Overview of results from MAST

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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
• Confinement and Transport
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$\delta r_{sep}$ plays a key role in MAST

MAST has fully symmetric upper and lower divertors and can operate from LSN to USN
CDND lowers $P_{L-H}$

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 $P_{L-H}$ 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 $P_{L-H}$

UKAEA Fusion
No significant changes to edge profiles

In L-mode (close to $P_{\text{L-H}}$) change from LSND-LDND-CDND not evident in edge $T_e$, $n_e$, $V_f$ and $M_\phi$ profiles
Only $V_\phi$ and $E_r$ influenced by CDND

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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 $\psi_{95}$, which characterises **suppression of long $\lambda$ drift wave turbulence** - but not quantitative.

Best quantitative separation achieved by critical $T_e$ at $\psi_{98}$ from **finite $\beta$ drift wave turbulence suppression** by self generated zonal flows

**Neither theory accounts explicitly for impact of CDND**

See H. Meyer EX/P3-8
• The L-H transition and H-mode Pedestal
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Confinement data at high $\beta$ and $\varepsilon$

Many new MAST points meeting stringent International Database criteria added to database
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MAST data expand the range of inverse aspect ratio ($\varepsilon = a/R$) by a factor 2.2 and in toroidal $\beta$ 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 $\varepsilon$ dependance
$\nu^*$ is a key parameter for ST scalings

MAST data alone support **favourable** $\nu^*$ dependence in dimensionless parameter scaling

See M. Valovic EX/P6-30
\( \nu^* \) is a key parameter for ST scalings

MAST data alone support **favourable** \( \nu^* \) dependence in dimensionless parameter scaling

Since \( \beta_N \) and \( \rho^* \) in MAST close to possible ‘next-generation’ ST - understanding \( \nu^* \) dependence especially important \( \nu^*,\text{MAST}/\nu^*,\text{CTF} \sim 90 \)

Link between dependencies of \( \beta \) and \( \varepsilon \) provided by MAST data may be useful

\( \Rightarrow \varepsilon \) should be included in recently identified interaction between \( \beta \) and \( \nu^* \) 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 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, $\chi_i$ is found roughly equal to $\chi_i^{NC}$, cf factor 4 larger in similar L-mode

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

Mixing length estimates $\Rightarrow \chi_i^{ITG} \sim 3-5 \, m^2s^{-1}$, close to TRANSP value

$v_\phi$ can dominate flow shear $\omega_{se} \Rightarrow$ possible ITG drive stabilisation and expect ITBs!

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

See A.R. Field EX/P2-11
Non-linear GS2 analysis for e⁻ transport

Nonlinear collisionless ETG calculations in flux-tube geometry, assuming adiabatic ions, at \( \Psi_n = 0.4 \) surface in MAST

- base case flux-tube dimensions:
  \[ \Delta x = 690 \rho_e = 8.7 \text{cm}, \quad \Delta y = 628 \rho_e = 7.9 \text{cm}, \]
  \[ 0.01 < k_y \rho_e < 0.31 \]
Radial electrostatic streamers predicted

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

- Base case flux-tube dimensions:
  $\Delta x=690\rho_e=8.7\text{cm}$, $\Delta y=628\rho_e=7.9\text{cm}$, $0.01<k_y\rho_e<0.31$

Radial electrostatic streamers observed in calculations up $\sim100\rho_e$ wide ($\sim1\text{cm}$)
Converged solution consistent with $\chi_e$

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Radial electrostatic streamers observed in calculations up $\sim100\rho_e$ wide ($\sim1\text{cm}$)

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

Indicates $\chi_e \sim 10\ \text{m}^2/\text{s}$ (cf Gyro-Bohm estimate of $\chi_e = 0.6\ \text{m}^2/\text{s}$) - within a factor 2 of TRANSP value
Highest confinement at largest $\nu_\phi$

Normalised confinement across range of L-mode, H-mode and ITB discharges increases with $\nu_\phi$
\( v_\phi \) driven by NBI torque

Normalised confinement across range of L-mode, H-mode and ITB discharges increases with \( v_\phi \).

\( v_\phi \) driven by torque from the neutral beam. Highest torque in counter-NBI discharges due to asymmetric (co-counter) fast ion losses.
Highest confinement at largest $v_{\phi}$

Highest confinement discharges are ITB formed with counter-NBI

$M_{\phi}$ approaches 1 in core

Very steep electron temperature gradient at $\rho \sim 0.6$

Very peaked density profile

See R. Akers EX/4-4
Density peaking dominated by Ware pinch

Highest confinement discharges are ITB formed with counter-NBI

$M_\phi$ approaches 1 in core

Very steep electron temperature gradient at $\rho \sim 0.6$

Very peaked density profile

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

See R. Akers EX/4-4
Flow shear exceeds ITG growth rate

TRANSP estimate of $\omega_{se}$ dominates ITG growth rate $\gamma_m$

$\gamma_m$ derived from a simple model, validated against GS2

$\omega_{se}$ 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 $\psi_N \sim 0.4$ 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
⇒ 200+ chord spectrometer

spatial resolution $\sim \rho_i$

poloidal and toroidal chords
separate views of two NBI beams
$v_\phi$ studied with future higher $P_{\text{NBI}}$, 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 $P_{\text{NBI}}$ available in most recent campaign
$v_\phi$ 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 - $\sim$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
Energetic particle modes explored

Future large fast ion component and super-Alfvénic beam \( \left( v_{\parallel, NBI} \sim 0.7 v_{NBI} \sim v_A \right) \) suggest EPMs may be significant. TAE and EAE activity both 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 $\beta$.

For $\beta > 5\%$ TAE and EAE activity become dominated by non-perturbative down-frequency chirping modes.

The amplitude of these modes falls sharply with increasing $\beta$, vanishing for $\beta > 15\%$.

$\Rightarrow$ AE activity likely to be absent in a future ST device where $\beta$ on axis would approach 100%.

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$_\alpha$ profile ...

.... and edge density profile (using high spatial resolution TS system)
TS profiles also show formation of ‘disconnected’ feature, late in ELM
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 $4 < q < 6$
Fast edge toroidal velocity measurements assembled from He Doppler diagnostic for similar ELMs

Strong edge **toroidal velocity shear** (1.8x10^6 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 $\sim 1\text{km/s}$

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
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 5-15x10⁶ ms⁻²
- Rotating with the measured edge $v_\phi$

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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Improved views with new divertor
Disruptions are complex in space and time.
$\Delta H$ 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 $\sim 2$ during current redistribution due to rapid loss (1-2ms) or remaining $W_{th}$
Power loading is, however, significantly ameliorated by factor $\sim 8$ 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
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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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.
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 ($9 \times 10^{19} \text{m}^{-3}$) plasma
Good target for NBI or RF current drive and heating
Conclusions

• Exact double-null geometry and high resolution edge diagnostics allow study of physics close to CDND, such as lowering of $P_{L-H}$ (now seen on other devices). Effect of CDND mostly on $E_r$.

• Addition of large $\varepsilon$ and high $\beta$ data (with conventional ‘D’ shape) to international database improves confidence in scalings and allows better exploration $\varepsilon$ dependencies.

• Normalised confinement linked to toroidal rotation, driven by neutral beam torque

• TRANSP and GS2 now implemented. $v_\phi$ dominates $\omega_{se}$, stabilising ITG (and possibly ETG) modes. $\chi_i$ at neo-classical levels. Well converged non-linear micro-stability calculations give $\chi_e$ 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 $\beta$.

• 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 $\omega_{th}$ 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