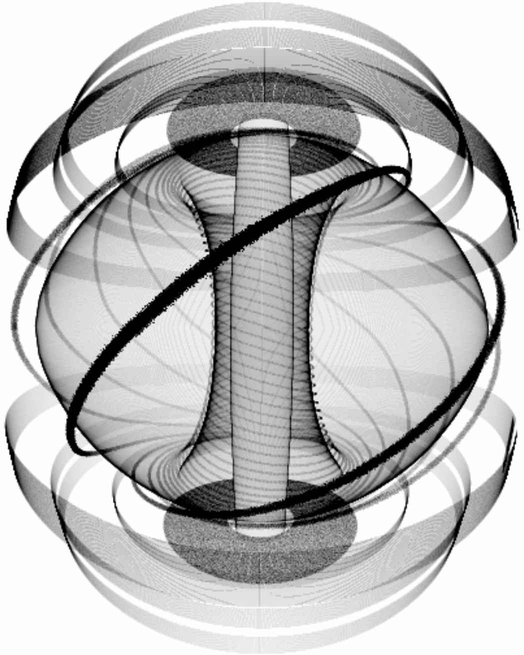

Overview of results from MAST

Presented by:
Glenn Counsell, for the MAST team

This work was jointly funded by the UK Engineering & Physical Sciences Research Council and Euratom

Focus on 4 areas

- The L-H transition and H-mode Pedestal
- Confinement and Transport
- Transients - ELMs and Disruptions
- Start-up without a central solenoid

- The L-H transition and H-mode Pedestal
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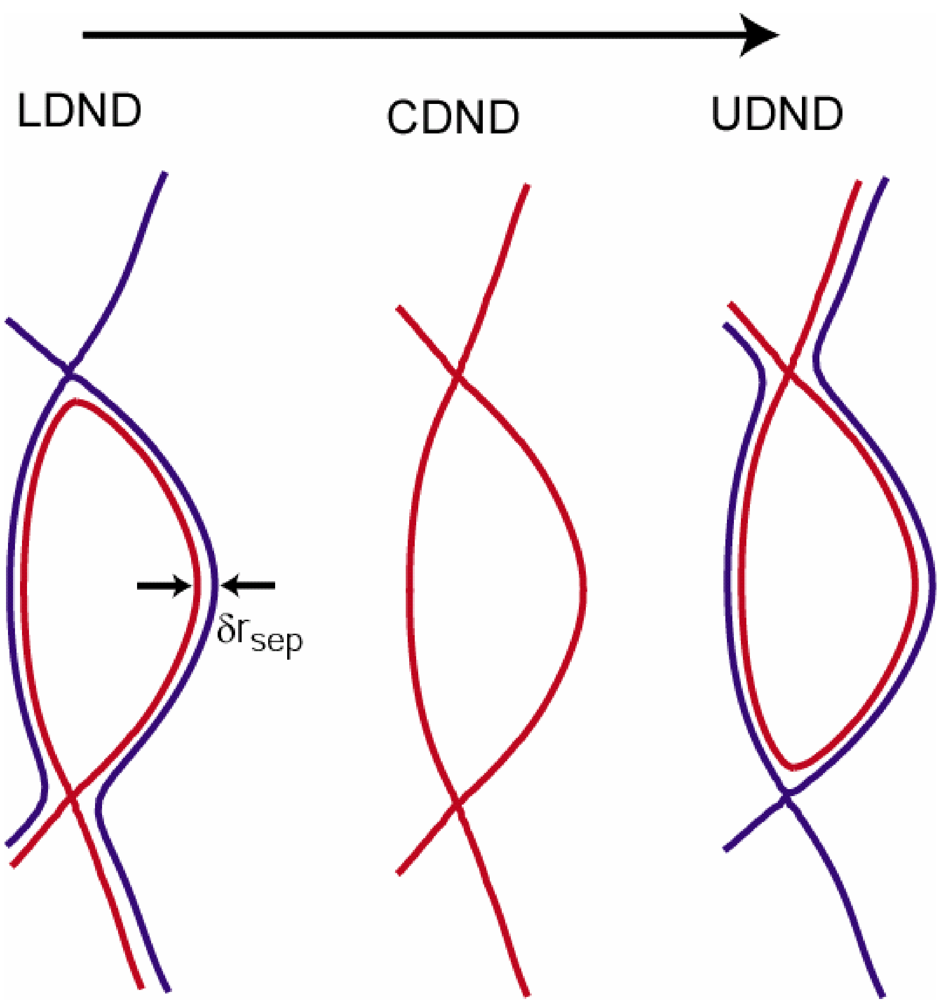
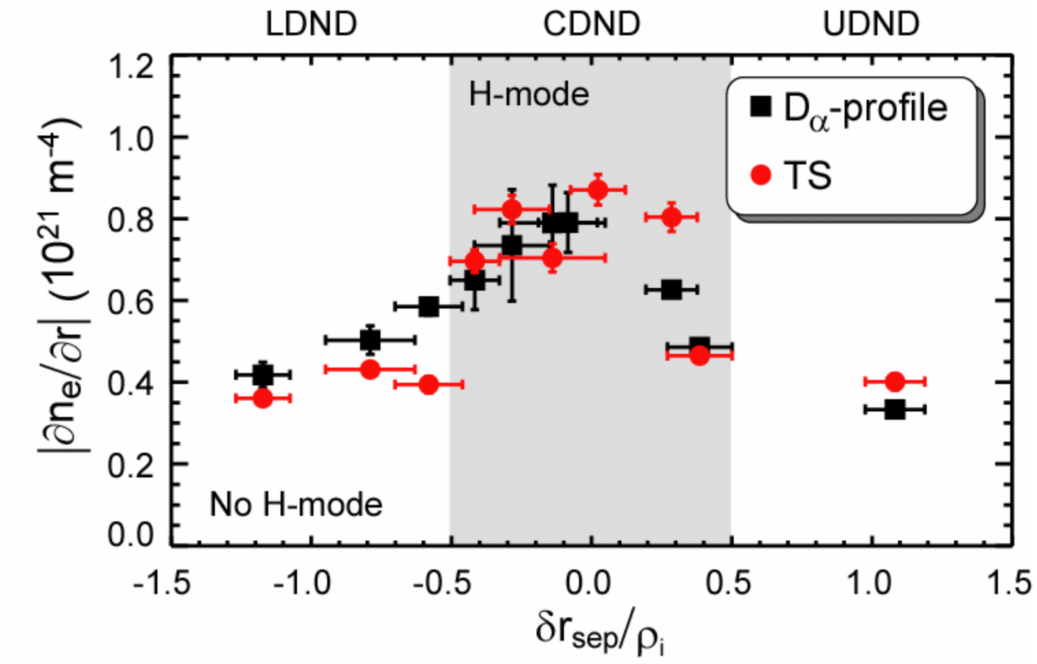
δr_{sep} plays a key role in MAST



MAST has fully symmetric upper and lower divertors and can operate from LSN to USN

CDND lowers $P_{L\text{-}H}$



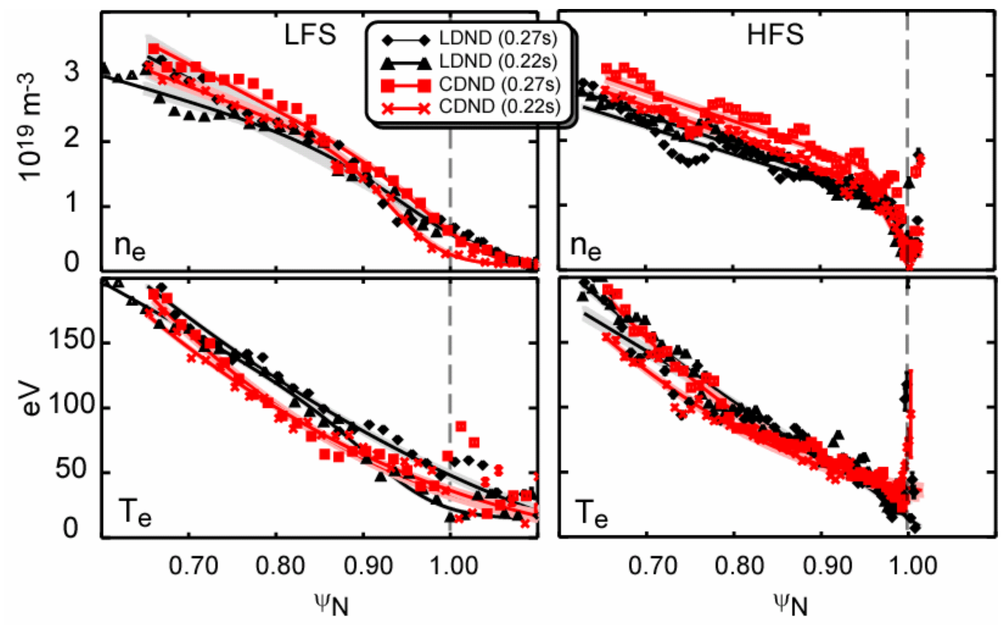
MAST has fully symmetric upper and lower divertors and can operate from LSN to USN

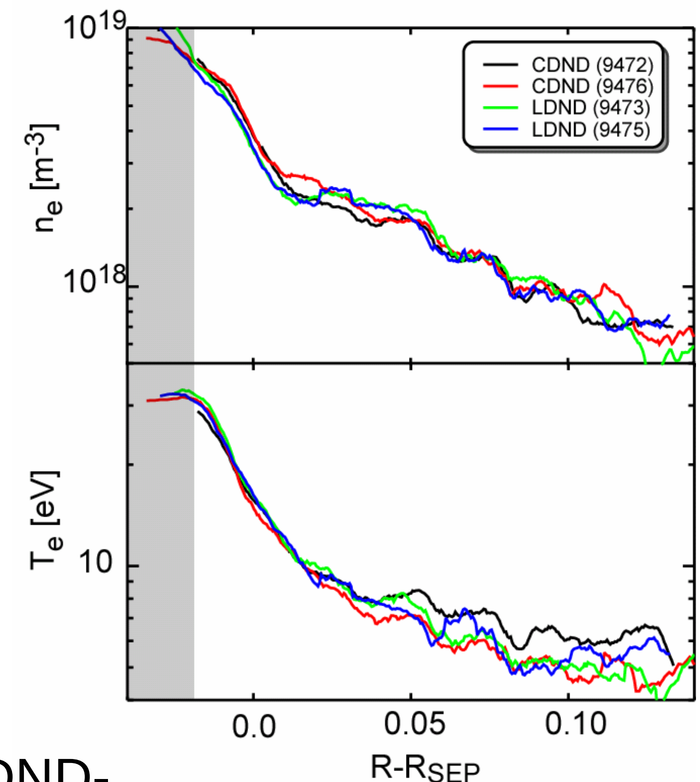
Previously reported that H-mode difficult to obtain on MAST away from Connected DND

New studies now show that **$P_{L\text{-}H}$ decreases by factor 2 in CDND** compared to similar shaped Lower SND plasmas

Same trend observed in MAST-**ASDEX upgrade** similarity experiments. **Factor 1.25 reduction in $P_{L\text{-}H}$**

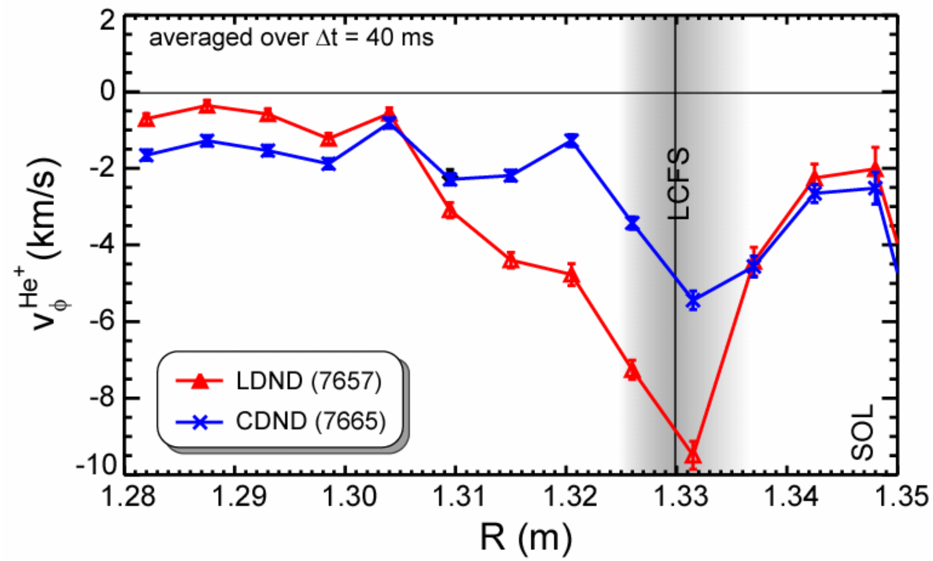
No significant changes to edge profiles

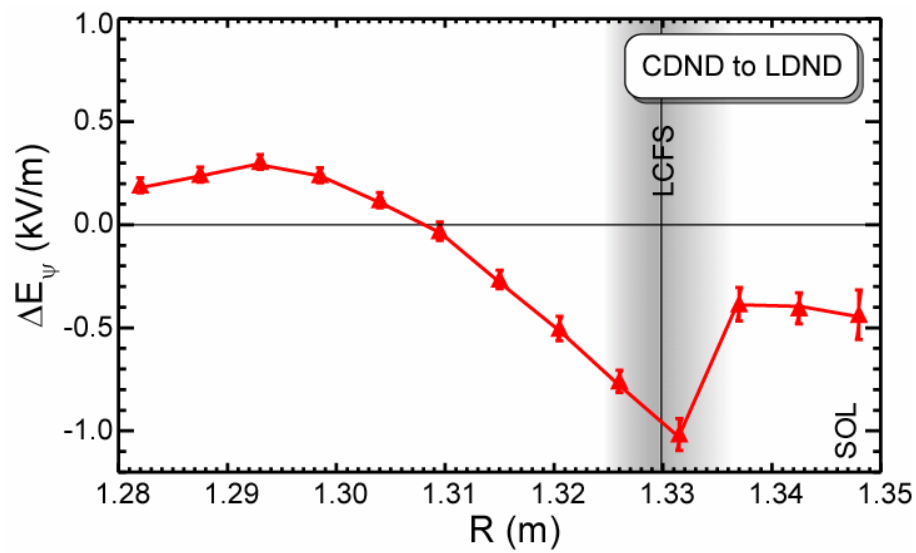




In L-mode (close to $P_{L\text{-}H}$) change from LSND-LDND-CDND **not evident in edge T_e, n_e, V_f and M_ϕ profiles**

Only V_ϕ and E_r influenced by CDND





In L-mode (close to $P_{L\text{-}H}$) change from LSND-LDND-CDND **not evident in edge T_e, n_e, V_f and M_ϕ profiles**

Only clearly observed on impurity rotation and thus radial electric field

Magnitude of change at LFS separatrix similar to that observed in ASDEX Upgrade similarity experiments

L-H transition models tested

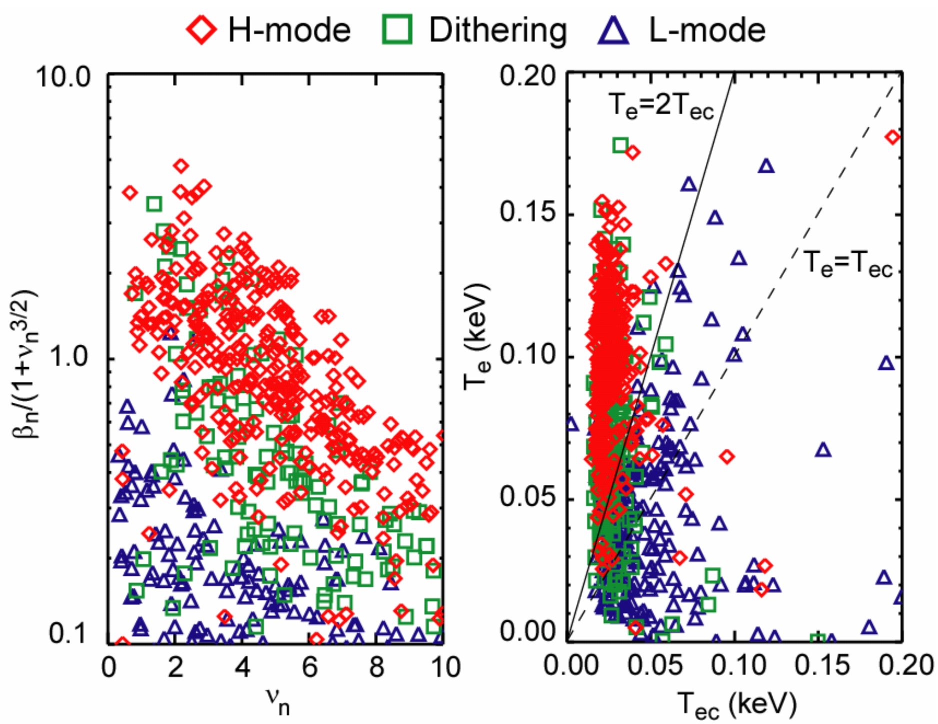
Common theories for L-H transition investigated

Two theories successful in separating L and H-mode data:

Best separation achieved by $\beta_n/(1+\nu_n^{3/2})$ at ψ_{95}, which characterises **suppression of long λ drift wave turbulence** - but not quantitative.

