Overview of Physics Studies on ASDEX Upgrade

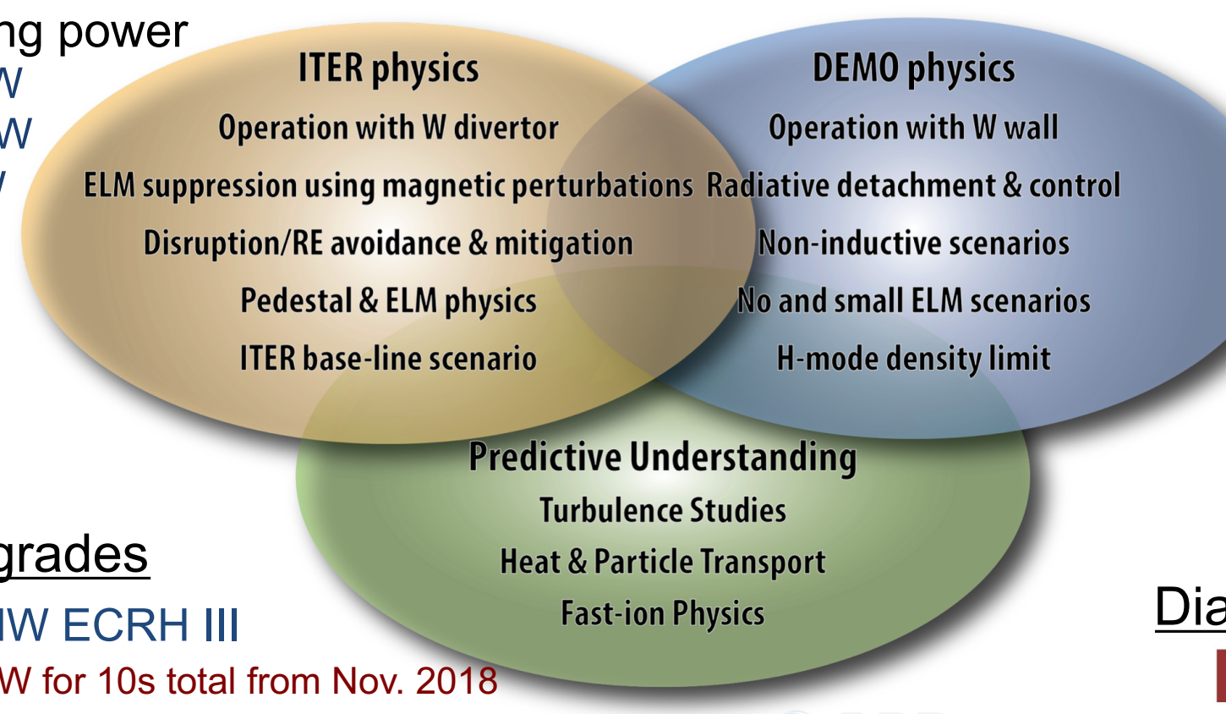
H. Meyer for the ASDEX Upgrade and EUROfusion MST1* Teams

CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

Corresponding author:
hendrik.meyer@ukaea.uk

AUG programme – To prepare ITER and DEMO

High heating power
P_{NBI}= 20 MW
P_{ECRH}= 8 MW
P_{ICRF}= 7MW



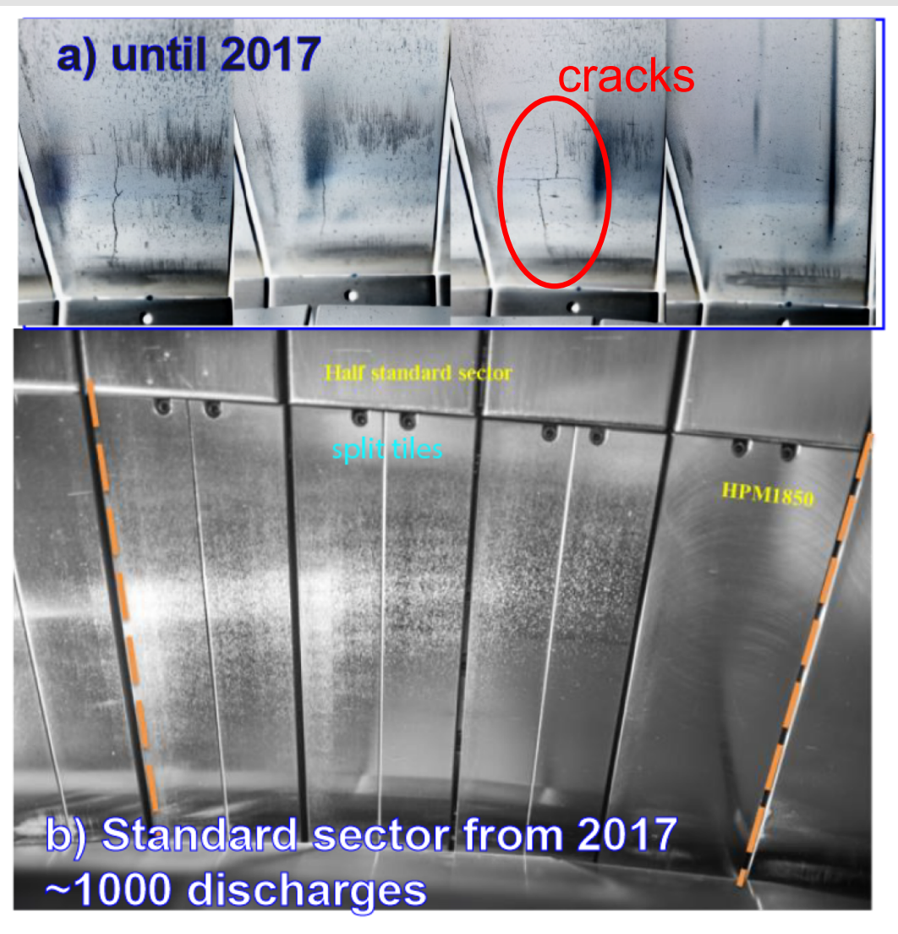
Medium size
R_0 = 1.65 m
a = 0.5 m
κ = 1.8
δ = 0.4
V_{pl} = 13 m^3
B_t = 3.2T
I_p = 1.4 MA

Plant upgrades
- 2 (4) MW ECRH III
  - 8 MW for 10s total from Nov. 2018
- 16 fast power supplies for internal coils
  - ELM control, MHD, scenarios
- Boron dropper R. Lunsford FIP/2-3 (Thu 15:00)

Diagnostic upgrades
- Correlation ECE
- Correlation Doppler Reflectometer
- Fast Edge Charge Exchange
- Fast Helium Beam Spectroscopy

New split W tile design avoids deep cracking

- Exposure ~1000 discharges
  - > 40 discharges with P_{heat} > 15 MW (max. 20 MW).
- No cracks observed with:
  - Split tile design and
  - Wide HPM1850 tiles.
    - Highest thermomechanical stress
    - More ductile heavy W alloy (97% W, 2% Fe, 1% Ni).



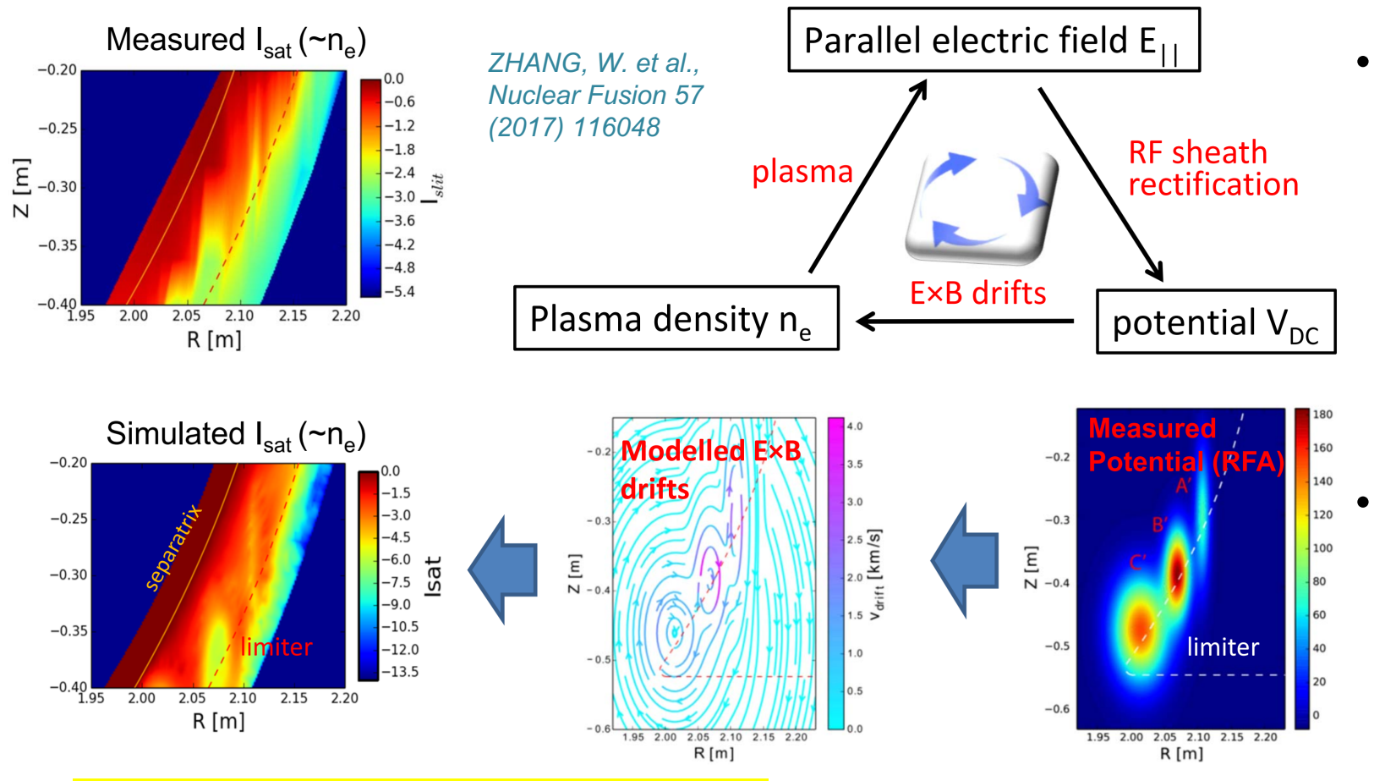
ZAMMUTO, I. et al. SOFT 2018, 16th - 21st Sep., Giardini Naxos, Italy, 2018.

