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# Misaligned Transport Barriers in Temperature and Density

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***Abstract***

*The curious observation has been made in optimised shear plasmas in JET that whilst both density and temperature profiles have a transition from a steep gradient region to a shallow gradient region, these generally occur at a different spatial location. This surprising result is shown to be consistent with the particle and thermal diffusivities falling in the same region of the plasma, if a particle pinch term which is proportional to the particle diffusivity is included. It is shown that such a pinch velocity is a natural feature of a random walk diffusion of particles and will be significant in other areas, particularly in the edge of H-mode plasmas.*

## INTRODUCTION

In optimised shear plasmas in JET, in which the current profile is carefully controlled to give a low shear region in the plasma centre, regions of very high density gradient and temperature gradient are observed [1]. This is also seen in similar experiments in other tokamaks [2,3,4]. In JET it is observed that these regions are not generally at the same location in the plasma. There is a region in which the density gradient is large but the temperature gradient is not increased. An example is shown in figure 1 which shows the profiles of electron density and ion temperature,(the

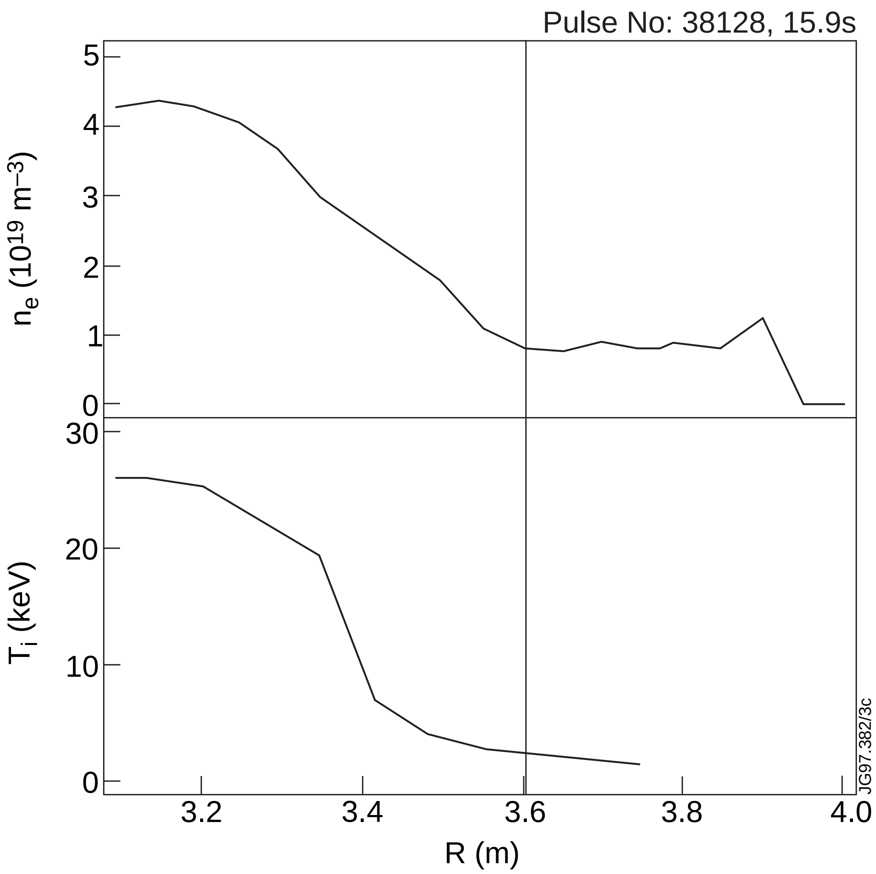


*Figure 1: The measured ion temperature and electron density profiles make a transition from a low gradient to a high gradient region. The location of the transition is generally different for the density and temperature*

electron temperature also has a transition in gradient at the same location as the ion temperature but with a less substantial change in gradient). All attempts to show that this is a diagnostic error or a limitation on spatial resolution have failed. The temperature and density are measured with diagnostics with similar spatial resolution and the positions of the maximum density and temperature agree. This appears to be a real physical effect.

