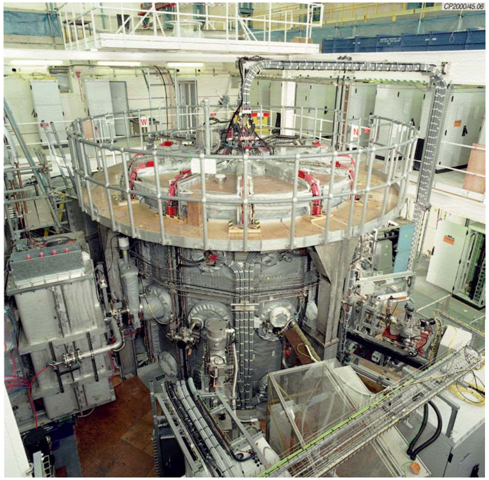
Recent Results from MAST



Mikhail Gryaznevich for the MAST Team
Euratom/UKAEA Fusion Association

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UKAEA Fusion Working in Europe

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Outline

Analysis of 2003 results

Recent modifications to MAST

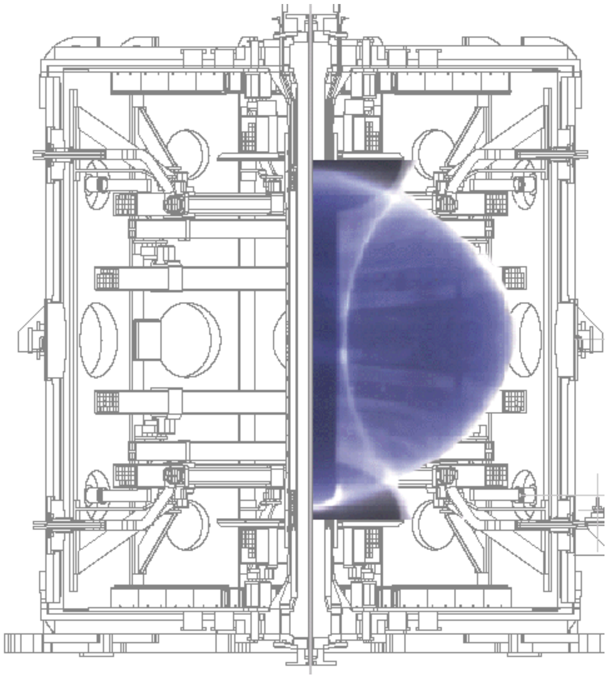
Main aims of M4 campaign

First Results:

- non-solenoid start-up
- EBW heating and current drive experiments
- Error field studies and control
- ELMs, SOL and exhaust studies

Future plans

MAST Parameters



			Design	Achieved
Minor and Major radii	a, R	[m]	0.65, 0.85	0.65, 0.85
Elongation	κ		≥ 2	2.45
Aspect ratio	A		≥ 1.3	1.3
Plasma current	I_P	[MA]	2	1.35
Toroidal field	B_ϕ@R	[T]	0.52	0.52
Aux. Heating				
NBI power	P_{NBI}	[MW]	5	3.3
ECRH power	P_{ECH}	[MW]	1.4	0.9
Pulse length	t_P	[S]	5	0.7

Open divertor, up-down symmetric - upgraded 2004

Graphite protection on all plasma contacting surfaces

Flexible configuration

Plasma cross-section and current comparable to ASDEX-U and DIII-D.

Adaptable fuelling systems - inboard & outboard gas puffing plus multi-pellet injector

Digital plasma control (PCS supplied by GA)

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Overall Focus

Three key elements:

- **Address key ITER physics issues**, driven by International Expert Groups (ITPA) and co-ordinated research activities
- Test aspects of **magnetised plasma physics at extreme conditions**, such as instabilities at high β
- **Explore long-term potential of the Spherical Tokamak,** guided by design studies for the ST power plant and component test facility

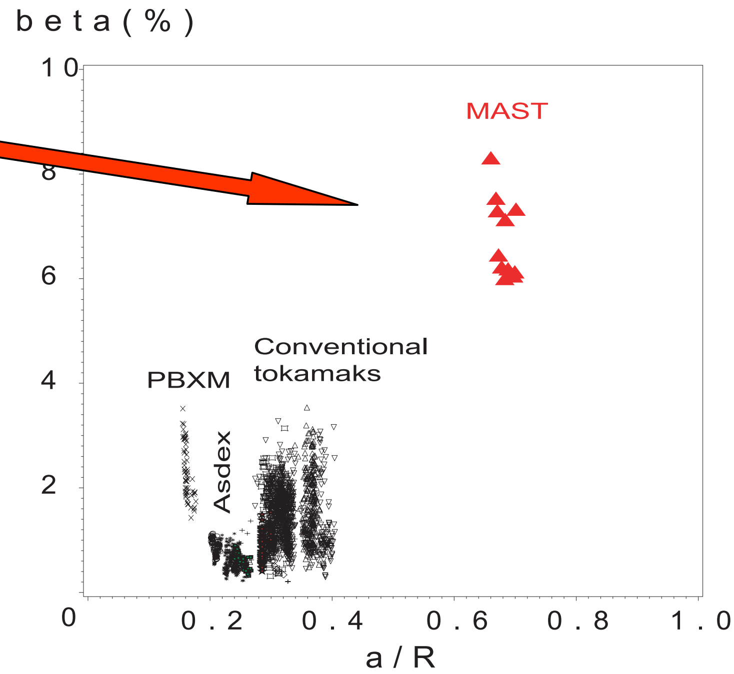
Analysis of 2003 Results

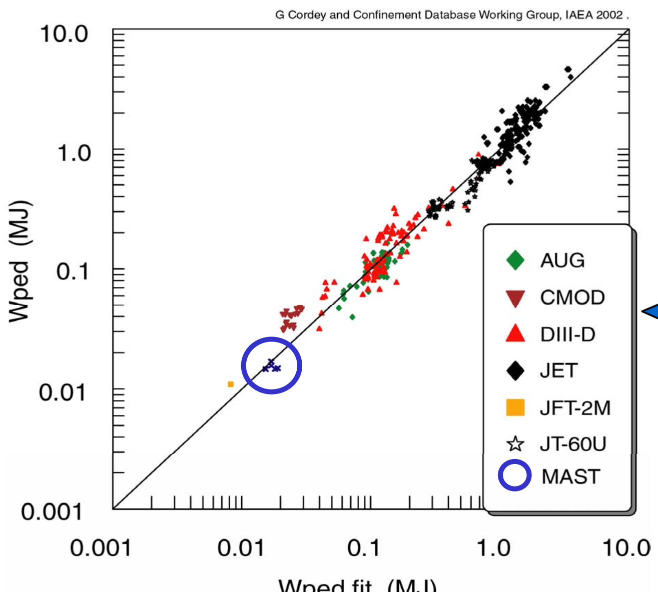
Confinement & Transport

MAST data significantly extend confinement databases e.g. should give greater confidence in ε and β dependencies

Dataset improved e.g. spread in ε mainly determined by plasmas with conventional D-shaped cross-section

$\Rightarrow \tau_E^{MAST} \sim \tau_E^{IPB98y2}$ but MAST data support somewhat stronger ε dependence ($\tau_E \propto \varepsilon^{0.8}$) than IPB98y2 scaling [**Valovic IAEA 2004**]

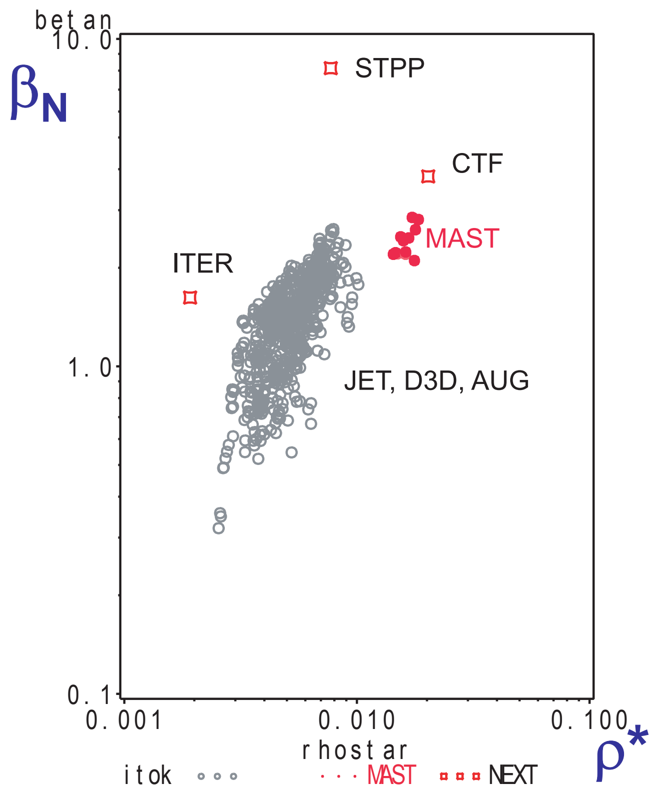




MAST data also exert strong leverage on two-term models of confinement:

$W_{ped} \propto \varepsilon^{-2.13\pm0.28}$ [Cordey et al NF 2003]

Dimensionless extrapolation to future devices



- Extrapolation to future STs is dominantly in υ^*

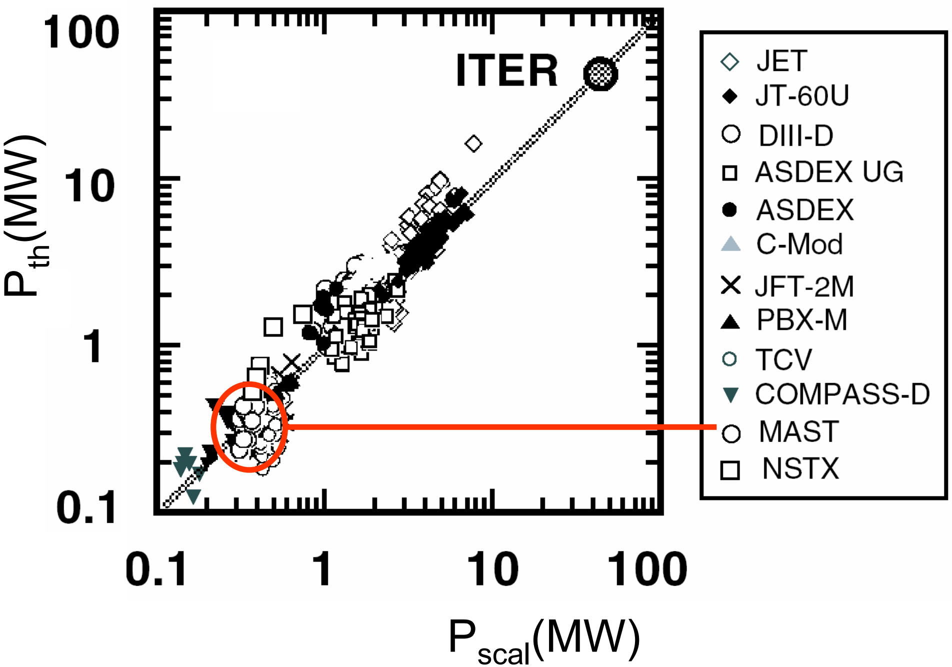
There are indications that $\tau_E / \tau_E^{IPB98y2}$ increases with decreasing collisionality on MAST [**Valovic IAEA 2004**] as in some other tokamaks (DIII-D, JET)

H-mode Power Threshold

Low A data:

- clearly favour $P_{th} \sim S$ rather than $P_{th} \sim R^2$
- favour dependence on $|B_{out}|$ rather than $B_t(0)$

$|B_{out}|^2 = B_t^2 + B_p^2$



The (non-linear) aspect ratio dependence is not yet well-determined - postulated by **Takizuka et al** that it may take a form related to fraction of untrapped particles

$P_{scal} \propto |B_{out}|^{0.7} n_e^{0.7} S^{0.9} F(A)^{\gamma}$

[Takizuka et al **PPCF 2004**]

