Power and particle exhaust in tokamaks

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UKAEA, EFDA-JET

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• Compatibility between the plasma scenarios and PFCs
  – Ignition vs. exhaust criteria
  – Impact of PFCs on fusion gain
  – Power balance on ITER

• Steady-state particle and power exhaust
  – Limiter vs Divertor exhaust
  – Steady plasma loads
    • on main chamber PFCs
    • on divertor PFCs
  – Divertor plasma detachment

• Transient particle and power exhaust
  – Edge localised modes (ELMs)
  – Plasma loads associated with ELMs
    • on divertor PFCs
    • on main chamber PFCs
  – ELM mitigations techniques
    • Magnetic perturbations
    • Pellet pacing
    • Impurity injection

• Conclusions
**Ignition vs. Exhaust criteria**

- **Achieve**
  - $Q_{DT} = \frac{P_{fus}}{P_{heat}} \sim 10$

- **Maintain**

**Fuelling**
- gas
- pellets
- beams

**Heating**
- RF
- NBI
- alpha

**Confinement**
- equilibrium
- stability
- transport

**Particle exhaust**
- He ash
- Intrinsic Z
- Extrinsic Z

**Power exhaust**
- neutron
- photon
- plasma

**First wall design**
- mechanical
- thermal
- nuclear

+ current drive, disruptions, tritium, dust, …
$\max Q_{DT} = \text{function(reactor design)}$

- **Ignition** systems
  - Fuelling systems
  - Heating systems
- **Exhaust** systems
  - Cooling circuit
  - Power exhaust
  - Impurity influx

**Maximum achievable $Q_{DT}$ determined by the reactor design, including PFC limits**

**Impact of a given PFC limit**

$\frac{\Delta Q}{Q_0} = 1 - \frac{Q(PFC)}{Q_0}$

$Q_{DT} = \frac{P_{\text{fus}}}{P_{\text{heat}}} \sim P_{DT} \tau_E f(Z_{\text{eff}})$
Impact of PFCs on fusion gain

\[ Q_{DT} = \frac{P_{fus}}{P_{heat}} \approx p_{DT} \tau_E f(Z_{eff}) \]

- Profile stiffness: \( \frac{T(0)}{T(a)} \approx \text{const} \)
- Critical temperature gradient
- Turbulent transport
- Core plasma DT pressure
- Edge plasma DT pressure

\[ Q_{DT} = \frac{P_{fus}}{P_{heat}} \approx p_{DT} \tau_E f(Z_{eff}) \]

- Must not exceed: \(~10 \text{ MW/m}^2; ~10 \text{ eV}\)

- Partially detached divertor operation
- Need cool, dense edge plasma
- Or active ELM size control: pellets, RMPs

- ELM size decreases with edge collisionality
- Turbulent transport
- Edge localized modes (ELMs)
- Turbulent transport

- Erosion, ablation, melting, cracking
- Profile stiffness: \( \frac{T(0)}{T(a)} \approx \text{const} \)

- Must not exceed: \(~0.5 \text{ MJ/m}^2 \text{ in 250 us}\)

- Need cool, dense edge plasma

- Or active ELM size control: pellets, RMPs

- Edge localized modes (ELMs)

- Edge & SOL transport: collisional and turbulent

- Erosion, ablation, melting, cracking

- Must not exceed: \(~10 \text{ MW/m}^2; ~10 \text{ eV}\)
Translucent heat load limits in ITER

ITER adopted 0.5 MJ/m² for the maximum allowed ELM energy load in 250 us

TRINITI plasma gun

~ 40 %

250 us
Power balance on ITER

Heating \( P_h = 40 \text{ MW} \)

Fusion
\[
\begin{align*}
P_{\text{fus}} &= 400 \text{ MW} \\
Q_{\text{DT}} &= 10
\end{align*}
\]

Alphas \( P_{\alpha} = 80 \text{ MW} \)

Neutrons \( P_n = 320 \text{ MW} \)

Photons (50%) \( \approx 800 \text{ m}^2 \)

Plasma \( P_{\text{SOL}} \approx 60 \text{ MW} \)

Neutrons \( P_{\text{rad \, core}} \approx 60 \text{ MW} \)

Photons (50%) \( \approx 800 \text{ m}^2 \)

ELMs \( P_{\text{ELM}} \approx 20 \text{ MW} \)

Inter-ELM \( P_{\text{inter-ELM}} \approx 40 \text{ MW} \)

In reality, must repeat backwards to find maximum achievable \( Q_{\text{DT}} \) for given PFC limits

Plasma purity (\( Z_{\text{eff}} \approx 1.7 \)) requires high density (\( f_{\text{GW}} \approx 0.85 \)) and cold divertor (< 5 eV)

