Overview of MAST results

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MAST
MEGA-AMPERE SPHERICAL TOKAMAK

Fusion
Working with Europe

Imperial College OF SCIENCE, TECHNOLOGY AND MEDICINE
Queen's University Belfast
THE UNIVERSITY OF STRATHCLYDE IN GLASGOW
WSL The way to success
UNIVERSITY COLLEGE, CORK
Coláiste na hOllscoile Corcaigh
AARHUS UNIVERSITET
University College Dublin
An Coláiste Ollscoile, Baile Átha Cliath

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On the top & inside MAST

2001

UKAEA Fusion Working with Europe

MAST

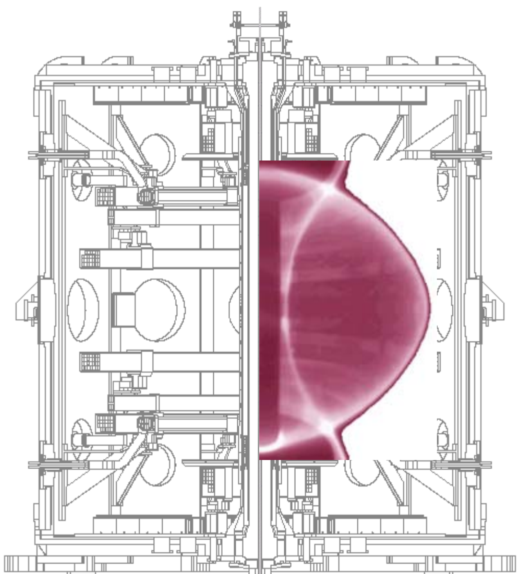
MAST Project mission:

- *to contribute to the resolution of key issues for **ITER***
- *to address outstanding issues specific to the **ST concept** which have a bearing on its viability as a potential fusion power plant*

First three years of physics operations:

Considerable advances in a range **of physics areas of direct relevance to ITER** *(H-mode access, confinement scaling, NTMs, halo currents, ELMs, SOL scaling, divertor power loading)*

and in **areas relevant to the physics basis for operations in next-step STs** *(start-up, current ramp, stability, confinement, current sustainment and exhaust issues)*



	Design	Achieved
Minor & Major radii a, R (m)	0.65, 0.85	0.65, 0.85
Elongation κ	$\geq$ 2	2.45
Aspect ratio A	$\geq$ 1.3	1.3
Plasma Current I_p (MA)	2	1.35
Toroidal Field $B_{\phi 0}$ (T) at R	0.52	0.52
Aux. Heating: P_{NBI} (MW) P_{ECH} (MW)	 5 1.4	 3 0.6
Pulse length (s)	5	0.7

Success of the first three years of physics operations was based on:

- Comprehensive diagnostics
- Flexibility of Magnetic Configuration
- Reliable operations in H-mode (OH or NBH) and easy H-mode access
- Low MHD and good confinement at high beta

Core and edge temperature and density measurements:

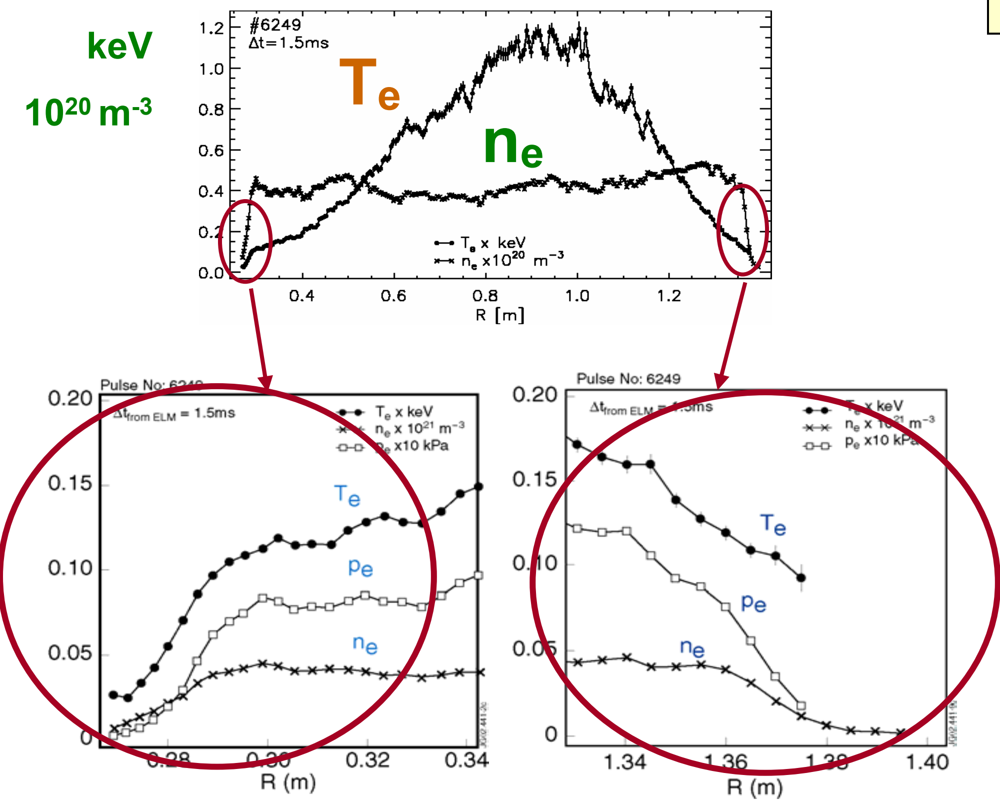
M Walsh E Arends A R Field N Conway G Counsell, A Kirk, M Tournianski

- $T_e(r)$, $n_e(r)$: Thomson scattering (TS)
  - 300 point single pulse Ruby
  - 100 Hz 20 points NdYAG
- Pedestal
  - T_e , n_e: TS and Helium line ratios (8 chords) HELIOS
  - n_o , dn_e/dr: 256 chords D_α camera
- $T_i(r,t)$, $V_f(r,t)$: Charge Exchange Radiation (CXR) 20 chords
- $T_i(t)$ and fast ions: Scanning neutral particle analyser (collab with PPPL)
- SOL temperature and density measured with reciprocating LP
- Target temperature and density measured with 576 LP

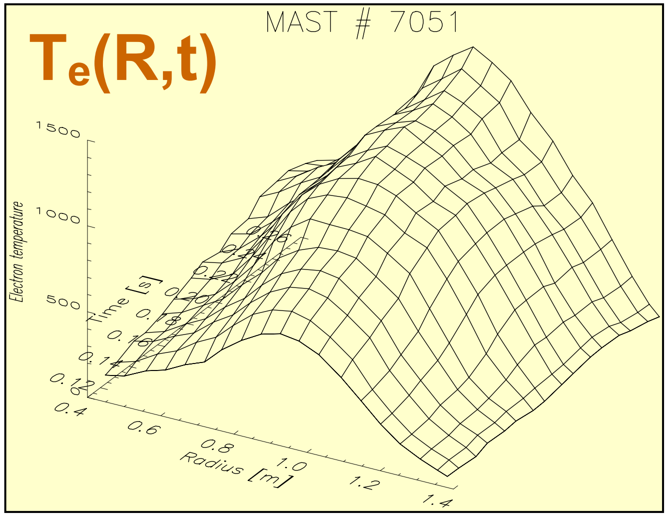
Electron temperature and density measurements:

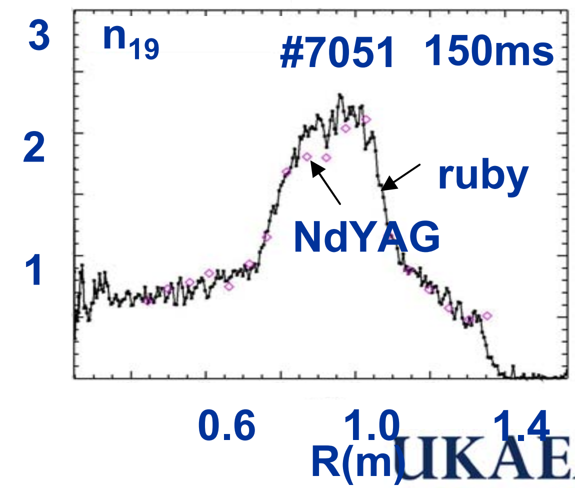
M Walsh E Arends M Dunstan

300pt TS



100 Hz 20 points NdYAG Thomson Scattering





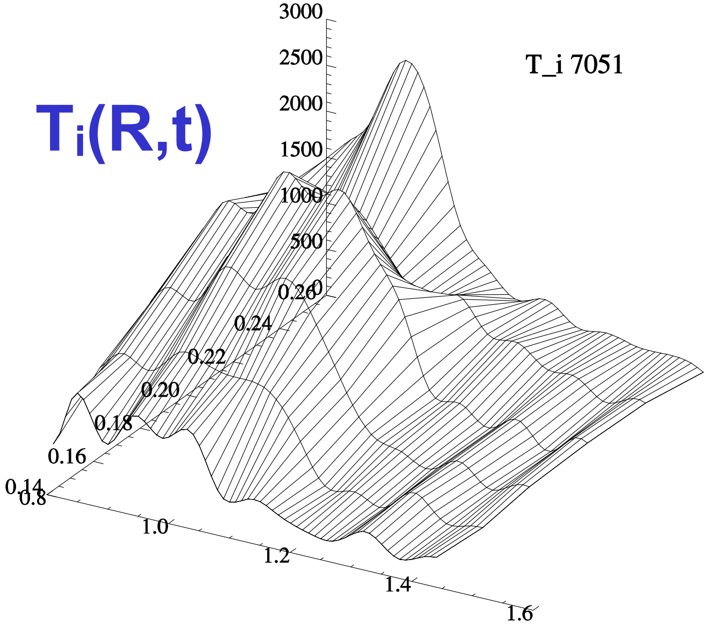
300 point high resolution Thomson Scattering gives i/b and o/b pedestal parameters in a single shot

Ion temperature and fast ion energy measurements:

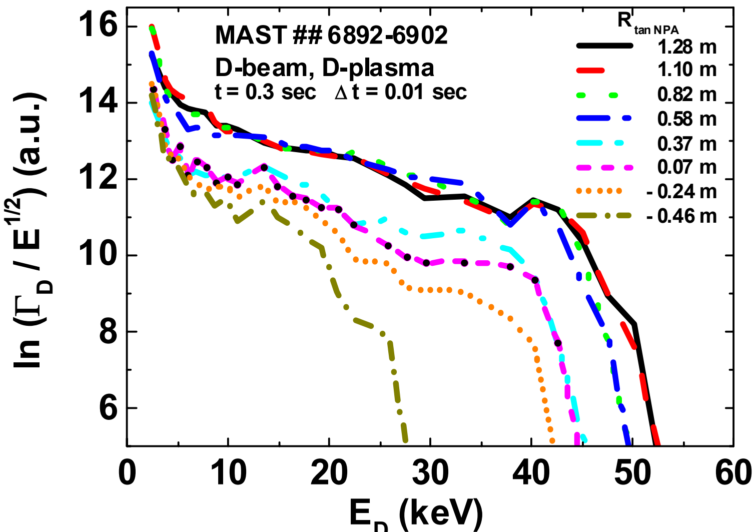
N Conway F Chernishev M Tournianski

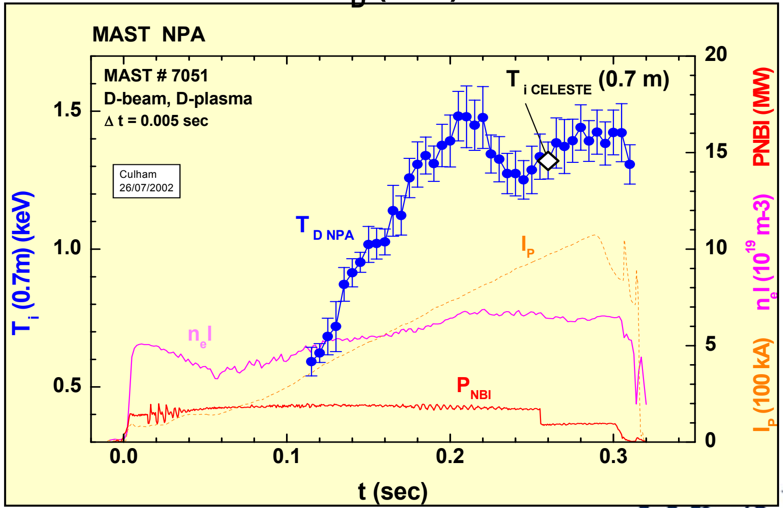
$T_i(R,t)$, $V_f(R,t)$ Charge Exchange Radiation (CXR) 20 chords

$T_i(R,t)$



$T_i(t)$ Scanning neutral particle analyser (PPPL)

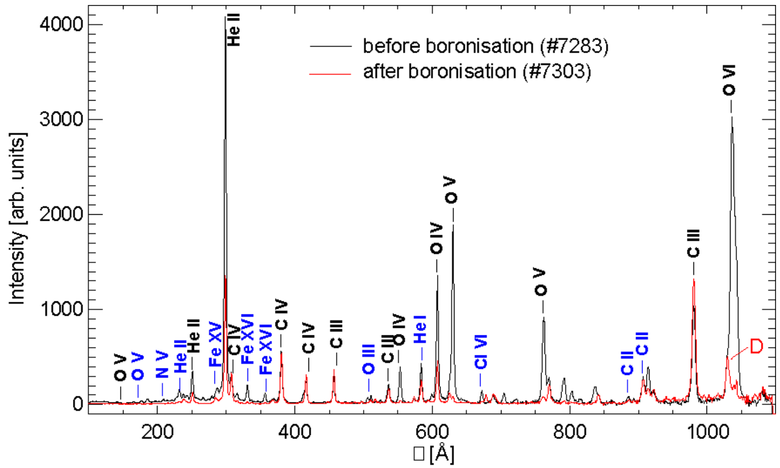




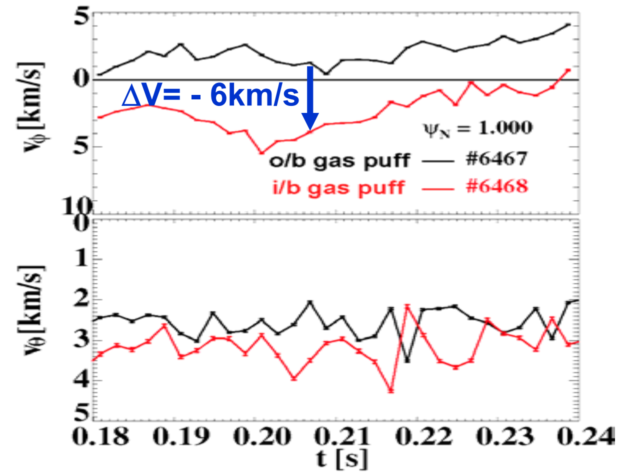
Impurities, rotation and Z_{eff} measurements:

A R Field, N Conway, H Meyer, I Lehane, A Patel, M J Walsh

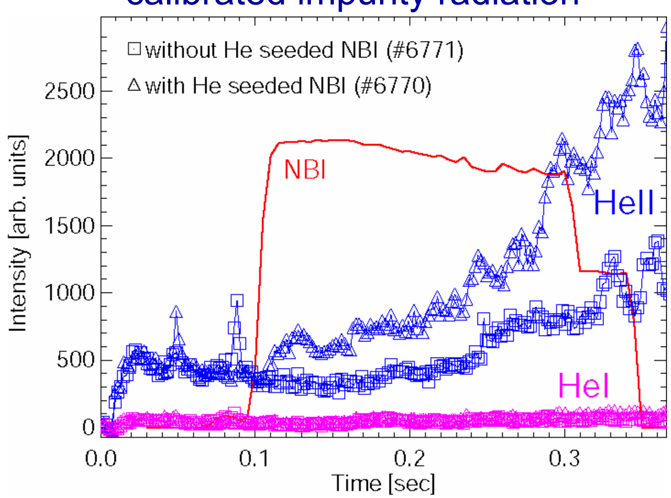
SPRED - impurity spectrum



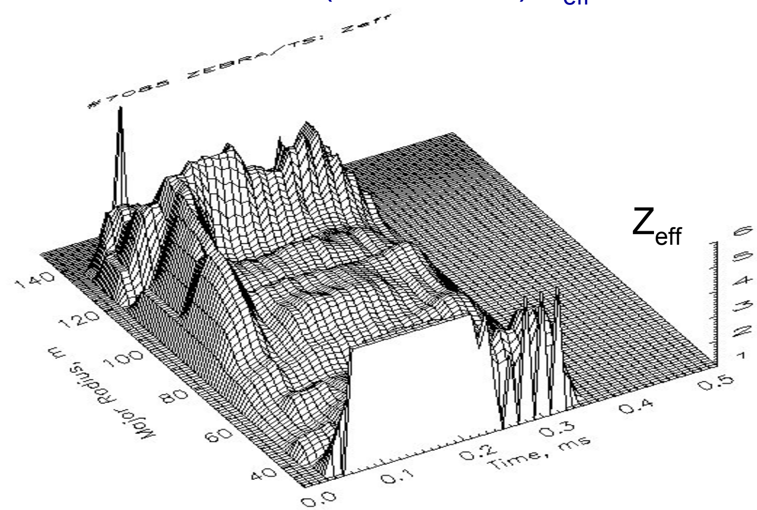
He II Doppler (20 chords) CELESTE



SPRED - fast time absolutely calibrated impurity radiation

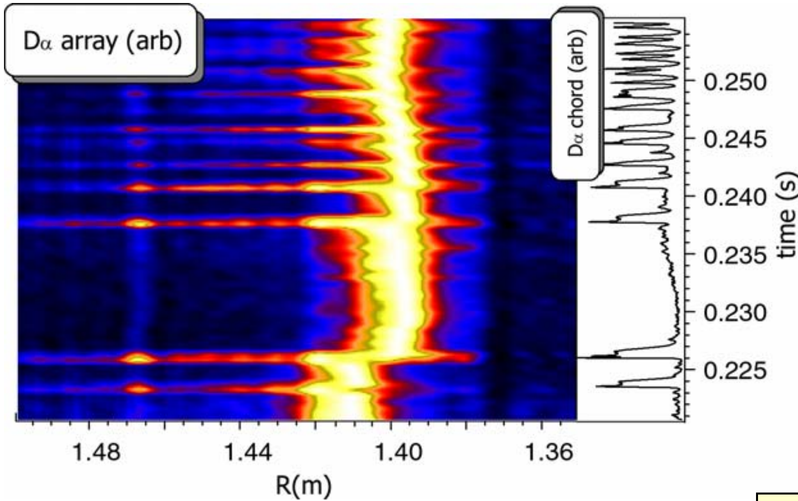


ZEBRA (200 chords) Z_{eff}

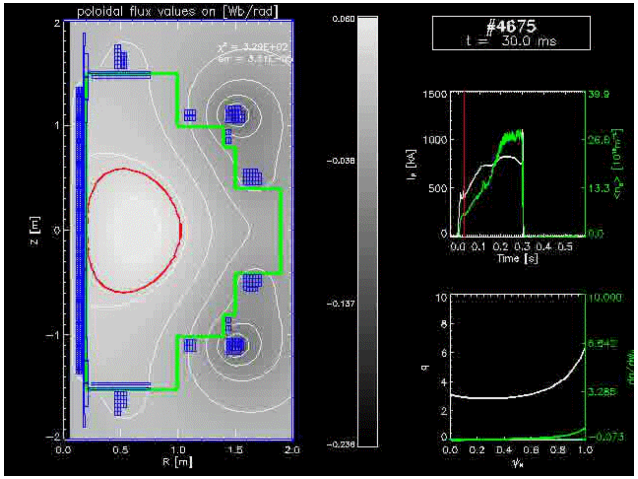


Visible and infrared emission measurements and LP:

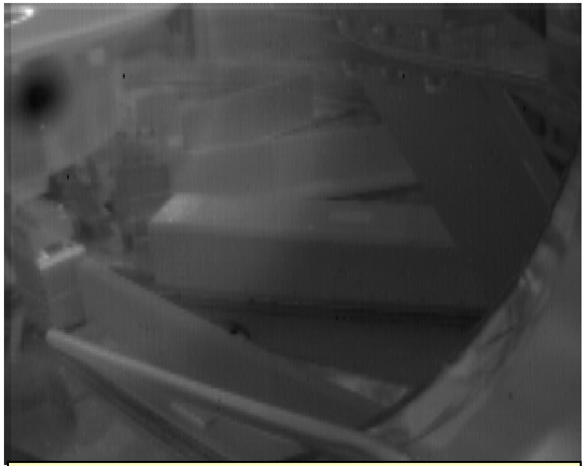
M Price, J Dowling, G Counsell, A Kirk, M Tournianski



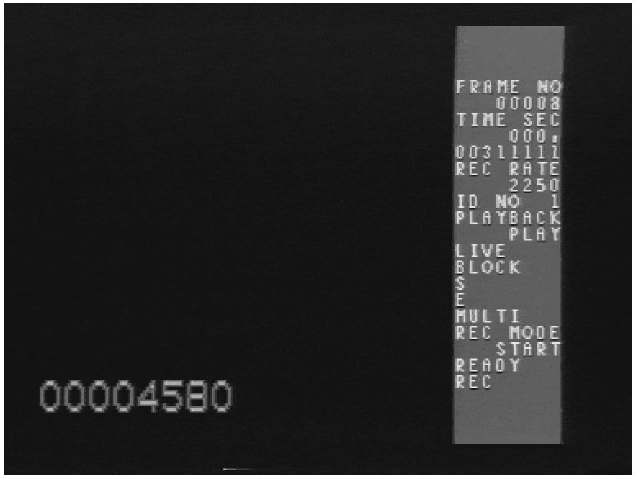
Linear CCD array



576 LPs measure target characteristics

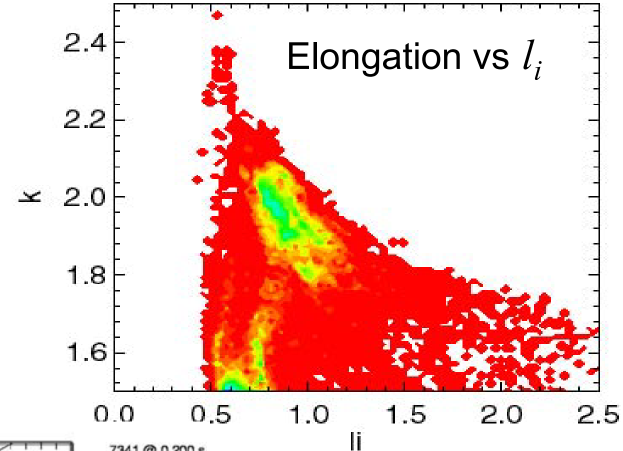


IR power video, divertor ribs

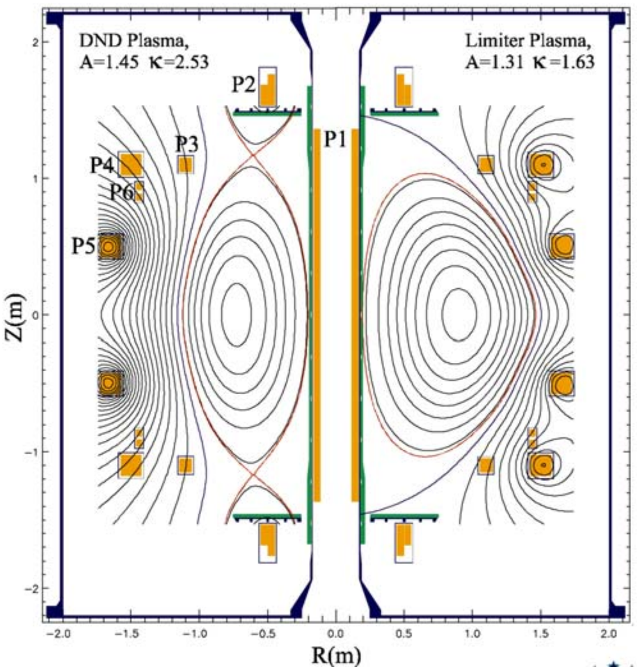


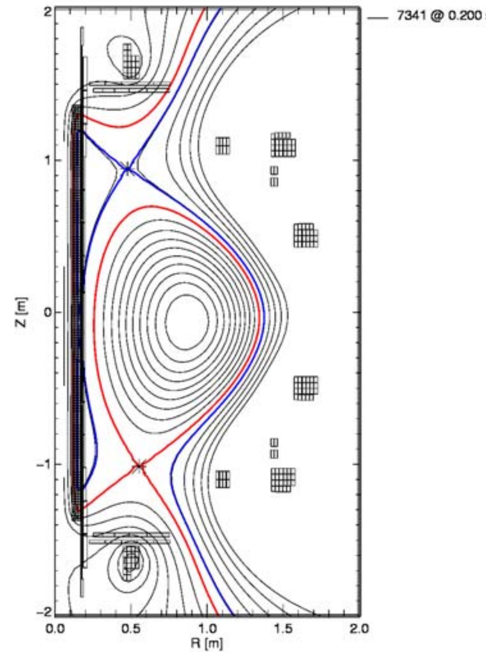
High speed video, up to 25000f/s

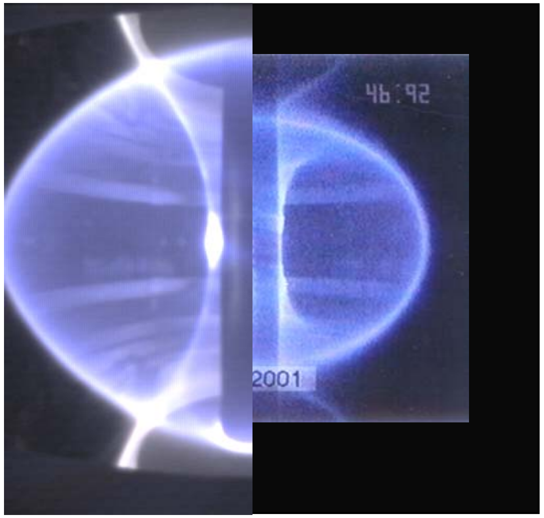
Flexibility of Magnetic Configuration:



Divertor configurations in MAST:







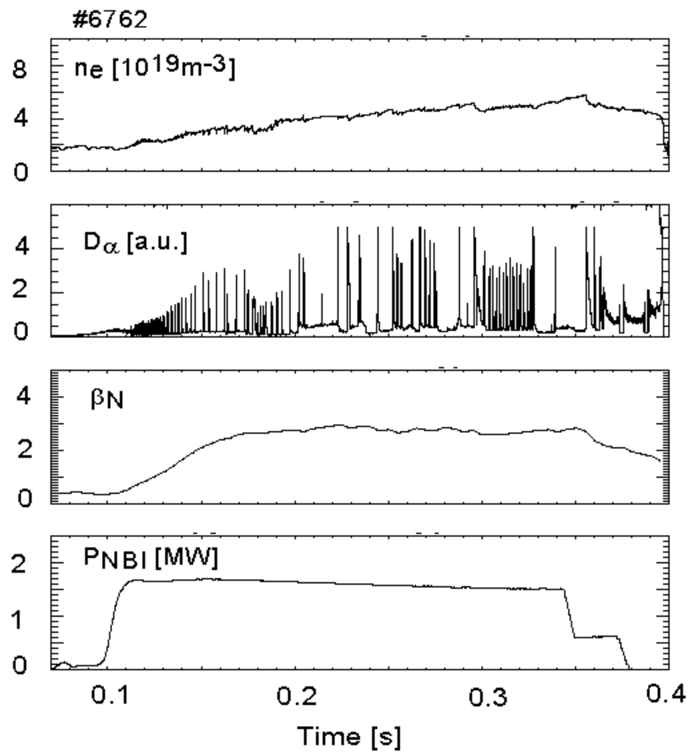
H-mode in DND and Natural Divertor plasmas

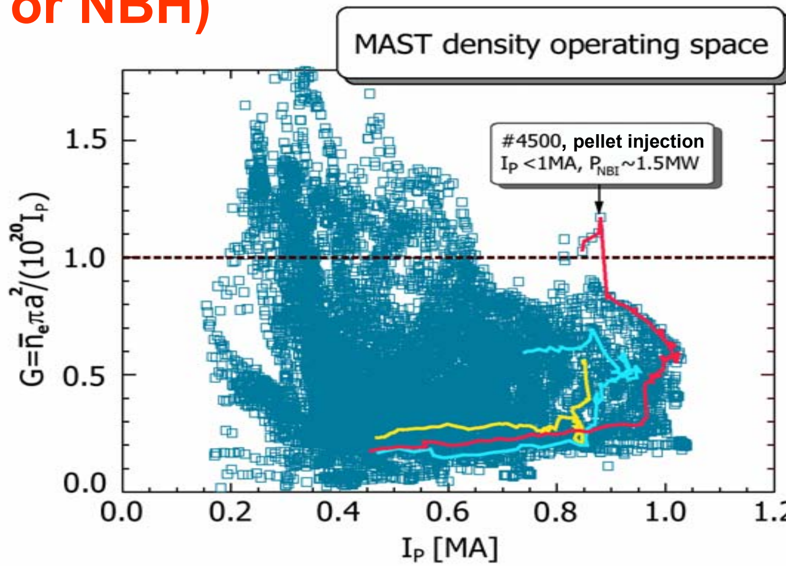
Double-Null Divertor (DND)

Limited, or Natural Divertor (ND)

First SND plasmas have been produced
G Cunningham, H Meyer

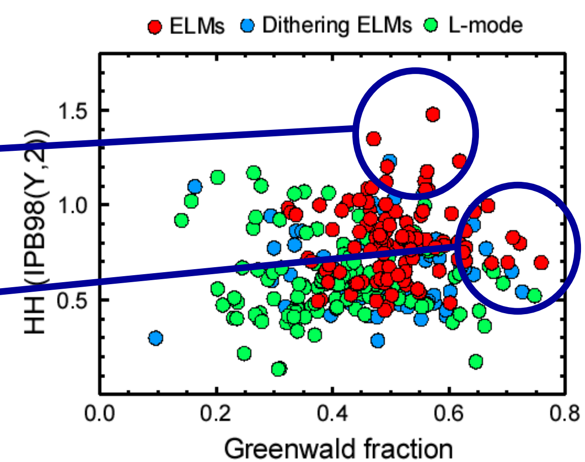
Reliable operations in H-mode (OH or NBH) and easy H-mode access:





HH(IPB(y,2)) up to 1.5 in ELMy H-mode (EFIT data)

ELMy H-mode with G up to 0.8



Sustained H-modes platform for studies:
β_N ~3, H_H ~ 1, n_e/n_{Gr} ~ 0.5 sustained for ~220ms (> 5τ_E), W_{kin}~W_{mag}, W_{fast}~10%
M Valovic

