Role of stationary zonal flows and momentum transport for L-H transitions in JET

26th IAEA Fusion Energy Conference
Kyoto, Japan – October 17-22, 2016

Presented by

J.C. Hillesheim

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.

Contributors

J.C. Hillesheim[1] E. Delabie[2], E. R. Solano[3], C. F. Maggi[1], H. Meyer[1], F. Rimini[1], I. Carvalho[4], I. Nunes[4], M. Barnes[5,1], E. Lerche[6], M. Stamp[1], A. Drenik[7], M. Mantsinen[8,9], C. Challis[1], J. Buchanan[1], F.I. Parra[5,1], L. Meneses[4], E. Poli[7], J. Hobirk[7], and JET Contributors*

EUROfusion Consortium JET, Culham Science Centre, Abingdon, OX14 3DB, UK

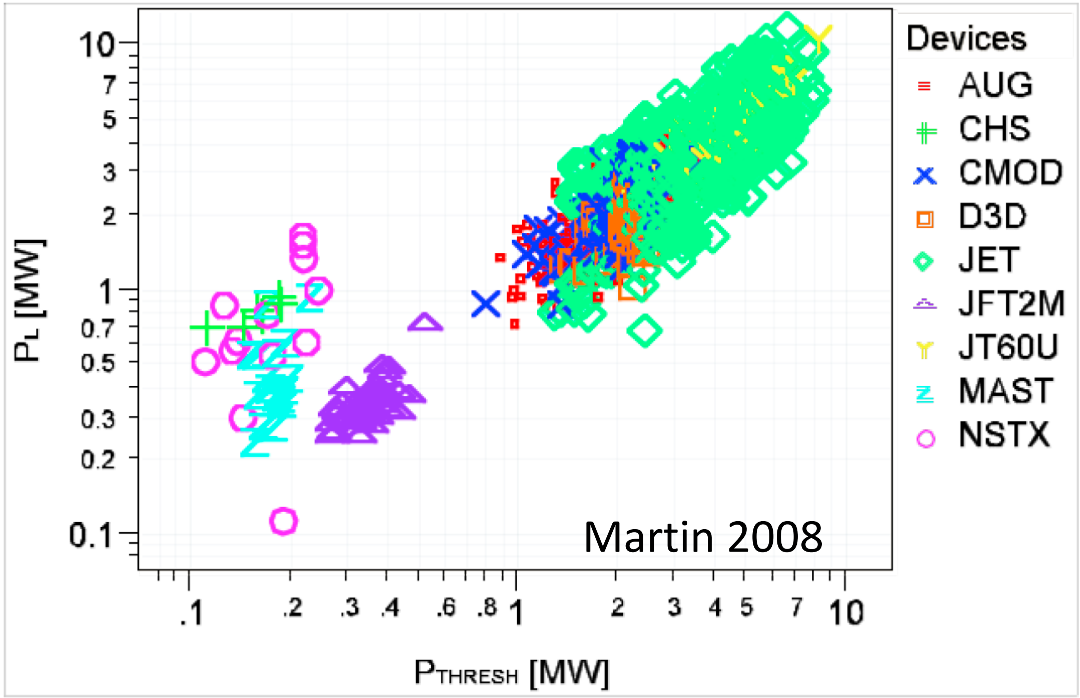
[1] CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[2] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[3] Laboratorio Nacional de Fusion, CIEMAT, Madrid, Spain
[4] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[5] University of Oxford, UK
[6] LPP-ERM/KMS, Association EUROFUSION-Belgian State, TEC partner, Brussels, Belgium
[7] Max-Planck-institut fur Plasmaphysik, Garching, Germany
[8] Barcelona Supercomputing Center, Barcelona, Spain
[9] ICREA, Barcelona, Spain

*See the author list of ``Overview of the JET results in support to ITER'' by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)

Power Threshold to Access H-mode Remains a Significant Uncertainty for ITER

- Work on L-H transition physics in JET-ILW:
  - Maggi NF 2014, Delabie EPS 2014, Delabie IAEA 2014, Meyer EPS 2014, Hillesheim PRL 2016

- Factors known to impact threshold not included in scaling law include
  - Rotation, divertor configuration, X-point height, connection length, low density branch, and others



$$P_L = P_{OHM} + P_{abs} - dW/dt - P_{Floss}$$

$$P_{Thresh} = 0.0488\ e^{\pm 0.057}\ n_{e20}^{0.717\pm 0.035}\ B_T^{0.803\pm 0.032}\ S^{0.941\pm 0.019}$$

Density $[10^{20} m^{-3}]$	Predicted threshold power [MW]	95% confidence interval [MW]
0.5	52	28 - 96
1	86	46 - 160

Outline

- L-H transition power threshold results at high magnetic field and plasma current in JET

- Scaling of zonal flow properties and comparison to width of edge radial electric field well

- Momentum transport during L-H transitions
  - Comparison to linear and non-linear gyrokinetic simulations

- Recent results in hydrogen/deuterium mixtures

Outline

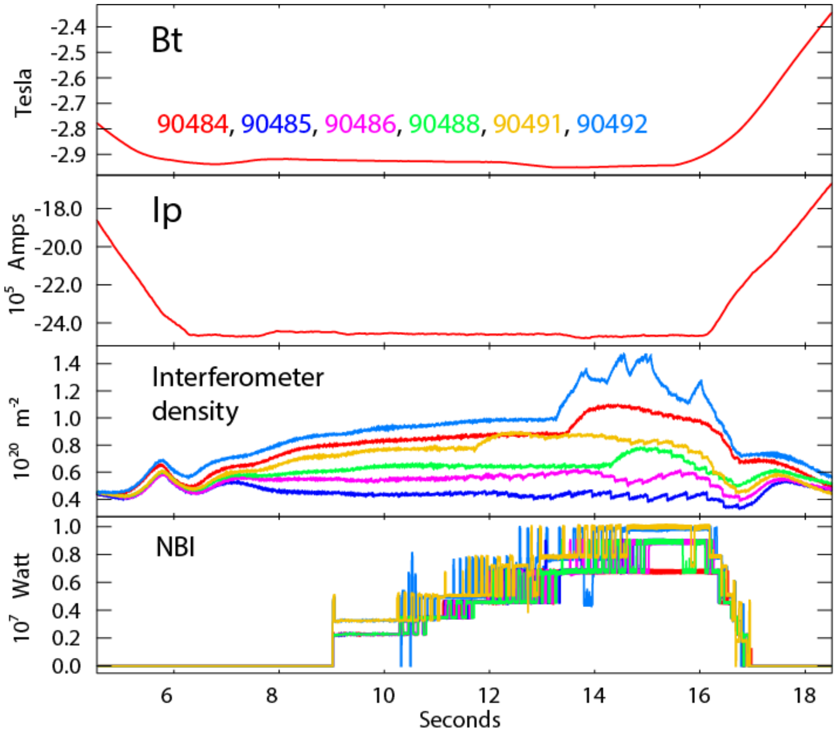
- L-H transition power threshold results at high magnetic field and plasma current in JET

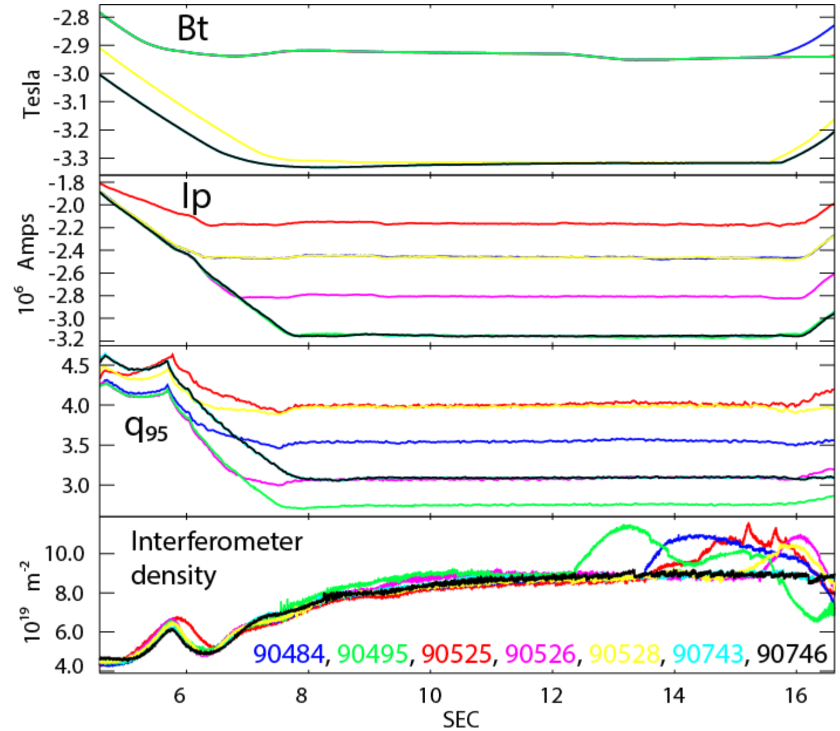
- Scaling of zonal flow properties and comparison to width of edge radial electric field well

- Momentum transport during L-H transitions
  - Comparison to linear and non-linear gyrokinetic simulations

- Recent results in hydrogen/deuterium mixtures

Density, current, and magnetic field scans performed in L-H transition experiments



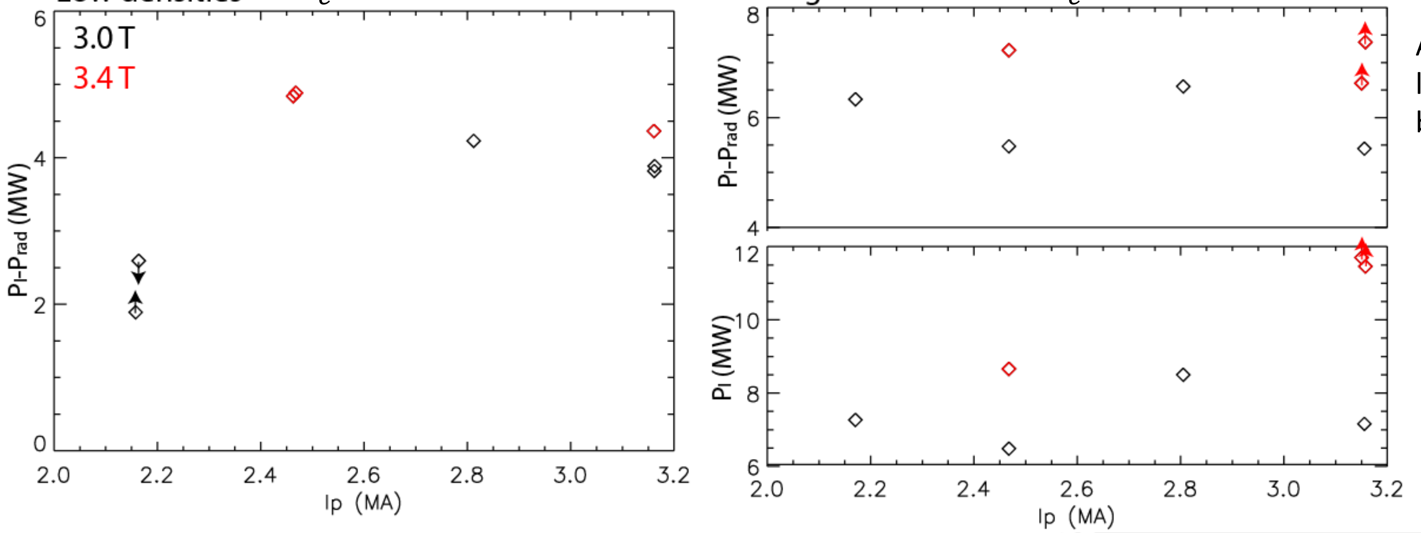


- Same divertor configuration used for baseline and hybrid scenarios
- Slow power ramp to identify L-H transitions
- Excellent density control in plasma current and magnetic field scans
- Scans of Bt (3-3.4 T) and Ip (2.2-3.2 MA) covering $q_{95} \approx 2.7 - 4.0$ at low ($\sim 2.0 - 2.3 \times 10^{19}\ m^{-3}$) and high density ($\sim 3.2 - 3.3 \times 10^{19}\ m^{-3}$)

