Overview of Physics Results from MAST towards ITER/DEMO and the Upgrade

Hendrik Meyer on behalf of the MAST Team and its Collaborators

EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

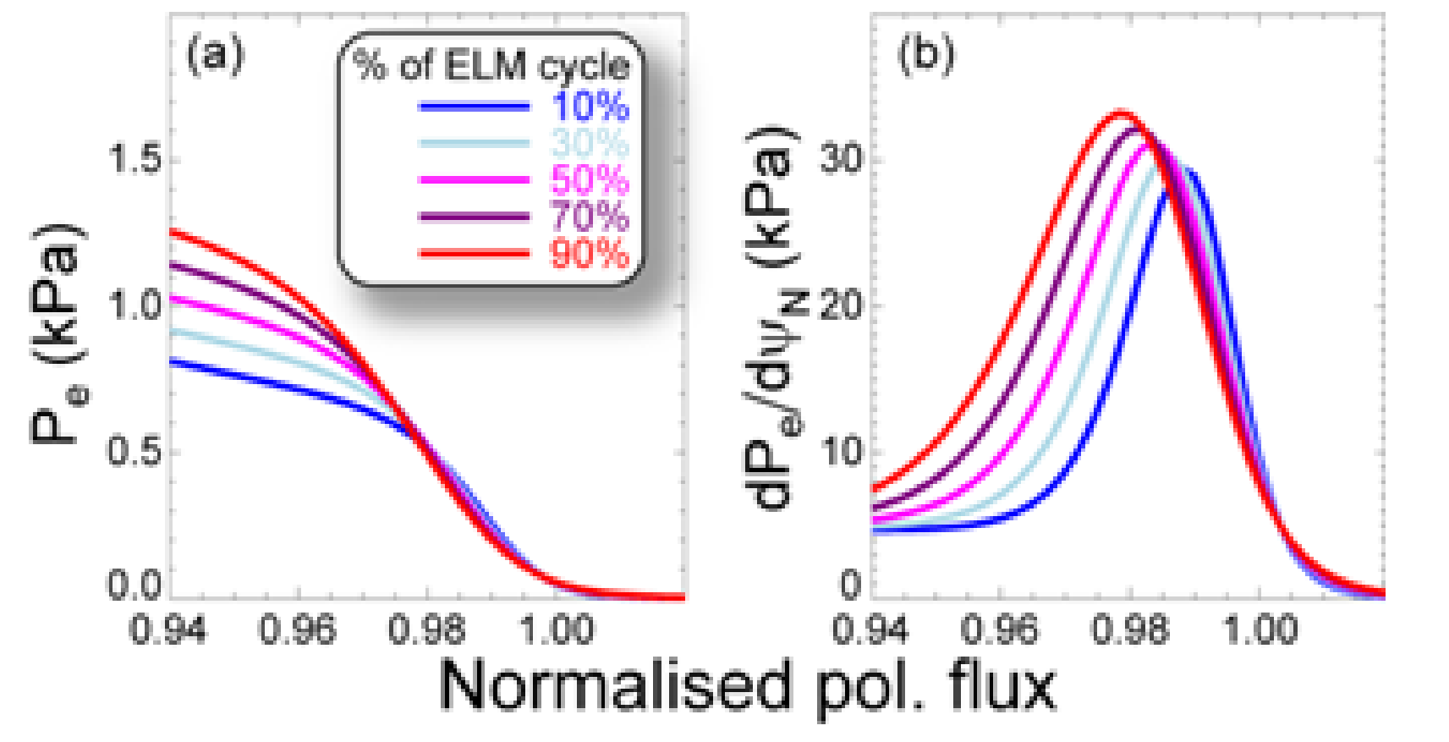
Research on MAST is aimed …

- Towards ITER:
  - Understanding pedestal and L-H transition physics.
  - ELM mitigation with resonant magnetic perturbations (RMP).
  - Pellet fuelling.
  - Fast particle physics with super Alfvénic ions.
- Towards DEMO:
  - Current drive in the presence of super Alfvénic ions.
  - Understanding macroscopic stability at high β.
  - The new MAST Upgrade divertor.
- Towards the MAST Upgrade: (under procurement)
  - Flexible, closed divertor including Super-X configuration.
  - On and off-axis beams for better current profile control.
  - Longer pulses with potential for fully non-inductive flat-top.

Pedestal & ELMs

Pedestal width grows at constant ∇p

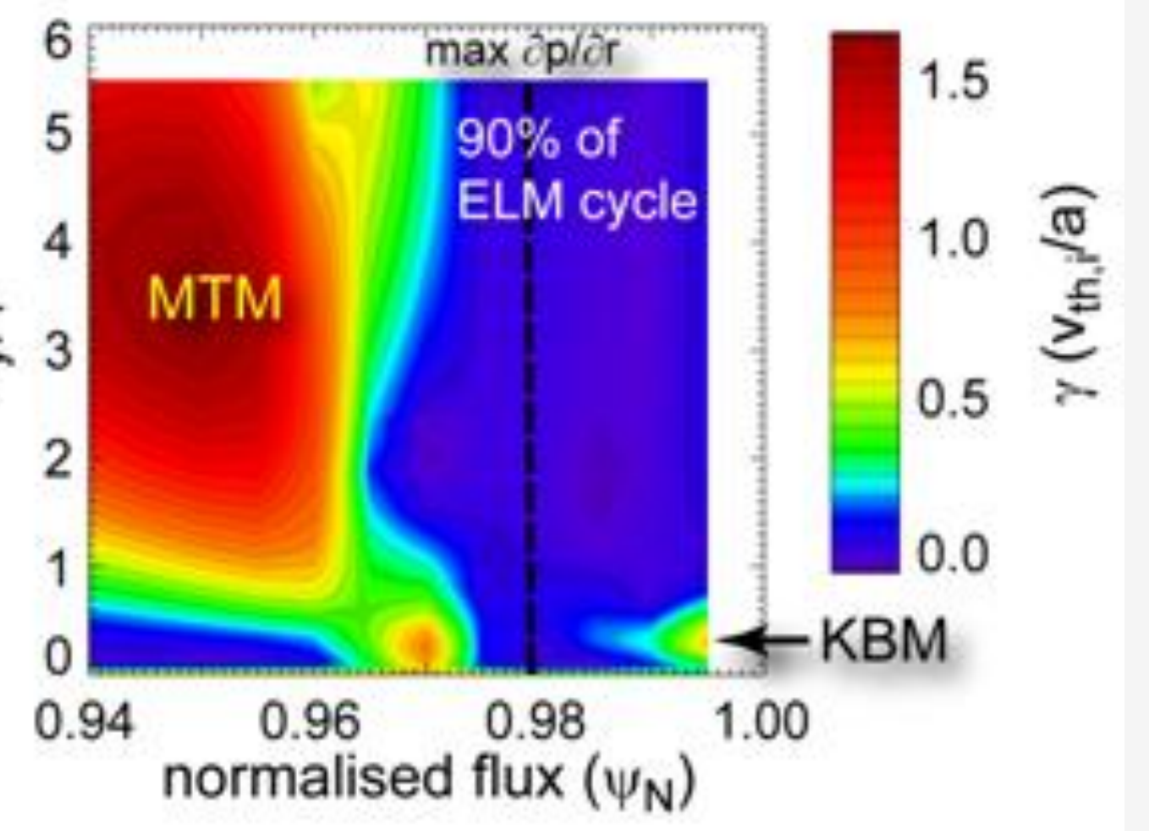
R. Scannell EX/P7-22 *D. Dickinson et.al, PPCF, **53** (2011)*



- ELM cycle profiles constructed from 50 profiles in 3 similar shots ⇒ good for micro-stability analysis.
- Widening of steep gradient region ⇒ peeling-ballooning modes unstable at lower gradient.

Micro-tearing may play a role for Δ_p^{ped}

- Micro-tearing modes (MTM) unstable at top of pedestal.
- MTM stabilised by increasing ∂p/∂r and ∂n/∂r ⇒ mode transition to kinetic ballooning mode (KBM).
- Increasing bootstrap current at low ν_*^{ped} increasing stabilises KBM.