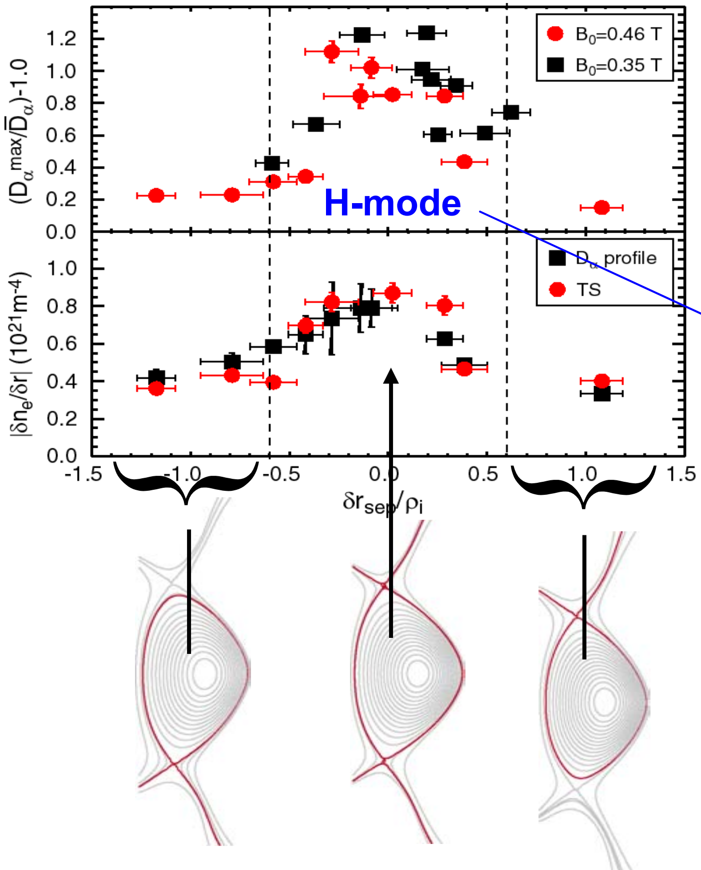
Good performance at high density
G F Counsell

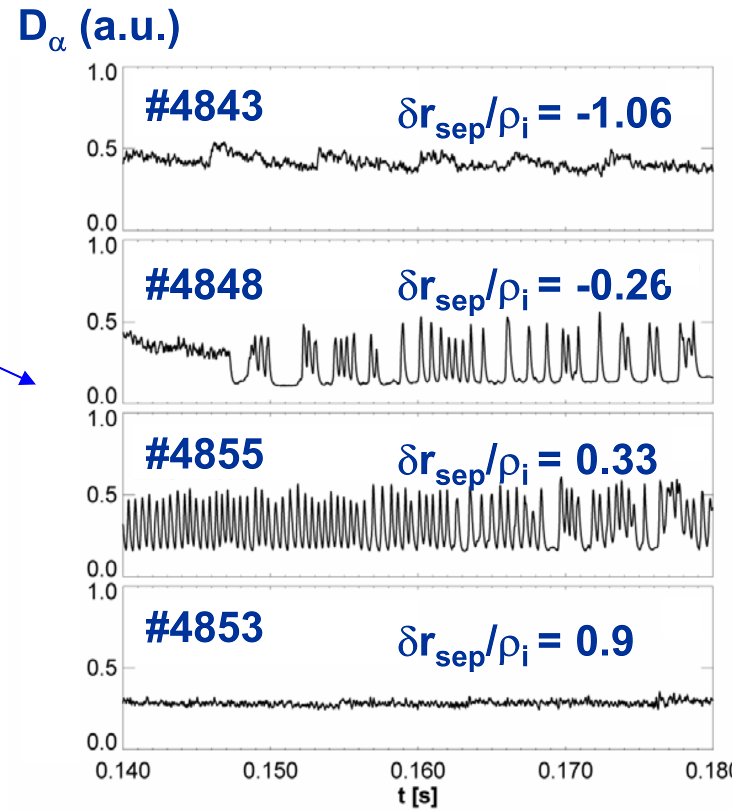
UKAEA Fusion Working with Europe

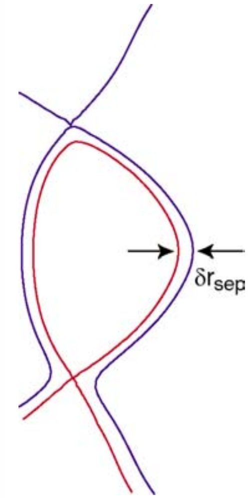
Effect of Magnetic Configuration on L-H Transition:

H Meyer

MAST







H-mode access optimised for $|\delta r_{sep}|/\rho_i \leq 0.5$, i.e. connected DND configuration (CDND)

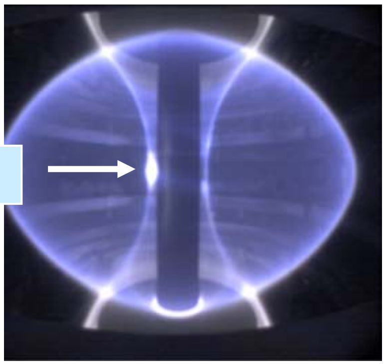
⇒ may be linked to large changes in parallel connection length

Subtle changes in the magnetic geometry are important for H-mode access - changes of the order ρ_i play a role.

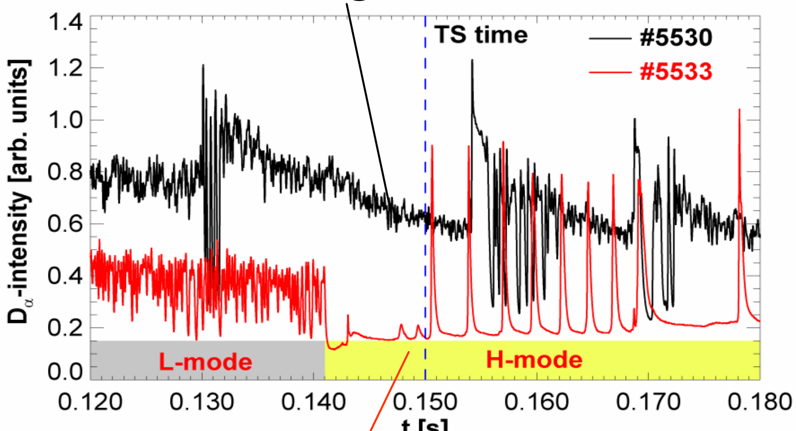
Inboard midplane fuelling improves H-mode access:

A Field

Inboard Gas Puff



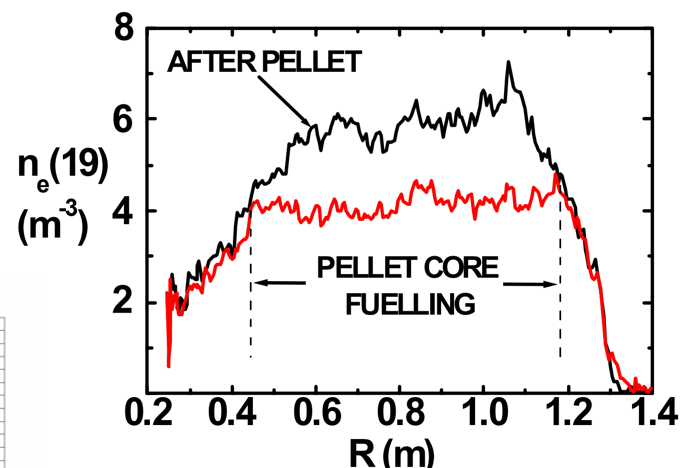
Outboard fuelling

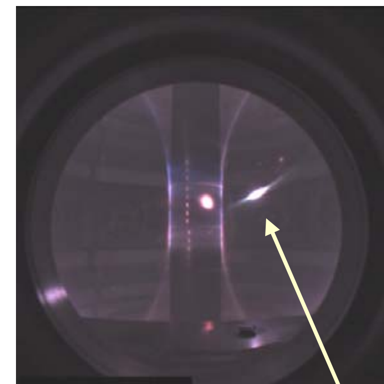


Inboard fuelling

Pellet injection provides internal fuelling in H-mode:

K Axon, C Ribeiro, S Shibaev





HSV frame showing PI

8-pellet Risø gas gun injector (used on RTP, FOM);

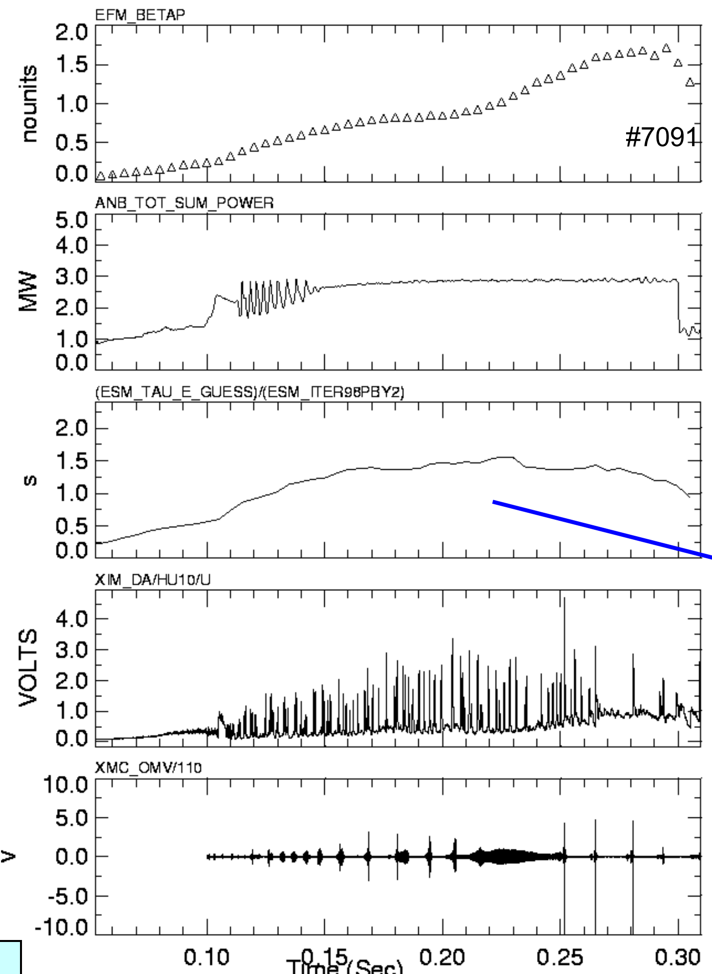
3 pellet sizes: 0.5, 1, 2×10^{20} atoms of deuterium

Pellet velocity 300 - 1200m/s

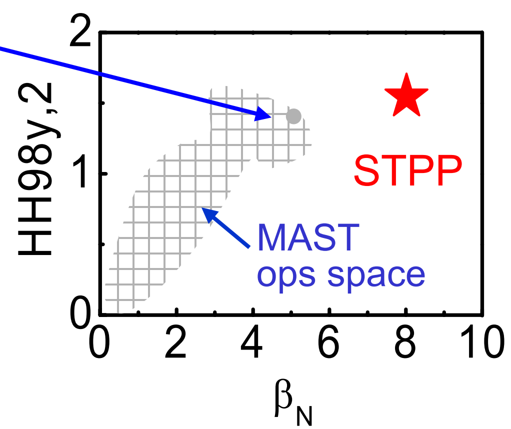
Initial estimates of fuelling efficiency ~ 50%

Low MHD and good confinement at high beta:

Highest β discharges had no disruption, little MHD and were limited mainly by operational constraints (position control, NB duration, etc.)



Increase in beta value have been achieved through confinement enhancement:



Typical high beta H-mode shot on MAST

Main Results in Heating & Confinement

- H-mode Access
- H-mode Confinement
- Internal Transport Barriers

H-mode access and pedestal studies

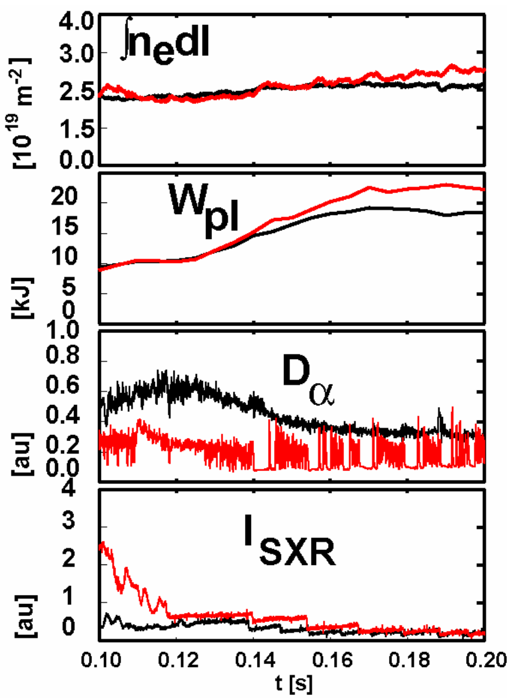
- **Parametric study of H-mode access (magnetic geometry of the edge, fuelling, plasma-wall separation)**
- **High resolution (300pt) TS system gives pedestal profiles in a single discharge**

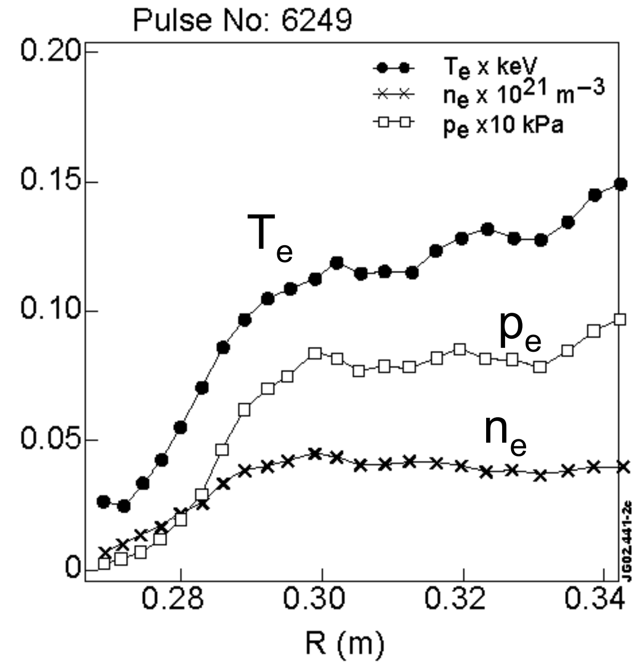
Inboard fuelling improves H-mode access

A R Field

Strong n_e pedestal ($n_e^{ped} \to n_{eo}$)
Weaker T_e pedestal ($T_e^{ped} \sim 0.1T_{eo}$)

Comparison of similar Ohmic discharges in MAST refuelled by inboard (#6108, red) and outboard (#6111, black) gas puffing. The D_α emission is from the upper divertor region.





