Spatio-temporal investigations on the triggering of pellet induced ELMs

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Outline

Introduction: ELM dilemma in large tokamaks
mitigation by frequency enhancement
pellet pace making

Motivation: understanding of pellet ELM triggering mechanism

Experiments: Pellet localisation
   Determination of the ELM onset time

Characterisation of the injection scenarios

ELM trigger: localisation of the seed perturbation

ELM energy loss

Conclusions and outlook
The ELM dilemma in large tokamaks: Confinement vs. divertor power load

ITER Standard operation: type-I ELMy H-mode

ELM (Edge Localised Mode): periodic energy pulses deposited on first wall components

Energy content ~ Volume ~ R³

Impact area ~ 2π R dR

Energy density ~ R² / dR

Large tokamak, severe problem

F. Federici et al., PPCF 45 (2005) 1523
Solving the ELM problem: mitigation by frequency enhancement

Envisaged solution:
Mitigate ELMs below damage threshold

Observation:
$$\Delta W_{\text{ELM}} \sim \frac{P_{\text{heat}}}{f_{\text{ELM}}}$$
for many scenarios with "natural" ELMs

Approach:
"Split" few large ELMs into many small ones

A. Herrmann, PPCF 44 (2002) 883
Pacing and mitigation by the injection of solid D pellets

P.T. Lang et al., Nucl. Fusion 43 (2003) 1110
Motivation

Injection of frequent small and shallow penetrating cryogenic pellets has been found a promising techniques to mitigate the ELM effect.

The technique works but the underlying physical processes of the ELM triggering are not well understood. Therefore our aim is to study how a pellet triggers an ELM.

The investigations presented in this talk were devoted to answer the questions:

**At which magnetic surface does the perturbation of the ablating pellet cause the ELM?**

**What is the corresponding local perturbation caused by the ablating pellet?**

To answer the questions the dynamics of the triggered ELMs has to be linked to the time history of the pellet position in the plasma.
The experiments have been performed on the ASDEX Upgrade tokamak injecting pellets from the high field side of the torus into the type-I ELM regime of an H-mode discharge.

Stable and robust operation in the type-I ELM regime with low natural ELM frequency (25 - 45 Hz) was achieved by keeping the auxiliary heating power just above the L-H transition power threshold.

To avoid the disturbance of the natural ELM cycle and parasitic plasma fueling, perturbative ELM triggering with driving frequency (6Hz) small compared to the natural ELM frequency was used.

Low pellet injection frequency: trigger events occur at different times in the ELM cycle that is we perform the analysis as a function of the time elapsed after the previous ELM.

In order to determine the delay of a triggered ELM relative to the pellet injection the time when the pellet crossed the separatrix was selected as reference time. Consequently the pellet trajectory has to be reconstructed.
Pellet localisation

- Short multiple exposures:
  - on time: 10µs
  - off time: 90µs

- Trajectory reconstruction

- Vide angle view

- Photodiode

- Ablation monitor signal

- Camera exposures
Pellet localisation

To determine the time when the pellet crossed the separatrix: trajectory has to be reconstructed

Simple method:
Pellet flies on a straight path from the looping end until the first exposure

More accurate method:
Takes into account that pellets are accelerated to the LFS, uses a fitting procedure maximising the pellet cloud radiation along the curved path

Simple method works for all cases and $t_{\text{pellet @ separatrix}}$ agreed with the more accurate one within 10µs for $V_p > 240$ m/s, 20µs for $V_p = 240$ m/s

simple method is used
ELM onset determination

Dynamics of the ELM MHD activity is monitored by magnetic coils:

- **Toroidal pick-up coil set**
  - About 180°, 5 coils, LFS

- **Mirnov coil set**
  - 360°, 30 coils, LFS-HFS

- **Poloidal pick-up coil set**
  - About 60°, 7 coils, LFS

Magnetic pick-up coils signals:
- Strong quasi periodic oscillation at the very beginning of the ELM event
For every ELM the Hilbert-Huang spectrogram was calculated and integrated in the typical 100-300kHz range (magnitude of the ELM related MHD activity).

Which magnetic coil should be used?

| Divertor Hα |
| Ablation monitor signal |
| Squared averaged pick-up coil signal |
| Pick-up coil signal |
| FFT spectrogram integrated over 100-300kHz |
| Hilbert-Huang spectrogram integrated over 100-300kHz |

$t_{ONSET}$: magnitude exceeds a predefined threshold
ELM onset determination

\[ V_P = 240 \text{ m/s} \]

Poloidal pick-up coil set

Toroidal pick-up coil set

Reference \( t_{\text{ELM\_ONSET}} \): averaged over poloidal set

Poloidal, toroidal pick-up coils, Mirnov coils:
\( t_{\text{ELM\_ONSET}} \) is within +/-10\( \mu \text{s} \)
ELM onset determination

Only a slight difference at HFS midplane:
Oscillations detected before the ELM onset, but after the pellet crossed the separatrix

