# Discussion of Progress and Workplan for ITER Urgent Issues in Pedestal Structure

*Pedestal Structure Working Group*

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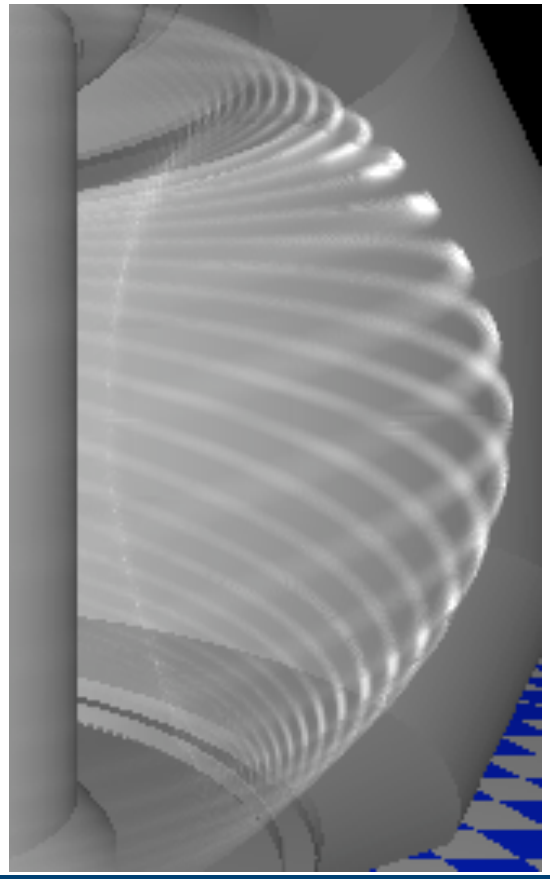
**Acknowledgments: E. Wolfrum, C. Maggi, N. Aiba,**

**T. Osborne, K. Burrell, J. Callen**



**ITPA Pedestal Meeting**
**Princeton NJ, USA**
**5 October 2009**

# Broad Goal of Pedestal Structure Group is Predictive Understanding of the Pedestal

| | | |
|---|---|---|
| 1015 | Effect of a pinch on inferred particle diffusion coefficients in the pedestal. | J Callen |
| 1035 | **Coffee** | |
| 1055 | A dynamic model of pedestal particle fueling during the ELM cycle | T Rognlien |
| 1115 | Implications of pedestal MHD stability limits on the performance of ITER | J Lonnroth |
| 1135 | Status and Plans for the European Transport Solver (ETS) code | R Zagorski |
| 1155 | JET experiment on comparison of H-modes with NBI only or ICH+ NBI with large ICH fraction | R Sartori |
| 1215 | Latest results on LH transition, ELMs and pedestal physics from C-Mod | J Hughes |
| 1235 | **Lunch** | |
| 1345 | Nonlinear peeling-ballooning simulations using BOUT++ code | X Xu |
| 1405 | Numerical Analysis of the rotation effect on the type-I ELMs in JT-60U | N Aiba |
| 1425 | Baseline pedestal structure from neoclassical and neutral particle physics in diverted geometry | CS Chang |

**Summary of recent progress in pedestal physics at H-Mode Workshop last week (C. Maggi)**

**Characterize and respond to urgent ITER needs, which impact ITER decisions on short timescales**

# Current List of ITER-urgent Objectives

Objectives:

- 4.1 Explore whether the pressure pedestal height and width depend on the heating source, quantify any differences and interpret in terms of emerging models for pedestal height
- 4.2 Explore whether the density pedestal properties depend on heating source (e.g. through modified fuelling sources; i.e. enhanced core fuelling with NBI compared to that with ICRF)
- 4.3 Assess the impact of heating source on ELM size and explore prospects for interpretation in terms of peeling-ballooning theory
- 4.4 Quantify the impact of torque on the pedestal structure and ELMs
- 4.5 Assess the potential viability of QH mode as a high pedestal, ELM-free regime for ITER (added 4/09)
- 4.6 Develop theoretical models for the observed scaling of pedestal width with plasma parameters

# Capabilities Statement

*Capability*

- **Several devices have the capability to address the urgent issue of the impact of heating mix on pedestal structure and ELMs. Ideally experiments would be done on a single machine to keep other variables fixed, but joint experiments may be appropriate in the future to develop understanding further. ASDEX Upgrade has ICRH, NBI and ECRH, Alcator C-Mod has LH and ICRH, DIII-D has ECRH and NBI (balanced and unbalanced), NSTX has NBI and HHFW, JET has ICRH and NBI, and JT-60U has data from negative and positive ion neutral beams (balanced and unbalanced). MAST heating is dominated by NBI, but also has a small amount of EBW. A number of gyro-kinetic turbulence codes are beginning to emerge that can treat the transport processes in the pedestal region and may provide some understanding on the pedestal width scaling with $\beta_p$ in the future.**

# Relevant PEP Joint Experiments

A number of the joint experiments make important contributions towards meeting the objectives:

- PEP-2 "Pedestal gradients and ELM energy losses in dimensionally similar discharges and their dimensionless scaling" JET, DIII-D and ASDEX Upgrade
- PEP-6 "Pedestal structure and ELM stability in DN" MAST, AUG, NSTX, (JET and C-Mod for analysis of existing data)
- PEP-18 "Comparison of Rotation Effects on Type I ELMing H-mode in JT-60U and DIII-D", JT-60U (analysis of existing data) and DIII-D
- PEP-20 "Documentation of the edge pedestal in advanced scenarios" AUG, DIII-D, JET, JT-60U (analysis of existing data)
- PEP-22 "Controllability of pedestal and ELM characteristics by edge ECD/ ECCD/LHCD" AUG, C-Mod, DIII-D, JT-60U (analysis of existing data)

PEP discussion Wednesday

# Timeline

| Objective | Task | Q1-09 | Q2-09 | Q3-09 | Q4-09 | Q1-10 | Q2-10 | Q3-10 |
|---|---|---|---|---|---|---|---|---|
| 4.1 | (a) Compare pedestal width scaling with different mixes of heating power (DIII-D, JET, AUG, NSTX, CMod,JT-60U) | | | | | | | |
| 4.1 | (b) Test EPED1 model for pedestal height holds independent of heating power mix (theory, All H-mode tokamaks) | | | | | | | |
| | | | | | | | | |
| 4.2 | (a) Compare density pedestal structure with different mixes of NBI and RF heating (DIII-D, AUG, JET, NSTX) | | | | | | | |
| | | | | | | | | |
| 4.3 | (a) Quantify impact of heating mix on ELM type (DIII-D, JET, AUG, NSTX, CMod, JT-60U) | | | | | | | |
| 4.3 | (b) Interpret experiments in 4.1(a) and 4.4(a) in terms of peeling-ballooning theory | | | | | | | |
| | | | | | | | | |
| 4.4 | (a) Quantify impact of torque input on pedestal structure for beam-heated discharges (DIII-D, JT-60U) | | | | | | | |
| | (b) Quantify impact of torque input on ELM type for beam-heated discharges (DIII-D, JT-60U) | | | | | | | |
| | | | | | | | | |
| 4.5 | (a) Identify the required range of density expected to allow QH mode operation in ITER | | | | | | | |
| | (b) Identify the required range of flow (or radial electric field) shear required for accessing the QH mode | | | | | | | |
| | | | | | | | | |
| 4.6 | (a) Provide a theoretical/computational model for observed scaling of pedestal width with plasma parameters. | | | | | | | |