NEU, R. et al., Journal of Nuclear Materials (2018)

Improved understanding of the edge ICRF interaction

J.M. Noterdaeme EX/P8-23 (Fri 14:00)

- Operation of ICRF with a W wall requires understanding of the edge interaction: *Avoid W sputtering, improve coupling*



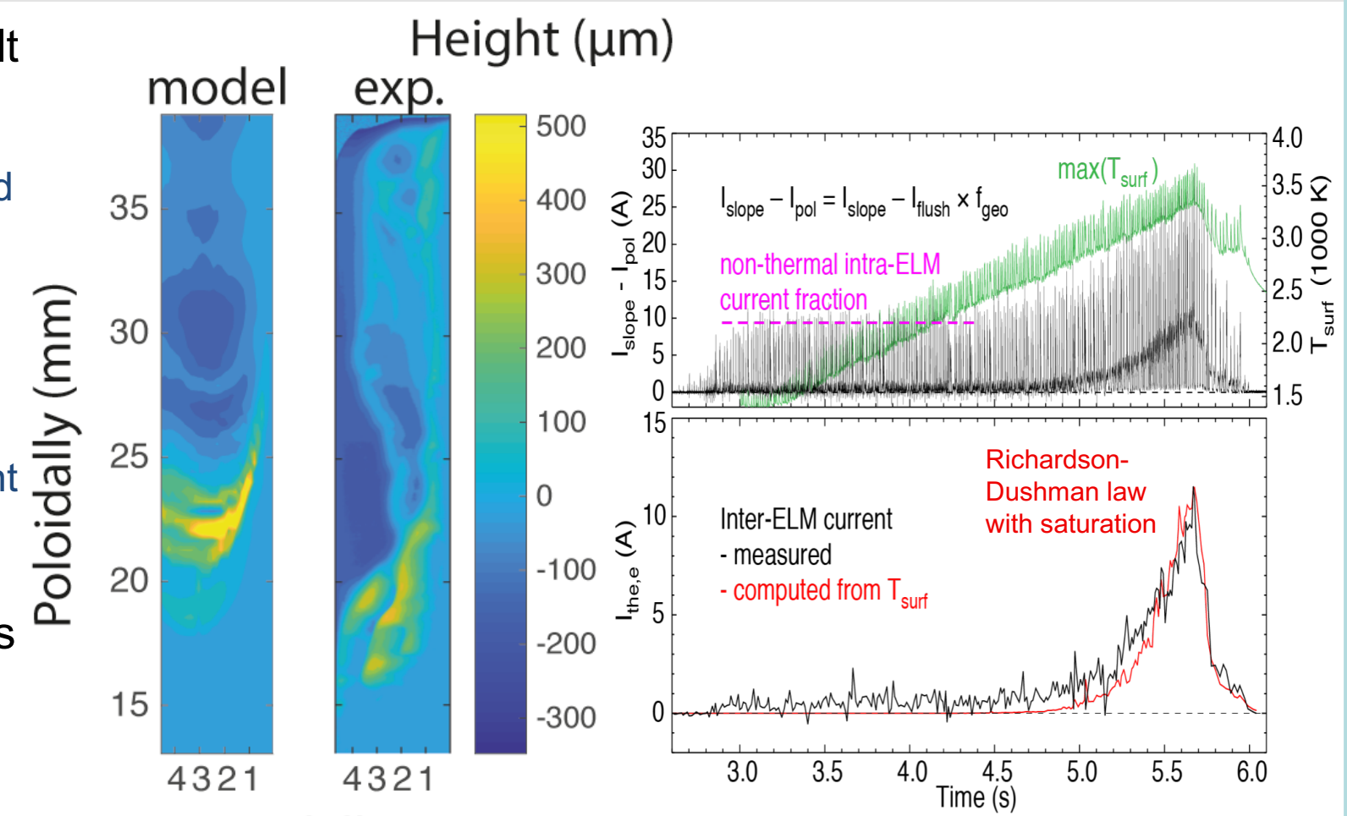
ZHANG, W. et al., Nuclear Fusion 57 (2017) 116048

- Self-consistently coupled codes
  - RF E-field (RAPLICASOL)
  - Sheath-rectified (DC) field (SSWICH)
  - Induced E×B convection (EMC3-EIRENE)
- Convective cells well modelled, in good agreement with measurements

New 3-strap antenna avoids the issue

Modelling of Melt-motion in good agreement with experiment

- First observation of melt motion due to ELM transient.
  - Exposure of misaligned targets on divertor manipulator.
- Simultaneous measurement of T_{surf} and I_{emiss}.
  - During ELMs significant non-thermal current fraction.
- MEMOS 3D simulations of surface deformation and melt displacement agree with experiment.
  - Dominant force: $j \times B$



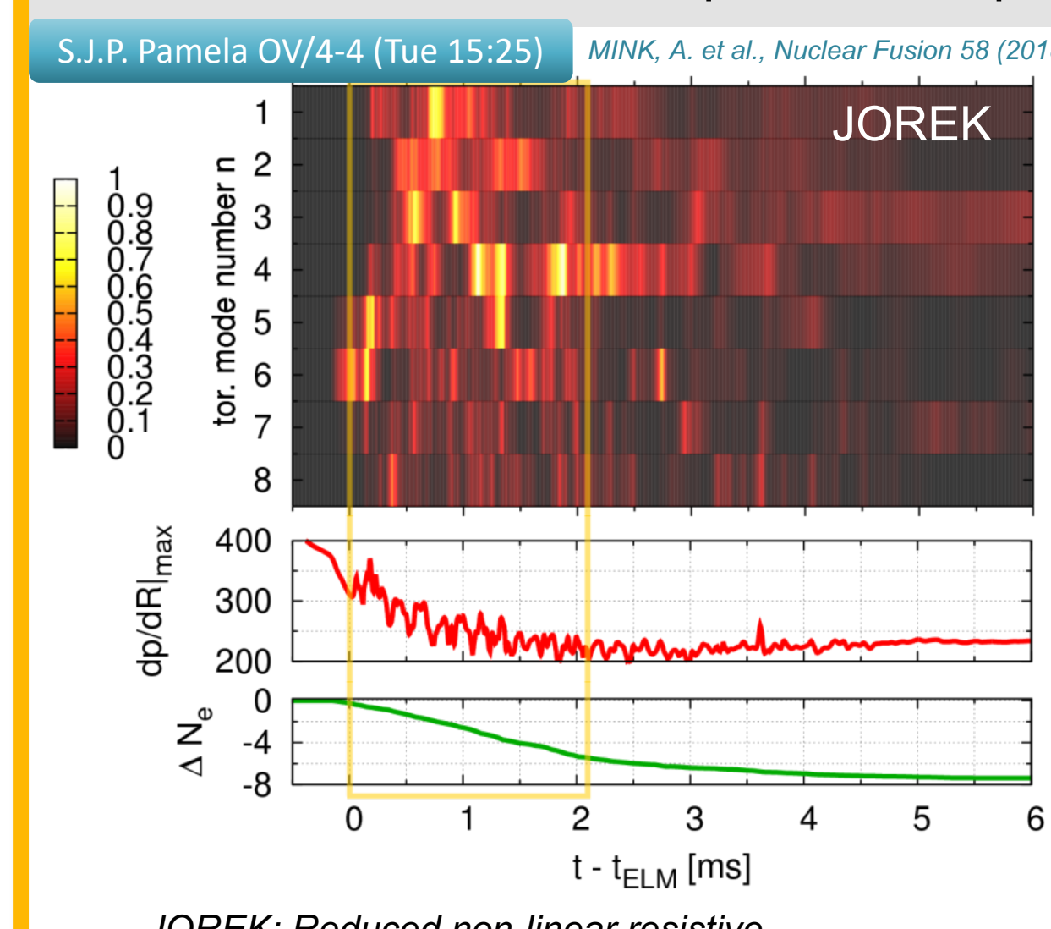
THORÉN, E. et al., submitted to Nucl. Mat. Energy