Best quantitative separation achieved by critical T_e at ψ_{98} from **finite β drift wave turbulence suppression** by self generated zonal flows

Neither theory accounts explicitly for impact of CDND



W. Kerner *et al*.   P. Gudzar *et al*.

See H. Meyer EX/P3-8

- The L-H transition and H-mode Pedestal
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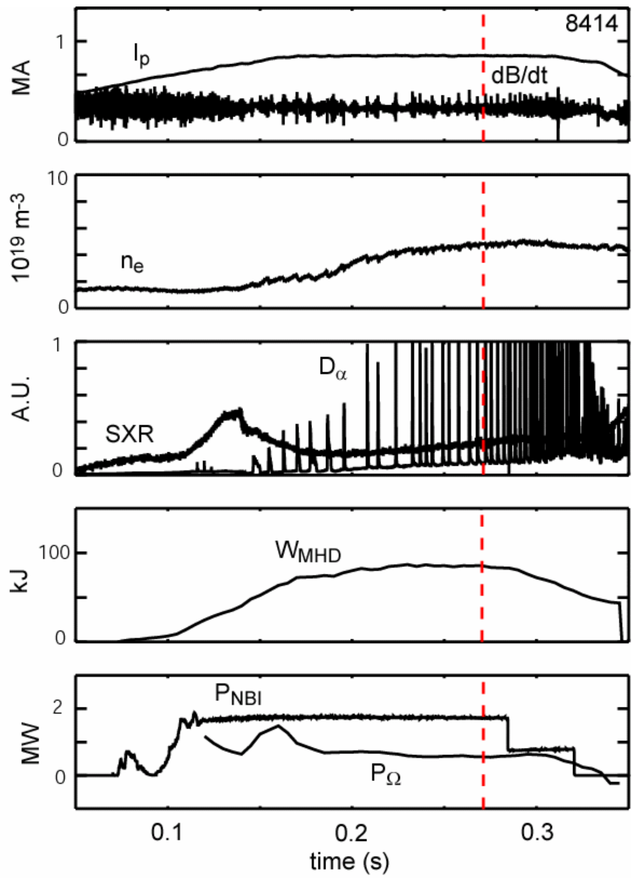
Confinement data at high β and ε

Many new MAST points meeting stringent International Database criteria added to database



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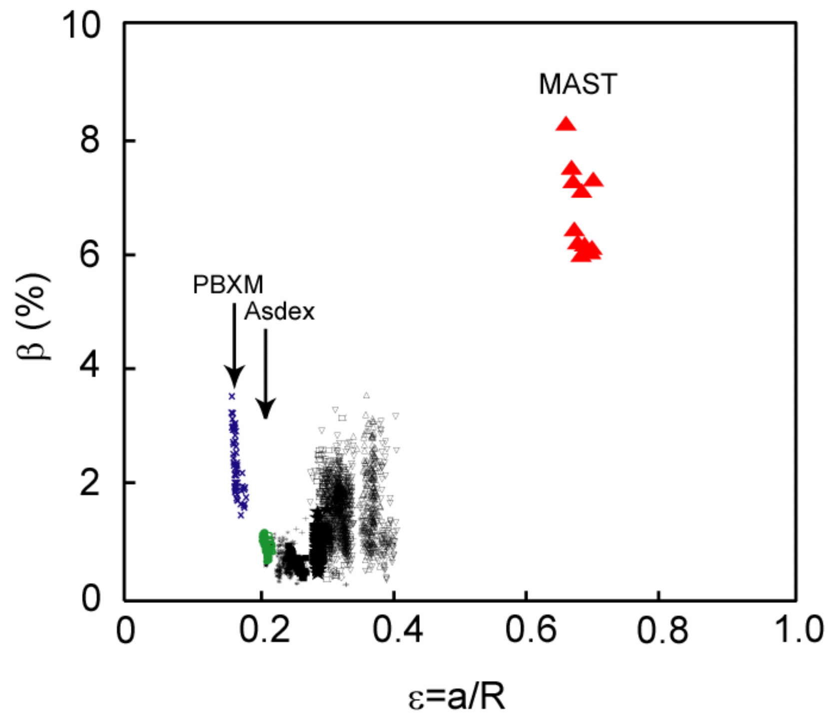
Confinement data at high β and ε

Many new MAST points meeting stringent International Database criteria added to database

MAST data expand the range of **inverse aspect ratio** ($\varepsilon = a/R$) **by a factor 2.2** and in **toroidal β by a factor 2.5**

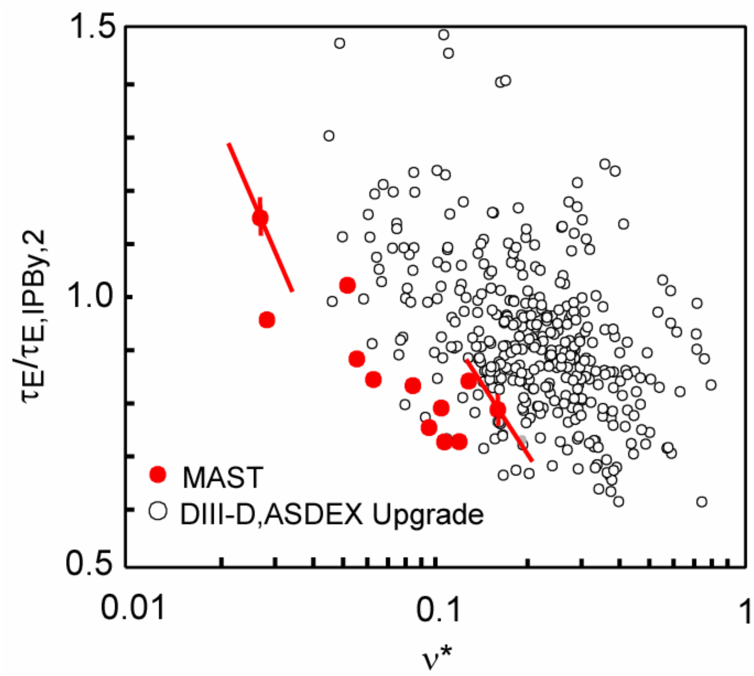
Improve confidence by allowing replacement of data from devices non-conventional cross-sections

Largely support existing IPB(y,2) scaling but slightly strengthen ε dependance



ν* is a key parameter for ST scalings

MAST data alone support **favourable ν* dependence** in dimensionless parameter scaling



See M. Valovic EX/P6-30

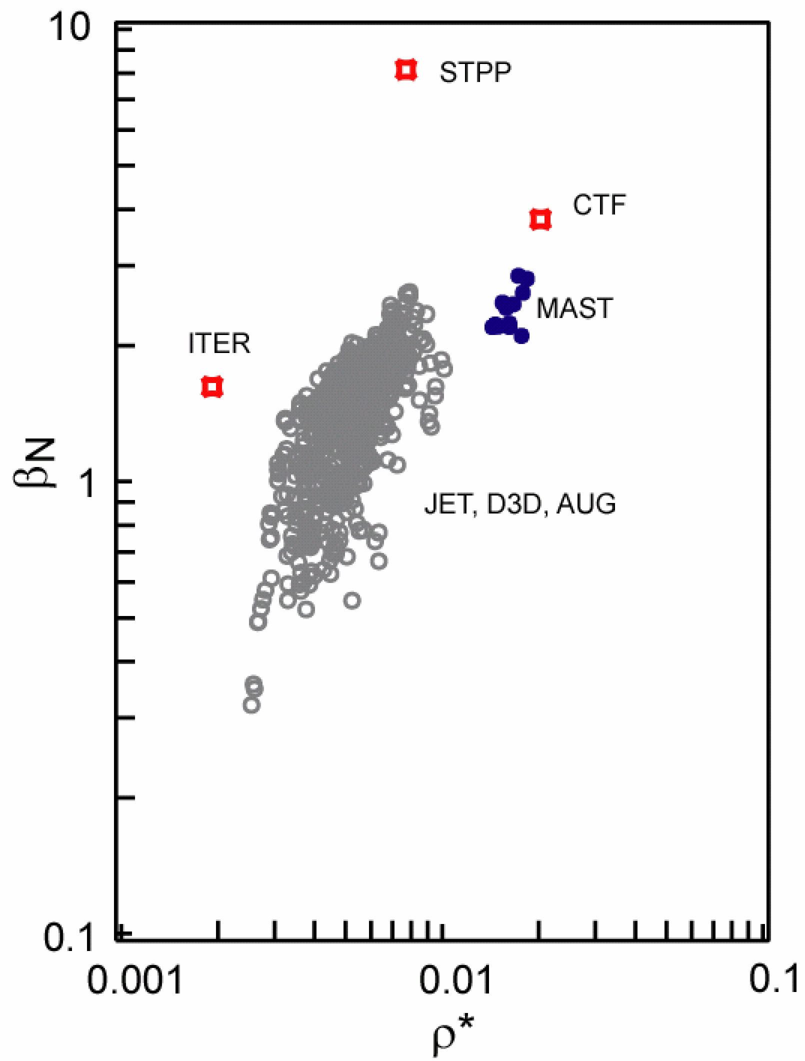
$\nu*$ is a key parameter for ST scalings

MAST data alone support **favourable ν* dependence** in dimensionless parameter scaling

Since **β_N and ρ* in MAST close to possible 'next-generation' ST** - understanding ν* dependence especially important $\nu^{*,MAST}/\nu^{*,CTF}$~90

Link between dependencies of β and ε provided by MAST data may be useful

$\Rightarrow$ ε should be included in recently identified interaction between β and ν^* exponents in dimensionless scaling)



See M. Valovic EX/P6-30, H.R. Wilson FT/3-1Ra

- The L-H transition and H-mode Pedestal
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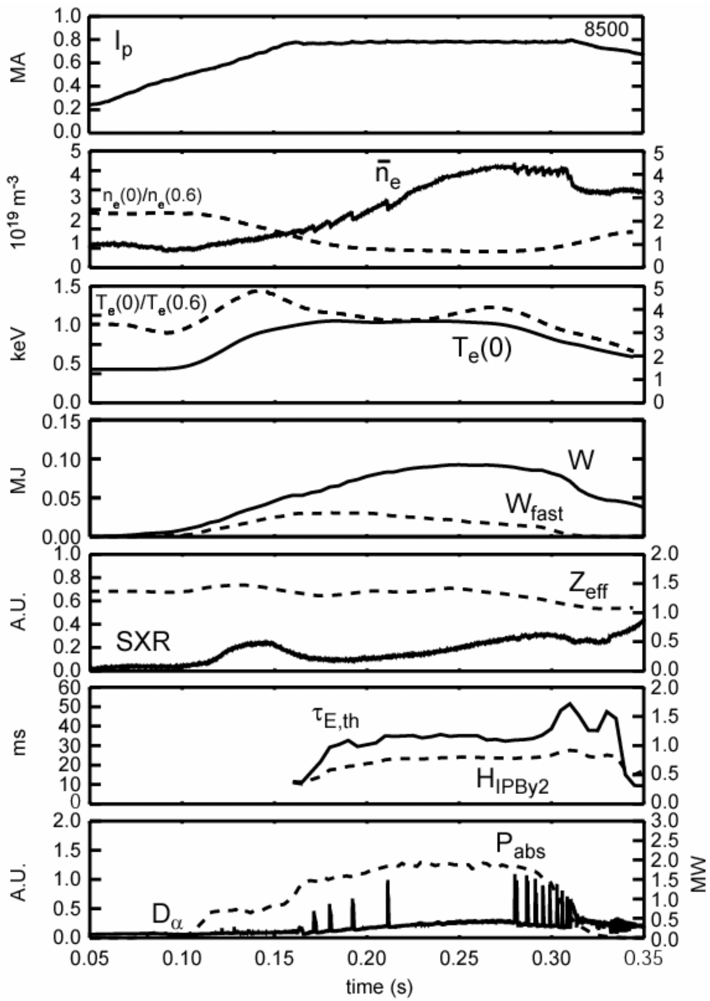
TRANSP analysis now regularly conducted

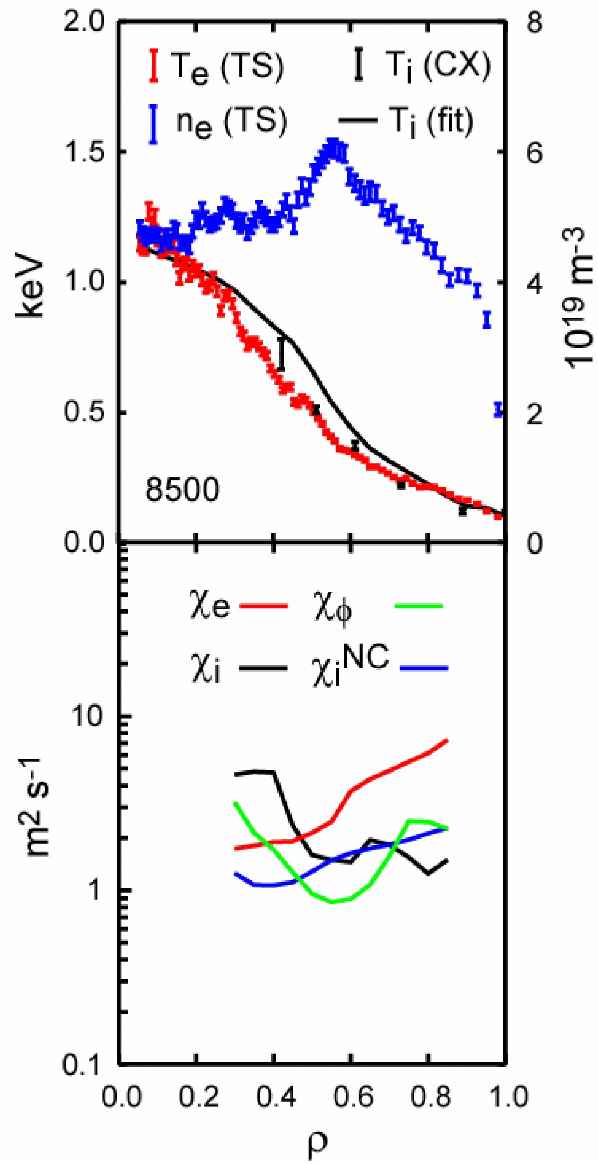
TRANSP analysis now regularly conducted for MAST discharges

Pre-processor ensures highest quality and greatest range diagnostic data used in analysis

Results validated and cross-checked against LOCUST full-orbit code



TRANSP analysis of ELMy H-mode



Results most accurate in region $0.3 < \rho < 0.8$ (avoiding low gradient regions and larger diagnostic errors)

For $\rho > 0.4$ the ion diffusivity, χ_i **is found roughly equal to χ_i^{NC}**, *cf* factor 4 larger in similar L-mode

Linear microstability calcs. using GS2 suggest ITGs unstable on all surfaces:

Mixing length estimates $\Rightarrow$ **χ^i_{ITG}~3-5 m^2s^{-1}, close to TRANSP value**

v_ϕ can dominate flow shear ω_{se} $\Rightarrow$ possible ITG drive stabilisation and expect ITBs!

