ELM STUDIES ON DIII-D

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General Atomics
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ELM Issues Important for ITER

- ITER requires H-mode τ_E for ignition and to maintain high P_F during burn, $H_{ITER93\text{-}H} > 0.8$.
- Since steady state ELM free discharges have not been demonstrated ITER must be prepared to operate with ELMs
- The current ITER divertor design can tolerate $1 MJ/m^2$/ELM or 10MJ/ELM (1% at ignition) assuming all the ELM energy loss arrives in the divertor with the same spacial distribution as the steady state heat flux.
- With these experiments we wish to answer the question: Is high τ_E ELMy H-mode with low ELM heat flux to the divertor possible for ITER ?

Discharges Studied

- ITER cross sectional shape and R/a (L_{DIII-D}/L_{ITER} 0.2).
  - $3 < q_{95} < 6$, ($q_{ITER} = 3$).
  - $0.75 < I(MA) < 1.5$, ($I_{ITER} = 22$).
  - $1 < B(T) < 2$, ($B_{ITER} = 5.7$).
- $0.06 < P_{IN}/S$ (MW/m^2) < 0.3, ($0.17_{IGNITION} < P/S_{ITER} < 1.25_{BURN}$).
- $0.2 < n_{GREENWALD} < 0.7$, ($n_{ITER}$ 1.0).
  - Gas Puff Fueled.
  - Open Divertor.
  - No Divertor Pumping.
  -   B Drift Toward the X-point.

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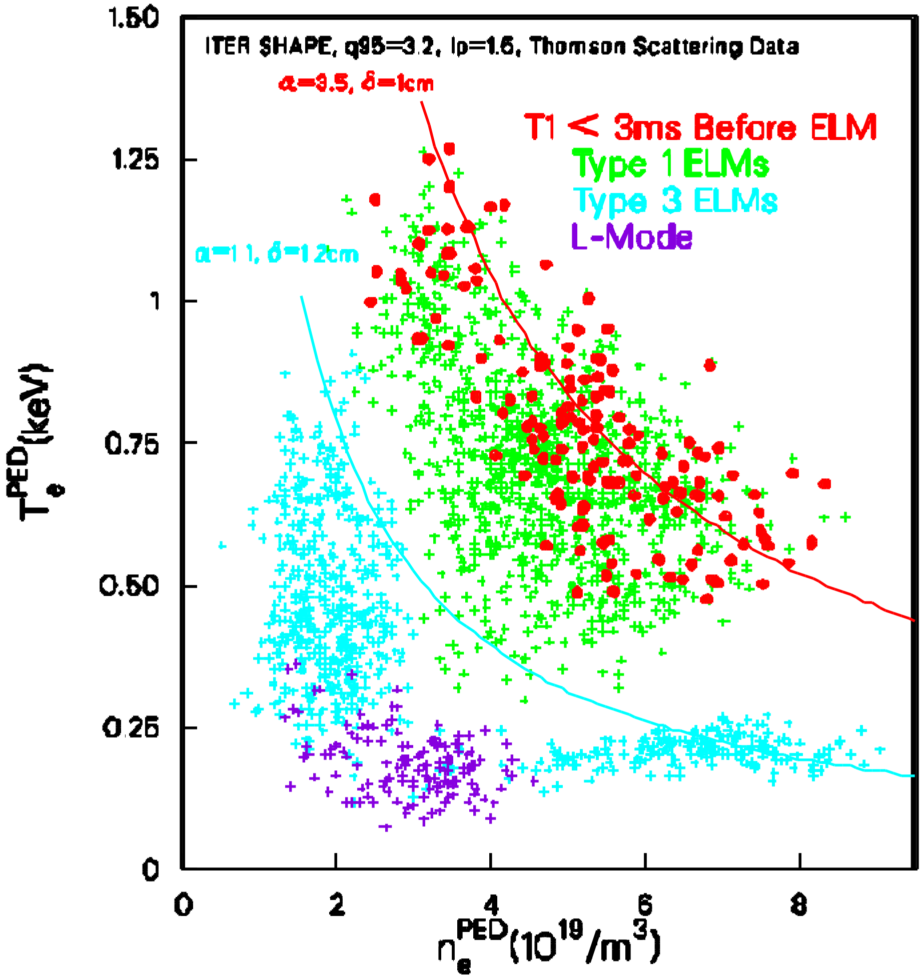
ELM Classification

