16th ISTW & 5th IAEA Technical Meeting on Spherical Tori, NIFS, Toki, Japan, September 2011

Progress & Developments on MAST

Brian Lloyd for the MAST Team
& Collaborators

EURATOM / CCFE Fusion Association

Research Councils UK
Energy
For a Low Carbon Future

CCFE is the fusion research arm of the **United Kingdom Atomic Energy Authority**

Jointly funded by EURATOM & RCUK Energy Programme

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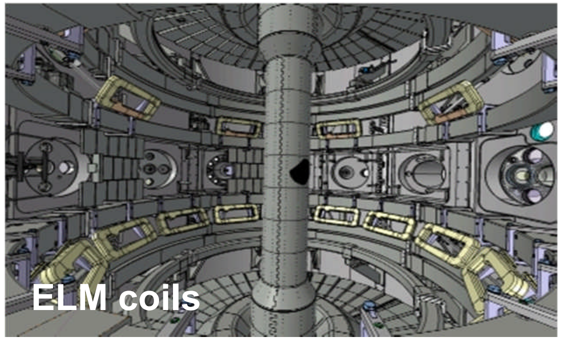
Introduction

❑ MAST is equipped with a wide range of tools e.g.

- long pulse, high power NBI
- digital plasma control
- error field compensation coils
- ELM control coils
- Adaptable fuelling incl. pellet injection
- divertor science facility (manipulator)
- disruption mitigation system

….etc



❑ …and powerful diagnostics e.g.

- (very) high resolution Thomson scattering
- MSE (35 chords, ~1ms resolution)
- CXRS (toroidal, poloidal)
- edge Doppler spectroscopy
- beam emission spectroscopy (BES)
- neutron camera
- FIDA
- EBW imaging
- high speed imaging (visible, IR)
- high frequency magnetics
- extensive edge measurements…etc

MAST Mission

☐ to explore the long term potential of the spherical tokamak as a fusion component test facility (CTF) and/or ST power plant (STPP)

☐ to advance key tokamak physics for optimal exploitation of ITER and DEMO design optimisation

☐ to provide unique insight into underlying tokamak physics

Main elements of 2011-12 programme*

☐ Physics of ELMs & their control by RMPs (incl. effects on pedestal transport, plasma screening effects etc..).

New ELMs coils

☐ L-H transition & pedestal physics (focus on the underlying physics of the L-H transition, impact of connection length and pedestal properties)

MSE, EBW imaging, ECELESTE upgrade

☐ Transport studies – impact of q(r) and flow shear on low-k turbulence

2D BES

☐ High beta macroscopic stability incl. NTM physics (e.g. critical island widths)

TS upgrade, ‘smart’ triggering system

☐ Fast particle instabilities (e.g. TAE damping), Fast ion losses/redistribution and impact on plasma performance (e,g, energy confinement, q(r) control by NBCD etc).

TAE coils, FIDA, neutron camera

☐ First wall/divertor heat loads (incl. toroidal asymmetries; effects of ELM control and disruption mitigation by massive gas injection; SOL width scaling; SOL T_i measurements)

DMV, LWIR, Retarding Field Energy Analyzers

* *Based on PAC recommendations*

Outline

☐ Introduction

☐ **ELM & Pedestal Physics**

☐ **Turbulence**

☐ **Fast Ion Physics**

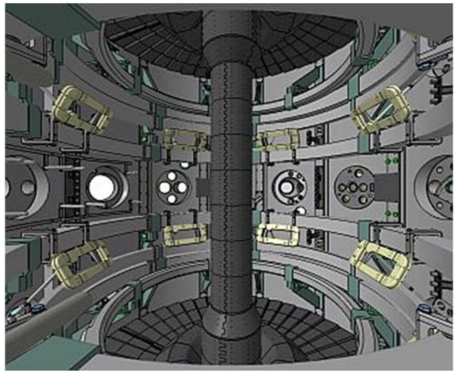
☐ **Exhaust Physics**

☐ **MAST Upgrade**

☐ **Summary**

ELM control

$\leq$ 2010 configuration



6 + 6 internal array: $\leq$ 1.4kA, 4-turn coils (n = 3)
- similar to DIII-D I-coils

Even parity
(Same sign current in upper and lower coils at same toroidal location)

I_{coil}^{up} + - + - + -
I_{coil}^{down} + - + - + -

Odd parity
(Opposite sign current in upper and lower coils at same toroidal location)

I_{coil}^{up} + - + - + -
I_{coil}^{down} - + - + - +

☐ Resonant effects observed in L-mode with similar I_{coil} threshold (~1kA)
  - density pump-out
  - enhanced fluctuations (inside LCFS)
  - increased (more positive) E_r^{ped}

☐ ELM mitigation observed in H-mode

☐ Important to include effect of plasma response in modelling. MARS-F $\Rightarrow$
- single fluid linear MHD code, which solves the full resistive MHD equations in toroidal geometry
- includes plasma response and screening due to toroidal rotation

A Kirk, Y Liu et al

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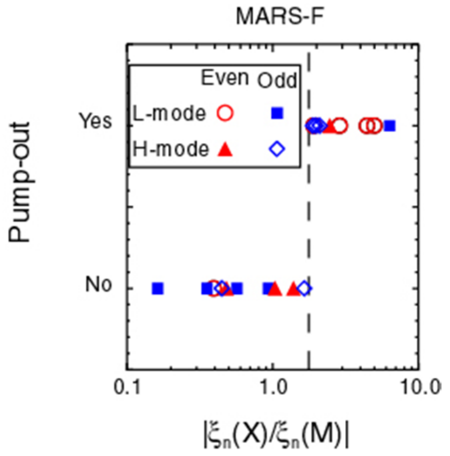
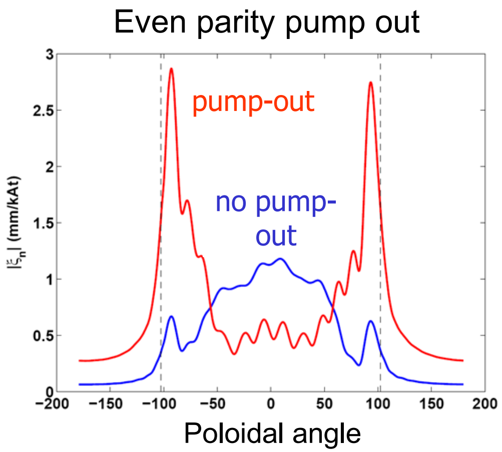
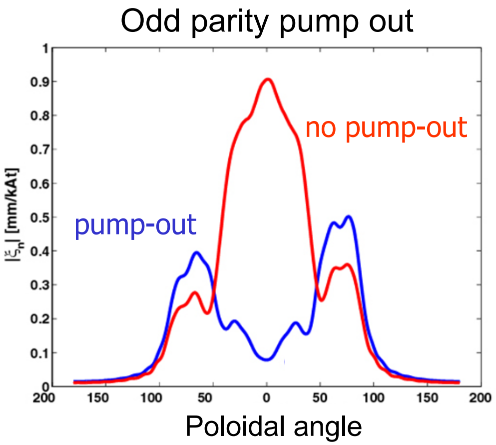
Plasma response (MARS-F)

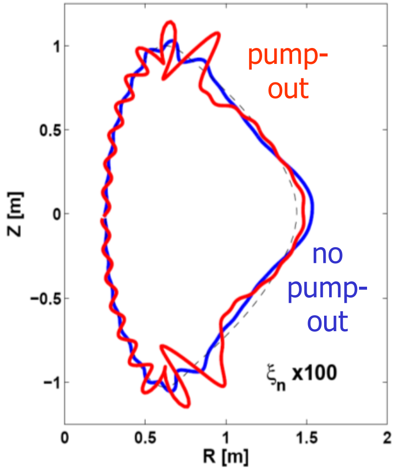
- In all L-mode and H-mode plasmas studied pump out is only observed when the plasma displacement is greater at the X-point than at the mid-plane

- Mid-plane peaking associated with the triggering of an n=3 global kink mode. X-point peaking due to triggering of a peeling mode with dominant high m mode number









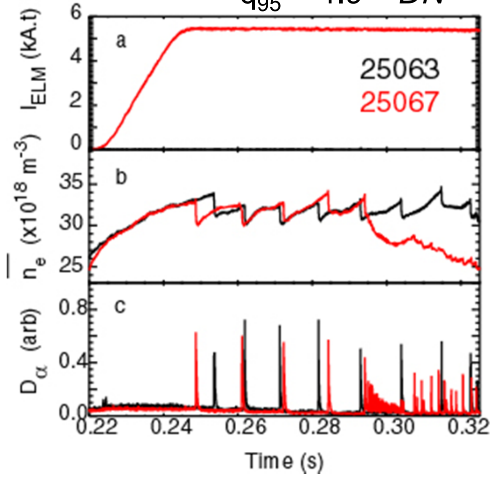
Energy

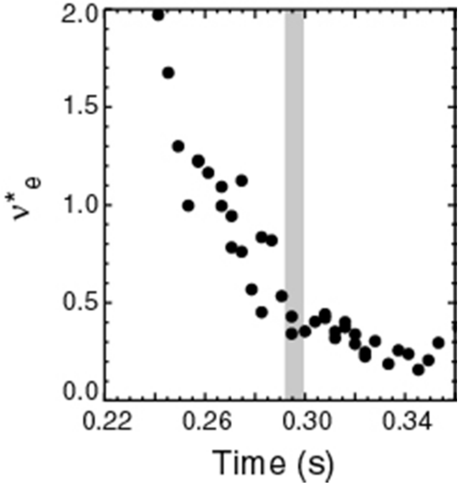
Mitigation of type I ELMs

- ❑ ELMs can be triggered in ELM free discharges or the ELM frequency increased in type III ELM-ing discharges

- ❑ Initially no effect on type I ELMs could be observed despite a wide region of island overlap (Chirikov parameter $\sigma_{chir} > 1$) – type I ELM mitigation subsequently observed if q_{95} carefully optimised

$q_{95} = 4.9$ *DN*





Pump out occurs when $\nu^* < 0.5$

f_{ELM} increases by 5
ΔW_{ELM} reduces from 5 kJ to ~ 1kJ ($f_{ELM} . \Delta W_{ELM}$ ~ constant)
W_{MHD} reduces by ~ 8%

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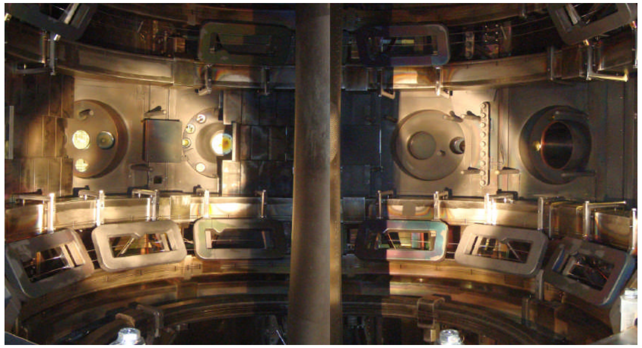
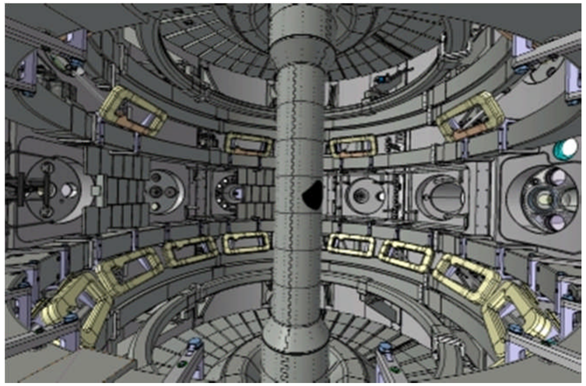
ELM control - 2011

