Imperial College
OF SCIENCE, TECHNOLOGY AND MEDICINE

UKAEA Fusion Working with Europe

Progress in Divertor and SOL Studies in the MAST Tokamak

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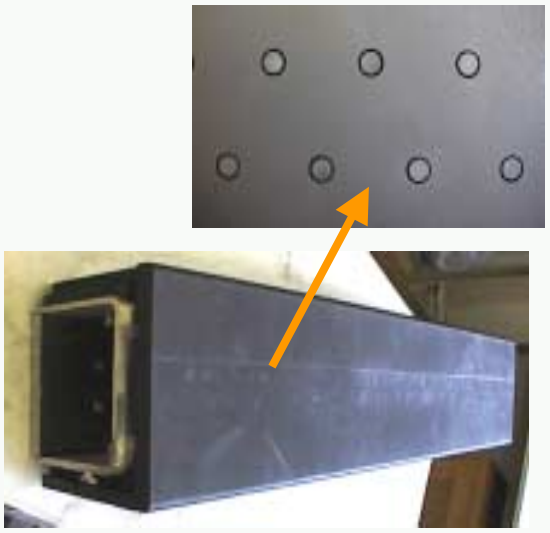
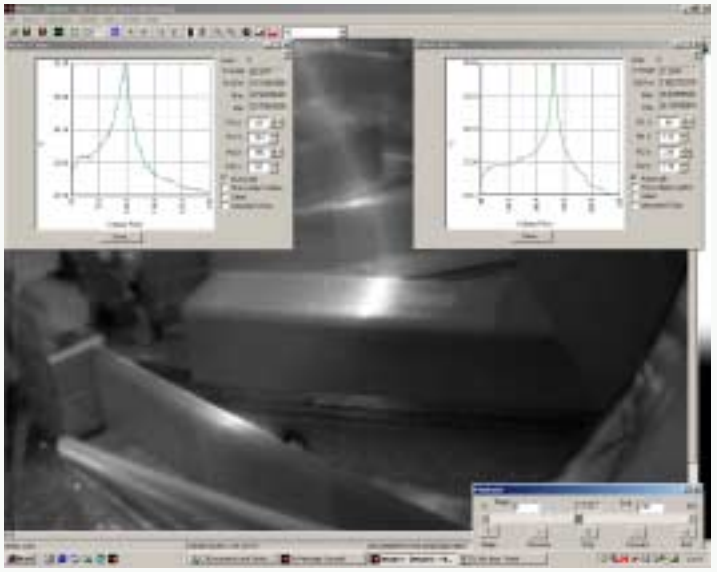
Divertor and SOL characterisation





Range of new and improved diagnostics

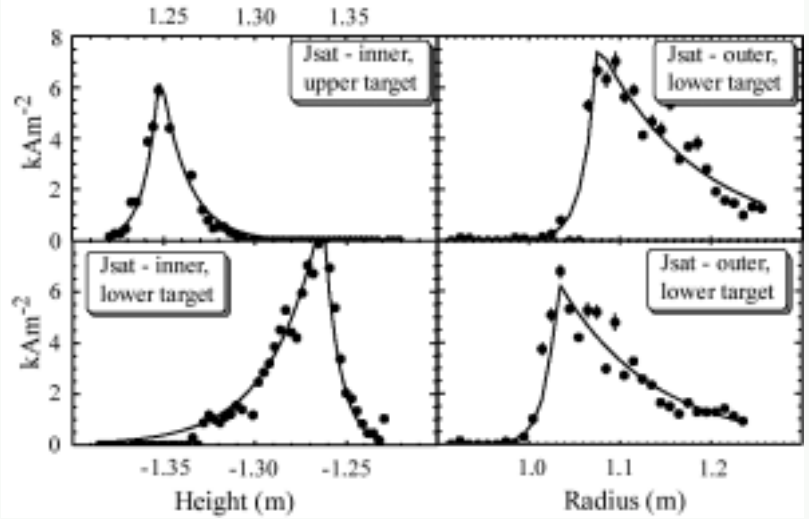
- Improved target probes
- Divertor IR Camera
- Divertor D_α Camera
- Mid-plane RP

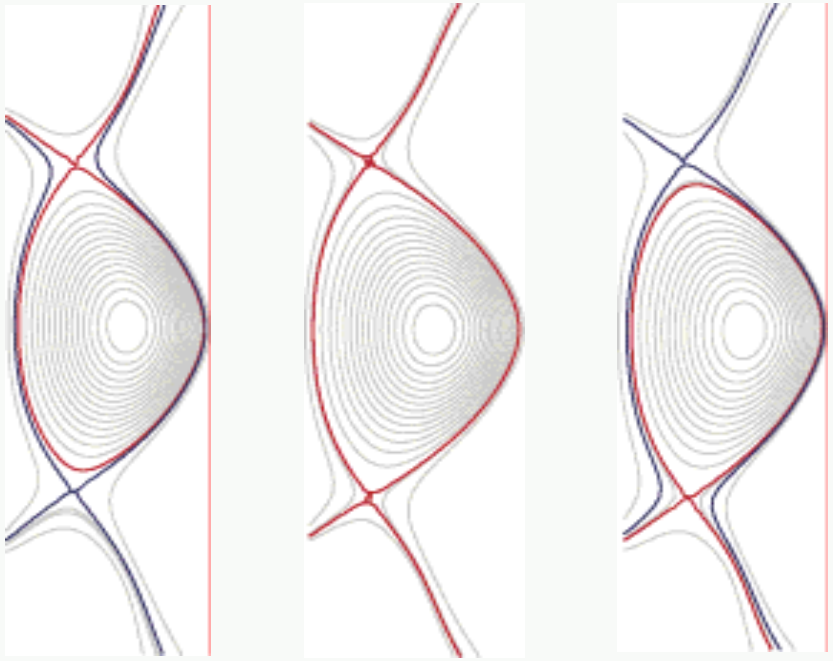
Characterisation of divertor and SOL plasma

- at all 4 strike zones
- in L and H-mode regimes

➔ 'ELM-free' and inter-ELM periods

- During ELMs





- Symmetric (CDN) and asymmetric double-null

➔ δr_{sep}>15mm (~upper SND)

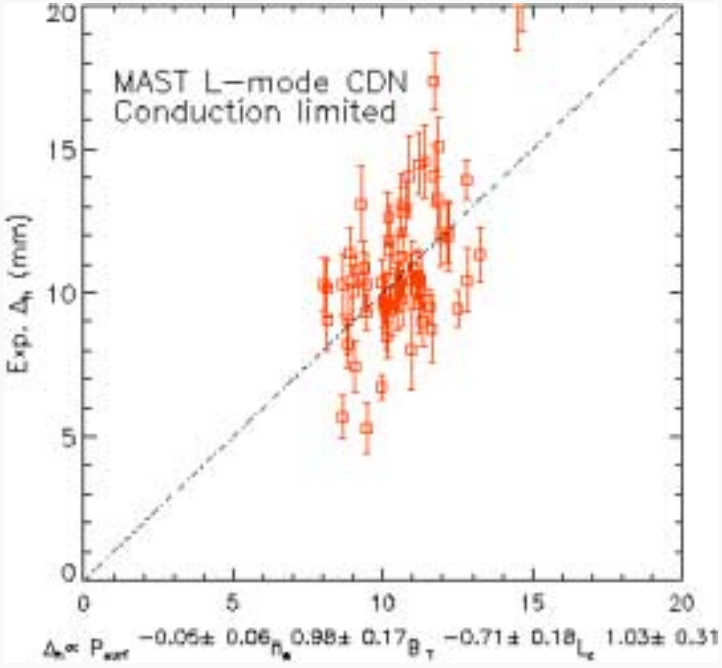
➔ $|\delta r_{sep}|$<3mm (CDN)

➔ δr_{sep}<-15mm (~lower SND)

