Opportunities for BOUT++ Pedestal Simulation at DIII-D

By

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For the DIII-D Pedestal and BPMIC teams

Particular contributions from

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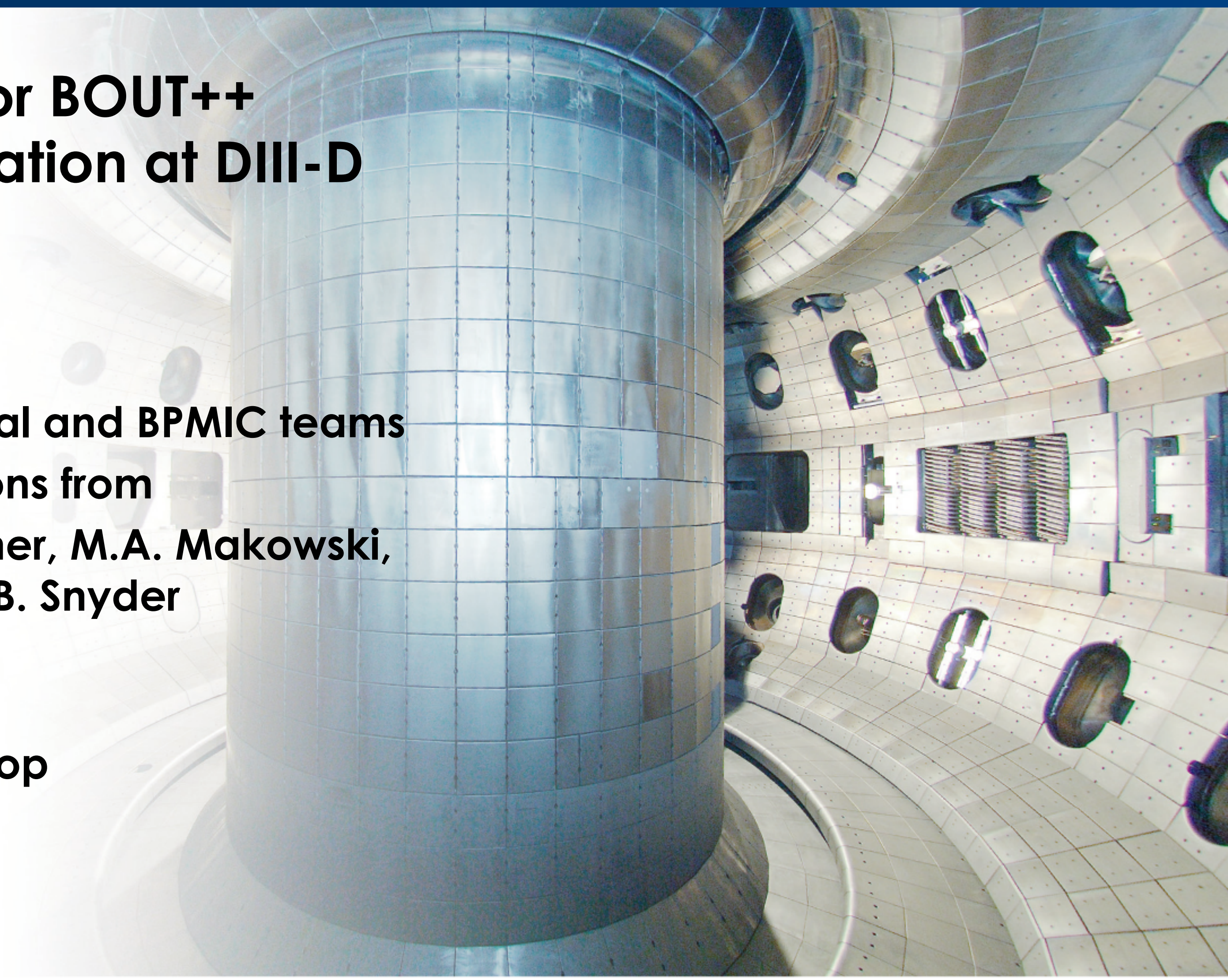

Presented to

BOUT++ Mini-workshop

Livermore, Ca

Dec. 16 – 18, 2015

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DIII-D has need of pedestal stability and transport simulation on several topics

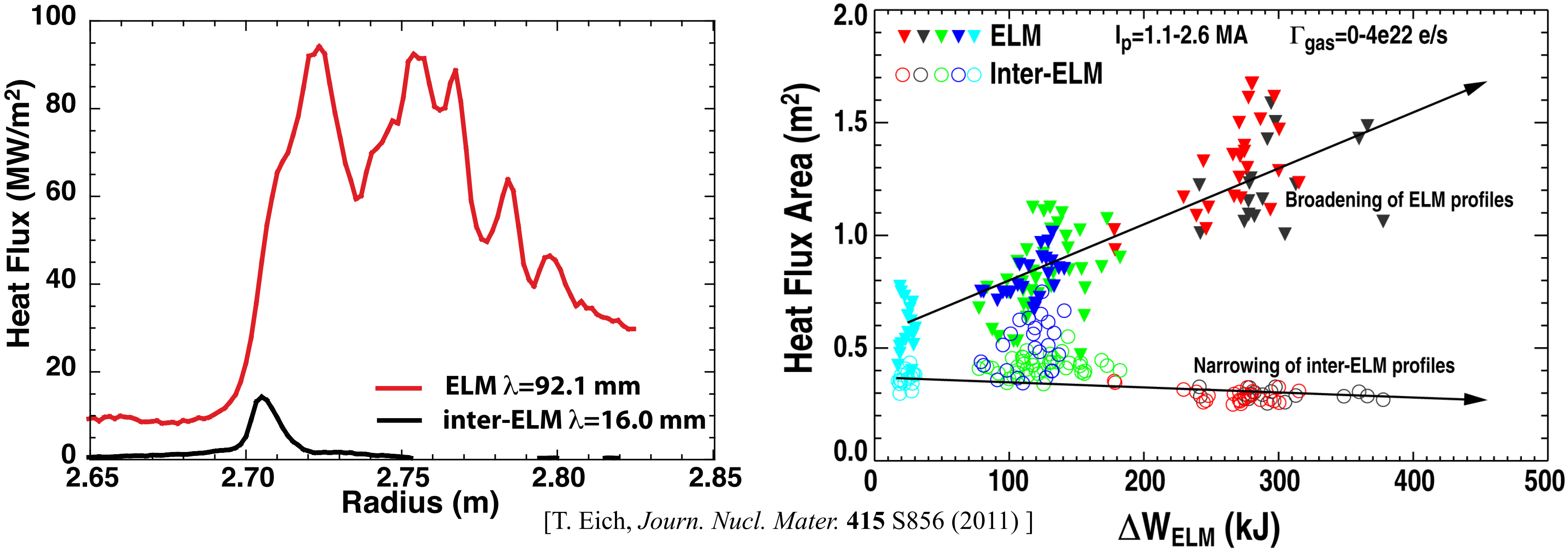
- **ELM transport**
  - Scaling of divertor peak energy density
  - Divertor in/out asymmetry of ELM deposition
- **Pedestal stability**
  - ELM growth rate criteria at higher collisionality
- **ELM control**
  - Lithium granule injection
  - QH-mode
- **Pedestal transport between ELMs**
  - Pedestal density response to ionization source
  - Mechanisms setting critical gradients
- **SOL transport**
  - Divertor heat flux width; Critical gradient at separatrix
  - Far SOL transport

Critical issue for divertor and ELMs is peak energy deposition

- **Surface melting/ablation** $$\Delta T \propto \frac{\Delta W}{A \bullet \Delta t^{1/2}} \geq 50\ MJ/m^2\ s^{1/2}$$
  - Δt measured at ion sound speed from pedestal
  - Critial parameter for melting is $\Delta W/A$, peak energy density
- **ITPA effort underway for multi-machine scaling of $\Delta W/A$**
  - Some initial scalings are finding $\Delta W / A \propto P_{ped}$ independent of machine size and fractional ELM size
- **ELM scaling issues include**
  - ELM deposition width/profile
  - ELM peak/profile vs. relative ELM size
  - ELM peak/profile vs. machine size
- **Analysis of DIII-D ELM heat flux data underway to add to ITPA database**

ELM Divertor Heat Pulse Broadens With Larger ELMs

JET Divertor ELM Heat

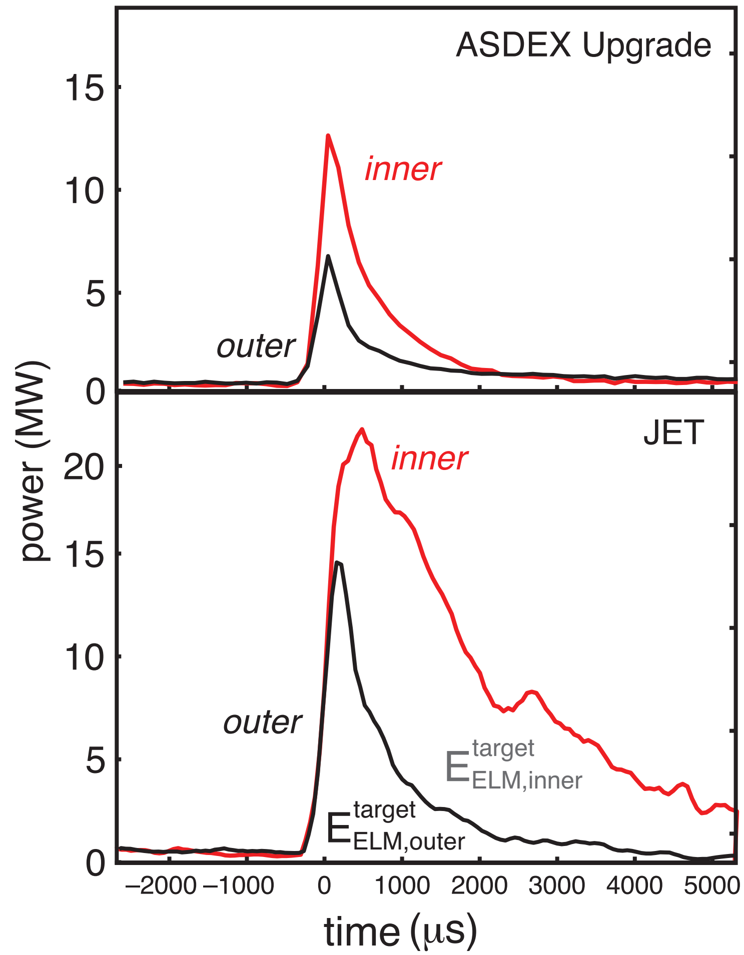


[T. Eich, *Journ. Nucl. Mater.* **415** S856 (2011)]

