Theory of Transport Barriers II

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ICTP May 14, 2026

Outline

Talk 1: Introduction to gyrokinetic model

Talk 2: overview of activities using gyrokinetic

Foundations—ITG instability, saturation

A taste of various topics—no claim to exhaustive references, etc.

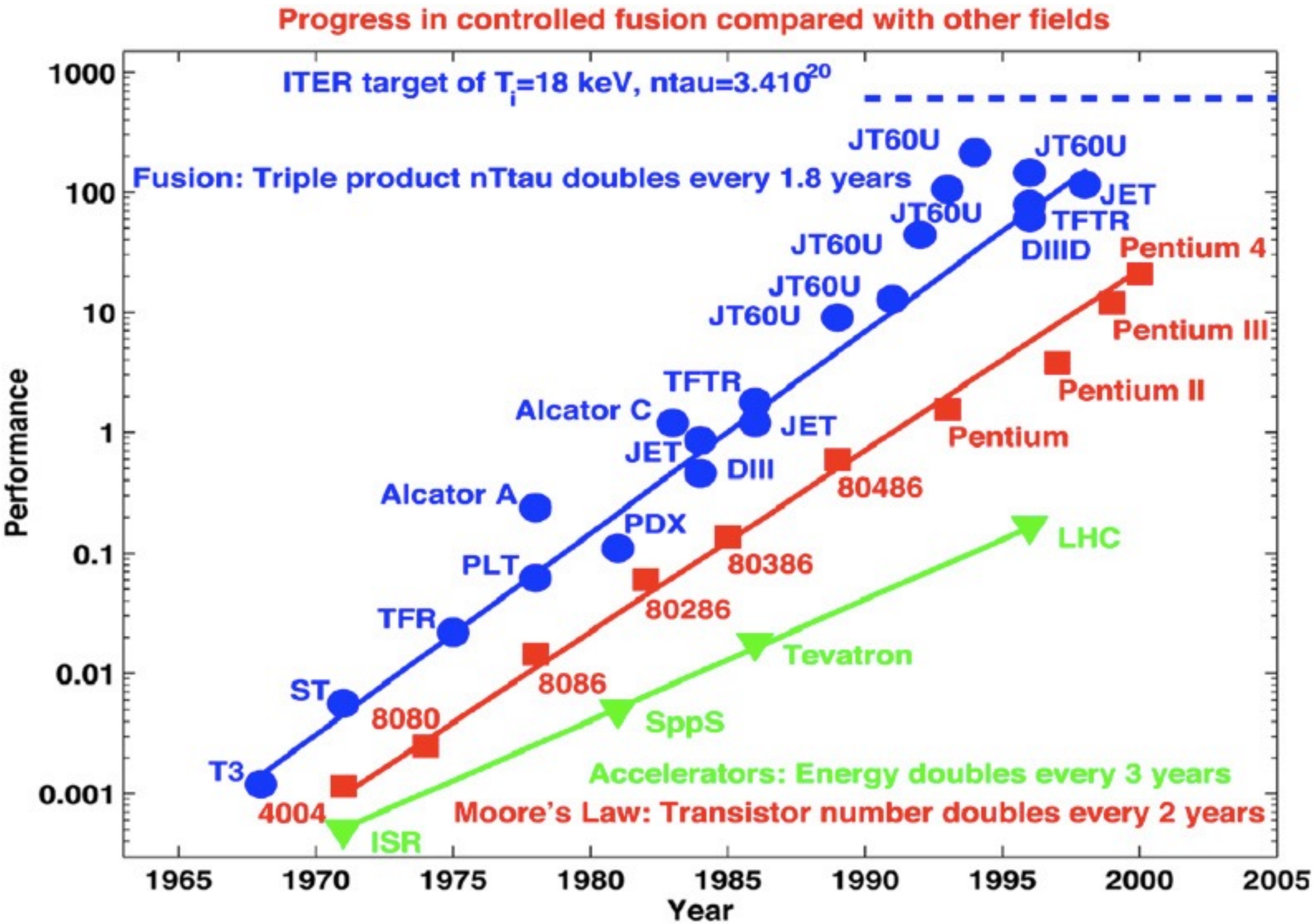
Material is mostly from the broader community (a little from our group)

Talk 3: Transport Barriers II

Foundations—pedestal, turbulence suppression

Building on excellent talks from Prof. Mahajan, Prof. Kim.

