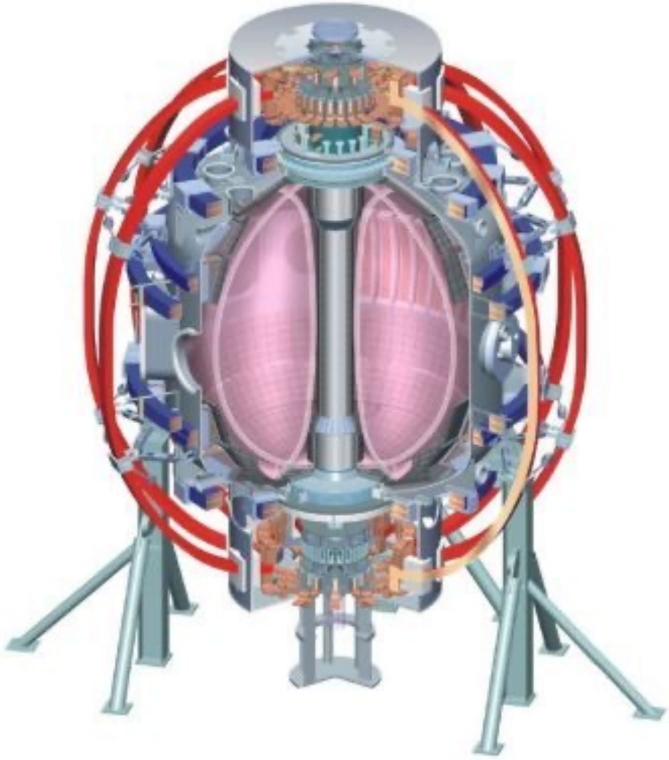
NSTX contributions to the FY22 JRT

D.J. Battaglia
On behalf of the NSTX-U team

NSTX-U Monday Science Meeting
October 11, 2021



JRT22: Increase confidence in scaling intrinsically non-ELMing regimes to next step devices

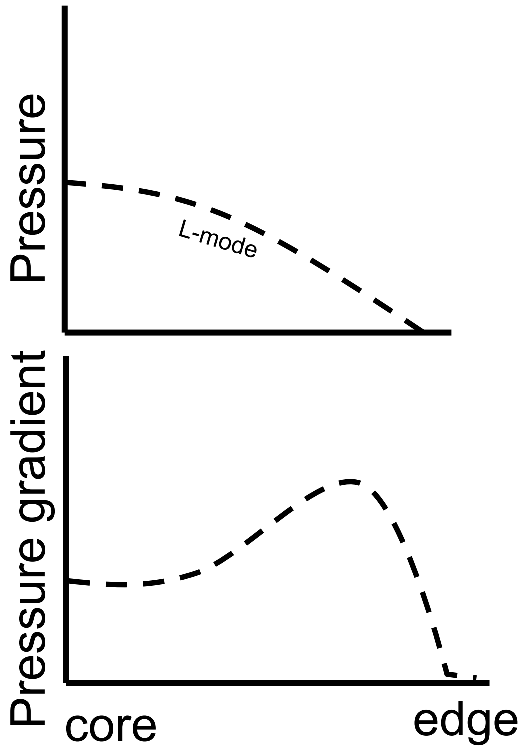
- DOE FES Joint Research Target (JRT): DIII-D, NSTX and C-mod facilities collaborate to address an urgent scientific topic
  - Increase coordination and awareness across institutions
  - Accelerate progress through coordinated experiments and analysis
- JRT reports directly to DOE via quarterly milestones and a final report
  - Opportunity to raise awareness and impact of research activities
- JRT22 topic aimed at expanding the physics basis needed to leverage intrinsically non-ELMing regimes in next-step devices
  - Specific emphasis on
    - QH-mode and Wide Pedestal QH-mode (DIII-D)
    - I-mode and EDA H-mode (C-mod)
    - Wide Pedestal and EP H-mode (NSTX)
  - Reduced emphasis on RMP suppressed ELMs, negative triangularity, small ELM regimes

Outline

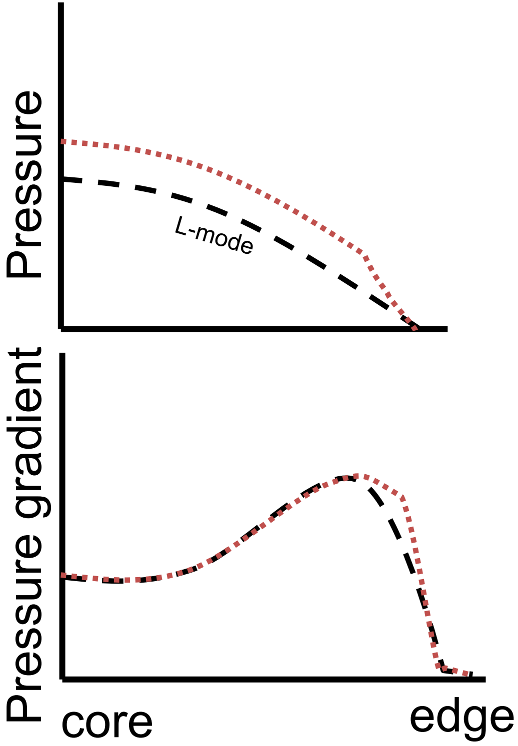
- The H-mode pedestal and non-ELMing regimes

- NSTX contributions to the JRT22

A cartoon for the H-mode pedestal

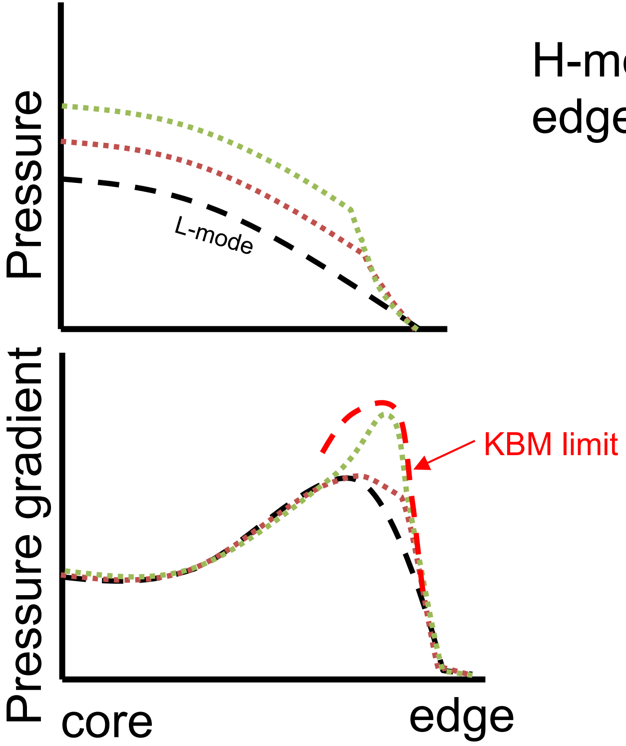


A cartoon for the H-mode pedestal



H-mode pedestal starts at the plasma edge and expands toward the core

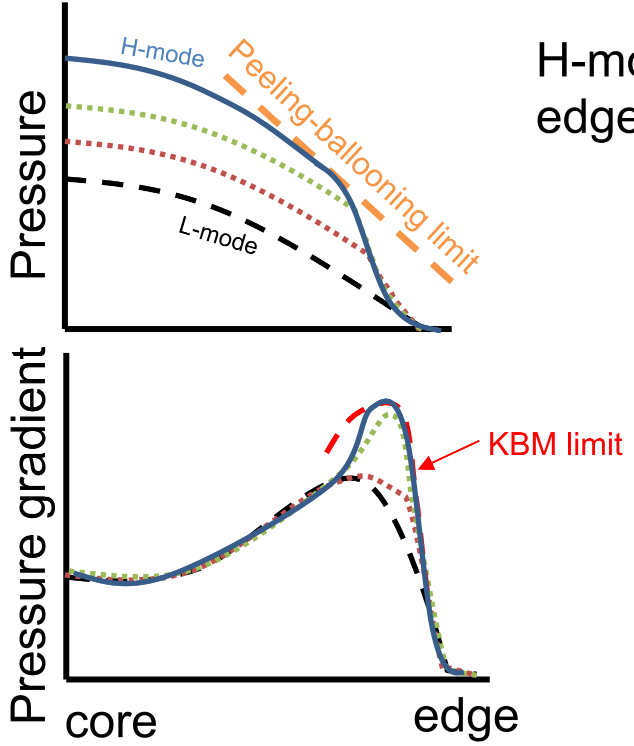
A cartoon for the H-mode pedestal



H-mode pedestal starts at the plasma edge and expands toward the core

Destabilizing Kinetic-balloon modes (KBMs) presents an upper limit to the pressure gradient in the pedestal

A cartoon for the H-mode pedestal

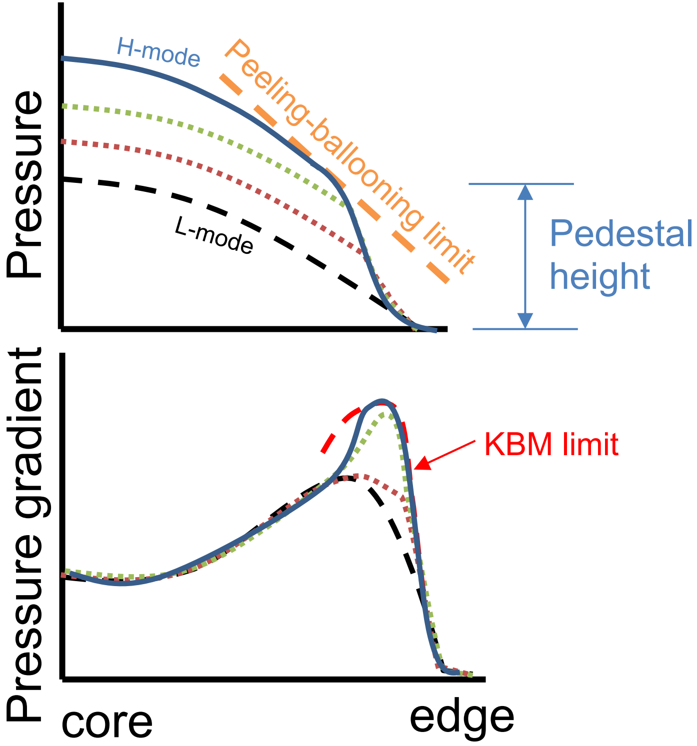


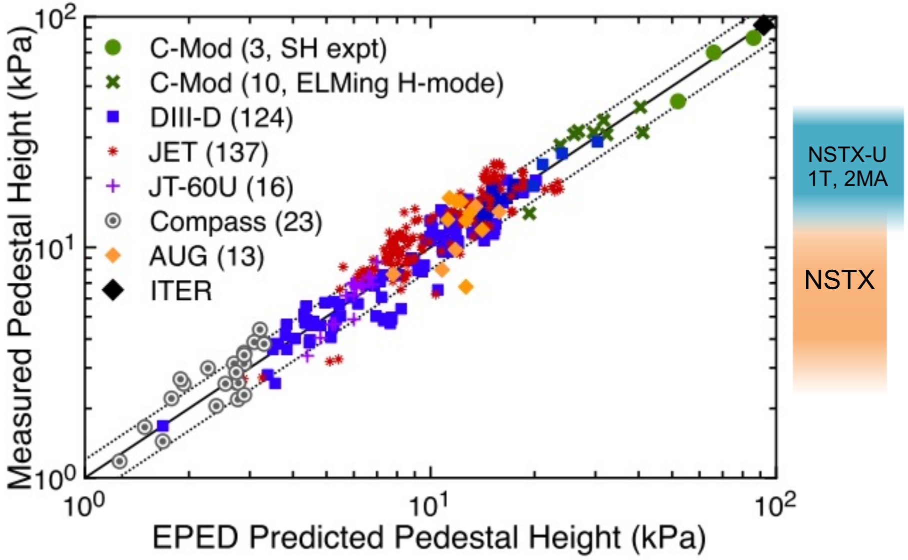
H-mode pedestal starts at the plasma edge and expands toward the core

Destabilization of peeling-ballooning modes initiates an ELM

Destabilizing Kinetic-balloon modes (KBMs) presents an upper limit to the pressure gradient in the pedestal

EPED model has been successful in predicting the maximum pedestal height assuming a KBM constraint

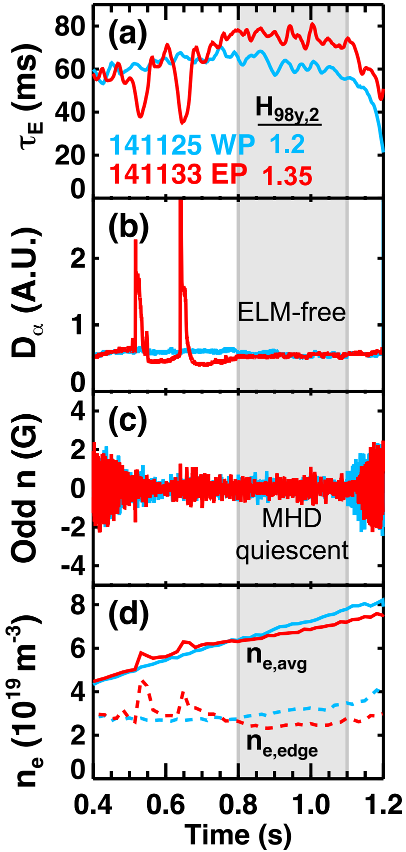




P.B. Snyder et al., Nucl. Fusion (2019) 086017

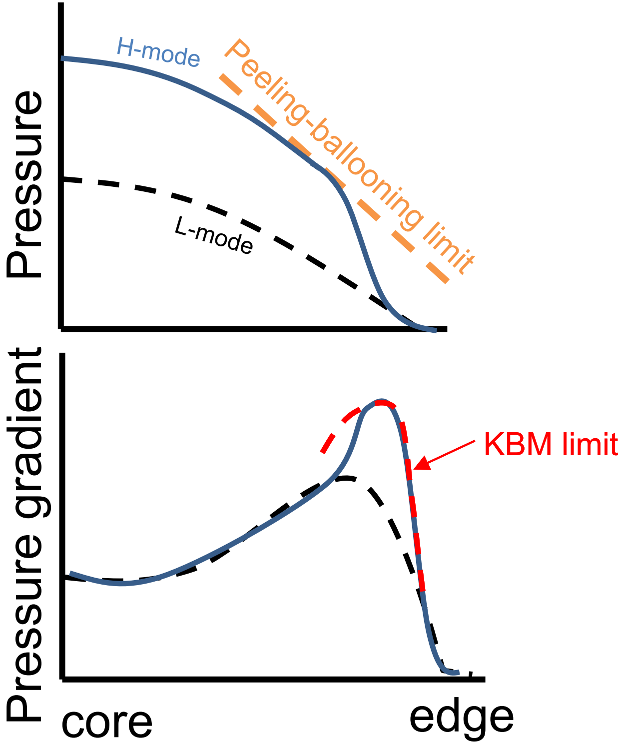
Fusion reactors will most likely require high energy confinement without ELMs

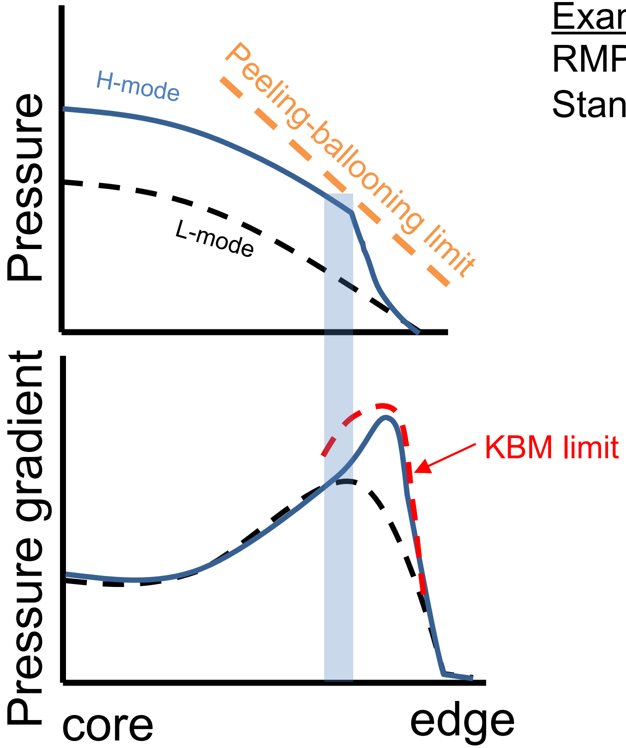
- Edge localized modes (ELMs): explosive bursts of particles and energy from the confined plasma
  - Impulse of energy liberates material from the plasma facing components (PFCs)
  - Tolerable in today's experiments, not tolerable in a reactor



- Goal: maximize pressure gradients (confinement) while robustly avoiding ELMs
  - Especially critical for compact concepts

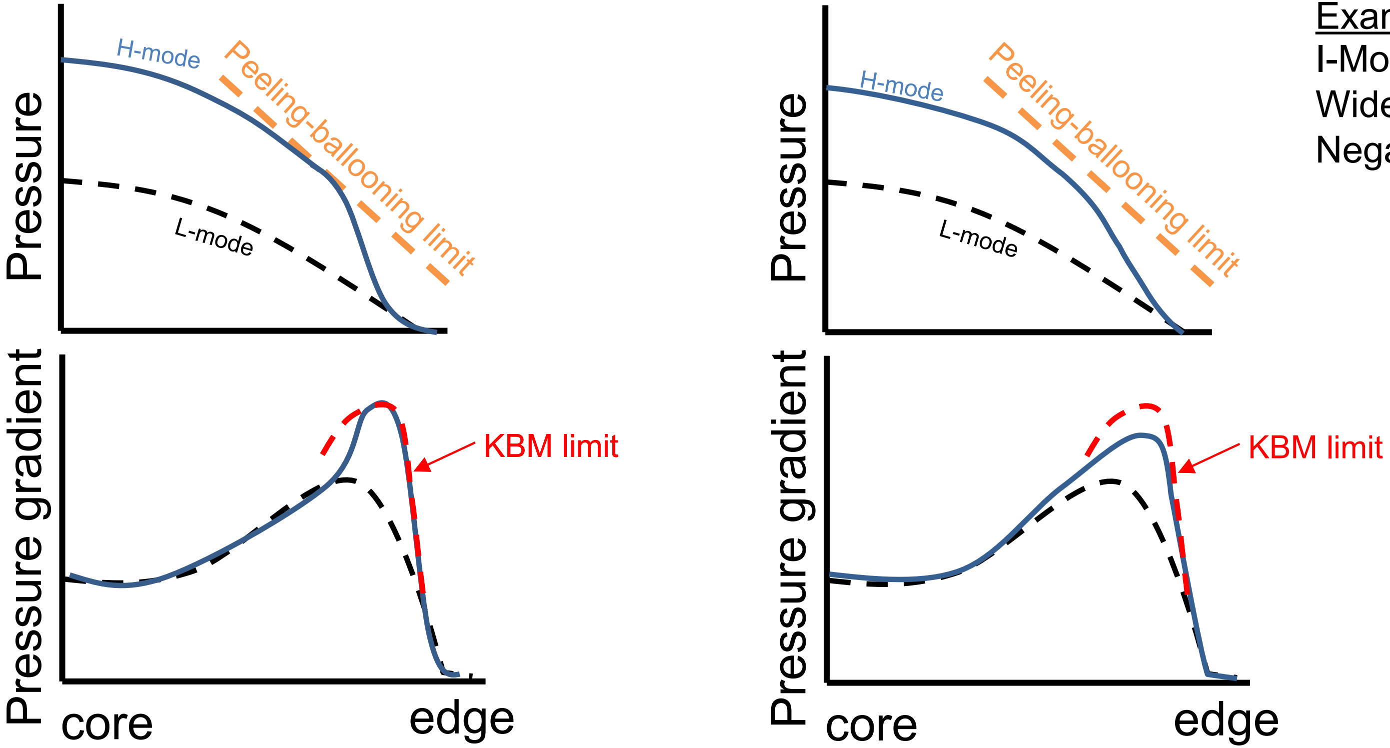
One way to prevent an ELM:
Induce transport at the top of the pedestal