- **ELM broader and more irregular than inter-ELM, up to 5× in JET**
- **ELM vs. inter-ELM width suggests different physical mechanisms**
- **Mitigated ELMs, gas puffing, RMP etc., with reduced $\Delta W_{ELM}/W_{ped}$ are narrower with similar peak deposition compared to unmitigated**

Surprisingly More ELM Energy Deposited to Inboard Divertor

- **2/3 of ELM energy deposited on inboard divertor**
  - Common observation across tokamaks
  - Asymmetry reduced/reversed for reversed B_t
- **Origin of asymmetry unclear**
  - Plasma drifts
  - Higher inboard inter-ELM density
  - IR camera diagnostic issue
- **In/out ratio an important parameter for determining required ELM mitigation factor**
- **DIII-D unique in ELM heat flux to both divertors routinely available**



[T. Eich, *Journ. Nucl. Mater.* **337-339** 669 (2005)]

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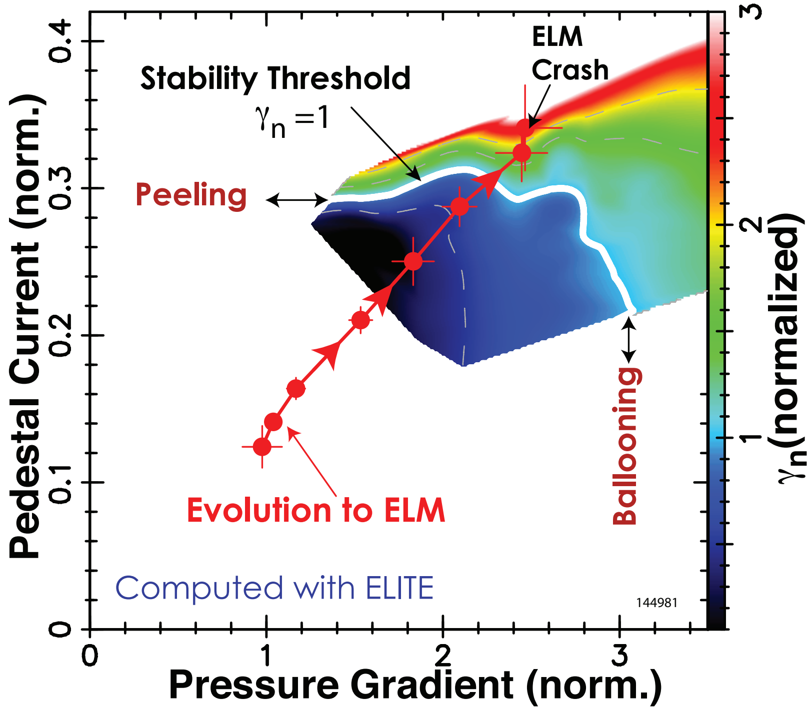
ELM transport issues to resolve

- **Is the peak ELM divertor deposition proportional to pedestal pressure and insensitive to relative ELM size, $\Delta W_{ELM}/W_{ped}$?**
- **How does peak ELM energy deposition scale with machine size?**
- **What physics mechanisms could lead to larger ELM deposition on inner divertor target?**
  - ExB Drifts
  - Target or sheath conditions
  - Parallel flows
- **Ion impact energy**
  - Between ELMs only impurity ions have enough energy to sputter tungsten
  - In JET high energy deuterons primarily responsible for tungsten erosion during ELMs

Improved understanding of diamagnetic stabilization of ballooning branch in PB model is needed

- **Peeling-Ballooning growth rate increases more slowly with p' along balloning branch than with j_{bs} along the peeling branch**
  - Ballooning stability more sensitive to stabilization criteria
- **Impacts pedestal pressure (EPED) for more weakly shaped plasmas (ITER)**
- **Impacts the prediction of Super-H regime**



- **Important for interpreting JET wall and impurity effects on pedestal pressure**
- **Important for interpreting existing experiments on compatibility of divertor detachment with the H-mode pedestal**

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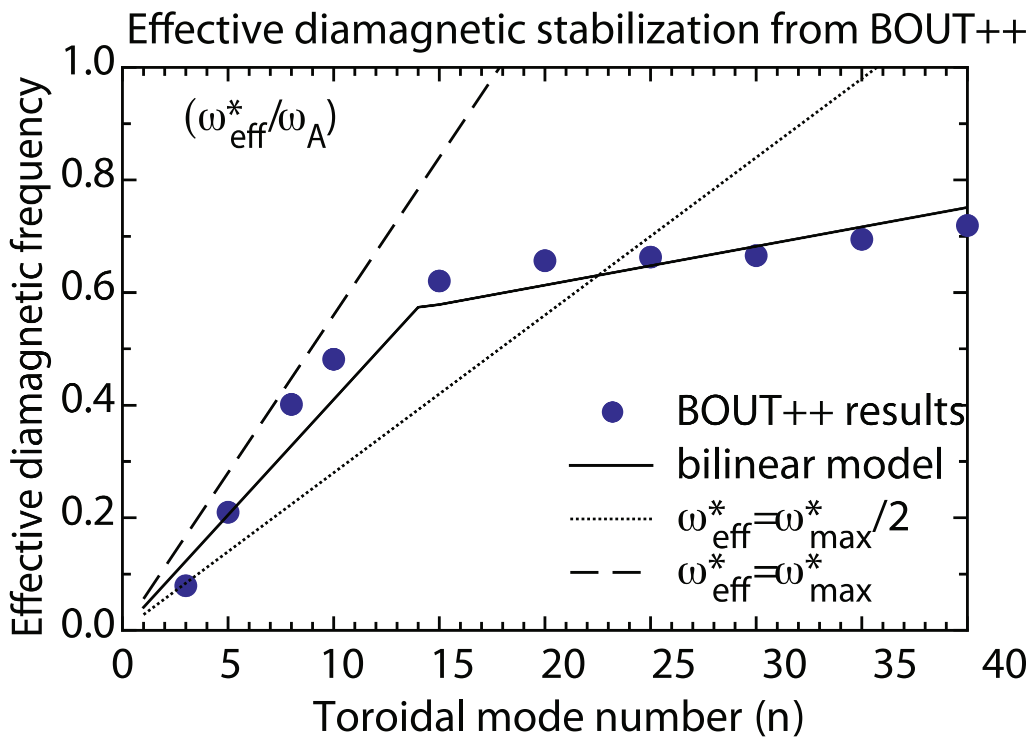
Pedestal Stability Limit Calculated with different Stability Criteria

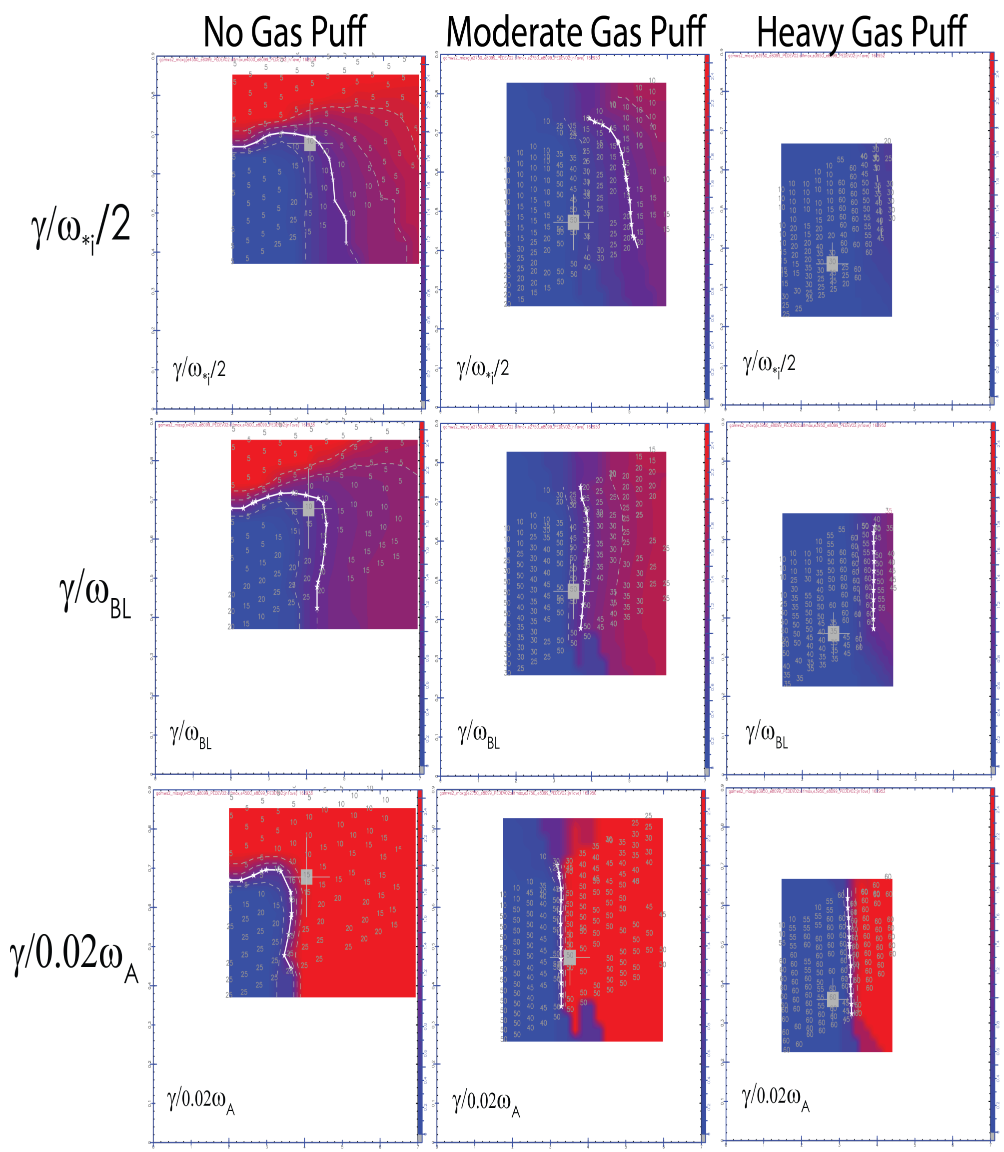
- **Magnetic equilibria reconstruction based on:**
  - **Measured pressure profile**
  - **Sauter Bootstrap current model**
- **Construct equilibria with varied edge pressure and current for 2D stability map**
- **Calculate Peeling-Ballooning growth rate with ELITE**