Dependence on plasma current characterized

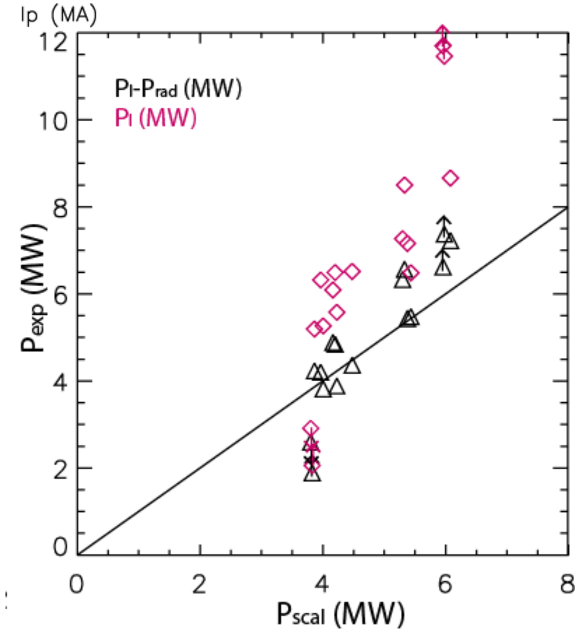
Low densities $<n_e> \approx 2.0 - 2.3 \times 10^{19}\ m^{-3}$

High densities $<n_e> \approx 3.2 - 3.3 \times 10^{19} m^{-3}$



Arrows indicate lower or upper bounds

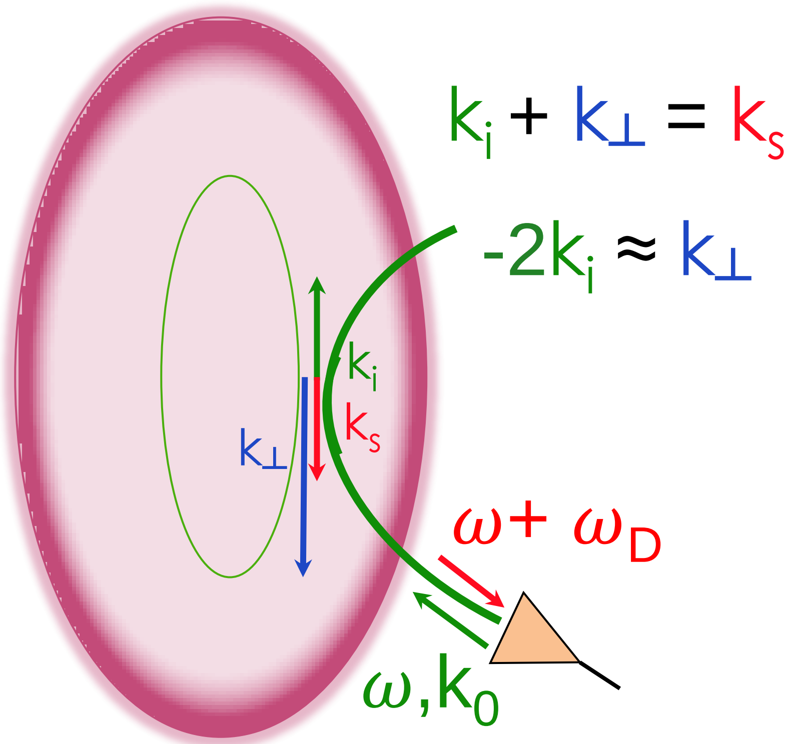
- No Ip dependence in 2008 scaling law
    - Weak dependence, $\sim I_p^{0.2}$, found in Maggi NF 2014
- Plasma current can impact power threshold in low density branch
    - Seen also in other cases in JET-ILW
- Highest threshold cases fall above scaling law prediction



Outline

- L-H transition power threshold results at high magnetic field and plasma current in JET
- Scaling of zonal flow properties and comparison to width of edge radial electric field well
- Momentum transport during L-H transitions
  - Comparison to linear and non-linear gyrokinetic simulations
- Recent results in hydrogen/deuterium mixtures

Doppler backscattering measures the radially-localized lab frame velocity and density fluctuation level



Starting during 2015 campaign, DBS measurements now routine in JET

- Doppler backscattering (DBS):
  - A refraction-localized scattering region is created near the cutoff
  - Amplitude of backscattered signal related to fluctuation level of density fluctuations
  - Doppler shift in backscattered signal induced by lab frame velocity of the turbulence

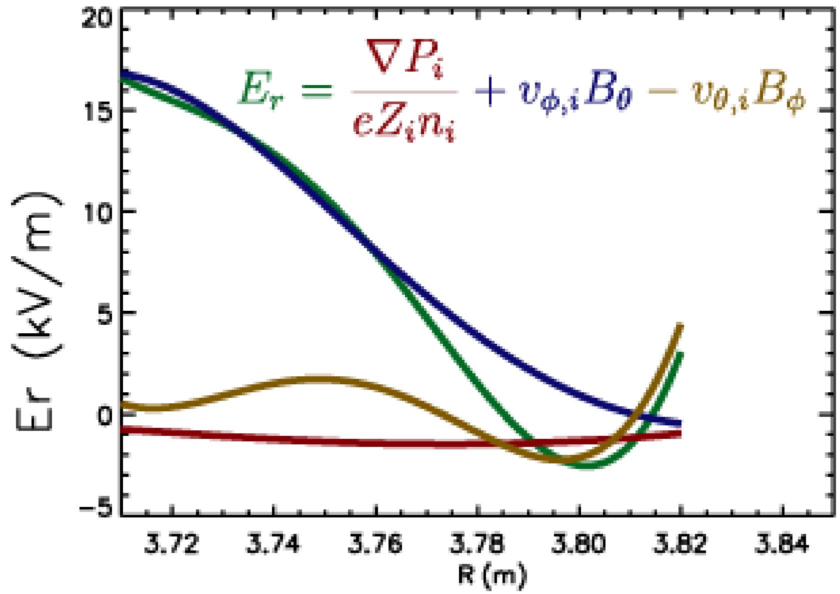
$$\omega_D \approx k_\perp v_{Lab}$$

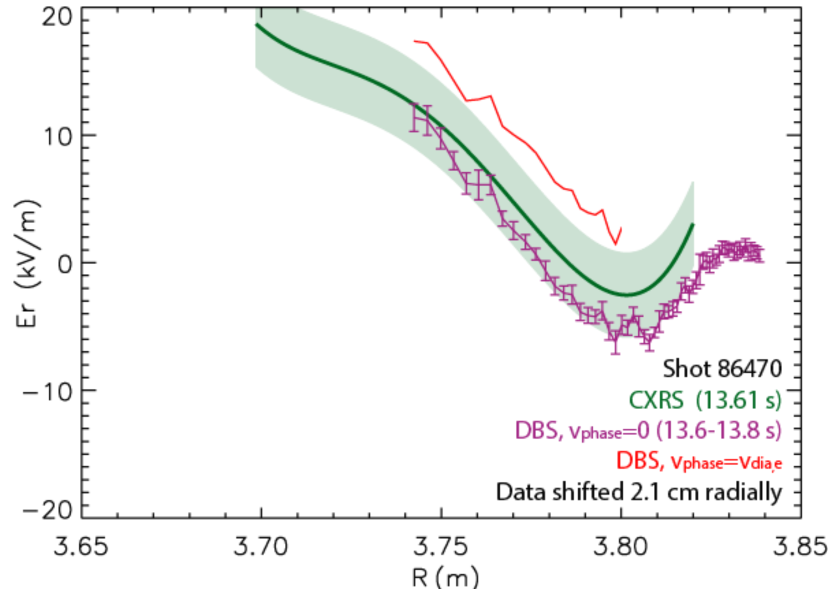
$$v_{Lab} = v_{E\times B} + \widetilde{v}$$

  - TORBEAM used to determine scattering position and wavenumber
    - $k_\perp \approx 3 - 5\ cm^{-1}$

JET CCFE

Comparison between DBS and CXRS in L-mode

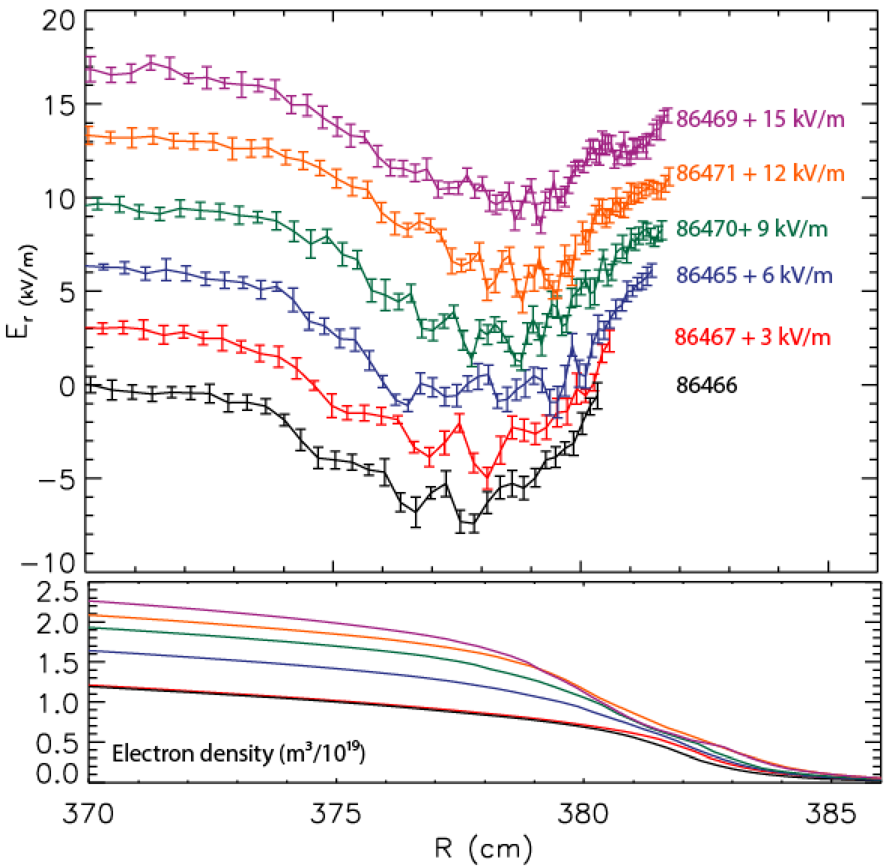




$$v_{turb,DBS} = \underbrace{\overbrace{\frac{\nabla P_i}{eBZ_i n_i} + v_{\phi,i}\frac{B_\theta}{B} - v_{\theta,i}\frac{B_\phi}{B}}^{CXRS} + v_{phase}}_{DBS}$$