- Ion ∇B drift to lower X-point

SOL width scalings

- **Scalings for L-mode SOL heat flux width in CDN**



- **P_{surf} (surface power density), $\bar{n}_e$, B_T, and L_c (parallel connection length)**

  ➔ weak/strong negative dependence on P_{surf}/B_T

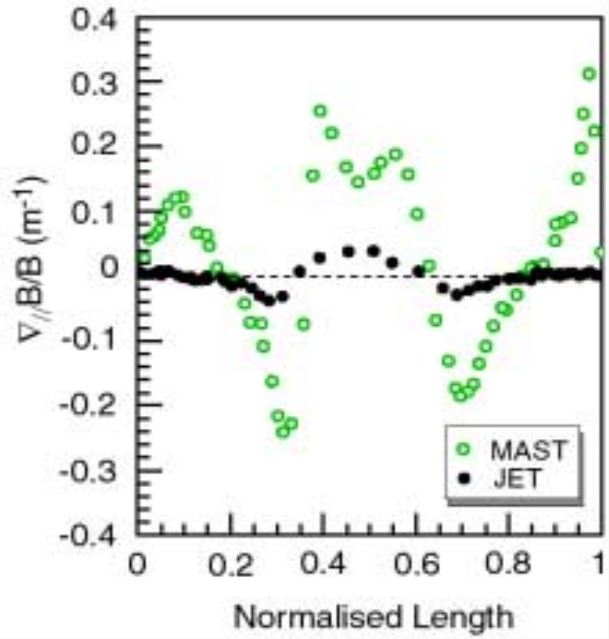
  ➔ approx. linear with n_e and L_c

$$\Delta_h \propto P_{surf}^{-0.05\pm0.06} \bar{n}_e^{0.98\pm0.17} B_T^{-0.71\pm0.18} L_c^{1.03\pm0.31}$$

- **Scaling based on classical // transport and $\chi_\perp$ from, eg. resistive MHD interchange model**

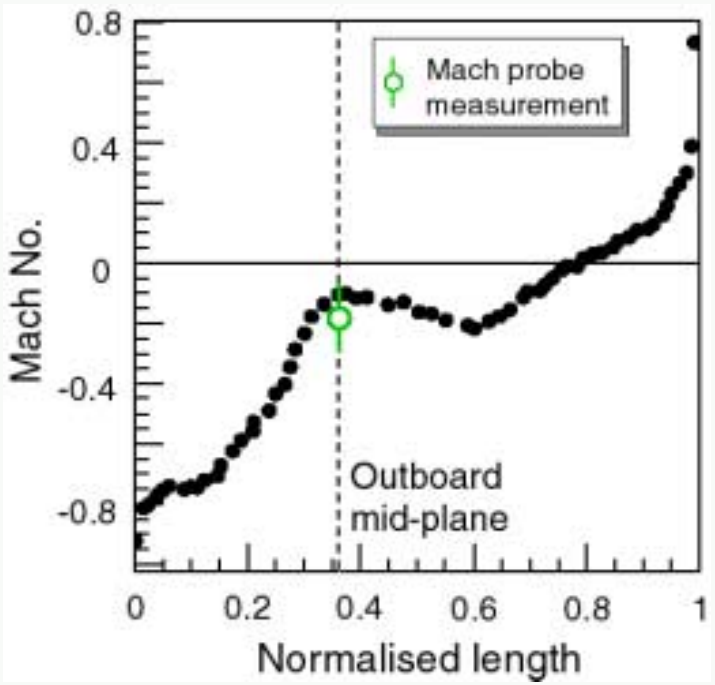
$$\Delta_h \propto P_{surf}^{-2/5} \bar{n}_e^{14/15} B_T^{-14/15} L_c^{16/15}$$

OSM-Eirene Modelling - importance of $\nabla_{//}B/B$



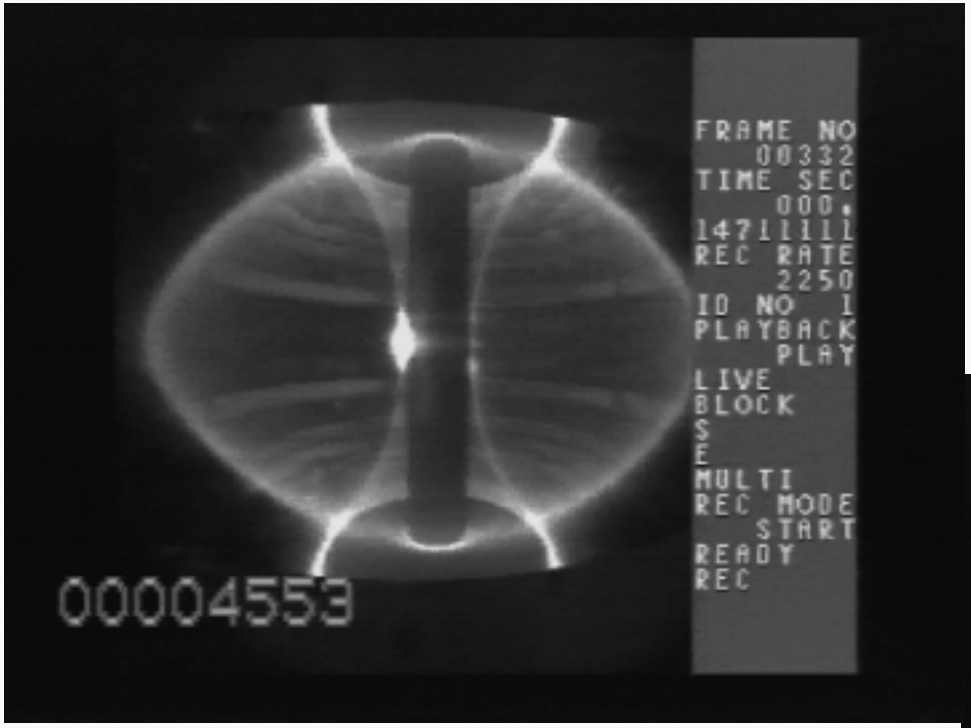
- **Key effect:**
  - **$\nabla_{//}B/B$ factor 10 larger in ST**
  - **➔ Changes in f(v,t)**
  - **➔ 'effective' large upstream source term**

- **Drives SOL flows**
- **Mid-plane Mach probe measures M~0.2 - in line with OSM**
- **Effect ignored in some fluid SOL models**



