ELM filament heat loads on plasma facing components in JET and ITER

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Divertor power deposition due to edge localized modes in JET and ASDEX Upgrade

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\textsuperscript{*} See Appendix of F. Romanelli, OV/1-2, this conference

15/10/2008, 22\textsuperscript{nd} IAEA, Geneva, Switzerland, rapported by Dr. W. Fundamenski
Growth stage:

- Linear instability (e.g. ideal/resistive MHD mode) forms n flute-like ripples in pedestal quantities

Saturation stage:

- These develop into n filaments during the non-linear phase of the instability; beginning of transport, parallel losses, magnetic reconnection, ergdodization?

Exhaust stage:

- Filaments move outward, driven by interchange (curvature + pressure), while draining to the divertor targets
Ions released during an ELM from an initially Maxwellian distribution stream freely along field lines to the (inner/outer) divertor targets (W.Fundamenski et al., PPCF48 (2006))

\[
P_{\text{div}}(t) = \frac{E_{\text{ELM}}^{\text{div}}}{\sqrt{\pi} \tau_{\text{FS}}} \times \exp \left( -\left( \frac{\tau_{\text{FS}}}{t} - M_{\text{ELM}} \right)^2 \right) \times \frac{\tau_{\text{FS}}^2}{t^2} \times \left( 1 + \frac{\tau_{\text{FS}}^2}{t^2} \right)
\]

Values observed

Power load can be fitted by 4 parameters \( E_{\text{in}} + E_{\text{out}}, \tau_{\text{in}}, \tau_{\text{out}} \) and \( M_{\text{ELM}} \)
Comparison with IR data: AUG

- In/out ELM energy asymmetry changes with field direction
- Inferred Mach number consistent with magnitude/direction of toroidal rotation
- Comparable FS times to both targets ($\tau_{in} \sim 1.1 \times \tau_{out}$); not affected by helicity
• Near separatrix profile shape roughly similar between and during ELMs
• Imprints of single filaments resolved in the far scrape-off layer
• Comparable radial power decay lengths observed at target and outer mid-plane

$\gamma T_e = 100$ – for this plot
Position of the Filament probe: Sep_dist + 1 cm

A. Herrmann, this conference
Pre-ELM magnetic equilibrium

- Near separatrix heat load profile roughly similar between and during ELMs.
- Heat load imprints of single filaments resolved in the far scrape-off layer.
- Using pre-ELM SOL magnetic field, the quasi-toroidal mode number can be found.
• ELM mode structure derived from striations in divertor heat fluxes
• Similar quasi-toroidal mode number, n~4-12, as observed previously on AUG
• Mode number increases with time, by a factor of ~ 2-3, during the ELM (exhaust)
• Suggests break-up into smaller structures

T.Eich et al., PPCF 47, p.841 (2005)
• New wide angle IR camera diagnostic using ITER-like front mirrors.

• 640x512 pixel FPA, max. full frame rate 100 Hz (E. Gauthier et al., CEA)

\[ \Delta W \sim 200 \text{ kJ} \]
\[ t = 7.6 \text{ s} \]
\[ \text{Exp. time } 300 \mu \text{s} \]
\[ \text{Frame time } 7.8 \text{ ms} \]
ELM filaments follow pre-ELM magnetic field lines in the poloidal-toroidal plane

Also observed on the upper dump plates
Pulse# 70372 t=46.833604s
33us exp.