Need \( \approx 85 \text{ MW} \) total radiation (70% total = 50% in core + 20% in SOL), and ELM frequency above \( \approx 20 \text{ Hz} \) (ELM size \( \approx 1 \text{ MJ} \) or \( \approx 1\% \) of \( W_{\text{ped}} \))
\[ \beta^m_{T \text{ MHD}} \propto \frac{\epsilon_a \kappa_a}{q_0 q_a}. \]

\[ \beta^{\text{exh}}_T \propto \left( \frac{q_{\perp \text{ exh}}}{a B_0^4} \right)^{1/2}. \]

\[ \beta^{\text{ign}}_T \propto B_0^{-2} \tau_E^{-1}. \]
Steady-state exhaust

• Compatibility between the plasma scenarios and PFCs
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• Conclusions
Physical vs chemical erosion

Eckstein et al.

Physical sputtering yield…

Chemical erosion yield (D on C)…

increases with projectile energy and mass, while decreasing with target (PFC) material atomic mass

decreases with D ion flux and is sensitive to C target temperature
Limiter vs divertor recycling

Limiter

- $D_2, D^0$
- Impurities, eg. $C^0, C_xD_y$
- $\lambda_{D^0} \sim \text{few cm}$, $\lambda_{C^0} \sim 1 \text{ cm}$, $\lambda_{CxDy} \sim \text{few mm}$

Intimate contact with edge plasma

Little recycling/cooling in the SOL results in a hot, tenous SOL plasma

High erosion yields, poor pumping

Strong influx of both fuel and impurity neutrals into the edge

Impure edge & core, i.e. high $Z_{\text{eff}}$

Divertor target

- $D_2, D^0$
- $C^0, C_xD_y$

PFCs removed from edge plasma

Colder, denser SOL plasma, due to local recycling / cooling

Lower erosion yields, improved pumping

Fuel and impurity sources screened from the edge by the divertor plasma

Improved plasma purity, i.e. lower $Z_{\text{eff}}$
Limiter vs divertor exhaust

Scrape-off layer (SOL) plasma

SOL width determined by competition between parallel and perpendicular transport

Vessel walls

Steady-state plasma loads determined largely by Edge/SOL turbulence!

SOL

Edge

Core

LCFS

upstream $n_u, T_u$

Target $n_t, T_t$

Limiter

Divertor targets

Private plasma

Separatrix
As expected, limiter SOL width decreases with increasing plasma current,

\[ \lambda_{T_e} \approx 3 \times 10^{-18} n_e I_p^{-1.3}, \]

\[ \lambda_{\Gamma} \approx 30 I_p^{-1}, \]

Physical mechanism not understood at the time!

J.A. Tagle et al, 14th EPS II C (1987) 662
Limiter heat loads in ITER

JET diffusivities combined with a 3D fluid-neutral code (EMC3/EIRENE)

Calculated limiter heat loads of several MW/m², increasing with $I_p$

MC simulation of impurity transport (DIVIMP) suggest W-limiter a problem

$q_{\text{max}}$ (MW/m²)

$M.Kobayashi$ et al, NF 47 (2007) 61

(a) $I_p=2.5$MA
   $D=2.0$, $\chi=6.0$ m²/s

(b) $I_p=4.5$MA
   $D=0.65$, $\chi=2.6$ m²/s

(c) $I_p=6.5$MA
   $D=0.3$, $\chi=1.2$ m²/s

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Describing SOL transport by standard parallel-perpendicular transport competition relations, reveals a roughly constant radial Mach number.

\[ \mathbf{v}_\perp = \Gamma / n \text{ and } \mathbf{v}_\perp T = q / \frac{5}{2} n T \]

\[ D_\perp = \Gamma / \nabla n \text{ and } \chi_\perp = q / n \nabla T, \]

\[ \lambda_\Gamma \approx v_\perp \tau || n, \quad \lambda_\perp \lambda_\Gamma \approx D_\perp \tau || n, \quad \tau || n \approx \frac{L ||}{c_s}, \]

\[ \lambda_q \approx v_\perp T \tau || T, \quad \lambda_T \lambda_q \approx \chi_\perp \tau || T, \quad \tau || T \approx \frac{L^2}{\chi || e}, \]

\[ \lambda_n \approx \lambda_\Gamma \sim \sqrt{\tau || n D_\perp}, \quad \lambda_T \sim \lambda_q \sim \sqrt{\tau || T \chi_\perp}. \]

\[ I_p \propto B_\theta \propto q^{-1}_95 \propto L^{-1}_\parallel \propto P^{0.85}_\Omega \propto (P_{\text{LCFS}}^{\text{LCFS}})^{0.85}. \]

\[ c_s = [(T_e + T_i)/m_i]^{1/2} \]

