EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Overview of recent physics results from MAST

Andrew Kirk

and the MAST team

Presented at the IAEA FEC, Kyoto
October 2016

Research Councils UK Energy For a Low Carbon Future

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

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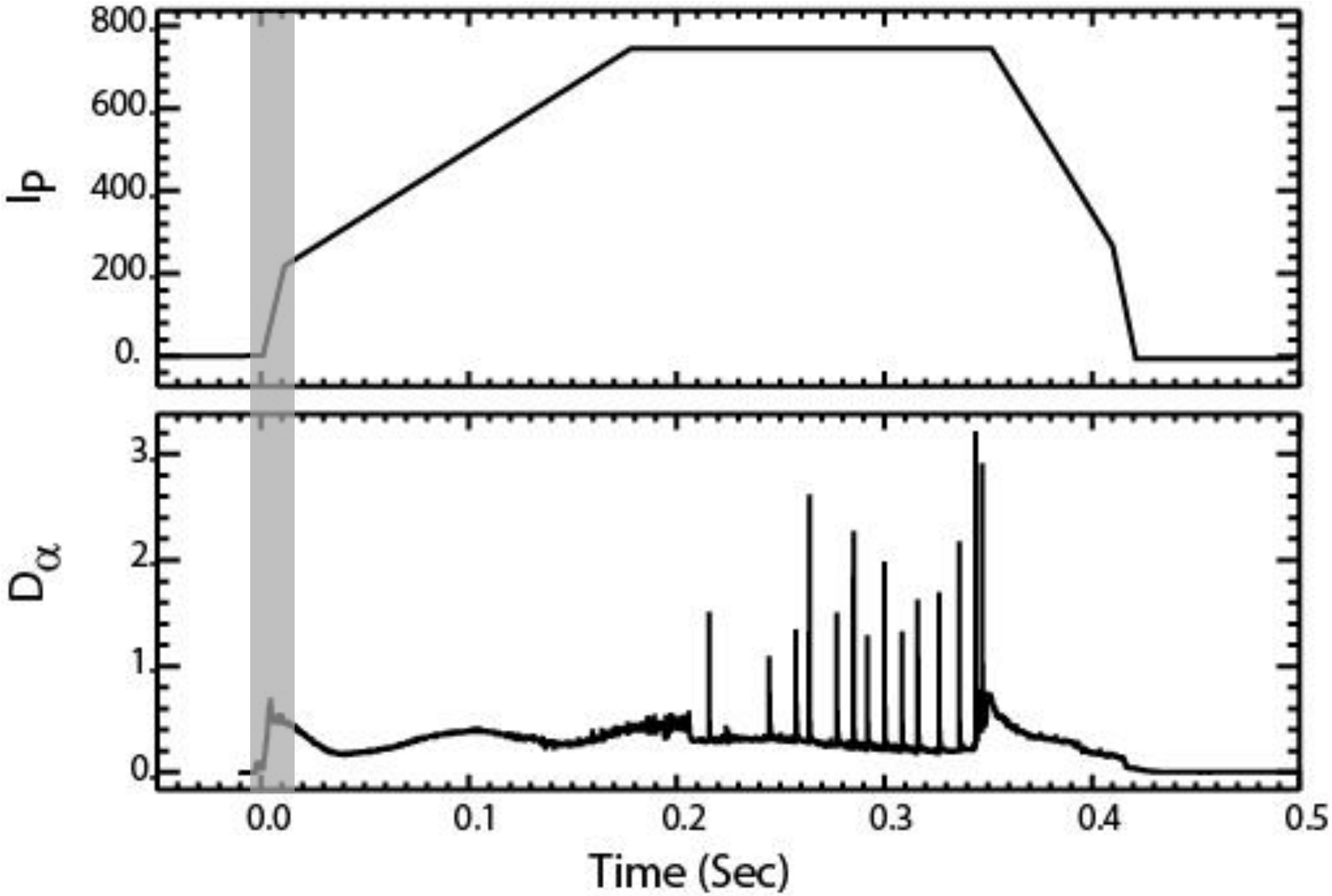
Overview of recent physics results from MAST

Andrew Kirk
On behalf of

The University of York
University of Bristol
Australian National University
TU/e Technische Universiteit Eindhoven University of Technology
ENEA C.R. Frascati
NFRI
University of Bath
Oak Ridge National Laboratory
University of Strathclyde Glasgow
FIU Florida International University
The University of Warwick
UCLA
Ioffe Physical Technical Institute
IPP
NIFS
Imperial College London
University of Liverpool
CRPP
Durham University
Jülich Forschungszentrum
Lawrence Livermore National Laboratory
University of Kent
Wigner
Risø DTU National Laboratory for Sustainable Energy
東京大学 The University of Tokyo
PPPL Princeton Plasma Physics Laboratory
iter
Kyoto University Founded 1897
cea
University of Oxford
DCU
Uppsala Universitet
IPP