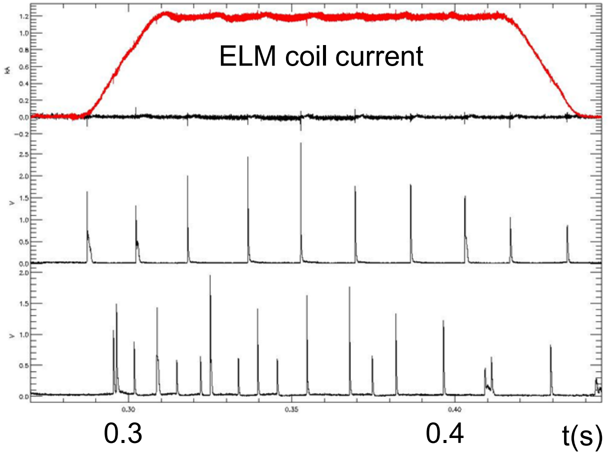




- New internal coils installed and tested 6 upper row + 12 lower allowing n=3,4,6 and ability to adjust alignment during shot

- To date experiments performed in L-mode investigating threshold effects, strike point splitting and changes in turbulence characteristics

- H-mode experiments just beginning – using n=6 from the lower coils gave density pump out and more frequent ELMs during H-mode in Lower SND shot



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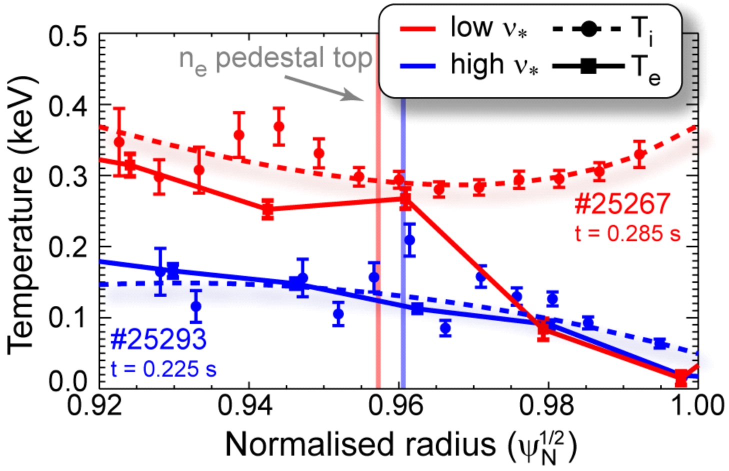
Pedestal – edge $T_i(r)$ measurements

❑ Detailed analysis of pedestal stability requires measurement of ion temperature and edge current density profiles

Edge T_i measurements

❑ Novel high resolution edge T_i measurements from CX emission (C^{6+}) using cold deuterium gas-puff to localize measurement

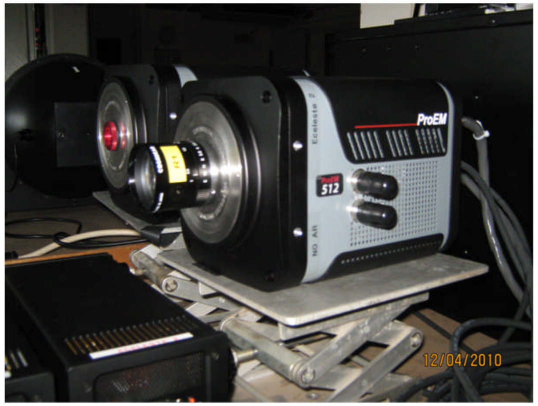


❑ Collisionality dependence consistent with analysis of Kagan & Catto (PPCF **50**, 085010 (2008)) which showed that in the banana regime $L_{Ti} >> \rho^i_{pol}$

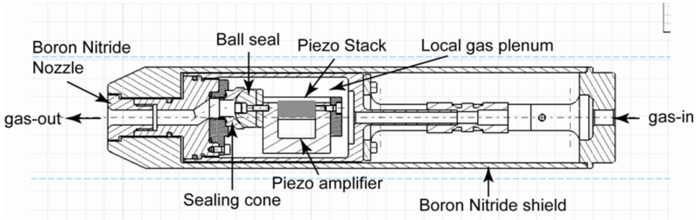
THE UNIVERSITY *of York*

T Morgan (U. York)   H. Meyer et al

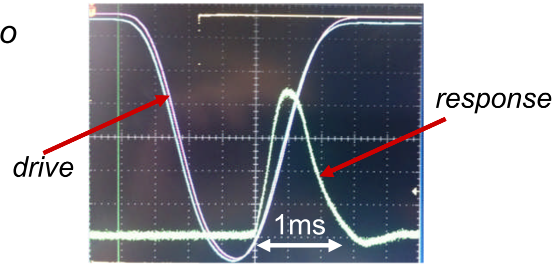
Edge Doppler spectroscopy (ECELESTE) upgrade



New ECELESTE detectors (≥ 40kHz)



New fast piezo valve



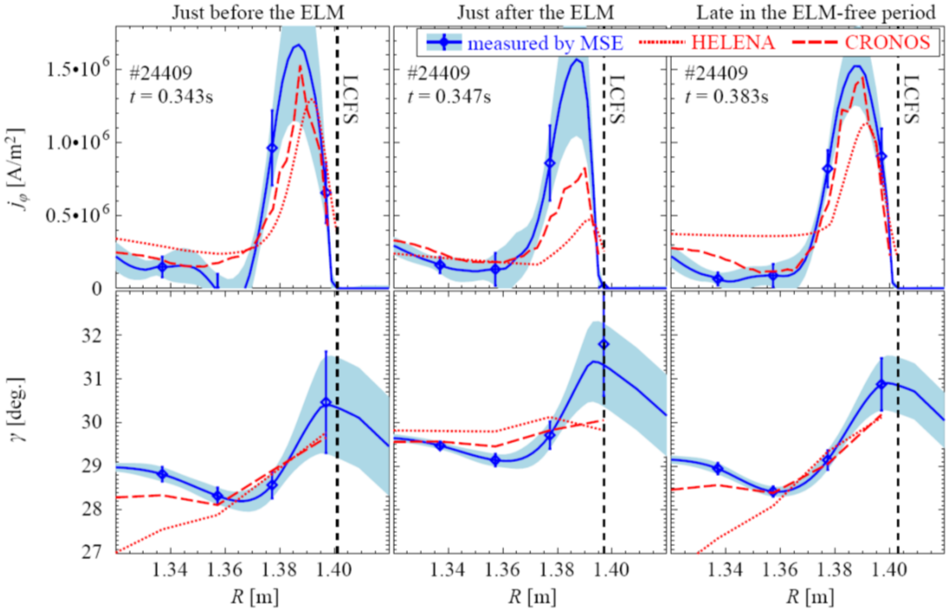
+ new poloidal in-vessel optics f/# ~ 2 (was ~ 7) and 2nd spectrometer

❑ Upgraded system gives:
- simultaneous measurement of E_r, $v_{i\theta}$, $v_{i\phi}$, and T_i
- increased sensitivity
- measurement of fluctuating fields with frequencies covering the GAM range (geodesic acoustic mode, a signature of the zonal flows believed to be responsible for the turbulence suppression leading to the edge transport barrier)

H. Meyer et al

Pedestal – edge j(r) measurements

- ☐ Large magnetic field line tilt in the ST enables MSE measurements of edge $j_\phi(r)$ evolution with 2ms resolution. Effect of measured radial electric field included (small)
- ☐ Large increase in edge current density observed at L-H transition



- ☐ Approx. agreement with neoclassical calculations when j(r) fully relaxed, but not just after ELM crash. Best agreement with CRONOS which includes current diffusion.

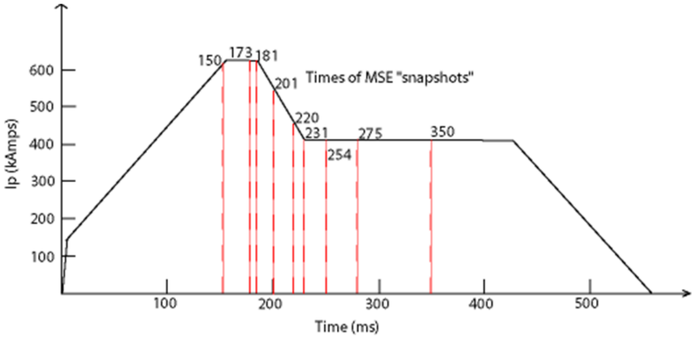
- ☐ EBW emission shows evidence of a more complex edge current structure – 2D EBW imaging system being developed to investigate further.

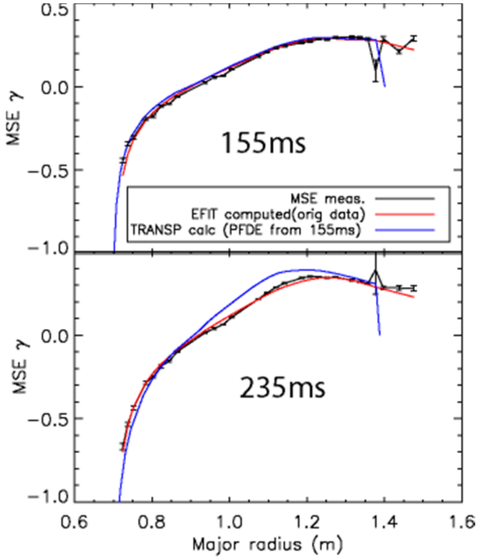
M. De Bock et al

Test of neoclassical current diffusion model

- Previous studies have indicated that current diffusion during the current ramp-up in MAST is *slower* than calculated using neoclassical resistivity

- New experiments test neoclassical current diffusion modelling during current ramp-down in a different collisionality regime





- Preliminary results indicate similar phenomenon c.f. previous ramp-up experiment results:

  Modelling plasma current evolution using neoclassical current diffusion does not accurately reproduce measurements.