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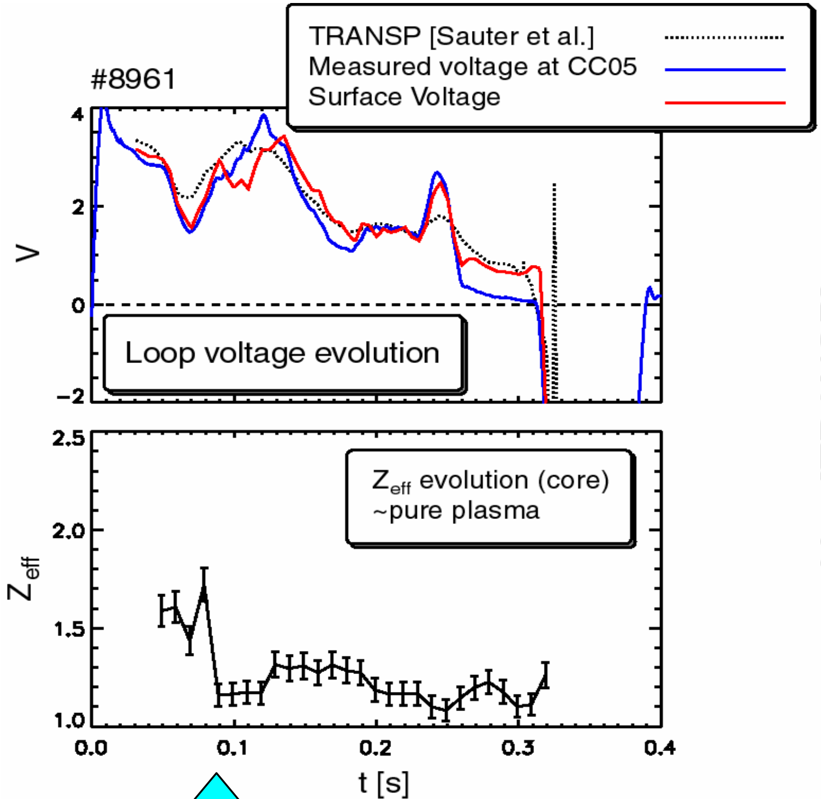
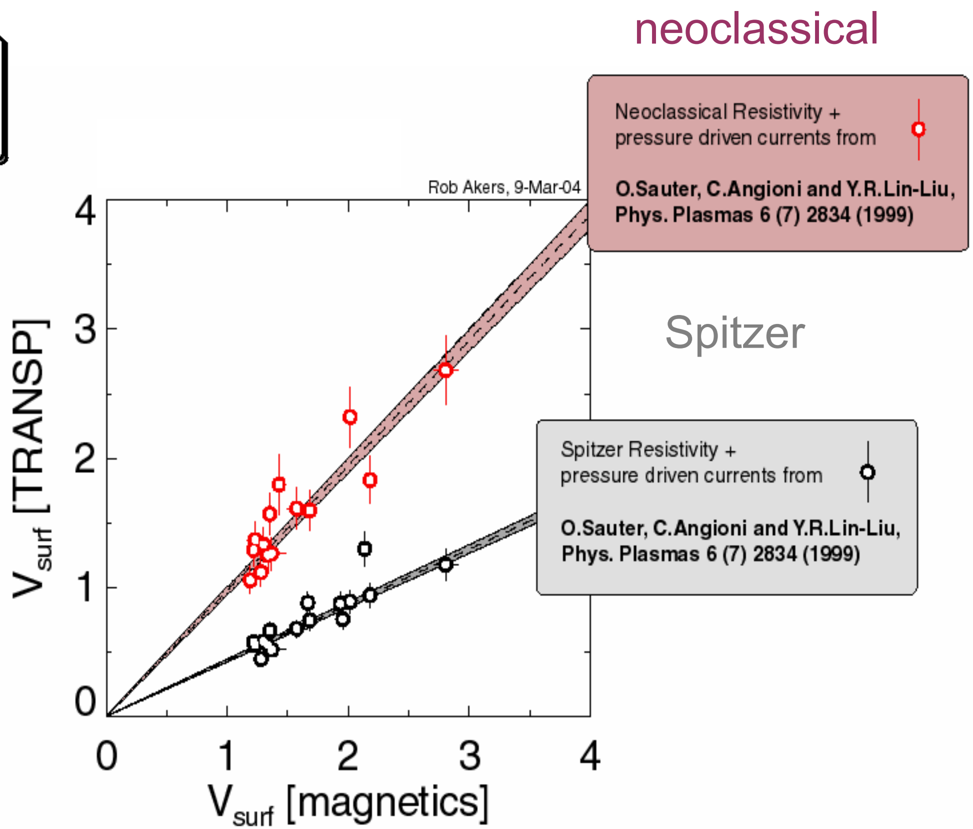
Significant neoclassical enhancement of plasma resistivity in ST:



q=1 surface appears
(from SXR data)



Example simulation of a high purity ohmic MAST plasma #8961

Ultra-high resolution TS and visible bremsstrahlung measurements of T_e and Z_{eff} in MAST allow **neoclassical resistivity** to be assessed with unique accuracy.

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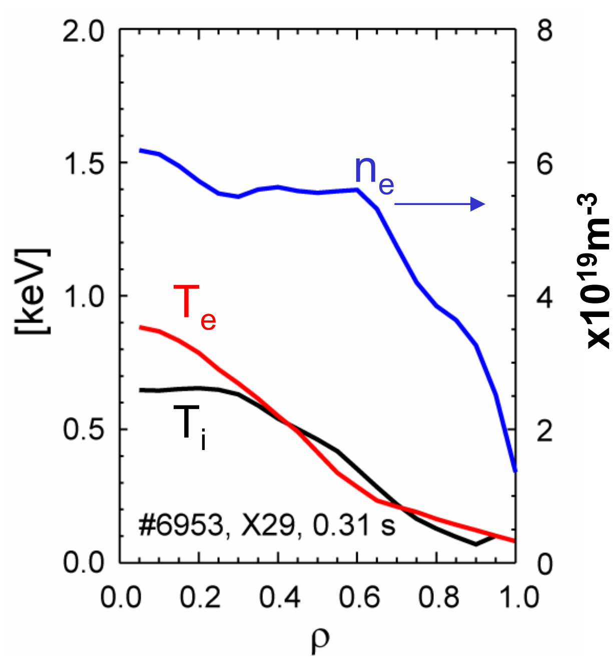
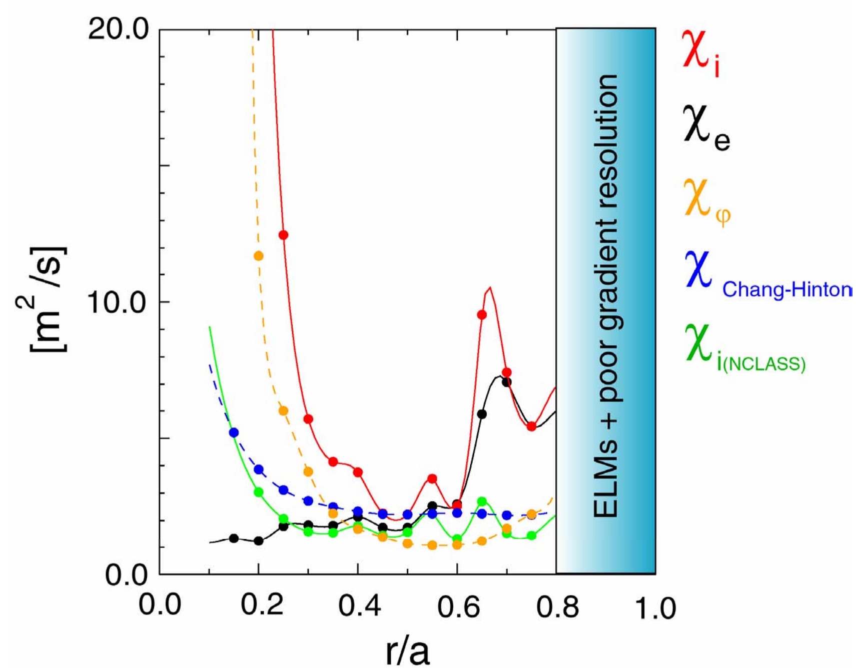
H-mode transport coefficients are close to neoclassical

$\chi_e \sim \chi_i$ around mid-radius & close to $\chi_i^{Z\text{-}CH}$ [Chang & Hinton]
[exact values very sensitive to relative values of T_e, T_i]





TRANSP simulations

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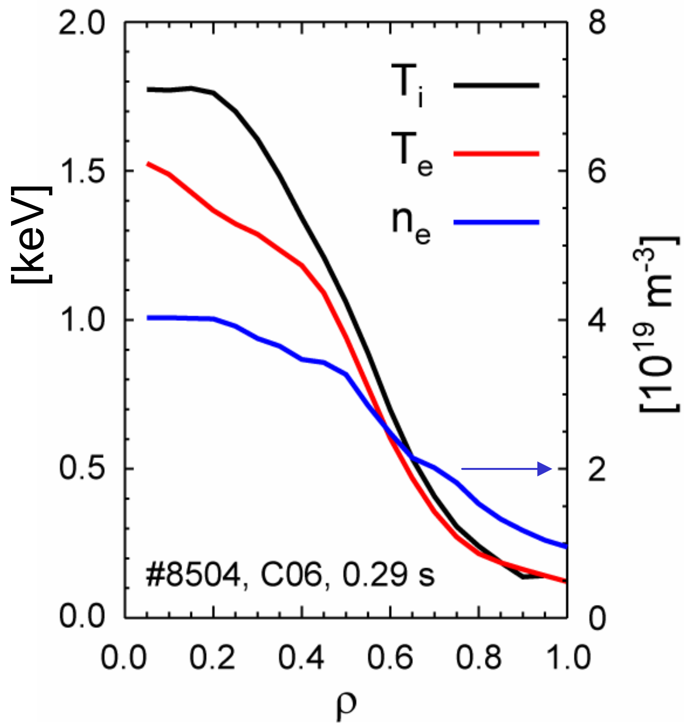
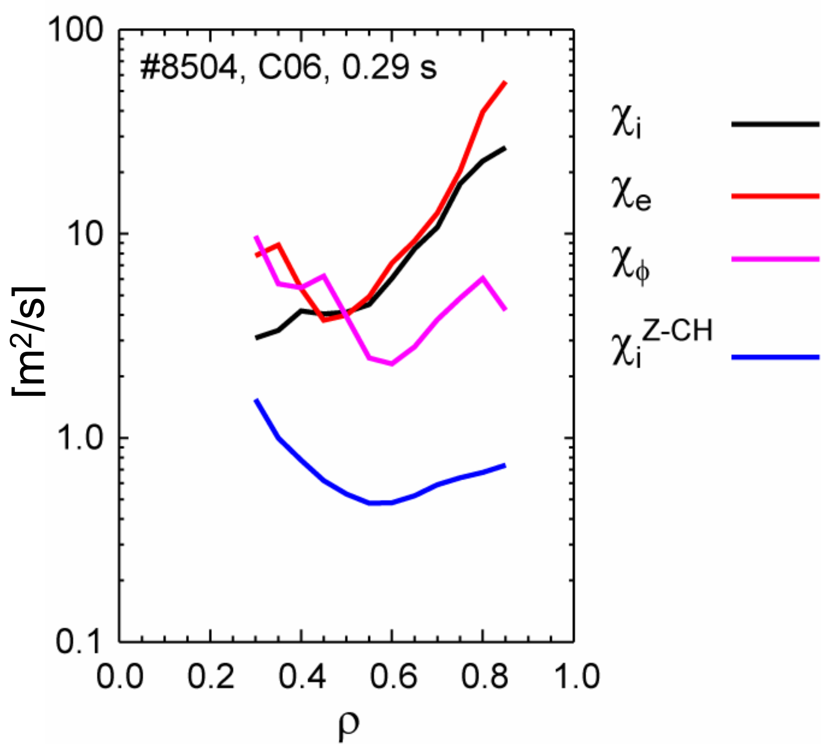
High performance in sawtooth-free L-mode

$H_H^{IPB98y2} \sim 0.85$

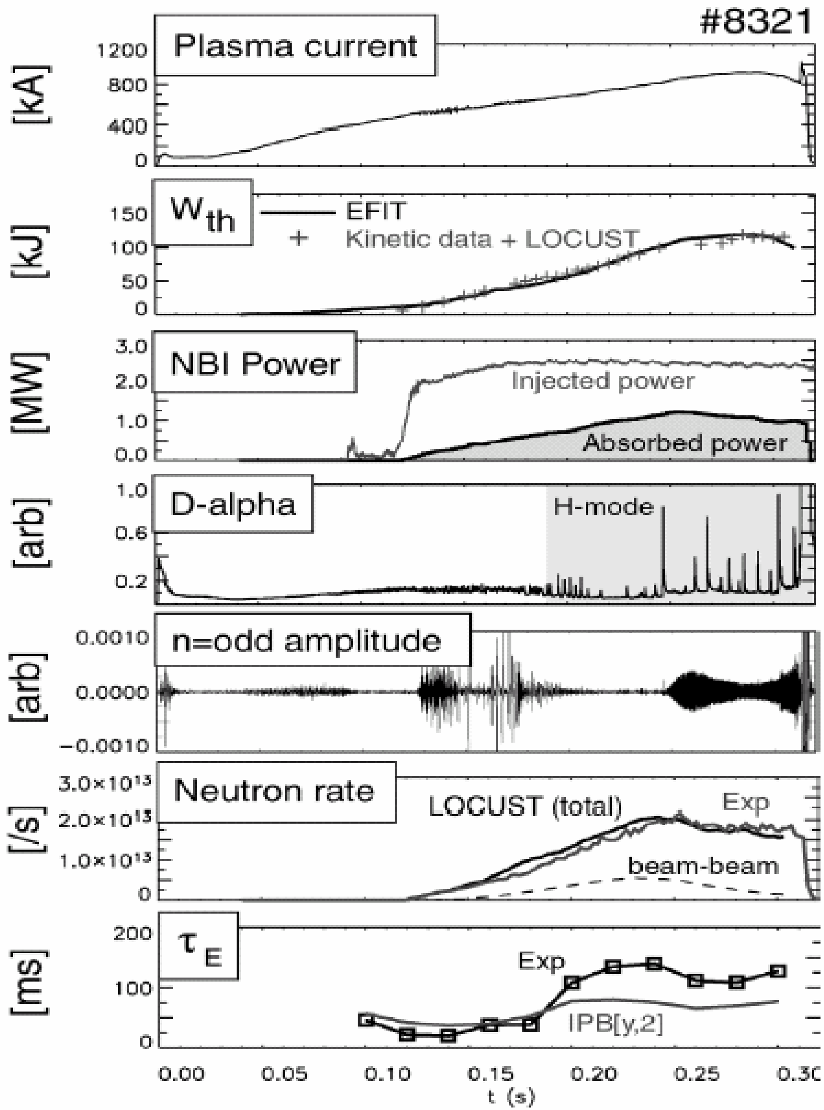
$\chi_e \sim \chi_i >> \chi_i^{Z\text{-}CH}$