Outline

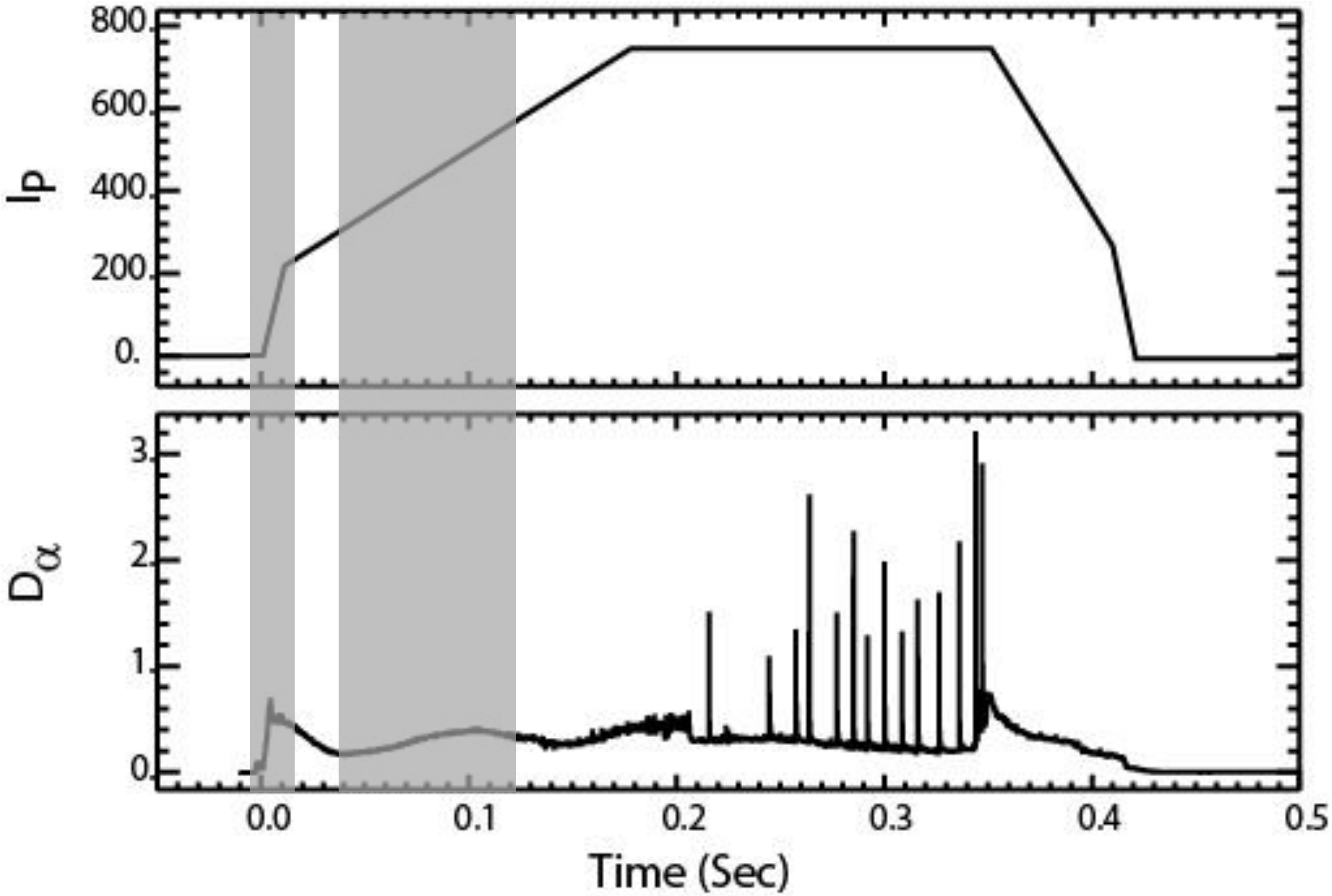
Start-up



Outline

Start-up

Current Ramp

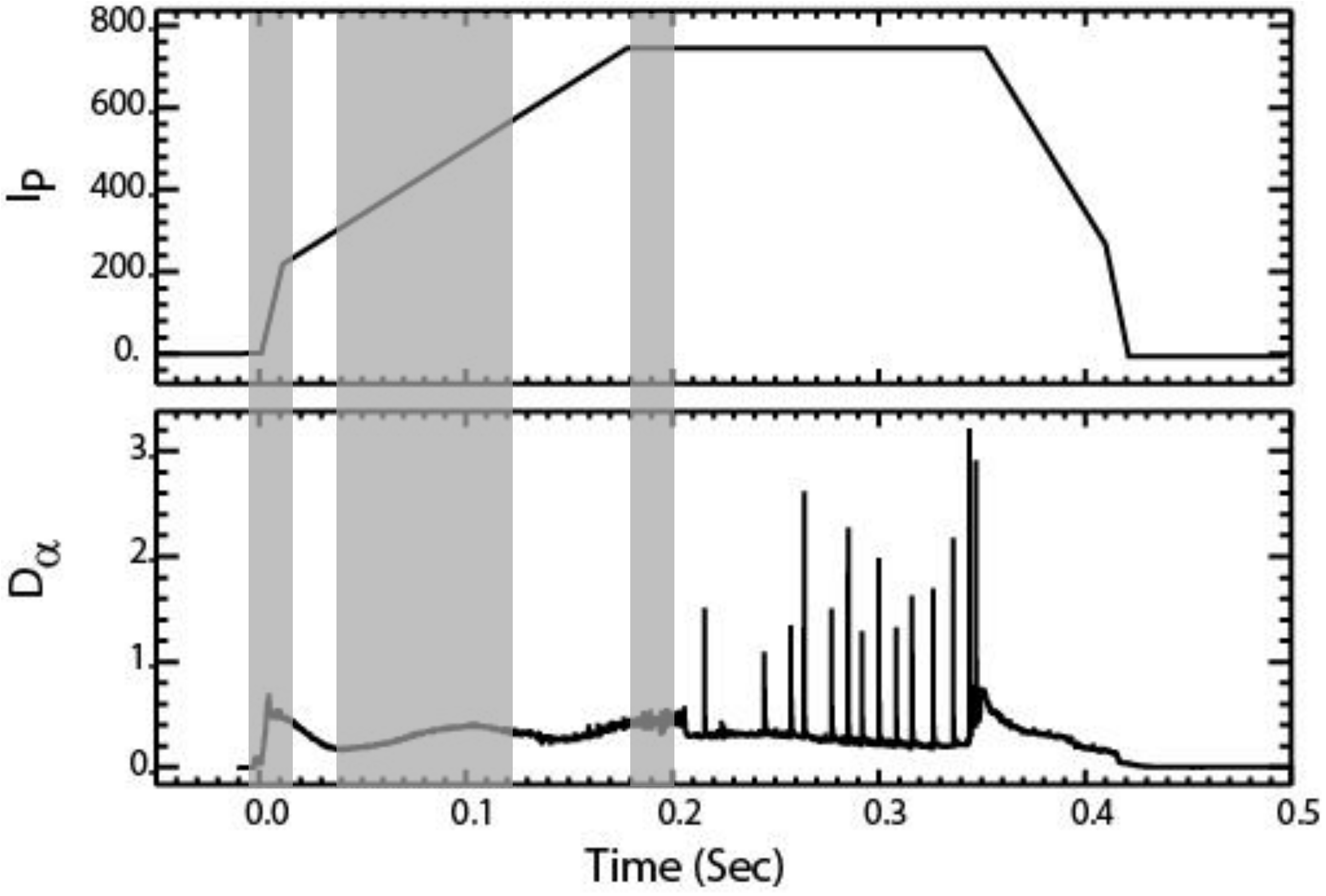


Outline

Start-up

Current Ramp

L-mode



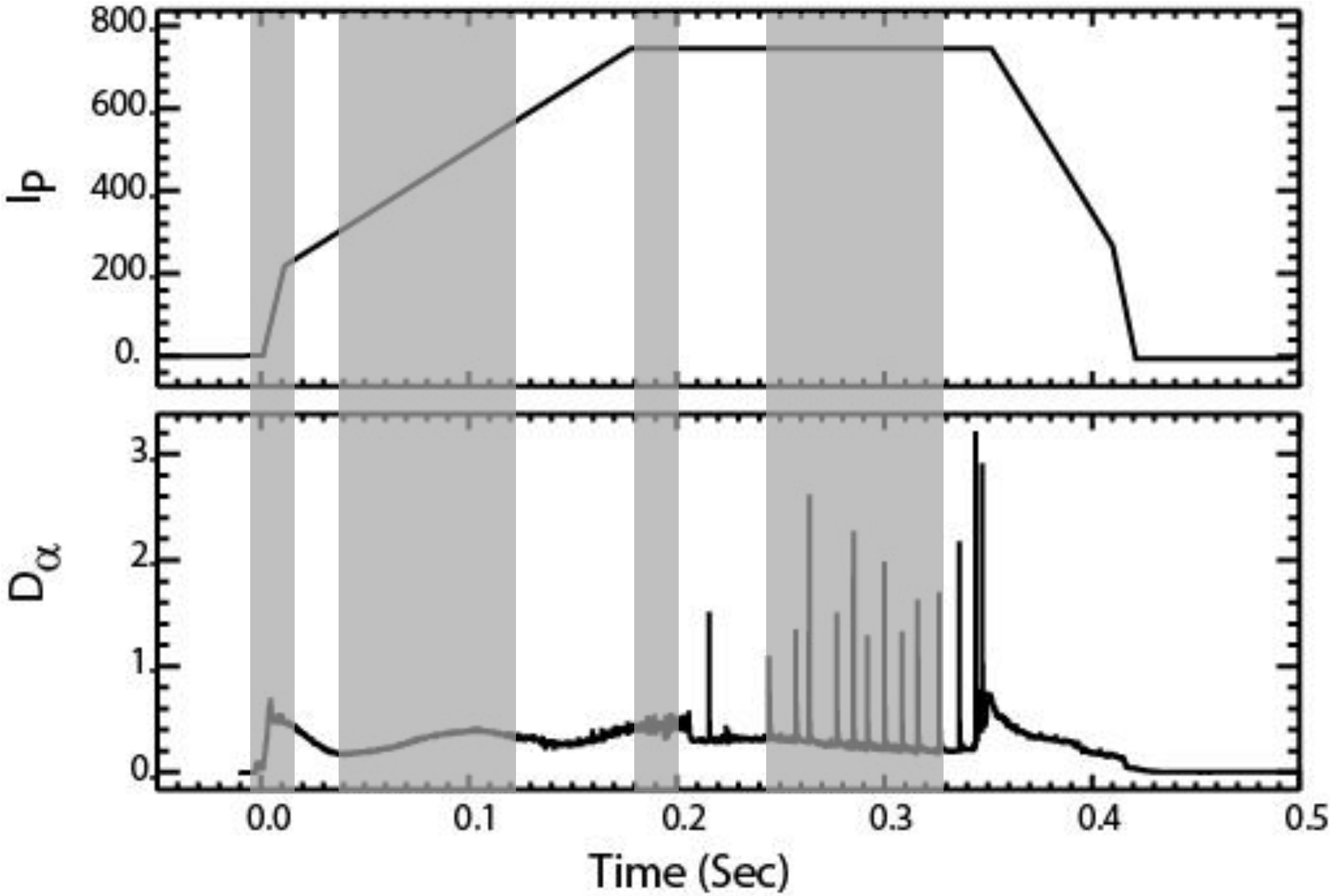
Outline

Start-up

Current Ramp

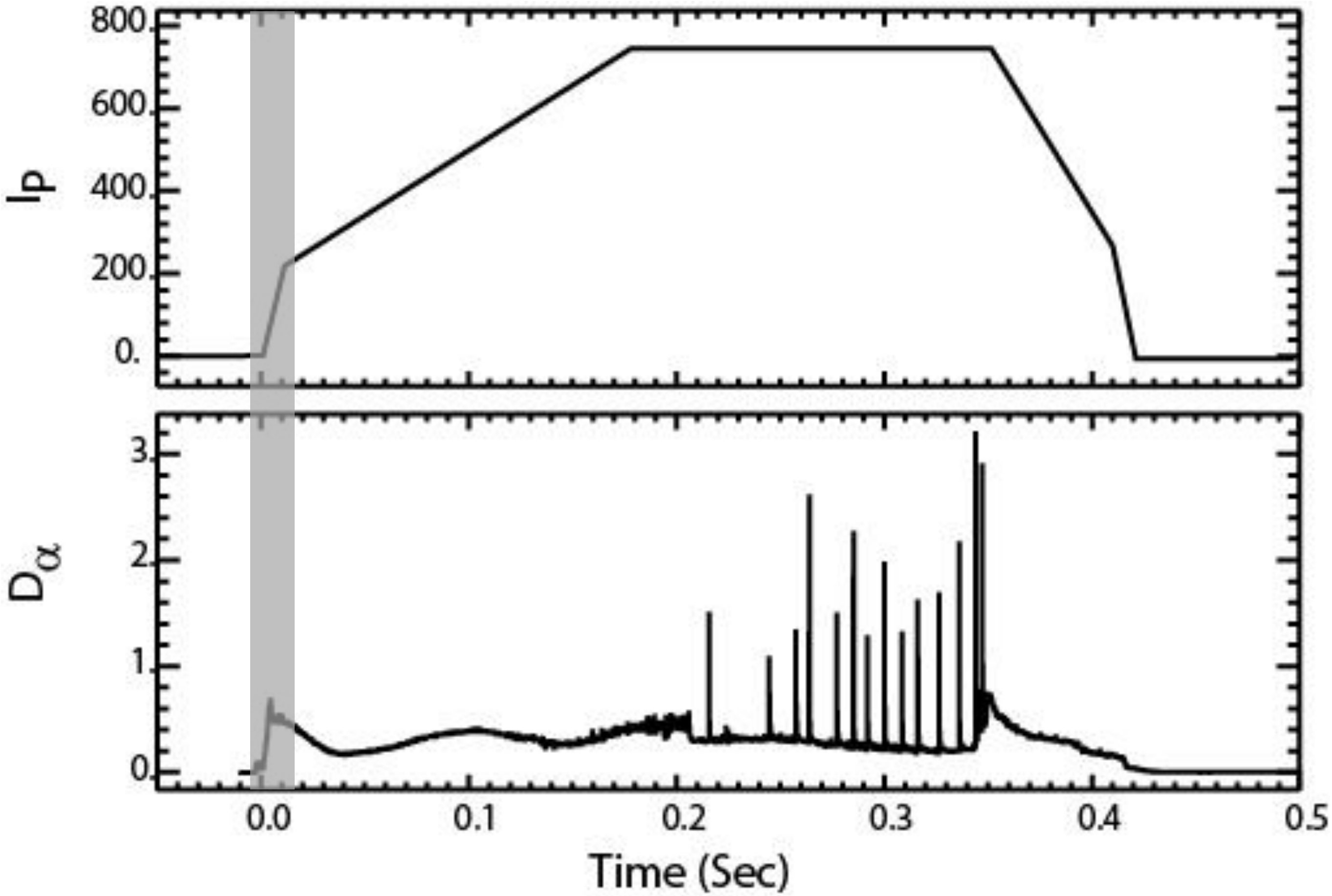
L-mode

H-mode

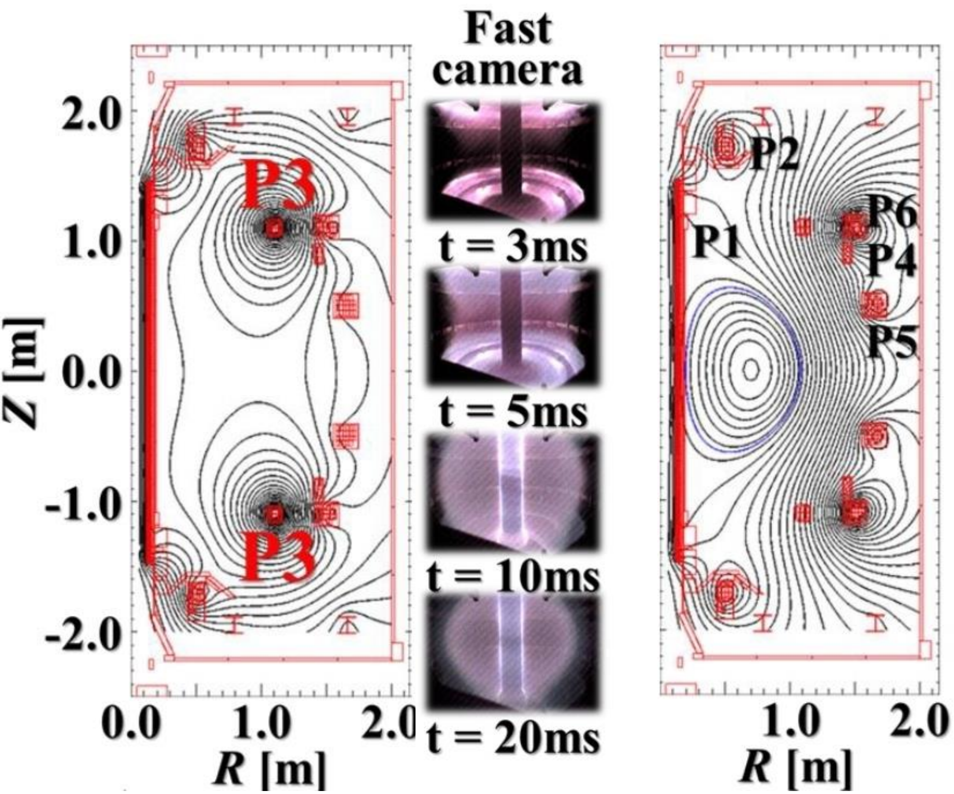


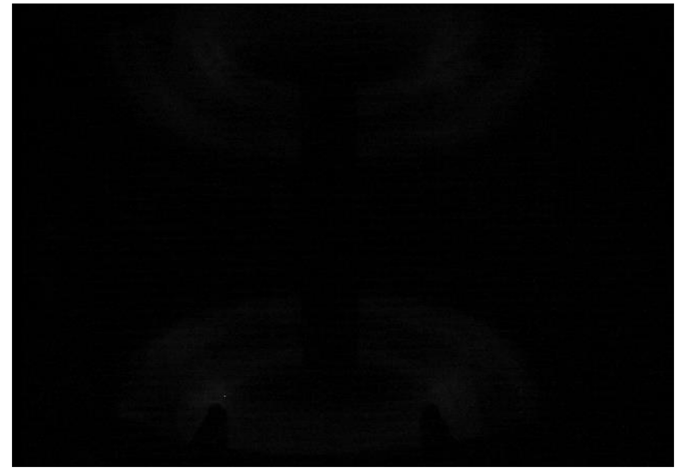
Start-up

Start-up



Merging compression startup experiments

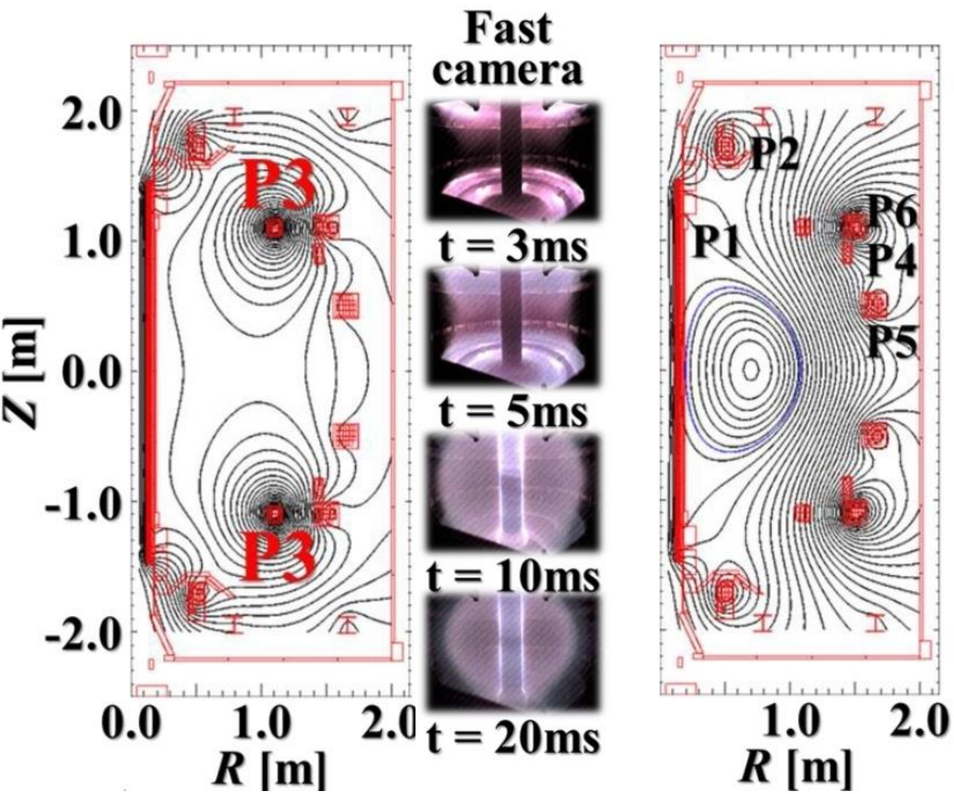




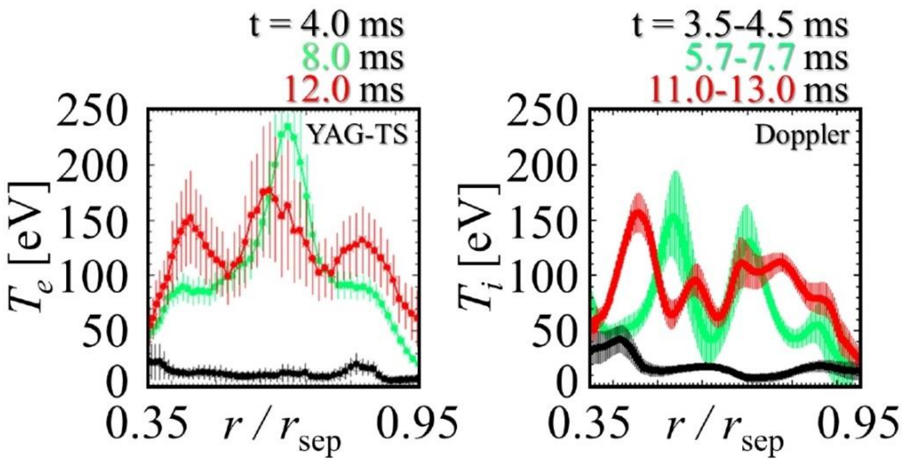
Effect of reconnection on ion heating

H. Tanabe et al., 115, 215004, PRL, (2015)

Merging compression startup experiments



The time evolution of T_e and T_i



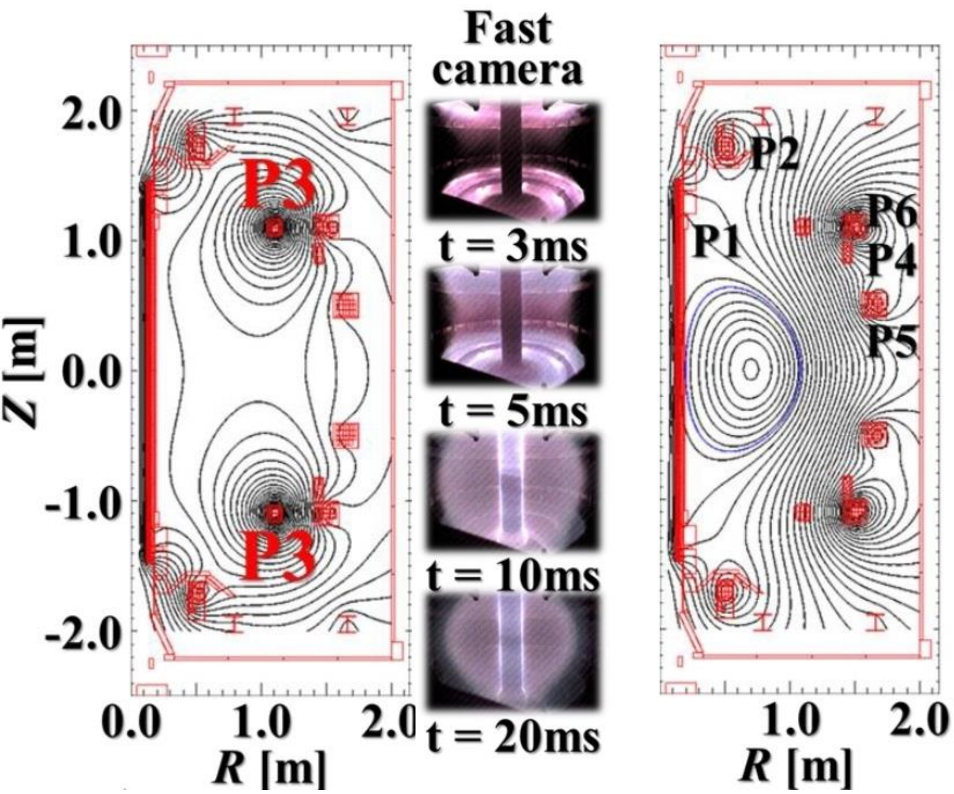
T_e Peaks at the X-point

T_i increases downstream

Modelling with HIFI code shows this is due to magnetic energy being converted to thermal energy

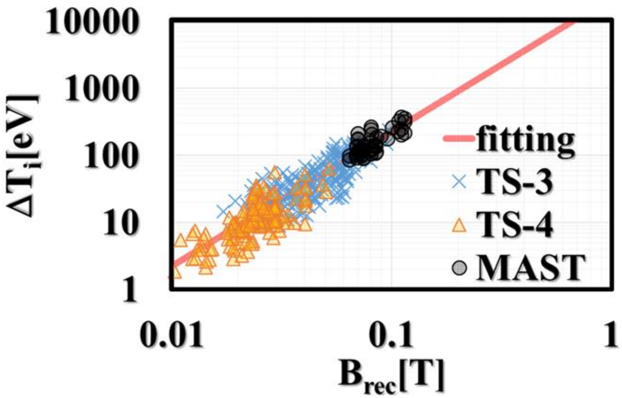
P. Browning et al., PPCF 58, 014041 (2016)

Merging compression startup experiments



The bulk ion temperature rises due to the reconnection process

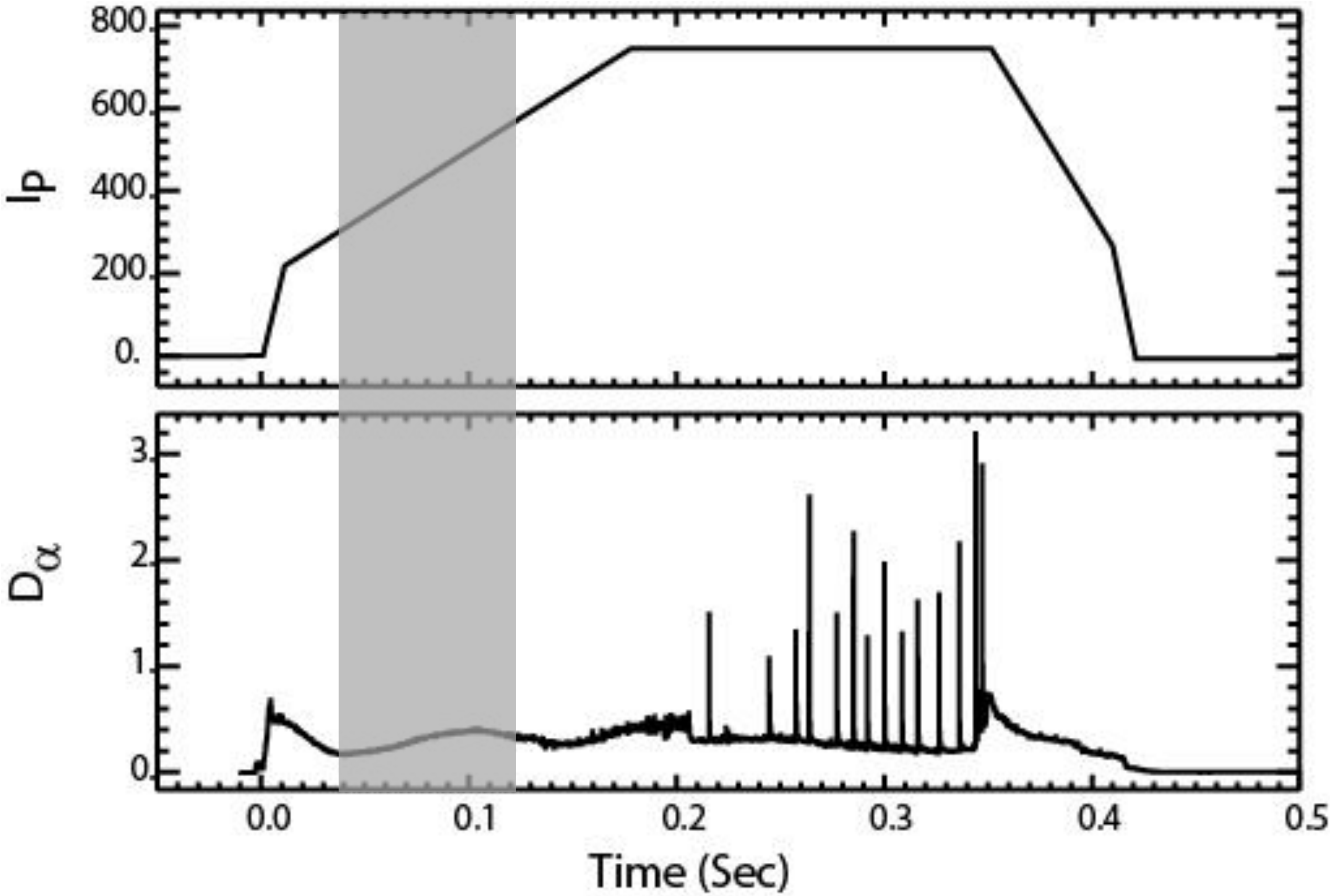
$$\Delta T^i \propto B_{rec}^2$$



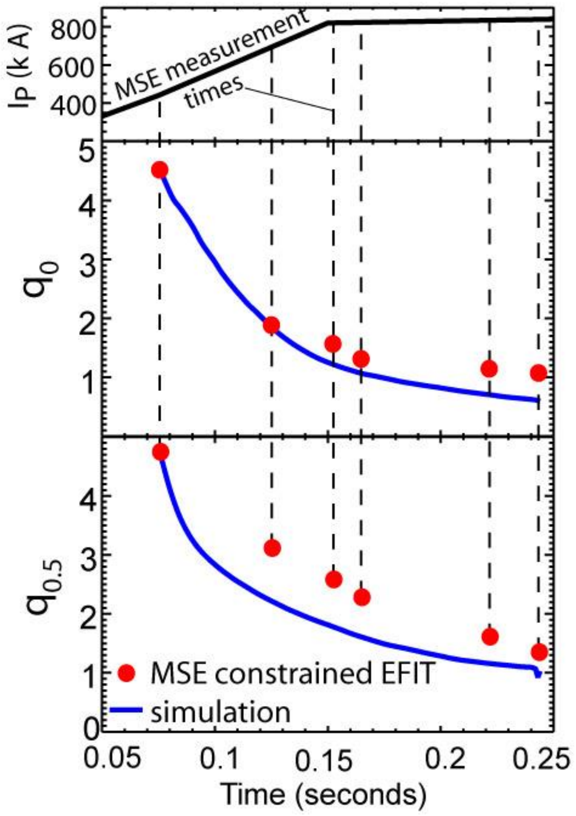
EX/P4-32 H. Tanabe

Current Ramp

Current
Ramp



Tests of current diffusion models



Previous experiments on MAST have shown that:

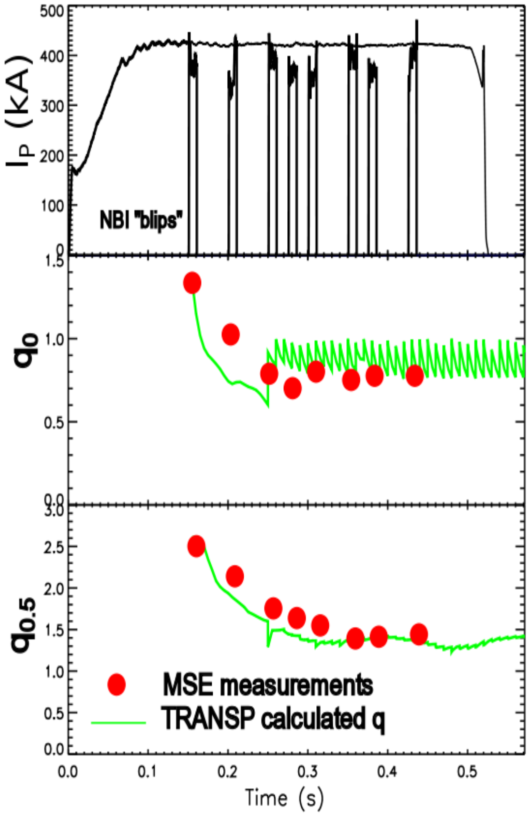
- In both Ip ramp-up and Ip ramp-down the current diffusion is not well modelled by TRANSP
- Current diffusion in model is faster than observed in experiments

NBI “notcher” used to take Motional Stark Effect (MSE) snapshots of q-profile

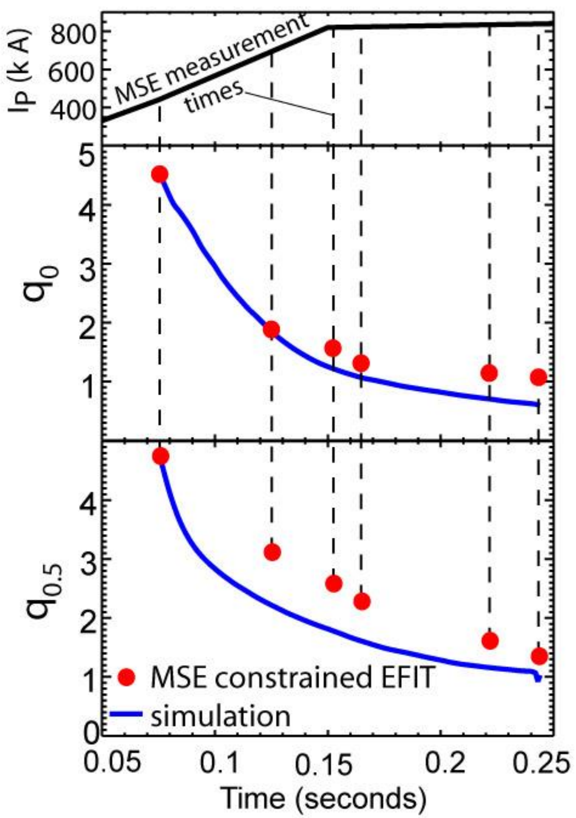
Tests of current diffusion models

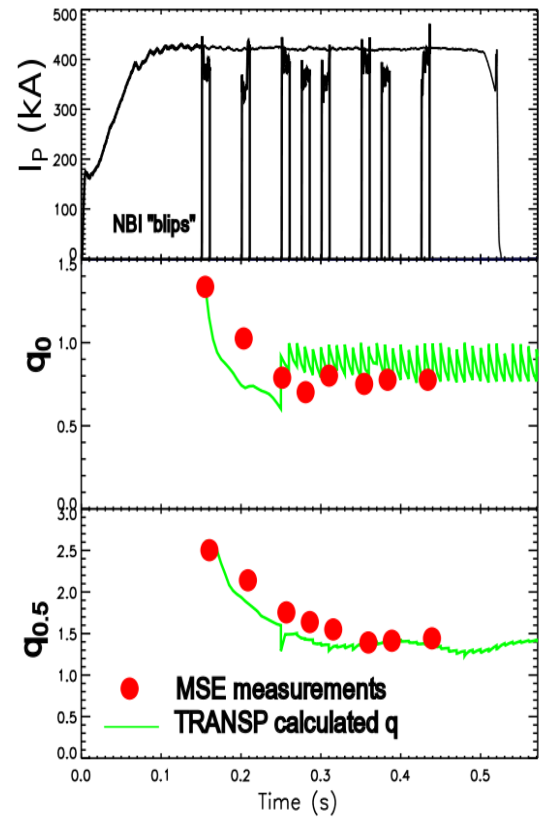
Experiments repeated in the flat top period

- q-profile match is achieved ~200ms into the flat top using neoclassical resistivity and a sawtooth model.



Tests of current diffusion models

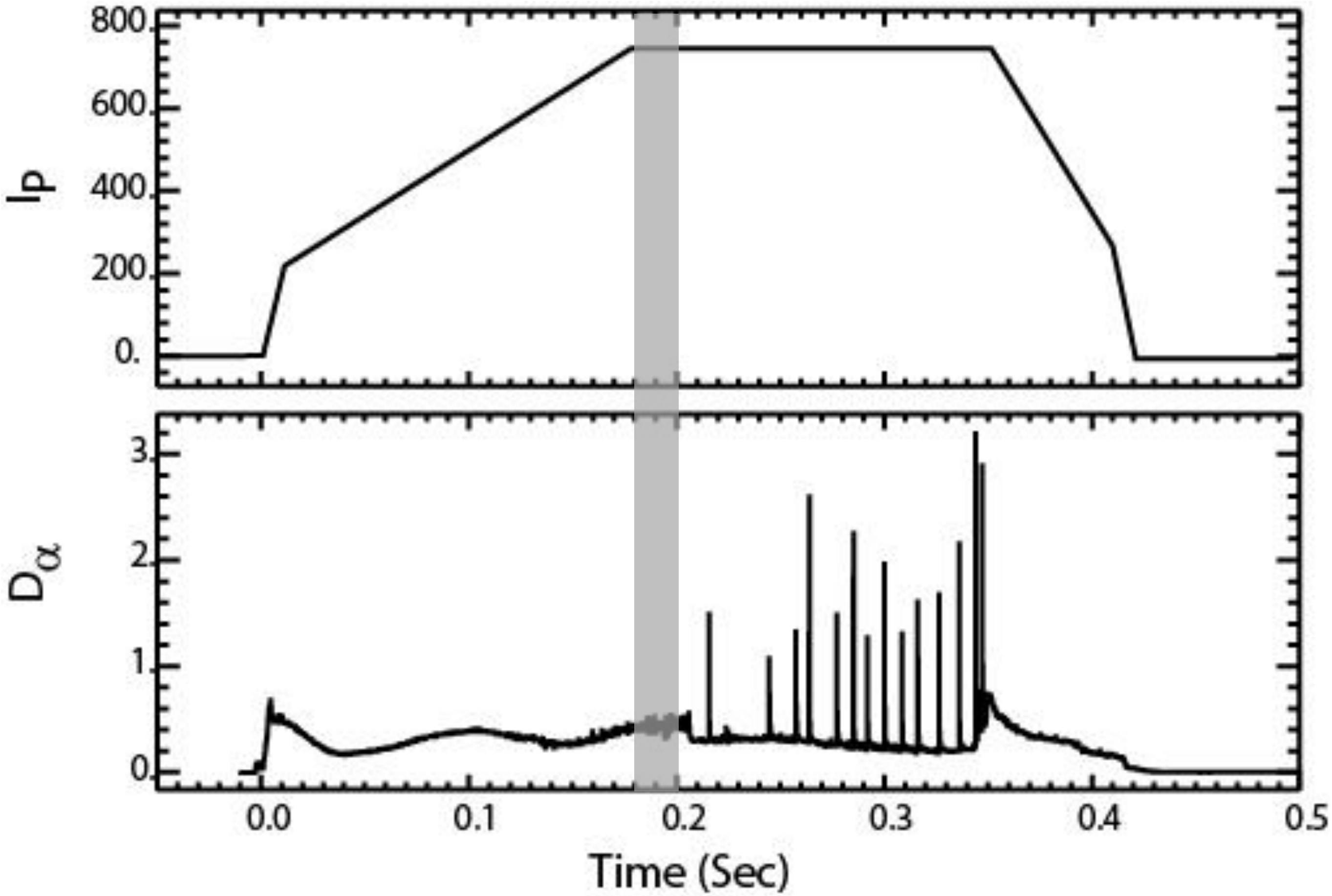




Conclusion: Our fundamental understanding of current diffusion appears correct but modelling does not accurately reproduce results during the ohmic current ramp

L-mode

L-mode



L-mode

SOL transport

Core transport

L-mode

SOL transport

Core transport

Filaments measured and simulated

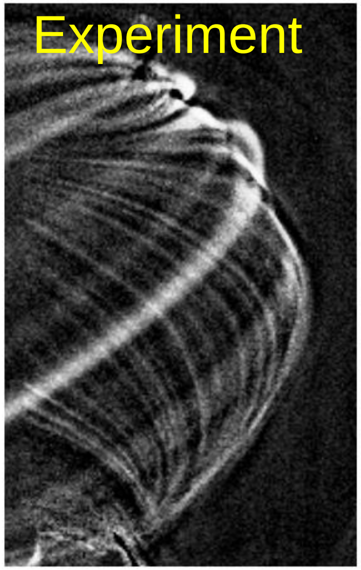
- Filament size and motion measured using fast visual imaging and a variety of probes

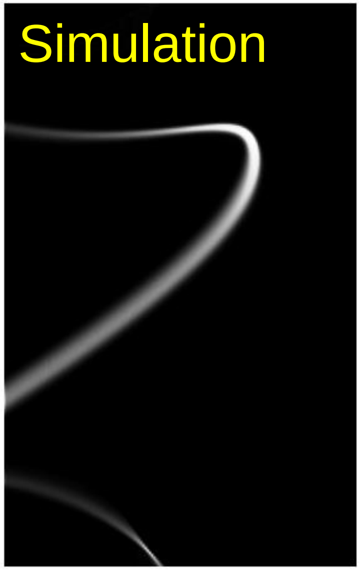
- Modelling has been performed using a 3D turbulence code (STORM), which has been able to reproduce most of the filamentary dynamics

STORM – 3D drift wave electrostatic module of BOUT++

Militello et al. PPCF 2016

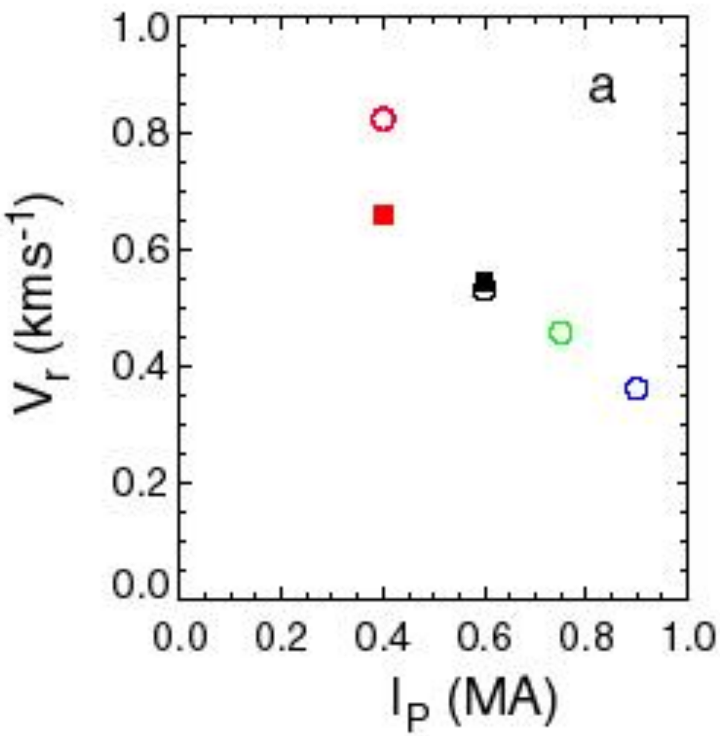
EX/P4-31 F. Militello



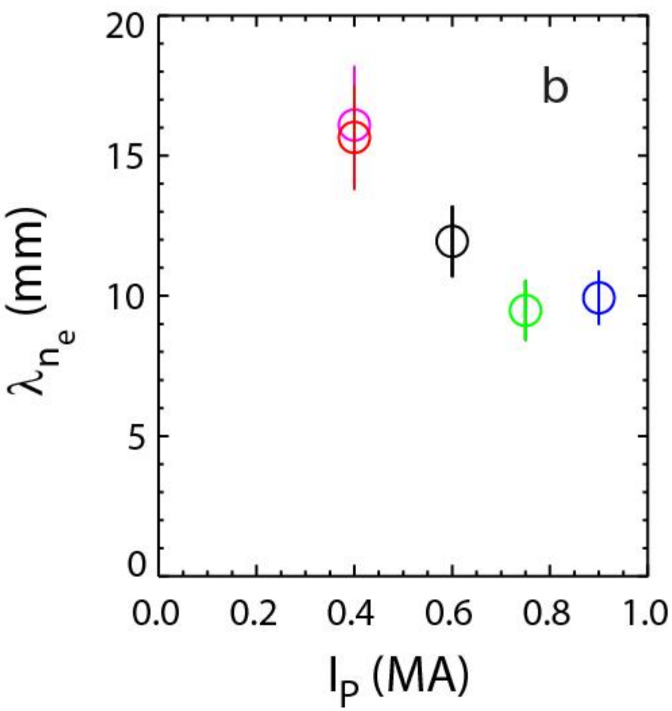


Role of filaments in L-mode SOL width

- Mid-plane radial velocity of L-mode filaments depends on plasma current *[A. Kirk et al, PPCF 2016]*



Radial velocity decreases with increasing plasma current



56% reduction in radial velocity consistent with ~60% reduction in density e-folding length at target