C.M. Roach TH/5-1
*D. Dickinson et.al, PRL, **108** (2012)*

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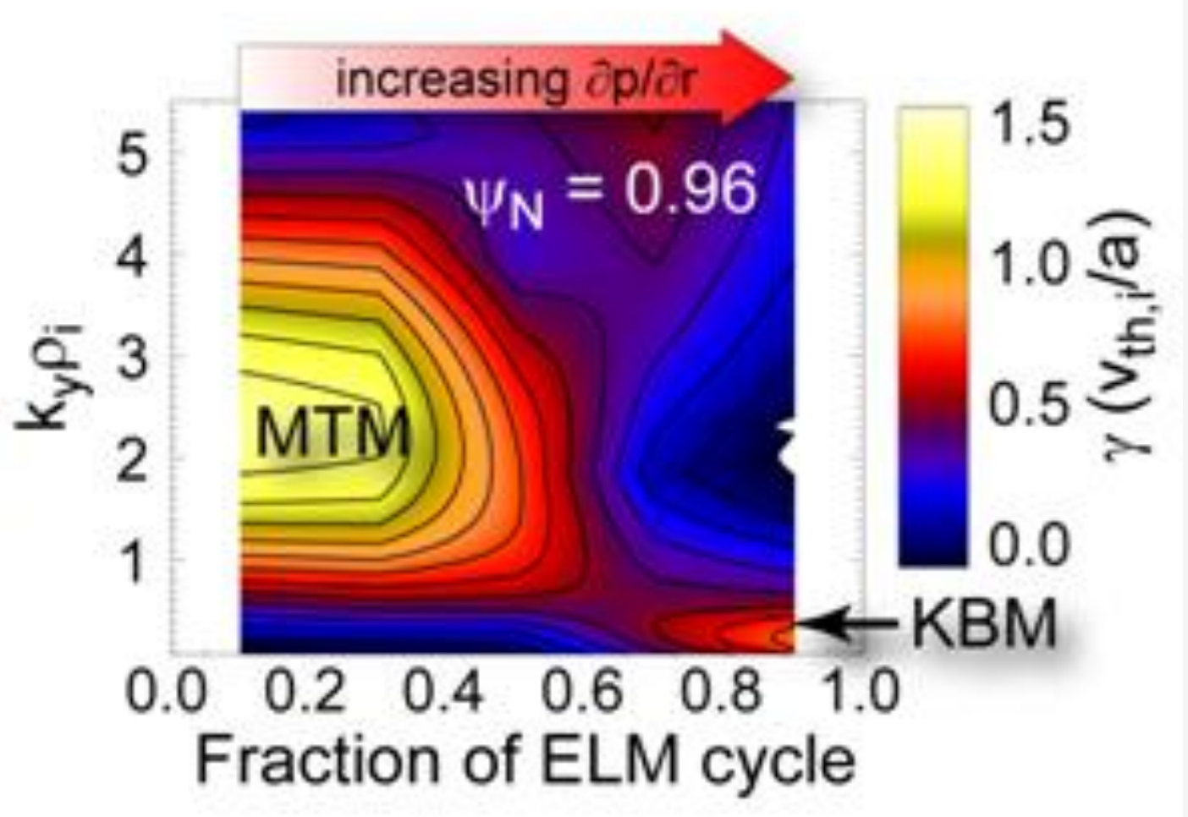
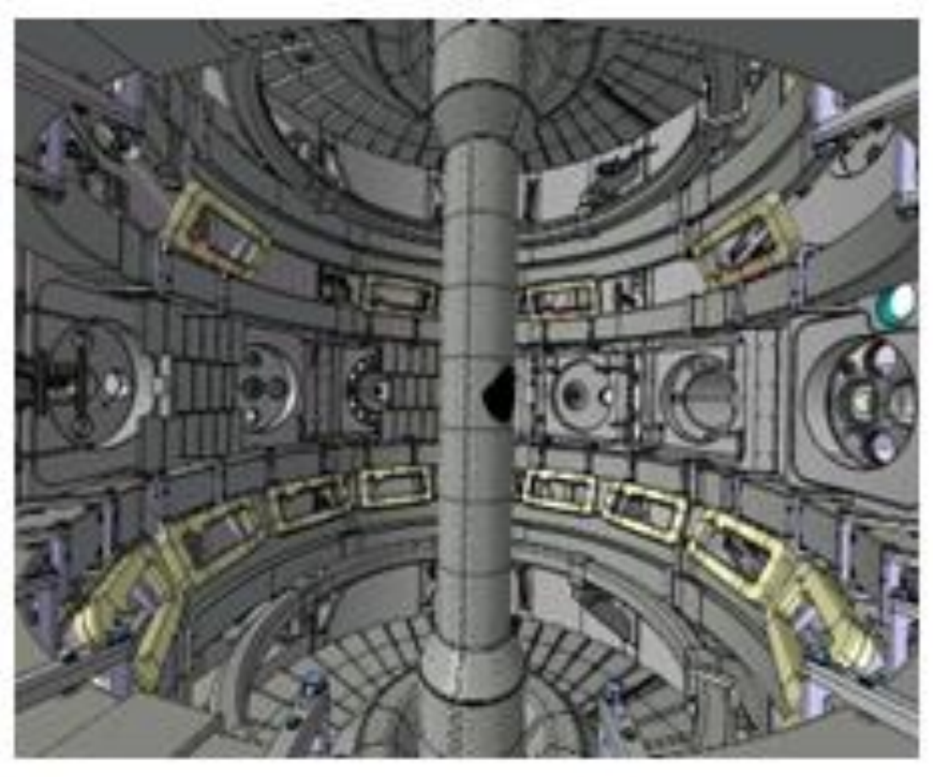


C.M. Roach TH/5-1
*D. Dickinson et.al, PRL, **108** (2012)*

Improved ELM coil set on MAST

A. Kirk, EX/3-2

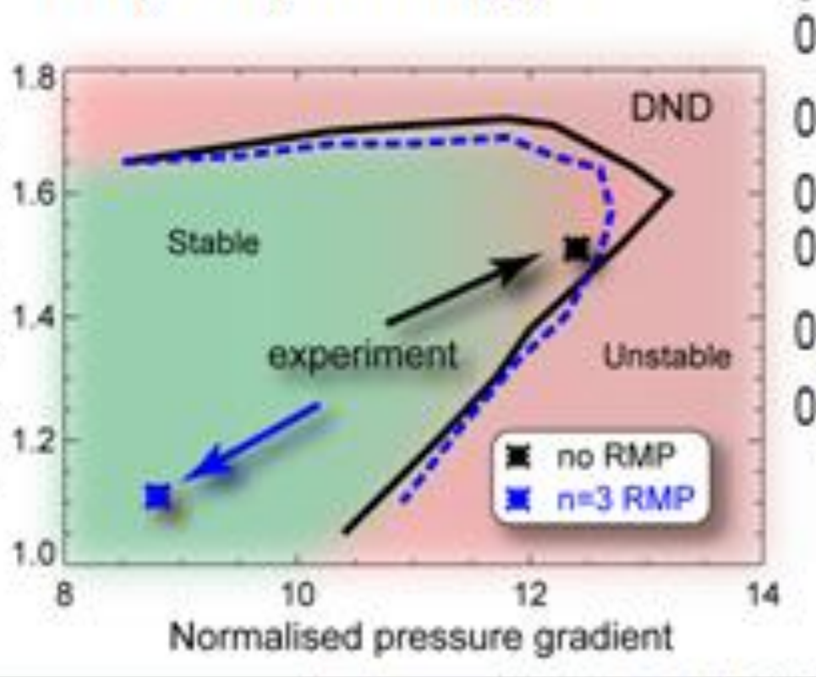
- 6 internal coils above mid-plane (<5.6 kA·turn).
- 12 internal coils below mid-plane (<5.6 kA·turn).
- 4 external coils at mid-plane (EFCC).
- Wide variety of perturbations:
  - n=3 (Even,Odd,30L,90L)
  - n=4
  - n=6
  - n=2 (external mid-plane)

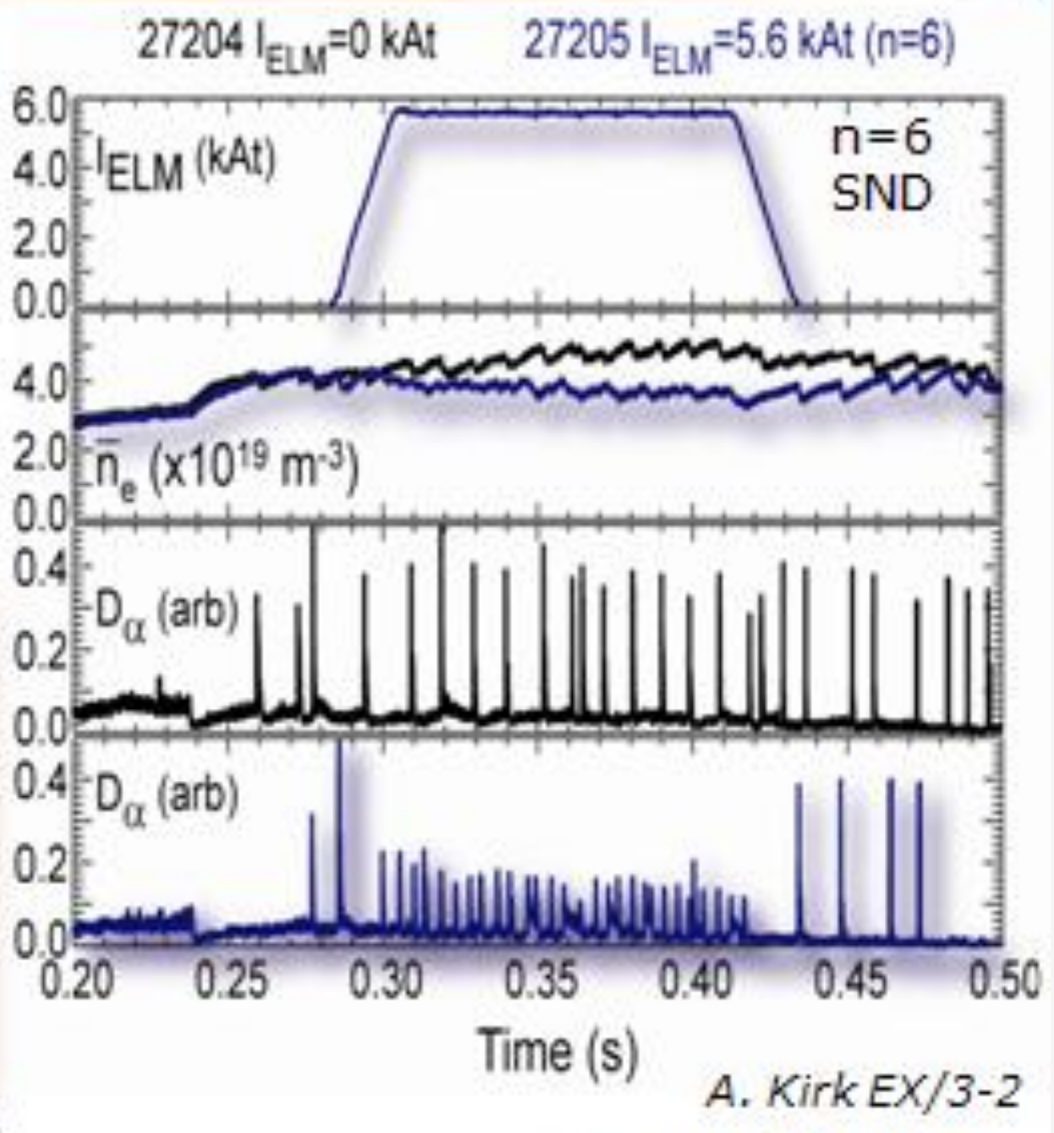


- Unique potential: adjust angle of pert. during shot.

ELM mitigation achieved with n=3,4,6

- f_{ELM} increased by up to factor of 9.
  - $f_{ELM} \cdot \Delta W$ = const.
- 2D stability analysis: ⇒ pedestal is stable, why higher f_{ELM}?