# Objective 4.1, 4.2 progress and plan

- **4.1 Explore whether the pressure pedestal height and width depend on the heating source, quantify any differences and interpret in terms of emerging models for pedestal height**
- **4.2 Explore whether the density pedestal properties depend on heating source (e.g. through modified fuelling sources; i.e. enhanced core fuelling with NBI compared to that with ICRF)**
  - 4.1 (a) Compare pedestal width scaling with different mixes of heating power (JET, AUG, DIII-D, NSTX, CMod,JT-60U)
  - 4.2 (a) Compare density pedestal structure with different mixes of NBI and RF heating (JET, AUG, DIII-D, NSTX): Q1-Q2 '09, & Q2-Q3'10
    - Initial focus on Type I ELM regime as reference for comparison. Should we also consider other regimes? TIII? QH?
    - To report here and next ITPA:

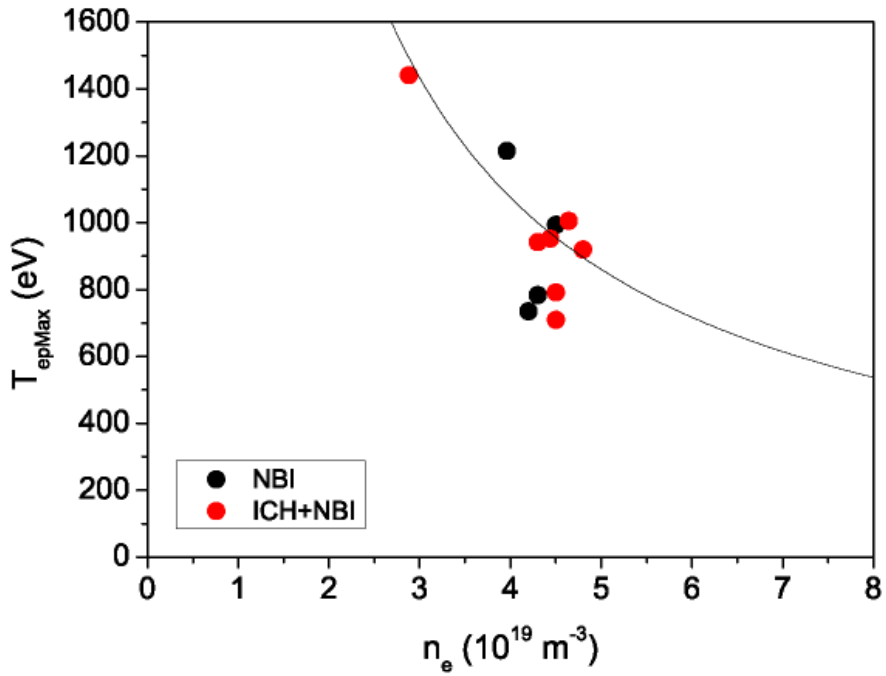
      JET (***Sartori***, Saibene, Beurskens): ICRF vs NBI

      AUG (Wolfrum): ECH vs NBI DIII-D (Osborne/Groebner): ECH vs NBI

      C-Mod (***Hughes***): ICRH and ICRF/LH (2011 for LH/Ohmic), DIII-D comparison with CXRS

# JET (preliminary): Pedestal height and width similar in NBI vs ICH expts

*R. Sartori et al ITPA10/09*

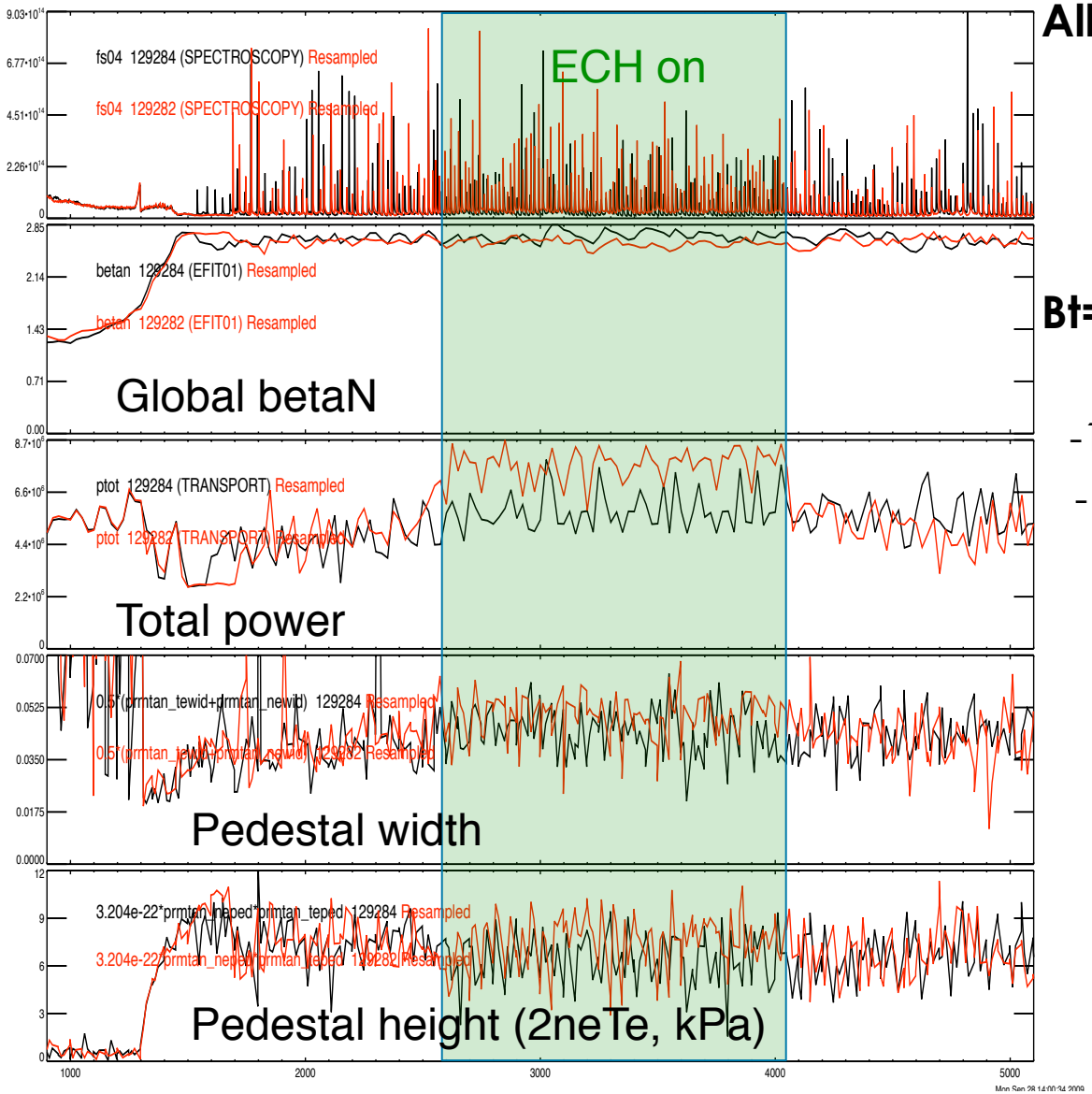



- **R. Sartori to report details in this session**
  - Scan from 50:50 ICH:NBI at 16MW to 100% ICH at 9MW, compare to 100% NBI at equal total power
  - Pedestal pressure (both from Te ECE and interferometer, assuming Te=Ti, and from HRTS) is similar with some degradation at lower power
  - Pedestal widths (n and Te) & pressures are independent of additional heating mix

# AUG (preliminary): Profiles unchanged in expts trading NBI for ECH at fixed power

- ***E. Wolfrum, C. Maggi et al for AUG***
  - used 2.5 MW NBI throughout + either 1.2 MW ECRH or + 1.2 MW NBI (1 source modulated), for constant $P_{tot}$~3.7MW
  - No differences in ne, Te and Ti profiles were observed. Only difference seen in vtor profiles (~50% higher pedestal top values with NBI only)
  - Also, previous results with large fractions of ICH power, will look at for next meeting