- **Employ two growth rate criteria for ELM stability**
  - Simple Diamagnetic stabilization, $\omega_{*i}/2$
  - Diamagnetic stabilization based on BOUT++
  - Alfven frequency normalization $\gamma/\omega_A \geq 0.02$

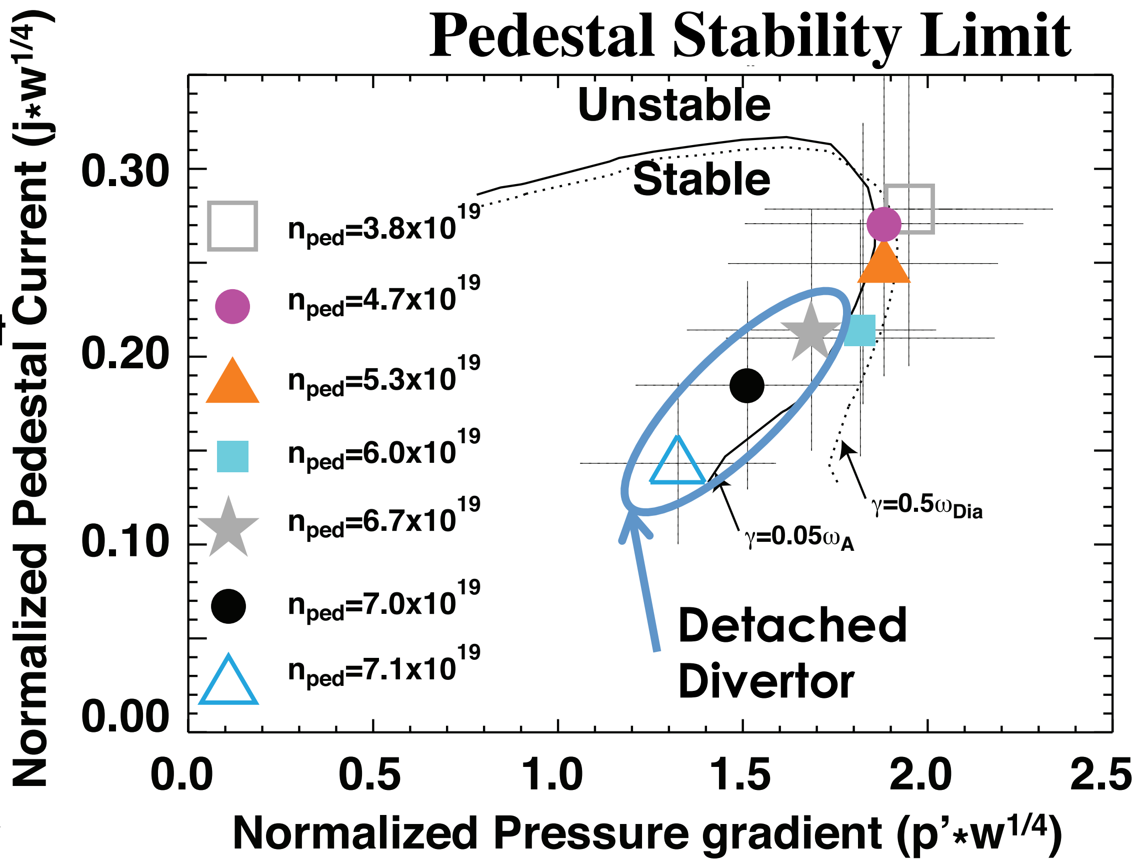
Improvement needed in diamangentic stabilization model to account for high density DIII-D discharges

- **Simple $\omega_{*i}/2$ formulation for diamagnetic stabilization inconsistent with data from DIII-D with D2 puffing to higher ν_***
- **Bi-linear form developed from BOUT++ simulations (Snyder, et.al, NF <u>51</u> 103016 (2011)) accounts for stability with moderate gas puff but is still too strong for high gas puff case at higher n**



Pedestal Stability Limit in Agreement with Measured Pressure Gradients

- General agreement in magnitude of stability limit
- Measured pressure gradient better matched by Alven criteria
- Gradient normalization
  - Current and pressure gradient normalized by width ($w^{1/4}$) for plotting different pedestals on same map
- Growth rate criteria essential for determining if pedestal degradation is due to MHD stability or divertor effect, i.e. neutrals, radiation, etc.



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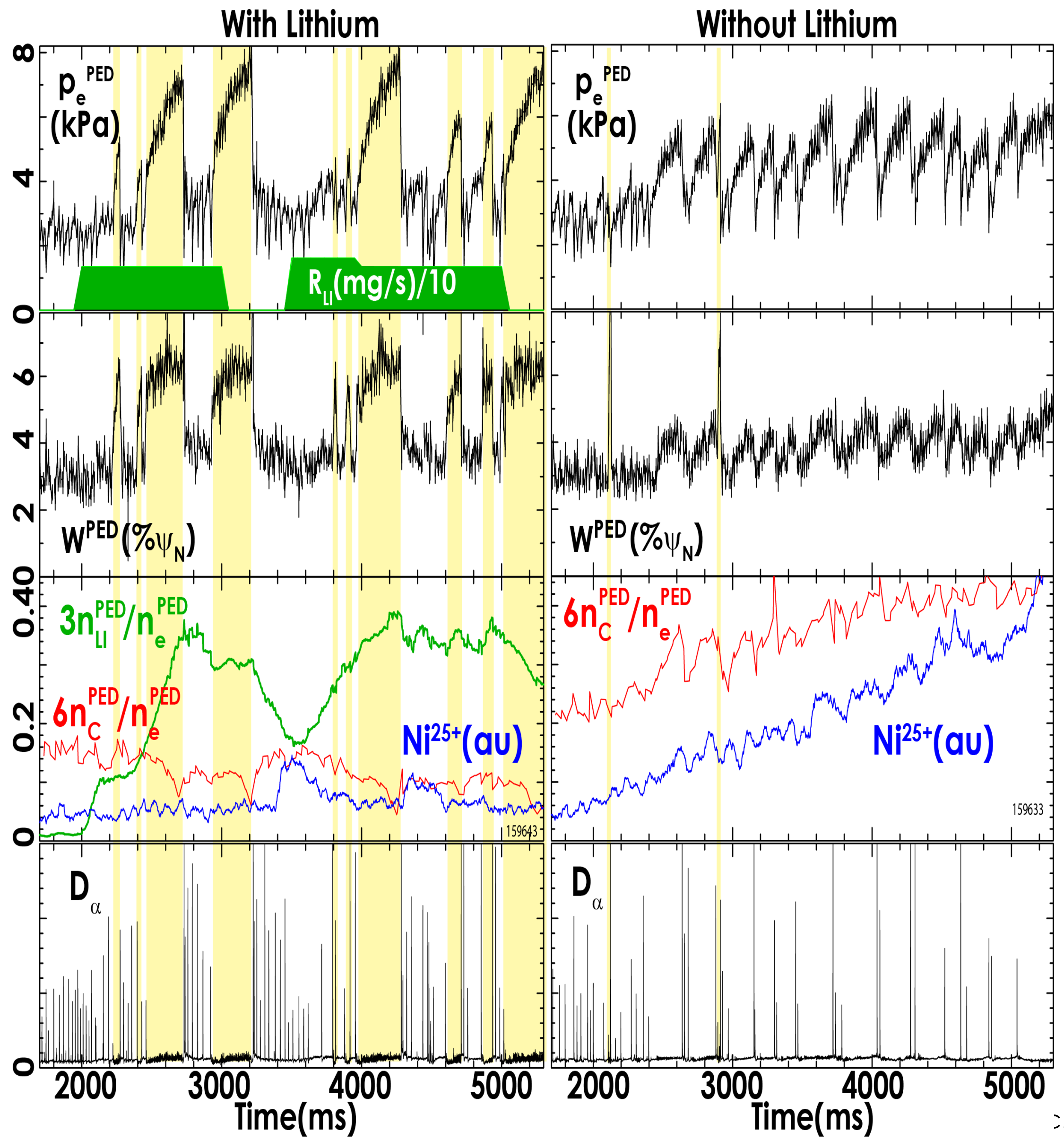
Li injection leads to Bursty Chirpy Mode (BCM) and pedestal enhancement in DIII-D

- **BCM localized to high collisionality region near separatix**
- **BCM results in local reduction of p´ in this region**
- **Local pressure profile flattening improves PBM stability allowing higher pedestal pressure**
- **Possibly the same physics involved in EAST long ELM free H-mode with Li injection**
- **BOUT++ could provide understanding to optimize BCM in DIII-D and project performance in future devices**

Extended Periods with Enhanced Pedestal Pressure and Width Observed with Li Injection

- **Frequent enhanced pedestal periods up to 350ms duration with Li**
- **Occasional short duration (20ms) enhanced pedestals without Li**
- **Rapid w^{PED} rise, < 10ms**
- **Significant Li in core but higher Z impurities reduced**



