Recent MAST results and status of MAST Upgrade project

IT Chapman

on behalf of the MAST and MAST Upgrade Teams

Seminar at PPPL, 11 June 2014

CCFE is the fusion research arm of the **United Kingdom Atomic Energy Authority.**
This work was funded by the RCUK Energy Programme [grant number EP/I501045] .

MAST

- Wide range of tokamak physics for ITER, DEMO and future STs
- MAST is one of 3 EU facilities supported by EUROfusion programme (+ ASDEX Upgrade and TCV)

	MAST	MAST Upgrade
R (m)	0.85	0.85
I_p (MA)	Up to 1	Up to 2
B_T (T)	~0.5	0.8
P_{NBI} (MW)	4	5 (7.5)
Divertor	SND, DND Open	SND, DND, super-X, snowflake Closed (pumped)

Last MAST campaign

- Focus the campaign around 6 headlines:
  1. ELM control with 3D magnetic perturbations
  2. Evolution and stability of the edge pedestal
  3. Role of ion-scale turbulence in core transport
  4. Development of integrated scenarios for MAST-U
  5. Development and benchmarking of edge modelling tools in support of the divertor upgrade
  6. Fast-ion transport to guide profile and heating optimisation

- Campaign from May – September 2013, comprising 66 run days

Collaborations

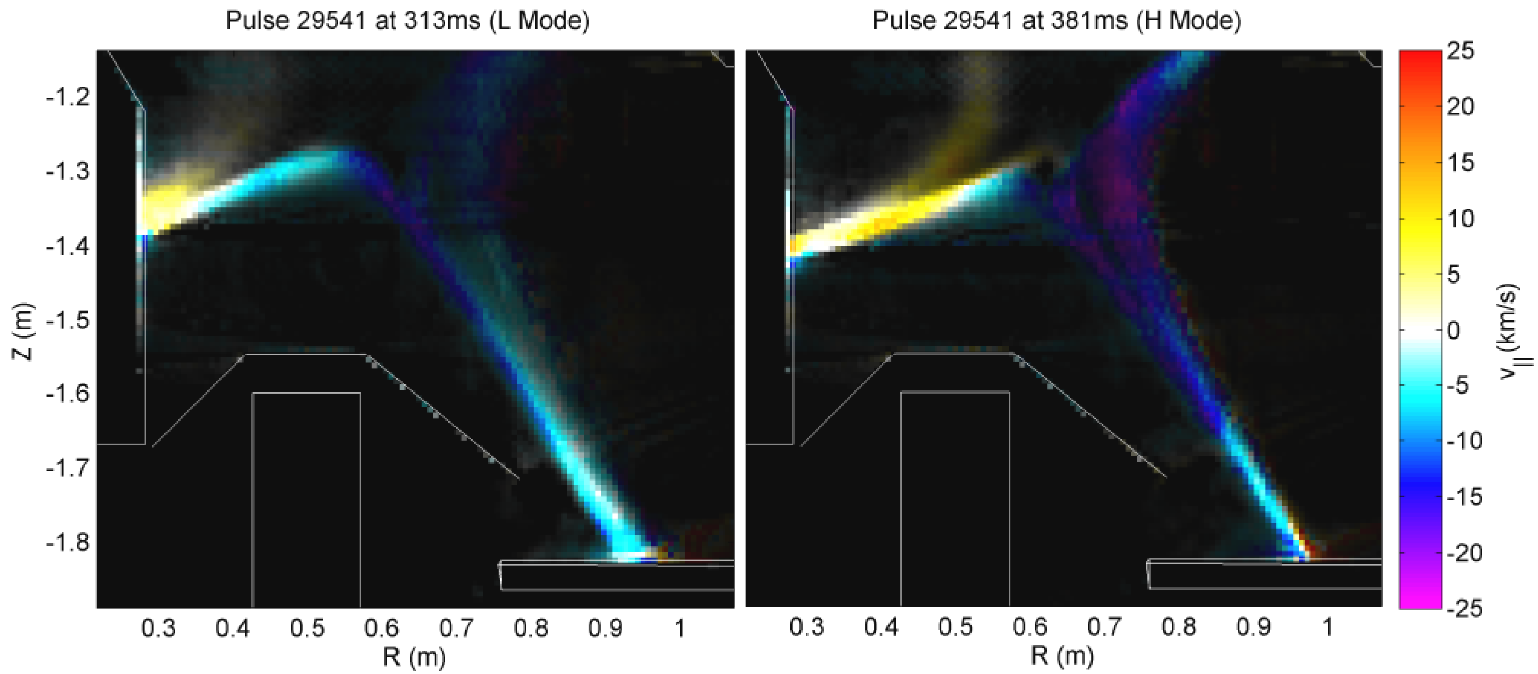
M9 was characterised by strong international collaborator involvement. Listed below are some new ones for the most recent campaign:

- *Proton detector (Florida, **PPPL**)
- *Doppler Back Scattering (UCLA)
- *Pellet imaging (NIFS)
- *Coherence Imaging (ANU)
- Pedestal scaling (**PPPL**)
- Perturbative particle transport (**PPPL**)
- Divertor impurity transport (DCU)
- TAE avalanches (**PPPL**)
- Momentum transport (**PPPL**)

** New diagnostics*

New diagnostics in last campaign

- Coherence imaging (with Australian National University, Durham University);
- Proton detector (with Florida International University, PPPL);
- Doppler back-scattering (with University of California, Los Angeles);
- Ball-pen probe (plasma potential fluctuations)
- Pellet imaging (with NIFS, Japan)



Initial tomographic inversions of divertor emissivity and parallel flow for C III in L and H modes

S Silburn et al, HTPD, 2014

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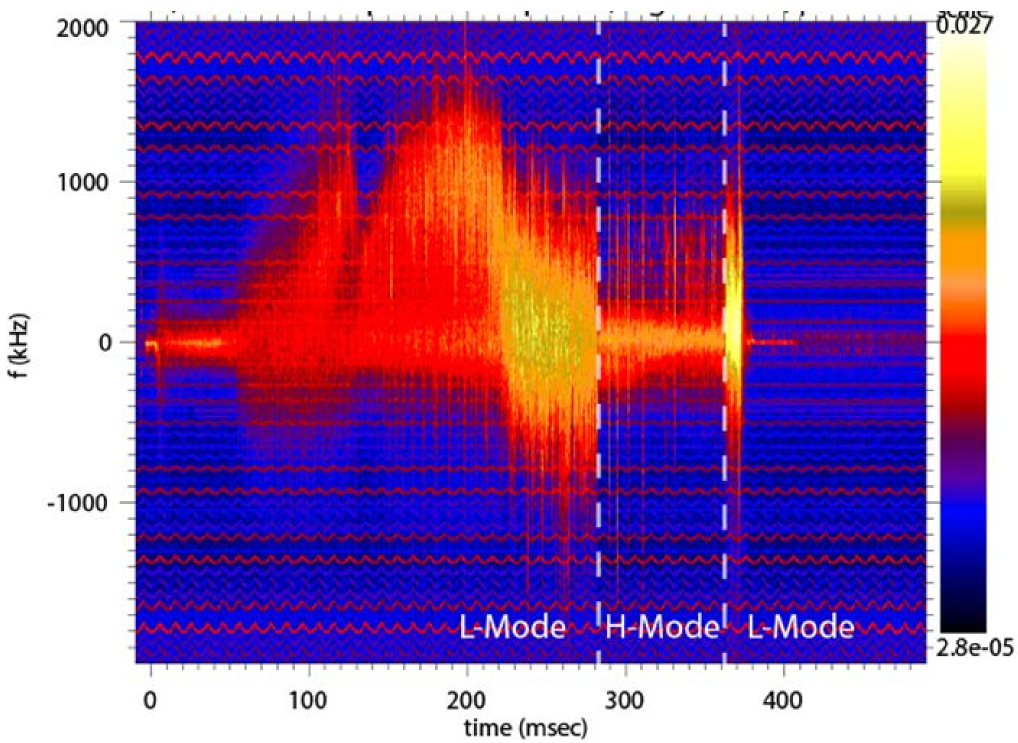
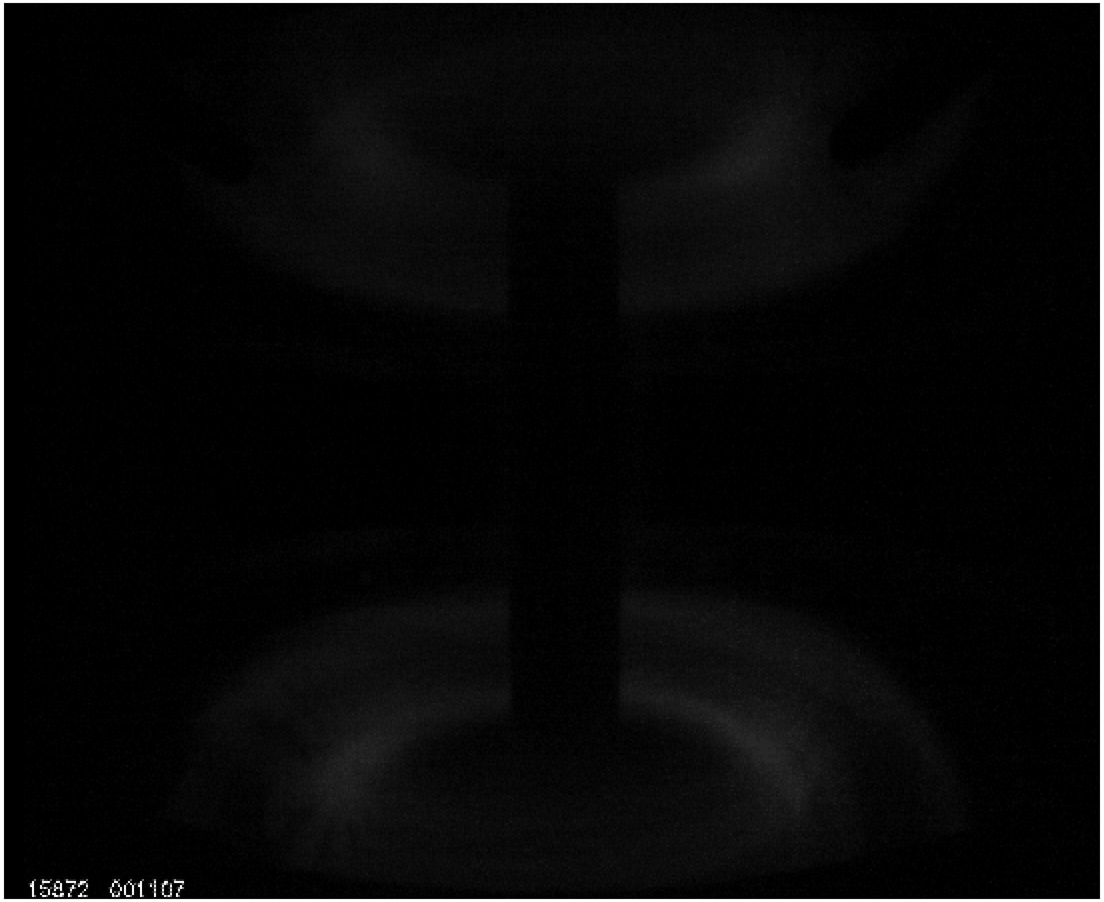


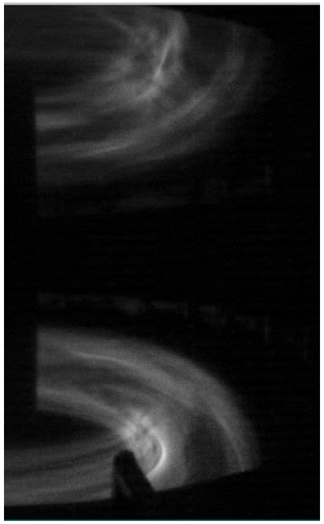
J Hillesheim et al, HTPD, 2014

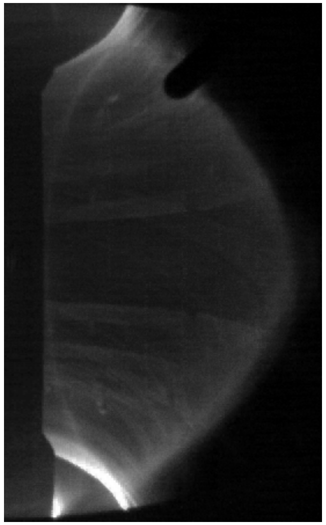
Doppler back-scattering (with UCLA)

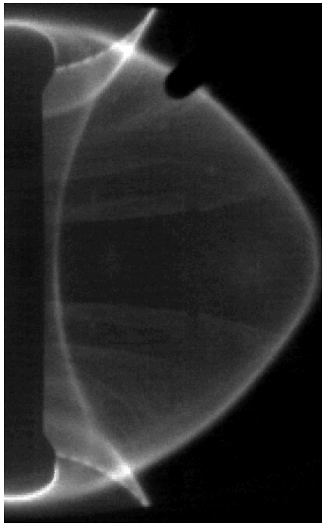
Typical MAST discharge

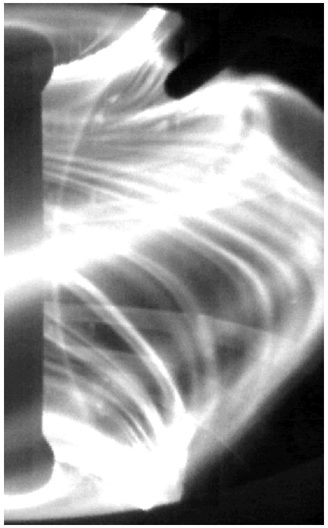


Outline of this talk









Start-Up

Ion scale Turbulence

Pedestal

ELM control

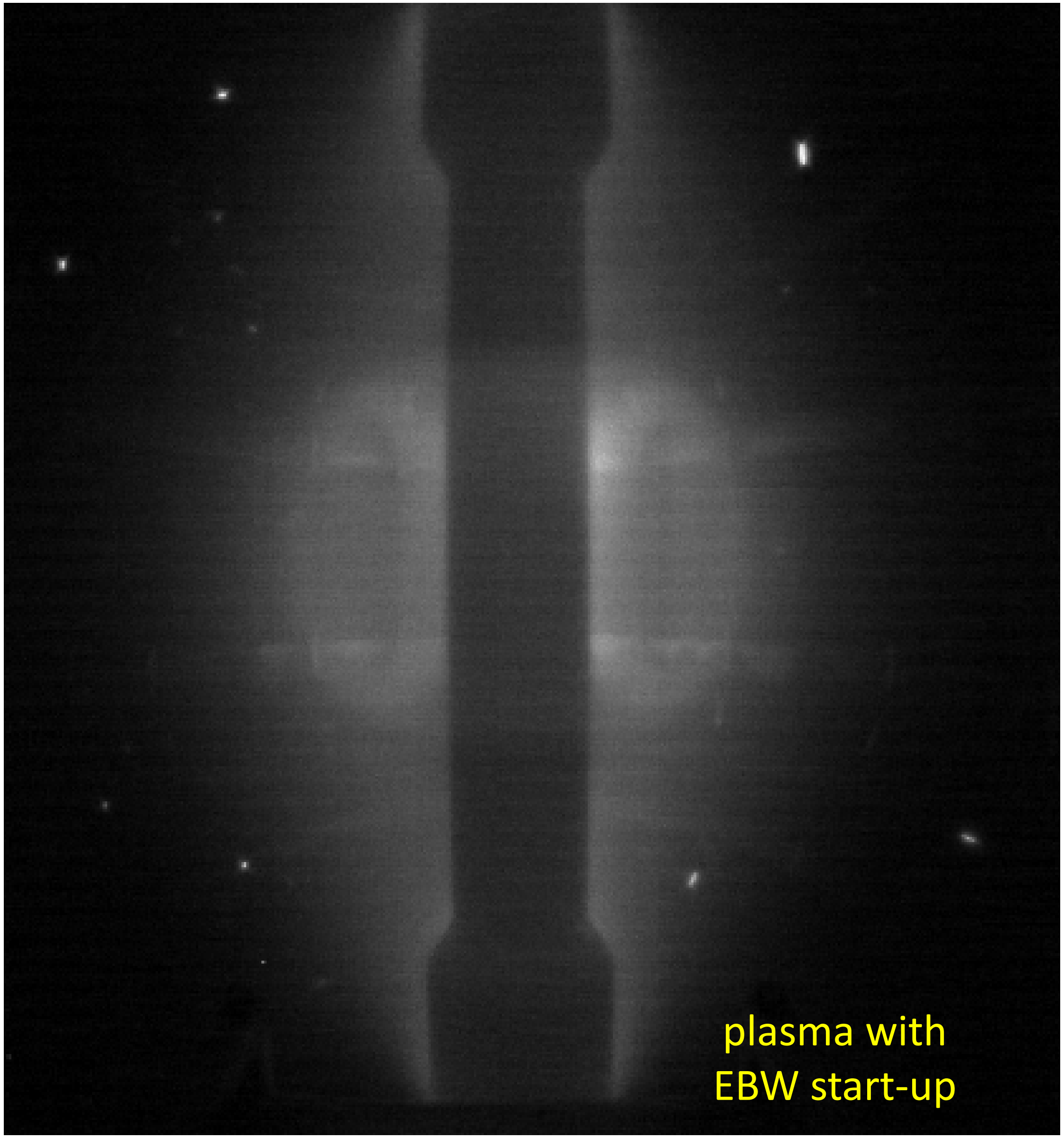
MAST-U Scenario Development

SOL Turbulence

Energetic Particle Losses

Pellet Fuelling & ELMs

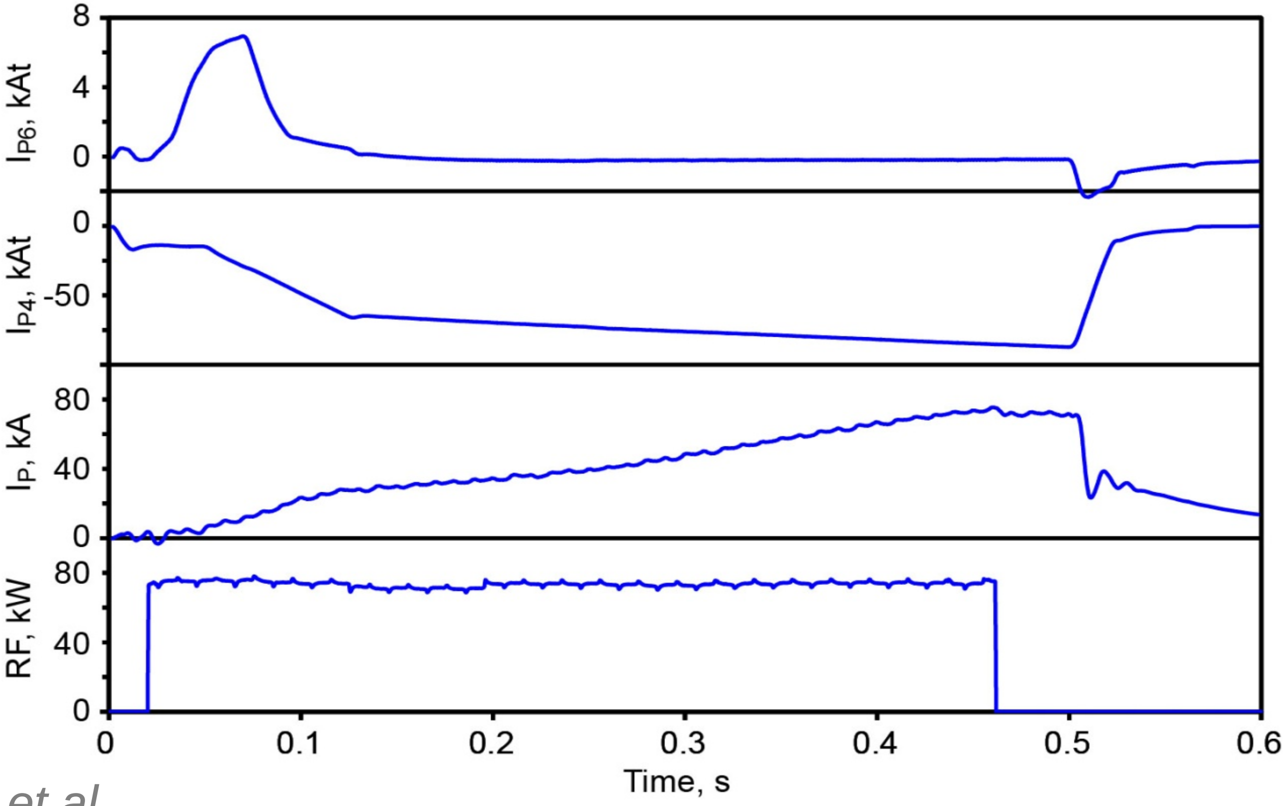
EBW start-up



- Hardware improvements for M9 experiments:
  - Waveguides (low loss waveguides designed & provided by ORNL)
  - Mirror-box
  - Gyrotron control system
- Significant runtime allocated with NBI power supply reconfigured for EBW on two separate weeks
- Collaboration with ORNL & Japan during experiments

EBW start-up

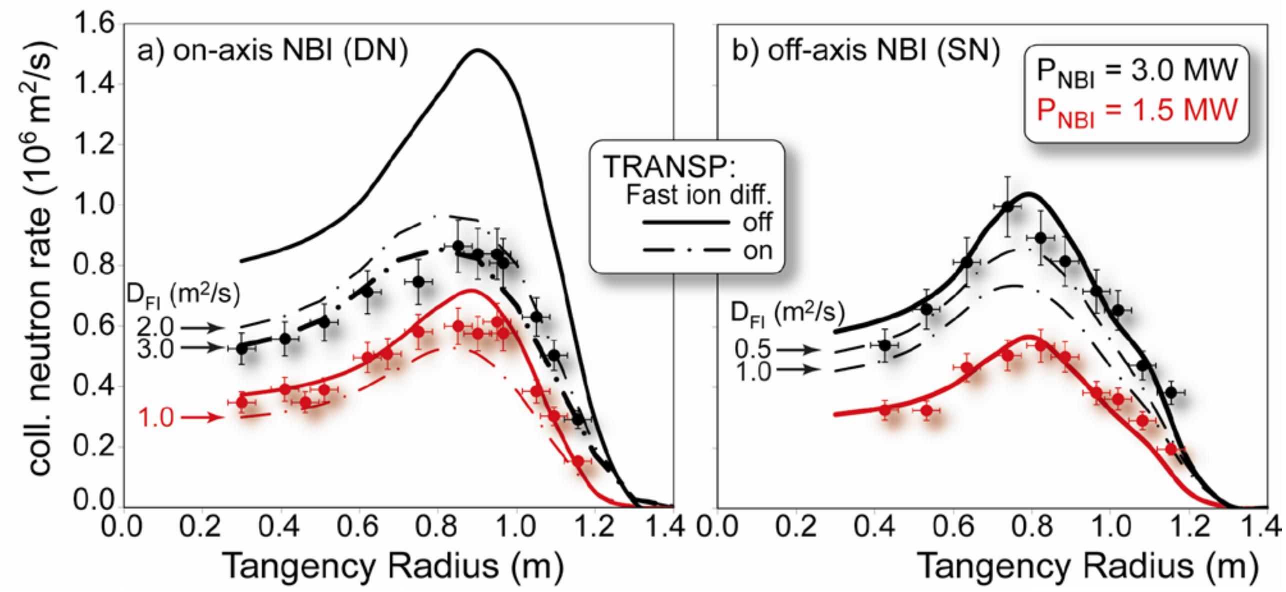
- Previous EBW start-up experiments achieved I_P~33kA with RF pulse duration ~90ms
- M9 experiments with longer RF pulse to increase plasma current (I_P~73kA achieved with ~73kW of RF power – i.e. ~1A/W)