**Effective radial velocity**

\[ \mathbf{v}_\perp n / c_s^{\text{LCFS}} \propto \text{const} \]

**Effective radial diffusivity**

\[ D_\perp \propto L || c_s^{\text{LCFS}} \]

**Physical mechanism not understood for a long time...**

but great progress made in the last few years !!!
**Plasma turbulence in the Edge-SOL**

### Density scan

<table>
<thead>
<tr>
<th>Pulse number</th>
<th>$\tilde{n}_e$ ($10^{19}$ m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24530</td>
<td>11</td>
</tr>
<tr>
<td>26092</td>
<td>8.4</td>
</tr>
<tr>
<td>26060</td>
<td>6.5</td>
</tr>
<tr>
<td>26084</td>
<td>4.8</td>
</tr>
<tr>
<td>24530</td>
<td>4.4</td>
</tr>
</tbody>
</table>

**ESEL**

### Current scan

<table>
<thead>
<tr>
<th>$m$</th>
<th>$\psi^*_{el} (\rho = 0.25)$</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td></td>
<td>△</td>
</tr>
<tr>
<td>130</td>
<td></td>
<td>□</td>
</tr>
<tr>
<td>105</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>85</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>●</td>
</tr>
</tbody>
</table>

**Wall flux ~ density$^2$**

- $\tilde{n}_e^{1.8}$
- $I_{(\rho=1)} [10^{20} \text{m}^{-2} \text{s}^{-1}]$ vs $\tilde{n}_e [10^{19} \text{m}^{-3}]$

**Wall flux ~ 1/current**

$O.E.\text{Garcia et al, PPCF 48 (2006) L1}$

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Density profiles in the Edge-SOL

TCV

SOL density profile broadens with increasing collisionality

\( \nu^* \)

Such broadening observed on many tokamaks

\( \tilde{n}_e = 2.6 \)

\( \tilde{n}_e = 1.0 \)

(\( 10^{20} \) m\(^{-3} \))

In radius, approaching unity in the far-SOL
Radial flow profiles in the Edge-SOL

- Radial plasma flux increases with collisionality
- Effective radial velocity is roughly constant with radius and increases with collisionality in the near-SOL

Such increase with radius observed on many tokamaks.
PDFs of fluctuations in the far-SOL

Temporal pulse shape of density ‘blobs’ reveals leading front & trailing wake
Interchange motion of plasma ‘blobs’

As collisionality increases, plasma filaments become electrically isolated from the sheath at the divertor target, making the interchange drive more effective. Dynamics of plasma filaments, or blobs, is determined by charge conservation = balance of divergences of polarization, diamagnetic and parallel currents dissipation.

\[ \nabla \cdot J = \nabla \cdot \left( J_p + J_\ast + J_\parallel \right) = 0 \]

O.E. Garcia et al, PPCF 48 (2006) L1

Plasma turbulence in the Edge-SOL

- Intermittent transport implies strong fluctuations in far-SOL quantities.
- Mostly drift-Alfvén dynamics in the edge region.
- Mostly interchange dynamics in the SOL region.
- Turbulence driven by edge pressure gradients, which build up together with poloidal flow shear, damped by parallel losses and sheath dissipation.
- Quiescent periods interrupted by intermittent ejection of plasma filaments.
- These advect mass and energy into the far-SOL, while draining to the divertor.

Local flux not related to local gradient!

Mean field approximation, used in most edge transport codes, is not accurate.

$\langle nT \rangle \neq \langle n \rangle \langle T \rangle$, etc.

Hence, need global edge turbulence codes.

Mean field approximation, used in most edge transport codes, is not accurate.

$\langle nT \rangle \neq \langle n \rangle \langle T \rangle$, etc.

Hence, need global edge turbulence codes.
Edge-SOL turbulence not anomalous

Edge/SOL turbulence is no longer anomalous. Predictive capability in sight.

Recall that anomalous = abnormal, irregular, not understood

Ironically, it is the absence, rather than presence of turbulence which now appears anomalous.

We know who did it. We still don’t know how.