- DBS profiles built up with 2 tunable channels over ~200 ms
- Spline fits performed to CXRS components from carbon impurity to calculate E_r
- Comparison between CXRS and DBS implies $0 < v_{ph} < v_{dia,e}$ in L-mode well region
  - Later linear gyrokinetic calculations consistent with modes propagating in electron direction
- All later DBS profiles assume $v_{ph} = 0$

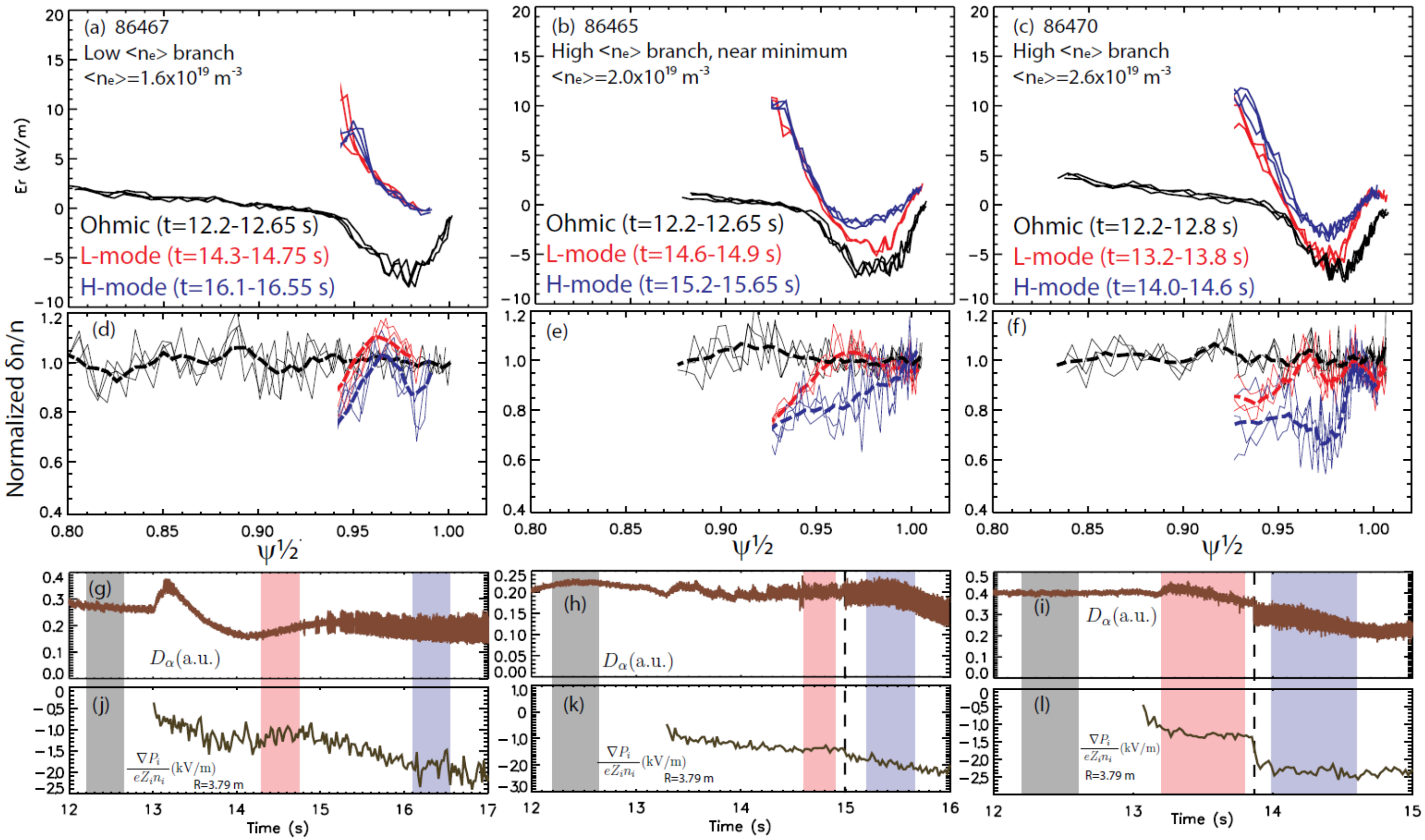
Fine-scale structure in E_r profile consistent with zonal flows observed at bottom of edge well



- Wavelength of zonal flow structures varies with density
- Zonal flows stationary in time
- Small experiments at larger ρ^* have observed variety of oscillatory ZF, but not stationary ZF
  - Conway PRL 2011, Estrada PRL 2011, Xu PRL 2011, Schmitz PRL 2012, Tynan NF 2013

JET CCFE CULHAM CENTRE FUSION ENERGY

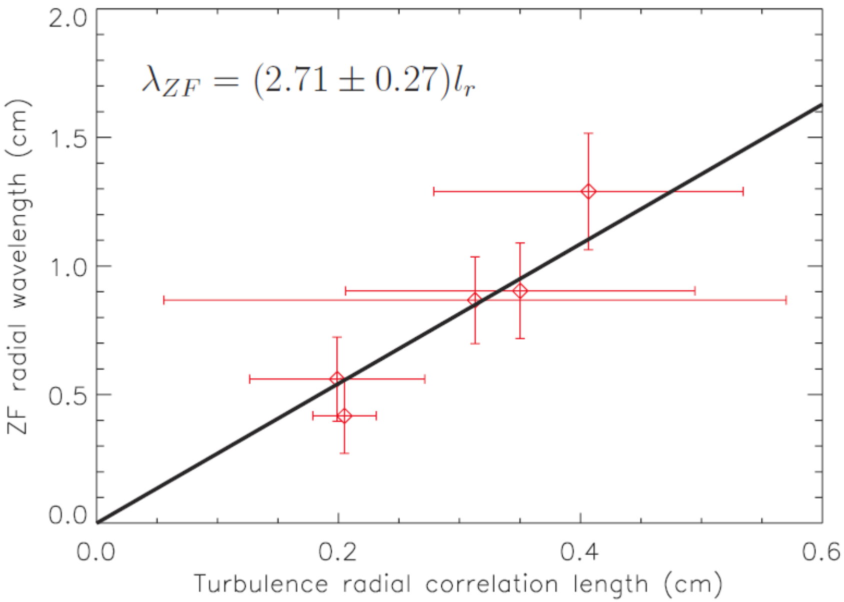
Measurements from Ohmic to L-mode to H-mode show differences with density



- Simultaneous collapse of density fluctuation levels, turbulence phase velocity, and zonal flows across transition in high density branch, but not low density branch
  - Hillesheim PRL 2016
- No clear ‘smoking gun’ relating stationary ZF to transition ‘trigger’

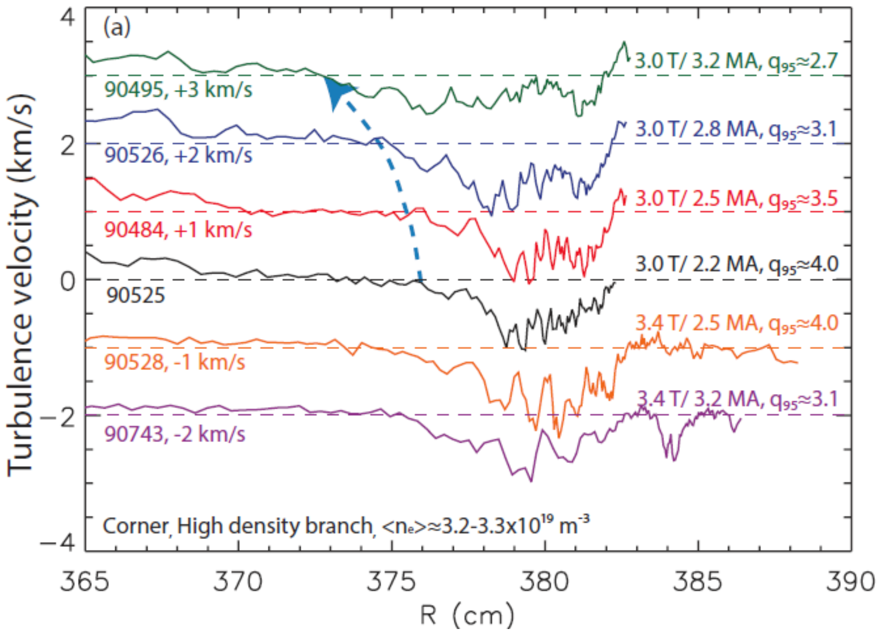
JET CCFE CULHAM CENTRE FUSION ENERGY

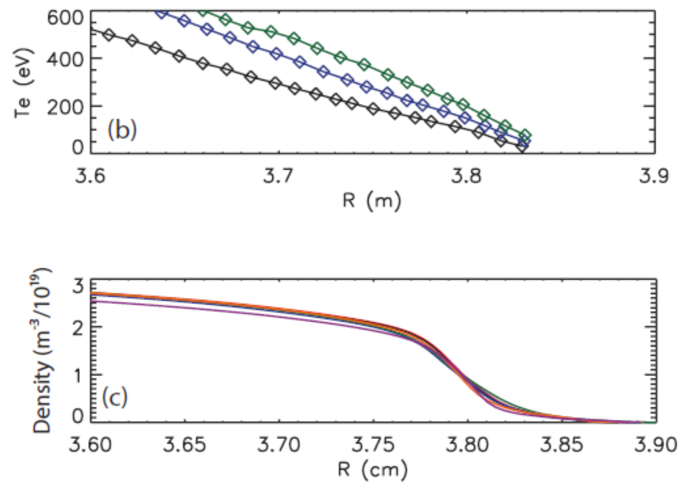
Data with periodic zonal flow structures used to characterize local parameter dependencies



