ITER ELM heat flux requirements

Alberto Loarte

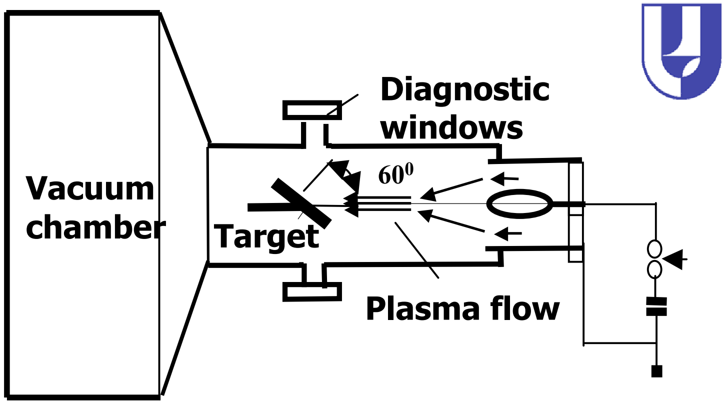
Outline

- Power fluxes to PFCs by ELMs in ITER present one of the main challenges for its operation (lifetime and operability)
- Review evidence for material erosion by ELM-like loads
- Review predictions of thermal loads on PFCs for ITER
- Describe proposed specifications for PFC design of ELM energy and power fluxes
- Describe ITER strategy for ELM heat load control
- Goals of ELM control R&D plan for ITER

Experiments to determine material erosion by ELMs (I)

QSPA facility provides adequate pulse durations and energy densities. It is applied for erosion measurement in conditions relevant to ITER ELMs and disruptions

The diagram of QSPA facility

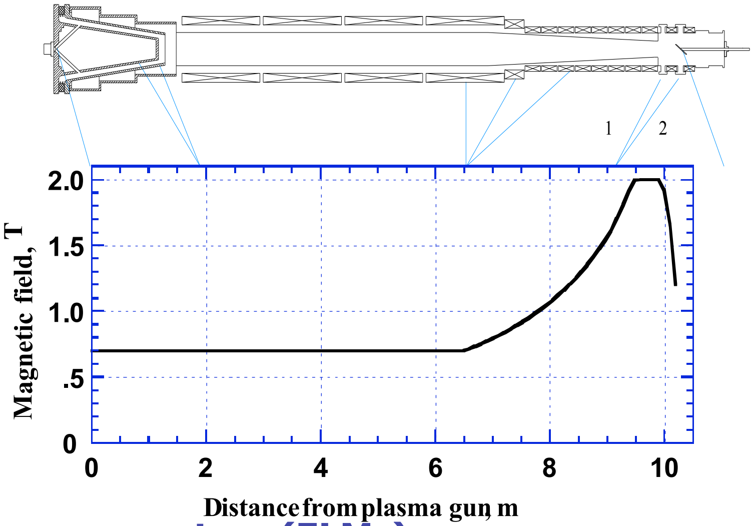


Plasma parameters (ELMs):

Heat load	0.5 – 2 MJ/m^2
Pulse duration	0.1 – 0.6 ms
Plasma stream diameter	5 cm
Magnetic field	0 T
Ion impact energy	≤ 0.1 keV
Electron temperature	< 10 eV
Plasma density	$\leq 10^{22}\ m^{-3}$

Plasma Pressure for same energy density as ITER with T_{ITER} ~ 3 keV → P_{QSPA}/P_{ITER} ~10

Diagram of MK-200UG facility and magnetic field distribution



Plasma parameters (ELMs):

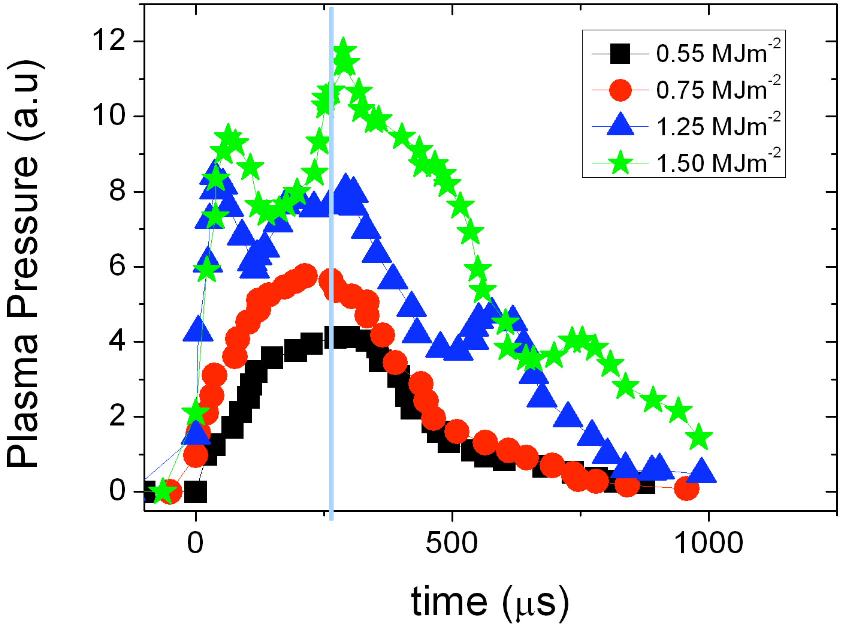
Heat load	0.6-1.5 MJ/m^2
Pulse duration	0.04 – 0.06 ms
Plasma stream diameter	6-10 cm
Magnetic field	0.5-1.2 T
Ion impact energy	2.5 keV
Electron temperature	100-200 eV
Plasma density	$\leq 5\ 10^{20}\ m^{-3}$

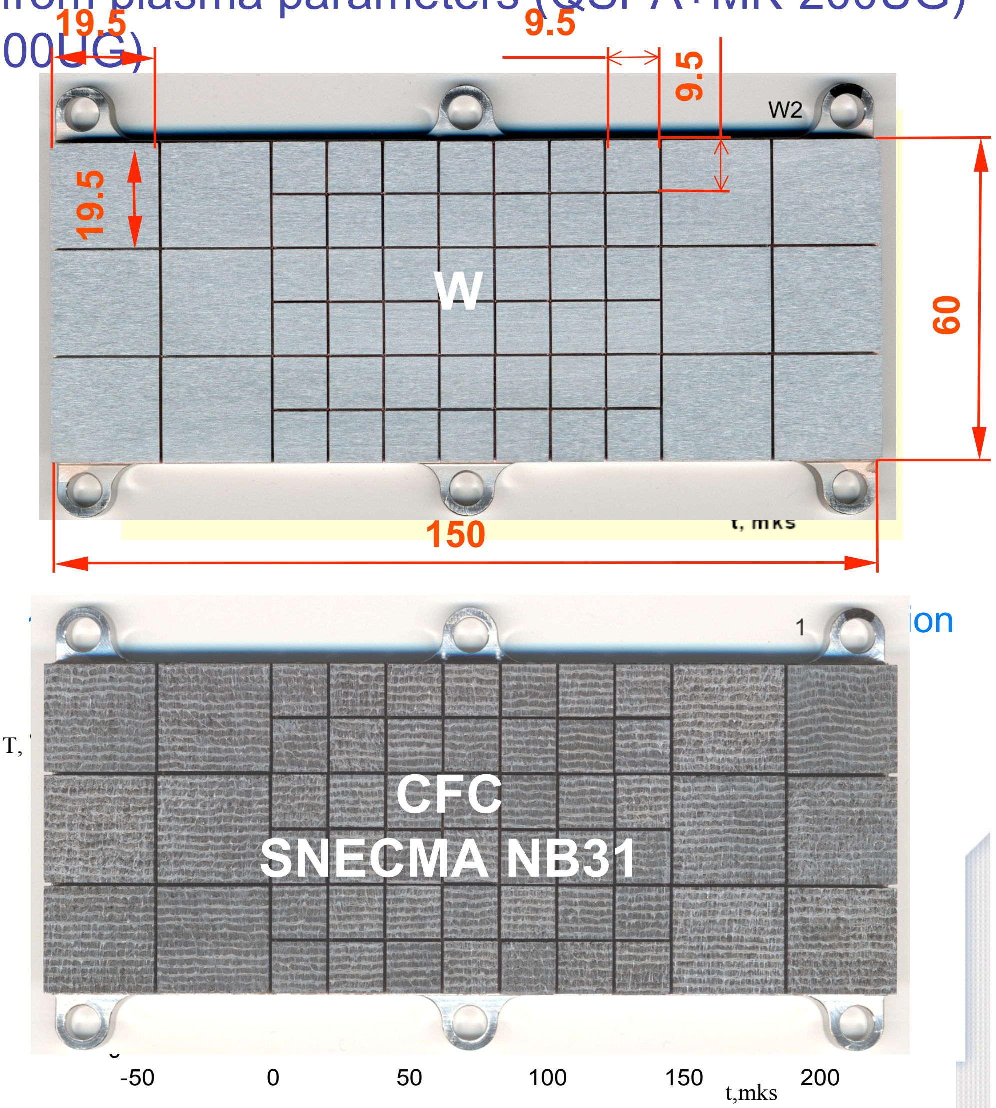
Time duration of power pulse ~ 0.1 τ_{ITER}

Experiments to determine material erosion by ELMs (II)

- Energy density on surface measured by calorimeter (QSPA+MK-200UG)
- Time dependence of power deposition from plasma parameters (QSPA+MK-200UG) and surface temperature (MK-200UG)

QSPA (V. Podkovirov)