There’s just one more thing that bothers me…
How do I get this H-mode ??!

\[ \nabla \cdot \mathbf{J} = \nabla \cdot \left( \mathbf{J}_p + \mathbf{J}_* + \mathbf{J}_\parallel \right) = 0 \]

flow shear: poloidal & toroidal rotation

magnetic shear, X-point geometry, ion orbit losses, bootstrap current,…

The Holy Grail of tokamak theory!
and main obstacle in predicting tokamak plasma exhaust (ITER)
Tokamak plasma scenarios

Baseline
- Current drive
- Inductive (pulsed)

Advanced
- Auxiliary + bootstrap
- Edge (ETB)
- Core (ITB)

Transport barriers
- dq/dr > 0
- q₀ ~ 1
- q₉₅ ~ 3

Safety factor, q
- dq/dr <= 0
- q₀ > 1
- q₉₅ ~ 4 - 5
Divertor heat loads in ELMy H-mode

\[
\lambda_{q,\text{all}} \propto A^\alpha Z^\beta B_\phi^{-1.03} q_{95}^{0.6} P_t^{-0.41} n_{e,u}^{0.25}, \quad \alpha + \beta = 1.04
\]

Averaged heat load profiles in natural density, ELMy H-mode

Integral power width decreases with field, current and power

Narrowest profile ~ ion poloidal gyroradius at pedestal temperature

Narrow inter-ELM profile confirmed by high resolution IR system on JET

Most of the energy arrives at the outer target; \( P_{\text{outer}} : P_{\text{inner}} = 2.5 : 1 \)
Turbulence reduction in the near-SOL

Obtained scaling is best explained by neo-classical ion conduction

\[ \lambda_q^{\text{con}} \propto B_x^{0.25} \left( \frac{P_{\text{SOL}}}{R} \right)^{0.25} \left( R g_{0.95} n_{\text{e,u}} \right)^{0.5} \propto B_x^{0.25} P_{\text{SOL}}^{0.25} n_{\text{e,u}}^{0.25} g_{0.95}^{0.5} R^{-0.5} \]

Consistent with partial extension of the ETB into the near-SOL

\[ \lambda_q^{\text{con}} \propto B_x^{0.25} \left( \frac{P_{\text{SOL}}}{R} \right)^{0.25} \left( R g_{0.95} n_{\text{e,u}} \right)^{0.5} \propto B_x^{0.25} P_{\text{SOL}}^{0.25} n_{\text{e,u}}^{0.25} g_{0.95}^{0.5} R^{-0.5} \]

Earlier analysis confirmed with multi-fluid (EDGE2D) simulations

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Divertor operating regimes

<table>
<thead>
<tr>
<th>Low recycling (sheath limited)</th>
<th>High recycling (conduction limited)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_t \sim n_u$, $T_t \sim T_u$, $p_t \sim p_u$</td>
<td>$n_t \sim n_u^3$, $T_t \sim n_u^{-2}$, $p_t \sim p_u$</td>
</tr>
</tbody>
</table>

Can this narrow heat load profile be broadened by a divertor 'buffering'?
Divertor plasma detachment

Loss of plasma pressure and energy by CX/ES & line radiation

Reduction of target plasma flux

Inner target typically detaches earlier, i.e. at lower upstream density, than the outer target

This asymmetry is consistent with power flow into divertor volume (ExB drifts, geometry, etc.)

Detachment of the outer divertor is needed for steady-state load reduction
Outer target detachment typically accompanied by an X-point MARFE

Results in substantial cooling of the edge plasma, reduction of pedestal stored energy and degradation of energy confinement

At higher densities transforms into an inner wall MARFE: density limit \( \sim n_{GW} \sim \frac{I_p}{a^2} \)

A. Huber et al, NF (2007)
Energy confinement (H98) decreases with density ($f_{GW}$) and radiation ($f_{rad}$)
Energy confinement degradation

Normalised energy confinement \( (H_{98}) \) reduced with line average density as it approaches the density limit \( (n_{GW}) \).

\[ H_{98} \text{ also reduced by } \sim 15\% \text{ after a Type-I to Type-III ELM transition} \]

Density (fuelling) scan:

H98 reduced with radiative fraction.

Radiation (impurity seeding) scan:

Caused by reduction of pedestal temperature and pressure.

Since \( W_{\text{ped}} \sim 1/3 \ W \), hence a 50% drop in \( W_{\text{ped}} \) means a \( \sim 15-20\% \) drop in H98.
Impurity accumulation in the core

with ITB

without ITB

\[ Z_{\text{eff}} - 1 \sim \frac{P_{\text{rad}}}{n_e^2} \]

Impurity density roughly uniform in the absence of an ITB

ITB acts as a barrier for impurity transport as well as for transport of fuel ions and energy

Inward velocity of impurities (neoclassical and turbulent pinch) overcomes outward diffusion

Impurity accumulation increases with ion charge

Cause for concern for both medium and high-Z impurities

H. Takenaga et al, NF 43 (2003) 1235
Transient exhaust

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Edge localized modes (ELMs)

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, ergodization?