TRANSP simulations

High performance in Counter-NBI



M Gryaznevich, Results from MAST, STW-04, Kyoto, 28-30/09/04

Measured neutron rates consistent with LOCUST modelling - only ~ 1/3 fast ion energy absorbed

But stored energy comparable to co-NBI

$\Rightarrow H_H^{IPB98y2} \sim 2$

$n_e(r)$ more peaked, $T_e(r)$ broader than co-NBI

High rotation ($V_{\phi 0}$ ~ 340km/s) due to rapid loss of co-moving ions

$\Rightarrow$ in-out Z_{eff} asymmetry x2 (dominated by C^{6+})

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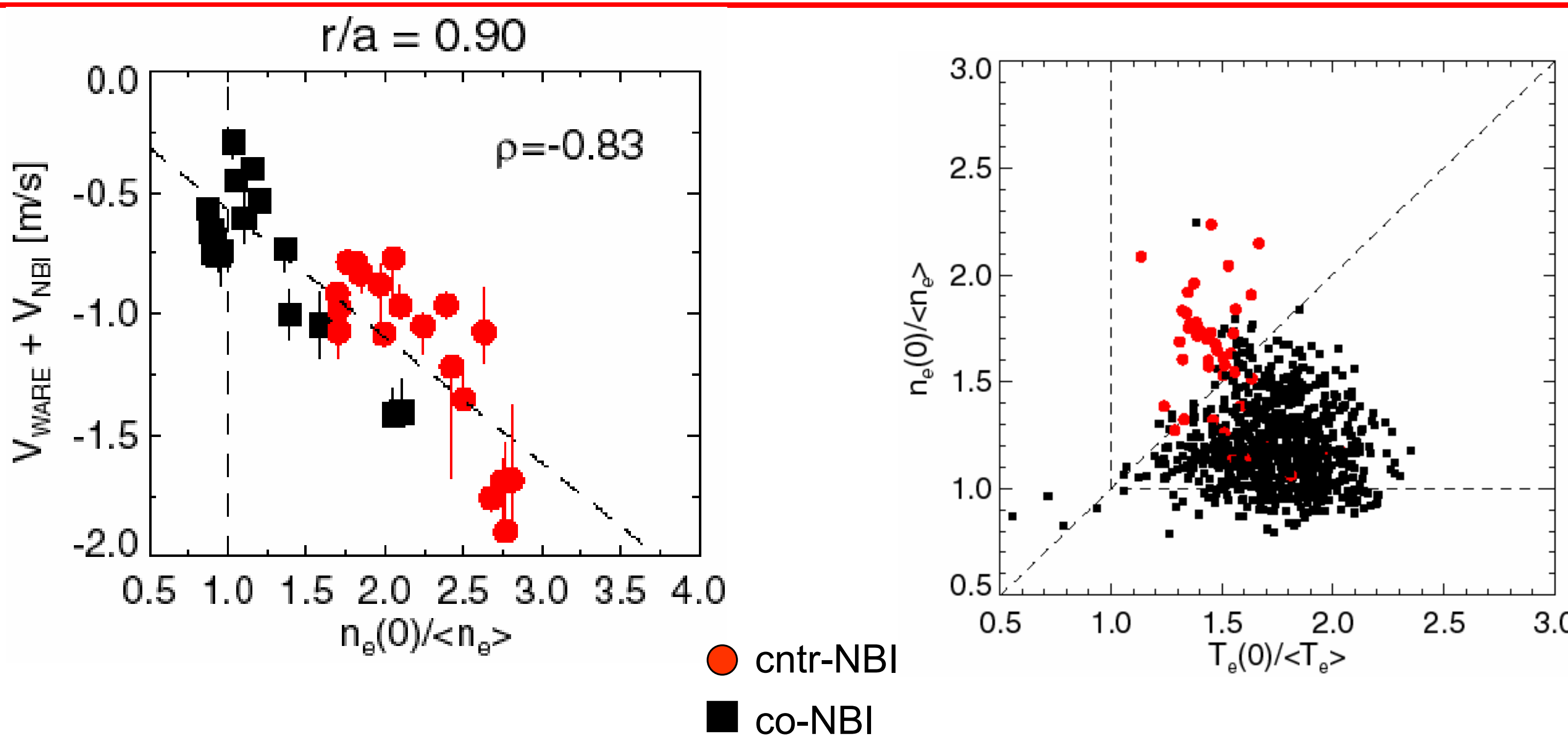
Density profile peaking strongly correlated with Ware pinch:

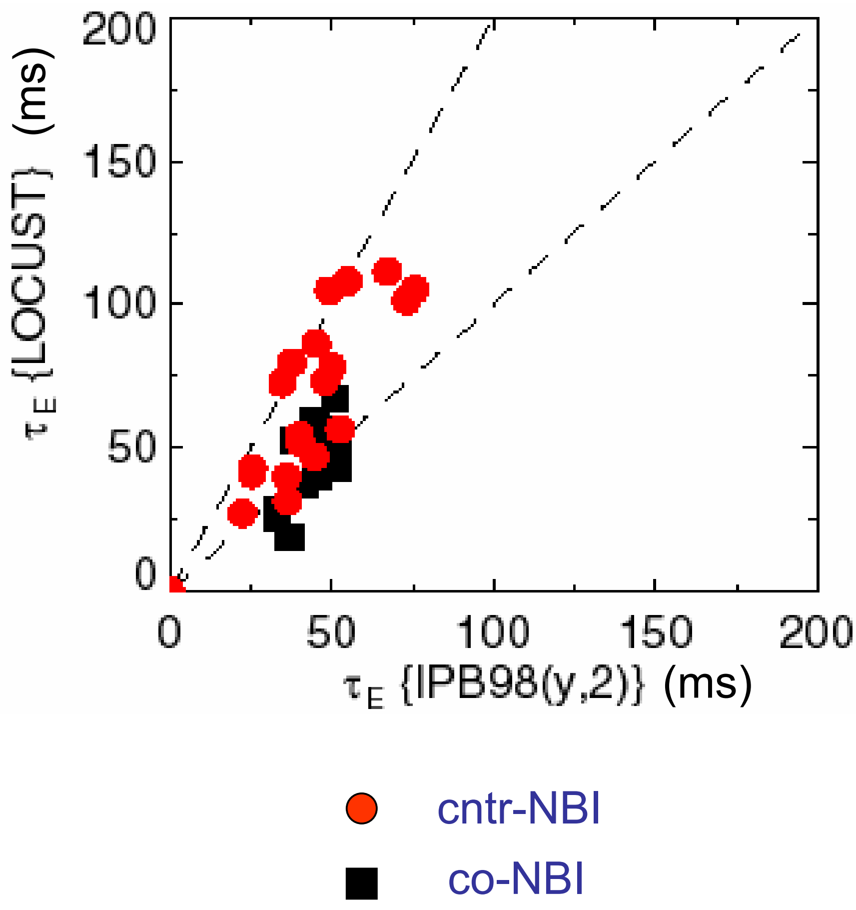


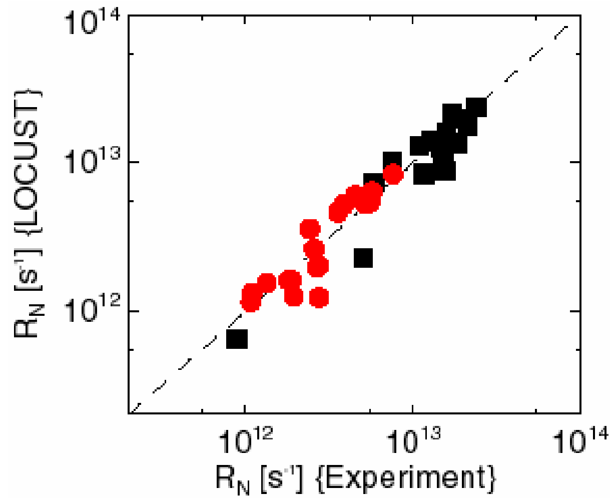
Neoclassical **Ware pinch** stronger at low A ($\Gamma \propto \varepsilon^{1/2}$) and augmented by beam-driven pinch for cntr-NBI (Ware pinch dominant)

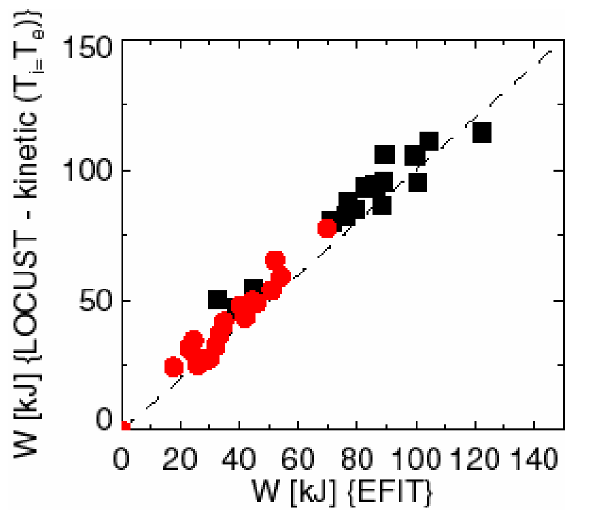
- further increased due to higher Z_{eff} of cntr-NBI discharges

[Akers et al EPS 2004]

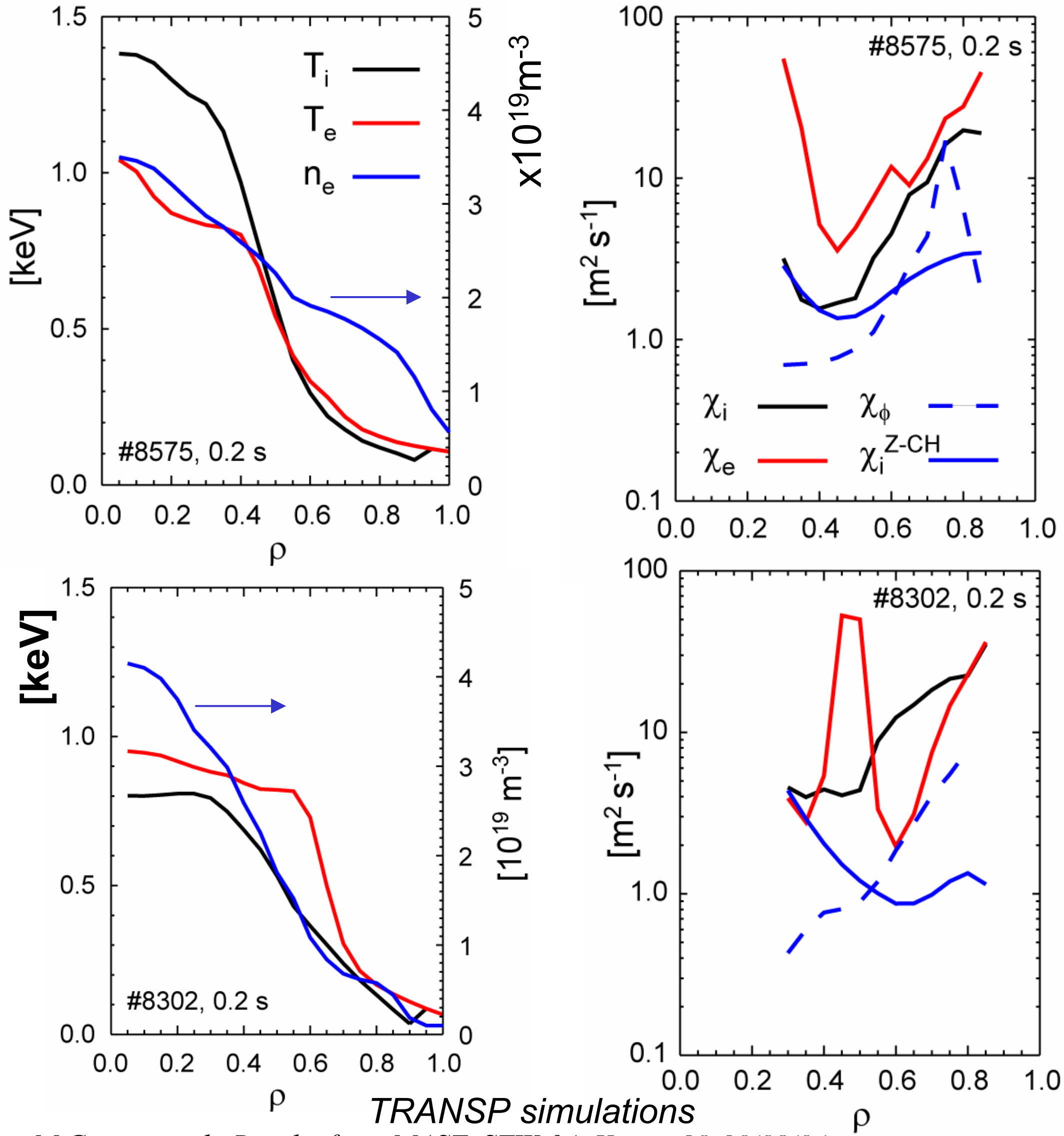
Sawtooth-free discharges $H_H \rightarrow 1.5$ with co-NBI; $H_H \rightarrow 2$ with cntr-NBI