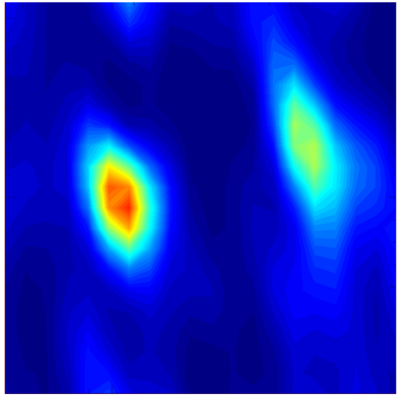
D. Keeling et al

EBW imaging

- ❑ High resolution (space and time) current density data needed to test ELM models (and neoclassical theory)
- ❑ Synthetic aperture microwave imaging (SAMI) 10-35GHz radiometer installed and first data – novel antennas
- ❑ Uses Field Programmable Gate Arrays for data acquisition: 16 channels, 14 bit, 250MHz, 0.5s
- ❑ First images obtained showing characteristic structure associated with B-X-O mode conversion

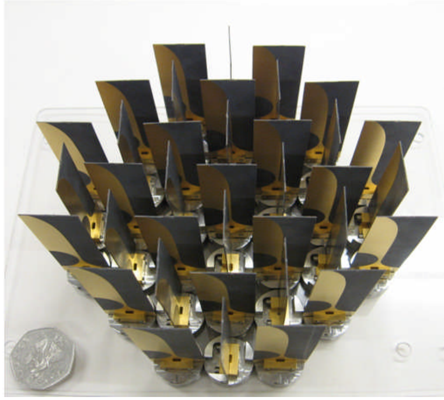
FPGA-based EBW data acquisition and signal processing

shot #26783, 180ms



V. Shevchenko, R. Vann, S. Freethy, B. Huang et al

Antenna array for MAST SAMI



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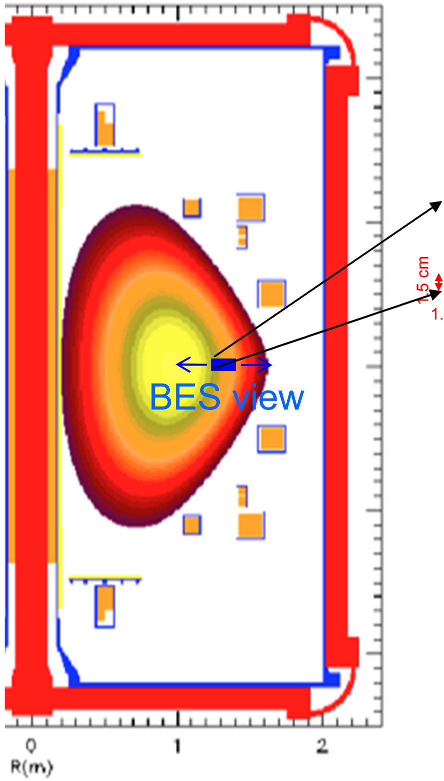
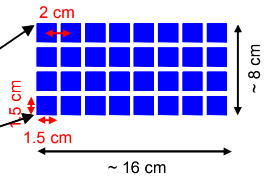
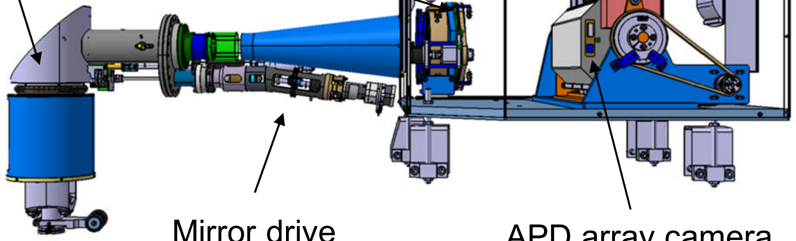
BES turbulence imaging system

- Views Doppler shifted D_α emission from heating beam
- APD array detector: 8 radial x 4 poloidal channels
- View location radially movable from R_m = 0.7-1.5 m





- 2 MHz digitization frequency, 0.5 MHz BW
- Resolution: $k_{r,\theta} < 2\,\pi/(2\mathrm{cm}) \sim 1.6\ \mathrm{cm}^{-1}$
- $k\rho_i < 1$ → ITG scale turbulence
- Sensitivity $\delta n/n \geq$ few 0.1% at a few 0.1 MHz



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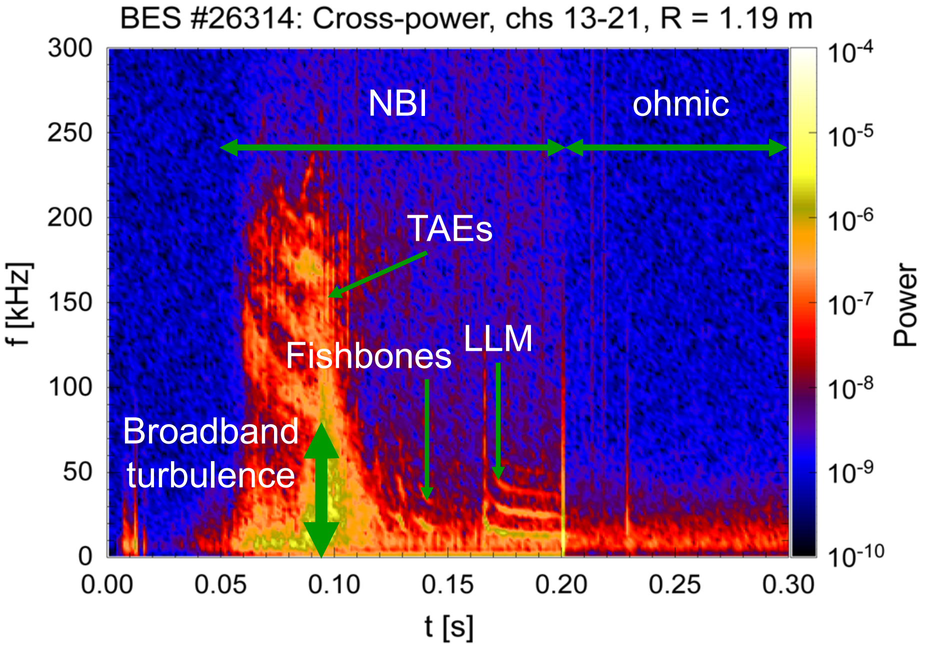
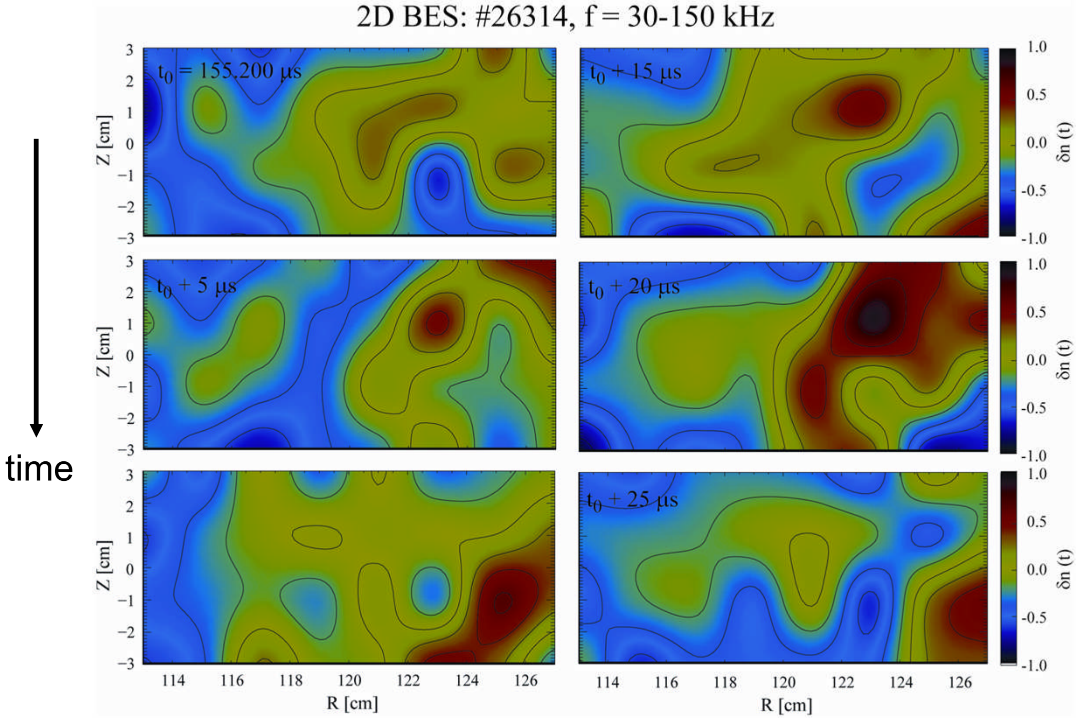
Characteristics of BES data



- ☐ Broadband turbulence in frequency range 0-100 kHz above noise floor
- ☐ Common mode component due to coherent MHD (TAE, fishbones, LLM, etc)
- ☐ Significant power from background signal during ohmic phase

A. Field, D. Dunai (RMKI), Y-C Ghim (Oxford) et al

2D turbulence ‘movie’



- ❑ Images (interpolated) of normalised density fluctuations in 30-150 kHz band
- ❑ Structures at ion scale ~ few cm extent persist for a correlation time ~ 10 µs

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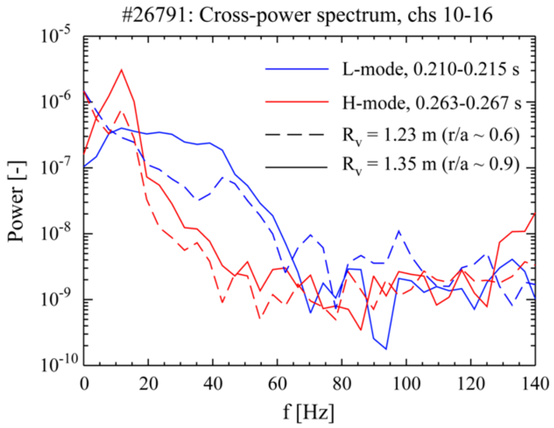
L/H-mode comparison



Outer region of SND plasma: r/a ~ 0.6-0.9

MHD quiescent L- and H-mode phases

❑ **H-mode:**

Reduced power in 20-80 kHz band

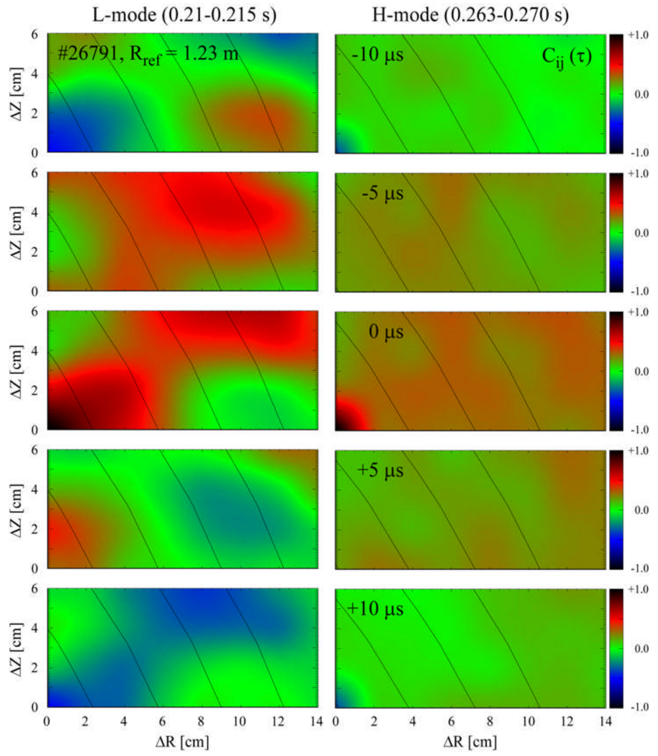
Short correlation lengths < 2 cm

❑ **L-mode:**

Longer radial correlation length ~ 4-6 cm

Propagation of eddies ⊥B due to ExB drift

Cross-correlation functions R_v = 1.23 m



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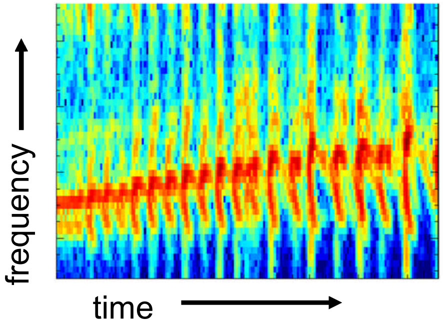
Fast ion physics