More focused on research from our group (UT-IFS). At the 'research frontier'.

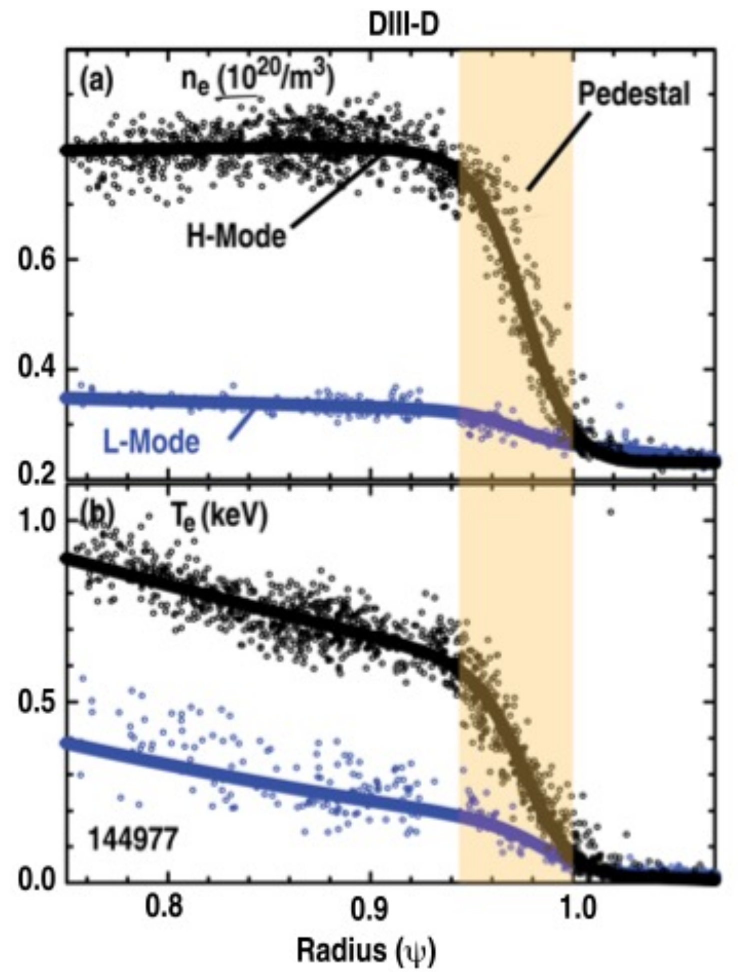

Progress in controlled fusion compared with other fields
ITER target of Ti=18 keV, ntau=3.410^20
Fusion: Triple product nTtau doubles every 1.8 years
Accelerators: Energy doubles every 3 years
Moore's Law: Transistor number doubles every 2 years
Performance
Year
1000
100
10
1
0.1
0.01
0.001
1965
1970
1975
1980
1985
1990
1995
2000
2005
T3
ST
TFR
PLT
Alcator A
PDX
Alcator C
JET
DIII
TFTR
JET
JT60U
JT60U
JT60U
JT60U
JT60U
JT60U
JT60U
JET
TFTR
DIIID
4004
8080
8086
80286
80386
80486
Pentium
Pentium II
Pentium III
Pentium 4
ISR
SppS
Tevatron
LHC

H-mode: Edge Transport Barrier

- H-mode: high confinement mode of operation
- Turbulence suppressed ➔ transport barrier