Ion & Electron ITBs



TRANSP simulations

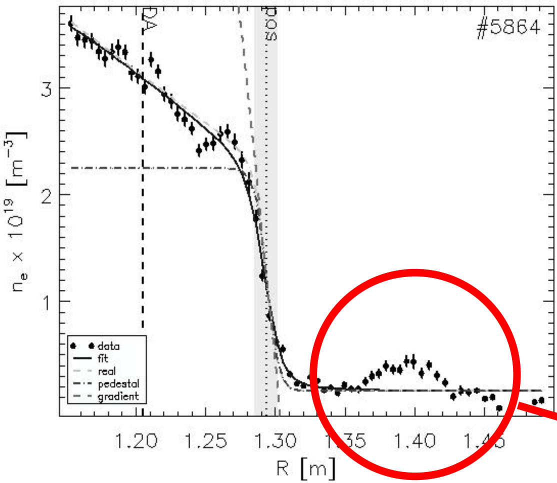
ITB existence criteria

Criteria based on critical values of R/L_T or ρ_s/L_T fail - readily satisfied even when no ITB

In these discharges the driven toroidal flow is the dominant contribution to the ExB flow shear - for cntr-NBI the pressure gradient contribution is additive

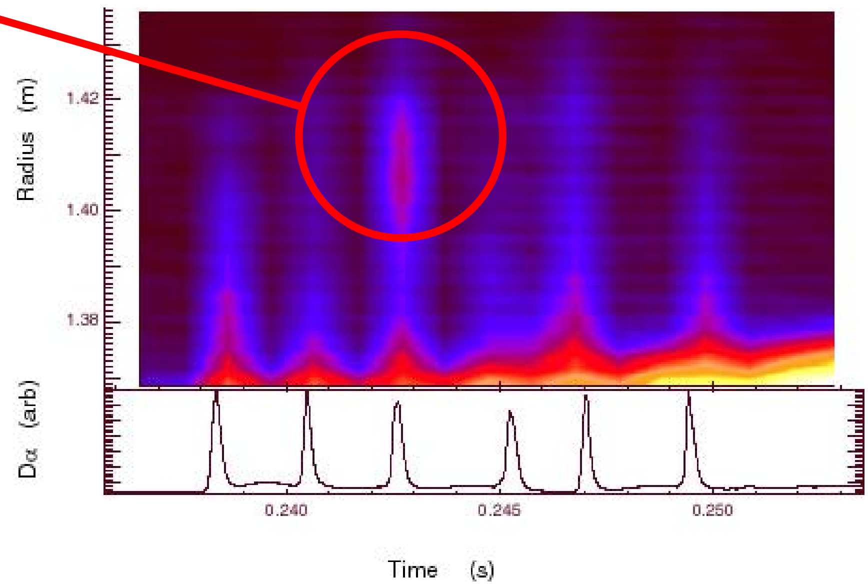
In this case ITB formation may be linked to a critical Mach number
[Field et al EPS 2004]

ELMs



Structure sometimes seen on TS profiles outboard of separatrix.

Also observed on the mid-plane linear D_α array but not on divertor target power footprint



Edge profile broadening or other structure only observed in 20 - 25% of cases in which TS fires during ELM D_α rise.

ELM spatial structure (theory+experiment)

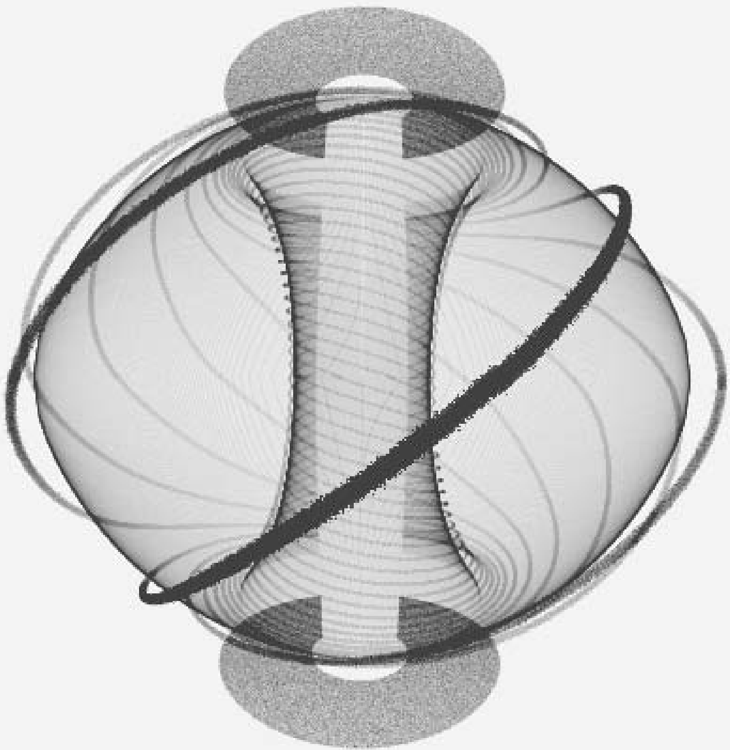
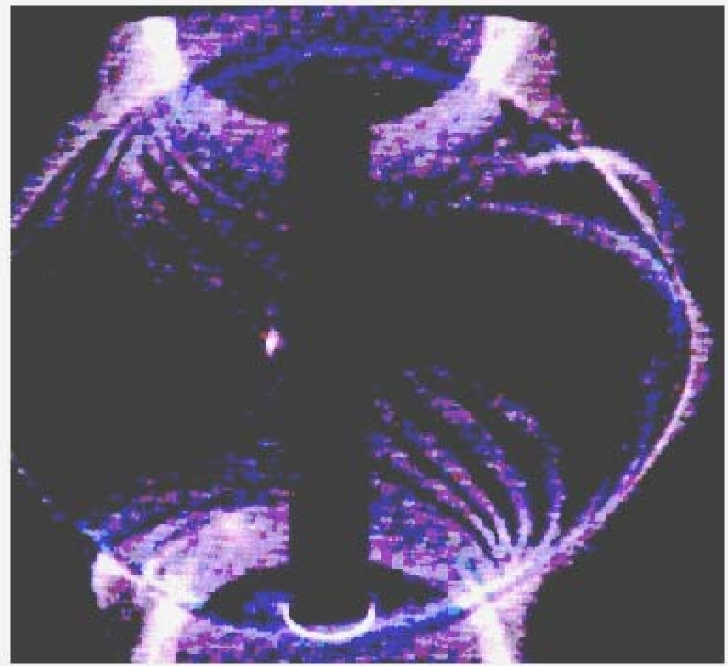
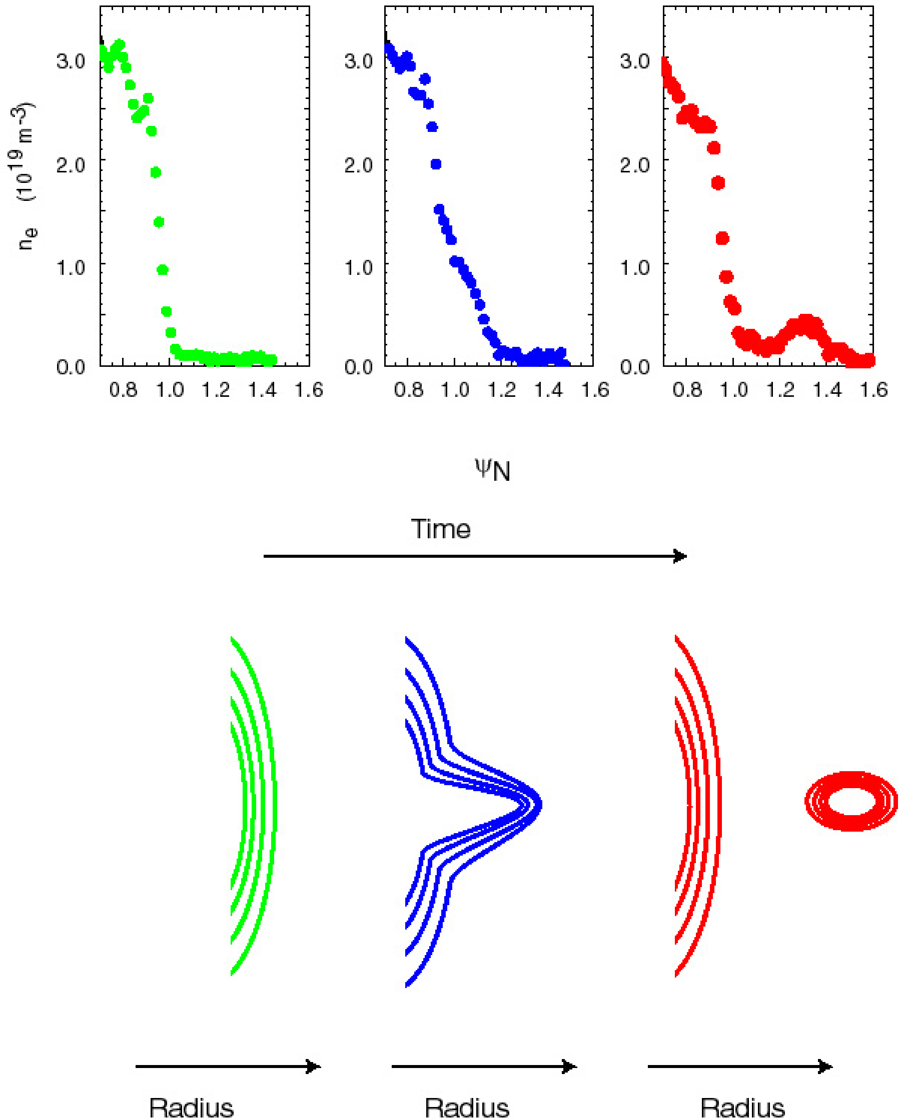


Image simulation of an extended structure @q=4, n=10, #8814



High-speed video image, #8814

The spatial and temporal evolution of an ELM:

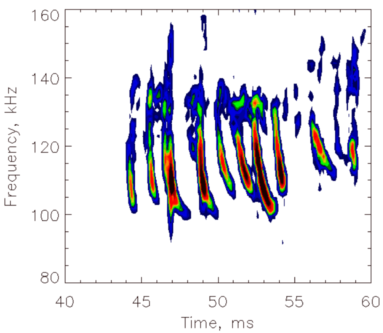


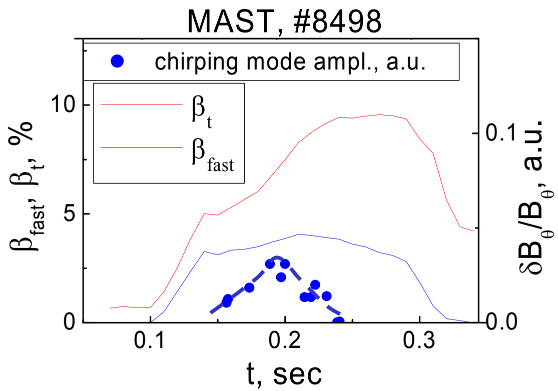
Filament eventually detaches at outboard mid-plane

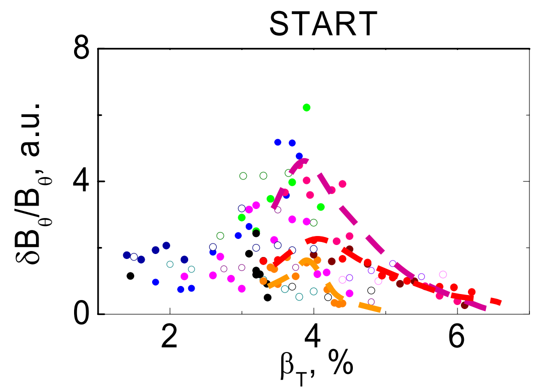
$W_{fil} < 0.03\Delta W_{ELM}$

TAE studies: β - dependence

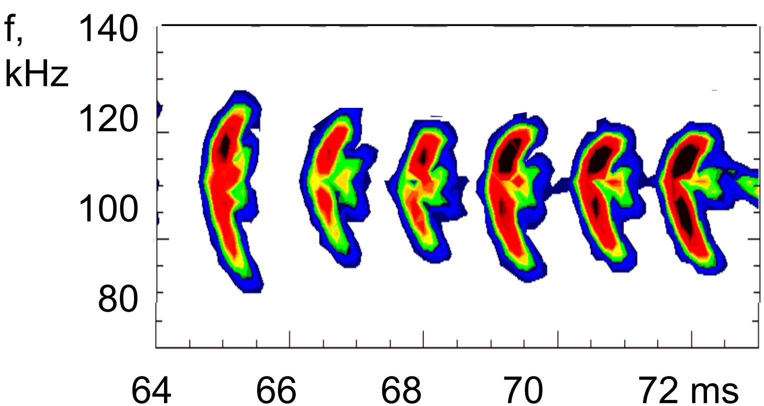
- Chirping modes studies: decrease in amplitude with β increase on MAST and START

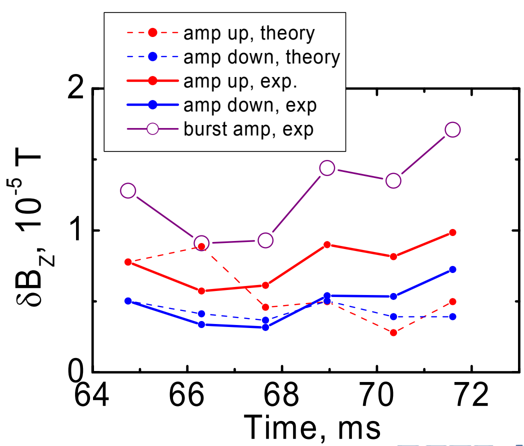






- Hole-clump modes observed, features agree with theory ***(more in Sharapov et al.)***