V Shevchenko et al

Avoidance of fast ion re-distribution

- Optimisation of beam injection geometry minimises the deleterious effects of energetic particle modes in MAST



- Fast ion redistribution may also be avoided by operating at sufficiently high density:

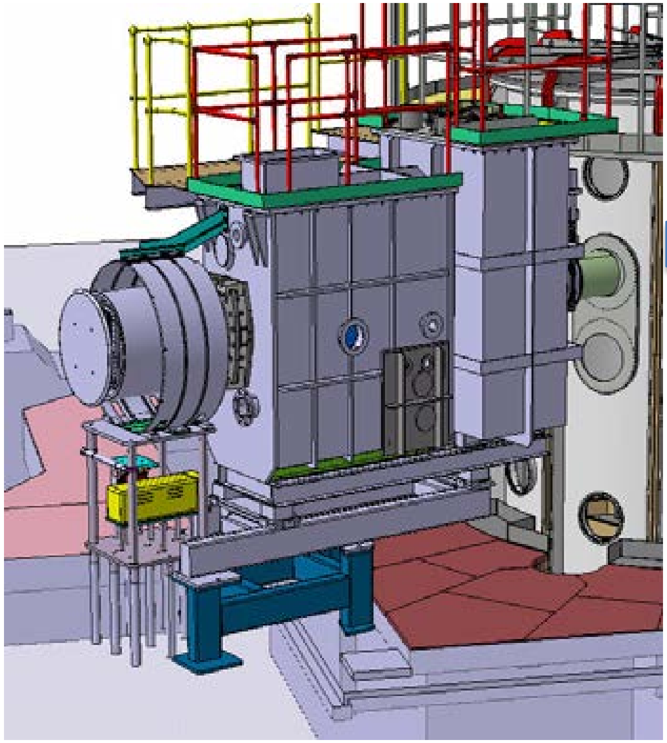
  $n_e > 3 \times 10^{19} m^{-3}$ at P=1.5MW

  $n_e > 4 \times 10^{19} m^{-3}$ at P=3.0MW

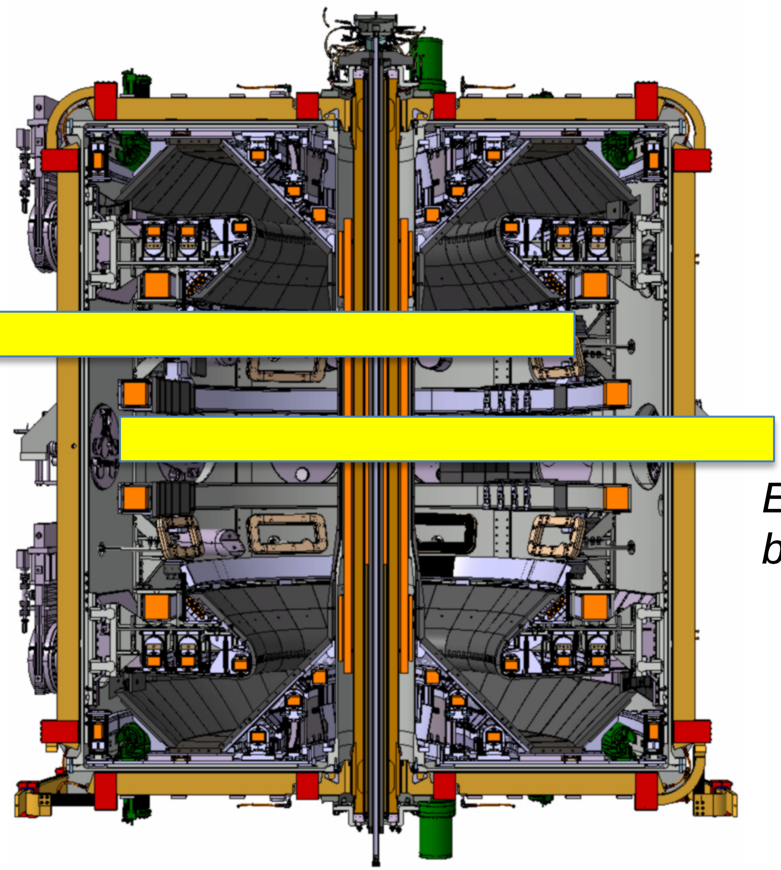
- Both approaches act to reduce the fast ion pressure gradient

Turnyanskiy et al, Nuc. Fus. ***53*** *(2013) 053016*

Neutral beams in MAST Upgrade



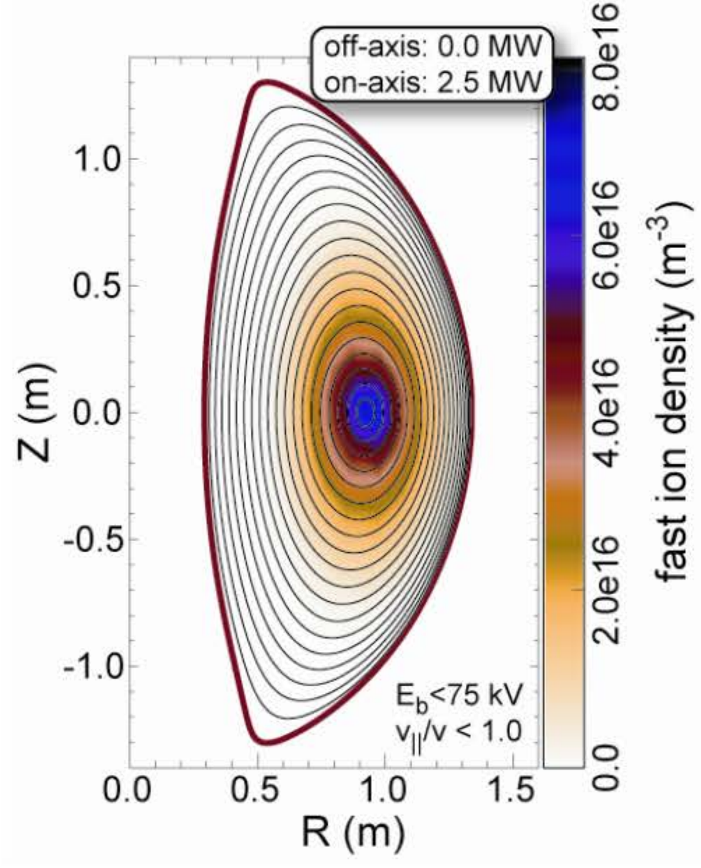
Jacked beam box



Existing mid-plane beam line

- One of the existing beam lines will be jacked up to enable off-axis injection giving improved control options (e.g. current profile, fast ion density profile)

Flexible fast ion density profile



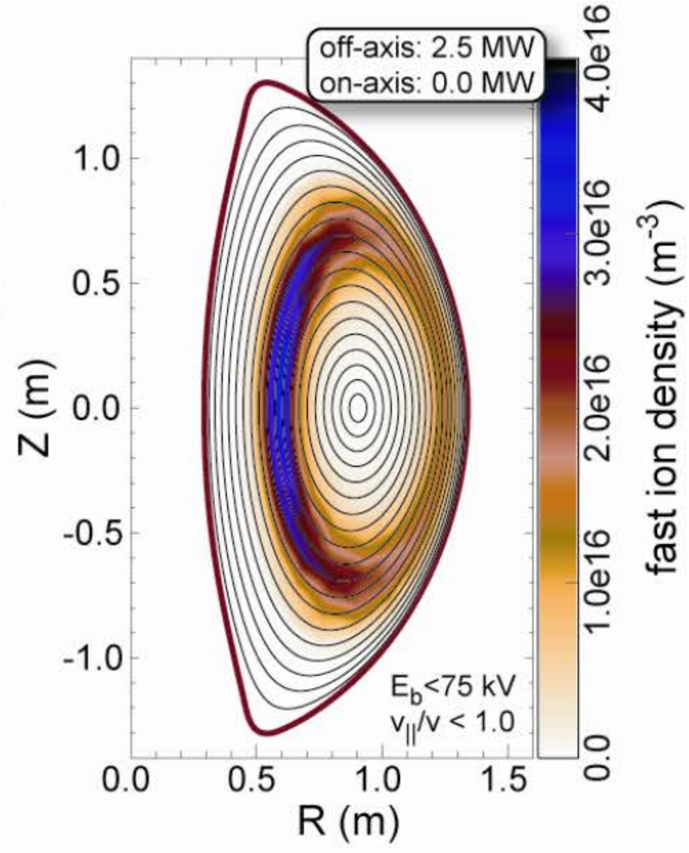
MAST Upgrade

Advanced profile control:

On-axis NBI only

- peaked fast ion density
- core current drive

Flexible fast ion density profile



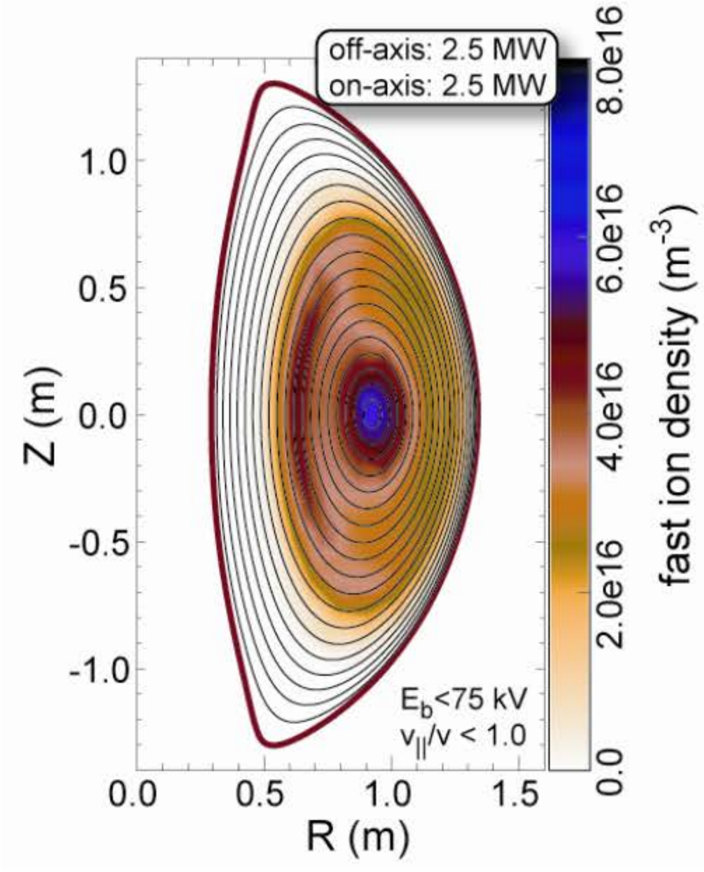
MAST Upgrade

Advanced profile control:

On-axis NBI only
- peaked fast ion density
- core current drive

Off-axis NBI only
- hollow fast ion density
- off-axis current drive

Flexible fast ion density profile



MAST Upgrade

Advanced profile control:

On-axis NBI only
- peaked fast ion density
- core current drive

Off-axis NBI only
- hollow fast ion density
- off-axis current drive

Off- and on-axis NBI
- broad fast ion density profile
- broad current drive profile

Physics studies:

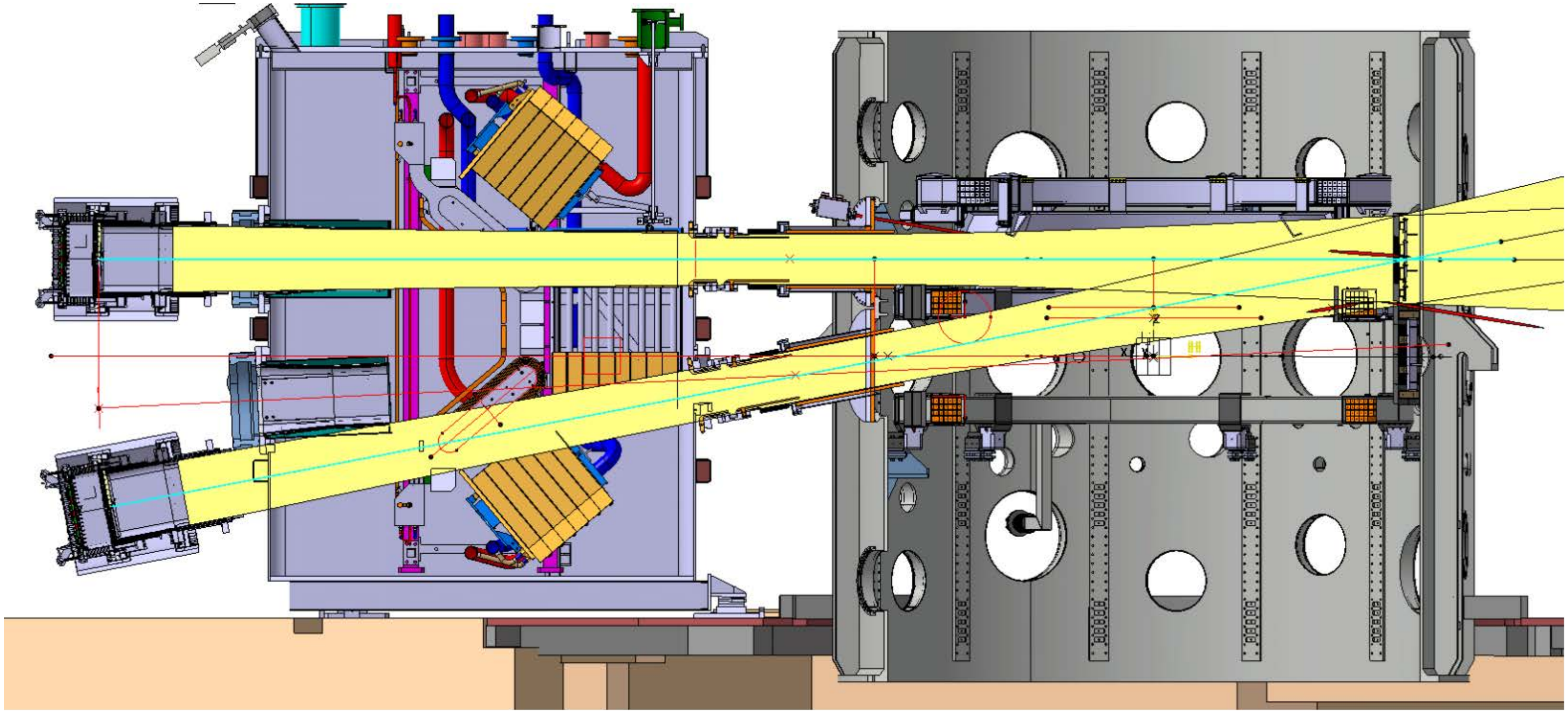
1MA non-inductive current; up to 5s pulse length

Advanced q profile (q_{min} > 2)

Vary $|\nabla f_{FI}|_{max}$ with respect to q

Neutral beams in MAST Upgrade

- In a later stage of the upgrade a double beam box will be added comprising an off-axis beam and a tilted beam
  - increased power
  - additional control flexibility



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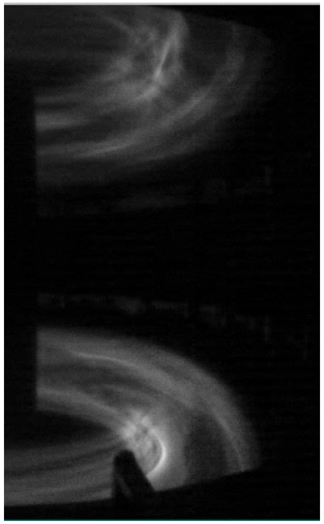

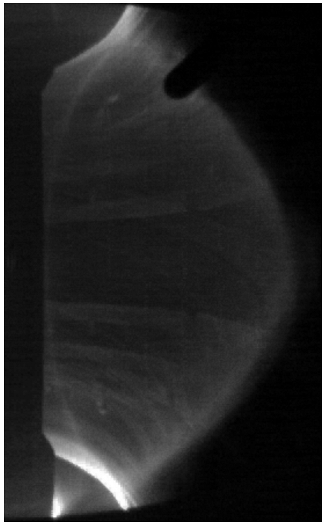

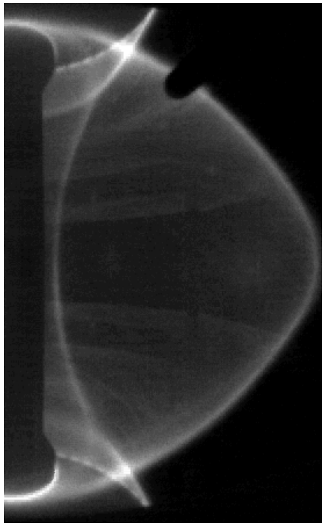

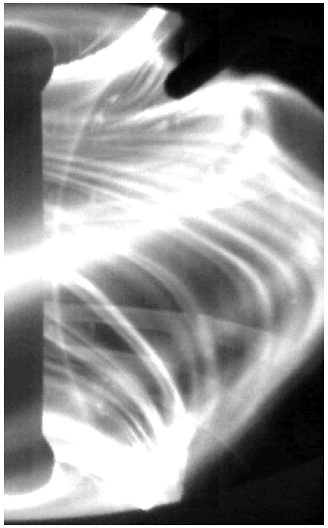

Start-Up

Ion scale Turbulence

Pedestal

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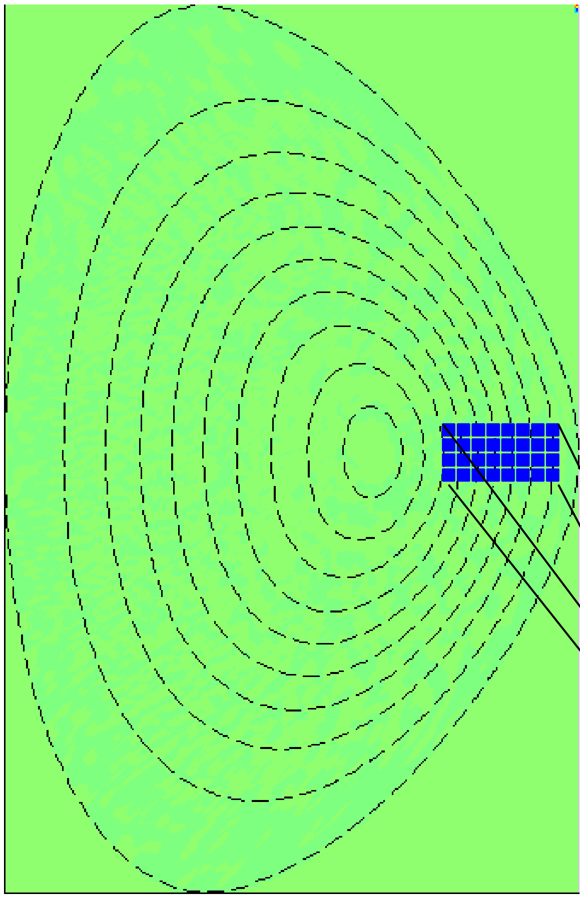
Imaging BES system

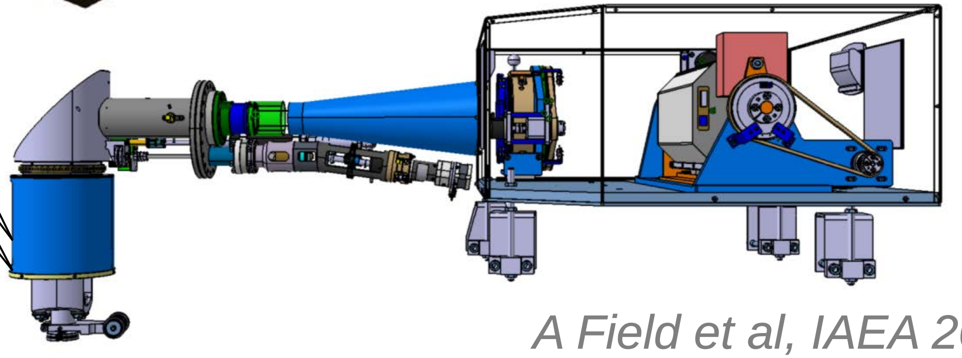
Non-linear Gyro-kinetic simulation of L-mode plasmas φ



- Views Dα emission of deuterium heating beam
- 2D measurements of density fluctuations
- 8x4 channels, 2 $\times$ 2 cm^2 spatial resolution at 2 MHz
- Observes turbulence at scales > ion Larmor radius