# DIII-D (preliminary): Profiles unchanged in expts trading NBI for ECH at fixed beta




**All NBI 129284 (black) vs ~60% NBI+ ~40% ECH 129282 (red)**
*[Osborne, Prater, Hudson et al]*

-NBI feedback used to fix betaN and rotation

**Bt=-1.27 T, Ip~1.19 MA, <ne>~ 3.5x10^19 m^-3**

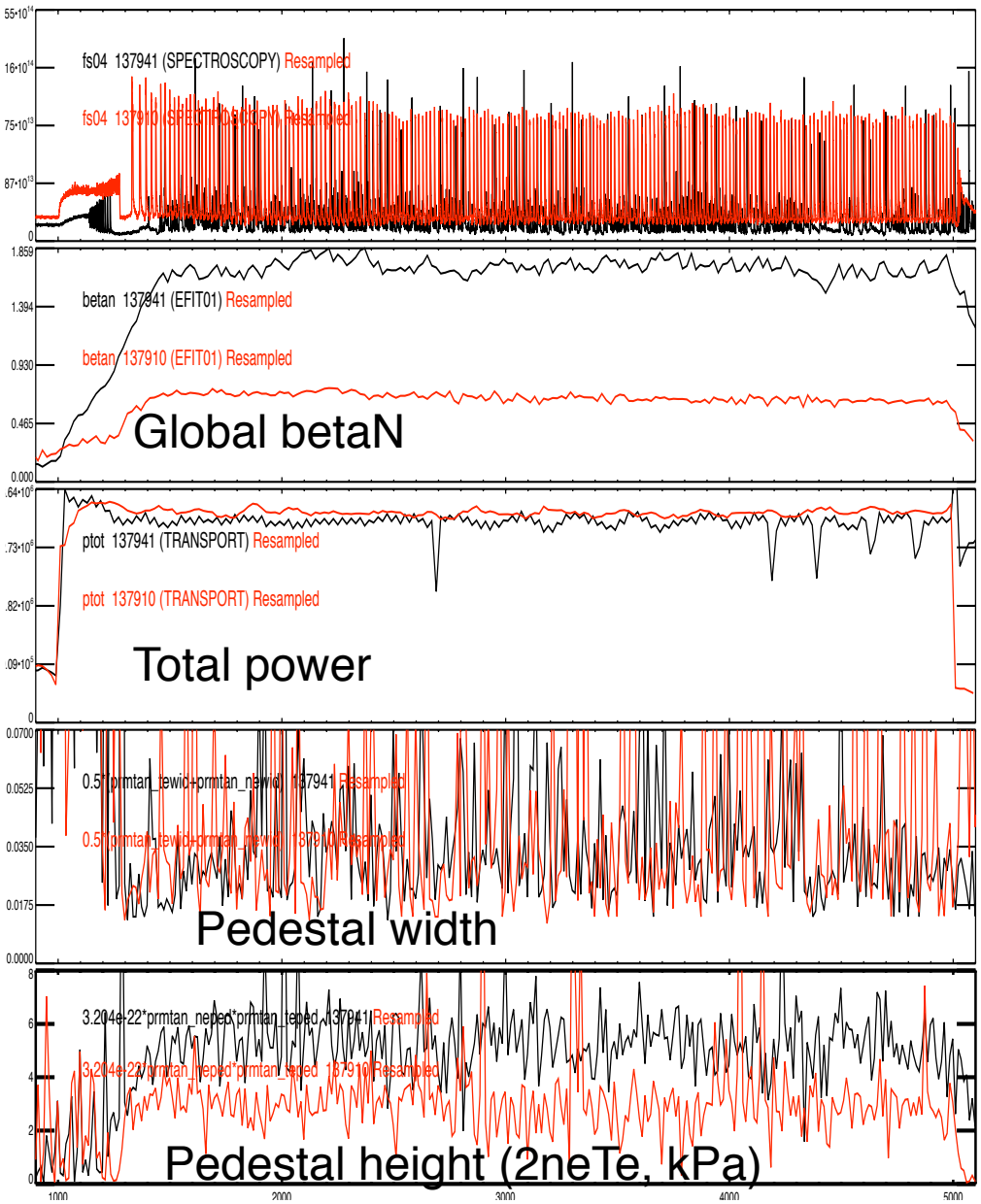
-129284: ~5.6 MW of NBI

-129282: 2.35MW ECH at rho=0.14, + NBI needed to fix betaN~2.6 and rotation ~ 66krad/s at rho=.5

-Core confinement reduced with ECH (H98y2 1.08 vs 1.27)

- No differences in ne, Te and Ti profiles were observed. Pedestal height and width ~unchanged
- Only difference seen in vtor profiles (~50% higher pedestal top values with NBI only)

# DIII-D (preliminary): Pure ECH discharge appears not to reach high confinement regime



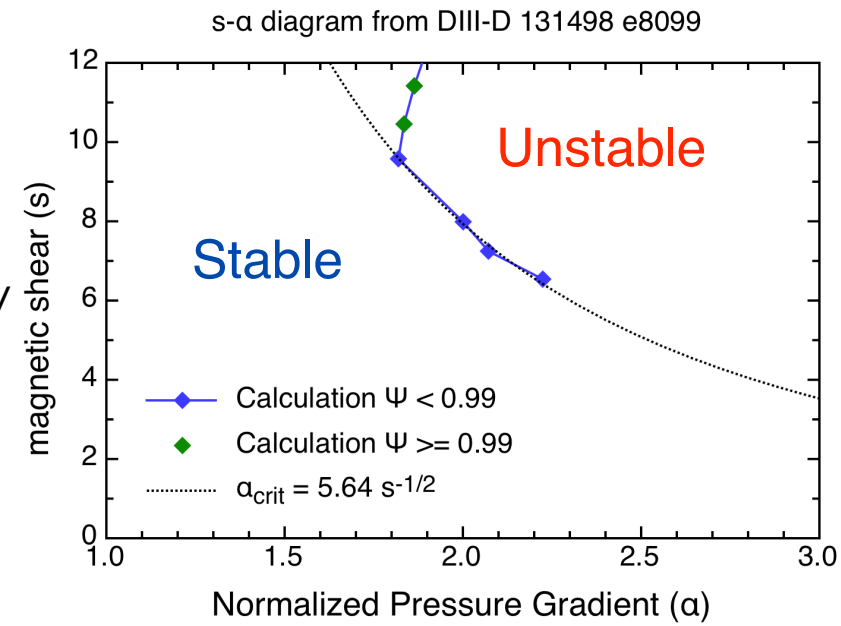

- **DIII-D 137941 (black, all NBI), 137910 (red, all ECH)**
  - Matched P~3.2MW, and density, coupled ECH power somewhat lower
  - Lower beta and pedestal height in ECH case
    - Type III ELM regime?
    - As before, appear to need more ECH power than NBI to reach same global parameters (in some regimes), even with matched rotation
  - More ECH power available after LTO2

# Objective 4.1 & 4.2 plan cont'd

- **4.1 (b) Test EPED1 model for pedestal height holds independent of heating power mix (theory, All H-mode tokamaks): Q2'09-Q3'10**
  - Initial, highly preliminary EPED1 comparisons to varied heat source on JET, DIII-D
  - Experiment to test EPED1 on all-RF C-Mod discharges carried out 9/14/09 (Hughes)
    - ELMing data at 2 values of Ip obtained
  - Development of EPED2 model ongoing (improved omegastar, GK based KBM model)
    - Inclusion of aspect ratio dependence in KBM constraint key for MAST, NSTX comparisons