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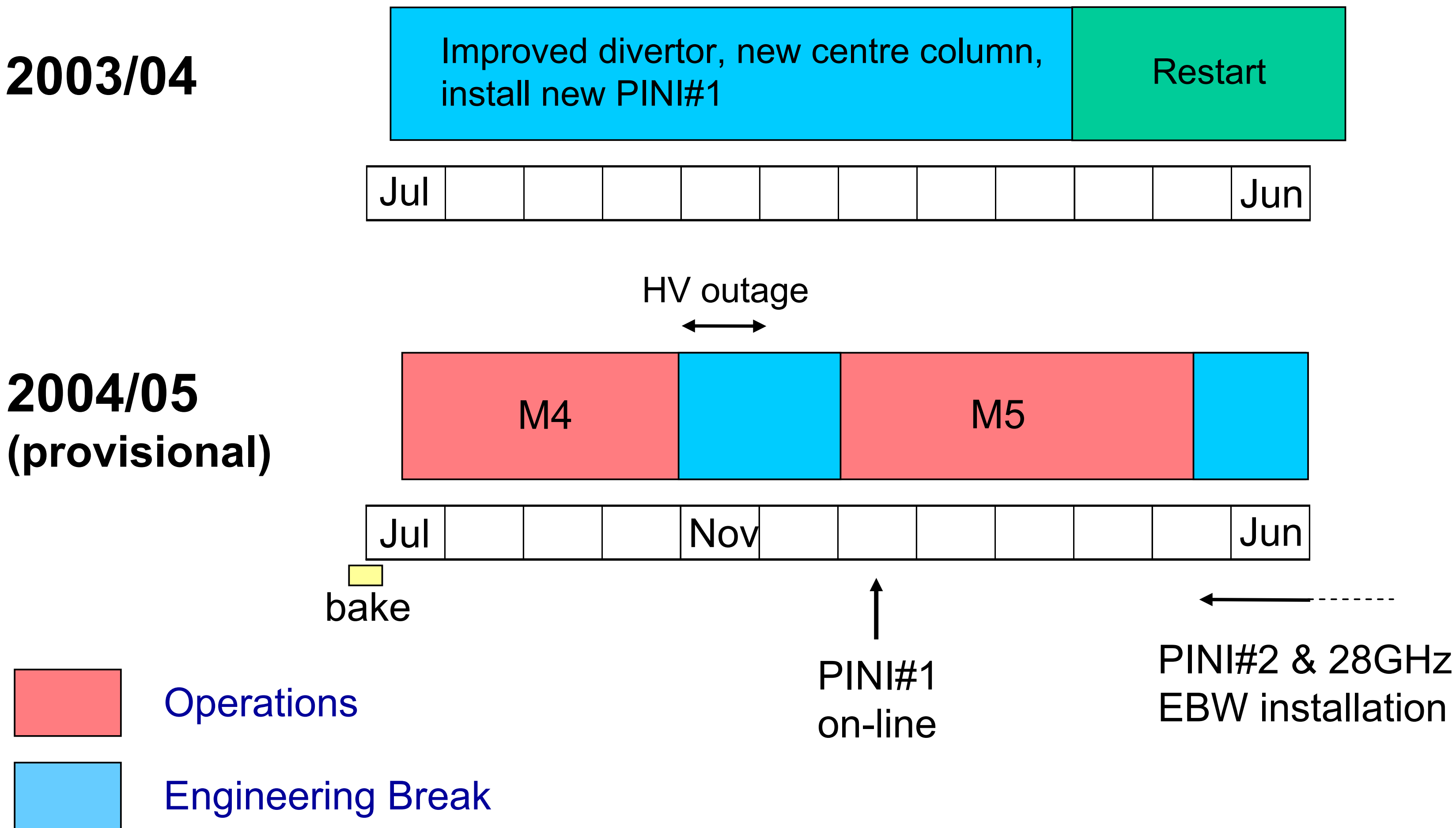
2004-05 Experimental Campaign

Operating schedule: 2004-2005



M Gryaznevich, Results from MAST, STW-04, Kyoto, 28-30/09/04

Recent modifications to MAST

Recent modifications to MAST

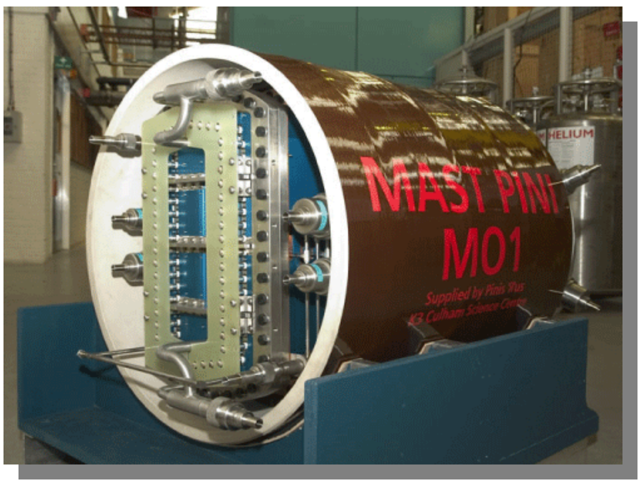
Experimental campaigns of 2004-05 will exploit improvements made during the 2003-04 shutdown (and on-going improvements due for completion in early 2005):

Recent modifications to MAST

Experimental campaigns of 2004-05 will exploit improvements made during the 2003-04 shutdown (and on-going improvements due for completion in early 2005):

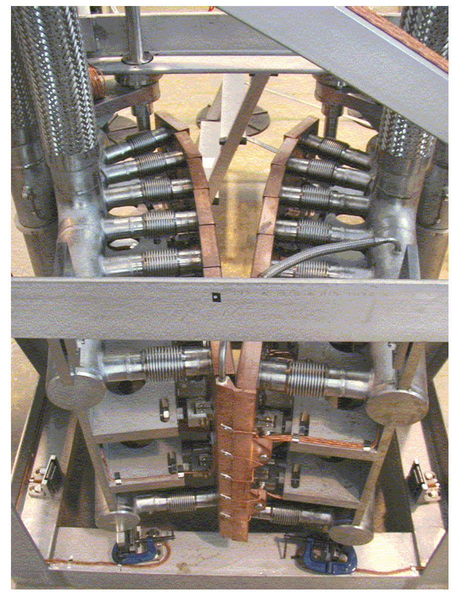
Neutral beam systems

- higher power, longer pulse, improved reliability
- 2 x 2.5MW for 5s capability



New JET-style PINI

Residual Ion Dumps



Actively cooled calorimeter (gate in closed position)

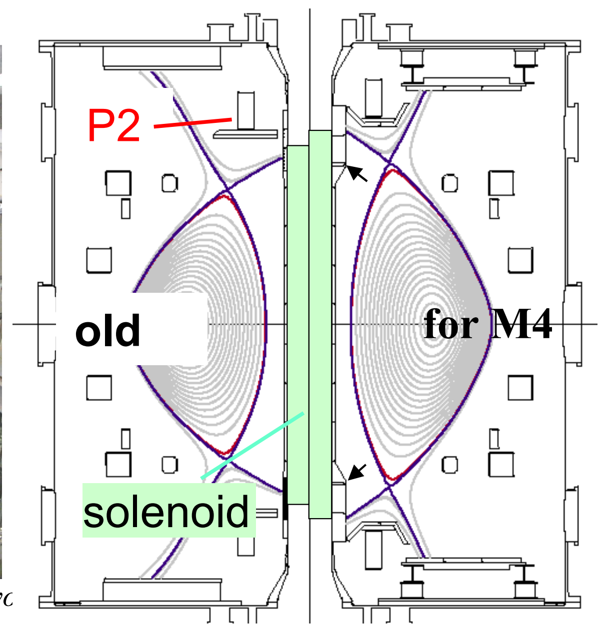
Recent modifications to MAST

Experimental campaigns of 2004-05 will exploit improvements made during the 2003-04 shutdown (and on-going improvements due for completion in early 2005):

Neutral beam systems

Centre column, solenoid and P2 coils

- longer and stronger solenoid
- more Vs and higher κ

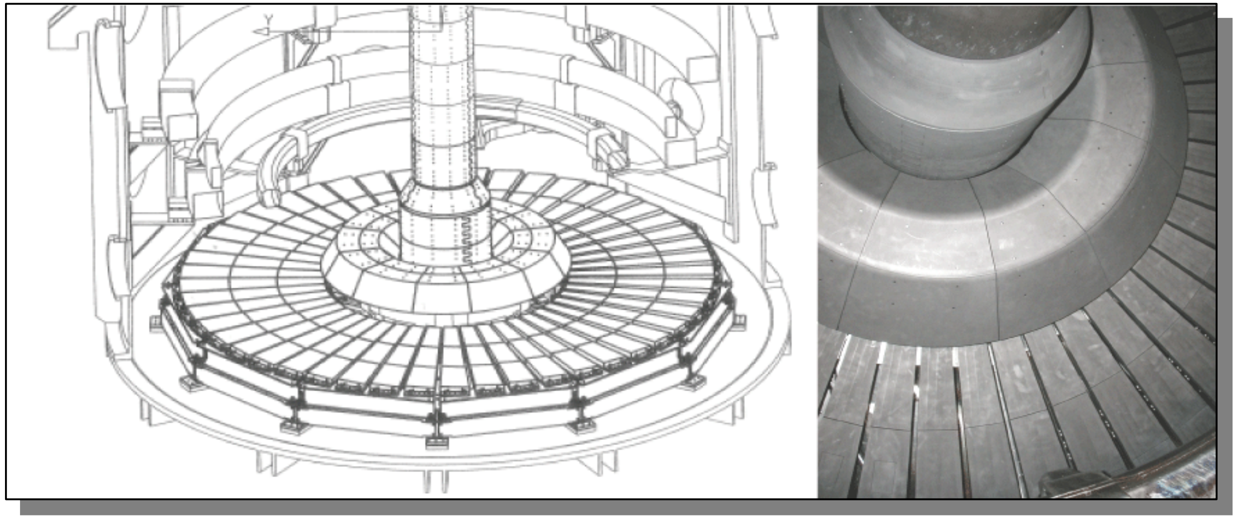


Recent

Experimental camp
made during the 20
due for completion

Neutral beam s

Centre column



Divertor

- better power handling, improved diagnostic access, tailored poloidal profile

s to MAST

exploit improvements
ɖ on-going improvements

Error field correction coils

- Reduced perturbation in poloidal field
- longer pulses at lower density

Recent modifications to MAST

Experimental campaigns of 2004-05 will exploit improvements made during the 2003-04 shutdown (and on-going improvements due for completion in early 2005):

Neutral beam systems

- higher power, longer pulse, improved reliability

Centre column and solenoid

- longer and stronger solenoid

Divertor

- better power handling, improved diagnostic access, tailored poloidal profile

Error field correction coils

- Reduced perturbation in poloidal field

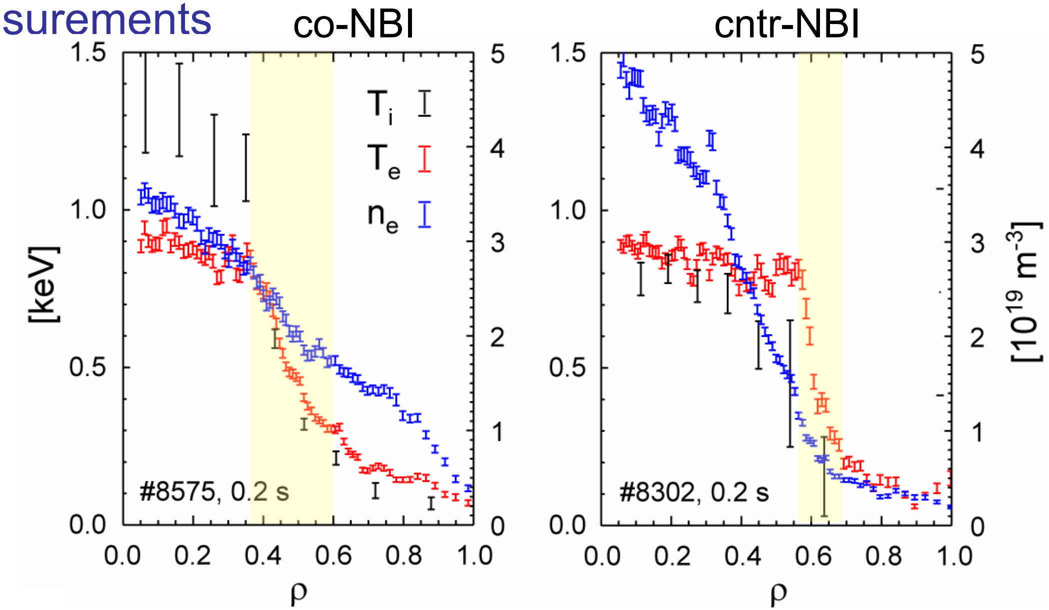
Range of diagnostic enhancements

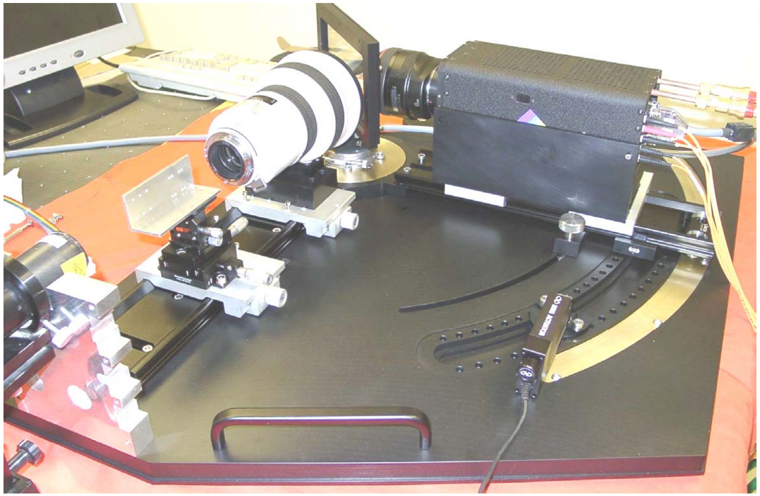
- including drilling two new ports in vessel