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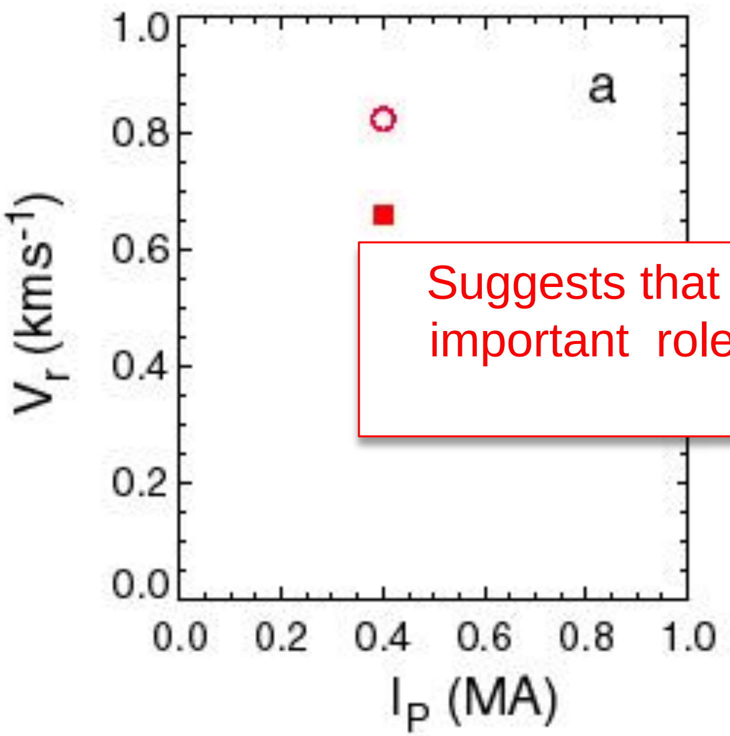
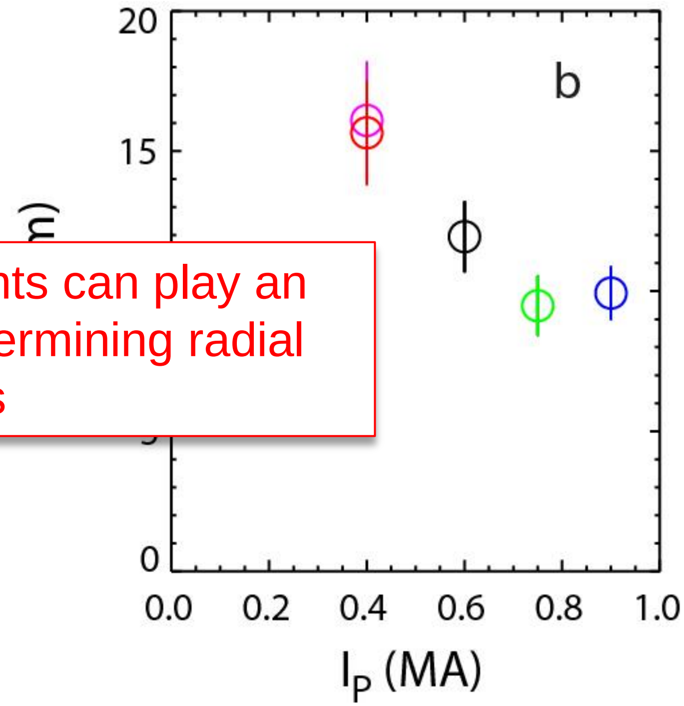




Suggests that filaments can play an important role in determining radial profiles

Radial velocity decreases with increasing plasma current

56% reduction in radial velocity consistent with ~60% reduction in density e-folding length at target

Effect of electron temperature

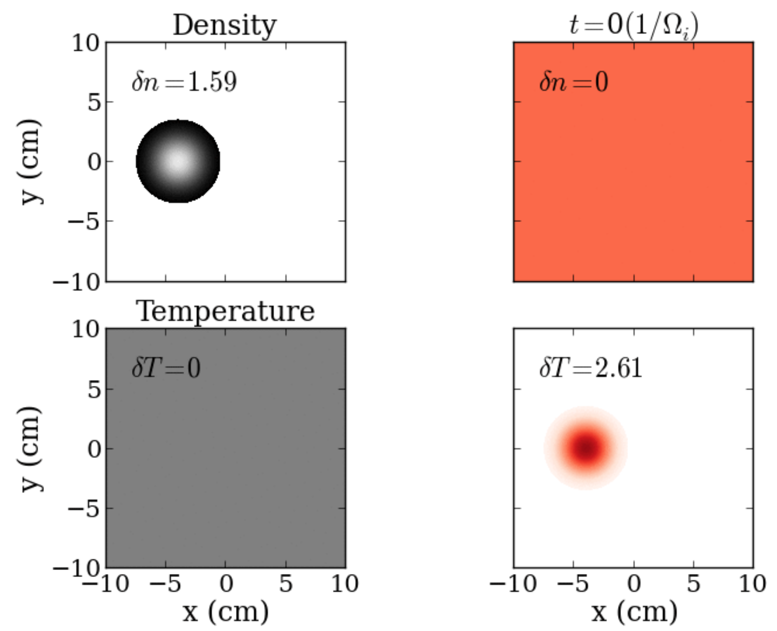
- Filament modelling using STORM at constant pressure, the electron temperature significantly affects filament dynamics

$$\delta T/_T \ll \delta n/_n$$

Propagate further radially

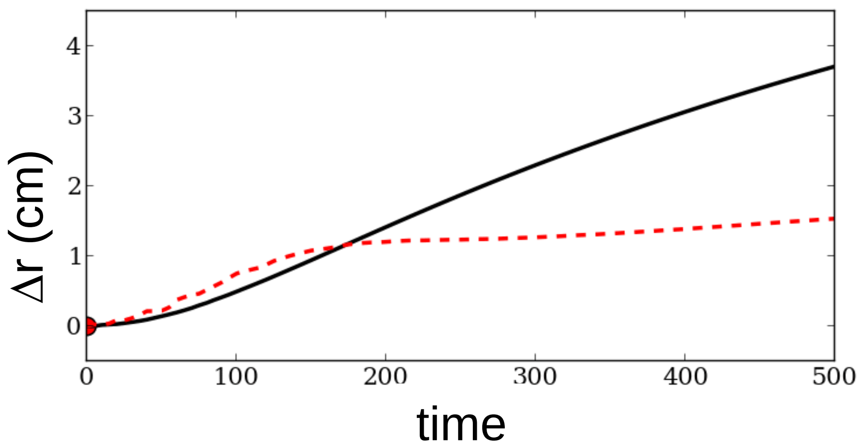
$$\delta T/_T \gg \delta n/_n$$

Localised near separatrix



Suggests a possible mechanism -> higher I_P leads to higher filament T_e and hence smaller V_r

This effect is robust to changes in other parameters of the filament

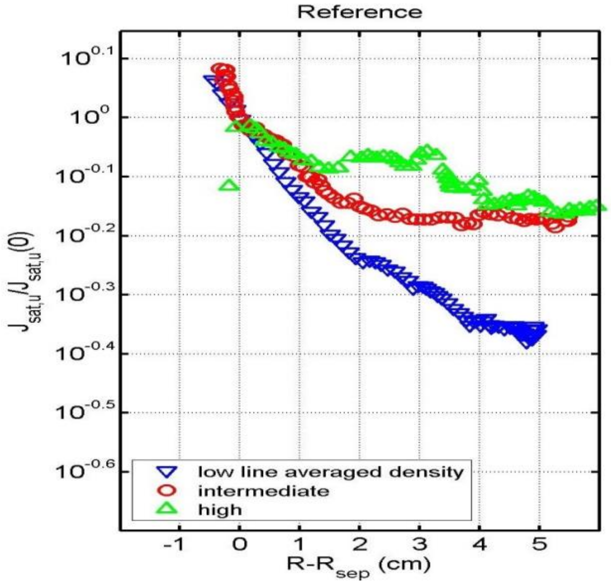


[N.R.Walkden et al, Sub. PPCF]

Density Broadening in MAST

- Flattening and broadening of SOL profiles observed with increasing the fuelling level.

Militello et al. NF 2016

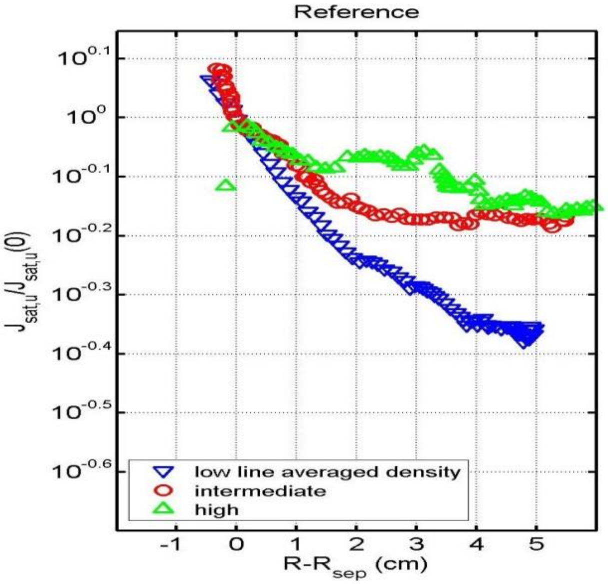


EX/P4-31 F. Militello

Density Broadening in MAST

- Flattening and broadening of SOL profiles observed with increasing the fuelling level.

- A theoretical model was developed to interpret the relation between filament dynamics and features of the profiles.

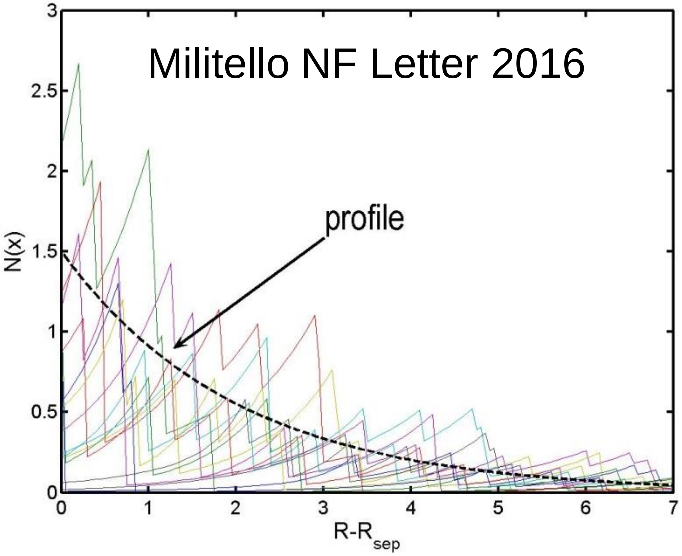


$$N(x) = \frac{1}{\tau_w}\int_{-\infty}^{\infty} dt \int_0^{\infty} d\eta_0 \int_0^{\infty} dw \left[\eta(x,t) P_{\eta_0}(\eta_0) P_w(w)\right]$$

Profile

Filament shape and dynamics

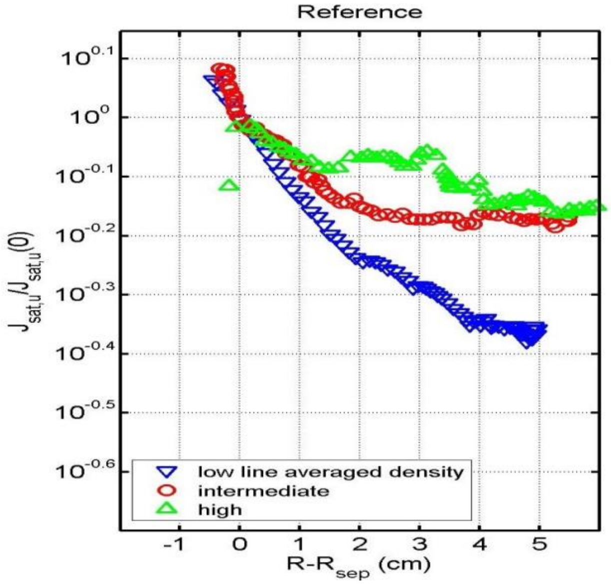
Filaments statistics

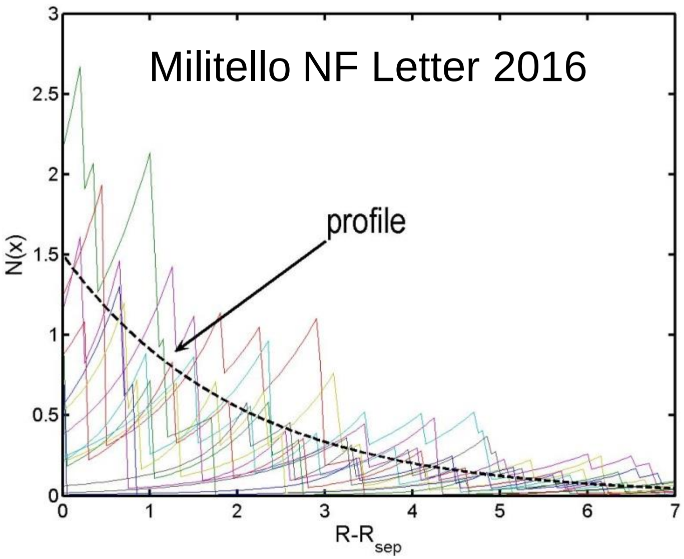


EX/P4-31 F. Militello

Density Broadening in MAST

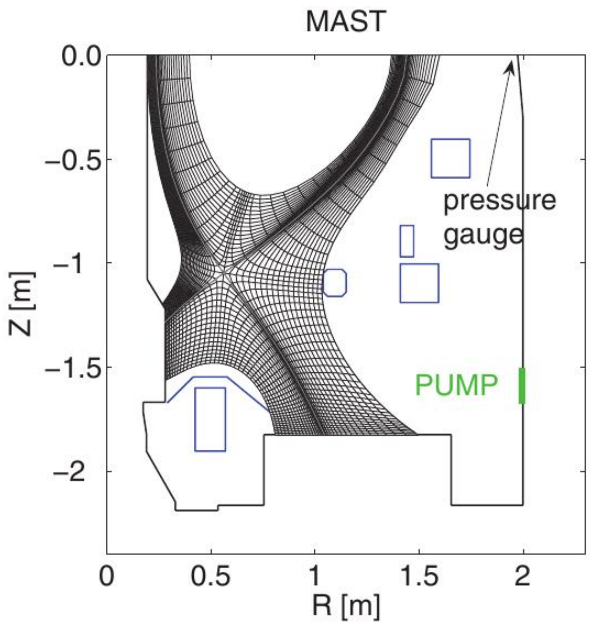
- Flattening and broadening of SOL profiles observed with increasing the fuelling level.
- A theoretical model was developed to interpret the relation between filament dynamics and features of the profiles.
- Shows that several effects can lead to the broadening including charge exchange and significant radial acceleration.





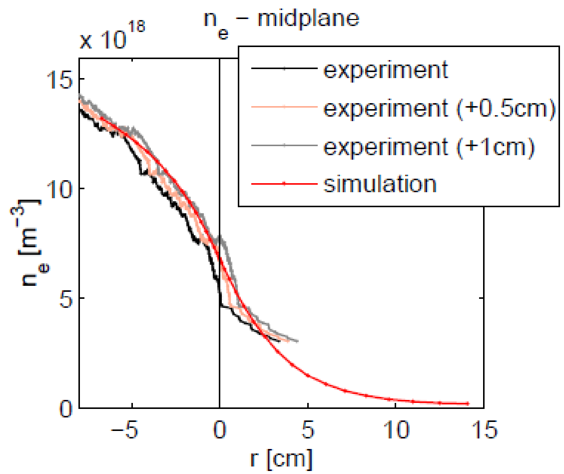
EX/P4-31 F. Militello

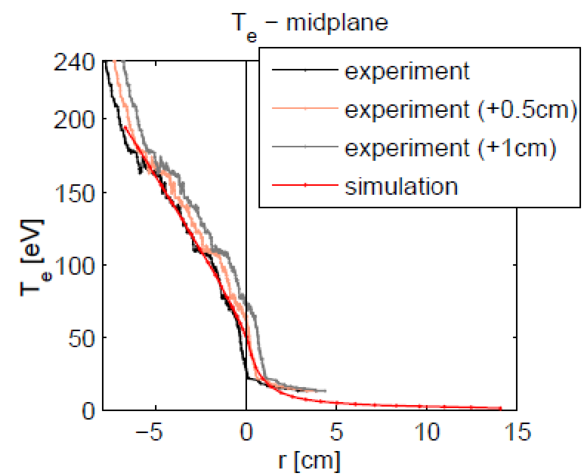
Benchmarking SOLPS on MAST



SOLPS has been Benchmarked against L-mode shot 30356 in MAST

Extracted radial transport coefficients that well describe midplane and target data

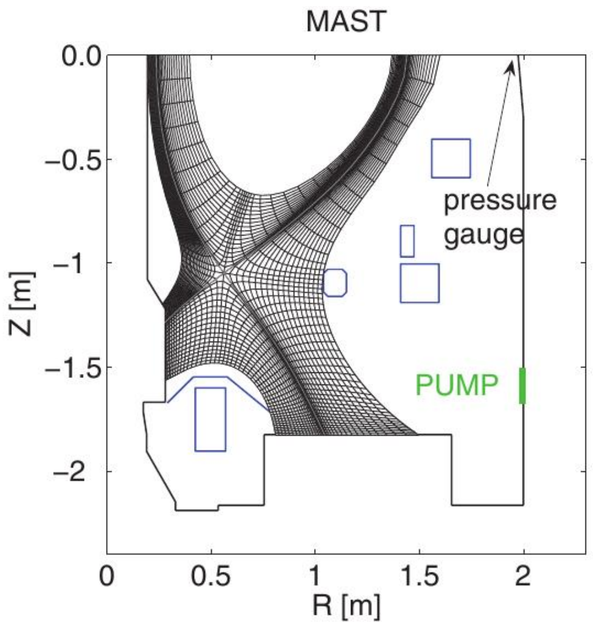




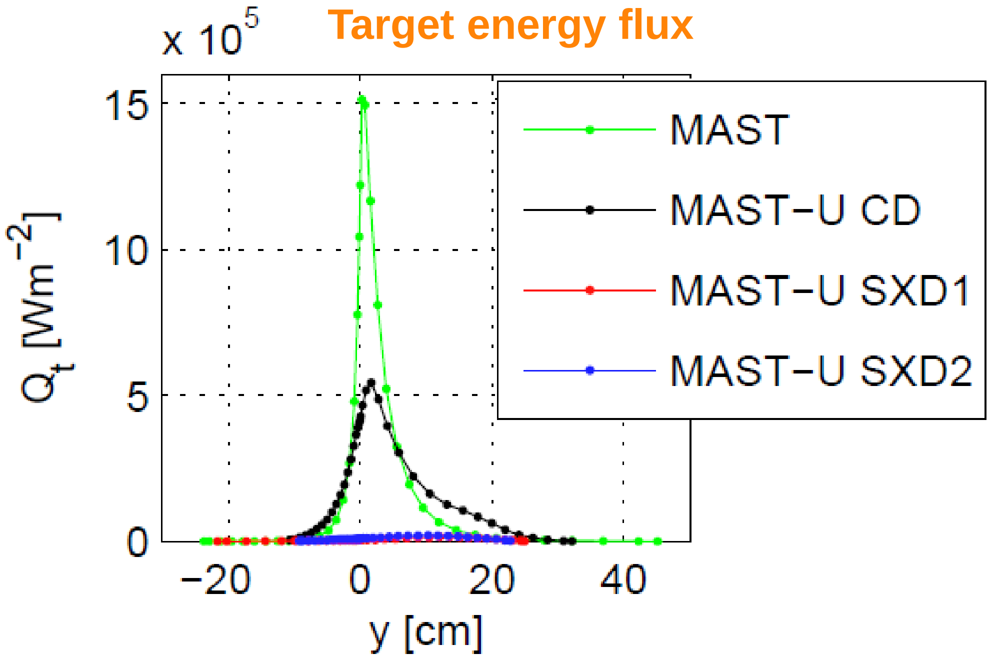
Then used these to extrapolate to MAST-U

