# TRANSPORT STUDIES USING PERTURBATIVE EXPERIMENTS

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## ABSTRACT

By inducing a small electron temperature perturbation in a plasma in steady state one can in principle determine the conductive and convective components of the electron heat flux, and the associated thermal diffusivity and convection velocity. The same can be done for other plasma parameters, like density or ion temperature.

In this paper experimental and analysis techniques are briefly reviewed. The fundamental question whether the fluxes are linear functions of the gradients or not is discussed. Experimental results are summarized, including so-called 'non-local' phenomena.

## I. INTRODUCTION

If one wants to learn to know a medium, a first step might be to study transport. Is there convection, how important is diffusion, radiation, etc. One may want to measure convective velocities, the electrical conductivity, the thermal conductivity, etc.

As to the diffusive fluxes: the more general problem is to find the relations between the fluxes on the one hand and the thermodynamic forces - the gradients - on the other. In a turbulent medium such as a plasma these relations may well be non-linear: perhaps the particle flux goes with the square of the density gradient; also they may be 'off-diagonal': for instance the density gradient might drive a heat flux. It is not even clear a priori that unique relations between fluxes and gradients exist at all.

The relations between fluxes and gradients can be probed experimentally by perturbative techniques: bring a plasma in a steady state (time derivatives zero), give it a small perturbation and watch the subsequent relaxation process. To give a specific example: induce a local temperature perturbation and measure how it propagates. If the gradient lengths of the perturbation are small compared to the size of the plasma, the transport mechanism that is driven by the highest spatial derivatives will be dominant, and that is usually diffusion. So, this experimental technique is very suitable to measure purely the diffusive part of transport, filtering out other possible contributions such as convection. The method is so powerful that also off-diagonal diffusion coefficients can be measured.

This method works provided transport can be described as a local phenomenon. In many experimental situations, this condition appears to be fulfilled, i.e. the diffusion equation is capable of giving a very accurate description of the observations. However, there are specific experiments in which the phenomenology can definitely not be described in terms of diffusion. An example are 'cold pulse' experiments: when the edge of the plasma is cooled quickly, then (under suitable conditions) a pronounced transient rise of the central temperature is observed. We come back to this in Sec.VII.

A comprehensive review of perturbative transport experiments in fusion plasmas can be found in [1].

## II. TOOLS

Perturbative transport began with the analysis of heat pulses induced by the sawtooth crash, which is naturally present in many plasmas [2]. Since, many different techniques have been developed to perturb the plasma, and these have been applied in a large variety of experiments. Usually, one of the input sources of the plasma is perturbed, often in a periodic way: the input power (modulated ECRH or ICRH), the particle source (modulated gas puff, pellet injection), the momentum input (modulated neutral beam injection), the plasma current (current ramps). Moreover, the position and shape of the plasma can be modulated, and the plasma edge can be cooled using laser ablation of impurity targets or peripheral pellet injection.

The art of data analysis has developed along with the development of perturbation techniques. The time dependent signals can be analyzed with Fourier techniques [3] or Laplace transform [4], or simulated traces can be fitted to the data in the time domain, e.g. [5].

We will discuss neither the perturbation techniques nor the analysis methods further here; the interested reader is referred to the original papers.

## III. RELATION FLUXES - GRADIENTS

In Fig.1 a few examples are sketched of how a plasma that initially is in steady state, may evolve after a perturbation:
a) the perturbation may drive the plasma unstable and initiate a disruption, which evolves with its own sequence of events that can not be stopped;
b) in case of a bifurcation such as the L- to H-mode

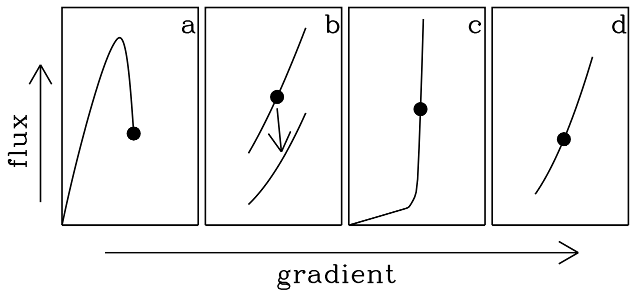


Figure 1: *Possible forms of the relation between flux and gradient (see text).*

transition, the perturbation may bring the plasma into another 'mode';
c) the plasma may be marginally stable, so that a variation of the flux does not change the gradient, and the quantity of interest is the critical gradient itself rather than a transport coefficient.