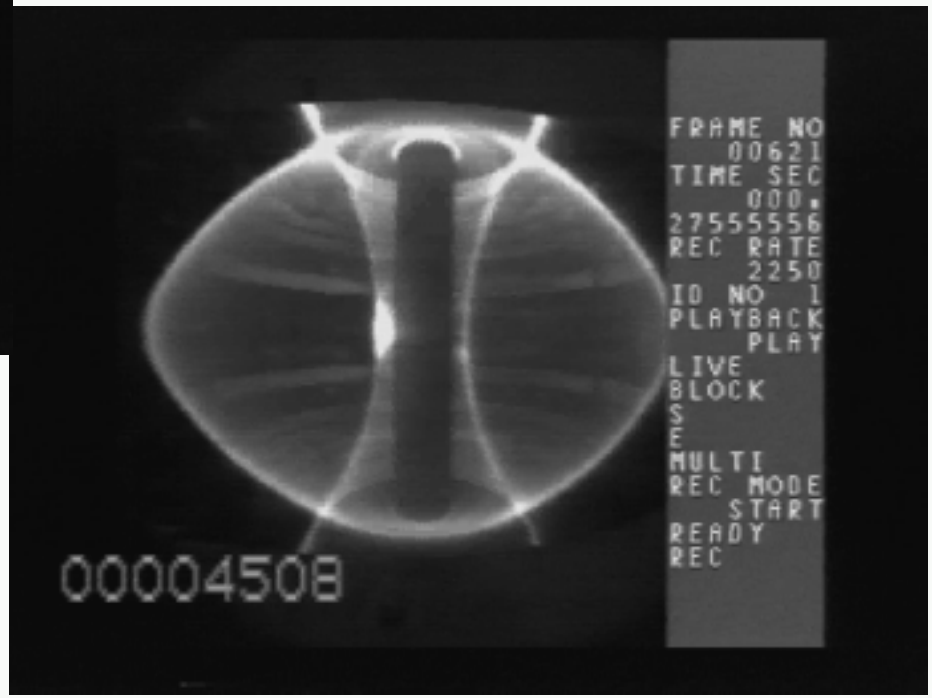
ELMs

LFS interactions during ELMs

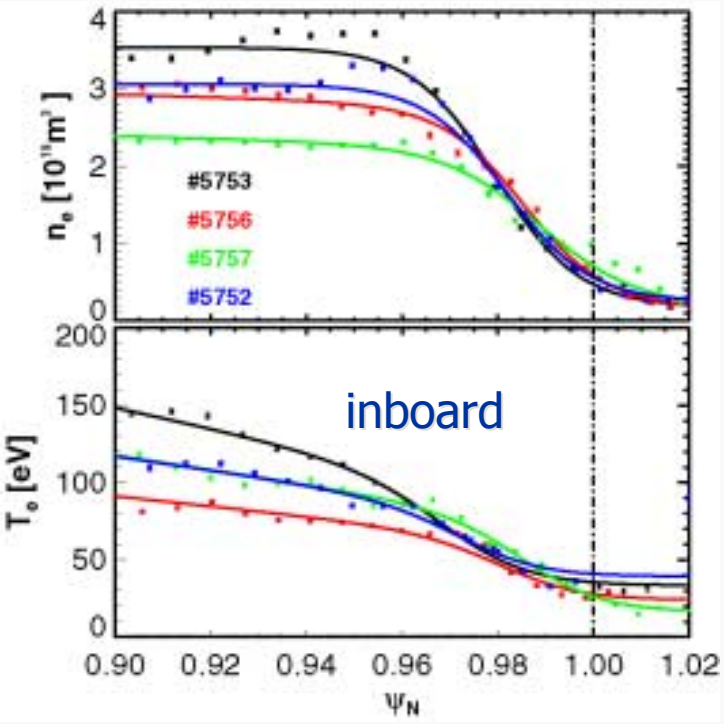


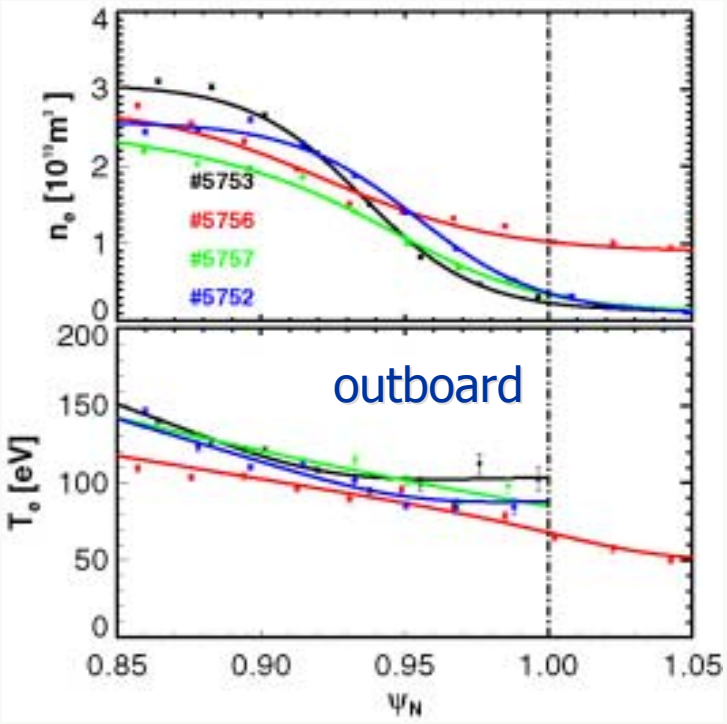
- Strong interactions with LFS reciprocating probe
- Very similar phenomenon now observed on JET

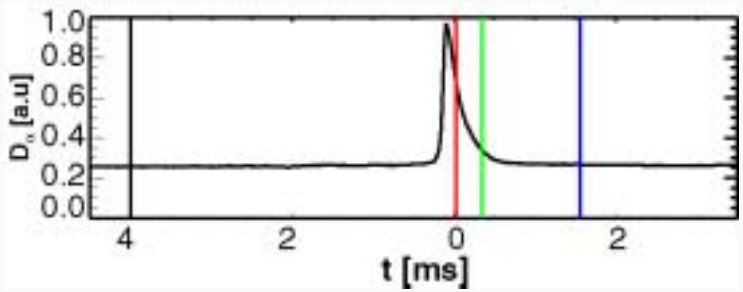
- ELMy H-mode shows clear reduction in edge fluctuations
- ELM bursts impact only LFS



ELMs not observed at HFS



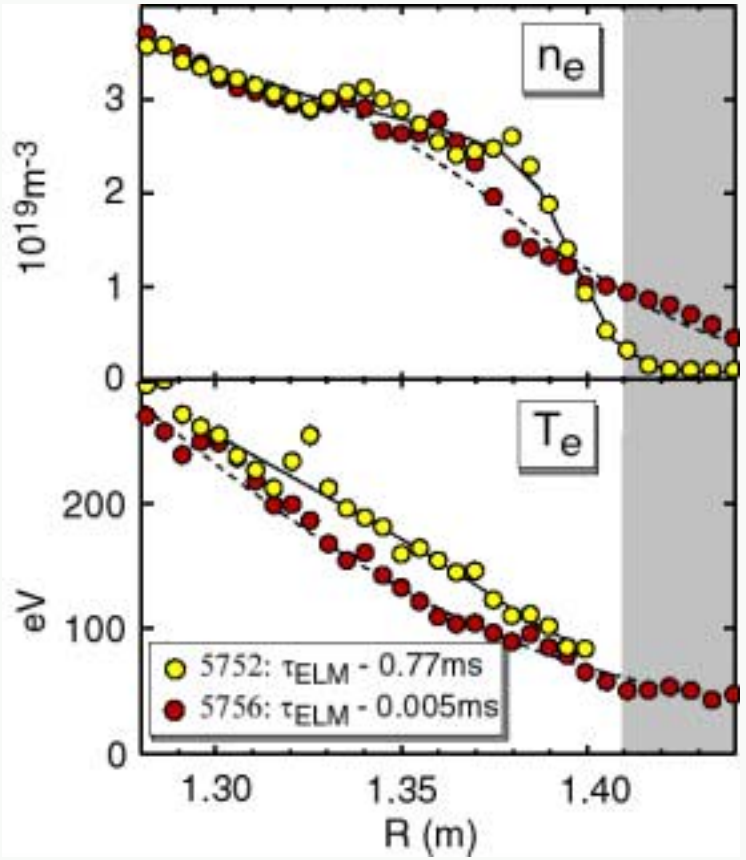




ELM losses dominated by convection

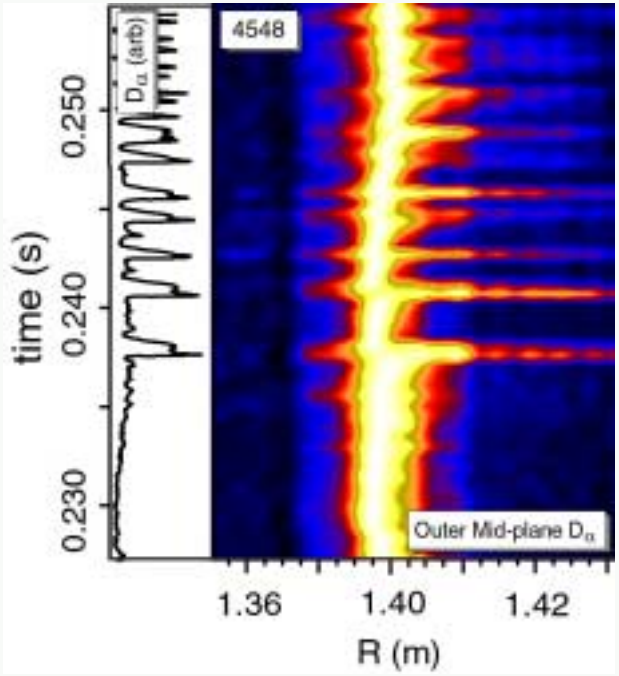
- **High Pedestal collisionality:**
  $\langle \nu_{ped}^{*} \rangle \sim 2.1 \pm 1.3$
- **TS profiles before and after ELM show** $\langle T \rangle \Delta n >> \langle n \rangle \Delta T$ ➔ **convective losses**
- **Modest** $\frac{\Delta W_{ELM}}{W}$ **(< 4%) and**