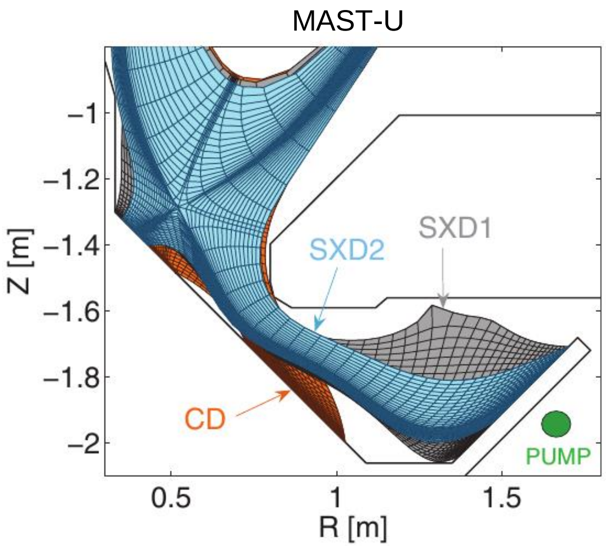
*E. Havlíčková et al, PPCF **57** (2015) 115001*

Predictions for MAST-U



Super-X geometry pushes the target plasma into detachment, reducing the heat flux density and temperature at the target to ~zero.





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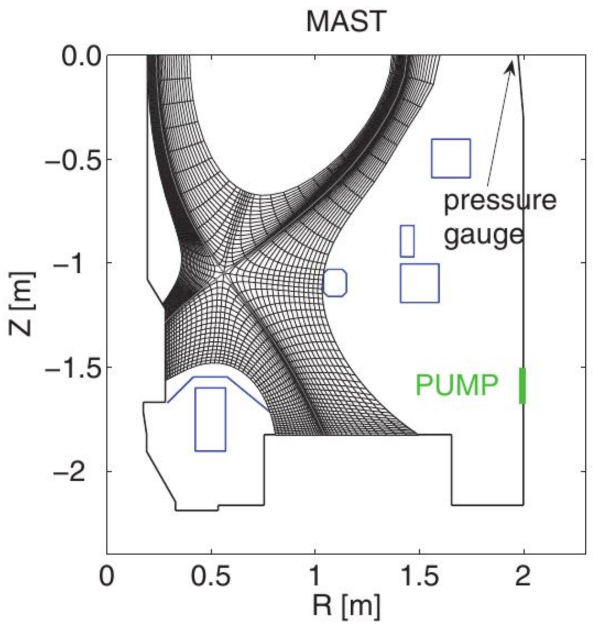

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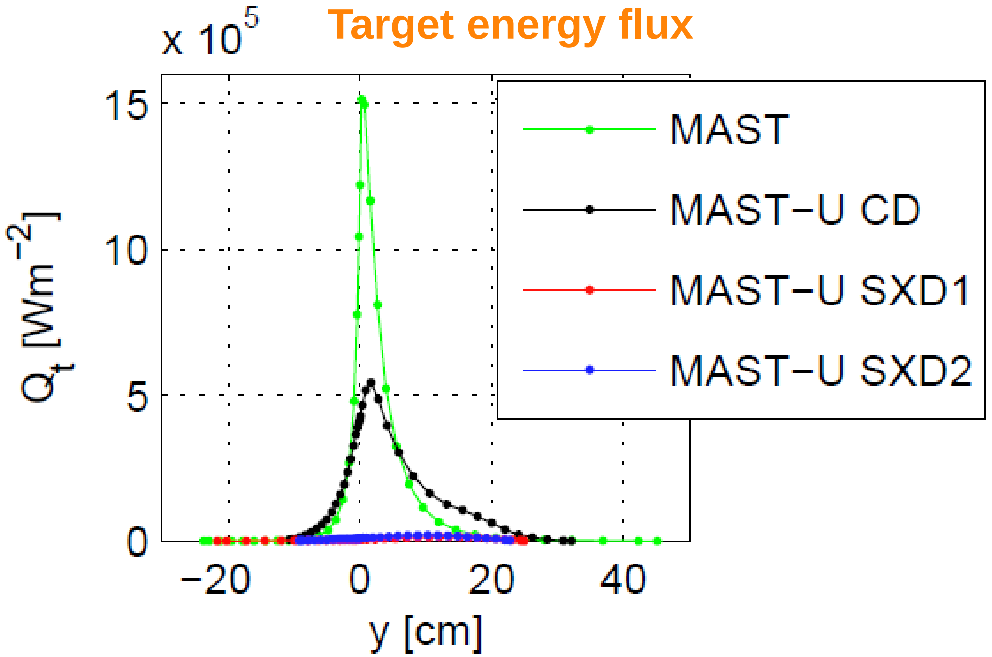
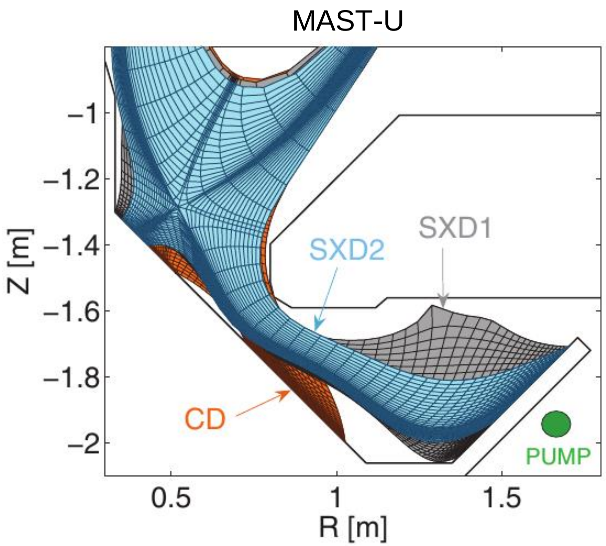




Attached regime in SXD in L-mode can be achieved if the heating power or the pumping speed is increased at the same density.

*E. Havlíčková et al, PPCF **57** (2015) 115001*

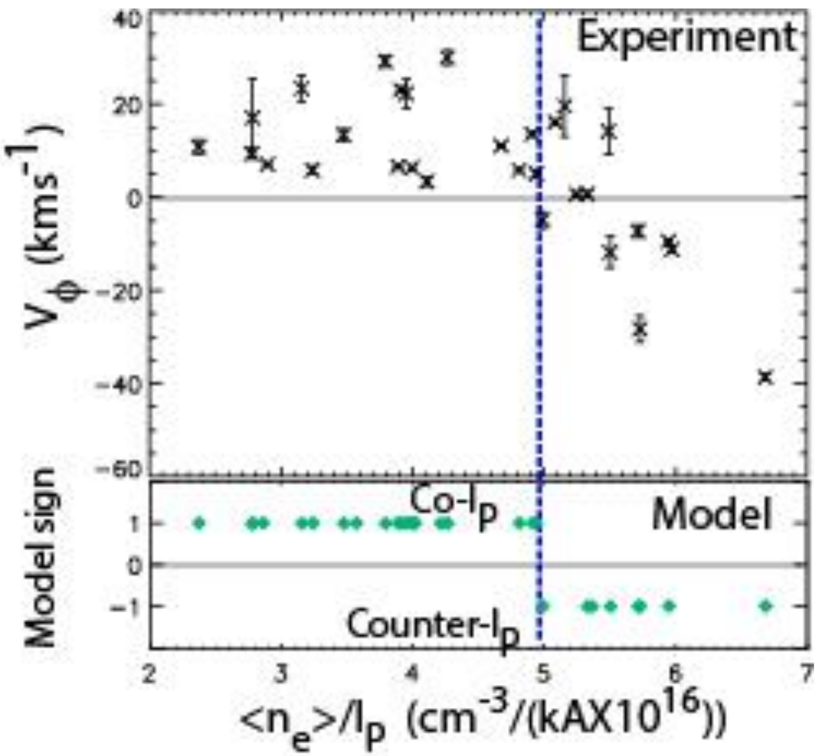
L-mode

SOL transport

Core transport

Intrinsic rotation

Measurements of intrinsic rotation using Doppler Back Scattering (DBS)



$< n_e >/I_p$~Collisionality

- Intrinsic toroidal rotation in MAST is large (up to $M_\phi \approx 0.2$) and depends on collisionality
- Experiment compared to model capturing effect of neoclassical flows on momentum transport
  - *Barnes Phys. Rev. Lett. 111, 055005 (2013).*
- Model correctly predicts sign in many cases, but….

Hillesheim, Nucl. Fusion 55, 032003 (2015).

Intrinsic rotation

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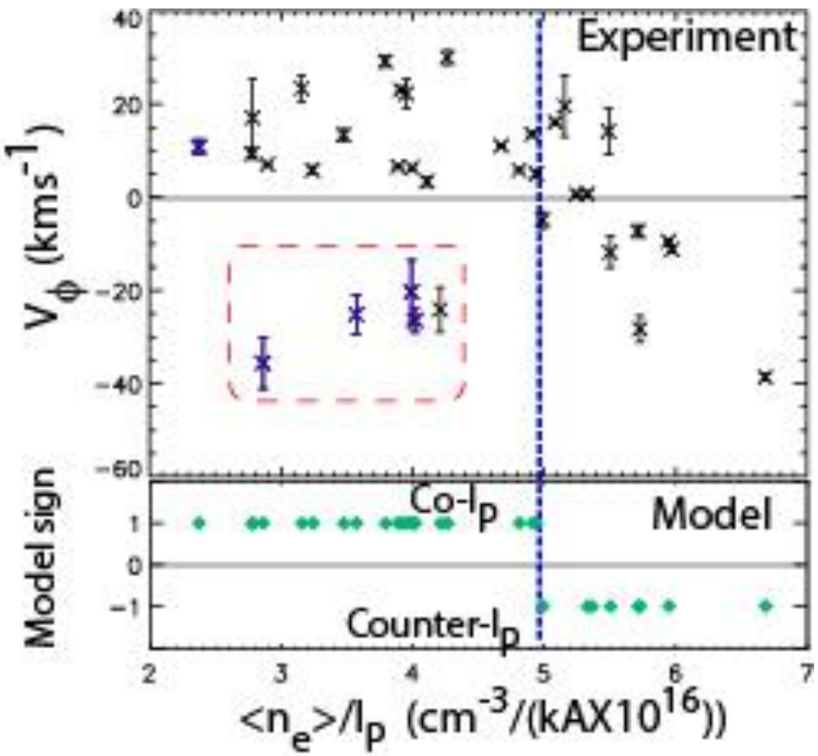

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- Experiment compared to model capturing effect of neoclassical flows on momentum transport
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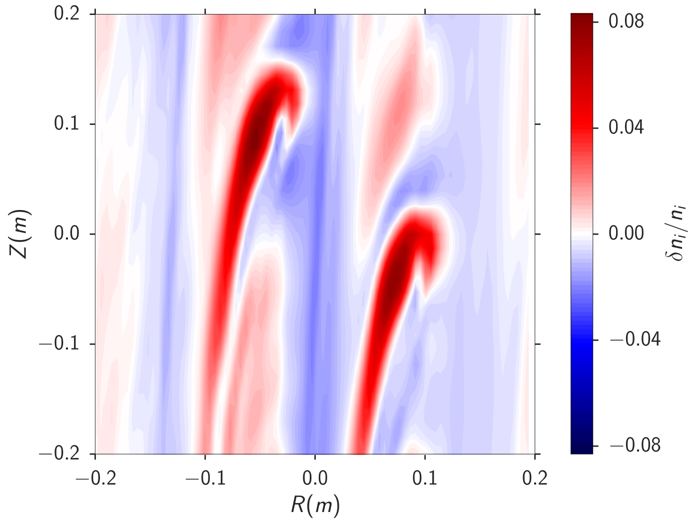
- Model correctly predicts sign in many cases, but there are some examples at low $<n_e>$, low I_p that clearly disagree which indicate there may be additional physics at play

Hillesheim, Nucl. Fusion 55, 032003 (2015).

Gyrokinetic simulations of turbulence



Ion scale turbulence $k_\perp \rho_i < 1.0$ is largely suppressed in STs by flow shear

In the periphery of an L-mode plasma weak ion scale turbulence can exist

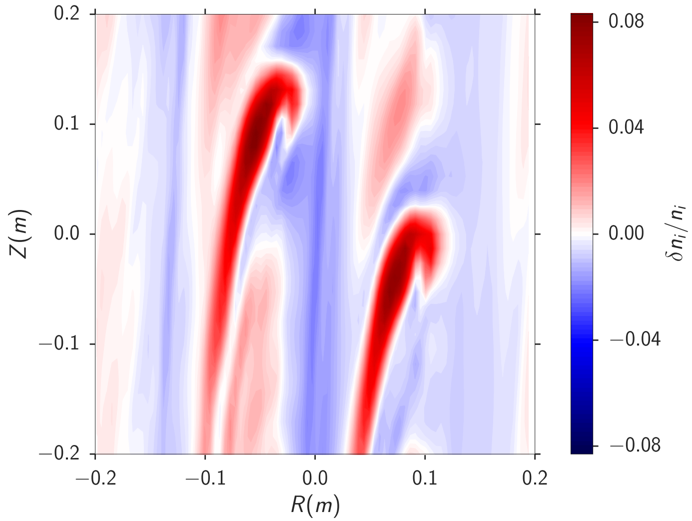
Local GS2 calculations at $\Psi_N \sim 0.7$ show that the experimental point is linearly stable

Non-linear simulations show that sub-critical turbulence can exist

For this sub-critical turbulence the heat flux is carried by a small number of long lived isolated structures

F. van Wyk Submitted to Nature

Gyrokinetic simulations of turbulence

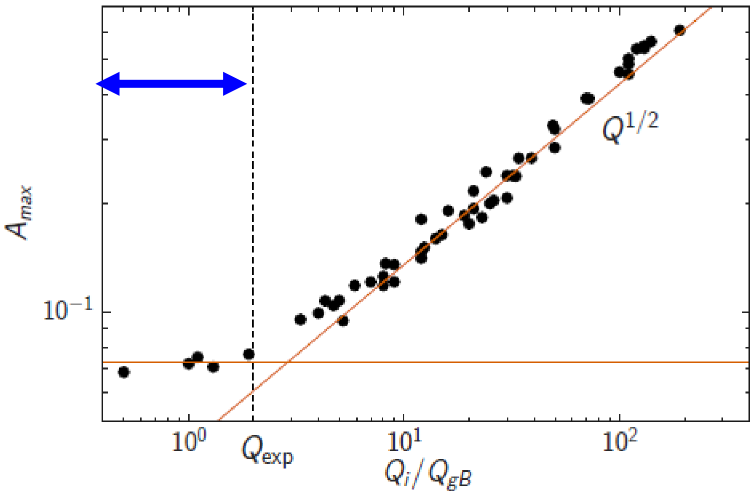


Close to "marginality" the heat flux increases with the number of structures rather than their amplitude increasing

$$Q/Q_{gB} \sim N$$

Further from marginality the heat flux increases as A^2 while the N remains constant

Marginal Strongly Driven



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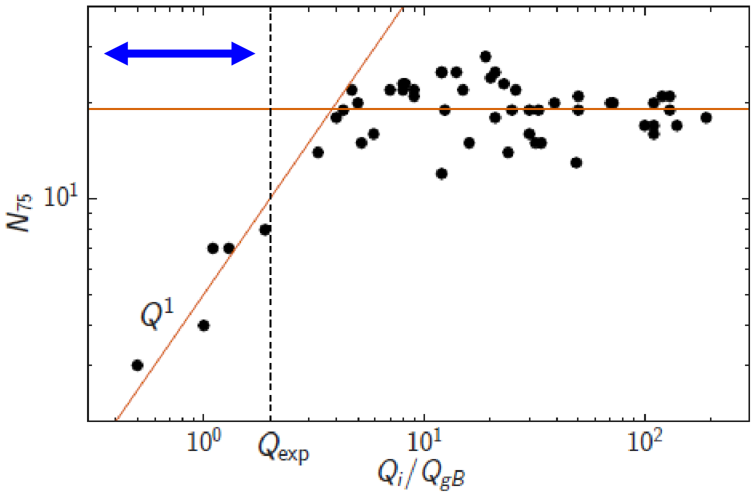

