditions, when heating is applied at the location of the barrier, a local maximum in the temperature can form. This happens both in the experiment (data points) and in the simulation (full line).

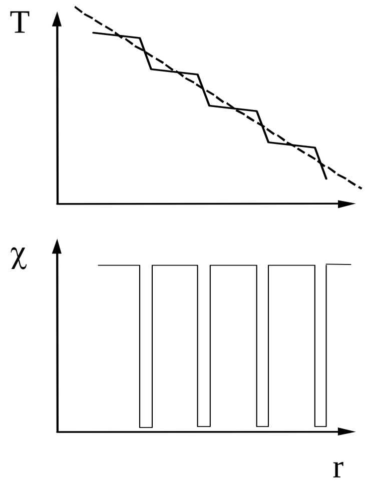


This model was tested against an extensive data set from RTP, and also successfully applied to JET data. Finally, it is remarked that also in stellarators, a strong correlation between the magnetic winding number and the energy confinement has been found. Indeed, this dependence has been successfully modelled by Brakel etal, with an empirical model that is quite similar - though developed independently and along a completely different route - to the RTP model described above.

II. A LAYERED TOPOLOGY: IMPORTANCE FOR TRANSPORT STUDIES

The measurements presented above show that there can be thin layers in the plasma where the electron thermal diffusivity (χ) drops by one to two orders of magnitude. This we take as an incentive to investigate the generic properties of transport in a medium in which the diffusivity is a strongly varying function of the spatial co-ordinate.

We consider a plasma slab with a sequence of conducting and insulating layers. Such a slab would feature a stair-step T_e profile. The question to be addressed is whether the macroscopic transport properties are influenced by the microscopic structure or not.



From elementary calculus it follows that if measurements of T_e are taken that do not resolve the structure, a power balance analysis yields a (macroscopic) χ^{pb} that is related to the local (microscopic) χ by

$$\chi^{pb} = \langle\chi^{-1}\rangle^{-1}$$

where <.> denotes spatial averaging.

An obvious but important consequence is that if χ varies by more than an order of magnitude, the measured value χ^{pb} is almost entirely determined by the insulating regions. Consequently, a theory that aims at predicting the macroscopic χ^{pb} needs to give the value of χ in the insulating layers, and the fraction of the space that is occupied by these layers. Interestingly, the 'turbulent' value of χ, i.e. the one that governs the conducting zones, is of no interest any more [21].

This implies a totally different perspective on the transport problem: not the turbulent transport coefficient, but the spatial distribution of insulating layers is the nut to crack.

The dynamic range of the diffusivity is much smaller for ions than for electrons, which strongly reduces the effect of the microscopic structure on the macroscopic ion transport. The reverse is true for suprathermal electrons. It has been pointed out in [22] that in a system with good and bad regions suprathermal electrons can have better confinement than thermal electrons, even if their transport in the stochastic regions is faster.

III. ESTIMATION OF THE SCALE SIZE OF MAGNETIC TURBULENCE IN TEXTOR-94, USING 30 MEV ELECTRONS [23]

As was seen above (eqn (1)), fast electrons are more sensitive to magnetic turbulence than thermal electrons, while for electrostatic turbulence the opposite is true. Therefore, it is a good idea to study confinement of runaway electrons (that go at the speed of light) in order to derive properties of magnetic turbulence. However, due to the orbit shift, which can be large for high energy runaway electrons, the fast electrons can be shifted with respect to the magnetic topology, and so effectively be decorrelated from the magnetic turbulence. For example, in TEXTOR-94 runaway electrons reach an energy of 30 MeV, at which energy their orbit shift is about 6 cm.

That this is a real effect is shown by the common observation that high-energy runaway electrons are extremely well confined. Thus, high-energy electrons appear to be unsuitable to probe magnetic turbulence, since they are insensitive to it. There is, however, a nice resolution to this problem.

In TEXTOR-94 a series of experiments was carried out, in which first a significant runaway population was created in an Ohmic plasma. The runaway population was diagnosed using the synchrotron radiation they emit, i.e. the measurement concerned runaway electrons in the centre of the plasma column. Their confinement in the Ohmic part of the discharge was extremely good, with an estimated confinement time of several seconds, i.e. two orders of magnitude longer than thermal confinement. It is important to note here that the synchrotron emission is a strong function of the electron energy, so that the measured signal entirely dominated by the highest energies in the distribution, in the TEXTOR-94 case between 20 and 30 MeV.

After some time additional heating was switched on. In reaction to this, the runaway population decayed, indicating that their confinement deteriorated. So far no surprises. However, the decay of the runaway population occurred only after a significant delay of up to a second.

The explanation for this delayed response is found in the energy dependence of the runaway confinement: high energy electrons are insensitive to magnetic turbulence with a scale size up to their orbit shift and thus nothing happens to them. So, when additional heating is switched on, the scale size of magnetic turbulence increases, and as a result runaway electrons are lost up to an energy corresponding to their orbit shift. This gap in the distribution function is than accelerated to higher energy. Only when the gap reaches the radiating energy rangy (20-30 MeV) does the measured signal decrease. Thus, the delay in the response of the signal maps out the energy to which the runaway electrons are lost, and this can be related to the scale size of magnetic turbulence via the orbit shift.

The result was that in TEXTOR-94 the radial correlation length of the magnetic turbulence increases from <0.5 cm in Ohmic discharges, to several centimeters with high power heating. This implies that the contribution of magnetic turbulence to thermal transport is negligible in Ohmic discharges, but it becomes the dominant electron heat loss channel with high power heating.

OVERALL SUMMARY

- The magnetic topology of a magnetically confined toroidal plasma is generally assumed to consist of nested flux surfaces.
- This paradigm is an idealisation: surfaces with rational q are topologically unstable. The generic topology consists of a mix of good surfaces, magnetic islands and regions with chaotic field.
- The level of magnetic perturbations needed to break up surfaces sufficiently to significantly affect transport, are very low: $(\tilde{B}/B)<10^{-4}$.
- Direct measurements of the magnetic turbulence level in Tore Supra did demonstrate a fluctuation amplitude of this order.
- There is a variety of indirect experimental evidences for the existence of a structured magnetic topology.
- Measurements with a highly localised heat source in RTP showed that the plasma consists of shells with alternating high and low electron thermal conductivity, of which the positions are determined by the q-profile.
- Transport studies are strongly affected by this structure. A measurement of a spatially averaged thermal conductivity is virtually meaningless. Instead, measurements of the number and strength of the transport barriers are required.

- High energy runaway electrons can be used to probe the scale size of magnetic turbulence. Experiments in TEXTOR-94 gave an estimation of the radial correlation length, which was <0.5 cm in Ohmic discharges, increasing to several centimetres with high power heating.

EPILOQUE

As an epiloque, two things may be added:

1. There is no evidence that in a normal, healthy tokamak discharge, chains of **fat** islands are present as a rule. Neo-classical tearing modes are being diagnosed routinely now, and they appear after they have been triggered. Nor is there evidence that the plasma is permanently in a strongly chaotic state: runaways would not be confined in that case. Thus, the magnetic perturbations are at a modest level at best, and their effect is subtle.
2. although normally electrostatic modes are not associated with specific q-values, there are theories in which this coupling does occur [24]. In which case the layered transport associated with rational q values may be a mixed electrostatic/magnetic effect. Numerical simulations in [25] do show such a coupling.

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