$$Q = -\chi \nabla (nT)$$

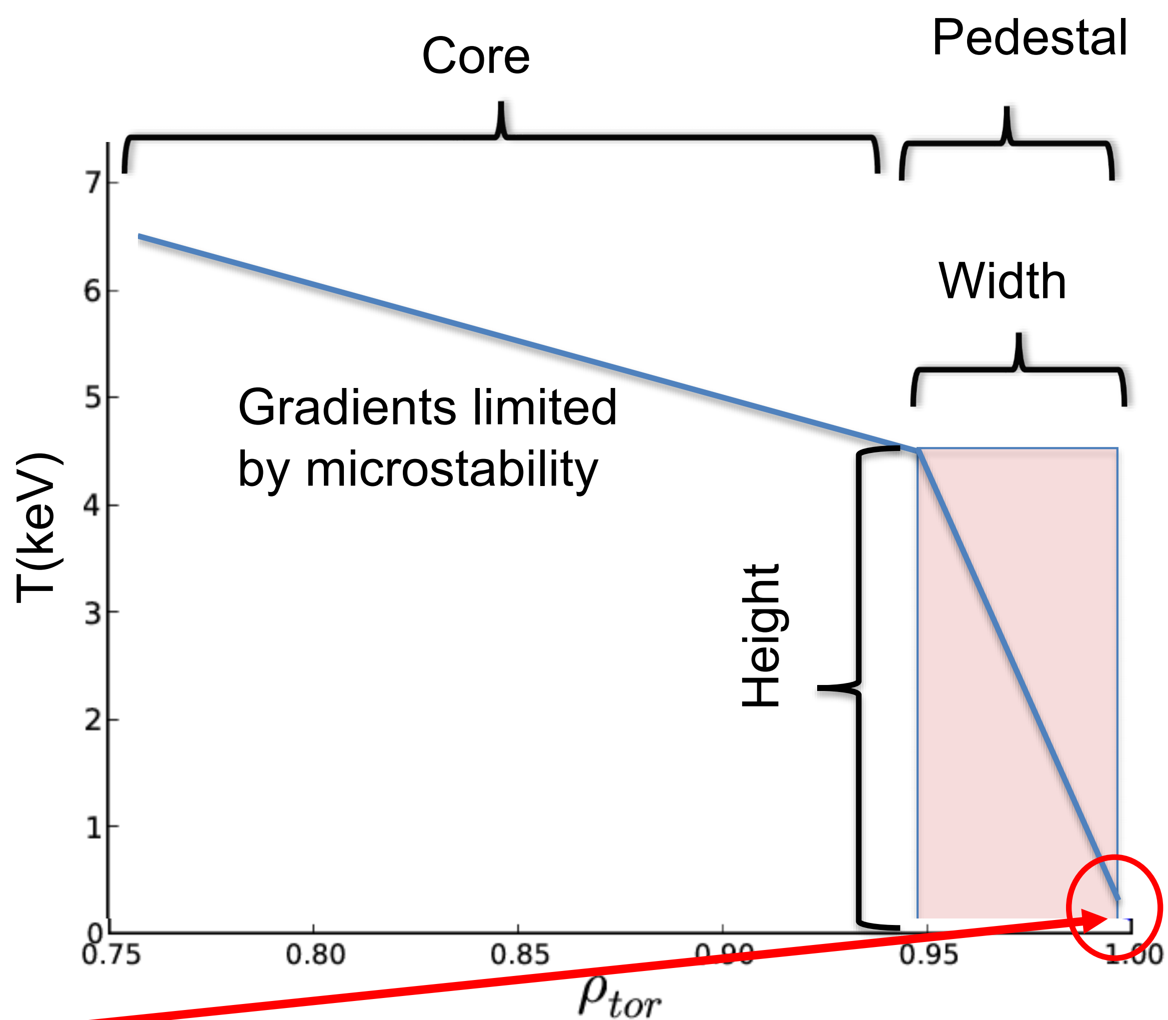
- Large increase in confinement time
- Big questions:
  - L-H transition remains one of the outstanding unsolved problems in fusion
  - 'Structure' of the pedestal—pedestal top pressure
  - ELM-free operation
  - Connection to SOL