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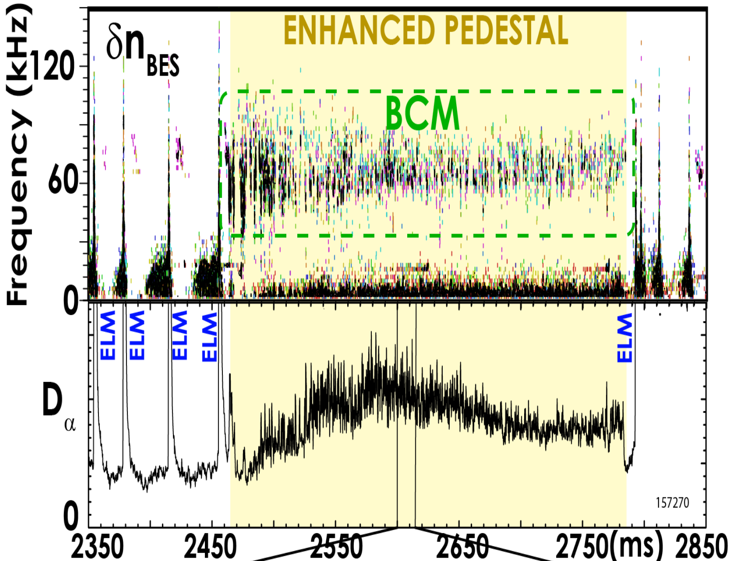
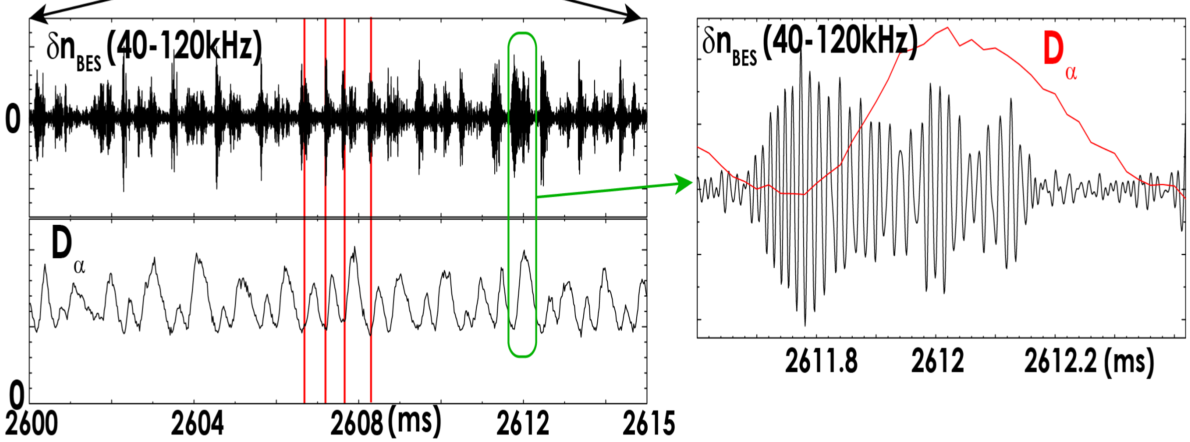
Bursty Chirping Mode Observed in Periods of Pedestal Enhancement



- $f_{MODE} \approx$ 70kHz, $\tau_{BURST} \approx$ 0.5 ms
  - Coherent within burst
  - f_{MODE} varies within burst
- $k_{POL} \approx 0.1\ cm^{-1}$, $k_{POL}\,\rho_s \approx 0.1$
- Rotates in electron drift direction in plasma frame ⇒ MTM or DTEM, not KBM[1]



- BCM not observed on magnetics

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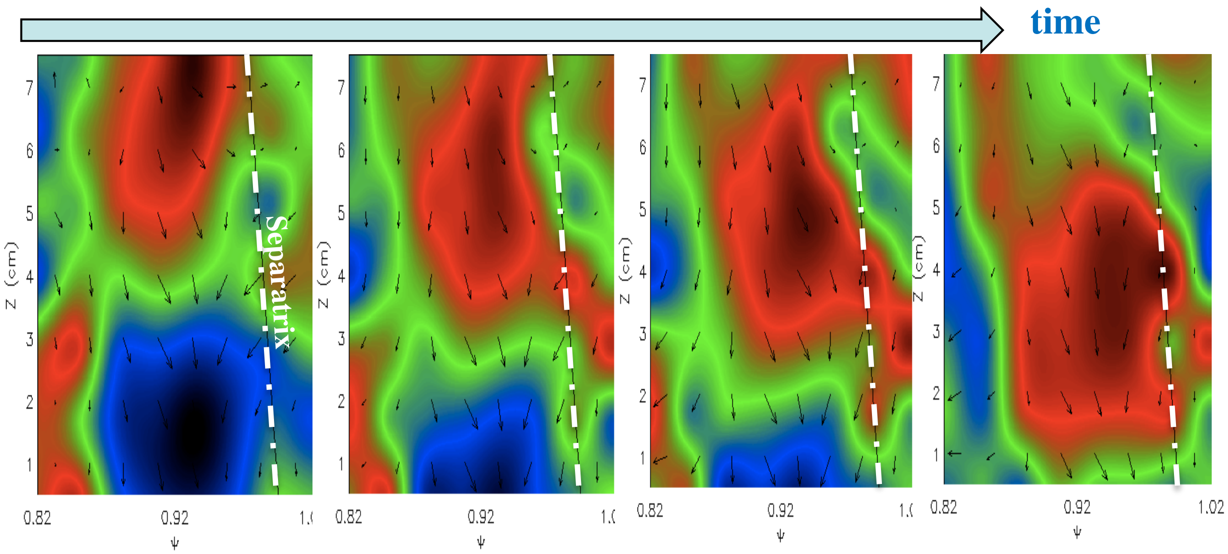
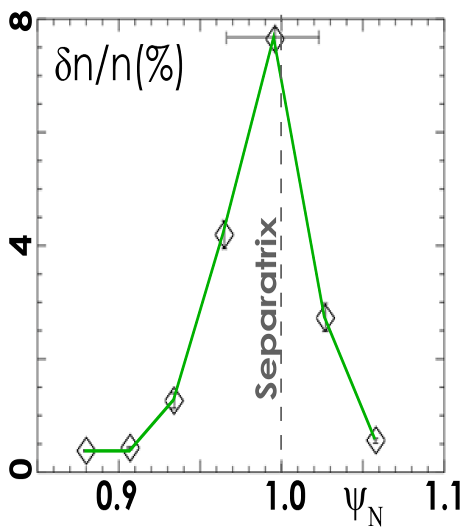
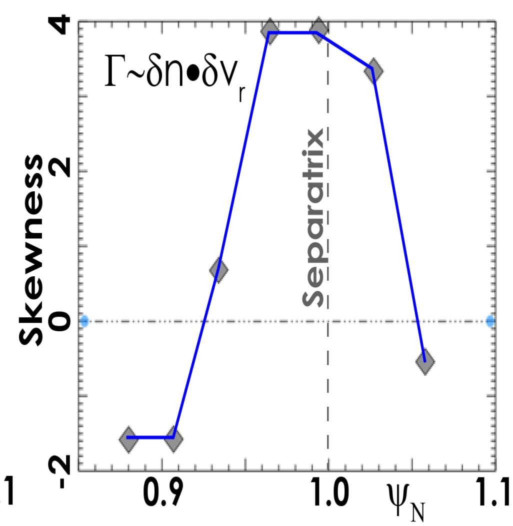
BCM Drives Outward Particle Flux Flattening Profiles in Region Near Separatrix



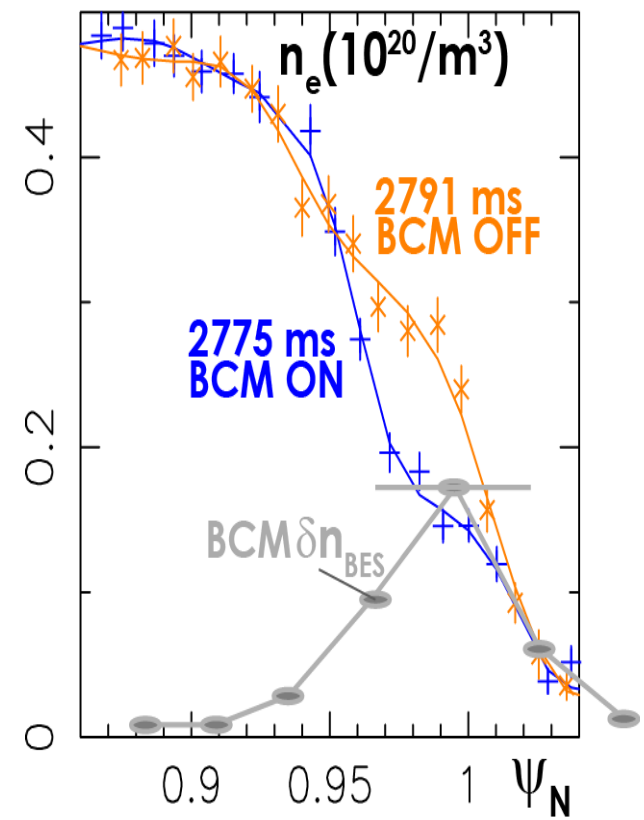
- Density fluctuations peak near separatrix
- Outward particle flux peaks near separatrix