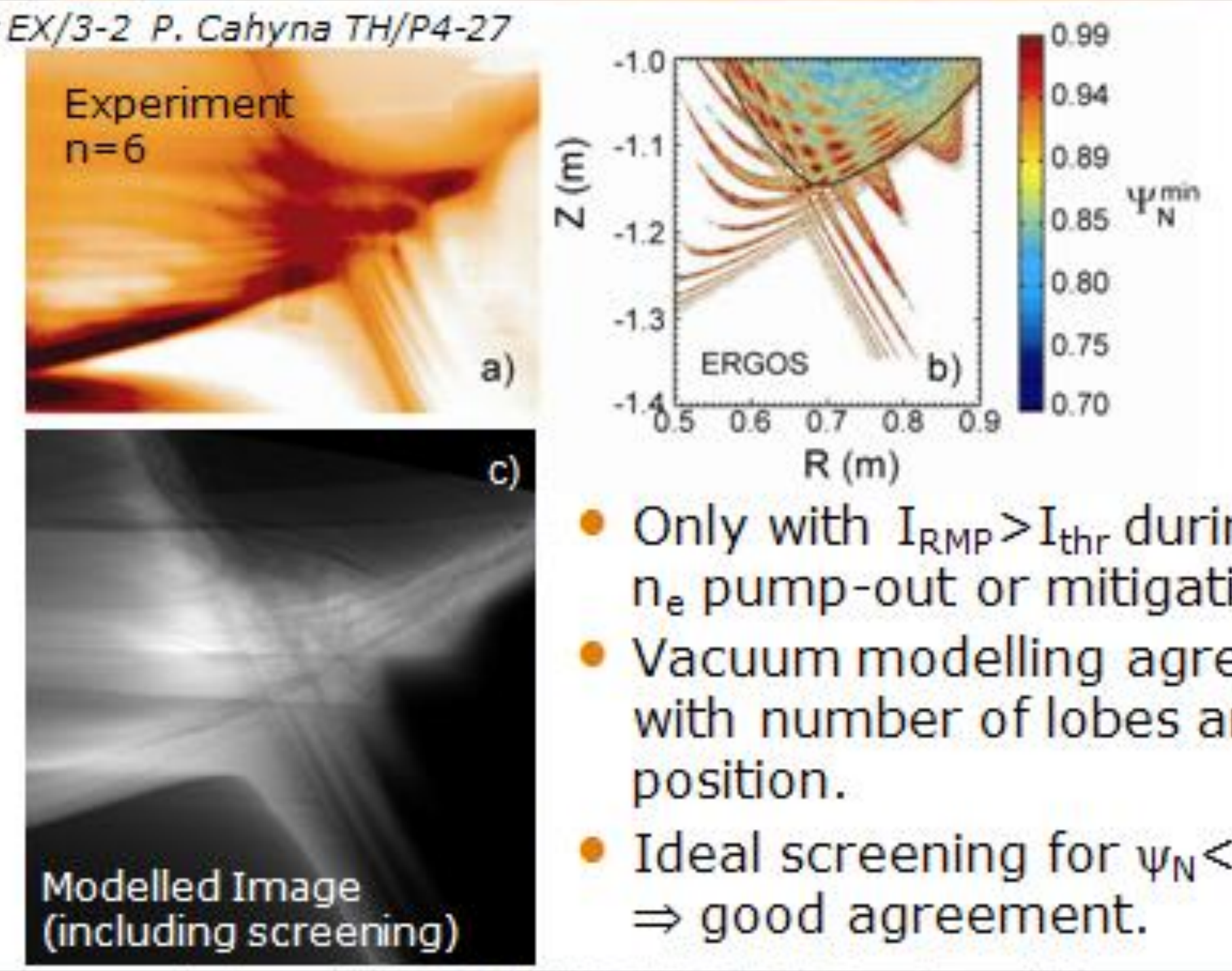




A. Kirk EX/3-2
R. Scannell EX/P7-22

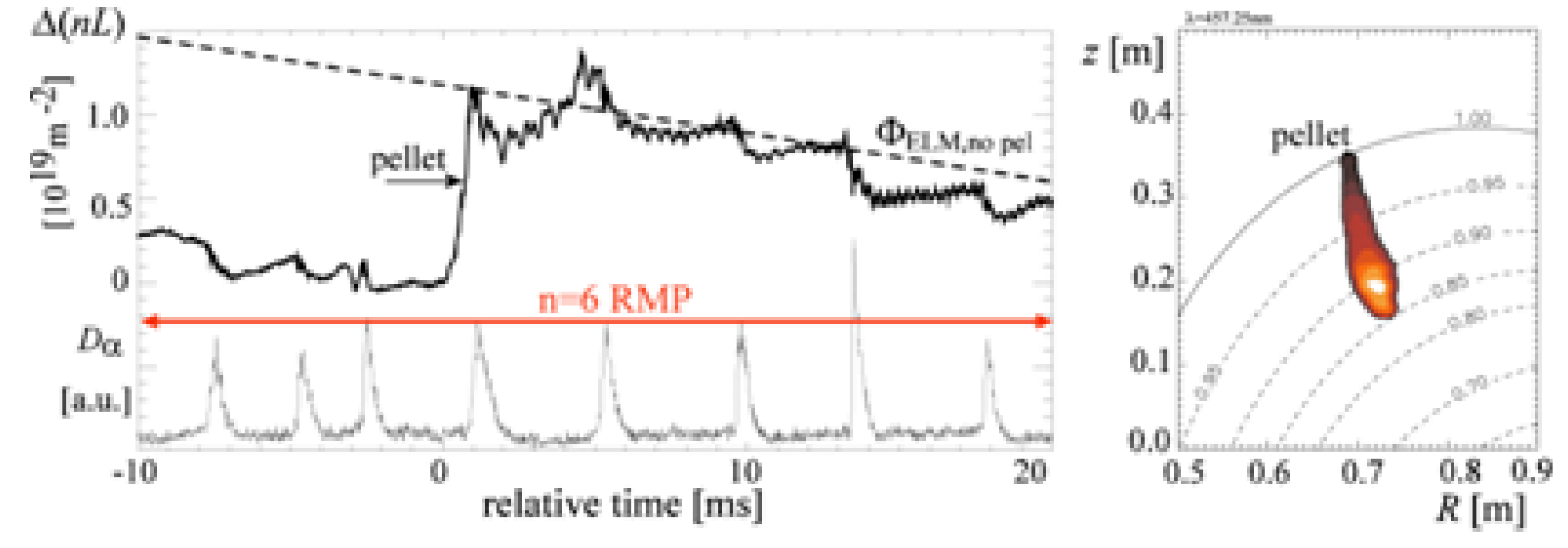
X-point Lobe structures observed

A. Kirk EX/3-2 P. Cahyna TH/P4-27



- Only with $I_{RMP} > I_{thr}$ during n_e pump-out or mitigation.
- Vacuum modelling agrees with number of lobes and position.
- Ideal screening for $\psi_N < 0.98$ ⇒ good agreement.

Pellets compatible with RMPs



- High similarity with ideal ITER pellet fuelling model.

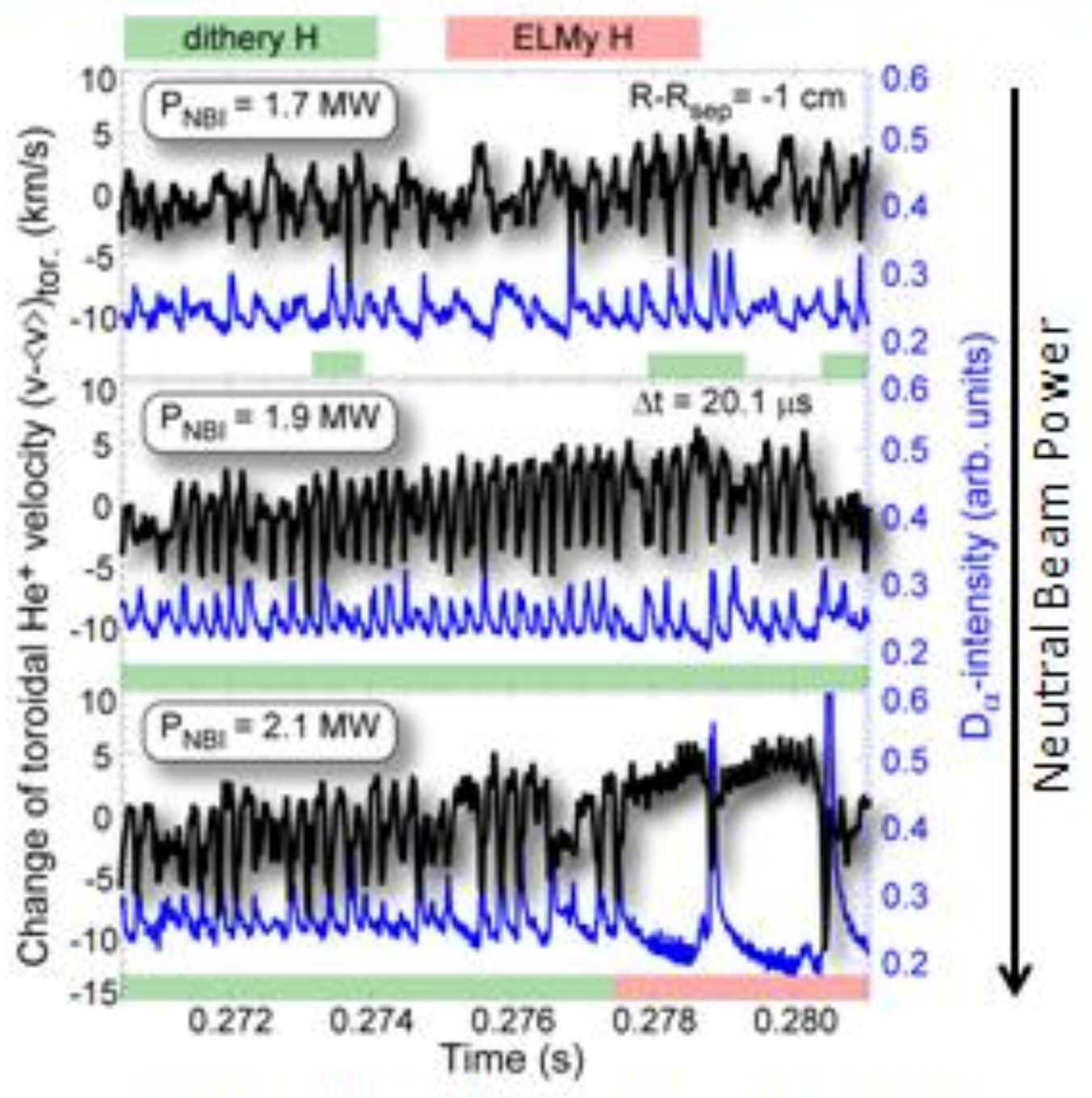
✓ HFS pellet with shallow deposition: $r_{pel}/a > 0.85$.
✓ pellet size equivalent to ~5 ELMs.
✓ ELM frequency, ELM size and particle loss not degraded by pellet, but counter examples exist
✗ relative size of pellets and ELMs ~8x larger than in ITER.