Charge-exchange recombination spectroscopy:

Ion temperature & flow velocity measurements

Resolution of **original CXRS** system (**19 chords**) marginal for steep ITBs





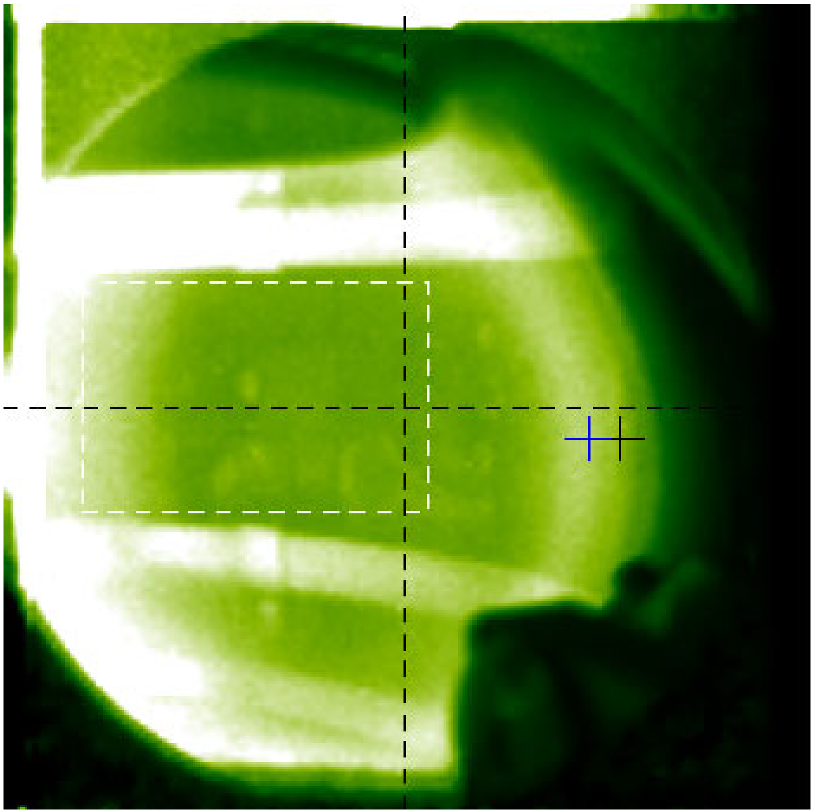
Upgraded CXRS facilitated by adaptable low A configuration

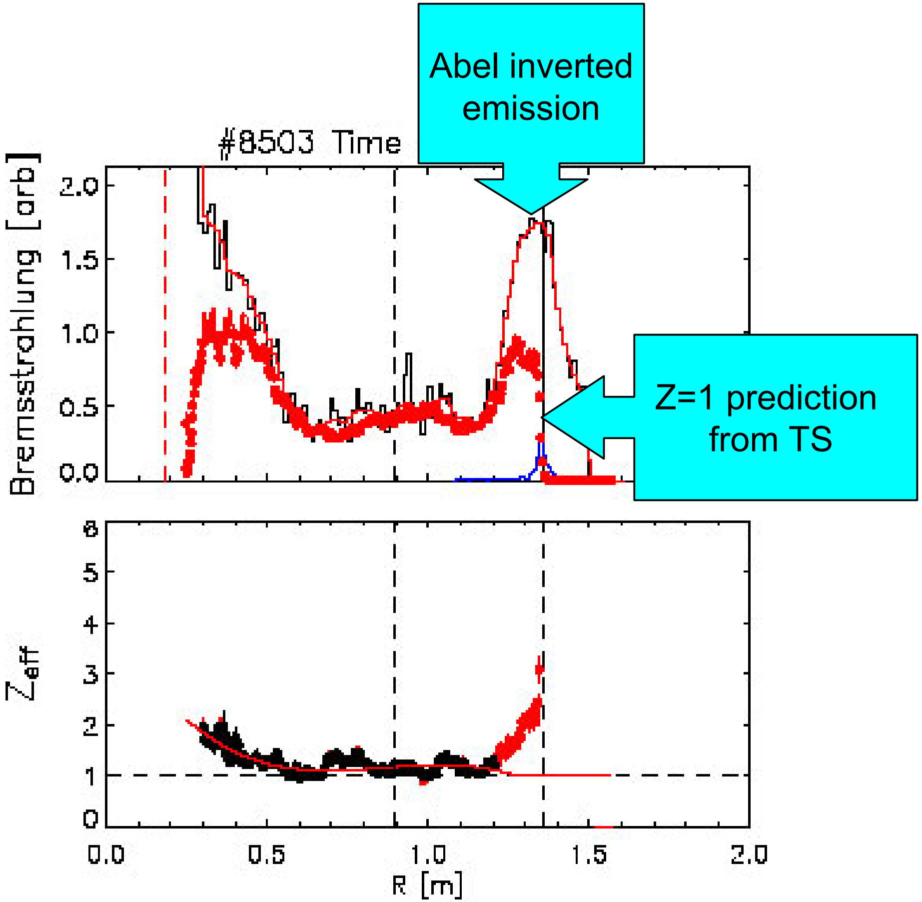
$\Rightarrow$ **200+ chord** spectrometer

- spatial resolution ~ ρ_i
- poloidal and toroidal chords
- separate views of two NBI beams

Reconstruction of Z_{eff} from visible bremsstrahlung:

ZEBRA 2D image





2D Z_{eff} CCD detector (ZEBRA)
128x128 @200Hz, 256x256 @100Hz

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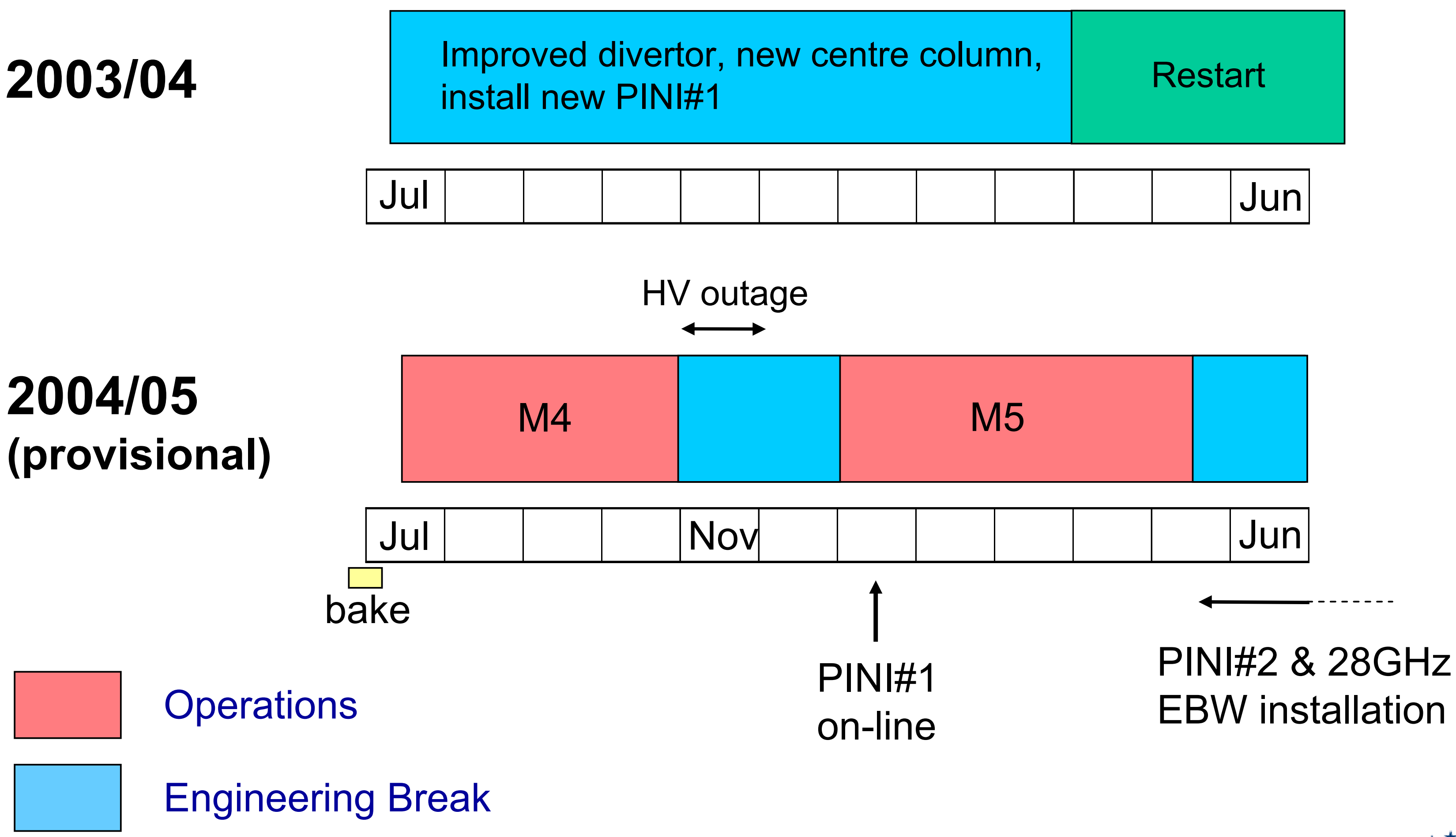
New Results:
- July - September 2004

Operating schedule: 2004-2005



2004 MAST Experimental Campaign Targets

Integrated Scenario Development

1. Quantify error field effects and extend MAST operational space by effective suppression.
2. Develop baseline operating scenarios to meet the needs of the physics programme.

Transport & Turbulence

3. Assess the relative roles of electron and ion transport in MAST and the impact of micro-instabilities (e.g. ETG and ITG modes) by detailed transport analysis of discharges with and without ITBs and modelling.
4. Identify the requirements for sustainable and wide ITBs in MAST.

Confinement

5. Expand the confinement database parameter range and identify scaling of confinement with the main engineering parameters (P, I, n ..)
6. Identify scaling of confinement with dimensionless parameters, particularly beta and aspect ratio, including joint experiments with other devices where appropriate.
7. Evaluate particle confinement in MAST; assess the relative roles of pinch and diffusive terms.

ELMs & Pedestal Physics

8. Measure ELM structure, evaluate the impact on plasma facing components and compare with ELM models.
9. Assess impact of aspect ratio, first wall proximity and magnetic field on pedestal characteristics and ELM behaviour *[ASDEX-U/DIII-D joint experiments]*

EBW

10. Demonstrate & optimise EBW heating at 60GHz.

Start-Up

11. Demonstrate & optimise start-up using the P2-P5 coils only without plasma formation around P3.

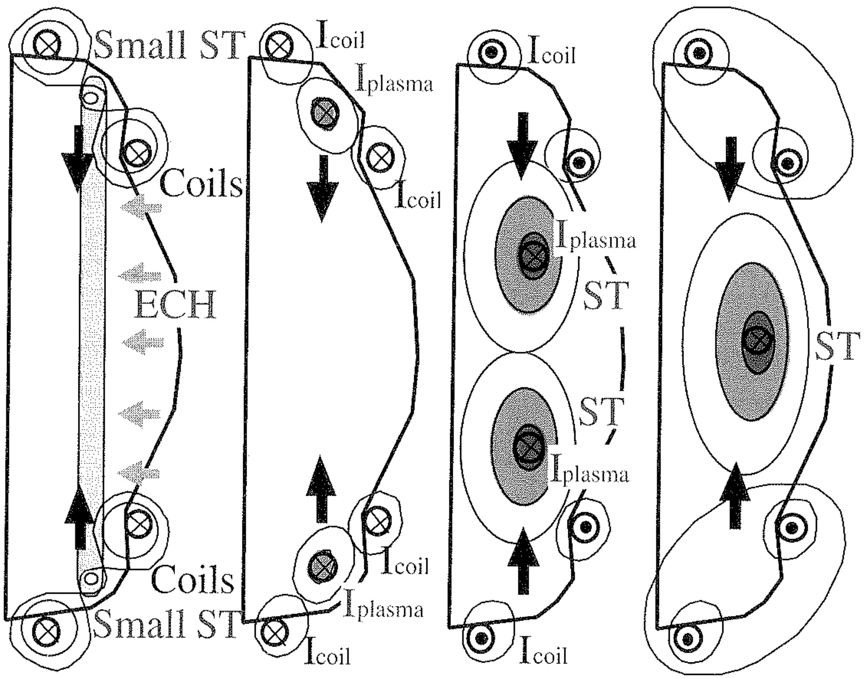
Disruptions & Divertor Biasing

12. Measure the distribution of energy to the first wall and divertor during disruptions.
13. Demonstrate effective divertor biasing in neutral beam heated discharges where the power input due to biasing is small compared to the total power input.
14. Test 'passive' biasing for ELM amelioration.