Z. Yan, et.al,
42nd EPS, Lisbon





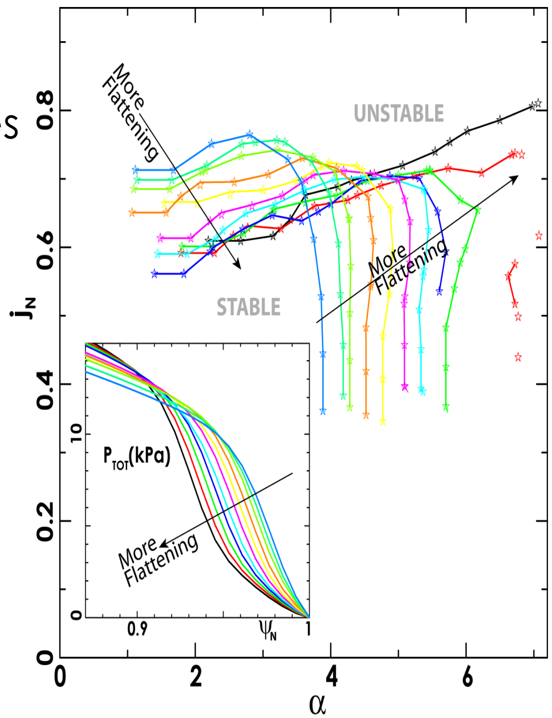
- **Profiles locally flattened by BCM**

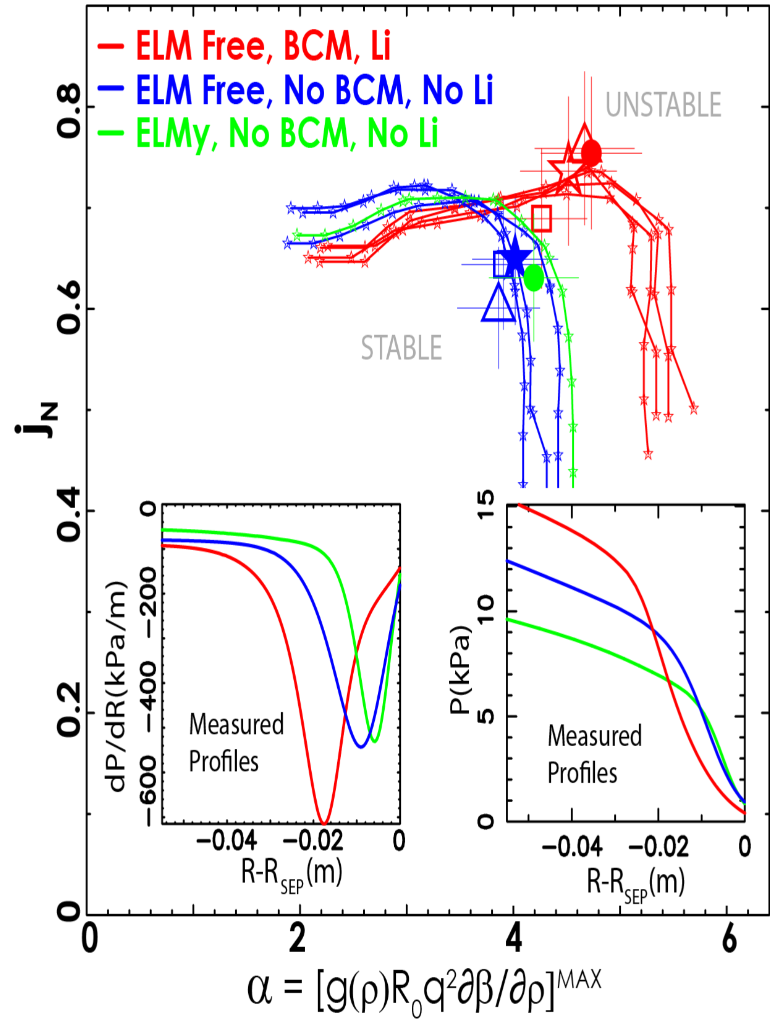


Reduced ∇p Near Separatrix with BCM Shifts High ∇p Region Inwards Improving PBM Stability

- **Ballooning branch stability improved with high p´ region shifted inward from separatrix**
- **dp/dR must be higher at lower q (lower radius) for a given value of α**

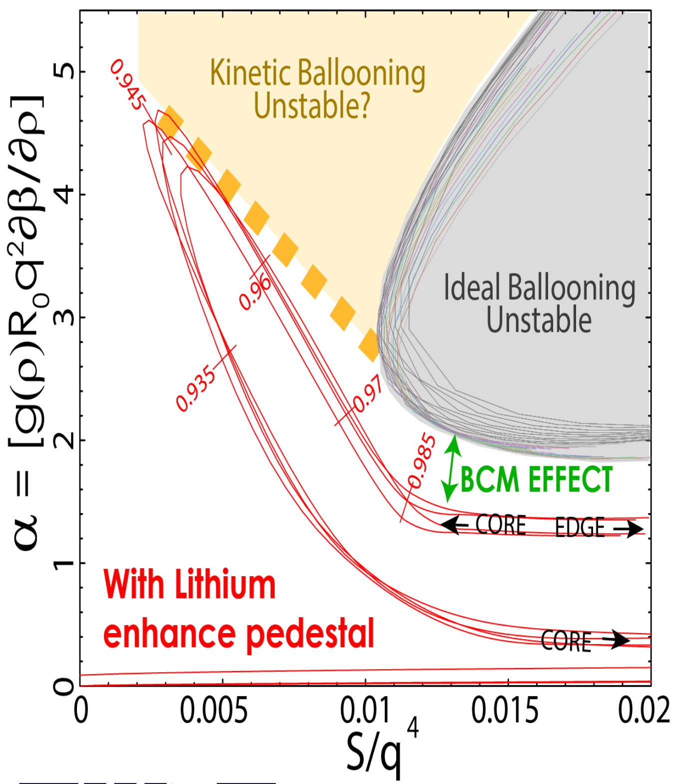
Simulation indicates ballooning branch stability continues to improve as flattened region expands



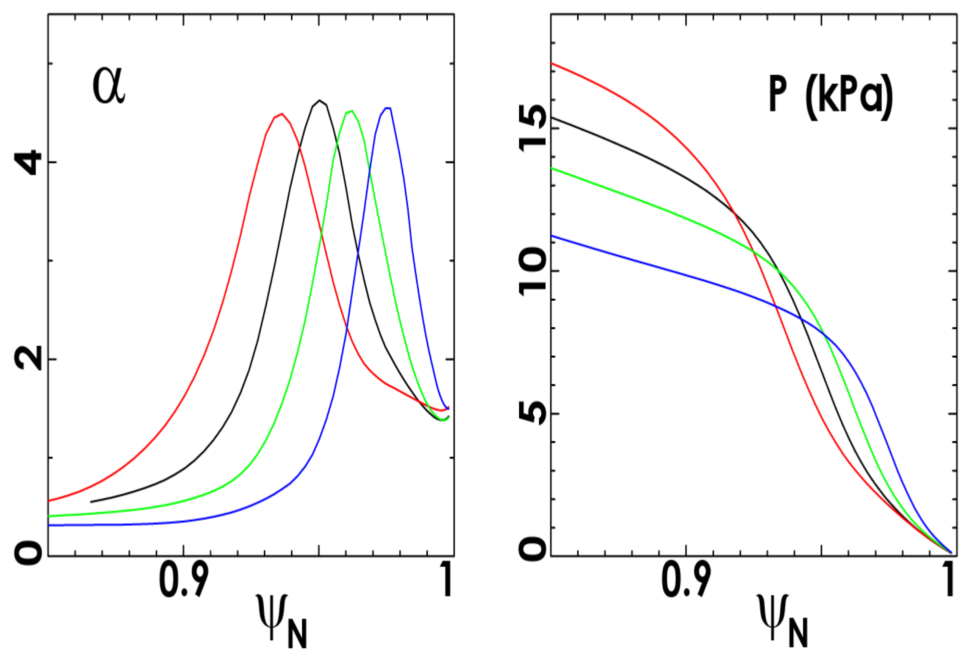


Further Expansion of BCM Affected Region Might Lead to Further Pedestal Pressure Increase

- **Because the BCM reduces p´ near the separatrix the KBM constraint in EPED does not apply and a model for the effect of the BCM is required to predict p^{PED} reached before the ELM at the PBM limit.**



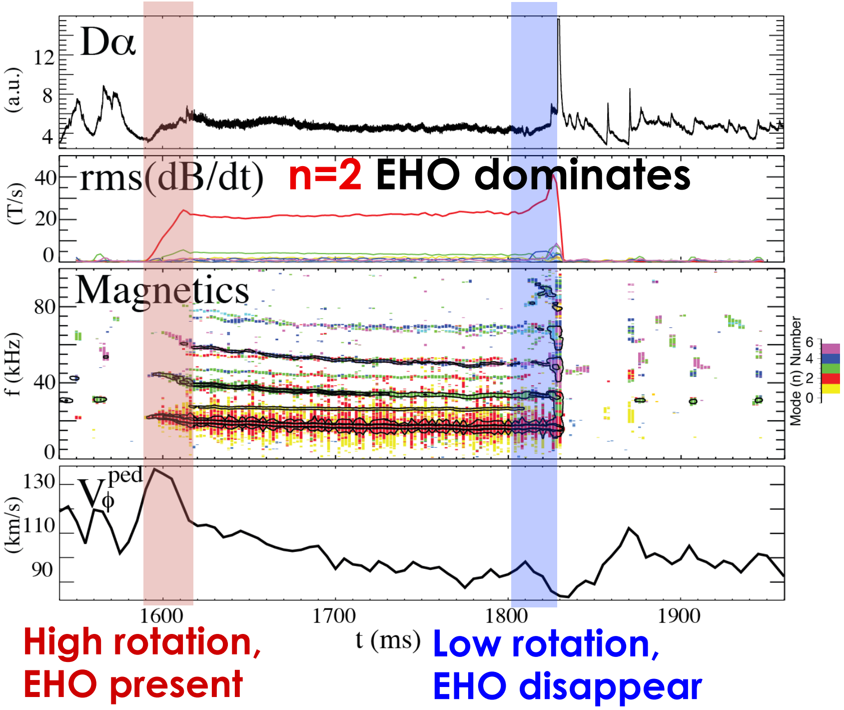
- **Keeping α_{MAX} and α_{SEP} fixed, p^{PED} at BPM limit increase as BCM flattened region expands**

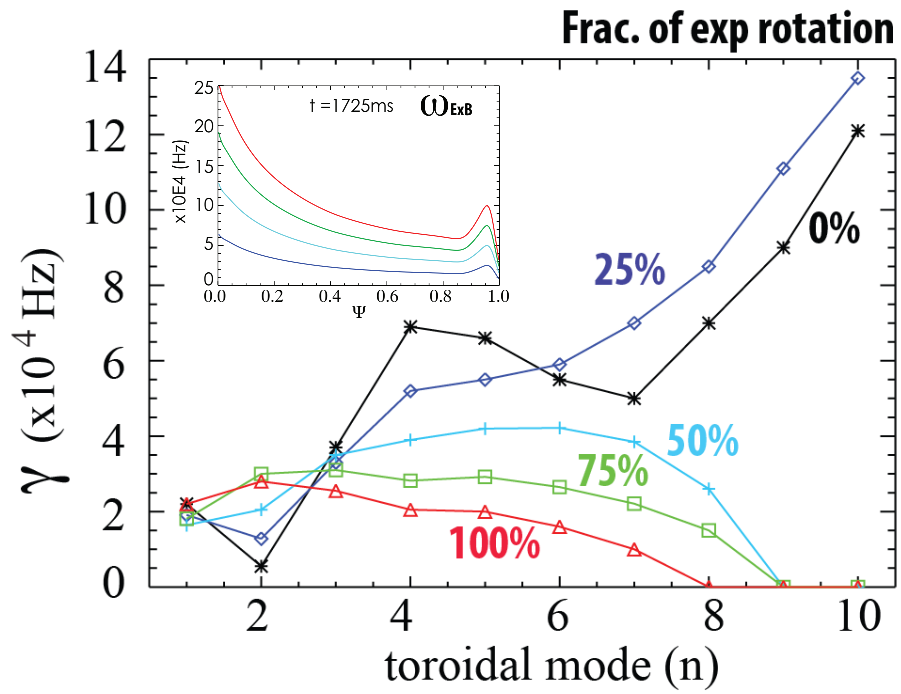


What is physics that controls Edge Harmonic Oscillation in QH-mode?