M.Valovič et.al. submitted to PPCF

L-H transition

I-phase like state observed

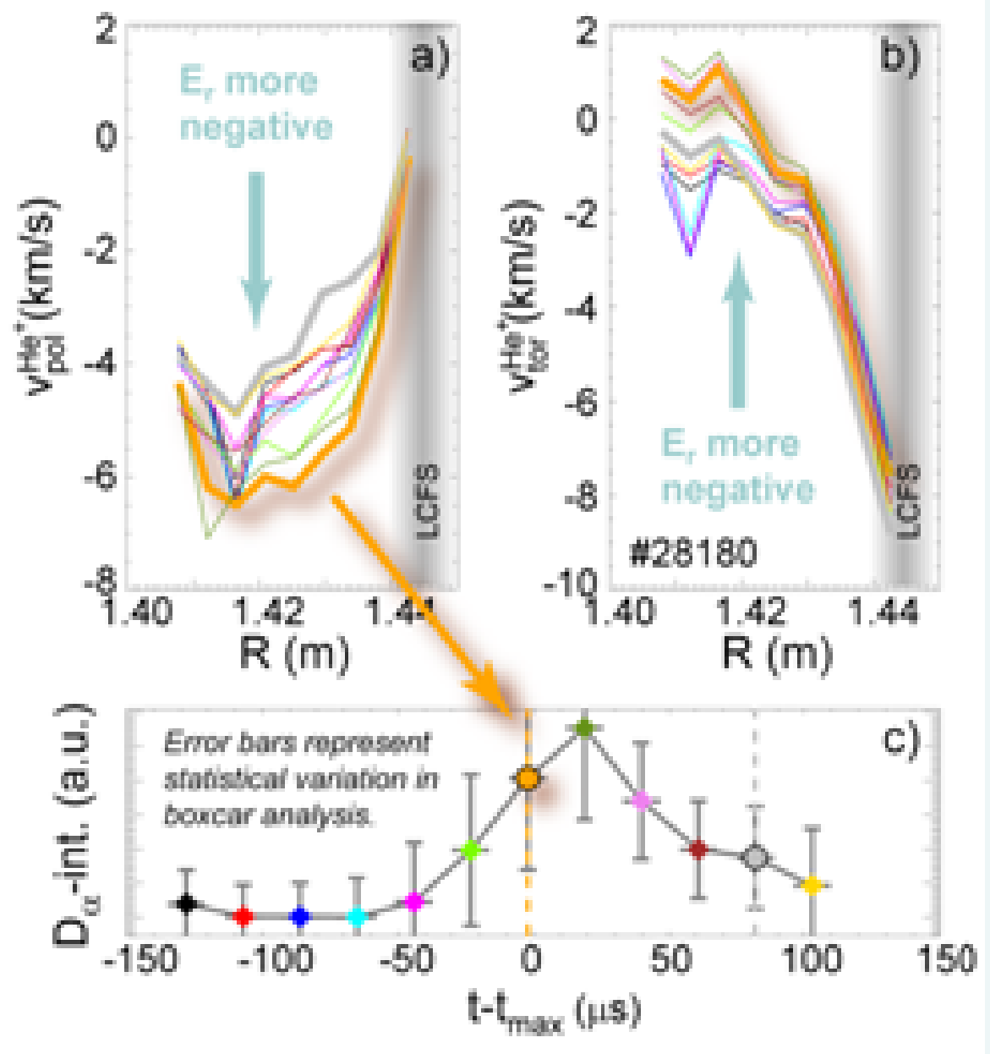
- 4–5 kHz D_α dithers precede ELMy H-mode ($\tilde{H}$).
- Correlation between He⁺ flow and reduced D_α
  - Doppler spectroscopy
- Power range were $\tilde{H}$ is observed decreases with increasing density.



H. Meyer ITPA 2012/R. Scannell EX/P7-22

Filaments erupt at high $\partial v^{He^+}/\partial r$

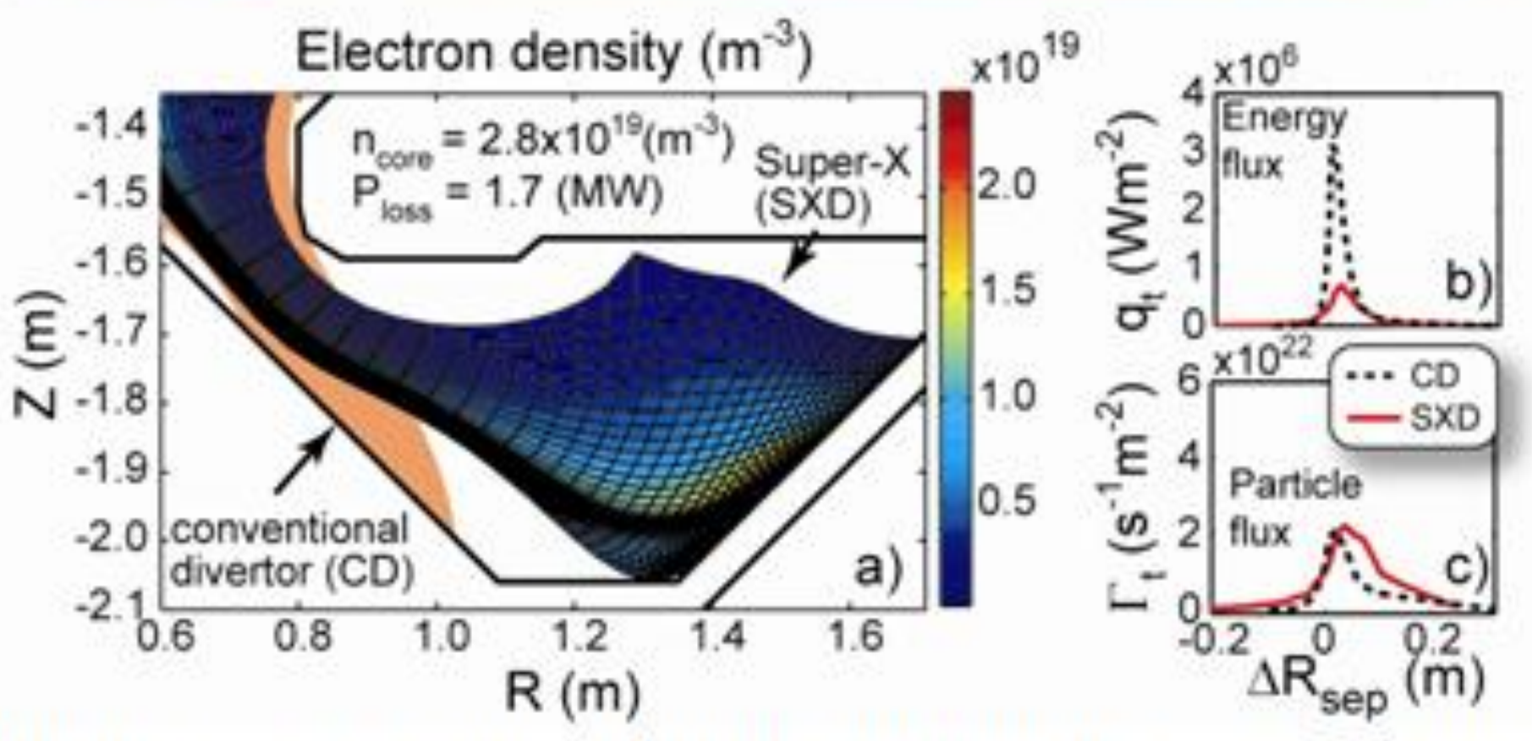
- Cycle start: $|\partial_r v^{He^+}|$ inreases as filamentary turbulence decreases.
  - Consistent with turbulence suppression by flow shear.
- Cycle end: Filaments erupt at highest $|\partial_r v^{He^+}|$
  - Consistent with vorticity being expelled by turbulence.
- Is this consistent with predator-prey dynamics?
  - No simple phase shift between flow and turbulence. *R. Scannell EX/P7-22*



Cond. averaging of (a) poloidal and (b) toroidal He⁺ flow from 50 kHz Doppler spectroscopy, time points in (c) D_α -intensity are colour coded.