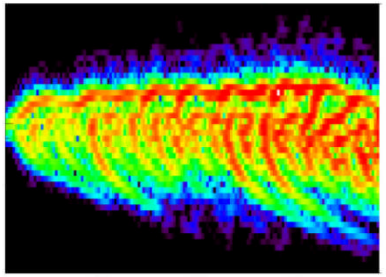
- ❑ Fast particle driven modes in MAST cover a broad frequency range
  - Alfvén Cascades (RSAE) → TAE ($\omega \sim v_A/2qR$) → CAE ($\omega \sim \omega_{ci}$)

❑ Dynamical friction important for describing nonlinear wave evolution with distribution of super-Alfvenic fast ions
– i.e. α-particles in ITER & DEMO and beam ions in MAST ($v_b >> v_A$)

❑ Drag and Krook relaxation have been introduced into HAGIS (non-linear drift-kinetic δf code) – quantitative comparison with MAST data underway



Frequency sweeping TAE in MAST #22807



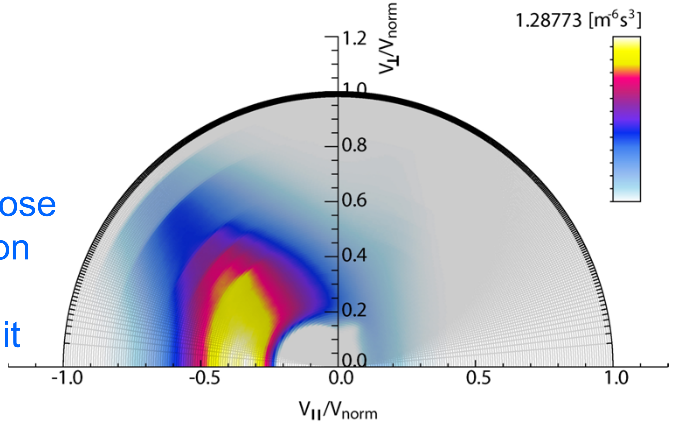
Realistic tokamak simulation of α-driven n = 3 core localized TAE using HAGIS

S Pinches, S. Sharapov, M. Lilley (Chalmers U.), B. Breizman (U. Texas) et al

Fast ion simulation

- GPGPU: supercomputer on desktop.
- Fast particle physics needs detailed distribution functions for
  - fusion product diagnostics (e.g. neutron cameras, proton first orbit detectors)
  - drive for and loss due to instabilities (e.g. HAGIS code)
- Full orbit, high resolution. Fast: 2 million orbits in ~6hrs.
- LOCUST-GPU calculates gyro-phase resolved, high resolution, smooth, fast ion distribution functions suitable for fast ion stability calculations – development of synthetic diagnostics to interpret neutron camera and FIDA data underway

GPGPU =
General Purpose
computation on
Graphics
Processor Unit



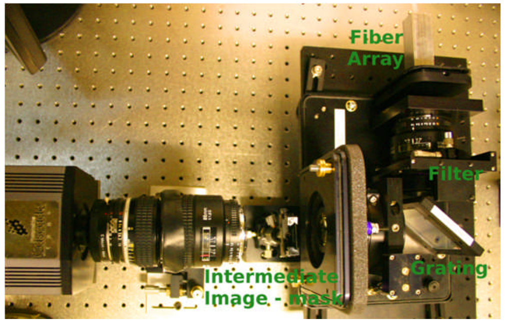
4 "gamer" GTX480 Fermi cards.

MAST steady-state fast ion distribution function. Two beams including E0, E0/2 E0/3 species (6 in all)

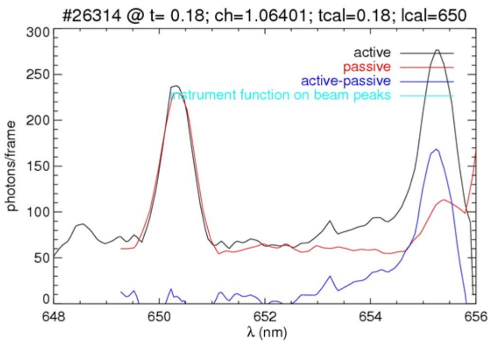
R. Akers

Fast ion $D\alpha$ (FIDA)

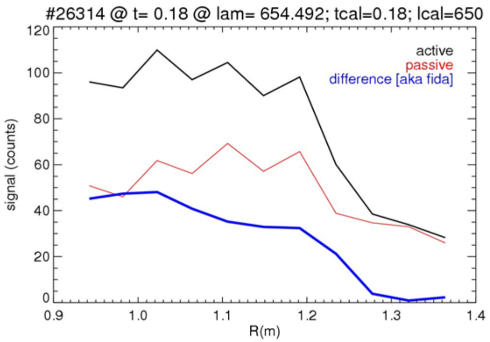
- Vertical and toroidal views - sensitive to passing & trapped populations.
- Background views to exclude edge D_α
- 32 fibres/view (~ 2cm between channels) with patch panel. 24 channels [2 x 12]; time resolution: 0.28ms



- Spectral shape gives information on energy/pitch distribution and allows exclusion of impurity/beam emission lines.
- System designed to give fast spectral information at the expense of spatial resolution in order to follow fast events e.g. fishbone instabilities.



Spectra



Profiles

- First FIDA data look promising

C. Michael et al

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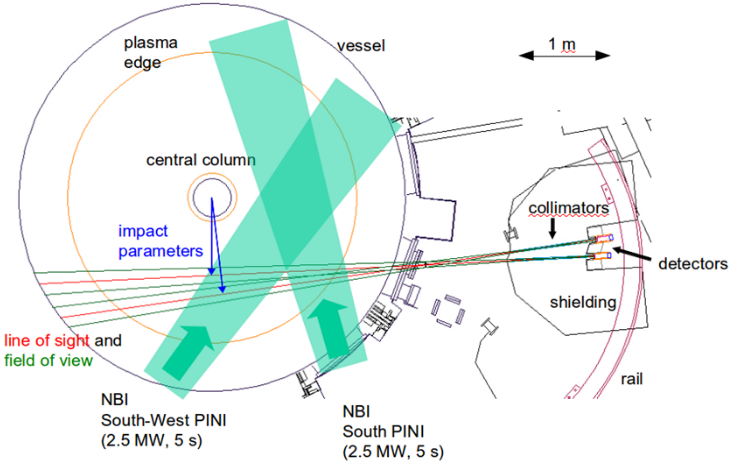
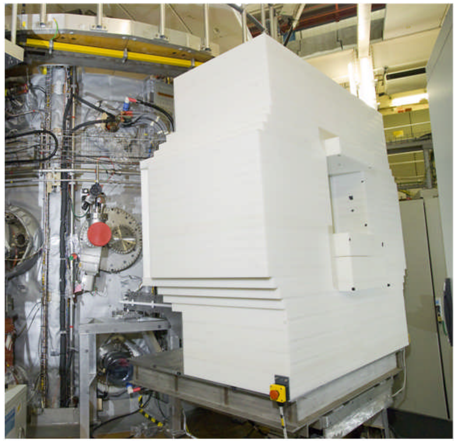
Neutron camera





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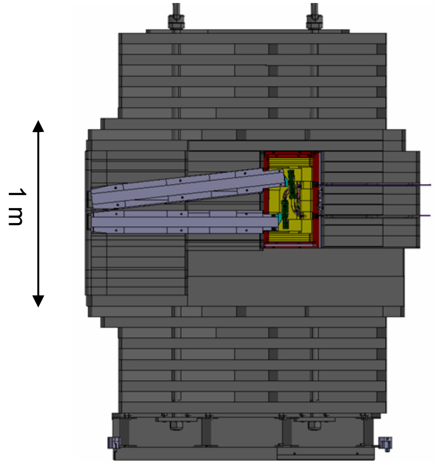
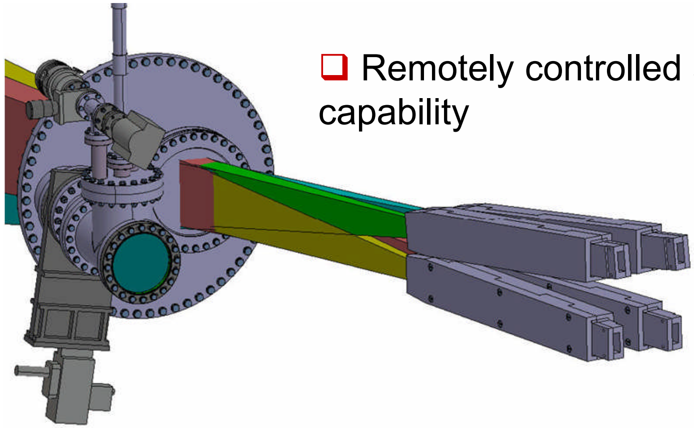
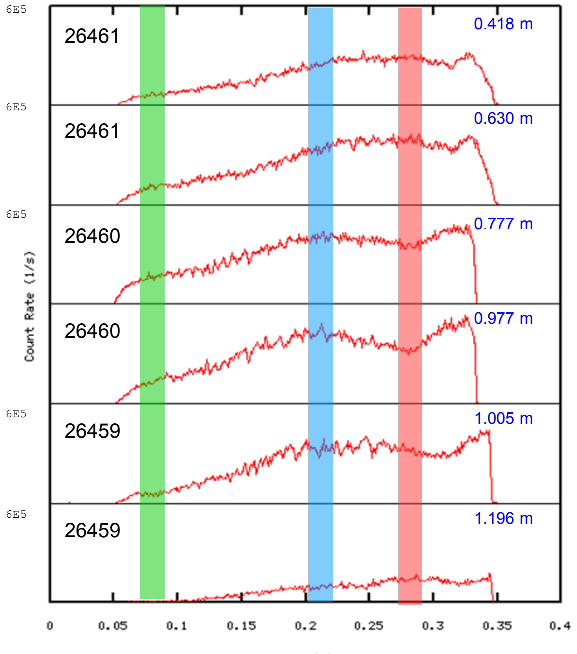