The natural conclusion of this strange physical effect is that the transport of particles and energy are unrelated since there appears to be a region in which the particle diffusivity is reduced but the thermal diffusivity is not. This is counter-intuitive and in conflict with existing results that thermal diffusivity and particle diffusivity are generally found to scale in the same way. An alternative interpretation seems necessary. If the observation is correct but the natural conclusion is unacceptable, what can be going on?

## MODEL

In fact the natural conclusion from the observations is erroneous. In the region where the density gradient becomes high the temperature gradient would be reduced if the thermal diffusivity were unchanged. This can be seen by determining the temperature gradient assuming the diffusive heat flux is the dominant power flow,

$$\frac{dT}{dr} = \frac{-P}{n\chi A}$$

where $P$ is the conducted power and $A$ the surface area. The density appears to double without reducing the temperature gradient implying that in the region with a steep density gradient but shallow temperature gradient, the thermal diffusivity is indeed decreasing. This offers some hope that we may be able to reproduce the experimental observation without invoking a different spatial location for the reduced particle and thermal diffusivities.

Two observations are important:

1) Even if the thermal diffusivity decreases across the whole of this region the temperature gradient will increase most dramatically as the diffusivity approaches its minimum value, particularly if the reducing diffusivity is compensated by the density increasing over most of the region.

2) The density gradient will be increased if there is an increased particle pinch term in this region. To relate the particle pinch to the reduced diffusivities in this region we will take the particle pinch to be proportional to the gradient of the particle diffusivity. We will see later that this is a physically reasonable assumption.

The model then is of a transition region over which the diffusivities fall from L-mode levels to values typical of the core of optimised shear plasmas. In this region there is a large particle pinch resulting from the gradient in the particle diffusivity. Both particle and thermal diffusivities fall over the same region. The problem remains whether any choice of profile of diffusivities can reproduce the experimental observations of a different spatial location of the transition in the profiles.

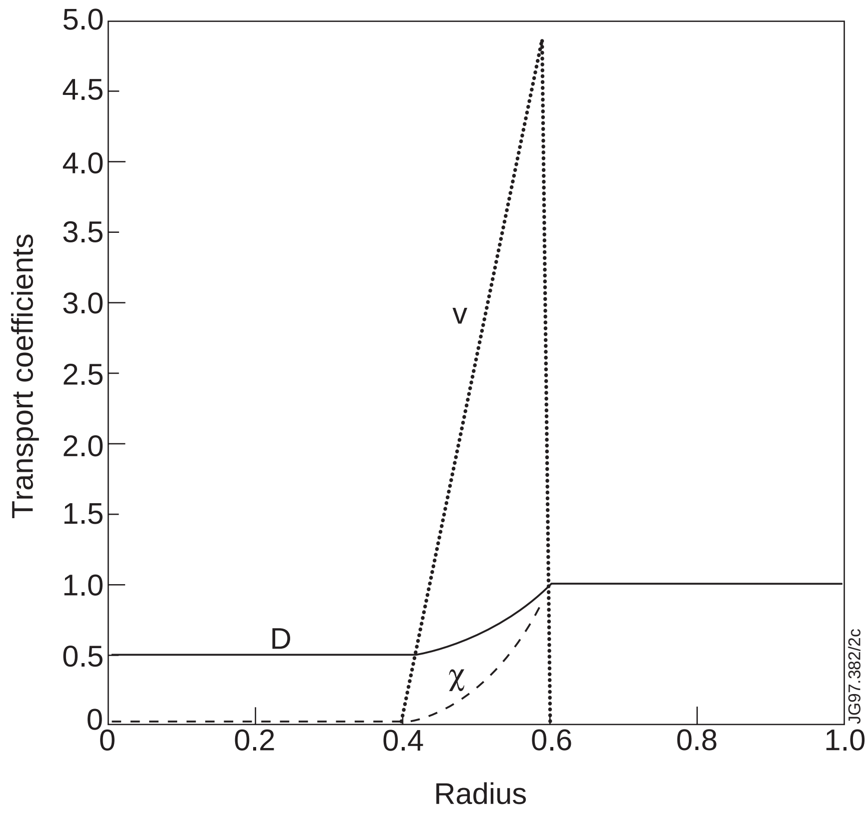


*Figure 2: The profiles of particle and thermal diffusivities assumed in attempting to reproduce the observed steep gradient regions. Also shown is the particle pinch velocity which is calculated from the gradient in the particle diffusivity.*