Divertor and SOL

Towards the MAST-U divertor

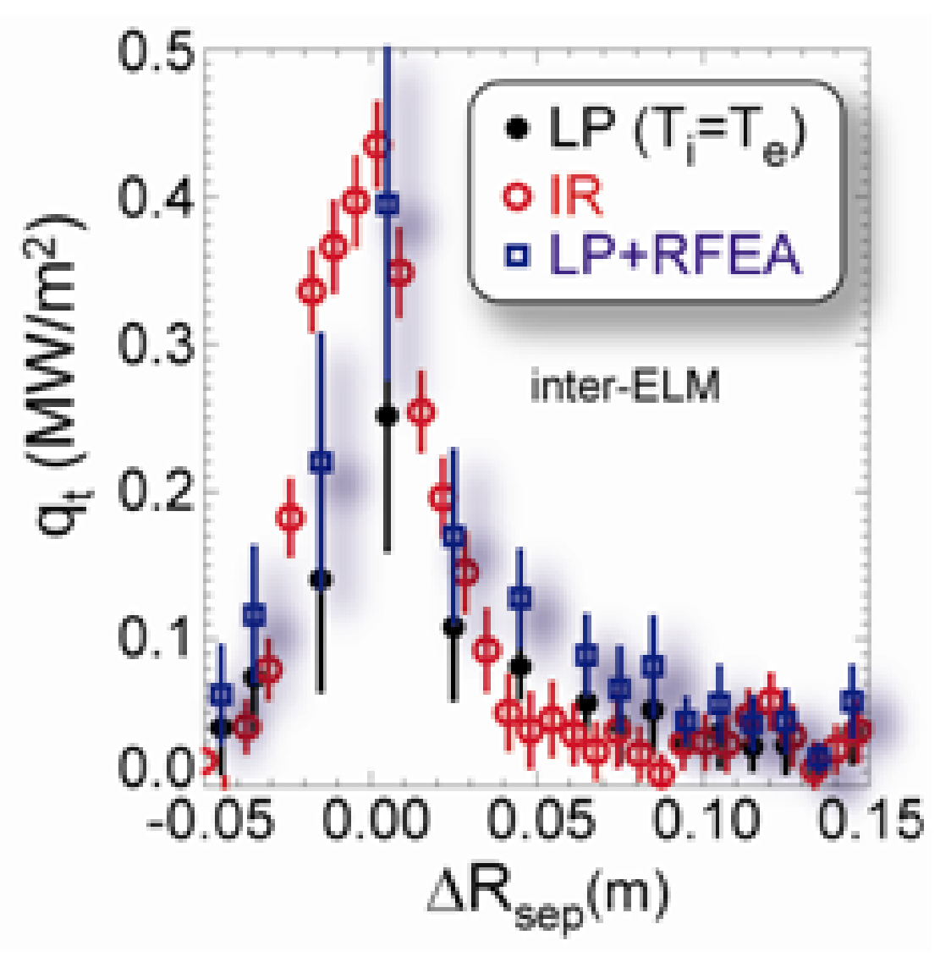


- What can be gained by changing flux expansion and connection length? – Flexible coil set on MAST-U.
- SOLPS simulations to guide design.
- Super-X ⇒ Reduction of energy flux and target T_e.

G. Fishpool EX/P5-17, PE. Havlíčková et.al., 20th PSI (2012)

First Divertor T_i measurements

- SOL T_i measured in divertor region with RFEA.
- $T_i/T_e \geq 1$ approaching unity at high ν_*^{SOL}.
- RFEA data improve comparison between probe and IR data.
  - More confidence in IR analysis α parameter.



S. Elmore et.al., 20th PSI (2012)
G Fishpool EX/P5-17

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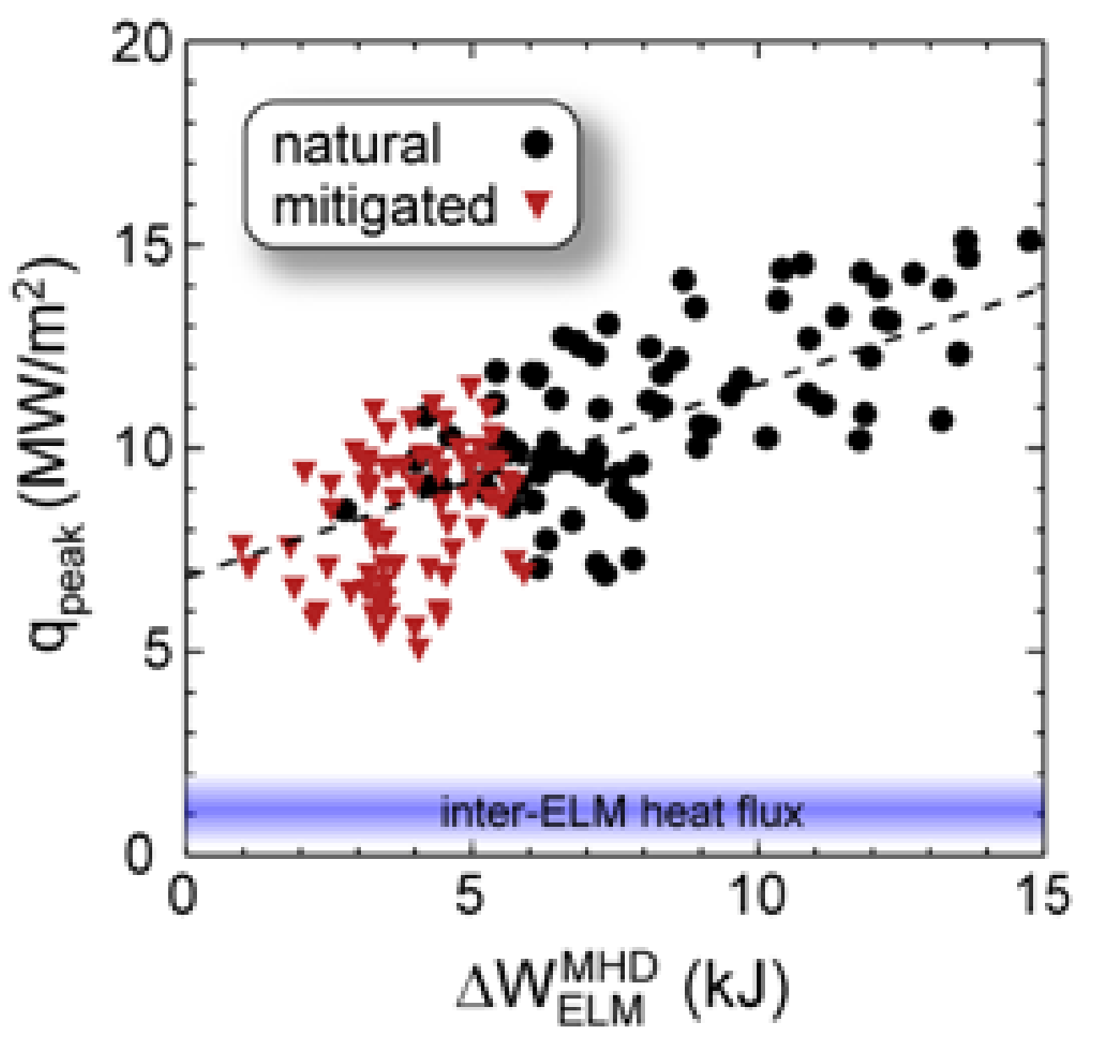
Peak heat flux proportional to ΔW_{ELM}

A. Kirk EX/3-2

- Peak heat flux increases linearly with ELM energy.
- Natural and mitigated ELMs follow the same trend.
  - Consistent with $f_{ELM} \cdot \Delta W_{ELM} = const.$
- For $\lim_{f_{ELM} \to \infty} \Delta W_{ELM}^{MHD}$ $q_{ELM} >> q_{inter\text{-}ELM}$
  - Trend should deviate from linear.



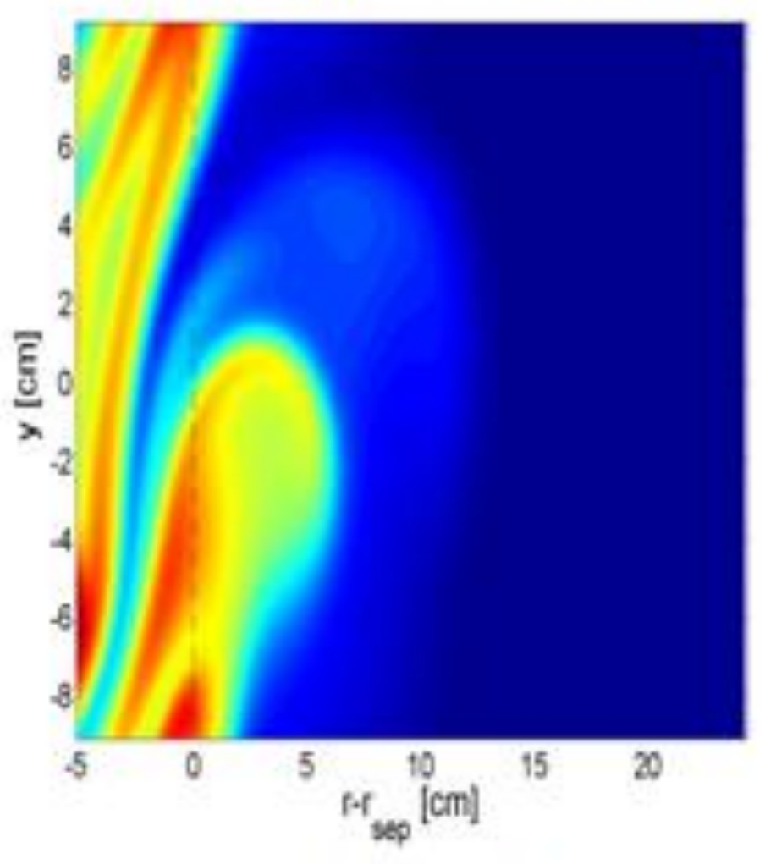
A. Thornton et.al., 20th PSI(2012)

ESEL reproduces SOL turbulence

Militello et al., PPCF, **54** (2012)

- Electrostatic interchange turbulence captures some statistical properties of MAST SOL turbulence.
- dimensionless parameter scans to arrive at mid-plane λ_q scaling.

