What Will We Learn from ITER?

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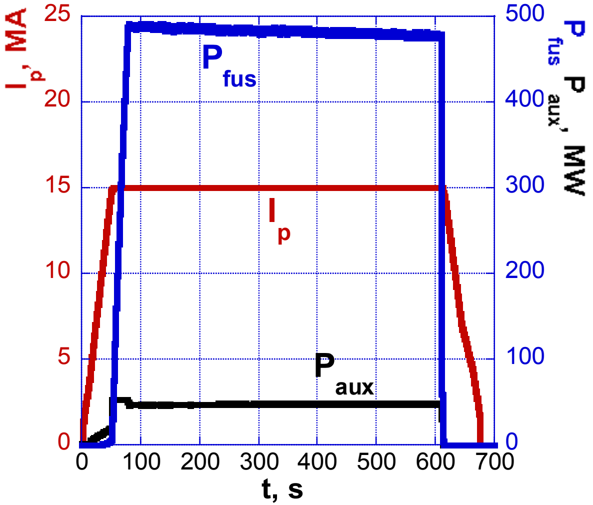
Mission of ITER

- Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes
  - Achieve fusion power of 500 MW with P_{fus}/P_{in} ($\equiv Q$) ≥ 10 for 300-500 s (i.e., stationary conditions)
  - Aim at demonstrating steady-state operation with $Q \geq 5$

ITER Will Provide a Unique Facility to Study Burning Plasmas



Q=10 scenario

Courtesy of Y. Gribov

- Q=10 will be a great scientific and technical achievement
- ITER will provide new scientific perspectives and answer key questions due to:
  - Lower ρ^*, ν^* while at high n_e/n^{GW}, alpha particles, self-heating from alphas
  - Larger size, current, power and long duration

What Will We Learn Scientifically?

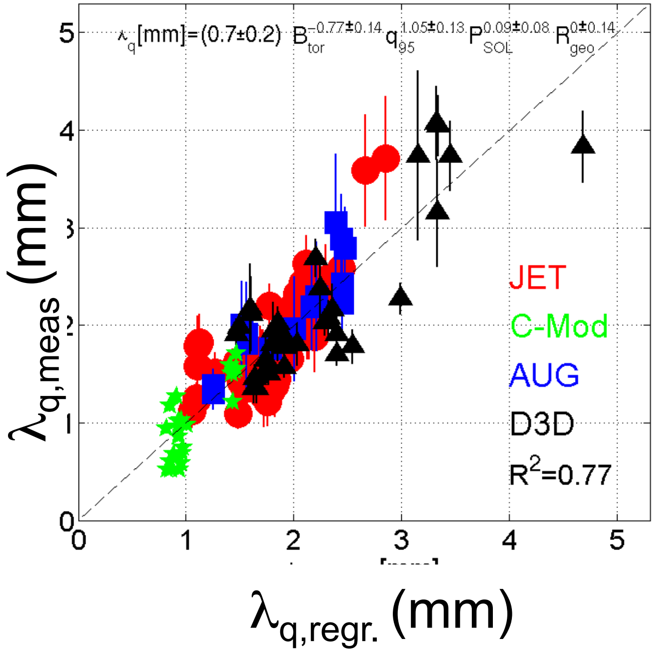
- My personal perspectives
  - What I hope we will learn from initial operation through Q=10 campaign
- Not comprehensive literature review
  - Influenced by relatively recent work
- Goal is to challenge us to address the many open issues in preparation for participation in ITER
- *Will not address the engineering/technological and regulatory issues, which are as important as the scientific issues*

Going from the Edge to the Core

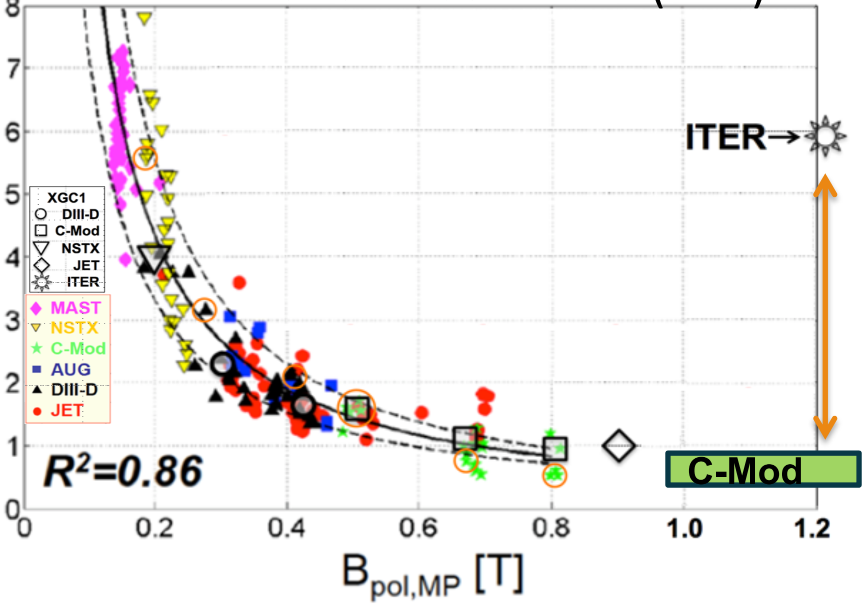
- *Plasma-Boundary Interactions*
- Pedestal performance
- Core transport
- Disruptions
- Alpha-particle physics
- Integrated performance

Will the Heat Flux Width Be Determined by Turbulence?

T. Eich, Nucl. Fusion **53** (2013) 093031



Power exhaust width (mm)



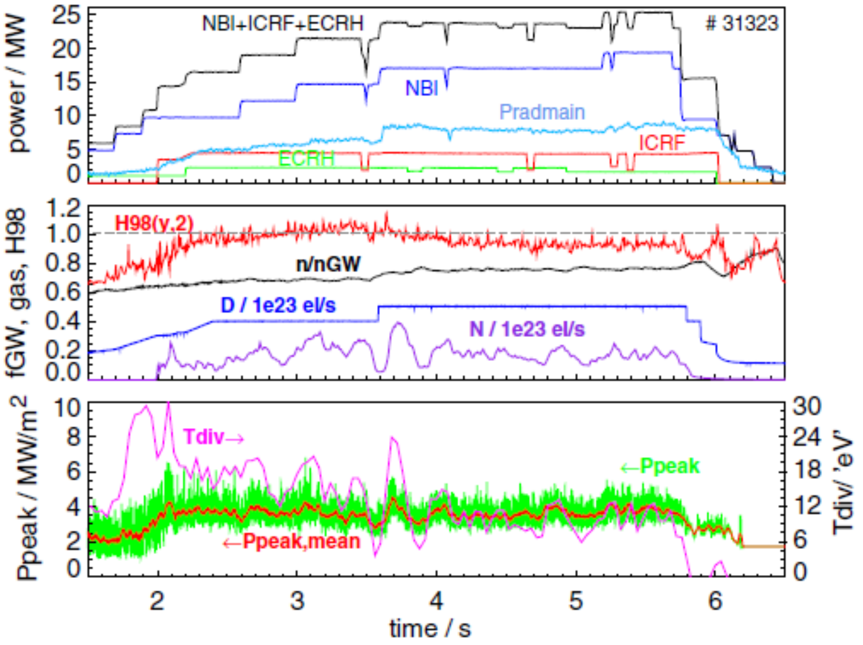
- $\lambda_q \propto 1/I_p \propto 1/B_{pol}$

- XGC1 (PPPL) reproduces existing data variation, but predicts turbulence broadens the width in ITER.
  - Is this correct?

Radiative Dissipation Demonstrated on ASDEX Upgrade

- Excellent results on AUG at high P_{sep}/R with nitrogen seeding
- But at ~$7P_{LH}$
  - (P_{LH} -- power threshold: L-mode to H-mode)
- No stable operation yet for power exhaust with neon
  - Implications for ITER remain to be determined.

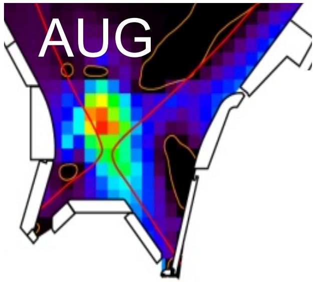
A. Kallenbach et al., Nucl. Fusion 55 (2015) 053026

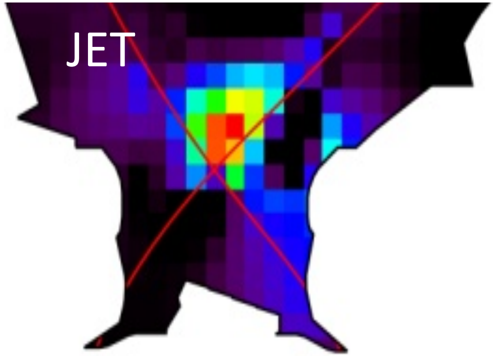


$(P_{sep}/R)_{max}$ = 10 MWm^{-1} (cf. ~15 MWm^{-1} for ITER)
Feedforward D puff, Feedback N puff

Will Radiative Dissipation Mitigate the ITER Heat Flux?

N-seeding examples (from M. Bernert et al., PSI 2016)





I_p = 1.2 MA, B_T = 2.5 T
P_{IN} = 18-21 MW
f_{rad} ~ 75%, H_{98} = 0.9
Type III ELMs

I_p = 2.5 MA, B_T = 2.6 T
P_{IN} = 18 MW
f_{rad} ~ 75%, H_{98} = 0.7
Type I/no-ELMs

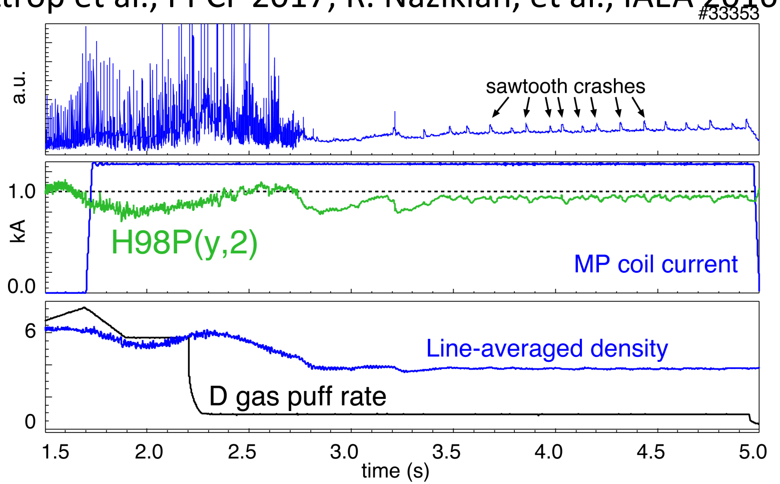
- Is an X-point radiator possible on ITER?
  - How is discharge performance affected during partial detachment when close to P_{LH} ~1?
- If λ_q is narrow, will required seeding rates be compatible with the burning plasma?
  - (see R.J. Goldston et al., PPCF **59** (2017) 055015 and M. Reinke Nucl. Fusion 57 (2017) 034004)
- Maximum ELM size that can be buffered by radiative divertor?