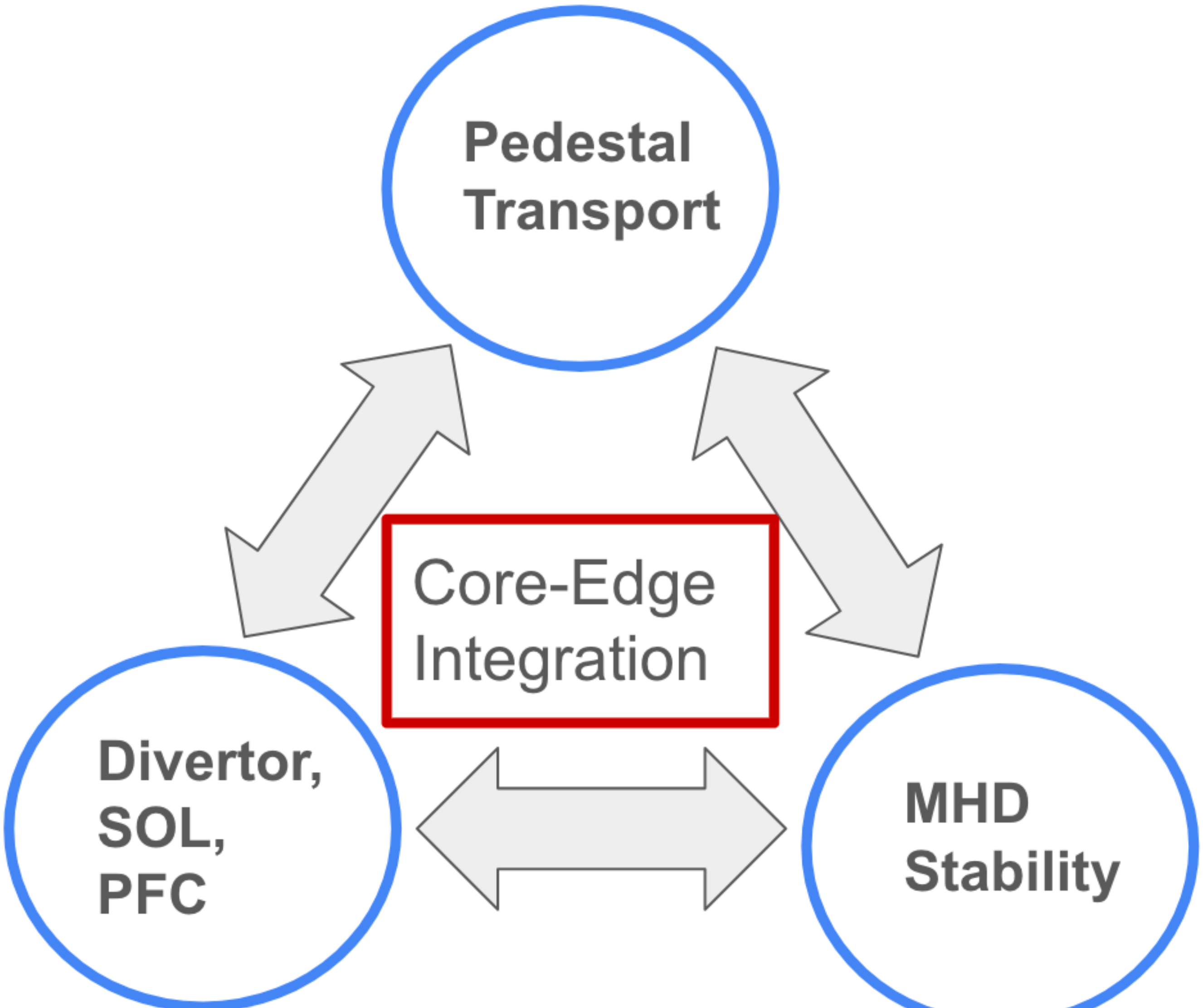
PHYSICS OF PLASMAS **21**, 090501 (2014)

H-mode Pedestal: Key to Fusion Performance

- Key question: how is the 'height' of the pedestal connected to the SOL?
- Last talk: sensitive connection between core confinement and pedestal—pedestal largely determines performance!
- Also: sensitive connection between pedestal and SOL!!