Custom APD camera

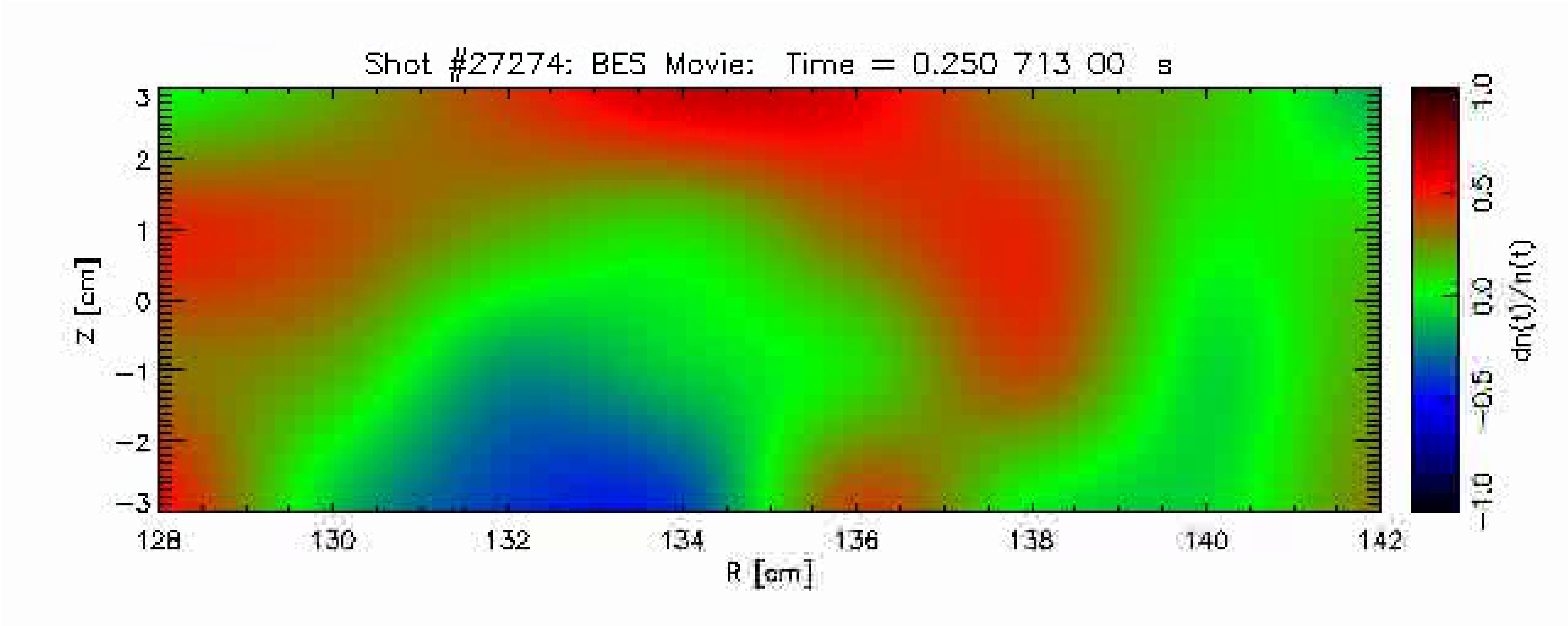
8x4 ch. APD detector



A Field et al, IAEA 2014

BES movie of turbulence

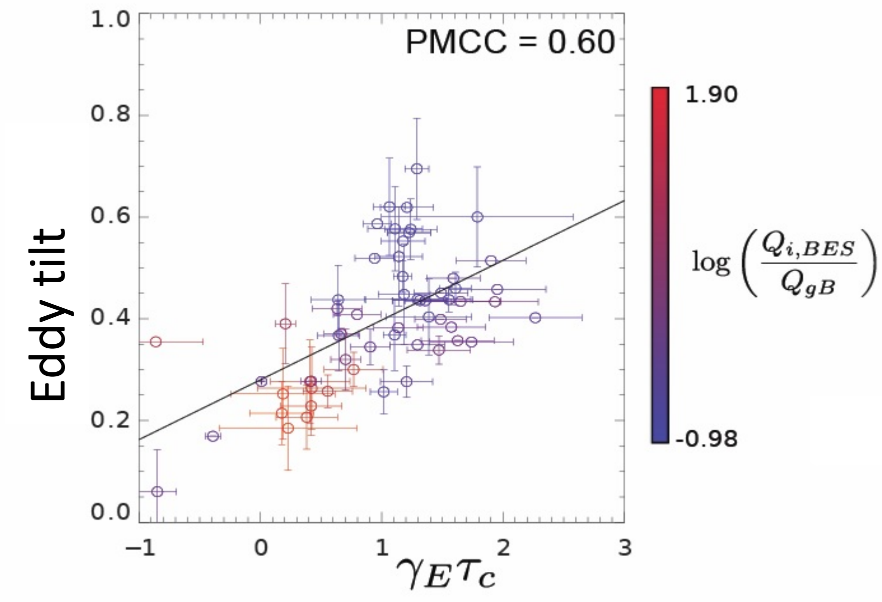
- Provides 2D 'movie' of normalised density fluctuations $\delta n/n$
- Here, the image resolution increased by factor ~ 30 by interpolation
- Turbulent 'eddies' evident with spatial scale of a few ion Larmor radii
- Lifetime τ_c of a few 10μs before de-correlation by non-linear interactions

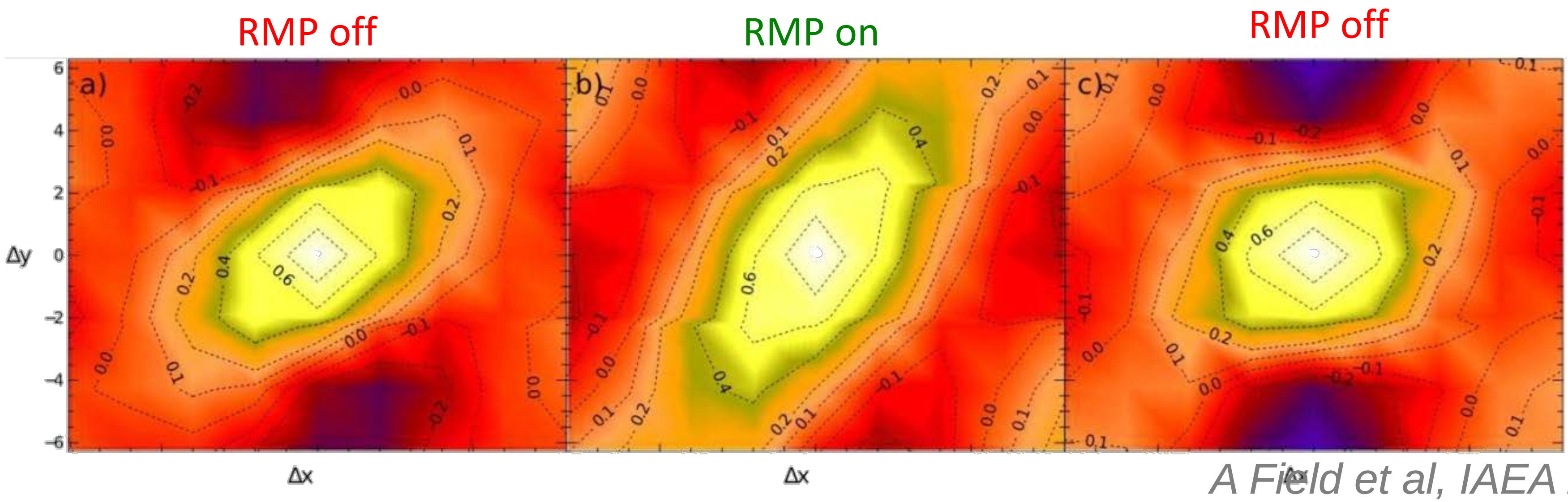


A Field et al, IAEA 2014

Effect of flow shear on low-k turbulence

- Applied RMPs and alter rotation profile
- With increasing flow shear eddy tilt increases and ion heat flux decreases, in accordance with prediction



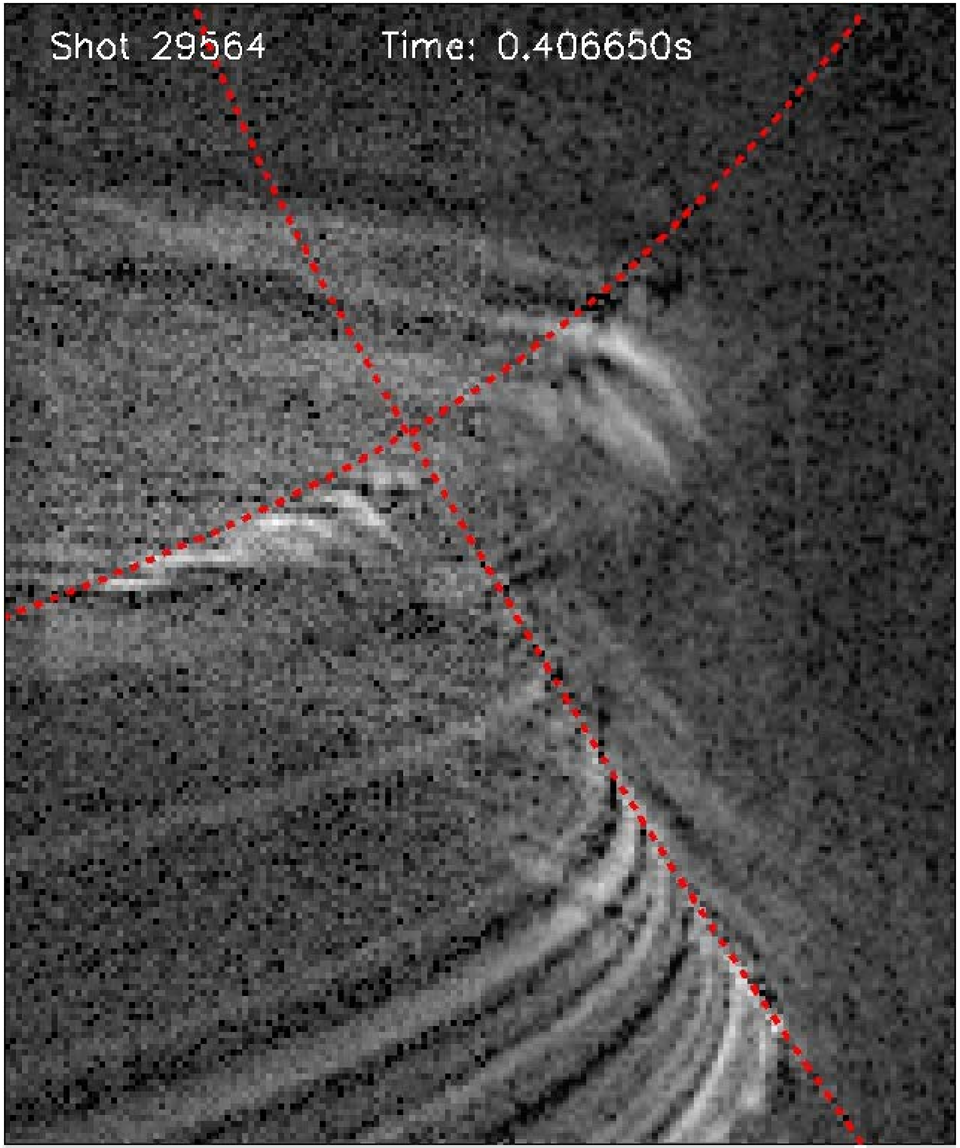


A Field et al, IAEA 2014

Filaments in the SOL

- Fluctuations within the divertor volume imaged with a high-speed camera
  - 120kHz time resolution, ~6mm spatial resolution
  - Unfiltered - detected light dominated by D_α line emission
  - Peak signal:noise 1000:1

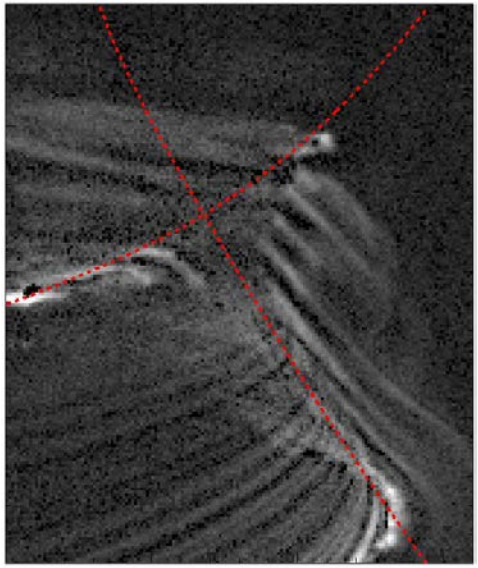
- Fluctuations are enhanced by subtracting a time-average background from the raw data



JR Harrison et al, PSI, 2014

Filaments in the SOL

- Camera data suggests there are 3 fluctuating regions in the divertor in L-mode and H-mode:



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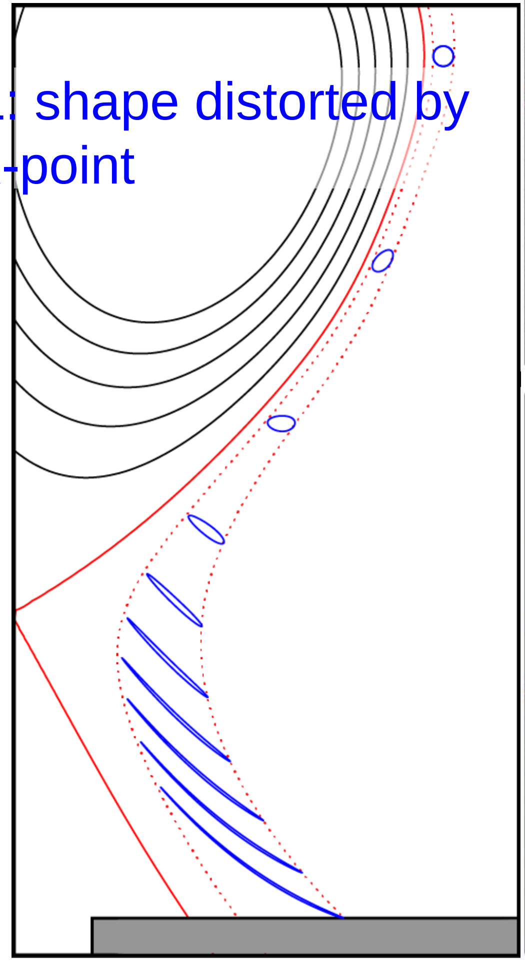
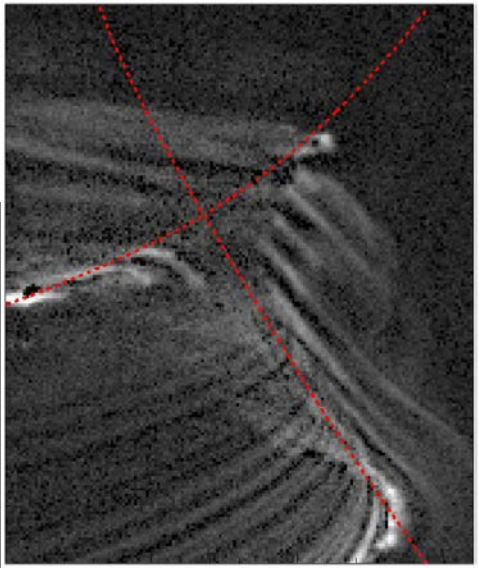
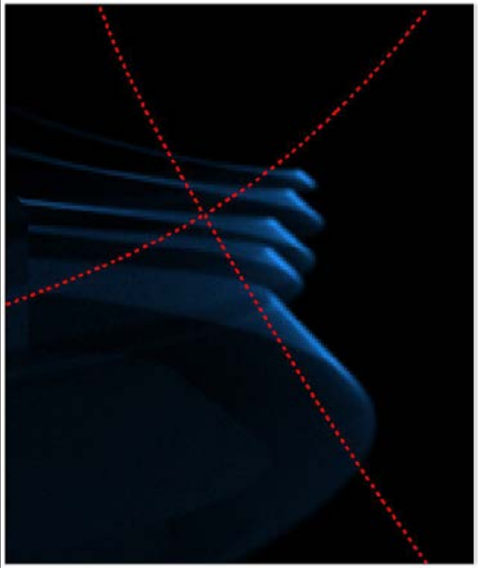
Filaments in the SOL

- Camera data suggests there are 3 fluctuating regions in the divertor in L-mode and H-mode:
  - Filaments in the main SOL: shape distorted by magnetic shear near the X-point







JR Harrison et al, PSI, 2014

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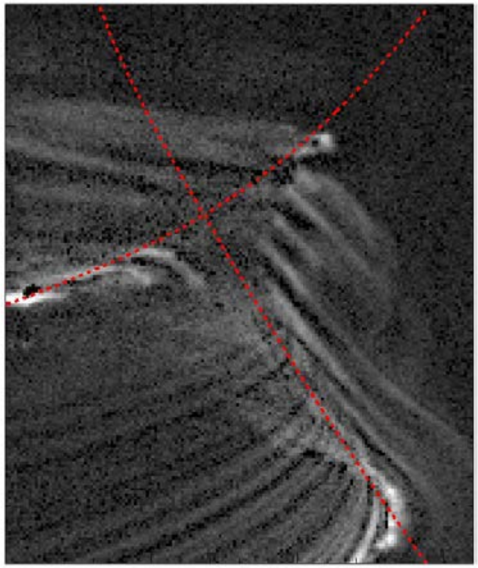
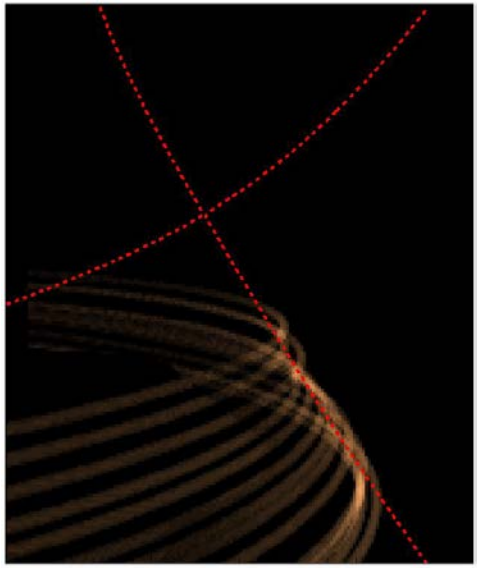
  - Localised near the separatrix: high frequency fluctuations; small cross-field extent (~1cm)





JR Harrison et al, PSI, 2014

Filaments in the SOL

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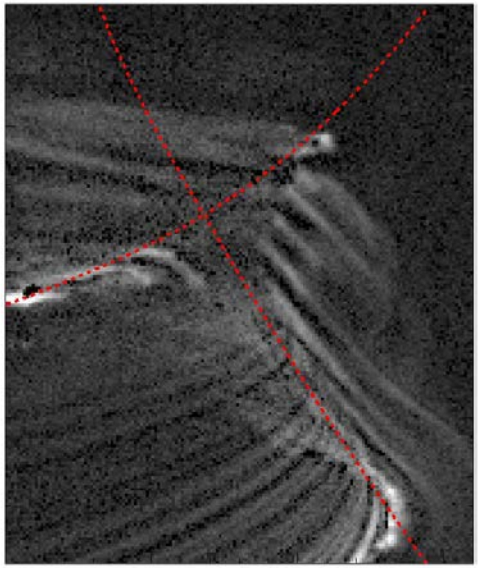
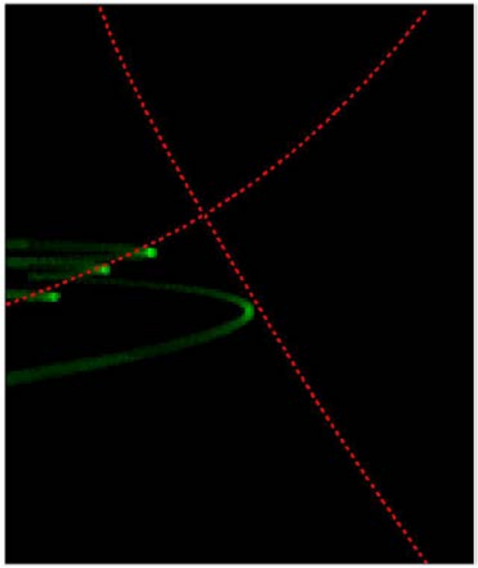
  - Filaments in the main SOL: shape distorted by magnetic shear near the X-point
  - Localised near the separatrix: high frequency fluctuations; small cross-field extent (~1cm)
  - Filaments in the PFR: generated in the bad curvature region of the inner divertor leg





JR Harrison et al, PSI, 2014

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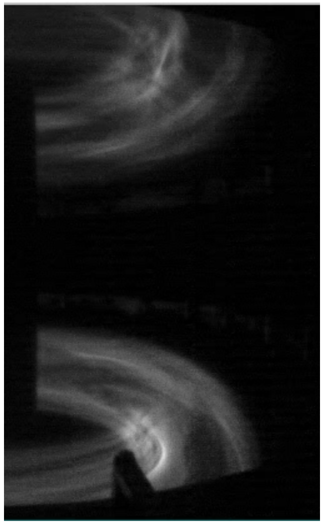
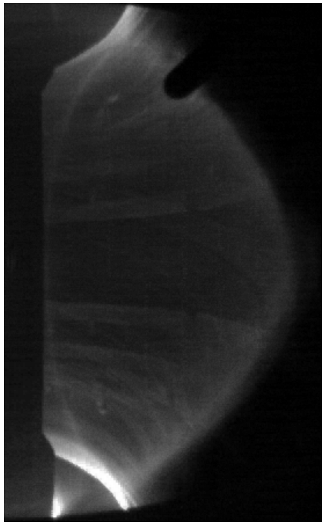
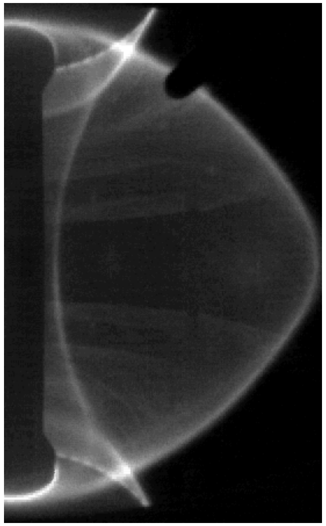
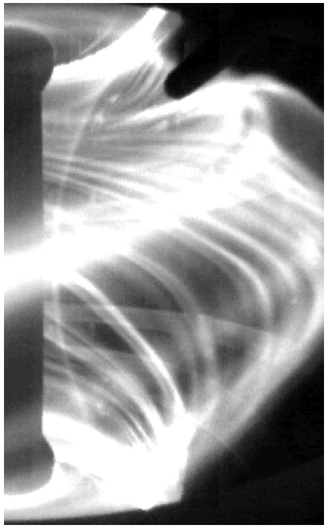

