HEAT TRANSPORT EXPERIMENTS IN JET: STIFFNESS AND NON-LOCALITY

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Outline

- Fast transient phenomena in JET-experimental observations;
- Concept of turbulence non-locality;
- Profile stiffness as an alternative approach to fast transient phenomena;
- Conclusions
I. Fast Transient Phenomena on JET- Experimental Observations

An unusually fast heat pulse, generated by L-H transition, has been first reported in 1993 (S. Neudachin et al., 20th EPS Conference, Lisbon, 1993)

![Graph showing temperature evolution with different densities](image-url)
Two unusual features of this heat pulse:

I. A very fast (sometimes beyond experimental resolution) propagation of the temperature rise;

II. Heat pulse amplitude does not decay (sometimes even rise) in the core quickly attracted attention of theoreticians and modellers.

Since then JET and many other tokamaks have reported a number of heat and cold pulses with the similar features;

Some tokamaks (starting from TEXT, K. Gentle, 1993) reported cold pulses which change polarity in the core;
Cold pulse triggered by a shallow pellet injection
Cold pulse triggered by type-I ELM

Pulse No: 30592

Te (kev)

ρ = 0.50
ρ = 0.66
ρ = 0.70
ρ = 0.74
ρ = 0.81
ρ = 0.84

Time (s)
Cold pulse caused by noble gas puffing into ELM-free H-mode
Cold pulse in plasma with ITB
A very recent example shows that cold pulse leads to erosion of the ITB (P. Mantica, EPS 2001)

Weak ITB can be completely destroyed by the cold pulse
Two unusual features of these heat pulses:

I. A very fast (sometimes beyond experimental resolution) propagation of the onset of the temperature rise;

II. Heat pulse amplitude does not decay (sometimes even rise) in the core quickly attracted attention of theoreticians and modellers.
Let us compare experimental results with the prediction from a simple diffusive model with the constant $\chi$.
The difference in the speed of cold pulse propagation and in the radial profile of the cold pulse amplitude is obvious.

How can we explain such a fast, non-diffusive kind of cold pulse propagation?

Two possible explanations are being considered by theoreticians at present:

- Non-local turbulence paradigm (streamers),
- Stiff local transport paradigm (avalanches).

**Non-local turbulence.**

Non-local turbulence as a mean of a fast L-H transition in JET has been proposed in *(J.G. Cordey et al., NF 1995)* and implemented in an empirical JETTO transport model *(M. Erba et al., PPCF, 1997)*;

Since then the model has been successfully applied to a number of transient phenomena.
The physics mechanism of the turbulence non-locality originates from:

- Toroidal coupling of unstable vortices,
- Inverse non-linear cascade of unstable modes into long wave length part of the wave spectrum;

Both mechanisms lead to a formation of long radially correlated structures (strimmers), which can explain fast non-local change in transport coefficients during transient phenomena (F. Romanelli, F. Zonca, PF, 1993; V. Parail et al., NF 1997; Y. Kishimoto et. al., IAEA, 1998; K. Itoh, S.-I. Itoh, 2001);

JET transport model assumes that the source of the turbulence localised near the separatrix, so that

$$\chi_{Bohm} \approx C \cdot c_s \cdot \rho_i \cdot q^2 \left| \frac{\nabla T_e}{T_e} \right|_{sep}$$

Next slide shows an example of L-H transition simulation with JET model;
Pulse No: 31078

\[
\begin{align*}
\rho &= 0.33 \\
\rho &= 0.40 \\
\rho &= 0.50 \\
\rho &= 0.60 \\
\rho &= 0.66 \\
\rho &= 0.76 \\
\rho &= 0.80
\end{align*}
\]

Time (s) vs. Temperature (keV) for different values of \( \rho \)
Pulse No: 31078

Time (s)

Te (keV)

\[ \rho = 0.33 \]

\[ \rho = 0.40 \]

\[ \rho = 0.50 \]

\[ \rho = 0.60 \]

\[ \rho = 0.66 \]

\[ \rho = 0.76 \]

\[ \rho = 0.80 \]
Profile stiffness.