KRIEGER, K. et al., Physica Scripta 2017 (2017) 014030
KRIEGER, K. et al., 23rd PSI, 17-22 June 2018, Princeton, USA

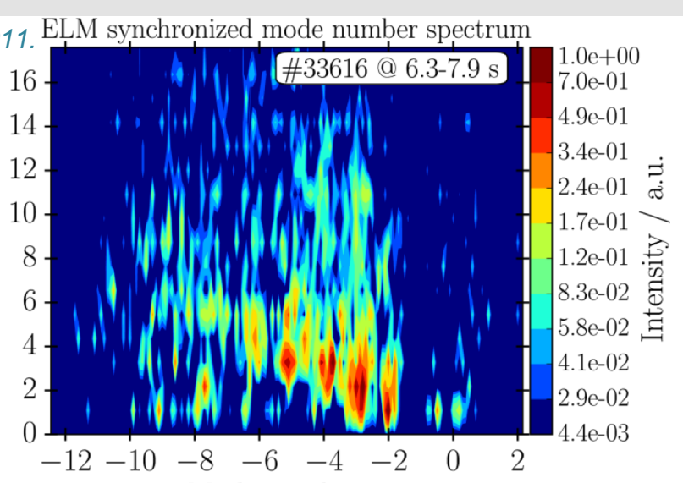
Non-linear resistive MHD reproduces experimental details of ELM crash

S.J.P. Pamela OV/4-4 (Tue 15:25)

MINK, A. et al., Nuclear Fusion 58 (2018) 026011.



JOREK: Reduced non-linear resistive MHD

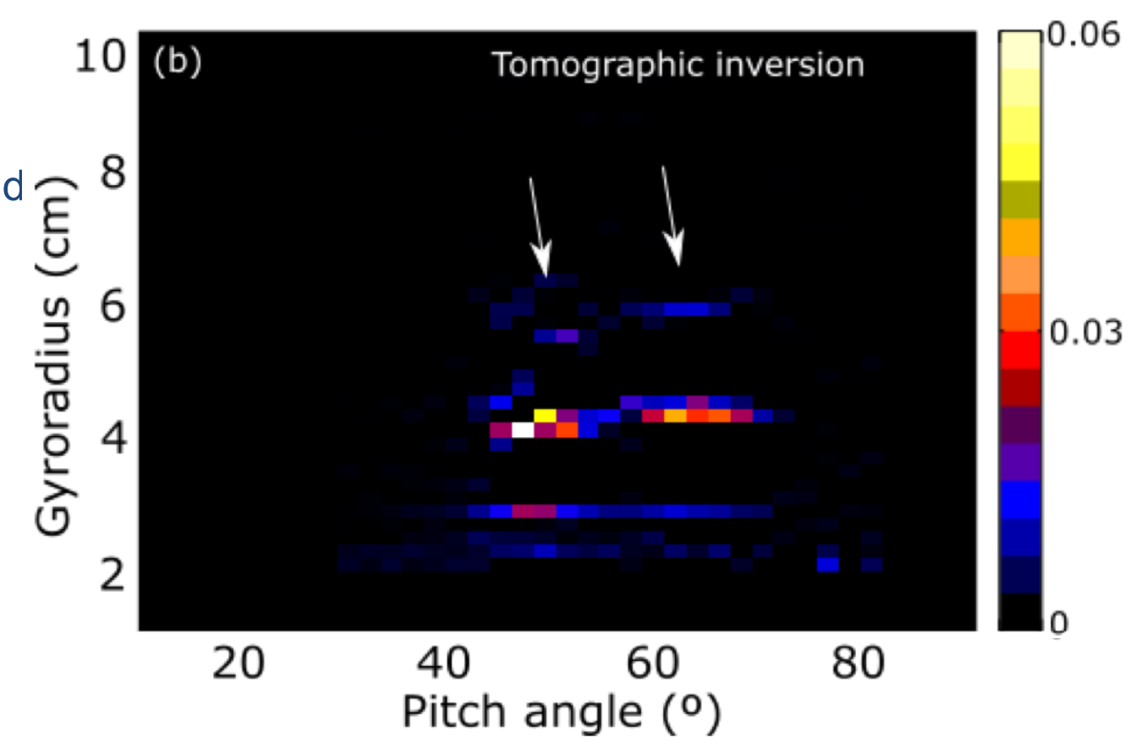


- New analysis technique ⟹ mode spectrum during the ELM crash.
- JOREK reproduces
  - Mode numbers
  - Gradients and particle losses
  - Here: Growth rates agree.
- n=1 is important for mode coupling.

Parallel E-field from reconnection during the ELM accelerates beam ions

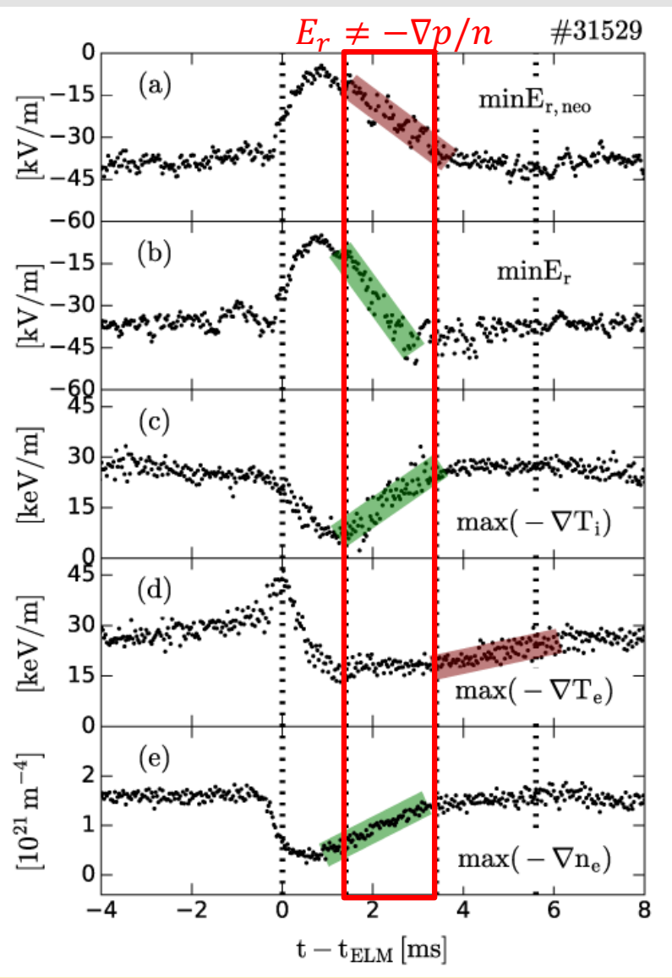
J. Galdon-Quiroga EX/P8-26 (Fri 14:00)

- Population of lost fast-ions measured with $E_{FI} \gg E_{inj}$.
  - Correlated with NBI sources and ELMs.
- Well localised velocity-space structures.
  - From inversion of FILD data.



GALDON-QUIROGA, J. et al., Phys. Rev. Lett. 121 (2018) 025002.

Edge radial E-field dominated by $\nabla p/n$ during most of the ELM cycle



- New fast edge charge exchange system.
  ⟹ E_r and T_i at $\Delta t = 200\ \mu s$
  - All kinetic profiles measurable on a fast time scale.
- E_r evolves on similar time scale as n_e and T_i, T_e evolves slower
- Different phases coincide with edge mode activity.