Start-Up

MAST-U Scenario Development

Ion scale Turbulence

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Pedestal

Energetic Particle Losses

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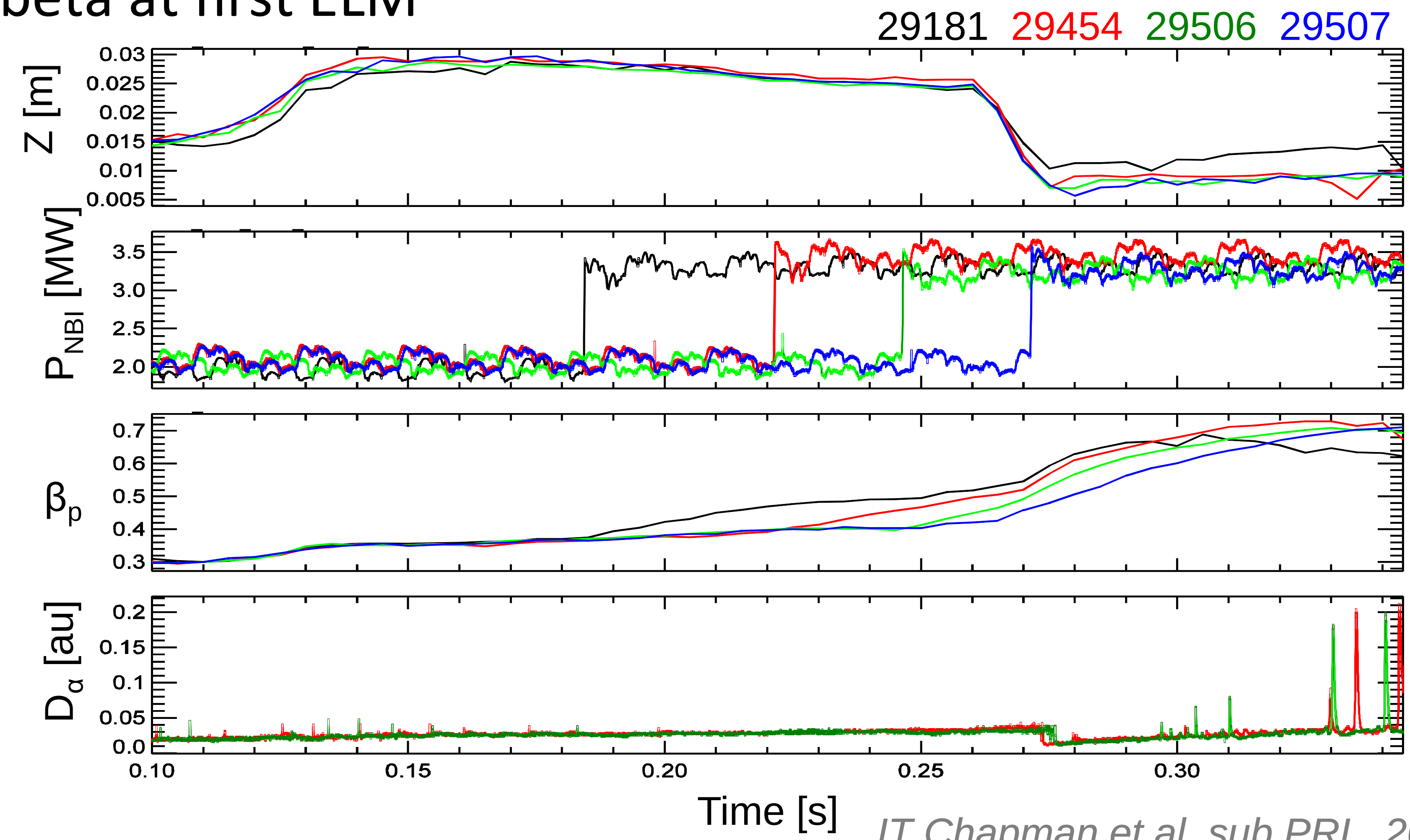
Pellet Fuelling & ELMs

Testing global β effect on pedestal

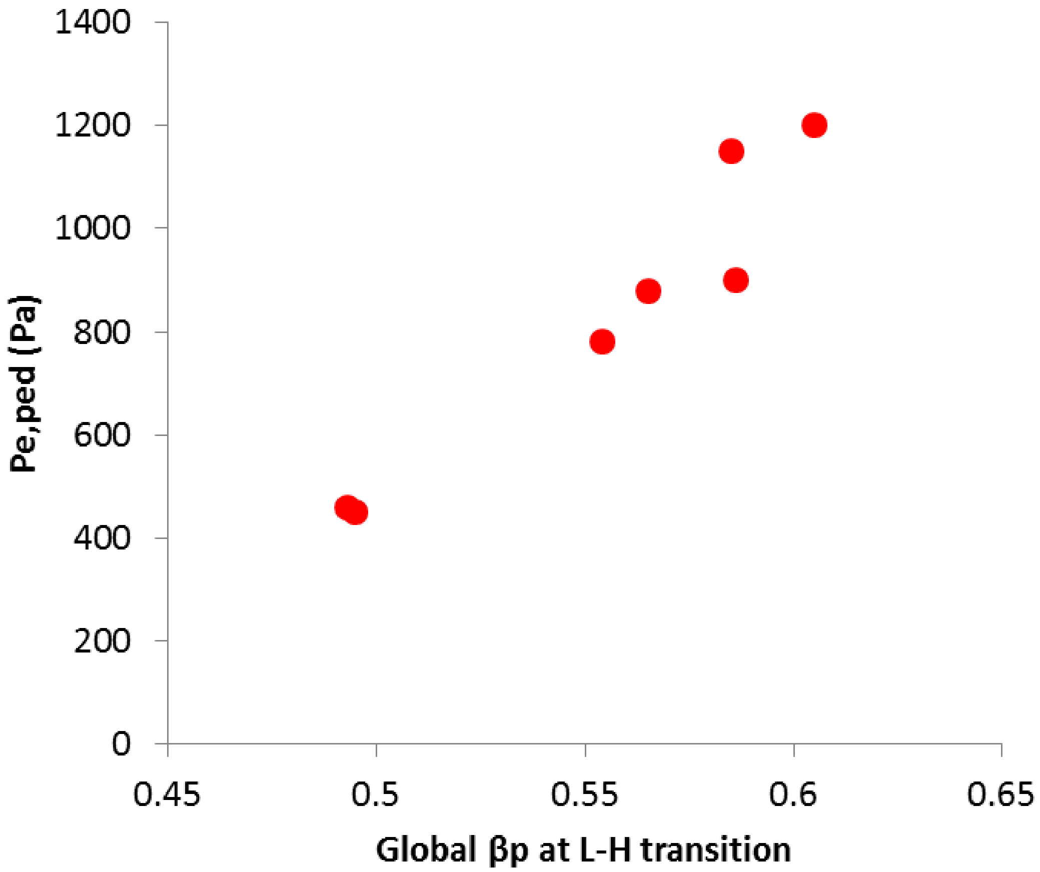
- MAST H-mode access sensitivity allows wide variation in beta at first ELM



IT Chapman et al, sub PRL, 2014

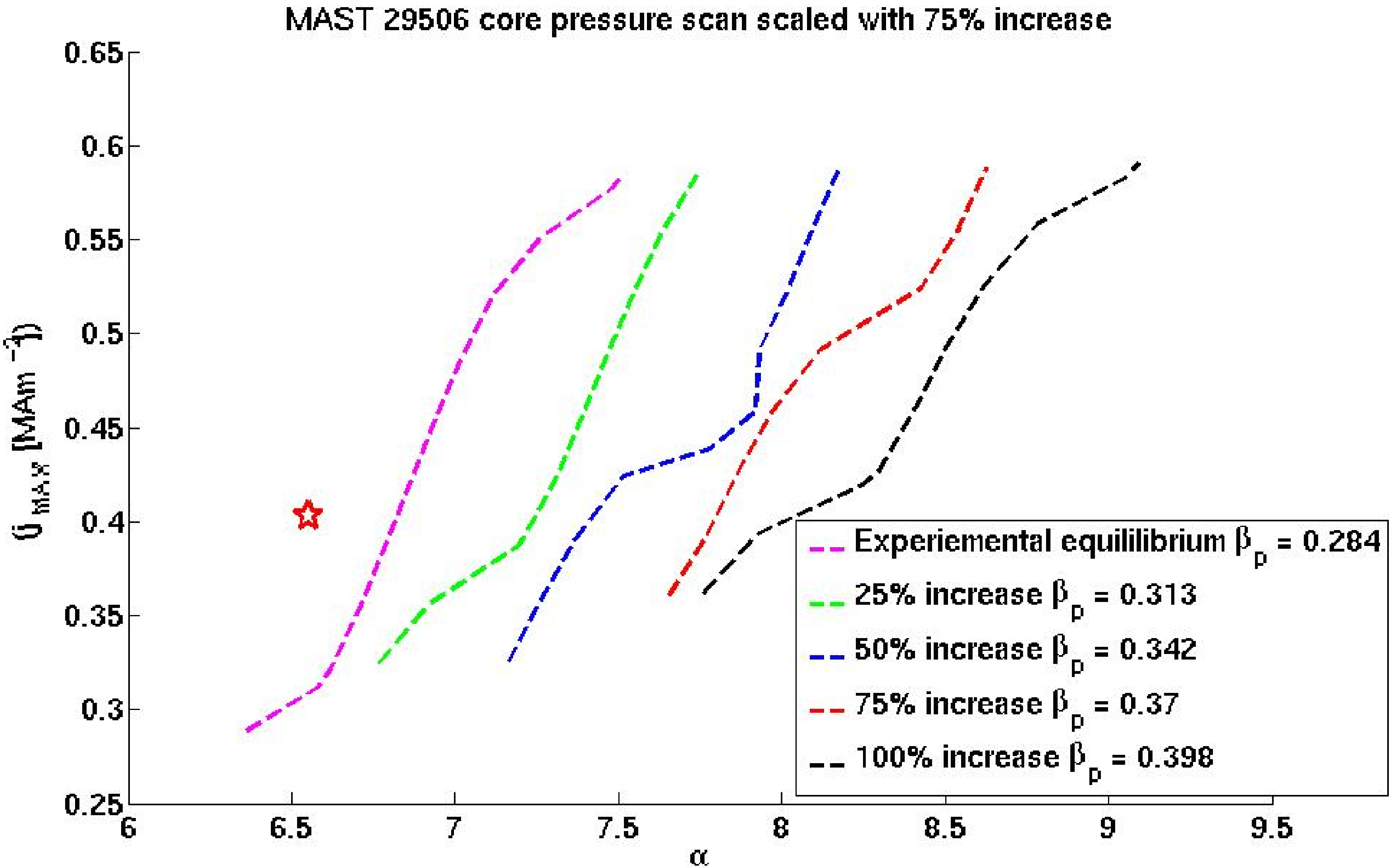
Higher core beta means higher pedestal

- Counter-intuitively, higher beta at L-H means higher pedestal height (as predicted by ELITE modelling)



IT Chapman et al, sub PRL, 2014

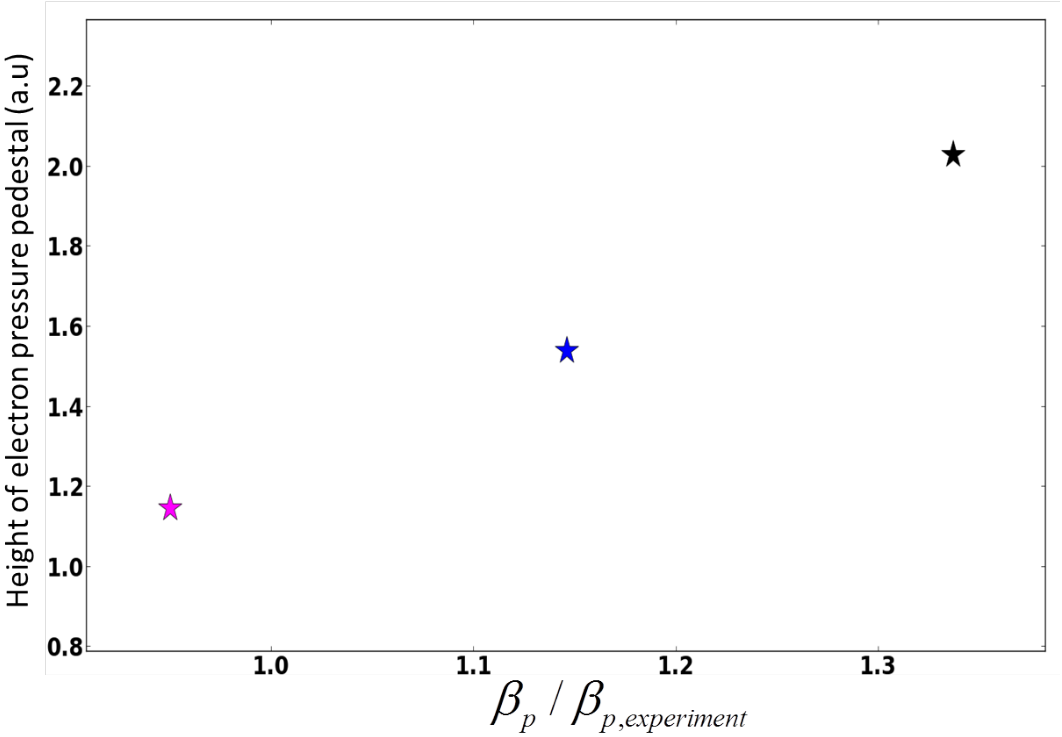
Modelling shows stabilisation from core beta



IT Chapman et al, sub PRL, 2014

Effect of core beta & ion dilution on pedestal

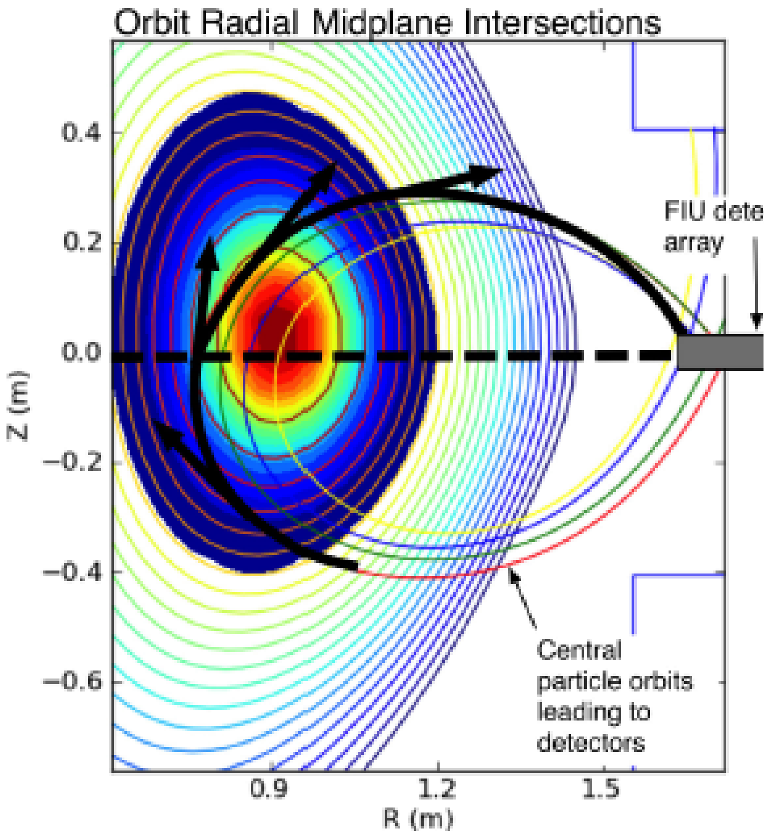
- As ELM period increases with beta, also see more C in pedestal, causing ion dilution to force up T_e
- By coupling ion dilution from C-influx with increase in core beta, the increase in T_e^{crit} can be replicated

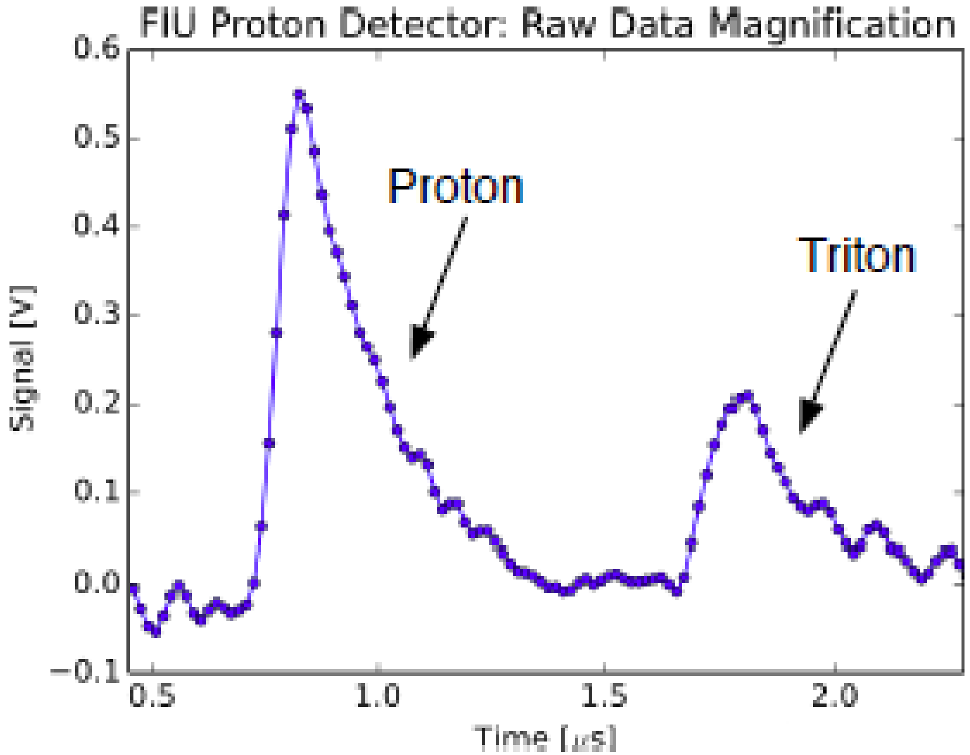


IT Chapman et al, sub PRL, 2014

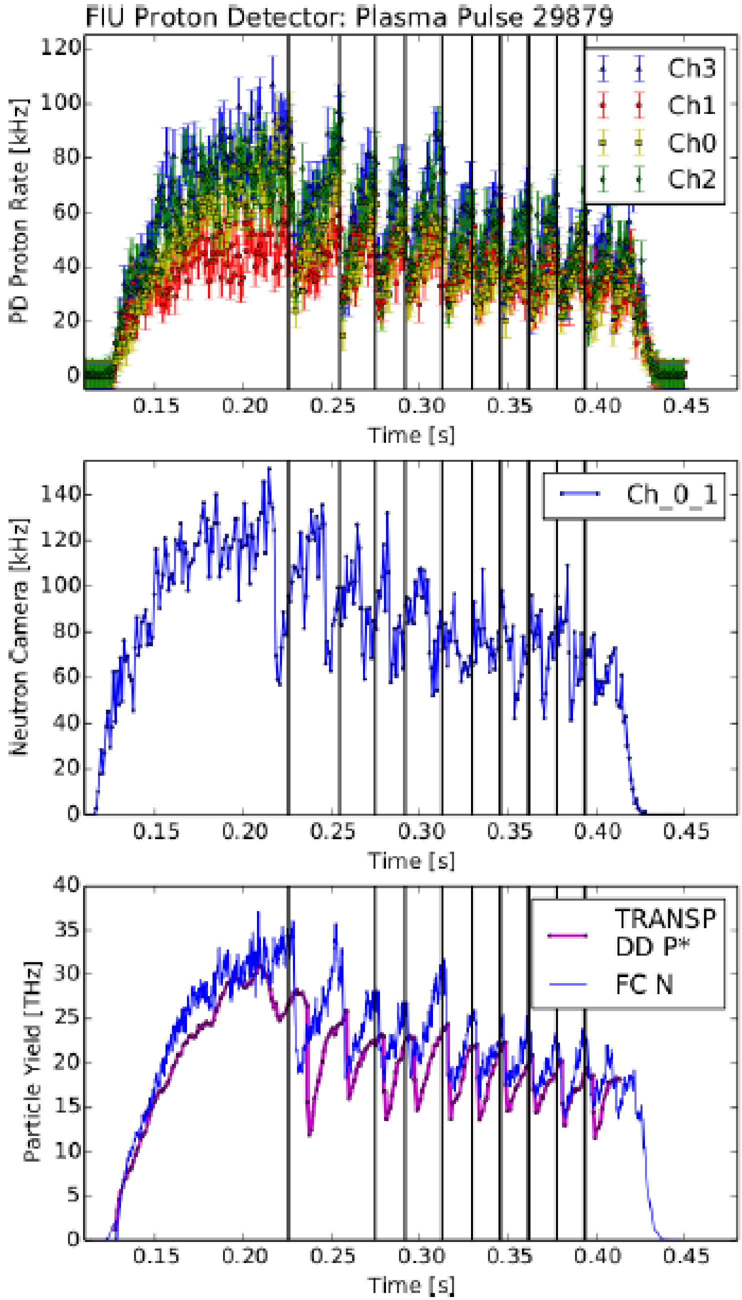
Fusion proton/triton measurements

- Four channels detect particles at different angles, corresponding to birth positions in midplane; moved radially between shots
- Raw data consist of ~100ns pulses produced by individual 3.0 MeV protons & 1.0 MeV tritons





RV Perez et al, HTPD, 2014



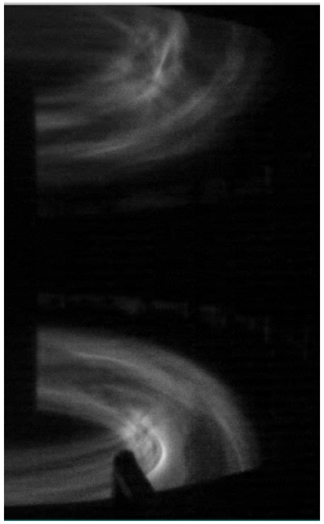
Fusion proton/triton measurements

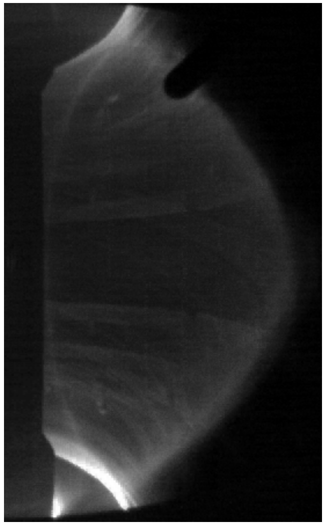
- First DD fusion proton data obtained with Proton detector up to 200kHz with 1ms time resolution
- Effect of sawteeth on fusion rate in sync with neutron camera and fission chamber data