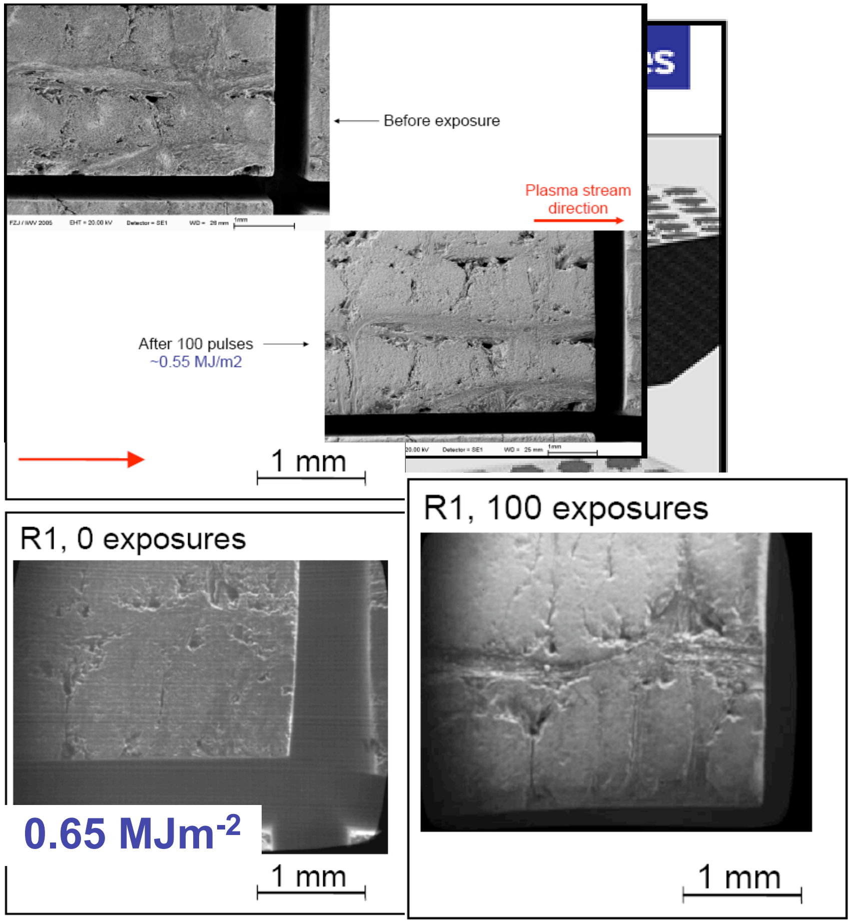




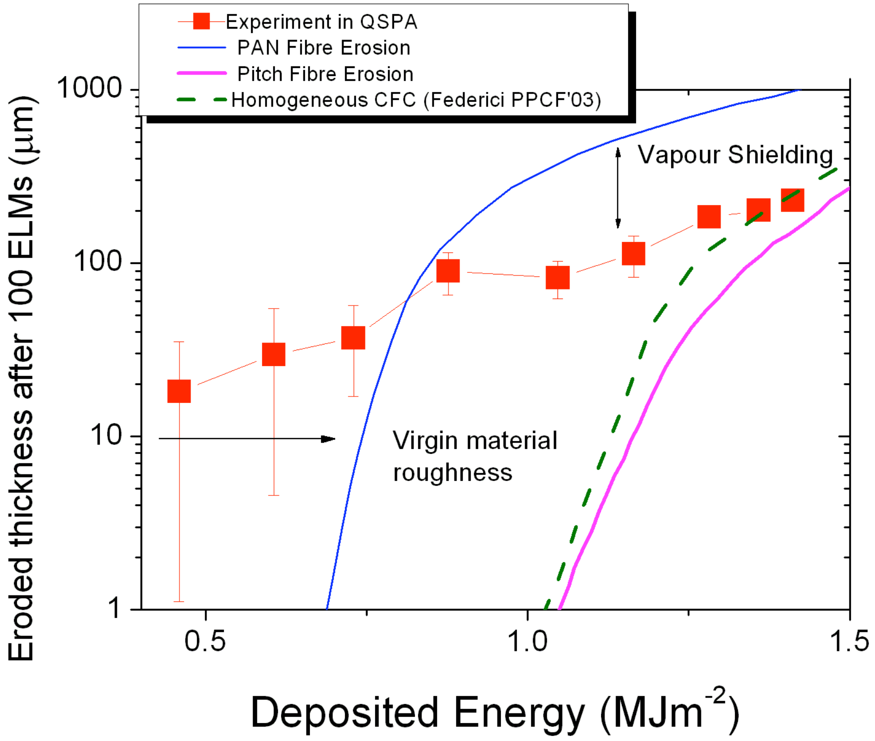
$$\Delta W_{ELM}(0\text{-}250\mu s)/\ \Delta W_{ELM}^{tot} \sim 0.4 - 0.5$$

CFC Erosion

CFC erosion caused by evaporation of material at high T_{surf} and enhanced by 3-D effects



N. Klimov + B. Bazylev + Federici

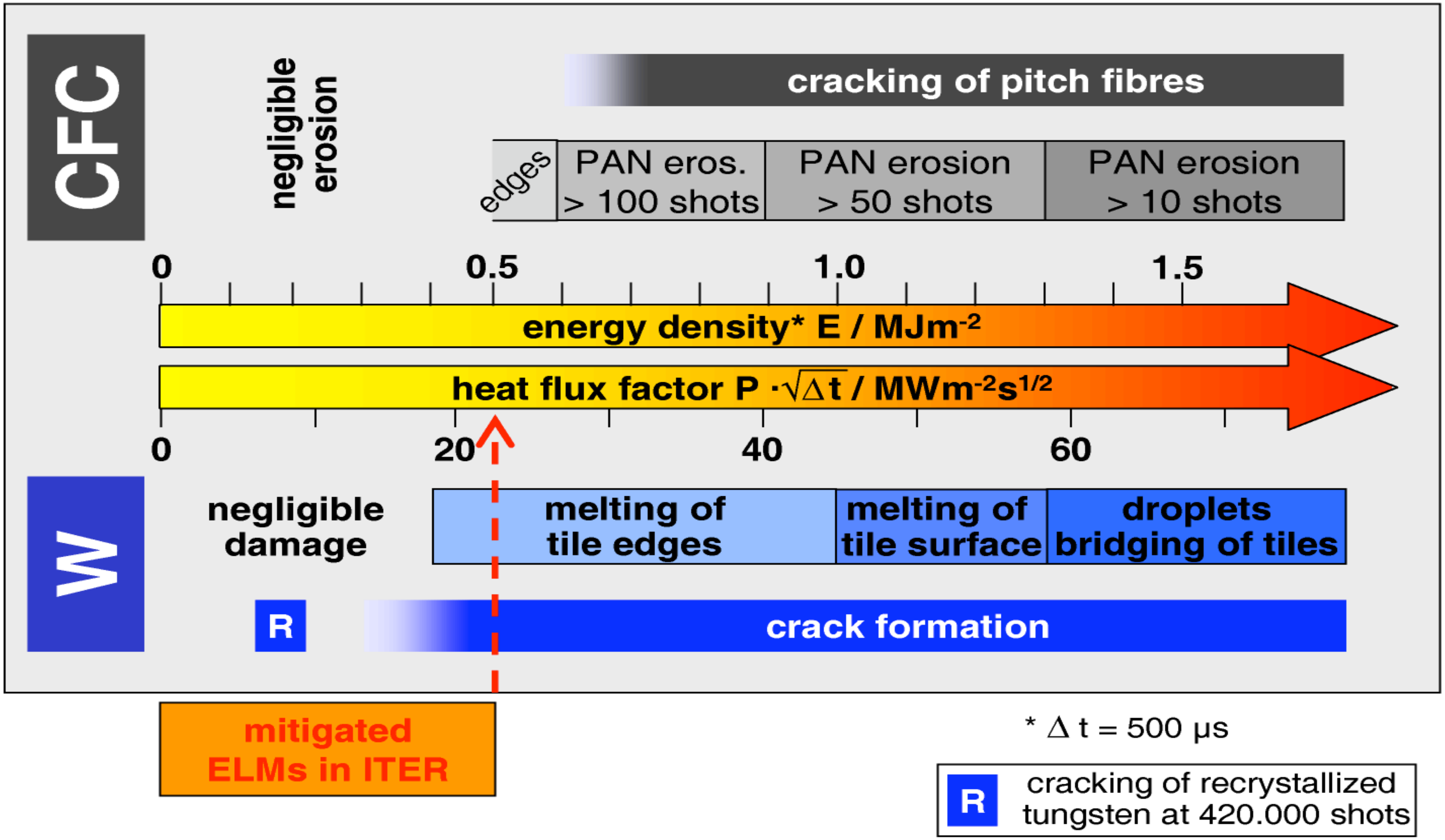


- ➢ Real erosion threshold for NB31 CFC ~ 0.5-0.6 MJm^{-2}
- ➢ Assume no ELM-caused erosion (beyond sputtering) up to ~ 0.6 MJm^{-2}

$$\delta_{ELM}\ (\mu m) = 3.05\ (E_{ELM}\ (\text{MJm}^{-2}) - 0.6)^2$$

W erosion

J. Linke



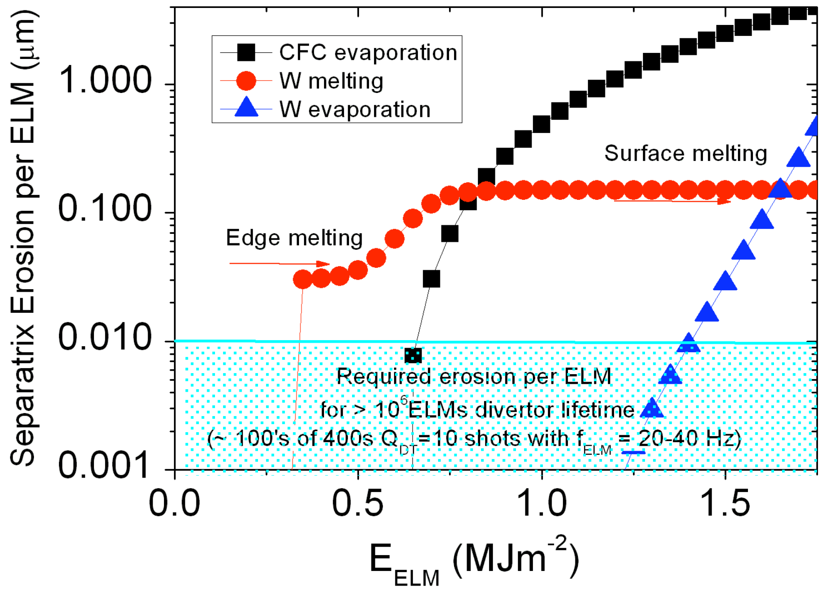
* Δ t = 500 µs

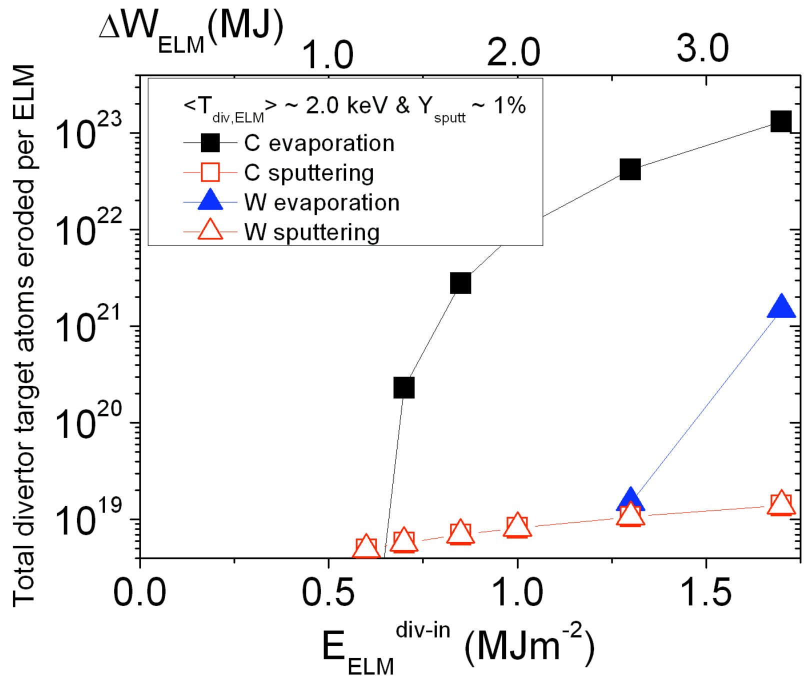
R cracking of recrystallized tungsten at 420.000 shots