In all these cases the response of the plasma to a perturbation will give results that are not very helpful in establishing the relation between the fluxes and gradients. However, the experimental evidence is that a plasma is normally in a state of the type indicated in Fig.1d, i.e. near the steady state there is a one-to-one (albeit often non-linear) relationship between the fluxes and the forces.

In this situation it makes sense to look for relations of the general form

$$\mathbf{F} = M \nabla v \qquad (1)$$

where $\mathbf{F}$ denotes a vector of all relevant fluxes and $\nabla v$ a vector of the corresponding gradients. The neoclassical transport matrix contains significant off-diagonal elements. For anomalous transport, the off-diagonal elements are not known from theory, but in those cases where they have been measured, they turned out to be of the same order as the diagonal elements. Therefore, any transport analysis should take into account the possibility of significant off-diagonal fluxes.

The matrix elements should be expected to be functions of local plasma parameters. Moreover, they may be functions of the gradients themselves, so that the fluxes are non-linear functions of the gradients. In fact, if instabilities driven by gradients play a role, this is to be expected. Experimentally, two types of measurements can be made:

- In a steady state plasma, a flux and gradient can be measured, yielding a transport coefficient defined as the ratio of the flux over the gradient. E.g., in an electron power balance analysis the measurement of the electron heat flux $q_e$ and gradient $\nabla T_e$ yields $\chi_e^{pb} = q_e / n_e \nabla T_e$.
- In perturbative experiments, the increment of a flux as a result of a change in a gradient is measured, yielding the 'incremental' transport coefficient (e.g. $\chi_e^{inc} = \partial q_e / n_e \partial \nabla T_e$)

Note that *only* if the transport matrix is diagonal and has fixed coefficients, the steady state and incremental transport coefficients are the same. In all other cases the two methods must be expected to yield different values, because they measure different quantities.

It can be difficult or impossible to vary only one gradient. In general, the perturbation must be decomposed in eigenvectors of the transport matrix. The plasma response will be characterized by several time constants, corresponding to various eigenvalues of the transport matrix. By correlating changes in fluxes and gradients with the same time constants, perturbative experiments can yield estimators of the diagonal elements of the transport matrix, as well as of the significant off-diagonal elements.

## IV. ILLUSTRATIVE CASE: TRANSPORT MATRIX WITH FIXED COEFFICIENTS

It is interesting to consider the simple case of a transport matrix $M$ with fixed (i.e. independent of plasma parameters) coefficients. In this case, the electron heat flux can be written as

$$q_e = -n_e \chi_e^{inc} \nabla T_e - q_{offset} = -n_e \chi_e^{pb} \nabla T_e \qquad (2)$$

with

$$\chi_e^{pb} = \chi_e^{inc} + \frac{q_{offset}}{n_e \nabla T_e} \qquad (3)$$

where $q_{offset}$ is a linear combination of unspecified gradients other than $\nabla T_e$ (see Fig.2).

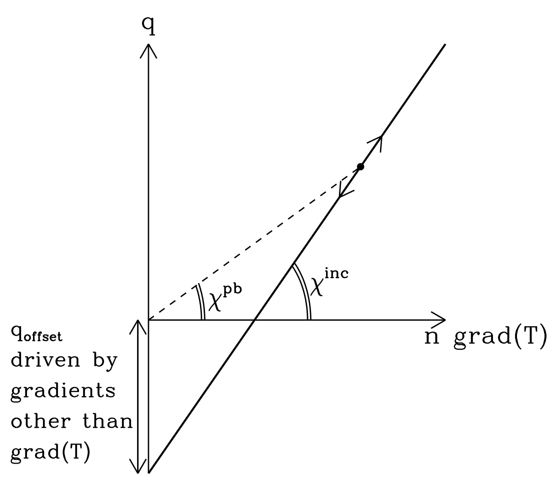


Figure 2: *Relation between $\chi_e^{pb}$ and $\chi_e^{inc}$ in case of a transport matrix with fixed coefficients.*

It is clear that, while the matrix has fixed coefficients, $\chi_e^{pb}$ depends on the actual gradients, and as such is less suitable to study the transport matrix: $\chi_e^{pb}$ may show *erratic* behaviour if the 'other' gradients vary independently of $\nabla T_e$. The incremental diffusivity $\chi_e^{inc}$, on the other hand, is in this case identical to the - constant - diagonal element of the matrix, and is immune to variations of the other gradients.