- QH-mode is an ELM-free regime in which an edge MHD mode – the Edge Harmonic Oscillation (EHO) – drives transport to keep plasma just below the ELM limit
  - Because of no ELMs, the regime is of interest for application to ITER
- DIII-D is studying physics of EHO to better understand how to extrapolate QH-mode to future devices
- Linear and non-linear MHD models can help provide insight into EHO physics
- BOUT++ may be a very useful tool for such studies

Open Questions: Critical Rotation Shear Level for Generating and Sustaining EHO





- Strong edge rotation and rotation shear are needed in exp. to excite EHO
- Theory and initial data suggest EHO to be a saturated low-n kink/peeling mode destabilized by ExB rotation shear
- Linear M3D-C1 modeling shows ExB rotation shear destabilize low-n modes while stabilizing high-n modes

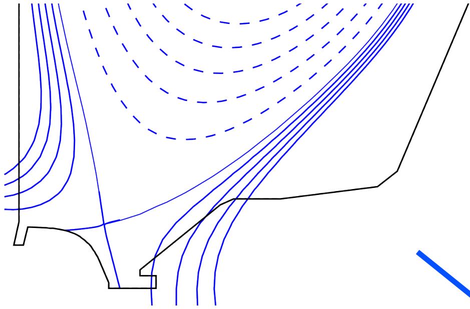
What is physics that controls particle transport in the pedestal?

- **Understanding pedestal density physics is important for moving towards more complete predictive capability for pedestal**
  - EPED predicts pedestal pressure with density as an input
  - Critical for H-mode compatibility and current drive efficiency
- **DIII-D has 2017 milestone to study: "Given an ionization profile, what is pedestal density that forms in response?"**

- **We wish to evaluate different transport models to determine if they can reproduce measured density profiles, given a source**
- **Initial data exhibits significant pedestal density changes between open lower divertor and closed upper divertor**

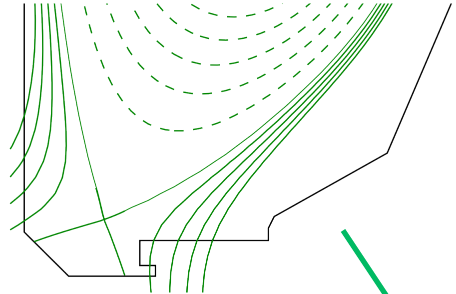
- **Can BOUT++ help evaluate different particle transport models?**

Initial Experiments Find Detachment onset at lower pedestal density for increased closure

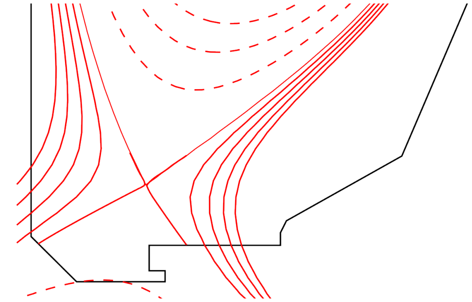


Most-closed geometry (ceiling)

Detaches at lower $n_{e,ped}$

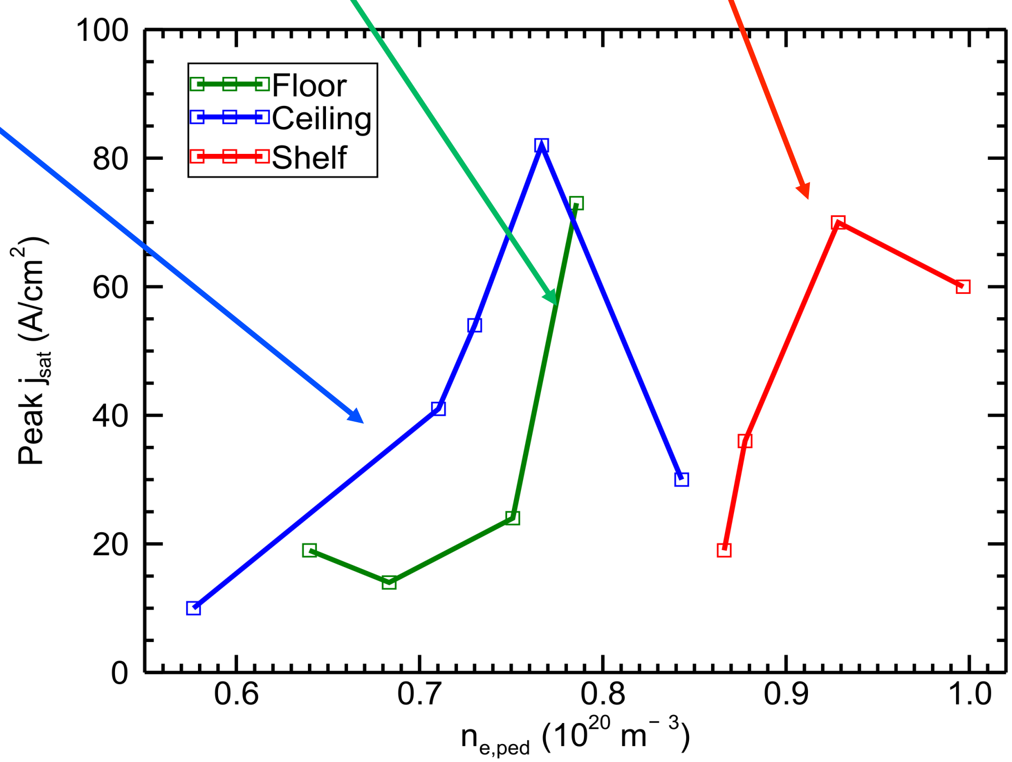


Intermediate geometry (floor)



Most-open geometry (shelf)

- **DB drift toward divertor for all cases**
- **ELMing H-mode density scan**
- **Lower pedestal density for similar divertor conditions in closed divertor**



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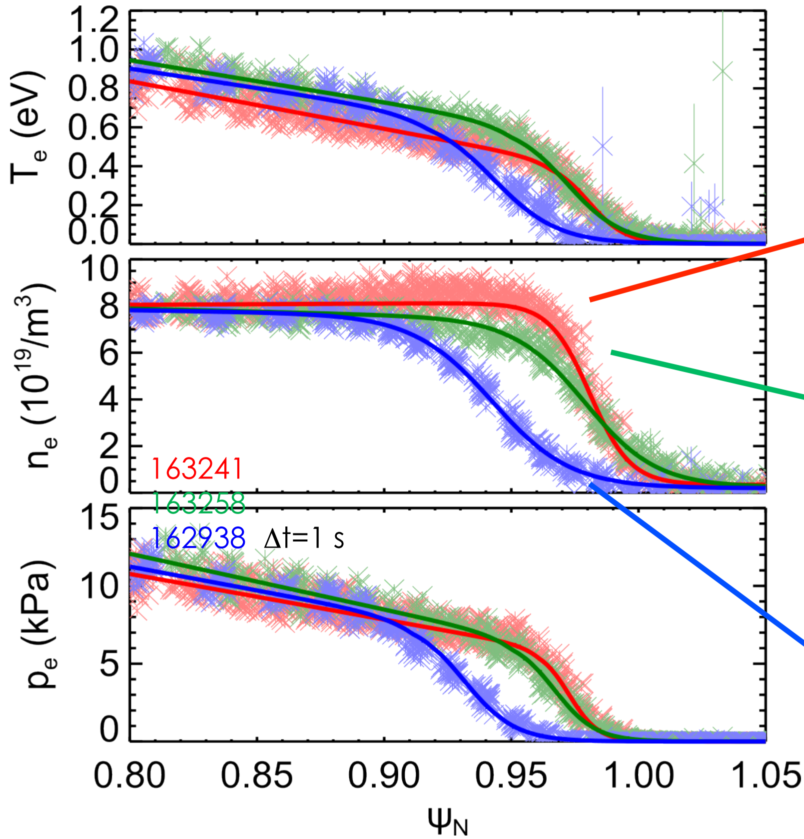
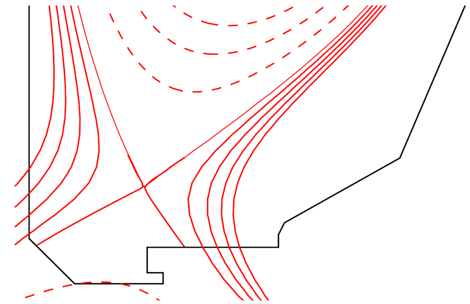
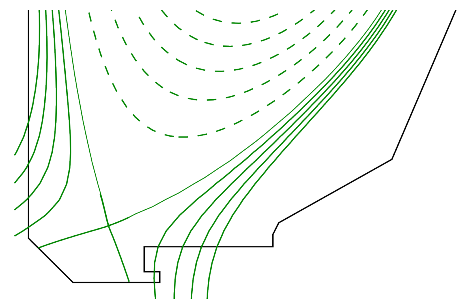
Divertor structure appears to affect pedestal density and temperature profiles

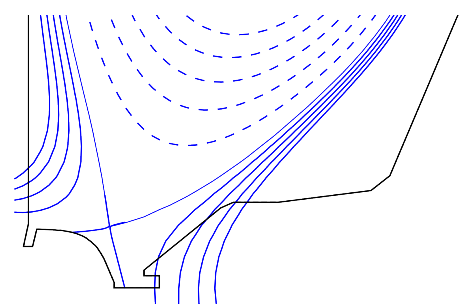




Most-open geometry (shelf):

- Higher pedestal density
- Lower temperature





Most-closed geometry (upper):