**Type-I ELM**

- Exposure time 33 µs
- Ten successive frames showing ELM-filaments striking the upper dump plate
- Less contact at outer limiter
- Wide angle IR image during an ELM
- Combined with EFIT reconstruction
- Helical stripes on upper dump plate
- Closely aligned with local magnetic field – smaller pitch angle than at omp
IR imprint on upper dump plate

**poloidal**

68913, $t=56.1\ \text{s}$

**Type-I ELM**

$68913, t=57.1\ \text{s}$

$68915, t=57.5\ \text{s}$

**toroidal**

68913, $t=58.5\ \text{s}$

68913, $t=58.7\ \text{s}$

68913, $t=60.1\ \text{s}$

**Type-III ELM**
Results of IR imprint analysis

• Quasi-toroidal mode number, $n_w \sim 2\pi/\Delta\phi$, inferred as:
  – $n_w \sim 30 – 40$ at the outer limiter ($\Delta r = r - r_{sep} \sim 5$ cm), with little dependence on ELM size, $\Delta W_{ELM}/W_{ped}$
  – $n_w \sim 20 – 60$ at the upped dump plate ($\Delta r \sim 2$ cm), with a roughly inverse linear dependence on ELM size, $n_w \sim 6/(\Delta W_{ELM}/W_{ped})$.

• The relative width, $\delta\theta/\Delta\theta$, is roughly independent of ELM size
  – Mean $\delta\theta/\Delta\theta \sim 0.6 \pm 0.2$ at the upper dump plates
  – Mean $\delta\theta/\Delta\theta \sim 0.8 \pm 0.2$ at the outboard limiters

• The observed range of quasi-toroidal mode numbers is somewhat higher than predicted by the Peeling-Ballooning model of the ELM instability:
  – in which $n_0 \sim 10$ at low density to $n_0 \sim 30$ at high density

• This suggests a break-up of initial ELM filaments into roughly $\sim 2 - 3$ smaller fragments in the SOL before hitting the wall
  – Consistent with IR observation at the divertor tiles
  – Consistent with break-up of filaments under interchange drive
- main chamber IR camera too slow to follow single ELMs and filaments
- hence, use energy balance for a single outboard poloidal limiter during H-mode phase

Assumptions:
- only ELMs can deposit energy on limiters
- no energy to upper dump plates
- no energy deposited in compound phases
- same energy on 16 limiters

R.A.Pitts et al, PSI-2008; submitted to JNM
Fraction of energy to limiters

\[ I_p = 3.0 \text{ MA}, \ B_\phi = 3.0 \text{ T}, \text{ gas scan. Separatrix-midplane outer wall gap fixed at } \sim 5.0 \text{ cm.} \]

\( \Delta W_{ELM} \) estimated for first ELM peak only

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>( \Gamma_{\text{gas}} ) (10(^{22})e/s)</th>
<th>No. ELMs</th>
<th>( \sum \Delta W_{ELM} ) (MJ)</th>
<th>( \sum E_{\text{LIM}} ) (MJ)</th>
<th>( \langle \Delta W_{ELM} \rangle ) (kJ)</th>
<th>( \sum \frac{E_{\text{LIM}}}{\Delta W_{ELM}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70221</td>
<td>1.47</td>
<td>133</td>
<td>29.7</td>
<td>1.49</td>
<td>224</td>
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<tr>
<td>70222</td>
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<td>87</td>
<td>23.9</td>
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<tr>
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<td>12.7</td>
<td>1.49</td>
<td>528</td>
<td>11.8</td>
</tr>
</tbody>
</table>

- For fixed wall gap, larger ELMs deposit (on average) more energy on to the outer limiters
- How does wall energy fraction compare with theory?

R.A. Pitts el al, PSI-2008; submitted to JNM
**Pedestal $n_e$ & $T_e$ profiles**

- Assume ELM filament begins to experience parallel losses from the mid-pedestal values of $n_e$ and $T_e$


- Pre-ELM profiles and ELM filament evolution measured using Thomson scattering

---

M. Beurskens et al, this conference
Consider the radial motion of the pedestal plasma subject to parallel losses.

Low $v^*$: plasma cools faster than it dilutes: mainly conductive losses

High $v^*$: less cooling, more rarefaction: significant convective losses

Evolve the density and temperature of the filament using a fluid model.
Comparison with model