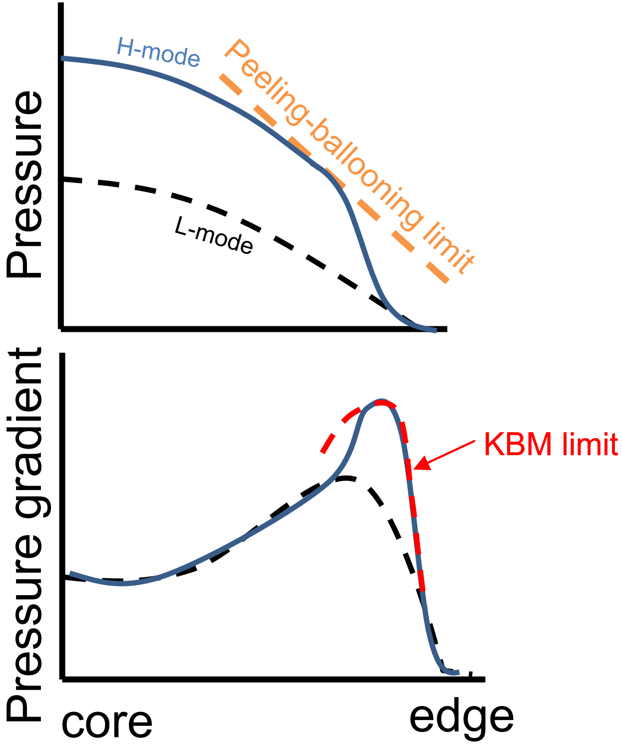
Examples:
RMP ELM-suppression
Standard QH-mode

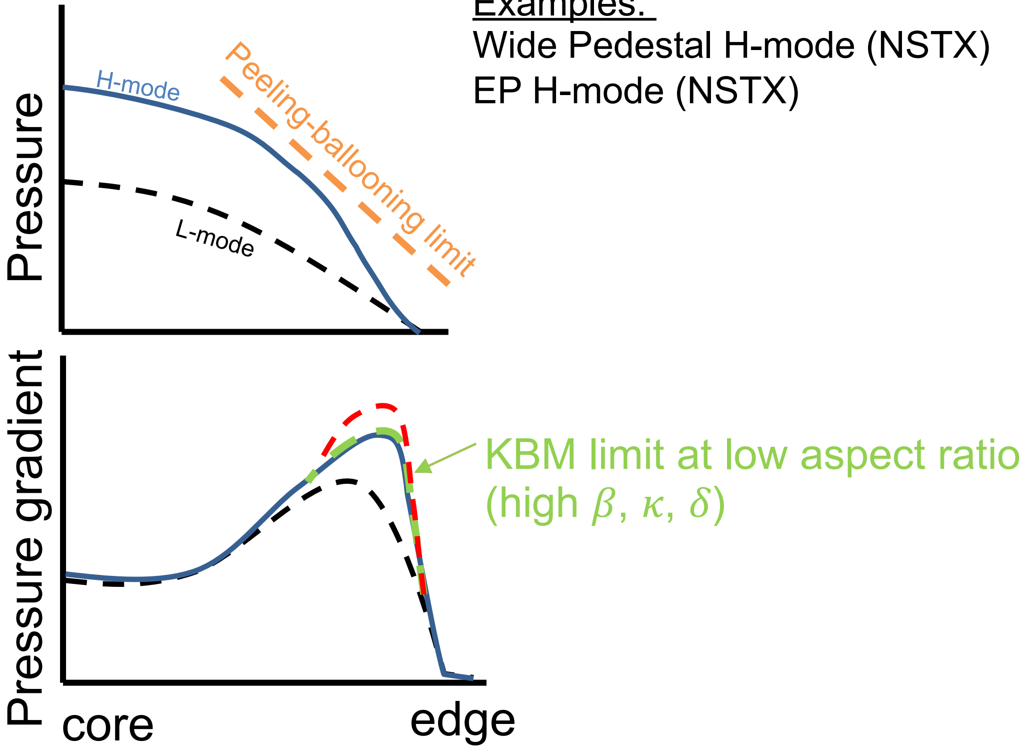
Another way to prevent an ELM: Induce transport within the pedestal



<u>Examples:</u>
I-Mode
Wide Pedestal QH-mode
Negative triangularity

… or operate in regimes with a lower KBM threshold





Examples:
Wide Pedestal H-mode (NSTX)
EP H-mode (NSTX)

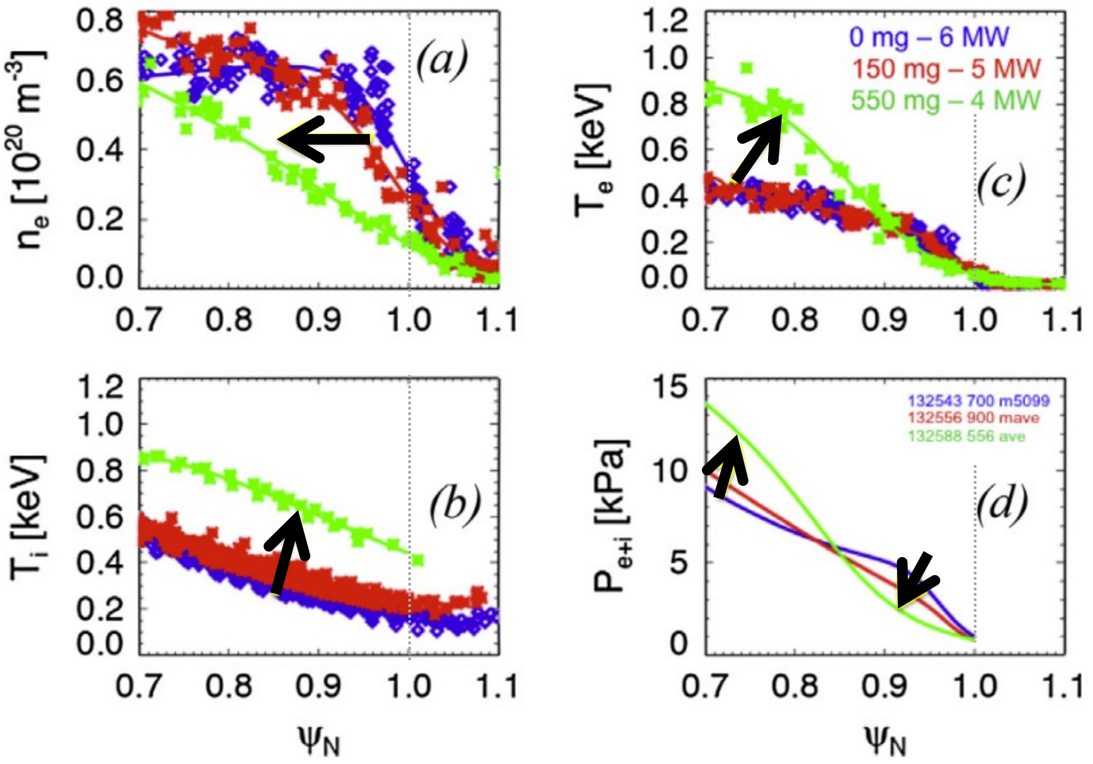
NSTX developed a non-ELMing regime by reducing the neutral recycling via lithium wall conditioning

	P_{NBI}	Lithium
ELMy H-mode	6 MW	0 mg
ELM-free H-mode	5 MW	150 mg
ELM-free EP H-mode	4 MW	550 mg

- Reduced deuterium recycling lowers $n_{e,sep}$ and ∇n_e
  - Pedestal becomes wider with significant improvement in energy confinement

J. M. Canik, et al. Nucl. Fusion 53 (2013)
R. Maingi, et al. Phys. Rev. Lett. 103 (2009)
M. Coury et al. Phys. Plasmas 23 (2016)

- EP H-mode: Enhanced Pedestal H-mode
  - Observed at the lowest ion collisionaltiy



R. Maingi, et al. J. Nucl. Mater. 463 (2015)

Outline

- The H-mode pedestal and non-ELMing regimes
- NSTX contributions to the JRT22

Research focused on establishing the physics basis needed to translate non-ELMing regimes to next-step devices

- JRT22 is organized into five Working Groups
  - Each WG responsible for ~ 10 pages of final report

Operational space database and 0-D Projections
Coordinator: Devon Battaglia (PPPL)

Characterization of Edge Transport Mechanisms
Coordinator: Xi Chen (GA), Darin Ernst (MIT)

Edge Macro-Stability and MHD-driven transport at strong shaping
Coordinator: Jake King (Tech-X)

Role of Wall Conditions and Divertor Compatibility
Coordinator: Alessandro Bortolon (PPPL)

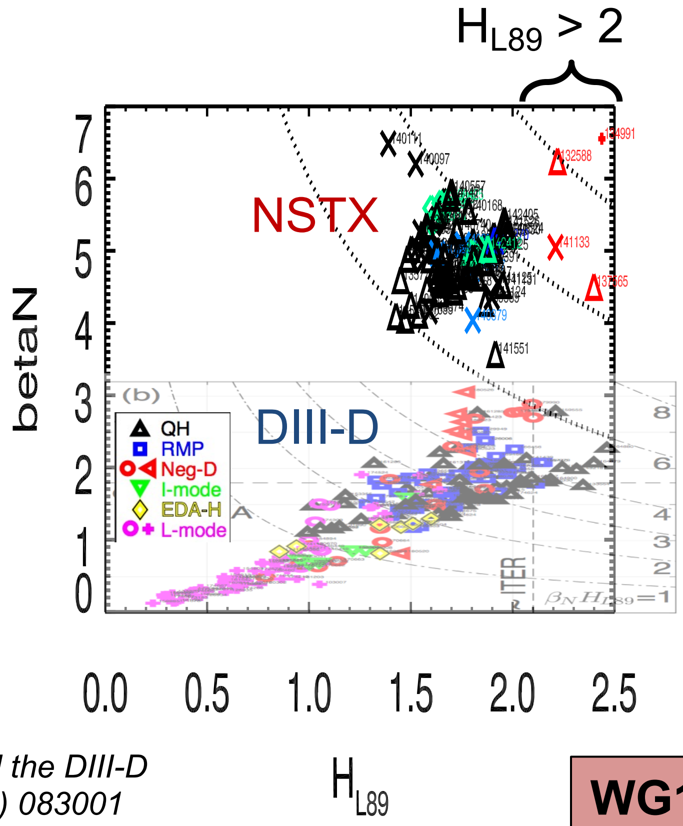
Expansion of Operating Space toward Burning-plasma Regimes
Coordinator: Darin Ernst (MIT), Xi Chen (GA)

General questions aimed at establishing the physics basis needed to translate non-ELMing regimes to next-step devices

- Working Group 1: Operational space database and 0-D Projections
  - How do the global properties and operational constraints of these regimes compare to ELMing regimes, particularly when moving toward reactor-relevant conditions?
- Working Group 2: Characterization of Edge Transport Mechanisms
  - What transport mechanisms are responsible for establishing the different non-ELMing regimes? How are these mechanisms expected to scale toward next-step devices?
- Working Group 3: Edge Macro-Stability and MHD-driven transport at strong shaping
  - What factors impact the peeling-ballooning (ELM) stability in these target regimes? Can regimes with saturated edge-localized MHD be scaled to next-step devices?
- Working Group 4: Role of Wall Conditions and Divertor Compatibility
  - Can suitable particle control, particularly impurities, be realized without ELMs? Are the target regimes compatible with divertor solutions required for next-step devices?
- Working Group 5: Expansion of Operating Space toward Burning-plasma Regimes
  - Perform new experiments to expand operating space of target regimes and support development of the physics basis required to scale regimes to next-step devices.

NSTX will contribute to a multi-machine database of non-ELMing regimes

- Aim of database is to collect 0-D values averaged over a "steady" period in the discharge
- Use common analysis and metrics to permit comparison across regimes and devices
- Support 0-D projections for next-step devices



DIII-D data from
C. Paz-Soldan and the DIII-D team, PPCF (2021) 083001

WG1

NSTX will contribute to a multi-machine database of non-ELMing regimes

- Target parameters for the database require completing transport analysis (NUBEAM/TRANSP) and pedestal structure

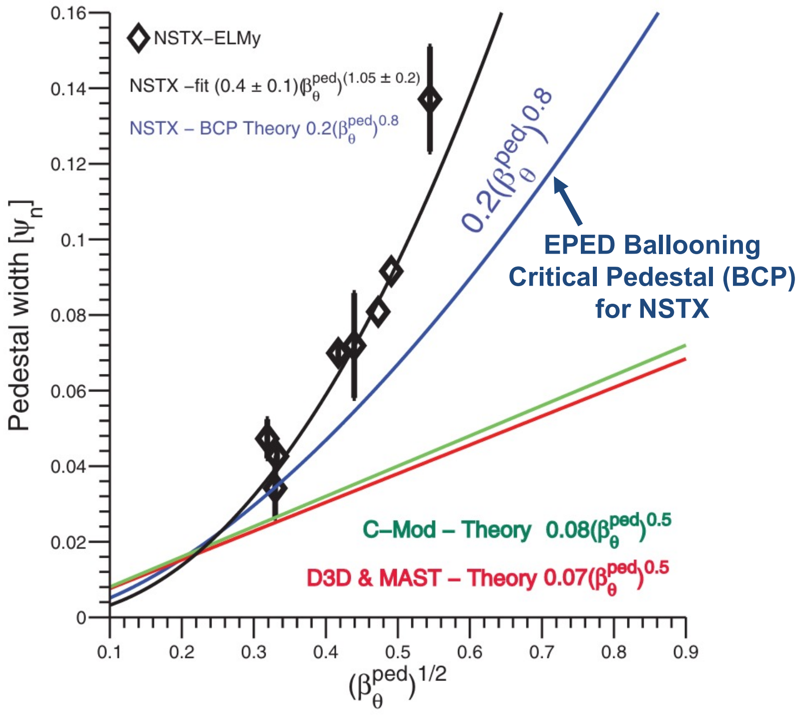
- Plan is to use the OMFIT framework to complete analysis
  - Thanks in advance to GA collaboration
    - Galina, Kathreen, Joey, Sterling, Orso, Tom, et al.

- Please let me know if you are interested in joining …
  - SQL database creation and management
  - Discharge analysis, particularly automated analysis
  - Database synthesis

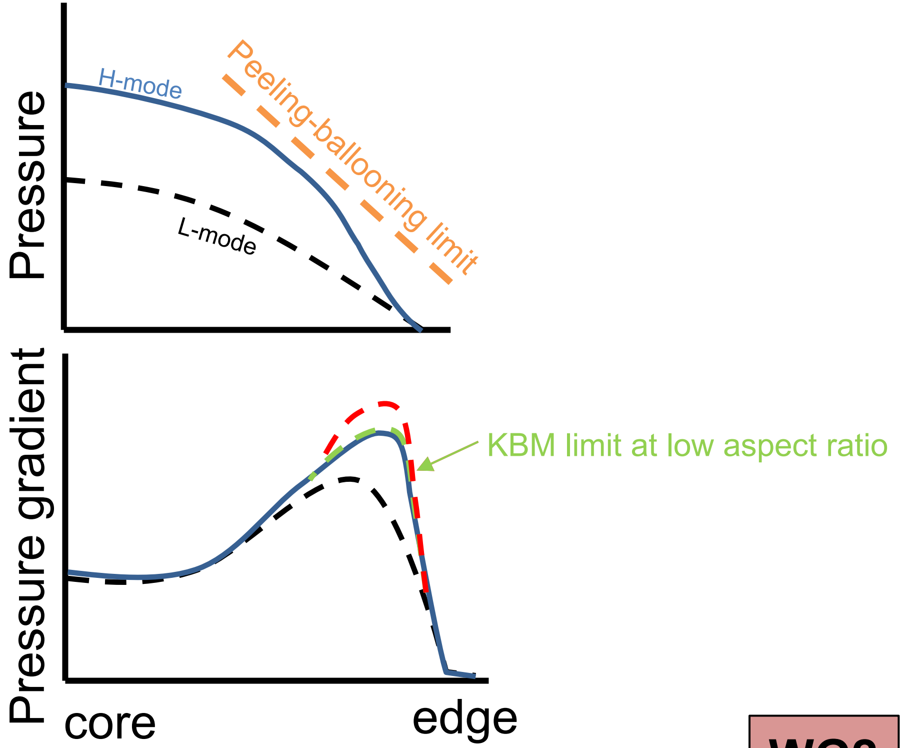
WG1

NSTX pedestal is uniquely wider for a given β_θ, consistent with expected KBM at strong shaping

Pedestal width vs. β_{pol} for NSTX ELMy H-mode



A. Diallo et al., Nucl. Fusion 53 (2013) 093026



WG2

Recent calculations with CGRYO consistent with NSTX pedestal pressure gradient limited by KBMs

- Lithium deposition on carbon PFCs used to reduce recycling and $n_{e,sep}$ on NSTX
  - Lower collisionality regime achieves larger confinement and is ELM-free
- CGRYO*: wide and narrow H-mode pressure pedestals near KBM limit
  - Changes to the KBM stability directly impact the pedestal structure