- Lower pedestal density
- Less steep density gradient

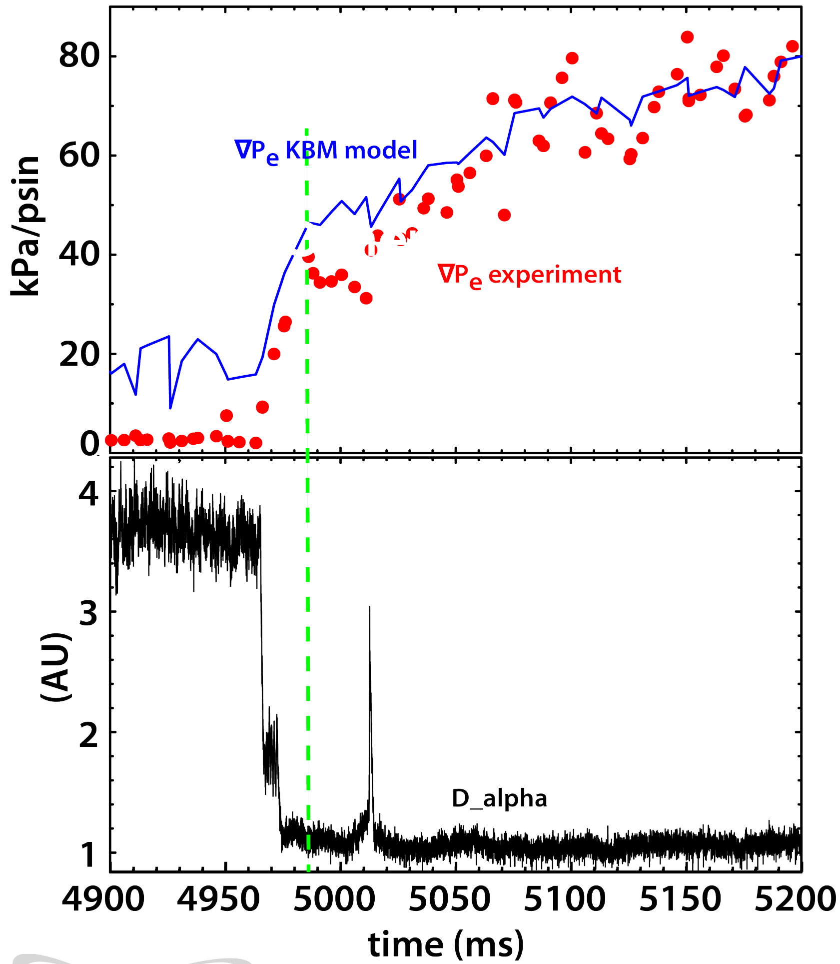
- **Shallower, wider density pedestal with closed divertor**
- **Initial modeling indicates factor of several reduction in pedestal ionization**

Can BOUT++ help with simulating density transport?

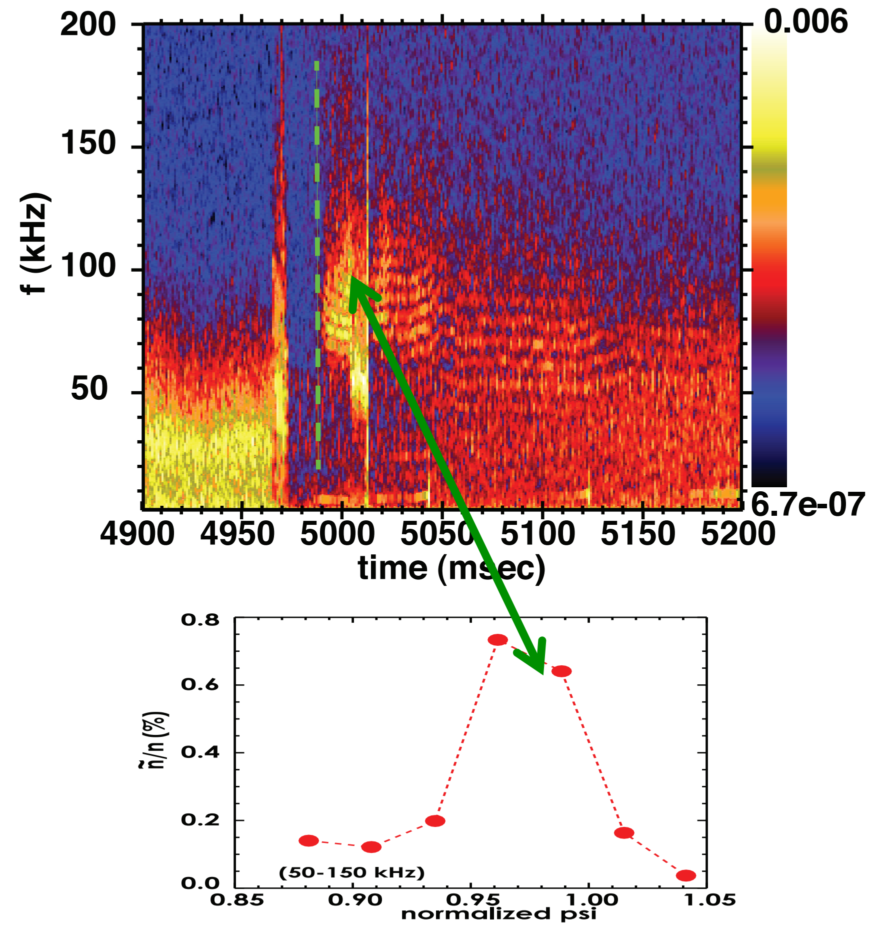
- **What BOUT++ modules are needed to study density transport?**
- **Further interpretive analysis of DIII-D data will provide the ionization source profile for open and closed cases**
- **Critical issue is whether a density pinch is significant in pedestal transport**
  - Future tokamaks will have very low pedestal ionization from recycling neutrals. Will a density pedestal still develop?

Onset of Density Fluctuations Correlated With Slowing of Pedestal Evolution

Pressure gradient quickly reaches KBM threshold



Coherent mode localized to pedestal



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What is physics that controls pedestal gradients?

- **Pedestal T_e, n_e, p_e and p_{tot} gradients typically evolve quickly in ELM cycle to a nearly saturated level**
  - This behavior suggests that one or more profiles are controlled by critical gradient phenomena

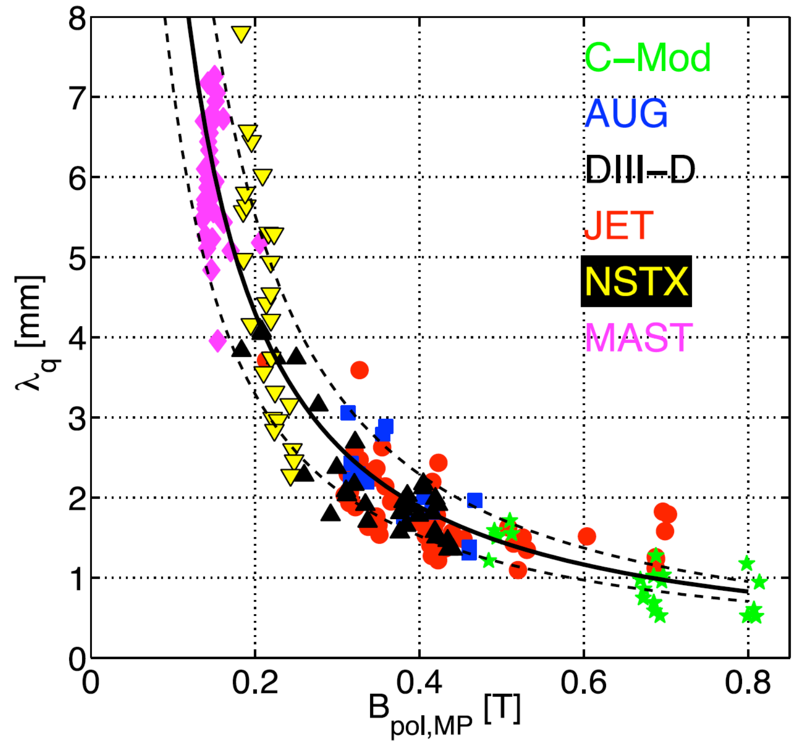
- **Can transport modeling uncover the physics that controls gradients?**

- **Can transport models based on fluctuation-driven transport reproduce measured pedestal fluctuation characteristics?**

- **Recent results from BOUT++ indicate that it can address these questions**

Divertor heat flux width may be controlled by critical gradients at the separatrix

- **ITPA scaling study found divertor heat flux width scales as**
  - $\lambda_q \propto 1/B_p$
  - Independent of machine size
- **Two leading candidate models for divertor heat flux width**
  - Heuristic drift model (HDM) scales with ion poloidal gyroradius
  - Critical edge pressure gradient, similar to KBM for pedestal
- **The two models may scale differently to ITER**
  - HDM projects to 1 mm for ITER
  - Critical gradient width may be greater due to ITER's high power density