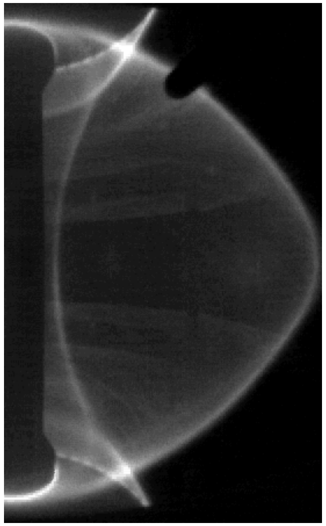
RV Perez et al, HTPD, 2014

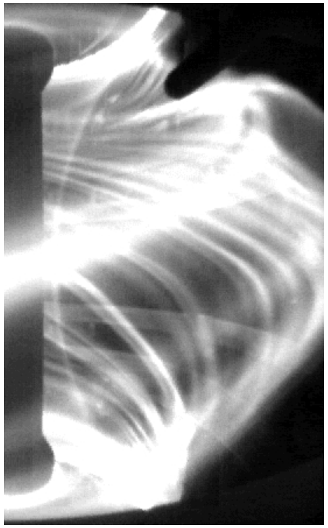
CCFE CULHAM CENTRE FOR FUSION ENERGY

Outline of this talk









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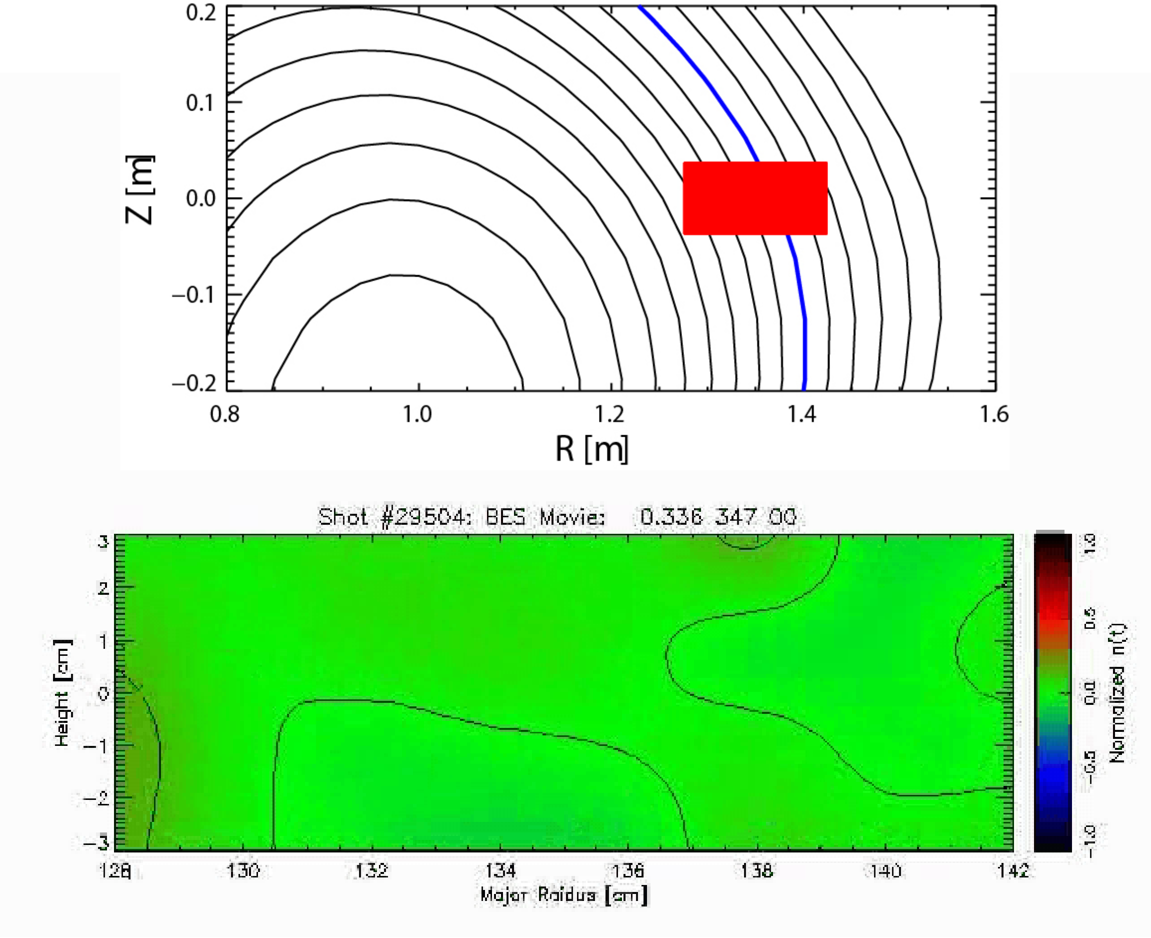
ELM Precursors

- BES imaging observes pre-cursor mode
  - Qualitatively similar to 2d ECE observations in KSTAR/AUG



~ 100 μs before ELM crash a mode grows up in the pedestal top region

- poloidal wavelength of ~ 10cm
- radial size of 2cm
- frequency~20 kHz

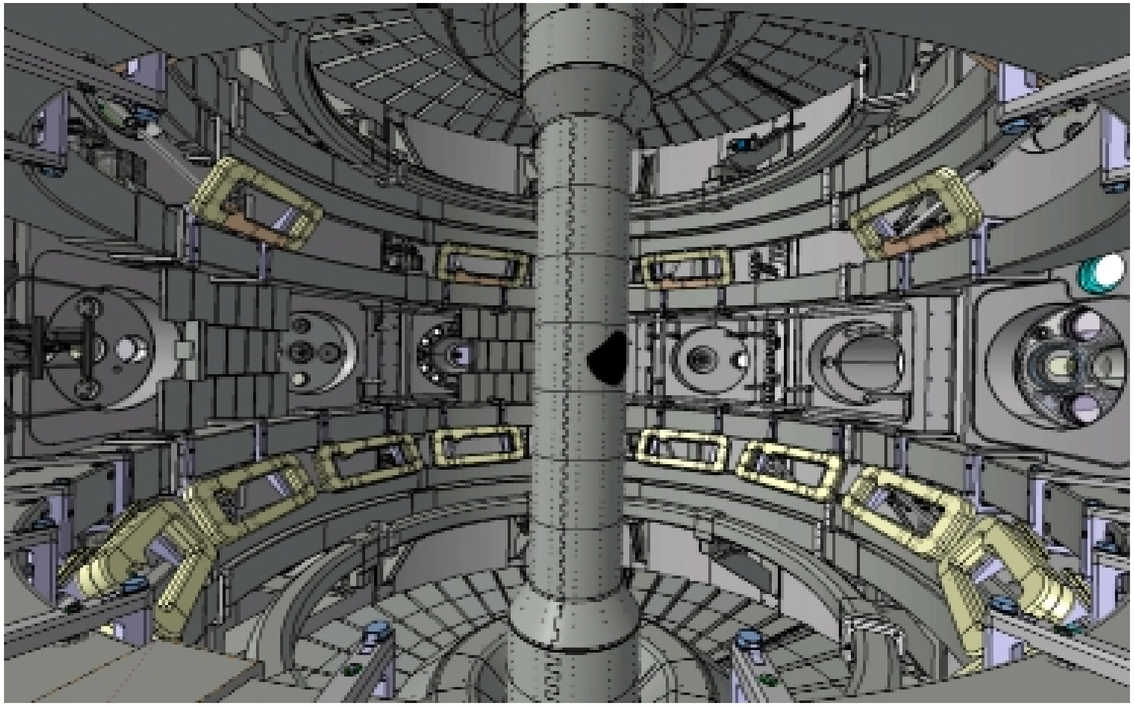
D Dunai et al, EPS, 2014

Dunai et al, in prep, 2013

CCFE CULHAM CENTRE FOR FUSION ENERGY

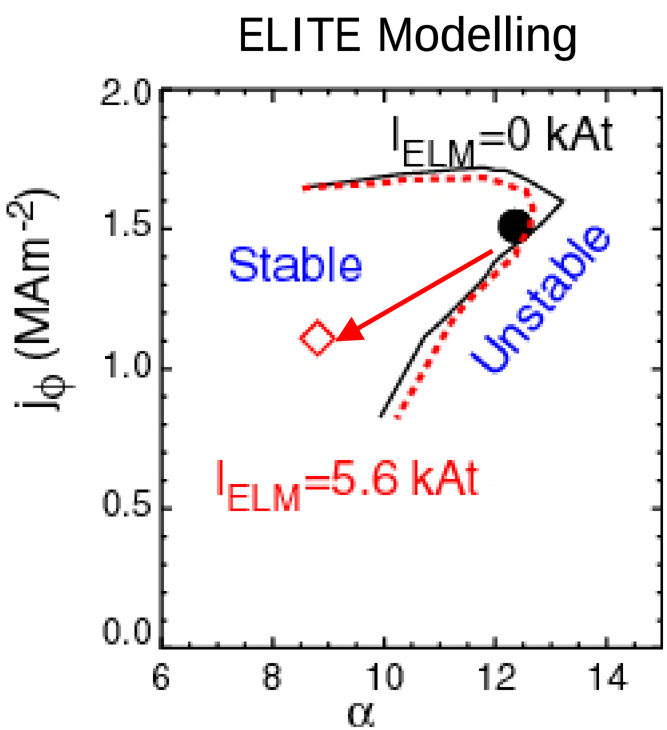
Controlling ELMs with RMPs

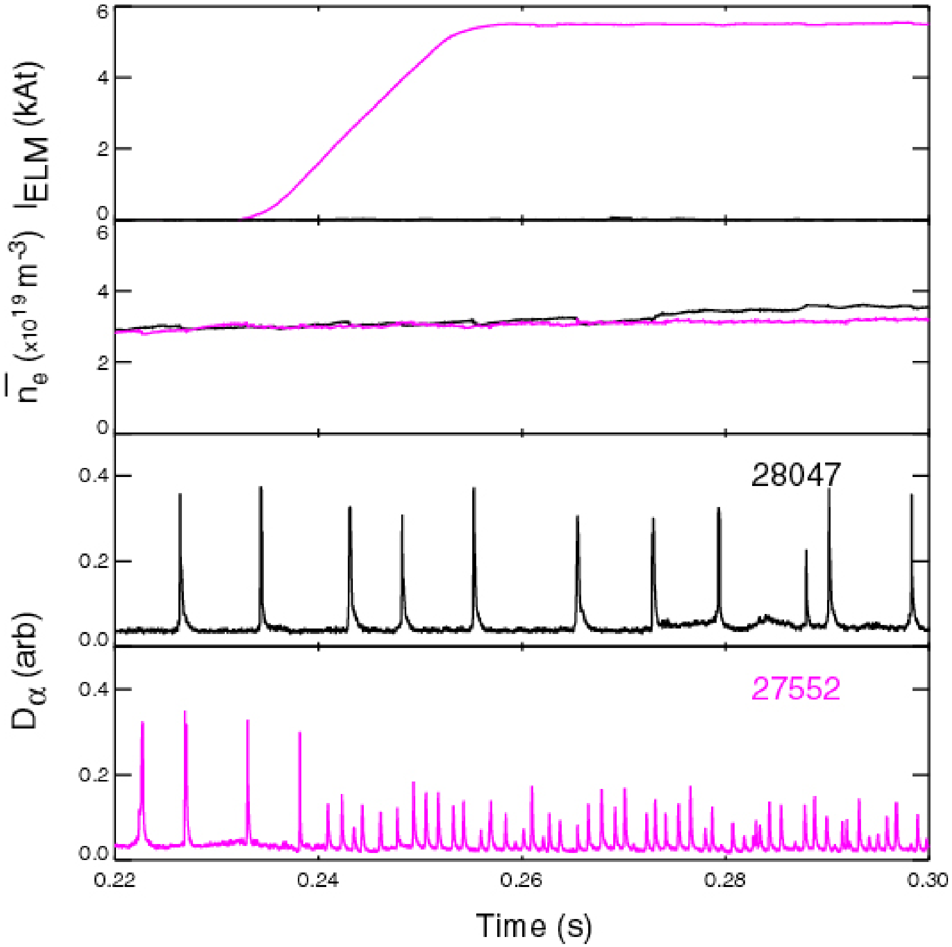
- MAST is uniquely placed to investigate RMP configurations with n=2,3,4,6 to provide an empirical assessment of merits of different configurations



Resolving the RMP dichotomy

- RMPs reduce ∇P → More stable → Suppress ELMs
- ...but why can they increase ELM frequency?

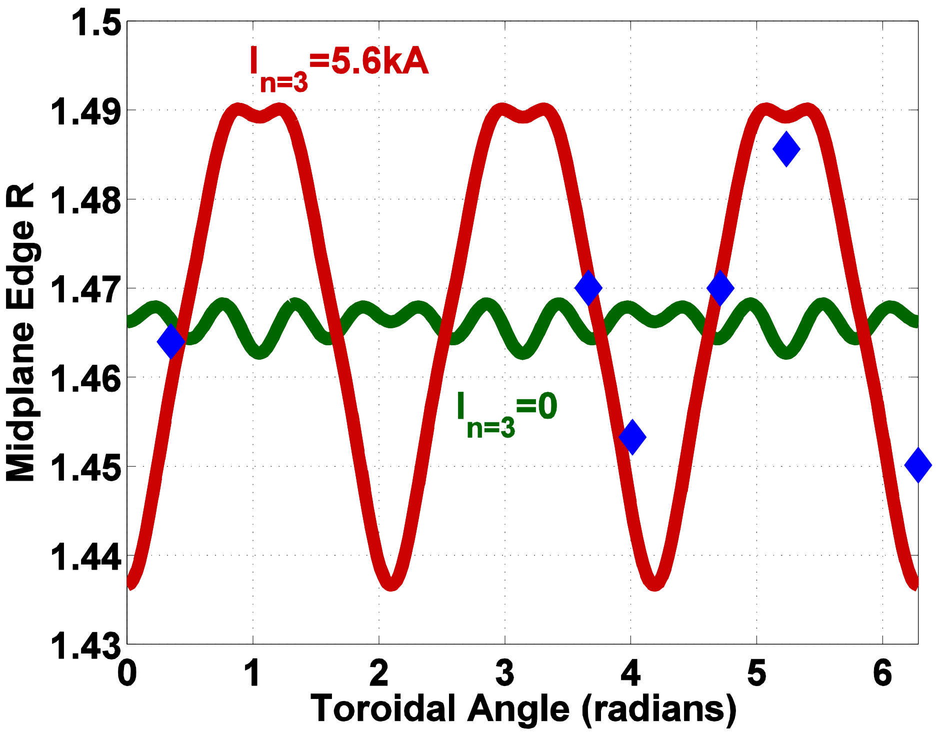


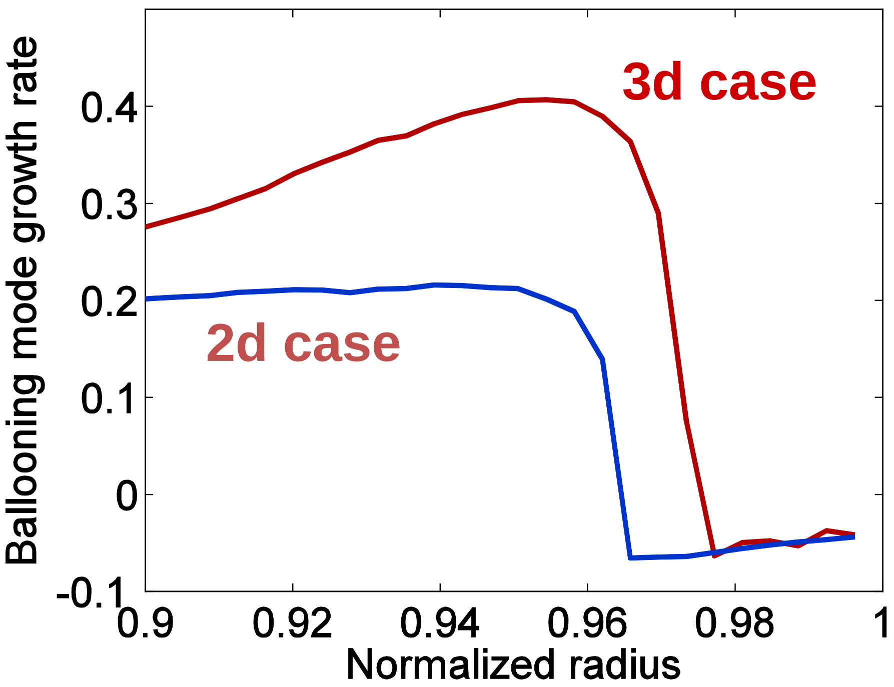


A Kirk et al, PPCF, 2013

Modelling with stellarator codes

- ±2cm displacement comparable to experiment
- Change in stability of plasma edge

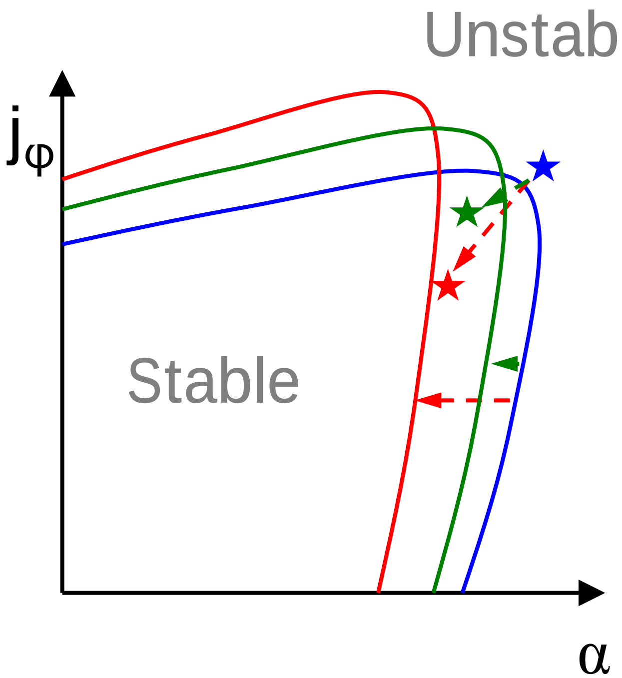


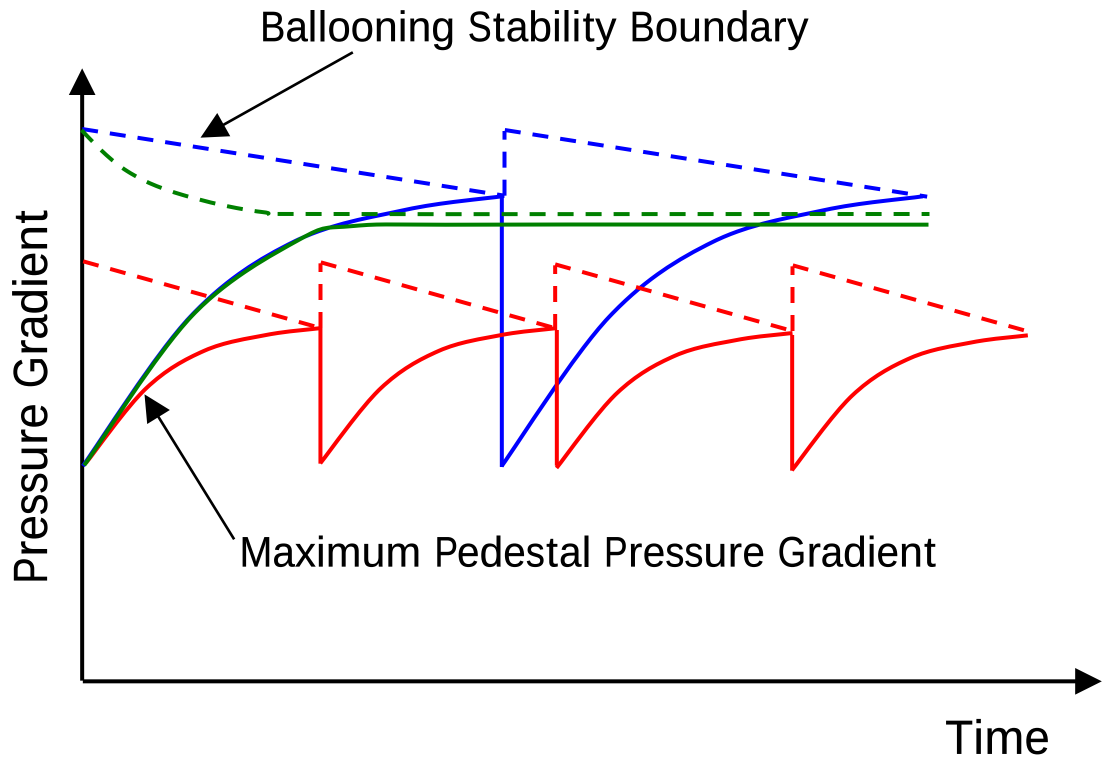


IT Chapman et al, Nucl Fusion, 2014

CJ Ham, sub PPCF, 2014

A picture for ELM control by RMPs



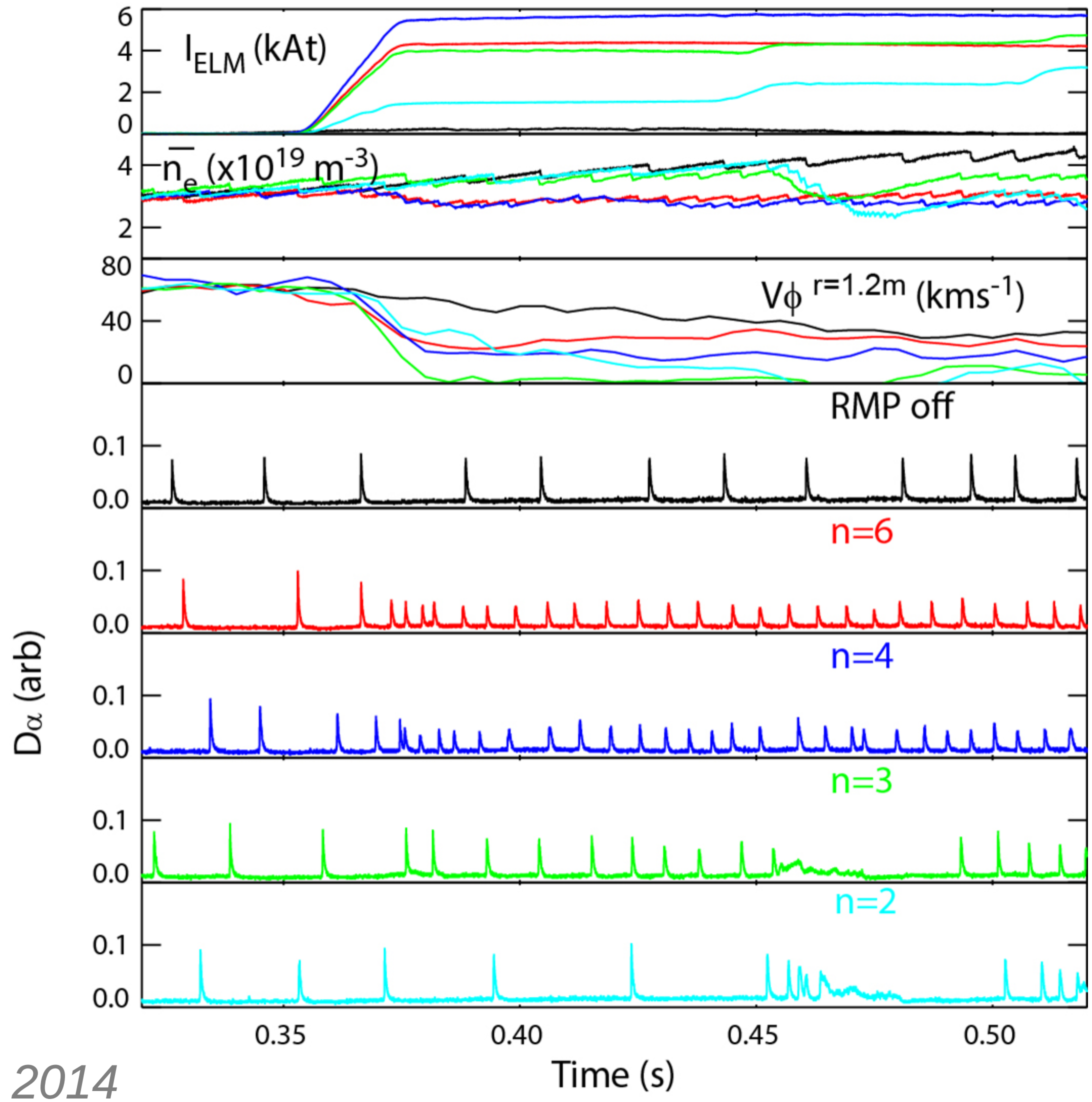


- Type-I ELMs: $\uparrow\Delta_{ped}$ → $\downarrow\alpha_{crit}$ → P-B triggers ELM
- ELM mitigation: $\downarrow\alpha_{crit}$ meaning $\nabla P = \alpha_{crit}$ sooner → $\uparrow f_{ELM}$
- ELM suppression: Pedestal width saturates, ∇P kept $< \alpha_{crit}$