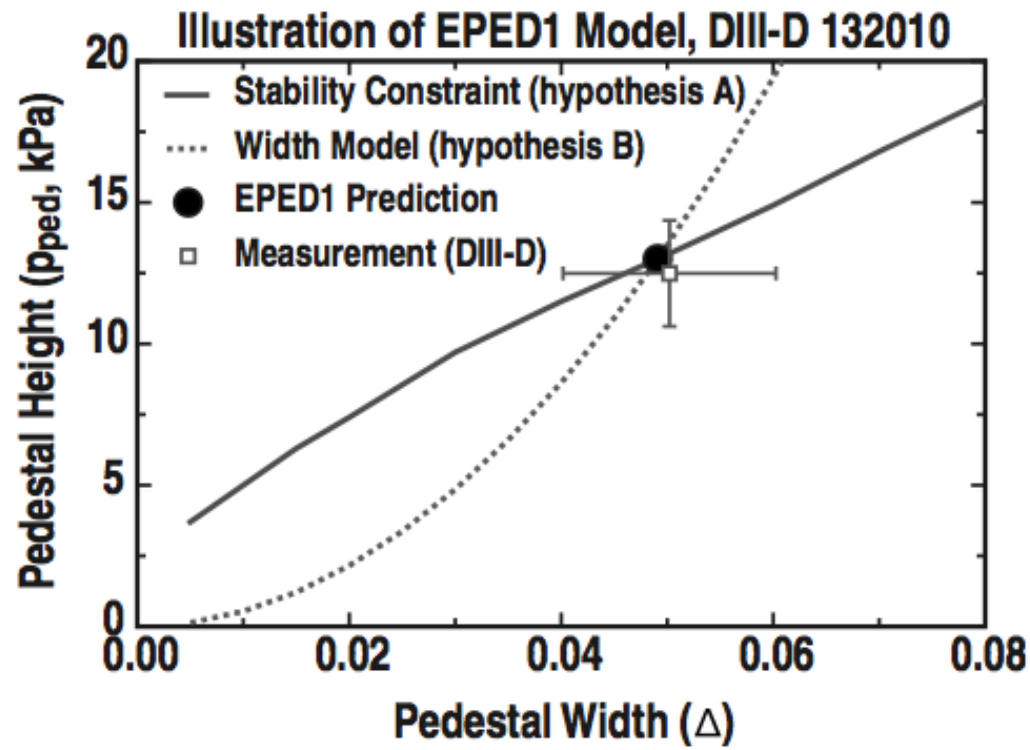
Core-Edge Integration



Current status of pedestal modeling: EPED

- EPED model
  - Turbulent transport suppressed by ExB shear
  - Pedestal properties determined solely by MHD stability limits

- Complete picture needs to understand and predict **turbulence and transport** (not just MHD stability)



Snyder '09

Neoclassical Flows

- Radial force balance in pedestal

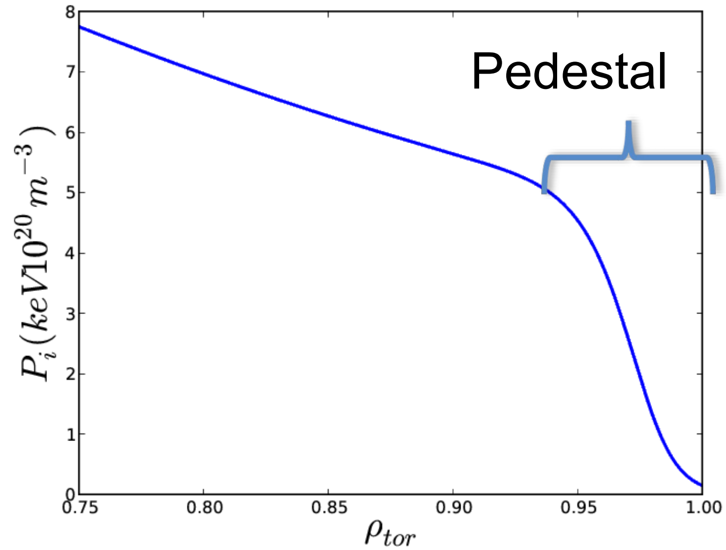
$$E_r \approx \frac{\nabla P_i}{n_i q_i}$$