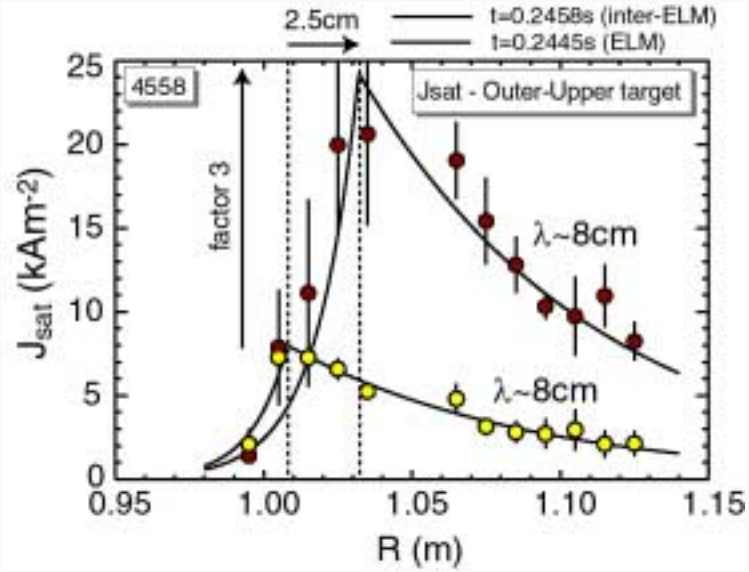
$$\frac{\Delta W_{ELM} f_{ELM}}{P_{heat}} \quad (< 5\%)$$



ELM impacts far into SOL

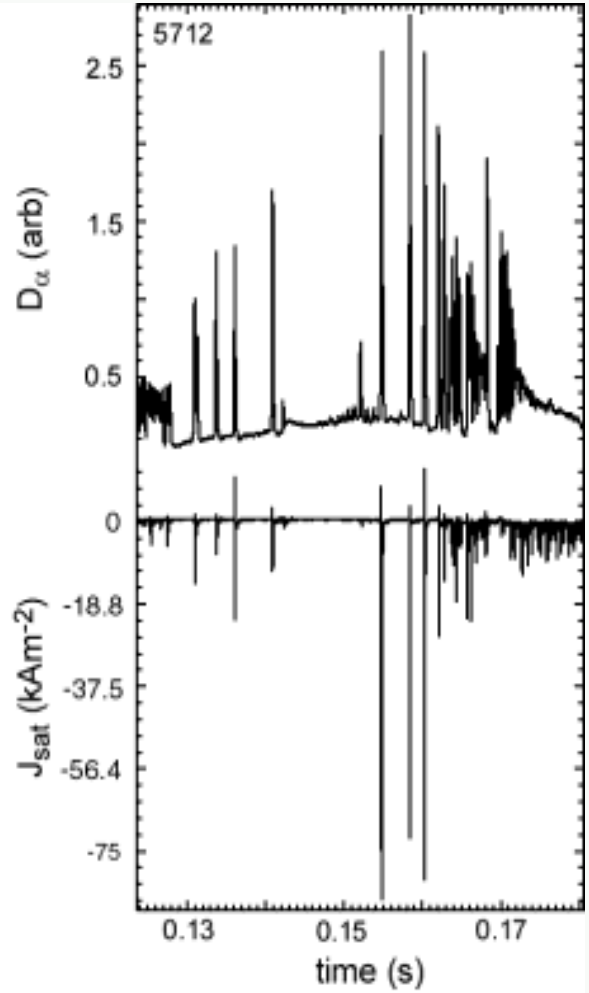
- Formation of broad outboard n_e and T_e tail at ELM peak on outboard mid-plane TS
- Broad outboard mid-plane D_α
- Up to several cm from separatrix





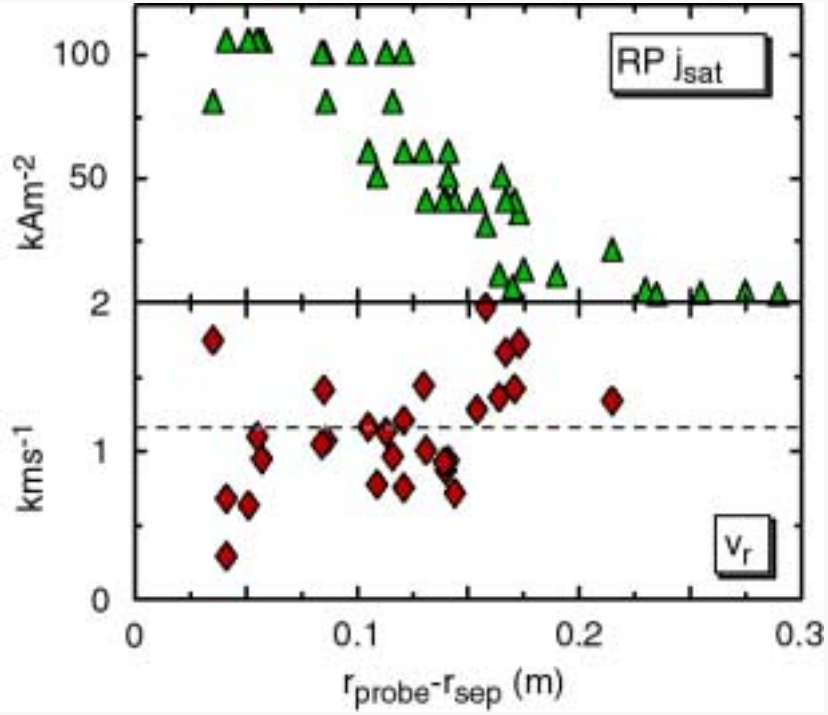
- However, no broadening of target profiles

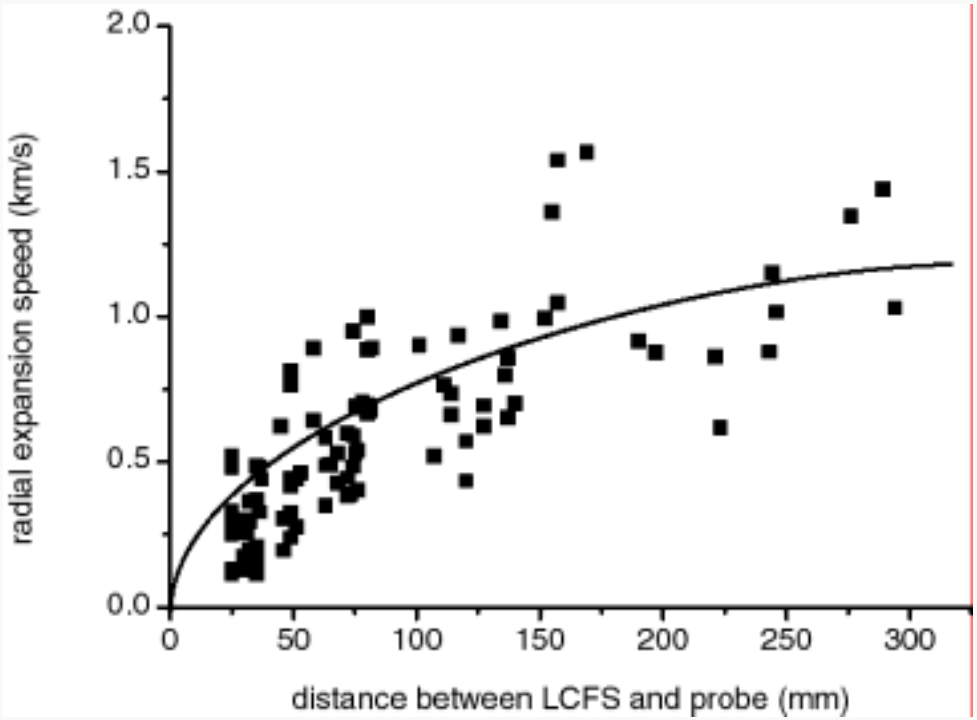
Strong efflux to LFS mid-plane probe



- j_{sat} at probe during ELM similar to peak strike-point values
- Magnitude uncorrelated to D_α intensity, sometimes not observed