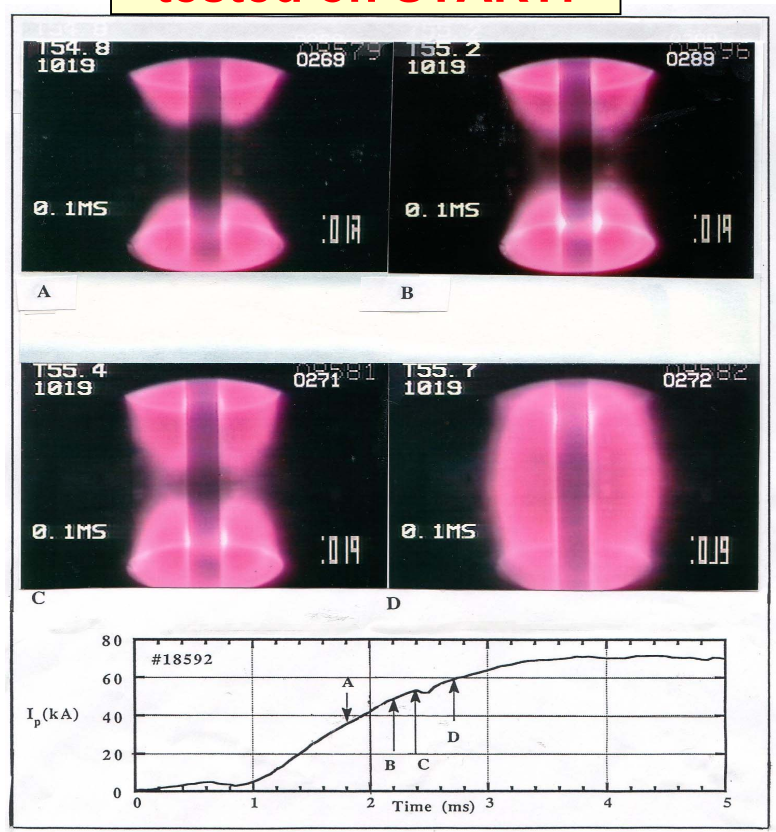
Non-solenoid start-up

- Objective: develop **effective non-solenoidal start-up** compatible with burning device

  - CHI (HIT, NSTX) and merging-compression (START, MAST) difficult to implement in future STs

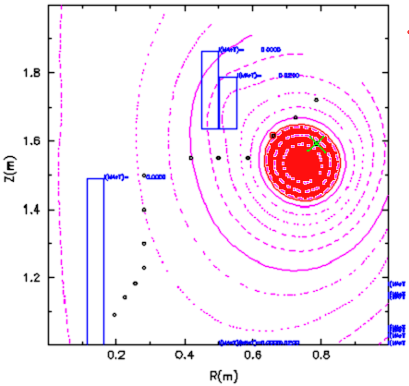


Similar scheme was tested on START:



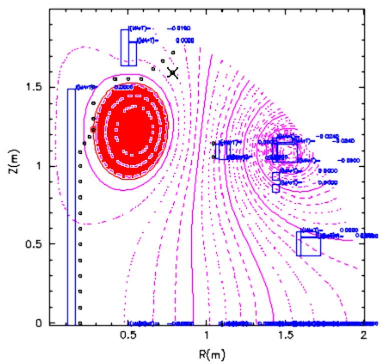
A different scheme is proposed by the TS-3/4 team

Double-Null Merging Modelling by Frascati team:

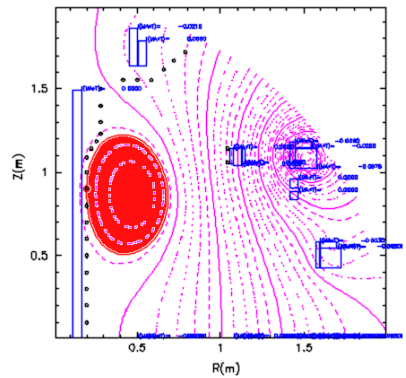


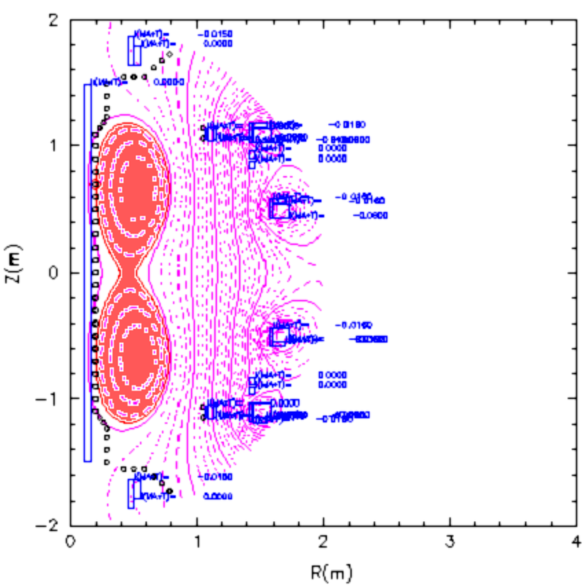
t=15ms I_p = 150 kA

t=21ms I_p = 250 kA



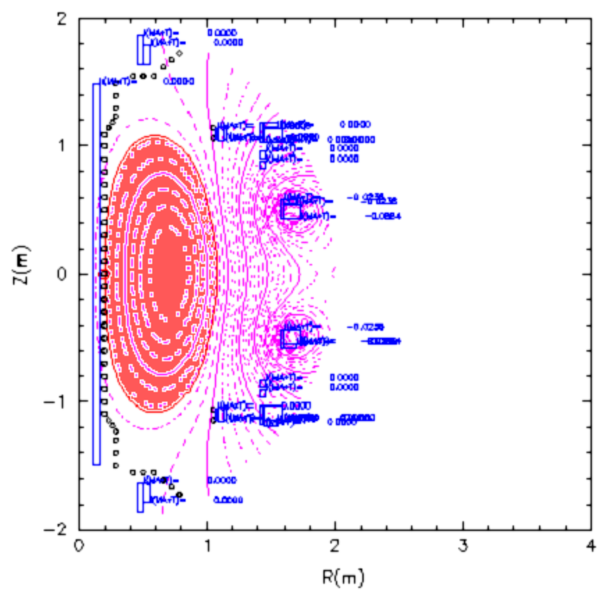
t=45ms I_p = 450 kA





t=60ms

I_p = 600 kA

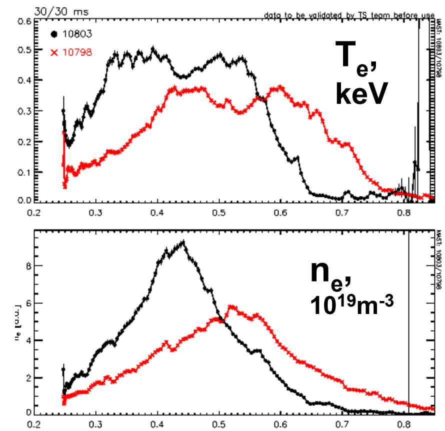


t=75ms

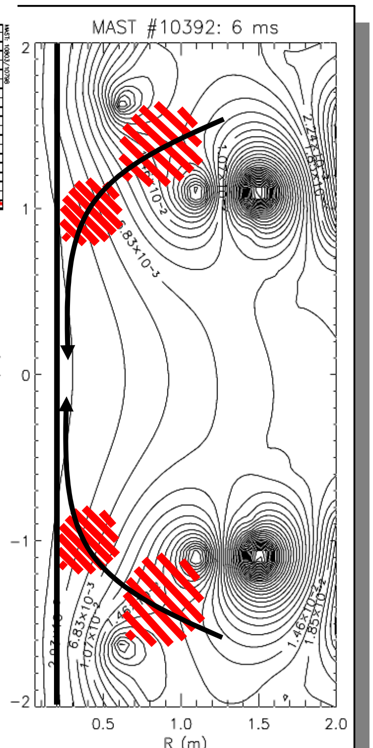
I_p = 600 kA

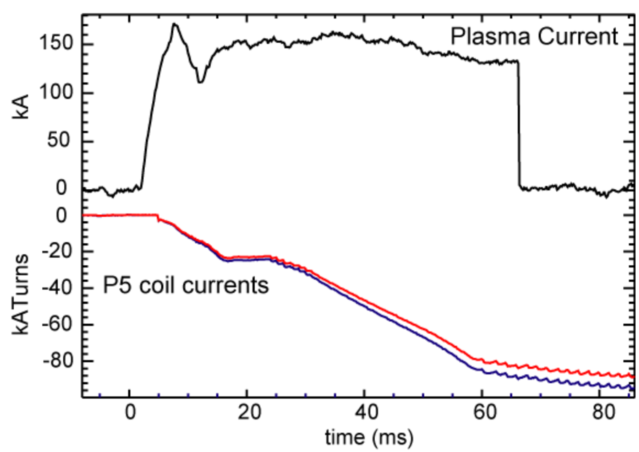
Non-solenoid start-up

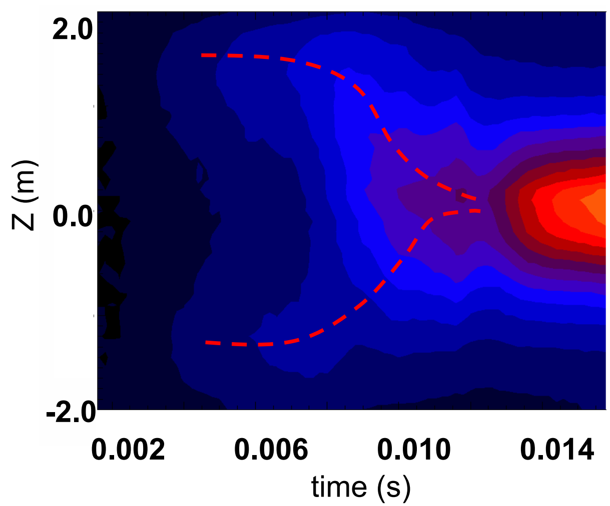
- First results of DNM on MAST are very encouraging:
  - **merging** of two plasma rings formed in **low-order null** between poloidal field coils
  - current ramp (up to **300kA**) using flux from vertical field coils
  - central solenoid **was disconnected** in these experiments



TS profiles after merging





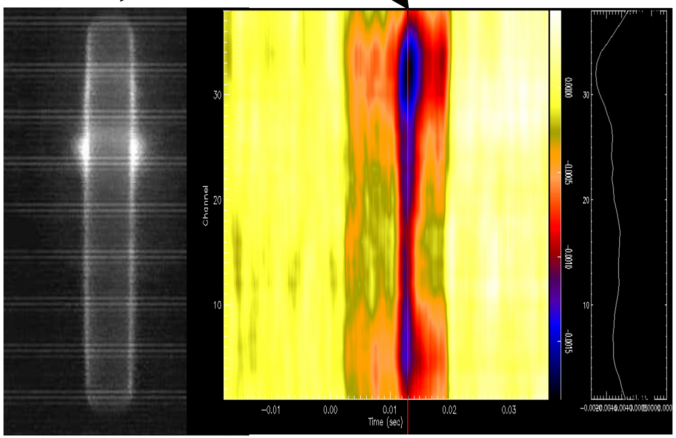


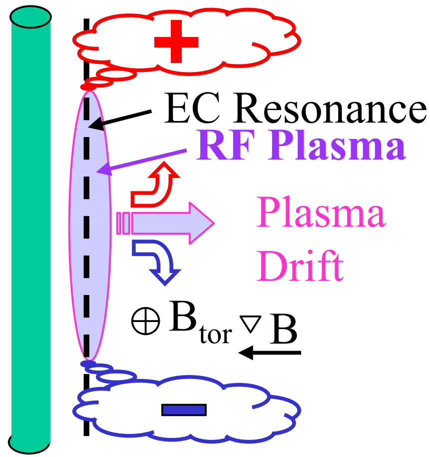
M Gr

ECRH/EBW plasma current formation

MAST experiment:
CCD and magnetics

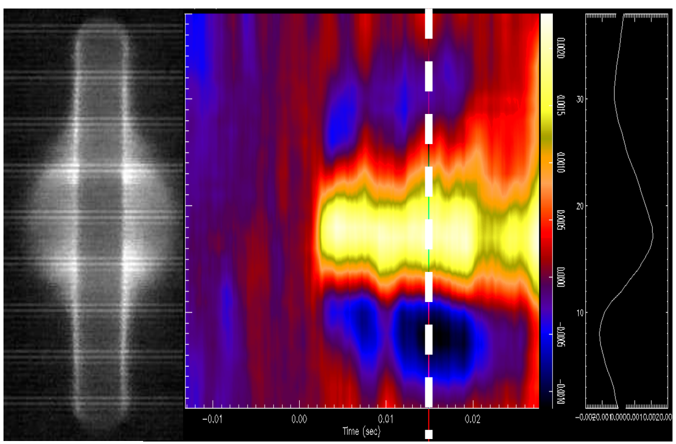
Schematic of current generation

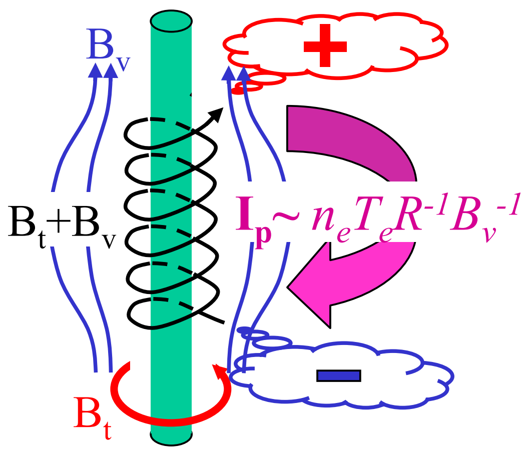




Pure toroidal field: some flash, but no current measured

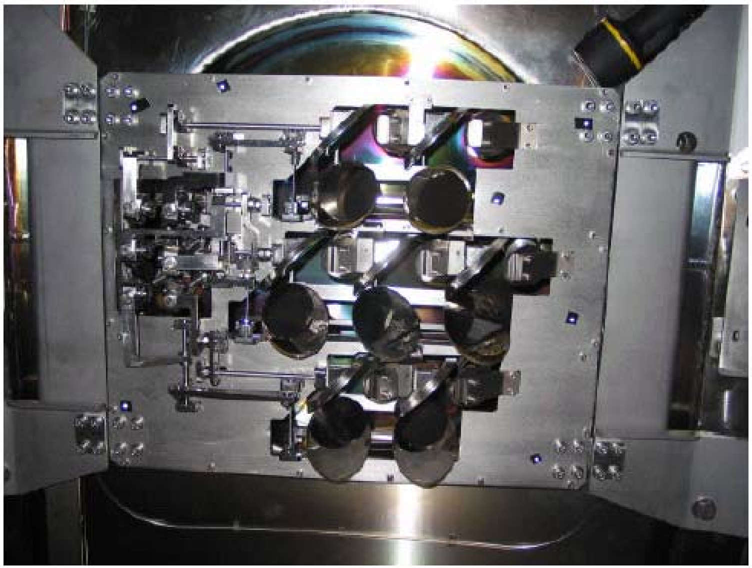
ECRH pulse of 60 GHz, 0-20 ms (0.3 MW), O-mode polarisation.