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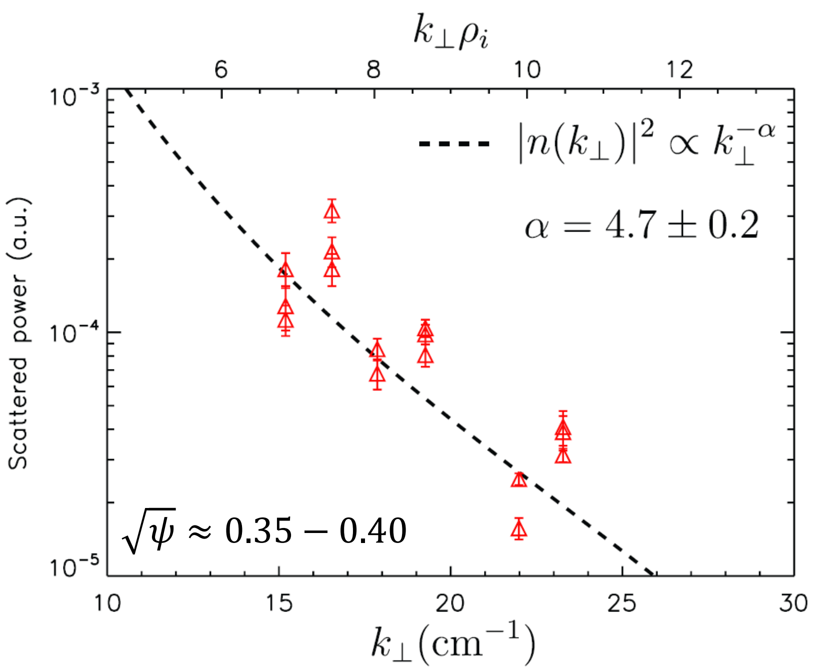
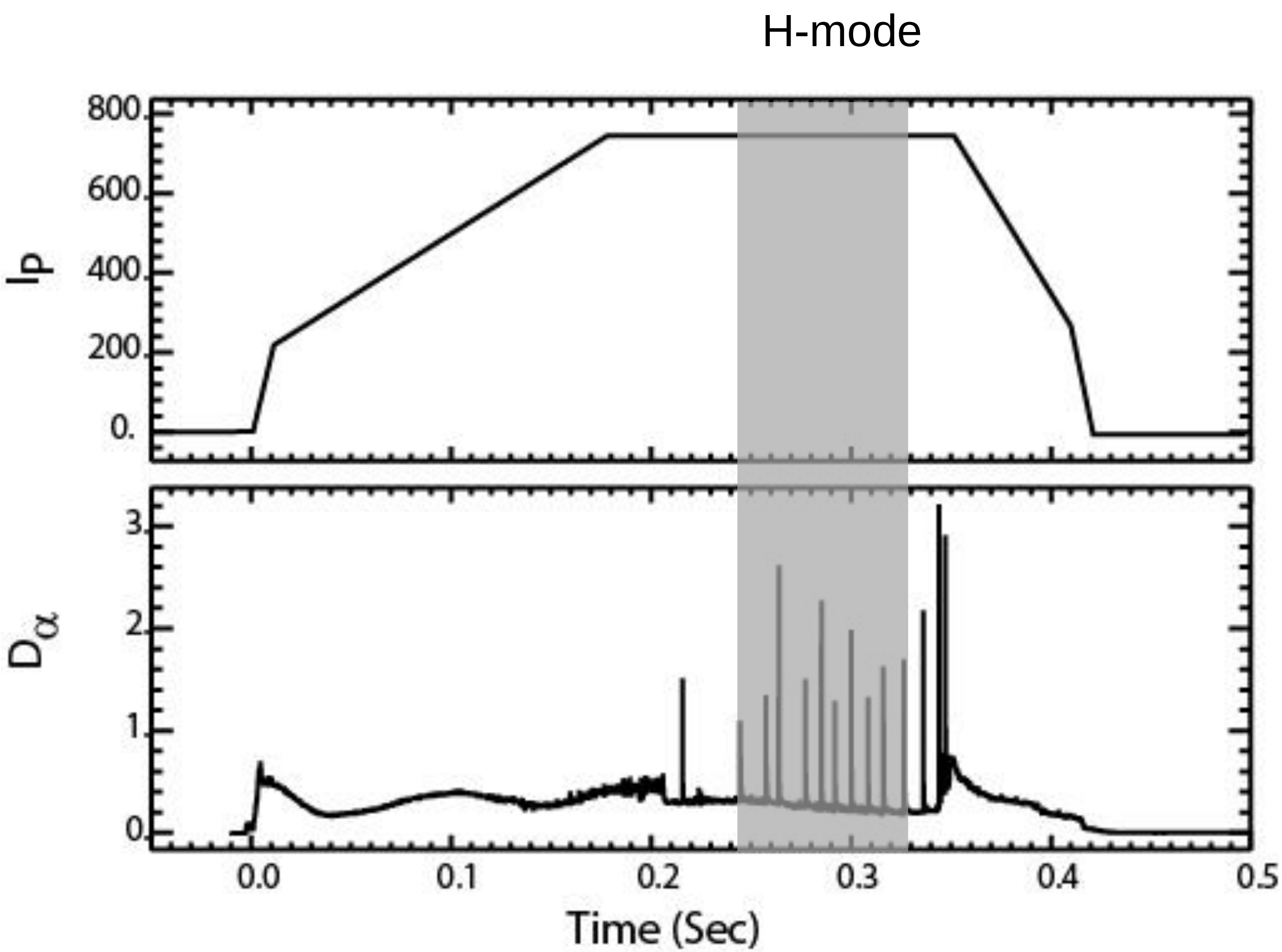
Core turbulence measurements



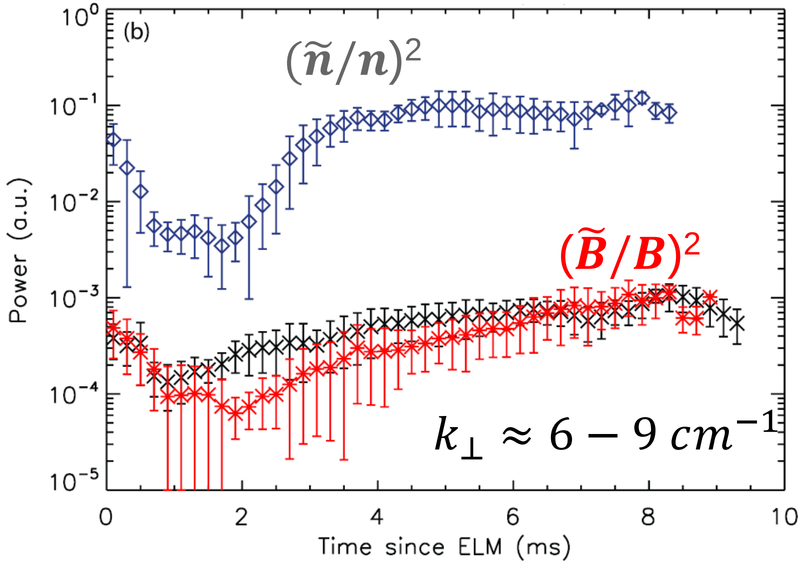
- Since Ion scale turbulence is largely suppressed in STs it is important to diagnose higher wavenumber turbulence
- A 2D beam steering of a Doppler Back Scattering system has been implemented to enable **high-k⊥** measurements in the core
- A power law decrease in fluctuations is observed consistent with a turbulent kinetic cascade

Hillesheim, Nucl. Fusion 55, 073024 (2015).

H-mode, pedestal and ELMs



Pedestal top evolution



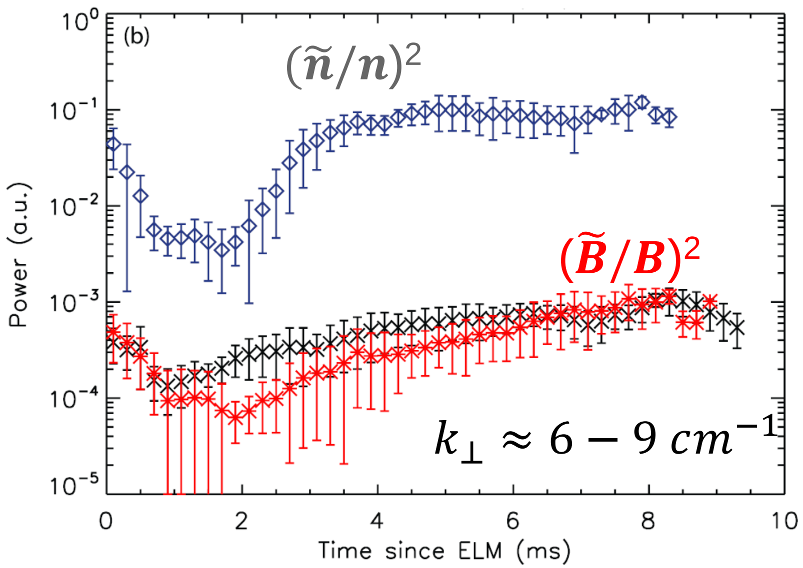
DBS used to measure density fluctuations $(\tilde{n}/n)^2$

Cross-polarization DBS used to measure the local magnetic field fluctuations $(\tilde{B}/B)^2$

At pedestal top dominant fluctuations at $k_\perp$~6-9cm^{-1}

Hillesheim, Plasma Phys. Controlled Fusion 58, 014020 (2015)

Pedestal top evolution



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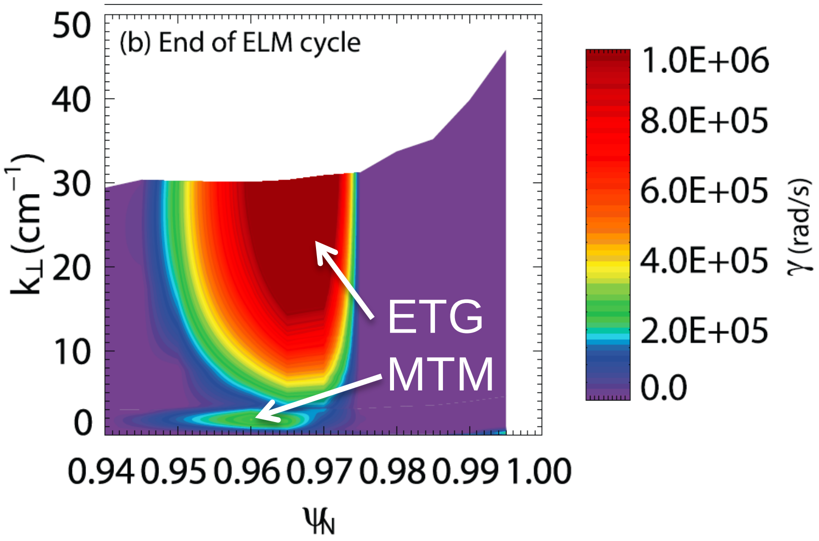
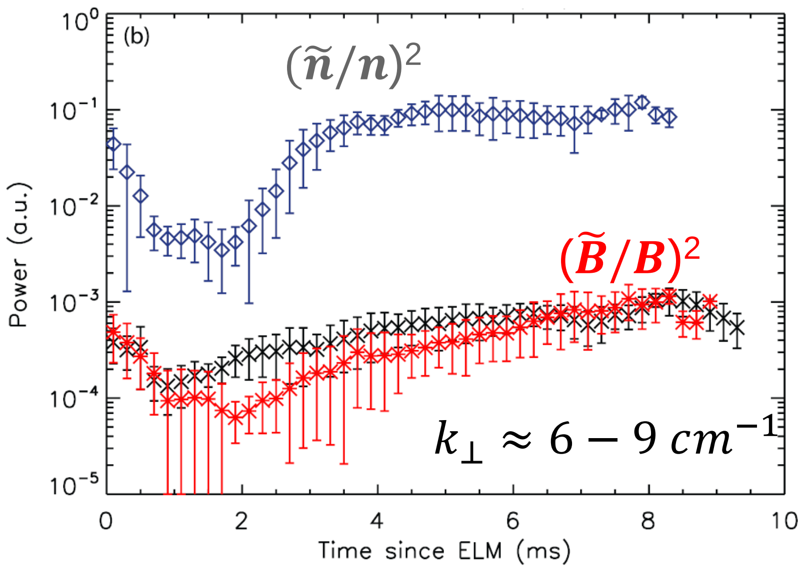


GS2 calculations show that both MTM and ETG are unstable at pedestal top

Pedestal top evolution



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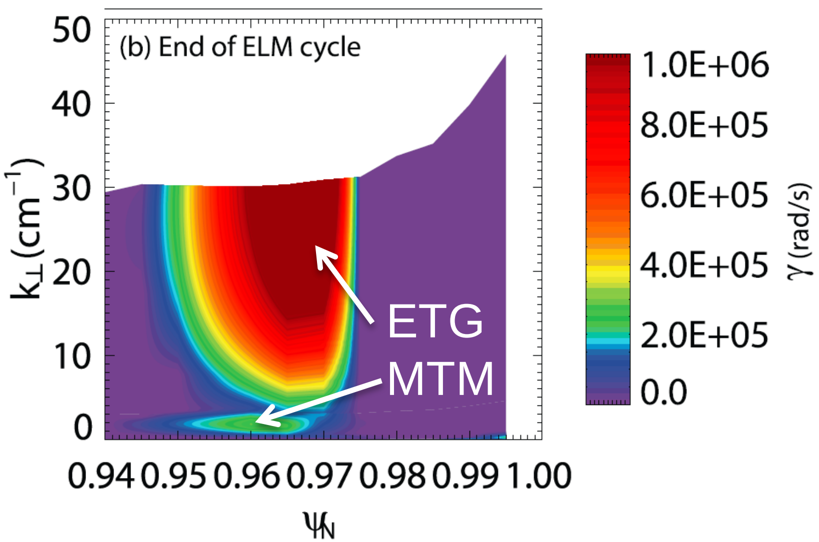


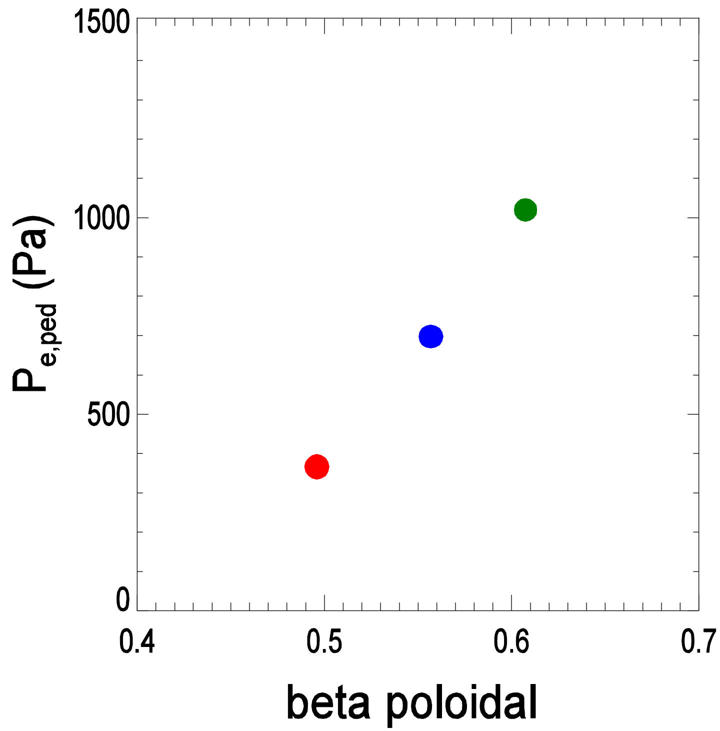
	$k_\perp$ (cm^{-1})	$(\tilde{B}/B)/(\tilde{n}/n)$
Experiment	6-9	0.05
MTM	0.5-4	0.4
ETG	4-30	0.02

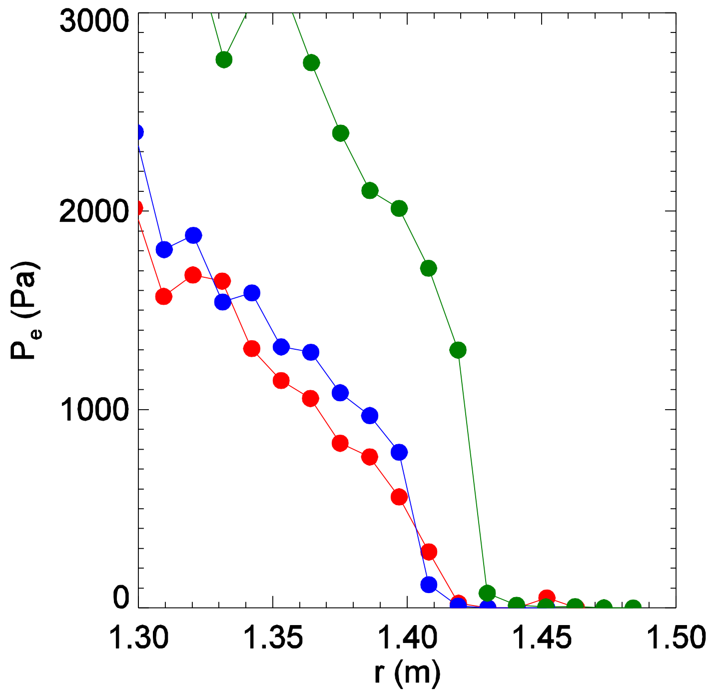
Consistent with ETG at pedestal top

Effect of core β on pedestal stability

Demonstration that core pressure affects the achievable pedestal height

- 36% increase in β core before the L-H transition produces a doubling of the pedestal height achievable before the first ELM