Plasma impact direction

Divertor erosion & impurity generation

- ➢ Divertor separatrix erosion evaluated from experiment & modelling
- ➢ No net melt layer loss (droplet ejection) assumed for W but only displacement→ net impurity generation <u>only</u> by evaporation
- ➢ Typical W melt layer depth few 10's of μm in W → net melt layer loss key issue for net erosion and impurity generation in ELMs





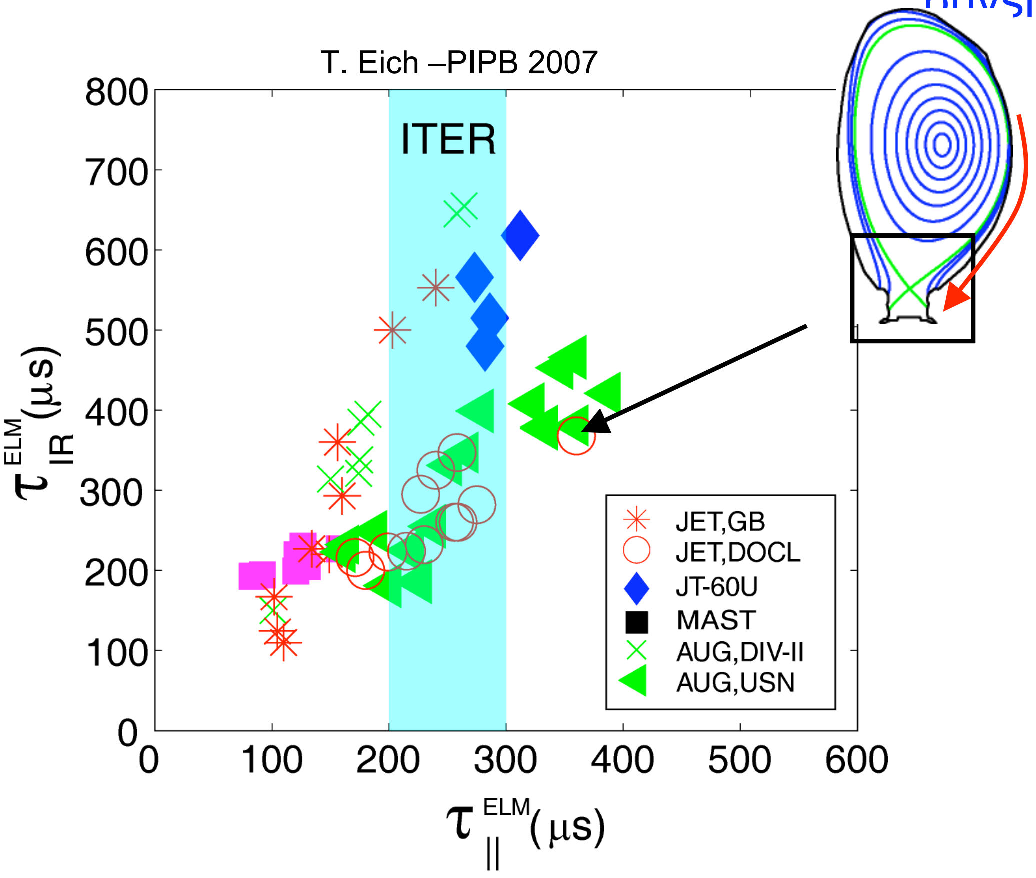
For f_{ELM} ~ 10's Hz with 0.1 μm/ELM erosion divertor lifetime ~ 10's Q_{DT}=10 discharges

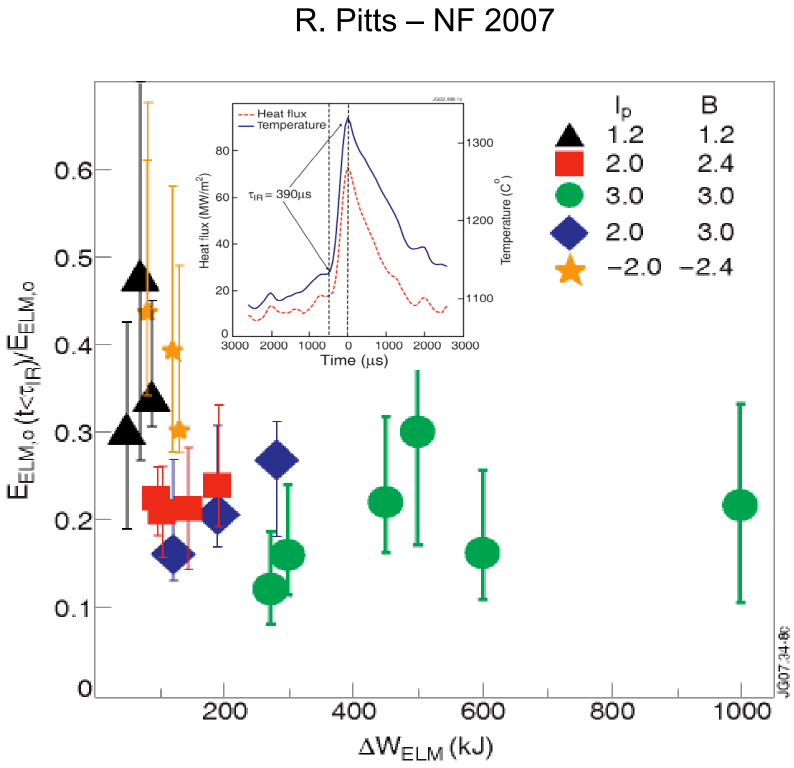
Plasma contamination can also be severe

ELMs in ITER cannot exceed damage threshold (~0.5 MJm^{-2})

Basis for definition of controlled ELMs in ITER (I)

Time scale of divertor ELM energy flux rise correlated with ion transport time + sheath physics


T. Eich –PIPB 2007


R. Pitts – NF 2007

$\tau_{rise,ELM}$ = 200-500 µs

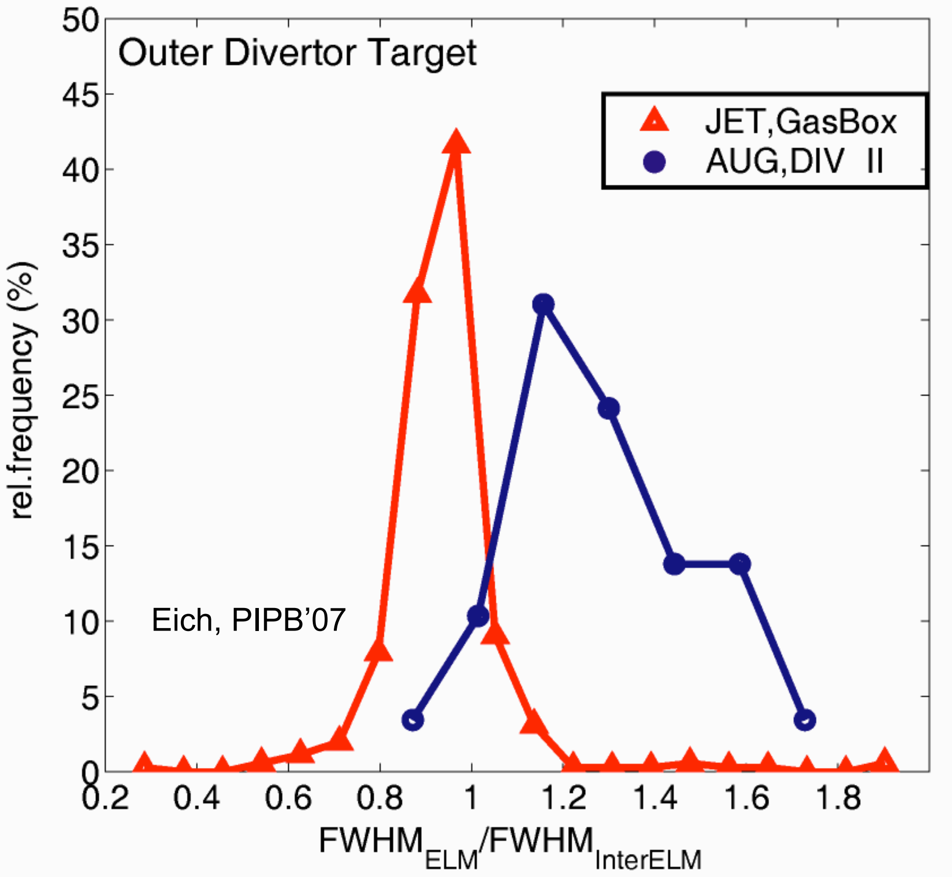
Plasma conditions affect $\tau_{ELM}^{IR} \sim \tau_{II}$ relation (pre-ELM divertor plasma, ΔW_{ELM}, etc.)

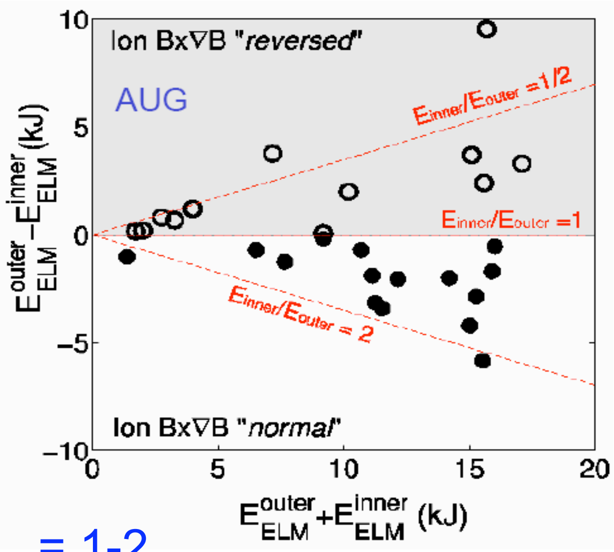
Large proportion of ΔW_{ELM} arrives after τ_{IR} → smaller ΔT_{surf} for given ΔW_{ELM}

$\tau_{down,ELM} = 1\text{-}2\ \tau_{rise,ELM}$

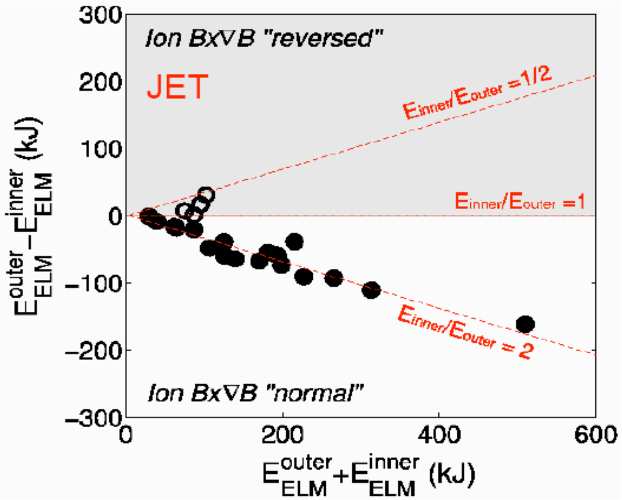
Basis for definition of controlled ELMs in ITER (II)