Courtesy of R. Pitts

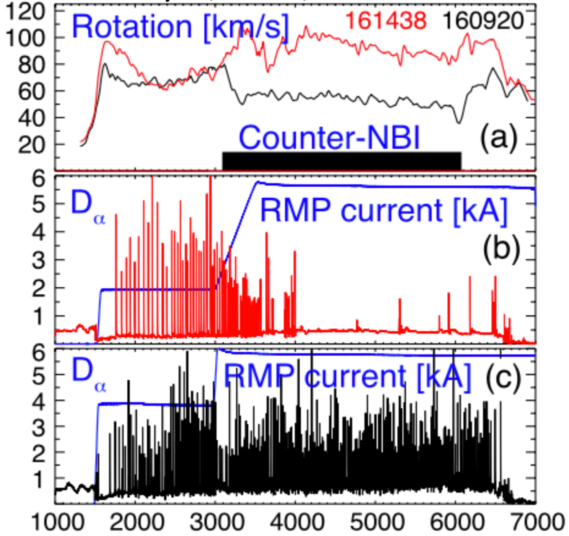
Can We Suppress ELMs in ITER with RMP Fields?

W. Suttrop et al., PPCF 2017; R. Nazikian, et al., IAEA 2016

AUG



R. Moyer, et al., PoP 2017



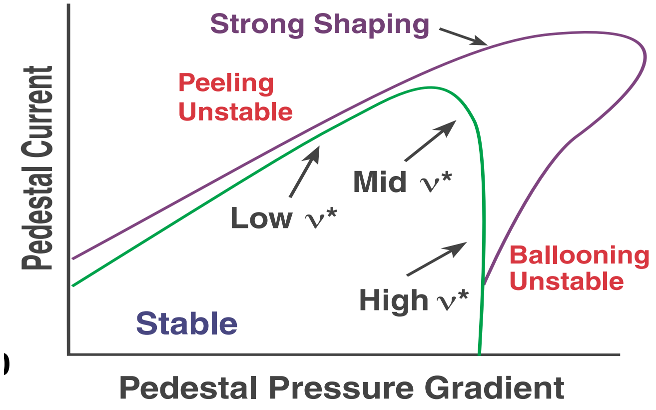
DIII-D

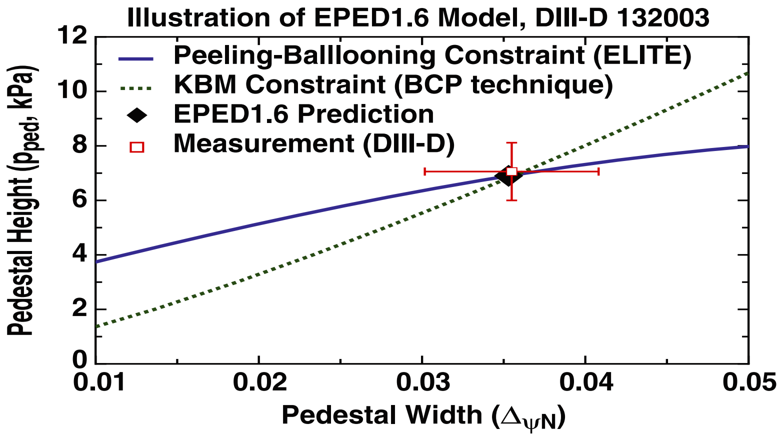
- RMP ELM suppression achieved on ASDEX Upgrade with metal wall
- Loss of ELM suppression at low rotation in DIII-D consistent with island model
  - Island model remains an active topic of discussion
- Need a dimensionless criteria for ELM suppression for ITER prediction

Going from the Edge to the Core

- Plasma-Boundary Interactions
- *Pedestal performance*
- Core transport
- MHD stability
- Alpha-particle physics
- Integrated performance

Height and Width of Pedestal Set by a Combination of Stability and Transport Mechanisms



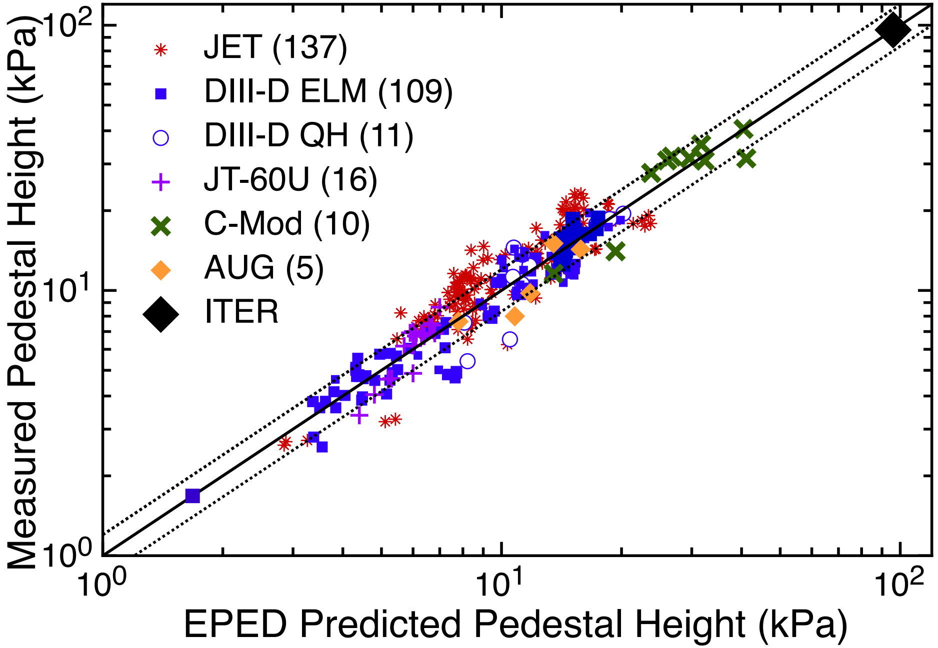


Snyder, P *et al,* Phys. Plasmas **16** 056118 (2009)

Snyder, P *et al,* Nucl Fusion **51** 103016 (2011)

- Stability defined by peeling-ballooning modes
- Kinetic Ballooning Modes (KBM) used in EPED model
  - Defines the pedestal pressure

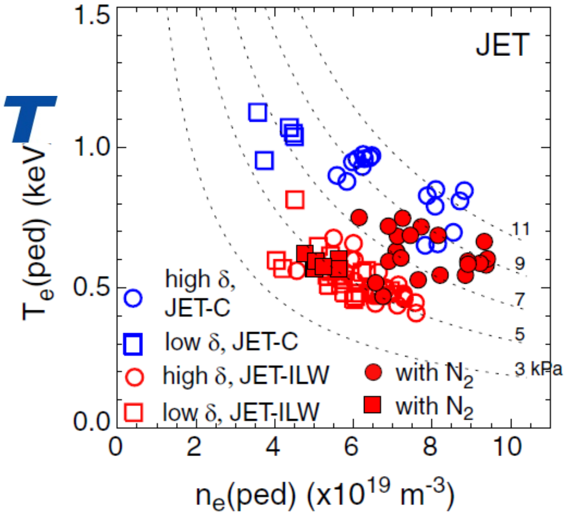
EPED Successfully Predicts the Pressure in the Pedestal in Current Experiments



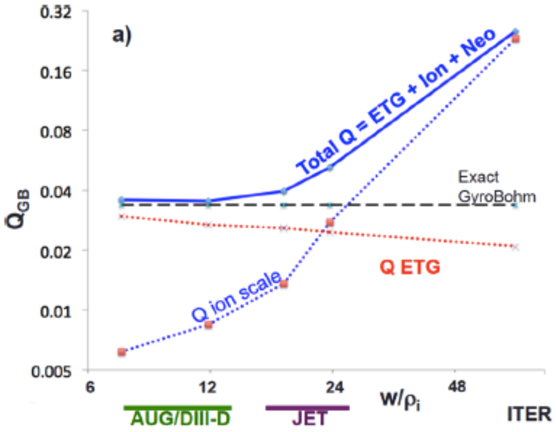
Snyder, P.B. et al., *Nucl. Fusion* **51**, 103016 (2011)

- The height of the pedestal is a key parameter in estimating the confinement time.

What will the Pedestal Parameters be in ITER?



M. Beurskens et al, PPCF (2013)

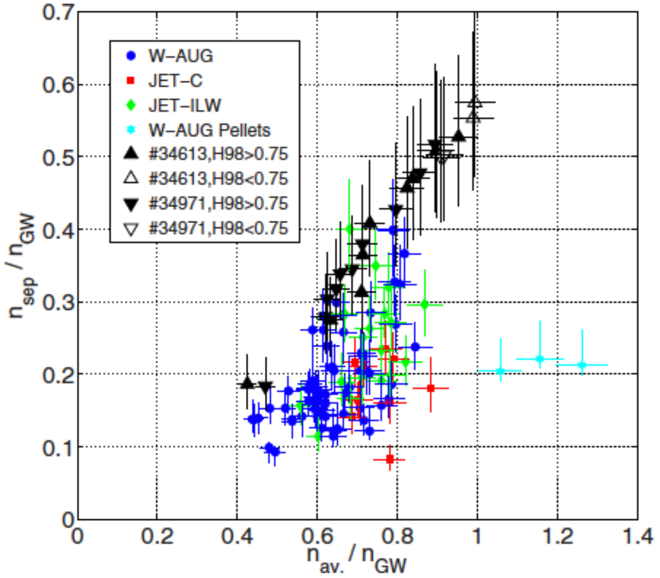


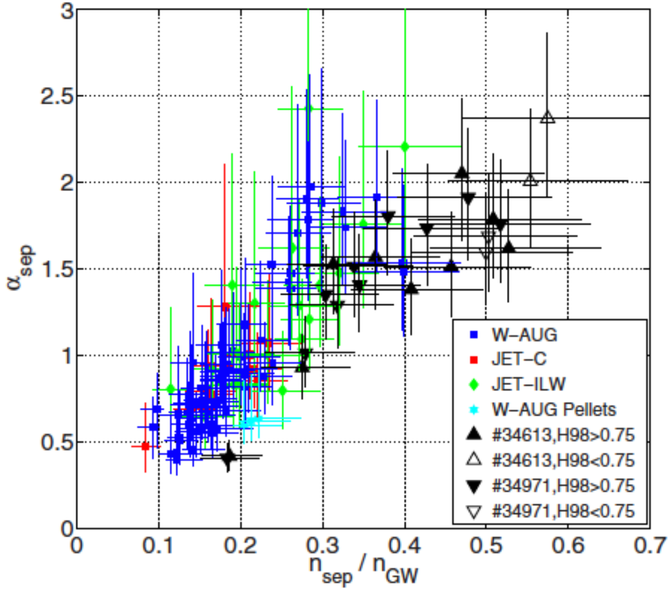
M. Kotschenreuther, Nucl. Fusion 57 (2017) 064001

- High gas fuelling to avoid W accumulation in the core, and this degraded the pedestal confinement.
- N_2 seeding helps partial recovery of the pedestal confinement

- GENE simulations indicate increased transport due to the ρ^* scaling of **ExB** shearing and lower Z_{eff} in the ITER-like Wall on JET

Will the H-mode Density Limit Be Set by the Ballooning Instability?