H-mode confinement

• Data-sets of power threshold and energy confinement of ELMy H-mode from MAST have been assembled

Comparisons with international scalings show that:

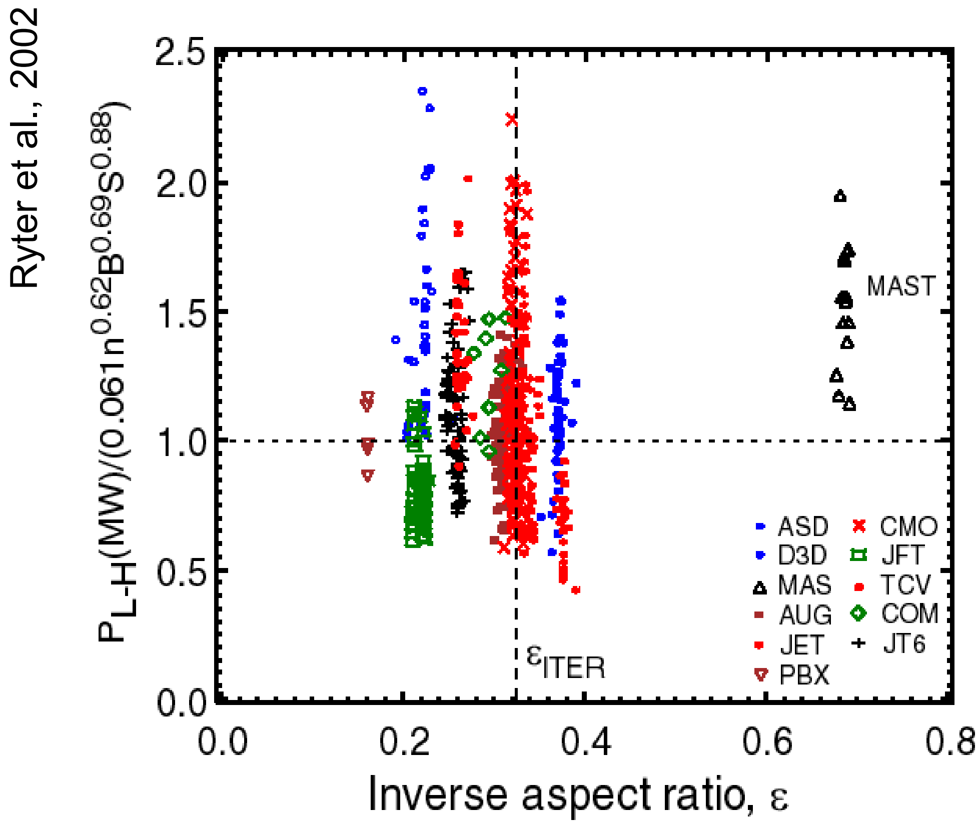
- MAST introduces a weak positive ε-dependence in the L-H power threshold

- MAST data is consistent with the global IPB98(y,2) scaling but supports a stronger aspect ratio dependence

- MAST indicates a quadratic R/a-dependence for pedestal energy scaling

H-mode power threshold scaling

- **MAST data significantly extends range of ε in ITPA database**



MAST data clearly favours scaling of the form **P_{L-H} ~ S**, rather than P_{L-H} ~ R^2

Enhanced threshold power in MAST would imply **P_{L-H} ~ $\varepsilon^{0.5}$** if not due to other factors (e.g. differences in divertor geometry)

MAST data is ~ 1.5x above scaling
M Valovic

H-mode confinement scaling

- **Data from in MAST extends global confinement database**

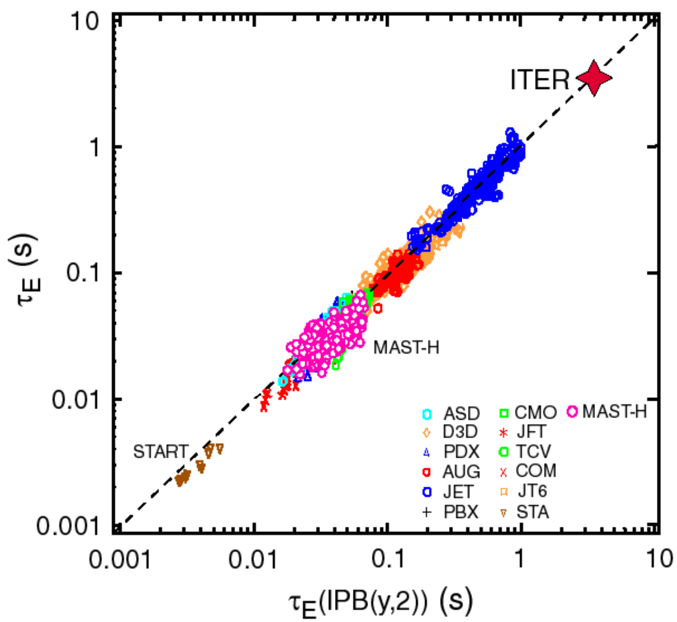
τ_E > 100ms obtained

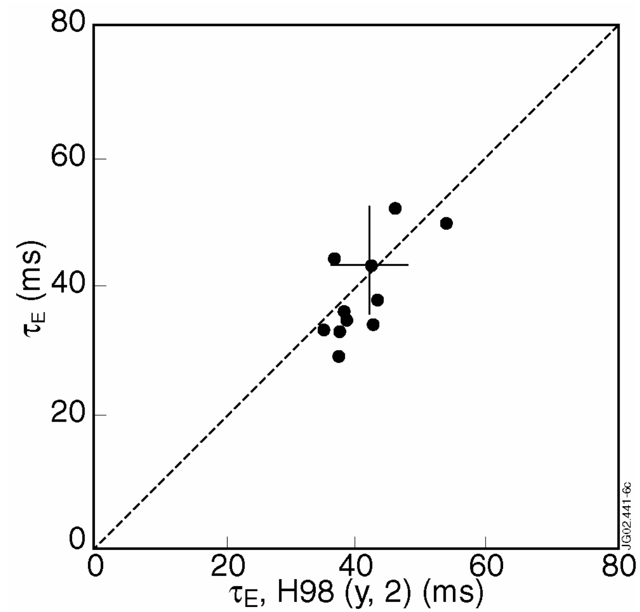
MAST τ_E in broad agreement with IPB98(y,2) scaling

MAST data doubles range of R/a in database

Kinetically validated data with low fast particle component and –0.05 ≤ (dW/dt) / P ≤ 0.35

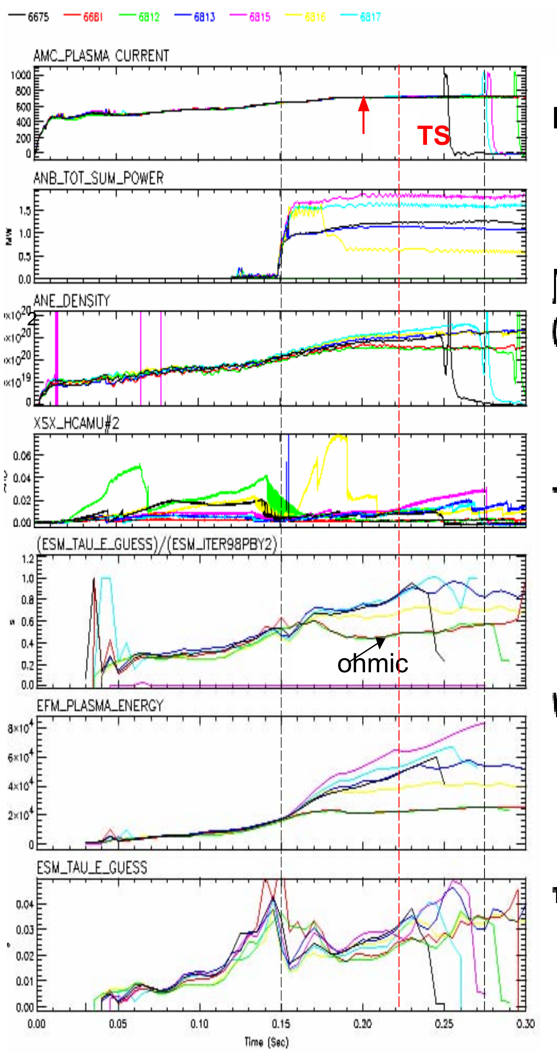
M Valovic





MAST data supports a stronger aspect ratio dependence: more detailed analysis indicates $\varepsilon^{0.8}$ may be better (cf $\varepsilon^{0.57}$ in IPB98(y,2)), **which is beneficial for STs**

NB Power scan in L-mode shows no degradation in confinement



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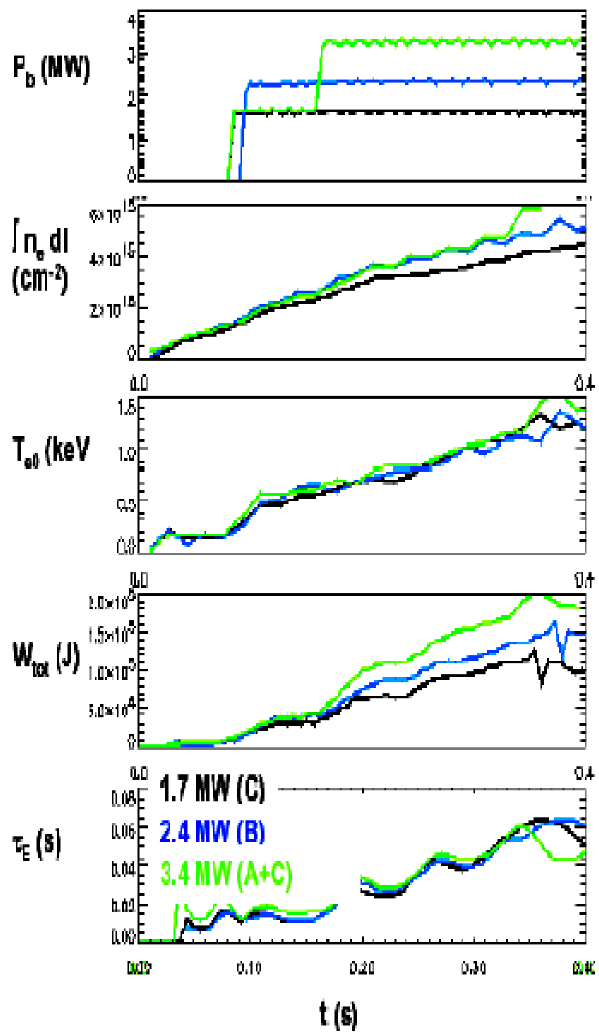
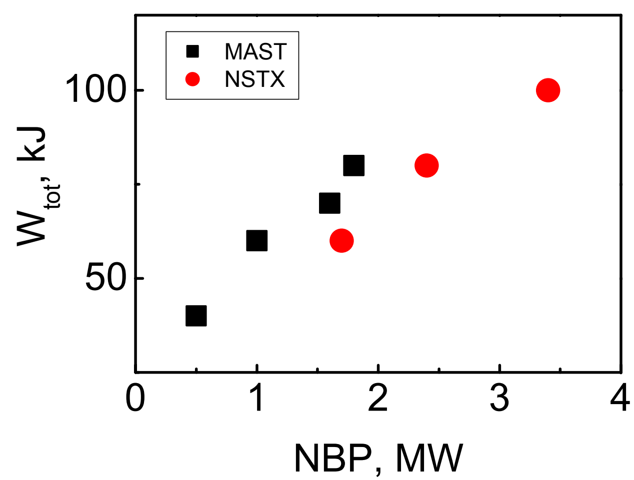


NSTX (D Stutman)

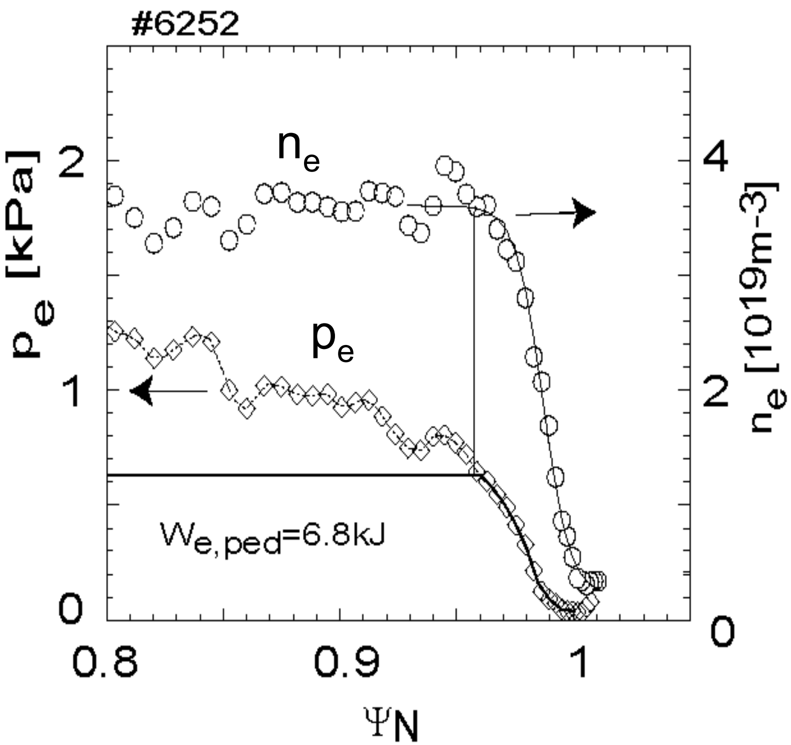
- **Similar results from MAST and NSTX (at high TF). Note, that dW/dt is high (transient regime).**



MAST

Pedestal Scaling

- **First data from MAST on pedestal scalings**



MAST W_e^{ped} ~ [0.5W_{scal}^{ped}]/4 , where $W_{scal}^{ped} = e^{-3.74} I_p^{1.71} R^{1.16} P^{0.31} M^{0.3} (q_{95}/q_{cyl})^{1.2}$ (Thomsen 2002)

$\Rightarrow$ if difference attributed to aspect ratio dependence, a scaling **$W_{scal}^{ped} \propto \varepsilon^{-2}$** is implied

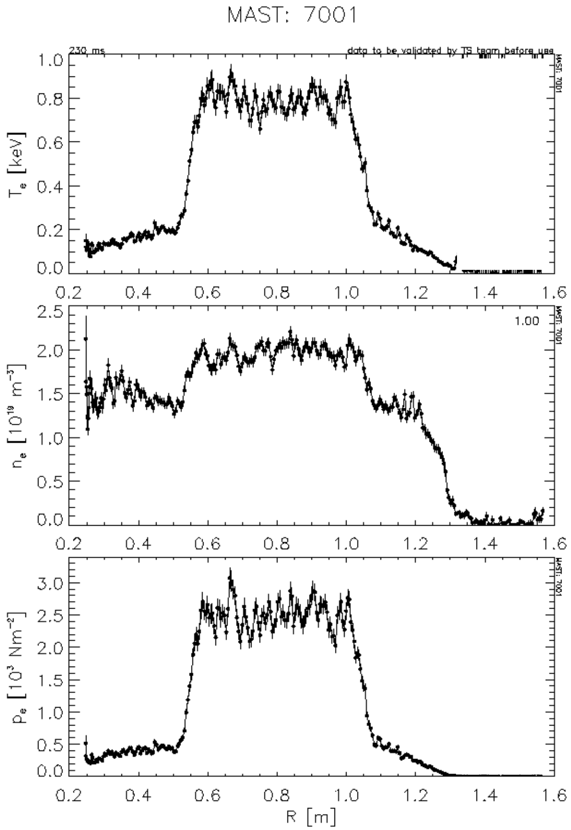
MAST data is significantly below scaling:
W_e^{ped} = 6.8kJ
(0.5W_{scal}^{ped}) = 30kJ
M Valovic

Internal Transport Barriers

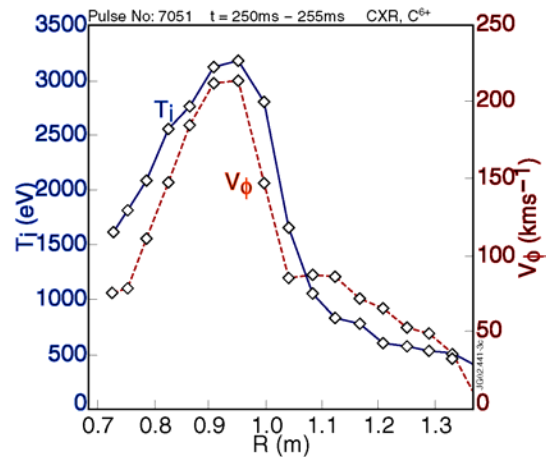
MAST

Strong indication of ITBs in MAST :

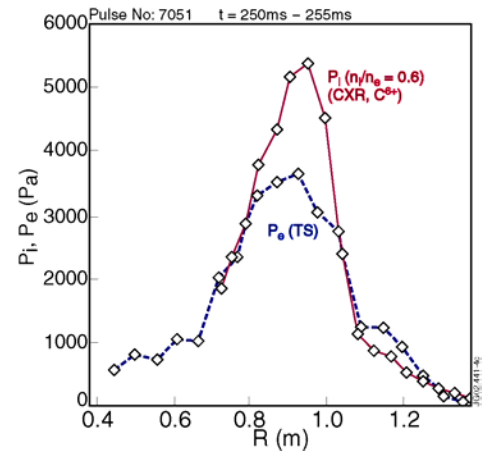
A R Field, C Challis



Electron temperature, density and pressure profiles, showing very steep gradients



T_i and V_ϕ profiles, from CXR C^{6+}, showing large thermal gradient at high velocity shear.



Electron and ion pressure profiles, showing steep gradients at position of high velocity shear.