Radial efflux up to 20~30cm from separatrix





- ELM ejection on mid-plane reciprocating probe j_{sat} up to 30cm
- Large j_{sat} out to ~10 cm, rapid rise time (< 50 μs)
- Radial expansion velocity: $\langle v_R \rangle \sim 1.0$ kms^{-1}
- 'turbulent' leading edge

Possible picture of the ELM structure

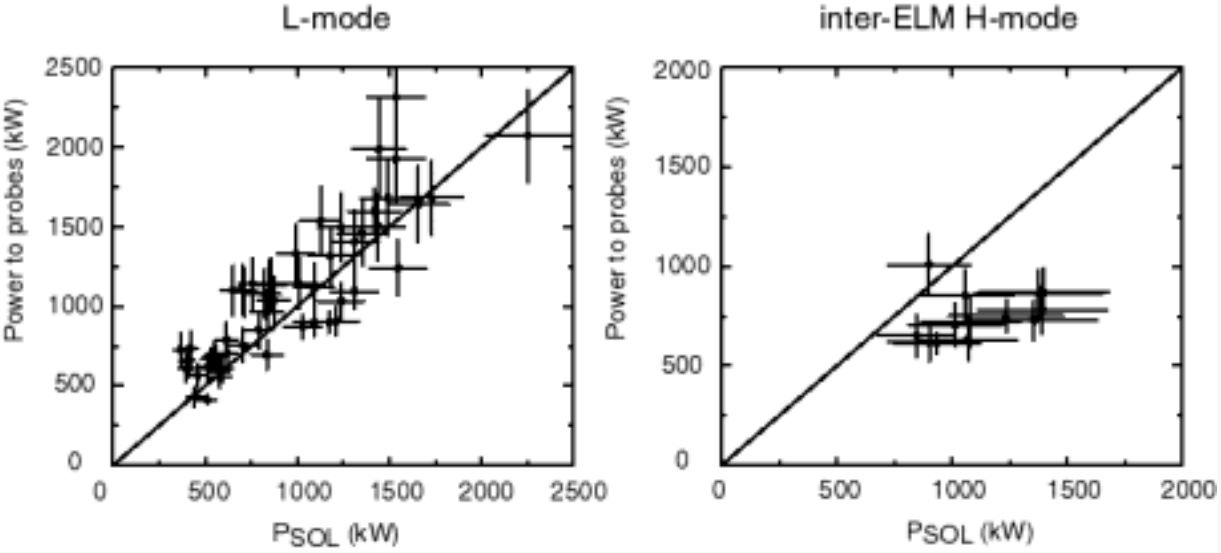
- Sum of data may be consistent with 'Cowley' ELM model
- ELM could be non-linear superposition of low and high n ballooning modes
- Forms narrow perturbation to flux surfaces at LFS
- Toroidally and poloidally localised, accelerating radially
- 'Compresses' SOL flux tubes increasing gradients and 'diffusive' losses

- Localisation could explain -
  - → lack of target broadening
  - → lack of target D_α correlation
- Ballooning nature could explain
  - → LFS bias

Power balance and accounting

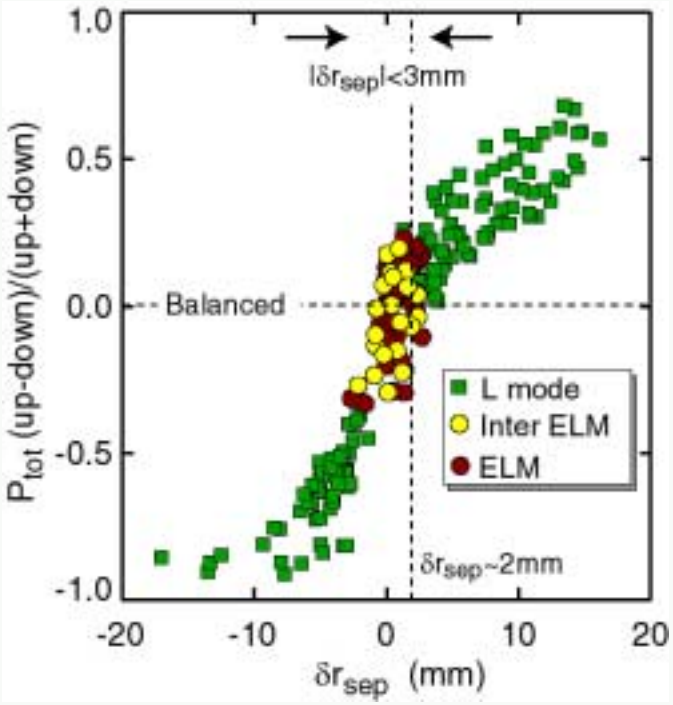
Good power accounting by probes

- ~100% of estimated P_{SOL} in L-mode
- ~70% of estimated P_{SOL} in inter-ELM H-mode
- ~50% of ΔW_{ELM}