Mid-pedestal:
\[ T_{e,0} = T_{i,0} \approx 800 \text{ eV} \]
\[ n_{e,0} \approx 3.0 \times 10^{19} \text{ m}^{-3} \]
\[ \Delta_{\text{ped}} \approx 4 \text{ cm} \]

\[ v = 600 \text{ ms} \rightarrow \]
from previous JET studies

\[ W' = 0.094 \]
(model)
\[ W' = 0.088 \]
(experiment)

Good agreement given the model approximations and measurement errors!

\[ W_0 = \frac{3}{2} n_0 (T_{e,0} + T_{i,0}) \]

R.A.Pitts el al, PSI-2008; submitted to JNM
Pedestal top:
$T_{e,0} = T_{i,0} \sim 1500 \text{ eV}$
$n_{e,0} \sim 5.0 \times 10^{19} \text{ m}^{-3}$

Separatrix:
$T_{e,0} = T_{i,0} \sim 200 \text{ eV}$
$n_{e,0} \sim 1.0 \times 10^{19} \text{ m}^{-3}$
$v_{ELM} = 600 \text{ ms}^{-1}$
Comparison with model

Filaments starting at:
- the pedestal top with twice higher $v_{ELM}$ deposit the same energy at the limiter
- the separatrix must travel much slower ~180 m/s to match the observation
- the separatrix with pedestal quantities, could explain the data

R.A.Pitts el al, PSI-2008; submitted to JNM
Simulations of filament motion

$$M_{\parallel}^{int} = \frac{V_{\parallel}^{int}}{c_s} = \left( \frac{2l \Delta p}{R p_0} \right)^{1/2}$$

Extrapolation to ITER

- JET results indicate that larger ELMs travel faster
- Consistent with mainly interchange driven filament motion

\[ M_{\perp}^{\text{int}} = \frac{V_{\perp}^{\text{int}}}{c_s} = \left( \frac{2 l \Delta p}{R p_0} \right)^{1/2} \sim \left( \frac{\Delta W_{\text{ELM}}}{W_{\text{ped}}} \right)^{1/2} \]

- use the parallel loss model with earlier measurements (\( v_{\text{ELM}} = 600 \, \text{m/s} \) for \( \Delta W_{\text{ELM}}/W_{\text{ped}} \sim 0.12 \))

\[ V_{\text{ITER}}^{\text{ELM}} [\text{m/s}] \sim 600 \left( \frac{T_{\text{ITER}}^{\text{ped}}}{T_{\text{JET}}^{\text{ped}}} \frac{\Delta W_{\text{ITER}}^{\text{ELM}}}{W_{\text{ITER}}^{\text{ped}}} \frac{1}{0.12} \right)^{1/2} \]

JET experiments \( \Rightarrow \) exponent \( \sim 0.4 \)

Hence, mitigated (~1 MJ) ELMs on ITER deliver a small fraction of their energy to wall
ELM divertor heat loads

- Heat load broadly consistent with free streaming of ions from mid-pedestal location
  - Scaling with sound speed confirmed by JET-AUG similarity experiment
  - Inner:outer energy asymmetry consistent with initial Mach number of pedestal ions
- ELM filaments observed on both AUG and JET
  - Temperature striations on divertor plates consistent with pre-ELM magnetic field
- Quasi-toroidal mode number increases with time
  - Suggests break up of filaments into ~ 2 – 3 smaller structures

ELM limiter heat loads

- ELM filaments observed at JET on both outer limiters and upper dump plate
  - Mode number decreases with ELM size, and ~2-3 times larger than on divertor tiles
- Most recent analysis of ELM heat loads on JET indicate that radial Mach number increases as \( (\Delta W/W_{\text{ped}})^{0.4} \), roughly in line with interchange scaling
- The parallel loss model, validated on JET measurements, used to predict fraction of ELM energy to the main chamber in ITER \( (r - r_{\text{sep}} > 5 \text{ cm}) \) as
  - 25% for natural (unmitigated) ELMs (20 MJ, \( \Delta W/W_{\text{ped}} \sim 13.3\% \))
  - 4% for small (mitigated) ELMs (1 MJ, \( \Delta W/W_{\text{ped}} \sim 0.66\% \))
FIN
Time scales roughly doubled, as expected from FS approximation (R doubled)

