Correlations of ELM frequency with pedestal plasma characteristics

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Theoretical study of ELMs as a relaxation phenomenon has been performed. It is motivated by the balance between plasma heating and the loss of energy during ELM turbulences. The energy balance is examined for particular heating scheme with neutral beam injection (NBI) in steady state scenarios of ASDEX Upgrade, JET, DIII-D and JT-60U with ELM oscillations. In this approach we have calculated the relaxation time in the pedestal region for corresponding plasma temperature and density. Apparent correlation is found between ELM frequencies and the relaxation time in the pedestal region. This correlation reveals a crucial role of pedestal properties in ELM triggering. It allows to derive predictions for the behaviour of ELMs in conditions of future experiments with ITER.

1 Introduction

Type I ELM is considered a reference regime for ITER due to the stationary plasma conditions in large time scale. This regime is widely investigated in ASDEX, JET, DIII-D and JT-60U experiments improving the time of plasma confinement. However an essential drawback is the presence of large power loads on the plasma-facing components during the short time interval of ELMy discharge. The understanding of the mechanisms and the control of ELMs is subject of intensive research. The reproducible characteristics of ELM oscillations point to MHD instability as a possible trigger of ELMs [1]. We start from first principles using balance of energy and assume that the stationary plasma conditions in ELMy discharges are maintained when energy and particle outward flux is compensated by the heating system. Here we consider the dominating heating with neutral (Deuterium) beam injection (NBI)and assume that ionized Deuterium atoms thermalise in the confined plasma due to Coulomb collisions. In this approximation the impact of other processes and the effect of the magnetic field configuration on the shape of plasma and ELMy discharges is neglected.

One of the main properties of ELM discharges is their frequency, f_{ELM}. Experimental data from JET [2], [3], ASDEX [4], DIII-D [5] and JT-60U [6] show strong correlations of ELMs frequency f_{ELM} with plasma pedestal properties. In order to understand the mechanism of ELM discharges some authors are examining the correlations of power and particle losses, ($\Delta W_{ELM}/W_{ped}$, $\Delta N_{ELM}/N_{ped}$), with the (neo) collisionality $\nu^* = \pi R_{q_{95}}/\lambda_c$, where λ is the electron-electron Coulomb collision mean free path [7]. These results motivate our interest in understanding the role of the transfer of energy from the outward flux to the edge of tokamak plasma during ELM phenomena.

2 Working hypothesis for ELMs

We hypothesize that the exchange of energy between electrons and ions in the pedestal plasma plays the role of a relaxation mechanism for ELM discharges. Such a role should be manifested by strong correlations between the time for relaxation of ELMs, $\tau_{ELM} = 1/f_{ELM}$ and the relaxation time of pedestal plasma, τ_{ped}.

The frequency f_{ELM} of ELMs is well measured while the relaxation time of plasma in the pedestal region of particular tokamak could be estimated only indirectly in the frame of a physical model for the processes in pedestal plasma during ELM turbulences. As a first approximation we neglect all processes except Coulomb collisions and express τ_{ped} as a function of pedestal plasma temperature and density within a general Fokker-Plank approach. The geometry of plasma connected with magnetic field configuration is neglected.

In accordance with the first principle of thermodynamics we assume that in ELM stationary regime the loss of pedestal power ΔW in a particular discharge is compensated by the power heating the plasma after the collapse during a relaxation time, $\tau_{ped} \simeq 20 - 30$ms. We call the post collapse plasma heating time the *pedestal plasma relaxation time*, neglecting the time of plasma collapse (about $200\mu s$).

In order to check this hypothesized relation between τ_{ped} and τ_{ELM} we use published data for correlations between ELM frequency, pedestal temperature and plasma density for fixed engineering conditions (input power P_{in},plasma current I_p, toroidal magnetic field B_t, triangularity δ). Only conductive ELMs are considered. Conductive ELMs appear at high pedestal temperatures which allow intensive soft X-radiation and large loss of energy in ΔW emission. The pedestal density is relatively low and remains almost constant during discharges in accordance with the assumption for constant power in the large time scale of stationary plasma confinement with ELM oscillations:

$$W_{ped} = \frac{3}{2}\, n_{ped}\, (T_e + T_i)\, V_{ped} = \text{const} \tag{1}$$

In this large time scale the volume V_{ped} is constant and in a first approximation the temperature of pedestal ions T_i is equal to that of electrons T_e (due to the exchange of energy between colliding particles).

Tokamak data [2],[3],[4],[5],[6] show that the loss of power $\Delta W_{ped}/W_{ped}$ and temperature $\Delta T_{ped}/T_{ped}$ in the pedestal region are strongly correlated with plasma density. On the other hand, the variation of pedestal density is in steady correlation with the frequency of ELM discharges. Experimental data [4] for conductive ELMs fit rather well the following functional dependence

$$f_{ELM} \sim n_{ped} \tag{2}$$

This dependence fails at high density in the range of convective discharges. The temperature of pedestal plasma remains relatively low and almost unaffected during convective ELM discharges. These discharges are characterized with large particle losses in accord with the assumption for constant power of stationary pedestal plasma during ELM oscillations (1).