# EPED1 combines nonlocal P-B constraint with EM KBM constraint based on stiff onset

- **EM GF and GK simulations: onset of strongly driven KBM turbulence near ballooning $\alpha_{crit}$** *[Snyder99, Scott01, Jenko01, Candy05…]*
  - kinetic effects drive onset slightly below ideal boundary
  - ExB shear can impact onset somewhat but not suppress
  - turbulence onset near nominal $\alpha_{crit}$ even with 2nd stability




**Implies** $\alpha \propto \alpha_c \propto \beta_{p,ped}/\Delta_\psi$ $\boxed{\Delta_\psi \propto \beta_{p,ped}/\overline{\alpha}}$ ($\Delta_\psi$ is width in normalized poloidal flux)

-Strong dependence of $\Delta$ on $\beta_{p,ped,}$ sub-linear due to *s* dependence

-pedestal is a *low* (local) magnetic shear region, $\alpha_c \sim 1/s^{1/2}$

-higher $J_{bs}$~$\beta_p$ reduces shear and increases $\alpha_{c,}$ $\overline{\alpha} \sim \beta_{p,ped}^{1/2}$

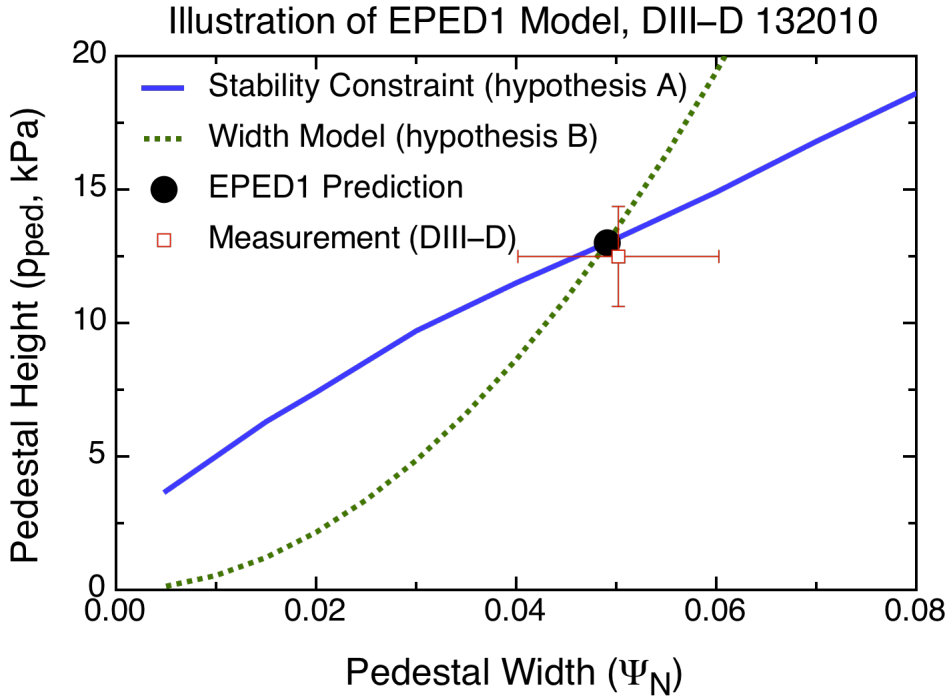
Yields: $\boxed{\Delta_{\psi_N} = 0.1\beta_{p,ped}^{1/2} G(\nu_*, \varepsilon \ldots)}$ where G~1 slowly varying

***EPED2 calculate G directly; EPED1 <G> taken from observations***

***-Observations consistent with theory, <G>~0.76, weakly varying (DIII-D)***

# Mechanics of the EPED1 Predictive Model

- **Input: $B_t$, $I_p$, R, a, $\kappa$, $\delta$, $n_{ped}$, $\beta_{global}$**
- **Output: Pedestal height and width**
  - *No power dependence, or power source dependence (except indirect through $\beta_{global}$)*
- **Stability calculated via a series of model equilibria with increasing pedestal height**
  - ELITE, n=5-30, $\gamma > \omega_{*pi}/2$




- **KBM (width):** $\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$

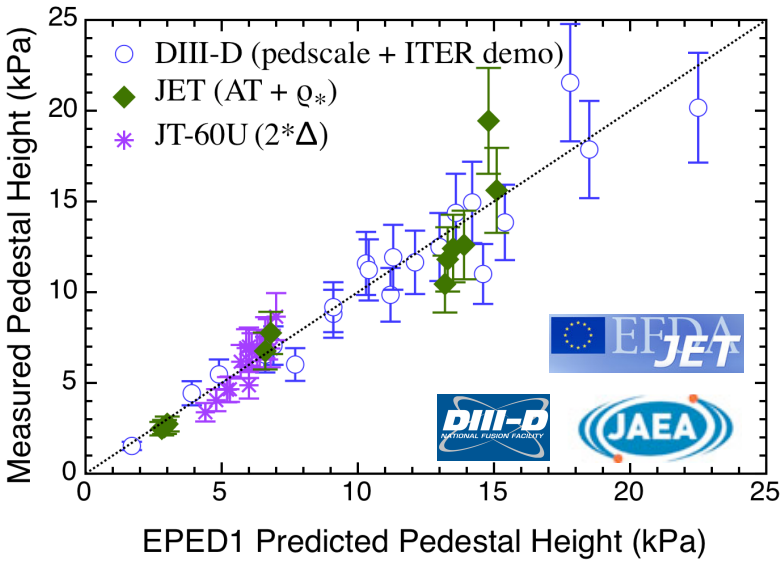
**Different width dependence of stability (roughly $p_{ped} \sim \Delta_\psi^{3/4}$) and width model ($p_{ped} \sim \Delta_\psi^2$) ensure unique nontrivial solution, which is the EPED1 prediction (black circle)** ***[both constraints needed to get height or width]***

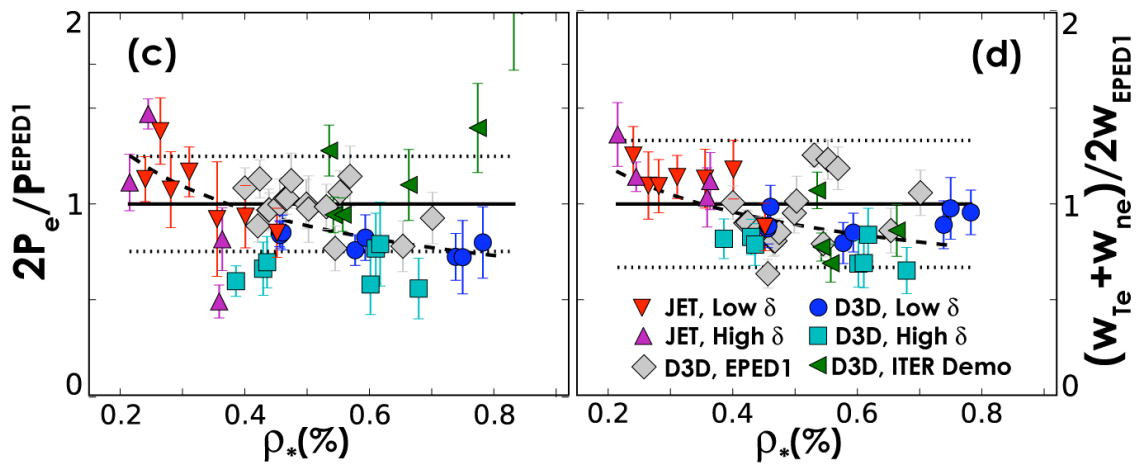
- Can be systematically compared to existing data or future experiments