χ^e_{ETG}~0.1 m^2s^{-1}, far below TRANSP value
$\Rightarrow$ need for non-linear calcs.

See A.R. Field EX/P2-11

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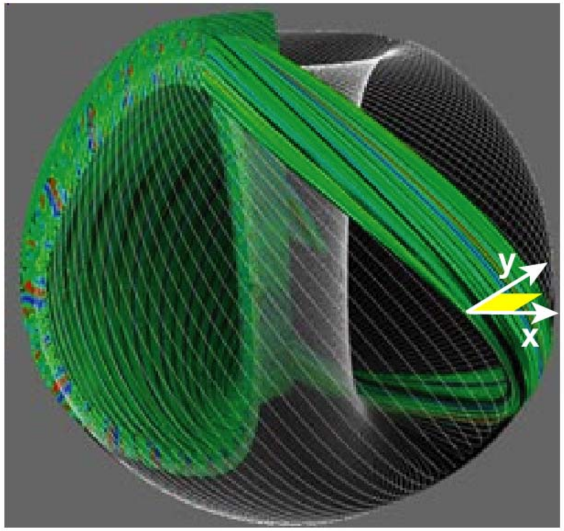
Non-linear GS2 analysis for e^- transport



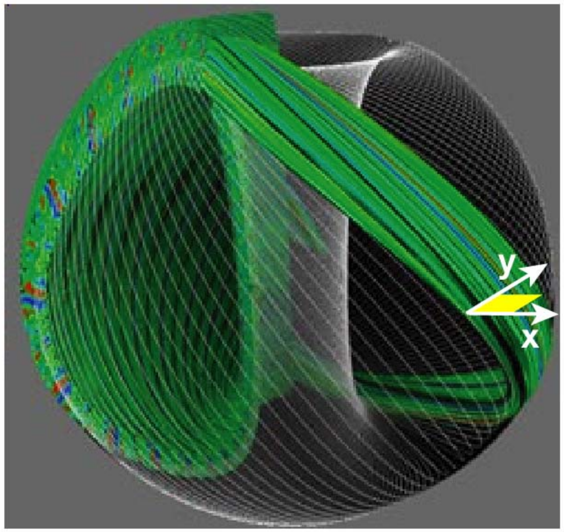
Nonlinear collisionless ETG calculations in flux-tube geometry, assuming adiabatic ions, at Ψ_n=0.4 surface in MAST

- base case flux-tube dimensions:

$\Delta x=690\rho_e=8.7$cm, $\Delta y=628\rho_e = 7.9$cm,

$0.01< k_y\rho_e<0.31$

Radial electrostatic streamers predicted



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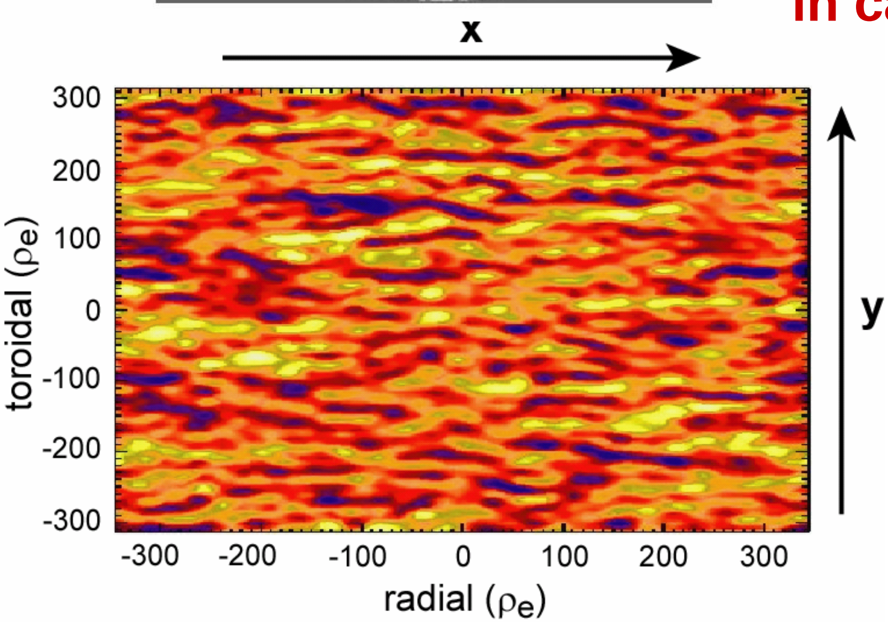
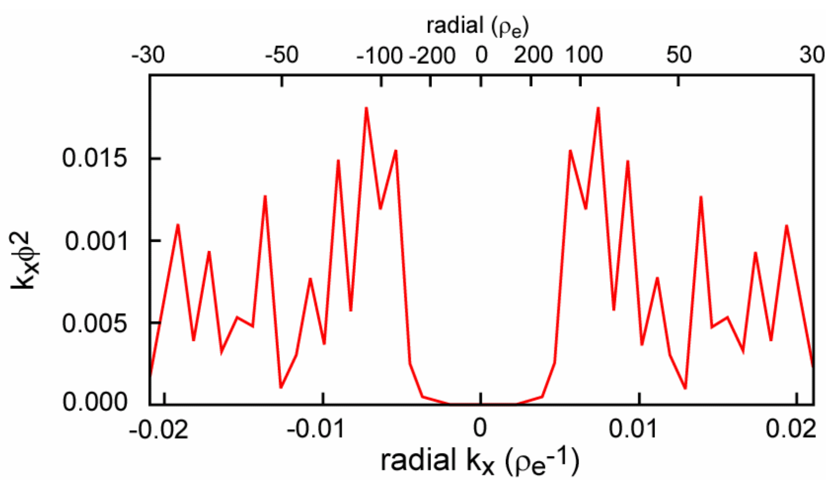
Radial electrostatic streamers observed in calculations up ~100ρ_e wide (~1cm)





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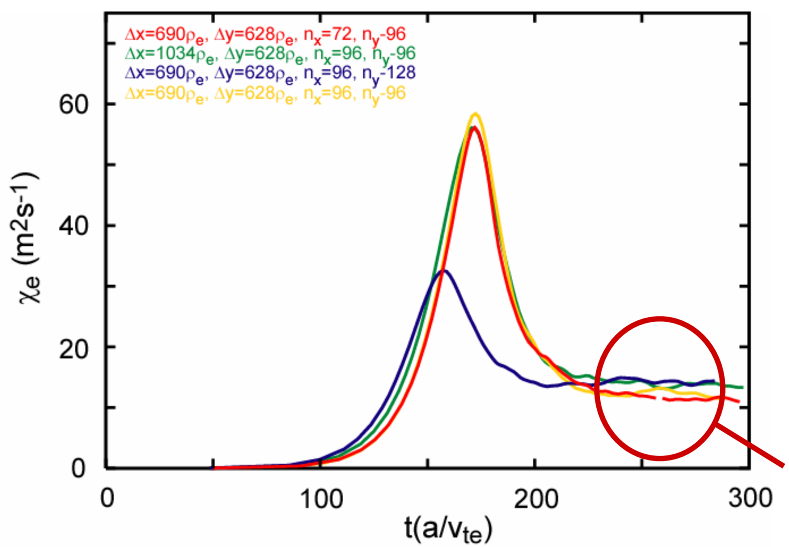
Converged solution consistent with χ_e



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Radial electrostatic streamers observed in calculations up ~100ρ_e wide (~1cm)

Nonlinear simulation **converges well for range of flux tube dimensions and wavenumbers**

Indicates **χ_e ~ 10 m²/s** (*cf* Gyro-Bohm estimate of χ_e = 0.6 m²/s) - **within a factor 2 of TRANSP value**

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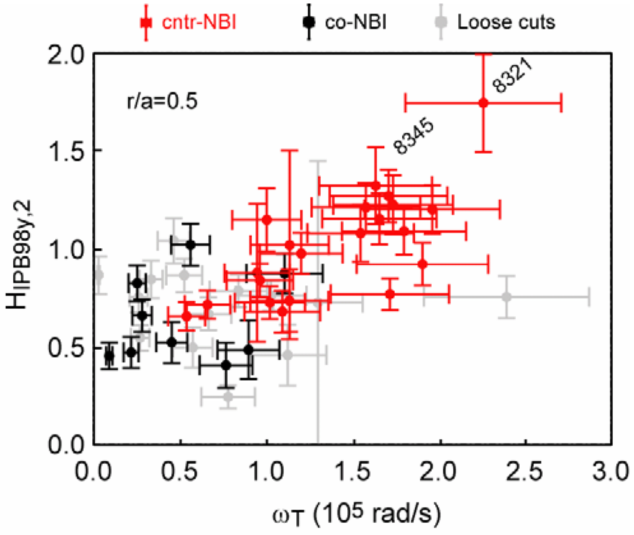
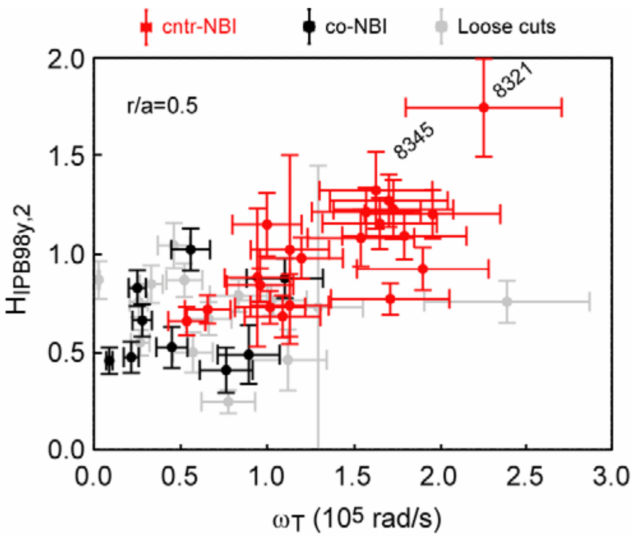
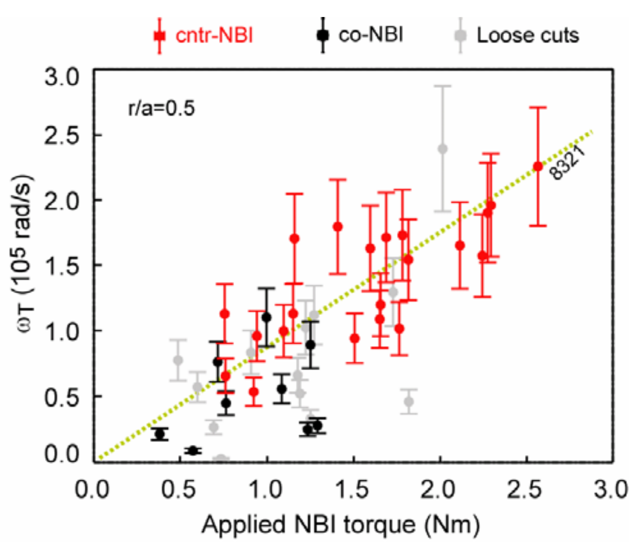
Highest confinement at largest v_ϕ



Normalised confinement across range of L-mode, H-mode and ITB discharges **increases with v_ϕ**

v_ϕ driven by NBI torque





Normalised confinement across range of L-mode, H-mode and ITB discharges **increases with v_ϕ**

v_ϕ driven by torque from the neutral beam. Highest torque in counter-NBI discharges due to asymmetric (co-counter) fast ion losses