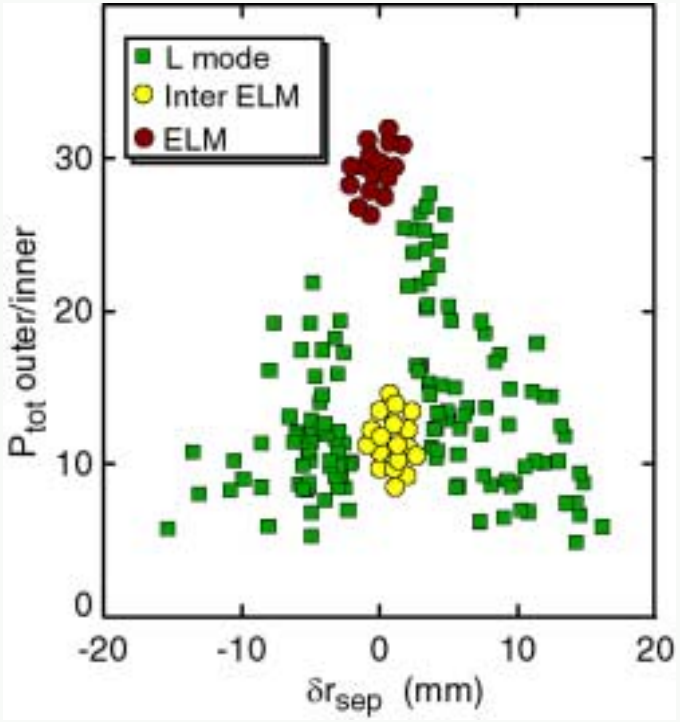


Differences in H-mode believed to arise from $T_i/T_e>1$

Power distribution favourable for ST

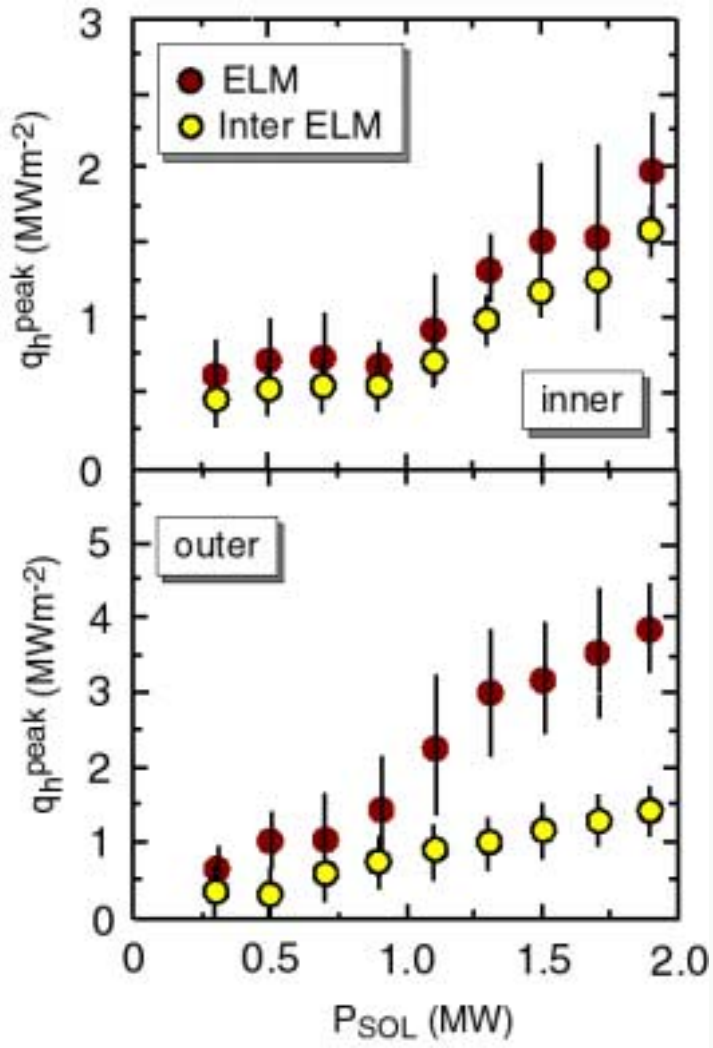


- **Up-down power distribution:**
  - ➔ **balanced for CDN with δr_{sep}~2 mm**
  - ➔ **asymmetric due to ion ∇B drift**



- **In-out power distribution:**
  - ➔ **strong function of δr_{sep} in L-mode**
  - ➔ **>90% outboard in CDN**
  - ➔ **different inter-ELM and during ELMs**

ELMs have little impact on HFS target q_h



- Modest level of q_h ($q_h < 4$ MWm^{-2})
- q_h rises by < 25% at inner target during ELMs
- q_h rises by factor ~3 at outer target during ELMs

Target power amelioration

Target detachment

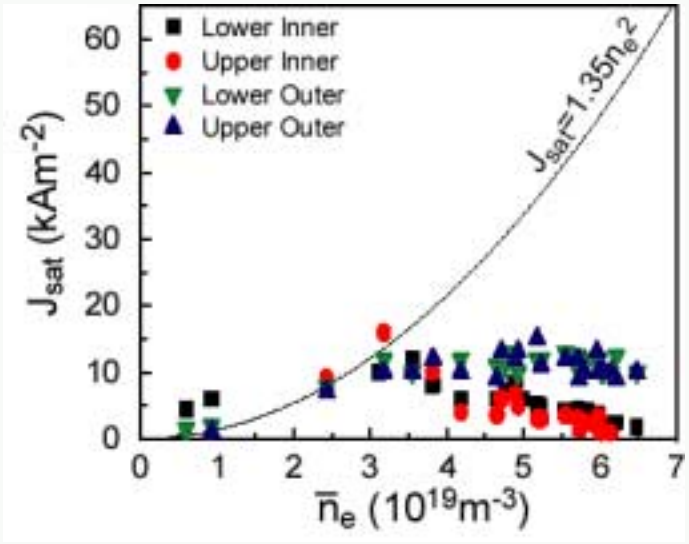
- **Detachment-like phenomena at high n_e (>3.5x10^{19} m^{-3})**

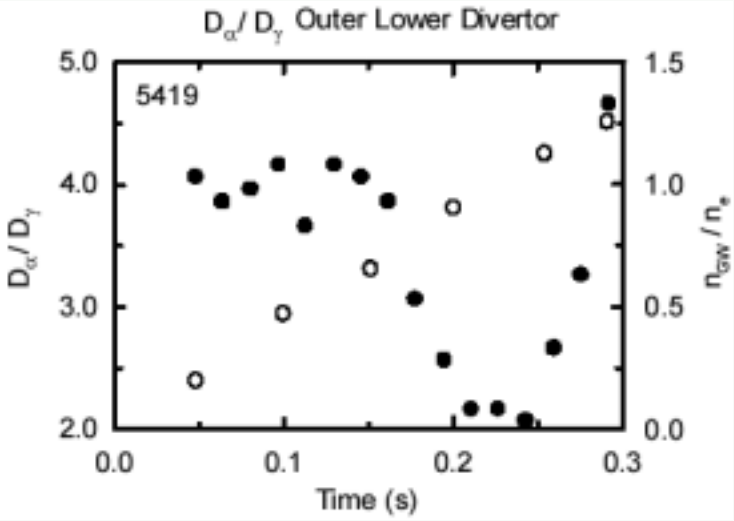
  → **target j_{sat} and q_h 'roll-over'**
  → **rise in target D_γ/D_α ratio**

but

  → **very low n_t ~ 3x10^{18} m^{-3}**
  → **λ_{ion} ~ 50 cm**

- **Possibly related to 'leading edges' on divertor components or large 'mirror force' in ST SOL**





SOL broadening by divertor biasing

Induce convective cells by divertor biasing:

- **Toroidally asymmetric biasing**

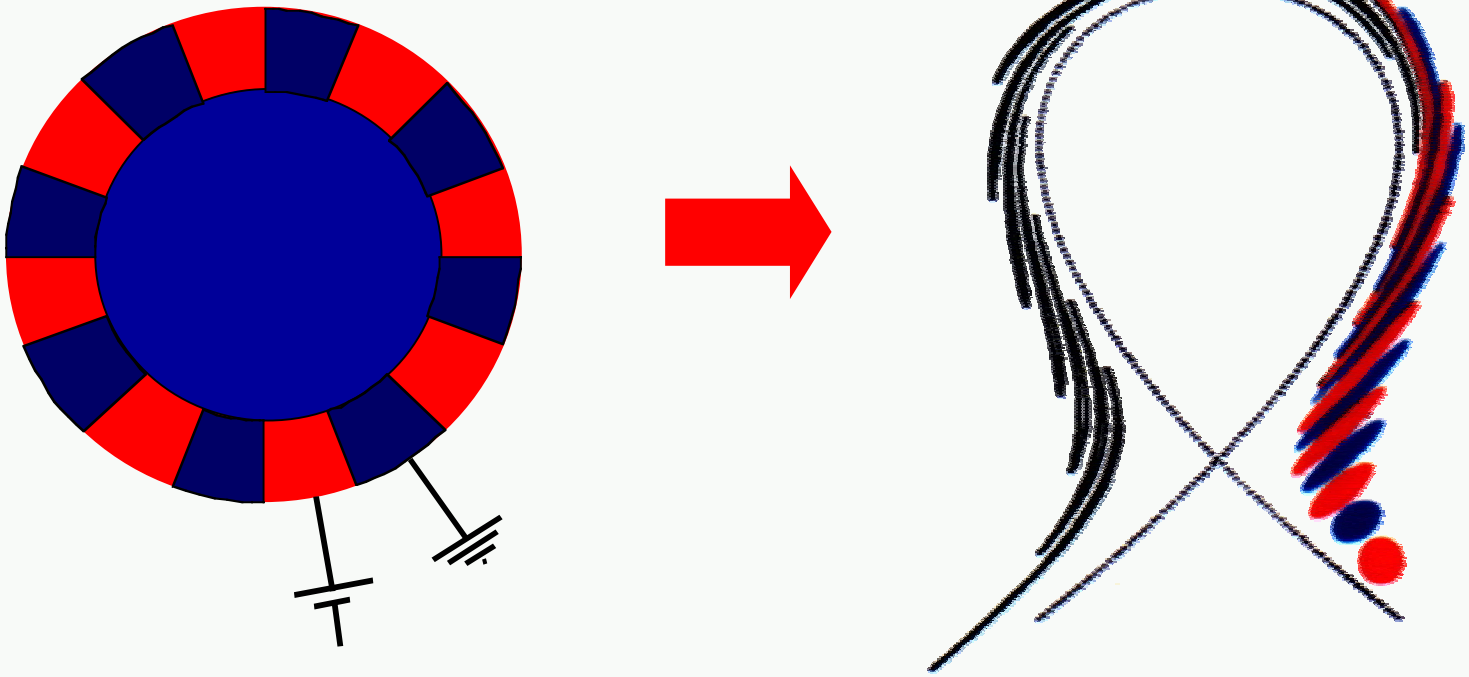
➔ Potential variations in SOL

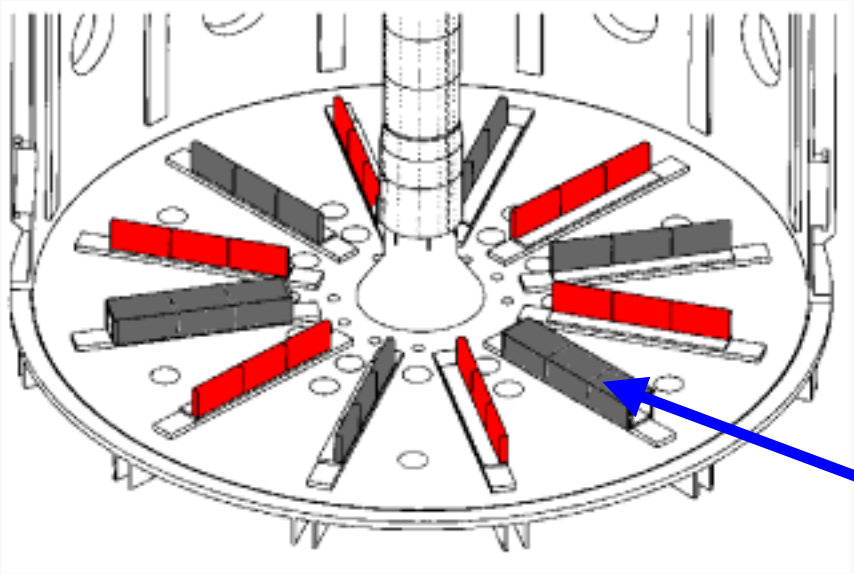
➔ ExB driven convective cells

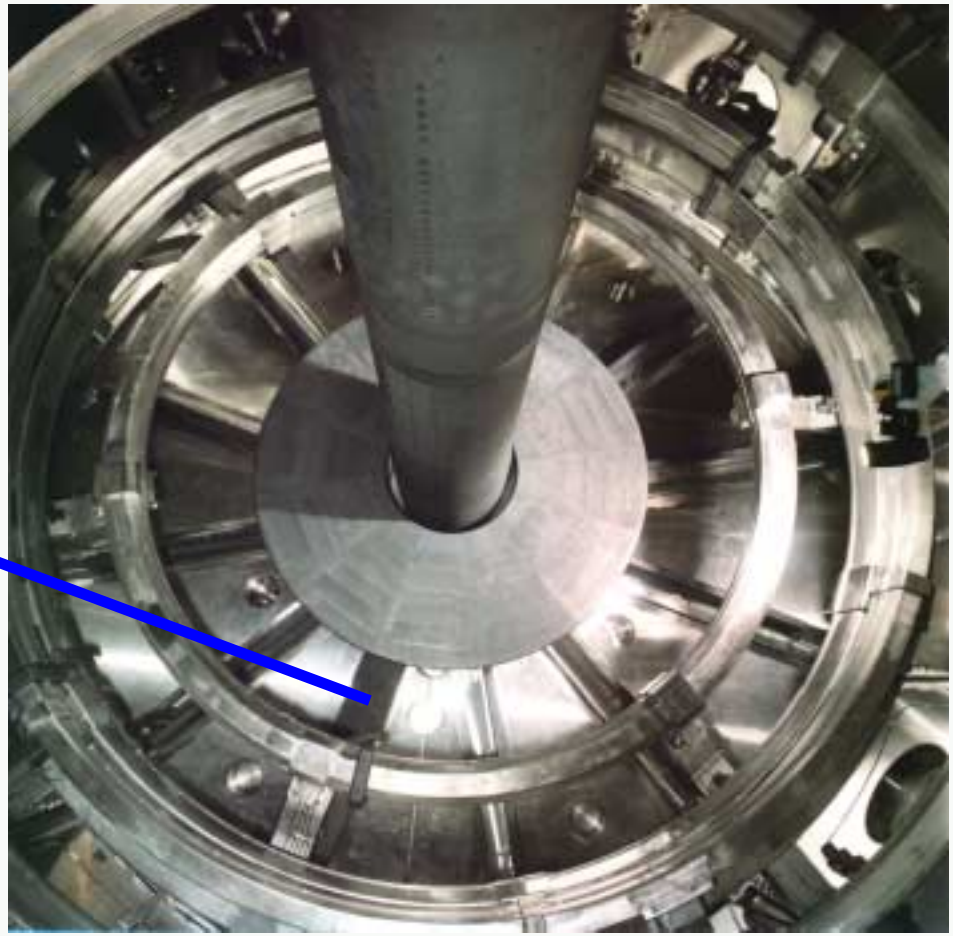
➔ SOL broadening

➔ **Reduction of power density**

Areas of different potential generate convection cells driven by the ExB drift.

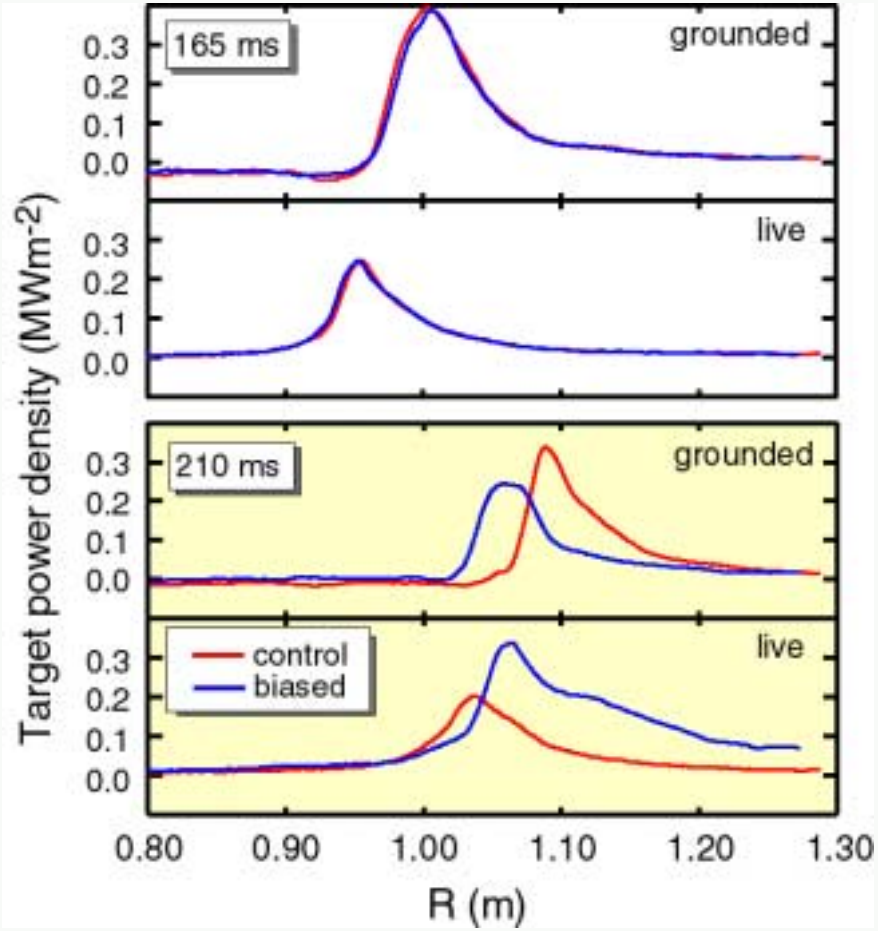






Schematic of lower outer divertor region showing location of biased divertor ribs (red)