- Type 1
  - d*freq*$_{ELM}$/dP$_{IN}$ > 0
  - No Precursors
  - $p'_{EDGE} \approx p'_{BALLOONING}$
  - Large $\Delta W_{ELM}/W \leq 6\ \%$
  - High $H_{ITER93\text{-}H} > 0.9$

- Type 3
  - d*freq*$_{ELM}$/dP$_{IN}$ < 0
  - Coherent precursors
  - $p'_{EDGE} \leq p'_{BALLOONING}$
  - Small $\Delta W_{ELM}/W \leq 1\ \%$
  - Low $H_{ITER93\text{-}H} < 0.9$
  - Two Regimes
    - Low n_e
    - Low T_e

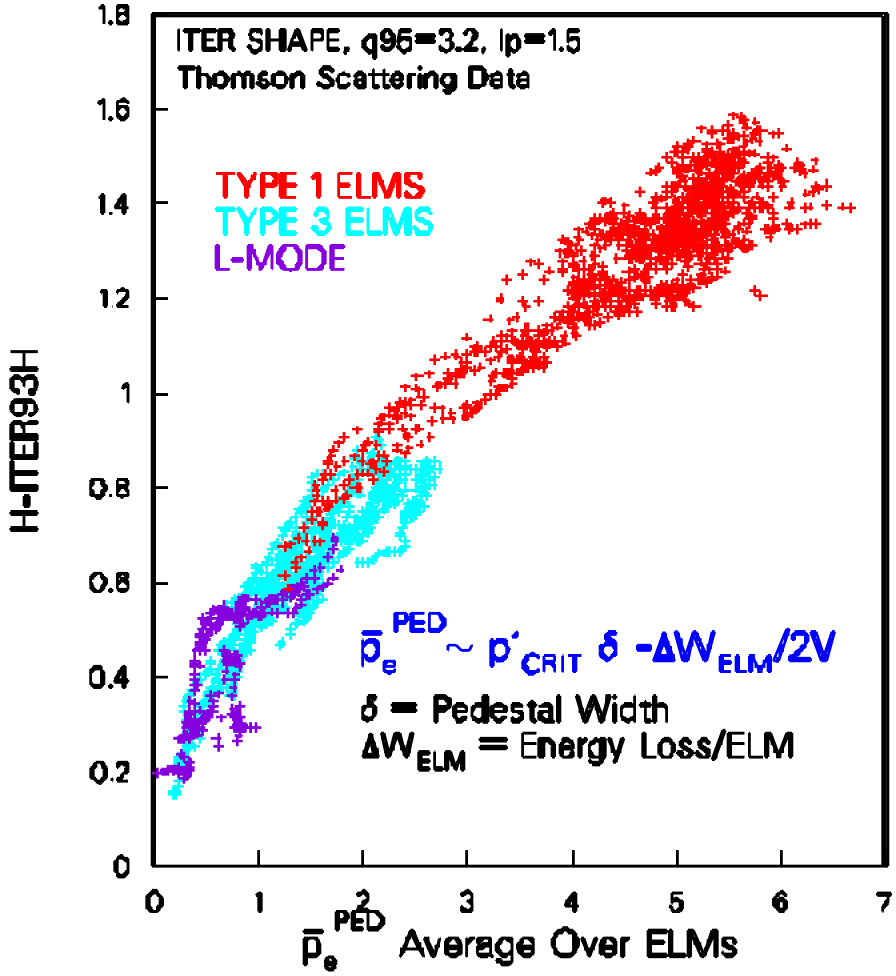
Pedestal Heights for Different ELM Classes

- Different classes of ELMs appear in distinct regions of electron density and temperature pedestal heights.
- Pressure gradient, α, at Type 1 ELMs is near ideal ballooning limit.
- Type 3 ELMs appear in two regions.
  - Low n_e Type 3 ELMs have $\alpha < \alpha_{CRIT}$.
  - Low T_e Type 3 ELMs have $\mathbf{T_e} < \mathbf{T}_{CRIT}$. In ASDEX-U these ELMS have been produced with $\alpha = \alpha_{TYPE\text{-}1}$ at high $\mathbf{n_e}$. In DIII-D, $\mathbf{n_e}$ was limited by marfing and return to L-mode.