T. Eich – JNM 2007





$E_{in,ELM}/E_{out,ELM}$ = 1-2



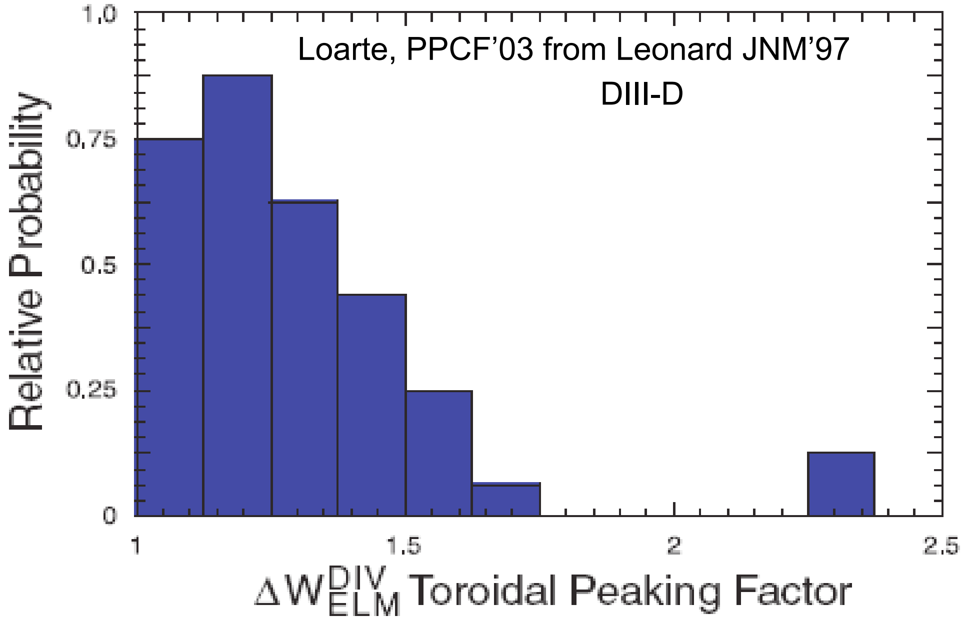
$A_{div,ELM} \sim 1.4\ m^{-2}$ (in) + $1.9\ m^{-2}$ (out)

Broadening ~ 1

Basis for definition of controlled ELMs in ITER (III)

Divertor ELM load near separatrix ~ toroidally symmetric but strong in/out asymmetries

$\mathrm{TPF}_{\mathrm{div,ELM}} \sim 1.0$



Tolerable ELM energy density 0.5 MJm^{-2} + no broadening + 2:1 in/out asymmetry +toroidal symmetry

→ $\Delta W_{\mathrm{ELM}} \sim 1\mathrm{MJ}$

$P_{\mathrm{ELM}} \sim 0.2\text{-}0.4\ P_{\mathrm{edge}}$

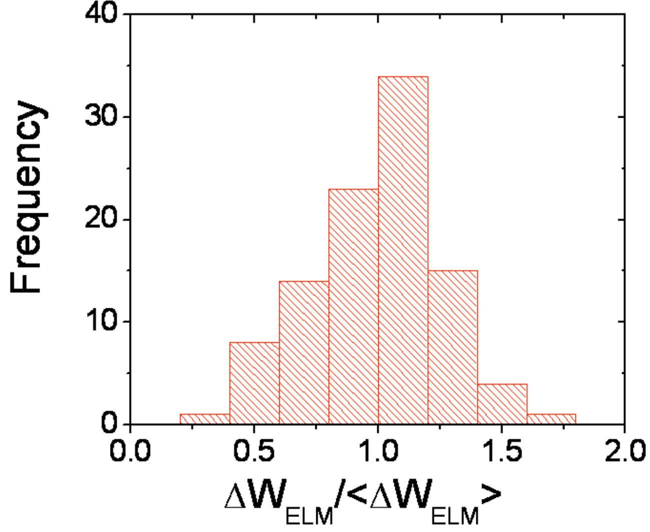
→ $f_{\mathrm{ELM}} \sim 20\text{-}40$ Hz

→ 8000-16000 ELMs per Q_{DT}=10 shot

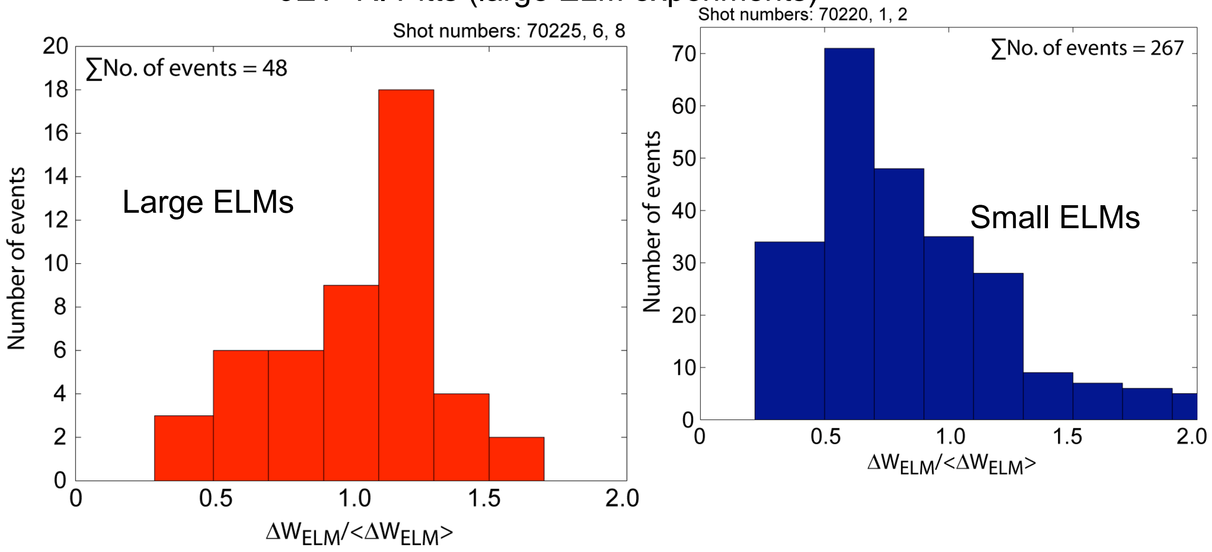
Basis for definition of controlled ELMs in ITER (IV)

ELM losses show variability but dependence on plasma conditions remains to be studied

JET- A. Loarte, APS 2003



JET- R. Pitts (large ELM experiments)



Due to material erosion being a threshold effect → controlled ELMs need to be small on average but also highly reproducible

If $<\Delta W_{ELM}>$ = 1.0 MJ & f_{ELM} = 20 Hz & 1% of ELMs at 2 MJ

CFC divertor lifetime 400 Q_{DT} = 10 pulses

Proposed divertor specifications for divertor ELM loads in ITER

Parameters	Unit	Controlled*	Uncontrolled
Thermal energy release during ELMs ΔW_{ELM}	MJ	1	20
Maximum energy in inboard divertor		2/3 ΔW_{ELM}	2/3 ΔW_{ELM}
Maximum energy in outboard divertor		1/2 ΔW_{ELM}	1/2 ΔW_{ELM}
ELM frequency	Hz	20-40	1-2
Energy deposition time on first wall and limiter	μs	125-250 (rising phase) decay phase 1-2 times rise phase	⇐
Energy deposition time on divertor	μs	250-500 (rising phase) decay phase 1-2 times rise phase	⇐
Maximum energy density on inboard divertor	MJ/m^2	0.5	10
Maximum energy density on outboard divertor	MJ/m^2	0.3	6
Maximum energy density parallel to B on inboard divertor	MJ/m^2	15	300
Maximum energy density parallel to B on outboard divertor	MJ/m^2	8	170
Expansion factor for width of scrape-off layer	-	1	1

ITER Wall ELM loads (I)

Wall ELM power/particle deposition starting to be characterised/understood → extrapolation to ITER uncertain

- For controlled ELMs instantaneous ELM energy fluxes are low ($\Delta W_{ELM}^{wall} <$ 0.05-0.2 MJ)

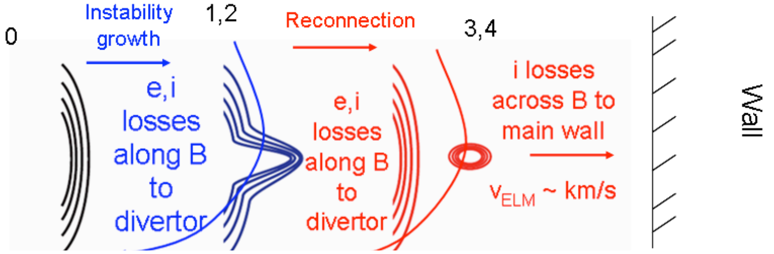
- $A_{IIELM} < A_{fil} \sim N_{fil}\ \delta_{pol}\ \delta_{r} \sim 10 * 0.25 * 0.1 = 0.25\ m^{-2}$ (A. Kirk H-mode workshop)
- Controlled ELMs → $E_{IIELM} \sim 0.2\text{-}1.0\ MJm^{-2}$

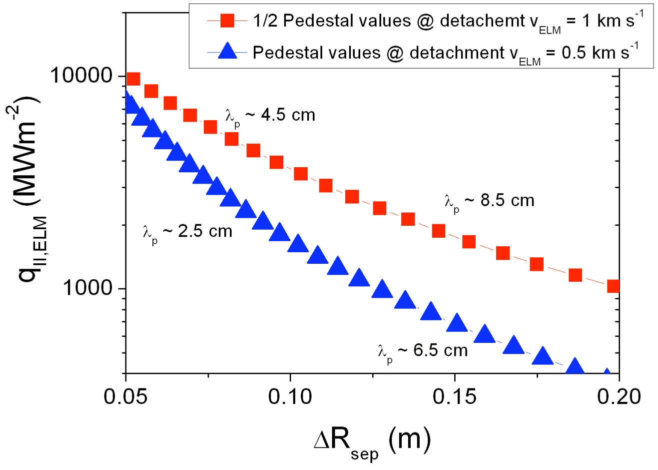
Controlled ELMs are not expected to cause surface melting of Be but could cause melting of exposed edges (> 0.25 MJm^{-2} for 250 μs pulse)

- Controlled ELMs lead to larger average power loads at likely impact points (surfaces closest to separatrix)