Interestingly, for particle transport an off-set flux - the inward pinch - is assumed even in steady state analysis. This is necessary because in steady state the net flux is zero while the gradient is not. Thus, the analog of $\chi_e^{pb}$ for particle transport is identical to zero, and never used.

From these very basic considerations, some important conclusions can already be reached:

- Even in the simple case of a transport matrix with fixed coefficients, $\chi_e^{pb}$ has awkward dependences on gradients if off-diagonal elements are significant. Experimentally, it is observed that the dependence of $\chi_e^{inc}$ on plasma parameters is much weaker than that of $\chi_e^{pb}$. It is an appealing thought that this difference can in part be due to the fact that in $\chi_e^{pb}$ dependences on plasma parameters are mixed in through the off-diagonal terms.
- The 'other' gradients - such as the velocity shear - may depend on external sources, so that $\chi_e^{pb}$ may seem to depend on external parameters, even for the simple case of a transport matrix with fixed coefficients.
- When comparing a theoretical expression with an experimental result, it is essential that like quantities are compared. In particular, it is very dangerous to compare an expression for the diagonal element giving the heat flux driven by $\nabla T_e$, to measurements of $\chi_e^{pb}$. Not only the numerical values may differ, but also the scaling with plasma parameters.

In conclusion, while $\chi_e^{pb}$ has the advantage of good experimental accessibility, it should be interpreted with great care. A more fundamental approach is to study the elements of the transport matrix separately. Below we sketch how this can be done.

## V. LINEARIZATION OF TRANSPORT EQUATIONS

The standard way of dealing with a small perturbation of an equilibrium is Linearization of the transport equation, see e.g. [2, 6, 7]. To illustrate the various effects that may play a role, we consider the heat flux over the electrons. The power balance equation reads

$$\frac{\partial}{\partial t}(\frac{3}{2}n_eT_e) = -\nabla q_e + S + \Gamma\{\nabla T_e + \frac{T_e}{n_e}\nabla n_e\} - \nabla(\frac{5}{2}T_e\Gamma) \tag{4}$$

where $q_e$ denotes the heat flux carried by the electrons, and $S$ the power source density, which implicitly includes the electron-ion energy equipartition. By definition the time derivative vanishes in the steady state, so that the perturbed equation reads:

$$\begin{aligned}\frac{3}{2}n_0\frac{\partial}{\partial t}\tilde{T} &= -\nabla\tilde{q} + \tilde{S} + \tilde{\Gamma}\{\nabla T + (T/n)\nabla n\}_0 \\ &\quad -\nabla(\frac{5}{2}T_0\tilde{\Gamma}) - \frac{3}{2}T_0\frac{\partial}{\partial t}\tilde{n}\end{aligned} \tag{5}$$

where the subscript e is omitted for clarity of notation, and the subscript 0 denotes the unperturbed state. In Eq.5 the net particle flux in the steady state has been put equal to 0. Terms due to $\Gamma_0 \neq 0$ are lower order spatial derivatives of perturbed quantities than the diffusive terms, and therefore they can be neglected, as will be argued below.