H-Mode Pedestal and Energy Confinement

- Discharges with large H-mode pedestals have high energy confinement enhancement, **H**.
  - Type 1 ELM discharges have large pedestals due to high edge pressure gradient.
  - Low n_e Type 3 ELM discharges have limited α and therefore poor **H.**
  - Low T_e Type 3 ELM discharges may reach higher **H** if α increases at high n_e as in ASDEX-U.



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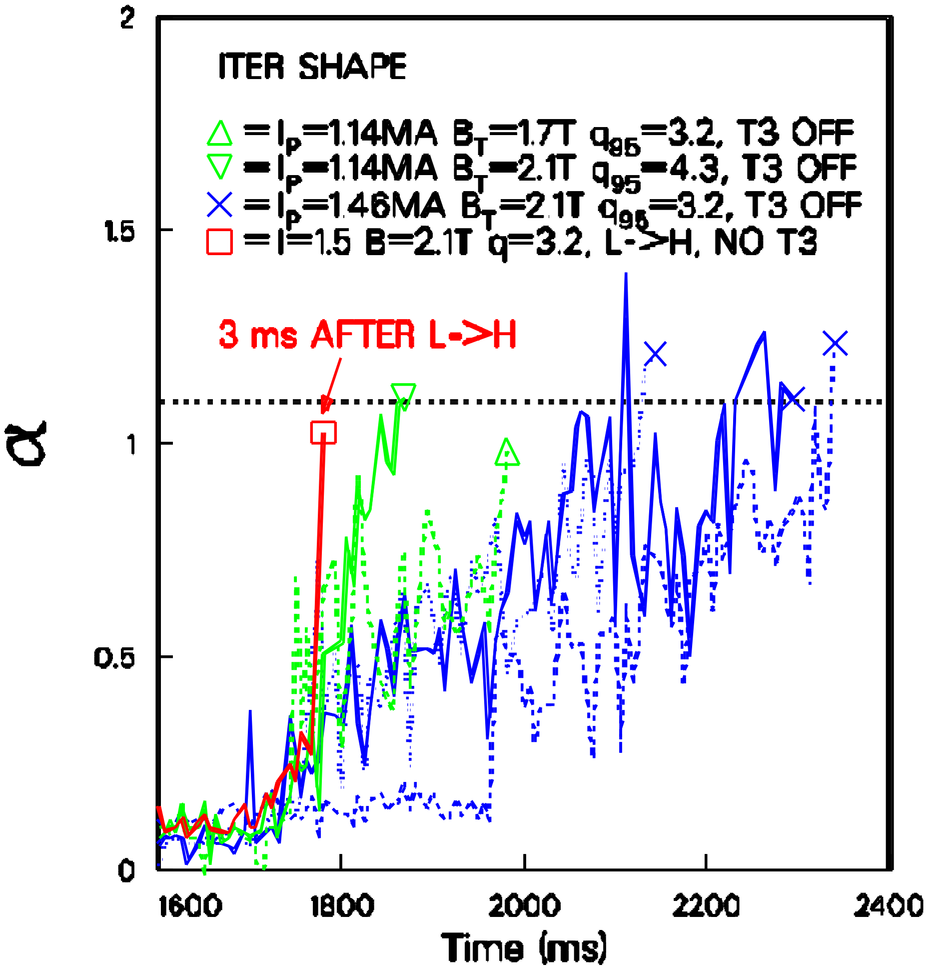
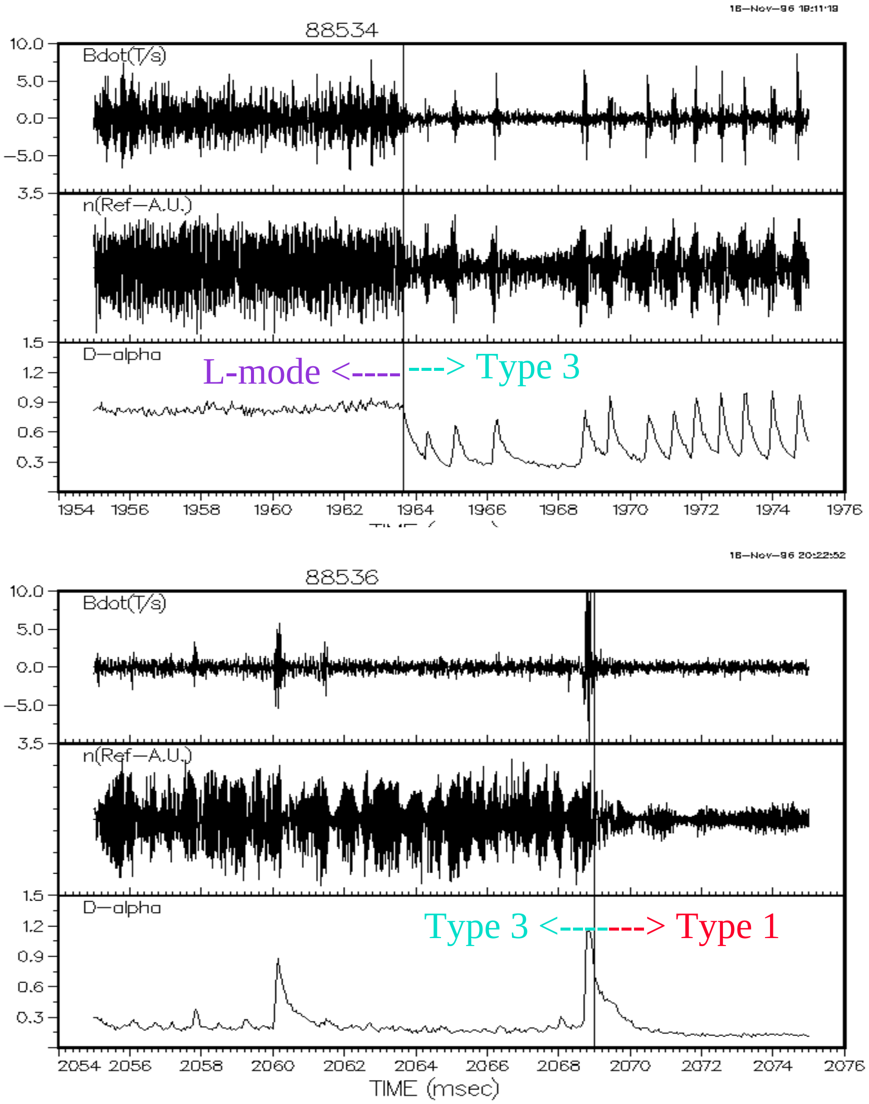
Critical Pressure Gradient for Low Density Type 3 ELMS