Combination of current ramp and NBI produced steep ion and electron pressure gradients in the plasma core

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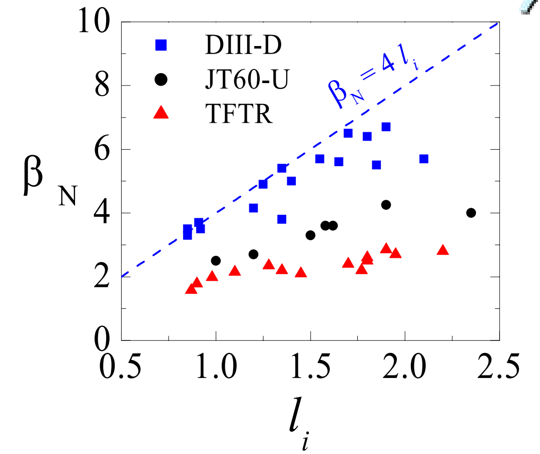
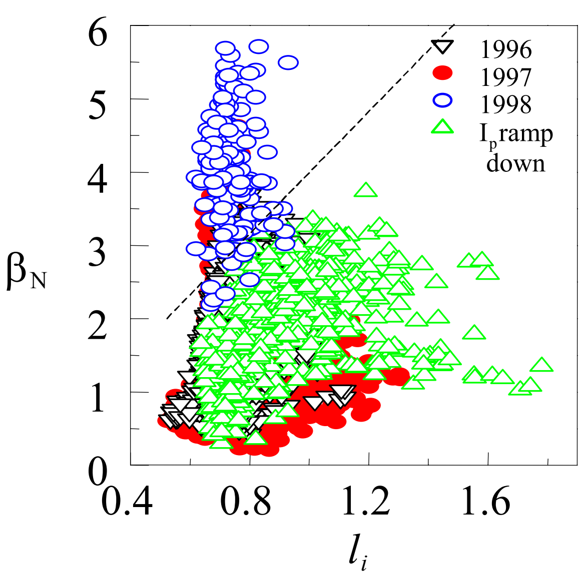
Main Results in High Beta & Stability

- **Good Stability at High Beta**
- **Good Confinement at High Beta**
- **Avoidance of Neo-classical Tearing Modes**

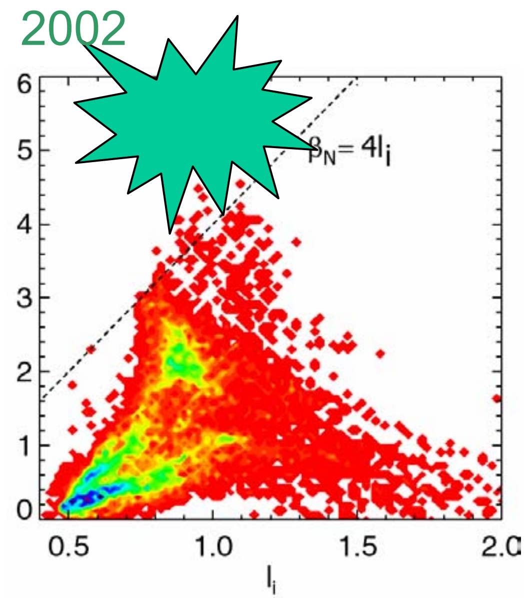
Route to high betas in STs: Limits

Unlike in conventional aspect ratio tokamaks, an empirical $\beta_N \leq 4l_i$ limit has not been justified in STs

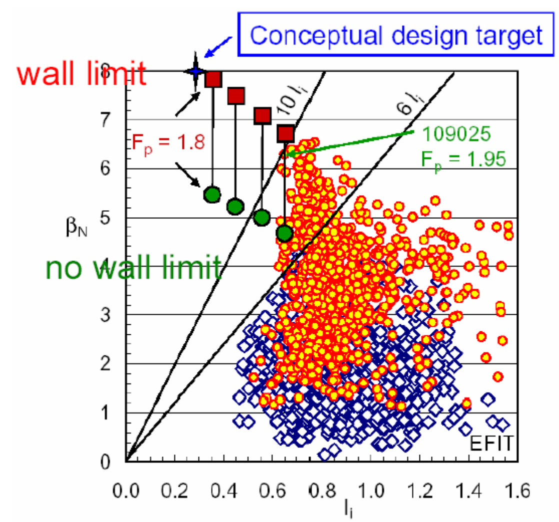




START



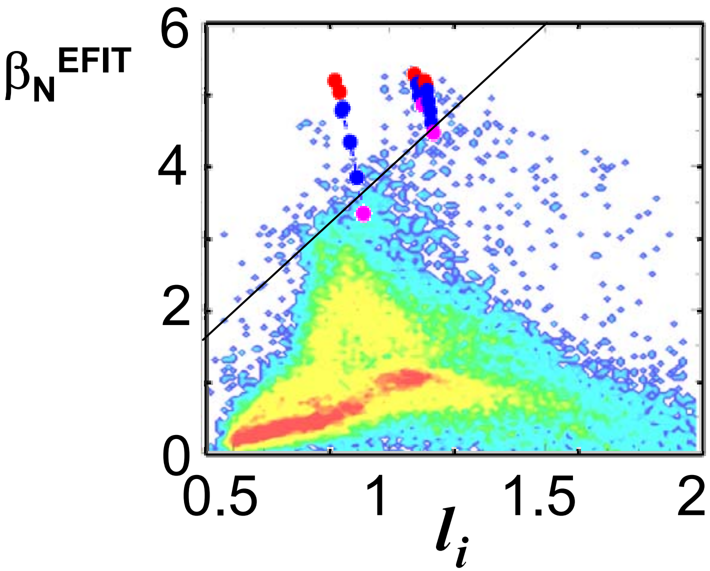
MAST



NSTX

Beta Operating Space

β_N > 5 achieved approaching ideal n=1 no-wall external kink limit



KINX simulations:
- ● unstable
- ● stable

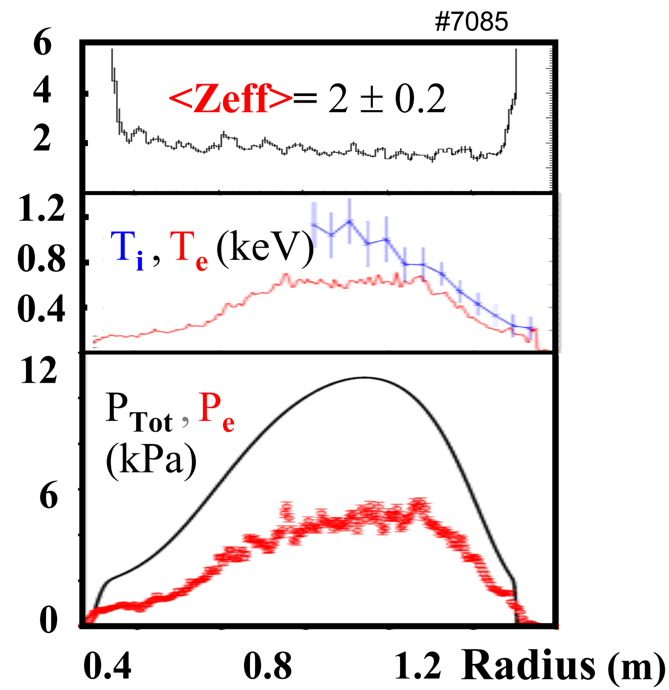
M Hole

KINX CODE:
DEGTYAREV, L., et al., Comp. Phys. Com. **103** (1997) 10.

Avoidance of neo-classical tearing modes (NTMs) by operating in regimes with no sawteeth (no seed)

R J Buttery

β values validated by kinetics:



$\Rightarrow$ $\beta_P = 2.1$

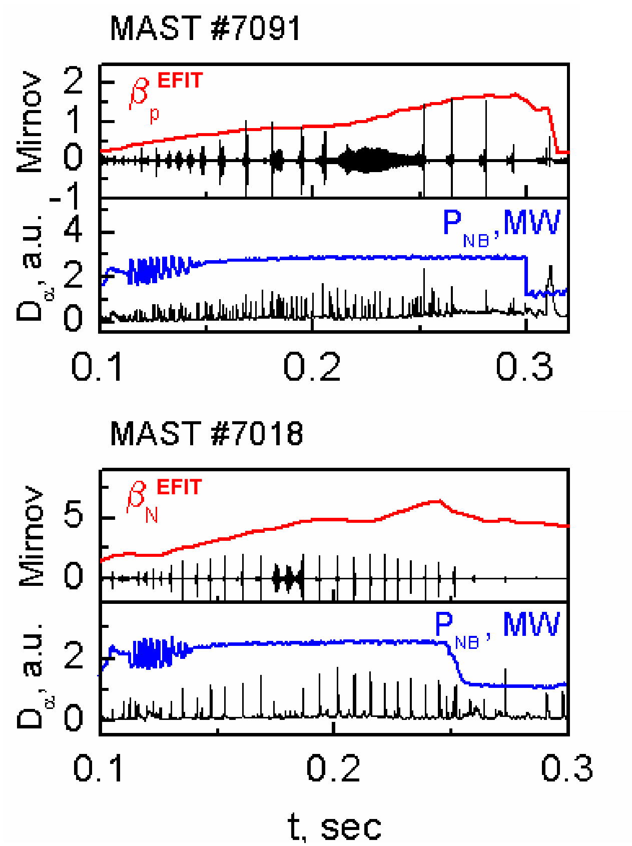
$\beta_N = 5.15$

bootstrap ~ 40-50%

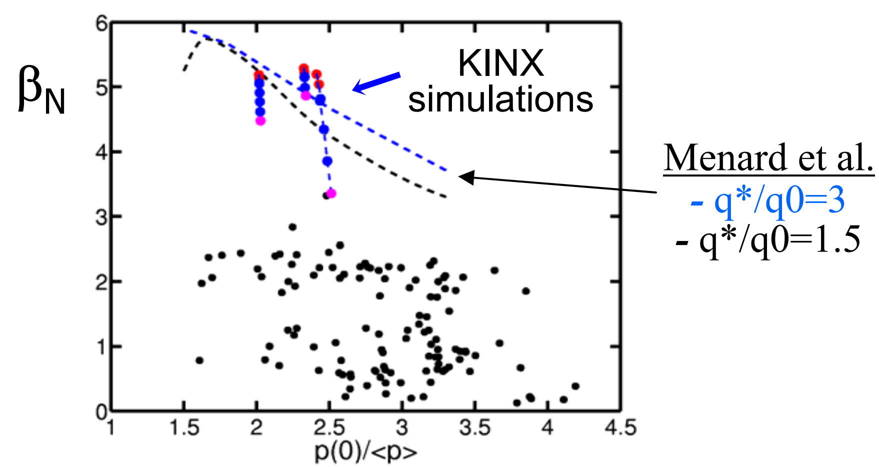
Beta Operating Space

High beta discharges have low MHD activity:

MHD activity is low at high beta:



Stability improves for broader (**H-mode**) profiles:
M Hole

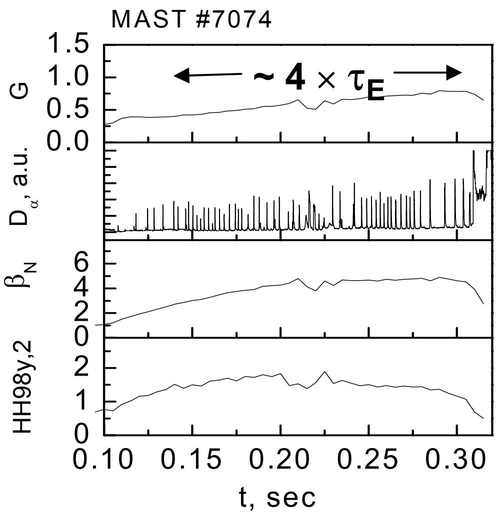


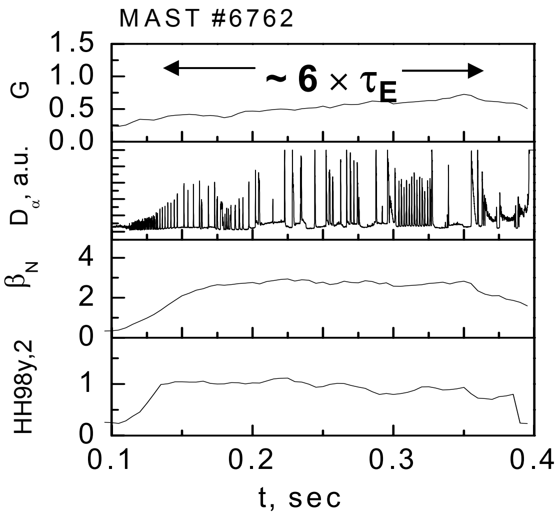
Scope for higher β_N by using less pressure peaked H-mode discharges

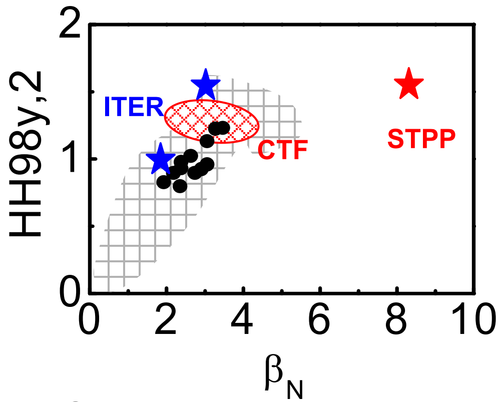
Contribution to the baseline ST scenario

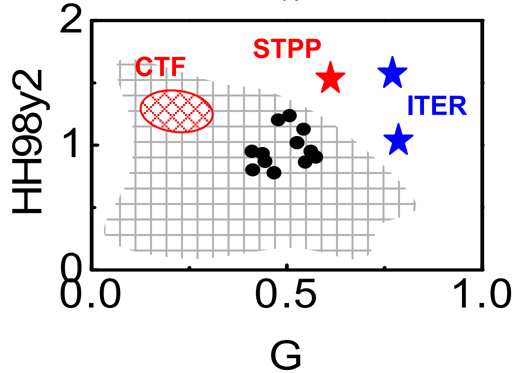
MAST

High beta sustained for several confinement times:









Many of parameters required for ST Component Test Facility have been achieved simultaneously

However, access to operating point of the ST Power Plant is a challenge for future experiments

MAST operating space with **future ST** and **ITER** parameters (**dots** - kinetically validated data with low FP component and $-0.05 \leq (dW/dt)/P \leq 0.35$)

H Wilson, M Valovic

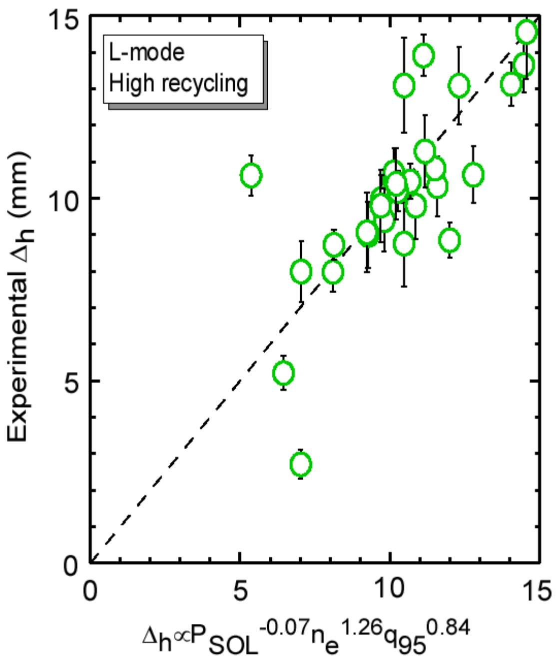
UKAEA Fusion Working with Europe

Main Results in
Exhaust, ELMs & Halo Currents

- Divertor Power Loading & ELMs
- Divertor Biasing
- Halo Currents

SOL physics development

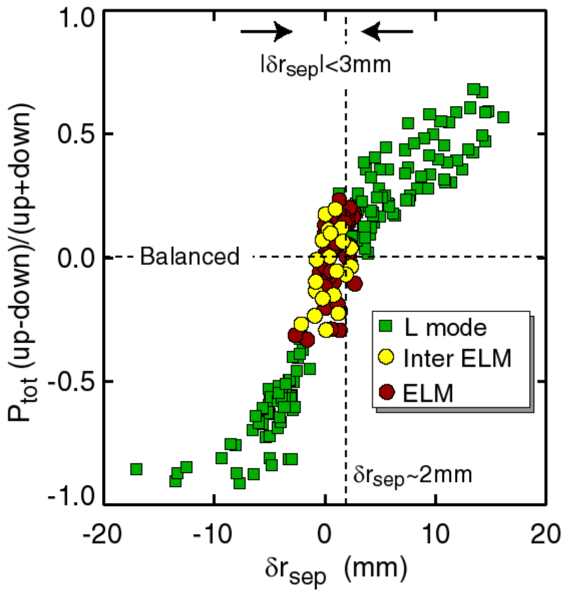
- **Scalings for L-mode SOL heat flux width developed**