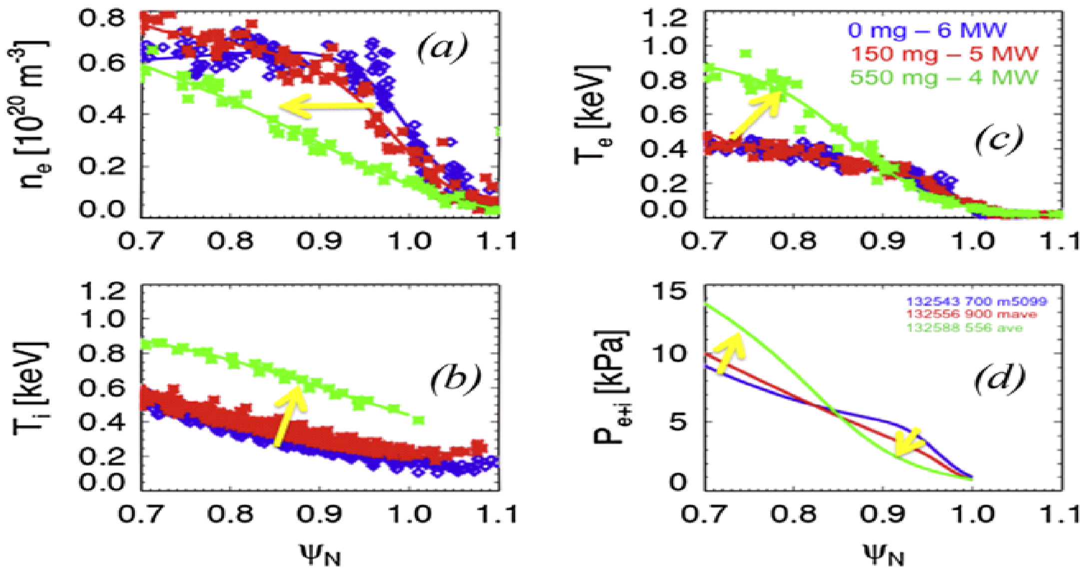


- High Z PFC is requiring gas puffing to increase the scrapeoff density.
- On ASDEX Upgrade and JET, when α_{sep} reaches ~ 2– 2.5, consistent with the theoretically predicted onset of ballooning modes, confinement degrades and the density limit of the H-mode is found.

T. Eich et al 2018 Nucl. Fusion **58** 034001

Shift of Density Profile In the Pedestal/Scrapeoff Region Is Important for Stability and Confinement and Not Explicitly Addressed in EPED

NSTX

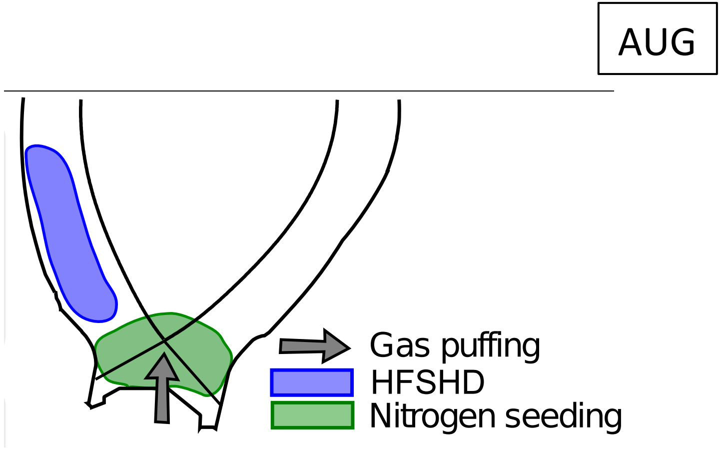


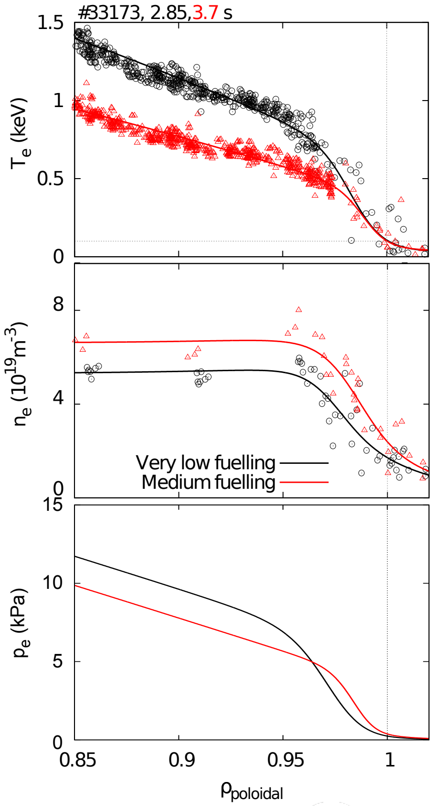
Maingi R. *et al.*, Journal of Nuclear Materials 463 (2015) 1134

- Lithium coatings/injection on NSTX-U and DIII-D have resulted in higher pedestal pressures and energy confinement times
- The shift of the density profile near the scrapeoff enables higher pedestal pressures.

ASDEX-Upgrade Observes Effect of Gas Fueling and Impurity Seeding on Density Profile

Dunne, M G, *et al.*, Plasma Phys. Control. Fusion 59 014017 (2017)





- Gas fueling shifts the density profile outward (reduced τ_E) while
- Impurity seeding shifts the density profile inward (improved pedestal temperature and τ_E)
  - – minimizes the role of the high field side density.

Role Density Profile Shifts Explains Several Important Observations

- ✓ Particle and energy reflection coefficients with W-PFCs are greater than C-PFCs resulting in higher pedestal densities and steeper density gradients.
  - Decreases the ion temperature and the edge stability
- Reduced recycling due to lithium coatings reduces the density gradients and improves edge stability
- Scrapeoff inboard high density region can create an inverted density profile and fuel the pedestal density, shifting the density gradient relative to temperature gradient and reduces confinement and stability.
- Nitrogen seeding cools the scrapeoff plasma reducing the density in the high density region shifting inboard the density gradient and improves confinement and stability
- ✓ Recently, combined pellet injection, gas puffing and nitrogen seeding has restored τ_E (Lang, NF 2018)
- ✓ One dimensional modeling is unlikely to capture all of the physics associated with pedestal.

Wolfrum, E. *et al.* Nuclear Materials and Energy **12** (2017) pg. 18

Going from the Edge to the Core

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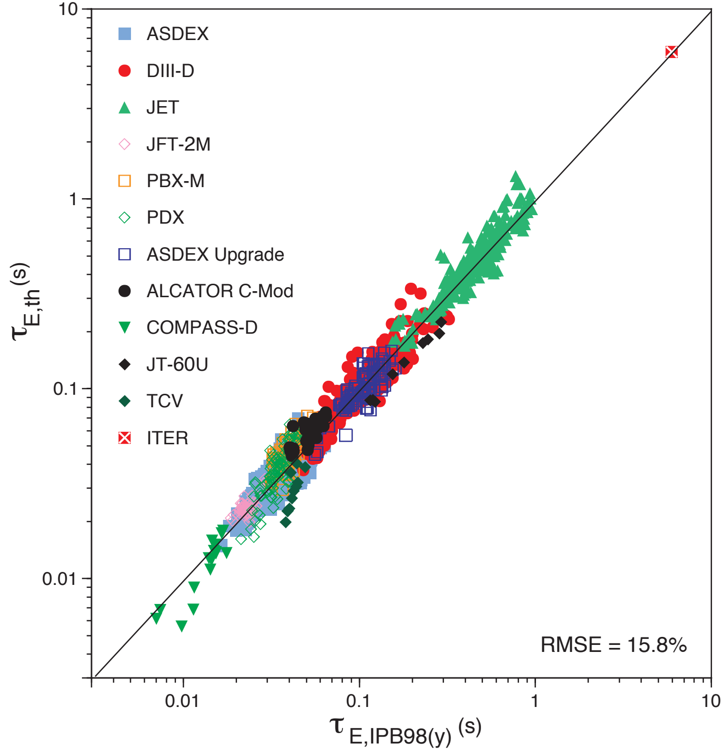
- Pedestal performance
- *Core transport*
- Disruptions
- Alpha-particle physics
- Integrated performance

Why Is Core Confinement (Still) Important?



Near ignition:

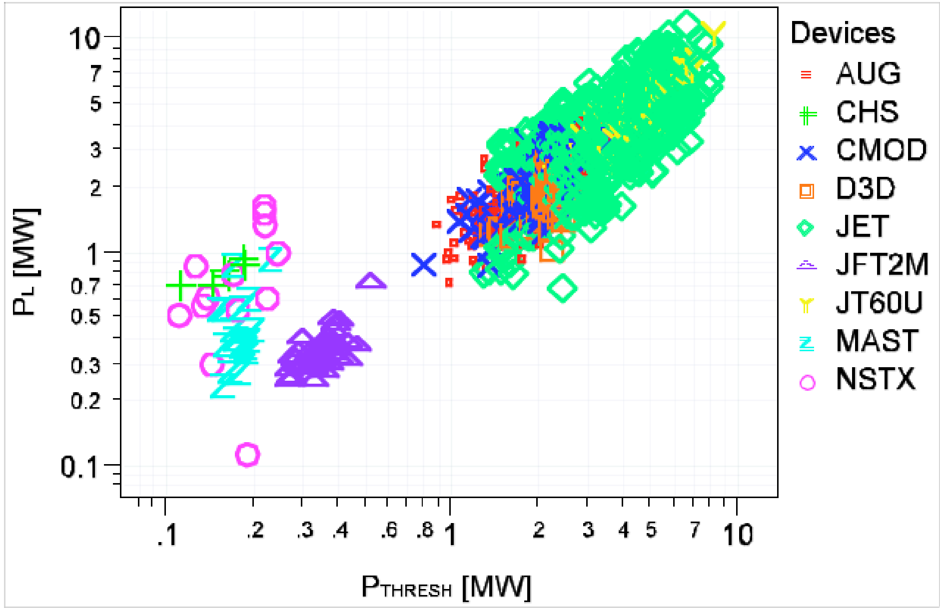
- $P_{fus} \alpha W^2$
- $W \sim P_{fus} {}^* \tau_E/5$
- $P_{fus} \alpha H_{IPB98(y,2)}^{5.3}$
  - assuming ITER scaling
- A 15% uncertainty translates into a factor of ~2 uncertainty in P_{fus}

$$\tau_{E,TH}^{IPB98(Y,2)} = 0.0562\ H_{IPB98(y,2)} I_p^{0.93} B_T^{0.15} n_e^{0.43} P^{-0.69} R^{1.97} M^{0.19} \kappa_a^{0.78} \varepsilon^{0.58}$$