IT Chapman et al, Phys Plasmas, 2013

Using RMPs with different mode number

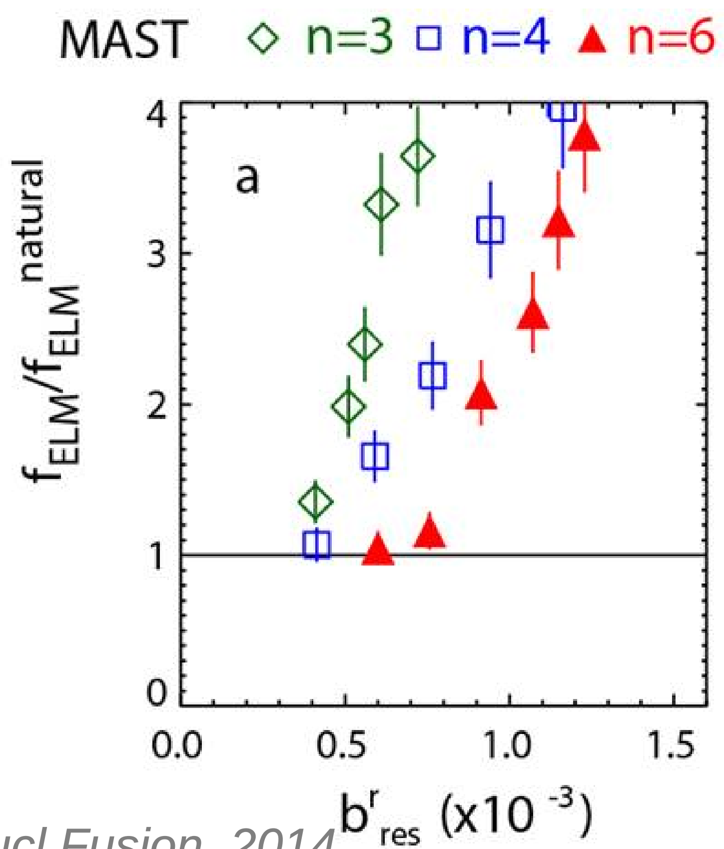
- All RMPs can mitigate ELMs
- Very small window for n=2 between ELM mitigation and H-L transition



IT Chapman et al, sub Nucl Fusion, 2014

Using RMPs with different mode number

- Linear increase in ELM frequency with RMP field
- Threshold to mitigate ELMs is lower for higher n_{RMP}

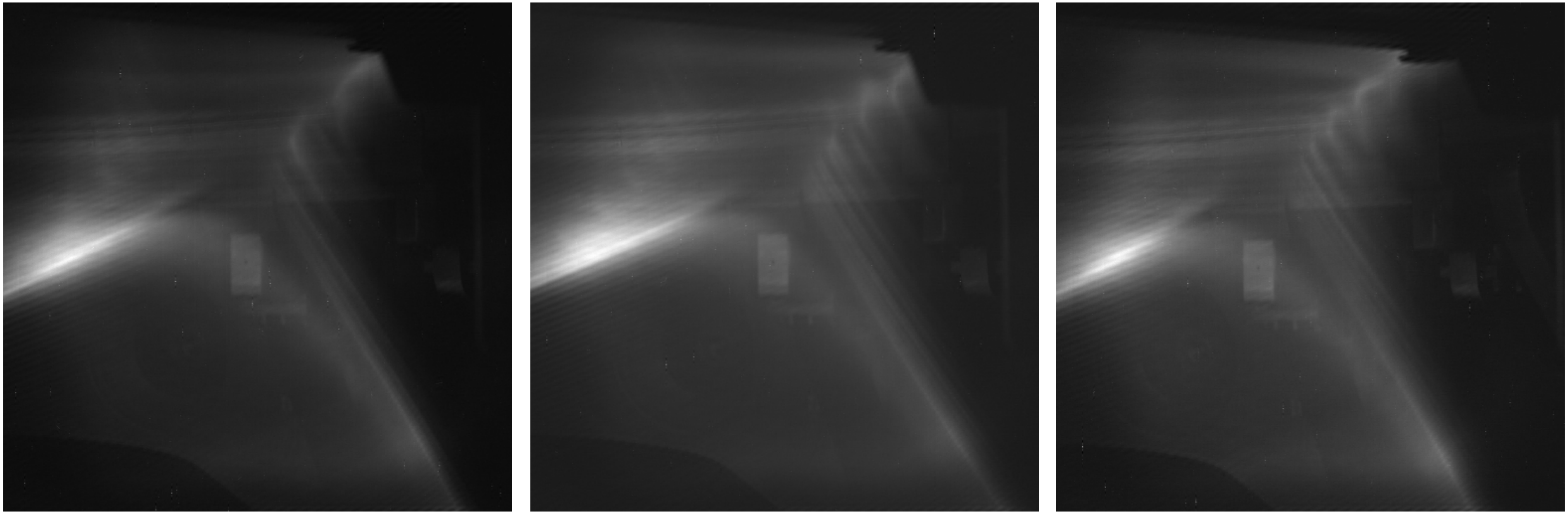


IT Chapman et al, sub Nucl Fusion, 2014

RMP lobe structures with different n_{RMP}

- Lobe structures are more radially extended and more poloidally localised for higher n_{RMP}

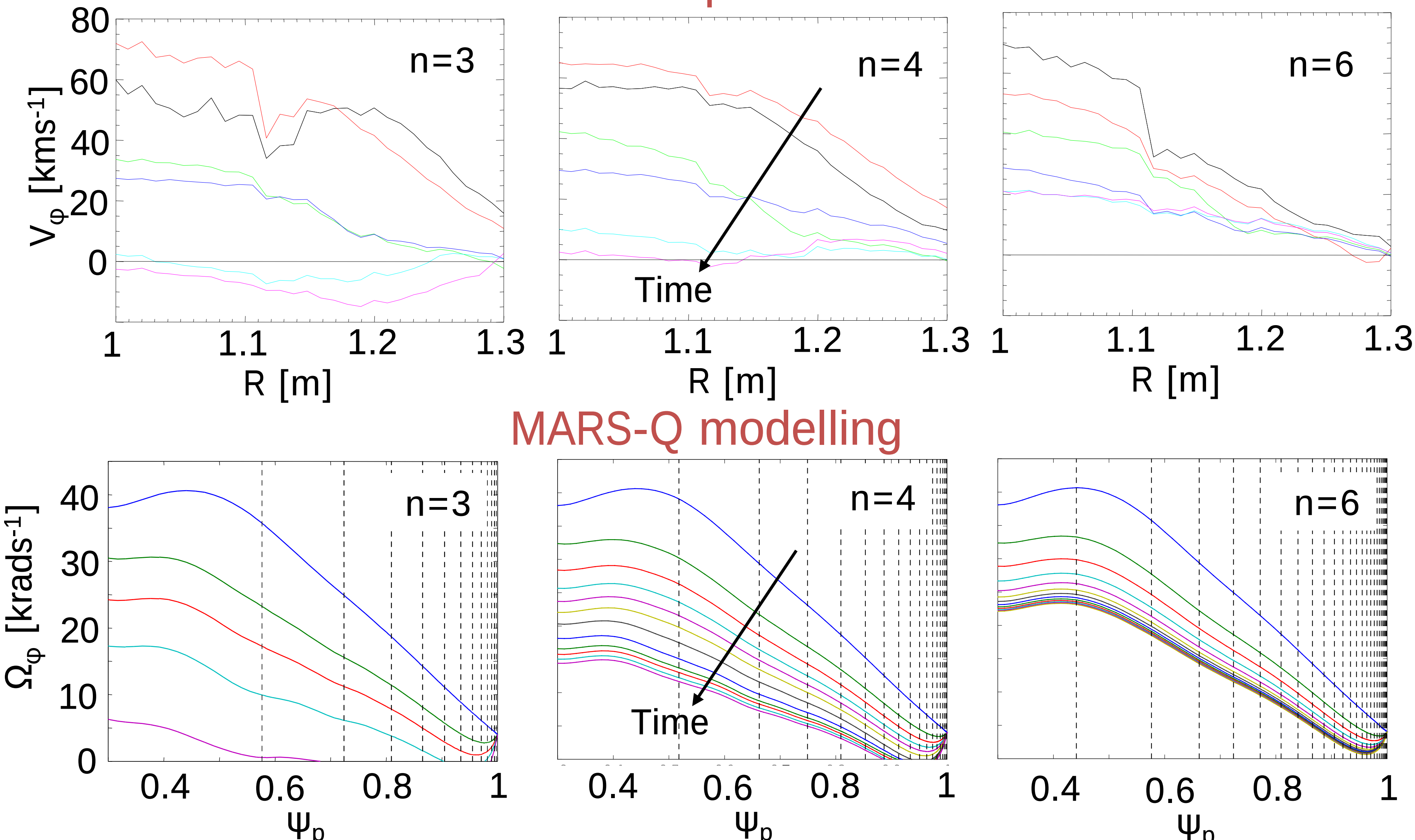
n=3 n=4 n=6



IT Chapman et al, sub Nucl Fusion, 2014

Modelling plasma braking

MAST experiment



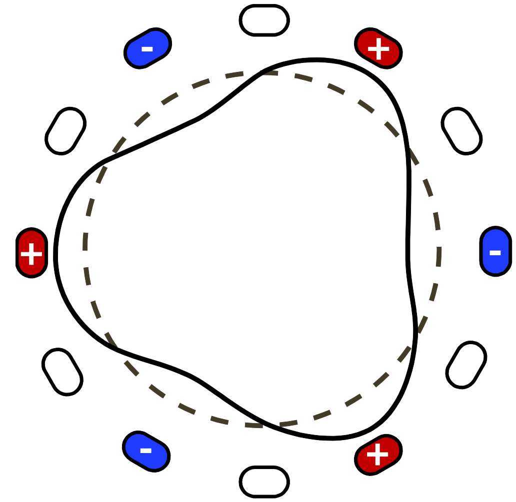
Overview of merits of different n_{RMP} in MAST

Criterion	$n_{RMP} = 2$	$n_{RMP} = 3$	$n_{RMP} = 4$	$n_{RMP} = 6$
Locked mode threshold	Lowest			Highest
Reduction in q_{peak}	Reduction scales with increase in f_{ELM} in all cases			
Critical b^r_{res} to mitigate ELMs	No data	Lowest		Highest
Power for H-mode	Highest		Lowest	
Fast ion loss	No data	Most (plasma)	Least	Most (vacuum)
Midplane displacement	No data	Least		Most
Lobe structures	No data	Shortest		Longest
Pedestal structure	Height reduces and width increases in all cases			
Infinite-n stability	Region and growth rate scales with b^r_{res} in all cases			
Rotation braking	Strongest			Weakest

IT Chapman et al, sub Nucl Fusion, 2014

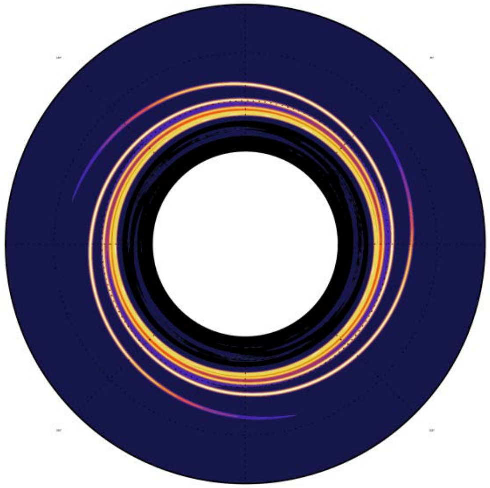
Rotating RMPs

- **Application of a non-axisymmetric RMP generates:**
  - Strike point splitting which varies as a function of toroidal angle
  - ELM mitigation: increased ELM frequency and decreased ELM size



- **Splitting generates non-uniform heat fluxes to the target**
  - Enhanced erosion which presents an issue for power handling

Outer divertor heat flux



- **Rotate the RMP toroidally to even out the wear on the divertor**

AJ Thornton et al, PSI, 2014

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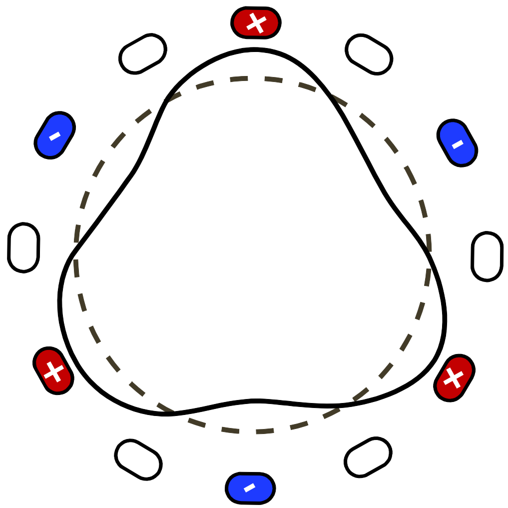

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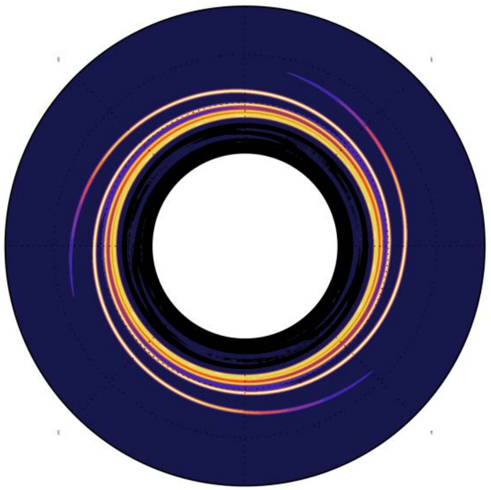
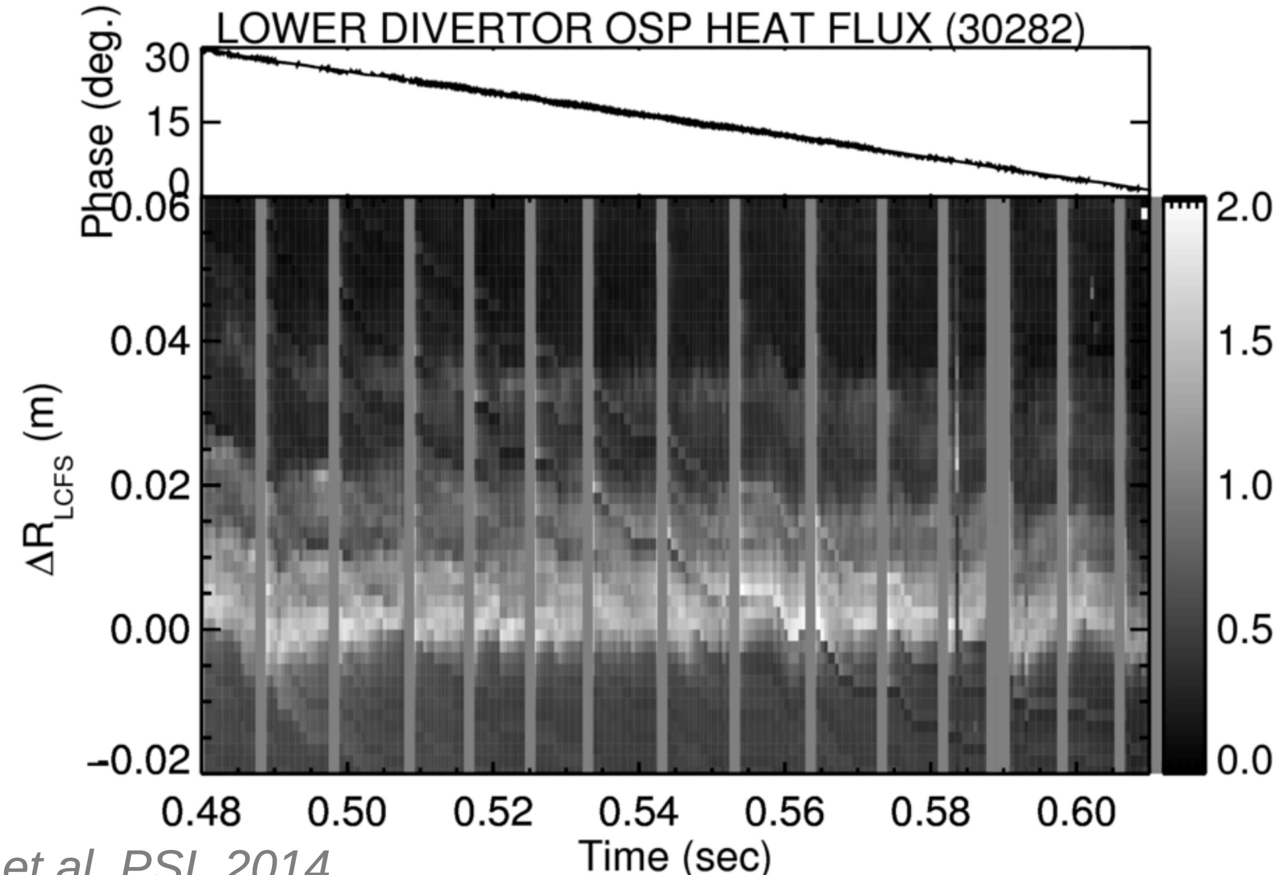


- **Rotate the RMP toroidally to even out the wear on the divertor**

AJ Thornton et al, PSI, 2014

Strike point splitting

- **Footprint narrows during rotation**
  - Strike point sweeping removed by normalising to the peak heat flux
  - Hotspots appear as diagonal lines in the normalised data

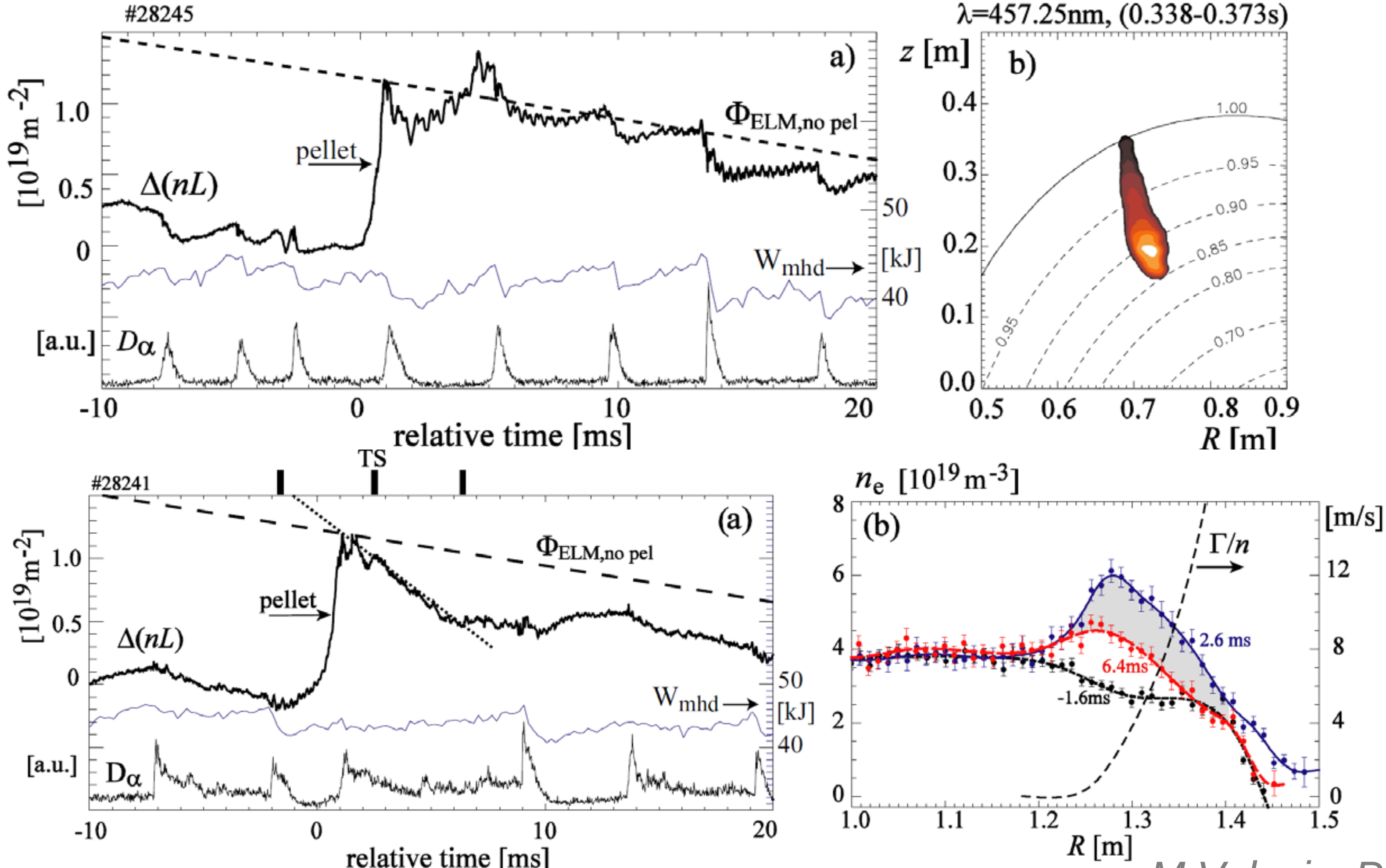


AJ Thornton et al, PSI, 2014

Pellet fuelling with RMPs: ELM effects

Good case – RMP-mitigated ELMs not changed, fuel retained

Bad case – pellet triggers compound ELM, fuel lost



M Valovic, PPCF, 2013

MAST Upgrade Project

CCFE is the fusion research arm of the **United Kingdom Atomic Energy Authority.**
This work was funded by the RCUK Energy Programme [grant number EP/I501045] .