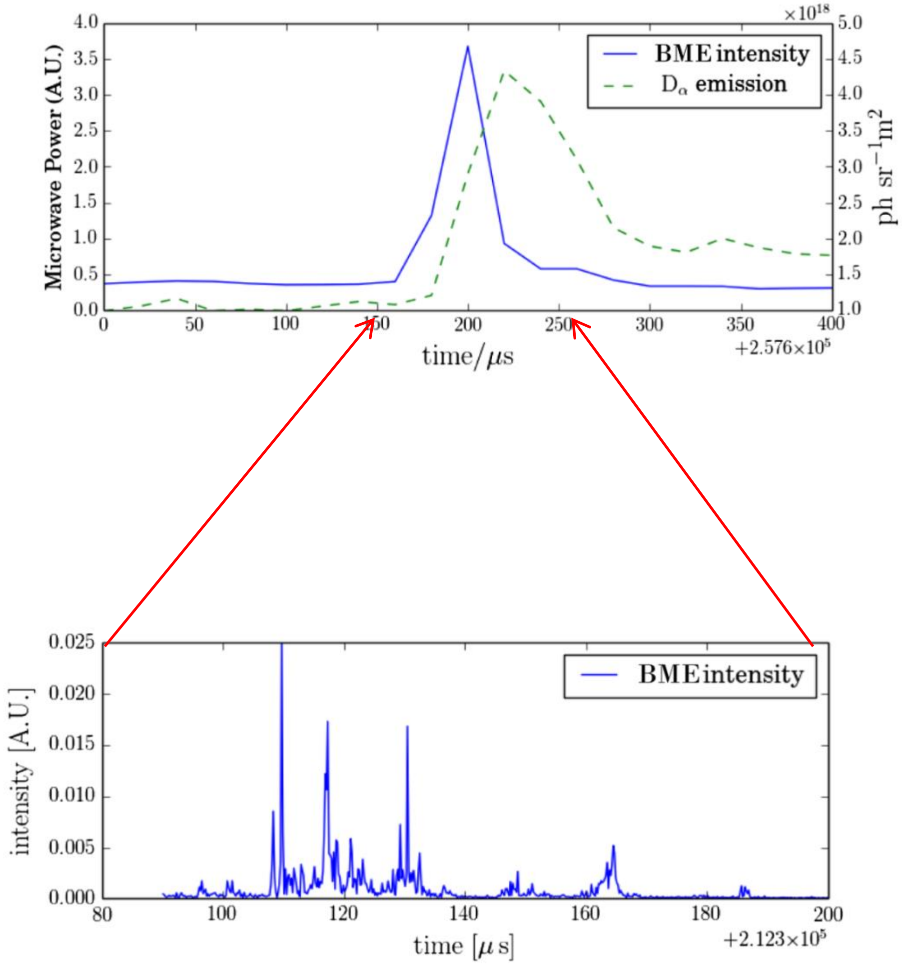




EX/3-6 I. Chapman

Chapman NF 2015

Electron acceleration during ELMs



The Synthetic Aperture Microwave Imaging diagnostic (SAMI) has observed bursts of microwave emission during ELMs

Each burst has a duration of a ~1μs and they exist during rise of Dα emission

Modelling suggests that the bursts are due to the generation of non-thermal electrons [via an anomalous Doppler instability with the acceleration site very close to the plasma edge]

-> Possible evidence of a reconnection process occurring during the ELM

Freethy et al. Phys. Rev. Lett. ***114*** *(2015) 125004*

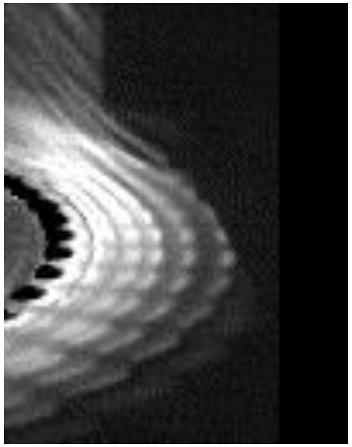
Effect of filaments on ELM wetted area

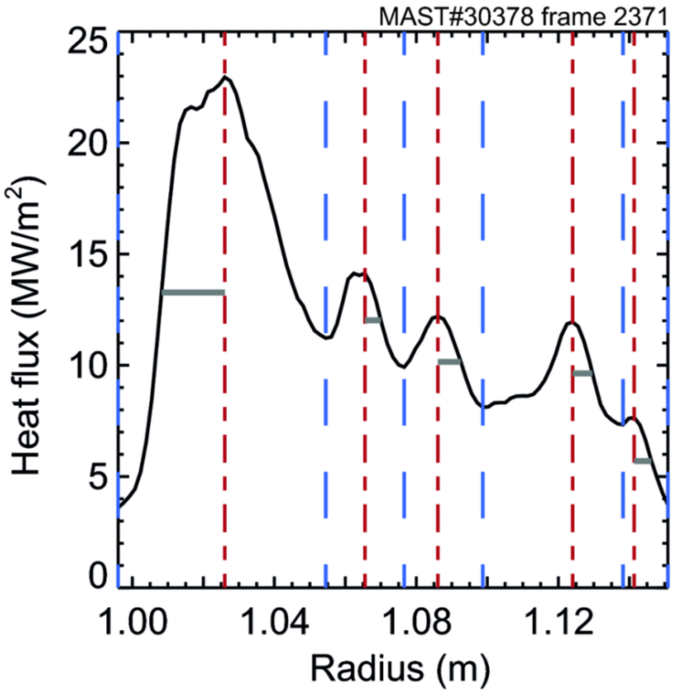
ELM filaments generate striations at the divertor

- lead to peaks in the heat flux profile that can be detected

- The number and size of these filaments affect the wetted area

$$A_{wet} = \frac{2\pi\int q(r)rdr}{q_{peak}} = \frac{P_{tot}}{q_{peak}}$$

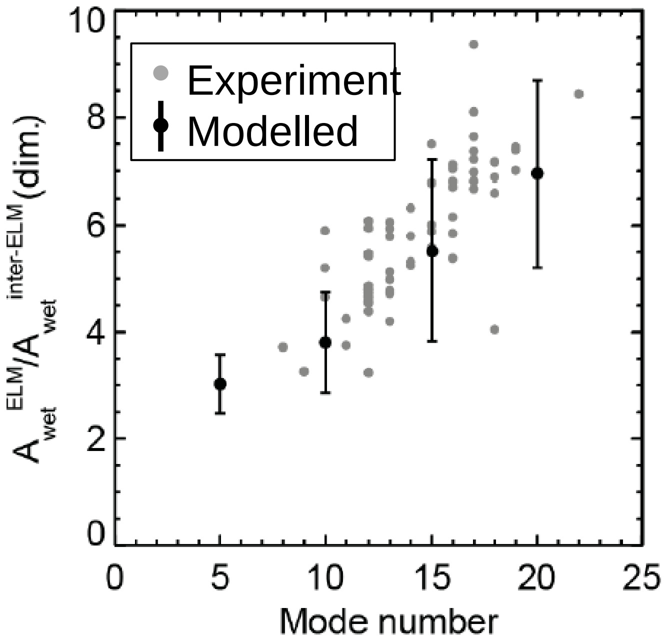




Effect of filaments on ELM wetted area

Wetted area increases with increasing mode number of ELM

A Thornton et al. PPCF 2016



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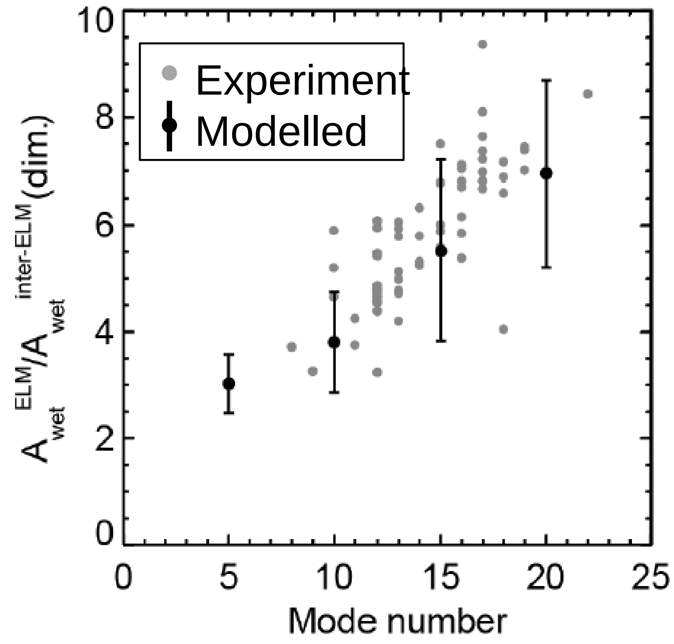
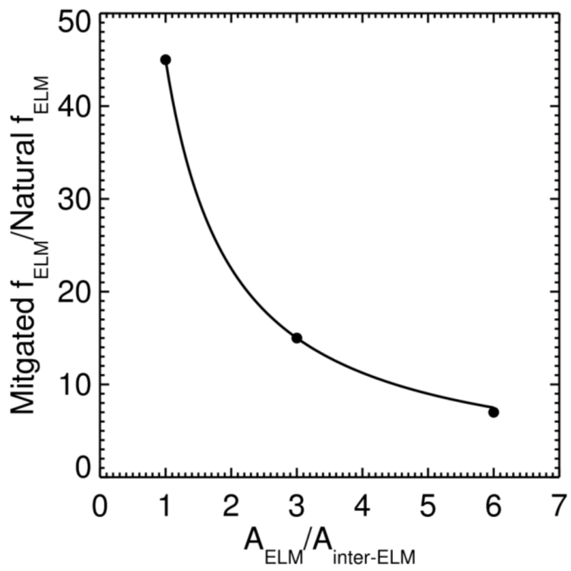


ITER I_P=15 MA



Level of ELM control required on ITER will depend on toroidal mode number of natural ELMs

Modelling of ELMs using JOREK

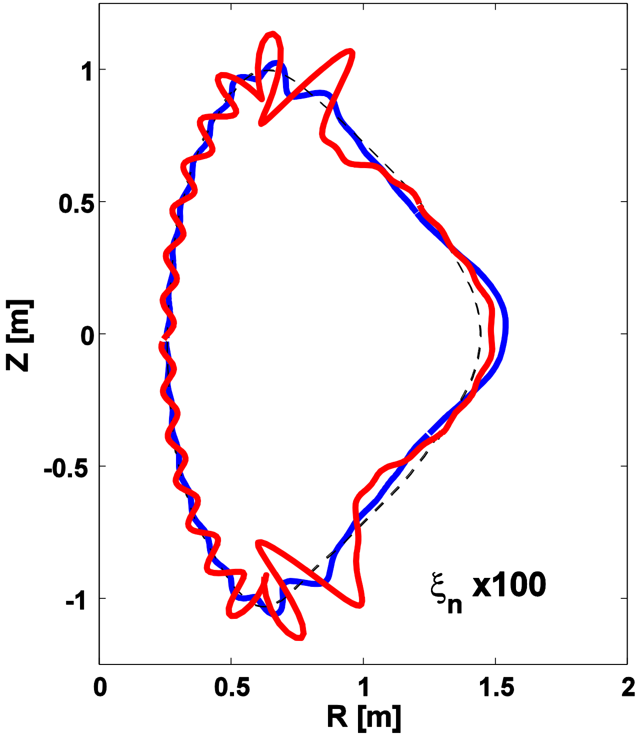
To reproduce observed filament behaviour in ELMs need to take into account the non-linear coupling of different toroidal mode numbers

TH/8-2 S. Pamela

ELM control using RMPs

Plasma displacement

The RMP field causes a 3D distortion of the plasma surface due to the plasma response to the applied field



A core kink response leads to a peaking of the displacement near the midplane

An edge peeling response leads to a peaking of the displacement near the X-point

YQ Liu et al. NF 51 (2011) 083002

Plasma displacement

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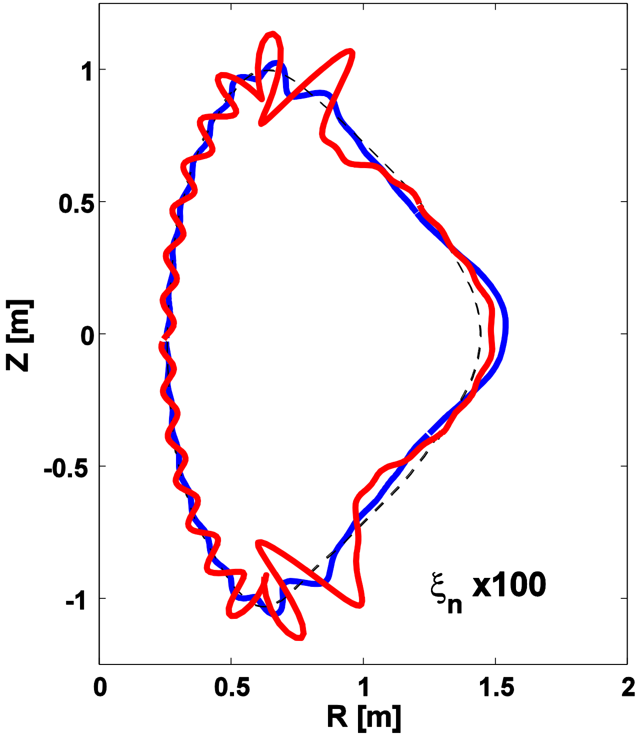

A core kink response leads to a peaking of the displacement near the midplane

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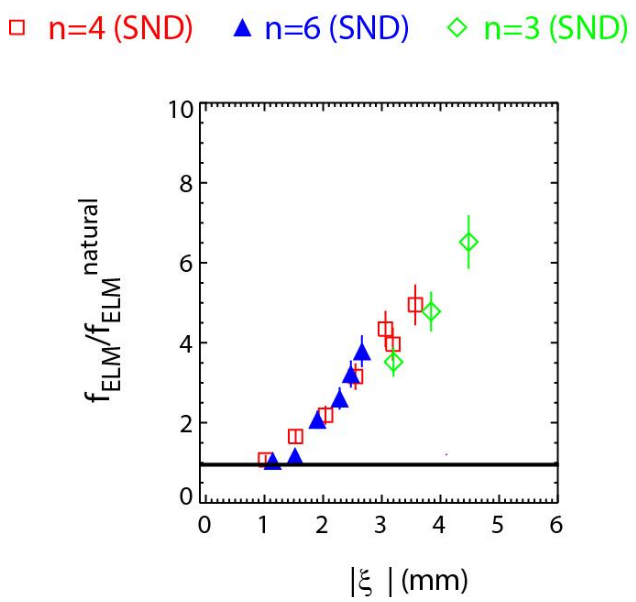


Increase in ELM frequency correlated with size of X-point displacement – appears to be threshold at ~ 1.5 mm

But is this the only criteria?

