Investigation of pellet-driven plasma perturbations for ELM triggering studies

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Outline

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Experimental set-up and data processing

Pellet caused MHD perturbation in type-I, type-III and ohmic discharges

Pellet caused plasma cooling in type-I ELMy H-mode

Summary and discussion: pellet ELM triggering
Introduction I

Type-I ELMs can cause critically high transient power load on plasma facing components.

Radiation in divertor (JET bolometry)

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

Before ELM

After 1MJoule type-I ELM

ITER Standard operation:
  type-I ELMy H-mode

Energy content ~ Volume ~ $R^3$
Impact area ~ $2\pi R dR$
Energy density ~ $R^2 / dR$
Large tokamak, severe problem

F. Federici et al., PPCF 45 (2005) 1523

Injection of frequent small and shallow penetrating cryogenic pellets has been found a promising technique to mitigate this effect.

The technique works but the underlying physical processes of the ELM triggering are not well understood. Therefore our aim is to study how and where a pellet triggers an ELM to be able to make predictions for future machines and to optimise the pellet pacing tool.
Investigation strategy

The experiments have been performed on the ASDEX Upgrade tokamak injecting pellets from the high field side of the torus into different ELMy H-mode and ELM free standard ohmic discharges to investigate and compare the pellet caused perturbations.

Standard OH

Type-I

Type-III

To minimise the disturbance of the target plasma low pellet injection frequency (5-6Hz) small compared to the natural ELM frequency was used with usually the smallest pellet size available.
Experimental set-up I

Pellet localization (space, time):
- fast CCD cameras + spatial calibration
→ def: penetration = distance from separatrix
Experimental set-up II

Toroidal pick-up coil set about 180°, 5 coils

Mirnov coil set 360°, 30 coils

Poloidal pick-up coil set, 7 coils about 60°

Calibrated Electron Cyclotron Emission (ECE) profiles are measured in second harmonic X-mode with a fast 60-channel heterodyne radiometer

Processing of the pickup coil signals
- eliminate LF component by moving box average
- calculate the envelope of the remaining HF component (25 μs box)
- assume: envelope ~ MHD perturbation magnitude

500 μs separatrix crossing

PELLET Ablation monitor

Pick-up coil signal

ELM-delay

B31-14

#20040, v_p = 240 m/s
### Experimental set-up III

**Processing of pick-up coil signals: spectral properties**

**Continuous analytical wavelet transform:**

Time shift and scaling invariant

\[
Wf(u, s) = < f, \Psi_{u,s} > = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{s}} \Psi^*(\frac{t-u}{s}) dt
\]

**Short-time Fourier transform (STFT):**

Time shift and frequency shift invariant

\[
Sf(u, \xi) = < f, g_{u,\xi} > = \int_{-\infty}^{+\infty} f(t) g(u-t)e^{-i\xi t} dt
\]

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**Mode numbers** as least squares fit to cross-phase

\[
\Theta_{x,y}(u, \xi) = \arg \langle CS_f, g(u, \xi) \rangle
\]
as function of relative probe position \( \varphi_{x,y} \):

\[
Q_m(u, \xi) = \sum_{x,y} w_{x,y}(u, \xi) \left( \Theta_{x,y}(u, \xi) - m \varphi_{x,y} \right)^2
\]
MHD activity magnitude

**Standard OH**

- MHD increases with penetration
- No velocity dependence

**Type-I**

- Clear separation (pellet, ELM)
- ELM burst seen deeper for faster pellets

**Type-III**

- More resembles to ohmic ELM amplitude ~ direct pellet

Assumption: ELM triggered at a specific location
⇒ use several speeds to rule out time of flight

Kocsis et al, NF, 47, 1166, 2007

\[
\Delta t_{\text{ELM ONSET}} = t_0 + \left( z_{\text{seed}} - z_{\text{separatrix}} \right) / V_p
\]

- \( t_0 = 50\mu\text{s} \)
- \( z_{\text{seed}} = 2.7\text{cm}, \text{ped. middle} \)
MHD magnitude, comparison

MHD envelopes - comparison of scenarios

Clear separation of type-I ELM-related and pellet-induced MHD activity

- type-I ELM-related MHD no longer related to pellet position (nor $p_e$)
- pellet-phase also visible for some type-I cases (long pellet lifetime)
- pellet-induced MHD independent of pellet parameters

BUT: depends on plasma parameters
Normalized decay of all type-I and OH

- same behaviour within the error bars
- higher „base” level for type-I

→ higher $T_e$ of the background plasma

⇒ the pellet-induced MHD activity is the same kind in all studied scenarios (except the ELM)
Standard ohmic and type-III

Standard OH

TAE: frequency is reduced by pellet fuelling

\[ f_{\text{TAE}} = \frac{1}{2\pi} \frac{v_A}{2qR} \sim \frac{B_i}{\sqrt{n_e}} \frac{1}{2qR} \]

Maraschek et al, PRL 79, p4186

Plasma edge turbulence driven
TAE: • amplitude enhanced by the polarised pellet cloud
• broadening by excitation
• Toroidal mode number \( n = -6 \) (ion diamagnetic drift dir.? )

before pellet during pellet ablation after pellet

PEL

Type-III

• frequency chirp during pellet ablation
• more resembles to ohmic?