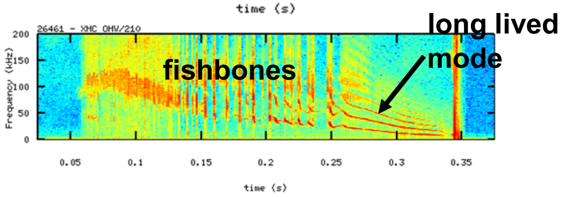


- ❑ Remotely controlled scanning capability
- ❑ 4 channels

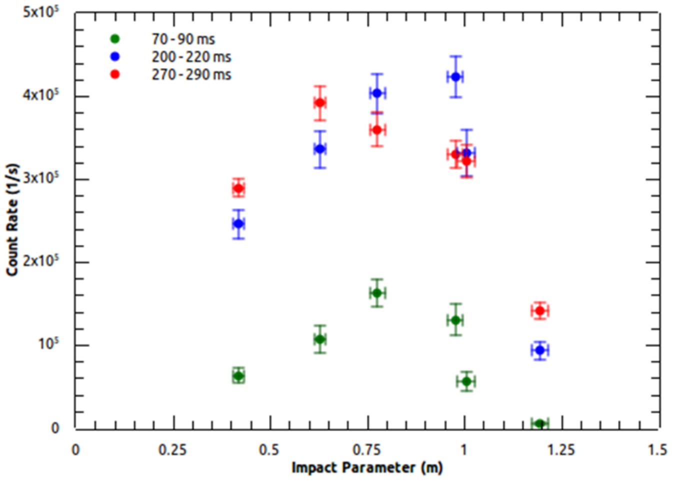
M. Turnyanskiy, M. Cecconello (Uppsala) et al

Neutron emission measurements





- ☐ Effects of ‘fishbone’ instabilities and the long lived mode (internal n = 1 kink mode)



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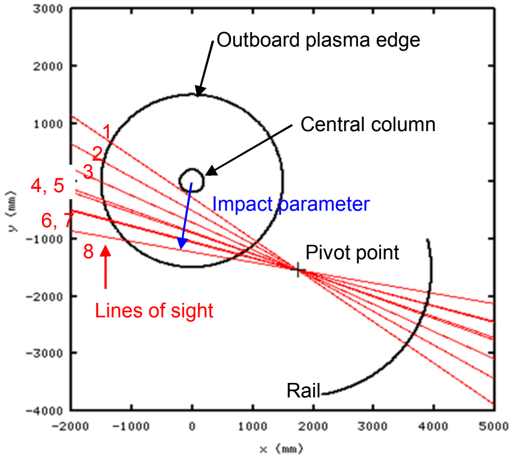
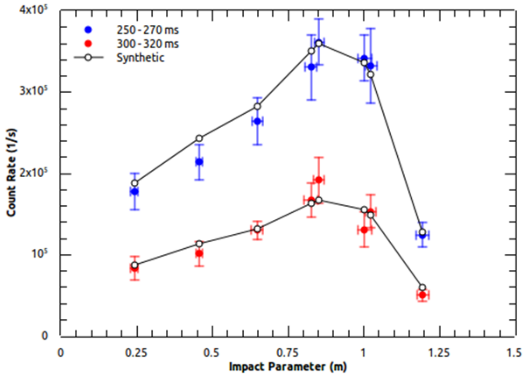
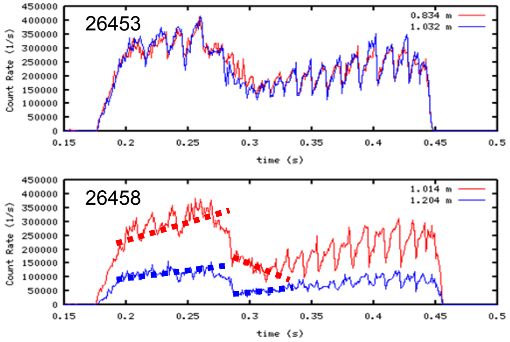
Neutron emission measurements

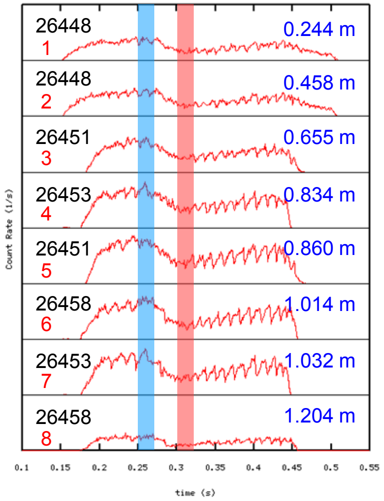
- ❑ Effect of 1,1 mode ('snake')







Core vs. edge effects



Profile effects – obtained from radial scan over 4 pulses

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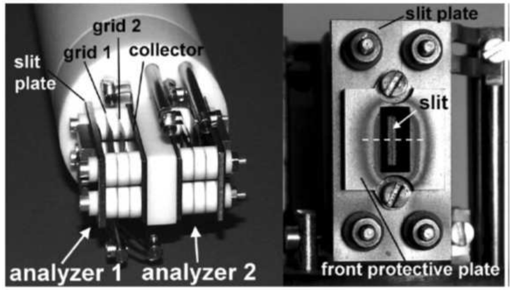
SOL ion energy measurements

- Motivation:
  - – interpretation of probe data (n_e, P_{div})
  - – determines physical sputtering rates from plasma facing materials
  - – ELM ion energies in the far SOL unknown

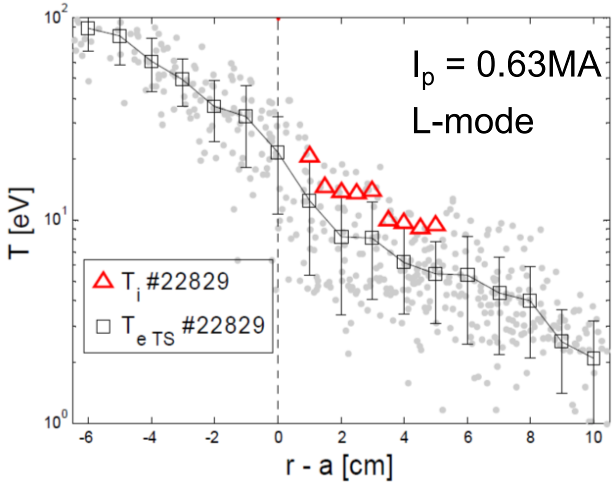
Retarding Field Analyzer (CEA)



- First measurements show $T_i \sim (1 – 2.6) \times T_e$ at outboard mid-plane (much higher energies observed in fluctuations)

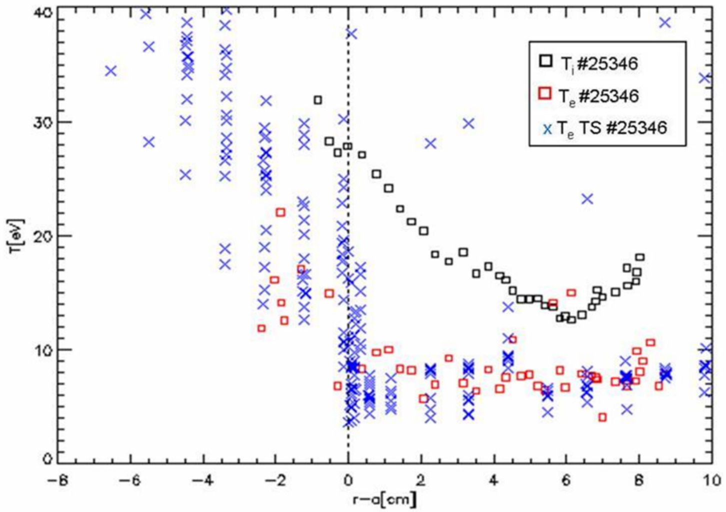
- Ion energy in ELM filaments - large signals observed as far as 20cm from the LCFS and up to 500V of biasing

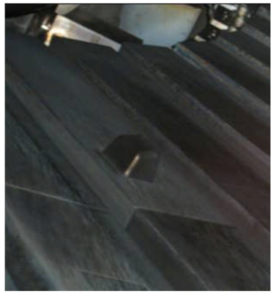
P. Tamain, S. Allan, S. Elmore (Liverpool U.)



RFA supplied by CEA Cadarache

SOL ion energy measurements

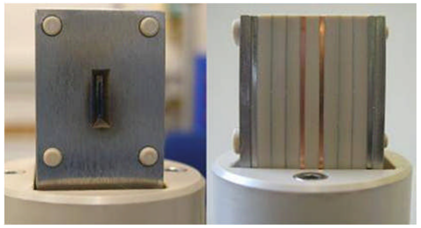




Divertor RFEA

Installation of two new retarding field energy analyzers now allows simultaneous ion energy measurements in the divertor and at the outboard mid-plane

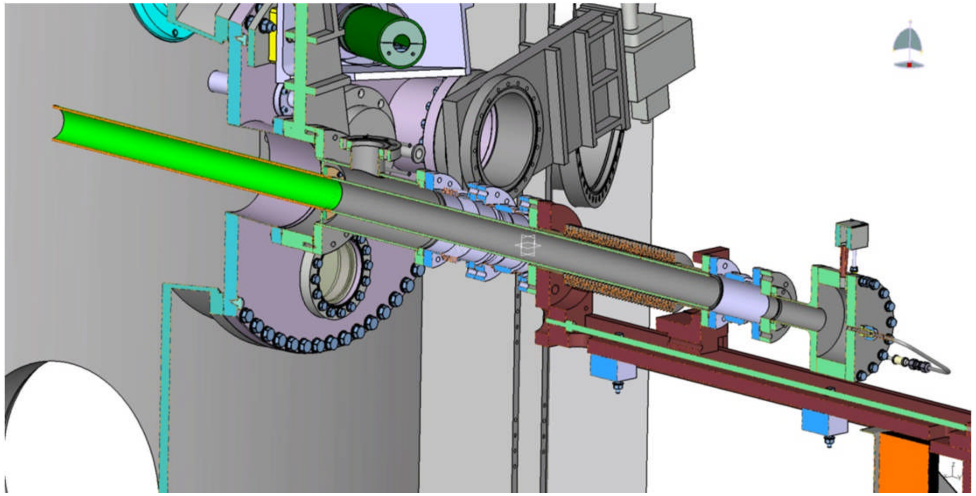
S. Allan, S. Elmore (Liverpool U.), P. Tamain (CEA), M. Kocan (IPP Garching)