Significant Scatter in the Power Threshold Required for L to H Transition

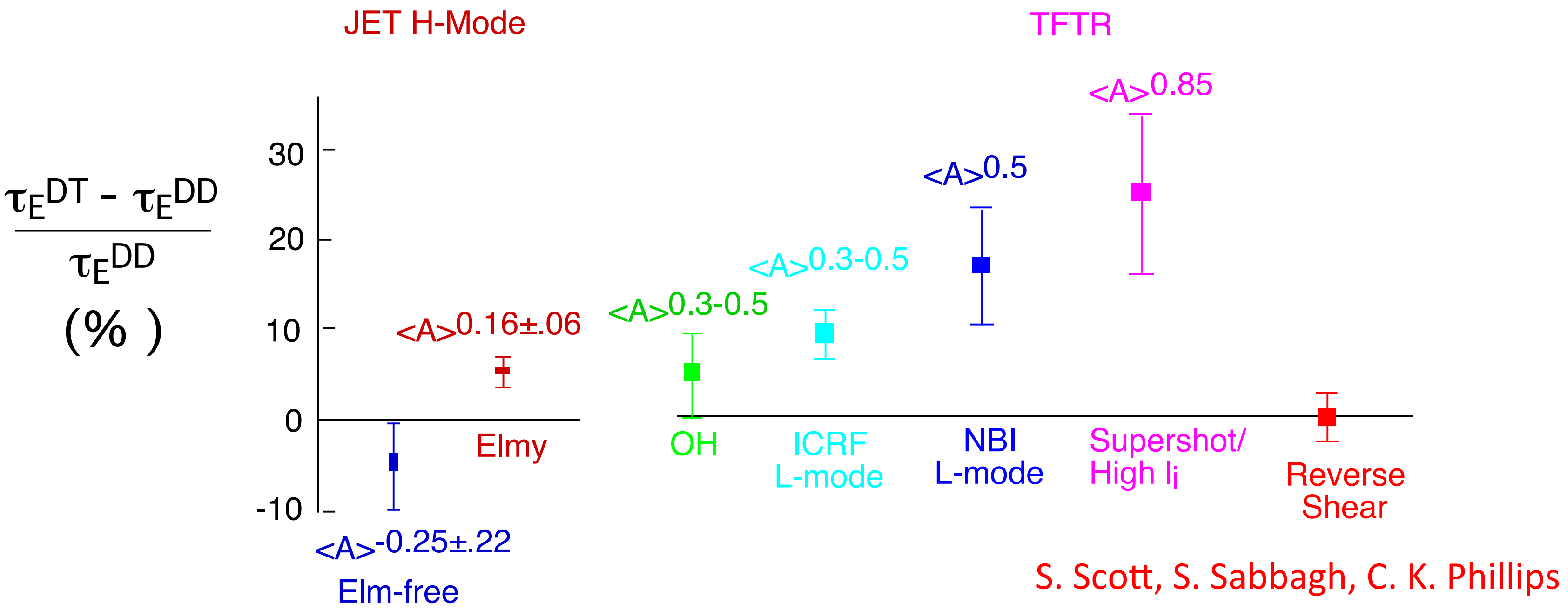
$$P_{\text{Thresh}} = 0.0488\ e^{\pm 0.057}\ n_{e20}^{\ 0.717\pm 0.035}\ B_T^{\ 0.803\pm 0.032}\ S^{0.941\pm 0.019}$$

- Scatter is attributed to "Hidden Variables" – recycling, height of the X-point, triangularity, rotation velocity, RMP perturbations…
- Power threshold is not a monotonic function of density
  - Role of ion transport identified by F. Ryter et al 2014 Nucl. Fusion 54 083003
- Do not have a predictive model for the power threshold.



Martin, Y.R. *et al.*, Journal of Physics: Conference Series **123** (2008) 012033

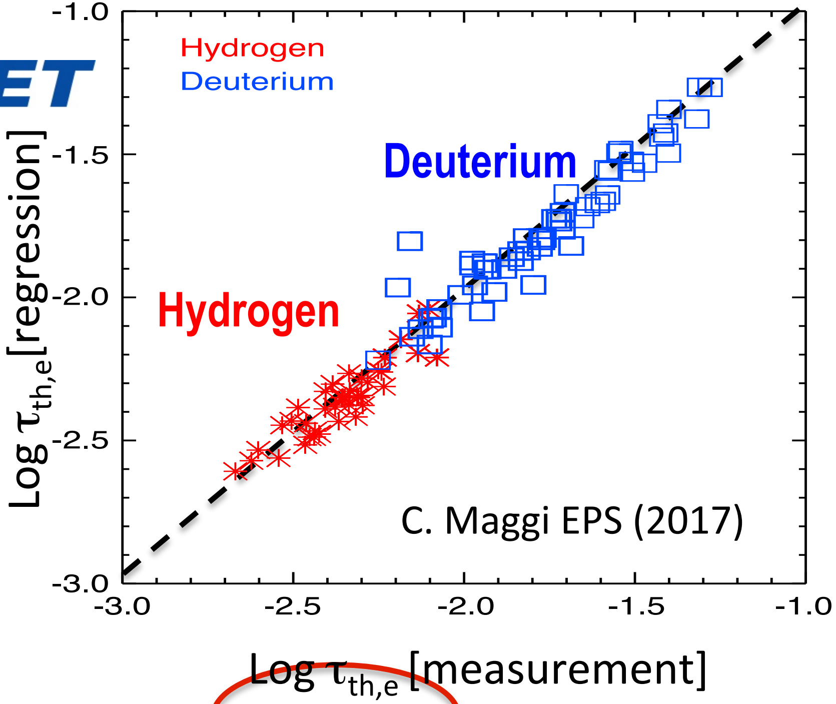
Isotope Effect on Confinement Varied Widely Depending on Operating Regime



S. Scott, S. Sabbagh, C. K. Phillips

- Diversity of scalings challenges theory and
  - gyro-Bohm scaling: $<A>^{-0.2}$
- ITER scaling for ELMy H-mode: $\tau_E^{thermal} \propto <A>^{+0.19}$

Recent JET Isotope Scaling of Confinement in H and D with the ITER-like Wall is $A^{0.4}$



Max H-NBI power = 10MW

H: 1.0MA/1.0T and 1.4MA/1.7T

D: 1.0MA/1.0T, 1.4MA/1.7T, 1.7MA/1.7T

- Favorable isotope effect on $\boldsymbol{\tau_{th,e}}$ in type-I ELMy H-modes
- Stronger isotope effect than in IPB98(y,2) scaling ($\tau_{th,IPB98(y,2)} \sim A^{0.2}$)

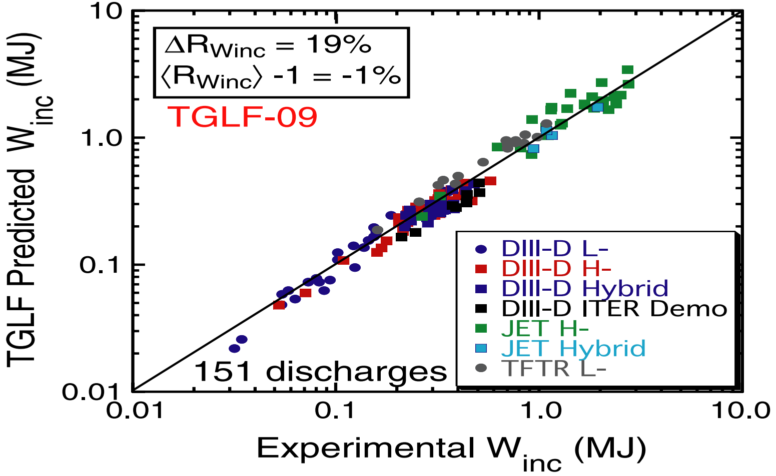
C. Maggi EPS (2017)

$$\tau_{th,e} \sim A^{0.40\pm0.04}\; P_{abs}^{-0.54\pm0.03}\; I_P^{1.48\pm0.17}\; B_T^{-0.19\pm0.09}\; n_e^{-0.09\pm0.10}\; f_{ELM}^{-0.12\pm0.02}$$

Caveat: A, n_e, f_{ELM} correlated and n_e, I_p correlated

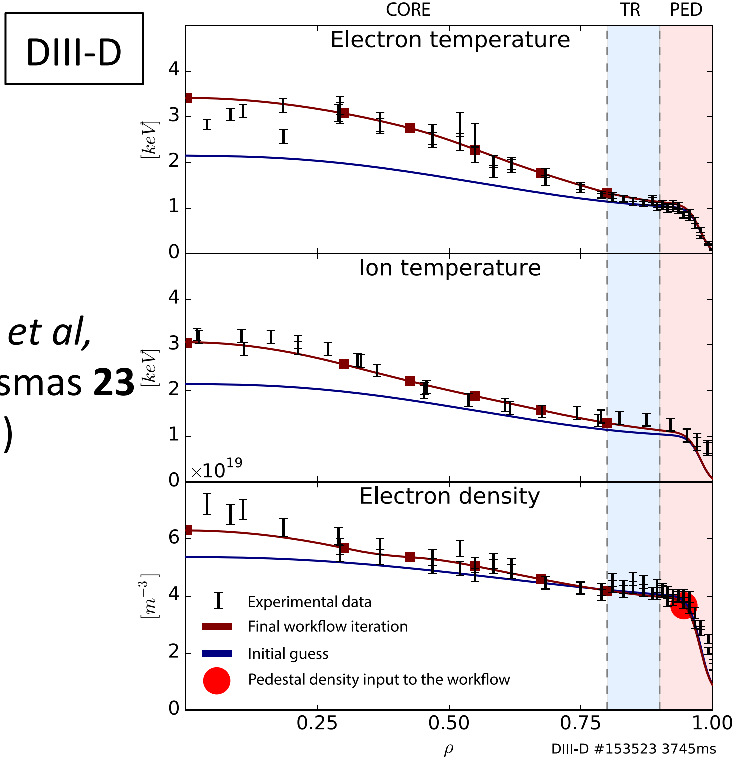
But $\tau_{th,e} \sim A^{0.4}$ robust against different choices of plasma parameters in regressions

Significant Progress in Modeling Transport in the Core Using Gyrokinetic Models



Kinsey J. E. *et al.*, Nucl. Fusion **51** 083001 (2011)

Meneghini O. *et al*, Physics of Plasmas **23** 042507 (2016)

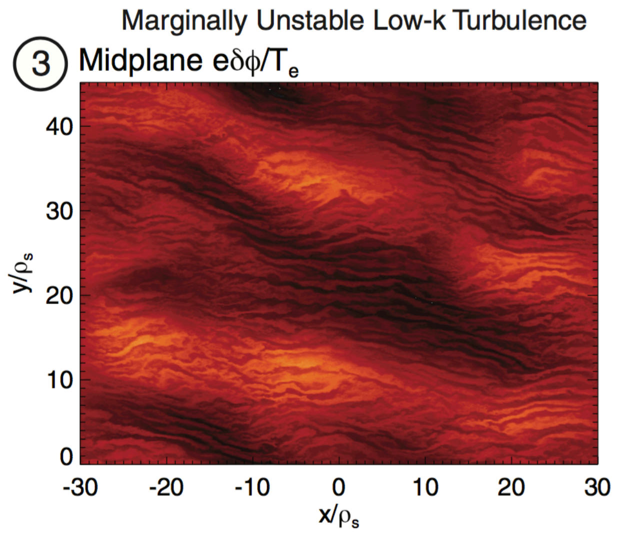


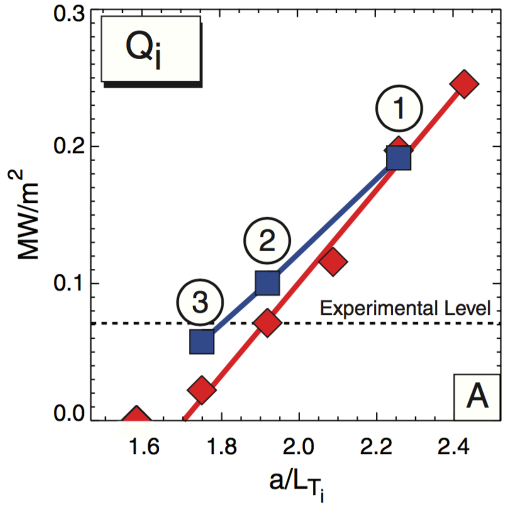
- Pedestal parameters were an input to this TGLF-09 study
- Outstanding issues include
  - Internal transport barriers
  - Regimes that are multi-scale (ion-scale and electron-scale turbulence)