In both AUG and JET, suggest parallel length $\sim 2.5\pi qR$

Not clear why time scales found show the observed long tail

+1.1MA/-1.0T (LSN): $E_i/E_o = 1.4$

<table>
<thead>
<tr>
<th></th>
<th>AUG</th>
<th>AUG</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field (MA/T)</td>
<td>+0.8/-2</td>
<td>+0.8/+2</td>
<td>+1/-1.1</td>
</tr>
<tr>
<td>Econd/Econv</td>
<td>~1</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>Ediv/Eloss</td>
<td>18kJ/25kJ</td>
<td>14kJ/20kJ</td>
<td>30kJ/40kJ</td>
</tr>
<tr>
<td>$\nu^*$</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$T_{e,ped}$</td>
<td>~500eV</td>
<td>~500eV</td>
<td>610eV</td>
</tr>
</tbody>
</table>

$\tau_{SF,o} = 1126 \mu s$
$\tau_{SF,d} = 1190 \mu s$
$M_{ti} = 0.105$
$E_i + E_o = 30 kJ$

$\nu^*_{ped, top} \sim 0.5$
ELM (40kJ) in JET (1.0MA/1.1T), ν* = 0.5, conductive / convective ~ 1

- For convective ELMs, no broadening wrt. inter-ELM profile
- no ELM structure observed
ELM (400 kJ) in JET, $\nu^* = 0.23$, conductive / convective $\sim 7.5$

- For conductive ELMs, broadening of near-SOL profiles by $\sim 50\%$ wrt. inter-ELM profile
- Movement of peak heat flux position

ELM filamentary structure becomes visible for larger ELMs, at lower $\nu^*$
Target coordinate (m), poloidal

74380 – ELM @ t = 0μsec
• Near separatrix profile during ELM roughly similar to Inter-ELM profile shape
• Footprints of single filaments are resolved in the far scrape-off layer

• By estimating the radial distance of filaments imprints on the target and using pre-ELM SOL magnetic structure, the toroidal distance between the energy efflux region can be inferred
• For the given example we find n~6-8
### Agreement with JET data

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Parallel loss model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limiter probes + TC:</td>
<td></td>
</tr>
</tbody>
</table>

**Experiment**

- **Limiter probes + TC:**
  - \( n_e \)\_\( ELM \) (r\_lim) \( \sim 2.4 \times 10^{18} \) m\(^{-3} \)
  - \( T_e \)\_\( ELM \) (r\_lim) \( \sim 25-30 \) eV
  - \( \lambda_n, max \)\_\( ELM \) \( \sim 50 \) mm,
  - \( \lambda_{T_e}, max \)\_\( ELM \) \( \sim 30 \) mm

- Nearly all power found on the divertor

**Parallel loss model**

- \( n_e \)\_\( ELM \) (r\_lim) \( \sim 2.2 \times 10^{18} \) m\(^{-3} \)
  - \( T_e \)\_\( ELM \) (r\_lim) \( \sim 30 \) eV
  - \( \lambda_n, max \)\_\( ELM \) \( \sim 47 \) mm,
  - \( \lambda_{T_e}, max \)\_\( ELM \) \( \sim 32 \) mm

- Fraction of ELM energy to wall \( \sim 5 \%

**Outer gap scan + IR & TC:**

- \( \lambda_W, max \)\_\( ELM \) \( \sim 33-35 \) mm,
  - \( \lambda_W, max \)\_\( ELM \) \( \sim 22-24 \) mm

- \( \lambda_{T_e}, max \)\_\( ELM \) \( \sim 36 \) mm,
  - \( \lambda_{W, max} \)\_\( ELM \) \( \sim 22 \) mm

- \( \lambda_{T_e, max} \)\_\( ELM \) \( \sim 30 \) mm,
  - \( \lambda_{W, max} \)\_\( ELM \) \( \sim 32 \) mm