Observation of high beta pellet cloud for larger velocities???
ELM onset determination

- Field line start points
- +180 (pellet trace), then field lines followed forward (+) & backward (-)

---> Subsequent field line intersections plotted on two poloidal planes at 0 and 180 degree;
Left-handed screw:
clockwise (+ from top) means towards inside (HFS) down,
clockwise (-) means over top to outside (LFS)

----> Flux bundle remains more compact on HFS than on LFS
Natural vs triggered ELMs

triggered ELMs

Natural ELMs:
Larger scattering probably caused by the ELM precursors observed by the onset evaluation algorithm

previous natural ELMs
Investigation strategy

Earlier observations:
- Every pellet injected into type-I ELMy H-mode plasma of ASDEX Upgrade triggered an ELM
- This ELM was observed only if the pellet entered into the confined plasma crossing the separatrix: $dt_{\text{ELM ONSET}} = t_{\text{ELM ONSET}} - t_{\text{pellet @ separatrix}} > 0$
- $dt_{\text{ELM ONSET}}$ depends on pellet velocities

Assumption: to trigger an ELM pellet has to reach a certain magnetic surface ($l_{\text{seed}}$) independently of the pellet mass and velocity

$$dt_{\text{ELM ONSET}} = \frac{l_{\text{seed}} - l_{\text{separatrix}}}{V_p} + t_0$$

Perturbation spreads and finally an instability starts to grow which develops into an ELM.

Pellet velocity scan: $t_0$, $l_{\text{seed}}$ can be determined

But first the dependence of the ELM onset delay on the pellet mass and the time elapsed after the prev. natural ELM has to be investigated.
Low pellet injection frequency: trigger events occur at different times in the ELM cycle. That is, we perform the analysis as a function of the time elapsed after the previous ELM.

Pellets can trigger ELMs at any time in the ELM cycle: plasma edge is not stable against a pellet induced seed perturbation.

\[ dt_{\text{ELM_ONSET}} \text{ saturates with increasing } dt_{\text{elapsed}} \]

\[ dt_{\text{elapsed}} > 8 \text{ms}: \quad dt_{\text{ELM_ONSET}} \sim \text{constant} \]
ELM onset delay vs pellet mass

$dt_{elapsed} < 8\text{ms}: \text{omitted!}$

$\text{shot: 20043, } v = 600\text{m/s}$

$\text{shot: 20041, } v = 240\text{m/s}$

$dt_{ELM\_ONSET}$ hardly depends on the pellet mass in the investigated mass range
Measurement of the ELM onset delay as a function of the pellet velocity →

\[ V_P = 240,600,880,1000 \text{ m/s} \]

HFS looping system: pellet erosion is velocity dependent →

\[ r_P = 0.71, 0.67, 0.58, 0.51 \text{ mm} \]

\[ N_P = 9, 7, 5, 3 \times 10^{19} \]

Characterization of the injection scenarios → Neutral Gas Shielding model calculation

\[ \frac{dN_P}{dt} = - \text{Const. } r_P^{4/3} n_e^{1/3} T_e^{1.64} \]

\[ \frac{dN_P}{dl} V_P = - \text{Const. } r_P^{4/3} n_e^{1/3} T_e^{1.64} \]

P.B. Parks et al., PoP 21 (1978) 1735

Integrating this diff. equation along the designated pellet path

the ablation rate (ablated particles /s) is calculated
Injection scenarios

240 m/s, r=0.71mm, N=9 \cdot 10^{19}
600 m/s, r=0.67mm, N=7.4
880 m/s, r=0.58mm, N=5.0 \cdot 10^{19}
1000 m/s, r=0.51mm, N=3.3 \cdot 10^{19}

In the pedestal region the ablation rate is nearly similar for all injection scenarios.

Pellets penetrate deep into the plasma crossing the pedestal region completely.

Particle deposition scales with $1/V_p$. 

[Graphs and diagrams showing plasma parameters and pellet penetration]
Method check: time of flight

Pellet flight time from the separatrix until the pellet onset: \( dt \sim \frac{1}{V_p} \)

\[
dt_{PEL\_ONSET} = 3.2(0.4)\text{cm}^2\text{V}^{-1}_p + 11.0(6.5) \times 10^{-6}\text{s}
\]

Method and strategy work!
error \( \sim 10 \) \( \mu \text{s} \)
ablation rate is similar

simulation: 4 diff. velocities

\[
dt_{PEL\_ONSET} = t_{PEL\_ONSET} - t_{\text{pellet@ separatrix}} = \frac{(l_{ONSET} - l_{\text{separatrix}})}{V_p}
\]
ELM onset delay, location of the seed perturbation

\[ dt_{\text{ELM\_ONSET}} = t_0 + \frac{(l_{\text{seed}} - l_{\text{separatrix}})}{V_p} + 50.1(7.1) \times 10^{-6} \text{s} \]

\[ dt_{\text{elapsed}} > 8.0 \text{ms} \]