PEL

Toroidal mode numbers #22310

\[ df = 15 \text{kHz} \]
\[ dn = 26 \pm 10\% \]

Toroidal mode numbers #22188

PEL
Type-I ELMy H-mode

**Type-I natural**

Inter ELM washboard modes: n=3,4 (electron diamagnetic drift dir.)

- The same mode as in ohmic n=-6,
  - but only for short time after the ELM termination
  - which is extended during pellet ablation

**Type-I triggered**

This method could not calculate mode number during ELM for high frequencies
Type-I ELMy H-mode

15 pellet induced ELMs have been analysed for their basic poloidal/toroidal structure.

The single, upward rotating structure represents a rather specific case. Typically, two or more such pronounced structures occur simultaneously.

Despite the fixed pellet launch position, they appear initially at a more or less random toroidal position relative to the pellet, i.e. they are not directly growing out of the pellet plasmoid.

Neuhauser et al, NF, 48, 045005, 2008
Pellet caused local cooling is homogeneously distributed on the magnetic surface in a few 10µs (fast electron cooling wave travels with electron thermal speed \( \sim 10^7\) m/s).

The local cooling appears on fast ECE electron temperature measurement located toroidally 90° from the location of the pellet injection in a few 10µs.
Pellet caused cooling:

- appears almost immediately after the pellet reached the according magnetic surface
- causing remarkable temperature drop on a short timescale
- the cooling front moves together with the pellet for all pellet velocities.
- pellet plasma cooling lasts until the pellet is completely ablated and the plasma starts to recover but on a ms timescale.
- relative temperature drop is in the range of few 10% seems to depend on the pellet velocity.
- temperature decrease caused by the triggered ELM is slower than direct pellet one, therefore they can be discriminated.
Summary of the observations

- every pellet triggers an ELM independently of the pellet velocity and mass at any time in the ELM cycle

- prompt triggering: ELM onset is detected typically within 50-150μs after pellet crossed the sep.

- pellet mass ablated until the ELM onset is few percent of the mass of the injected pellet

- for type-I ELM the location of the seed perturbation is in the pedestal; internal delay: 50 μs

- direct pellet driven MHD perturbation depends on the local plasma parameters

- type-III MHD amplitude and mode number resembles to that of the direct pellet driven

- type-I MHD amplitude is about 100x larger than the direct pellet driven

- type-I ELM mode structure different from the direct pellet driven

- pellet caused axisymmetric cooling appears almost immediately, cooling front moves with the pellet causing 10-40% temperature drop
Discussion: Pellet ablation I

Pellet ablation in the first 50-100μs:

→ neutral cloud formed on μs timescale

→ ionised cloud elongated along field lines
   expansion velocity: ion sound speed < 10⁵m/s
   localised in non-axisymmetric filament < 10m

→ pellet cloud absorbs the incoming energy
   flux, cooling wave travels with electron
   thermal speed ~ 10⁷m/s
   → homogenised on the
   whole magnetic surface in a few 10μs

→ diamagnetic pellet cloud launches
   broadband Alfvén waves (v_A~5 · 10⁶m/s)
   that communicated on the whole magnetic
   surface on a few 10μs

→ further complicated by grad B caused
   cloud drift to LFS

Geometry at ASDEX Upgrade:

Type-I ELMy H-mode pedestal along the pellet trajectory ~ 6cm
Pellet cloud radius perpendicular to the magnetic field ~ 1cm
Pellet velocity: 240-1000m/s, pellet mass: 3-9(20) 10¹⁹ deuterium
Discussion: Pellet ablation II

Estimation of the **pellet cloud pressure** and **plasma pressure drop**

Pellet affects the plasma at a magnetic surface as long as

\[ t = \text{Diam}_{\text{CLOUD}} / \nu_p = 20-100 \mu s \]

→ the incoming energy flux is absorbed and concentrated in the HFS localised helical non axisymmetric cloud causing a cloud pressure higher than that of the target plasma

**rough estimate:**

\[
P_c = \frac{CK \nu_{e\text{th}}^2}{6 c_s} P_e > 10P_e
\]

→ axisymmetric decrease of the plasma pressure causing a pressure gradient increase in front of the pellet

**rough estimate:**

\[
P_c^r = P_e [1 - C \cdot \frac{2 A_c \nu_{e\text{th}}}{3 A_m \nu_p}] \quad 10-30\% \text{ for AUG}
\]
Discussion: Pellet ELM triggering

Trigger mechanism for type-I ELM triggering

The most probable mechanism is the axisymmetric cooling of the pedestal region causing a sudden increase of the pedestal plasma pressure gradient driving the plasma to the linearly unstable region of the ballooning mode.

The large local particle deposition building the non-axisymmetric HFS localised high pressure pellet cloud may also be the seed perturbation. The non-axisymmetric extremely high pressure gradient can nonlinearly drive the ELM instability. As a contradiction the observation revealed that the typical MHD modes are not directly growing out of the pellet cloud/plasmoid.

The moving high beta pellet cloud generated MHD perturbation plays probably a minor role in the ELM triggering, because the direct pellet driven MHD modes are different from the typical ELM related ones and their amplitudes are orders of magnitude smaller, too.

Trigger mechanism for type-III ELM triggering

The structure and the amplitude of the MHD modes observed in the type-III ELM My H-mode resemble to that of the direct pellet driven, therefore this trigger mechanism can also be a candidate for type-III ELM triggering.
Discussion