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))

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

Power load can be fitted by 4 parameters $E_{\text{in}} + E_{\text{out}}$, $\tau_{\text{in}}$, $\tau_{\text{out}}$ and $M_{\text{ELM}}$
• 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
Heat load imprints of individual ELM filaments

• 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)

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

Also observed on the upper dump plates
Fast-visible images of filaments

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
Pre-ELM

- 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 atomp

Post-ELM

Courtesy of G. Arnoux
IR imprint on upper dump plate

Type-I ELM

Type-III ELM

poloidal

68913, t=56.1 s

68913, t=57.1 s

68913, t=58.5 s

68913, t=58.7 s

68913, t=60.1 s

68915, t=57.5 s

IR imprint on upper dump plate
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 el al, PSI-2008; submitted to JNM
$I_p = 3.0$ MA, $B_\psi = 3.0$ T, gas scan. Separatrix-midplane outer wall gap fixed at ~5.0 cm. $\Delta W_{ELM}$ estimated for first ELM peak only

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>$\Gamma_{gas}$ ($10^{22}$e/s)</th>
<th>No. ELMs</th>
<th>$\sum \Delta W_{ELM}$ (MJ)</th>
<th>$\sum E_{ELM}$ (MJ)</th>
<th>$\langle \Delta W_{ELM} \rangle$ (kJ)</th>
<th>$\sum \frac{E_{ELM}}{\Delta W_{ELM}}$ (%)</th>
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<tbody>
<tr>
<td>70221</td>
<td>1.47</td>
<td>133</td>
<td>29.7</td>
<td>1.49</td>
<td>224</td>
<td>5.3</td>
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<tr>
<td>70222</td>
<td>1.24</td>
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<td>23.9</td>
<td>1.02</td>
<td>275</td>
<td>4.3</td>
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<td>18.0</td>
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<tr>
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<tr>
<td>70226</td>
<td>0</td>
<td>24</td>
<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
Simulations of filament motion

Radial distance

\[ M_{\perp}^{\text{int}} = \frac{V_{\perp}^{\text{int}}}{c_s} = \left( \frac{2l \Delta p}{R \rho_0} \right)^{1/2} \]

\[ \text{Ra} = 10^4 \quad \text{and} \quad \text{Pr} = 1. \]

Interchange driven amplitude scaling with convective ion losses

\[ \lambda_W \approx V_\perp \tau_\parallel \approx \frac{V_\perp L_\parallel}{C_s} \quad \Rightarrow \quad \frac{\lambda^{ELM}_W}{L_\parallel} \approx \frac{V^{ELM}_\perp}{C_s} \propto \left( \frac{W^{ELM}}{W^{ped}} \right)^{1/2} \]

combined with moderate-ELM (\(\Delta W/W = 5\%\), \(\Delta W/W^{ped} = 12\%\)) e-folding length, yields

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

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

\[ \frac{W^{ELM}_{wall}}{W^{ELM}_0} \approx \exp \left( -\frac{1}{2} \Delta_{ped} + \Delta_{SOL} \right) \approx \exp \left( -\frac{\text{const}}{\sqrt{W^{ELM}/W}} \right) \]

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

eg. when \(\Delta W/W\) reduced by a third, then (\(W_{wall}/W_0\)) = 10 \% for 3 cm gap, see below.

*W.Fundamenski et al, PSI 2006; subm. to J.Nucl.Mater*
Small ELMs = less energy to the wall

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

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

- For a natural (unmitigated) ELM on ITER, expect \( \sim 10\% \) 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.
- 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 \( \sim 10\% \) 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 !!!
• Assume ELM filament begins to experience parallel losses from the mid-pedestal values of $n_e$ and $T_e$

• Apply the parallel loss model of ELM filament evolution (W. Fundamenski, R. A. Pitts, PPCF 48 (2006) 109)

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

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

**Low ν*: plasma cools faster than it dilutes:** mainly conductive losses

**High ν*: cooling and rarefaction comparable:** significant convective losses

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

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

Mid-pedestal:
- $T_{e,0} = T_{i,0} \approx 800$ eV
- $n_{e,0} \approx 3.0 \times 10^{19}$ m$^{-3}$
- $\Delta_{ped} \approx 4$ cm
- $v_{ELM} = 600$ ms$^{-1}$ → from previous JET studies

Good agreement given the model approximations and measurement errors!