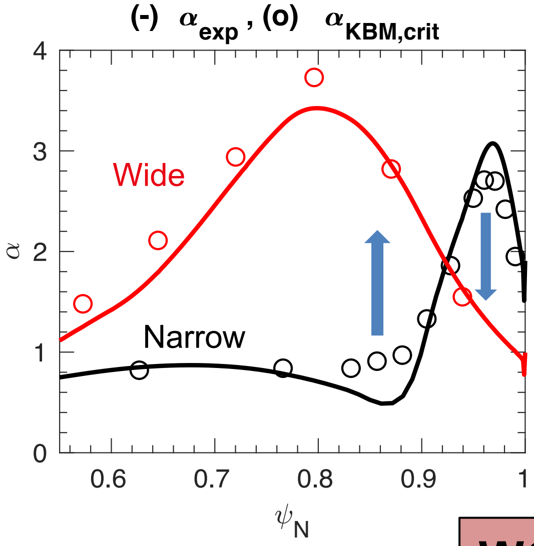
* J. Candy, E.A. Belli, JCP (2016)

- Edge collisionality has a significant impact on the KBM stability via the bootstrap current profile**
  - Drives changes in q, shear, β_θ, and f_{BS}

**From NEO: E.A. Belli, J. Candy, PPCF (2008)

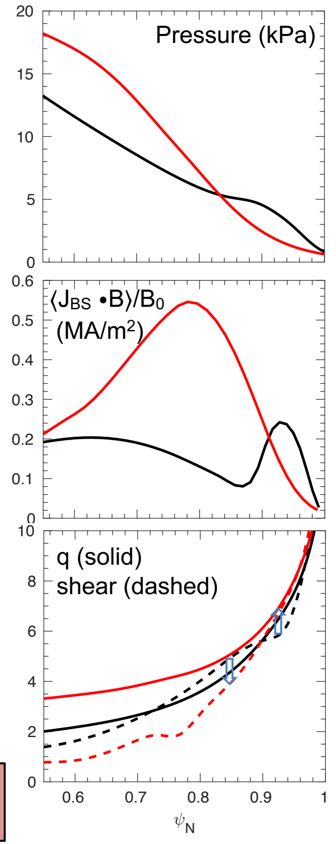
ELMy H-mode	ELM-free H-mode
No lithium	A lot of lithium
132543	132588
6 MW NBI	4 MW NBI

R. Maingi et al., JNM 463 (2015) 1134–1137



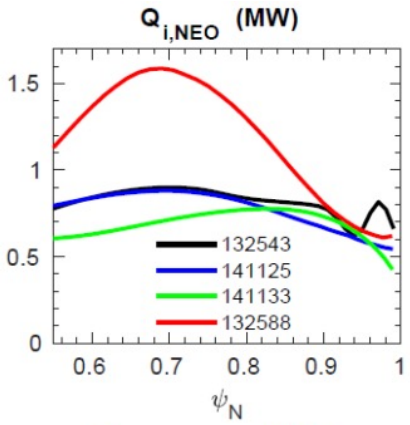
Walter Guttenfelder, 2020 APS

WG2

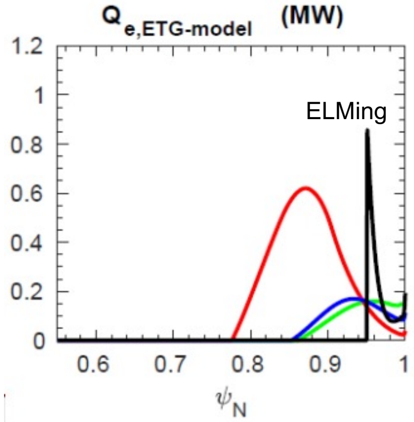


Predictive calculations require a suitable model for all transport channels

- KBM primarily limits pressure gradient by inducing particle transport
  - If energy transport is reduced, particle transport is enhanced such that pressure gradients remain near KBM threshold
    - EP H-mode → positive feedback between reduced neoclassical transport and increased particle transport



- What sets thermal and particle transport through the pedestal?
  - Ion neoclassical thermal transport is significant
  - Recent non-linear ETG simulations indicate ETG is significant as well
    - ETG + NEO in the range 50% of total heat flux in non-ELMing scenarios



Walter Guttenfelder, 2021 AAPPS

WG2

Recent XGC1 calculations include electromagnetic turbulence in a global simulation

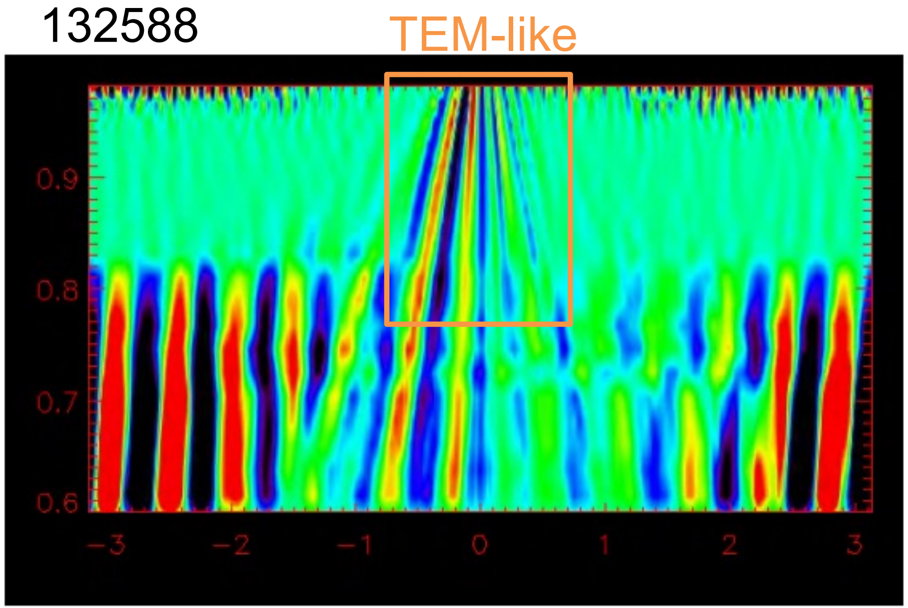
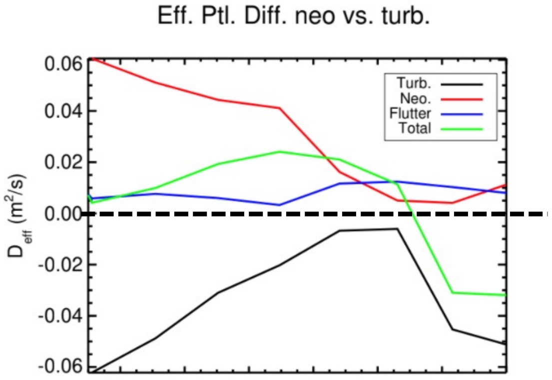


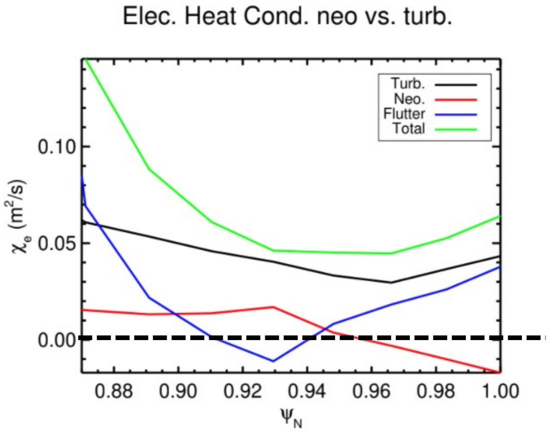
Figure 27: Edge $\delta\phi$ turbulence structure in the ψ_N-θ space in the NSTX lithiated plasma #132588. Horizontal axis is the poloidal angle, with zero denoting the outboard midplane, and the vertical axis is ψ_N. Three distingtive modes can be seen.

FY21 Theory Notable, C.S. Chang et al.

TEM-like modes drive an inward particle pinch

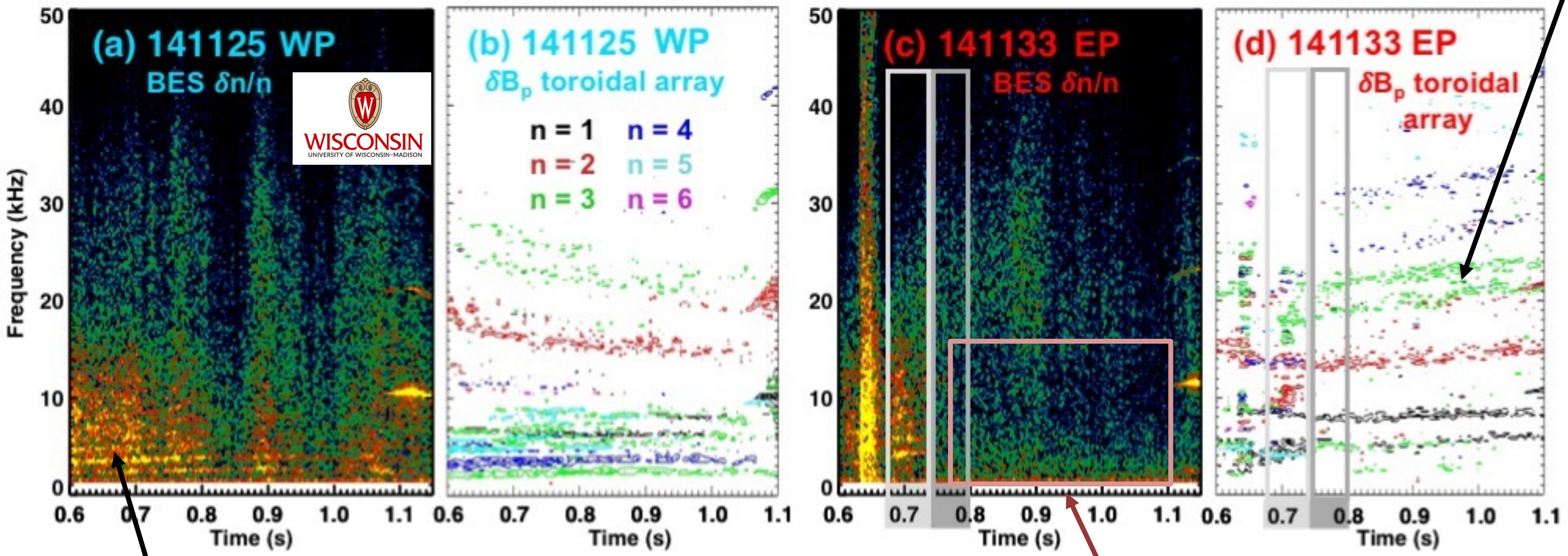
And significant outward energy transport





Fluctuation measurements can be used to guide and test simulations

Harmonic modes (magnetics)



Low frequency, low-n coherent modes (BES and magnetics)

Reduction in low frequency fluctuations in EP H-mode (BES)

WG2

Possible topics that could contribute to Working Group 2 of the JRT22 report

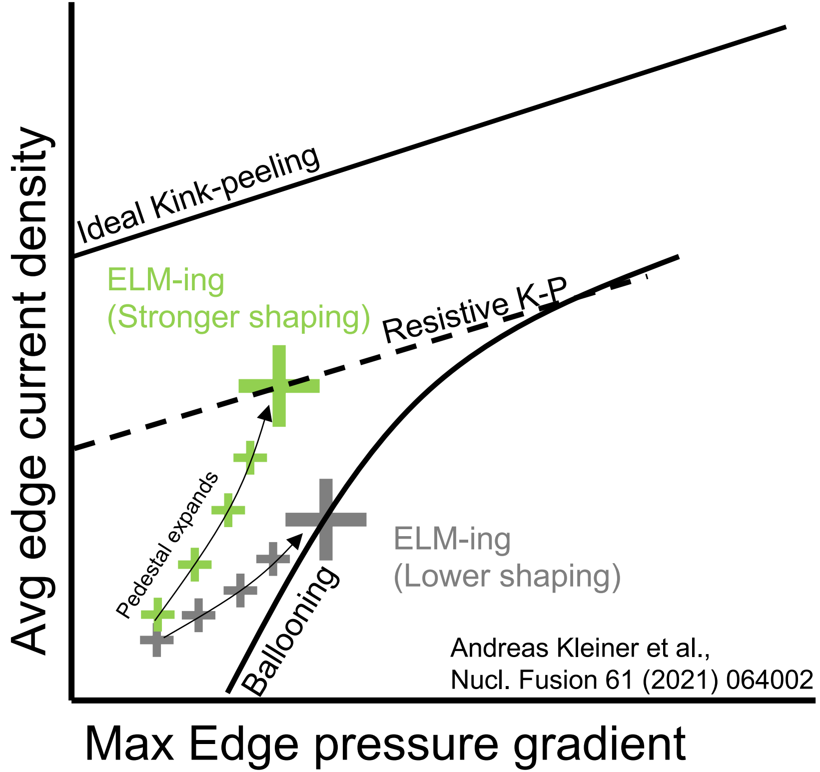
- Why does reducing deuterium recycling alter the KBM stability threshold throughout the pedestal leading to an ELM-free regime?
  - Chicken and egg: collisionality, bootstrap, shear, q profile …
  - How will these mechanisms scale with lower collisionality?
  - Main contact: Walter Guttenfelder

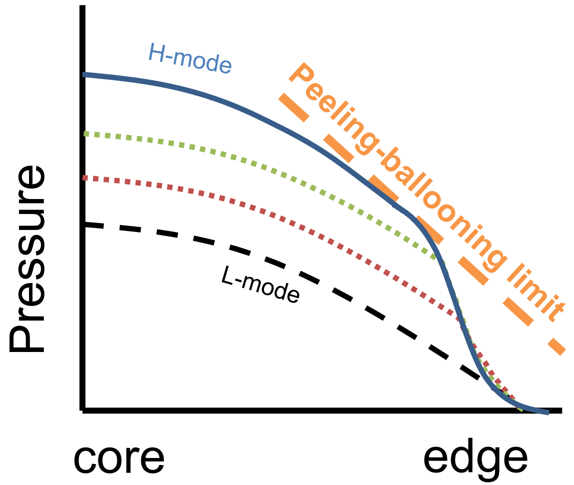
- What are the primary electron energy and particle transport mechanisms?
  - Complete non-linear calculations in order to assist in the development of reduced models
  - Calculations aided by direct comparison to measured fluctuations
  - Main contact: Walter Guttenfelder, CS Chang

- Quantify neoclassical ion transport in the pedestal at low collisionality
  - Kinetic and neutral effects on thermal and momentum transport
  - Main ion profiles relative to measured carbon profiles
  - Main contact: Devon Battaglia, CS Chang

WG2

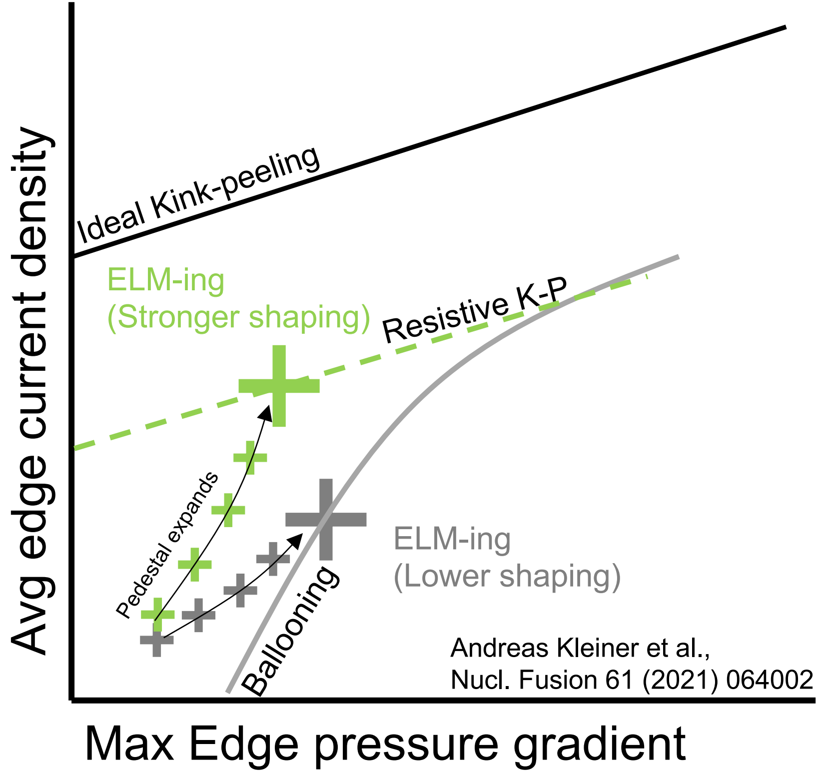
A cartoon of pedestal stability on NSTX





WG3

A cartoon of pedestal stability on NSTX



- NSTX operates near the "nose" of the kink-ballooning stability
  - Recent calculations with M3D-c1 including resistivity show quantitative agreement with kink boundary
- Reducing collisionality raises the resistive kink stability
  - Discharges become ELM-free and are transport limited
- ELMs can return at widest pedestals
  - ELMs can facilitate access to lower collisionality and ELM-free EP H-mode

WG3

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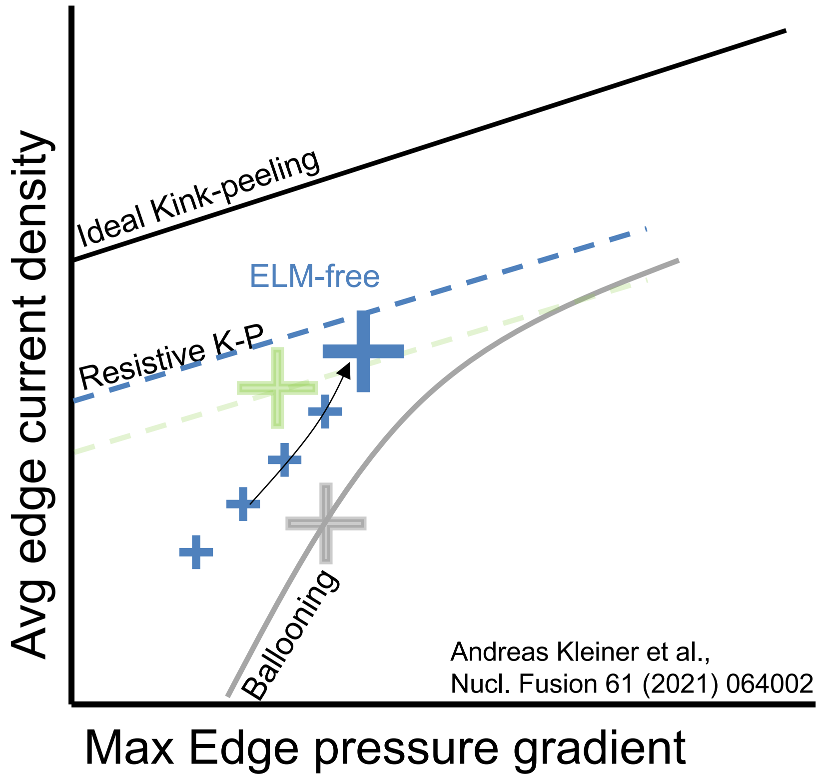