- Coupled TGLF-EPED model

Multi-scale (Ion and Electron) Turbulence Is now Being Studied on Leadership Computing

C-Mod

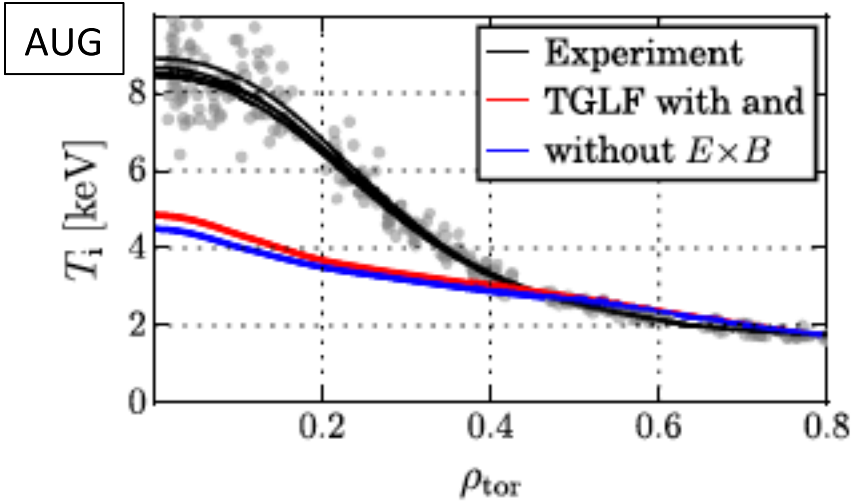


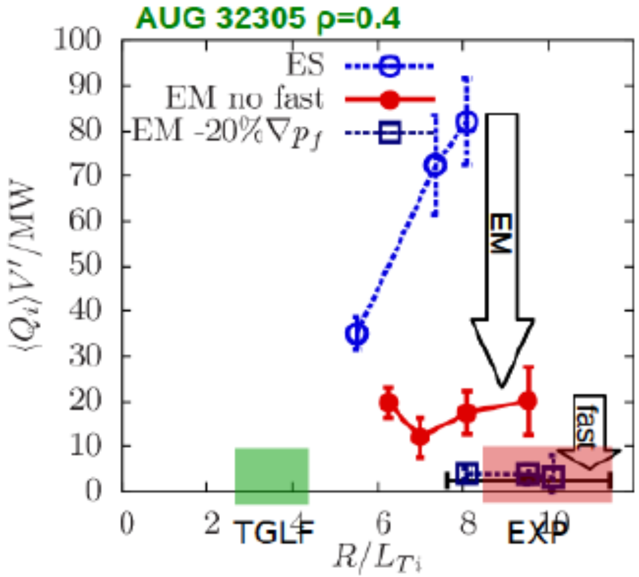


N.T. Howard *et al* 2016 *Nucl. Fusion* **56** 014004

- Only with full fidelity can the experimental levels of electron thermal transport be understood in Alcator C-Mod
- Coupling of electron and ion scale instabilities produces a lower critical a/L_{Ti} than ion-scale simulations

Will Alpha Particles Affect Thermal Transport?





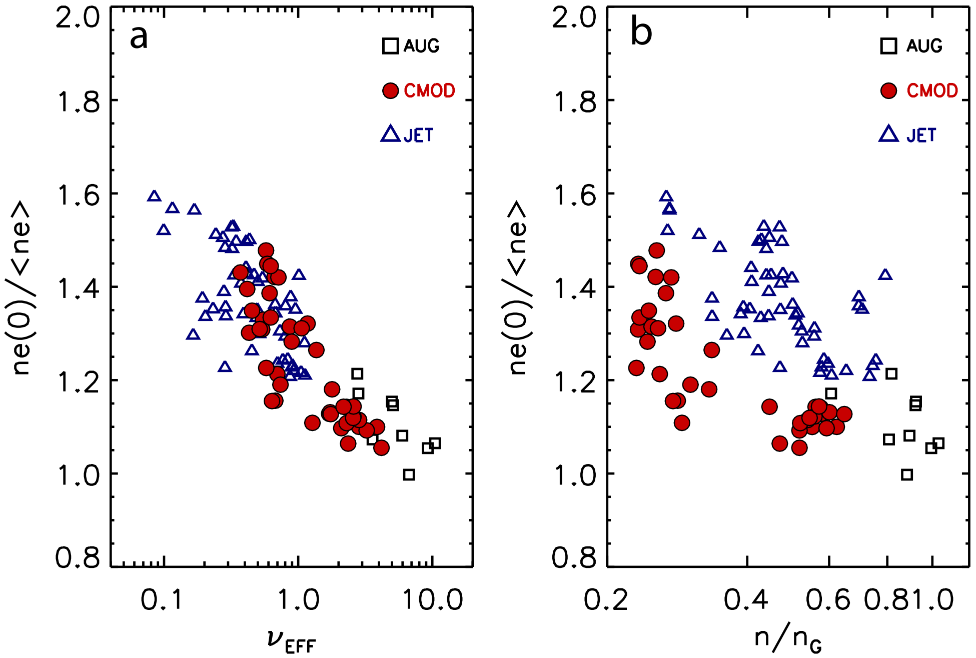
H. Doerk et al. 2018, Nucl. Fusion **58 016044**

- Improved core confinement in ASDEX Upgrade relative to TGLF predictions attributed to electromagnetic and fast ion effects using GENE.

See also J. Citrin et al., PRL **111,** 155001 (2013)

How Peaked will ITER's Density Profile Be?

C-Mod



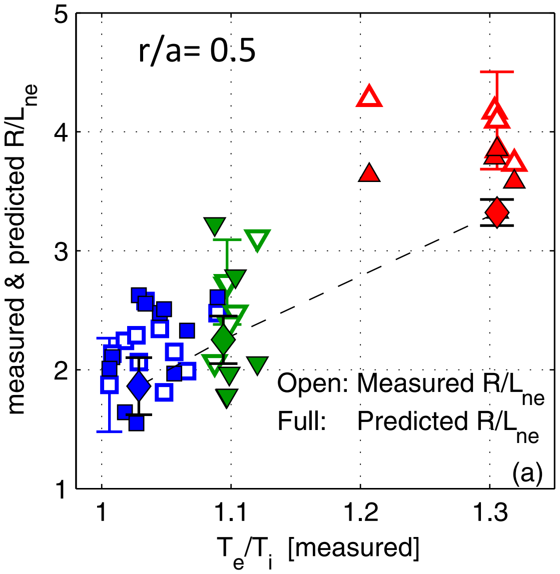
- The density peaking is better correlated with ν_{eff} than n/n_G
- C-Mod not affected by central fueling
- ITER will have minimal central fueling, except for pellet injection.

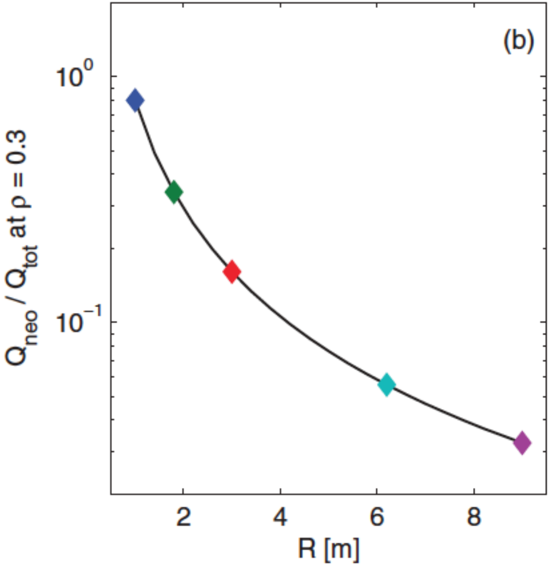
Greenwald M. *et al.* Nuclear Fusion 47, L26 (2007)

Will Gyrokinetic Modeling Describe Particle and Impurity Transport?

AUG

Angioni, C. *et al.*, Nucl Fusion **53** 023006 (2011)



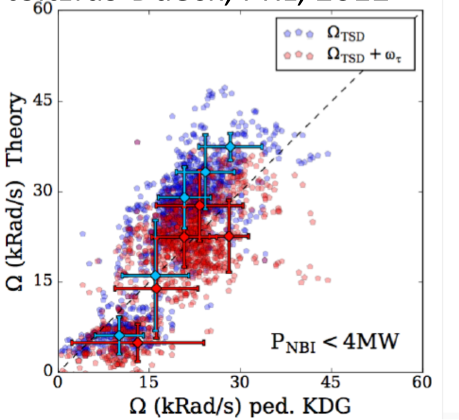


Angioni, C. *et al*, Nucl Fusion **57** 02209 (2018)

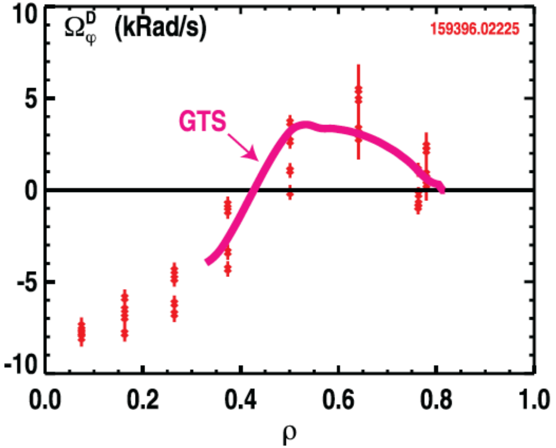
- Gyrokinetic modeling reproduces the density profile peaking in ASDEX-Upgrade
- In some current experiments, core impurity transport is dominated by neoclassical effects.
  - Simulations indicate that in ITER turbulent transport will dominate neoclassical

What will be the Rotation and Velocity Profile in ITER?