3 Verification of relaxation property of ELM

We hypothesize that relaxation time of ELMs in the stationary conditions of pedestal plasma is approximately equal to the mean value of the time for plasma heating after each particular discharge. Here we intend to verify the hypothesis for relaxation nature of ELM turbulence using a simple physical model. According to this model after each collapse the pedestal plasma is heated by particles of expanding core plasma in Coulomb collisions with a rate $1.5\, n_{ped}\, \dfrac{T_e - T_i}{\tau_{ped}}$ depending on the pedestal plasma relaxation time. The latter can be expressed by the electron collision time:

$$\tau_e = 1.09\, 10^{16}\, \frac{T_e^{3/2}}{n_{ped}\, Z\, ln\Lambda} \quad s \tag{3}$$

derived from the Fokker-Planck coefficients in the case of Coulomb collisions of electrons with Maxwellian distribution of velocities. This expression for τ_e is expected to be valid also for the case of energy loss of a particle beam [8].

Taking into account that $\tau_{ped} = \frac{m_i}{2m_e}\tau_e$ we obtain from (3) the following simplified formula for the pedestal plasma relaxation time in terms of experimentally measured electron temperature and density :

$$\tau_{ped} = 1.2\, 10^{18}\, \frac{T_{ped}^{1.5}}{n_{ped}}\, s \tag{4}$$

where T_{ped} is measured in KeV, n_{ped} is measured in m^{-3}, and the Coulomb logarithm is 17.

Now, we will use (4) to find similarity between τ_{ped} and ELM relaxation time, $\tau_{ELM} = 1/f_{ELM}$. For this purpose we analyze experimental data correlations between ELM frequency, f_{ELM}, plasma density, n_{ped} and electron temperature, T_{ped} in the pedestal.

First, we derive linear dependence of f_{ELM} on n_{ped} using ASDEX data [4] (for plasma current $I_p = 1$MA, toroidal magnetic field $B_T = 1.5 - 2.7$T, triangularity $\delta = 0.2$ and separatrix power $P_{sep} = 4$MW):

$$f_{ELM} = a + b\, n_{ped}\, Hz, \tag{5}$$

where $b = 3.33\, 10^{-18}\ s^{-1} m^3$, $a = -100\ s^{-1}$. Next, from the hypothesis $\tau_{ELM} = \tau_{\text{ped}}$, (5), and (4) suggests the following relationship between the density n_{ped} and the pedestal temperature

$$n_{\text{ped}} \sim 0.121\, 10^{25} \frac{T_{\text{ped}}^{3/2}}{40293\, T_{\text{ped}}^{3/2} - 1000} + \text{const.} \tag{6}$$

This dependence can not be expected to hold for very high temperatures where other processes begin to affect the relaxation time of stationary plasma. In Fig. 1 we compare the postulated estimate (6) with the compiled

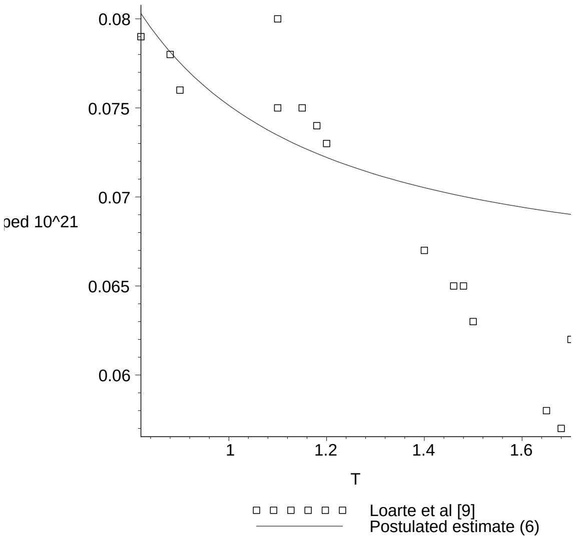

Fig. 1 Density-temperature correlation: Postulated curve (6) vs experimental data from [9]

data from JET [9]. Similar correlations between pedestal temperature and density are found in different operation conditions of JET [10].

To test our hypothesis that for temperatures up to $1.4\ KeV$ the ELM relaxation time is approximately equal to the relaxation time of pedestal plasma we use JET data [3] compiled in Fig. 2 and Fig.3. These are typical measurements for steady state type I ELMs in JET experiments($I_p = 2.5$MA,$B_T = 2.7$T, $P_{NBI} = 16\ MW$). From both figures we estimate $f_{ELM} = 35\ Hz$. This implies $\tau_{ELM} = 1/f_{ELM} = 0.0286\ s$ which is comparable to the relaxation time of pedestal plasma, $\tau_{ped} = 0.0213\ s$. The pedestal plasma relaxation time τ_{ped} has been calculated using formula (4) with electron temperature $T_{ped} = 0.738\ KeV$ (shown by dotted line in Fig. 2) and $n_{ped} = 3.59510^{19}\ m^{-3}$ the mean value of the registered plasma density (shown in Fig.3). In fact these are the averaged values of the minimal temperature and of the minimal density, measured after each particular collapse during ELM oscillations. For comparison of the magnitudes of the oscillations of the both variables we show their upper limits registered in this experiment. The minimal temperatures and the minimal densities of pedestal plasma in each particular collapse are presented by boxes in both plots. The of each of these sample points positions indicate the initial moments (in time) of pedestal plasma heating after each successive collapse during a time interval $0.6\ s$. The chosen interval contains 21 registered oscillations of pedestal temperature and density. The data in [3] shows perfect synchronization between each plasma collapse and radiated energy flux in opposite phases revealing the relaxation nature of ELMs.