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WG3

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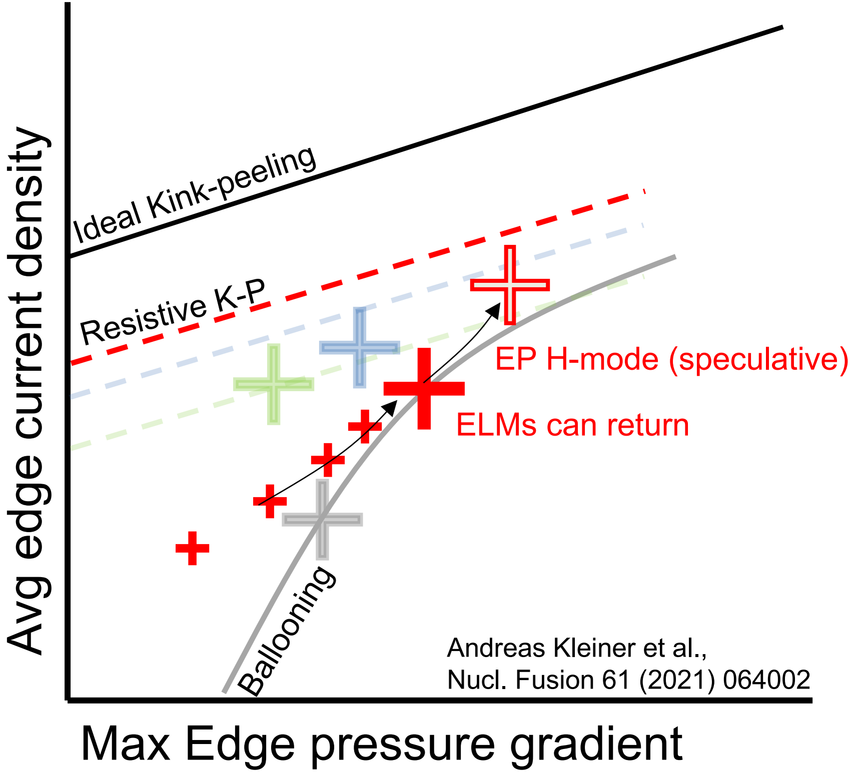

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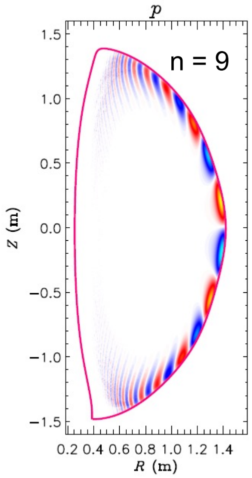
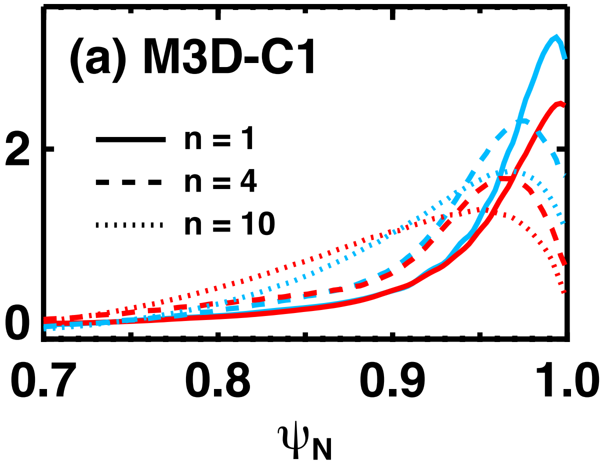
WG3

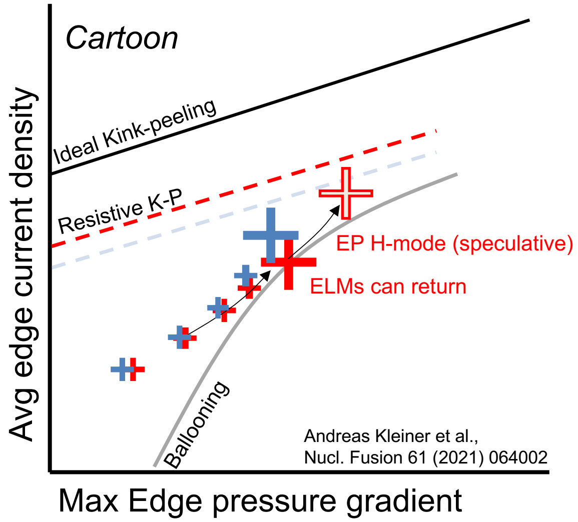
Linear calculations suggest non-ELMing discharges are near the P-B "nose"

- M3D-C1* computes linearly unstable modes
  - n =1 – 20 predicted to be linearly unstable in both regimes (WP and EP)
  - Amplitude peaks near edge
  - Initial two-fluid calculations: harmonic modes at n x 11 kHz (co-I_p in lab frame)

* N. M. Ferraro et al., PoP 23, 056114 (2016)



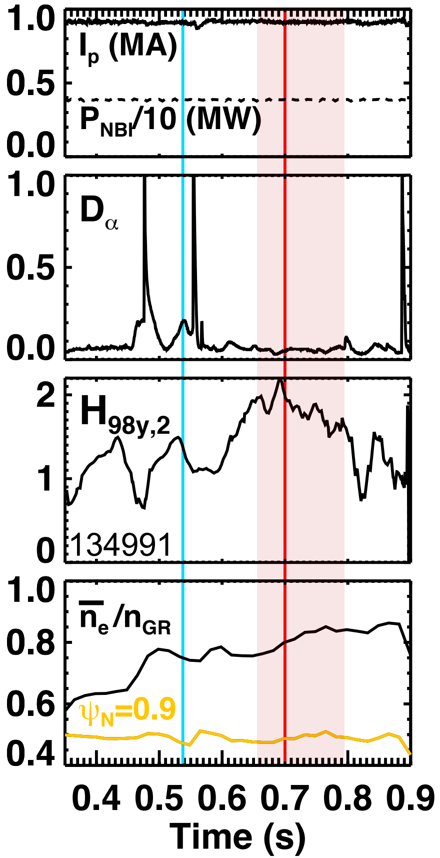


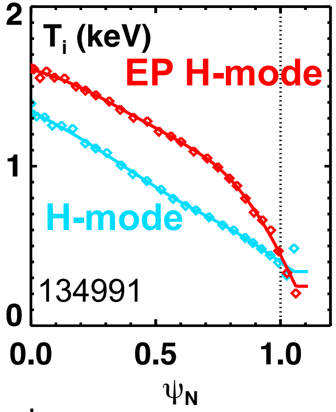


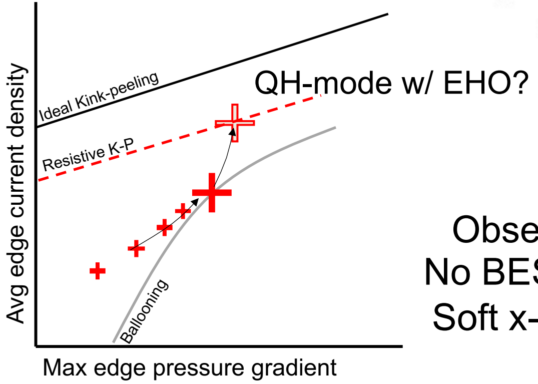
Are there saturated kink-peeling modes (similar to QH-mode)?

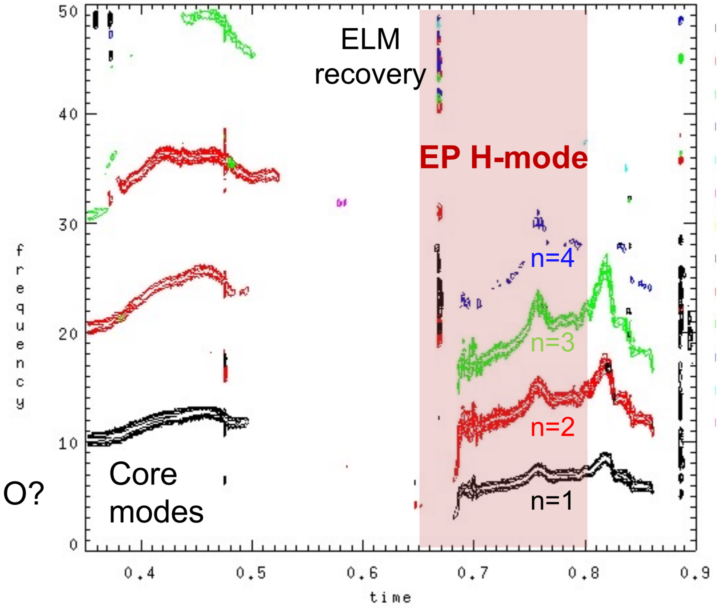
WG3

One of the highest-pressure EP H-mode examples has distinct harmonic modes on magnetics







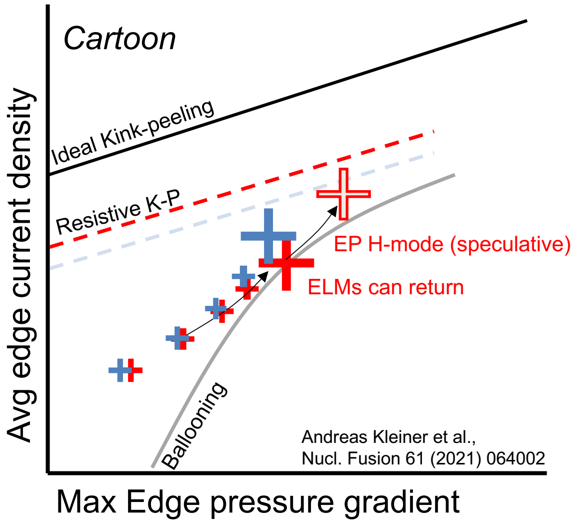


Observed when shaping comes closer to DN.
No BES available to help localize modes to edge
Soft x-ray consistent with edge-localized modes

WG3

Possible contributions to Working Group 3 of the JRT22 Report

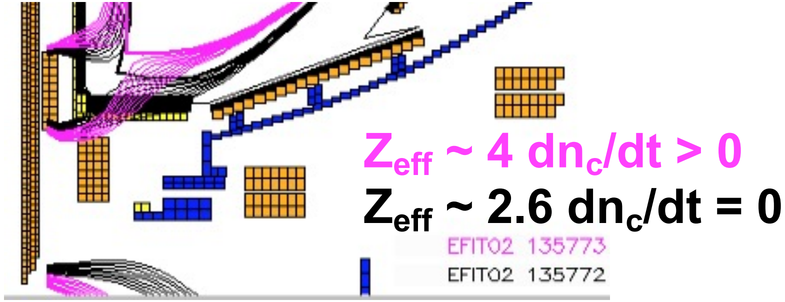
- Where do non-ELMing regimes on NSTX reside relative to peeling-ballooning stability?
- What parameters impact P-B stability? How will the stability boundaries scale to next-step low-aspect-ratio devices?
- Do saturated MHD modes exist in non-ELMing discharges on NSTX? Is the stabilization similar to QH-mode at low collisionality?
  - Benefits from comparison to measured fluctuations
- Main contact: Andreas Kleiner
- Particularly need high-resolution kinetic EFITs for cases of interest

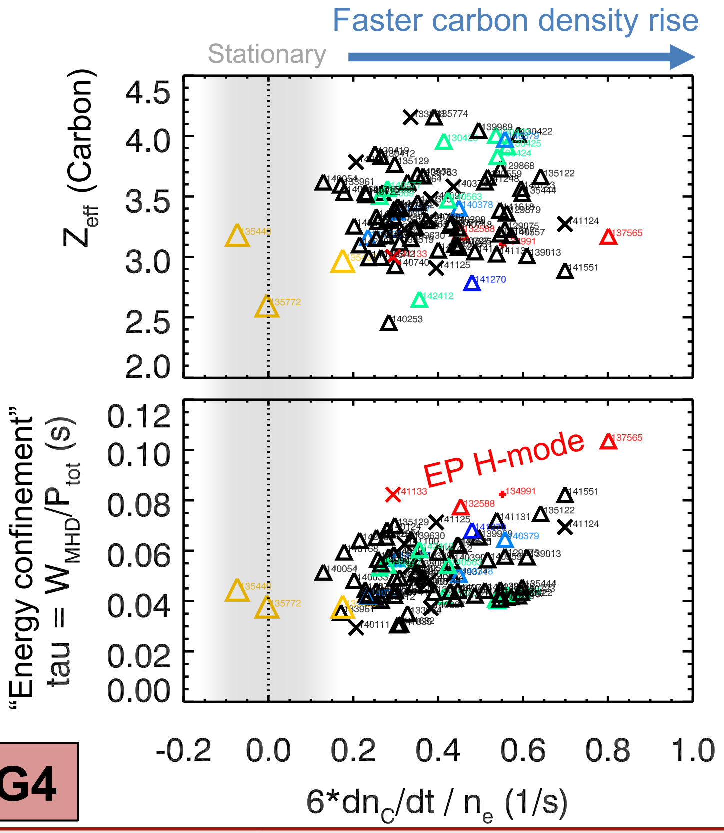


WG3

Accumulation of impurities was the biggest challenge to non-ELMing regimes on NSTX

- Orange points are discharges that achieve lower Z_{eff} and rate of carbon accumulation
  - Lower energy confinement with lower I_p and B_T
  - Large flux expansion with shallow incidence angle at lower divertor
    - Smaller X-point height, larger inner gap
- Pair of sequential shots demonstrate impact of divertor topology on carbon accumulation

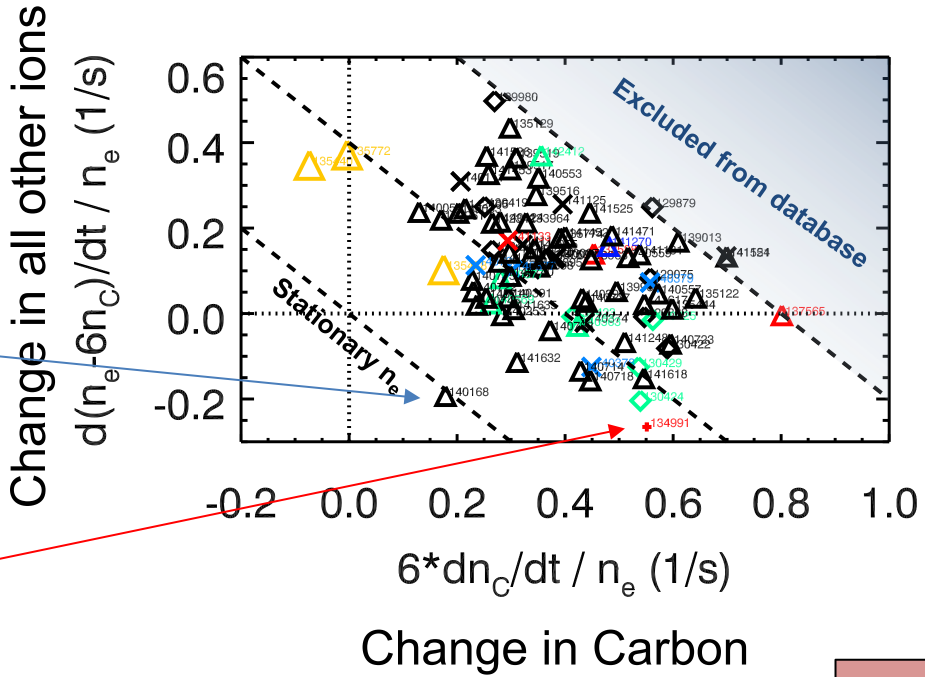




WG4

Inferred deuterium inventory can decrease as carbon is increasing

- "Change in all other ions" can be positive or negative
  - No strong correlation with neutral fueling, NBI fueling and/or lithium conditioning was found
  - HFS fueling roughly adjusted with wall pumping conditions
- 140168 achieves stationary n_e
  - Carbon increasing, deuterium decreasing
  - Due to lithium chunk
- 134991 has largest decrease in "ions that are not carbon"
  - Strong SGI fueling, large lithium deposition, strikepoint on LLD



WG4

Any takers?