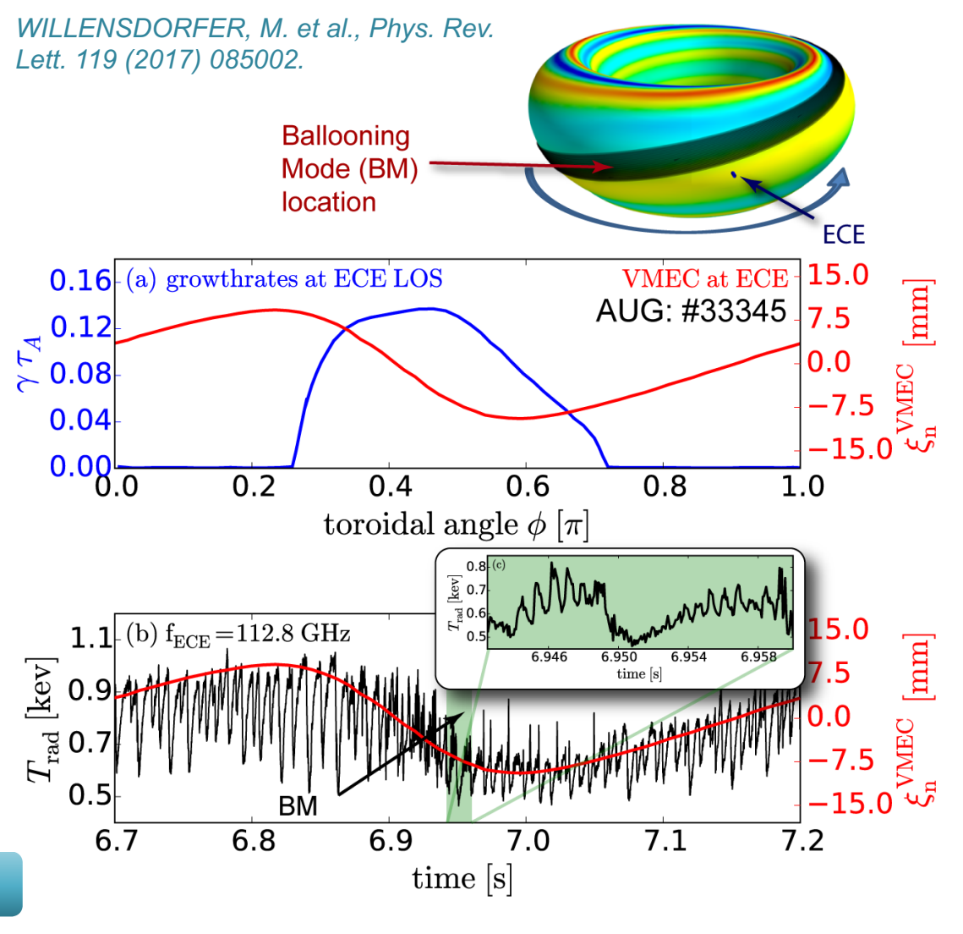
CAVEDON, M. et al., Plasma Physics and Controlled Fusion 59 (2017) 105007

Helical localised Ballooning Mode destabilised by 3D perturbation

- Direct evidence for altered edge stability due to magnetic perturbations (MP).
- Mode observed in particular time during static rotation of MP field.
  - Localised on particular field line.
- No tearing signature, no phase delay between n_e and T_e ⟹ ideal mode.
- Ideal ballooning theory ⟹ mode grows on least stable field line.

COTE, T. B. et al., Submitted to Nucl. Fusion, 2018.

WILLENSDORFER, M. et al., Phys. Rev. Lett. 119 (2017) 085002.



M. Willensdorfer EX/P8-20 (Fri 14:00)

ELM suppression with $\omega_{e,\perp} \neq 0$ – no rotation threshold

Hypothesis:

- Island forms at the pedestal top ⟹ pedestal below PB stability limit.
- Tearing requires $\omega_{e,\perp} \approx 0$ at rational q.
- Supported by JOREK modelling.

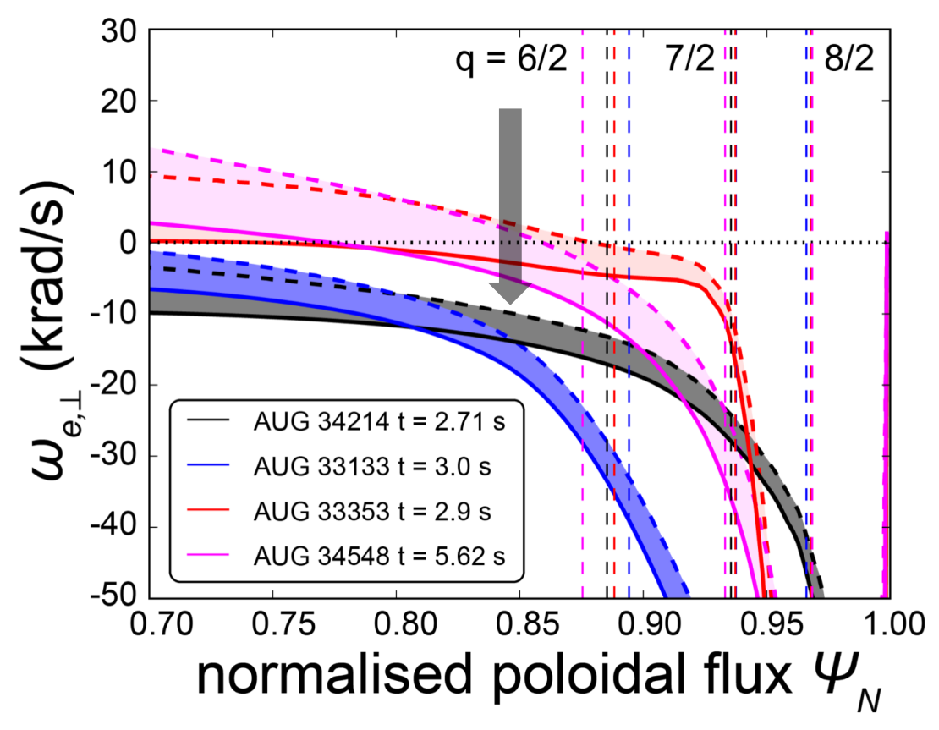
Experiment:

- No rotation threshold found.
- ELM suppression with finite $\omega_{e,\perp}$.
- No experimental evidence of island.

Possible Solution:

- ELM suppression through resistive response **if** kinetic effects destroy shielding of perturbation.

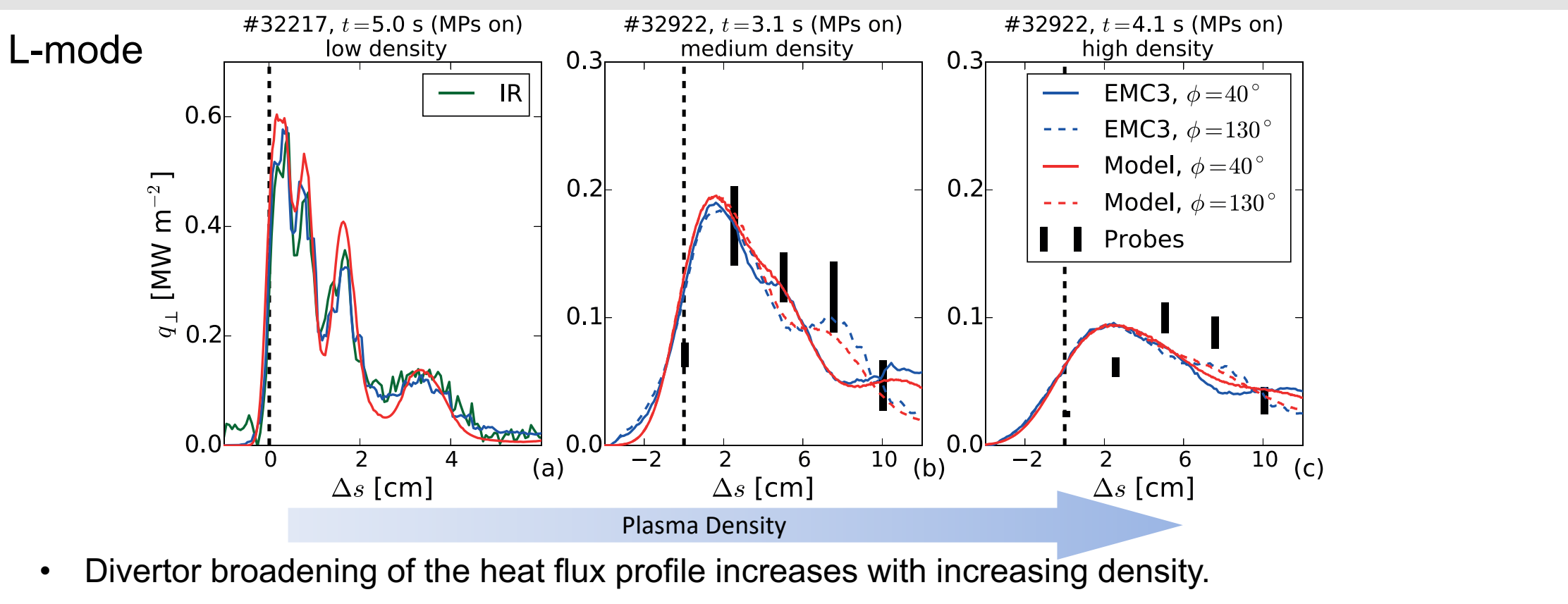
SUTTROP, W. et al., Nuclear Fusion 58 (2018) 096031



W. Suttrop EX/7-3 (Fri 9:10)

2D target footprint from 3D magnetic perturbations vanishes approaching detachment

L-mode



- Divertor broadening of the heat flux profile increases with increasing density.
- 2D spiral pattern is "washed" out.
- Good agreement between EMC3-EIRENE modelling and measurements for attached profiles.