Locally Broadened SOL width



- Effect only at lower, outer SP
- Unbiased rib:
  - → λ_q slightly broadened
  - → P_{peak} reduced by 30%
- Biased rib:
  - → λ_q factor 3 broadened
  - → P_{peak} rises
- Rise in P_{peak} to biased rib result of large P_{bias}/P_{Ω}~0.3

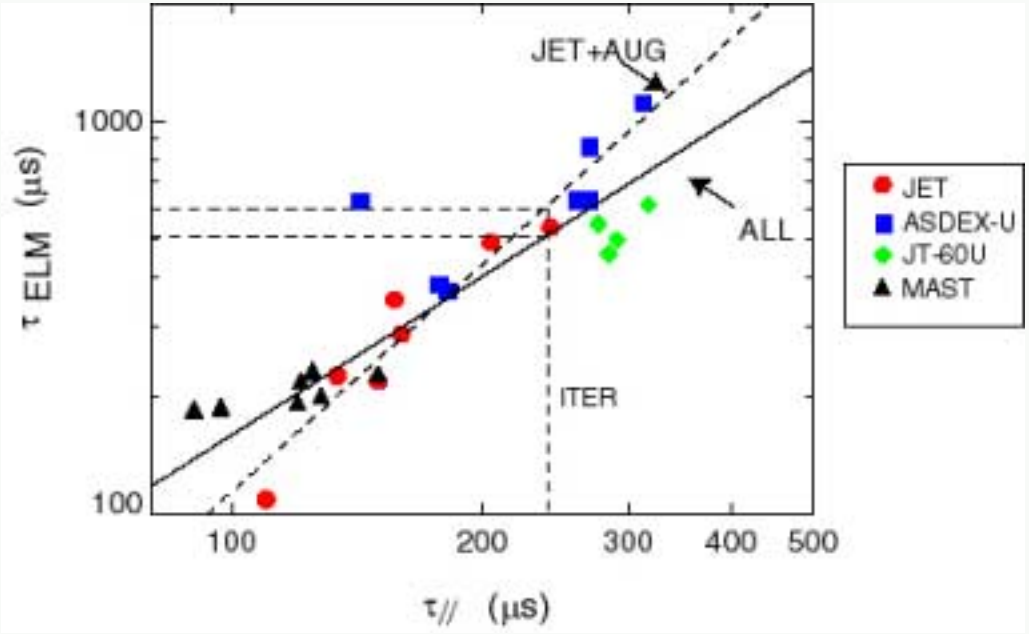
Conclusions

Boundary plasma research in MAST: contributing and understanding of the ST physics as well as in conventional tokamaks and ITER preparations

- ➔ **SOL width scalings: several dependencies on plasma parameters**
- ➔ **Importance of mirror force term in ST: $|\nabla_{//}B/B|$**
- ➔ **Far ranging radial efflux during ELMs: additional first wall erosion if exhibited in ITER**
- ➔ **ELM losses nearly 100% to LFS: in-out ratios in SND devices probably dominted by // transport in SOL**
- ➔ **ELM losses may be consistent with 'Cowley' model : non-linear superposition of ballooning modes**
- ➔ **Target power loading mitigated by divertor detachment and toroidally asymmetric divertor biasing**

τ_{ELM} versus $\tau_{//}$

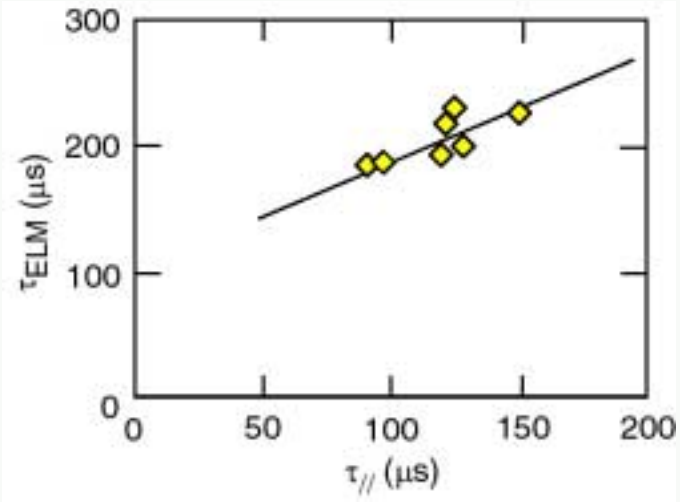
- **MAST data broadly in line with conventional devices**



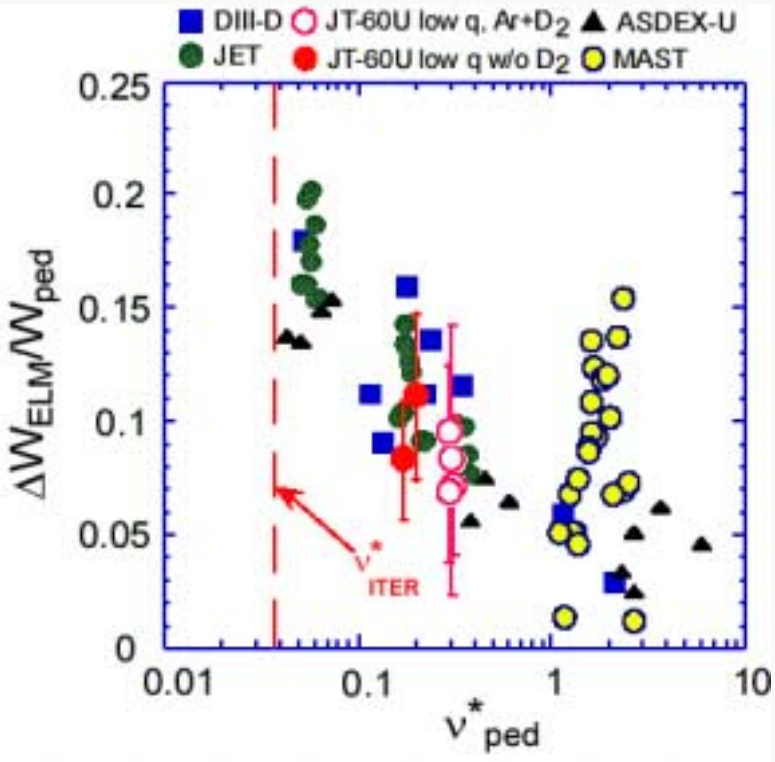
$\tau_{ELM} \propto \tau_{//}^{2}$ JET+AUG

$\propto \tau_{//}^{1.3}$ All

- **MAST only data shows weaker trend and more reasonable τ_{ELM} offset at $\tau_{//}$=0 (ELM MHD time)**



Losses don't support ν^*_{ped} scaling



Loarte, 9th EFPW, 2002
- MAST data added

- Pedestal collisionality always high:
  $\langle \nu^*_{ped} \rangle \sim 2.1 \pm 1.3$
  even for P_{NBI} up to 2.5MW (steep edge density gradient)
- TS profiles before and after ELM show $\langle T \rangle \Delta n >> \langle n \rangle \Delta T \Rightarrow$ convective losses
- Modest $\frac{\Delta W_{ELM}}{W} < 4\%$ and $\frac{\Delta W_{ELM} f_{ELM}}{P_{heat}} < 5\%$
- ELM energy losses show no correlation to ν^*_{ped} - result of convective-only losses?