Increasing;	λ_q
n_{edge}	weak increase ☺
T_{edge}	strong decrease ☹
I_p	decrease ☹
$L_{//}$	increase ☺

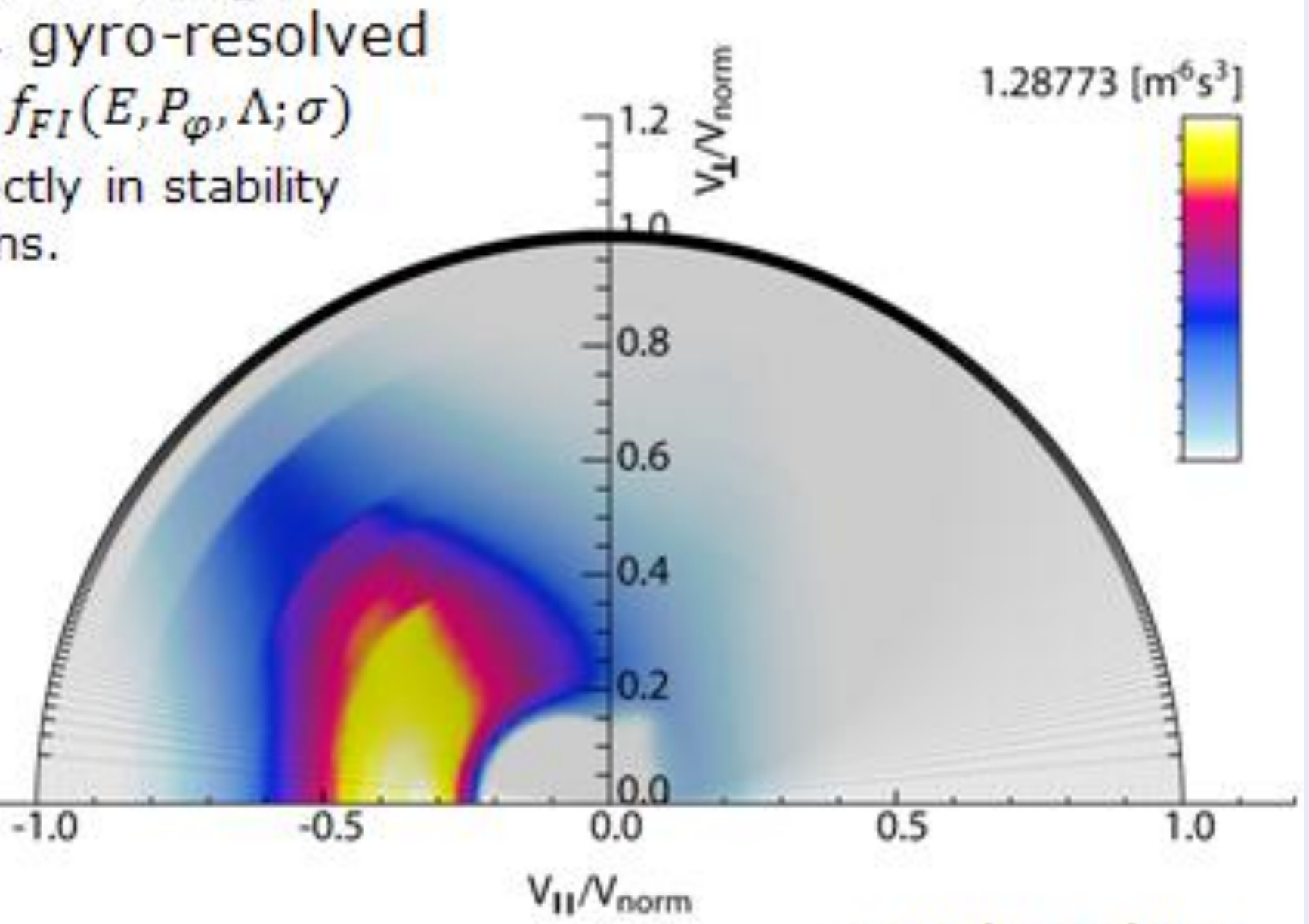


G Fishpool EX/P5-17

MAST-U super-X

Towards predictive FI capability

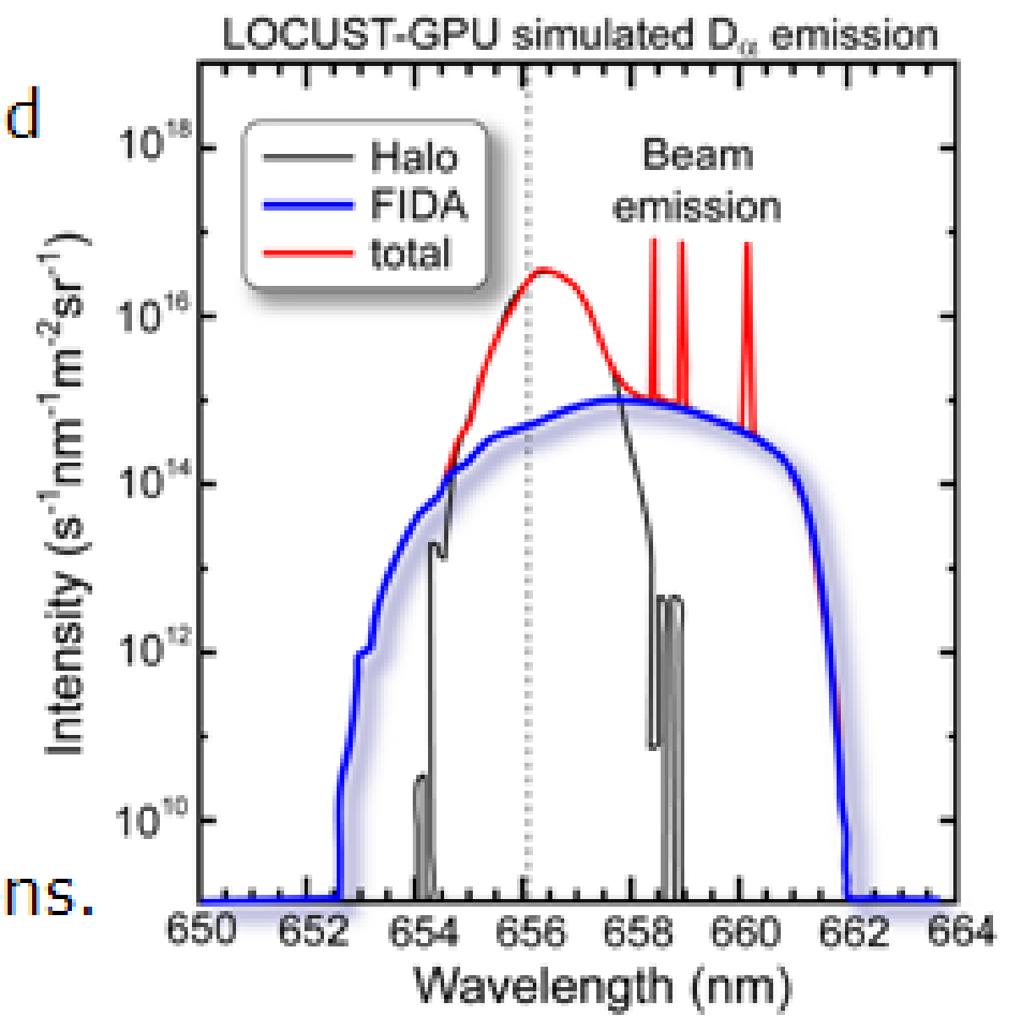
- LOCUST-GPU ⇒ high resolution, gyro-resolved $f_{FI}(\vec{x},\vec{v})$ or $f_{FI}(E,P_\varphi,\Lambda;\sigma)$
  - Used directly in stability calculations.



S. Pinches TH/P3-34

Towards predictive FI capability

- LOCUST-GPU ⇒ high resolution, gyro-resolved $f_{FI}(\vec{x},\vec{v})$ or $f_{FI}(E,P_\varphi,\Lambda;\sigma)$
  - Used directly in stability calculations.
- HAGIS δf ⇒ FI redistribution (non-linear)
  - m=n=1 fishbone modes.
- Synthetic diagnostics to compare to measuremens.
  - Neutron Camera.
  - Fast-ion D_α emssion (FIDA)



S. Pinches TH/P3-34

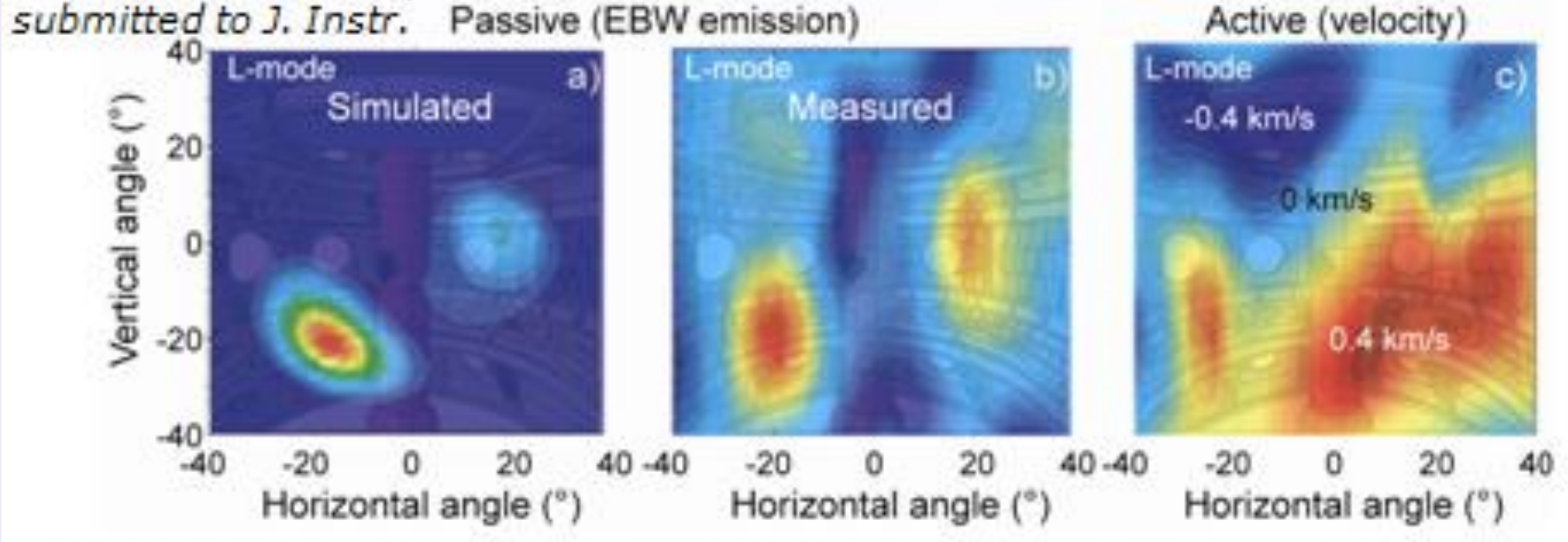
New Tools on MAST

New diagnostic and plant capabilities

- Improved ELM coil set
  - 6 upper and 12 lower coils.
- Beam emission spectroscopy for ion turbulence.
- Neutron camera for fast ion profiles.
- Fast ion D_α emission to sample f_{FI}
  - Poloidal views ⇒ sensitive to trapped FI.
  - Toroidal views ⇒ sensitive to passing FI.
  - Spectrum ⇒ sensitive to FI energy.
- 50kHz edge Doppler spectroscopy for edge E_r fluctuations.
- FPGA technology improves diagnostics (SAMI) and data acquisition (event triggering).