***Stability and width physics are tightly coupled: If either stability or width physics model is incorrect, predictions for both height and width will be systematically incorrect***

*P.B. Snyder et al PoP **16** 056118 (2009); P.B. Snyder et al Nucl Fusion **49** 085035 (2009).*

# EPED1 tested on additional cases

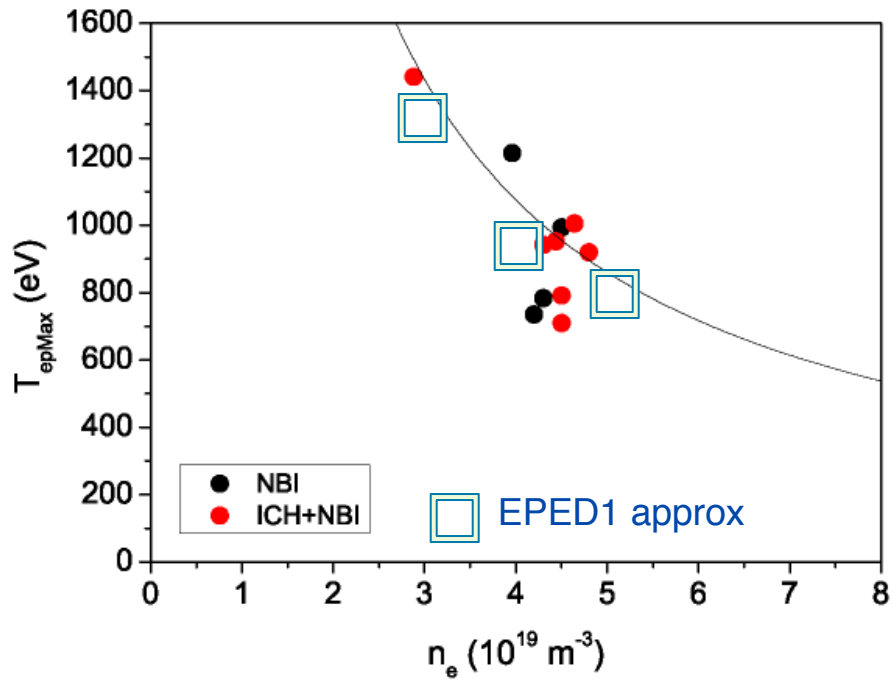



*Osborne et al H-ModeWS'09*

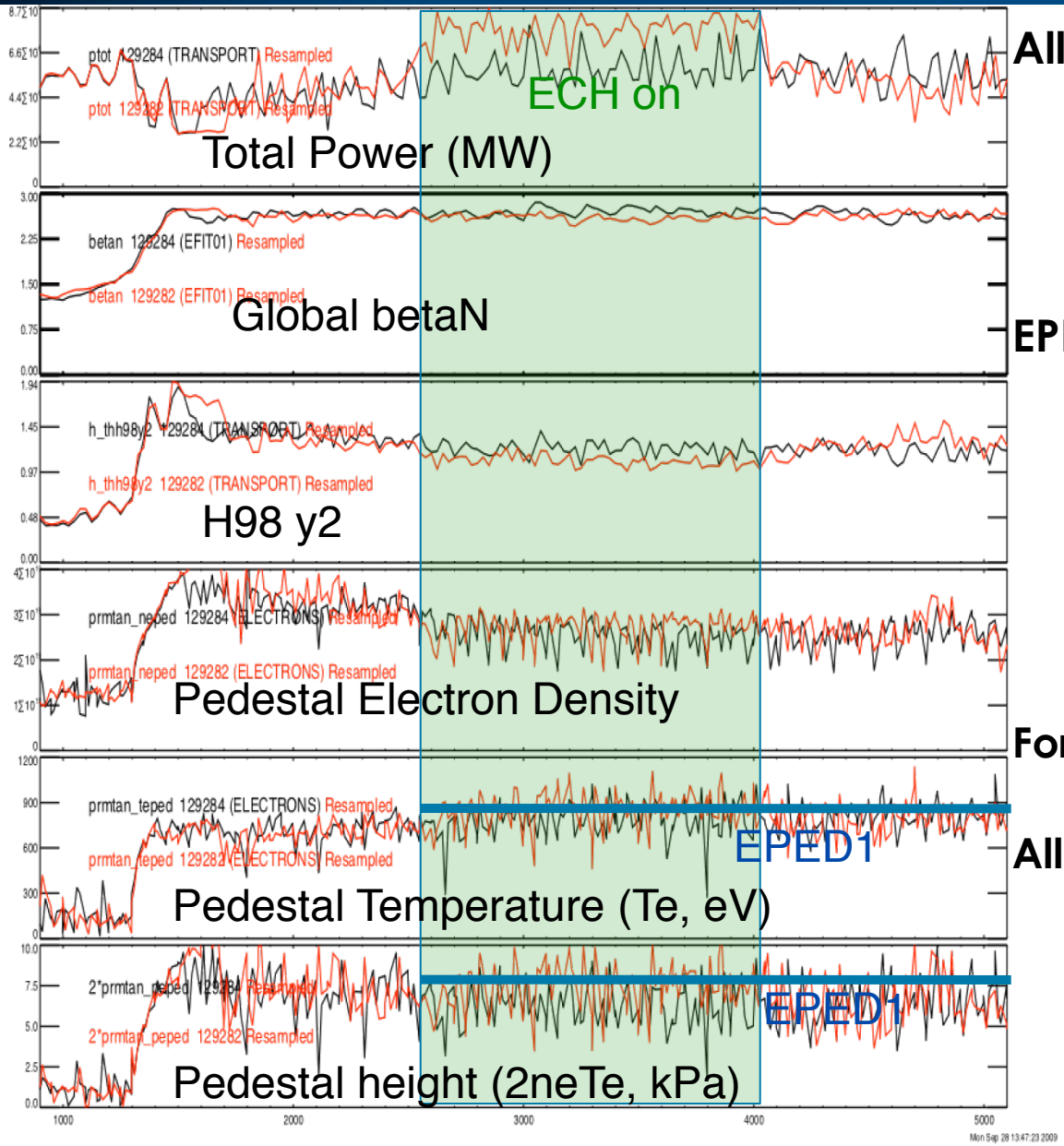
- **Predicted/Measured pedestal height= 1.02 ±0.14** ***(21 DIII-D, 16 JT-60U,11 JET)***
- **Compared to JET-DIII-D rhostar expt** ***(Beurskens & Osborne EPS09, PPCF, H-ModeWS09)***
- **Initial comparison on AUG, plan wider range (low for improved H-mode)**
- **Expt conducted on C-Mod 9/14/09 to test model** ***(Hughes & Snyder)***
  - Data at 2 values of $I_p$ obtained

# JET (preliminary): Pedestal height and width similar in NBI vs ICH expts: Highly preliminary EPED1 comparison




- **R. Sartori to report preliminary expt details in this session**
  - Scan from 50:50 ICH:NBI at 16MW to 100% ICH at 9MW, compare to 100% NBI at equal total power
  - Pedestal pressure (both from Te ECE and interferometer, assuming Te=Ti, and from HRTS) is similar with some degradation at lower power
  - Pedestal widths (n and Te) & pressures are independent of additional heating mix
- **Highly preliminary EPED1 runs with estimated values for inputs**
  - Inputs: $B_t$=2.7T, $I_p$=2.5MA, $\delta$~0.25, R~2.9m, a~0.95m, $\kappa$~1.69, $\beta_{global}$~1.5, $n_{ped}$=3,4,5,
  - Outputs: $\beta_{N,ped}$~0.4-0.45, $T_{ped}$~1275, 925, 775eV for $n_{ped}$~3,4,5 $10^{19}$
  - EPED1 has no dependence on power or power type, agrees reasonably well here