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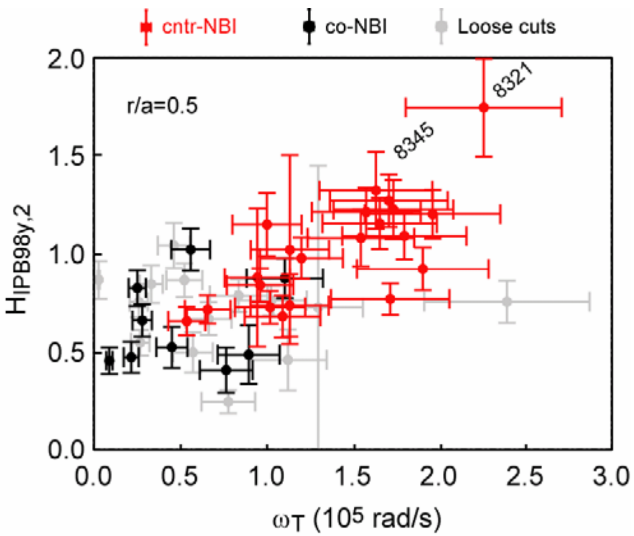
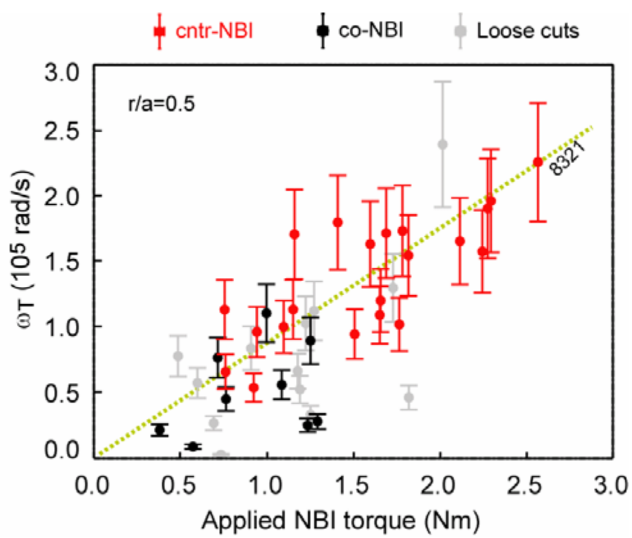
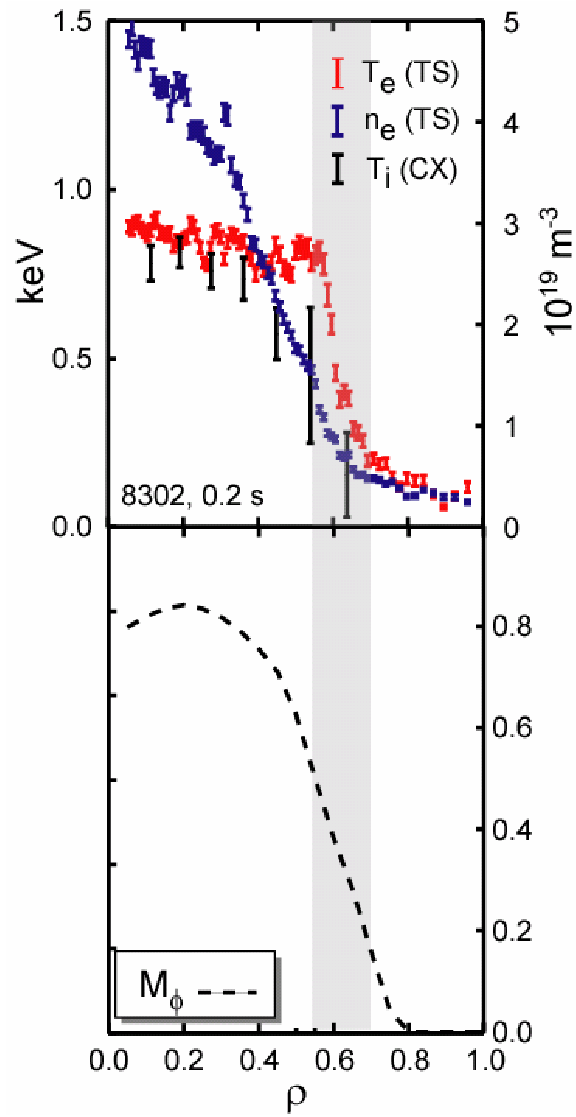
Highest confinement at largest v_ϕ







Highest confinement discharges are **ITB formed with counter-NBI**

M_ϕ approaches 1 in core

Very steep electron temperature gradient at ρ~0.6

Very peaked density profile

See R. Akers EX/4-4

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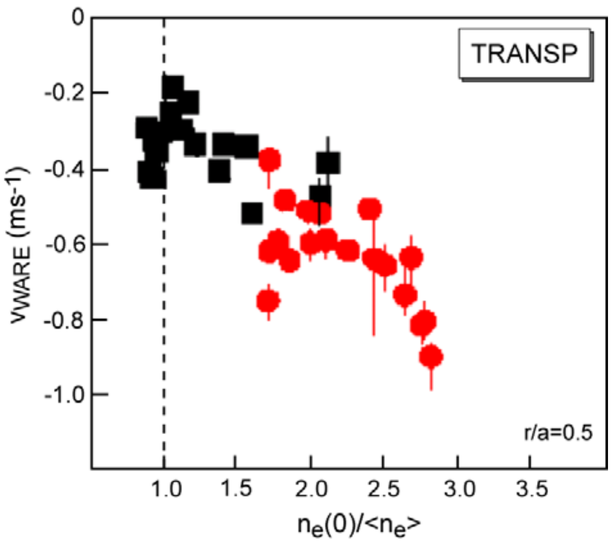
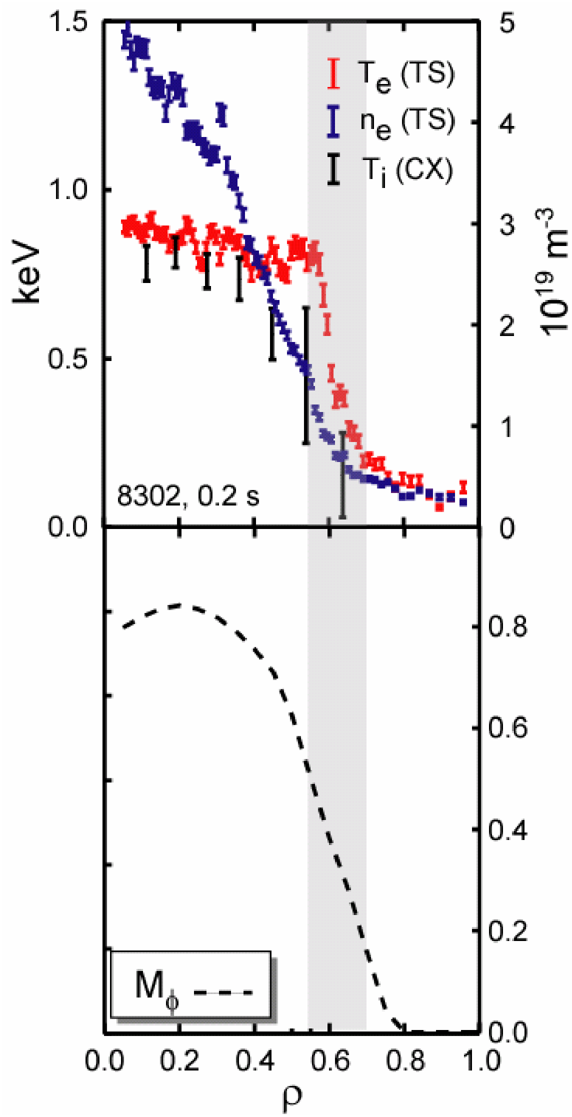
Density peaking dominated by Ware pinch





Highest confinement discharges are **ITB formed with counter-NBI**

M_ϕ approaches 1 in core

Very steep electron temperature gradient at ρ~0.6

Very peaked density profile

Dominated by Ware pinch, supplemented by neutral beam current drive term

See R. Akers EX/4-4

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Flow shear exceeds ITG growth rate

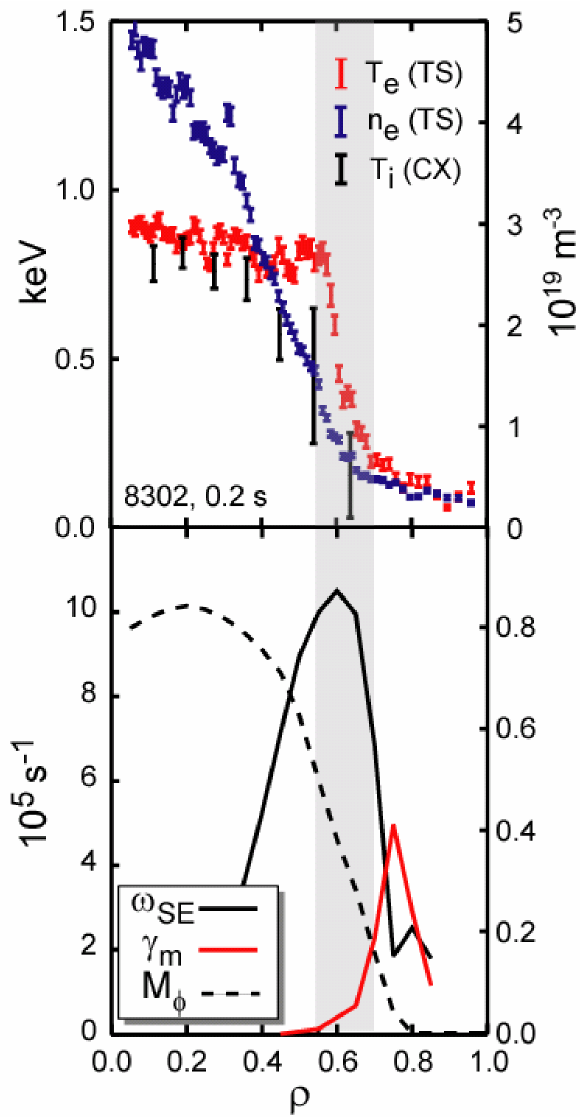
TRANSP estimate of **ω_{se} dominates ITG growth rate** γ_m

γ_m derived from a simple model, validated against GS2

ω_{se} comparable with estimates of the *ETG* growth rate from GS2 $\Rightarrow$ **ETG drive stabilisation may be a possibility**

2 surprises:

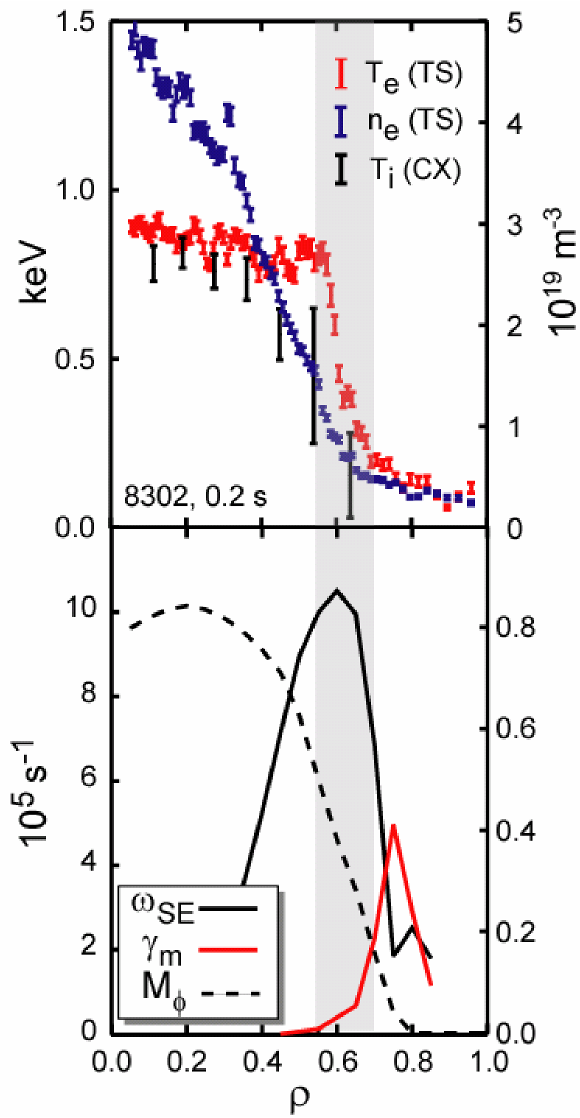
- flat T_e profile inside ITB
- no clearly diagnosed T_i barrier

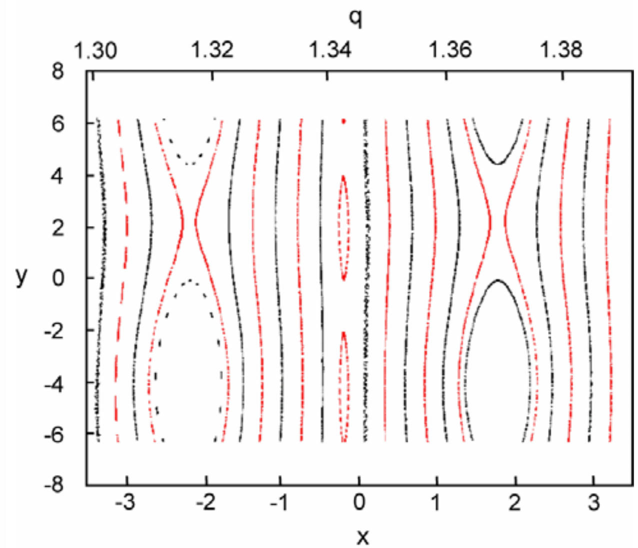


Tearing parity modes unstable in core

Flat T_e profile inside ITB may be explained by micro-tearing modes

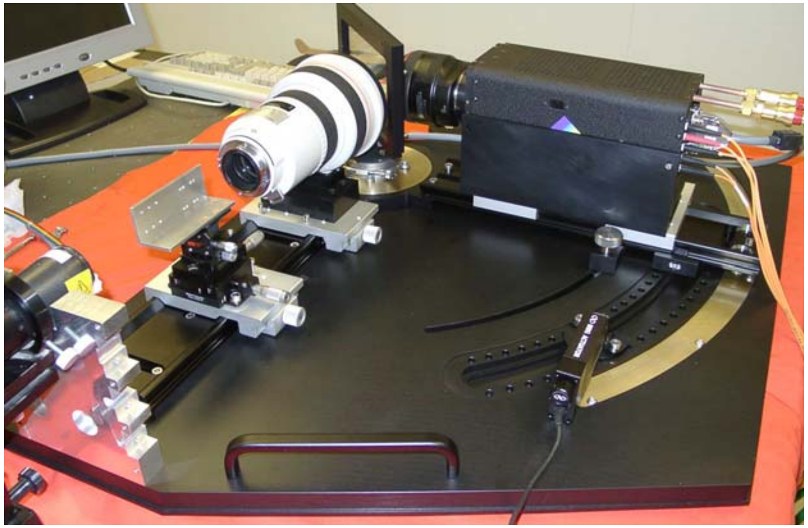
Tearing parity modes demonstrated unstable on ψ_N~0.4 in GS2 runs with EM effects turned on

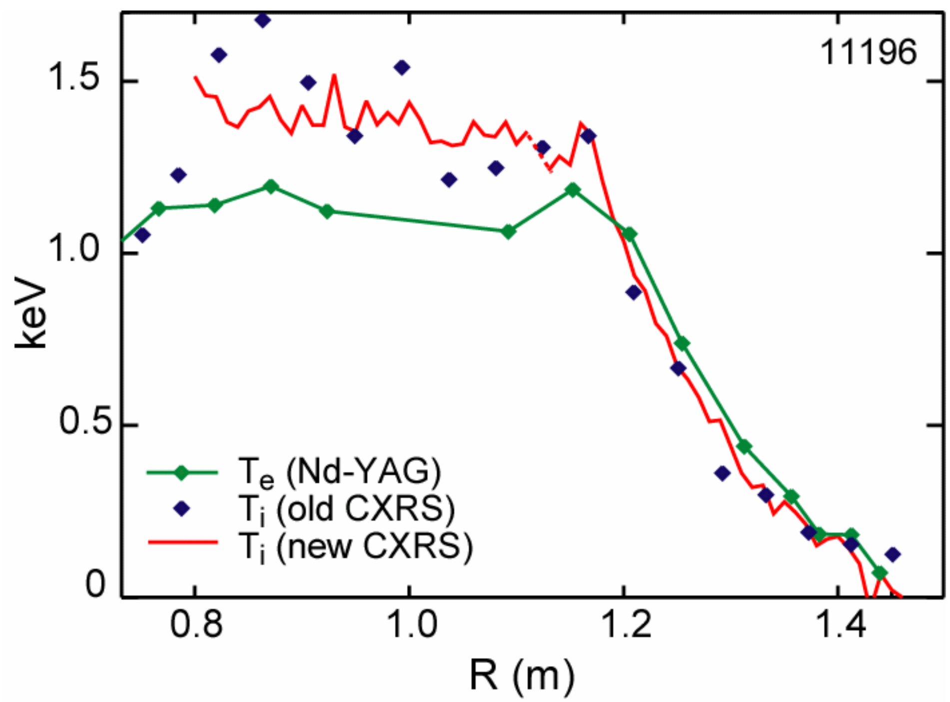




Small islands on high order rational surfaces 25/19, 26/19 and secondary islands between them