- Low n_e Type 3 ELMs shut off at approximately the same edge pressure gradient, α.
- Discharges at high density which do not have Low n_e Type 3 ELMs reach the critical α shortly after the L->H transition.
  - Rapid build up of α may be due to a large neutral influx following the L->H transition in this case.



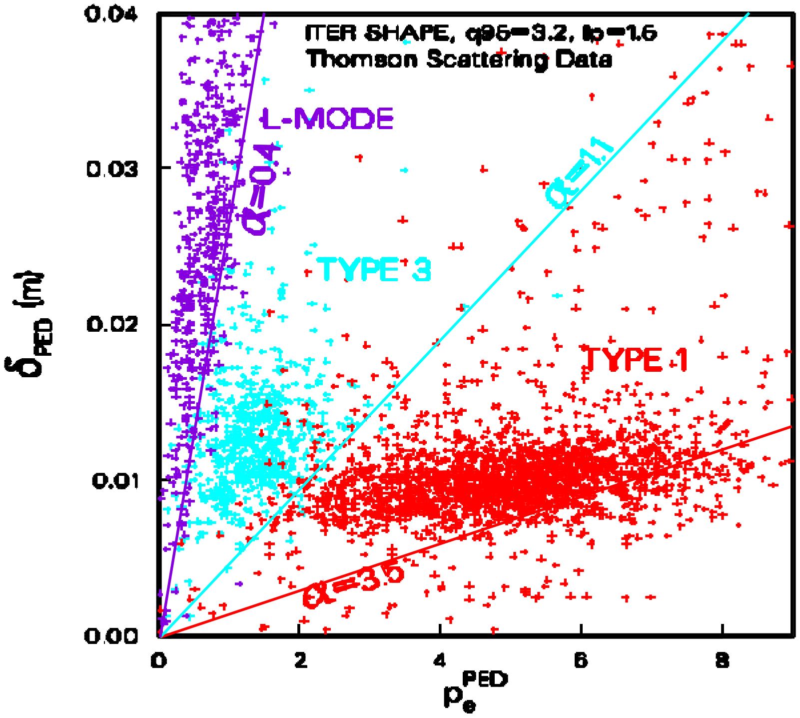
Low Density Type 3 ELM Regime

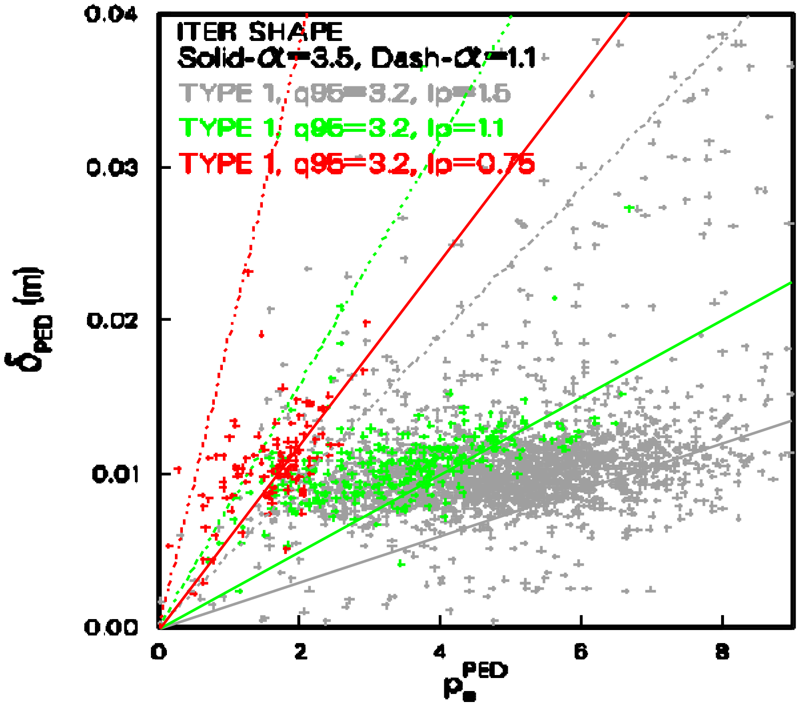
- The end of the low density type 3 ELM phase has the characteristics of a secondary transition.
  - Density fluctuations are reduced both at the L->T and T3->T1 transitions.
  - A sudden reduction in th width of the H-mode pedestal, δ_{PED}, is also observed at the T3->T1 transition.



H-Mode Pedestal Characteristics

- The width of the steep gradient region is relatively constant and similar for Type 1 and Type 3 ELMs.
  - The width is independent of $\mathbf{I_P}$ at fixed **q** for Type 1.
- The range of pressure gradient, $\Delta\alpha$, spanned in Type 1 ELMs is constant at fixed **q**.
- The lower bound in α for Type 1 is roughly the upper bound for Type 3.