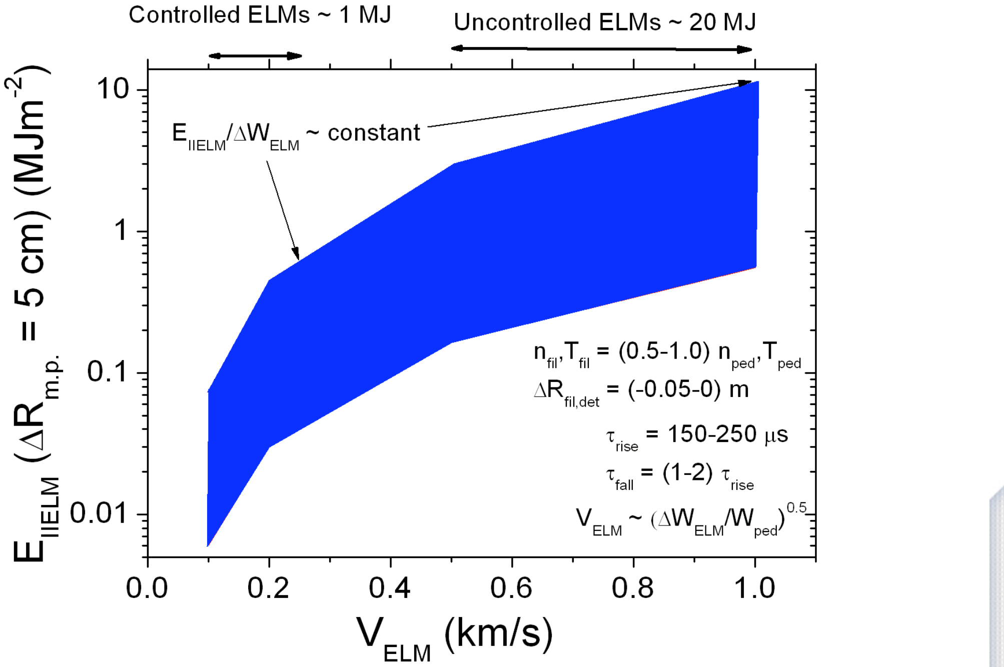
ITER Wall ELM loads (II)

- Precise value of energy flux on the wall depends on many parameters : plasma parameters at filament detachment, radial propagation velocities, losses IIB, duration of power pulse (losses IIB, filament dimension, propagation velocity) which are poorly known
- Estimate for ITER based on simple model + uncertainties



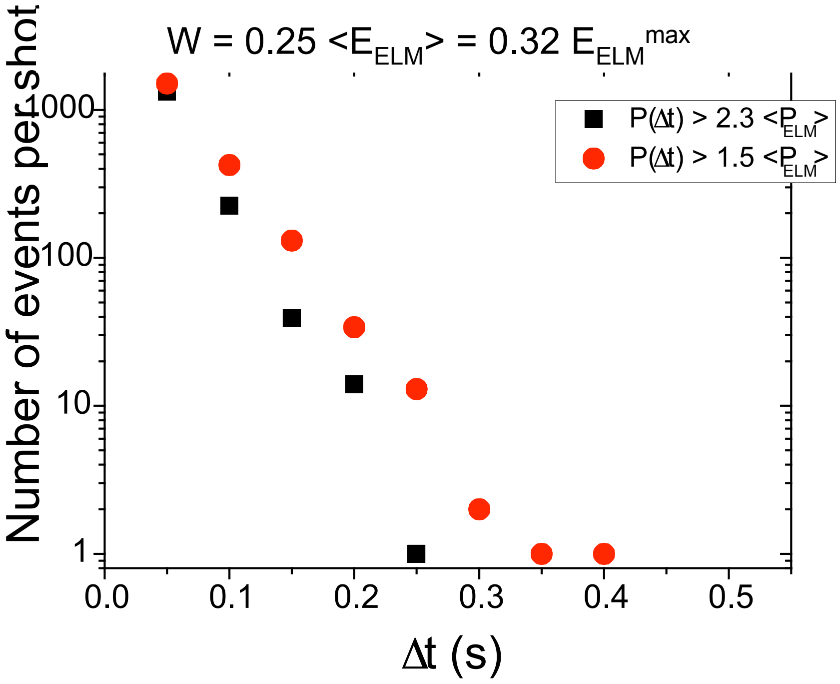


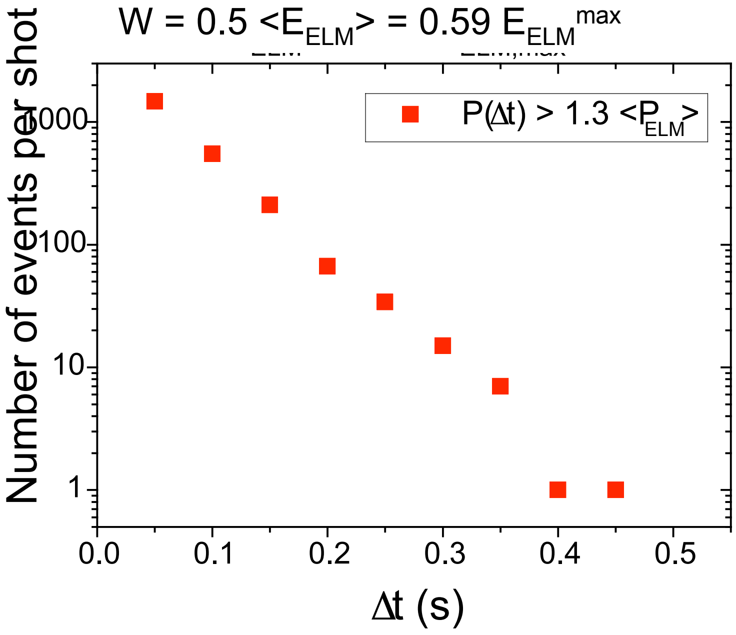
Fundamenski PPCF'06



ITER Wall ELM loads (III)

- Typical ELM power footprint FWHM/separation = 0.25-0.5
- ELMs impact randomly on the main wall → decreases of average heat load by ELMs
- Periods with consecutive ELMs hitting the same place < 0.5 s





Proposed divertor specifications for wall ELM loads in ITER

Parameters	Unit	Controlled*	Uncontrolled
Energy deposition time on first wall and limiter	μs	125-250 (rising phase) decay phase 1-2 times rise phase	⇐
Energy conducted on FW near outer midplane parallel to B (Lc = 60 m)	MJ/m^2	0.2	3.5
Energy conducted on ceiling near second X point parallel to B	MJ/m^2	1.0	20
ELM energy deposition decay length beyond seccond X point parallel to B (Lc = 60 m)	m	0.025-0.08	0.025-0.08

Maximum time-averaged power parallel to B conducted by controlled ELMs at FW near outer midplane	MW/m^2	5
Maximum time-averaged power parallel to B conducted by uncontrolled ELMs at FW near outer midplane	MW/m^2	5
Time-averaged power parallel to B conducted to the ceiling near second X-point by controlled ELMs	MW/m^2	25
Time-averaged power parallel to B conducted to the ceiling near second X-point by uncontrolled ELMs	MW/m^2	25
Maximum power parallel to B for controlled ELMs conducted to the ceiling near second X-point by controlled ELMs for duration Δt	MW/m^2	35
Duration of high power deposition phase Δt	s	0.5

ITER ELM Control Strategy

- Install in-vessel RMP coils for ELM control designed according to present physics understanding (required ergodisation & plasma rotation)
- Enable installation of pellet system adequate for ELM control (f_{ELM}=20-40 Hz, pellet size velocity to be defined)
- “None of these methods are fully assured to resolve the issue of ELM energy deposition. Hence, the STAC recommends that IO organize (through ITPA, etc) an aggressive R&D program world-wide to address ELM mitigation”

R&D on ELM load mitigation and control

- ➢ Extensive on-going R&D to develop active ELM control methods and/or alternative operational scenarios for ITER (applicablity/extrapolability?)
- ➢ Coordinated R&D programme to speed-up process and provide input to ITER design
  - ✓ Detailed specifications/operation of foreseen active ELM control systems in ITER (pellet pacing and RMP coils)
  - ✓ Development of new ELM control strategies to be implemented in ITER with the existing hardware or minor modifications of it (control of edge current by plasma wobbling using the internal coils, other methods of edge current control?, etc.)
  - ✓ Determination of operational conditions required to achieve regimes with small ELM loads or ELM-free which satisfy the requirements for Q_{DT}=10 and Q_{DT}=5 operation in ITER

R&D programme for discussion (I)

1. Determination of magnetic field perturbation characteristics for ELM control and integration with scenario requirements (possible contributors DIII-D, JET, ASDEX-Upgrade, MAST, NSXT, Alcator C-mod, …) for both reference scenarios $Q_{DT} = 5$ & $Q_{DT} = 10$

1.1. Determination of the need of ergodisation and resonance for ELM suppression versus ELM control in comparable ITER-like low collisionality and high density conditions

1.2. Comparison of in-vessel versus ex-vessel coil systems for ELM suppression and control in comparable ITER-like low collisionality and high density conditions

1.3. Evaluation of effects of ELM suppression/control methods on core plasma (density, NTM threshold, plasma rotation, etc.) in comparable ITER-like conditions

1.4. Integration of ELM control/suppression by magnetic field with ITER scenario requirements (required <ne>, peak divertor power flux, divertor radiation, pumping and He removal, etc.) in comparable ITER-like conditions

R&D programme for discussion (II)

2. Development of pellet pacing for ELM control and integration with scenario requirements (DIII-D, JET, ASDEX-Upgrade, …)

2.1. Optimisation of pellet size/speed/launch location for ELM control in comparable low collisionality ITER-like conditions.

2.2. Determination of additional power and particle outflux associated with ELM control and consequences for plasma confinement, particle pumping and compatibility with ITER-like low collisionality and with high density conditions (e.g. combined ELM control and core fuelling by pellets).

2.3. Determination of ELM power flux characteristics for pellet-controlled ELMs and compatibility with low average power fluxes at the divertor (e.g. divertor radiation behaviour in pellet-controlled ELMy H-modes with high radiation fractions)

R&D programme for discussion (III)

3. Development of alternative methods for ELM control and integration with scenario requirements (possible contributors DIII-D, JET, ASDEX-Upgrade, MAST, NSXT, Alcator C-mod, JT-60U, TCV, …)

3.1. Characterisation of ELM control by modification of edge current by plasma displacement and effects on core and divertor plasmas in comparable ITER-like low collisionality and high density conditions.

3.2. Characterisation of ripple effects on ELMs and effects on core and divertor plasmas in comparable ITER-like low collisionality and high density conditions.

3.3. Characterisation of plasma rotation on ELMs and effects on core and divertor plasmas in comparable ITER-like low collisionality and high density conditions

3.4. Demonstration of ELM control by novel methods such as edge current modification by external means (e.g. edge current drive by ECRH, etc.)