Synthetic aperture microwave imaging

V. Shevchenko et. al., submitted to J. Instr.

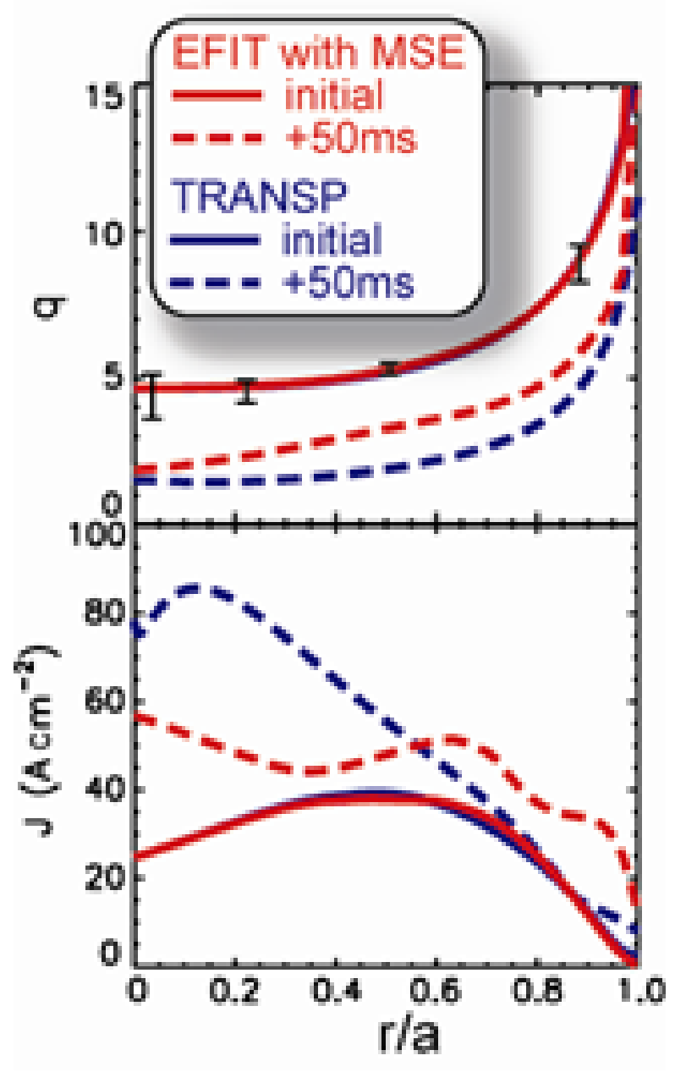


- Measure EBW emission with 8 antennas at 16 frequencies ⇒ 3D emission pattern with 100 kHz.
  - Access to edge current profile.
- 3D ray tracing agrees well with observed emission.
  - Vertical elongation due to shape of antenna array.
- Active probing gives access to 3D velocity profile.

Current drive and Fast ions

Slower than NC current diffusion

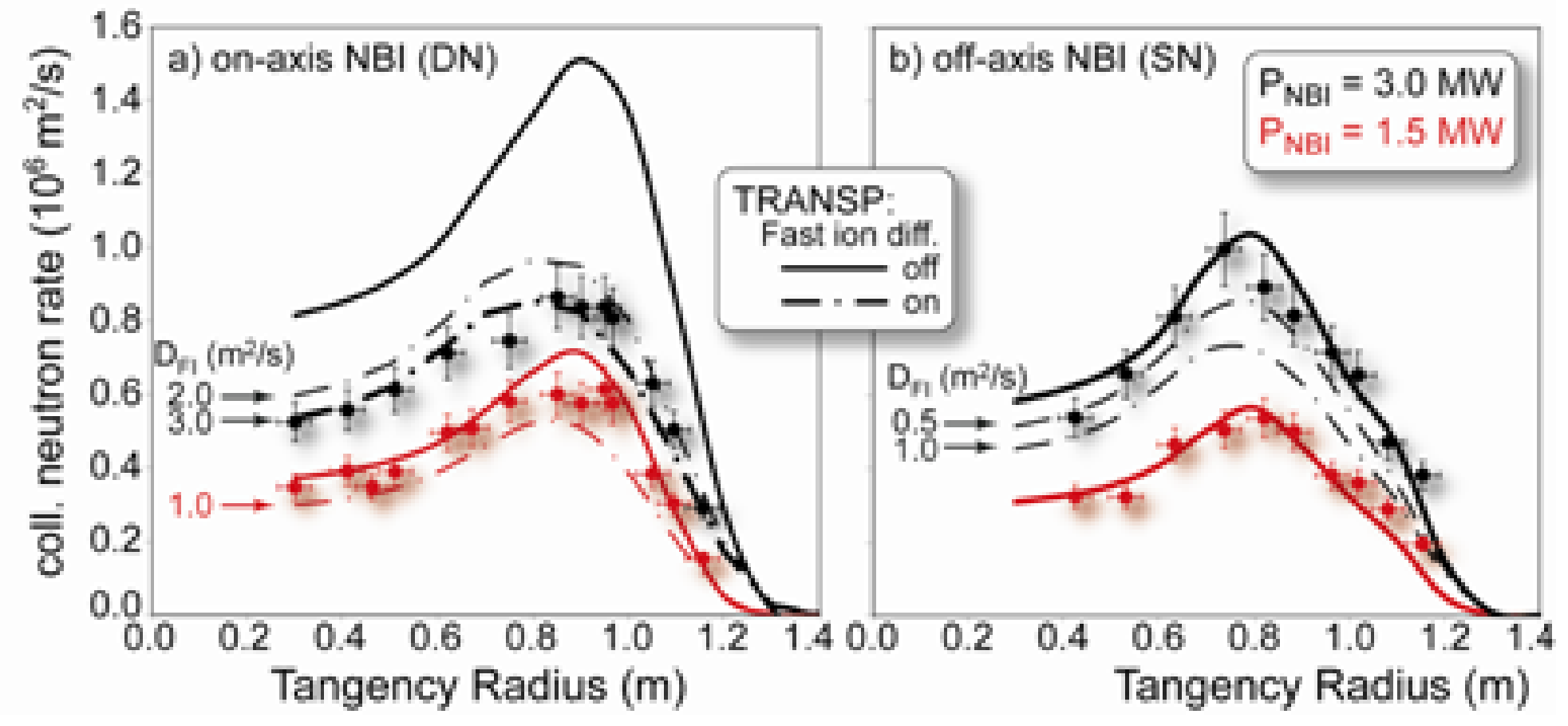
- Poloidal field diffusion is slower than predicted by neoclassical (NC) modelling in dynamic phase.
- Use shot to shot MSE at NBI start to measure j(r,t).
  - Use to benchmark modelling.
- New capability on MAST: JINTRAC integrated modelling suite.
  - JETTO ⇒ 1.5 D transport.
  - UEDGE ⇒ 2D SOL
  - ASCOT-GC/FO ⇒ NBI



D. Keeling et.al., EPS (2011)
O. Asunta, et.al., EPS (2012)

Off-axis NBCD close to classical

M. Turnyasnkiy EX/P6-06



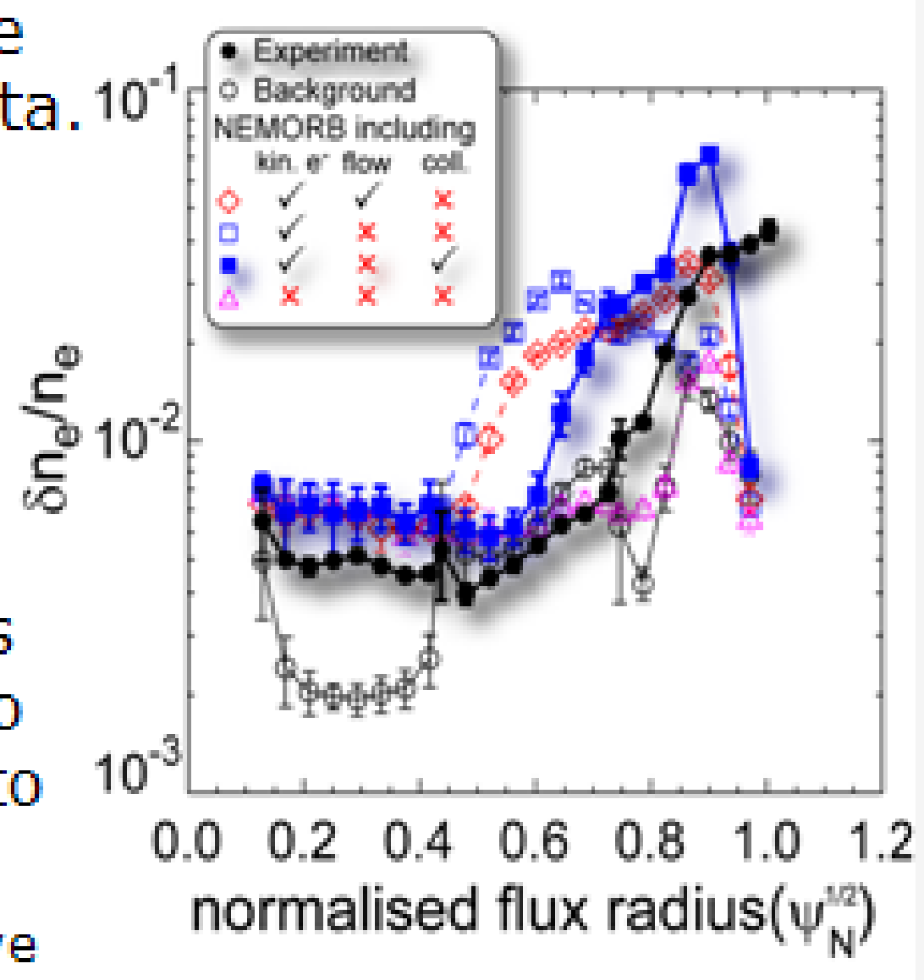
- Fishbone modes redistribute fast-ions (FI).
  - Instability driven by gradient in fast ion distribution f_{FI}.
- Off-axis beam deposition should reduce gradients.
- Confirmed by matching neutron emission profile:
  - DN/On-axis: D_{FI}~3 m²/s; SN/Off-axis: D_{FI} < 0.5 m²/s.