- weak negative dependence on P_{SOL}
- approx. linear with n_e and q_{95}
- inner and outer SOL comparison gives robust B_T scaling $\propto B_T^{-0.8}$

$\nabla_{//}B/B$ factor 10 larger in ST, which drives strong upstream flows

- Mid-plane Mach probe measures M ~ 0.2

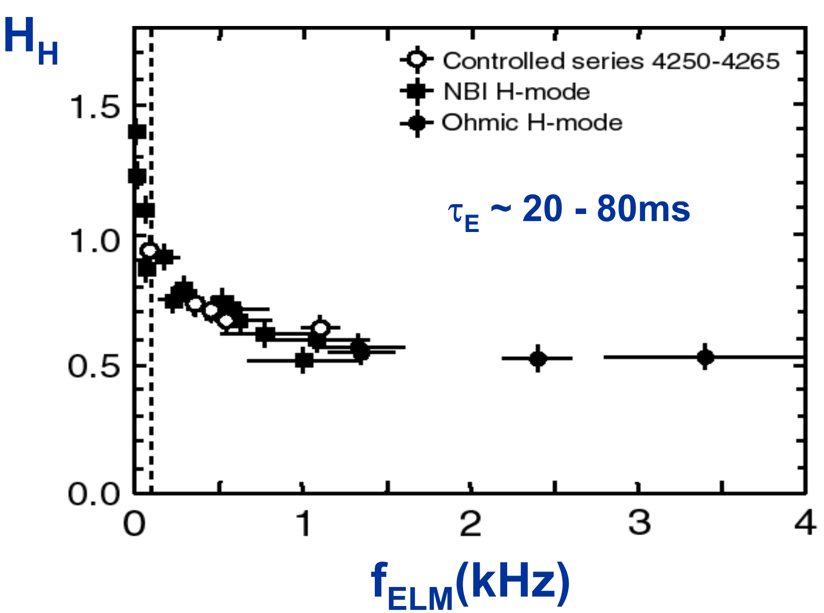


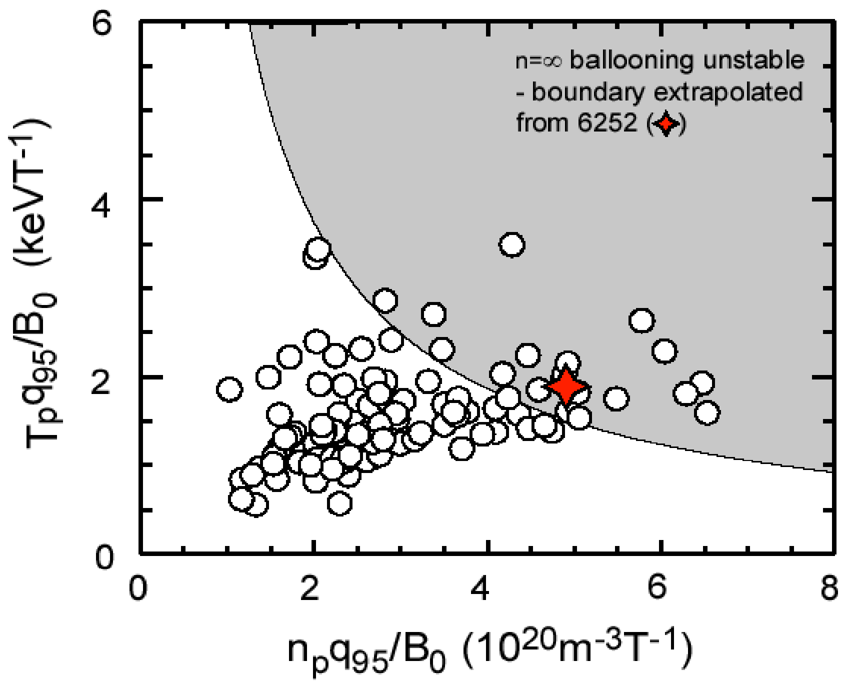
Up-down power distribution: balanced for CDN with dr_{sep}~2mm asymmetric due to ion ∇B drift
Balanced operation is important for minimising power loading in Next Step STs

Power efflux & impact of ELMs

MAST

H_H increases at low ELM frequency:





ELMs exhibit Type III characteristics

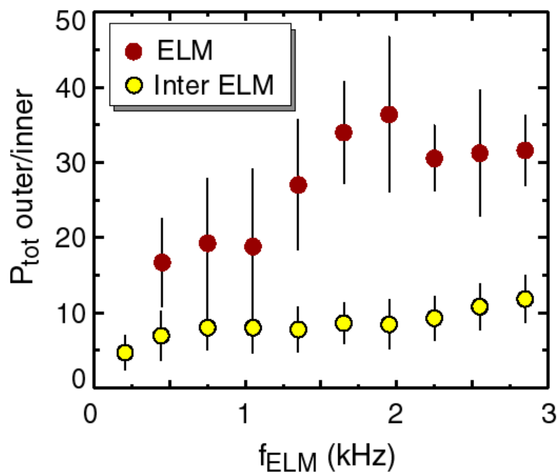
Stability analysis indicates that pedestal parameters in some discharges approach high-n ballooning limit (Type-I ELMs)

but $\Delta W_{ELM}\, f_{ELM}/P_{heat}$ < 5% under all conditions so far

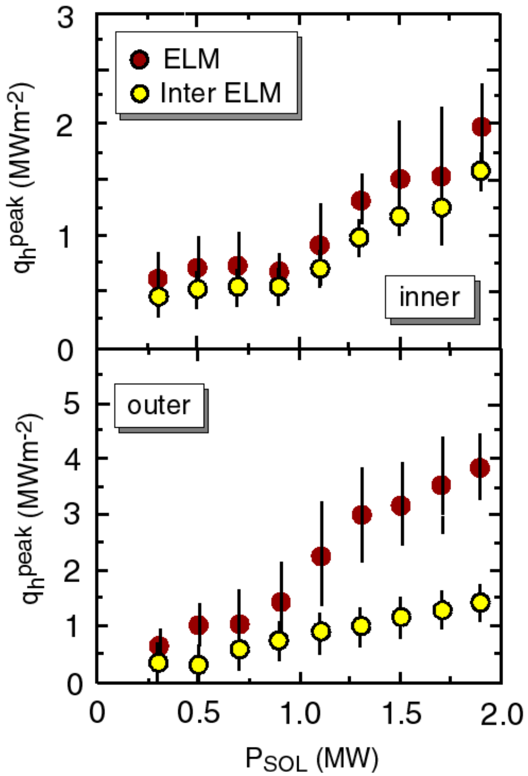
UKAEA Fusion Working with Europe

Power efflux & impact of ELMs

Power distribution favourable for ST:



and power load is tolerable:

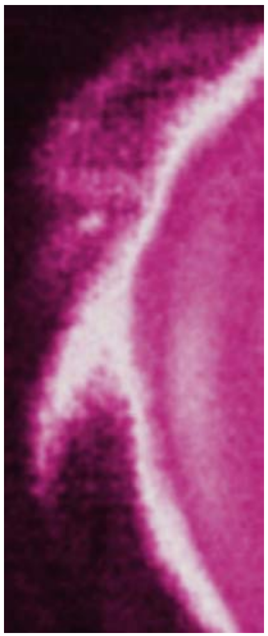


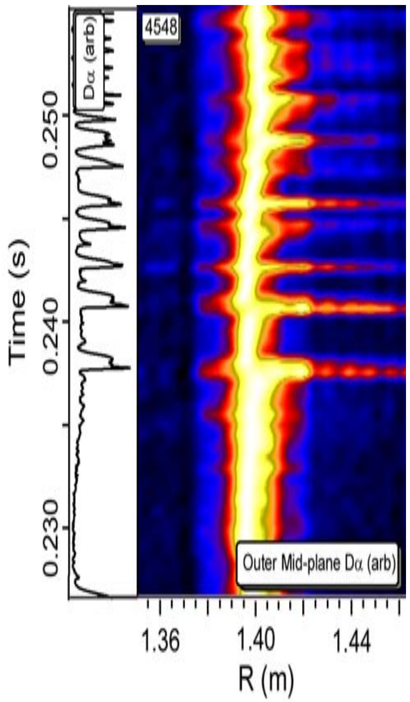
Both steady-state and transient (i.e. due to ELMs) power efflux strongly biased to outboard side where it is more easily handled

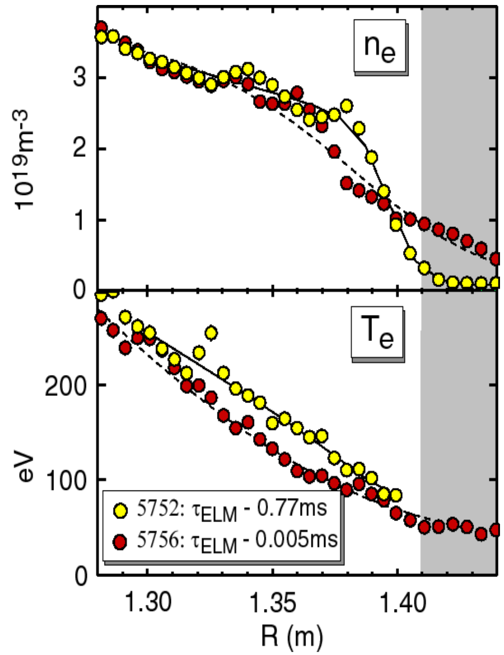
At ELM peak P_{max} = 2MWm^{-2} (inboard)
= 4MWm^{-2} (outboard)

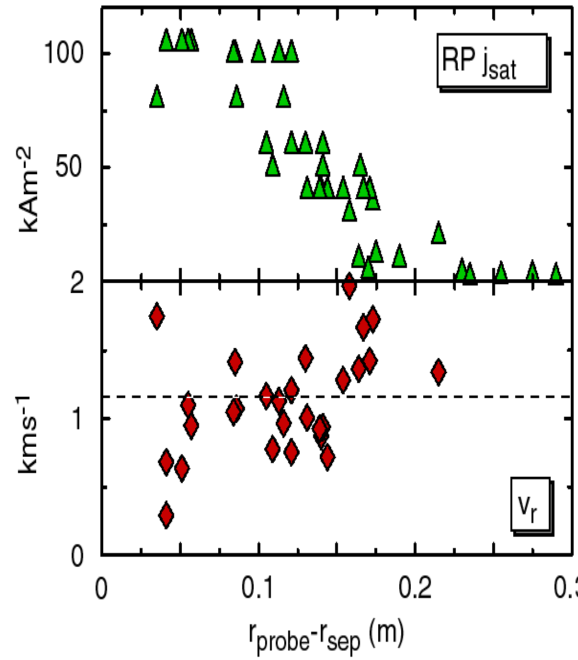
ELM effluxes far into SOL

ELM effluxes extend up to 30cm beyond separatrix at outboard side









Plasma edge on START (L-mode)

Linear D_α camera shows outboard expansion of ELMs

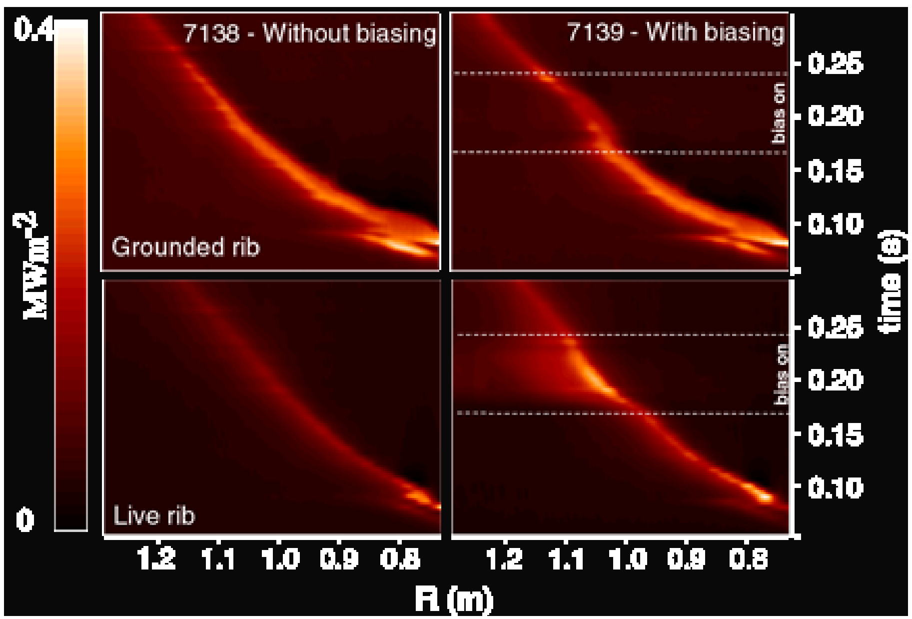
Density and T_e profiles before and during ELM also show formation of outboard tail

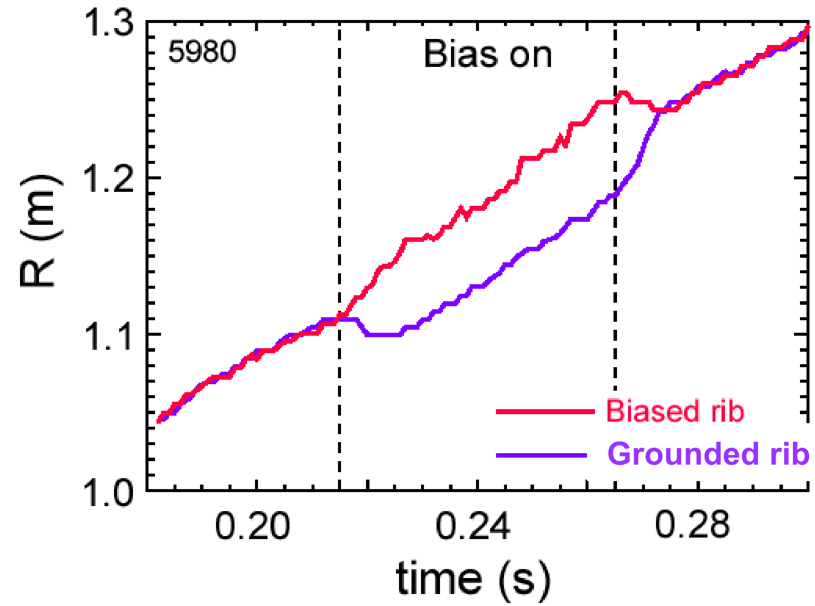
Radial expansion of outboard localised structure at ~ 1km/s
"ballistic" mechanism ?