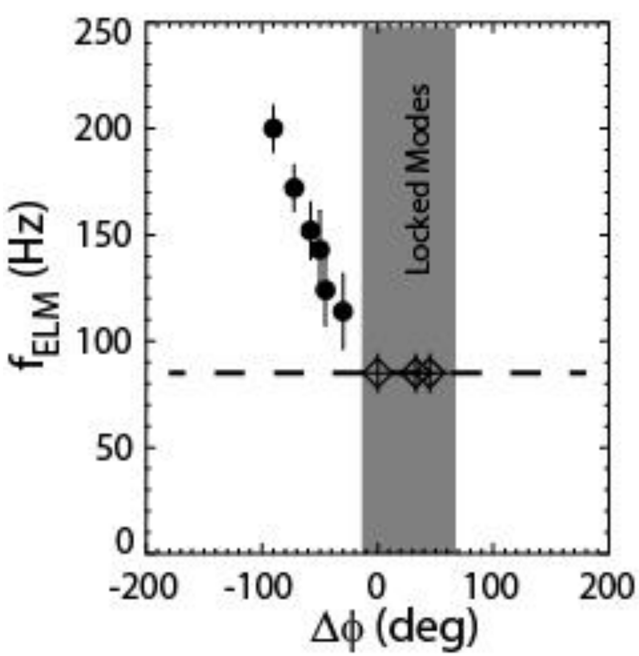
Alignment of applied field

$\Delta\phi$ scan used to adjust the alignment of the perturbation while keeping the plasma constant

$\Delta\phi = -90^0$

1	2	3	4	5	6	7	8	9	10	11	12
+		-		+		-		+		-	
	+		-		+		-		+		-

f_{ELM} measured in repeat shots

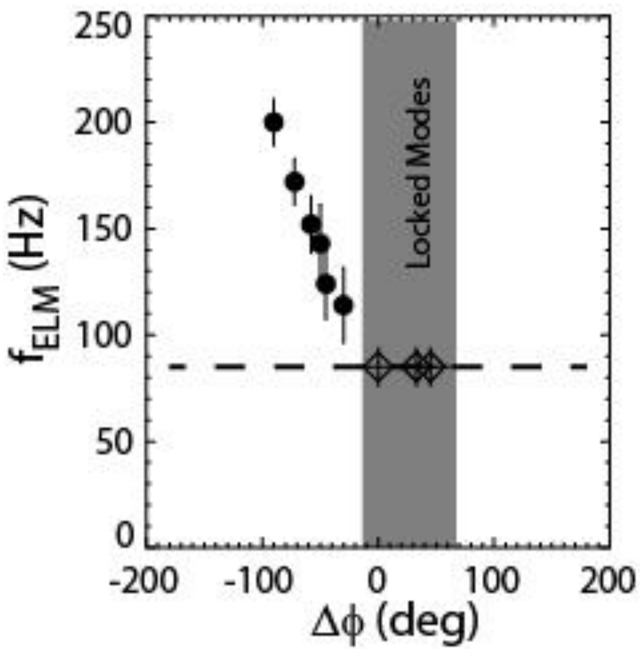


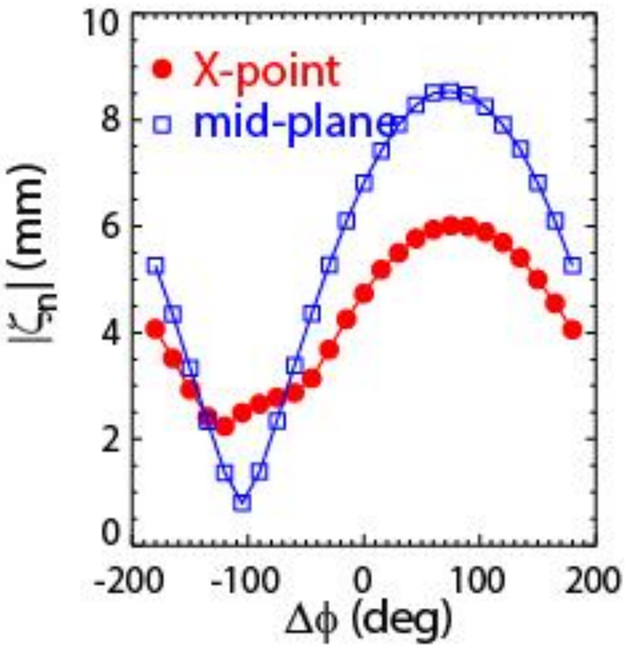
ELM mitigation only occurs in a narrow window of $\Delta\phi$

Plasma displacement

MARS-F plasma response calculations show that ELM mitigation only occurs where the X-point peaking is greater than the mid-plane peaking

– not necessarily where the X-point peaking is largest

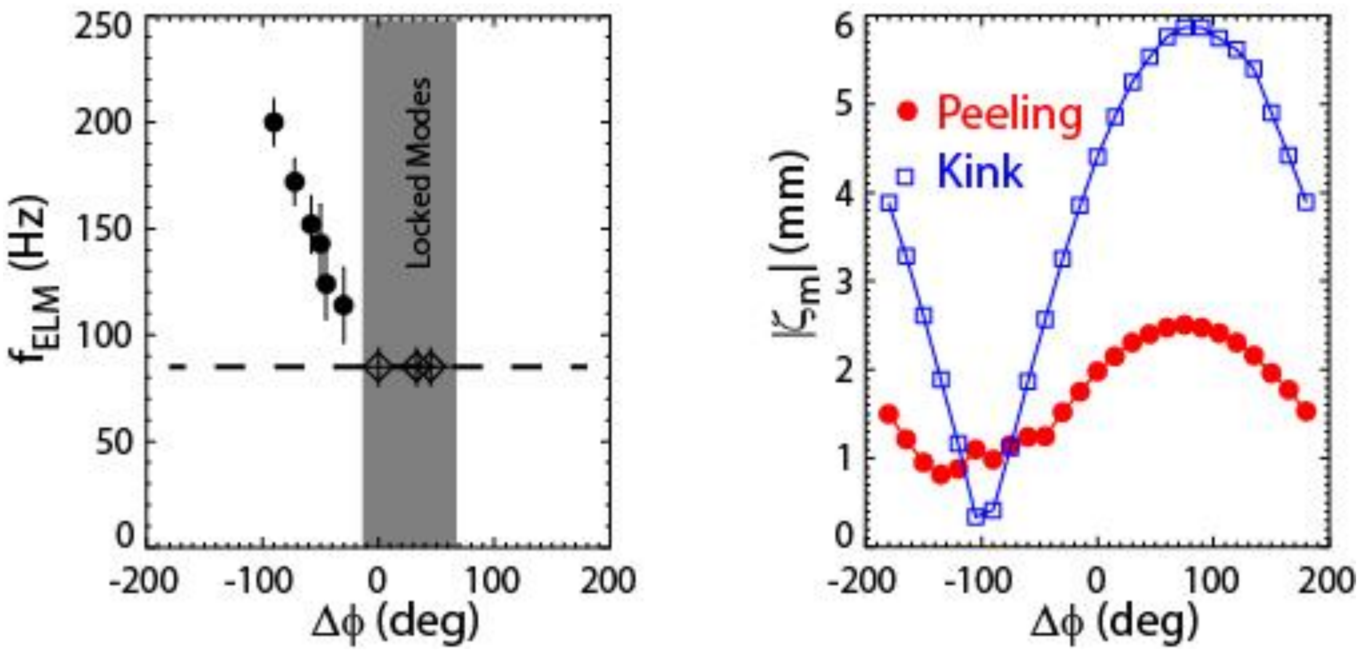




Alignment of applied field

Outside this window the core kink response is so large it causes locked modes

Access criteria: Optimise Peeling response while minimising the kink response



Summary and future plans

Although MAST has not operated since the last IAEA there has been substantial analysis and modelling performed on the data obtained previously

The aim has been to validate models which can then be used to extrapolate to future devices including MAST-U

Summary and future plans

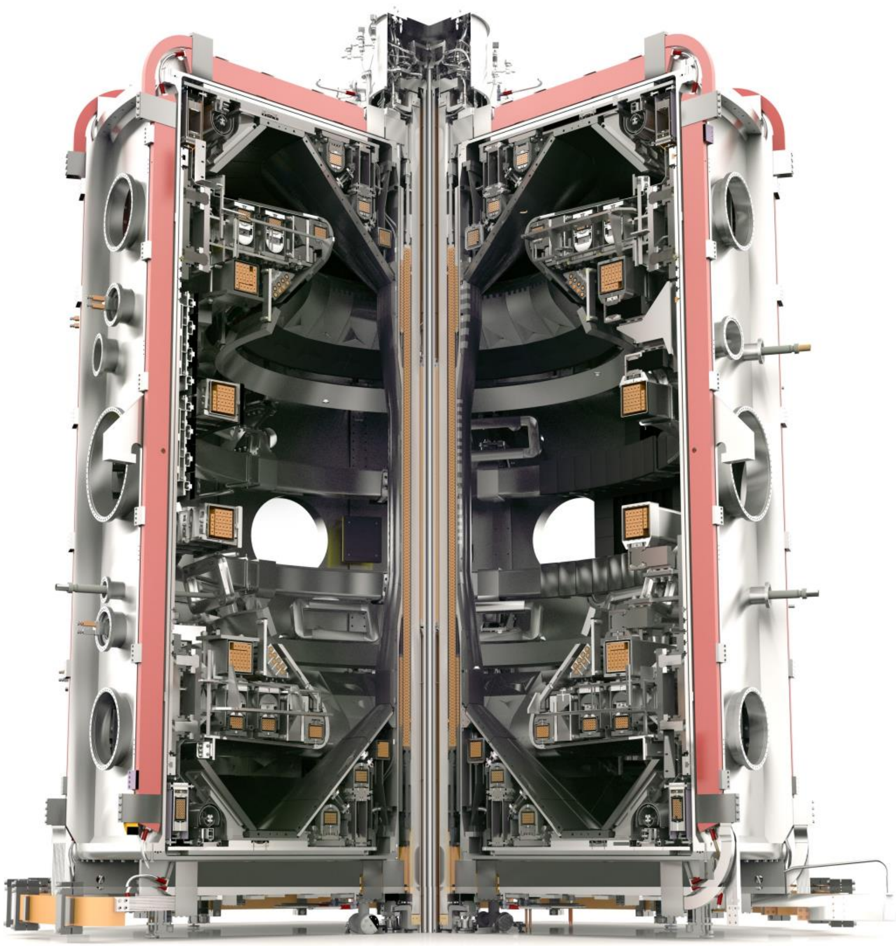
Increased TF
Improved confinement

New Solenoid
Greater I_p, pulse duration

19 New PF Coils
Improved shaping

Off-Axis NBI
Improved profile control

MAST-Upgrade nearing end of construction ("core scope")



Summary and future plans

Increased TF
Improved confinement

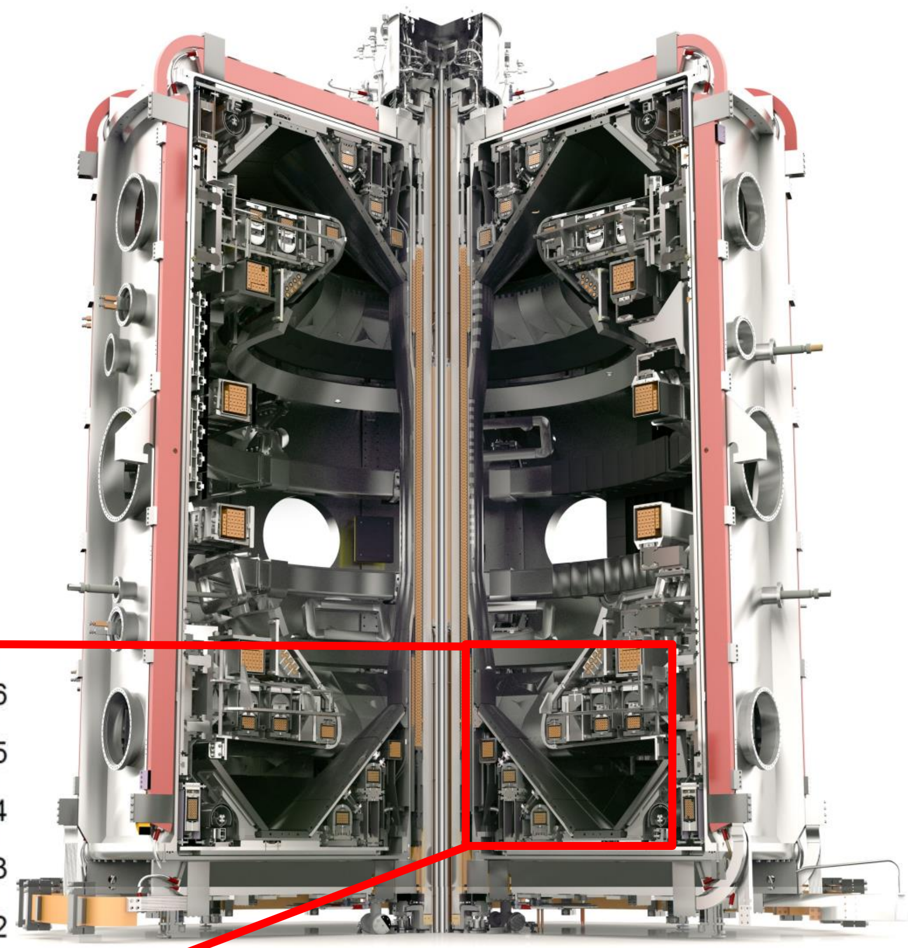
New Solenoid
Greater I_p, pulse duration

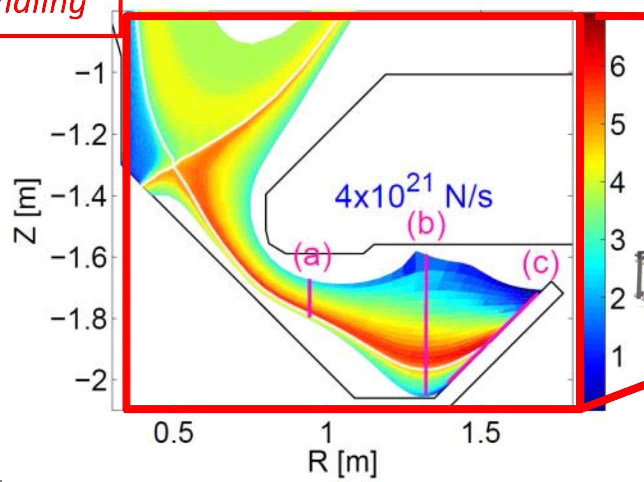
19 New PF Coils
Improved shaping

Off-Axis NBI
Improved profile control

Super-X Divertor
Improved power handling

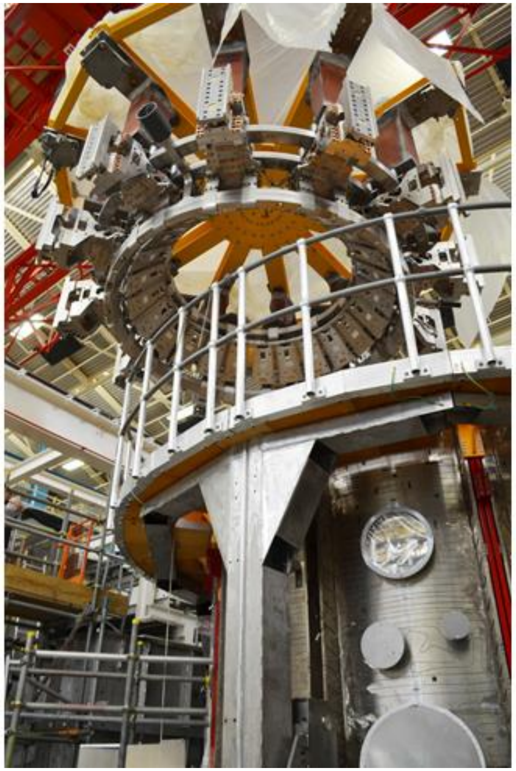
MAST-Upgrade nearing end of construction ("core scope")

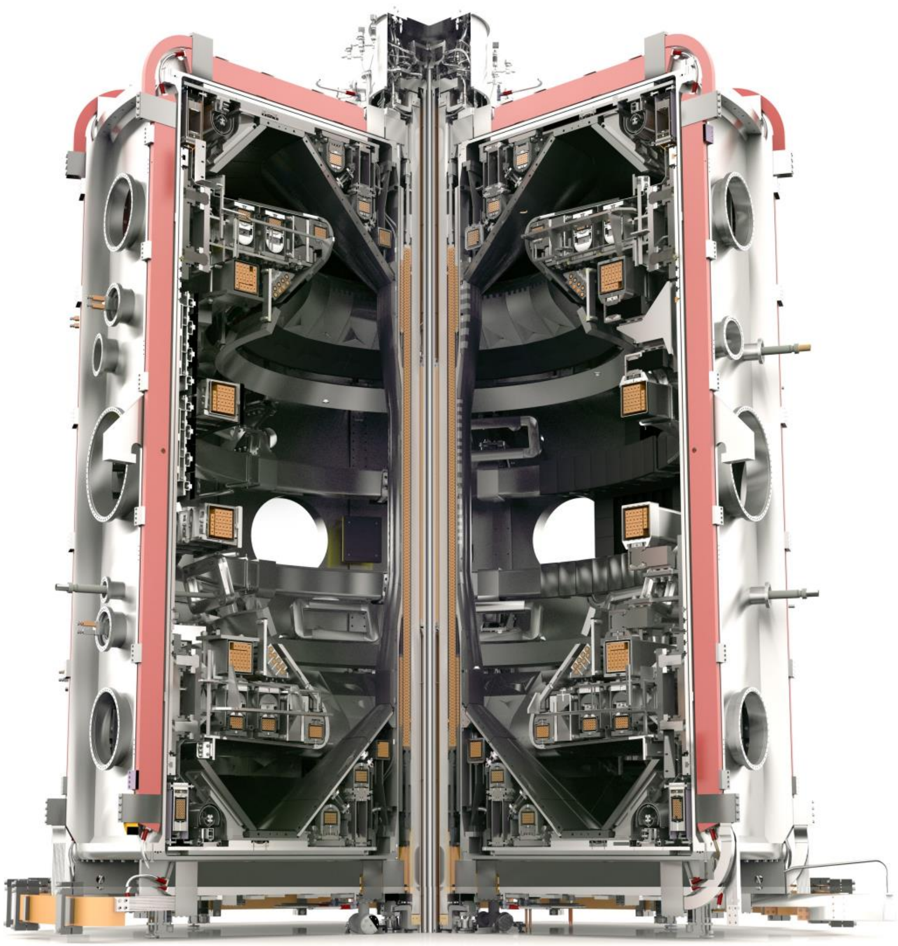




Summary and future plans

MAST-Upgrade nearing end of construction ("core scope")





Most of the Load assembly is now complete

Summary and future plans

MAST-Upgrade nearing end of construction ("core scope")

We look forward to welcoming you to take part in the physics campaigns which will begin towards the end of 2017 when MAST-U will be operating as one of EUROfusions Medium sized tokamaks