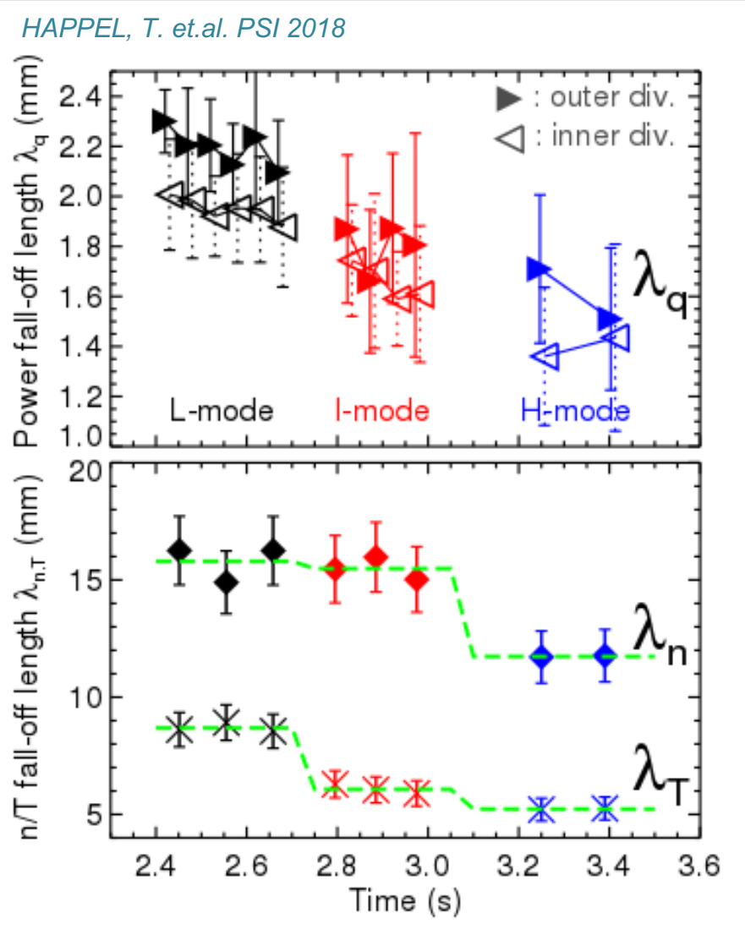
FAITSCH, M. et al., Plasma Physics and Controlled Fusion 59 (2017) 095006.
BRIDA, D. et al., Nuclear Fusion 57 (2017) 116006.

Heat loads in I-mode have been characterised

- I-mode operating space has been extended to higher Greenwald fraction.
  - Stationary: $\bar{n}/n_{GW} = 0.58$
  - Transient: $\bar{n}/n_{GW} = 0.7$
- β_{pol} feedback allows access to stationary I-modes at $H_{H98(y,2)} = 0.8$ and $\bar{n}/n_{GW} = 0.58$.
- Stationary power fall of length of I-mode are in between L-mode and H-mode.
  - Intermittent density bursts could lead to high heat loads in the divertor.

T. Happel EX/2-3 (Wed 11:25)

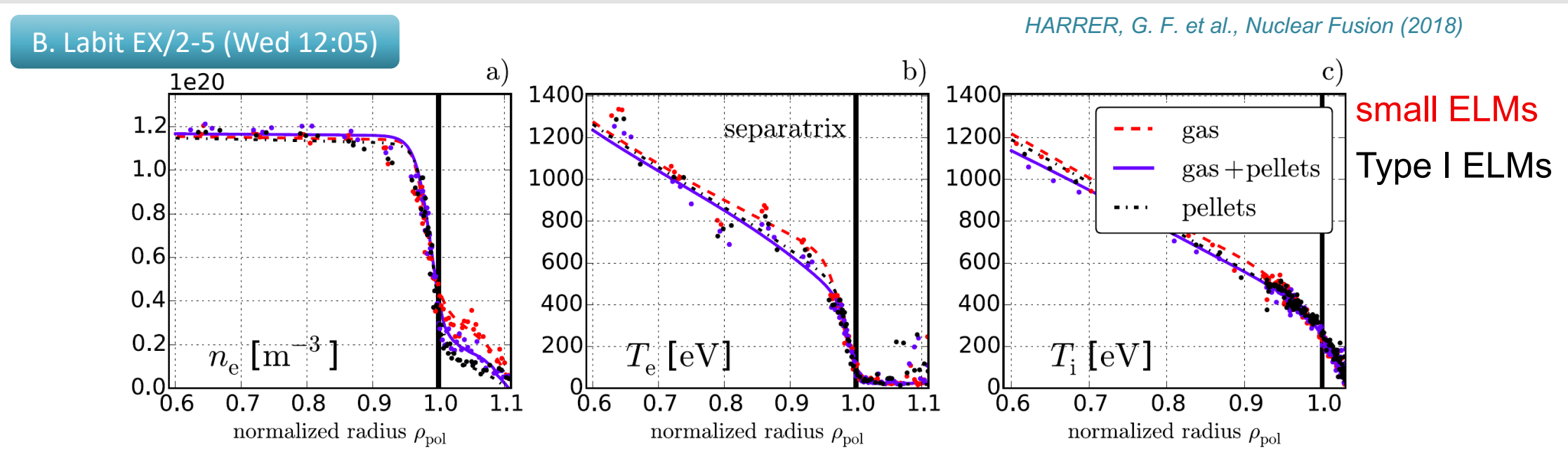
HAPPEL, T. et.al. PSI 2018



Increased ballooning transport at separatrix ⟹ small ELMs

B. Labit EX/2-5 (Wed 12:05)

HARRER, G. F. et al., Nuclear Fusion (2018)



- Higher separatrix density or lower q'/q promote access to small ELM regime.
  - n_e^{sep} controlled by pellet vs. gas fuelling; q'/q controlled by vertical shift.
- Occurrence of small ELMs consistent with drift-ballooning stability.
- Transport at separatrix reduces pedestal width ⟹ ***no type-I ELMs***
- Scenario is close to high density ($\bar{n}/n_{GW} = 0.85$) ITER base-line scenario.

Ballooning limit at pedestal foot consistent with high density limit

- Measured Ballooning parameter

$$\alpha_{sep} = \frac{R q_{cyl}^2}{B_{tor}^2/2\mu_0} \cdot \frac{p_{sep}}{\langle\lambda_p\rangle}$$

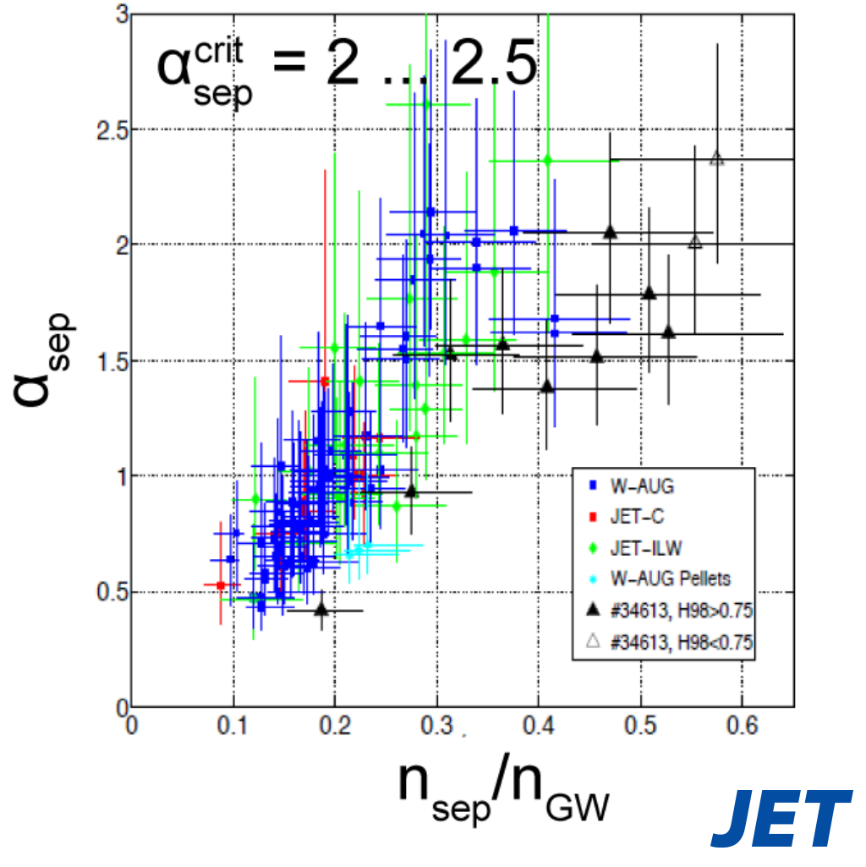
saturates at $\alpha_{crit} \approx 2.5$.
  - Data from edge Thomson Scattering.
- Limit to separatrix density.