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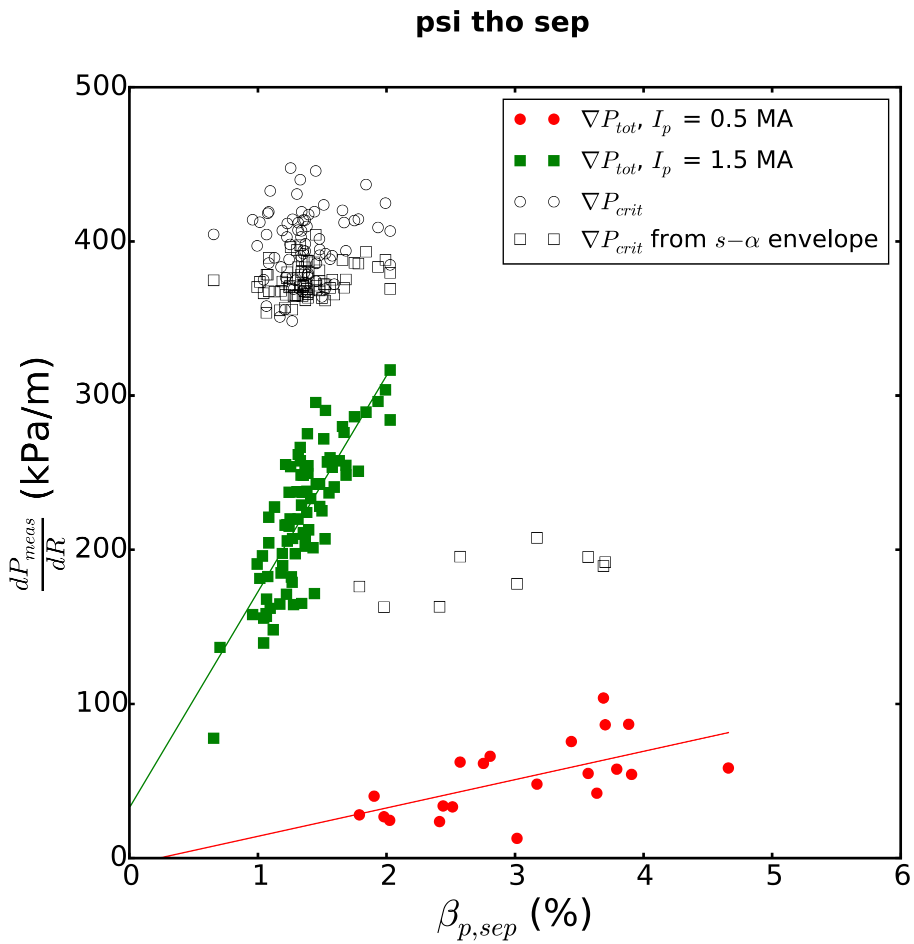
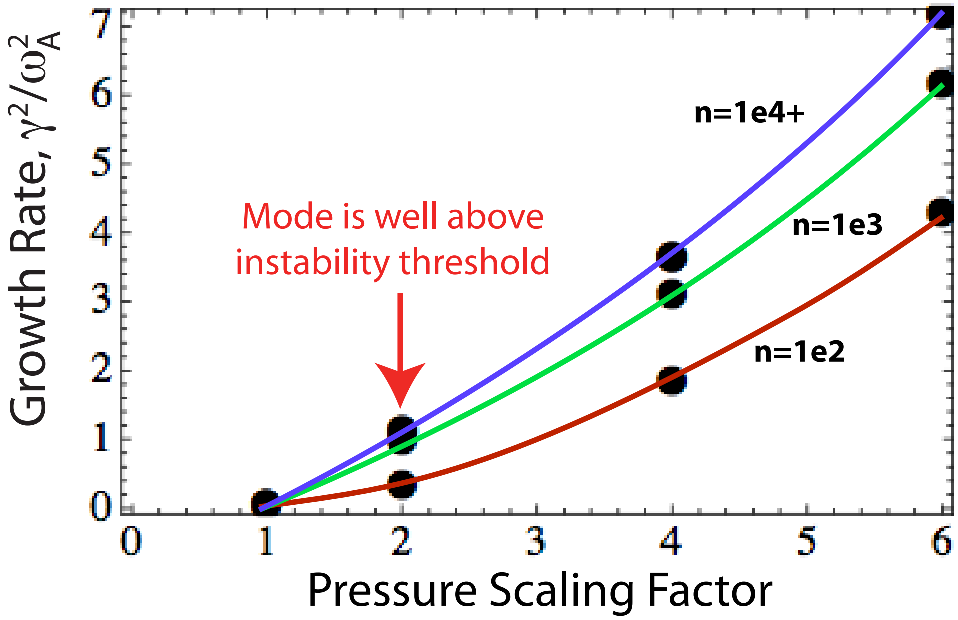
Test of Critical Gradient Model in DIII-D

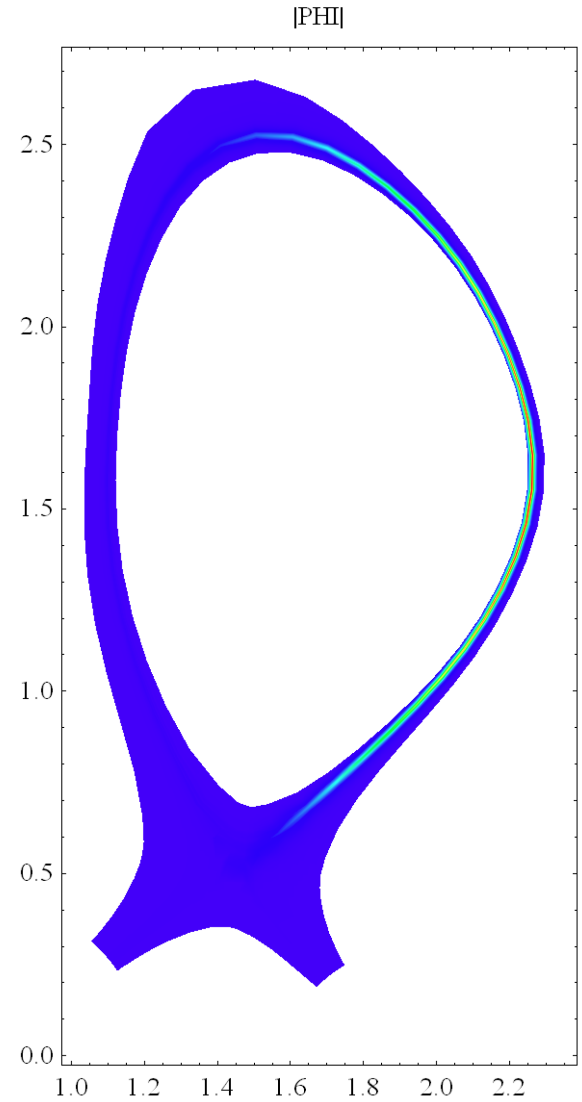
- **Scan separatrix pressure**
  - Power and density scan
  - Two plasma currents; 0.5 and 1.5 MA
- **Calculate ideal ballooning limit with BALOO**
  - Proxy for KBM
  - Minimum in S-α for 2nd stable cases
- **Measured dp/dr below calculated limit**
  - Separatrix density increases with density but not ideal limit
- **Need more accurate calculation of gradient limit**
  - Separatrix, collisionality, FLR, etc.



Initial efforts with 2DX Code Are Consistent with BALOO Result

- **2DX* solve a generalized linear eigenvalue problem in R-z for a given toroidal mode number, *n***
- **Reduced ideal MHD stability model used**
  - More sophisticated models will be used in the future



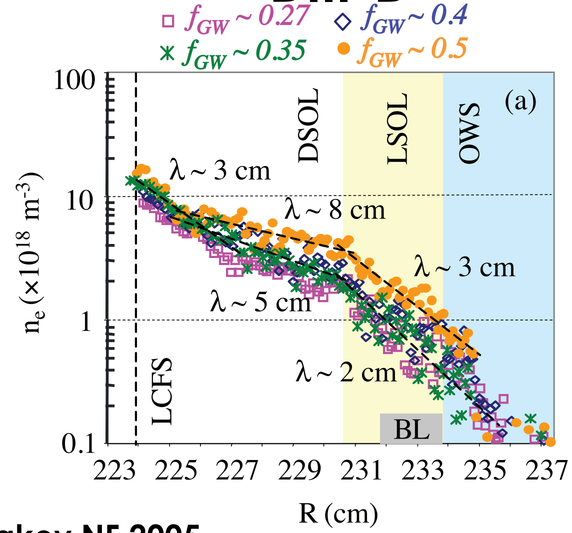


*D.A. Brava, et al., Comp. Phys. Comm. **182** (2011) 1610.

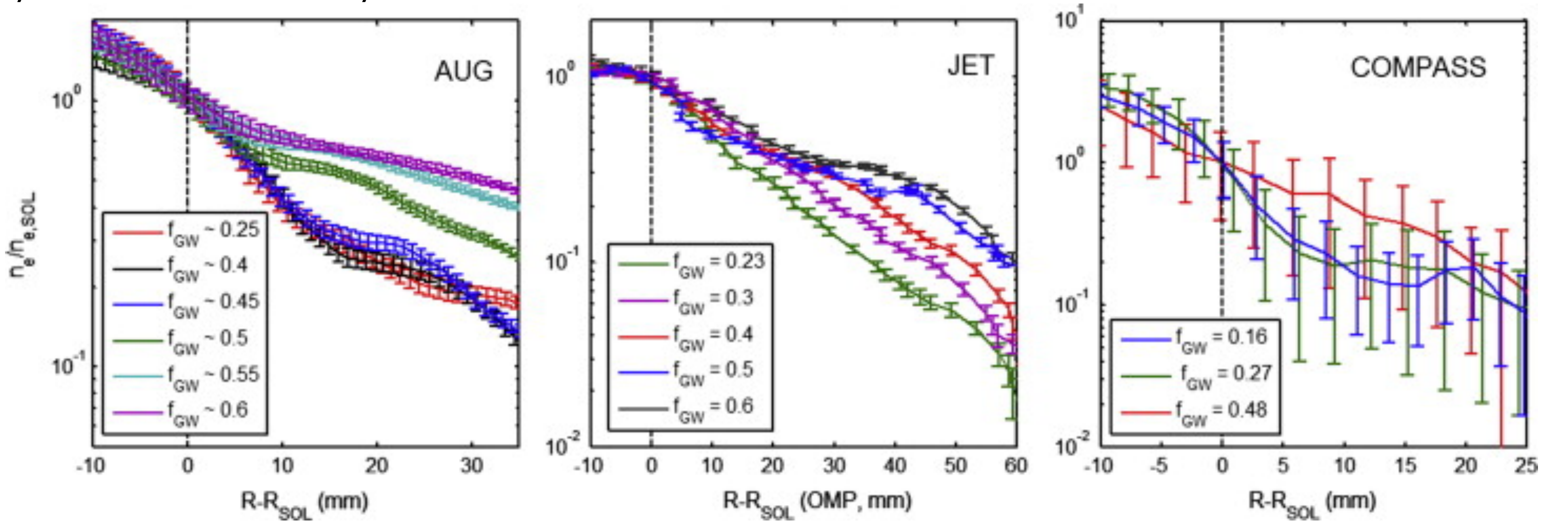
SOL Turbulent Transport May Limit Compatibility of Divertor Detachment with H-mode

- **As density increases:**
  - Far SOL turbulence with rapid radial transport moves inward towards separatrix
  - SOL radial transport correlated with collisionality
- **If increased SOL turbulence linked with collisionality at field-line/material interface:**
  - Divertor detachment may inherently induce excessive turbulence at midplane separatrix
  - Potentially linked to density limit

DIII-D



D. Rudakov NF 2005



D. Carrarelo JNM 2015

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How can new users learn to use BOUT++ and to perform simulations with the code?

- Recent developments of BOUT++ have made the code very useful for studying a variety of pedestal problems
- There is interest in expanding the user base to people at some of the experimental labs
- This raises a number of questions
  - How can these new users efficiently learn to run the code?
  - On which computers can they run the code and what is the cost for computing time?
  - Are there agreements that they should sign?
  - …