- Fraction of ELM energy to wall \( \sim 15 \%

**ELM energy deficit based on IR:**

- \( \sim 30 \% \) for \( \sim 3 \) cm gap and \( \Delta W/W \) \( \sim 5 \%
  - \( \sim 28 \% \) for \( \sim 3 \) cm based on \( \lambda_W, ELM \) \( \sim 35 \) mm

RFA measurements of ion energies:

- \( J_{sat}, \lambda_{coll} \), \( T_{i, max} \)\_\( ELM \) (reproduced by model)
  - \( T_{i, max} \)\_\( ELM \) (r\_lim) \( \sim 100 \) eV,
  - \( T_{e, max} \)\_\( ELM \) (r\_lim) \( \sim 40 \) eV,
Key elements of parallel loss model

- Temporal evolution of $n$, $T_e$ and $T_i$ in the filament frame of reference
- Above quantities represent averages over the filament volume
- Time and radius related by filament radial velocity, which is not calculated by the model
- Parallel loss treated by convective and conductive removal times
- Acoustic loss of plasma
- Electrons cooled faster than ions

\[
\frac{\partial}{\partial t} + \frac{1}{\tau_n} n = S_n,
\]
\[
\frac{\partial}{\partial t} + \frac{1}{\tau_{\varepsilon,i}} \varepsilon_i + \frac{\varepsilon_i - \varepsilon_e}{\tau_{i,e}} = S_i
\]
\[
\frac{\partial}{\partial t} + \frac{1}{\tau_{\varepsilon,e}} \varepsilon_e - \frac{\varepsilon_i - \varepsilon_e}{\tau_{i,e}} = S_e
\]

\[
\tau_n \approx \frac{L_\parallel}{Mc_s}, \quad \tau_{\varepsilon,a} = \frac{5}{2} \frac{L_\parallel^2}{\chi_{\parallel,a}}
\]
\[
\tau_{\varepsilon,a} = \frac{3}{5} \left( \tau_n^{-1} + \tau_{\varepsilon,a}^{-1} \right)^{-1} = \left( \tau_n^{-1} + \tau_{T,a}^{-1} \right)^{-1}
\]

Consider the radial motion of the pedestal plasma subject to parallel losses.

Low $\nu^*$: plasma cools faster than it dilutes: mainly conductive losses

Describe as an ‘effective’ plasma filament, moving with some average radial velocity.

High $\nu^*$: cooling and rarefaction comparable: significant convective losses

Evolve the density and temperature of the filament using a fluid model

\[ \Delta T_e \gg \Delta n \]

\[ \Delta T_e \sim \Delta n \]
Extrapolation to ITER

ITER wall filament relative energy: $T_{\text{midped}} = 2\text{keV}$, wall gap = 5 cm

- $v_{\text{ELM}} = 1000 \text{ m/s (1/2)}$
- $v_{\text{ELM}} = 224 \text{ m/s (1/2)}$
- $v_{\text{ELM}} = 975 \text{ m/s (1/4)}$
- $v_{\text{ELM}} = 460 \text{ m/s (1/4)}$
- $v_{\text{ELM}} = 990 \text{ m/s (2/5)}$
- $v_{\text{ELM}} = 298 \text{ m/s (2/5)}$

Distance from mid-pedestal (cm)
Measured PDFs of Type-I ELM amplitudes and waiting times

- Compare normal fit to Cauchy fit for both $\tau$ and $\Delta W$

\[
\text{pulse numbers: } 52009 \; 52306 \; 52735 \; 52025 \; 52015 \; 52022 \; 52014 \; 52736
\]
Details of model: ELM

- Model the ELM energy density as a slab.

\[
q_{\text{ELM}} = q_{\text{max}} e^{-t/\tau_{\text{imp}}}
\]
Details of model: ELM