Toroidally Asymmetric Divertor Biasing

Initial divertor biasing experiments show promising effects

G F Counsell





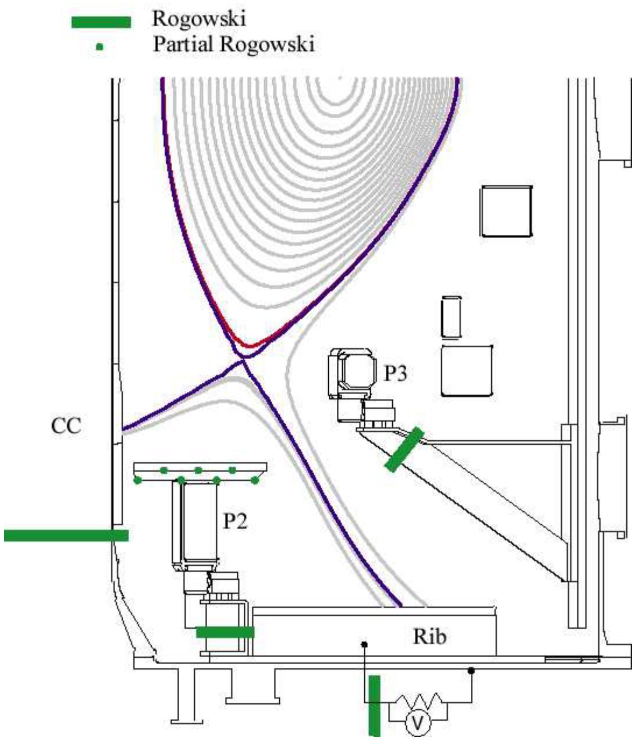
Strike point movement in accordance with theory

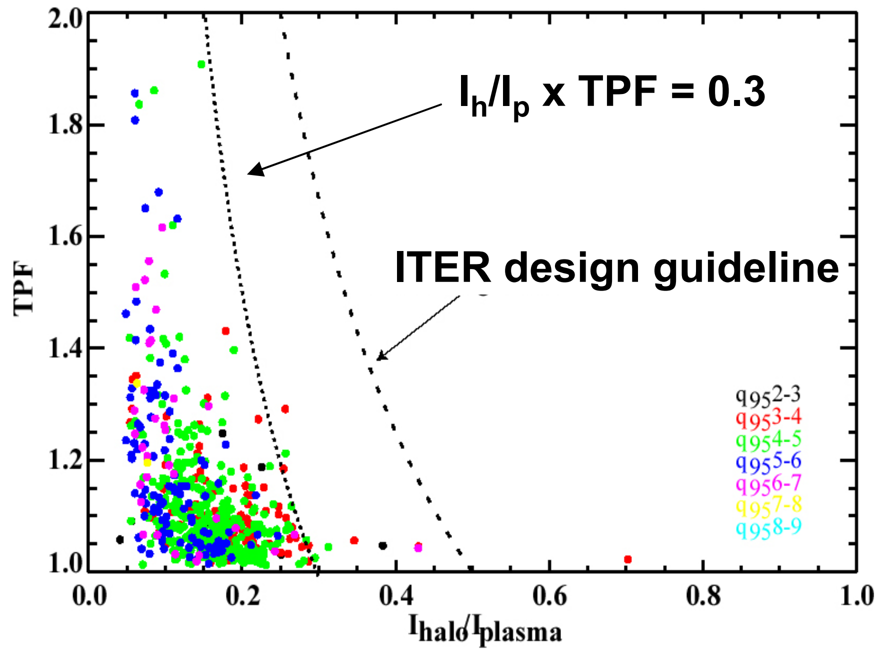
No significant changes to other 3 strike points or core plasma, consistent with theory

Applications to ITER using self-biasing of components (different materials, angled tiles etc.)

Halo Currents

I_h/I_p x TPF < 0.3 in MAST





All halo current paths monitored:
current entering structures ~ current returning to plasma
Currents and asymmetries smaller than other tokamaks

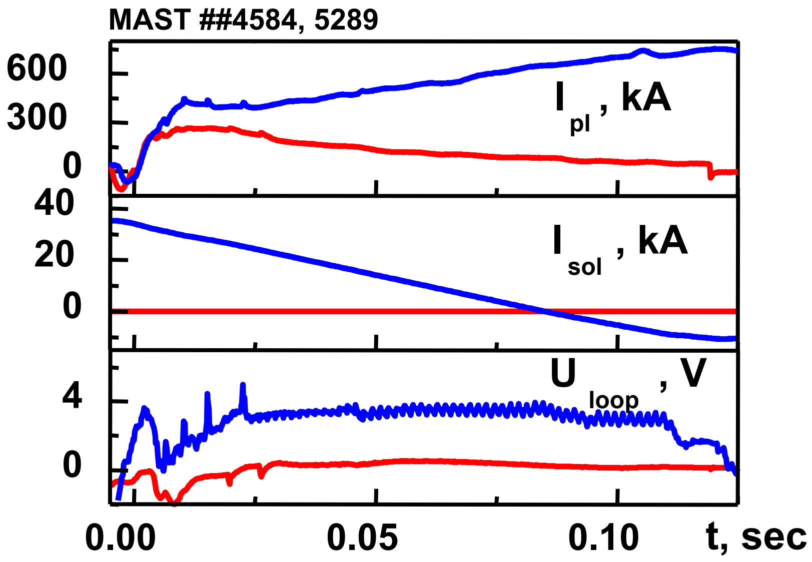
R Martin

Main Results
ST steady-state issues

- Non-solenoid start-up and current ramp
- Current sustainment, bootstrap, current drive

Non-solenoid start-up and current ramp

Plasma formation without use of solenoid flux demonstrated



Merging-compression minimises use of central solenoid flux during start-up

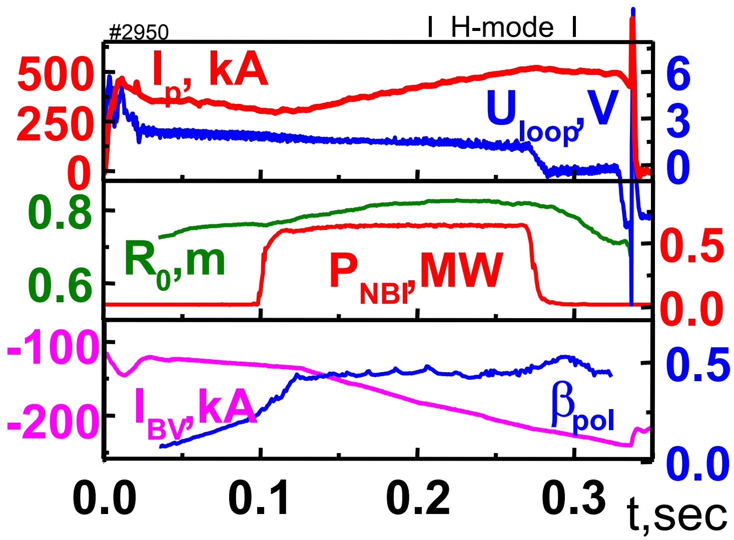
Reliably used in most MAST regimes

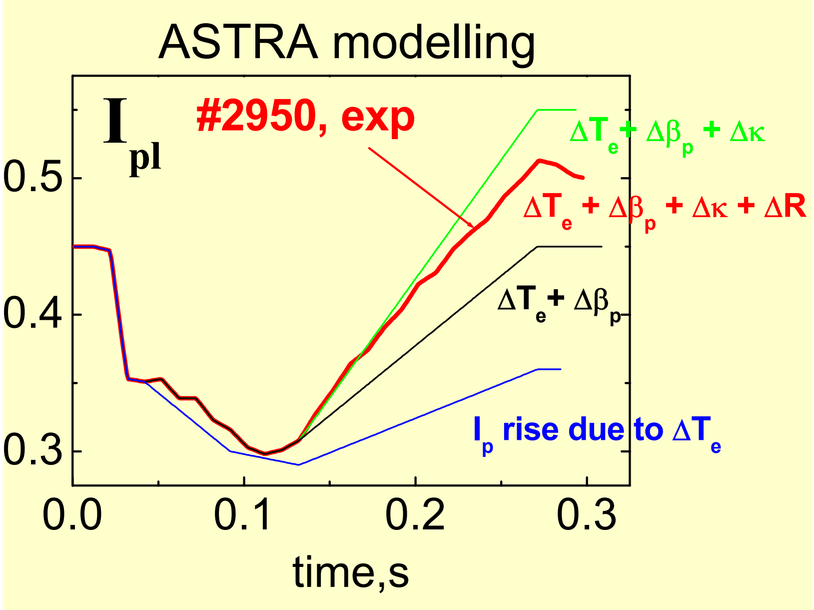
0.5 MA achieved on MAST

Good target for non-solenoid current ramp

Non-solenoid start-up and current ramp

Plasma current can be ramped-up using only flux from BV coils during NB heating and sustained for τ > resistive time





Plasma current doubled at constant U_{loop} during NBH
only 20% assigned to change in resistivity

Plasma current sustained at zero U_{loop} for 0.2s, which is ~ resistive time

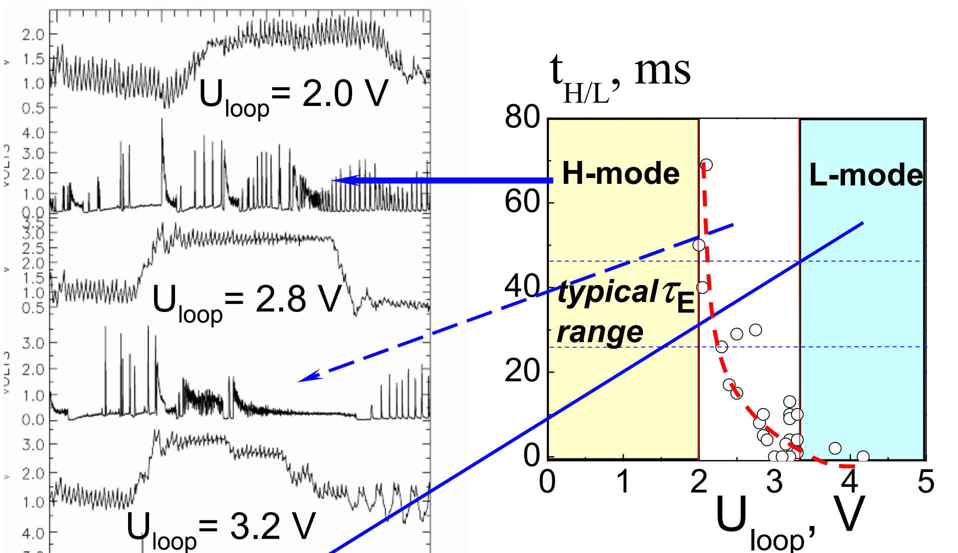
Current ramp in H-mode

I_{pl} ramp in H-mode allows high dI_{pl}/dt and uses BV flux more efficiently

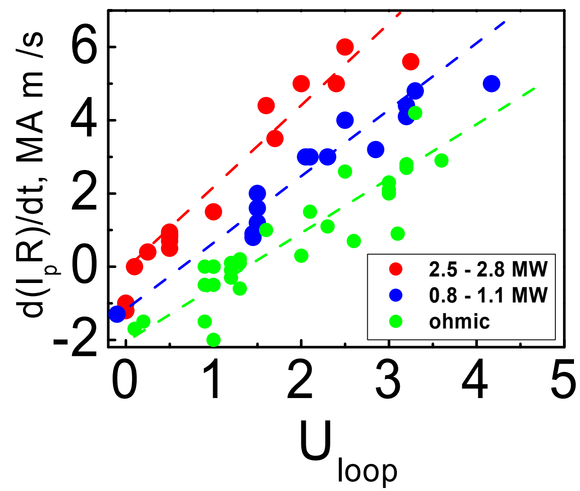
Current ramp-up speed up to 8MA/s achieved without increase in MHD

H-L transition depends on the **applied loop voltage** but is not directly connected with plasma current ramp-up speed ...

… plasma current ramp-up speed can be more than doubled without increase in MHD activity when more NB is applied



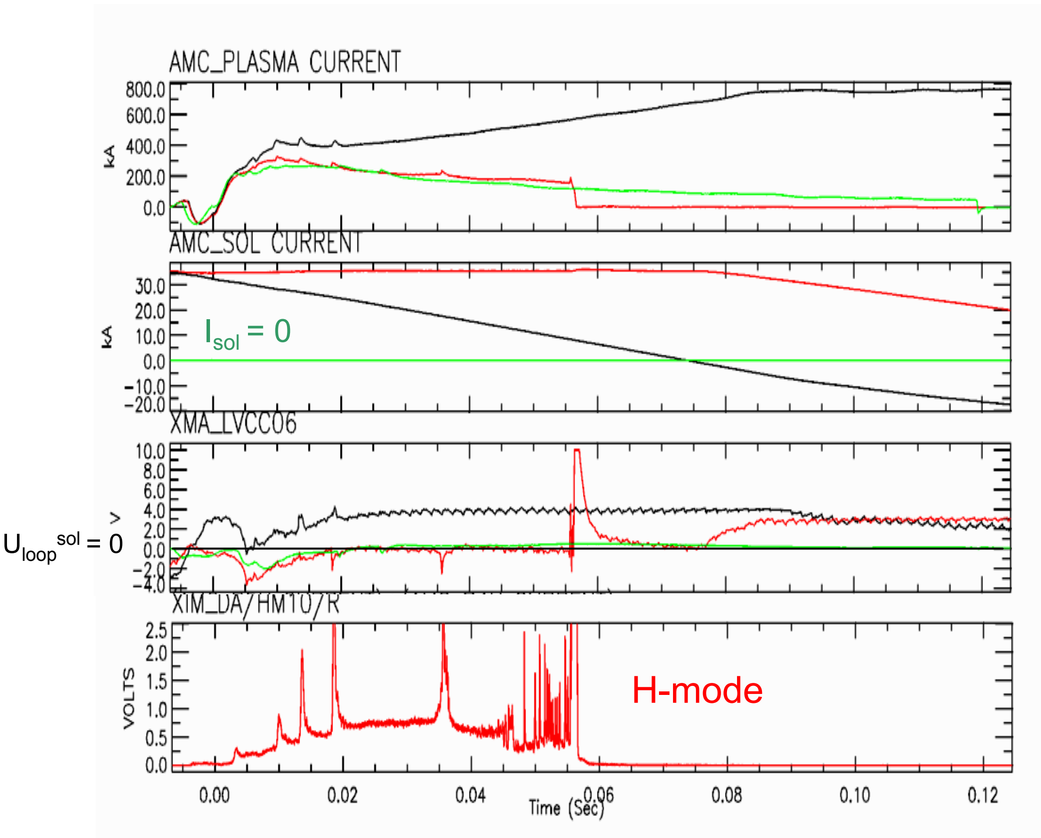
Time of H-L transition vs applied U_{loop}

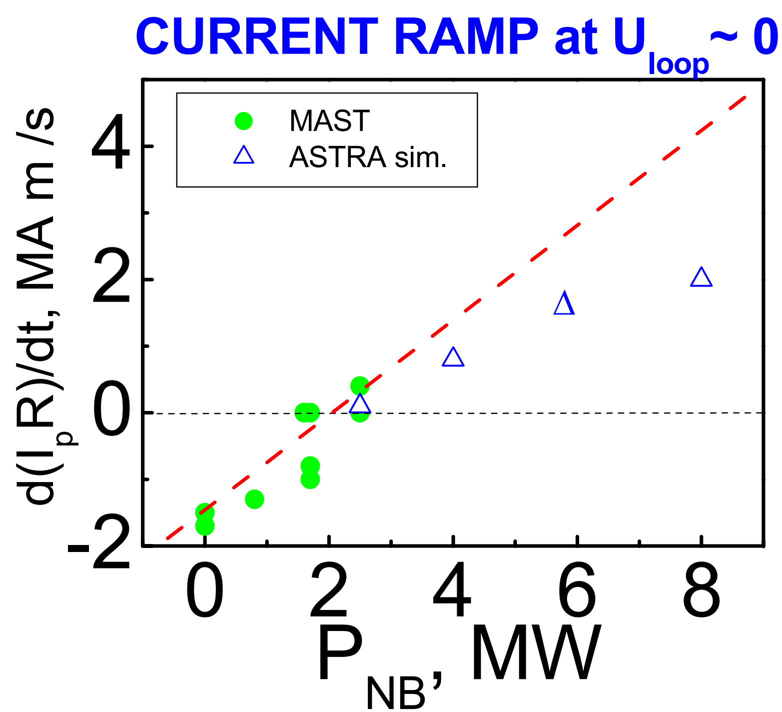


Plasma current ramp-up speed vs applied U_{loop}

Non-solenoid start-up and current ramp

- I_p > 0.3MA obtained using "merging-compression" formation without use of solenoid flux. Similar currents have been achieved on JT-60U