- So far, the WG4 contributors are all focused on DIII-D data
  - Impurity sources and transport in non-ELMing regimes
  - Analysis of recent experiments looking at the impact of impurity seeding in the divertor on heat flux & sputtering with a low collisionality SOL

- Please let me know if there is recent or planned work looking at the impact of divertor topology on impurity generation and/or transport using NSTX data

- Modeling with divertor concepts that are compatible with a low collisionality SOL is also of interest
  - Liquid lithium could be an enabling technology for target regimes

WG4

Working Group 5 is tasked with organizing input from FY22 experiments

- DIII-D will have a research forum to solicit experimental proposals later this year
  - Please consider proposals for DIII-D experiments that support NSTX-U science
    - For example, impurity mitigation with a low collisionality SOL

- Any US-led experiment on an international device is fair game for contributing to the JRT report

- Contacts: Darin Ernst, Xi Chen and me

WG5

Summary

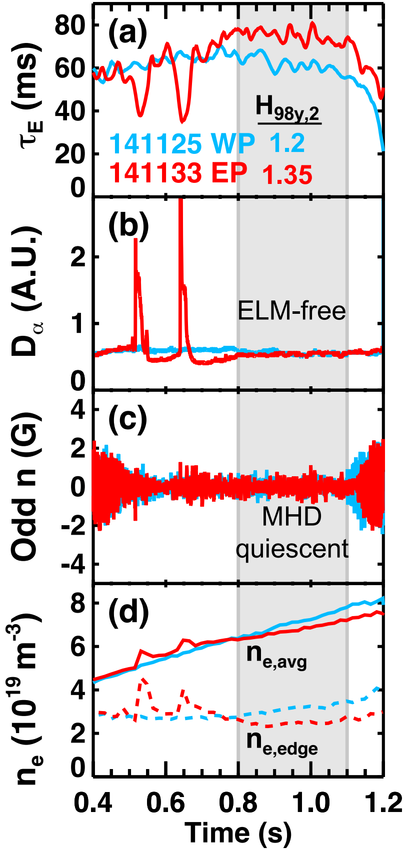
- NSTX developed non-ELMing wide-pedestal regimes with the reduction of neutral recycling via lithium wall conditioning
  - Recent results suggest changes to KBM stability are responsible for widening the H-mode pedestal

- JRT22 is an opportunity to focus efforts on a topic of mutual interest within the US community
  - New analysis with NSTX data will contribute
  - Please join us! https://sites.google.com/pppl.gov/jrt22/home

Backup

Wide Pedestal → Enhanced Pedestal H-mode transition observed at lowest edge ion collisionality on NSTX

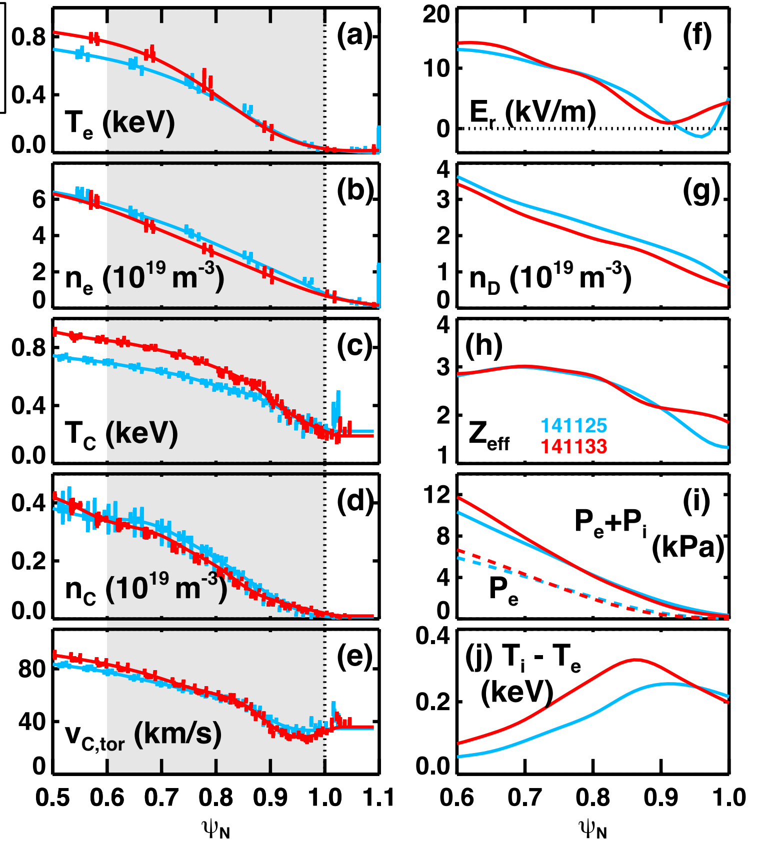
- Analysis that follows focuses on two discharges that bracket the EP H-mode transition
  - "Matched" discharges with lithium wall coatings
  - 300 ms ELM-free and MHD-free period used for comparisons
- ELM-free wide pedestal (**WP**) H-mode
- Enhanced pedestal (**EP**) H-mode
  - Often triggered by a large ELM
- Common features of EP H-mode:
  - Improved ion energy confinement
  - Beneficial decrease in edge particle confinement



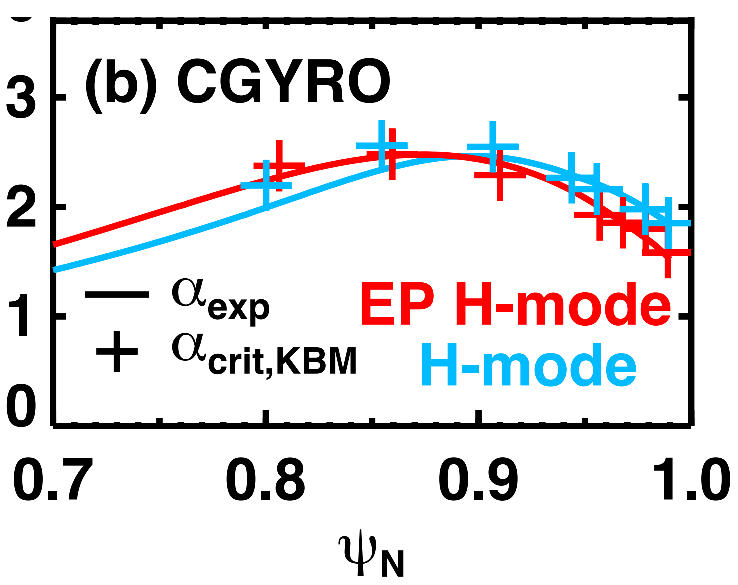
EP H-mode has lower edge n_e, larger ∇T_i compared to Wide Pedestal H-mode

- T_e similar in edge
  - Region where ETG is unstable
- Location of minimum E_r shifts inward
  - Larger gradient in rotation
- Edge n_e, n_D is reduced in EP H-mode
  - n_C less affected, Z_{eff} larger for $\psi_N > 0.9$
- Characteristic increase in edge ∇T_i
  - Larger core T_i and T_e
  - Bigger increase in core T_i
- Pressure similar for $\psi_N > 0.8$

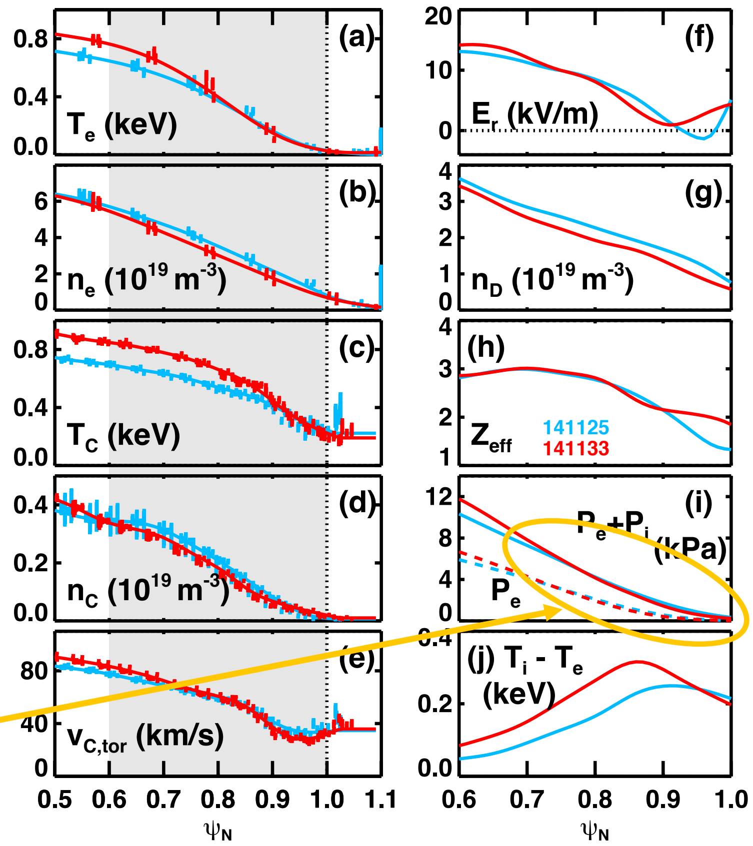
WP H-mode 141125
EP H-mode 141133



CGYRO calculations suggest profiles are near KBM limit



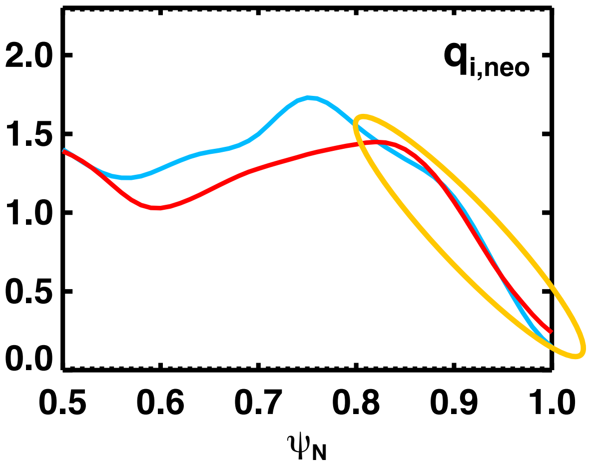
Consistent with similar pressure profiles for ψ_N > 0.8

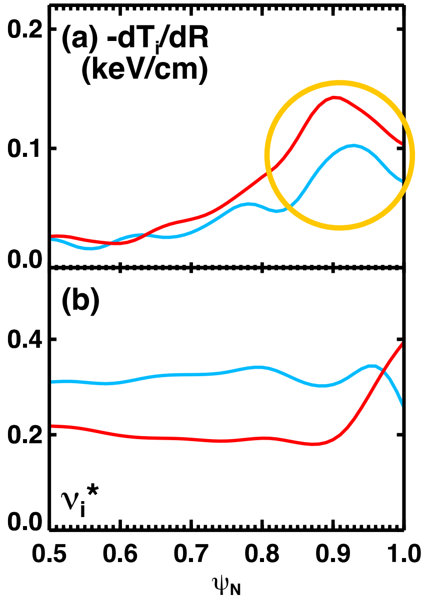


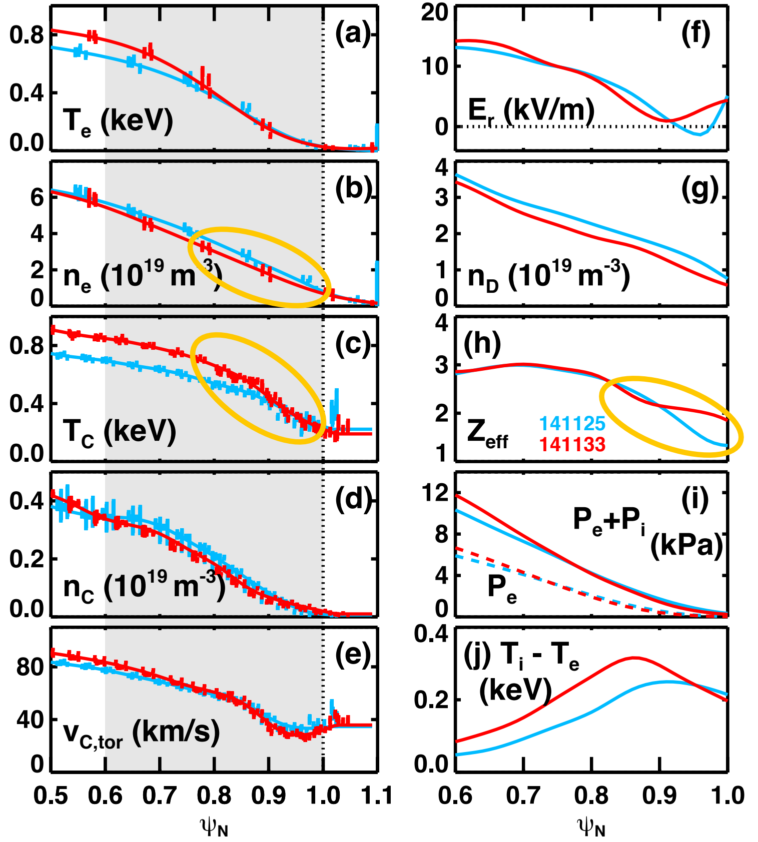
Larger edge T_i gradients in EP H-mode are consistent with neoclassical scaling

- Neoclassical (banana regime) energy transport produces leading order scaling:

$$q_{i,neo} \propto -\nabla \mathrm{T}_i \; \frac{Z_{eff} n_e^2}{I_p^2 \, T_i^{1/2}}$$







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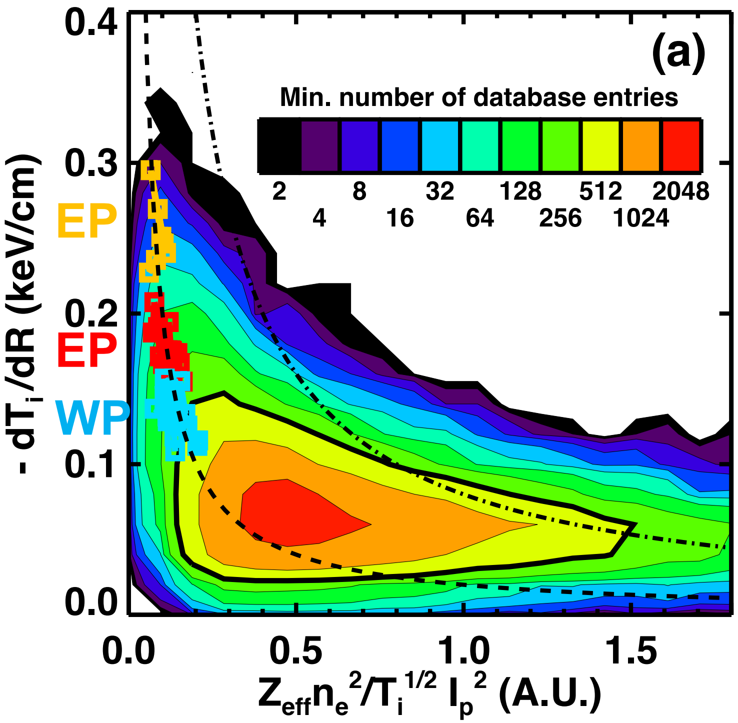
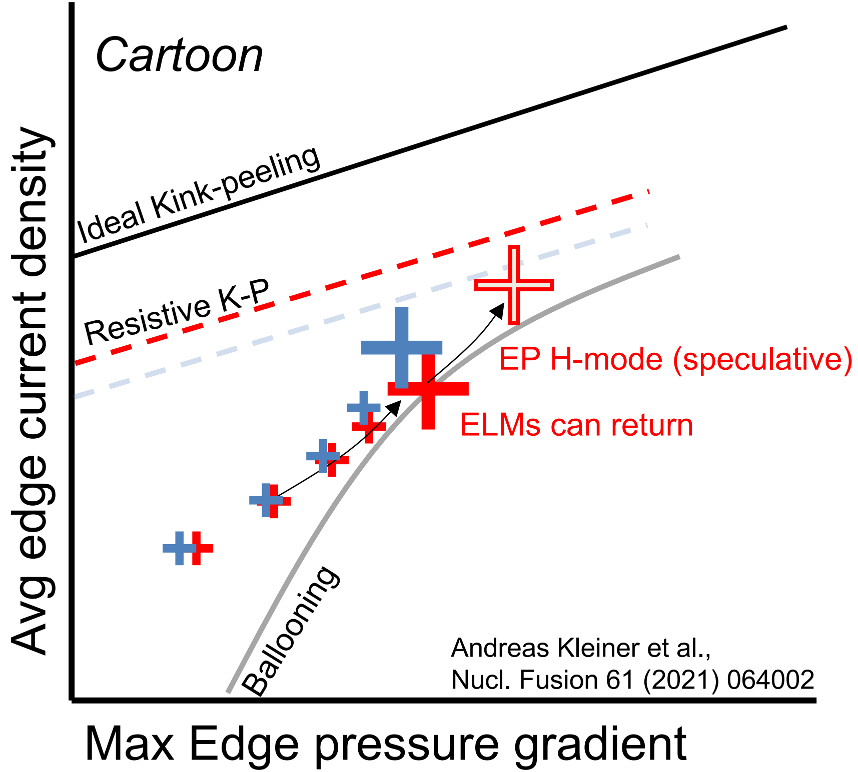
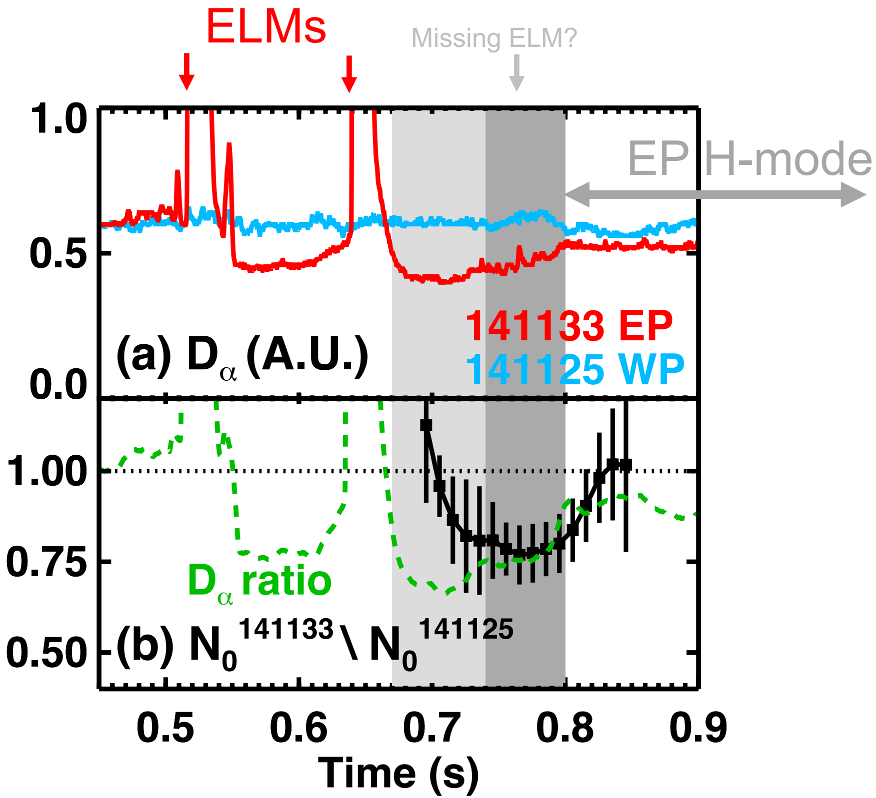
$$q_{i,neo} \propto -\nabla T_i \; \frac{Z_{eff} n_e^2}{I_p^2 \, T_i^{1/2}}$$

- Database of H-modes maximum ion temperature gradient on NSTX
  - 85% of discharges sit inside bold line
  - Dashed lines show constant $q_{i,neo}$
- Key observation: largest edge T_i gradients occur when n_e/I_p is small
  - Ongoing analysis challenge: inferred $q_i < q_{i,neo}$ with larger ∇T_i