Enhanced T_i spatial resolution required





Upgraded CXRS facilitated by adaptable low A configuration

$\Rightarrow$ 200+ chord spectrometer

spatial resolution ~ ρ_i

poloidal and toroidal chords

separate views of two NBI beams

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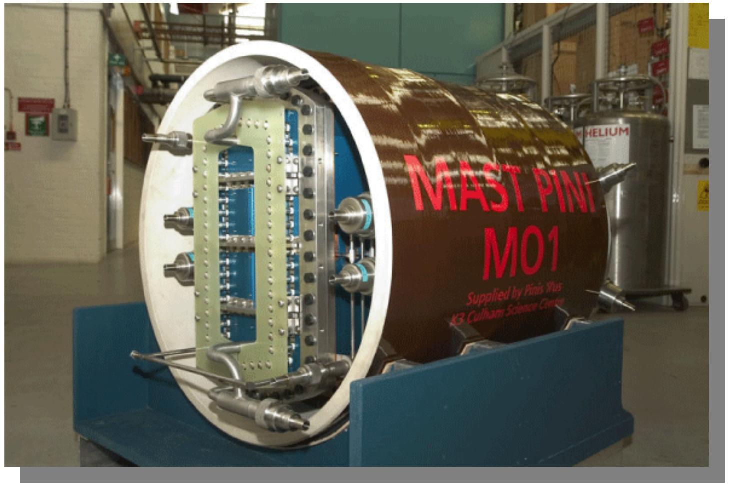
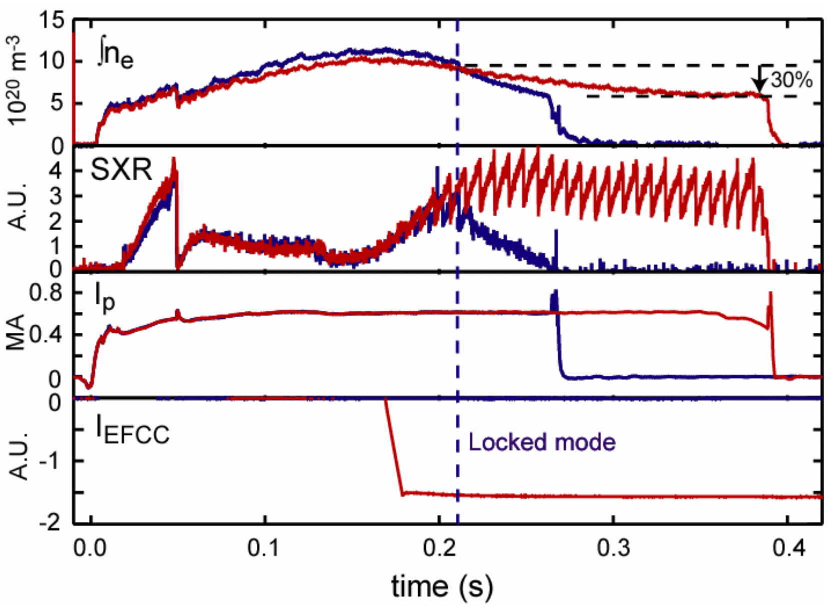
v_ϕ studied with future higher P_{NBI}, longer pulse



High rotation with modest beam power makes MAST ideal for rotation studies (a result of good momentum confinement but low moment of inertia)

Beam upgrade to JET-style PINIs ongoing - ~double P_{NBI} available in most recent campaign

v_ϕ studied with future higher P_{NBI}, longer pulse



High rotation with modest beam power makes MAST ideal for rotation studies (a result of good momentum confinement but low moment of inertia)

Beam upgrade to JET-style PINIs ongoing - ~double P_{NBI} available in most recent campaign

Increased beam power together with newly installed Error Field Correction coils should give long pulses with high rotation and large fast ion component

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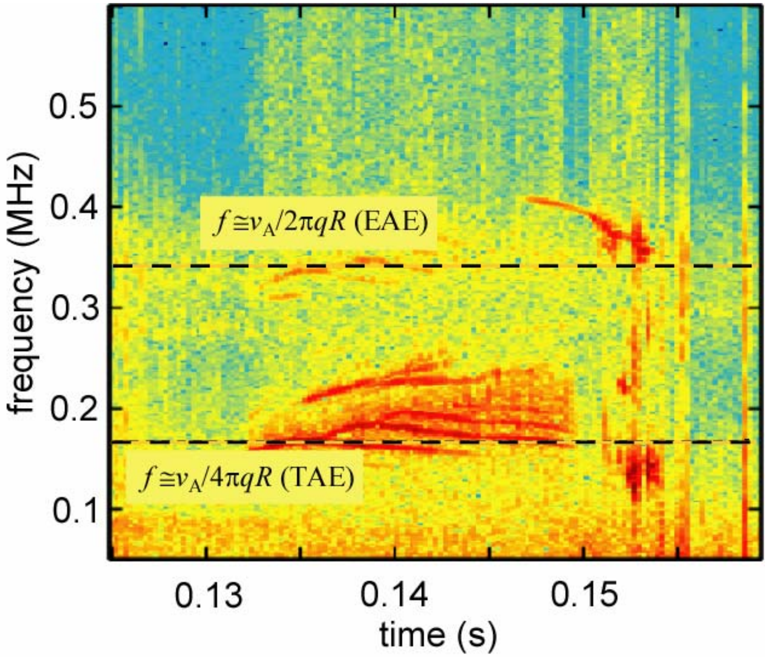
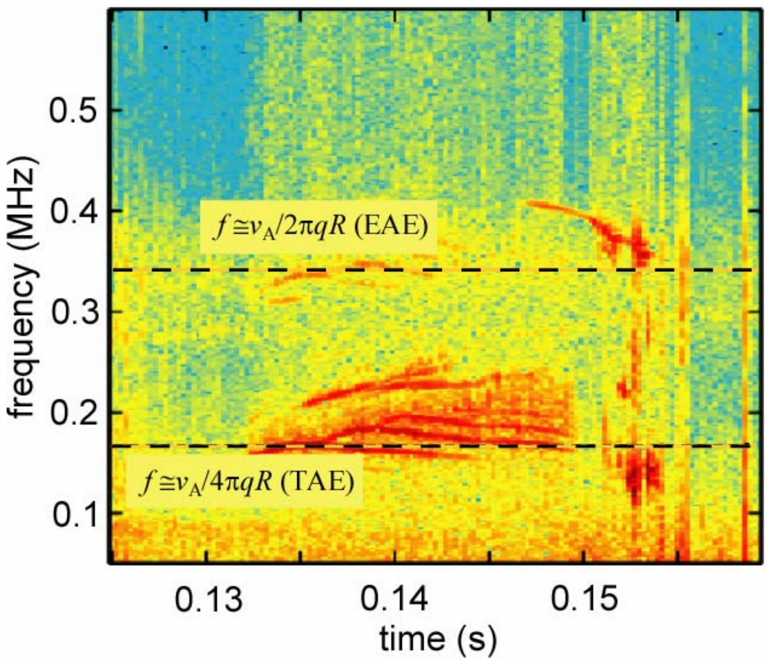
Energetic particle modes explored

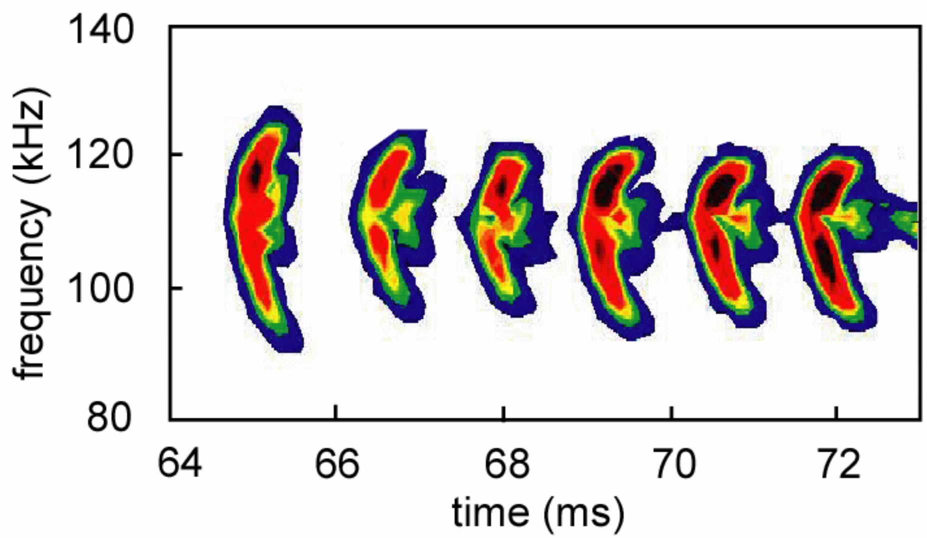


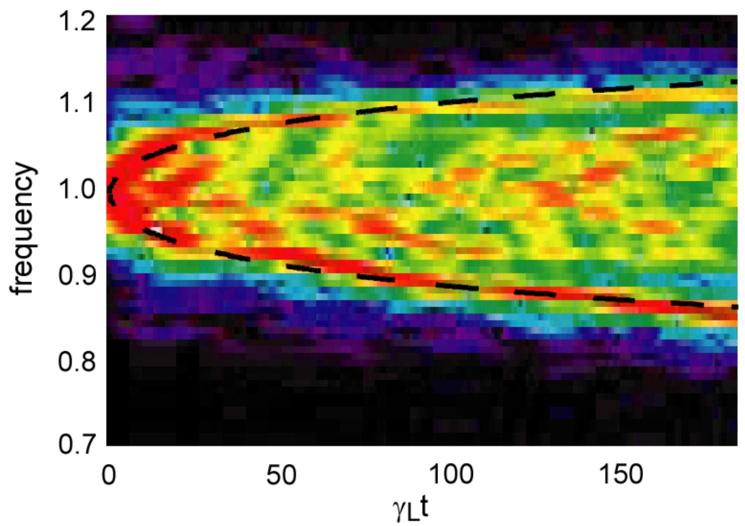
Future **large fast ion component and super-Alfvénic beam** ($v_{//,NBI} \sim 0.7 v_{NBI} \sim v_A$) suggest EPMs may be significant

TAE and EAE activity both observed

Frequency sweeping modes observed





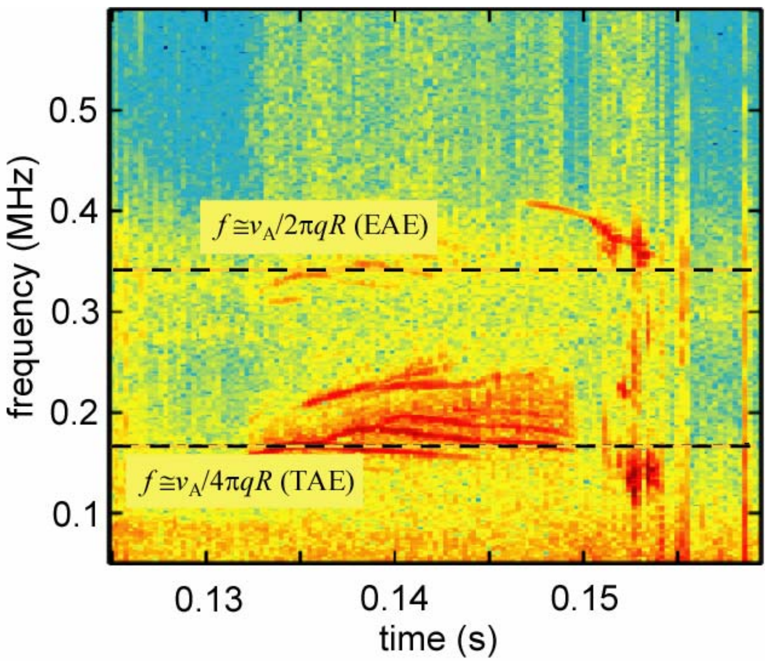


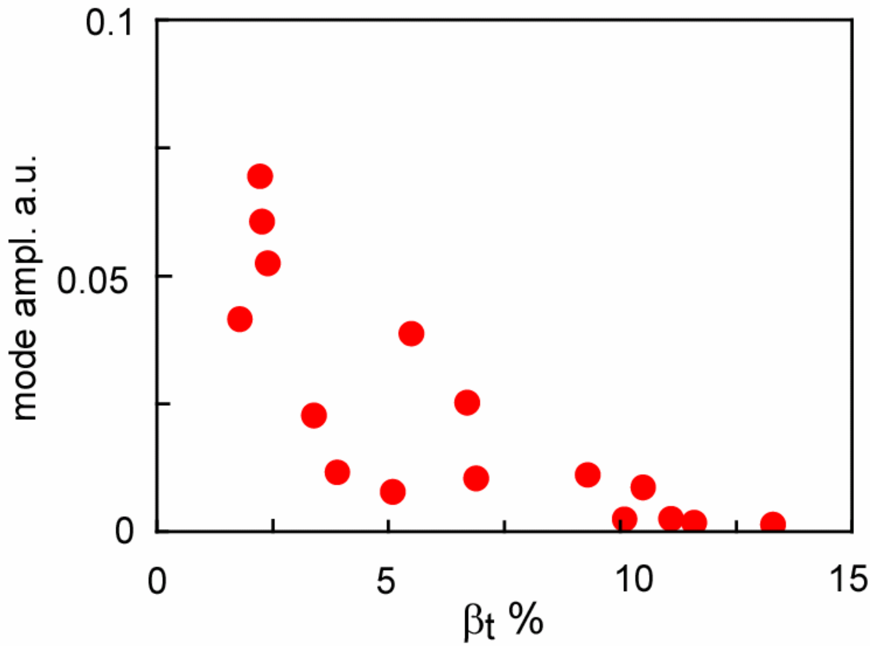
Up-down frequency sweeping modes also observed

Supports model for non-linear evolution of TAE's in the 'explosive' regime - predicts formation of Bernstein-Green-Krushal non-linear waves

Well modelled by HAGIS MHD code

EPM activity reduces with β





For β > 5% TAE and EAE activity become dominated by non perturbatuive down-frequency chirping modes

The **amplitude of these modes falls sharply with increasing β**, vanishing for β > 15%

⇒ AE activity likely to be absent in a future ST device where β on axis would approach 100%

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See S. Sharapov EX/5-2Ra

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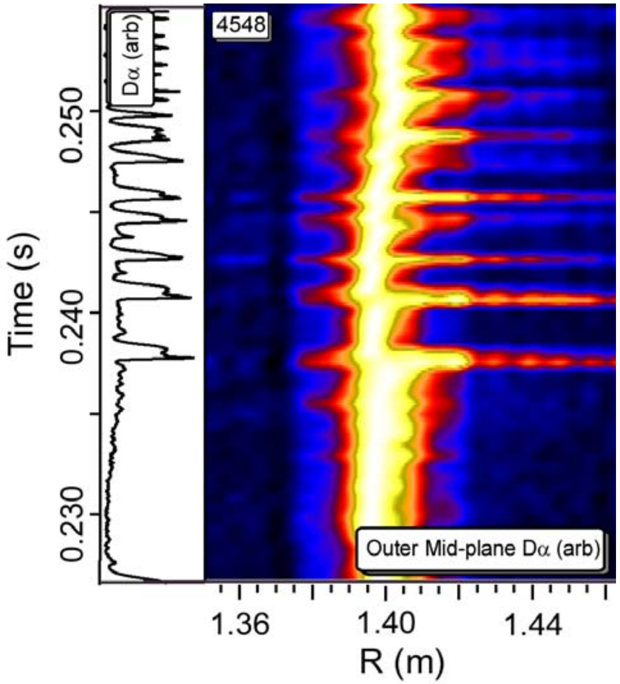
ELM structure exploration continues