R&D programme for discussion (IV)

4. Development of alternative regimes providing Q_{DT}=10 (inductive) and Q_{DT}=5 (steady-state) performance in ITER without ELMs or with small ELM losses compatible with overall scenario requirements (possible contributors DIII-D, JET, ASDEX-Upgrade, MAST, NSXT, Alcator C-mod, JT-60U, TCV, …)

4.1. Evaluation of shape and q_{95} effects on H–mode ELM energy losses and plasma confinement/core density for collisionality/density conditions applicable to QDT=10 (inductive) and QDT=5 (steady-state) ITER reference regimes (e.g. access to Type II ELMs, low collisionality small Type I ELMs, etc.)

4.2. Development of EDA/QH-mode regimes towards ITER-relevant conditions and compatibility with scenario requirements (grad-B direction, divertor power loads, etc.)

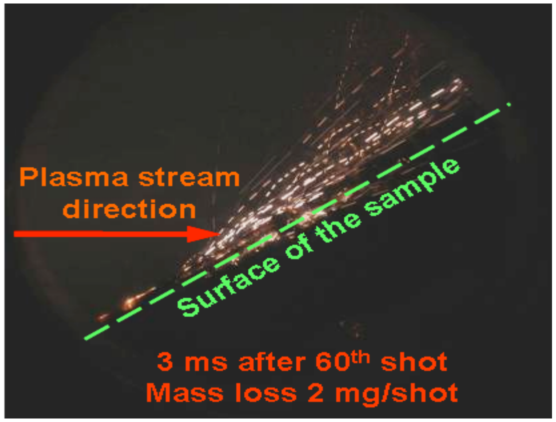
4.3. Evaluation of ELM energy losses and plasma confinement/core density for Type III ELMy H-mode in low collisionality and high density conditions

Conclusions

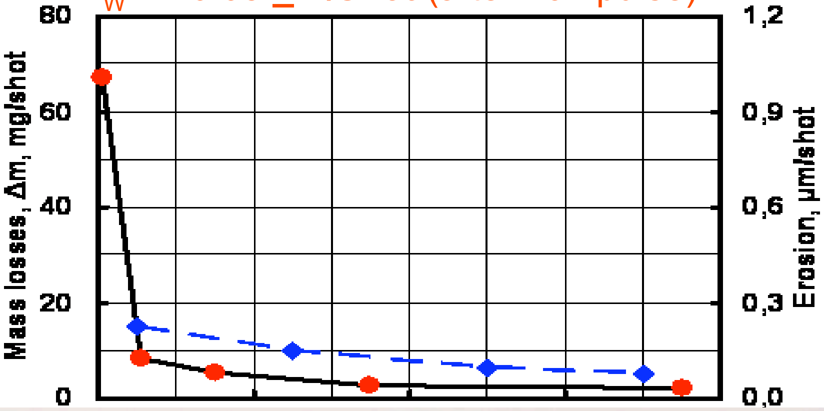
- ➢ Lack of control of ELM power fluxes has been identified as a major risk to ITER's mission
- ➢ Most promising systems for active ELM control being incorporated into the design even if their successful application in ITER is far from proven
- ➢ Extensive R&D remains outstanding to :
  - ✓ Develop the application of foreseen ELM control methods in ITER
  - ✓ Develop other methods for ELM control that can be implemented in ITER
  - ✓ Develop small-ELM or ELM-free regimes which are compatible with all requirements for ITER Q_{DT}=10 & Q_{DT}=5 operation

- Ejection of droplets from molten corners dominant mechanism for target erosion and plasma contamination for large loads

N. Klimov



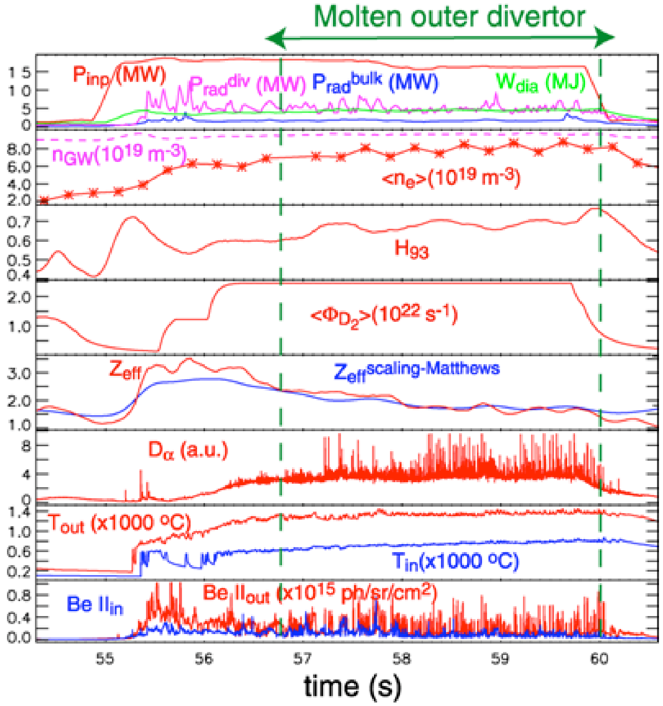
$<E_W>=$ **0.03 _m/shot** (after 40th pulse)



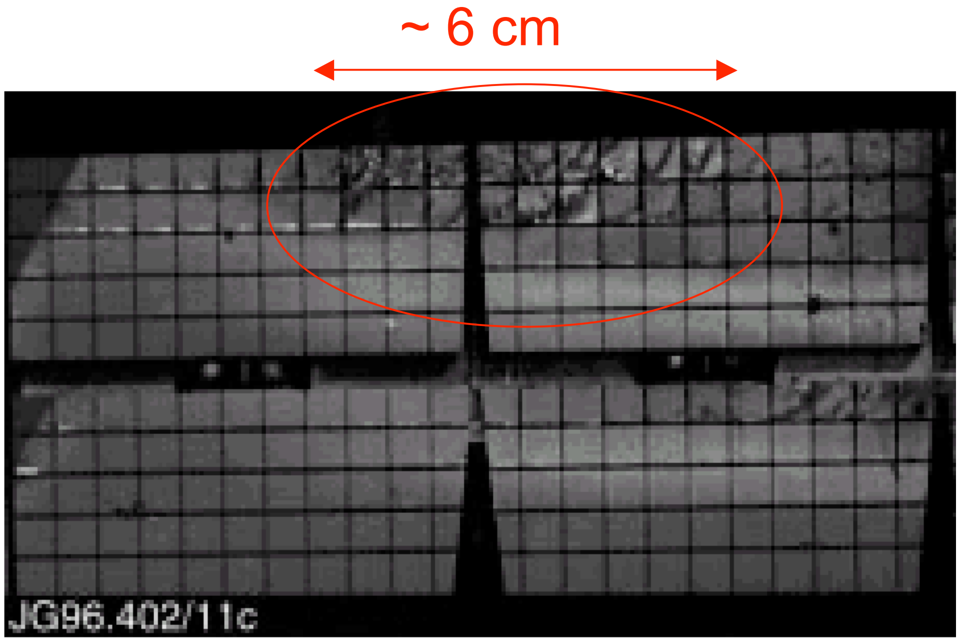
100 Elms @ 1.0 MJm^{-2}

- Localised surface damage caused by uncontrolled ELMs
  - ✓ Probably more important for divertor than first wall (variability of ELM impact on first wall is larger and loads are lower
  - ✓ Critical issue is operability of device with damaged PFC (not quantified for W but low $<n_e>$ operations with Be damage target at JET difficult/high $<n_e>$ OK)
  - ✓ Divertor damage localised on ~ 5 cm wide region → strike point position control to maintain operations if events number is small

JET high $<n_e>$ H-modes on damaged (molten) Be target

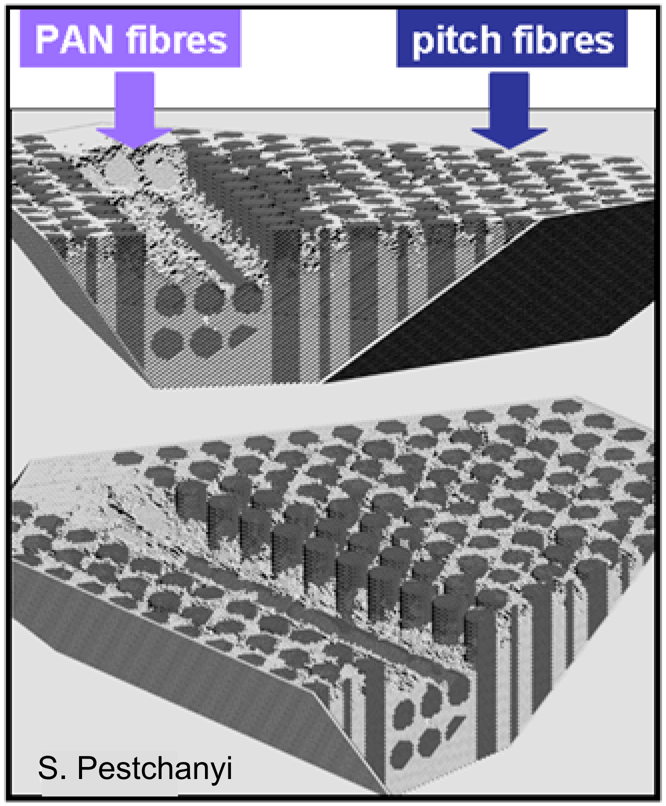


Localised Be damage by large ELM at JET

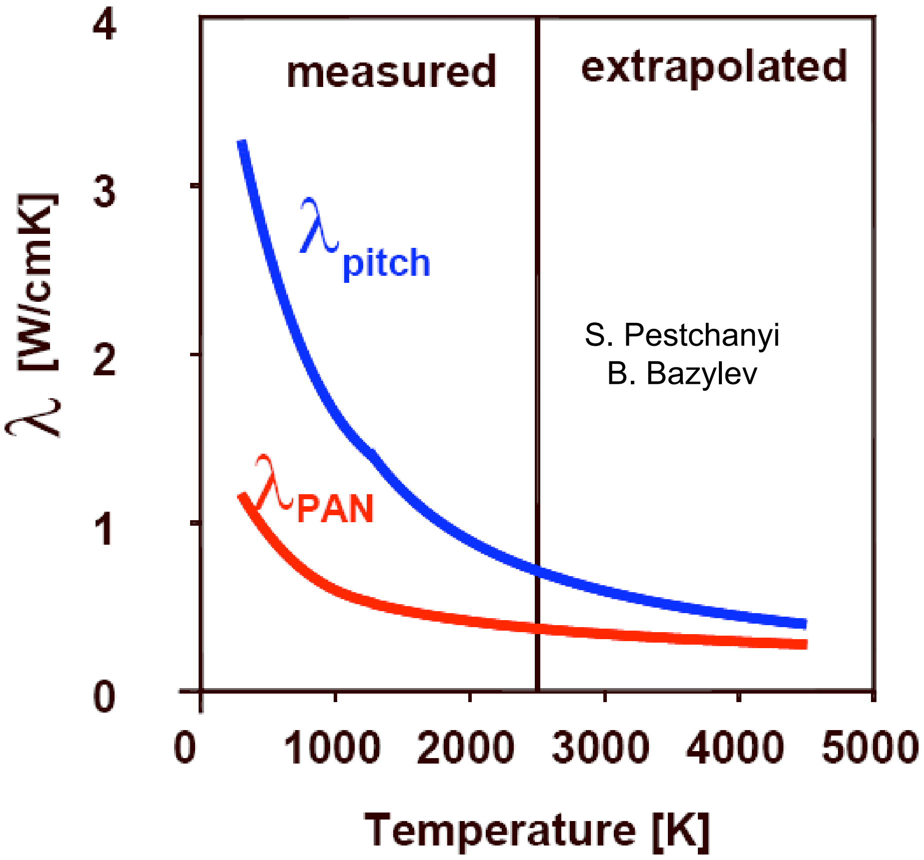


Basis for definition of controlled ELMs in ITER (III)