Applying the definition of $\chi_e^{pb}$, the heat flux over the electrons is expressed as

$$-q_e = n_e\chi_e^{pb}\nabla T_e \tag{6}$$

By allowing $\chi_e^{pb}$ to be a function of local plasma parameters $n_e, \nabla n_e, T_e, \nabla T_e$, ..., this formulation is still completely general. The perturbed heat flux takes the form:

$$\begin{aligned}-\tilde{q}_e &= \frac{\partial q_e}{\partial(\nabla T_e)}\nabla\tilde{T}_e + \text{ (diagonal diffusive term)} \\ &\quad \frac{\partial q_e}{\partial(\nabla n_e)}\nabla\tilde{n}_e + \text{ (off-diagonal diffusive term)} \\ &\quad \frac{\partial q_e}{\partial T_e}\tilde{T}_e + \frac{\partial q_e}{\partial n_e}\tilde{n}_e + \cdots \text{ (convective terms)}\end{aligned} \tag{7}$$

This can be used in Eq.5 to obtain an expression for the evolution of the temperature under the various perturbations. The important thing to notice is that if $\chi_e^{pb}$ has functional dependences on plasma parameters, this leads - through the partial derivatives - to contributions in the matrices that describe the linearized fluxes.

If not all perturbed quantities are measured, and this is always the case, Eq.7 contains too many unknowns. One way to solve this, is to neglect effects of all perturbed quantities except one. This is allowed if experimentally a situation can be reached in which one quantity is perturbed much more strongly than all others (which is difficult to ascertain for quantities that are not measured!). In the above example, keeping only the terms with $\tilde{T}_e$, this yields

$$\begin{aligned}\frac{3}{2}n_0\frac{\partial}{\partial t}\tilde{T}_e &= -\nabla\tilde{q}_e + \tilde{S} \\ &= \frac{\partial q_e}{\partial(\nabla T_e)}\nabla^2\tilde{T}_e + \frac{\partial q_e}{\partial T_e}\nabla\tilde{T}_e + \frac{\partial S}{\partial T_e}\tilde{T}_e\end{aligned} \tag{8}$$

which is a transport equation with diffusion, convection, and damping. This type of equation has been treated in many papers, e.g. [3, 5, 6]. The basic idea is that for different frequencies of the perturbations ($f_{pert}$), different effects are dominant. The reason is that the gradient length decreases with $f_{pert}$, and therefore the highest order spatial derivatives (i.e. the diffusive terms) become dominant at high $f_{pert}$. Hence, from a frequency scan in principle all three components can be determined. For heat transport, unfortunately, this does not work out: $f_{pert}$ is often so high that diffusion dominates, and the process appears to be fully diffusive. In particle transport experiments, on the other hand, $f_{pert}$ is often low enough to make both the diffusive and the convective component visible [8]. It is very important to realize that if the response of the plasma to a perturbation appears to be purely diffusive, this does not exclude convection as an important contributor to the steady state fluxes.

With the off-diagonal contributions taken into account, the equivalent of Eq.8 in matrix form is obtained:

$$\frac{\partial \mathbf{u}}{\partial t} = A\nabla^2\mathbf{u} + B\nabla\mathbf{u} + C\mathbf{u} \qquad (9)$$

where $\mathbf{u}$ is the vector of perturbed quantities, and the matrices $A, B, C$ represent the diffusive, convective and damping terms, respectively. To get more insight in the effect of off-diagonal contributions, we will now specialize to coupling of particle and electron heat transport, and to the diffusive part of the equation (limit of high frequency). The explicit form then is (see e.g. [7]):

$$\frac{\partial \mathbf{u}}{\partial t} = A\nabla^2\mathbf{u} \qquad (10)$$

where

$$A = \begin{pmatrix} D^{inc} & A_{12} \\ A_{21} & \frac{2}{3}(\chi^{inc} + A_{12}) \end{pmatrix}, \ \mathbf{u} = \begin{pmatrix} \tilde{n}/n_0 \\ \tilde{T}/T_0 \end{pmatrix} \qquad (11)$$

with

$$D^{inc} = D_0 + \frac{\partial D}{\partial \nabla n}\nabla n_0 \ , \ \chi^{inc} = \chi_0 + \frac{\partial \chi}{\partial \nabla T}\nabla T_0$$
$$A_{12} = \frac{T_0}{n_0}\frac{\partial D}{\partial \nabla T}\nabla n_0 \ , \ A_{21} = \frac{2}{3}(D^{inc} + \frac{n_0}{T_0}\frac{\partial \chi}{\partial \nabla n}\nabla T_0) \qquad (12)$$

with, for ease of notation, $-\Gamma = D\nabla n$ and $-q = n\chi\nabla T$.