$w' = \frac{3}{2} n_0 (T_{e,0} + T_{i,0})$

W.A.Pitts el al, PSI-2008; submitted to JNM
Comparison with model

**Pedestal top:**
- $T_{e,0} = T_{i,0} \approx 1500$ eV
- $n_{e,0} \sim 5.0 \times 10^{19} \text{ m}^{-3}$

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

$$v_{r,\text{ELM}} = 0.6 \text{ kms}^{-1}$$

R.A.Pitts et al, PSI-2008; submitted to JNM
Comparison with model

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

R.A.Pitts el al, PSI-2008; submitted to JNM
• Results indicate that larger ELMs travel faster
• Consistent with mainly interchange driven filament motion

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

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

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

JET experiments ⇒ exponent ~ 0.4

Hence, mitigated (~1 MJ) ELMs on ITER deliver a small fraction of their energy to wall
Predicted peak ELM filament quantities on JET and ITER (moderate Type-I ELMs)

- **JET**: $T_{i,\text{max}}(r_{\text{lim}}) \approx 185$ eV (ion impact energy $\approx 0.6$ keV) at 4 cm
- **ITER**: $T_{i,\text{max}}(r_{\text{lim}}) \approx 350$ eV (ion impact energy $> 1$ keV) at 5 cm; $\approx 100$ eV at 15 cm
- Lower bound estimates for moderate ($\Delta W/W \approx 5\%$) 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>
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<tr>
<td>$\lambda_{n,\text{max}}$ (mm)</td>
<td>47</td>
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<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>

*Graph showing peak ion impact energy as a function of radial distance from mid-pedestal location.*

\[ E_{\text{imp,max}} = 2T_{i,\text{max}} + 3T_{e,\text{max}} \]

- **Peak ion impact energy**
- **Radial distance from mid-pedestal location**
- **W Sputtering Threshold**
- **$\sim 1.1$ keV**
- **$\sim 590$ eV**
- **$\sim 270$ keV**

Steady-state power deposited mostly on the outer target (factor of ~ 2.5).

ELM energy deposited mostly on the inner target (factor of ~ 2).

What is the reason for these opposite in-out energy asymmetries?
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 ?!
Parallel transport of ELM energy

When $M = 0$, the energy deposition is symmetric. However, $M \approx 0.2$, towards the inner target, can account for the observed out energy asymmetry.

$$P_{\alpha,E_{\text{ELM}}}^E(t) / E_{\alpha,E_{\text{ELM}}}^E = \frac{2}{3\sqrt{\pi}} \left[1 + x_{\alpha}^2\right] x_{\alpha}^2 e^{-\left(x_{\alpha} - M\right)^2},$$

$$x_{\alpha} = \tau_{||\alpha} / t, \quad \tau_{||\alpha} = L_{||\alpha} / \nu_{Ti}, \quad M = \frac{u}{\nu_{Ti}}$$

In the diagram, the experimental data for AUG and JET are shown, with parameters such as $P_{\text{in}}, P_{\text{out}}, T_i, T_{\text{ELM}}$, and timescales for different energy components. The inset graph shows the heat flux and temperature with time, indicating a heat pulse at 300 and 1300 degrees Celsius, and the heat flux at 200 to 600 kJ with time.

$\sim 18\%$
ITER Summer School

W.Fundamenski

Aix-en-Provence, 23/06/2009

ITER adopted 0.5 MJ/m² for the maximum allowed ELM energy load in 250 us

Transient heat load limits in ITER

TRINITI plasma gun

~ 40 %

250 us
Combining the above estimates for the ELM wetted area, in-out energy asymmetry and PFC transient energy limits one finds:

$$\Delta W_{ELM} = Q_{ELM} \times S_{in} \times (1 + \frac{P_{out}}{P_{in}}) = 0.5 \text{ MJ/m}^2 \times 1.2 \text{ m}^2 \times 1.5 \sim 0.9 \text{ MJ}$$

Assuming $W \sim 400 \text{ MJ}$, $W_{ped}/W \sim 1/3$, then $\Delta W_{ELM} / W_{ped} < 1 \%$

This requires a decrease in the ‘natural’ ELM size by a factor of ~ 20!

Some caveats:

- Difference in temporal pulse shape and absolute plasma pressure between plasma gun and ELM
- Not all ELMs are equal. Amplitude and temporal PDFs are intermittent. Large ELMs cause most damage.
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 \((\Delta W/W_{ped})^{0.4}\), 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 \((r - r_{sep} > 5 \text{ cm})\) as
  – 25% for natural (unmitigated) ELMs (20 MJ, \(\Delta W/W_{ped} \sim 13.3\%\))
  – 4% for small (mitigated) ELMs (1 MJ, \(\Delta W/W_{ped} \sim 0.66\%\))
Only a small fraction (~10-20 %) of the ELM energy radiated during the ELM.

Consistent with multi-fluid edge/SOL simulations, which indicate that ELM energy buffering occurs only for very small ELMs (below 20 kJ on JET).

However, impurities released from the targets by the ELM lead to large post-ELM radiation (comparable to the ELM energy itself)!!!