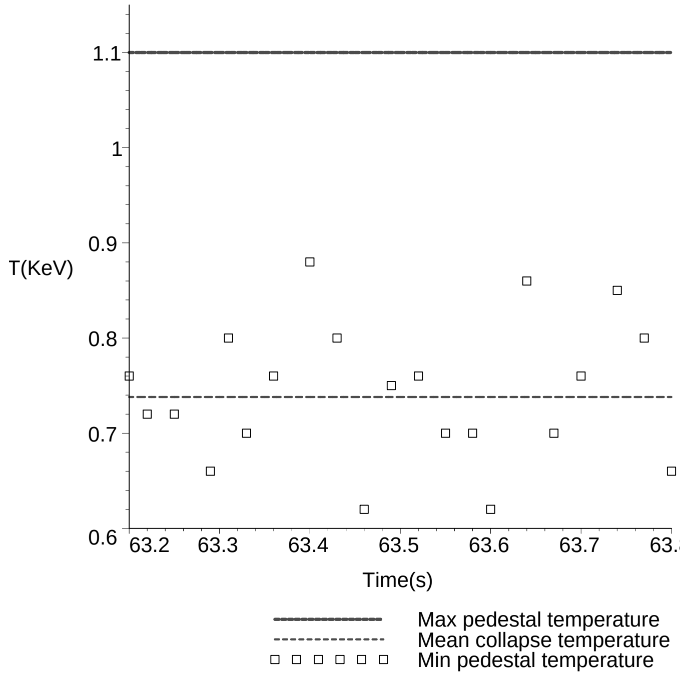

Fig. 2 Time variation of pedestal temperature data during ELM oscillation. (Compilation of data from [3])

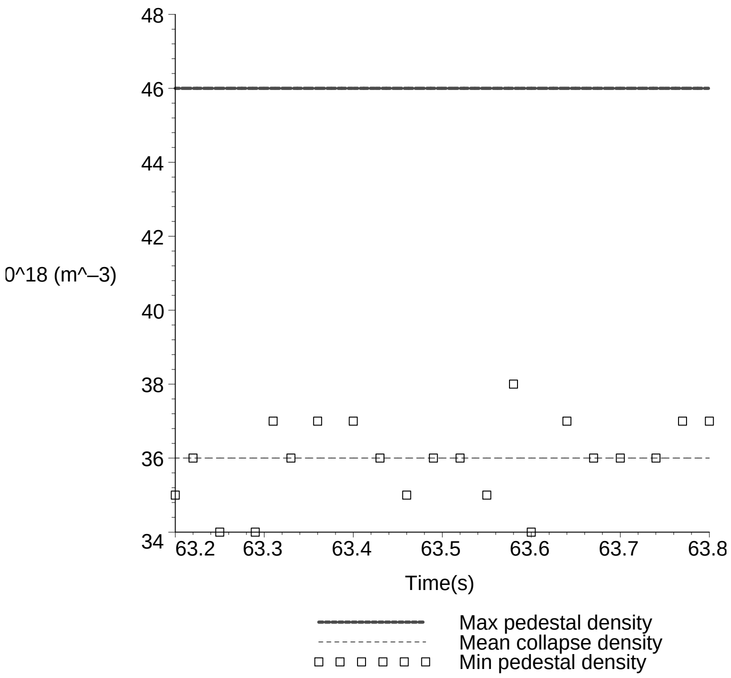

Fig. 3 Time variation of pedestal density data during ELM oscillation. (Compilation of data from [3])

4 Summary and Conclusions

We hypothesize a relaxation nature of ELMs. It is verified with experimental data for conductive discharges using published data for the correlations of ELM frequency, plasma temperature, and density in typical conditions for type I ELM discharges with NBI.

The hypothesis suggests a postulated temperature-density functional dependence based on the Fokker-Planck formula for the relaxation time of pedestal plasma considering only Coulomb collisions of plasma particles and Maxwellian distribution of velocities. This dependence fits with available experimental data ([9]) up to $\approx 1.4\ KeV$.

At temperatures above $1.4\ KeV$ the theoretical $T_{ped} - n_{ped}$ dependence derived within the present simple model is not confirmed by the experimental data. The disagreement in Fig. 1 indicates that the relaxation time of stationary plasma becomes larger than that derived with the Fokker-Planck formula accounting only for Coulomb collisions. Obviously the impact of processes with larger loss of energy in radiation (as the electron Bremstrahlung in the field of Deuterium nuclei) become essential at such high energies. More realistic physical model is needed to predict ELM properties in conditions of future ITER experiments.

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