In case of a steady state transport matrix $M$ with fixed coefficients, the relation between $M$ and $A$ is trivial. However, if the elements of $M$ are functions of the gradients, then the perturbative diffusion matrix $A$ can be completely different from $M$ [6, 7].

Importantly, if $A$ has non-zero off-diagonal elements, then $\tilde{n}$ and $\tilde{T}_e$ are not the eigenvectors of the coupled transport problem. Instead, the eigenvectors are linear combinations of $\tilde{n}$ and $\tilde{T}_e$. Thus, $\tilde{n}$ and $\tilde{T}_e$ have common modes, at different amplitudes. Analysis of any of these modes, yields an eigenvalue of $A$, *not* the diagonal element of $A$. Since the eigenvalues of $A$ differ an order of magnitude, one can speak of a "slow" and a "fast" eigenmode.

Observations of sawtooth induced $\tilde{n}$ and $\tilde{T}_e$ show that this exercise is not trivial: In TEXT $\tilde{n}$ propagates like $\tilde{T}_e$, i.e. is dominated by the "fast" eigenmode. On the other hand, in JET $\tilde{n}$ shows both a "fast" and a "slow" component; see Fig.3 (see also next Section).

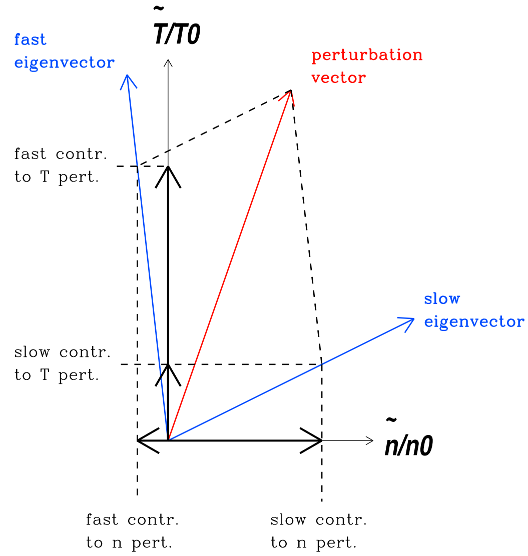


Figure 3: *Decomposition of $n$ and $T_e$ perturbation into eigenmodes of the coupled equations. The figure shows the decomposition for the perturbation induced by a sawtooth collapse in JET.*

The Linearization game can also be played in the Fourier domain, which is in particular useful for periodic perturbations like modulated ECRH or ICRH. A periodic heat (or density) pulse translates in a phase ($\phi$) and amplitude ($A$) in the Fourier domain. The radial propagation translates in a phase *delay* and amplitude *decay*. In fact, either of them is sufficient to determine the diffusion coefficient in case of pure diffusion in slab geometry:

$$\chi_e^{inc} = \frac{\frac{3}{4}\omega}{(\phi')^2} = \frac{\frac{3}{4}\omega}{(A'/A)^2} = \frac{\frac{3}{4}\omega}{\phi'(A'/A)} \qquad (13)$$

where the primes denote radial derivatives and $\omega/(2\pi)$ is the frequency of the modulation. The fact that $\chi_e^{inc}$ can be estimated from $\phi$ alone, is very useful then the available data are non-trivial functions of temperature, i.e. Soft X-Ray data. Damping causes a faster propagation, i.e. a decrease of $\phi'$ and an increase of $A'/A$; since these effects cancel, the last expression of Eq.13 is still valid in the presence of damping. In cylinder geometry the formula is

$$\chi_e^{inc} = \frac{\frac{3}{4}\omega}{\phi'(A'/A + 1/2r)} \qquad (14)$$

More general formulas, taking into account heat convection etc., are derived in [3].

## VI. SOME EXPERIMENTAL RESULTS

Results have mainly been obtained for $\chi_e^{inc}$ and $D^{inc}$, and a very limited data base exists for the 2x2 matrix of coupled particle and electron heat transport.

Generally the dependences on plasma parameters are found to be rather weak.