Conjecture:

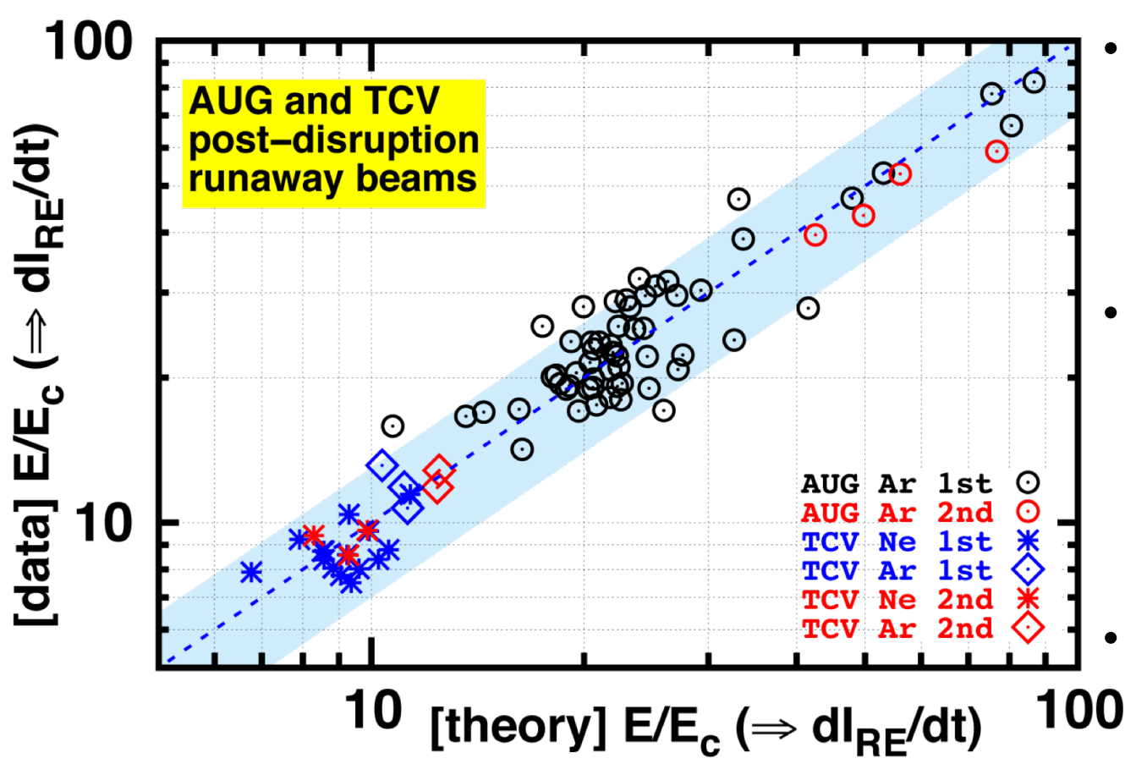
- Increased turbulent transport leads to H-mode density limit (HDL).

$\langle\lambda_p\rangle$: poloidially averaged pressure decay length a separatrix

EICH, T. et al., Nuclear Fusion 58 (2018) 034001.



Runaway Electron beam dissipation by mass injection agrees with modelling



- Fast electron energy dissipated by Coulomb collisions.
  - Quantum mechanical processes need to be considered.
- Good agreement between data and theory on a statistical level.
  - Effective critical field from Fokker Planck solver.
    HESSLOW, L. et al., Phys. Rev. Lett. 118 (2017) 255001.
- Confidence in predicting mass needed for ITER RE mitigation with 2nd injection.

G. Papp et.al. 15th IAEA TM EP, Princeton, NJ, USA

Lower Confinement in H Explained by Larger Ion Heat Flux

Experiment:

- Profile matched D and H L-mode discharges.
  - Dominant e⁻-heating ($P_{net}^D = 1.06\ MW$, $P_{net}^H = 1.39\ MW$).

Simulation: (ASTRA)

- Critical gradient model for χ_e and χ_i without mass dependence *[Garbet PPCF 2004]*.
  - Model adjusted to fit D and then applied to H.
- Only collisional energy exchange is mass dependent.

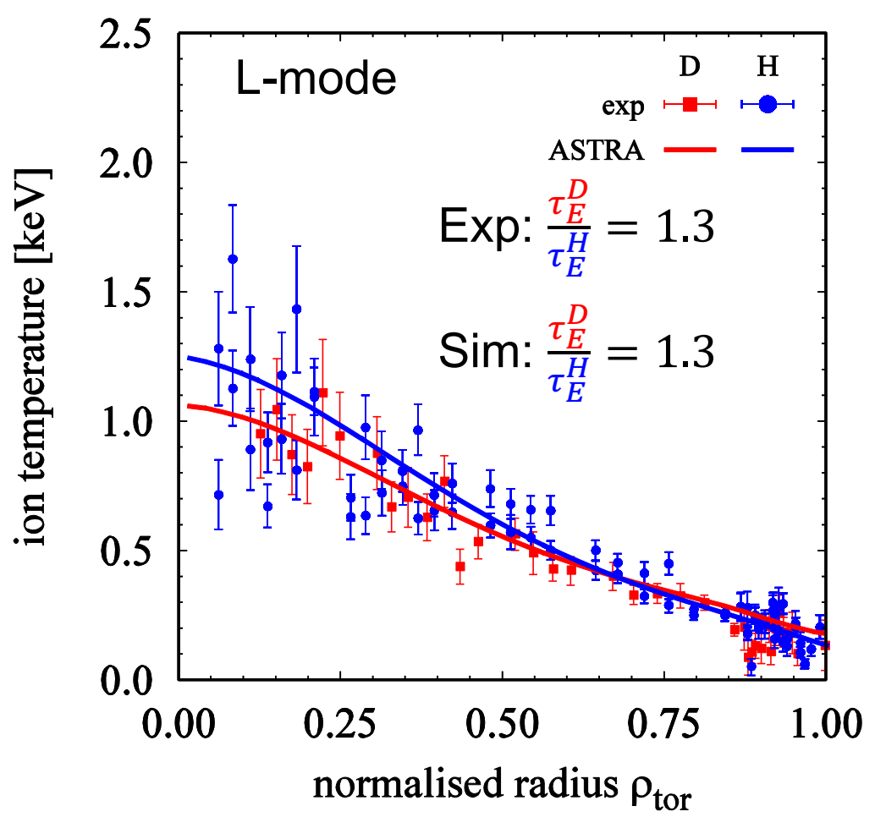
$$P_{ie} \propto \frac{m_e}{m_i}\frac{n^2}{T_e^{3/2}}(T_e - T_i) \Longrightarrow P_{ei}^H = 2P_{ei}^D$$

- Profiles and confinement degradation reproduced.

Matched D and He discharges highlight the importance of zonal flows. MANAS, P. et al., Submitted to Nucl. Fusion.

A. Kappatou EX/P8-1 (Fri 14:00)

SCHNEIDER, P. et al., Nuclear Fusion 57 (2017) 066003.

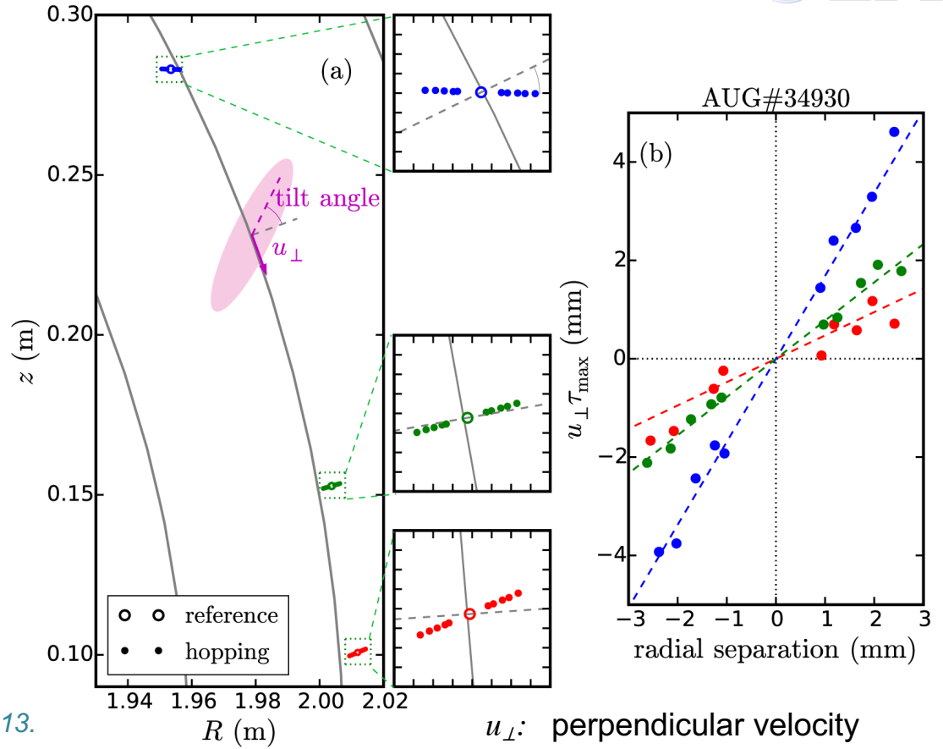


First measurements of tilting of density structures

- Eddy tilt angle identified using Doppler-correlation reflectometry.
- Comparison of NBI and ECRH heated plasmas ⟹ change in tilt angle.
  - Measured change in tilt angle mainly from different $E \times B$ flow shear.
- Should allow to further substantiate the finding that LOC-SOC transition is independent of TEM-ITG transition

Phase velocity: LEBSCHY, A. et al., Nuclear Fusion 58 (2018) 026013.
ASTRA/TGLF: EROFEEV, I. et al., Nuclear Fusion 57 (2017) 126067.