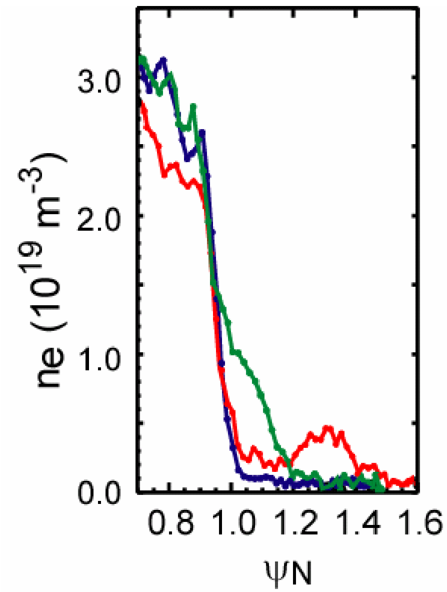


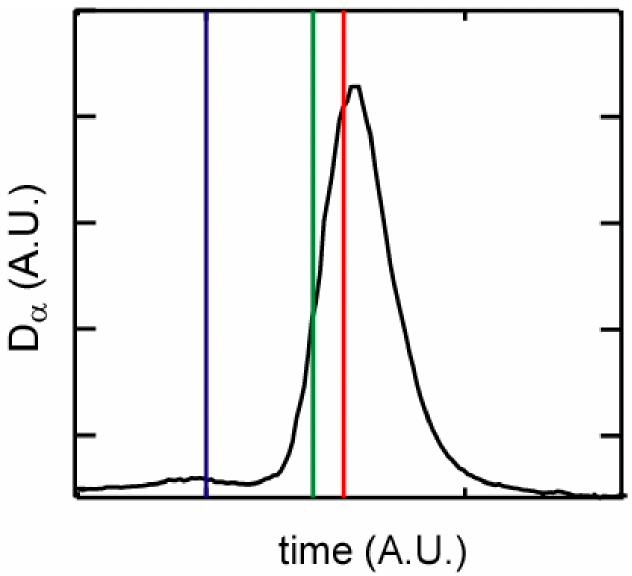
Previously presented observations of 'radial bursts' during edge localised modes

Visible in edge D_α profile ...

…. and edge density profile (using high spatial resolution TS system)

TS profiles also show formation of 'disconnected' feature, late in ELM





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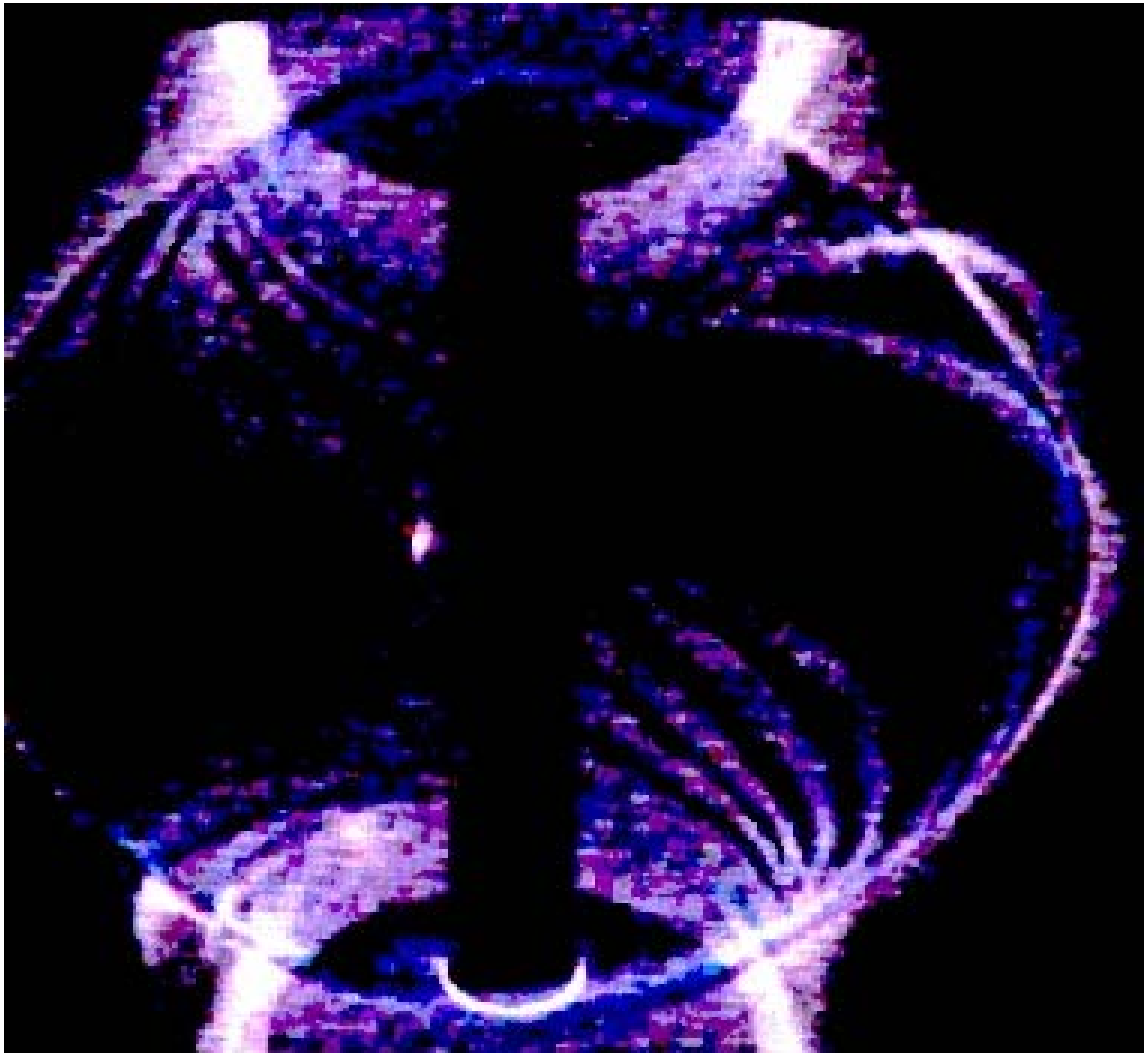
2D fast camera reveals ELM filaments



New 2D visible light images on whole plasma clearly show ELM bursts are, in fact, **filaments**

Toroidal mode number of filaments in the range $8 < n < 14$

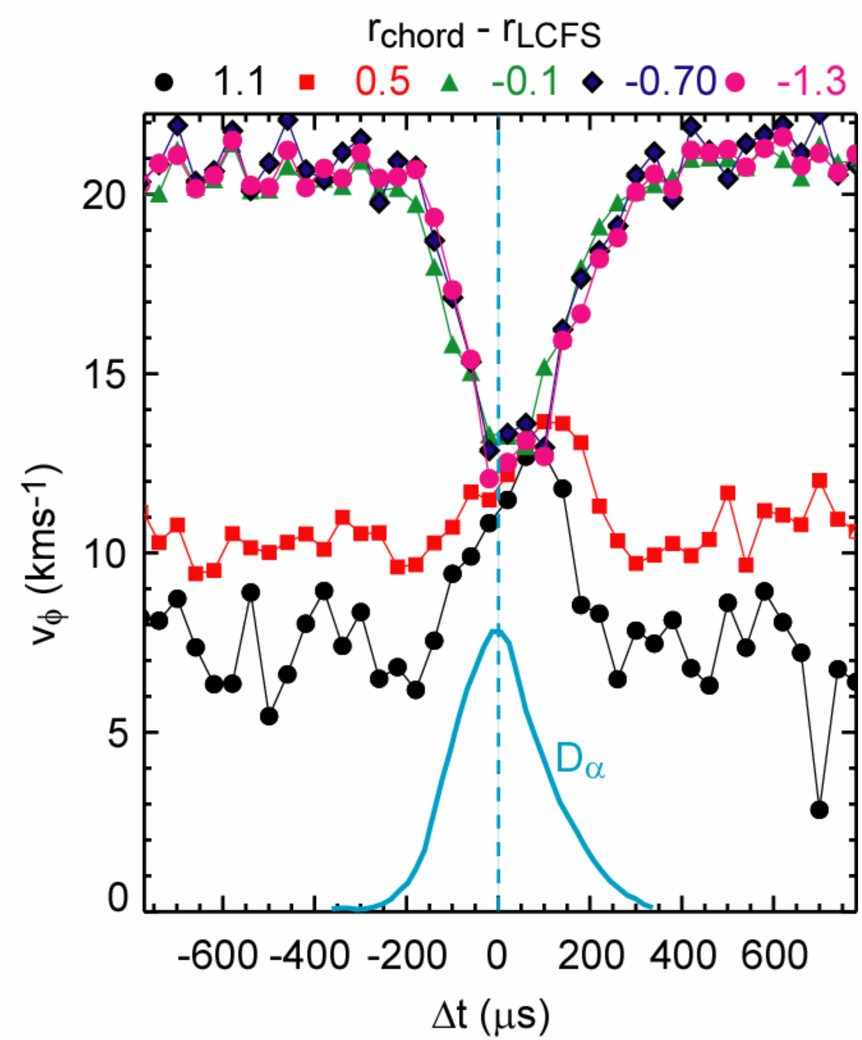
Filaments appear to push out beyond separatrix, following field lines with $4 < q < 6$

Edge velocity shear disappears at ELM

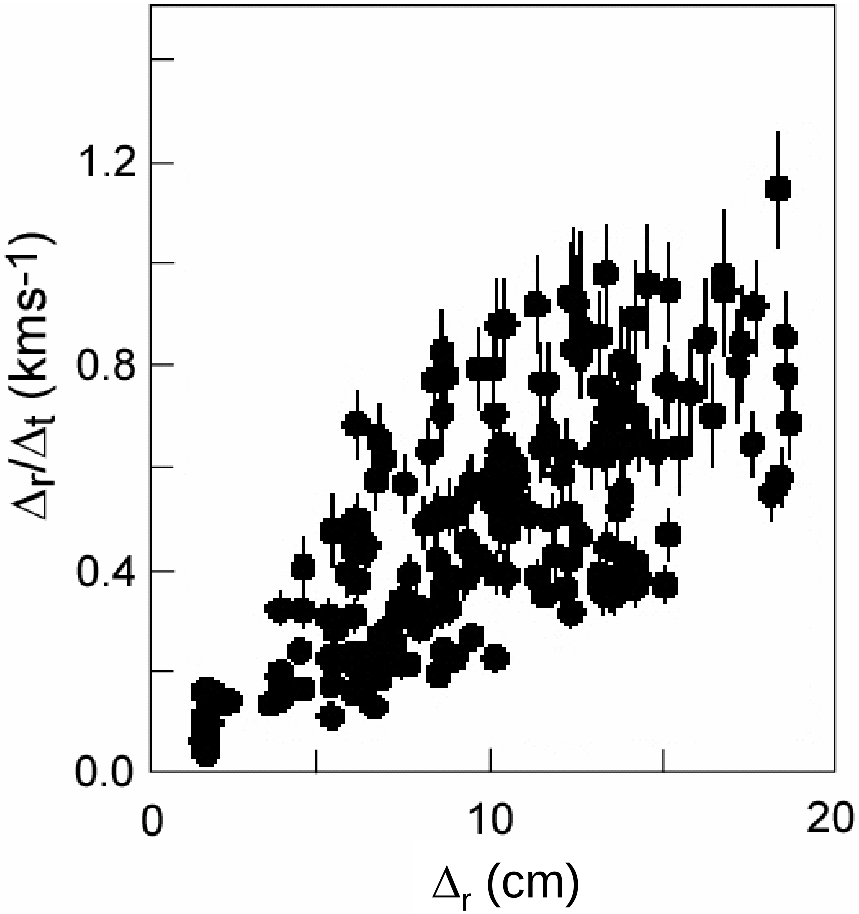
Fast edge toroidal velocity measurements assembled from He Doppler diagnostic for similar ELMs

Strong edge **toroidal velocity shear** (1.8×10^6 s^{-1}) **vanishes around time of ELM** (also observed on COMPASS-D)

May explain how ELM filament can protrude beyond separatrix without being destroyed



Average filament v_r up to ~1km/s



Average radial velocity of ELM filament varies with distance from separatrix (measured by time for interaction with mid-plane reciprocating probe)

See A. Kirk EX/2-3

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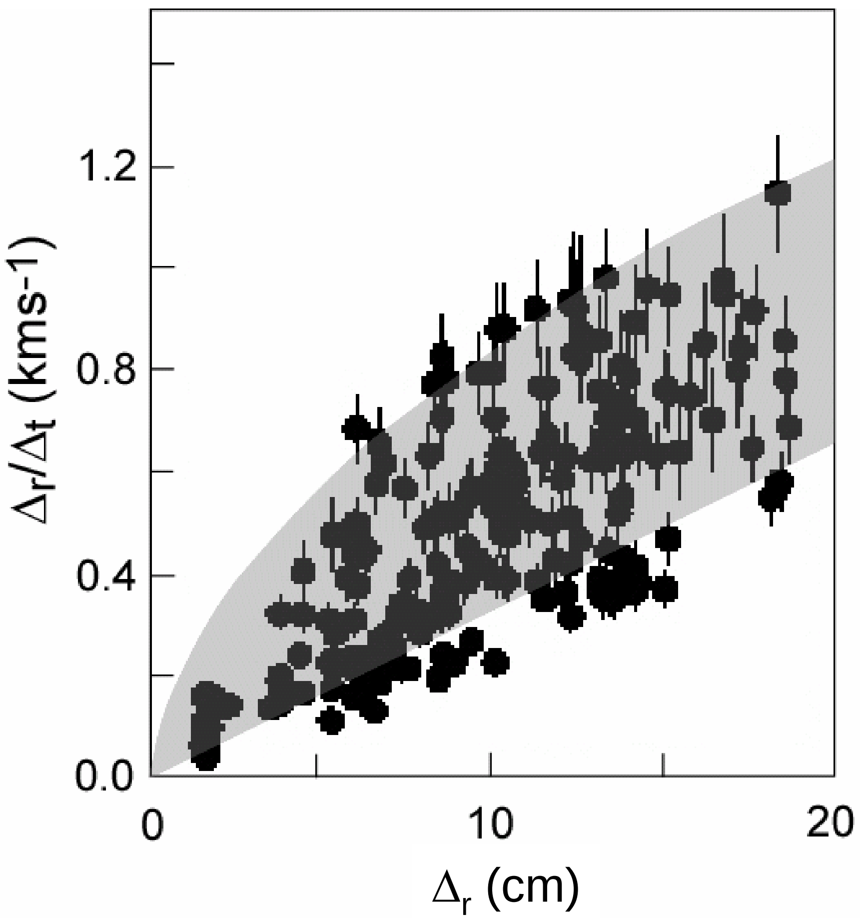
Filaments are actually accelerating