# DIII-D (preliminary): Reasonable agreement with EPED1 with NBI or NBI+ECH




**All NBI 129284 (black) vs ~60% NBI+ ~40% ECH 129282 (red)**
*[Osborne, Prater, Hudson et al]*

-NBI feedback used to fix betaN and rotation

**EPED1 run on preliminary set of inputs**

- inputs don't depend on power or type of power
- Outputs: $\beta_{N,ped}$~0.8, $T_{ped}$~850eV for $n_{ped}$~2.9 $10^{19}$

**For all NBI shot (137941), also find good agreement with EPED1**

**All ECH shot (137910), pedestal height well below 137941 and EPED1 prediction**

Consistent with insufficient power for high performance H-mode

# Objective 4.3 plan

- **4.3 Assess the impact of heating source on ELM size and explore prospects for interpretation in terms of peeling-ballooning theory**
  - 4.3(a) Quantify impact of heating mix on ELM type (DIII-D, JET, AUG, NSTX, CMod, JT-60U): Q1-Q3'09 & Q2-Q3'10
    - Closely related to 4.1 and 4.2 operationally, requires ELM measurements & analysis (same set of expts as in 4.1/4.2, extended analysis)
    - R. Sartori: ELM behavior complex, but not dramatically different in NBI vs ICH+NBI expt on JET
    - DIII-D: ELM behavior similar in NBI vs ECH+NBI when conditions for high confinement H-mode achieved

# Objective 4.3 plan, Cont'd

- **4.3 Assess the impact of heating source on ELM size and explore prospects for interpretation in terms of peeling-ballooning theory**
  - 4.3 (b) Interpret experiments in 4.1(a) and 4.4(a) (4.3a?) in terms of peeling-ballooning theory: Q2'09-Q3'10
    - Linear P-B theory predicts no effect if core parameter and rotation fixed

      Weak effect of rotation on stability boundaries, but possibly significant in some regimes (*N. Aiba, this session*)

      -N. Aiba: some destabilization of P-B due to counter-rotation

      Will be an effect if core beta is not held fixed (Shafranov shift), or if density changes
    - Nonlinear simulations: how would heating source enter?

      Kinetic effects possible due to differences in Te vs Ti
    - Ongoing linear P-B studies in concert with expts (Aiba, Konz, Lonnroth, Saarelma, Snyder…)
    - ELM dynamics modeling (*X. Xu this session*, Pankin, Huysmans, JET group? …), starting spring'10

# Objective 4.4 and plan

- **4.4 Quantify the impact of torque on the pedestal structure and ELMs**
  - (a) Quantify impact of torque input on pedestal structure for beam-heated discharges (DIII-D, JT-60U): Q4'09-Q3'10
    - JT-60U results find slightly lower pedestal height in counter injection
      May be a core confinement effect: fixed power (not fixed beta)
    - DIII-D results so far suggest weak or no effect at fixed core beta
    - [Previous studies (4.1 and 4.2) of RF vs NBI, particularly JET and AUG]
    - DIII-D rotation expt planned for upcoming campaign
    - Others?

  - (b) Quantify impact of torque input on ELM type for beam-heated discharges (DIII-D, JT-60U)
    - JT-60U finds strong correlation between ELM frequency and size and rotation
    - DIII-D does not find such a strong correlation
      Experiments planned to further explore this issue
    - Can other expts contribute? Timescale? (as above)
      MAST results with counter-rotation (H. Meyer, H-ModeWS'09)

    - Peeling-ballooning theory suggests only a weak effect of rotation linearly, though this small effect can be amplified by coupling to core (increase pedestal slightly -> higher core beta -> improved edge stability -> slighly higher pedestal ….) [Aiba this meeting, Snyder NF07]
    - toroidal torques can have significant effects on the toroidal rotation (radial electric field), but are likely to have little effect on at least the net ambipolar radial particle fluxes (Callen PoP09)

# Discussion of Objective 4.5 and plan

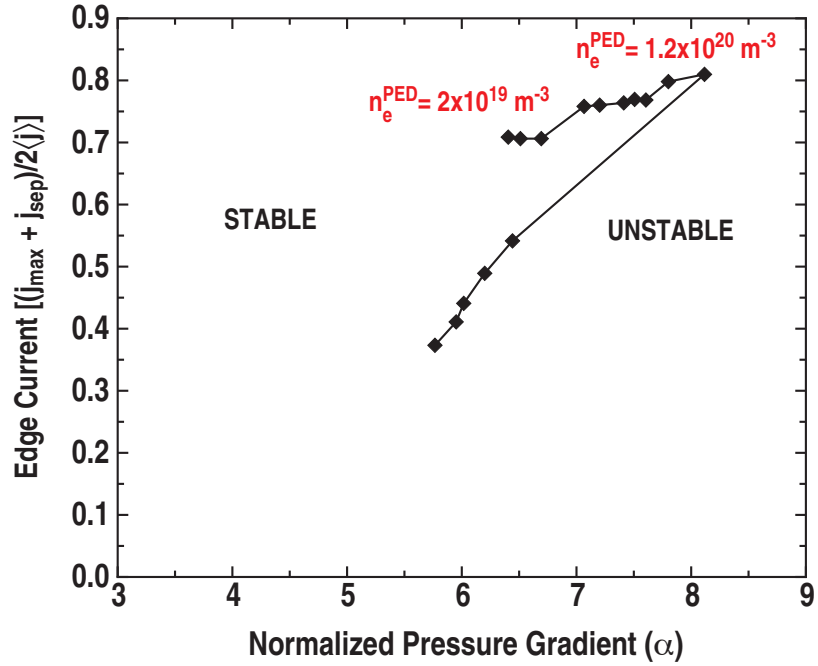
**4.5 Assess the potential viability of QH mode as a high pedestal, ELM-free regime for ITER (added 4/09)**

- **4.5(a) Identify the required range of density for QH mode operation in ITER**
  - Calculation based on EPED1 model finds all relevant densities in QH range
    - Calculation in approximate agreement with observed QH density requirements on DIII-D
- **4.5(b) Identify the required range of flow (or ExB) shear required for QH mode operation in ITER**
  - Recent QH mode progress on DIII-D summarized by Burrell at H-Mode WS'09
    - Limited plans for near term follow-up. Can/should we try to increase emphasis here?
  - Others?

# Peeling Ballooning Stability Calculations Predict that ITER Pedestal Will Operate on Peeling Boundary Where QH-mode Can Exist

*Burrell, H-ModeWS'09*

- **Theory model (P.B. Snyder) applies EPED1 pedestal model to ITER**
- **Model allows calculation of edge pedestal stability for various assumed pedestal densities**
- **Results show that ITER edge will be on the peeling stability boundary for pedestal densities below $1.2 \times 10^{20}$ m$^{-3}$**
  - Pedestal density of $1.2 \times 10^{20}$ m$^{-3}$ is well above ITER design value




- **All QH-mode plasmas analyzed to date operate at or near the peeling boundary**
- **Accordingly, ITER's pedestal will be in the QH-mode parameter range of collisionality and beta**

# Conclusions

*Burrell, H-ModeWS'09*

- **Demonstrated QH-mode operation with all co-injection and strong edge co-rotation**
  - Counter-NBI and counter rotation of plasma edge are not essential for QH-mode
- **Achieved QH-mode operation over a continuous torque range, from all counter-injection to near balanced injection**
  - More highly shaped plasmas allow QH-mode operation at lower input torque and lower edge rotation
- **Discovered that EHO-induced transport can be continuously adjusted by varying edge rotation**
  - Allows optimization of H-mode pedestal density and pressure
- **Use of nonresonant magnetic perturbations allows QH-mode operation with even lower torque and rotation**
- **Peeling-ballooning mode theory used to guide experiments**
  - Effect of rotational shear on edge modes provides basis for theory of the EHO
  - Theory predicted existence of co-NBI QH-mode prior to experiments
  - Theory predicts ITER pedestal will operate in QH-mode parameter range