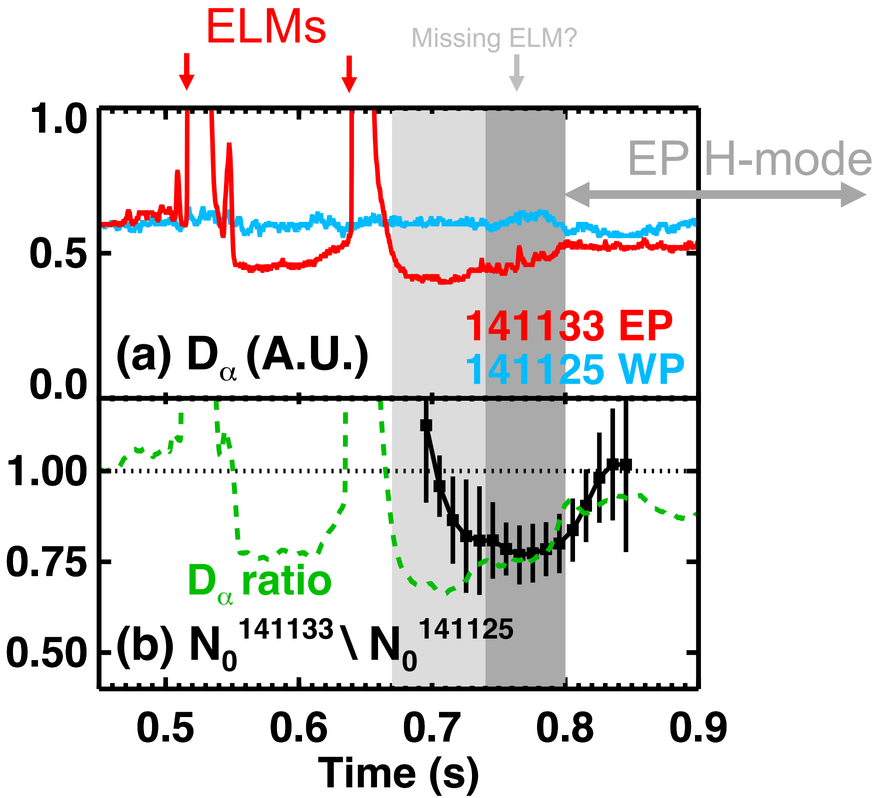
A large ELM can trigger EP H-mode due to a transient period of lower neutral fueling





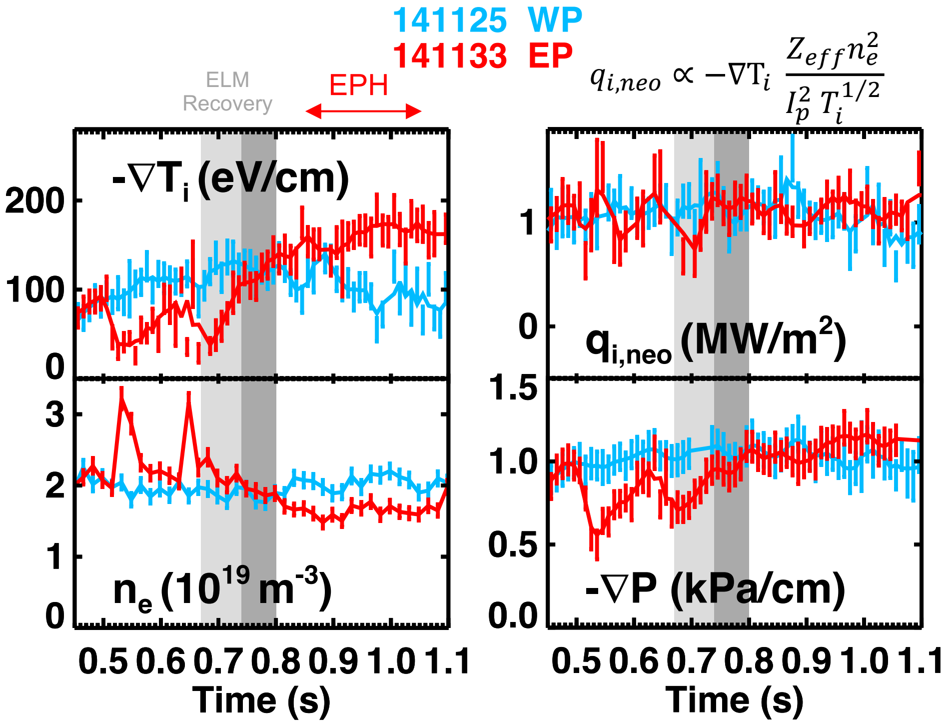
A large ELM can trigger EP H-mode due to a transient period of lower neutral fueling

- ELM liberates neutrals from the divertor PFCs
  - Neutral recycling reduced while PFC neutral inventory recovers
- Ratio of neutral density at T_e = 100eV between two shots (black) similar to ratio of divertor D_α
  - Measurement from passive CHERs
- Lower neutral density facilitates entry into EP H-mode



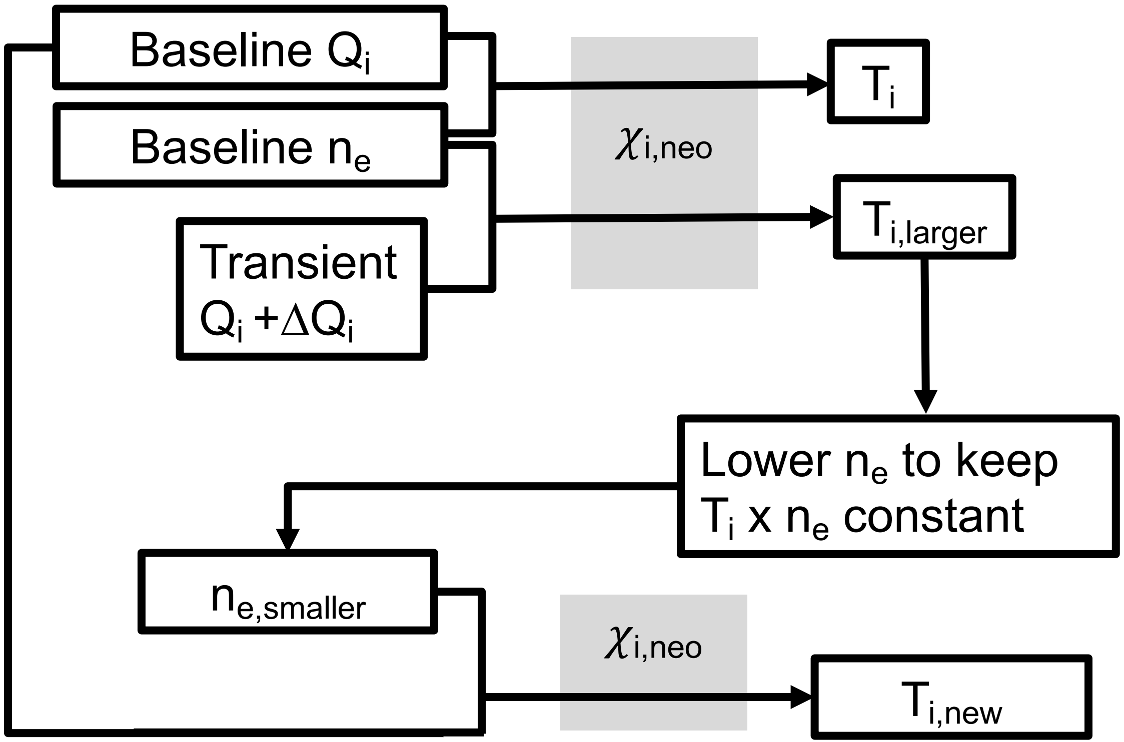
∇T_i "overshoot" following ELM recovery can provide the necessary trigger for the EP H-mode transition

- ∇T_i "overshoots" after recovery
  - Reduced charge-exchange losses with lower neutral density is a suspected cause
- Pressure gradient saturates following ELM recovery
- Density pushed lower reinforcing larger ∇T_i at fixed $q_{i,neo}$
  - Presume KBM is responsible for extra particle transport to maintain ∇P



Local parameters at $\psi_N \sim 0.9$

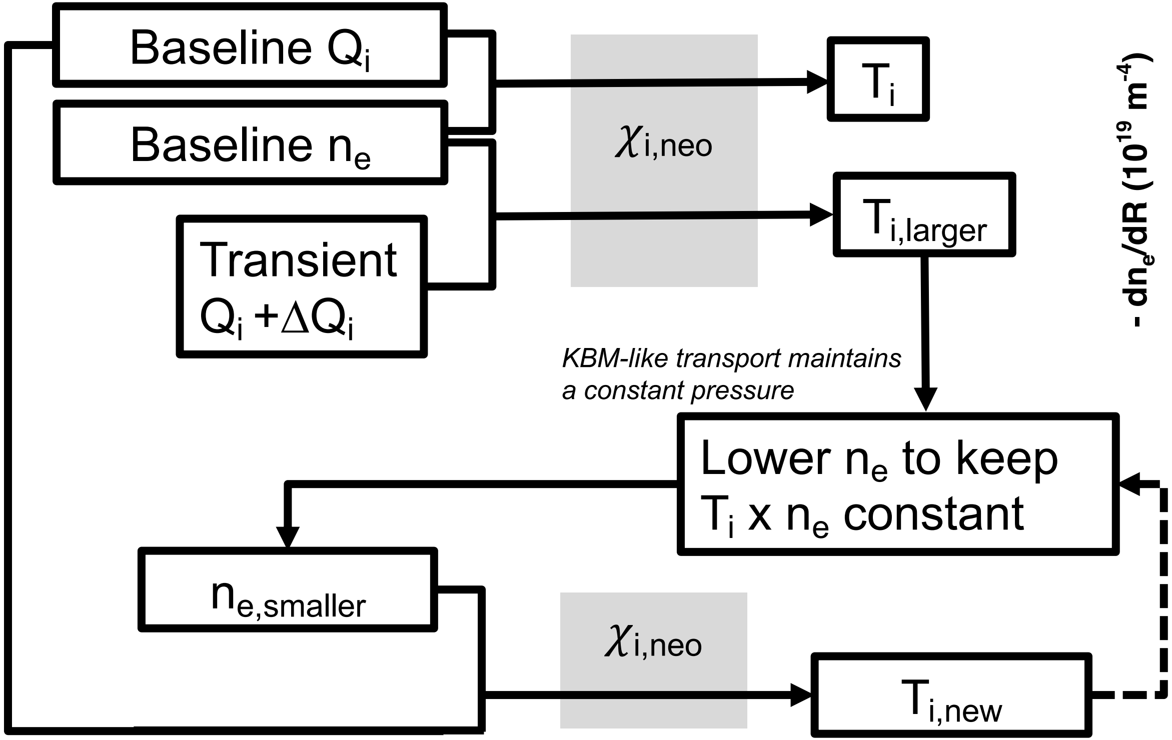
Simple model to examine EP H-mode transition: **ion neoclassical + KBM-like particle** transport

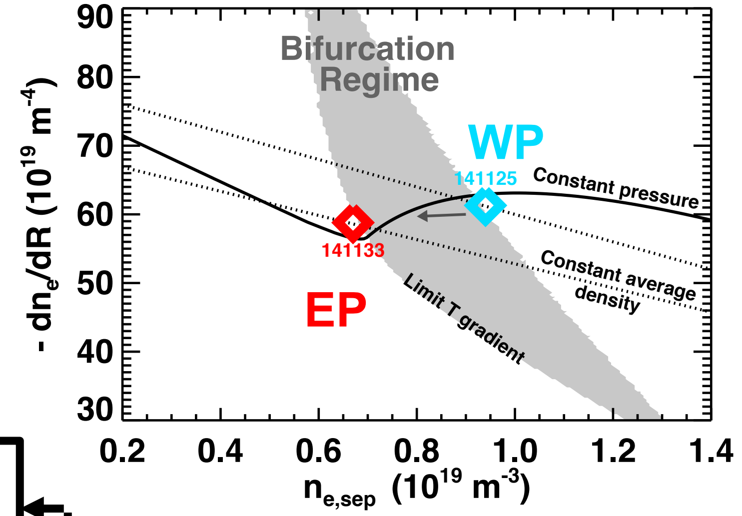


- KBM-like transport induces particle and energy transport
  - $\chi_{MHD} << \chi_{neo} \approx \chi_{Total}$
  - $D_{MHD} \sim D_{Total}$
- Result: KBM transport lowers n_e to keep pressure below instability onset

Battaglia D J, Guttenfelder W, et al., Phys. Plasmas ***27*** *(2020)*

Simple model to examine EP H-mode transition: **ion neoclassical + KBM-like particle** transport





If $T_{i,new} > T_{i,larger}$ then
ΔQ_i triggers a transition

Battaglia D J, Guttenfelder W, et al., Phys. Plasmas ***27*** *(2020)*

Summary of the proposed model of EP H-mode

- At sufficiently low ion collisionality, a positive feedback can be induced between KBM and ion neoclassical thermal transport

- ∇T_i overshoot during ELM recovery can facilitate access to lower collisionality
  - KBM onset induces transport to moderate pressure pedestal
    - Largest impact on the particle transport (density)
  - ∇T_i increases with small reduction in density to maintain constant $q_{i,neo}$

- Discharges evolve to a new pedestal solution
  - ELM-free: reduced collisionality may drive discharge away from ballooning instability
  - EP H-mode transport saturation mechanisms under investigation

Is the particle transport part of the story correct?

- Pretty confident in the ion thermal transport part of the picture

- Is the KBM responsible for changes in particle transport in the transition to EP H-mode? Is it some other instability?

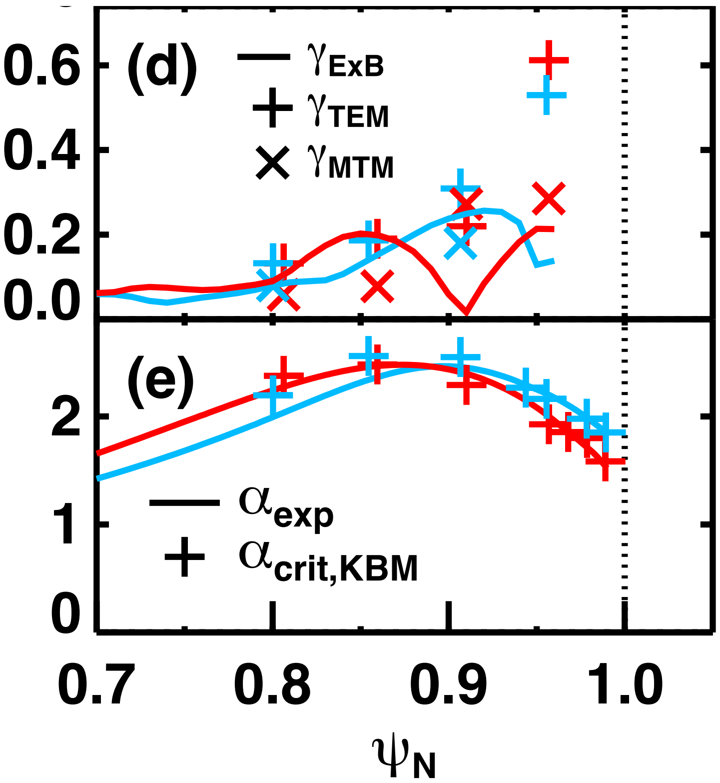
- Answer isn't conclusive yet …
  - Linear calculations indicate discharges reside near the KBM limit
  - ELM-free discharges may also approach kink-peeling stability boundary
  - BES and magnetic spectroscopy show features consistent with ion-scale TEM and MHD-like modes in edge
    - EP H-mode: Reduction in TEM-like modes, possible increase in MHD-like modes

CGYRO calculations predict MTM and TEM are linearly unstable near plasma edge

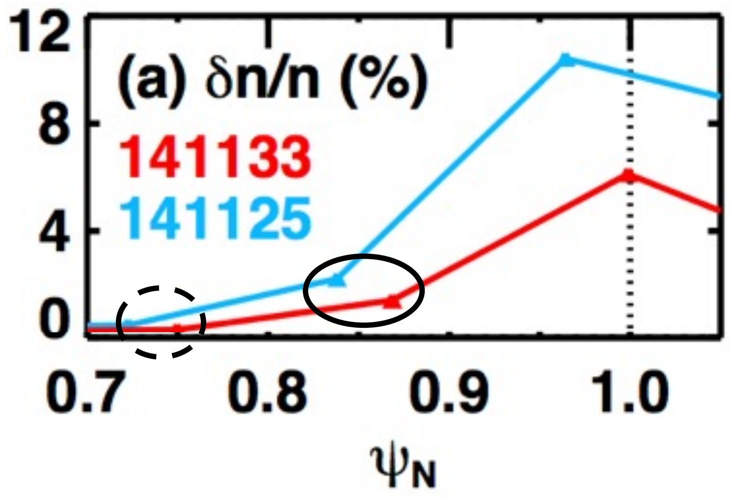
- TEM and MTM: $\gamma > \gamma_{ExB}$ for $\psi_N > 0.9$
  - Inward shift of E_r minimum in EP H-mode may widen unstable region
  - MTM typically subdominant to TEM, but less susceptible to E x B stabilization

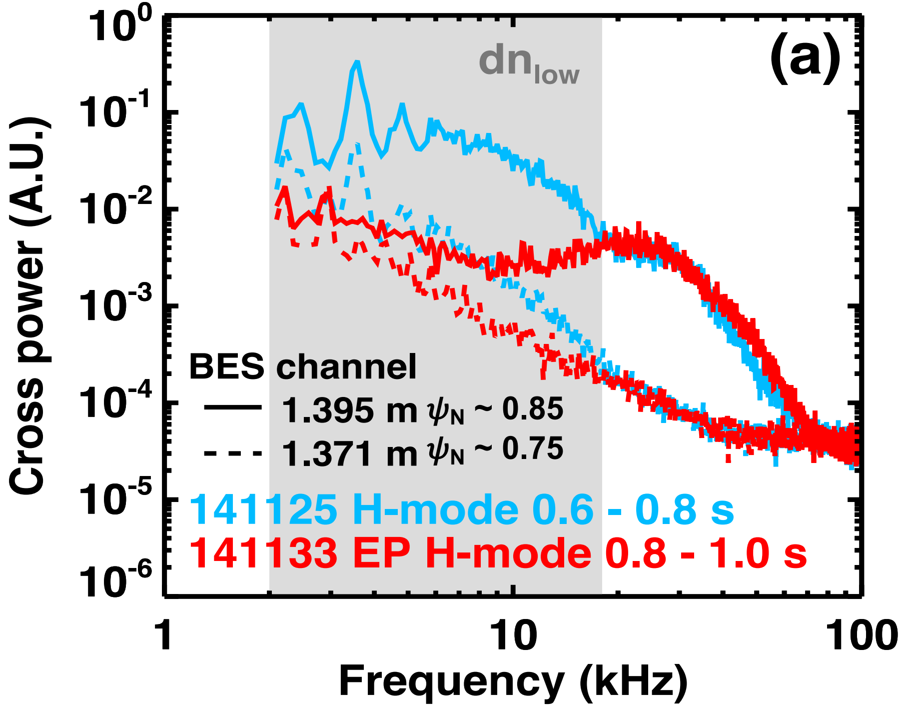
Possible instabilities at $\psi_N \sim 0.85$