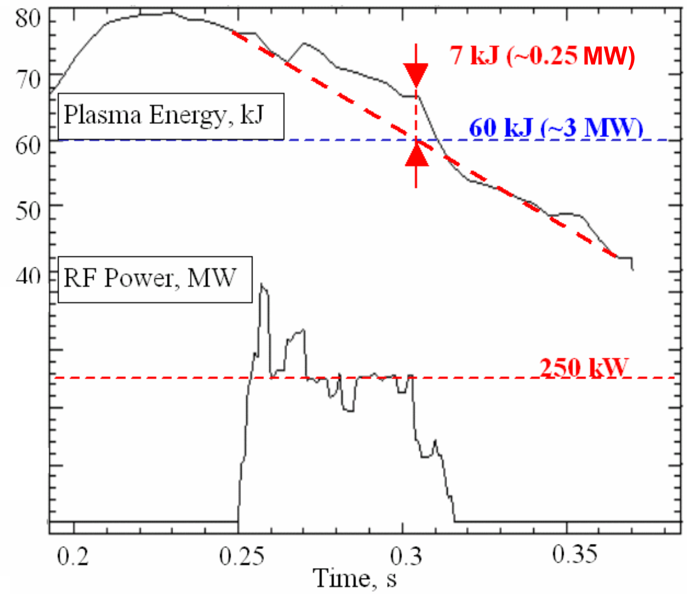




With 5 mT vertical magnetic field: current up to 10 kA.

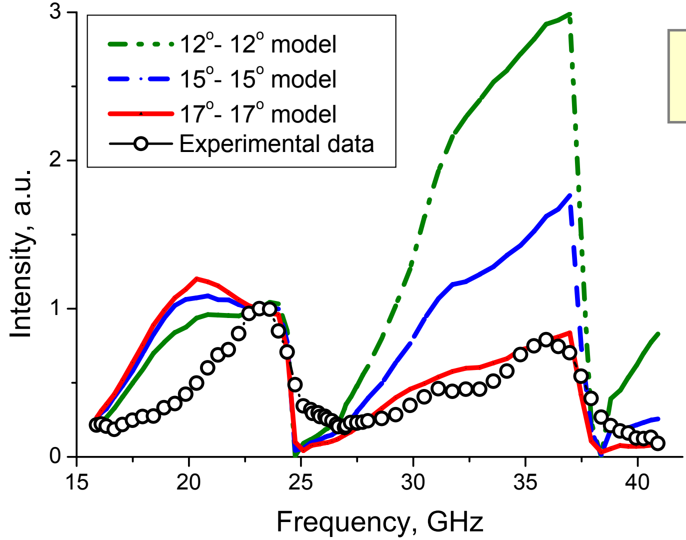
First results of EBWH





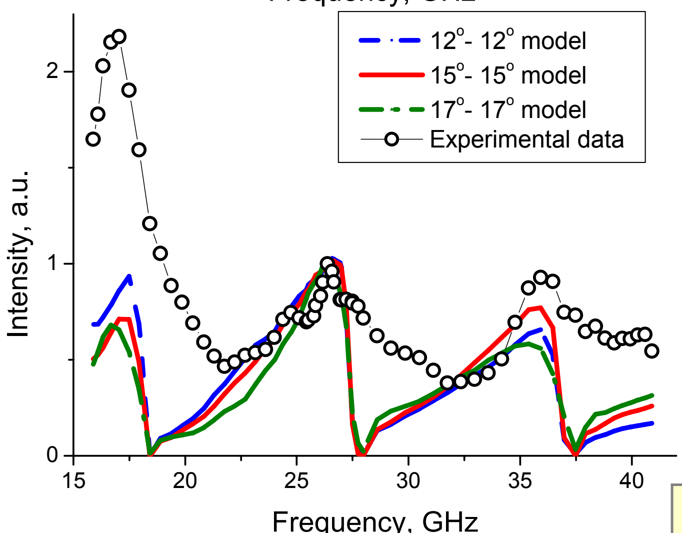
- First experiments show increase in stored energy and central electron heating

EBW Spectra in L-mode and in H-mode



Measured and simulated EBW spectra in high density L-mode in MAST, shot #7798 at 0.24 s.

- **Model: 1D full wave mode coupling, EBW ray-tracing including collisional and non-collisional damping, radiative transfer for non-local wave damping.**
- **Good agreement in L-mode plasma**
- **Disagreement is strong in high beta plasmas and in a long sustained high density H-mode.**



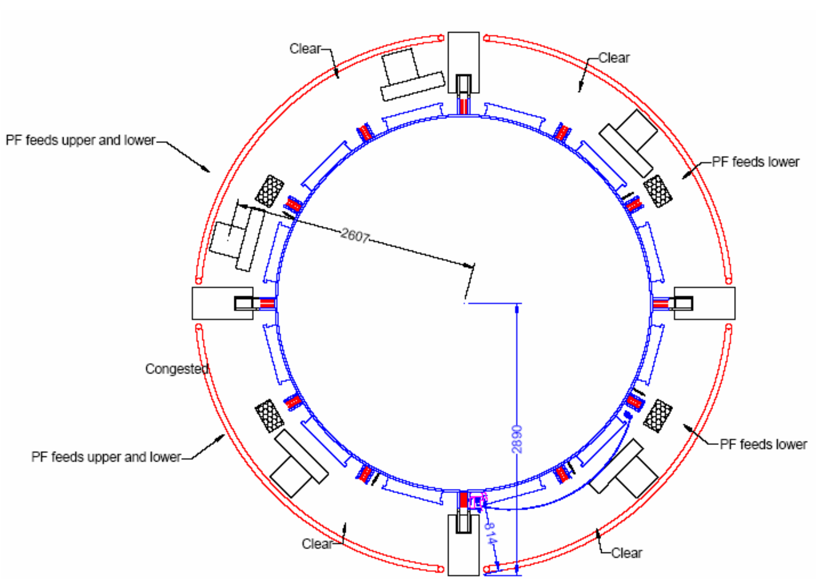
Harmonic overlap & large field line pitch angle in STs pose difficulties for heating but open up new diagnostic possibilities by EBW emission studies

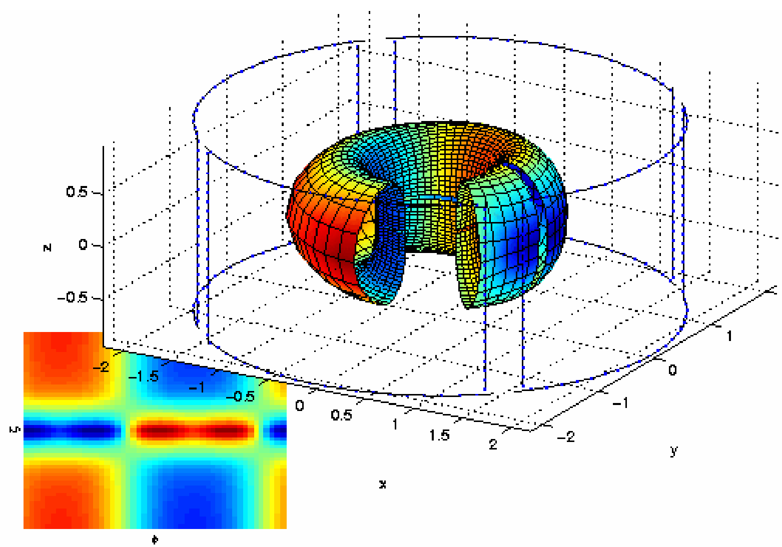
q-profile diagnosis *(Shevchenko 2000, Plasma Phys. Rep.* ***26*** *1000)*

Measured and simulated EBW spectra in high density H-mode in MAST, shot #7786 at 0.24 s.

Error field correction

Four error field correction coils have been installed outside the vacuum vessel





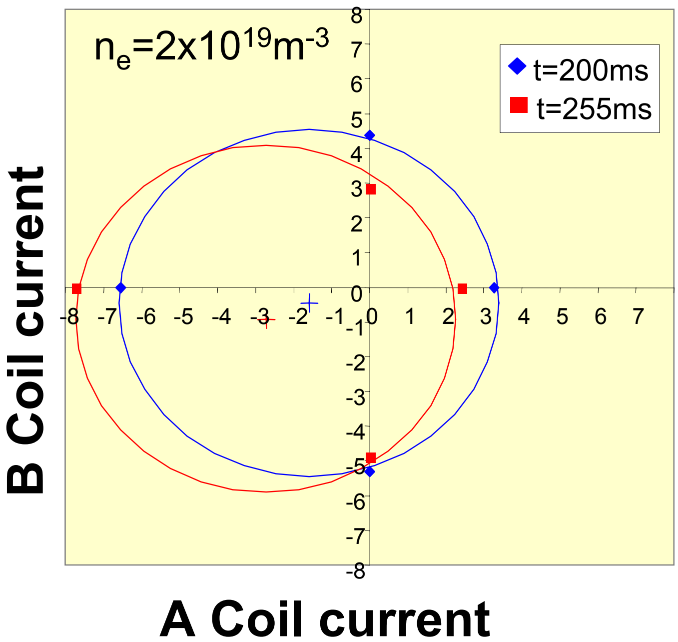
Modelling of field structure from EFCC

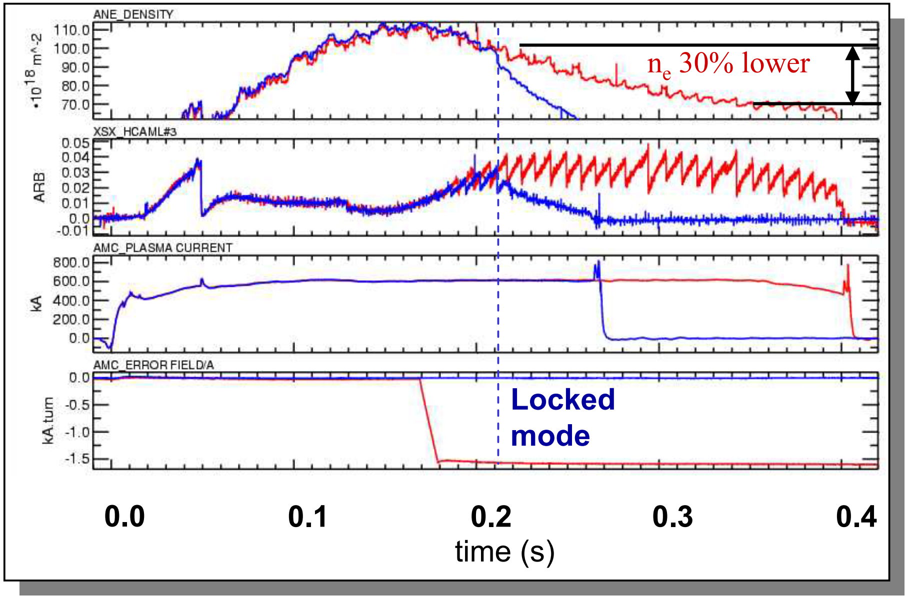
UKAEA Fusion Working in Europe

M Gryaznevich, Results from MAST, STW-04, Kyoto, 28-30/09/04

Error field correction

Determination of the necessary EFCC current ***(also shows variation of intrinsic error field with time)***





Compensation of error field with EFCC

- **Application of external helical field allows reduction of plasma density in discharges previously limited by locked modes**

Longer term: 2005-2006

- **Design and approval** for **comprehensive upgrade to MAST** (subject to spending review, large facilities roadmap)

- **No interruption to MAST** operation during this phase

- Upgrade will significantly enhance load assembly, heating systems, divertor and diagnostics

  - Increased heating power (~50% increase)
  - Long pulse capability (e.g 4s flat-top at 1MA)
  - Adaptable heating and current drive for plasma control and state-state scenarios
  - Actively pumped divertor for density control in long pulses
  - Test bed for first wall materials and novel divertor concepts