- Profile stiffness is a known concept, based on theoretical finding that both electron and ion anomalous transport increases rapidly when some plasma parameters (\( \frac{\nabla T_i}{T_i} \) in case of ITG) exceed a certain limit (F. Romanelli, F. Zonca, PF 1993; A. Dimits et. Al., PP 2000);

- Generally, transport coefficient with a profile stiffness has the following form:

\[
\chi_i = \chi_i^{\text{res}} + C \frac{\rho_i^2 \cdot V T_i}{R} a \cdot \left( \frac{\nabla T_i}{T_i} - \left| \frac{\nabla T_i}{T_i} \right|_{\text{crit}} \right) \times H \left( \left| \frac{\nabla T_i}{T_i} \right| - \left| \frac{\nabla T_i}{T_i} \right|_{\text{crit}} \right)
\]

- Usually \( \chi_i^{\text{res}} \ll C \frac{\rho_i^2 \cdot V T_i}{R} \), therefore
transport changes rapidly in the region

\[ \frac{\nabla T_i}{T_i} \approx \frac{\nabla T_i}{T_i} \bigg|_{\text{crit}} \]

\[ \chi_{iL^2} / \rho_i^2 v_{ti} \]

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The figure allows concluding:

- Temperature profile keeps the same shape in case when heating power exceeds critical level;

- Core temperature depends on the edge temperature rather than on the level of transport;

- Cold pulse can propagate rapidly (like avalanche) with the characteristic $\chi$

\[
\chi_i^{HP} \equiv C \frac{\rho_i^2 \cdot V_{Ti}}{R} a \cdot \left| \frac{\nabla T_i}{T_i} \right|_{crit} \gg \chi_i^{PB}
\]
Profile stiffness is a recognised concept, which has been found in practically every tokamak;

The question is whether this concept can explain all experimentally observed fast transient phenomena, or we still need a non-local transport on the top;
Profile stiffness vs. non-locality

- Before going to a detailed comparison of two concepts, let us look at some recent result of cold pulse modelling which uses stiff transport models (J. Kinsey, 2000-01)
- Three theory based transport models (MMM-95, IFS/PPPL and GLF-23) have been used to simulate the same recent cold pulse from JET;

![Graphs showing T_e vs. t for different values of \(\rho\)]
Now we can try to answer the question: "Can we explain all fast transient phenomena by a stiff local transport or we still need a non-local transport?"

- Stiff models should have a problem reproducing L-H transition (the perturbation should actually reduce transport rather than increase it);

- It will be difficult to reproduce experimentally observed asymmetry in propagation of the cold pulse, triggered at the edge and in the core;

![Graph showing χ_eff vs ω](image.png)

\[ \omega \text{ (Hz)} \]

\[ \chi_{\text{eff}} (m^2/sec) \]

\[ \chi_{\text{cp}} \]

\[ \chi_{\text{st}} \]

**JET, 1994**

ITC-12 and APFA’01, December 11-14, 2001, Toki, Japan
Very fast cold pulse propagation requires extremely high level of stiffness, which has only a limited support from the theory;

**Conclusions**

- Fast transient phenomena found on JET and other tokamaks make a big impact on a theory of plasma turbulence.
- It led to a development of a non-local approach to plasma turbulence (streamers) as well as to a development of stiff local transport models (avalanches);
- A single theoretical model able to reproduce all experimentally observed phenomena (both steady state and transient) has yet to be found;
- Most probably such a model will be a combination of stiff transport with elements of non-locality in it.
Pulse No: 31341

Time (s)

11.48 11.50 11.52 11.54 11.56

$T_e$ (keV)

1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 5.0 5.2

R = 3.0 m

R = 3.4 m

R = 3.7 m

JG96.292/3c

Pulse No: 31341