Mid-plane RFEA

Disruption mitigation

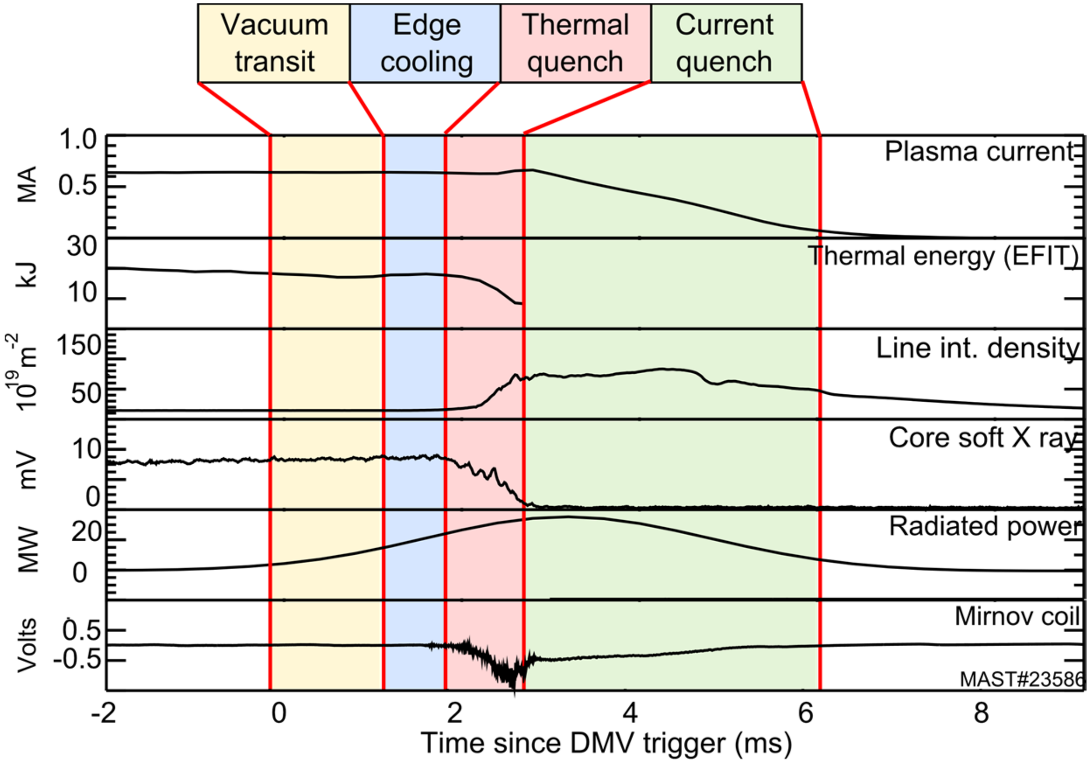
- **MAST disruption mitigation valve supplied via collaboration with FZJ**
  - 65ml injection volume
- **Gas delivered via 1.5m long, 50mm diameter pipe**
  - Pipe outlet located within 30cm of outboard midplane separatrix
- **Injection of a range of noble gas species and quantities:**
  - Ar(10%)/He mixture, Helium, Argon and Neon
  - 5 to 40 x10^{21} particles injected (10 – 300 times the plasma inventory)



A. Thornton, M. Lehnen (FZJ) et al

Disruption sequence

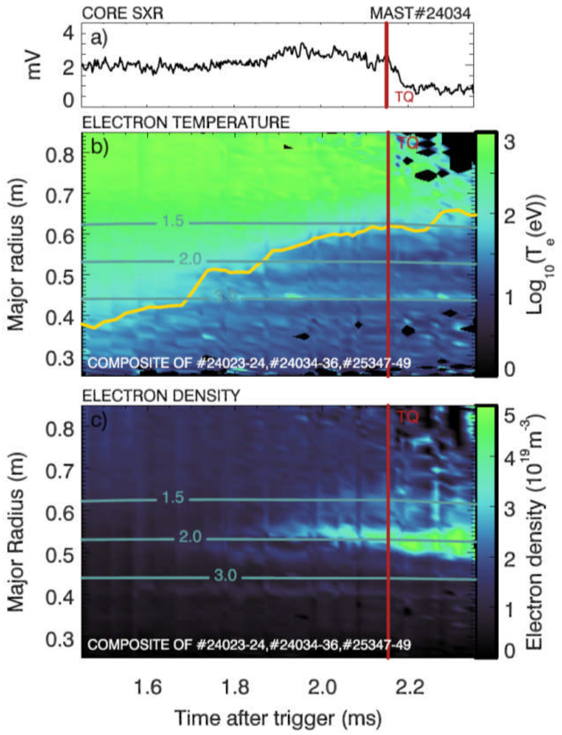
Four stages to a mitigated discharge



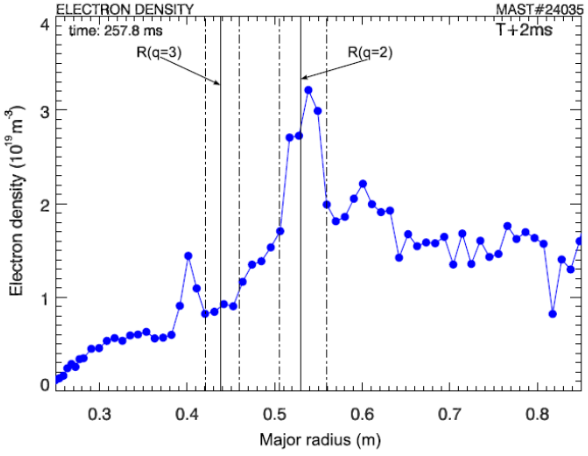
A. Thornton et al

Disruption mitigation

10% Argon 90% Helium



- Impurity ions penetrate to q = 2 surface prior to thermal quench (high speed imaging)
- Local density build-up and initiation of thermal quench when cooling front reaches q = 2 surface



- 60 – 70% reduction in peak divertor power loads

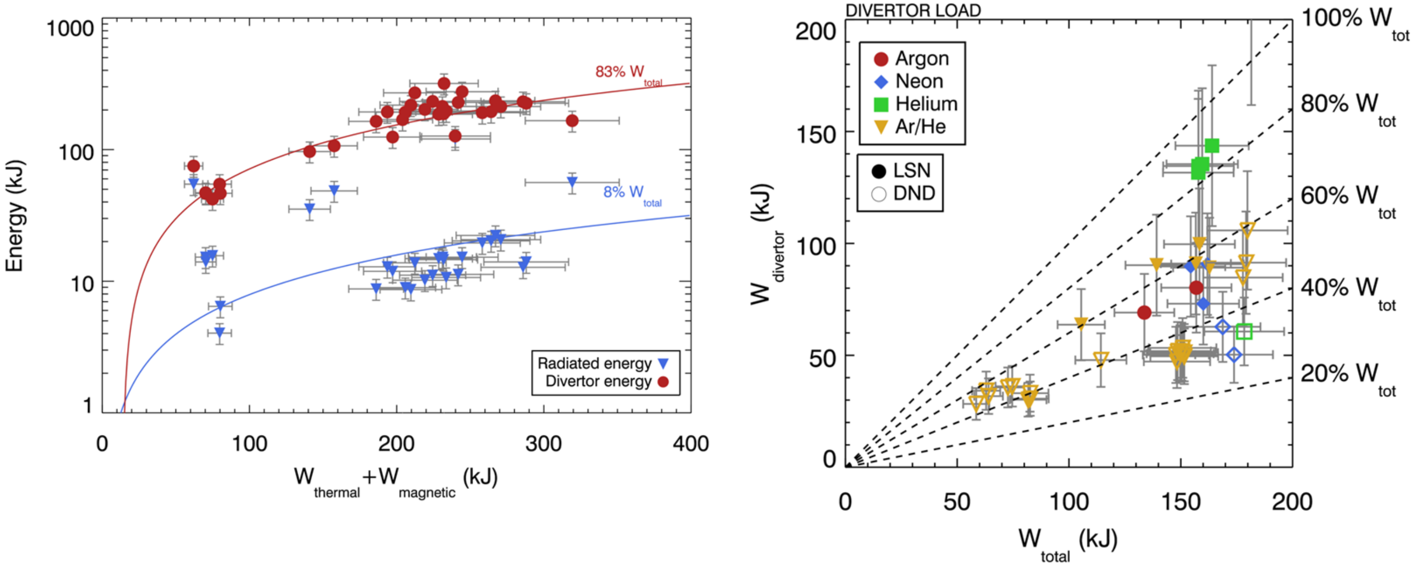
A. Thornton et al

Disruption mitigation

Energy to divertor can be reduced by a factor ~ x2 to ~ 40% of the total stored energy

Unmitigated disruptions

Mitigated disruptions



[Total stored energy ⇒ EFIT, radiated energy ⇒ bolometry, divertor energy ⇒ IR]

A. Thornton et al

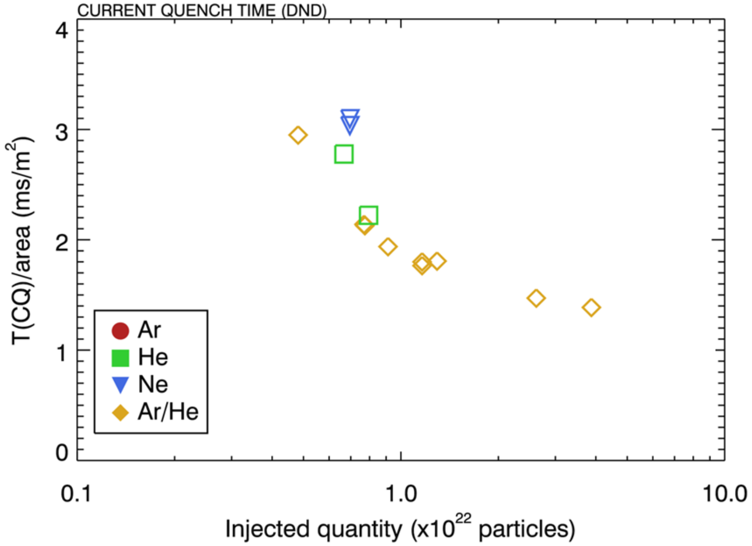
Disruption mitigation – current quench

Mitigated current quench times in double null discharges (DND)

Extrapolated from a decay of 100% to 70% Ip

Saturation of the current quench time with increasing quantity

Mitigated timescales similar to unmitigated disruptions (typically between 2.5 and 1.2 ms/m^2)