- ZF wavelength correlates with radial correlation length of turbulence
  - $k_{ZF} l_r \approx 2.3$
- Radial correlation length much smaller than well width
  - w_{E_r} ~5-8 cm
- When stationary ZF are observed, $\frac{\ell_r}{w_{E_r}} \ll 1$

Width of radial electric field well varies in plasma current scan





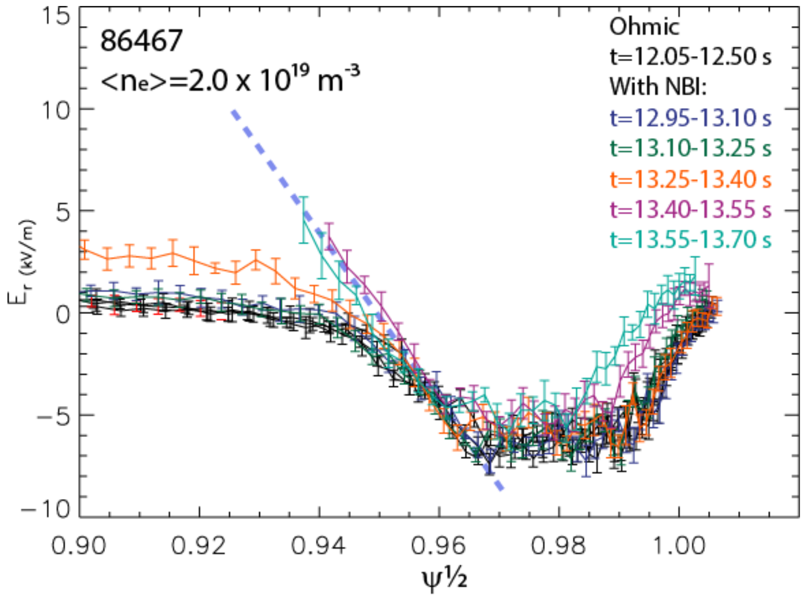
Profiles translated for radial alignment

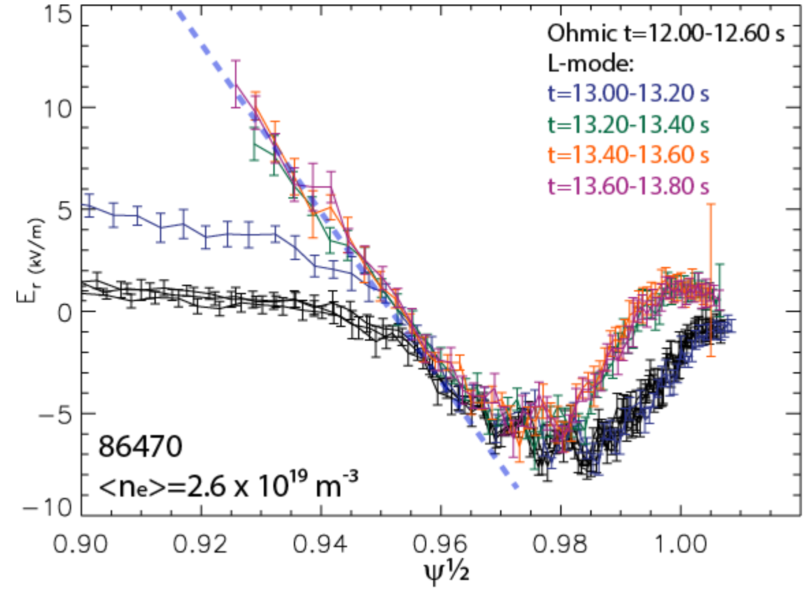
- Plasma current increased ~50% and edge temperature approximately doubles in Ip scan at 3 T, such that banana orbit width changes only marginally
  - T_e=T_i within uncertainties in similar conditions where CXRS available
- Independent variation of E_r well width and radial correlation length may play role as effective ρ^* development of the edge transport barrier
  - May explain why stationary zonal flows observed in JET, but not in smaller experiments

Outline

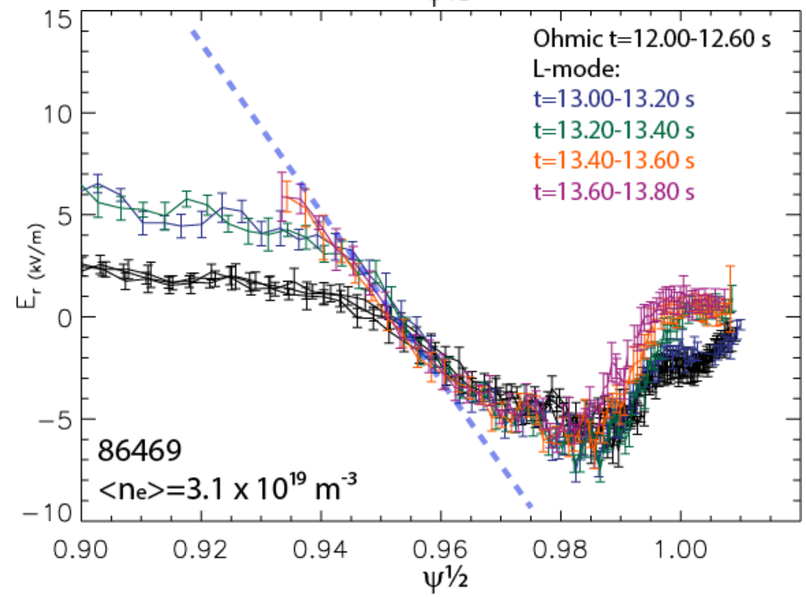
- L-H transition power threshold results at high magnetic field and plasma current in JET
- Scaling of zonal flow properties and comparison to width of edge radial electric field well
- Momentum transport during L-H transitions
  - Comparison to linear and non-linear gyrokinetic simulations
- Recent results in hydrogen/deuterium mixtures

In region where E_r dominated by toroidal rotation, flow builds into core at constant gradient value

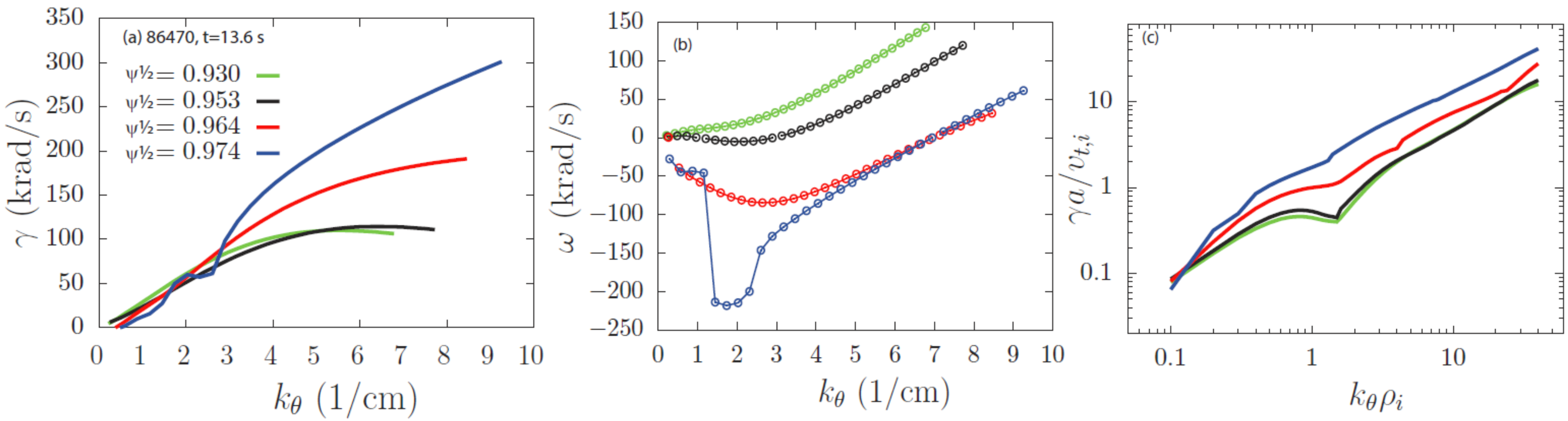




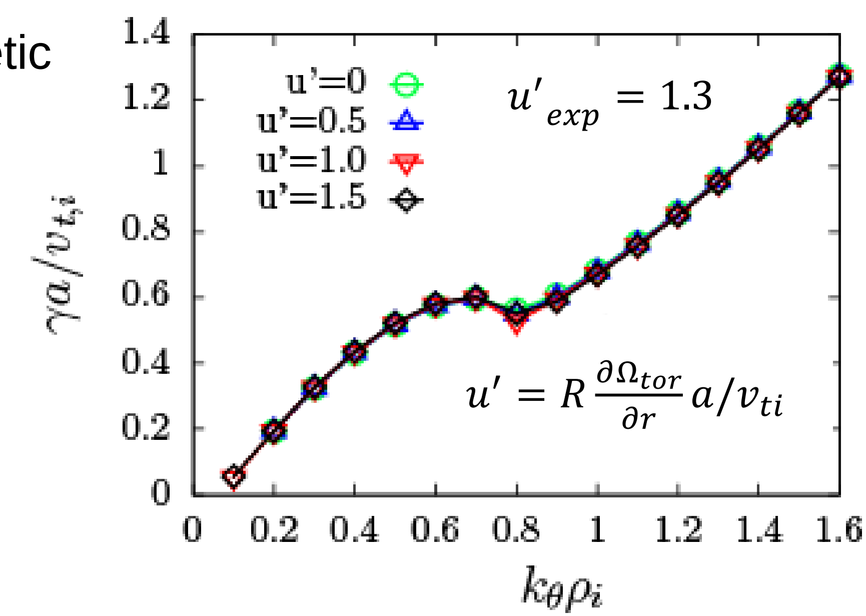
- Dashed lines at same constant slope
- Critical gradient behavior expected for temperature gradients, but surprising for rotation



Linear GS2 growth rate calculations performed in edge



- Propagation direction in electron diamagnetic direction at bottom of well, consistent with DBS vs CXRS comparisons
- Large growth rates across broad wavenumber range
  - Multi-scale effects could be important
- Growth rates insensitive to flow shear, no linear critical gradient