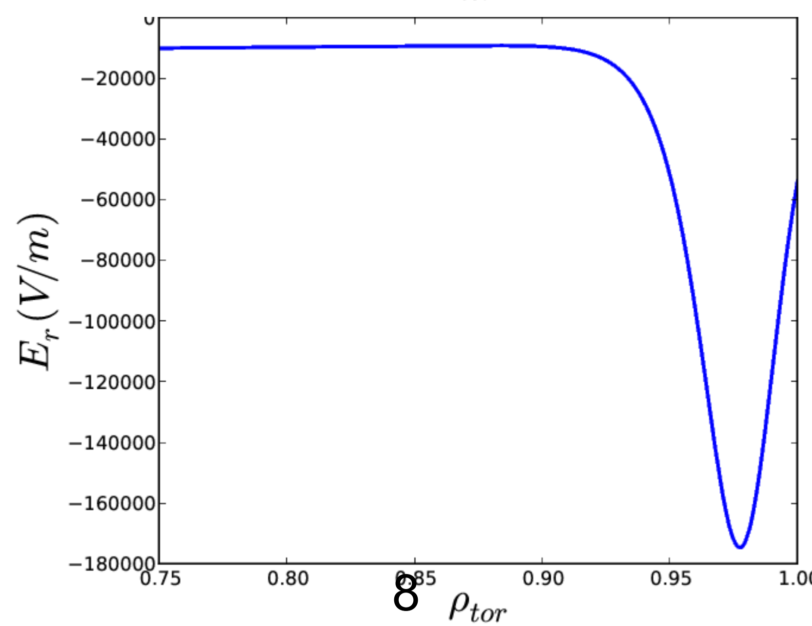
- Produces large ExB flow

$$v_{E\times B} = \frac{E \times B}{B^2}$$

- Flow is strongly sheared due to sharp pressure gradient
  - Shear rate:

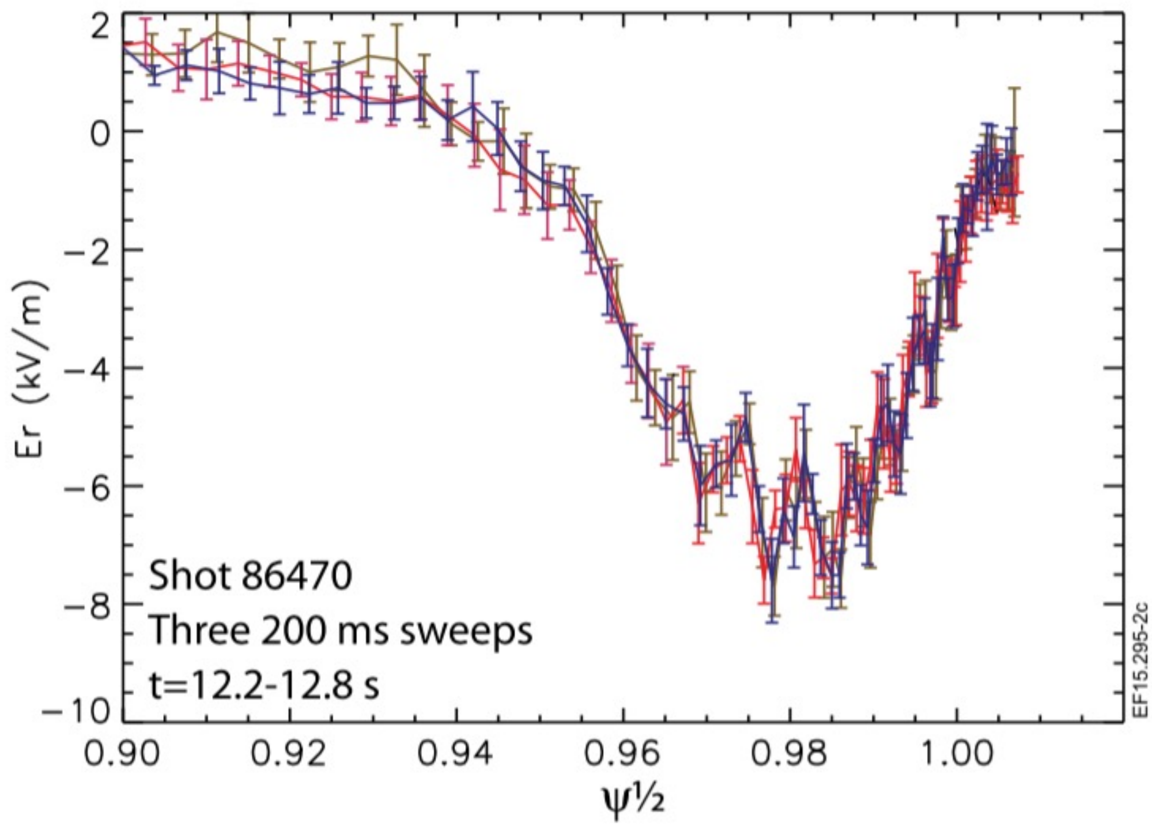
$$\gamma_{E\times B} \approx \frac{dv_{E\times B}}{dr}$$





Both Neoclassical and Zonal Flows Observed on JET

- Neoclassical: large Er ‘well’
- Zonal Flow: smaller scale corrugations



Hillesheim et al PRL 2016

How Does Shear Suppression Extrapolate?