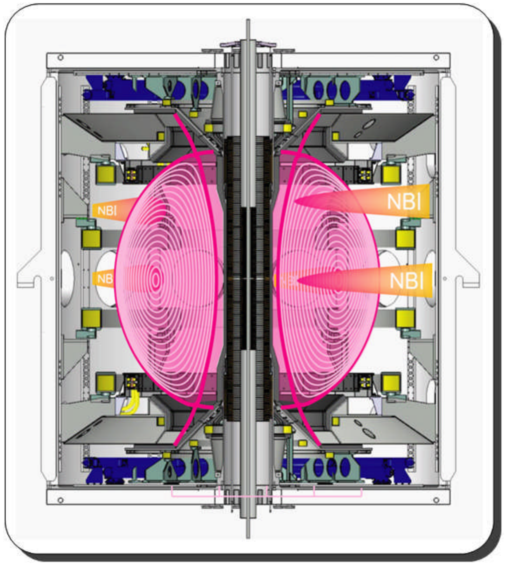


A. Thornton et al

MAST Upgrade

Goals

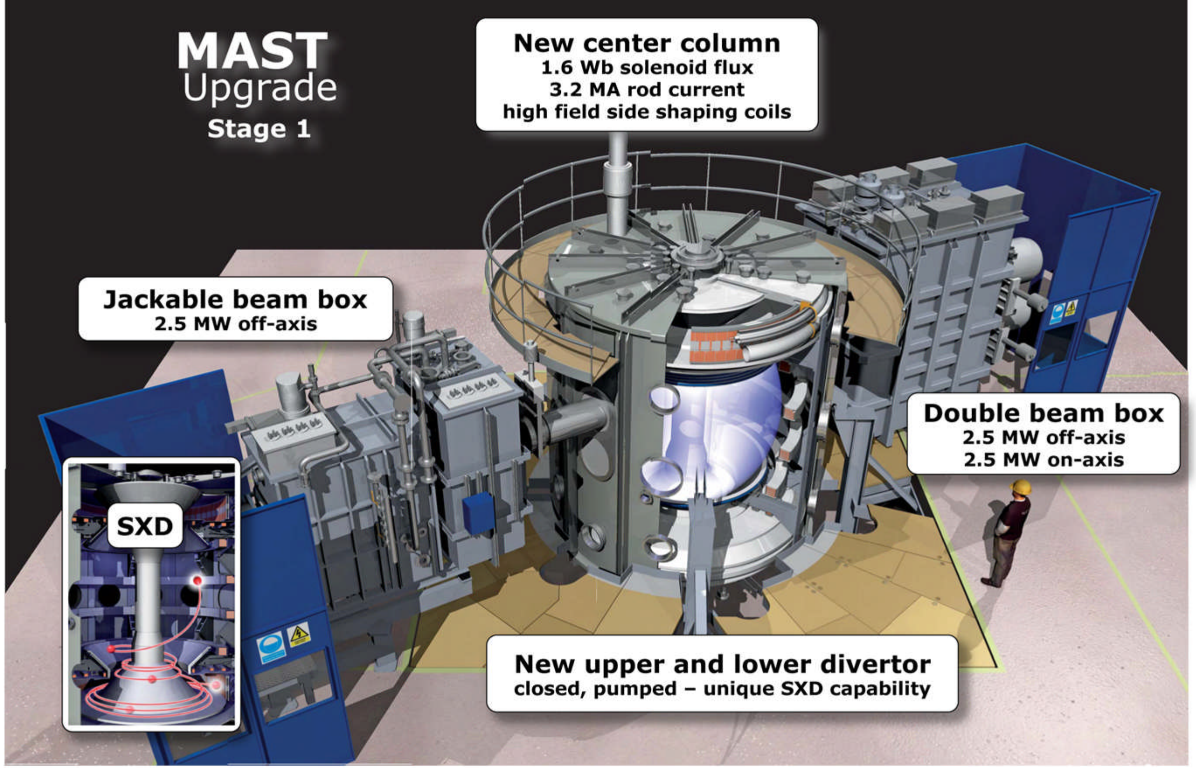
- Demonstrate physics viability of a ST– based Component Test Facility
- Contribute to the ITER/DEMO physics base
- Demonstrate effectiveness of a flexible Super-X divertor



- Increased heating power (NBI, EBW)
  - adaptable system providing control of j(r), p(r), v(r)
- Relaxed current profile
  - fully non-inductive operation possible
- Increased TF, increased solenoid flux
  - higher current, longer pulse routine operation
- Improved exhaust and density control
  - closed cryopumped divertor

MAST Upgrade

- ☐ Project kick-off July 2010
- ☐ Construction 2013 - 2015



New center column
1.6 Wb solenoid flux
3.2 MA rod current
high field side shaping coils

Jackable beam box
2.5 MW off-axis

Double beam box
2.5 MW off-axis
2.5 MW on-axis

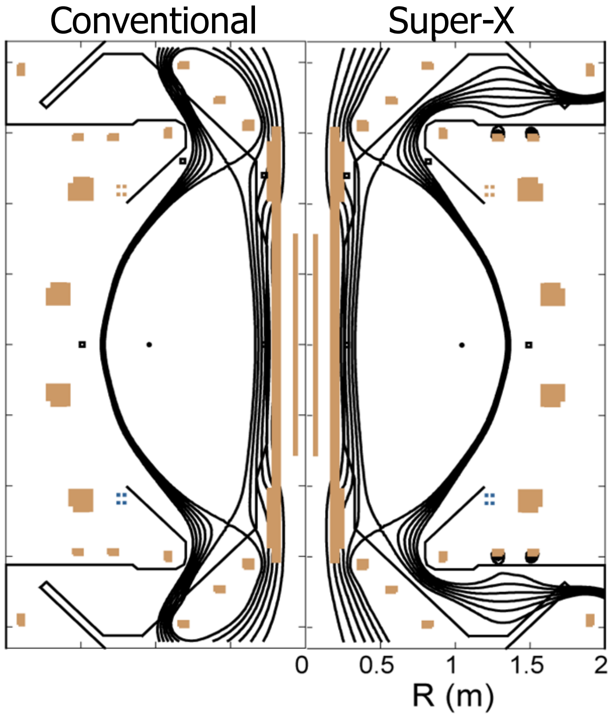
New upper and lower divertor
closed, pumped – unique SXD capability

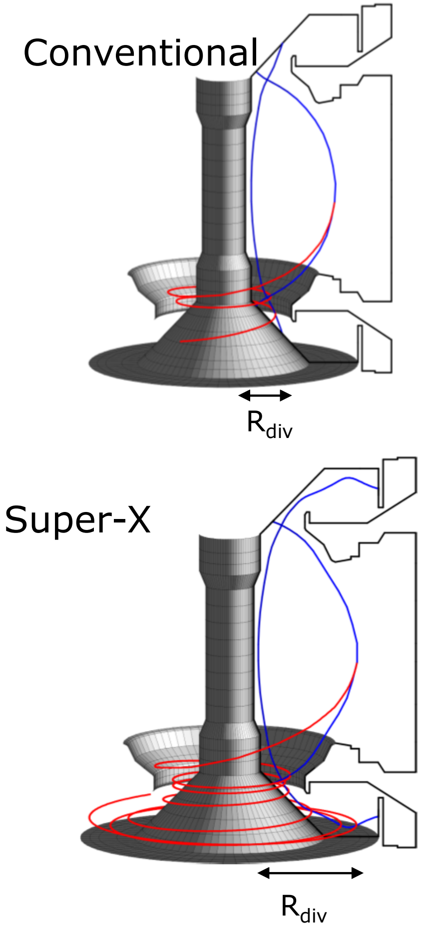
MAST Upgrade – stage 1 and full compared

	MAST	MAST-U Stage 1	 Stage 2 (proposed)
Power injected (NBI)	~5 MW	**~7.5 MW**	12.5 MW
Power injected (RF)	< 0.3 MW	**<0.3 MW**	1-2 MW
Toroidal field (R=0.8m)	0.55 T	**0.84 T**	
Energy deposited at I_P=1 MA	~5-10 MJ	**< 30 MJ**	< 63 MJ
Pulse length at I_P=1 MA (B_t>0.5T)	> 0.5s	**~2-4s**	< 5s
Plasma current flat-top	1.2 MA	**~ 2 MA**	
Profile control (J, p, flow)	~none	**moderate**	extensive
Particle control	~none	**active**	
'Routine' high elongation[2]	1.8-2.1	**2.5-2.7**	
Divertor design	open	**closed + SXD**	

MAST Upgrade divertor

Both super-X and conventional divertor operation are possible.



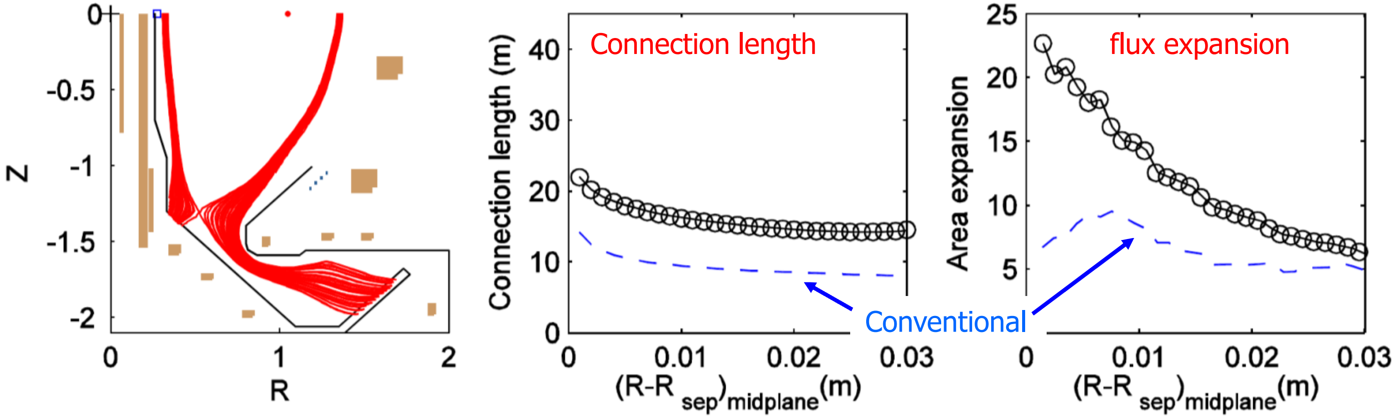


Valanju et al Phys. Plasmas 2009

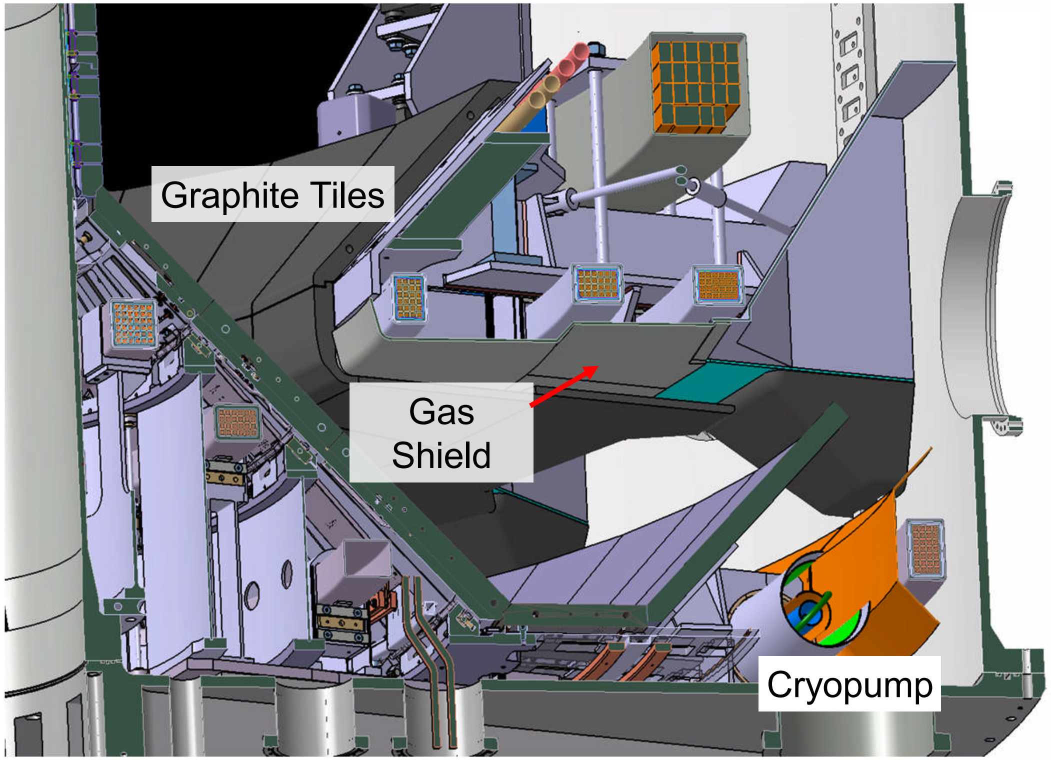
MAST super-X divertor

- Super-X combines
  long connection length,
  flux expansion and
  large volume to radiate power
  to get cold low power density plasma at target