Average radial velocity of ELM filament varies with distance from separatrix (measured by time for interaction with mid-plane reciprocating probe)

Modelling of data from toroidally separated RPs on MAST indicates:

- ELM filaments are, in fact, **accelerating away from separatrix at 5-15x10^6 ms^{-2}**
- Rotating with the measured edge v_ϕ

Observations consistent with ELM description as non-linear expansion of intermediate-n ballooning mode

See A. Kirk EX/2-3, H.R. Wilson TH/P1-5

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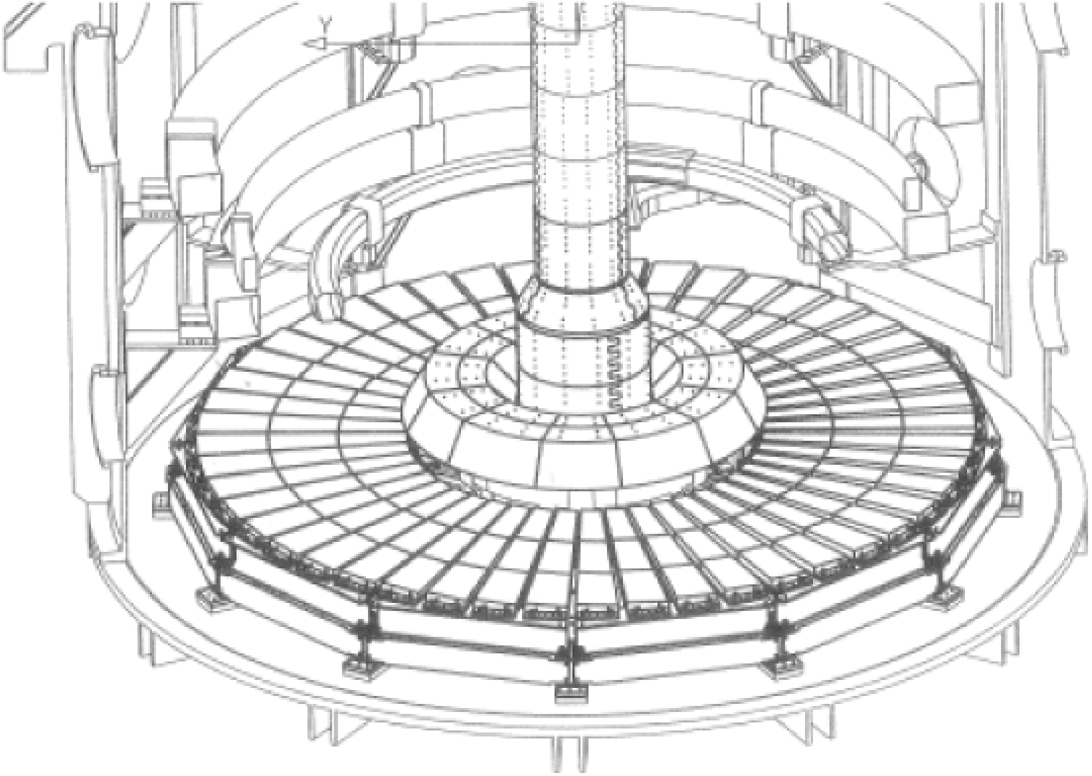
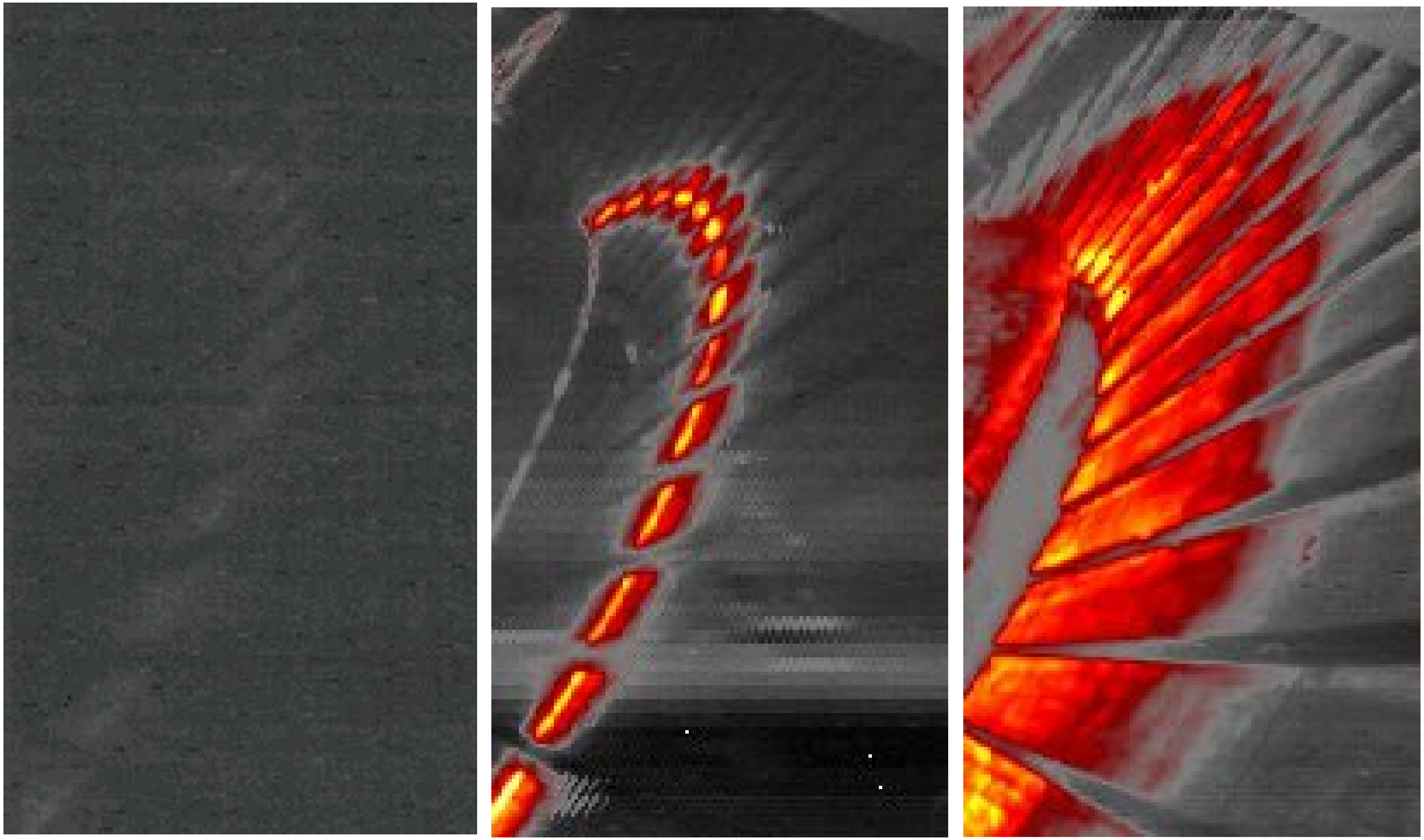
- Start-up without a central solenoid

Improved views with new divertor



Disruptions are complex in space and time

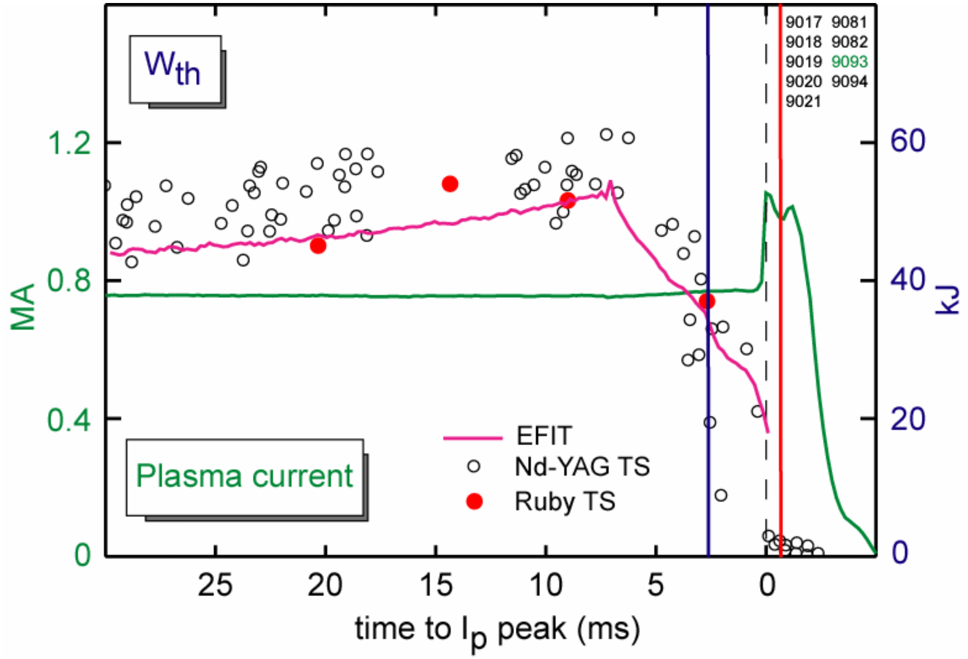


Well before disruption

Few ms before
current redistribution

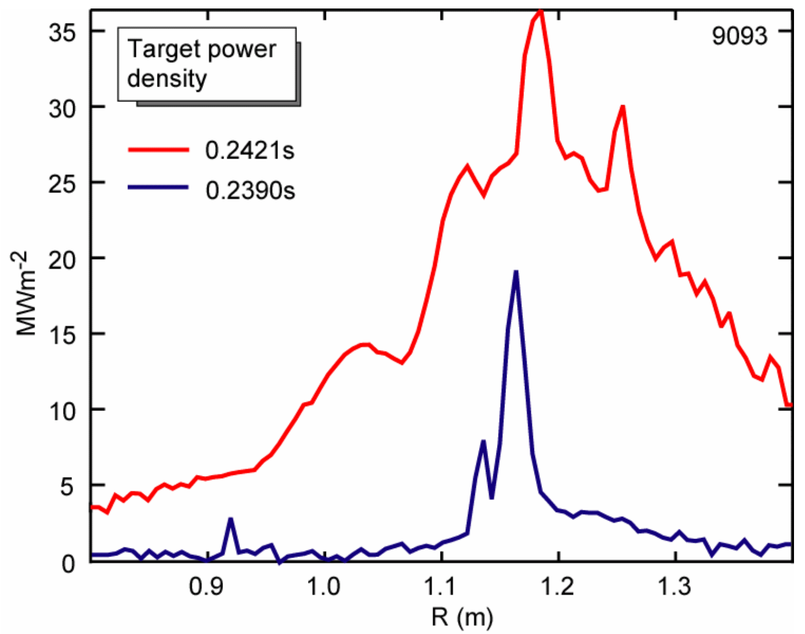
Before current quench

Δ_H broadening reduces peak power loading



Divertor **power loading rises by factor 2-10** (depending on disruption type) **several ms before current redistribution**

Result of 30-40% of W_{th} losses

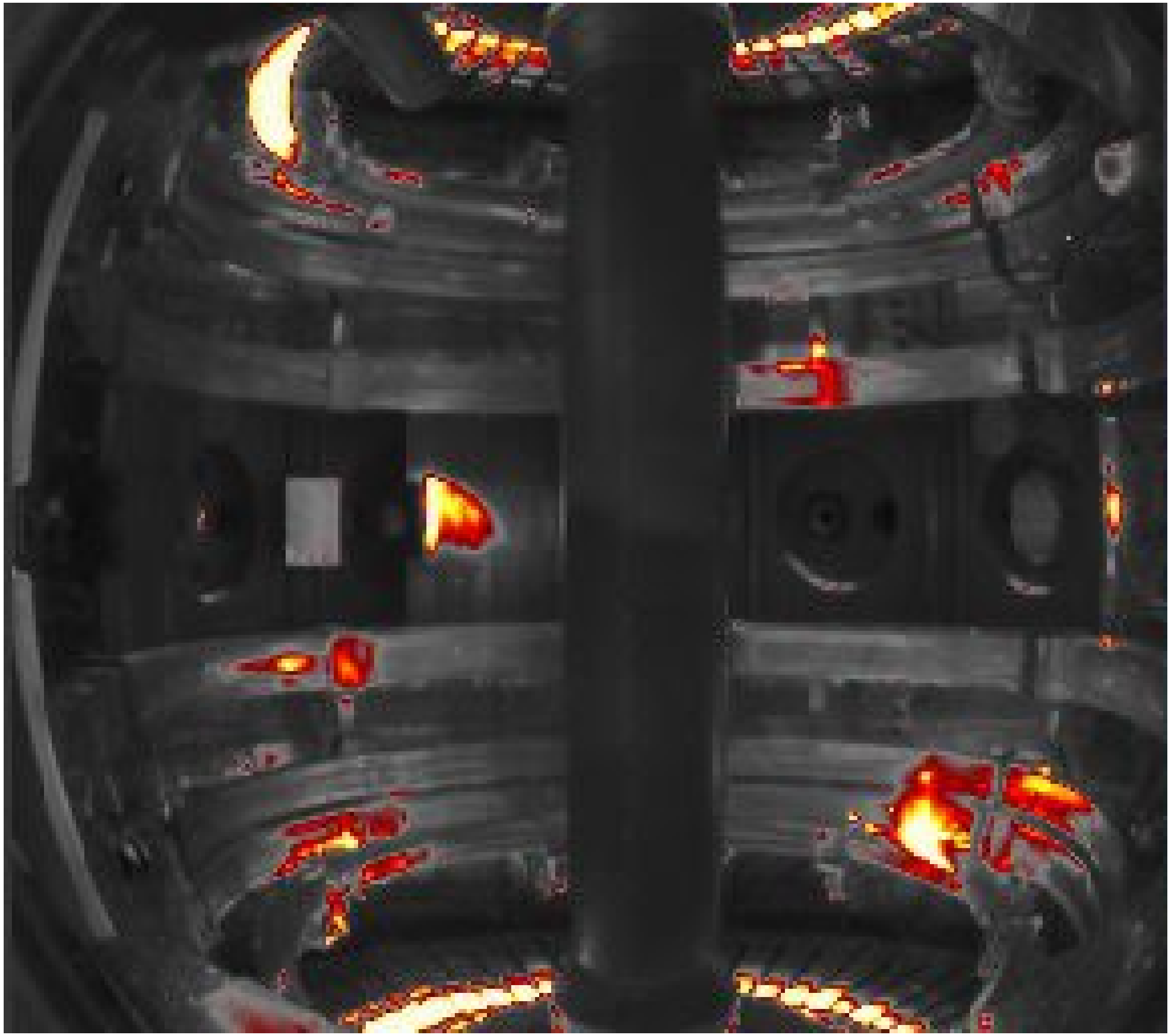


Power loading rises by a further factor ~2 during current redistribution due to rapid loss (1-2ms) or remaining W_{th}

Power loading is, however, significantly ameliorated by **factor ~8 broadening of heat flux width**