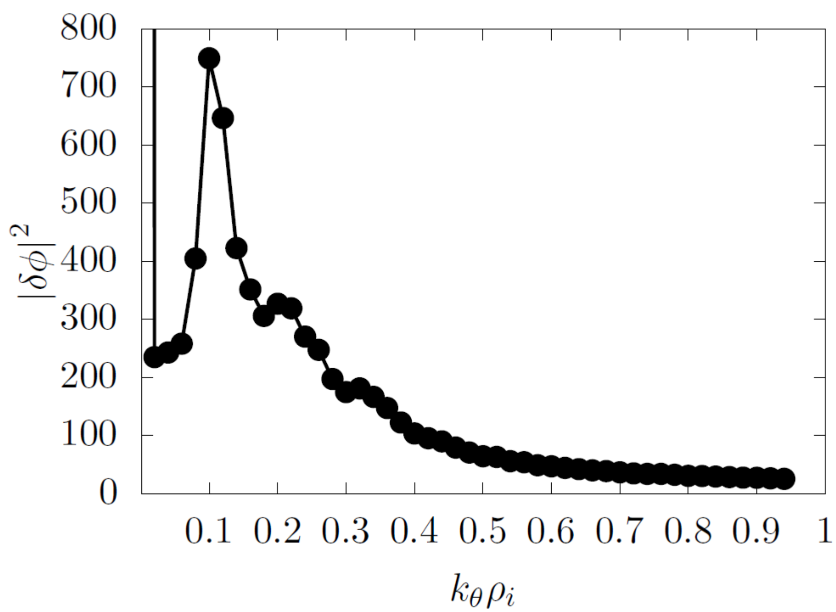
JET CCFE CULHAM CENTRE FUSION ENERGY

Non-linear gyrokinetic simulations used to investigate momentum transport close to plasma edge

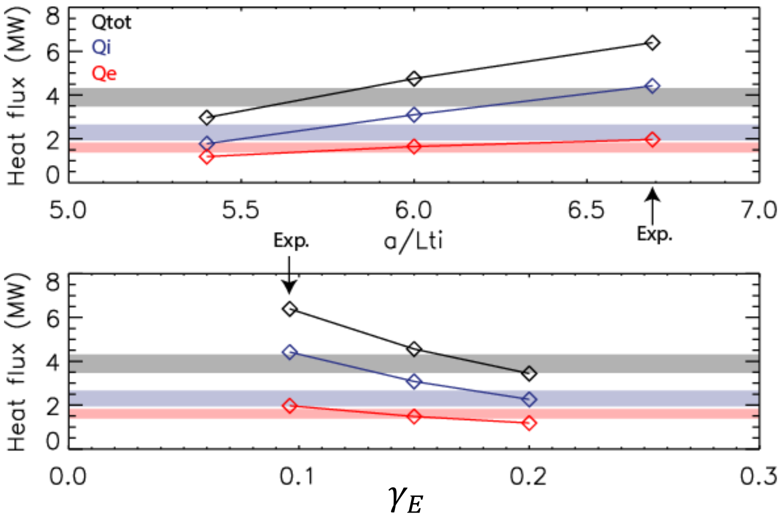
- Momentum transport effects could explain apparent critical gradient behavior
  - Ratio of momentum to heat flux set by NBI input
  - Temperature held at critical gradient
  - Prandtl number constant
    - If above conditions are met, rotation gradient also held constant

$$P_r = \chi_\phi / \chi_i \propto \frac{\partial T_i/\partial r}{\partial \Omega_\phi/\partial r} \frac{\Pi}{Q_i}.$$

- Long wavelengths only, with hyperviscosity
  - $0.02 < k_\theta \rho_i < 0.94$
- Kinetic ions and electrons
  - Electrostatic, full GS2 collision operator
- For radius $\sqrt{\psi} = 0.93$, shot 86470, where rotation gradient builds up

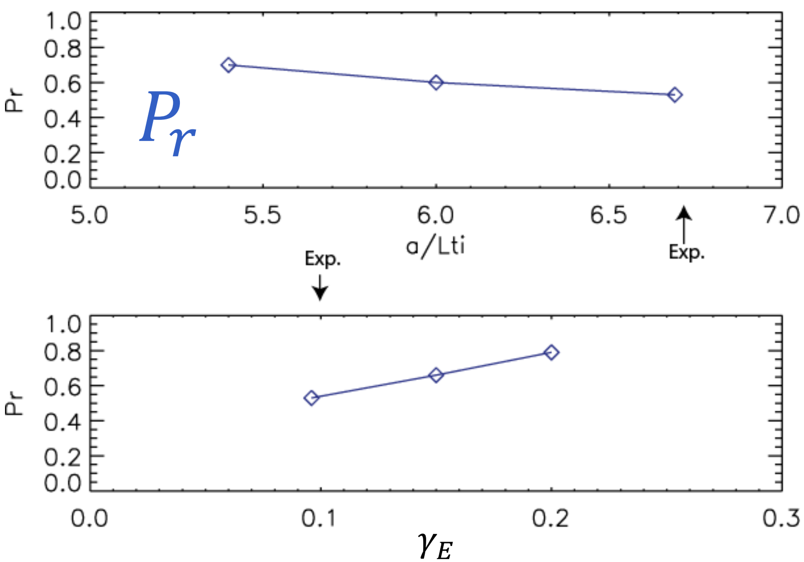


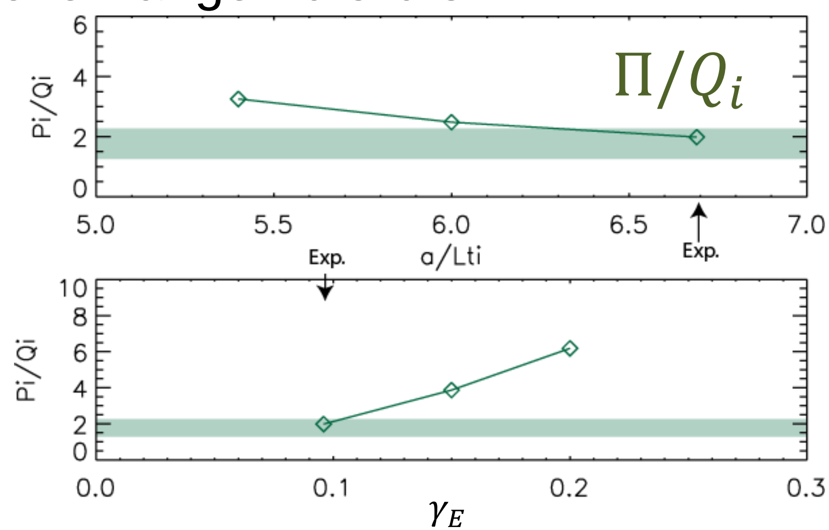
Non-linear consistency relation can explain apparent critical gradient behavior



$$P_r\left(\frac{a}{L_{T_i}}, \gamma_E\right) \sim \frac{\partial T_i/\partial r}{\partial \Omega_\phi/\partial r} \frac{\Pi}{Q_i}$$

- **Ion heat transport stiff**, GS2 over-predicts experimental values of Qi, Π
  - Multi-scale effects could be important
- Flux ratio set by **NBI** & well matched by simulation
- Prandtl number varies systematically over range ~0.5-0.8





Shaded regions from TRANSP +/- 100 ms from simulation time

Outline

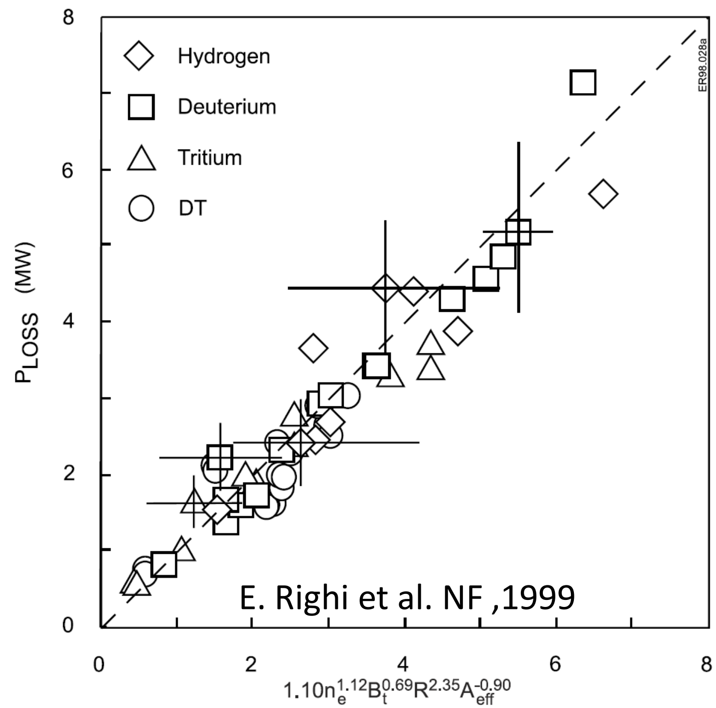
- L-H transition power threshold results at high magnetic field and plasma current in JET
- Scaling of zonal flow properties and comparison to width of edge radial electric field well
- Momentum transport during L-H transitions
  - Comparison to linear and non-linear gyrokinetic simulations
- Recent results in hydrogen/deuterium mixtures

Mass scaling of L-H transition

- Empirically P_{LH}~$1/m_i$
  - Consistent with results from multiple experiments
    - Righi NF 1999, Gohil IAEA 2012, Ryter NF 2013

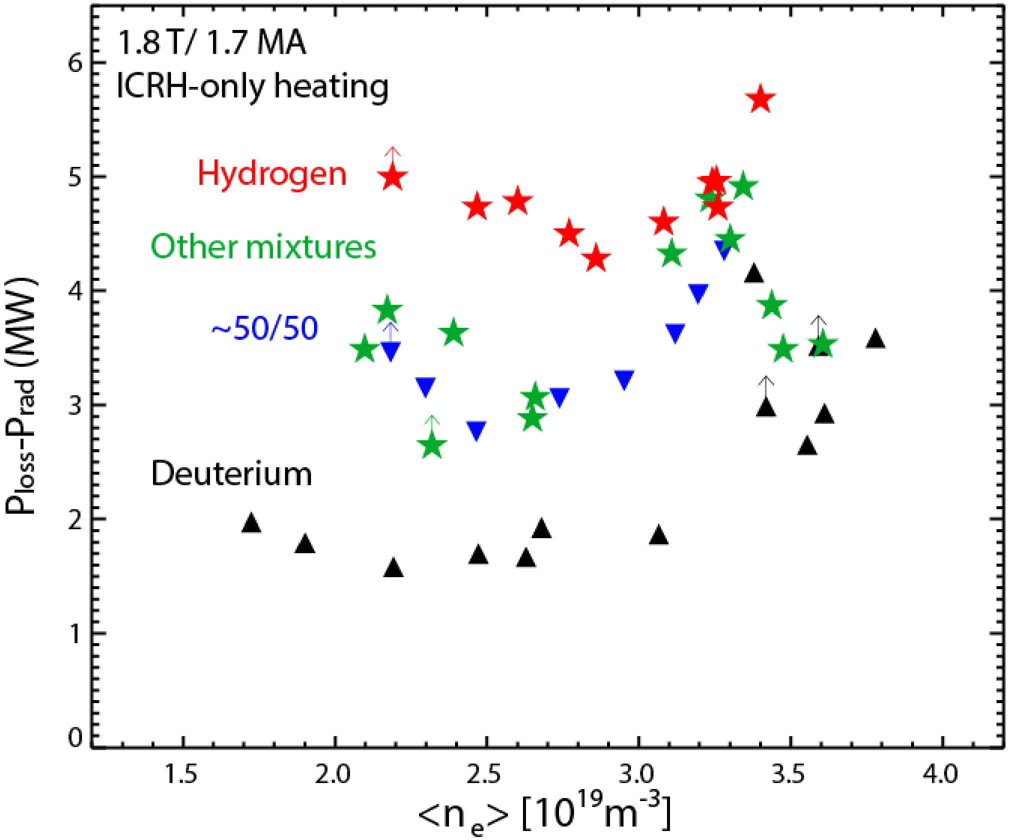
- Very little existing results in mixed species plasmas
  - Results in 50/50 D-T plasmas were consistent with ~$1/m_i$