Figure 2 shows the diffusivities and pinch velocity for a specific case in which the particle diffusivity falls by a factor of 2 across the transition region whilst the thermal diffusivity falls by a factor of 33. The pinch velocity is large only in the transition region. The resulting profiles of density and temperature are shown in figure 3 where the profiles of heating and particle fuelling are assumed to be the same, and very peaked as in the experiment. It is clearly seen that the transport ‘barrier’ in density begins at the outer edge of the transition region whilst the barrier in temperature begins at the inner edge. The steep gradient regions in density and temperature are displaced by the width of the transition region, consistent with experimental observation. Figure 3 does not represent a full calculation of the plasma transport but only allows for diffusive heat flux. In a full calculation the convection of heat tends to flatten the temperature gradient in the core. The Ware pinch of particles is also neglected which, if included, would increase the density gradient in the plasma core. The purpose of the calculation shown here is only to illustrate the possibility of a displacement in the steep gradient regions of density and temperature.

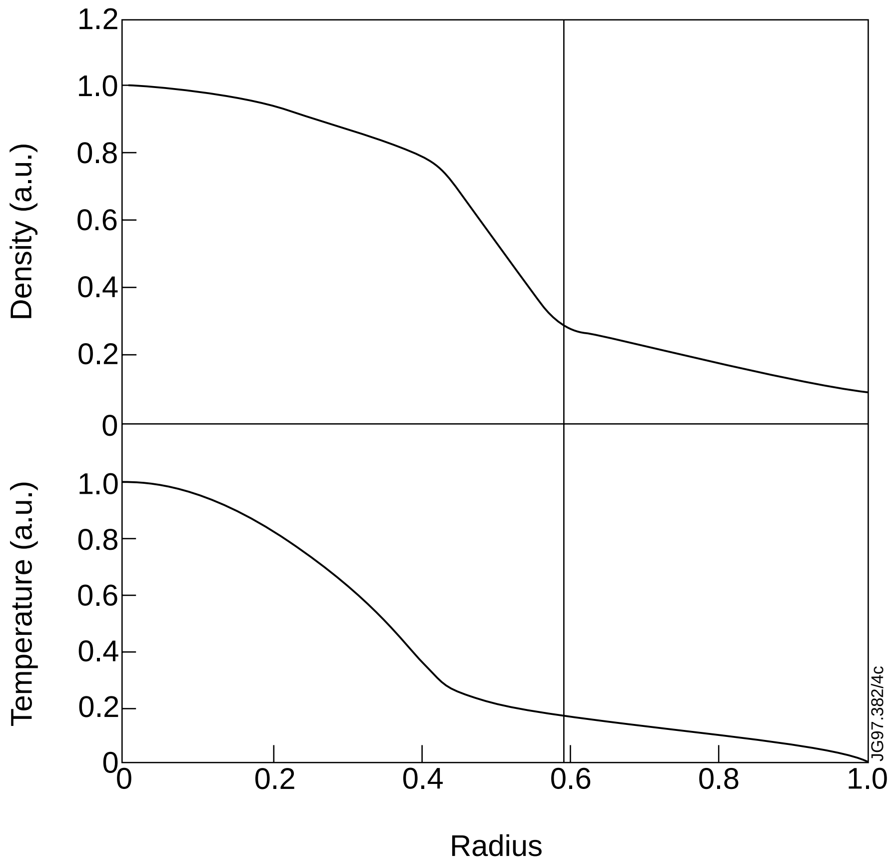


*Figure 3: Calculated profiles of density and temperature. The only transport of energy allowed is thermal diffusion, (convection is neglected). The model calculation is only intended to show that the steep gradient region in density and temperature can indeed be displaced even though the diffusivities fall in the same region.*

It is possible to explain the observation of a displacement between particle and temperature transport barriers, and it is clear that the natural conclusion that the region over which particle and thermal diffusivities fall is very different is not correct. It is interesting that it is necessary to invoke a particle pinch velocity given by the gradient of the particle diffusivity and an explanation of why this might come about is necessary.