See A. Loarte IT/P3-34

Wide-angle IR views reveal wall loads



MAST IR camera can view around 70% of the vessel

Provides **unique data on first wall interactions and power loading asymmetries**

For example, early phase of disruptions often show n=1 wall interaction

Also shows W_{th} losses ~evenly distributed between targets

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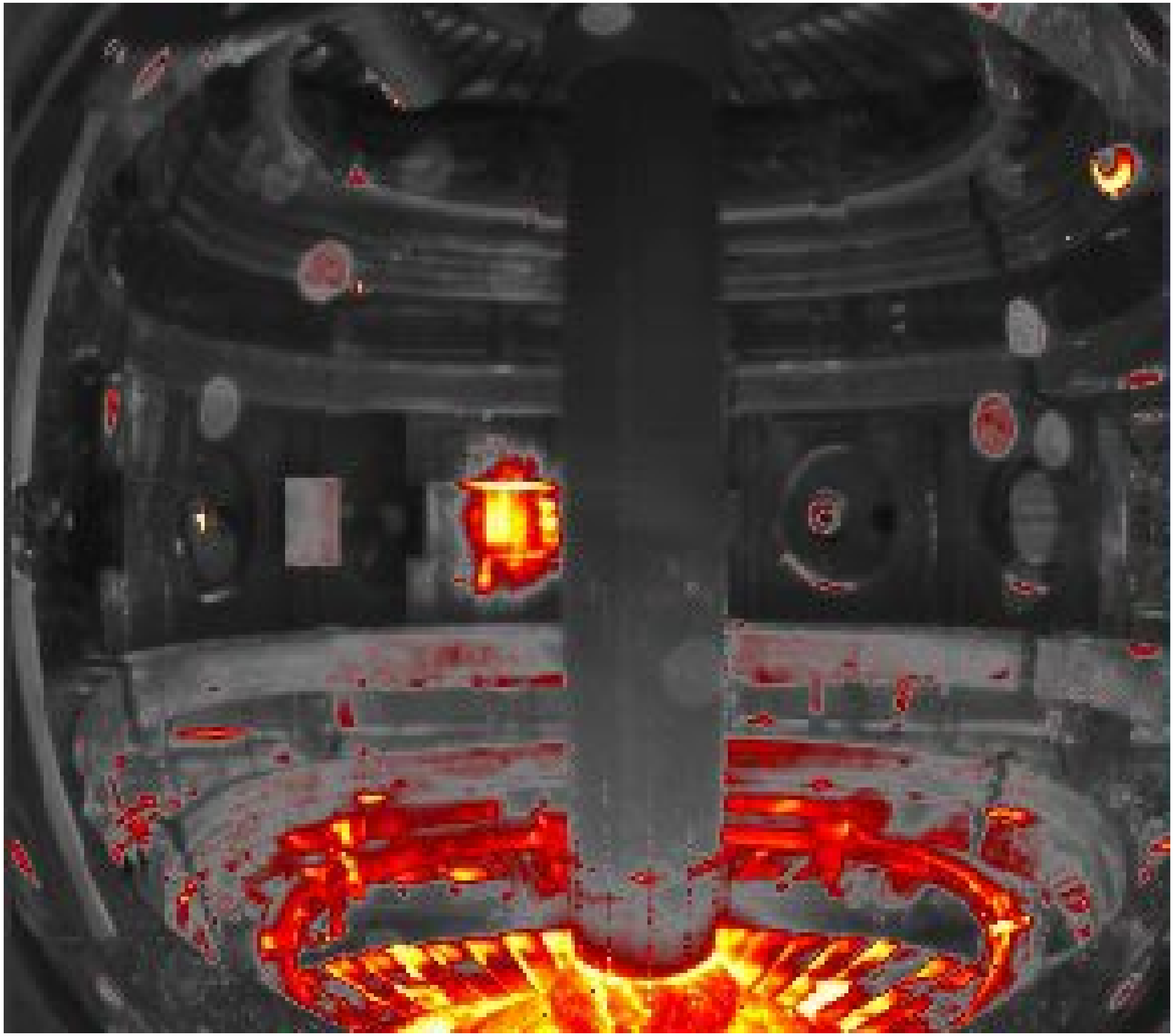
Toroidal non-uniformity clearly visible



MAST IR camera can view around 70% of the vessel

Provides **unique data on first wall interactions and power loading asymmetries**

Later phase of this VDE disruption show all remaining Wth going to lower target

Note the substantial toroidal asymmetry in the target power load

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- The L-H transition and H-mode Pedestal
- Confinement and Transport
- Transients - ELMs and Disruptions
- Start-up without a central solenoid

Future ST's may not have central solenoid

- ST design allows excellent access to the centre column
- Even complete replacement for upgrade or repair is relatively straightforward
- Future ST devices operating with a DT mix, however may not have space for central solenoid due to need for neutron shielding
- Alternative schemes for plasma start-up are therefore an important issue for the ST

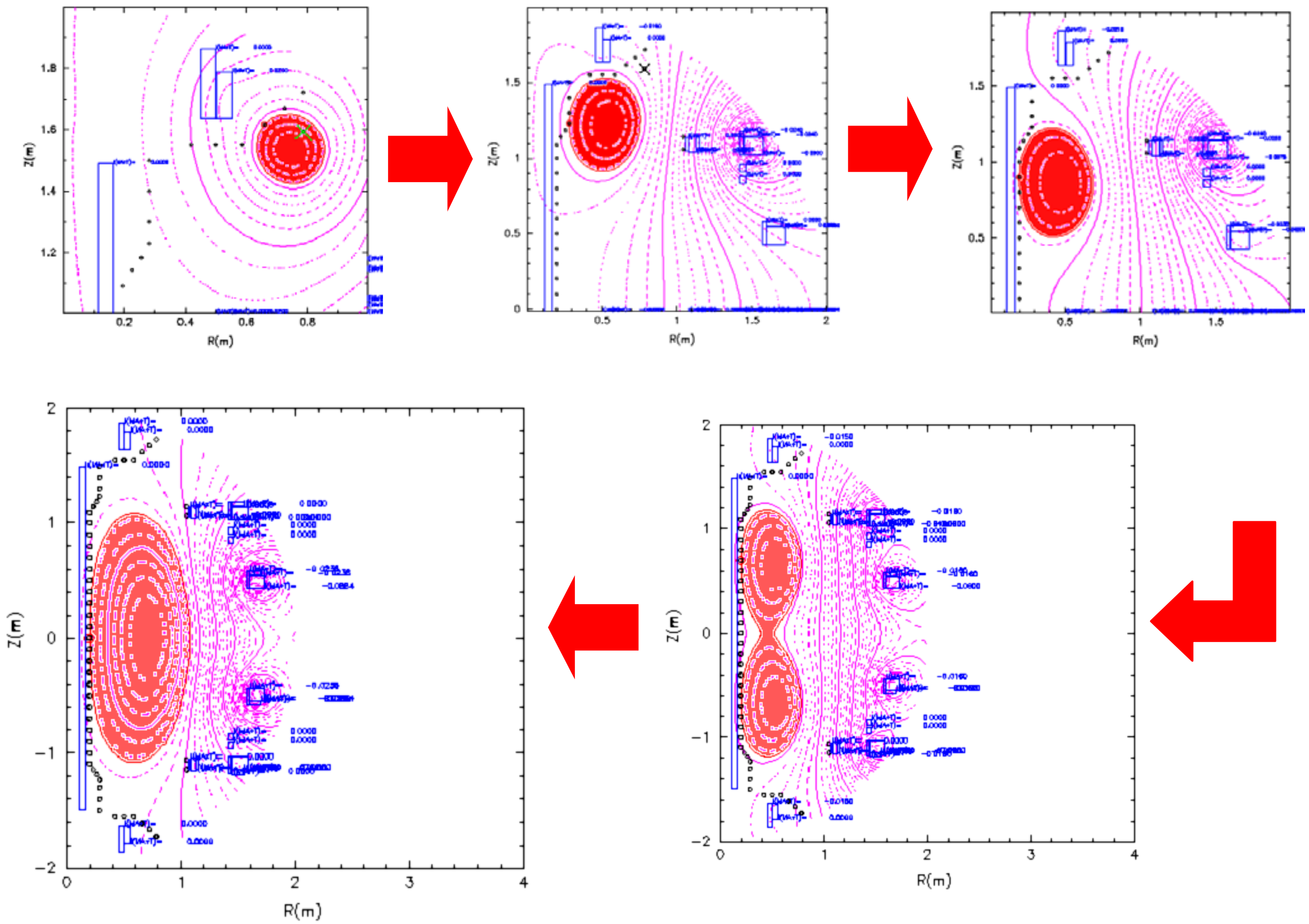
Alternative start-up schemes investigated

One such scheme is being developed in association with ENEA

Double-null merging (DNM) involves **breakdown at a quadrupole null** between pairs of poloidal coils in upper and lower divertor

Modelling predicts **merging of plasma rings** as current in coils ramped to zero

DNM is compatible with future ST design



ENEA

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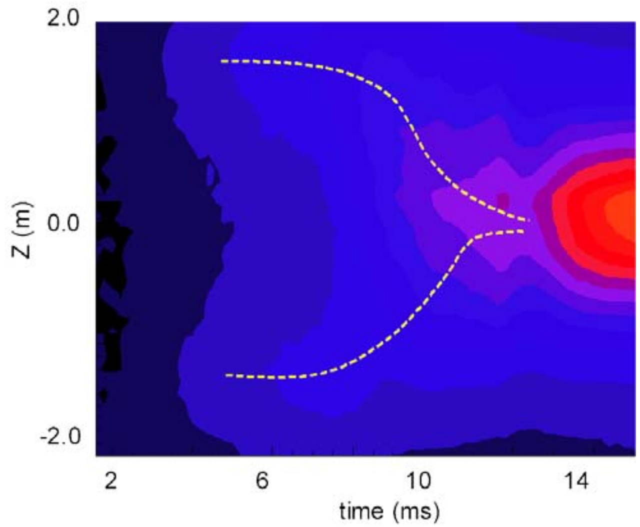
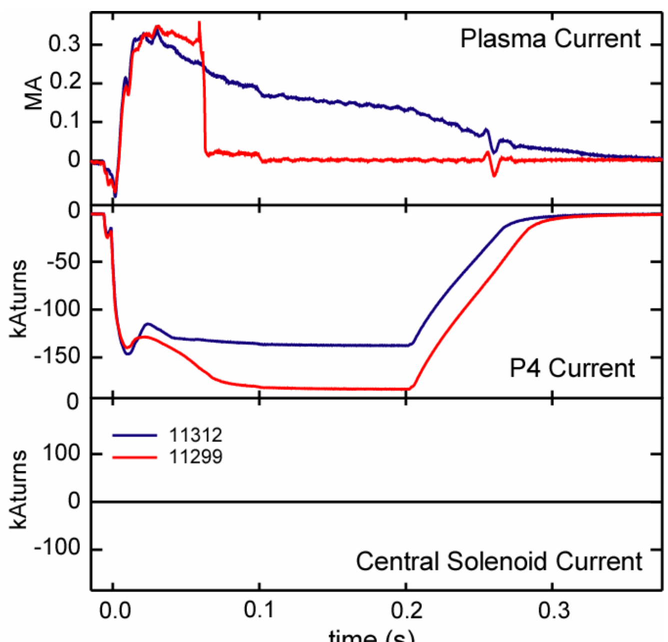
340kA target plasma obtained with DNM

Plasma ring formation and merging clearly seen on centre column magnetic array

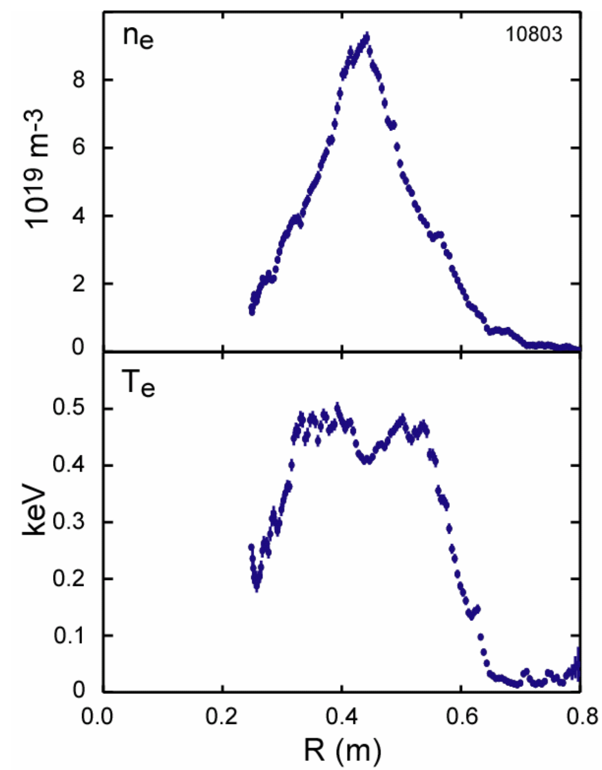




So far, **over 340kA driven for >50ms**, sustained by B_v ramp

Hot (0.5keV), dense ($9 \times 10^{19} m^{-3}$) plasma

Good target for NBI or RF current drive and heating



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Conclusions

- Exact double-null geometry and high resolution edge diagnostics allow study of physics close to CDND, such as lowering of $P_{L\text{-}H}$ (now seen on other devices). Effect of CDND mostly on E_r.
- Addition of large ε and high β data (with conventional 'D' shape) to international database improves confidence in scalings and allows better exploration ε dependencies.
- Normalised confinement linked to toroidal rotation, driven by neutral beam torque
- TRANSP and GS2 now implemented. v_ϕ dominates ω_{se}, stabilising ITG (and possibly ETG) modes. χ_i at neo-classical levels. Well converged non-linear micro-stability calculations give χ_e of same order as TRANSP.
- Super-Alfvénic fast ions (from neutral beam) generate variety of Alfvén Eigenmode activity, including frequency sweeping modes. TAE/EAE activity falls with increasing β.
- ELMs appear as filamentary structures following perturbed field lines. Rotate with edge plasma, push out beyond separatrix (through region of low velocity shear) and accelerate radially outwards
- Heat flux width broadening (factor ~8) during disruptions reduces peak power loading but significant ω_{th} losses can take place before broadening occurs.
- Double-null merging scheme developed for plasma start-up without central solenoid. Hot, dense tokamak plasma formed with 340kA driven for >50ms

MAST related presentations at 20th IAEA FEC

A Kirk "The structure of ELMs and the distribution of transient power loads in MAST" EX/2-3 Tuesday

RJ Akers "Comparison of plasma performance and transport between tangential co- and counter-NBI heated MAST discharges" EX/4-4 Wednesday

SE Sharapov "Experimental studies of instabilities and confinement of energetic particles on JET and on MAST" EX/5-2Ra Thursday

HR Wilson "The Spherical Tokamak as a Components Test Facility" FT/3-1Ra Friday

M Valovic "Energy and Particle Confinement in MAST" EX/P6-30 Friday

H Meyer "H-mode transition physics close to double null on MAST and its applications to other tokamaks" EX/P3-8 Thursday

AR Field "Core Heat Transport in the MAST Spherical Tokamak" EX/P2-11 Wednesday

H.R. Wilson "Theory of plasma eruptions" TH/P1-5 Wednesday

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