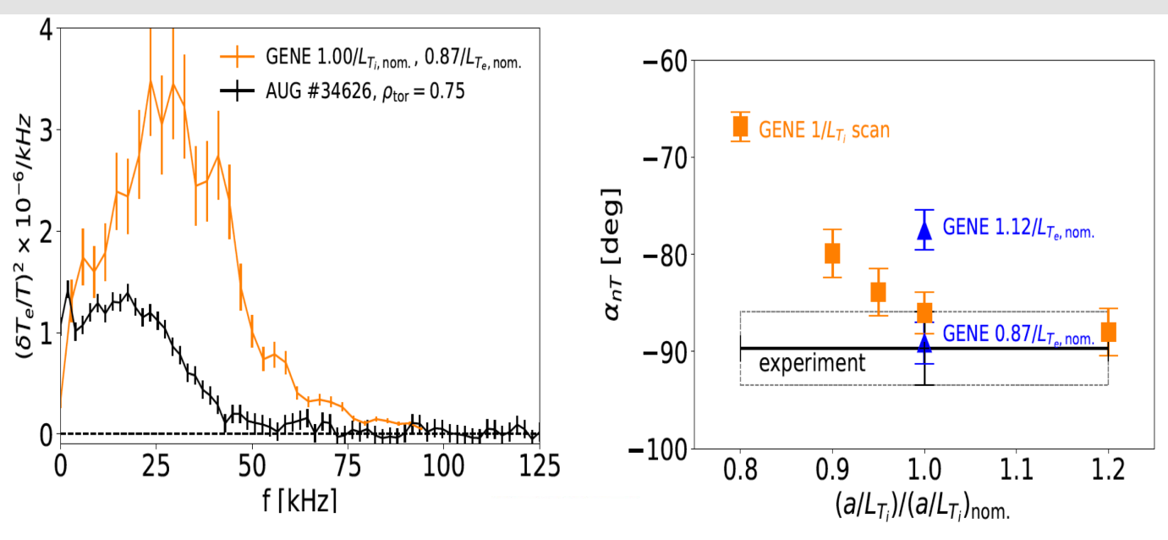
PINZON, J. et.al. subm. to PRL



$u_\perp$: perpendicular velocity
τ_{max}: time delay of cross correlation function

Measured ($\tilde{n}_e$, $\tilde{T}_e$) phase angle agrees with Gyrokinetics

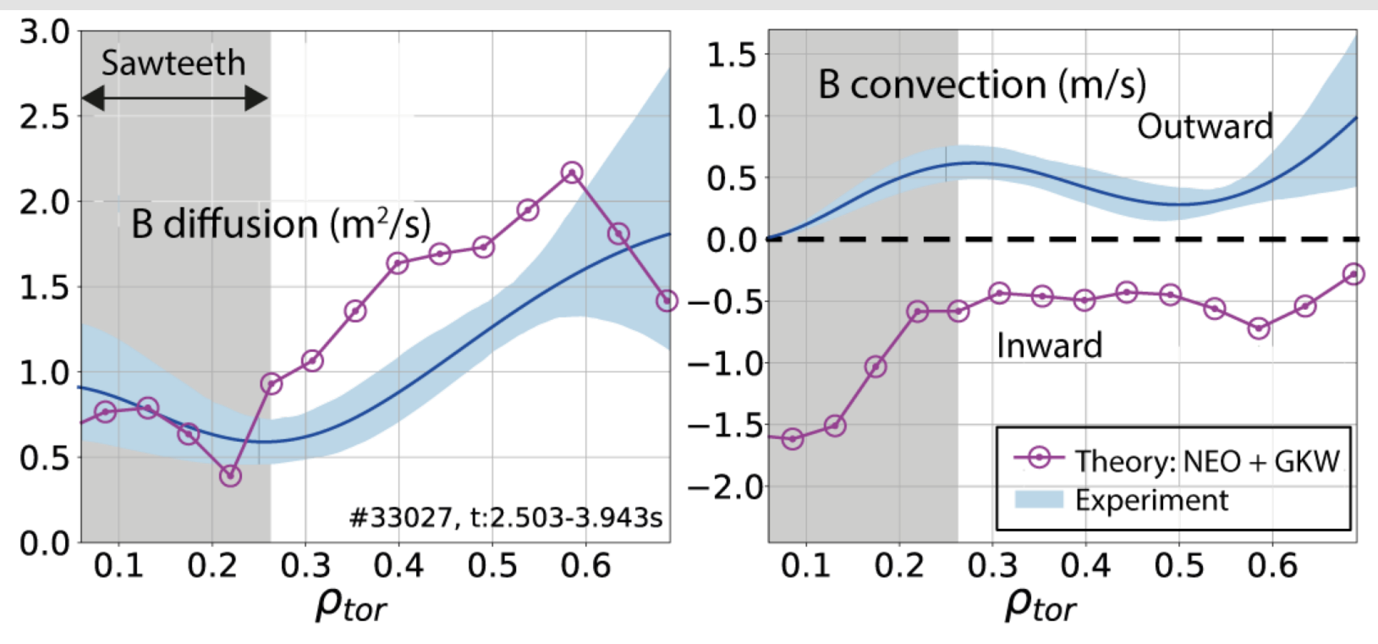
T. Görler TH/P6-5 (Thu 14:00)



FREETHY, S. J. et al., Physics of Plasmas 25 (2018) 055903.

- Phase angle α_{nT} between $\tilde{n}_e$ and $\tilde{T}_e$ is a **strong constraint for gyro-kinetic simulations**.
- Good agreement with Q_i, Q_e, correlation length $L_r(\tilde{T}_e)$ and α_{nT} with GENE within the experimental uncertainties.
  - Calculated $\tilde{T}_e$ fluctuation spectra tend to be broader and with larger amplitudes then measured.

Gyrokinetics fails to predict convection for light impurities



BRUHN, C. et al., Plasma Physics and Controlled Fusion 60 (2018) 085011

Quasi linear GKW:
= linear + saturation

- Large database: R/L_{n_α} for He and B profiles disagree with GKW.
  - Facilitated by Improved analysis of CXRS[1)] and He plume forward modelling[2)] ⟹ accurate impurity density gradients.
- Modulation experiments to determine D and v of B.
- Neocl. + GKW modelling agrees with D, **but predicts v to be in the opposite direction**.

[KAPPATOU, A. et al., To be submitted to Nucl. Fusion.]

[1)] McDERMOTT, R. . et al., Plasma Phys. Contr. Fusion, 60 (2018) 095007
[2)] KAPPATOU, A. et.al. Plasma Phys. Contr. Fusion, 60 (2018) 055006

Significant progress in predicting ITER and DEMO

Device
- Upgraded long pulse ECRH (6 MW, 10s)
  - Up to 8 MW by end of 2018.
- New internal coil power supplies.

Edge
- Deep insight into 3D edge physics
  - ELM suppression – achieved with finite $v_{e,\perp}$ over the whole pedestal
  - Helical localised ballooning mode destabilised by bad curvature on field line.
- Reconnection during ELM causes fast ion acceleration.

Core
- New measurements challenge gyro-kinetic modelling
  - Eddy tilt angle measurements consistent with ITG to TEM transition
  - $\tilde{T}_e/T_e$ and (n_e, T_e) phase angle.
- Series of experiment highlight importance of P_{ei} for isotope studies.
  - Important to match electron and ion heating for extrapolation.