**Pinch Term**

A particle pinch which varies like the gradient of particle diffusivity is in fact a natural feature of a random walk diffusion of particles, as is illustrated below. Assume the transport process can be described as a random walk, with step length $\delta$ and characteristic time $\tau$. Consider the particles to be contained in small cells of width $w$ (larger than a step length). The residence time of a particle in a cell is given by the mean time to random walk out of the cell, that is

$$\frac{w^2\tau}{4\delta^2}$$

A steady state is reached when the product of density and inverse residence time is the same in each cell, that is

$$\frac{n\delta^2}{\tau} = \alpha$$

where $\alpha$ is a constant. Diffusion in this system continues even when there is a uniform density if there are gradients in step length or characteristic time since particles spend longest in regions with short step length or long characteristic time.

The particle flux across a surface for this random walk model is given by the difference between flows between neighbouring cells, that is

$$\Gamma = \frac{(n+\Delta n).(\delta+\Delta\delta)^2}{(\tau+\Delta\tau)w} - \frac{n\delta^2}{\tau w}$$

The particle flow arises because of gradients in the scale length and the characteristic time as well as in the density, for instance particles will tend to accumulate in a relatively 'collisionless' region. The resulting particle flux is

$$\Gamma = \left( \Delta n\frac{\delta^2}{\tau} + 2n\delta\frac{\Delta\delta}{\tau} - n\delta^2\frac{\Delta\tau}{\tau^2} \right)/\, w$$

Using the gradient and scale length to evaluate the differential quantities gives

$$\Gamma = -\frac{\delta^2}{\tau}\frac{\partial n}{\partial r} - n\left(\frac{2\delta}{\tau}\frac{\partial\delta}{\partial r} - \frac{\delta^2}{\tau^2}\frac{\partial\tau}{\partial r}\right) = -D\frac{\partial n}{\partial r} - n\frac{\partial D}{\partial r}$$

where $$D = \frac{\delta^2}{\tau}$$

The particle flux is driven by gradients in the diffusivity as well as gradients in the density itself. The same result does not apply generally to the diffusive heat flux since there is no interchange of heat between particles of the same temperature even if there is a gradient in step length or characteristic time. This additional flux does not always occur. For instance in classical cylindrical transport there is no flux in the absence of density and temperature gradients even if there is a gradient in magnetic field and hence Larmor radius [5].

## Discussion

The concept of a pinch term proportional to the gradient of the diffusion coefficient, used in attempting to reproduce the experiment has a physical basis and allows a reasonable explanation of the observations. The description of the observation is the following. The density rises not because the diffusivity is low but because of the large pinch term. The temperature gradient does not increase in spite of the reducing thermal diffusivity because of the increasing density. The transition to a steep temperature gradient occurs where the second derivative of temperature is large

$$T'' = -T'\left(\frac{n'}{n} + \frac{\chi'}{\chi}\right)$$

But if both particle and thermal diffusivities fall together, i.e. $D \propto \chi$ and a pinch term given by $v = D'$ is included, the resulting density gradient

$$\frac{n'}{n} = -\frac{v}{D} = -\frac{D'}{D} = -\frac{\chi'}{\chi}$$

is such as to cancel out the reducing thermal diffusivity and keep the temperature gradient constant. It is for this reason that in the transport coefficients used above to approximately reproduce the experimental observations, it was necessary to reduce the thermal diffusivity by more than the particle diffusivity. Otherwise the steep gradient in temperature would not be reproduced. Generally speaking, if the diffusivities fall over a region of plasma, the density gradient should change at the outside of this region, where the gradient in particle diffusivity becomes large, whilst the temperature gradient should change at the inside, where the value of thermal diffusivity becomes small. If the region is very narrow, of course, the increased gradients of the temperature and density will coincide. In JET the transition region over which the diffusivities fall appears to be approximately 0.2m wide.