- Monte Carlo simulation
- Parameters which we can sample from PDFs:
  - time between ELMs, $\tau \sim \text{Cauchy}(50\text{ms}, 7.5\text{ms})$
  - ELM size, $\Delta W \sim \text{Cauchy}(1\text{MJ}, 0.25\text{MJ})$

\[ q_{\text{ELM}} = q_{\text{max}} e^{-t/\tau_{\text{imp}}} \]
Results of model: ITER scenario

Without filamentation or variability: \( P(T_{\text{s}}>613K)=0 \)

With filamentation and variability: \( P(T_{\text{s}}>1560K)=1.8\times10^{-3} \), i.e. ~ once every 30 s

ITER-like input parameters:
- \( \delta_r=5\text{cm} \)
- \( n_w=30 \)
- \( q_{95}=3 \)
- \( r_{\text{travel}}=7.5\text{cm} \)
- \( W_{\text{ped}}=150\text{MJ} \)
- \( n_{e,\text{ped}}=5\times10^{19} \)
- \( T_{e,\text{ped}}=T_{i,\text{ped}}=\text{keV} \)
- \( \alpha=5^\circ \)
- \( L=1\text{cm} \)
- \( T(\text{coolant})=T(\text{surrounds})=600K \)

Only ELM heat loads considered; no inter-ELM plasma loads, radiation or neutrals.

Results of model:
- ITER scenario
  - No filamentation or variability
  - With filamentation and variability

Be melting point
Edge localized modes (ELMs)

Difference between ELM and pre-ELM infra-red images

Growth stage:
Linear instability (e.g. ideal/resistive MHD mode) forms ~ 10-20 flute-like ripples in pedestal quantities

Transport stage:
These develop into ~10-20 filaments during the non-linear phase of the instability (beginning of transport)

Exhaust stage:
Filaments move outward, driven by interchange (curvature + pressure), while draining to the divertor targets

I-5: Kirk
P1-24: Jakubowski

Consider a typical Type-I ELM on JET

Use mid-pedestal values of n, Te, Ti and effective radial velocity of 600 m/s measured using limiter probes

This yields an estimate of 10 % of ELM energy to wall, in agreement with the infra-red measured value.

IR measurements indicate that smaller ELMs deposit a smaller fraction of energy on the wall

Also observed as the energy missing from the divertor

Smaller ELM filaments must travel slower, consistent with interchange dynamics

\[
\frac{C_b}{C_s} \approx \left( \frac{2\ell \Delta P}{R \beta_1} \right)^{1/2}
\]

\[
\frac{\lambda_{ELM}}{L_{\parallel}} \approx \frac{V_{ELM}^\perp}{C_s} \propto \left( \frac{W_{ELM}}{W_{ped}} \right)^{1/2}
\]

How can this be understood ?!
Pedestal changes during an ELM

Pedestal plasma eroded during the ELM:
- Density drop = ‘convective’ losses
- Temperature drop = ‘conductive’ losses

Small ELMs are mostly convective

ELM size decreases with collisionality
Small ELMs = less energy to the wall

\[
\lambda_{W, ELM}^{\perp} / L_{||} \approx \frac{V_{ELM}^E}{C_s} \propto \left( \frac{W_{ELM}}{W_{ped}} \right)^{1/2}
\]

\[
\lambda_{W, ELM, ITER}^{\perp, [mm]} \approx 30 \left( \frac{W_{ELM} / W}{0.05} \right)^{1/2} \approx 30 \left( \frac{W_{ELM} / W_{ped}}{0.12} \right)^{1/2}
\]

Smaller ELM filaments travel slower, consistent with interchange dynamics

Predicted power width scaling on ELM filament energy in the far-SOL

For a natural (unmitigated) ELM on ITER, expect ~ 10 % of its energy to main wall PFCs

For a small (mitigated) ELM expect only a tiny fraction (<<1%) of ELM energy to main wall PFCs

Maximum ELM size on ITER determined by divertor PFCs !!!
Same prescription as used to match JET data (Type-I ELMs, $\Delta W/W = 5\%$)