The typical result for $\chi_e^{inc}$ and $D^{inc}$ is [1]:

$$\chi_e^{inc} \propto q_a^{-(1-2)} T_e^{0-0.5} n^{-(0-1)} \quad (15)$$

$$D^{inc} \propto q_a^{-(1-2)} T_e^{0-2} n^{-1} \quad (16)$$

Since all studies refer to ohmic and L-mode plasmas, in which profiles are mainly parametrized by $q_a$, the $q_a$-dependence could well represent a dependence on local plasma parameters. For the particle transport also an incremental convective velocity could be determined, which scales the same way as $D^{inc}$, see e.g. [8]. A strong $T_e$ dependence was reported in [9], but not found in other experiments.

The 2x2 transport matrix $A$ was measured in JET using several methods [5, 7, 10], with as a typical result

$$A = \begin{pmatrix} 0.3 & -0.5 \\ 0.2 & 2 \end{pmatrix} \quad (17)$$

The characteristic is that $\chi_e^{inc}/D^{inc} \gg 1$, and that $A_{12} = (1-2) \cdot D^{inc}$ but of negative sign. The effect of this term is readily visible in the shape of sawtooth induced density pulses in JET, see Fig.4. The $\nabla n_e$ driven heat flux is relatively unimportant.

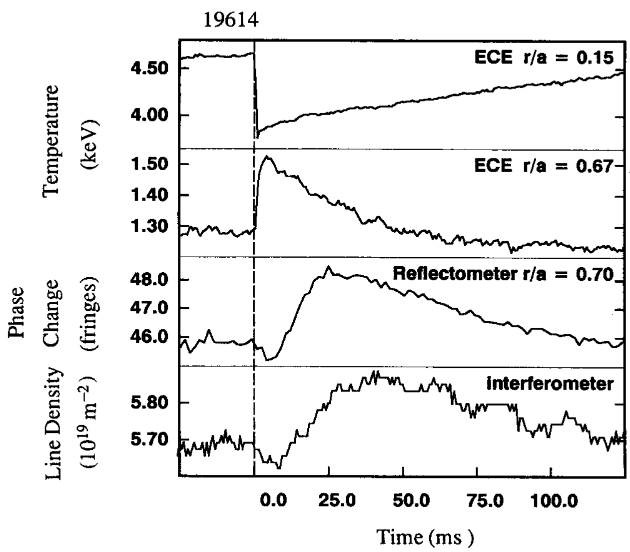


Figure 4: *JET time traces of a sawtooth induced heat and density pulse. The upper two panels show $T_e$ inside the inversion radius and in the propagation region. The lower two panels show $n_e$ in the propagation region: a local measurement from reflectometry, and a line integrated measurement from interferometry. Note that the density pulse propagates much slower than the heat pulse (indicating $D^{inc} \ll \chi_e^{inc}$), and is preceded by a small negative excursion on the time scale of the heat pulse (indicating a negative term $A_{12}$ in the transport matrix, see Eq.17.*

Measurements of $\chi_i^{inc}$, using sawtooth induced ion heat pulses [11, 12], showed $\chi_i^{inc}$ of the same order as $\chi_e^{inc}$ and an order of magnitude larger than $D^{inc}$.

## VII. UNEXPECTED PHENOMENA

Sometimes, the measurements show features that appear to fall outside the standard description. Naturally, it is always the question whether these are artifacts of the data or genuine plasma physical effects.

A good representative of this class is the so-called ballistic contribution to the sawtooth induced heat pulse [13]. With this is meant the observation that during the sawtooth crash heat is deposited quite a bit outside the $q = 1$ surface. This can influence the sawtooth heat pulse, but the effect on the analysis can be minimized by restricting the analysis to a region not too close to the mixing radius [14]. However, the rapid heat redistribution itself is an interesting transport phenomenon.

A more recent example is the observation of 'non-local' transport in many experiments: features which apparently cannot be explained within the framework of local transport. These experiments include inward propagation of cold [15, 16, 17, 18, 19] and heat [17, 19] pulses, and stepped input power level experiments [20].

The experiments with inward propagating cold and heat pulses are characterized by the fact that the response of the centre of the plasma to the edge perturbation is (i) of opposite sign and (ii) faster than could be expected on the basis of the known transport processes. This type of response can empirically be described by an instantaneous change of $\chi_e$ throughout the plasma.