Staged MAST Upgrade

Increased TF
Improved confinement

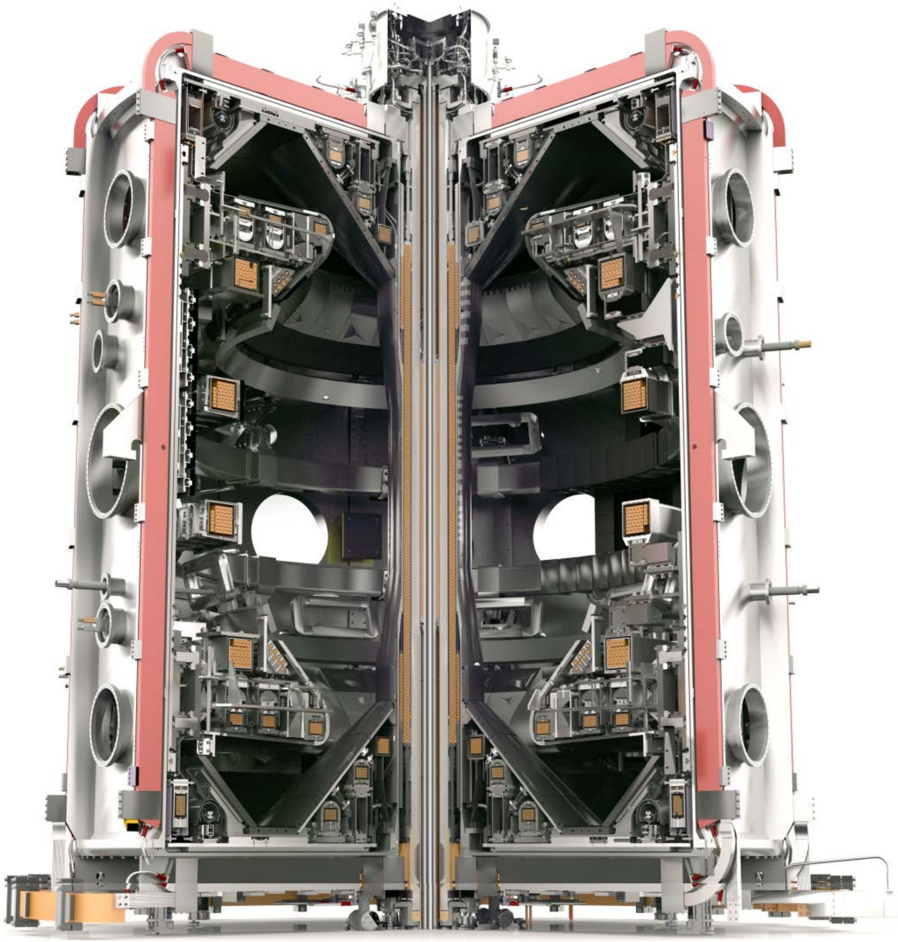
New Solenoid
Greater I_p, pulse duration

19 New PF Coils
Improved shaping

Super-X Divertor
Improved power handling

Off-Axis NBI
Improved profile control

MAST-Upgrade after initial construction ("core scope")



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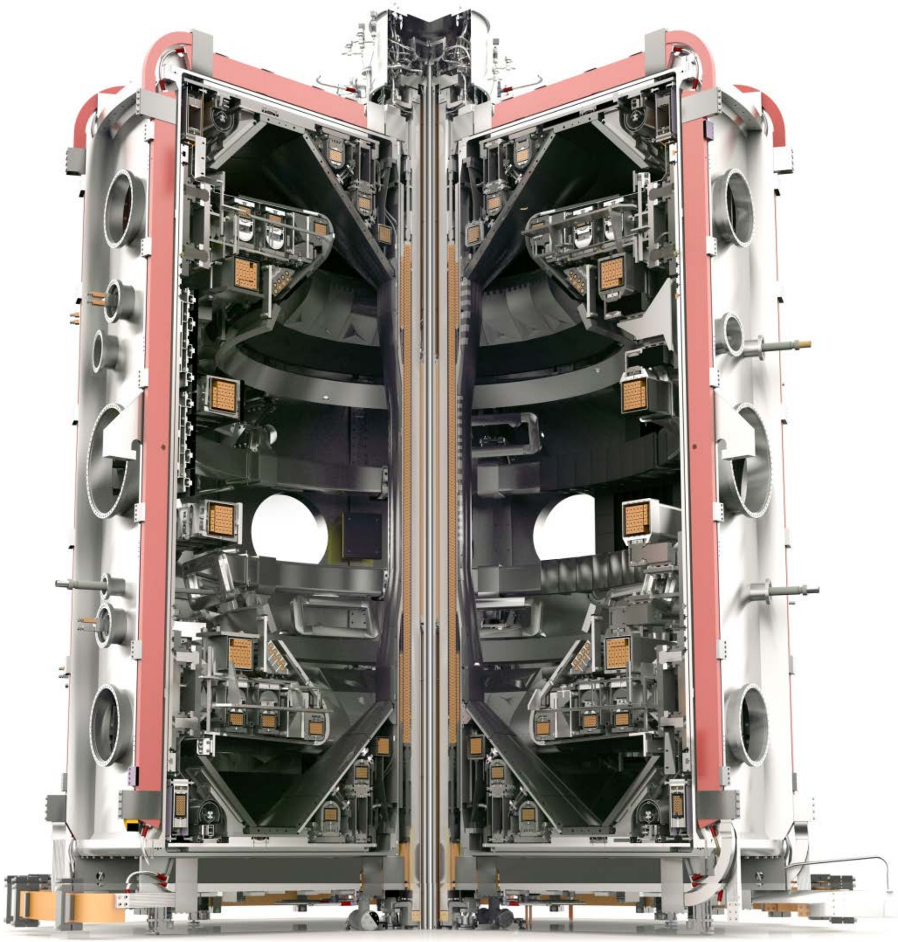
Improved profile control

Cryoplant
Divertor particle control

Double NBI Box
7.5MW in total.
Only one PINI in DBB

MAST-Upgrade after Stage 1



Staged MAST Upgrade

Increased TF

New Solenoid

19 New PF Coils

Super-X Divertor

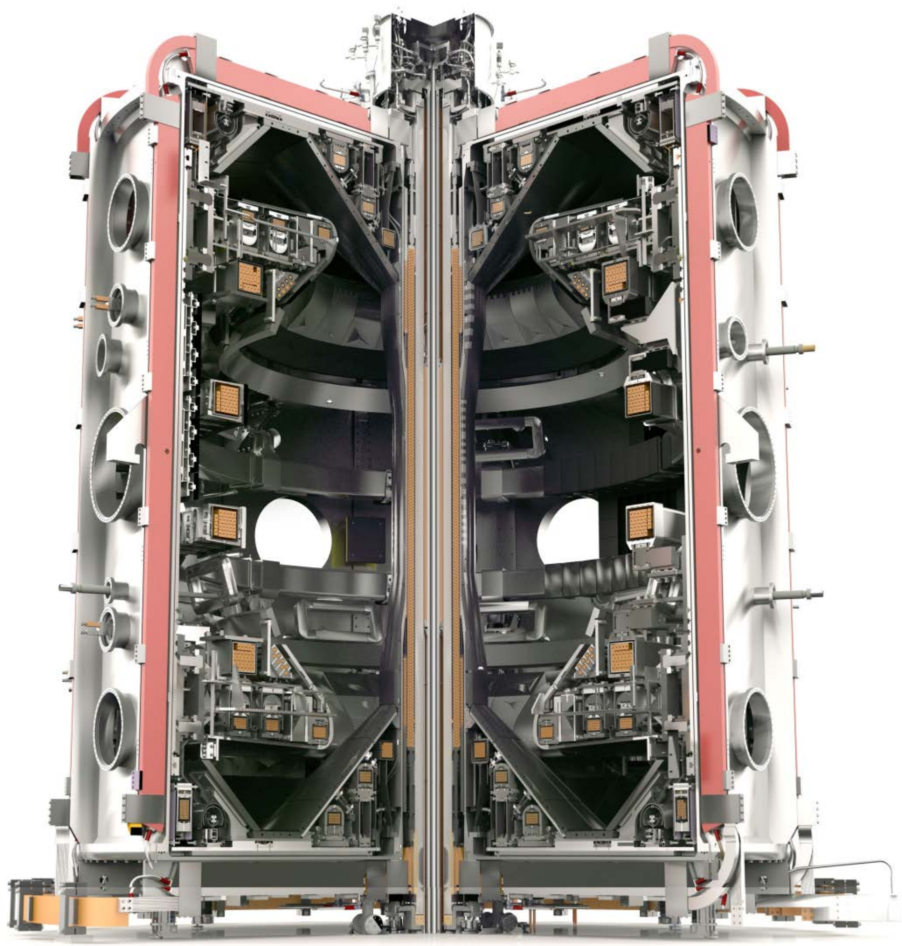
Off-Axis NBI

Cryoplant

Double NBI Box
10MW. 2nd PINI in DBB

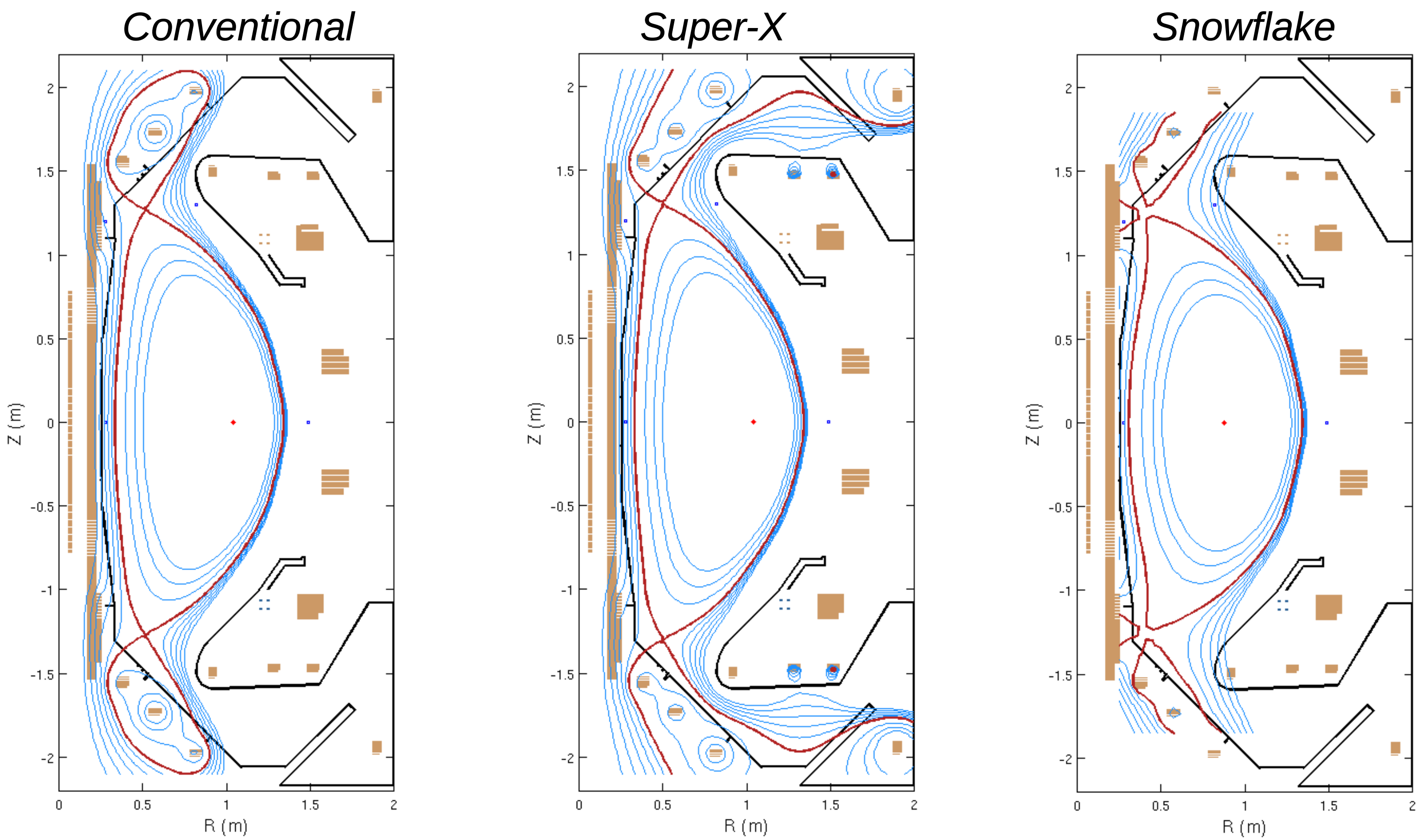
2MW EBW Heating
Solenoid-free startup
Increased auxiliary heating

MAST-Upgrade after Stage 2



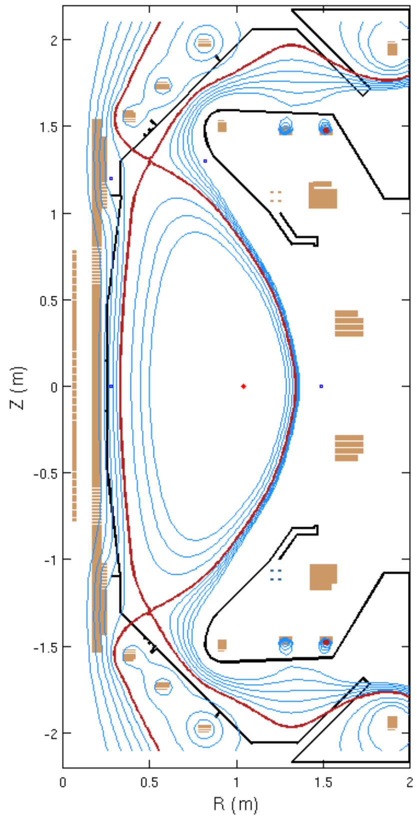
Divertor configurations

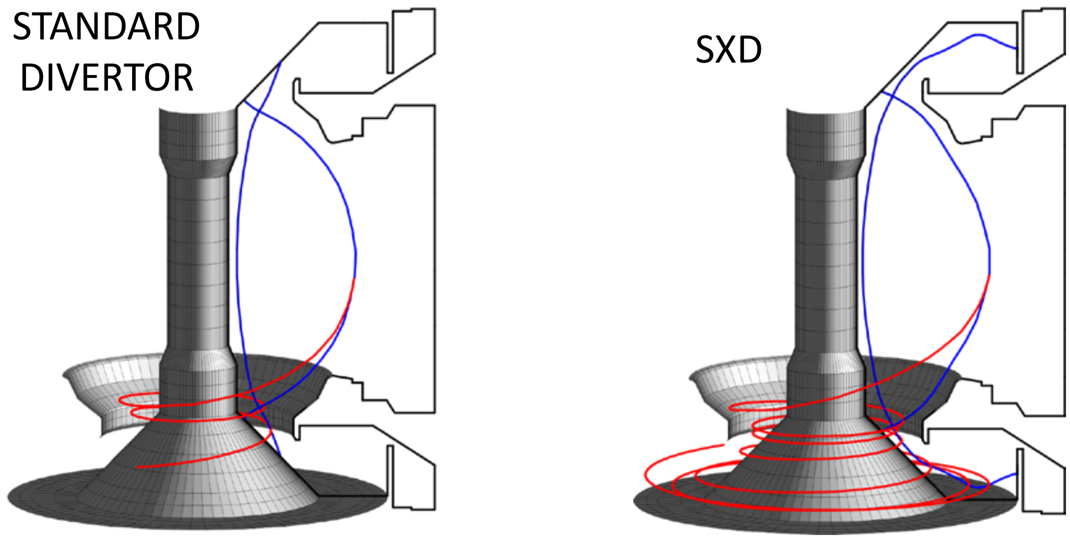
- Flexible poloidal field coil set allows for a wide variety of magnetic geometries in MAST Upgrade



Super-X divertor

- Divertor physics programme will focus on studying the Super-X divertor configuration*
  - larger R_{div} → larger wetted area
  - lower poloidal field in divertor → larger connection length $L_{||}$
  - lower toroidal field in divertor chamber → lower parallel power density $q_{||}$





- MAST Upgrade will be equipped with an extensive range of divertor diagnostics

Valanju et al., Phys. Plasma* ***16* *(2009) 056110*

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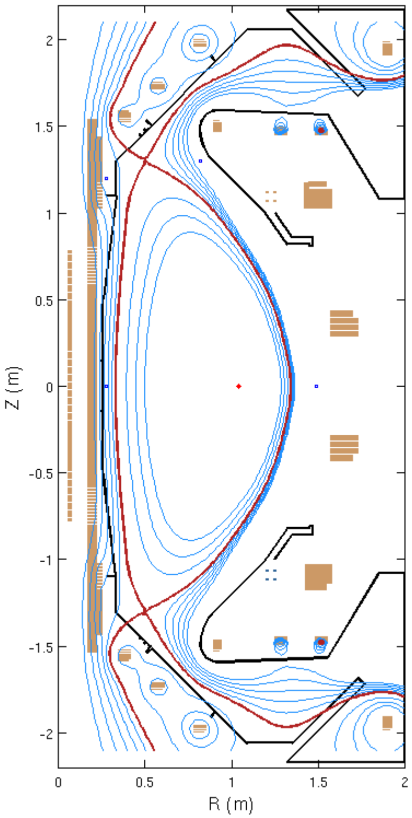
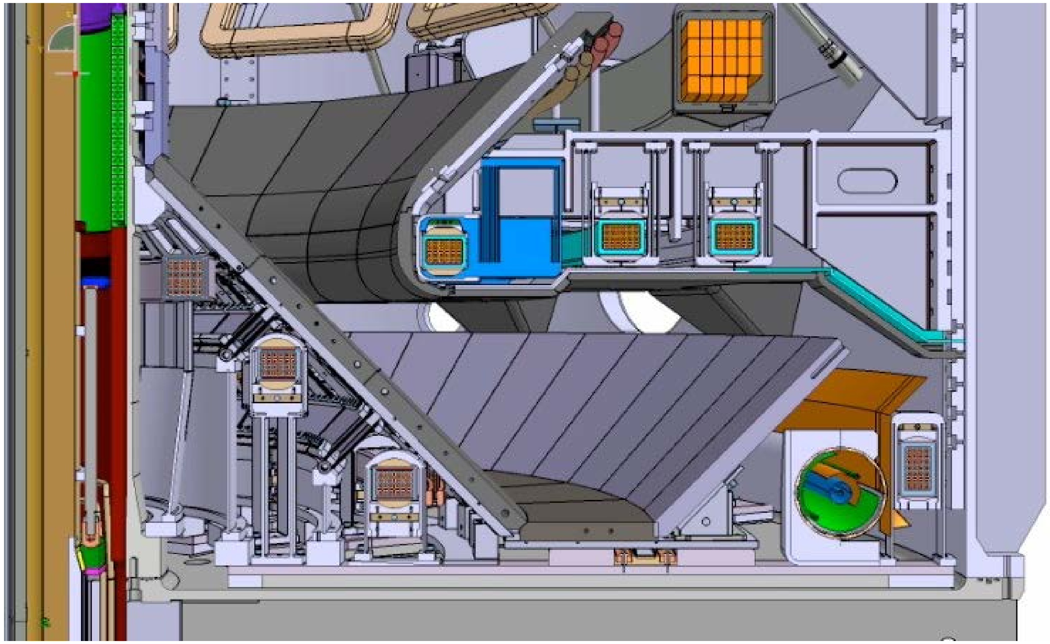
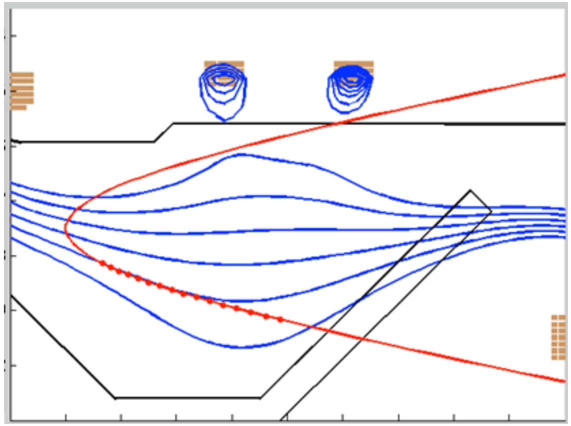




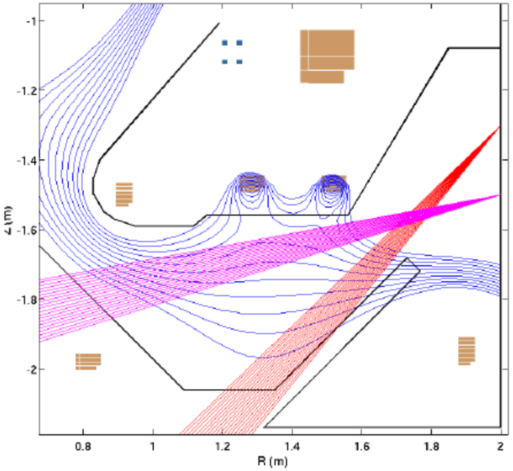
- MAST Upgrade will be equipped with an extensive range of divertor diagnostics

*Valanju et al., Phys. Plasma **16** (2009) 056110*

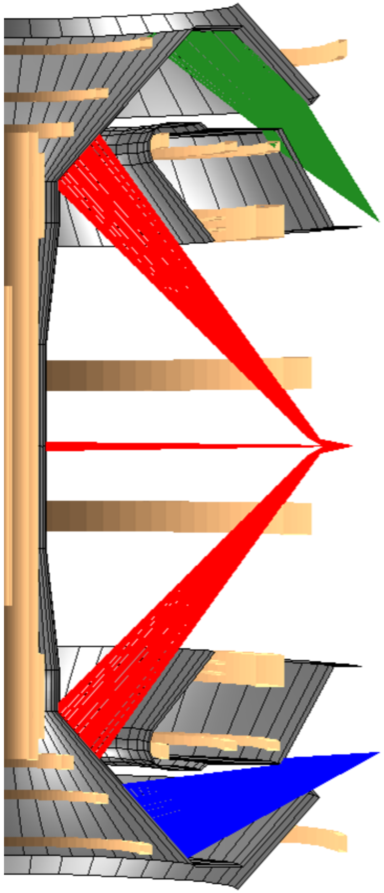
Divertor diagnostics (main systems)