~ 8 % of ELM energy onto main wall at 5 cm (omp)

~ 1.5 % of ELM energy onto limiter at 15 cm (omp)
• Type-I ELM-filaments clearly observed with $\Delta r \sim 2$ cm-omp (top)
• No Type-III ELM-filaments, despite proximity to upper dump plate (~1.5 cm)

**Type-I ELMs**

**JET:** $\Delta r /a = 2\%$

**ITER:** $\Delta r /a = 2.5\%$
Predicted peak ELM filament quantities on JET and ITER (moderate Type-I ELMs)

- JET: $T_{i,\text{max}}(r_{\text{lim}}) \sim 185 \text{ eV}$ (ion impact energy $\sim 0.6 \text{ keV}$) at 4 cm
- ITER: $T_{i,\text{max}}(r_{\text{lim}}) \sim 350 \text{ eV}$ (ion impact energy $> 1 \text{ keV}$) at 5 cm; $\sim 100 \text{ eV}$ at 15 cm
- Lower bound estimates for moderate ($\Delta W/W \sim 5 \%$) Type-I ELMs

<table>
<thead>
<tr>
<th></th>
<th>JET</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{max}} (m^{-3})$</td>
<td>$8.25 \times 10^{18}$</td>
<td>$1.2 \times 10^{19}$</td>
</tr>
<tr>
<td>$T_{i,\text{max}} (eV)$</td>
<td>185</td>
<td>350</td>
</tr>
<tr>
<td>$T_{e,\text{max}} (eV)$</td>
<td>74</td>
<td>140</td>
</tr>
<tr>
<td>$\lambda_{n,\text{max}} (mm)$</td>
<td>47</td>
<td>54.5</td>
</tr>
<tr>
<td>$\lambda_{T_{i,\text{max}}} (mm)$</td>
<td>41</td>
<td>42.5</td>
</tr>
<tr>
<td>$\lambda_{T_{e,\text{max}}} (mm)$</td>
<td>25</td>
<td>27.5</td>
</tr>
</tbody>
</table>

• Plot frequency histograms of measured waiting times ($\tau$) and $\Delta W$ on JET

• Bars represent the limits between which the observed data are expected to fall on 99% of occasions, given that the model is the true PDF.

-D.Moulton, PSI-2008, Toledo, Spain-
Details of model: limiter

• Question: What is the probability that the (surface) temperature of the ITER first wall tiles rises above some value (e.g., Melting point of Beryllium ~ 1560 K)

Model limiter as a 1D Beryllium slab, inclined at angle $\alpha$ (5°) to $B(q_{95}=3)$, with radial distance $L$ from surface to coolant.

Solve heat diffusion equation using finite difference scheme

BCs:

- $q_{\text{rad}}(T_s)$
- $q_{\text{ELM}}(t)$
- $r=0$
- $r=L$
- $T(L)=600\text{K}$
- Temperature of surrounds = 600K

Heat load minus radiative cooling ($\propto T^4$) at front surface

Constant temperature at back surface
Details of model:

- $\Delta W$ sampled from experimentally derived distribution

\[
v_{\text{ELM}} = 600 \left( \frac{2}{0.8} \right)^{1/2} \left( \frac{3}{q_{95}} \right)^{1/2} \left( \frac{\Delta W/W_{\text{ped}}}{0.12} \right)^{0.4}
\]
Radial electric field in the edge and SOL regions points in opposite directions !!!

For normal field direction:

Electric drifts in the SOL increase the convective power flow to the outer target

Electric drifts in the edge increase the convective energy flow to the inner target

Parallel motion of ions and electrons convects energy towards both targets

Net poloidal velocity determines the in-out energy asymmetry

Link to plasma rotation ?!