Location of the seed perturbation: at the middle of the pedestal

Pellet cloud diameter: 2 cm

Careful error estimation:
- inaccuracy of the
  - separatrix reconstruction,
  - camera spatial calibration,
  - separatrix crossing time calc.,
  - ELM onset time determination
were taken into account

\[ t_0 = 50 \pm 7 \mu s \]
\[ l_{\text{seed}} = 2.7 \pm 0.4 \text{ cm} \]
ELM energy loss

The relative energy drop does not depend on $dt_{\text{elapsed}}$
The normalised energy loss (triggered/natural) tends to 1 for smaller perturbation and slightly drops for larger perturbation → fuelling → modified pedestal.
Pellet triggering of ELMs was investigated by probing the natural ELM cycle injecting pellets with much lower frequency than the natural ELM frequency. Every injected pellet can trigger an ELM independently of its velocity and mass and the time elapsed after the previous natural ELM.

Only 5-15% of the expected pellet mass is ablated until the position of the seed perturbation.

Assumption: to trigger an ELM a pellet has to reach a certain closed magnetic surface independently of its mass and velocity, location of the seed perturbation: at the middle of the pedestal where the plasma pressure gradient reaches its maximum.

Consistently with peeling-ballooning model of the ELM predicting instability onset localized to the pedestal steep gradient region

Leonard et al, PPCF (48) 2006 A149, Snyder et al, PoP (12) 2005 056115

Still question: smaller pellets still reaching the same location of pedestal gradient region can trigger an ELM or not (according perturbation reduces with pellet size).
Conclusions

Origin of 50µs intrinsic delay time (perturbation spread time + instability growth time) is unclear → in absence of the full understanding of the trigger mechanism only speculative answer can be given.

The perturbation caused by the ablating pellet:

large local particle deposition (comparable to the particle inventory of the pedestal) spreading with ion sound speed \(10^5\) m/s → 50µs delay time is not long enough for spreading of ions deposited on the HFS to the LFS, that is this perturbation can not trigger an ELM on the LFS

local cooling which homogeneously distributed on the whole magnetic surface on a few 10µs timescale (electron cooling wave travels with electron thermal speed \(10^7\) m/s) → ELMs can be triggered by the cooling of the pedestal region by sudden increase of the pedestal plasma pressure gradient driving the plasma to the unstable region of the ballooning mode

moving high beta pellet cloud generates a strong MHD perturbation propagating with Alfven speed \(5 \times 10^6\) m/s, which also appears on the LFS within this 50µs → ELMs may be triggered by the strong MHD perturbation triggering an instability developing into an ELM.
Outlook

To further investigate the trigger mechanism and validate our present observations, ELMs will be triggered by LFS pellet injection.

New pellet injector was developed and taken into operation in the last campaign.

Injector works, but majority of pellets are probably broken because of large aspect ratio: $\phi=2\text{mm}$, $l=0.5\text{mm}$.

$\rightarrow$ smaller one $\phi=2\text{mm}$, $l=1\text{mm}$

in the next campaign.
Outlook

Next experimental campaign at ASDEX Upgrade:

New port for Leidenfrost gun

Two different injection directions:

nearly tangential to the separatrix combined with horizontal shifting of the plasma → mapping the location of the seed perturbation.

nearly perpendicular to the magnetic surfaces intrinsic delay measurement → investigation of HFS/LFS asymmetry of the ELM triggering if it exists et al.

Detailed discussion: tomorrow 14:30 in Edge Physics Forum
Pellet database development

1. step: pellet lifetime + plasma parameter database (Eva Belonohy)
2. step: video observation database with real spatial informations: trajectories, profiles (Tamas Szepesi)

Pellet video observation database

→ curved trajectory (acceleration!)

\begin{align*}
R(t) &= R_0 + v_0 t \cos(\phi) + b \cdot t^a \\
z(t) &= z_0 + v_0 t \sin(\phi) \\
\theta(t) &= 0
\end{align*}

⇒ video measurement tends to give higher values than abl. monitor

• project \( \lambda_{\text{video}} \) to the injection line
• a correction formula can be defined

\[ \lambda_{\text{video}} = \lambda_{\text{diode}} + a \cdot \lambda^b \]

projected penetration (+) in good agreement with the TOF measurements

the correction formula fits the data (◊) quite well
Injection scenarios

- Pellets penetrate deep into the plasma crossing the pedestal region completely.

- In the pedestal region the ablation rate is nearly similar for all injection scenarios.

- Particle deposition scales with $1/V_P$.

- Injection parameters:
  - 240 m/s, $r=0.71\text{mm}$, $N=9 \cdot 10^{19}$
  - 600 m/s, $r=0.67\text{mm}$, $N=7.4$·$10^{19}$
  - 880 m/s, $r=0.58\text{mm}$, $N=5.4\cdot10^{19}$
  - 1000 m/s, $r=0.51\text{mm}$, $N=3.3\cdot10^{19}$