For sufficient large ELMs, the cooling of the X-point can result in a back transition to L-mode (loss of ETB).
ELM induced impurity inflows

Inter-ELM W influx from outer divertor is strongly reduced as outer divertor plasma is cooled, consistent with the physical sputtering threshold.

With the outer divertor detached, the average W influx is dominated by ELMs!

Transient W influx increases with ELM energy.

In all cases, dominated by impurity sputtering.

Argon seeding increases W erosion during ELMs, decreases erosion between ELMs.

Optimum seeding rate (smallest W influx) is determined by competition between erosion by Ar ions and cooling by Ar radiation!!!
ELM control: Type-III ELMs

ELM frequency can be increased substantially (> factor of 10), by cooling the pedestal and thus replacing Type-I, by Type-III, ELMs.

At present, the only scenario compatible with all ITER exhaust requirements:

- \( f_{\text{rad}} \approx 75\% \)
- \( f_{GW} \approx 0.85 \)
- \( q_{95} \approx 3 \)
- \( Z_{\text{eff}} < 2 \)
- Divertor detachment
- \( \Delta W/W_{\text{ped}} < 1\% \)

\( Q=10 \) can be recovered by increasing the current by \( 13\% \) (to 17 MA):

\( \beta_N \approx 2.5 \)

However, pedestal pressure reduced by \( \sim 50\% \), energy confinement (H98) by \( \sim 15-20\% \), so that \( Q_{DT} \) reduced by \( \sim 50\% \) (Q_{DT} \approx 5 at 15 MA).
Type-I ELM frequency can be increased by injection of small fuel ice pellets, provided that pellet frequency > 1.5 times the natural ELM frequency.

Pellets provide a perturbation, correlated to penetration depth, which leads to an MHD instability. It triggers a Type-I ELM at any point in the ELM cycle!

In AUG, stored energy and energy confinement ($H_98$) reduced by ~10-20%, due to increased convective losses. Pellets are too big!!

Can the effect of plasma fuelling and ELM pacing be decoupled? Can pellet pacing be demonstrated at high density ($f_{GW} \sim 0.85$)?

Can pellet injection produce a strong enough perturbation on ITER to trigger edge MHD (Type-I ELM) but not core MHD (e.g. NTM)?
Type-I ELMs can be suppressed entirely by resonant magnetic perturbations

Edge plasma density is reduced due to magnetic field ergodization, which increases parallel convection to the divertor.

This effect, known as ‘magnetic pump-out’, is well documented with ergodic divertors, e.g. Tore-Supra. It represents edge plasma rarefaction, in the absence of cooling!

Pedestal density and pressure reduced by ~15-30%, energy confinement \( H_{98} \) \( \sim \) const

In ITER, ‘magnetic pump-out’ must be compensated by additional pellet fuelling to ensure \( f_{GW} \sim 0.85 \). Can ELMs still be suppressed in this case? If so, what is the reduction of \( p_{ped}, H_{98} \) due convective losses?
ELM frequency can also be increased by both low \( n \) (1,2) and high \( n \) (16) toroidal field perturbations, generated with external coils. The former with error field correction coils (EFCCs), the latter due to toroidal field (TF) ripple. In both cases, the pedestal density reduced due to ‘magnetic pump-out’.

For the same collisionality, ELM size reduced by a factor of 2, when TF ripple increased from 0.1% to 1%. Change related to smaller conductive losses, i.e. mainly convective ELMs. Reduction much less pronounced at higher density (\( f_{GW} \approx 1 \)).

Saibene EPS 2007

ELM control by EFCC discussed in ITER
### ELM control: summary

Consider the best results achieved so far

* = technique not optimized

<table>
<thead>
<tr>
<th>Method (machine)</th>
<th>Increase in $f_{ELM}$ vs Type-I</th>
<th>Density ($f_{GW}$) confinement</th>
<th>Energy (H98) confinement</th>
<th>Issues &amp; problems</th>
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</thead>
<tbody>
<tr>
<td>Type-III (JET)</td>
<td>x 30</td>
<td>~ 0.85 (-0%)</td>
<td>~ 0.85 (-15%)</td>
<td>Energy confinement</td>
</tr>
<tr>
<td>Pellets (AUG)</td>
<td>x 2*</td>
<td>~ 0.5*</td>
<td>~ 0.8*</td>
<td>Decoupling from fuelling</td>
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<tr>
<td>RMPs (DIIID)</td>
<td>Complete suppression</td>
<td>~ 0.25*</td>
<td>~ 1* (-15-30% in $p_{ped}$)</td>
<td>Density confinement</td>
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<tr>
<td>RMPs (DIIID)</td>
<td>x 20</td>
<td>~ 0.6*</td>
<td>~ 0.9* (-0% in $p_{ped}$)</td>
<td>Energy confinement</td>
</tr>
<tr>
<td>EFCC (JET)</td>
<td>x 10</td>
<td>~ 0.78* (-10%)</td>
<td>~ 0.85* (-15%)</td>
<td>Density confinement</td>
</tr>
<tr>
<td>TF-ripple (JET, JT60U)</td>
<td>x 2</td>
<td>~ 0.8 (-5%)</td>
<td>~ 0.85 (-15%)</td>
<td>Density and energy conf.</td>
</tr>
<tr>
<td>Vertical kicks (JET, TCV)</td>
<td>x 15</td>
<td>~ 0.5*</td>
<td>~ 0.85* (-15%)</td>
<td>Magnetic shielding</td>
</tr>
</tbody>
</table>
Compatibility between plasma and PFCs is not a binary signifier! Best measured as the impact on reactor performance, e.g. fusion gain, Q.