22nd IAEA FEC
W. Fundamenski
**Parallel ELM transport**

Significant progress being made in realistic parallel transport modelling of ELM pulse with the BIT1 PIC code

- Treat ELM as a square wave pulse launched upstream over time $\tau_{\text{ELM}}$ with specified $T_{\text{ped}}$, $n_{\text{ped}}$
  \[ \Delta W_{\text{ELM}} \sim \tau_{\text{ELM}} 3 n_{\text{ped}} T_{\text{ped}} 2\pi L_{\text{pol}} R dR \]

- Plasma expelled into 1D SOL with cosine distribution centred on midpoint between targets.
  - $B = \text{const.}$, inclined targets ($\sim 5^\circ$)

N\textsubscript{particles} = 0.8 – 5.0 $\times$ 10\textsuperscript{6}, N\textsubscript{cells} = 6000

High resolution, low noise

- $T_{\text{ped}} = 0.5 – 5$ keV
- $n_{\text{ped}} = 0.15 – 15 \times 10^{19} \text{ m}^{-3}$
- $\Delta W_{\text{ELM}} = 0.025 – 2.5$ MJ

$\tau_{\text{ELM}} = 200 \mu$s

Post ELM

150 $\mu$s

2$L_{\|}$ = 80 m

D. Tskhakaya et al., EPS 2007

22nd IAEA FEC

W. Fundamenski

Test case: PIC vs. expt.

Example: $\Delta W = 400$ kJ
$T_{ped} = 1.5$ keV
$n_{ped} = 5 \times 10^{19}$ m$^{-3}$

and ion ($\sim 100$ $\mu$s) transit times

Assumed “ELM duration” 200 $\mu$s

$\tau_e$, $\tau_i$, $\tau_{ELM}$

![Graph showing peak power flux vs. time with ELM duration notation.](image)
IR data obtained at outer target (no layers) from coherent average of 20 similar ELMs with $\langle \Delta W_{ELM} \rangle \sim 310 \pm 66$ kJ

Time resolution artificially enhanced to 50 $\mu$s

Good agreement in shape of pulse rise

Width a question of time and shape of ELM pedestal loss

PIC overestimates expt. by $\sim$ factor 5

Factor $\sim 2$ due to known in-out ELM loading asymmetry

Factor $\sim 2$ due to 1D nature of PIC

Reasonable agreement given how $\Delta W_{ELM}$ specified in the code

$W_{ELM} = 340$ kJ

$T_{ped} \sim 1.5$ keV

$n_{ped} \sim 5.0 \times 10^{19}$ m$^{-3}$

$W_{ELM} = 310$ kJ

$T_{ped} \sim 1.9$ keV

$n_{ped} \sim 5.5 \times 10^{19}$ m$^{-3}$
Interchange driven amplitude scaling with convective ion losses

\[ \lambda_W \approx V_\perp \tau_{||} \approx \frac{V_\perp L_{||}}{C_s} \quad \Rightarrow \quad \frac{\lambda_{W,\text{ELM}}}{L_{||}} \approx \frac{V_{ELM}}{C_s} \propto \left( \frac{W_{ELM}}{W_{ped}} \right)^{1/2} \]

combined with moderate-ELM \((\Delta W/W = 12\%)\) e-folding length. yields

\[ \lambda_{W,\text{ELM,JET}} \text{[mm]} \approx 35 \left( \frac{W_{ELM}/W}{0.05} \right)^{1/2} \approx 35 \left( \frac{W_{ELM}/W_{ped}}{0.12} \right)^{1/2} \]

so that fraction of ELM energy to wall can be approximated as

\[ \frac{W_{\text{wall}}^{ELM}}{W_0^{ELM}} \approx \exp \left( -\frac{1}{2} \Delta_{ped} + \Delta_{SOL} \right) \approx \exp \left( -\frac{\text{const}}{\sqrt{W_{ELM}/W}} \right) \]

where \(\Delta_{ped}\) is the pedestal width and \(\Delta_{SOL}\) is the separatrix-wall gap.

$W' = \frac{W}{W_{ELM}}$

- upper baffle (5 cm)
- mid-SOL (10 cm)
- outer limiter (15 cm)