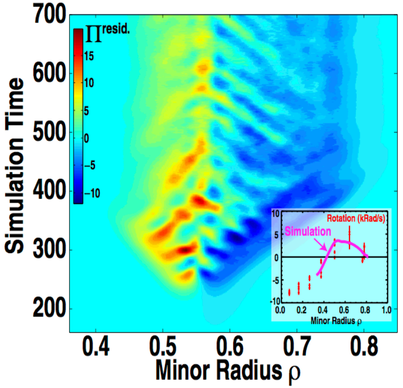
A. Ashourvan, et al., PoP 2017;
T. Stoltzfus-Dueck, PRL, 2012



B. Grierson. et al.. PRL 2017



DIII-D



- Core rotation consistent with turbulent Reynold's stress in L-mode
- Global gyrokinetic codes are predicting core rotation in these experiments fairly well, despite concern that additional terms not in present codes might be important (Parra & Catto PPCF 2010)
  - (see also W. A. Hornsby et al., Nucl Fusion **58** 056008 (2018)
- ITER will validate models of intrinsic rotation in low torque plasmas and low ρ*

Going from the Edge to the Core

- Plasma-Boundary Interactions
- Pedestal performance
- Core transport
- *Disruptions*
- Alpha-particle physics
- Integrated performance

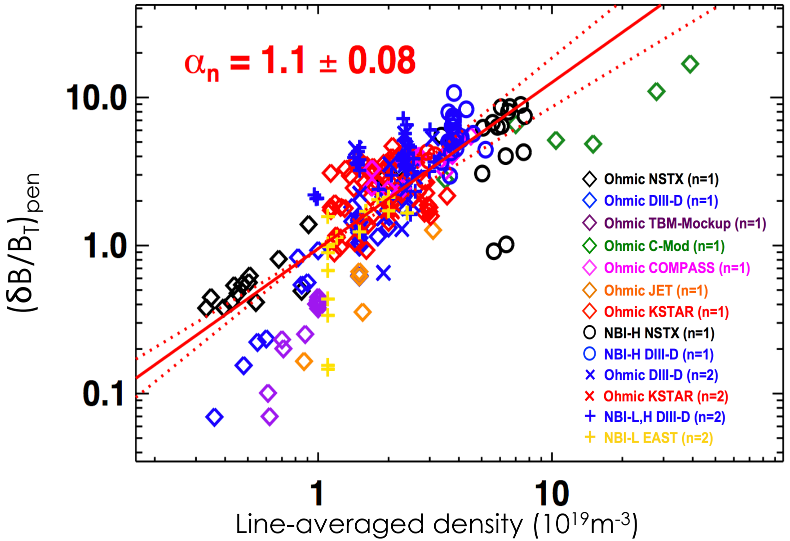
Some Recent Issues on Disruptions and Runaways

- Locked modes and Resistive Wall Modes
- Asymmetric Halo Currents
- Disruption and Runaway Electron Mitigation
- Role of Whistler Waves
- Disruption prediction
- *Most significant issue for PFCs – emphasis is on successful mitigation*

Will ITER Need to Control n=1 and n=2 Locked Modes?

- Using 3D MHD plasma response metrics
- Combined resonant n=1,2 EF criterion for Ohmic, L, H-mode scenarios:
- $(\delta B/B_T)_{pen}=0.0001(n_e)^{1.1}B_T^{-1.3}R^{0.8}(\beta_N/li)^{-0.7}(\omega/\omega_D)^{0.2}$
- Implies need to correct n=2 as well as n=1
  - Change the how the correction coils are wired?
  - Top and bottom coils may not be needed
- ITER will explore mode locking in new regime of τ_R/τ_A, $\chi_{||}/\chi_{perp}$ and collisionality.
  - Will non-resonant error fields become a consideration?

Error field penetration thresholds vs. density

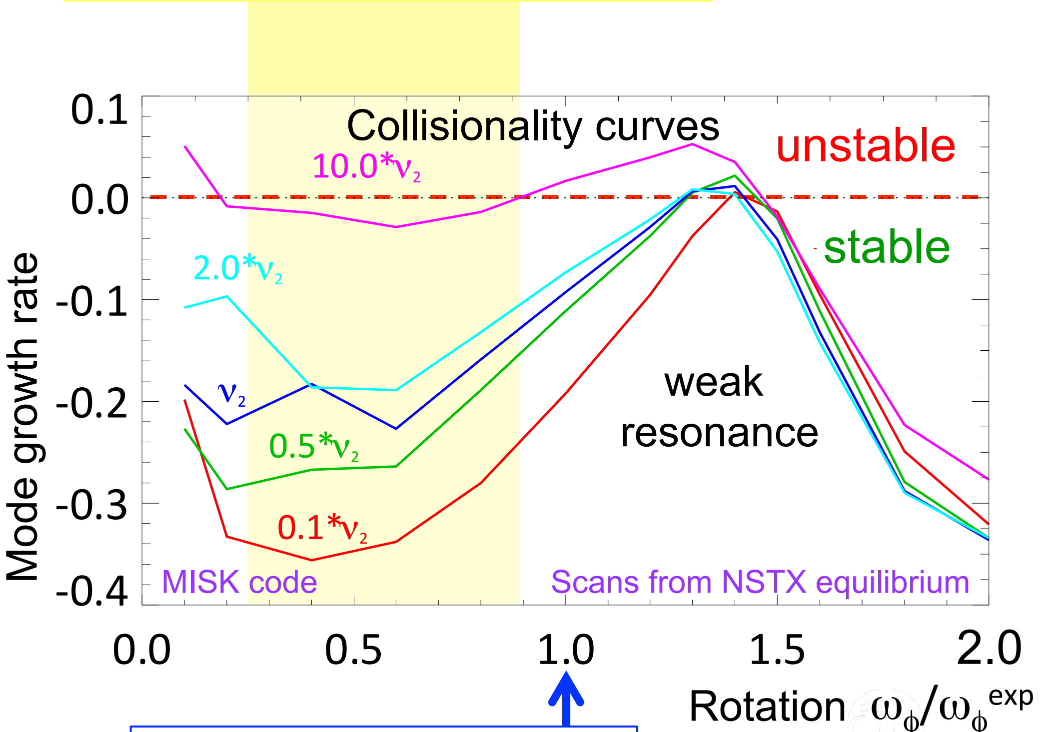


* See IDM# UMLSUW "Assessment of error field correction criteria for ITER" (Park, Logan et al., April 27)

How Will Kinetic Effects Alter Resistive Wall Mode Stability in ITER?

- <u>Past models/ideas</u>
  - Collisions provide stabilization
  - stability decreased with decreasing collisionality, ν
  - Unfavorable for ITER
- Present model
  - Collisions spoil broad stabilizing resonances
  - Mode stabilization vs. ν depends on rotation profile, ω_ϕ
  - At strong resonance: mode stability increases with decreasing ν

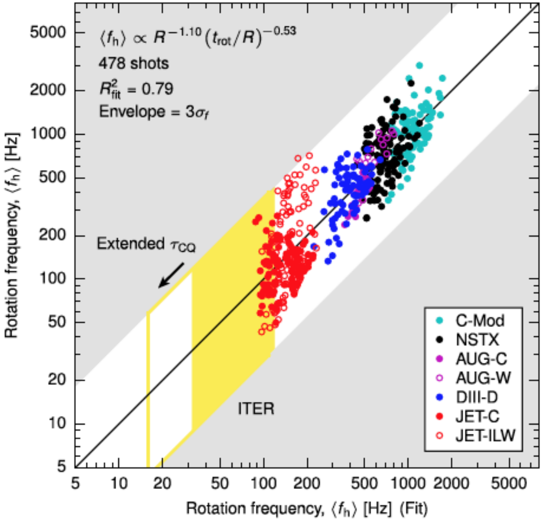
Ion precession drift resonance stabilization



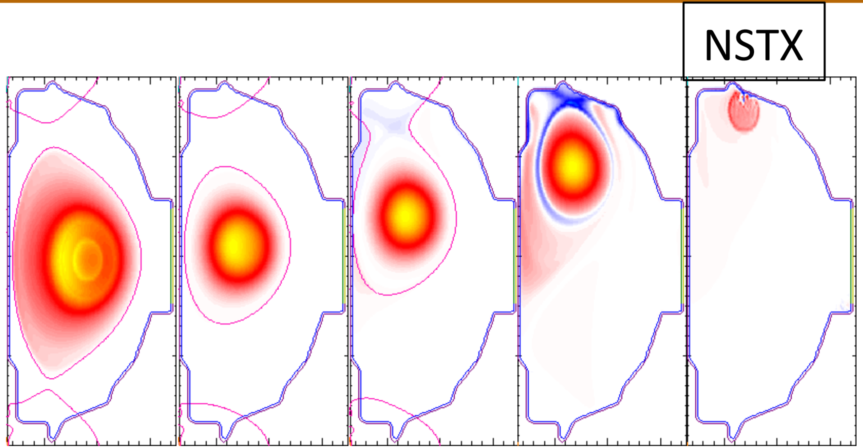
Experimental rotation profile

J. W. Berkery, PRL 106, 075004 (2011)

What will be the Role of Rotating Halo Currents in ITER?



C. E. Myers, Nucl. Fusion 58 (2018) 016050



Pfefferle, D., et al. Phys. Plasmas 25 056106 (2018)

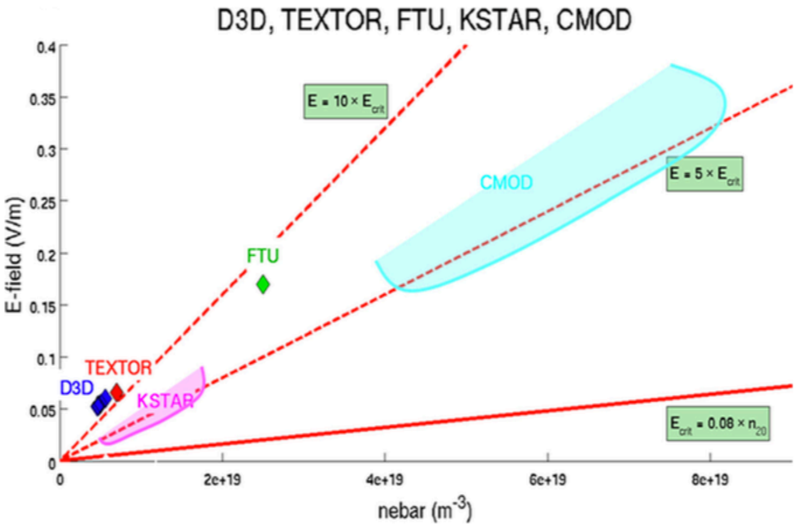
- Multi-machine characterizes the halo current rotation frequency
- M3D-C1 now has thick wall capability
- No magnetic boundary conditions are applied at wall.
- Extended these results to 3D and realistic η_W and 3D RWM
  - To assess rotating halo currents in ITER, need to couple M3D-C1 to 3D wall model

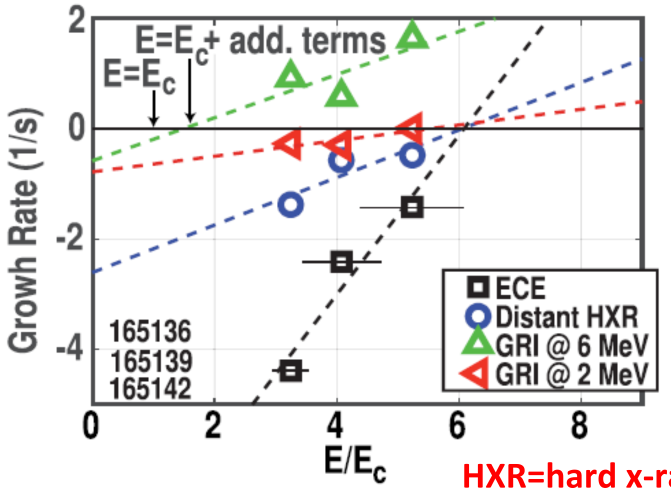
What Will Be the Recipe for Disruption and Runaway Electron Mitigation on ITER?