- CFC erosion larger than expected due to : 3-D CFC effects + decrease of χ with T



S. Pestchanyi



S. Pestchanyi
B. Bazylev

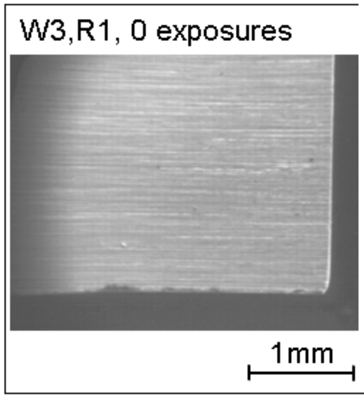
Erosion threshold for NB31 CFC ~ 0.75 MJm^{-2} & no ELM-caused erosion ~ 0.5 MJm^{-2}

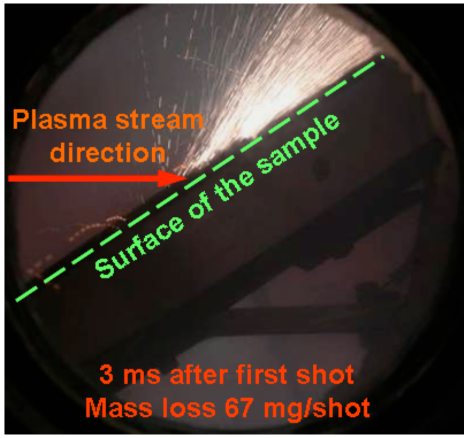
Basis for definition of controlled ELMs in ITER (IV)

- Local W erosion up to 1.0 MJm^{-2} dominated by edge melting and displacement along edges (30^o in QSPA vs. ~ 3^o in ITER)
- W cracking seen from 0.2 MJm^{-2} but severity of problem increases beyond 0.7 MJm^{-2} and is very large once molten layer is formed
- Net W erosion dominated by evaporation in absence droplet loss

N. K

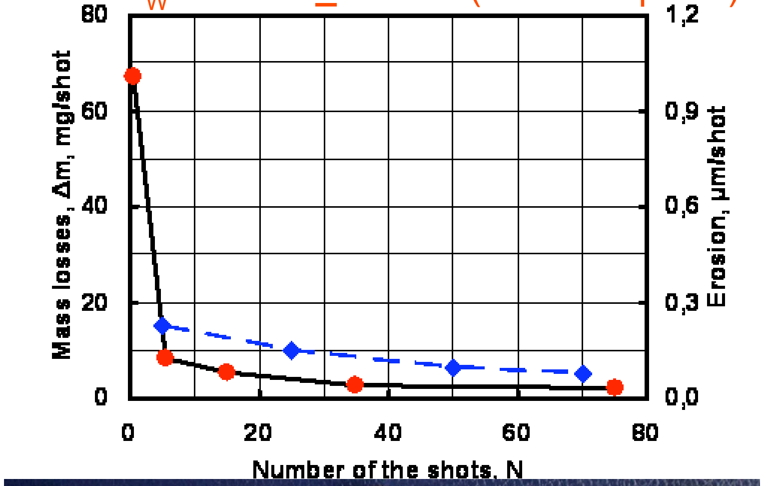
0.8 MJm^{-2}

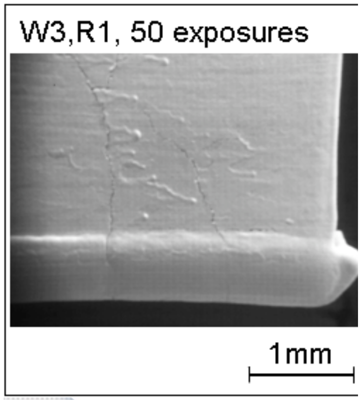


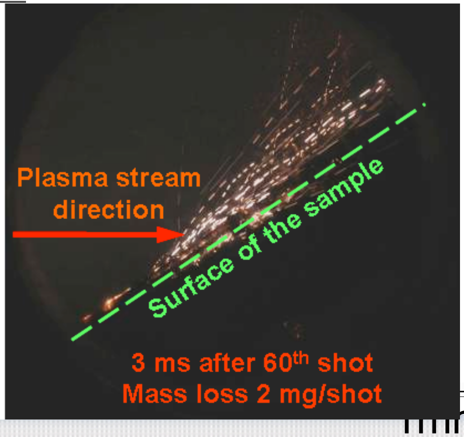


N. Klimov

$<E_W>=$ **0.03 _m/shot** (after 40th pulse)







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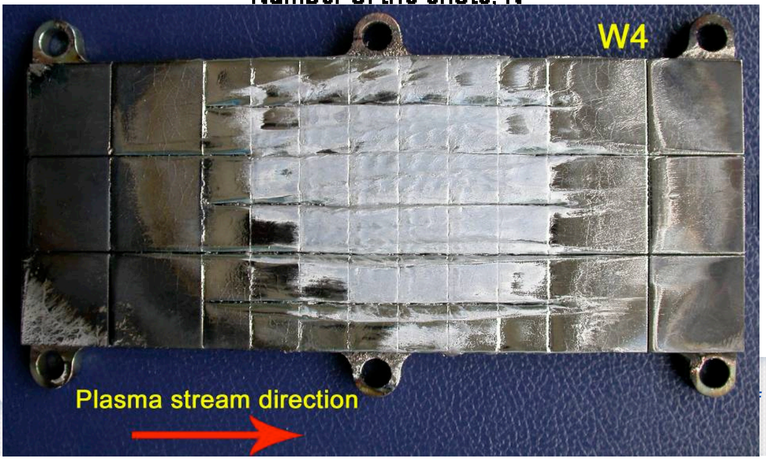
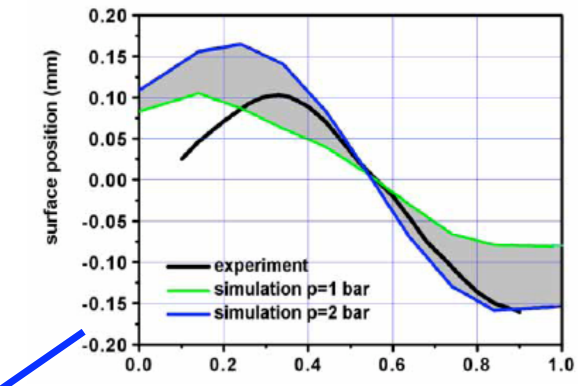


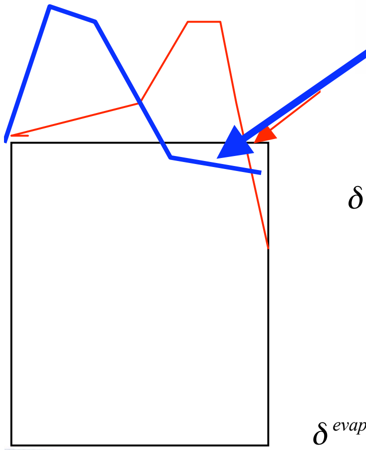
W Erosion (II)

- Net W erosion dominated by evaporation in absence droplet ejection (not expected for ITER-like conditions for $E_{ELM} < 3.0$ MJm^{-2}) based on MEMOS results without current flows
- Local W erosion dominated by melt layer movement within each macrobrush
- Predictions of melt layer movement for ITER and droplet ejection still very uncertain (forces on molten layer during ELMs) but edge melting is a key issue (edge power densities typically 2-3 times larger than at front face (PIC-Dejarnac))

100 ELMs @$_{2}$1.5 MJm^{-}

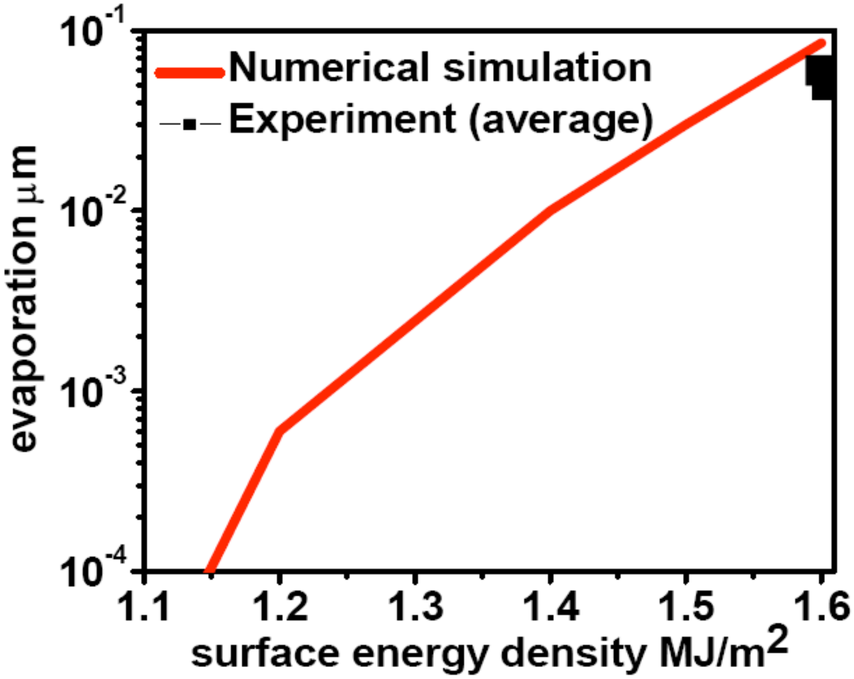
Klimov, Bazylev Zhitlukhin, Linke, et





$$\delta^{melt}{}_{ELM}(\mu m) = 0.15 - \frac{0.12}{1+e^{\frac{E_{ELM}(MJm^{-2})-0.65}{0.05}}}$$