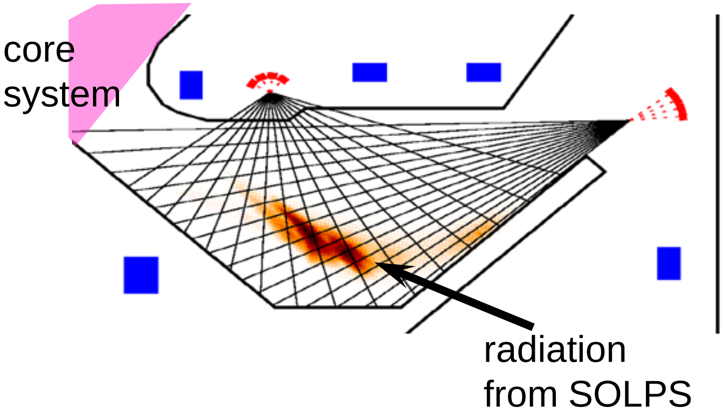
Divertor Thomson scattering



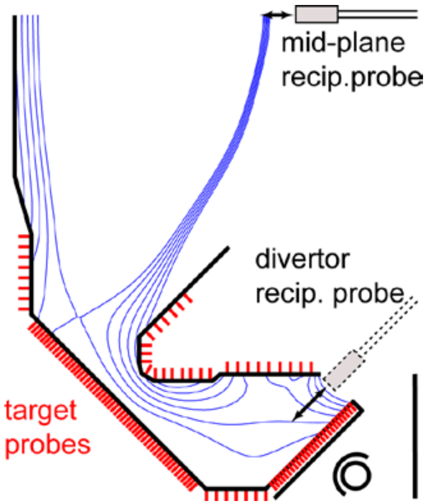
Spectroscopy



Infra red views of PFCs



Bolometer arrays for divertor



Langmuir probes

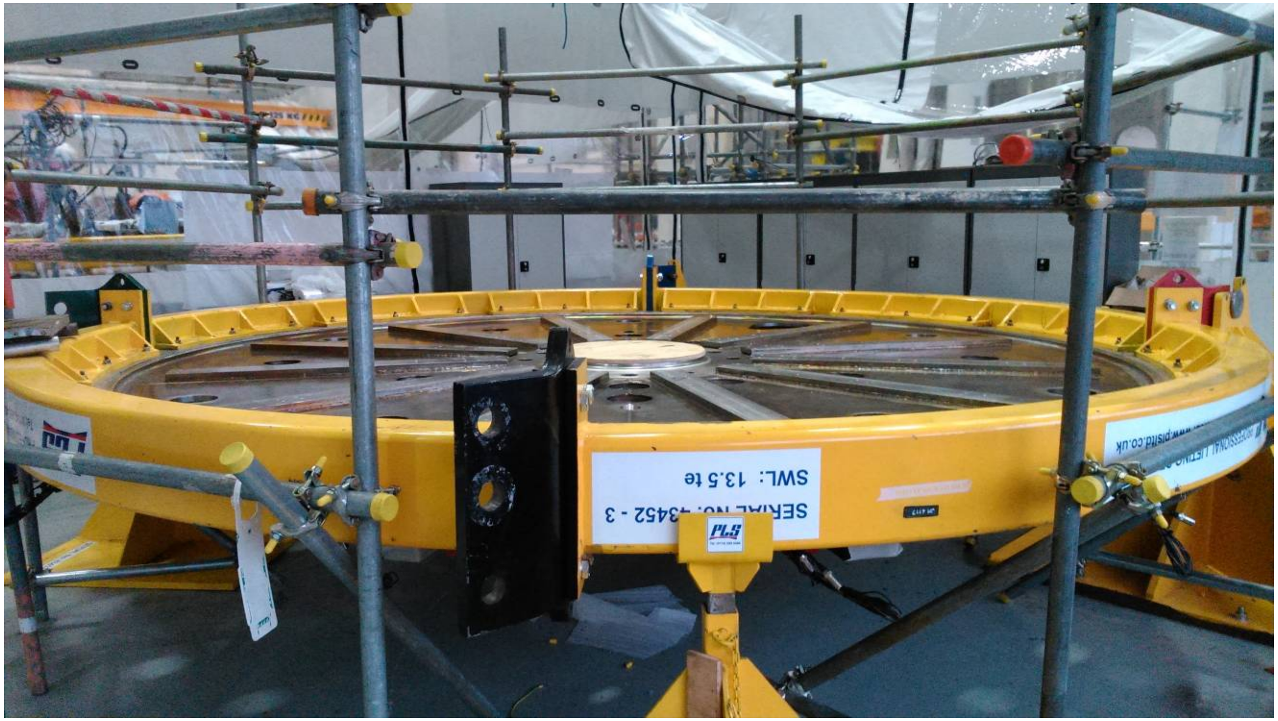
Others, especially

- Coherence imaging (flows)
- Divertor science facility (a bit like DIMES)

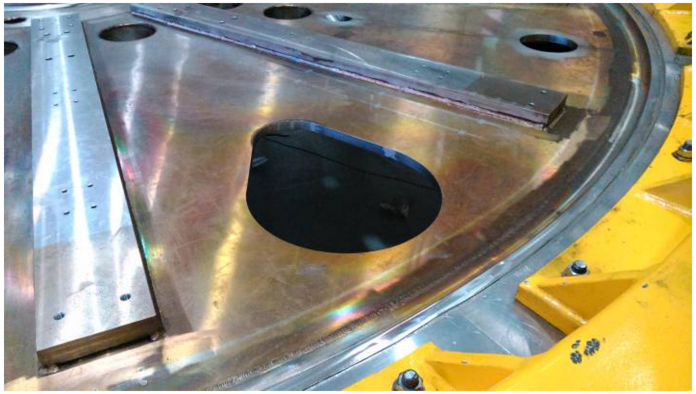
Early research goals (example ideas)

- Exhaust
  - Nature of cross-field transport, effect of connection length
  - Parallel transport and propagation of transients
  - Detachment physics and stability, e.g. throttling effects ($dq_{parallel}/dl_{parallel}<0$), impurity transport
- Pedestal and ELMs
  - 3d fields at low collisionality, compatibility with Super-X
  - Effect of divertor configuration on pedestal formation and structure
- Fast particle physics
  - On and off-axis beams, new scintillator probe
- Core transport
  - Turbulence fundamentals, lower ν^*, perhaps subcritical turbulence and self-regulating high performance regimes
- Actual programme and further enhancements will be developed with collaborators

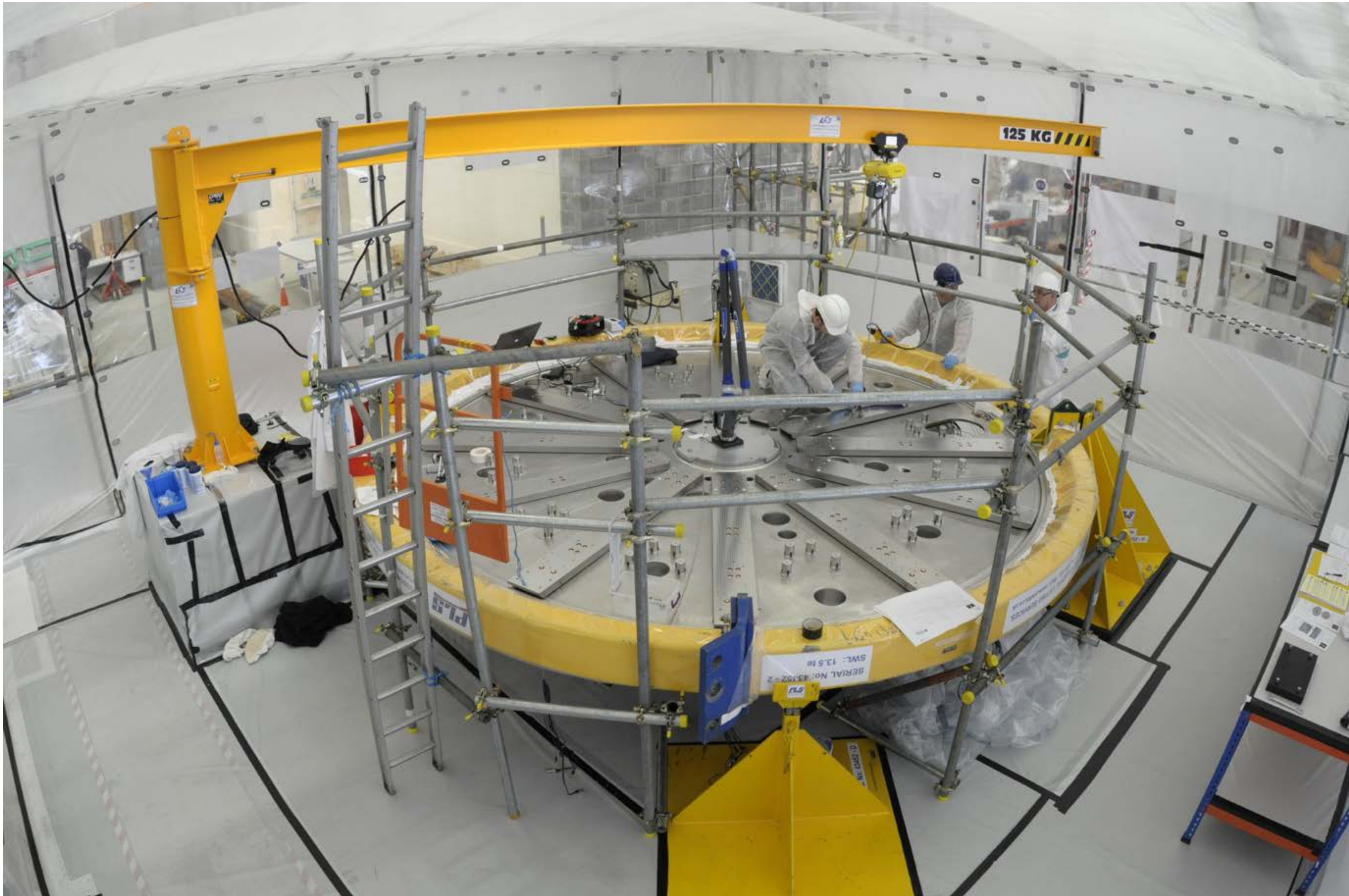
Shutdown progressing well



- Vessel removed from blockhouse. Upper end plate machining completed



End plate machining



Coil manufacture

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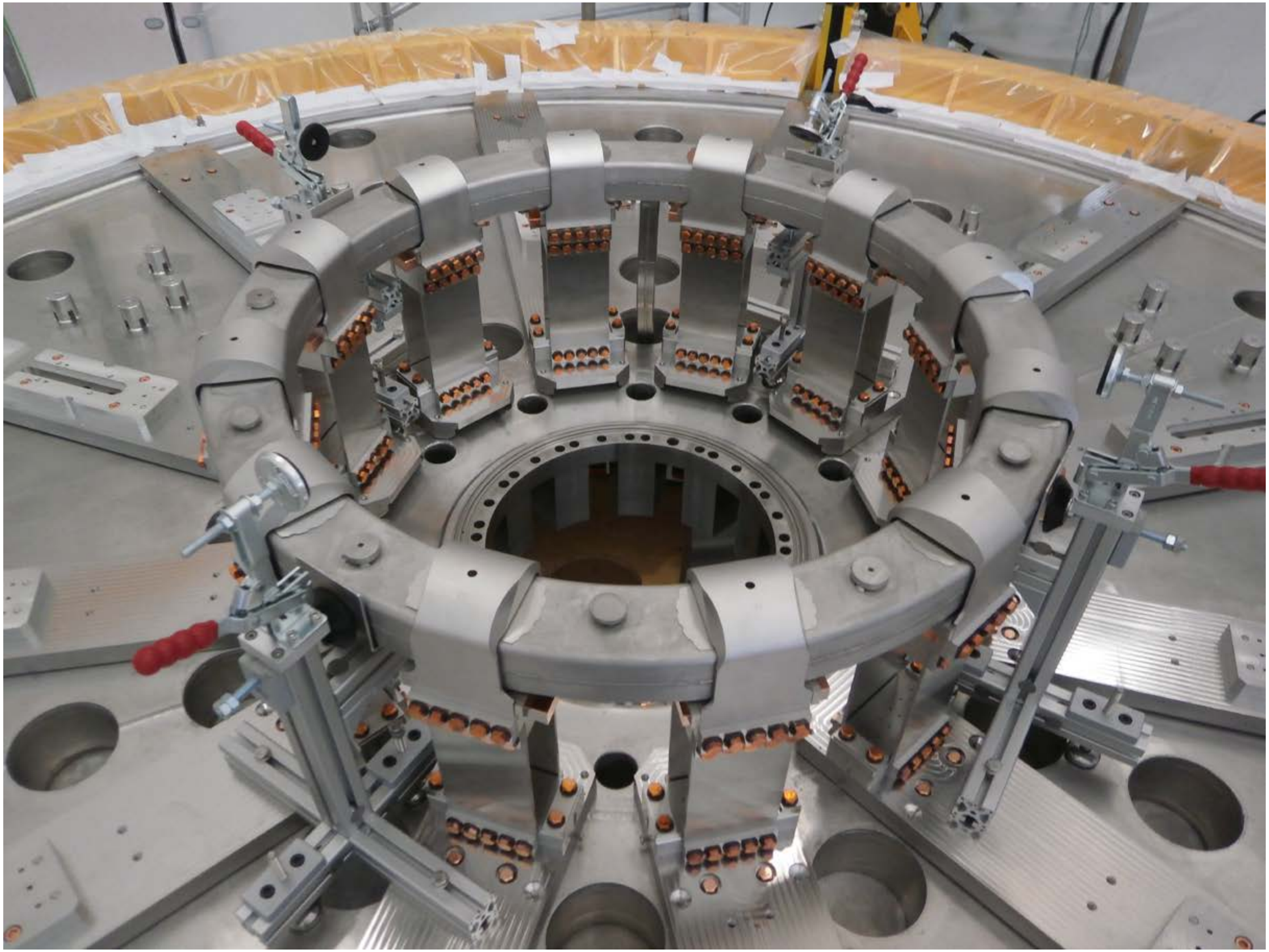
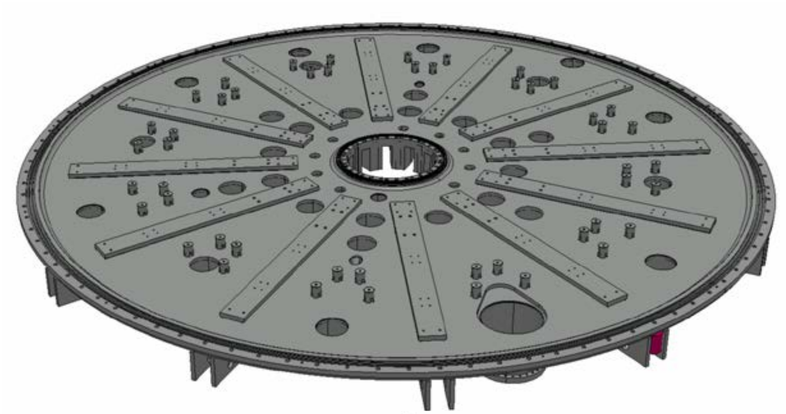
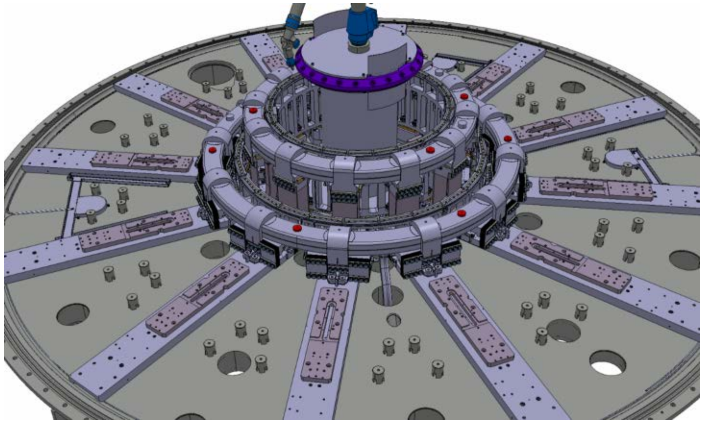
First coils now installed



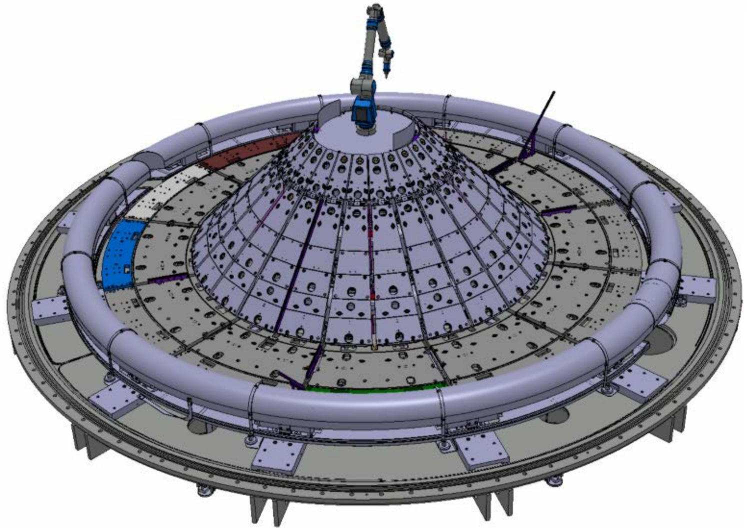
Cassette build to expedite load assembly

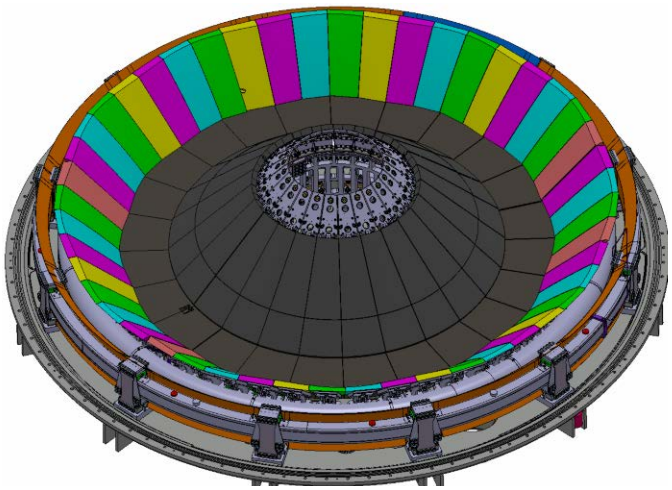
<u>End plate snapshots</u> *(actual sequence many hundreds of lines…)*





Starting now!



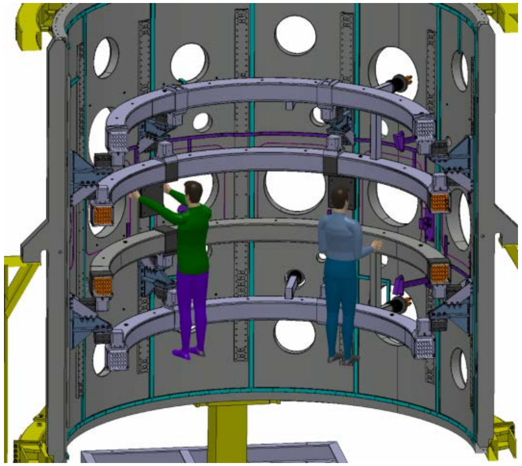


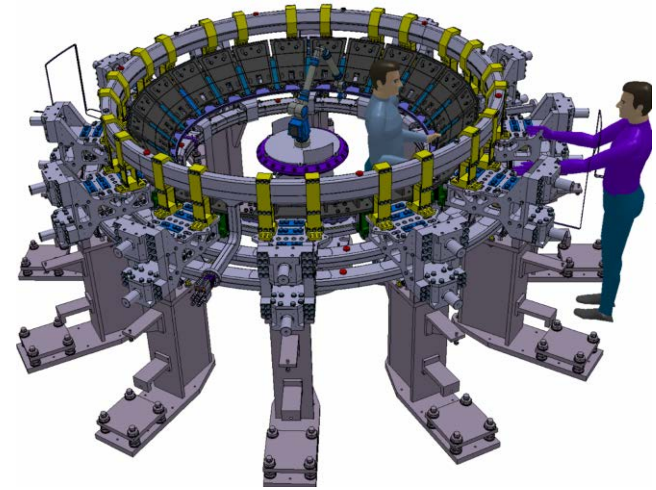
Expected end 2014

Cassette build to expedite load assembly

Outer cylinder snapshots *(actual sequence many hundreds of lines…)*

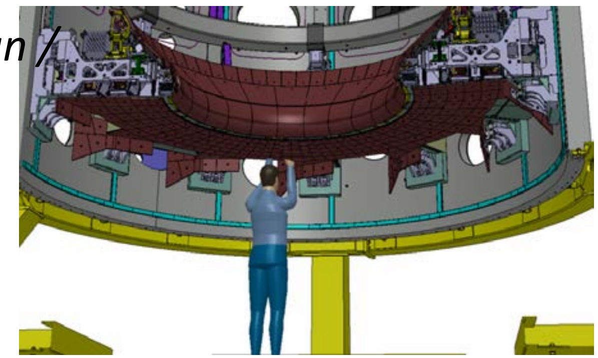
Starting June 2014

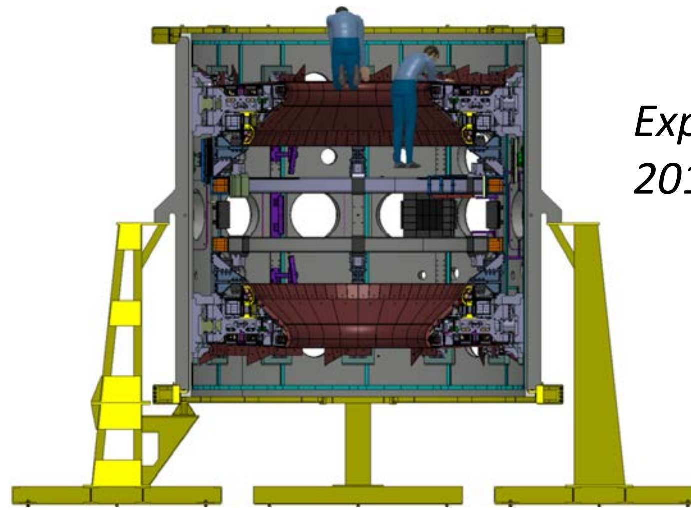




Starting ~July 2014

Expected Jan / Feb 2015 (TBC)





Expected April 2015 (TBC)*

**in blockhouse, with lower end plate in position*

Timeline

- Build timeline shows pump down starting in June 2015 (2 months later than foreseen)
- Note: completion of TF coils, in particular sliding joints, now scheduled AFTER pump down but planning still to be optimised
- Primary causes of slippage are delays to delivery of in-vessel coils and completing the design on some critical in-vessel components. Efforts are ongoing to recover this slippage

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Operating MAST Upgrade

- Expecting to hold a Forum in Spring 2015 to outline machine capabilities and discuss programme priorities with collaborators

- NSTX-U scientists are very welcome!