	Frequency (lab frame)	Plasma frame
MTM	10 – 50 kHz (e-dia)	e-dia
TEM	5 – 40 kHz (i-dia)	e-dia
KBM (1.1xβ_e)	15 – 50 kHz (i-dia)	i-dia
Kink-peeling	n x 11 kHz (i-dia)	i-dia



BES measurements show broad mode spectrum localized to $\psi_N > 0.85$



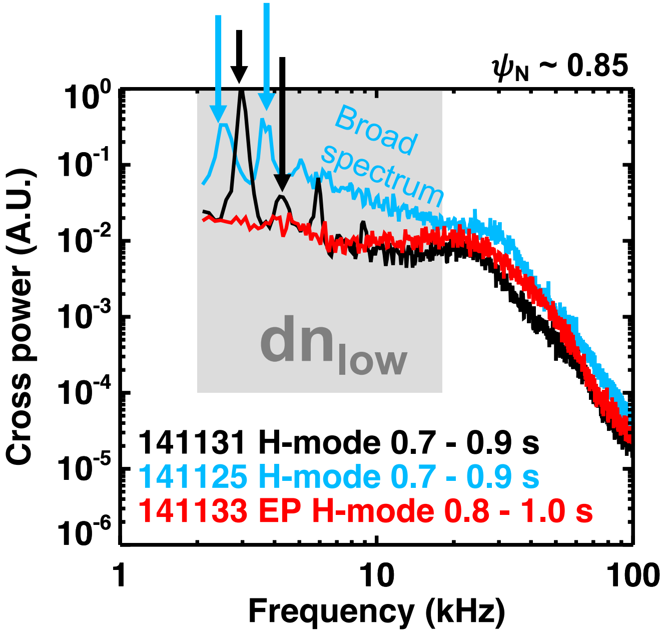


NSTX H-modes often observe low frequency edge-localized coherent modes

- Coherent modes observed below 10 kHz
  - Maximum amplitude at separatrix
  - Usually observed with harmonics, Δf ~ 2 kHz
    - Low-n (n = 1 - 6)
  - Detected in H-mode on magnetics, soft x-ray, divertor probes, reflectometer, BES …

Sontag et al. *NF* **51**, 103022 (2011) Park et al. *NF* **54**, 043013 (2014)
Gan et al. *NF* **57**, 126053 (2017) Zweben et al. PoP, 27 052505 (2020)

- Coherent modes can be replaced by a broader spectra < 18 kHz (ex: **141125**)
  - dn_{low}/dn_{tot} ratio consistent in H-mode examples



dn_{low}/dn_{tot} = 0.75

dn_{low}/dn_{tot} = 0.75

dn_{low}/dn_{tot} = 0.50

Low-frequency modes consistent with TEM + sub-dominant KBM

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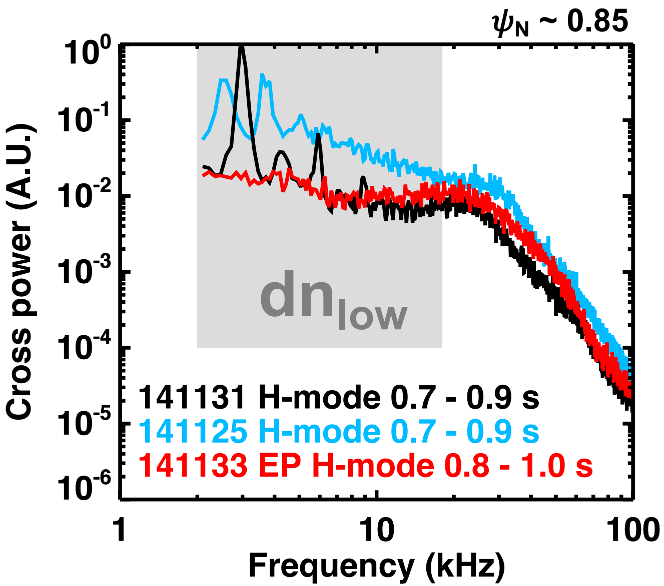
UNIVERSITY OF WISCONSIN–MADISON

- Modes below 18 kHz are TEM-like in H-mode cases
  - Ion-dia in lab frame, e-dia in plasma frame
  - Low-n exists at low kHz ($f_{TEM} \sim -n^*f_{Doppler}$) with positive E_r
  - Localized to $\psi_N > 0.85$

- Cross phase power < 18 kHz reduced in EP H-mode
  - Residual modes i-dia in plasma frame (KBM-like)
  - Similar to core BES channels (residual modes not edge localized)

	Frequency (lab frame)	Plasma frame
MTM	10 – 50 kHz (e-dia)	e-dia
TEM	**5 – 40 kHz (i-dia)**	**e-dia**
KBM ($1.1x\beta_e$)	15 – 50 kHz (i-dia)	i-dia



$dn_{low}/dn_{tot} = 0.75$

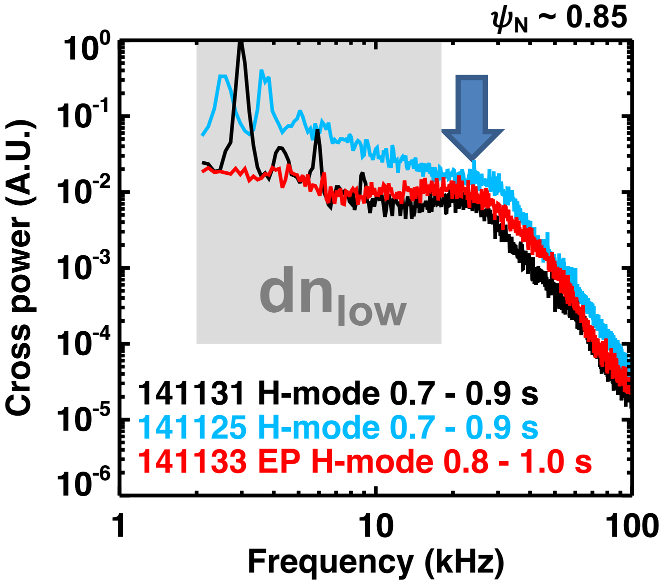
$dn_{low}/dn_{tot} = 0.75$

$dn_{low}/dn_{tot} = 0.50$

WP and EP H-mode have a peak in the BES cross-power spectrum near 25 kHz

- Peak extends from 10 – 70 kHz
  - Localized to $\psi_N > 0.85$
- Mixed modes suspected
  - Ion-dia propagation in laboratory frame
    - WP: e-dia directed in plasma frame (TEM or MTM)
    - EP: i-dia, but close to Doppler velocity (KBM or K-P)

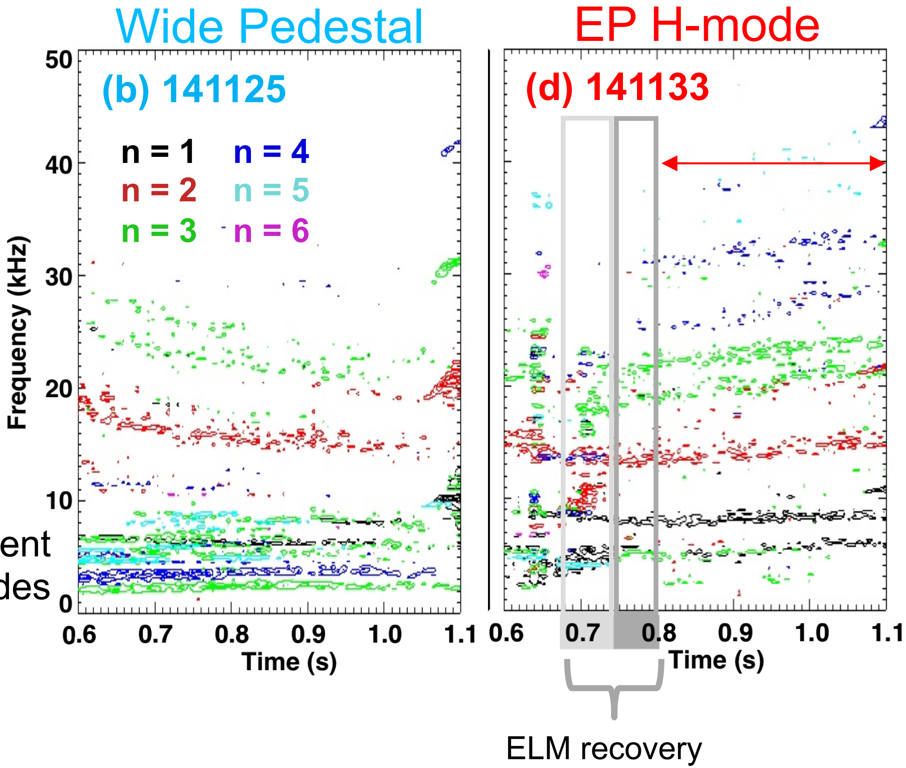
	Frequency (lab frame)	Plasma frame
MTM	10 – 50 kHz (e-dia)	e-dia
TEM	5 – 40 kHz (i-dia)	e-dia
KBM (1.1xβ_e)	15 – 50 kHz (i-dia)	i-dia
Kink-peeling	n x 11 kHz (i-dia)	i-dia



Magnetics detect harmonic modes consistent with kink-peeling

Faint harmonic modes

Coherent modes



Stronger harmonic modes

Faint coherent modes

- $\Delta f \sim 7$ kHz, counter I_p
  - Ion diamagnetic rotation in plasma and lab frame
  - Consistent with Kink-peeling (EHO-like)
  - M3D-c1: $\Delta f \sim 11$ kHz
- Faint harmonic modes do not correlate with BES
  - BES localized to outboard, slightly above midplane
- MTM is also considered
  - But no modes detected in e-dia direction

Summary

- NSTX produced ELM-free regimes by reducing the edge recycling
  - Pedestals became wider due to changes in the KBM stability
- In some cases, ELMs returned and could facilitate entry to EP H-mode
  - A large ELM led to a brief period of reduced ion collisionality
- EP H-mode transition: positive feedback between ion neoclassical transport and particle transport driven by pressure-driven modes (MHD-like)
  - Linear calculations + BES + magnetics show existence of MHD-like transport is plausible
- Open questions:
  - What is the role of the TEM-like low-frequency coherent modes? Is it significant that they are typically suppressed in EP H-mode? Is there a TEM-driven particle pinch?
  - Are WP and EP pedestals in a second-stability regime (no KBM)? What primarily drives the changes in KBM stability as the edge density is reduced?
  - What is the relative contribution of ETG, TEM, MTM, NEO and MHD-like instabilities to the transport channels? What sets the final EP H-mode state?

Generalization of H-mode transport in ELM-free regimes at strong shaping on NSTX

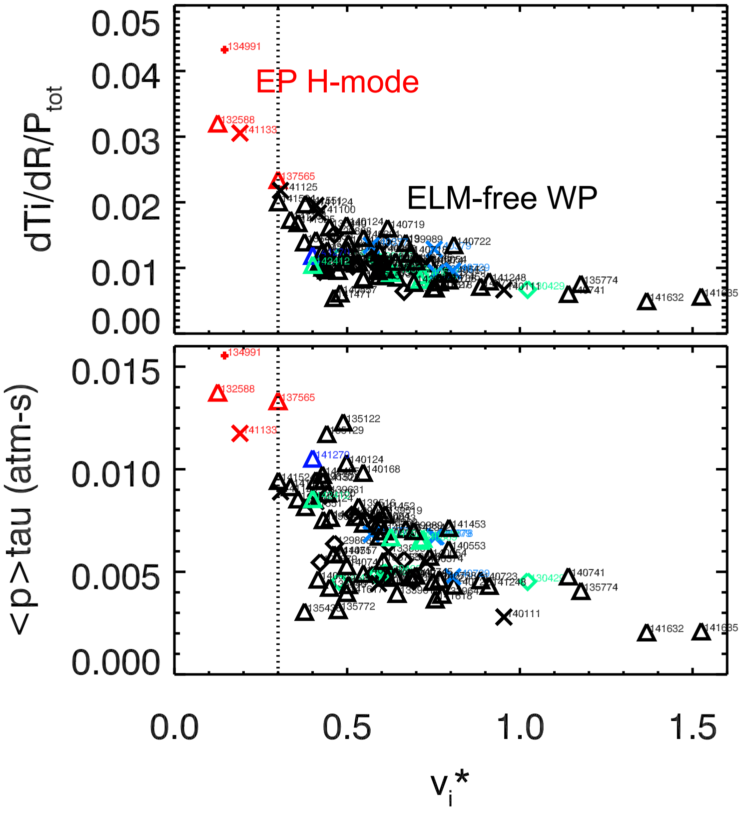
		Core $\psi_N \lesssim 0.6$	Pedestal $0.6 \lesssim \psi_N \lesssim 0.9$	Near separatrix
Thermal	Ion	NEO + KBM	NEO + TEM + KBM	NEO + ...
	Electron	MTM + Fast ion instabilities + KBM	MTM + TEM + KBM $(\chi_e/D_e \sim 3 - 5)$	ETG + KBM + TEM + … $(\chi_e/D_e \gtrsim 10)$
Particle		NEO + KBM	KBM + TEM + NEO + ...	

$T_i > T_e$

Focus of this talk

EP H-mode observed at the lowest ion collisionality in ELM-free discharges on NSTX

- Data suggest possible threshold at $\nu_i^* \sim 0.3$ in plasma edge for accessing EP H-mode
- EP H-mode discharges achieve largest edge ∇T_i normalized to total heating power
  - Generally, triple product improves with lower edge ion collisionality



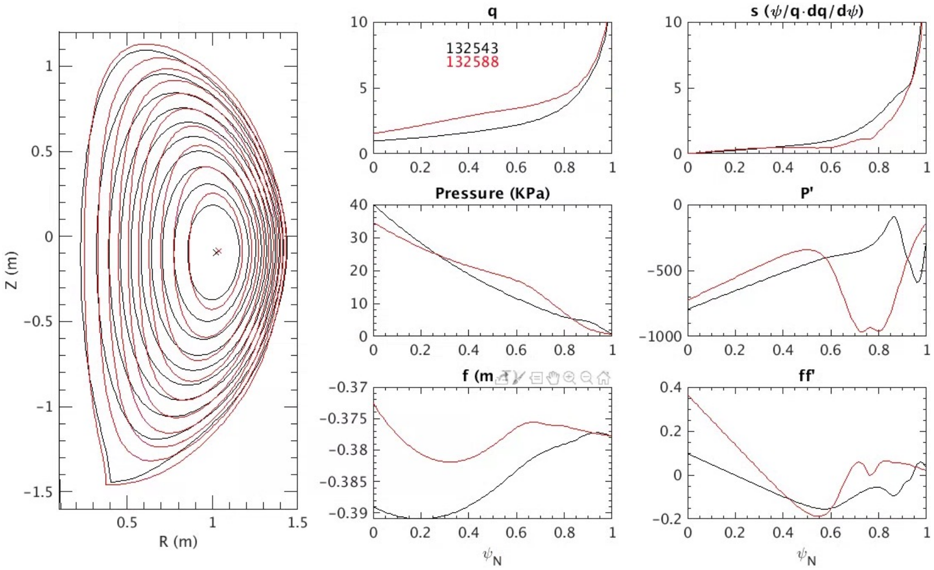
Generalization of H-mode transport on NSTX

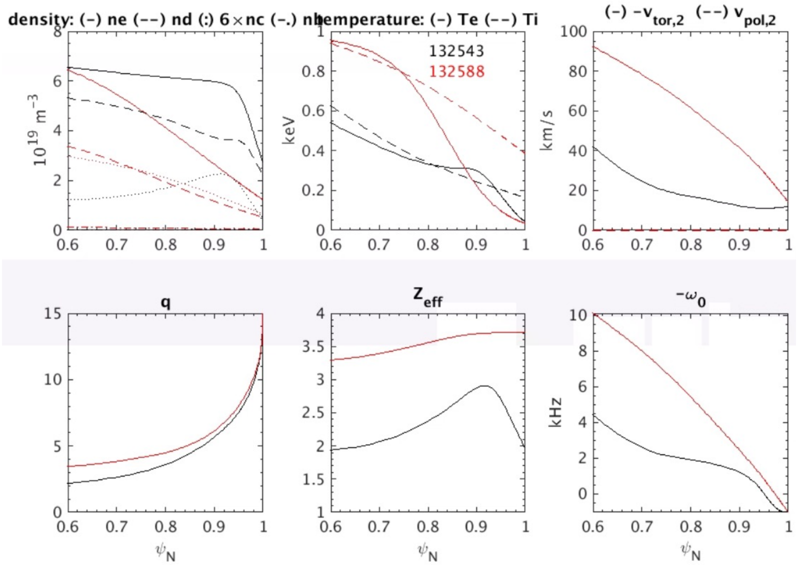
- KBM can induce transport across the profile
  - Main impact is to modify the particle transport, especially in the edge region
- Ion thermal transport is neoclassical
  - ITG often suppressed
  - Ions lose energy to electrons through collisions ($T_i \sim T_e$)
- Electron thermal transport is primarily due to …
  - MTM + energetic particle modes + KBM in core
  - ETG near separatrix
  - TEM/KBM + MTM in pedestal
- Particle transport is primarily due to …
  - Neoclassical in core
  - TEM + KBM + any edge-localized MHD in edge
- Impurity transport is primarily neoclassical
  - Strong impurity accumulation in ELM-free regimes