Bazylev - MEMOS

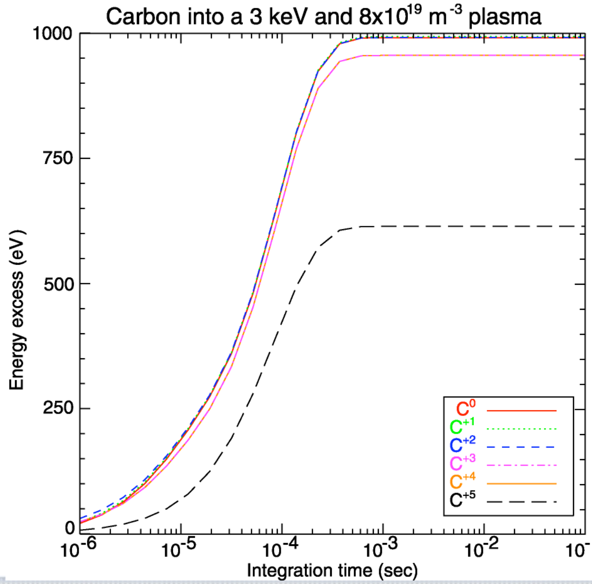


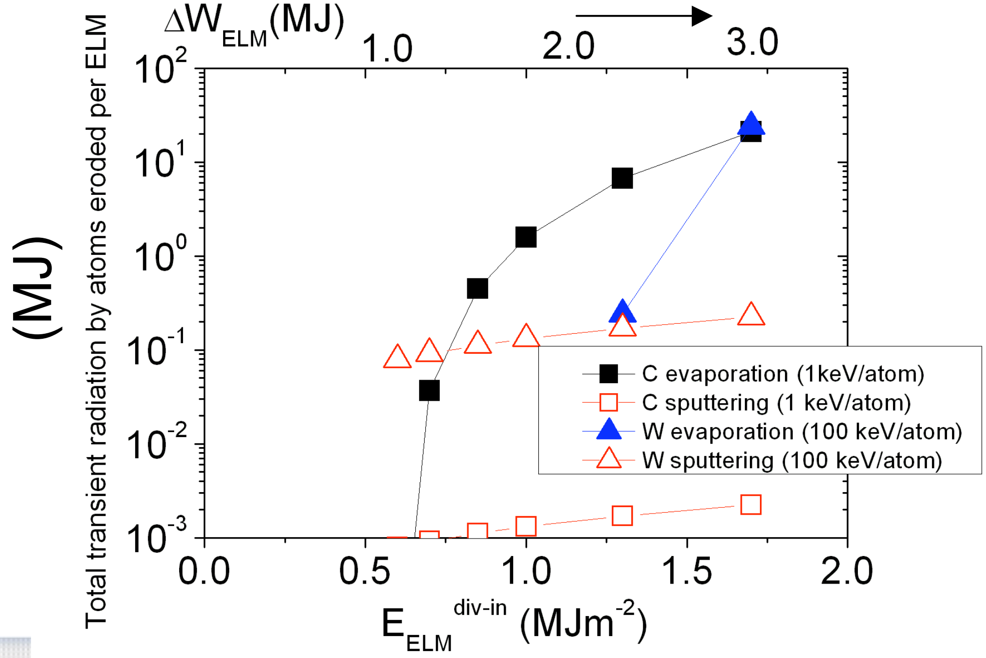
$$\delta^{evap}{}_{ELM}(\mu m) = -1.2\,10^{-3} + 1.27\,10^{-9}\,e^{11.25 E_{ELM}(MJm^{-2})} + 2.0\,10^{-5}\,e^{3.19 E_{ELM}(MJm^{-2})}$$

Effect of ELM-caused impurities on Plasma (I)

- ➢ Estimating effect on ELMs to ITER plasmas involves evaluation of very uncertain phenomena
  - ✓ Transient radiation following the ELM (disruption by radiative collapse)
  - ✓ Impurity transport following ELMs and bulk plasma contamination (reduction of plasma performance)
- ➢ Transient P_{rad} by C in an ionizing plasma is low but formation of optically thick plasmas due to massive evaporation (FOREV-2 show SOL plasma collapse to 1-2 eV once C vaporisation starts) ?
- ➢ Transient P_{rad} for W could be worse (100 times larger per atom?) ?

ADAS, Ó' Mullane

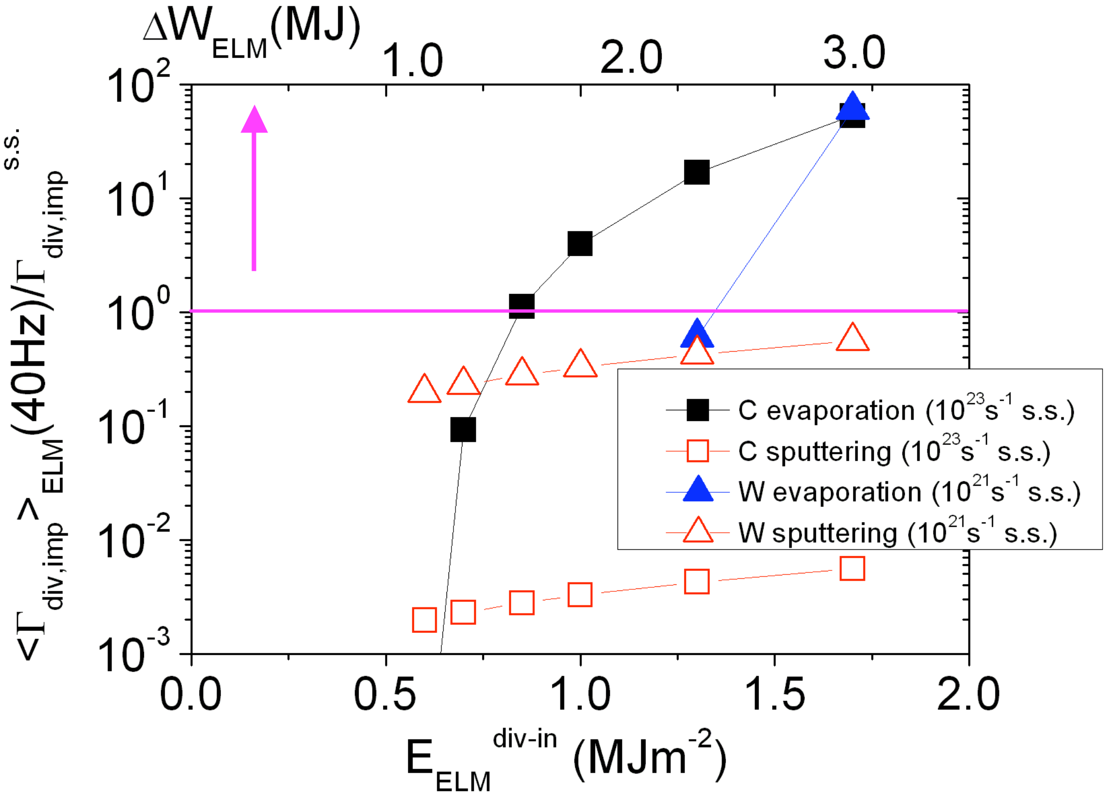




Effect of ELM-caused impurities on Plasma (II)

- Evaluation of plasma contamination by ELMs very uncertain
- Penetration probability of ELM produced impurities expected to be larger than in steady-state (~ 10 % from FOREV-2 for C)

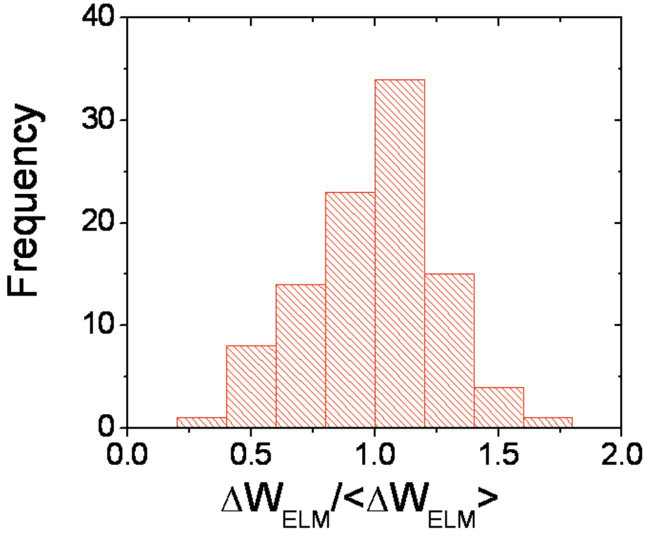
→ Compare average influxes from steady-state modelling and from ELMs



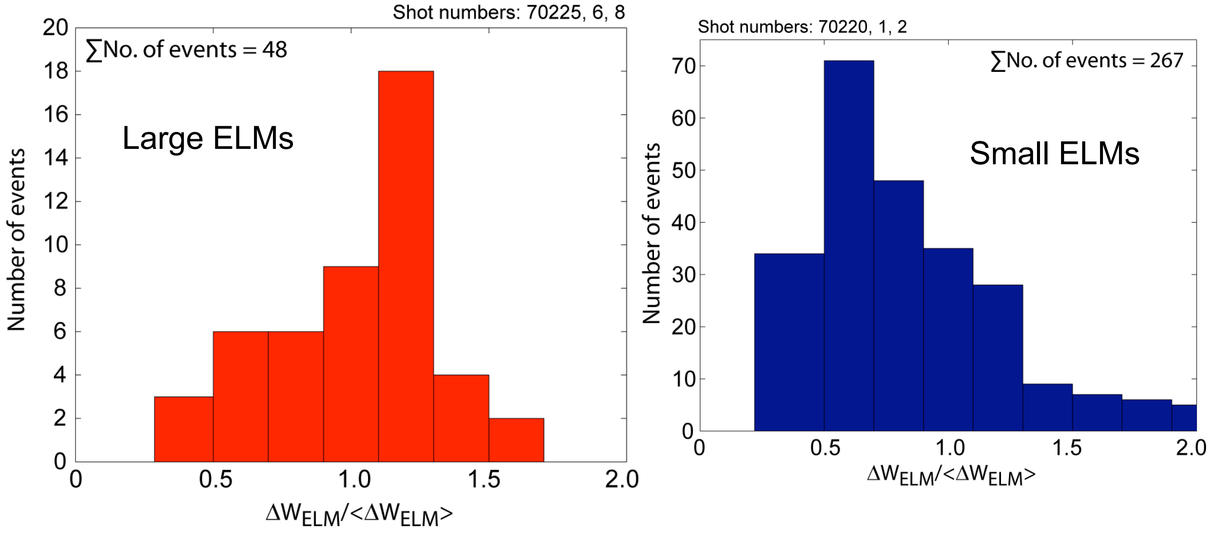
ELM variability

ELM losses show variability but dependence on plasma conditions remains to be studied → particularly important for controlled ELMs with “forced” f_{ELM}

JET- A. Loarte, APS 2003



JET- R. Pitts (large ELM experiments)



Estimates of variability done with Gaussian distribution and σ/μ ~ 0.25 & 0.5

Divertor Erosion and ELM variability

ELM variability leads to two effects :

- Decease of threshold for erosion
- Increase of absolute erosion by ELMs in tail of distribution (more drastic for exponentially growing processes W evaporation without shielding) → ELM control method should control $<\Delta W_{ELM}>$ & σ