On the basis of our present knowledge (experiment) and understanding (theory), it appears that this impact, $\Delta Q/Q_0$, is negligible in existing tokamaks with C walls, but could be significant (~30-50% or more) for ITER and DEMO with metal walls.

The dominant contribution to $\Delta Q/Q_0$ is the transient heat load limit and hence the requirement of small ELMs ($\Delta W/W_{ped} < 1\%$), which entails a reduction of the pedestal pressure by ~30-50% and $H_{98}$ by ~10-15%.

Although active ELM control by pellet injection and magnetic perturbations hold much promise, it remains to be seen whether these methods offer a smaller $\Delta Q/Q_0$ than the more conventional method of Type-III ELMy H-mode.

Since high density ($f_{GW} \sim 0.85$) and high radiation ($f_{rad} \sim 0.75$) are necessary in ITER to ensure detached divertor operation and reduce core plasma dilution, and the exact criteria governing the Type-I to Type-III transition are not fully understood, one may yet find that the transition to Type-III ELMs becomes unavoidable…
Quo Vadis?

Teoria

Praxis

Integrated core-edge-SOL

Use validated codes to predict impurity levels in hydrogen phase in ITER

Impurity seeding experiments in full metal machines, e.g. JET ILW, AUG W

Edge-SOL turbulence modelling: link to transport models

Hydrogen experiments in existing devices

Predict hydrogen phase in ITER

Iterative core-edge-SOL

ELM control experiments

Use hydrogen phase of ITER to validate edge-SOL codes under Ohmic conditions

Kinetic ELM simulations

Use validated codes to predict ITER exhaust under Ohmic and L-mode conditions in deuterium plasmas

ITER Summer School  W.Fundamenski  Aix-en-Provence, 23/06/2009
The End
Edge localized modes (ELMs)

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

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

Describe it as a plasma filament moving with some effective radial velocity.

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

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

\[ \Delta T_e \sim \Delta n \]
Consider a typical Type-I ELM on JET

Use mid-pedestal values of $n$, $T_e$, $T_i$ 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.

How can this be understood?!
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)


---

**Normalised ELM filament quantities**

- Normalised ELM filament parameters
- Normalised time since start of parallel losses


---

* ITER 2nd separatrix | movable limiter

* R. Aymar et al., PPCF 44 (2002) 519*
Conclusions

- JET data indicates that bigger (more intense) ELMs deposit a larger fraction of their energy on the main chamber wall, which suggests that the radial Mach number increases with ELM size.
- Two-field interchange model used to study size & amplitude scaling.
- It was found that over a wide range of conditions, the radial Mach number is expected to increase as the square root of both ELM size and amplitude.
  \[ \frac{V}{C_s} \sim \left( \frac{2\ell}{R} \frac{\Delta \theta}{\Theta} \right)^{1/2} \]
- This implies that radial e-folding length of ELM filament energy also increases
  \[ \lambda_W \approx V_\perp \tau_\parallel \approx \frac{V_\perp L_\parallel}{C_s} \quad \Rightarrow \quad \frac{\lambda_{W,ELM}}{L_\parallel} \approx \frac{V_{\perp,ELM}}{C_s} \propto \left( \frac{W_{ELM}}{W_{ped}} \right)^{1/2} \]
- Model predictions in fair agreement with JET data.
- Preliminary predictions for ITER indicate the added benefit of reducing the ELM size: for small ELMs, \( \Delta W/W_{ped} < 5\% \), less than 2% of ELM energy deposited on the wall (near 2\textsuperscript{nd} separatrix at upper baffle); contact with limiters is negligible.
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 ($\sim 1.5$ cm)

**ITER-like ELMy H-mode equilibria**

**Type-I ELMs**

**ITER**

$\Delta r = 5$ cm

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

ITER: $\Delta r /a = 2.5\%$

#68193/JETPPF/EFIT/0 t=56.997005