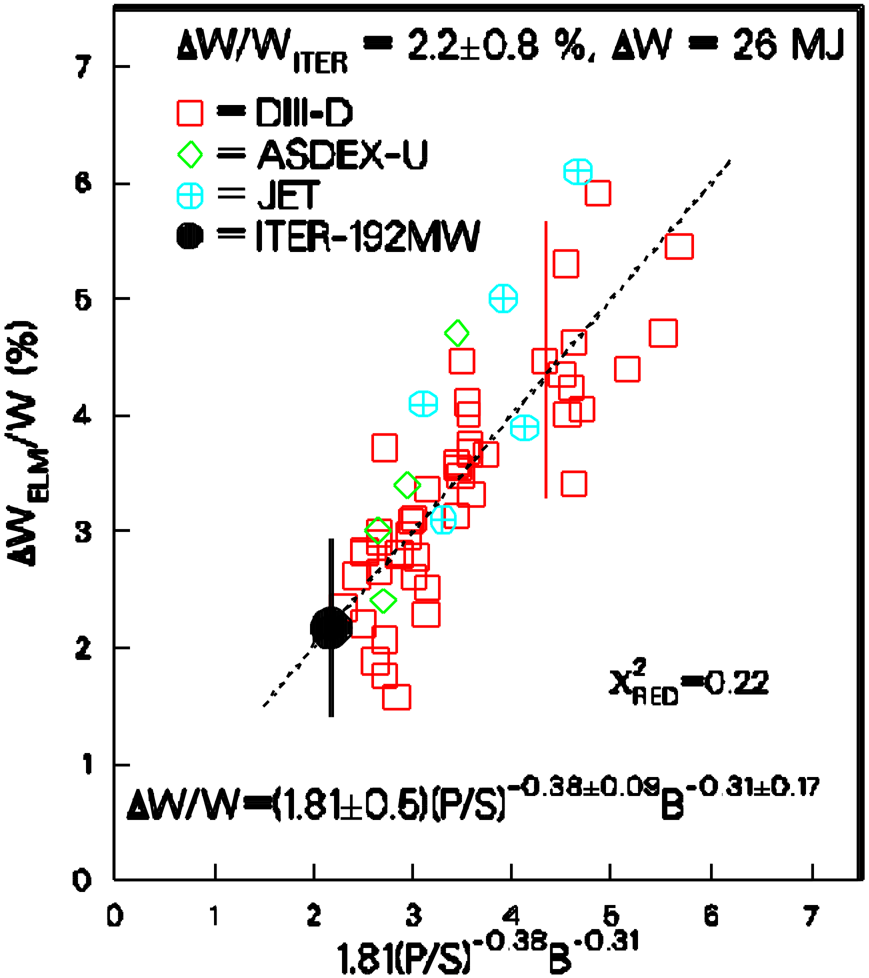


Estimate of Type 1 ELM Energy Loss for ITER

- The DIII-D data for ITER shape discharges suggest that:
  - The range in edge pressure gradient, $\Delta\alpha$, spanned in Type 1 ELMs remains constant at fixed **q**.
    - The same $\Delta\alpha$ might be expected in ITER since the magnetic shear is independent of size.
  - The width of the steep gradient region, $\delta_{\mathbf{PED}}$,is fixed through most of the ELM cycle and is fixed at fixed **q.**
- Assuming the type 1 ELM energy loss represents a change in the H-mode pedestal height: $\Delta W_{ELM} = \delta_{PED}\ \Delta p'_{PED}\ V$.
- Assuming δ_{PED} $\rho_P{}^g\ L^{1-g}$ where L is the length scale gives for
  - $g=0$, $\Delta W_{ITER} = 32$ MJ (suggested by $\delta_{\mathbf{PED}}$=const at fixed **q**)
  - $g=0.5$, $\Delta W_{ITER} = 11$ MJ, $g=1$, $\Delta W_{ITER} = 1$ MJ
  - δ_{PED} $T^{1/2}$ (JET), $\Delta W_{ITER} = 7$ MJ

Scaling of Type 1 ELM Energy Loss

- A scaling of the energy loss per Type 1 ELM with global parameters gives 26 MJ for ITER.
- Using ITER93-H scaling for energy confinement time implies ΔW_{ELM} depends strongly only on plasma current and geometry.



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Type 1 ELM Effects in the Divertor