- Disruption Mitigation has reduced the thermal loads and the electromagnetic forces in current experiments
  - Radiation saturates with both Massive Gas Injection and Shattered pellet injection
- Disruption mitigation using massive gas injection has not triggered runways in JET up to 3.5MA
  - ITER may be different due to avalanche effect
- Massive gas injection so far has not satisfied the Rosenbluth criteria for runaway electron suppression in the core
  - Post thermal quench the RE beam has not been suppressed with MGI on JET
- Shattered pellet injection is the baseline approach for ITER
  - Can we get the impurities into the plasma?
  - Performance to date comparable to MGI
  - Can we further optimize the performance?

S. Jachmich *et. al.* TSDW-workshop 2016; M. Lehnen, TSDW workshop, 2016

Discovery of Anomalous RE Dissipation in Mid-size Experiments may be Good News for ITER





DIII-D

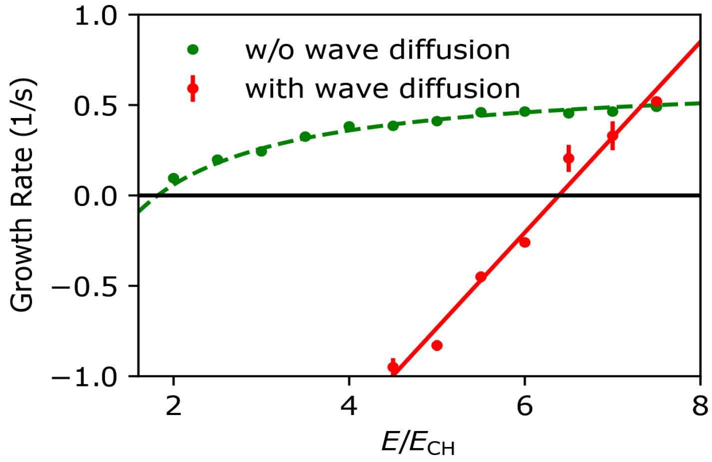
HXR=hard x-ray
GRI = gamma ray imaging

- Transition from negative to positive RE growth rate at 5-10x classical E_{crit}
- Key is to understand physics of anomalous dissipation and ITER relevance
- ITER will yield new insights on RE seed and avalanche generation

R. Granetz et al., Physics of Plasmas 21, 072506 (2014).
C. Paz-Soldan et al., Physics of Plasmas 25, 056105 (2018).

Whistler Waves Enhance Runaway Electron Diffusion – Raising Critical Electric Field in Experiments

- Whistler waves enhance runaway avalanche for high *E* field, but suppress it in low *E* field
  - Wave scattering raises the threshold electric field of avalanche to ~6 E_{CH}
    - In agreement with DIII-D observations in flattops.
    - Same trends found for ITER post-disruption.



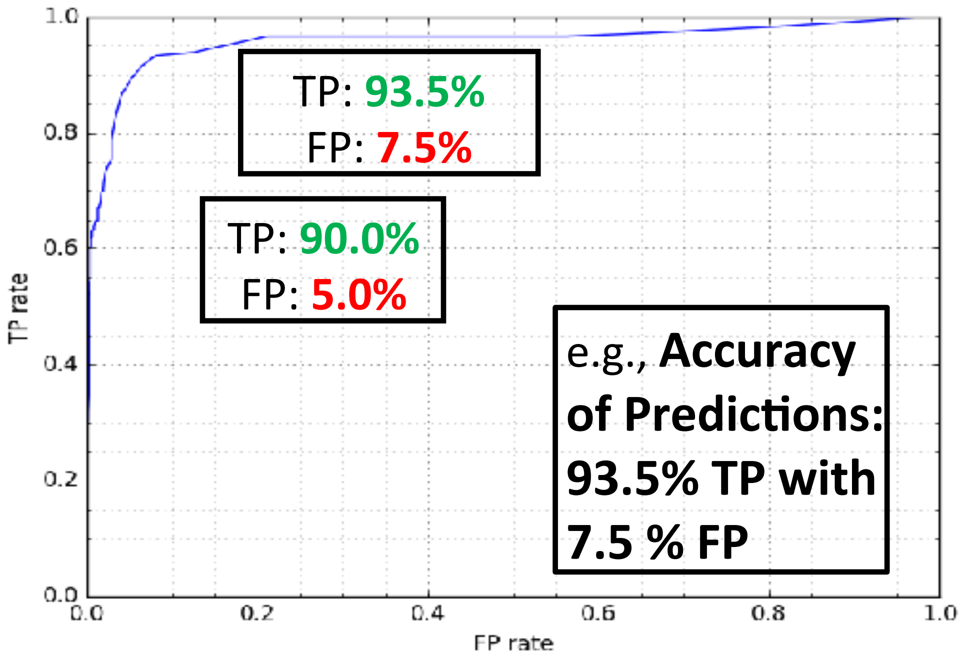
- Is it possible to suppress the RE beam in ITER post-disruptions with self-excited whistler waves?
  - Can external heating help waves overcome collisional damping in very low T_e.

C. Liu et al., in review, Phys. Rev. Lett., arXiv:1801.01827 (2018).
C. Paz-Soldan et al., Physics of Plasmas 25, 056105 (2018).

Will We Be Able to Train Disruption Prediction Algorithms on Other Facilities and Apply it to ITER?

- Application of new deep learning code (FRNN) has shown promising results for predicting:
  True Positives (TP) → "good" - correctly labeled a disruptive shot
  vs.
  False Positives (FP) → "bad; actual safe shot *incorrectly labeled disruptive*.

- Now training the algorithm on DIII-D and applying it to JET data with a >80% true positives
  - In contrast with earlier work, which did not show transferability



Courtesy W. Tang

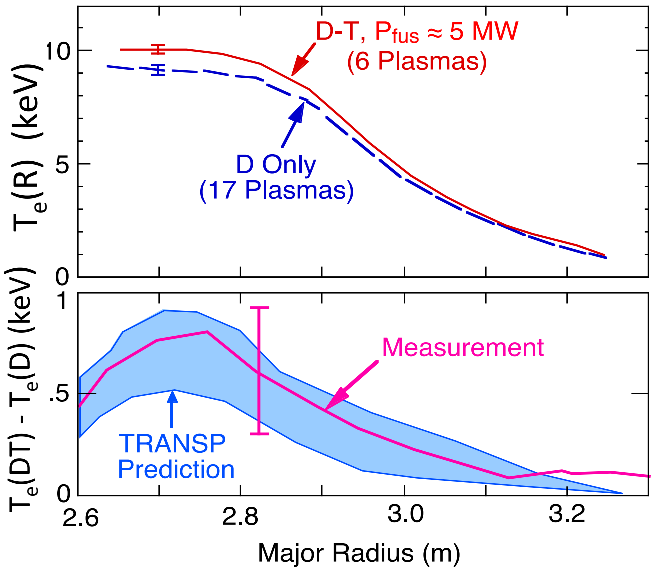
Going from the Edge to the Core

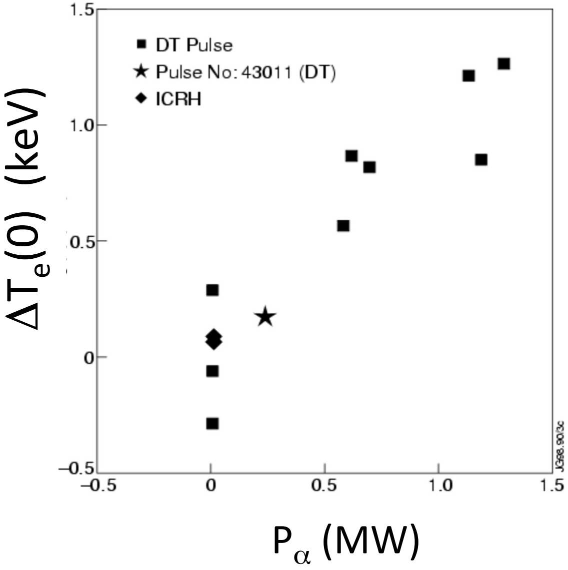
- Plasma-Boundary Interactions
- Pedestal performance
- Core transport
- Disruptions
- *Alpha-particle physics*
- Integrated performance

Initial Evidence of Alpha-particle Heating on TFTR and JET

TFTR

G. Taylor,
J. Strachan





JET

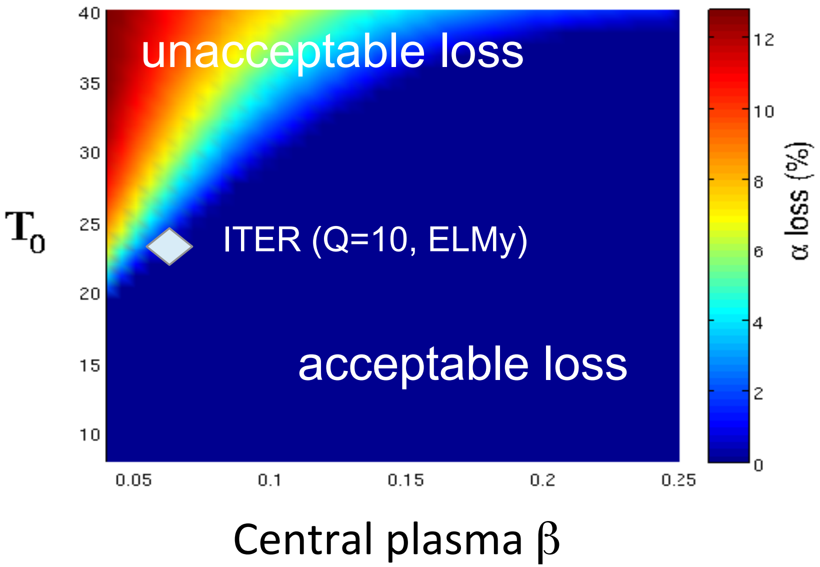
P. Thomas

- Alpha heating ~15% of power through electron channel.

- P_{alpha}/P_{heat} ~12%
  - 30-40% through the electron channel

- Significant uncertainty in the analysis.
- Comprehensive study of alpha heating requires higher values of P_{alpha}/P_{heat}.