Because this result is generally applicable to diffusion of particles through a simple random walk process, the possible implications for other areas of plasma physics must be considered. In particular, there is a steep density gradient in the edge of H-mode plasmas. If the diffusion gradient pinch term is neglected this is ascribed to a reduction in particle diffusivity in the plasma edge. Including the pinch term, however, leads to the opposite conclusion, that the diffusivity is increasing rapidly in the plasma edge leading to a large pinch term and a steep gradient. As in the case of the internal transport barrier, the steep gradient is then due to the large pinch term and not to the low diffusivity. This is illustrated in figure 4 which shows a model density profile with an increased edge gradient and the two calculations of diffusion coefficient, including or neglecting the pinch term. As expected, without the pinch term, the diffusion coefficient falls near the plasma edge but including the pinch term the diffusion coefficient rises towards the edge to reproduce the same density profile with the same source profile. Alternatively, if the particle diffusion coefficient does in fact fall near the plasma edge, this should generate an outward convection and hollow density profiles.

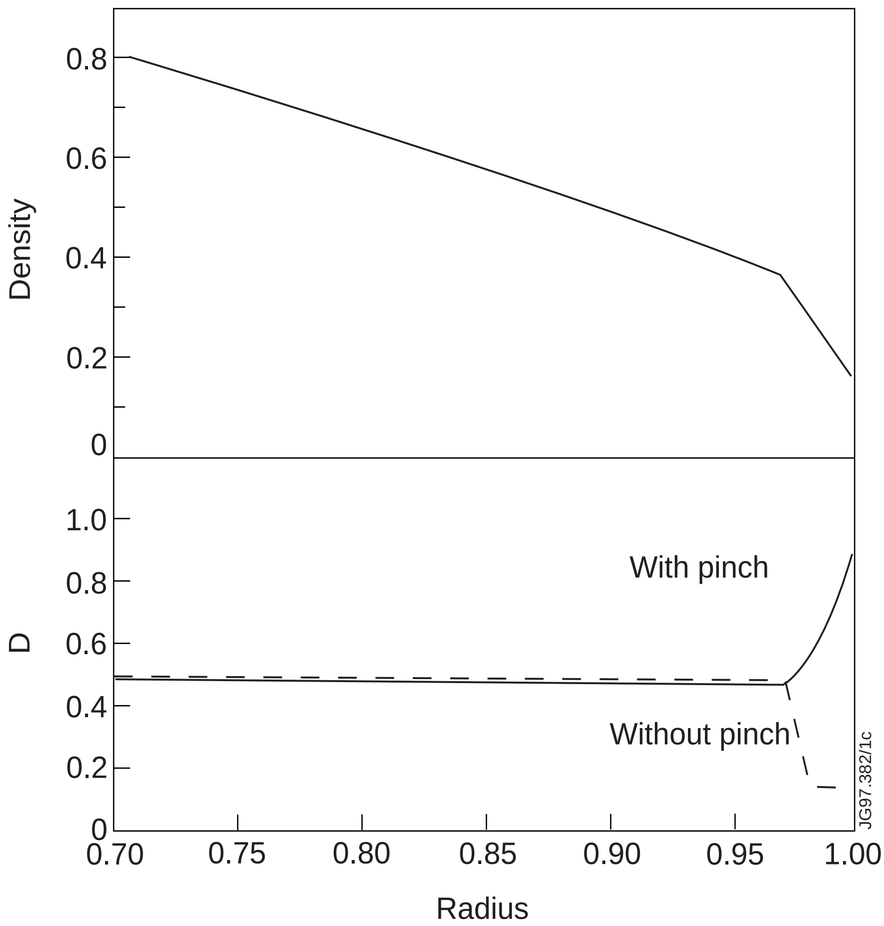


*Figure 4: Model density profile with increased gradient near the edge and the particle diffusion coefficients required to reproduce that density profile, with and without diffusivity gradient pinch term.*

## Conclusions

In optimised shear plasma in JET, steep gradient regions are observed in both density and temperature but at different locations. The observations are explainable with particle and thermal diffusivities which fall in the same region, the transition region, if a particle pinch term that is proportional to the gradient in particle diffusivity is included. The large change in density gradient is expected to occur at the outer edge of the transition region whilst the large change in temperature gradient is expected to occur at the inner edge. If the transition region is very narrow the steep gradient regions are expected to coincide.

It is shown that such a particle pinch velocity is in fact a natural consequence of a random walk diffusive process. Such a particle convection velocity, although not a general feature of plasma transport, would explain the observed results in optimised shear plasmas. In addition it would be important in other areas such as H-mode plasmas where there is a rapid radial variation of transport coefficients near the plasma edge.

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