The future: New upper divertor to study alternative configurations

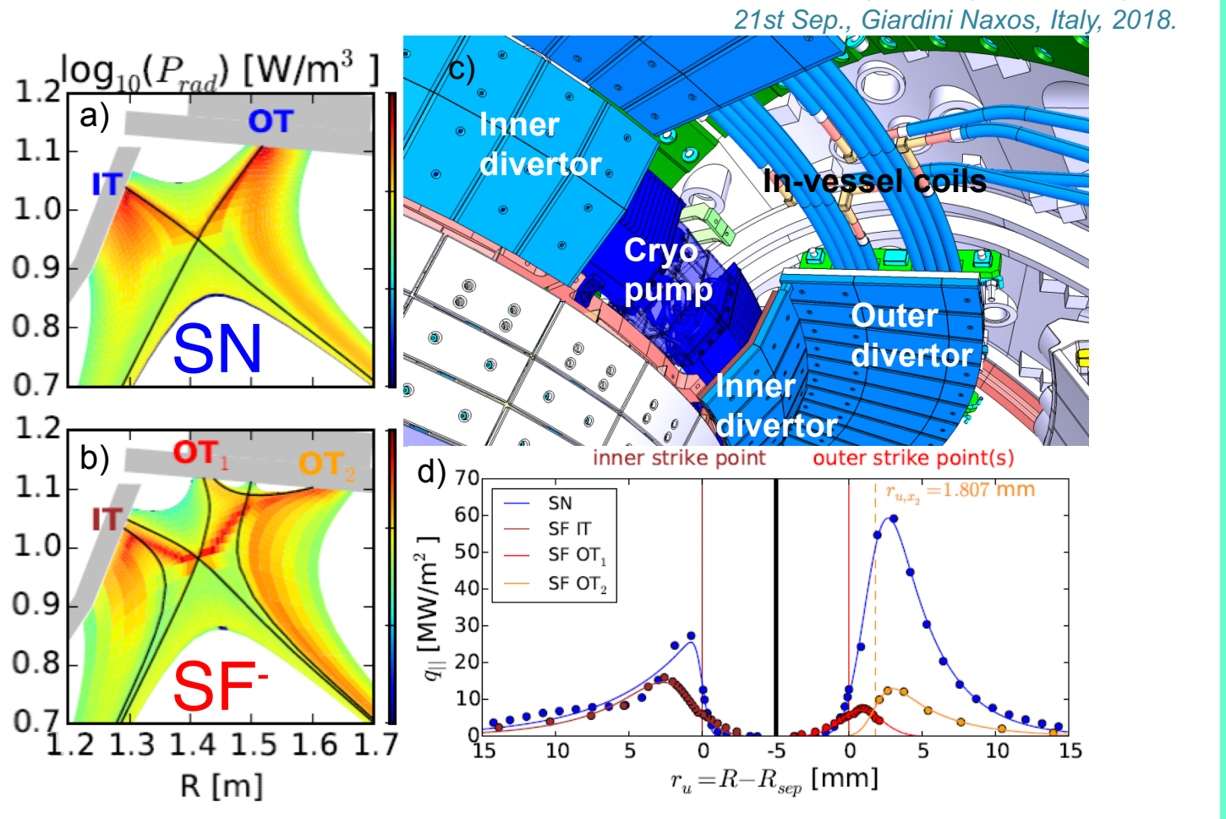
Hardware:

- Two new in-vessel coils
- Cryogenic pump
- Better diagnostics

Studies:

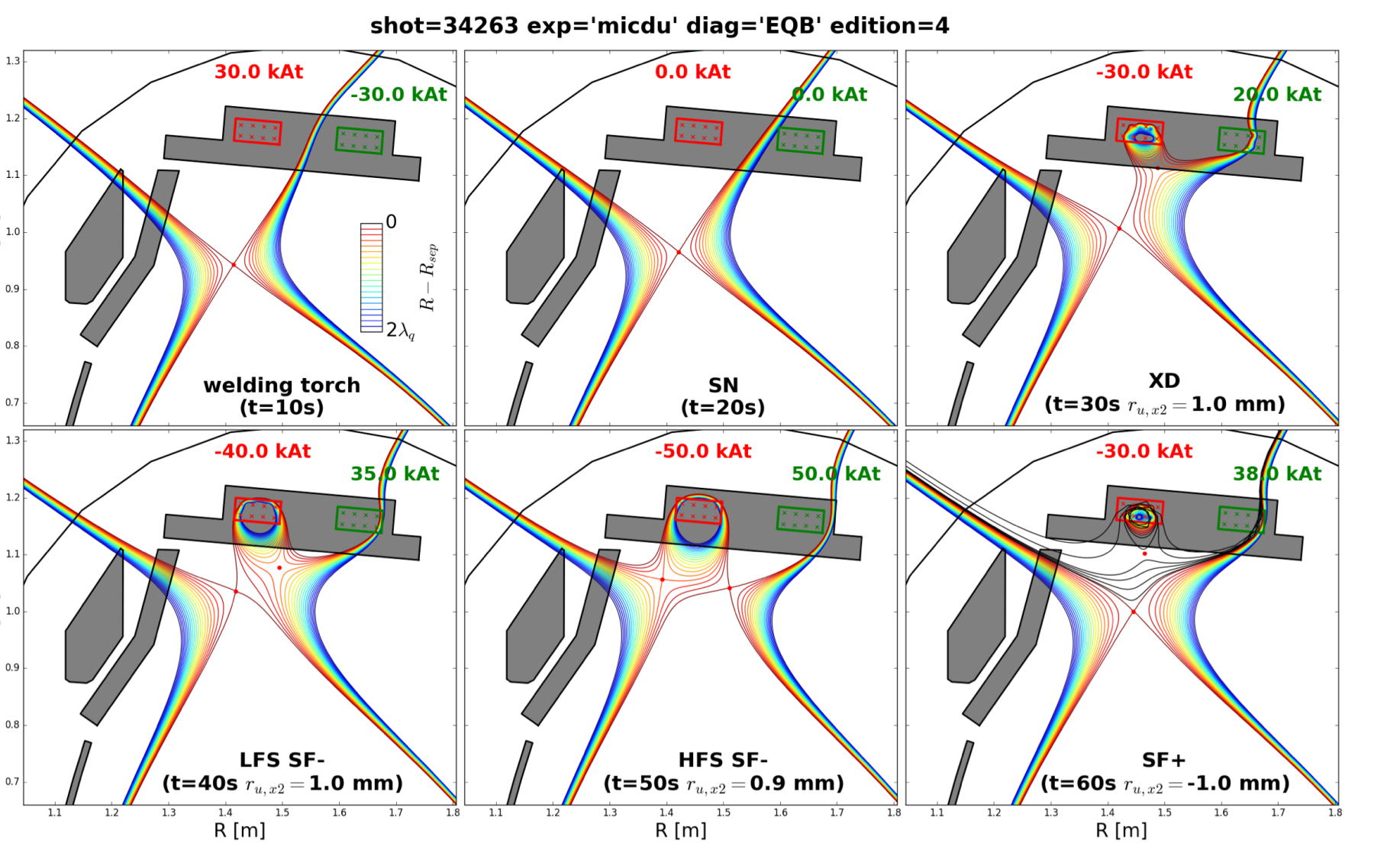
- Alternative configurations at high heat flux
  - X-divertor.
  - Snow-Flake divertor.
  - Flux expansion.
- Two fluid simulations (SOLPS) predict strong reduction in heat-flux

HERRMAN, A. et al., SOFT 2018, 16th - 21st Sep., Giardini Naxos, Italy, 2018.



PAN, O. et al., Plasma Physics and Controlled Fusion 60 (2018) 085005

The future: New upper divertor to study alternative configurations



---

[*] See the author list H. Meyer et al 2017 Nucl. Fusion **57** 102014

Pedestal & ELMs
S.J.P. Pamela OV/4-4 (Tue 15:25) - oral
B. Labit EX/2-5 (Wed 12:05) – oral
W. Suttrop EX/7-3 (Fri 9:10) - oral
F. Laggner EX/P6-4 (Thu 14:00)
M. Dunne EX/P8-2 (Fri 14:00)
E. Viezzer EX/P8-5 (Fri 14:00)

SOL & Divertor
R. Lunsford FIP/2-3 (Thu 15:00) - oral
A.H. Nielsen TH/P7-4 (Fri 8:30)
M. Wischmeier TH/P7-5 (Fri 8:30)
N. Vianello EX/P8-13 (Fri 14:00)
C. Silva EX/P8-11 (Fri 14:00)

Scenario & Heating:
T. Happel EX/2-3 (Wed 11:25) - oral
Y. Kazakov EX/8-1 (Fri 15:20) - oral
T. Pütterich EX/P8-4 (Fri 14:00)
L. Frassinetti EX/P8-22 (Fri 14:00)
J.M. Noterdaeme EX/P8-23 (Fri 14:00)

Transport & Confinement:
F. Ryter EX/P8-3 (Fri 14:00)
T. Görler TH/P6-5 (Thu 14:00)
G. Verdoolage EX/P7-1 (Fri 8:30)
A. Kappatou EX/P8-1 (Fri 14:00)

MHD:
E. Strait OV/4-5 (Tue 15:40) – oral
F. Lui TH/P5-18 (Thu 8:30)
A. Snicker TH/P2-8 (Tue 14:00)
M. Willensdorfer EX/P8-20 (Fri 14:00)
V. Igochine EX/P8-21 (Fri 14:00)

Fast Ions & Current Drive
P. Lauber EX/1-1 (Tue 10:45) – oral
M. Weiland TH/6-3 (Fri 14:00) - oral
B. Geiger EX/P8-24 (Fri 14:00)
D. Rittich EX/P8-25 (Fri 14:00)
J. Galdon-Quiroga EX/P8-26 (Fri 14:00)

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.