Evidence of non-local heat transport in JET plasmas

Indication of non-local heat transport in JET plasmas

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In most common transport models both in fluid and plasma dynamics, the hierarchy of the moment equations is closed by applying the Boussinesq hypothesis that turbulent stresses are linearly proportional to mean strain rates. The reasoning behind this is the assumption of Markovian, Gaussian, uncorrelated stochastic processes which allow for a relaxation of the energy of the turbulent fluctuations to dissipative scales much the same way as molecular frictions similar to the Newton's law of viscosity. This implies for example in plasmas, the divergence of the heat flux can be defined as a local, diffusive process :

$$\nabla \cdot Q(\mathbf{r},t) = \frac{\partial}{\partial \mathbf{r}}(\chi(\mathbf{r},t)\frac{\partial}{\partial \mathbf{r}}P(\mathbf{r},t)), \qquad (1)$$

with $P = nT$ being the plasma pressure and n and T are the plasma density and temperature respectively. χ is the diffusion coefficient with the dimensionality of $[L^2/s]$. A fundamental limitation with this approximation is that it can not reproduce key features of nonlinear systems, that can display a tendency toward self-organisation. They can be non-local and intermittent in space and time, e.g., fluctuations can be bursty in time and be distributed sparsely in space, with turbulent patches intermixed with laminar ones. It is nowadays recognised that transport phenomena induced by turbulence must be interpreted in the framework of anomalous diffusion. Anomalous transport is characterised by non-Gaussian (e.g. exhibit power-law tails) self-similar nature of the PDFs of particle displacement, and the anomalous scaling of the moments. There is a wealth of experimental evidence that in fusion plasmas the nature of turbulent heat transport is anomalous, and non-local (non-diffusive) [1,2].

In order to go beyond the limiting assumptions made to obtain (1), we introduce the following generalised form for the divergence of the flux as:

$$\nabla \cdot Q(\mathbf{r},t) = S\,\frac{\partial^\alpha}{\partial \mathbf{r}^\alpha}\,P(\mathbf{r},t), \qquad (2)$$

where α is the index of the corresponding fractional derivative [3]. S is the anomalous-diffusion transport coefficient with the dimensionality of $[L^\alpha/s]$. Thus, for $\alpha = 2$, we will recover a similar diffusive model as (1), and for $\alpha = 1$ we obtain a convective transport model. For $\alpha < 2$ the transport is so-called super-diffusive while for $\alpha > 2$ the transport is considered sub-diffusive. To understand the implications of super- or sub- diffusive transport, it is easier to consider the Fourier representation where the rate of the decay of the energy from large scales to small, dissipative scales is of the form of $|k|^\alpha$. This means that the rate of dissipation of the turbulent energy is determined by the exponent α. For a diffusive system ($\alpha = 2$) thus, the transport processes lead to a stronger energy dissipation than for a super-diffusive

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system (e.g. $\alpha = 1$), where the energy remains significantly high even at smaller scales. This will have an important consequence on the active energy channels in the system, since this means that the turbulent energy of smaller scales, e.g. electron scales, will not be as strongly damped as assumed with a diffusive model.

Here a method is proposed in order to determine the values of the fractional index of the heat flux α through power balance analysis. To define α_s ($s = e, i$ indicates the species), we propose to make use of the Fourier representation of the energy conservation equation in the general form as (see Ref. [3]):

$$\frac{3}{2}\frac{\partial}{\partial t}\hat{P}_s(\mathbf{k},t) - |\mathbf{k}|^{\alpha_s}\hat{P}_s(\mathbf{k},t) = \hat{H}_s(\mathbf{k},t). \tag{3}$$

Here, H is the net heating due to Ohmic, NBI and RF heating minus the radiation losses and we have assumed $S_s = 1$, which means that all the physics of collisional, neoclassical and turbulence processes, is contained within the fractional index α_s. Through power balance analysis using (3), we can find the following expression for α_s:

$$\alpha_s = \frac{\log(\frac{\hat{H}_s-(3/2)\partial_t\hat{p}_s}{-\hat{P}_s})}{\log|k|}. \tag{4}$$

The method is used to study the nature of the heat transport in a selected set of recent JET H-mode plasmas using the data from TRANSP interpretative runs [4].

Both ion and electron energy transport channels are found to be of super-diffusive nature in all the selected plasmas with significantly higher degrees of super-diffusivity in the electron energy transport channel than for the ions with $\alpha_e \sim 0.5$ while $\alpha_i \sim 1$. The super-diffusivity level of the energy transport in the plasma edge is found to be lower than in the plasma core in both ion and electron channels, in agreement with the reduced transport observed in the pedestal region of the plasma edge. The proposed fractional transport model therefore, is expected to reproduce local as well as non-local aspects of heat transport in fusion plasmas, which will be an important factor for the successful operation of the future machines such as ITER tokamak.

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