# Discussion of Objective 4.6 and plan

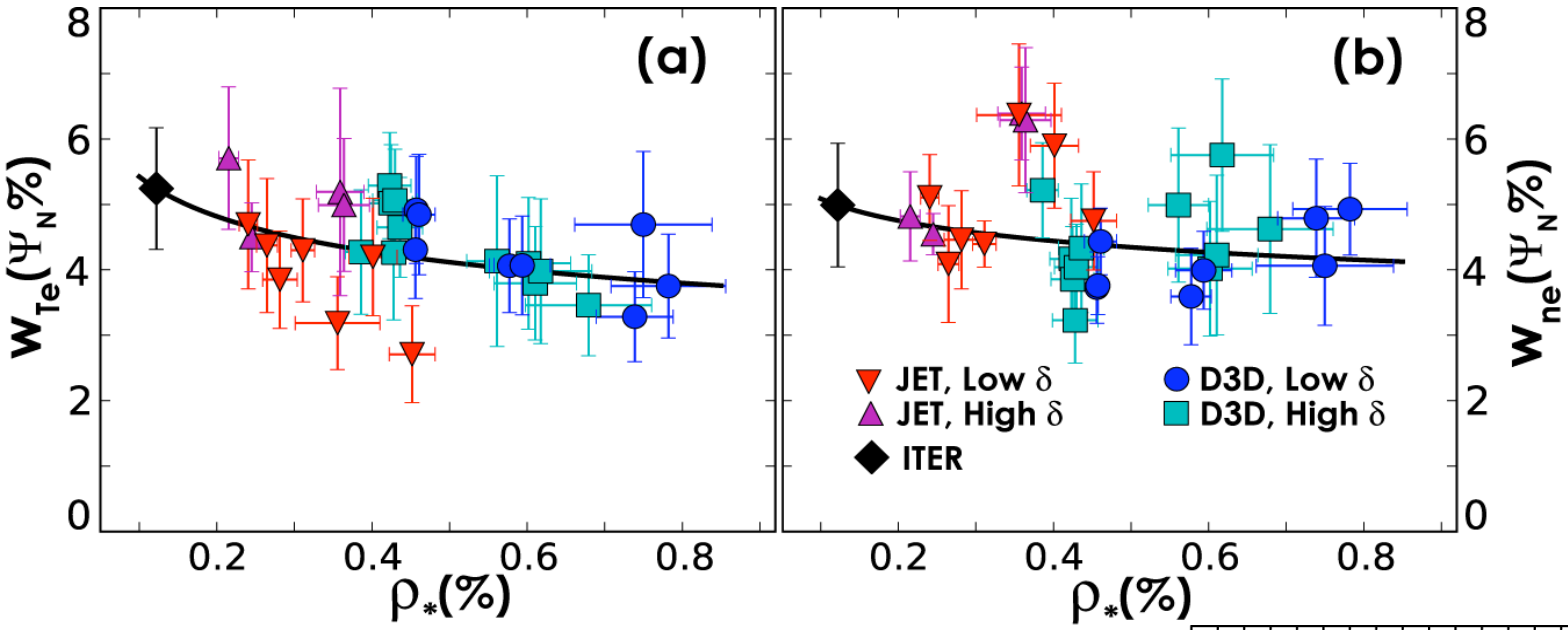
- **4.6 Develop theoretical models for the observed scaling of pedestal width with plasma parameters**

  (a) Provide a theoretical/computational model for observed scaling of pedestal width with plasma parameters (full timescale)

  - ExB stabilization of traditional drift modes (rho scaling) seems to be ruled out by observation *[JT-60U+DIII-D isotope, Osborne H-Mode WS'09, next page]*
    - How firm is this conclusion? Are further expts needed?
    - Can/should we do a better job communicating this to theory community?
  - New data on dynamics of pedestal structure during ELM cycle, suggestion of quenching of $p_e$ gradient before ELM (Wolfrum, Groebner HMWS'09)
  - EPED1 model proposes combination of P-B & KBM (Snyder HMWS'09)
    - Further work to better quantify KBM (GK including a/R, nustar) + omegastar -> EPED2
    - P-B on profile variations, implications for ITER (Lonnroth, this session)
  - Neoclassical studies (eg XGC, TEMPEST, NEO) find neoclassical transport important, but insufficient to explain observed pedestal structure
    - How firm is this conclusion? Additional work needed? Efficient tools for routine inclusion in models?
    - *Chang update in this session*
  - Edge gyrokinetic and kinetic simulation codes
    - Linear to contribute to model development
    - Comprehensive nonlinear: EM, collisions, geo. Realistic in this timeframe? Ped top (eg XGC1, HMWS90)?
    - ETG feasible if ion scales can be decoupled: progress reported by Told & Jenko at H-ModeWS'09
  - Paleoclassical (Callen,): What further theory and/or expt is needed?
  - Role of particle source: (Callen, Rognlien, Chang); Integrated modeling: (Zagorski)

# Both $n_e$ and $T_e$ widths are relatively unchanged over the $\rho_*$ range

*Osborne, Beurskens et al H-ModeWS'09*

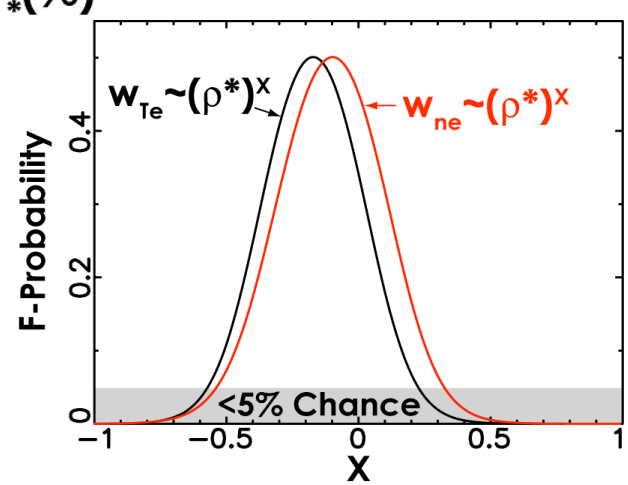



- **Fits of w in normalized poloidal flux, $\psi_N$, for combined low and high δ data give weak inverse dependence on $\rho_*$**

  $w_{Te}(\psi_N\%) = (3.65\pm0.27)(\rho_*(\%))^{-0.17\pm0.08}$

  $w_{ne}(\psi_N\%) = (4.06\pm0.34)(\rho_*(\%))^{-0.10\pm0.08}$

- **Statistics indicate $w \propto \rho_*^X$ where x>0.25 is unlikely**



# Preliminary conclusions for discussion: heating source impact on pedestal structure & ELMs

- **In high performance H-mode, if global beta similar, pedestal height, width, ELMs ~independent of heating source (JET, AUG, DIII-D)**
  - Core confinement sometimes does and sometimes does not depend on heating source

    -Theory explanation: ExB vs drift, Te/Ti ?
  - A key issue is power (and heating source?) requirement for high performance H-mode (not just L-H)
  - Structure consistent with EPED1 in highly preliminary tests
  - Variation of ELM size with rotation in JT-60U yet to be explained (+QH issue)
- **Most mechanisms for NBI-specific impact on pedestal structure appear to be ruled out**
  - Beam orbit physics ruled out by isotope, rhostar, RF expts
  - Rotation observed/predicted to have only small impact at matched core parameters (but rotation can impact core confinement)
  - Fuelling effects appear weak at matched density
- **Concerns about type of input power should focus on issues of H~1 power threshold, core confinement, impurity generation/wall conditioning, and possibly QH mode access**
- **Discussion?**