Ion scale turbulence

Heat flux modelled with NEMORB

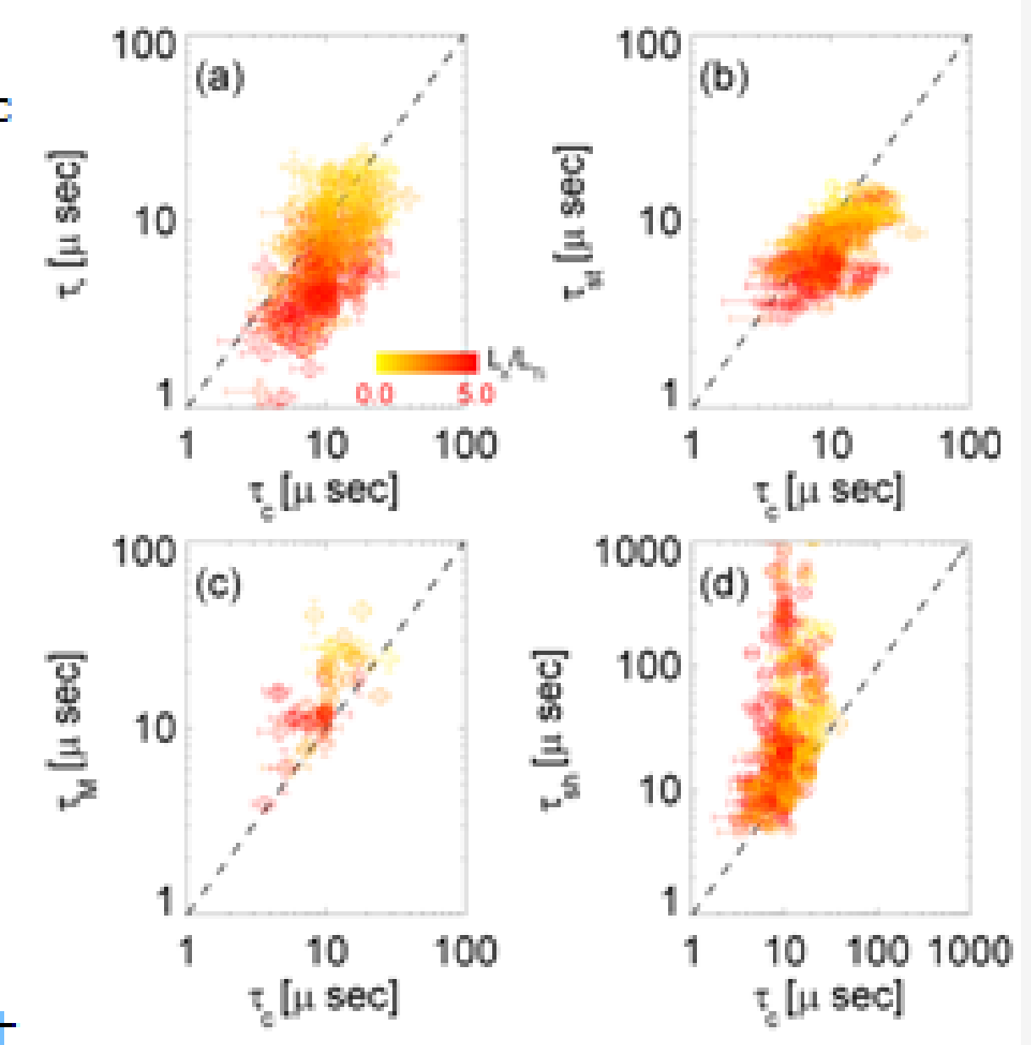
A.R. Field, EX/P7-1

- Global gyro-kinetic modelling (NEMORB) shows reasonable agreement with new BES data.
- Turbulence is sensitive to:
  - Flow,
  - Kinetic electrons (KE),
  - and collisions (C).
- Inclusion of kinetic electrons (KE) and collisions needed to bring fluctuation amplitude to within a factor of 2–3.
  - Inclusion of flow should improve agreement further.



Ion turbulence is inherently 3D

- Statistical comparison of turbulence correl. time τ_c with associated time scales.
  - Drift: $\tau_* = \frac{l_y L_*}{\rho_i v_{th,i}}$
  - ∥ streaming $\tau_{st} = \frac{\pi r B}{v_{th,i} B_p}$
  - Mag. drift: $\tau_M = \frac{l_x R}{\rho_i v_{th,i}}$
  - Shearing: $\tau_{sh} = \left[\left(\frac{B_p}{B}\right)\frac{\partial v_\phi}{\partial r}\right]^{-1}$
- Grand critical balance ⇔ $\tau_c \sim \tau_{st} \sim \tau_M$.
- $l_\parallel$ and $l_\perp$ not independent ⇒ 3D turbulence.



A.R. Field, EX/P7-1

In Summary

- MAST research has strengthened the tokamak physics basis in many areas:
  - ELM mitigation, pedestal stability, L-H transitions, pellet injection, SOL physics, fast-ion physics and current drive physics.
  - New and sometimes unique measurements are fundamental to this progress.
- Experiments and modelling aid the MAST-U design and solidify the physics research plan.
  - The findings with respect to off-axis current drive and SOL width bode well for the MAST-Upgrade.

MAST contributions at this conference

Orals:
A. Kirk EX/3-2 Wed 11:05
C.M. Roach TH/5-1 Thu 14:00
S.E Sharapov OV/4-3 Tue 14:50

Posters:
M.R. Turnyanskiy EX/P6-06 Thu 14:00-18:45
G. Fishpool EX/P5-17 Thu 8:30-12:00
S.D. Pinches TH/P3-34 Wed 8:30-12:30
R. Scannell EX/P7-22 Fri 8:30-12:30
A.R. Field EX/P7-01 Fri 8:30-12:30
P. Cahyna TH/P4-27 Wed 14:00-18:45
P. Gohil ITR/P1-36 Tue 8:30-12:30 (ITPA)

The MAST Team

H. Meyer[1], I.G. Abel[2], R.J. Akers[1], A. Allan[3], S.Y. Allan[1], L.C. Appel[1], O. Asunta[4], M. Barnes[2,5], N.C. Barratt[3], N. Ben Ayed[1], J.W. Bradley[6], J. Canik[7], P Cahyna[8], M. Cecconello[9], C.D. Challis[1], I.T. Chapman[1], D. Ciric[1], G. Colyer[1], N.J. Conway[1], M. Cox[1], B.J. Crowley[1], S.C. Cowley[1], G. Cunningham[1], A. Danilov[10], A. Darke[1], M.F.M. De Bock[11], G. De Temmerman[12], R.O. Dendy[1], P. Denner[3], D. Dickinson[1], A.Y. Dnestrovsky[10], Y. Dnestrovsky[10], M.D. Driscoll[1], B. Dudson[3], D. Dunai[13], M. Dunstan[1], P. Dura[14], S. Elmore[1,6], A.R. Field[1], G. Fishpool[1], S. Freethy[1], W. Fundamenski[1], L. Garzotti[1], Y.C. Ghim[1,2], K.J. Gibson[3], M.P. Gryaznevich[1], J. Harrison[1], E. Havlíčková[1], N.C. Hawkes[1], W.W. Heidbrink[15], T.C. Hender[1], E. Higchock[2], D. Higgins[14], P. Hill[2], B. Hnat[14], M.J. Hole[16], J. Horáček[8], D.F. Howell[1], K. Imada[3], O. Jones[17], E. Kaveeva[18], D. Keeling[1], A. Kirk[1], M. Kočan[19], R.J. Lake[14], M. Lehnen[20], H.J. Leggate[21], Y. Liang[20], M.K. Lilley[22], S.W. Lisgo[23], Y.Q. Liu[1], B. Lloyd[1], G.P. Maddison[1], J. Mailloux[1], R. Martin[1], G.J. McArdle[1], K.G. McClements[1], B. McMillan[14], C. Michael[1], F. Militello[1], P. Molchanov[18], S. Mordijck[24], T. Morgan[12], A.W. Morris[1], D.G. Muir[1], E. Nardon[25], V. Naulin[26], G. Naylor[1], A.H. Nielsen[26], M.R. O'Brien[1], T. O'Gorman[3], S. Pamela[27], F.I. Parra[2,5], A. Patel[1], S.D. Pinches[1,23], M.N. Price[1], C.M. Roach[1], J.R. Robinson[14], M. Romanelli[1], V. Rozhansky[18], S. Saarelma[1], S. Sangaroon[8], A. Saveliev[28], R. Scannell[1], J. Seidl[7], S.E. Sharapov[1], A.A. Schekochihin[2], V. Shevchenko[1], S. Shibaev[1], D. Stork[1], J. Storrs[1], A. Sykes[1], G.J. Tallents[3], P. Tamain[25], D. Taylor[1], D. Temple[22], N. Thomas-Davies[1], A. Thornton[1], M.R. Turnyanskiy[1], M. Valovič[1], R.G.L. Vann[3], E. Verwichte[14], P. Voskoboynikov[18], G. Voss[1], S.E.V. Warder[1], H.R. Wilson[3], I. Wodniak[8], S. Zoletnik[13], R. Zagórski[29] and the MAST and NBI teams.

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