Comparison of narrow and wide pedestal

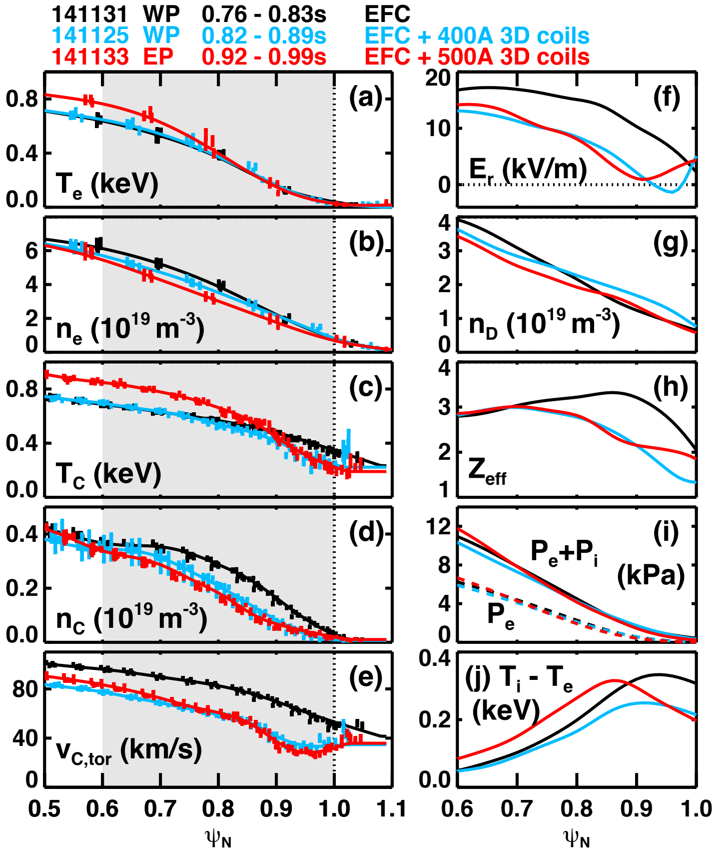
ELMy H-mode
No lithium
132543
6 MW NBI

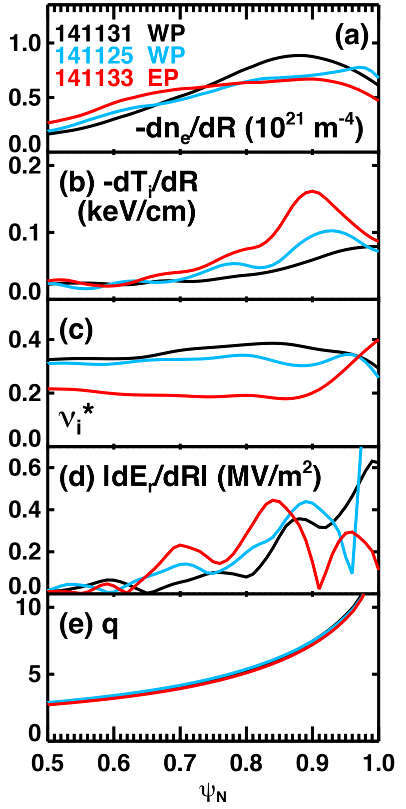
ELM-free H-mode
A lot of lithium
132588
4 MW NBI



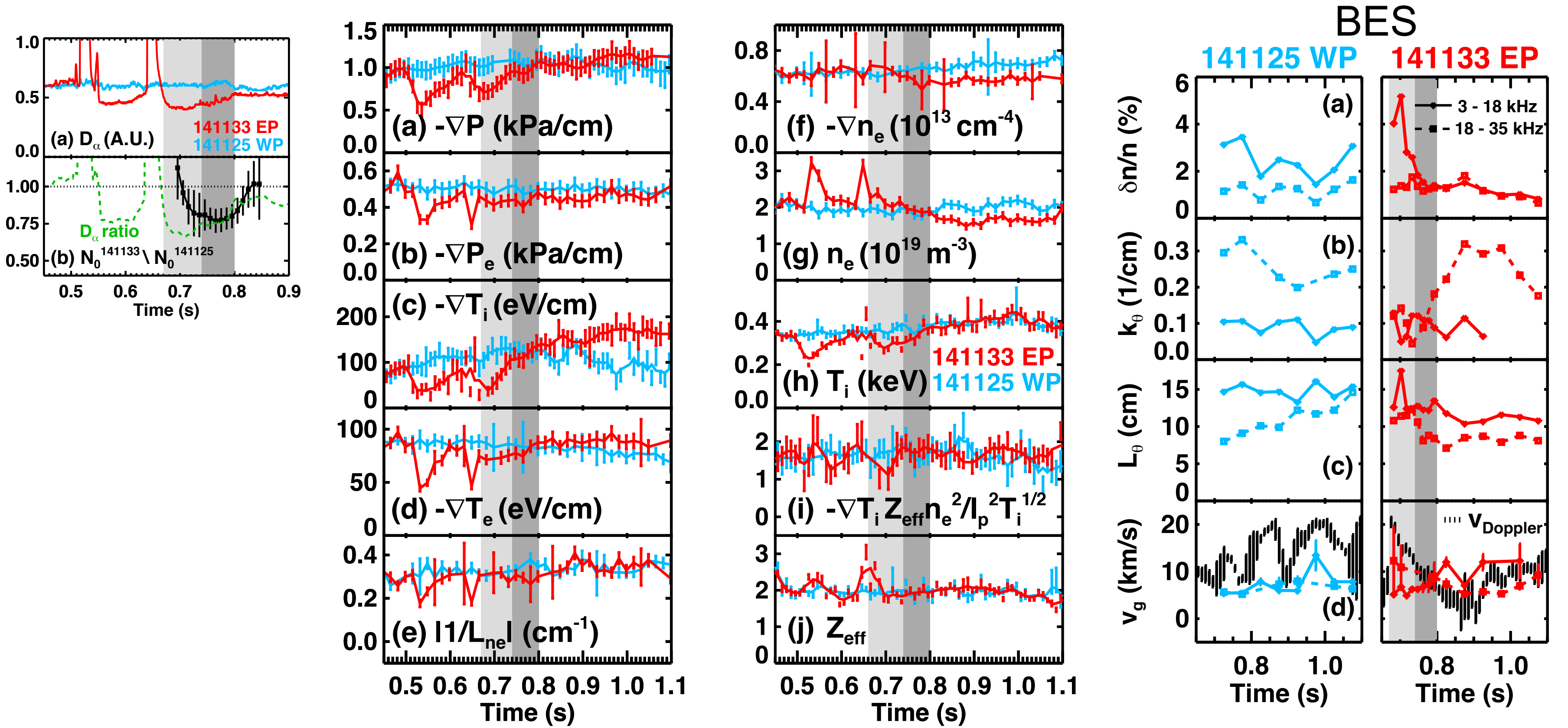


Profiles

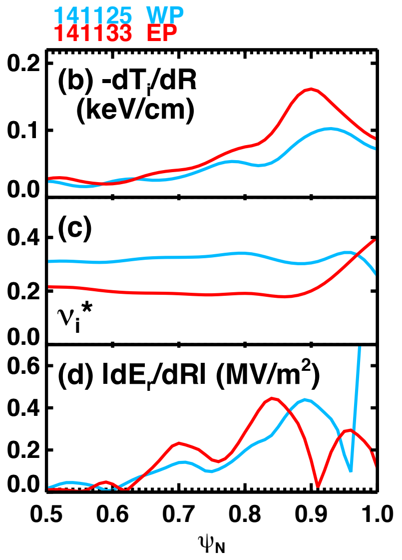

141131 WP 0.76 - 0.83s EFC
141125 WP 0.82 - 0.89s EFC + 400A 3D coils
141133 EP 0.92 - 0.99s EFC + 500A 3D coils
(a)
Te (keV)
(b)
ne (10^19 m^-3)
(c)
TC (keV)
(d)
nC (10^19 m^-3)
(e)
vC,tor (km/s)
(f)
Er (kV/m)
(g)
nD (10^19 m^-3)
(h)
Zeff
(i)
Pe+Pi
(kPa)
Pe
(j) Ti - Te
(keV)
ψN

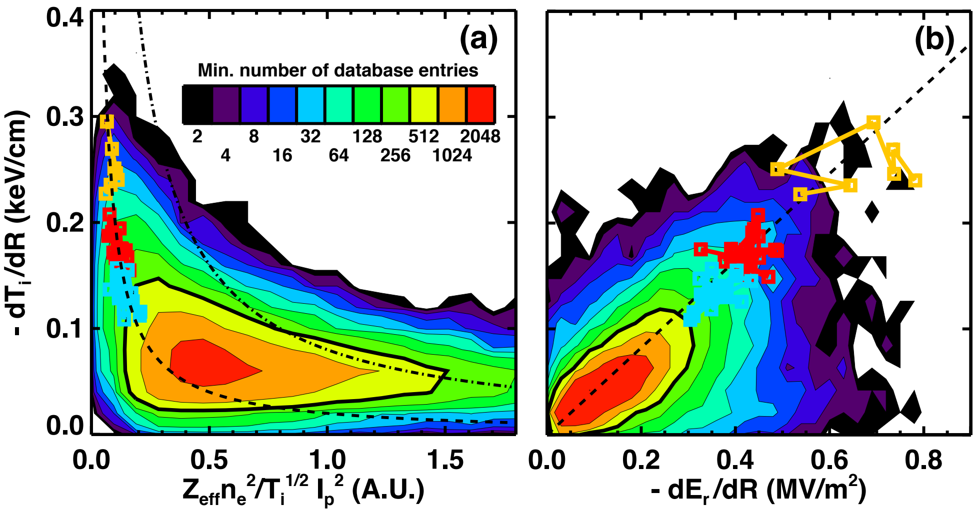

141131 WP
141125 WP
141133 EP
(a)
-dne/dR (10^21 m^-4)
(b) -dTi/dR
(keV/cm)
(c)
νi*
(d) |dEr/dR| (MV/m^2)
(e) q
ψN

Evolution of local parameters



Larger T_i gradient has corresponding larger maximum E_r gradient



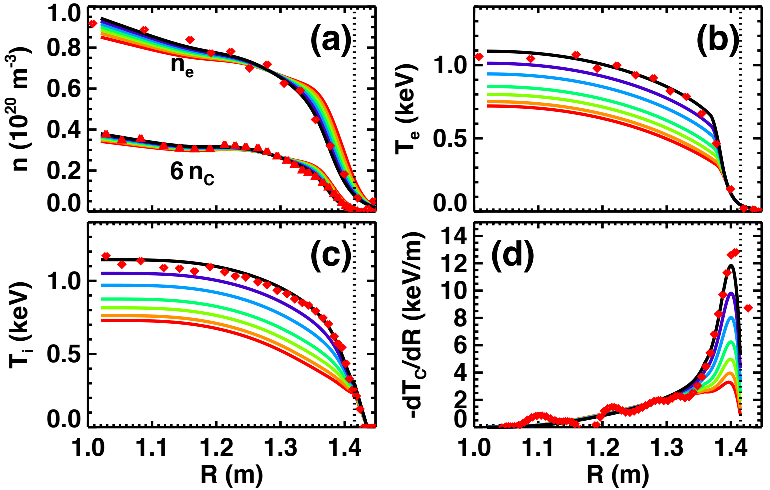


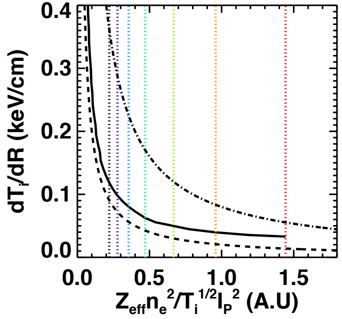
- Max T_i gradient sits near minimum of E_r well
- E_r gradient inside this location becomes steeper in EP H-mode
  - Shown later that ExB impacts TEM and MTM stability
  - Can drive improvement in electron energy confinement in core

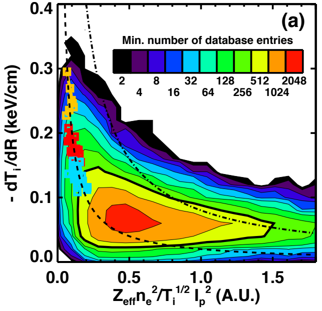
Simple model reproduces trend of database

- Develop simple 1-D model
  - Fixed heating density profile
  - Ion to electron energy exchange
  - Analytic neoclassical ion energy transport
  - T_i separatrix proportional to q_{isep}
  - Fixed T_e at sepatratrix
  - Stiff L_{Te} at edge until $T_e = 0.95\ T_i$
  - Fixed Z_{eff} profile

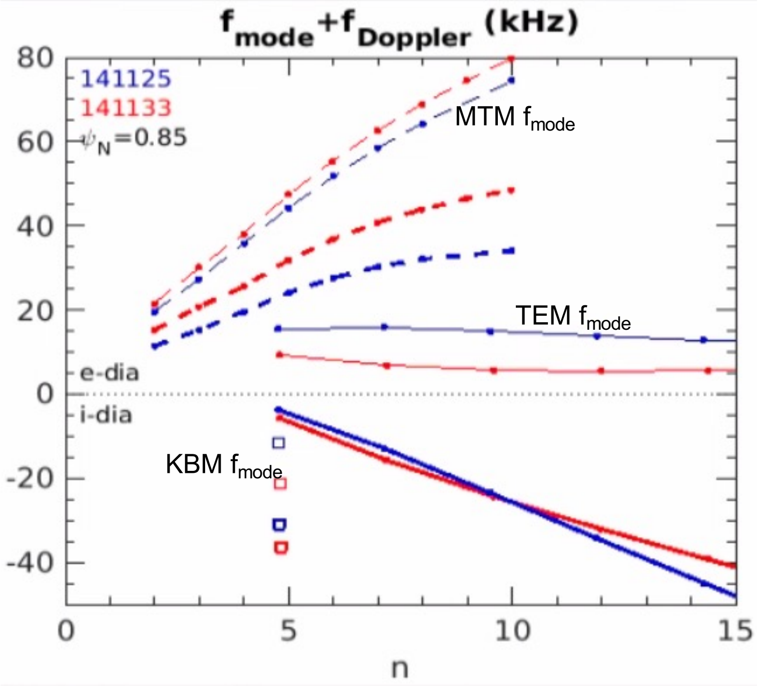
- Shape of n_e profile varied
  - Black is more peaked
  - Red points from EP H-mode shot

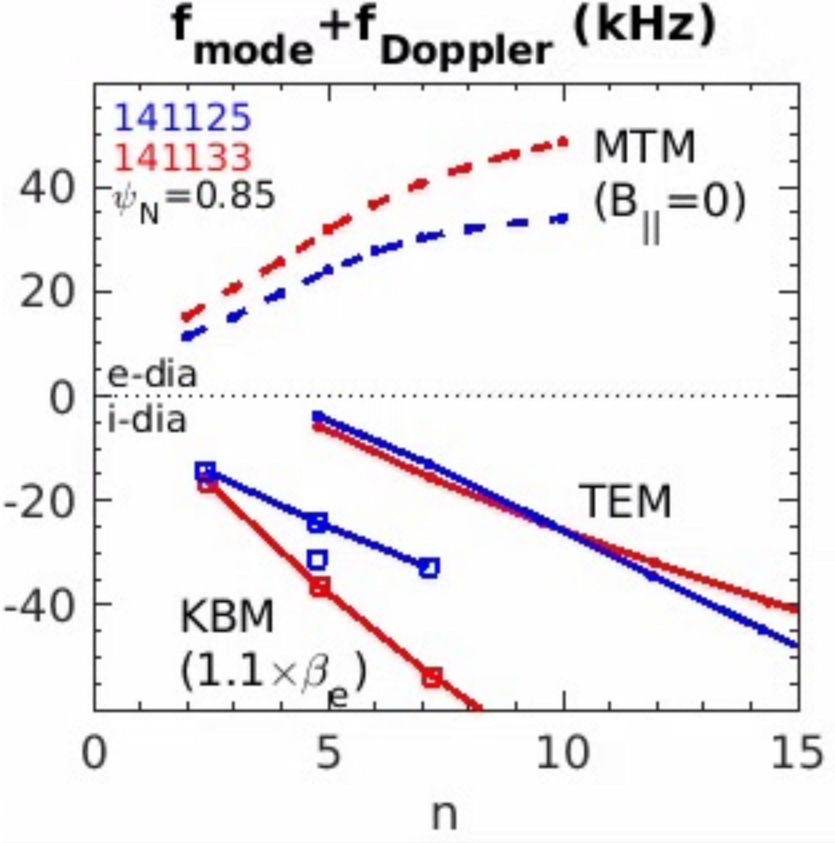




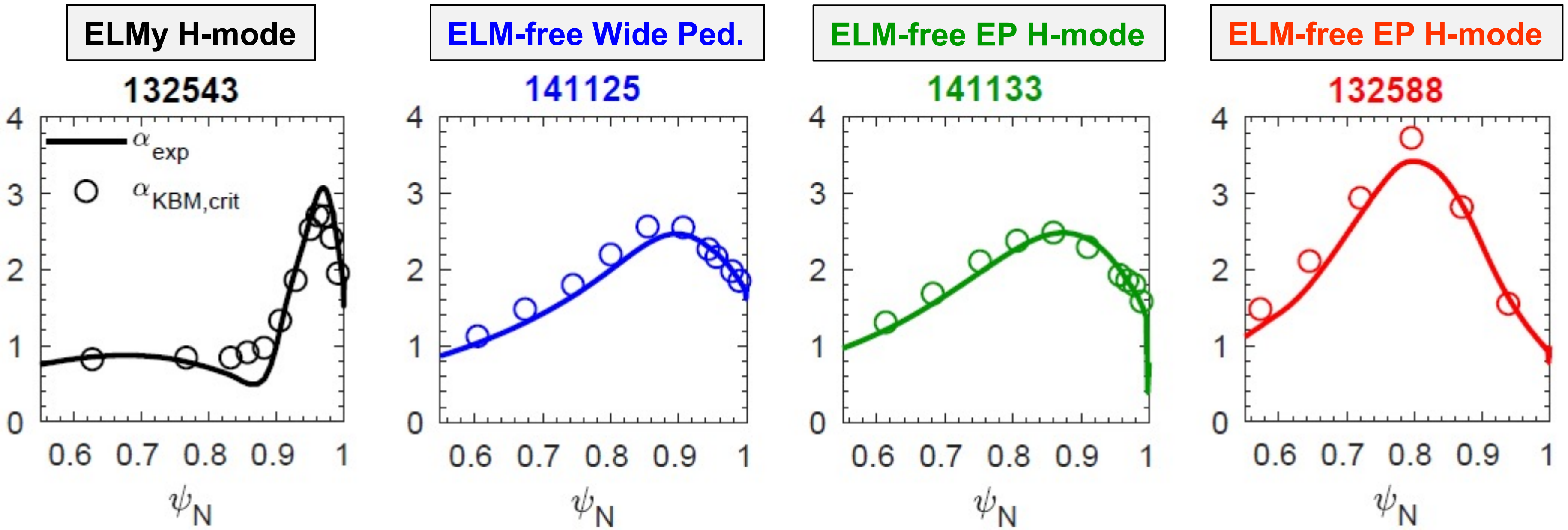


Lab frame frequencies





Recent work demonstrates NSTX pressure profile operates close to the KBM limit



Critical point: Pressure profiles can be at the KBM limit edge to core and be ELM-free