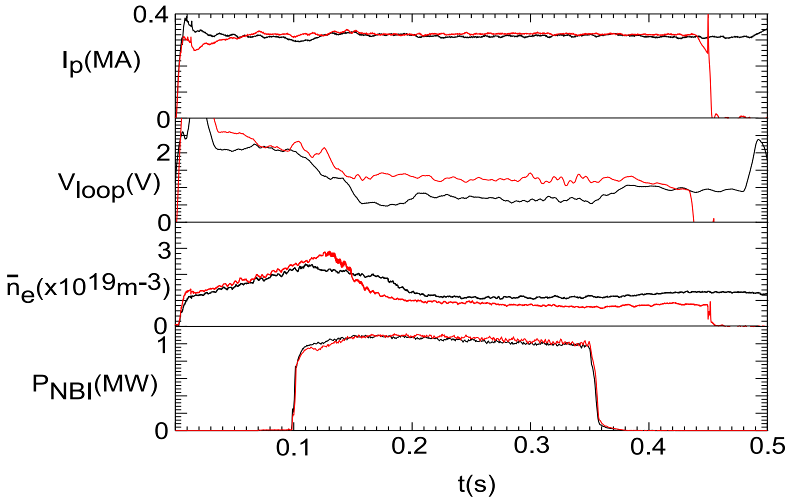


Plasma current can be ramped-up without use of the solenoid flux (ASTRA simulations)

NBCD and Bootstrap

Preliminary neutral beam current drive studies indicate beam driven current comparable with theoretical predictions (I_{NB}/I_p ~ 0.3)

- Current ramp-up and sustainment using bootstrap overdrive for STs appears promising
- Large $\varepsilon\beta_{pol}$ is achievable ($\varepsilon\beta_{pol}$~1.6) and stability to ideal and resistive MHD is favourable in STs

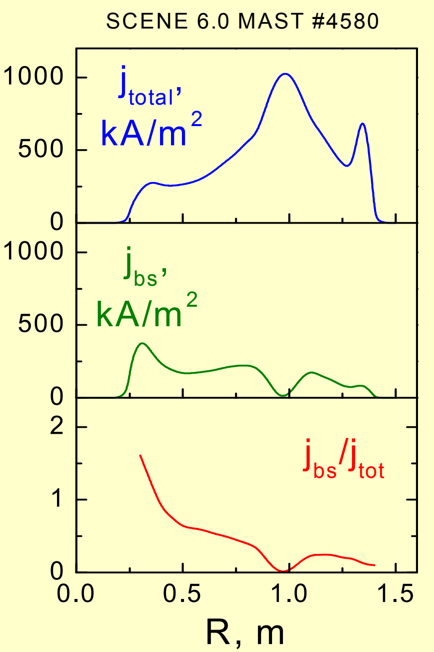


Counter-NBI (#6612)

Co-NBI (#6536)

#7085 $\beta_P = 2.1$
$\beta_N = 5.15$

bootstrap ~ 40-50%



Bootstrap current in high-performance shot 4580 calculated using SCENE equilibrium code and confirmed by TSC simulations. $I_{non-ind}/I_{total}$ ~ 0.48

H Wilson, A Nicolai (Julich)

Conclusions

MAST data are making important contributions to key physics R & D issues for ITER, as well as helping to establish the viability of the ST concept

Considerable advances in areas relevant to the physics basis for operations in next-step STs *(start-up, current ramp, stability, confinement, current sustainment and exhaust issues)*

Together with the extensive array of high quality diagnostics on MAST, these results provide an excellent platform for further input to key ITER physics studies and issues of specific relevance to the viability of the ST concept

Forward Programme

Autumn 2002 - April 2003:

EBW antenna, P_{NBI} > 3MW & continuation of key ITER physics studies

Sustained high beta operation (incl. NTM studies)
Increased elongation
Non-inductive current drive (NBCD, high bootstrap current regimes)
Confinement optimisation (energy/particle), H-mode dynamics
EBW tests
Divertor power loading studies (SOL scaling, detachment, divertor biasing) and ELM characterisation/impact
Implement digital control system

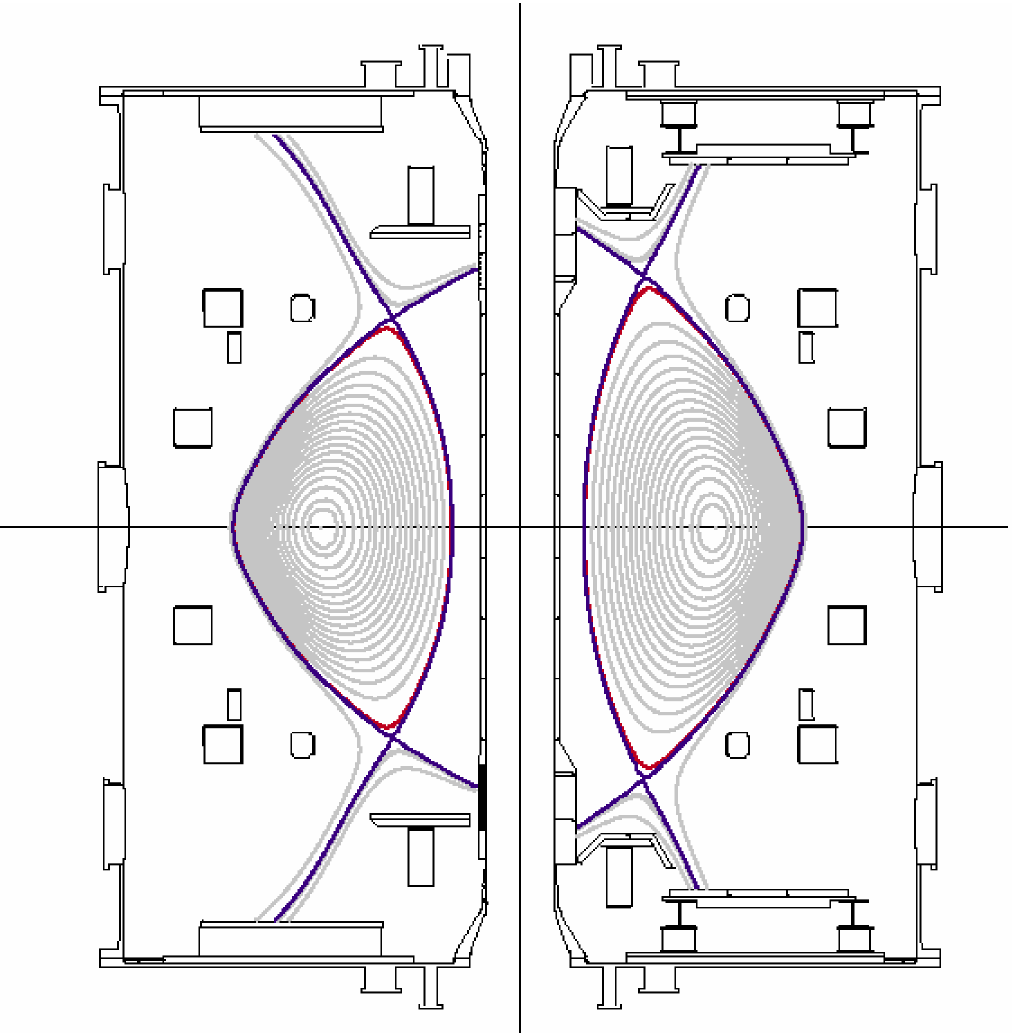
May - December 2003

Install MAST improved divertor
Install new centre column
PF coil modifications

2003 on - ITER studies + focus on key issues for development of ST concept

Extend pulse length to 5s, P_{NBI} to 5MW exploiting improved power handling capabilities
Exploit strong shaping capabilities of the ST ($\kappa \rightarrow 3$)
Integrated scenarios (sustained high beta with high bootstrap fraction, NBCD, optimised fuelling and effective exhaust)
Innovative start-up/heating/current drive schemes (e.g. EBW)

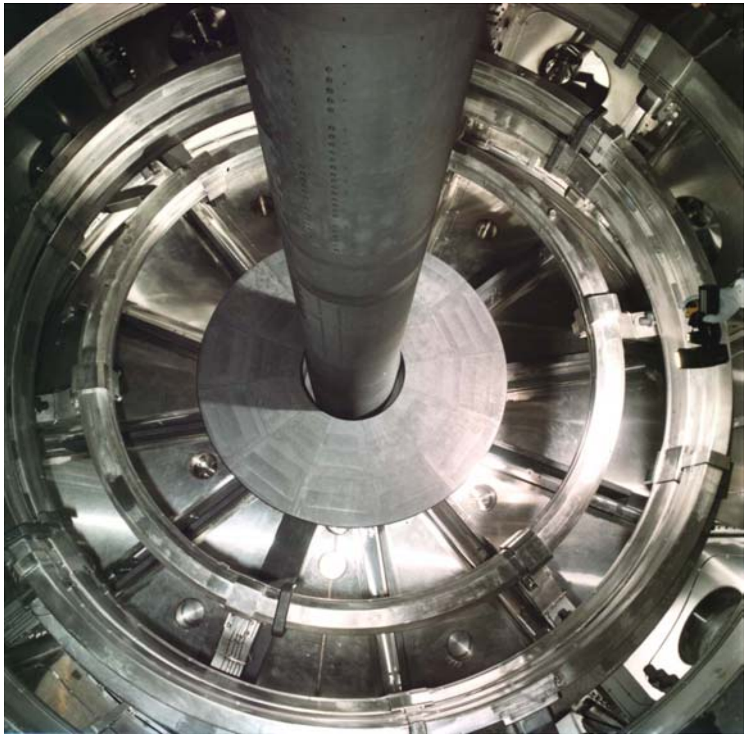
MAST Improved Divertor (MID)



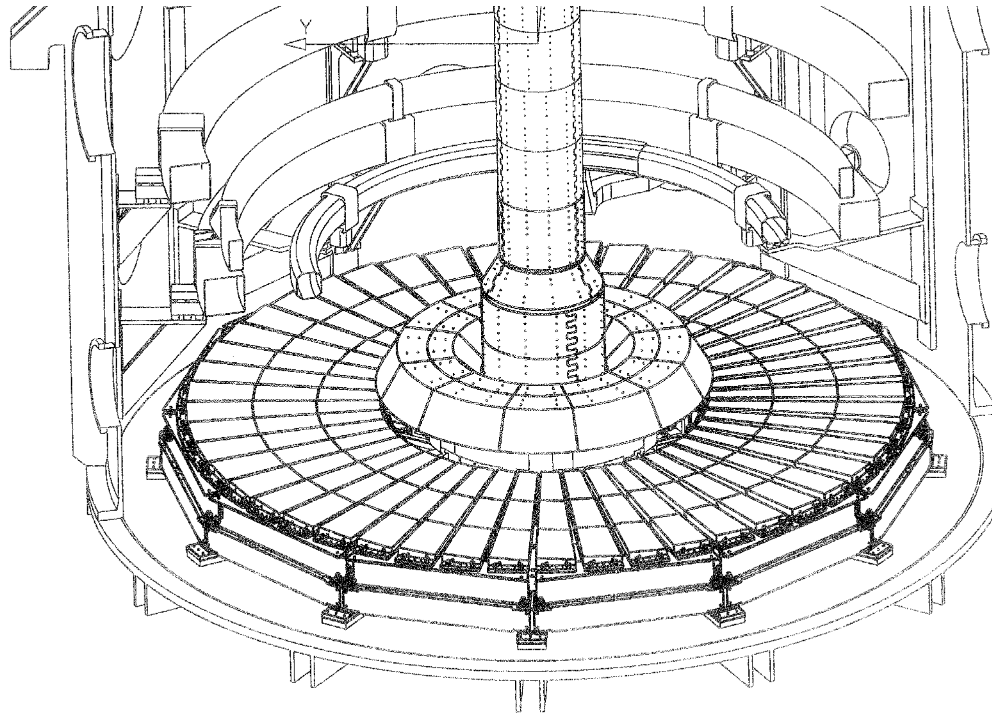
The design features:

- Controllable inboard gas puff
- Larger footprint for inner SOL strike points
- Smaller flat section of P2 armour, to ease H-mode access
- Longer solenoid & 10cm higher P2 coils/plates to aid high k studies

MAST Improved Divertor (MID)



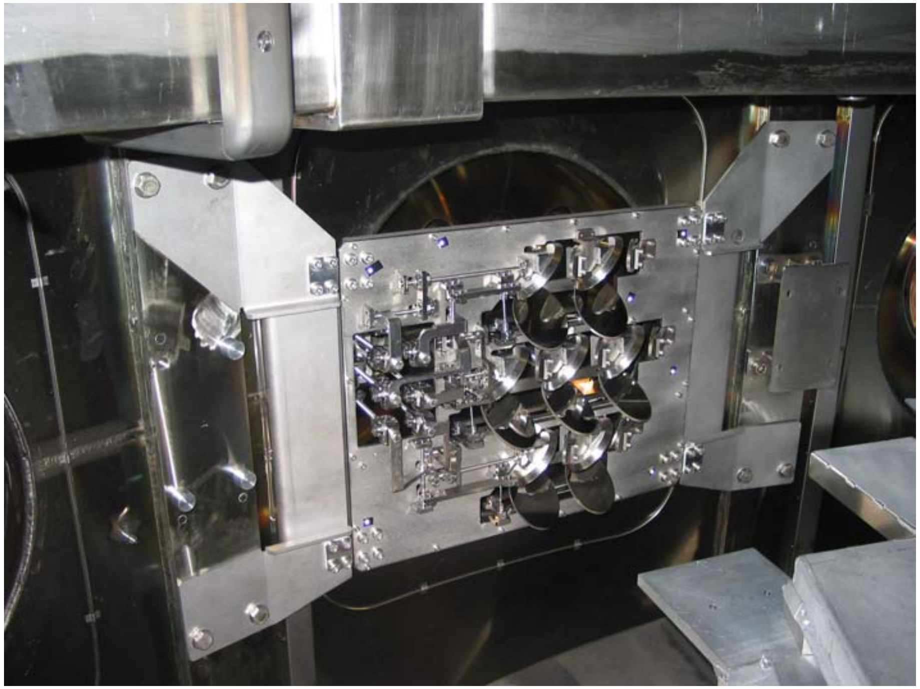
Present divertor



MID, to be installed in 2003

Plant Improvements

New centre column



60GHz EBW Heating in MAST
(new antenna installed Sep 2002)

Summary

Reliable H-mode access established allowing input to ITPA databases

H-mode access optimised for
(i) inboard fuelling - link between neutral distribution & plasma rotation
(ii) connected DND configuration (favourable exhaust properties)

Quasi-stationary H-modes established with good confinement $\tau_E \sim \tau_E^{IPB98(y,2)}$

Indications of both particle and energy internal transport barriers;

High normalised beta ($\beta_N > 5$) close to the ideal no wall stability limit;

Strong bias of steady-state & transient power efflux to outboard divertor targets where it is more easily handled; $\Delta W_{ELM} / \Delta W < 4\%$ to date but ELM effluxes up to 30cm beyond outboard separatrix

Initial divertor biasing tests promising - several results in accordance with theory

Low halo current magnitudes and asymmetries, I_h/I_p x TPF < 0.3;

Promising indications of neutral beam current drive.