- Zonal flows have been suggested as being responsible for mass dependence through ion collisions



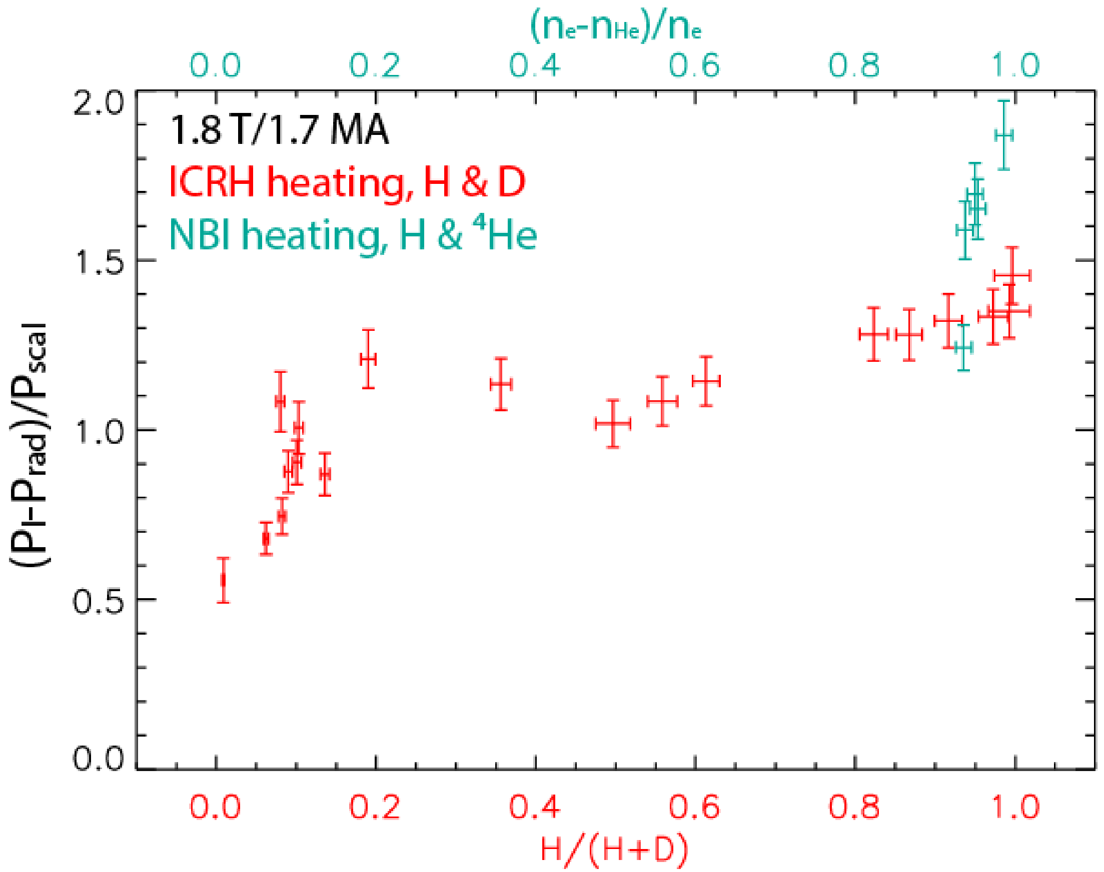
Power threshold studied in hydrogen-deuterium mixtures in JET

- Slow, ~8 s, power ramps used to identify transition
- Same shape used for extensive mixture and isotope data set
- $Z_{eff} \approx 1.0 - 1.2$
- Minimum threshold moves to higher density due to stronger dependence in low density branch



Non-linear dependence of power threshold observed in mixed species plasmas

- Largest variations observed at high and low H/(H+D)
- Little variation in range $0.2 < \frac{H}{(H+D)} < 0.8$
- Experiments at end of campaign with H-^{4}He mixtures show drop of power threshold with helium seeding in hydrogen plasmas
  - Effect could be used during non-active phase of ITER operation



$$P_{scal} = 0.0488 < n_e >^{0.717} B_T^{0.803} S^{0.941}$$

Summary

- Fine-scale structure in edge flows consistent with stationary zonal flows observed during L-H transitions in JET & can vary independently of well width

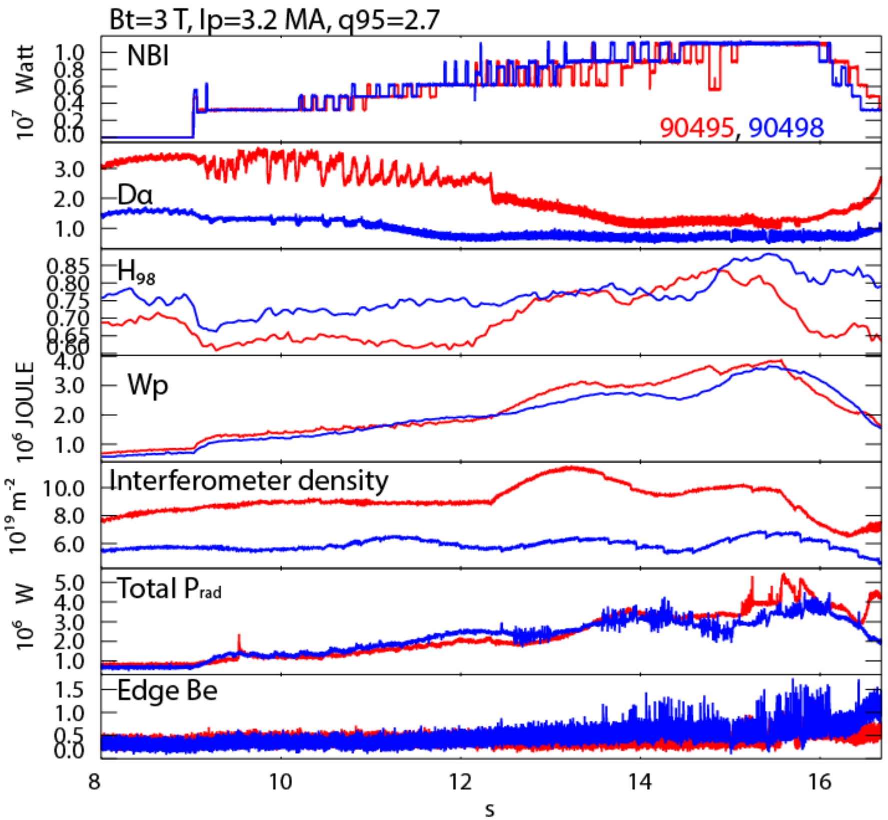
- Radial correlation length of turbulence much smaller than well width, $\frac{\ell_r}{w_{E_r}} \ll 1$,which may be important effective ρ^* for development of edge transport barrier
  - Planned diagnostic upgrades at JET will allow DBS measurements at lower magnetic field in future, enabling this to be tested

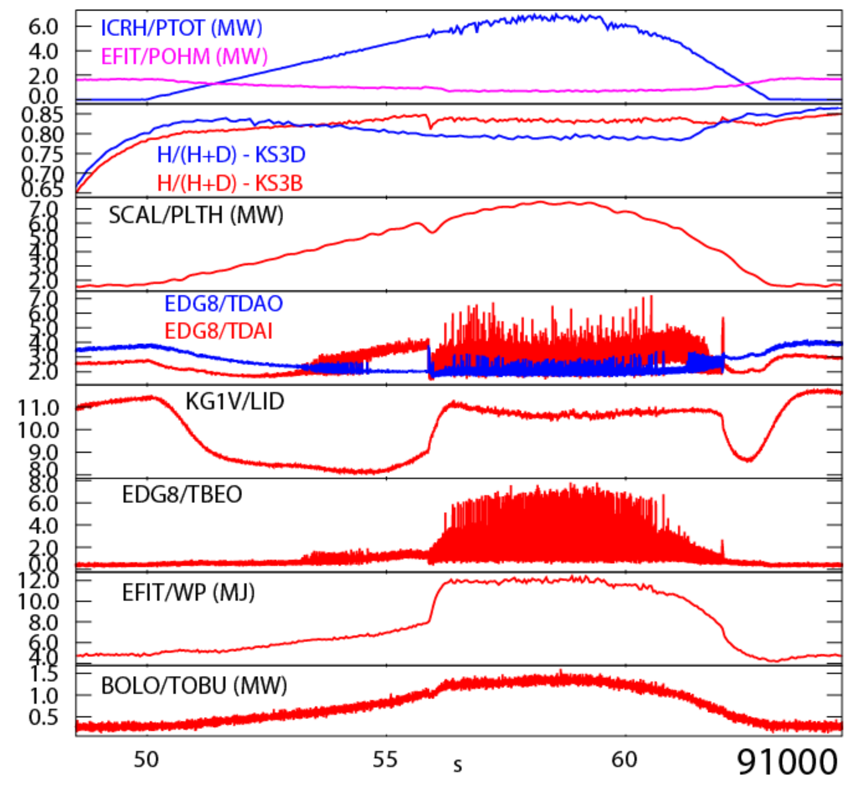
- Momentum transport limits development of inner shear layer of well
  - Non-linear gyrokinetic simulations show consistency relation between momentum and heat flux can explain apparent critical gradient
  - Implies in strongly driven regime that Π/Q_i (e.g. NBI voltage) can act as control knob for rotation shear

- Non-linear dependence of P_{LH} in mixed species plasmas
  - Reduction of P_{LH} in H-^{4}He mixture shows potential path to access H-mode in hydrogen during non-active phase of ITER operation