This effect was first discovered at TEXT-U [15], and later reported on many tokamaks, e.g. TFTR, RTP (see Fig.5), Tore Supra and ASDEX-U [16, 17, 18, 19]; see [21] for an overview and discussion. Interestingly, the response on the W7-AS stellarator to edge cooling is fully 'normal', i.e. diffusive [22].

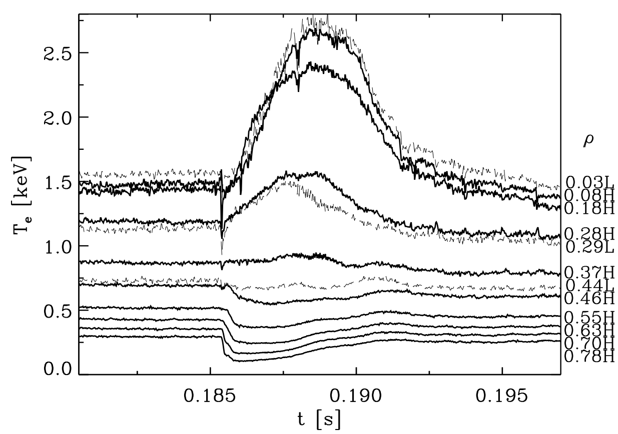


Figure 5: *ECE $T_e$ time traces of EC-heated RTP discharge r19980618.027, where a pellet is injected peripherically at 185.4 ms. Note the strong and nearly instantaneous heating of the core.*

The non-local effect disappears above a certain threshold density, which appears to coincide with the transition from linear to saturated ohmic confinement. It is conjectured that the electron-ion coupling plays a role in undoing the non-local effect.

## VIII. MODELLING

The challenge for modelers goes into two directions: (i) to understand the cause of non-local transport, and (ii) to find a model that simultaneously predicts the steady state and perturbative data.

Regarding non-local transport, various models have been proposed, from empirical (e.g. [17]) to theory based [23, 24], with partial success. The interested reader is referred to these papers.

Regarding simultaneous modeling of steady state and perturbative data: modern predictive transport codes like ASTRA, make it now possible to predict the evolution in time of the four major plasma parameters ($n, T_e, T_i$ and $E_{\|}$) together with the corresponding fluxes ($\Gamma, q_e, q_i$ and $j$), for a given model of transport and given source terms. The challenge is, to reconcile the apparent difference in behaviour of the steady state and perturbations, see e.g. [25, 26]. In DIII-D transport models were systematically scrutinized using well-devised Modulated ECH experiments [27].

Another new development is, that perturbations are used to test internal transport barriers [28]. This, too, is a very sensitive test for transport models.

## IX. DISCUSSION

Returning to the experimental values of incremental transport coefficients, it is a striking observation that there is such a large degree of similarity between results obtained in different experiments. This holds for the values - typically $0.1 < D^{inc} < 1$ m$^2$/s and $1 < \chi_e^{inc} < 10$ m$^2$/s, with profiles increasing towards the edge of the plasma - but also for the (absence of) scaling with plasma parameters: $q_a$ is generally identified as an important (though global) scaling parameter, at low density there is an inverse density dependence which saturates, and other dependences are generally weak. All this seems to suggest that transport in a tokamak could simply be described by a transport matrix with constant coefficients. Indeed, with off-diagonal elements in the transport matrix a number of typical transport features, such as the well-known density pinch and the sometimes observed heat pinch [29] can be accommodated.

Several experiments have been carried out to look specifically for non-linear flux-gradient relations: changing the amplitude of the perturbation [30], changing the $T_e$ gradient of the unperturbed plasma [31], etc, but these have not shown any significant non-linearities.

The reason for the search for non-linear transport relations is that virtually any theoretical model for anomalous transport predicts non-linear relations, with strong parametric dependences. A possible solution to this paradox might be that the fluxes depend on a heterogeneous product of gradients, including gradients other than $\nabla n$ or $\nabla T$, and that these 'other' gradients are characterized by long time constants, so that they appear constant in perturbative experiments. It is a major challenge for perturbative transport investigations to identify gradients which could play this role.

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