# Broader Discussion

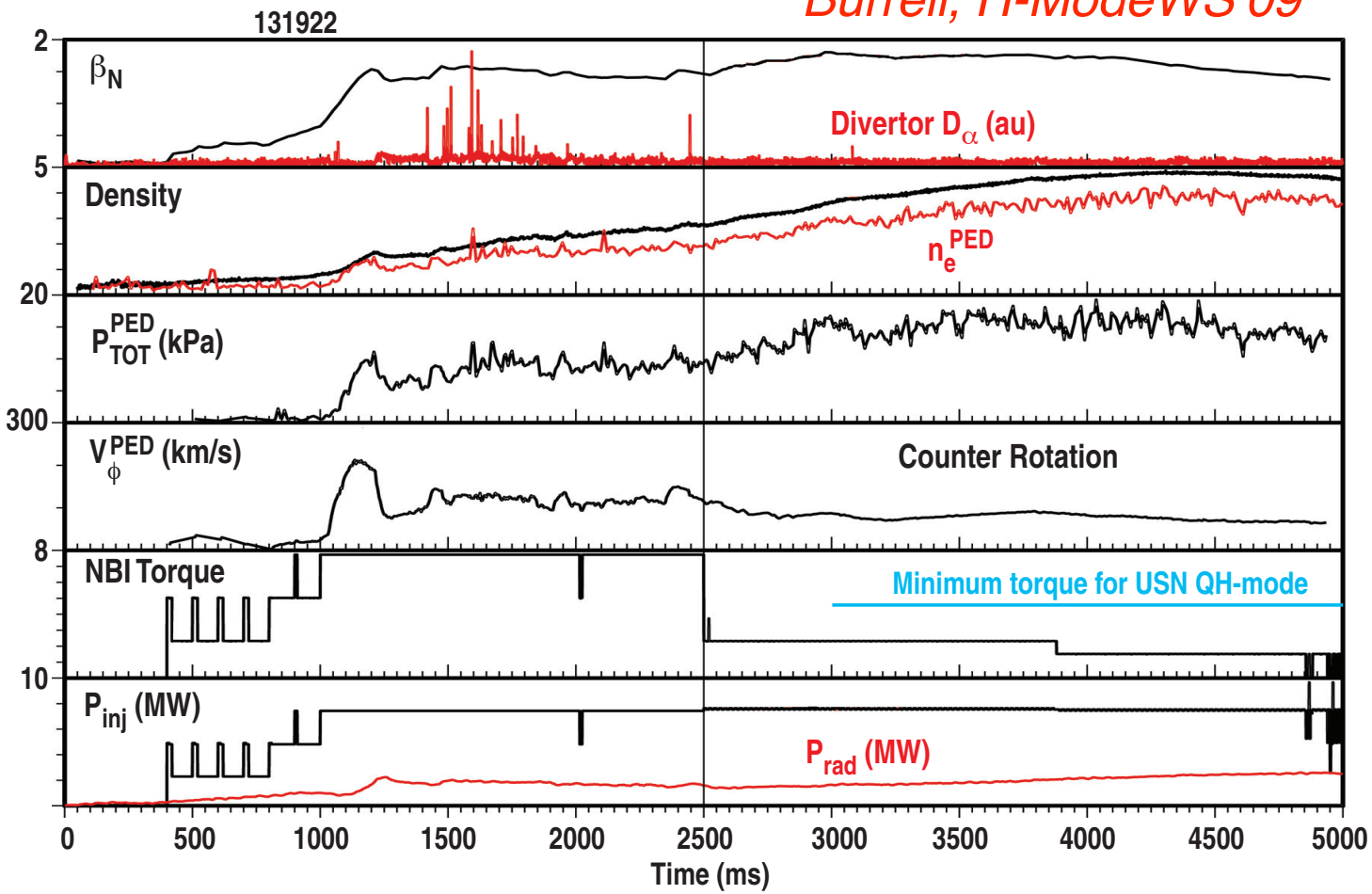
- **Additional ITER urgent issues?**
- **Heating source focus brings in coupling with L-H, core and ELM control**
- **Focus on fuelling: pellets and particle pinch?**
- **Renew focus on QH mode?**
  - Method to achieve very high pedestal without ELMs
    - Good overall performance with little torque input
  - P-B calculations suggest ITER density should be well within QH range (necessary but not sufficient condition)
  - QH now demonstrated for strong counter, weak counter, and strong co-rotation (all high Er shear)
    - Possible rhostar dependence key issue for ITER projection
    - Possibility of using non-resonant B perturbations to generate weak counter rotation
    - Efforts to better quantify and test NTV theory, impact for flow shear?

# Extra Slides

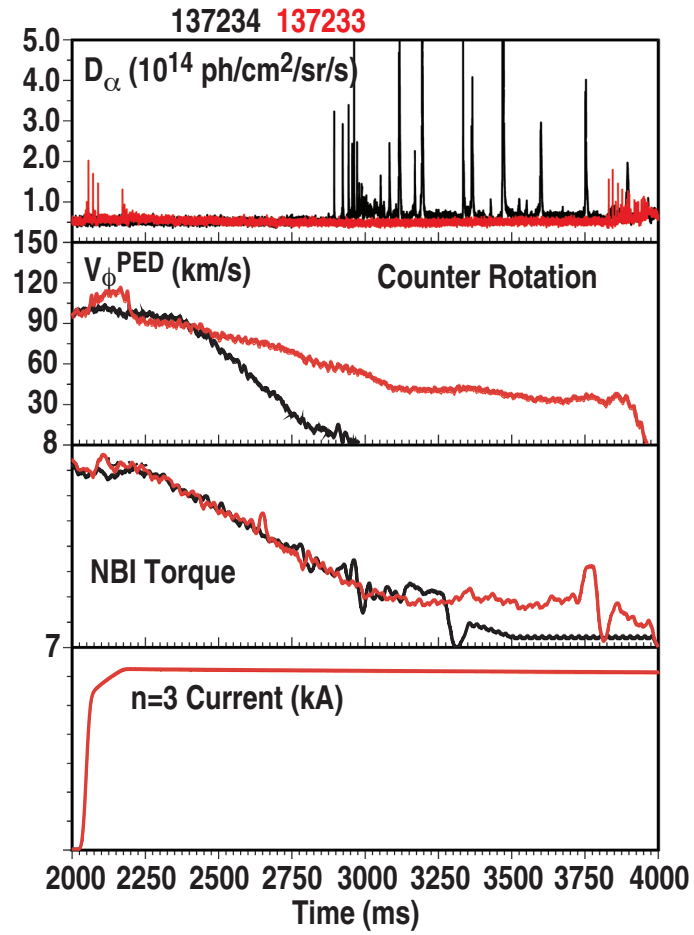
# Rotation Control of Density and Improved Shape Allow QH-Mode Operation at Higher Pedestal Pressure and Higher Stored Energy

- Compared to upper single null shape, optimal shape allows QH-mode at factor 2.5 lower input torque

*Burrell, H-ModeWS'09*



# Applying n=3 Nonresonant Magnetic Perturbations Using DIII-D I-Coil Sustains Rotation and QH-mode at Lower Input Torque

- **Static, n=3 nonresonant magnetic perturbations drive plasma rotation towards the neoclassical offset velocity [A.M. Garofalo et al, PRL 2008]**
  - Offset velocity is in counter direction
- **n=3 fields can be used to maintain counter rotation and QH-mode when input torque is reduced**

*Burrell, H-ModeWS'09*