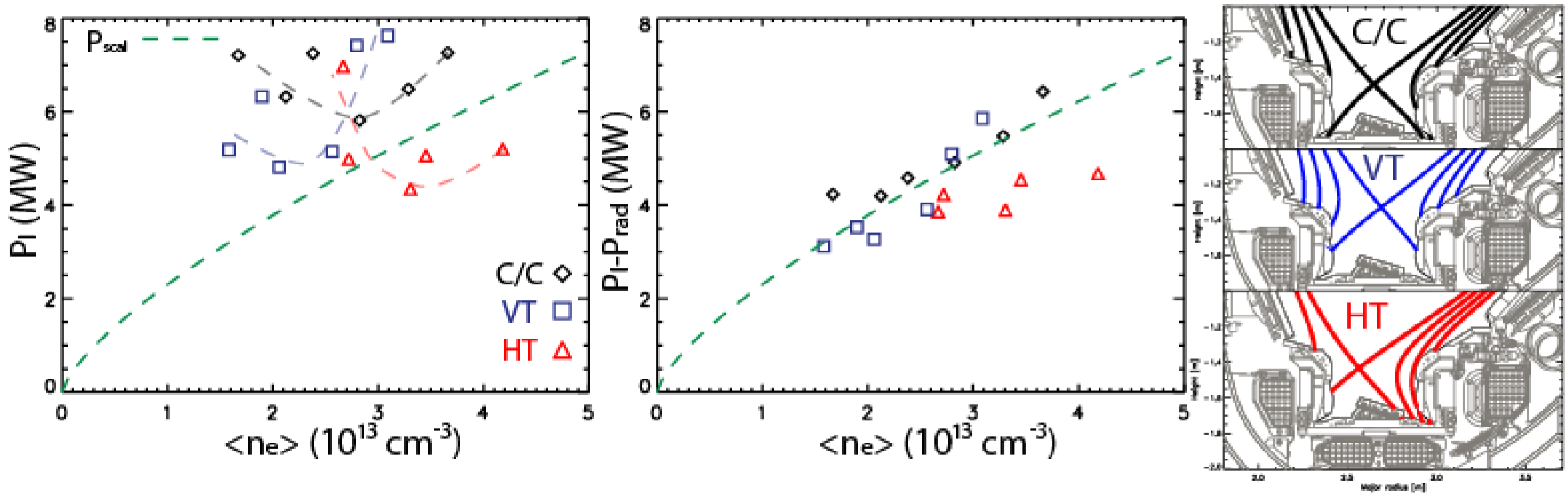
Extras

L-H transition time traces



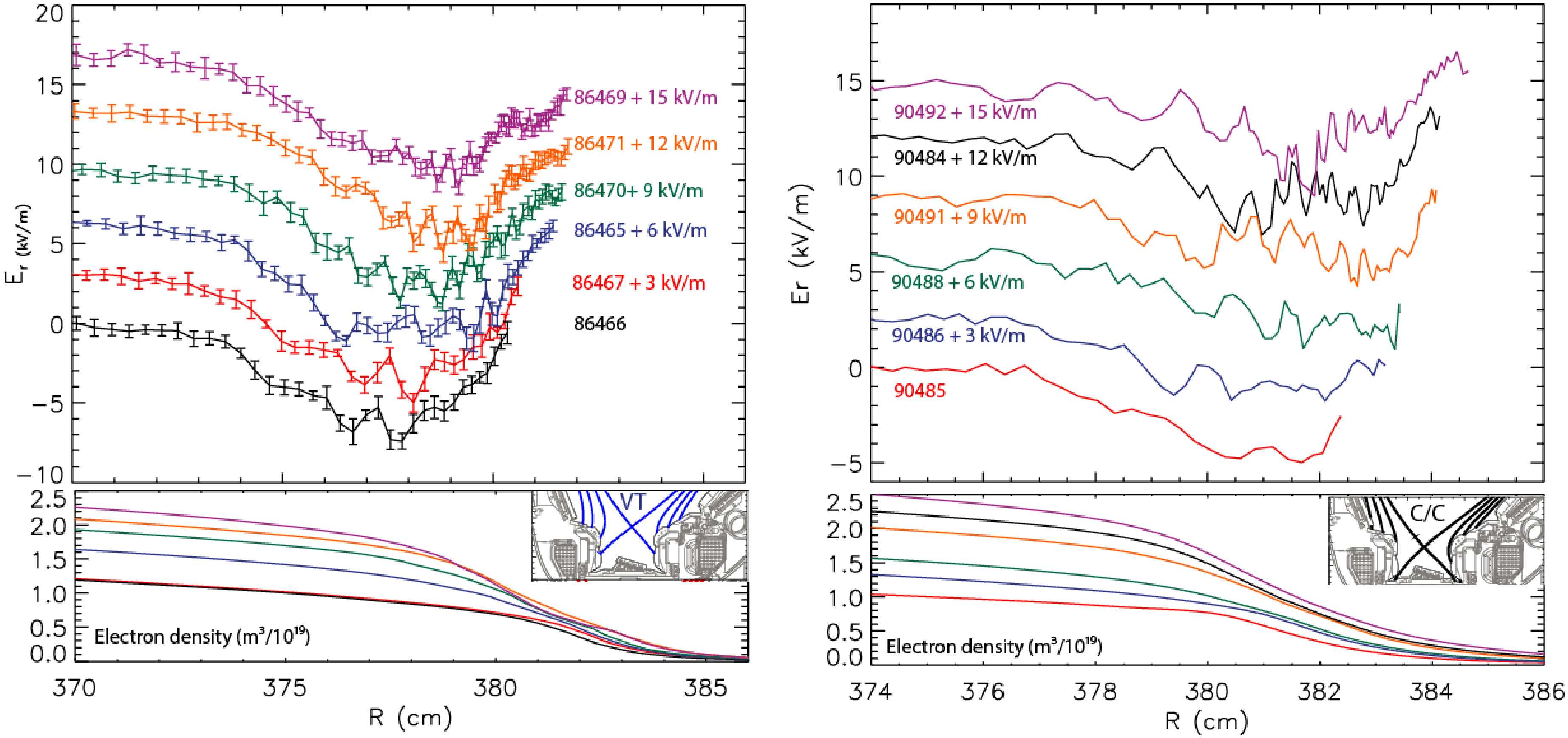


L-H threshold on density characterized in three divertor configurations



- 3 T/2.5 MA in C/C and VT; 3 T/2.5-2.75 MA in HT
  - C/C shape used for hybrid and baseline scenario development
- Power threshold lowest in horizontal target
- Threshold similar in C/C and VT, even though pumping and X-point height very different
- Note: Core P_{rad} estimated from weighted bolometer chord average; tomographic inversions may modify results

Variation in edge profiles in different divertor configurations, both at 3 T/ 2.5 MA

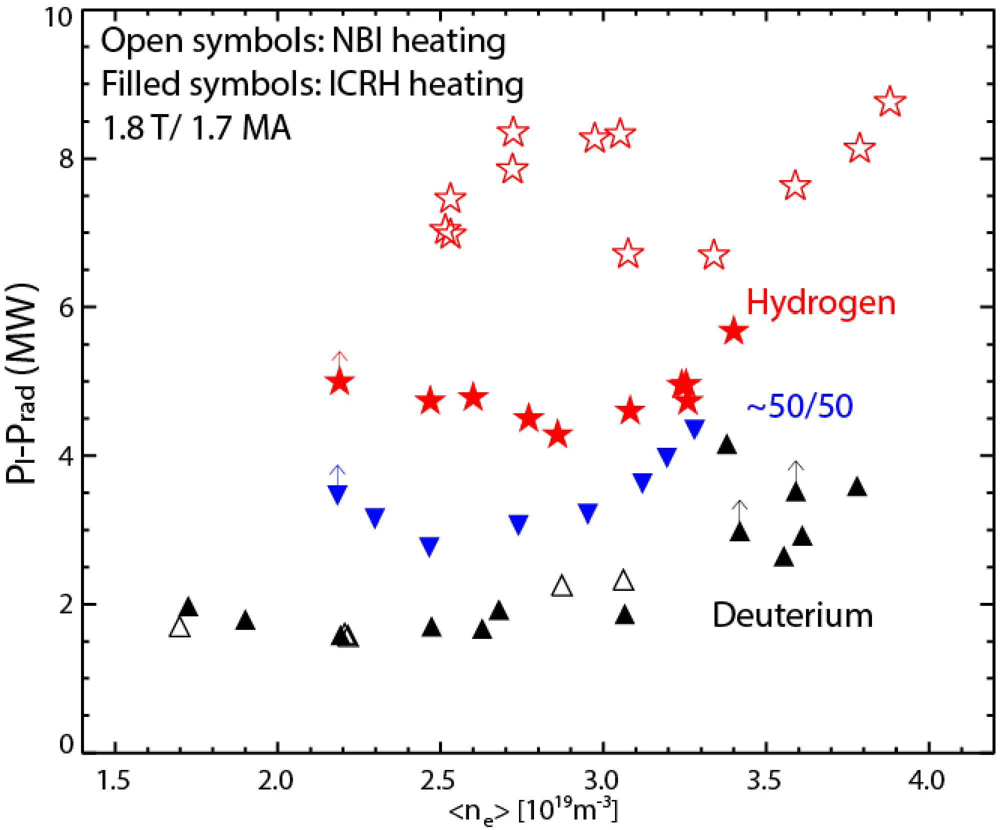


- Edge well shallower in C/C in Ohmic conditions
- Fine-scale zonal flow structure in E_r profile coincident with steeper density gradient in C/C
- Small experiments have observed variety of oscillatory ZF, but not stationary
    - e.g. Conway PRL 2011, Estrada PRL 2011, Xu PRL 2011, Schmitz PRL 2012

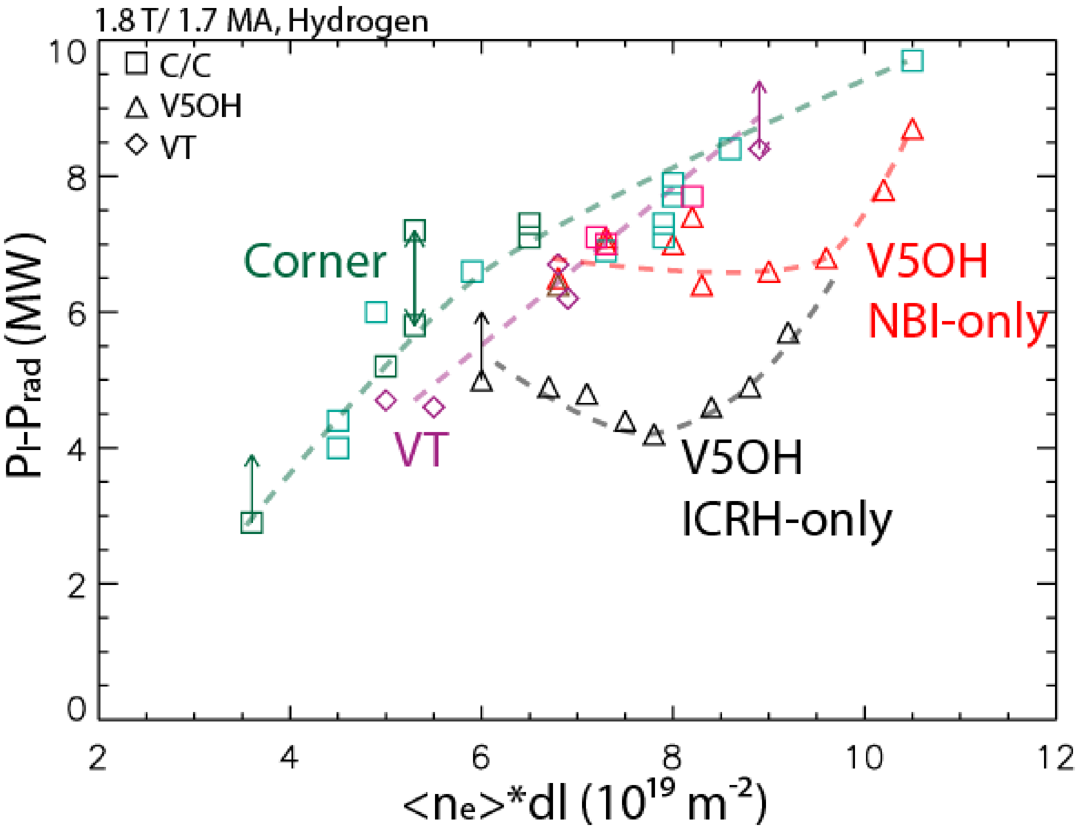
Strong dependence on heating source in hydrogen, but not deuterium