Alpha-Particle Loss from Alfvénic Instabilities is Dependent on Central Temperature

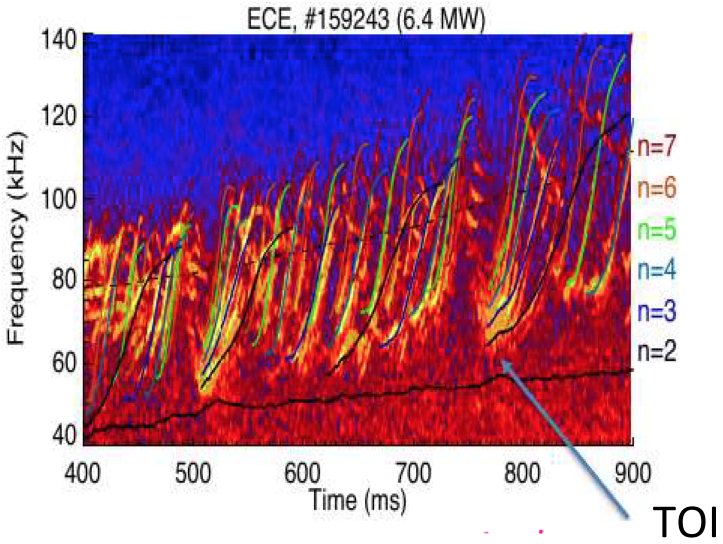


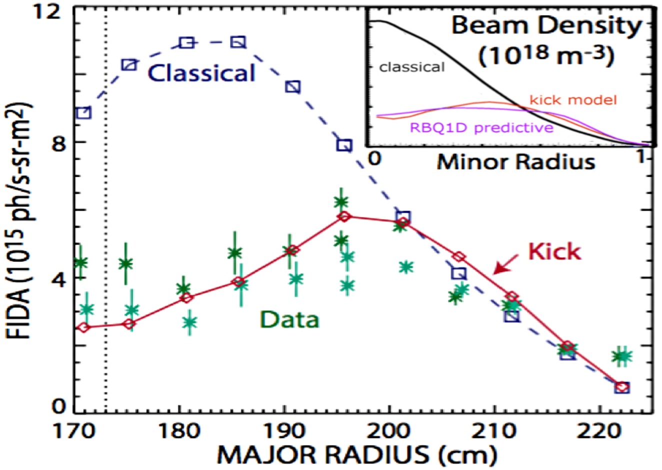
- Critical Gradient Model - **CGM** (Gorelenkov, Berk, NF'05, Ph.Pl.'12) indicates that higher temperature (lower density operation) can lead to alpha particle loss

Reduced Fast-Ion Transport Models Successful in Predicting Low-n Multi-mode Transport in DIII-D

TAE/RSAEs

N.Gorelenkov, M. Podesta et al., IAEA TCM (2017)
W. Heidbrink et al., Phys. Plasmas, 24 (2017)

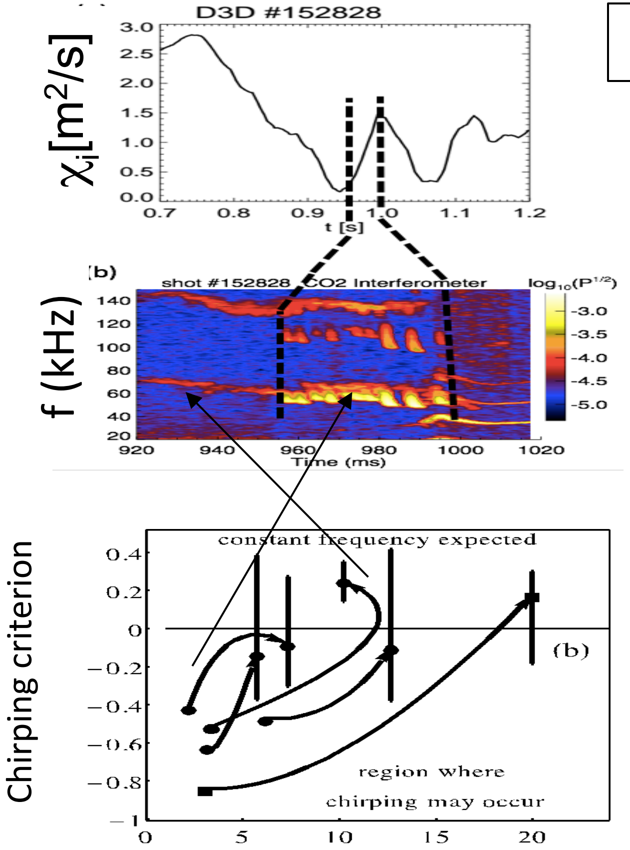




DIII-D

- Resonance Broadened Quasilinear model in good agreement with "kick model"
- Need to extend V&V to different plasma regimes/facilities
- ITER predictions must address multi-mode transport (n~15-30) with overlapped phase space resonances

Will Chirped Frequency Alfvénic modes Occur in ITER?



DIII-D

- Drop in plasma turbulence (TRANSP) results in chirping frequency AEs:
  - smaller effective pitch angle scattering and
  - chirping behavior

- PPPL/IFS collaboration developed a chirping **criterion** for Alfvénic instabilities in NOVA-K

  (Duarte, Berk, Gorelenkov, NF'17)

- ITER is predicted by this model to have such chirping regimes for AE instabilities:

Pitch angle scattering / collisional slowing down (frequencies)

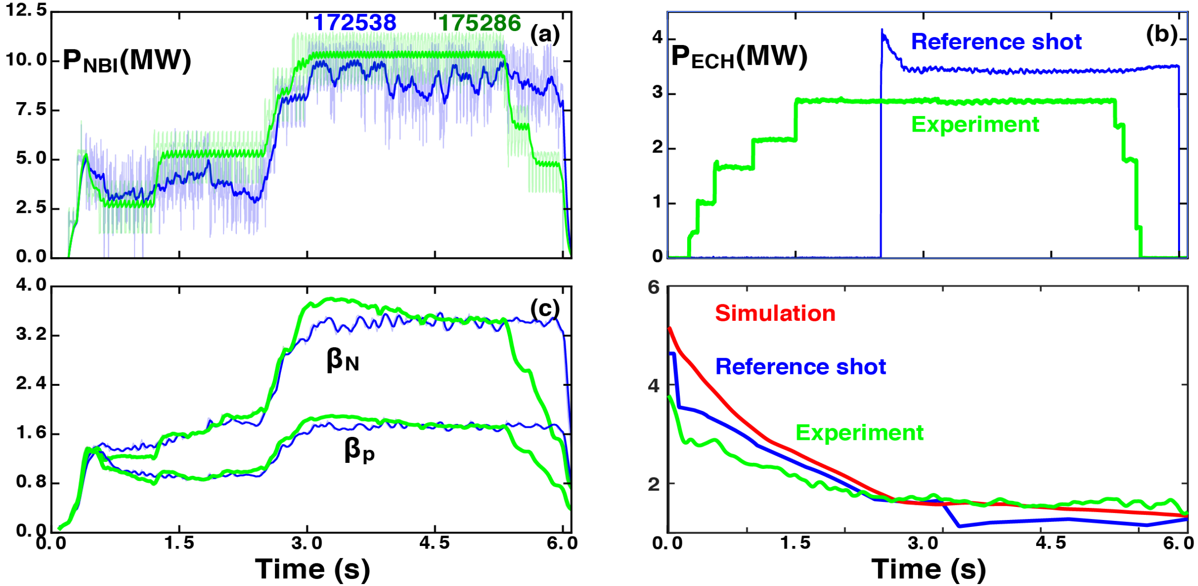
How Successful Will Burn Control Be on ITER?

- On the basis of global scaling of confinement, ITER is expected to be globally stable, operating in the high temperature regime
- Will nonlinear effects affect burn stability?
  - Can internal transport barriers be triggered by alpha heating?
  - Can improved transport trigger chirping instabilities?
  - Complex dynamics in the pedestal, scrapeoff and plasma boundary as discussed earlier
- Possible actuators: Heating power, fueling, Impurity injection and RMP coils to affect confinement time
  - Will this ensure a stable equilibrium or a time evolving state?
- Routine operation with strong alpha heating will enable the exploration and optimization of burn control

Going from the Edge to the Core

- Plasma-Boundary Interactions
- Pedestal performance
- Core transport
- Disruptions
- Alpha-particle physics
- *Integrated performance*

Time Dependent Whole Discharge Modeling Will Be a Requirement for ITER



DIII-D

Courtesy F. Poli, B. Grierson

- Fast neural-net algorithm for EPED and GLF23 coupled to TRANSP allow for rapid time-dependent simulation
- Essential for recent improved high-q_{min} experiments in DIII-D

What Will Be the Minimum Required Modeling for the Next Shot on ITER?

- Time dependent core-pedestal 1.5 D model
- Divertor model including PFCs
  - 2 D physics
- MHD and Alpha-particle stability
- Will all of these models be strongly coupled?
  - The experiment is!
- ***We will need a mix of reduced models and comprehensive whole device models, such as those that are part of the Exascale Computing Project***
- Will we use these models to optimize performance or merely enforce limits on operation?
- What will be the role of machine learning in optimizing performance?

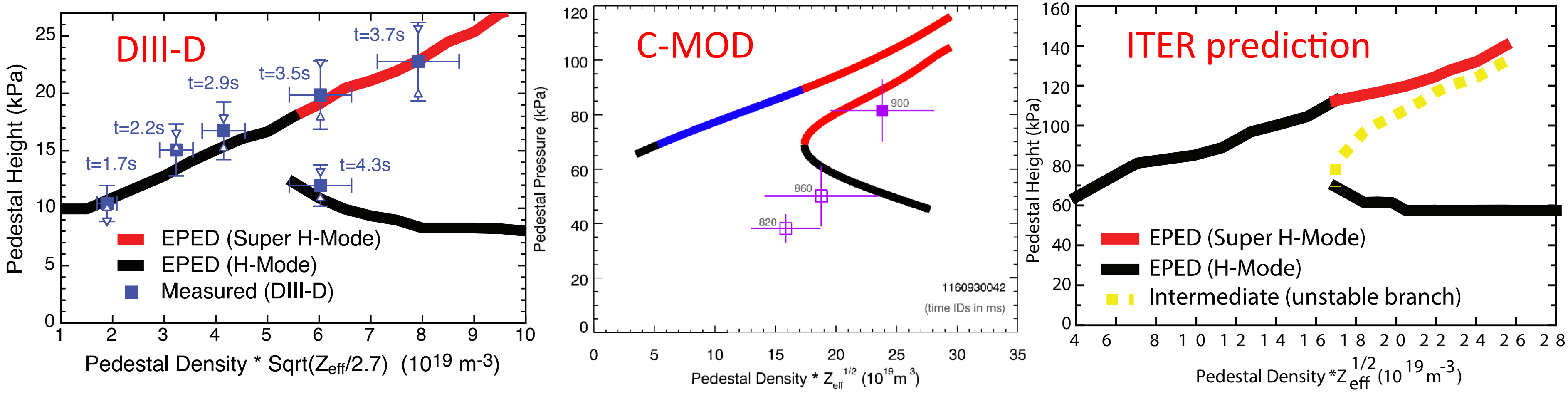
Will the Standard ITER H-mode Be the Route to Q=10?

- There are several promising approaches to high fusion power
  - Advanced inductive
  - Super H-mode
  - I-mode

- What new ideas will be generated between now and the high fusion power experiments on ITER?

Discovery of Super H-mode Regime May Open a Path Towards Enhanced Fusion Gain in ITER

P.B. Snyder, et al., NF 2015 | J. Hughes, et al., accepted, NF 2018 | P.B. Snyder, et al., NF 2015



- Super H-mode regime led to record pressure is C-Mod and DIII-D
- Challenge is to design reliable access to Super-H modes and ensure sustained operation

Will ITER Define the Transition from Empiricism to Prediction?

- ITER was designed on a solid empirical basis
- ITER will provide new scientific perspectives and answer key questions due to its unique parameters and alpha heating
- *Full potential and consequences of alpha heating have not been explored!*
  - *Opens the possibility of new scientific discoveries*
- Will ITER and the work in preparation for it enable the validation of theoretical and simulation models to provide a predictive basis for a power plant?

Thank you!