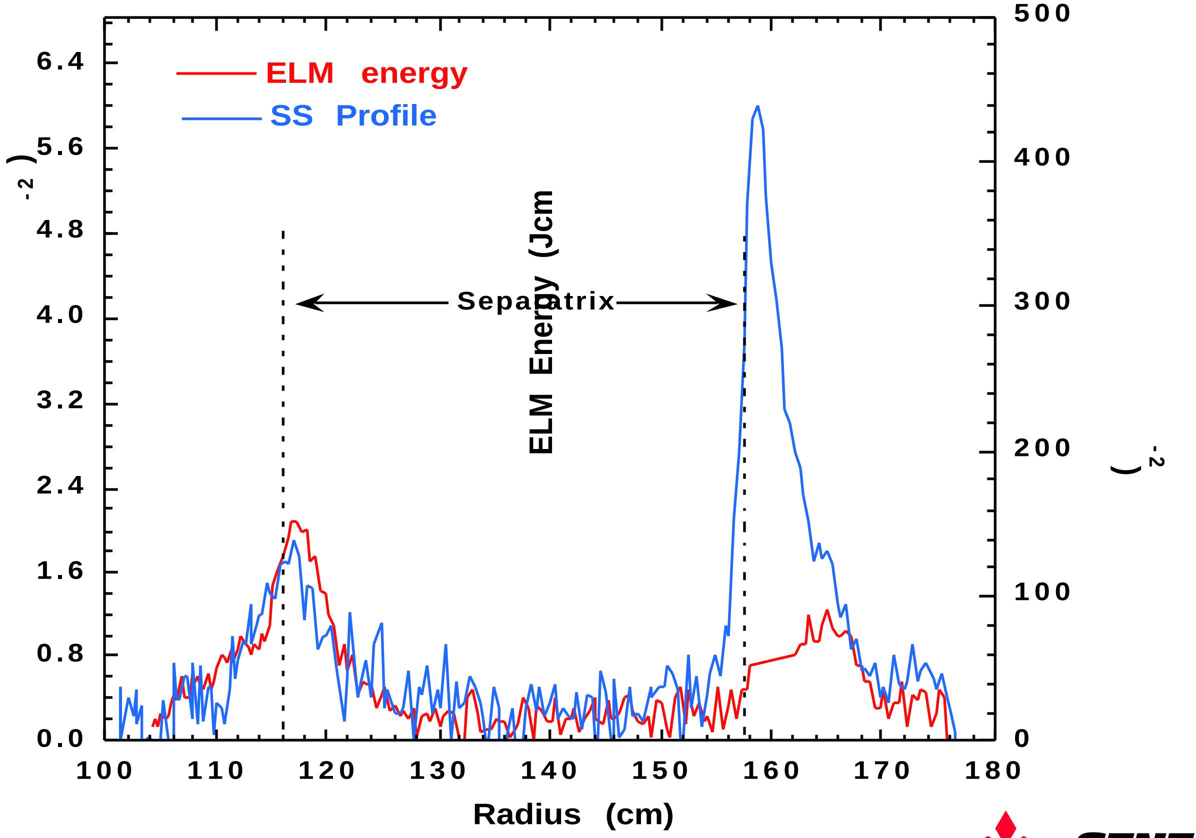
- For ITER shaped plasmas with $q_{95} = 3.2$ most of the ELM energy loss reaches the divertor with the majority to the inner leg (which is typically detached in DIII-D).

$$\Delta W_{DIV} = (0.75 \pm 0.25)\ \Delta W_{ELM}$$
$$\Delta W_{INNER} = (0.50 \pm 0.16)\ \Delta W_{ELM}$$
$$\Delta W_{OUTER} = (0.23 \pm 0.11)\ \Delta W_{ELM}$$

- The ELM heat flux is distributed over about a factor of two larger area than the time averaged heat flux.
- The ELM energy loss arrives in the divertor on a millisecond time scale.

Divertor Heat Flux During Type 1 ELM

- The ELM heat flux dominates the inboard heat flux since the inboard leg is typically detached.
- The ELM profile is broader at the outboard strike point than the steady state.



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Conclusions

- Prospects for high energy confinement ELMy H-mode with low ELM heat flux to the divertor in ITER.
  - Although Type 3 ELMs have low $\Delta \mathbf{W}$ they may not be compatible with high **H** factor.
    - If the low n_e regime is limited to $\alpha < \alpha_{\mathrm{TYPE\text{-}1}}$ and δ_{PED} are similar, then **H** will be reduced.
    - In the low T_e regime **H** might reach Type 1 values at high n_e where possibly $\alpha_{\mathrm{TYPE\text{-}3}} = \alpha_{\mathrm{TYPE\text{-}1}}$ (Asdex-U).
      - ⑦ $\mathbf{T}_{\mathrm{PED}}$ for ITER would be 6.4, 2.2, or 0.25 that of DIII-D for **g** of 0, 0.5, or 1.0. If the low T_e regime represents a resistive effect it might not occur in a higher $\mathbf{T}_{\mathrm{PED}}$ ITER.

Conclusions, continued

- Prospects for high energy confinement ELMy H-mode with low ELM heat flux to the divertor in ITER.
  - Estimates of Type 1 ELM energy loss and divertor effects for ITER are near the limit of what is acceptable.
    - Need to develop techniques for controlling either the ELM energy loss or the fraction which arrives in the divertor.

Conclusions, continued

- The oscillation of the edge pressure gradient between two limits for Type 1 ELMs is suggestive of the recent CDBM theory of S. Itoh, et. al[1] in which the plasma oscillates between M-Mode and H-mode.

[1] Sanae-I Itoh, Kimitaka Itoh, Atsushi Fukuyama, and Masatohi Yagi, *Plasma Phys. Control. Fusion*, **38** (1966) 527-549.