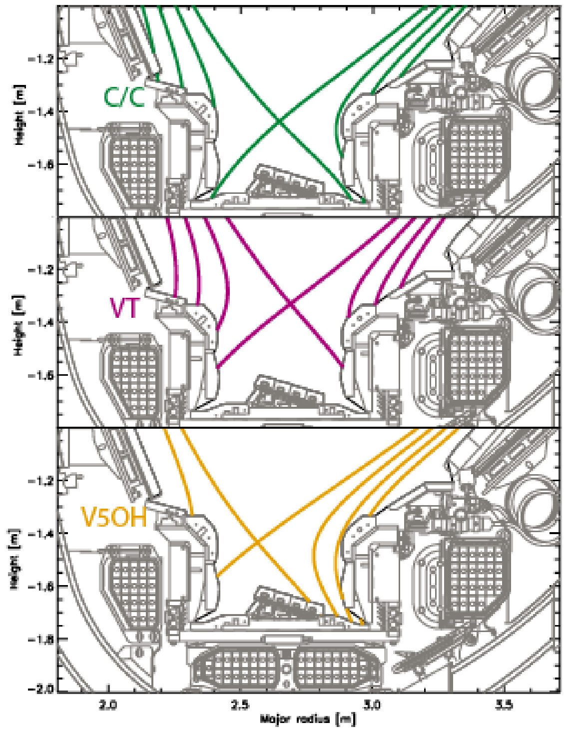
- Similar to Gohil NF 2010, threshold much higher in hydrogen with more input torque

- Power threshold so low in deuterium that NBI provides little momentum input



Dependence on divertor configuration

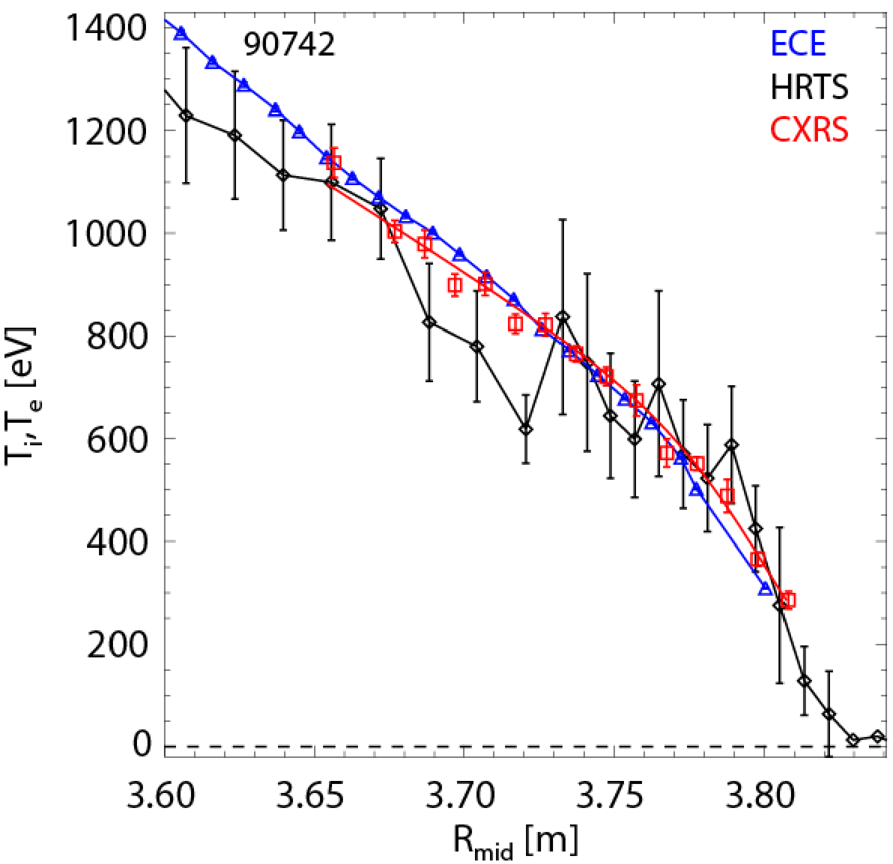




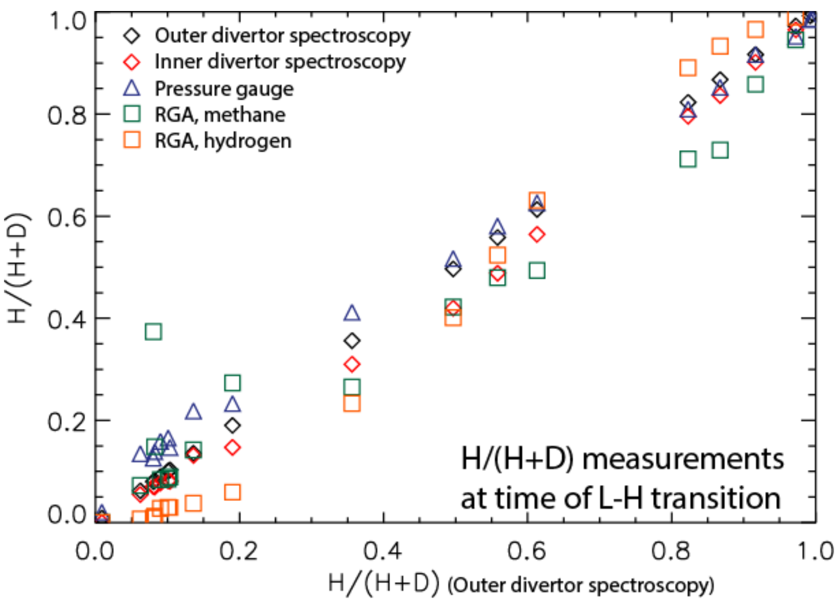
- VT and corner, with different X-point height and pumping efficiency have similar threshold
- V5OH has lower threshold

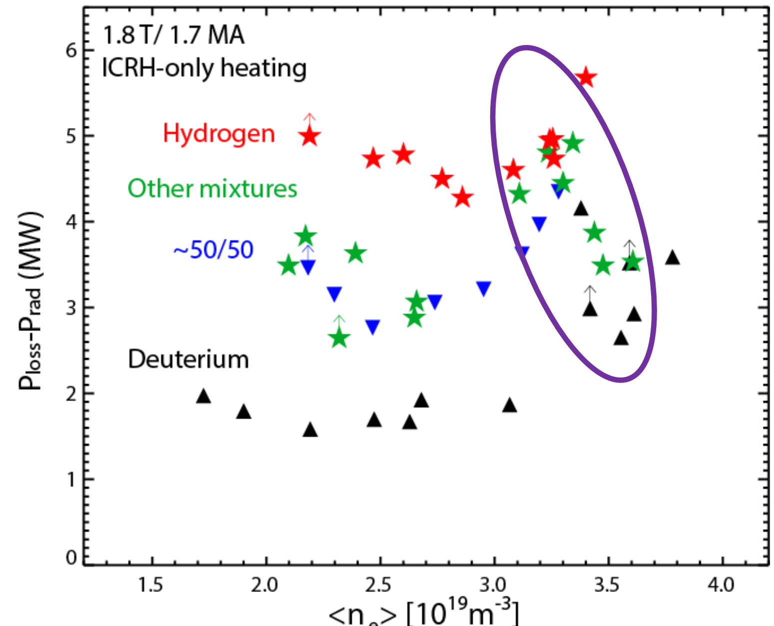
Edge temperatures within uncertainties for ions and electrons

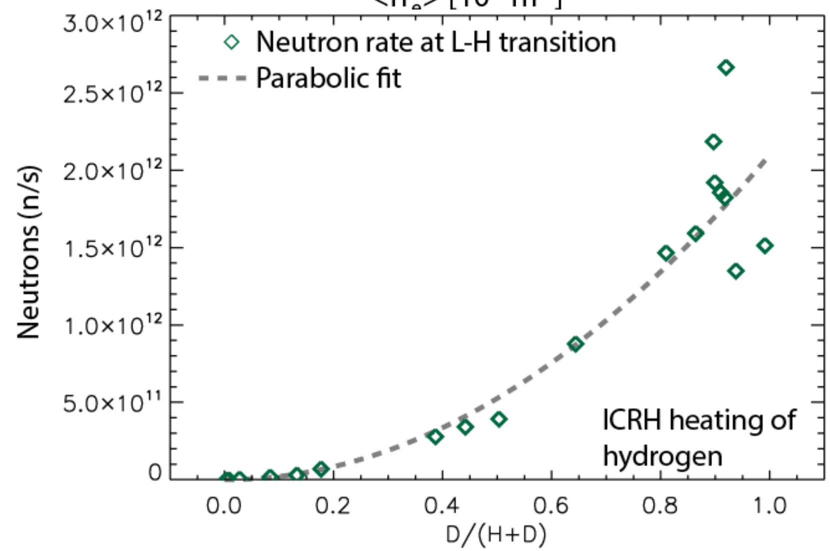
- 90742: 3.4 T/ 3.2 T
  - $\langle n_e \rangle = 2.2\ m^{-3}$
- High field, high current, low density
  - Extreme case where one might expect separation of temperatures
- $T_e = T_i$ within uncertainties during time leading up to L-H transition



Hydrogen-deuterium mixture scan performed in high density branch







- Multiple H/(H+D) ratio measurements consistent
- Neutron rate consistent with square of thermal deuterium density over broad range

H/(H+D) measurements