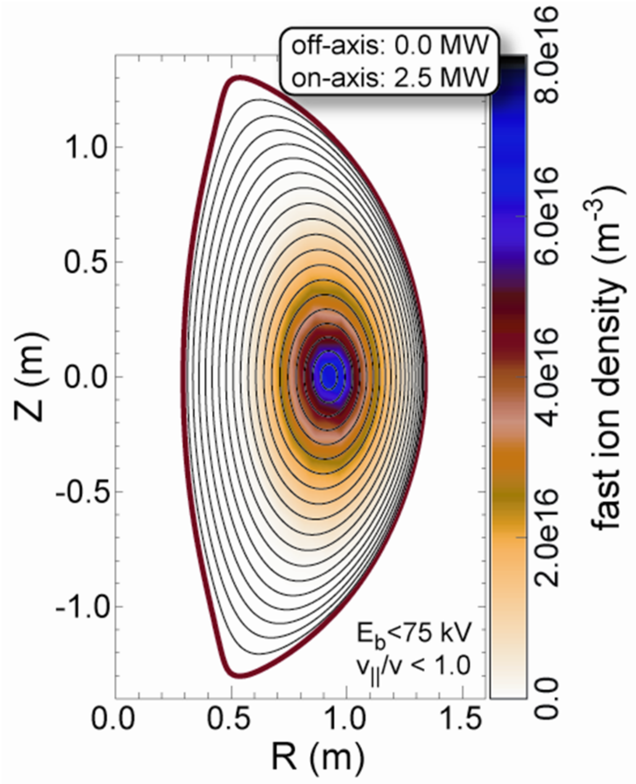
- MAST super-X has a low poloidal field region to increase connection length in limited space



Super-X mechanical design



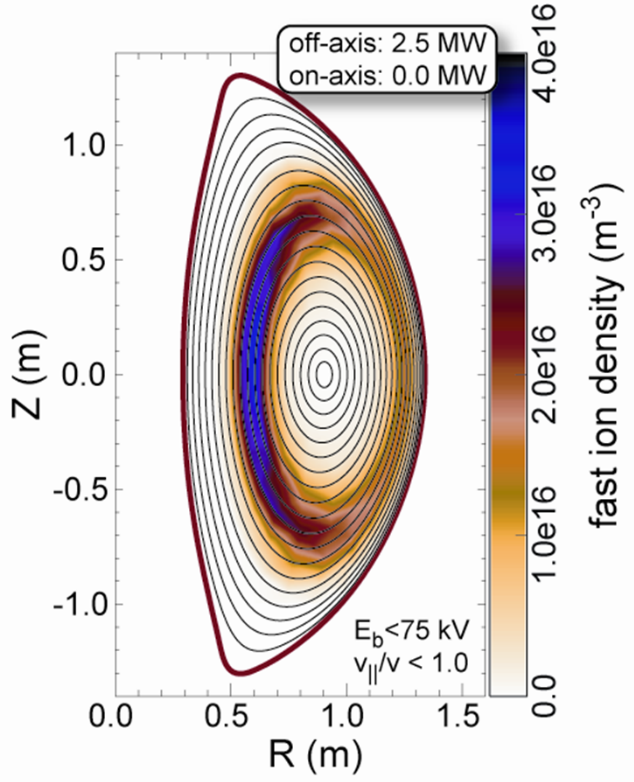
Flexibility on fast ion density profiles



Advanced profile control

- On-axis ⇒ peaked.

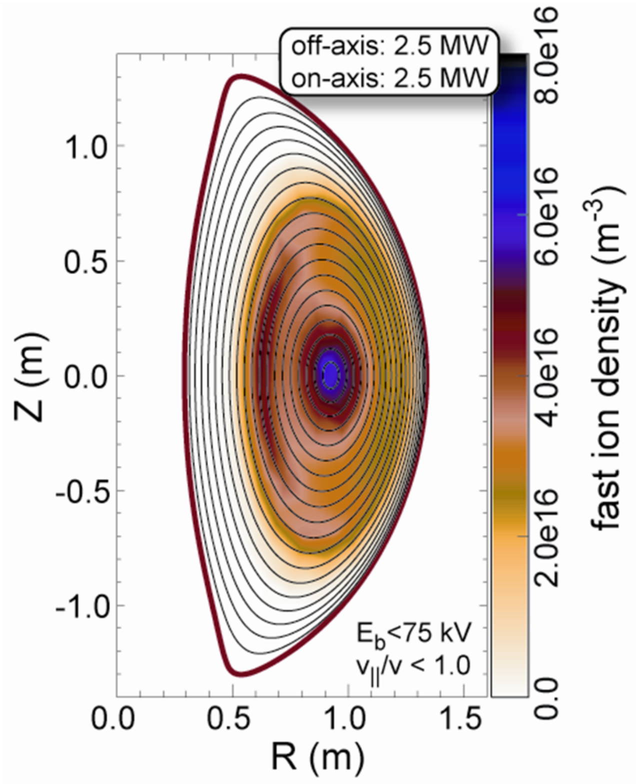
Flexibility on fast ion density profiles



Advanced profile control

- On-axis ⇒ peaked.
- Off-axis ⇒ hollow.

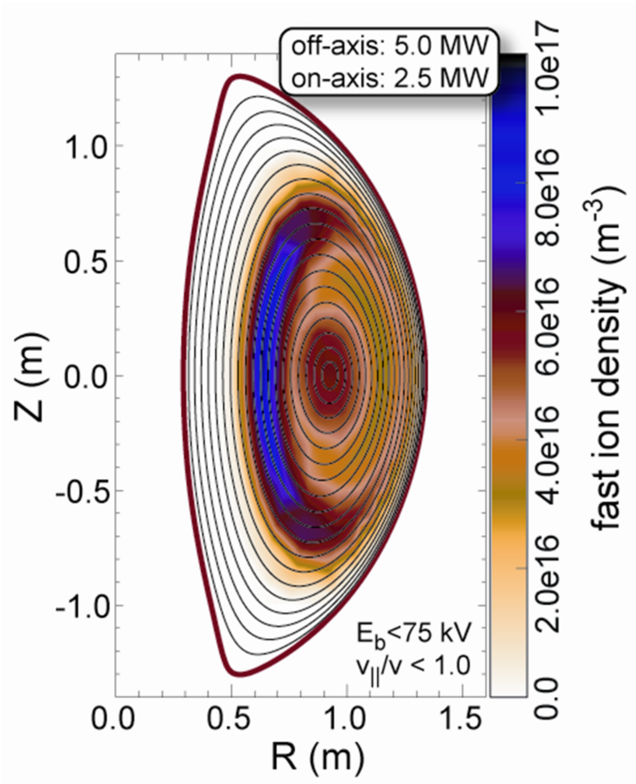
Flexibility on fast ion density profiles



Advanced profile control

- On-axis ⇒ peaked.
- Off-axis ⇒ hollow.
- On- and off-axis ⇒ broad.

Flexibility on fast ion density profiles



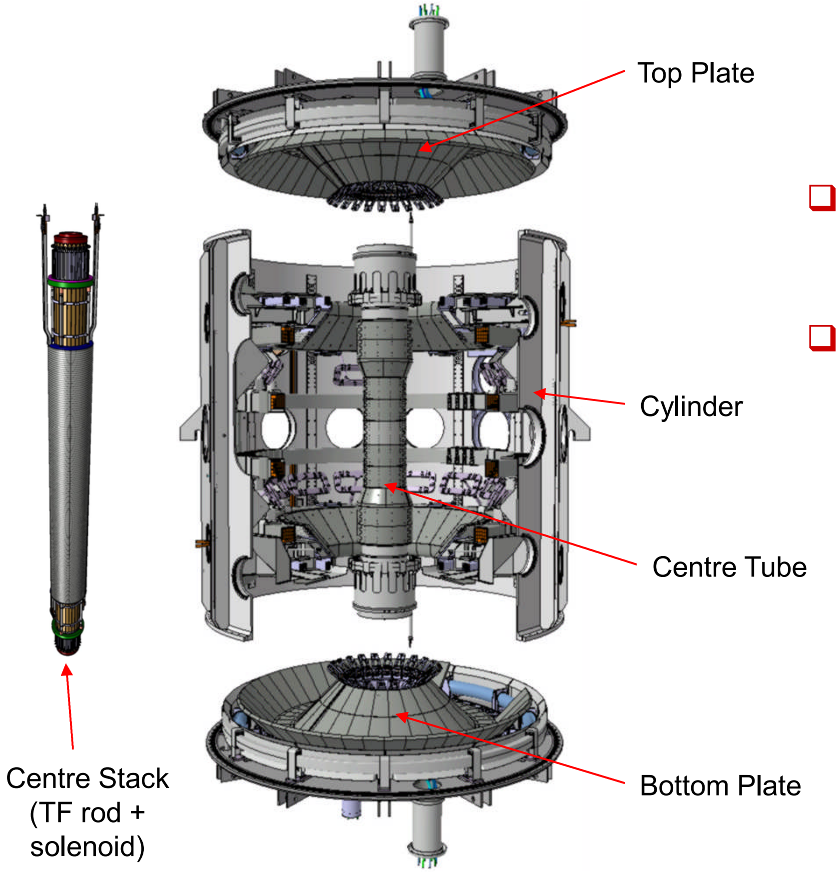
Advanced profile control

- On-axis ⇒ peaked.
- Off-axis ⇒ hollow.
- On- and off-axis ⇒ broad.

MAST-U physics studies

- High fast-ion pressure (60% of total pressure)
- About 1 MA of non-inductive current drive
  ⇒ long pulse length.

MAST-U load assembly

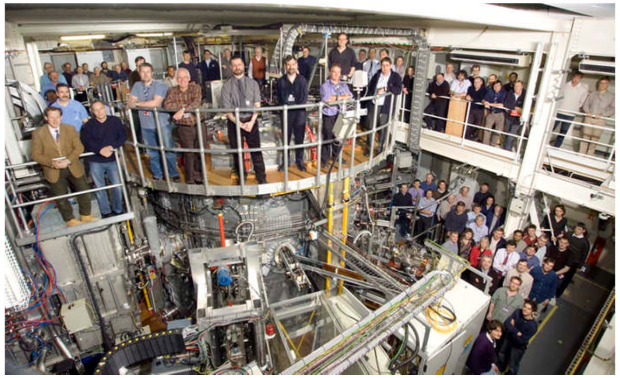


- ☐ Modular design option for parallel assembly (keep shutdown short)
- ☐ Main engineering issues:
  - Centre rod+solenoid thermal + e.m. stresses
  - TF sliding joints – thermal + e.m. stresses
  - Super-X divertor assembly and maintenance
  - magnetic alignment of coils

Summary & Future Plans

☐ MAST is addressing a wide range of important physics issues for ITER and future STs, exploiting powerful control tools (e.g. ELM control coils, disruption mitigation system etc), increasingly sophisticated diagnostics and supported by extensive theory and numerical modelling capability.

☐ The MAST programme is underpinned by strong and wide-ranging collaborator contributions



New capabilities in 2011-12

Additional ELM control coils

2D BES system (with RMKI Hungary)

collimated neutron detector (with Uppsala U.)

fast ion D_α (FIDA) diagnostic

fast edge Doppler spectroscopy (≥ 40kHz)

electron Bernstein wave imaging (with University of York)