- Neoclassical flow dominates in fully formed pedestal
- Simple and robust scaling arguments ➔shear suppression parameter scales like $\rho^*=\rho/a$

$$\gamma \sim v_{th} / a$$

$$E_r \sim \frac{\nabla P_i}{n_i q_i}$$

$$\gamma_{ExB} \sim \frac{dE_r / B}{dr} \sim \frac{E_r / B}{L}$$

$$\Rightarrow \quad \frac{\gamma_{ExB}}{\gamma} \sim \rho_* = \rho / a$$

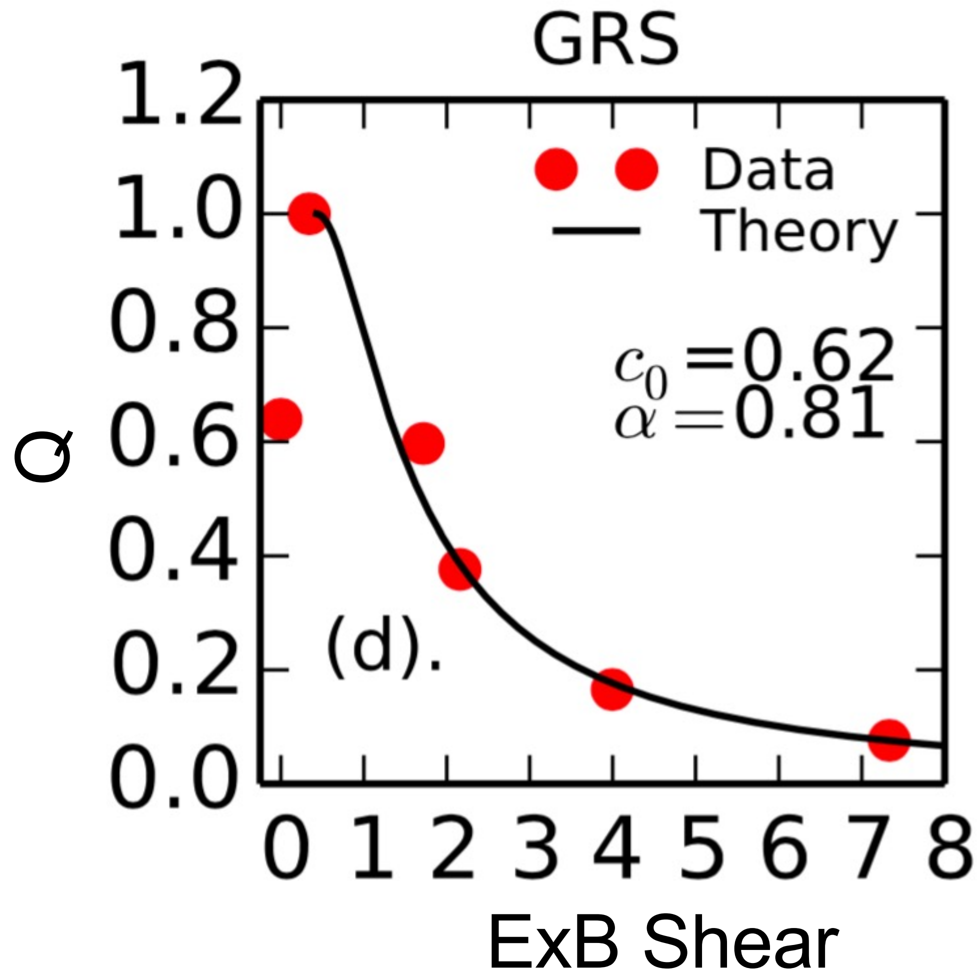
- ITER ρ^* inaccessible on present-day experiments
- Important question: how does shear suppression scale?

Comparison: Global ρ* Scan

- Global simulation (includes profile variation)
- ρ* scan (fixing other dimensionless parameters)
- Need to generalize to fully capture r* effects

$$\frac{\langle \tilde{T}^2/T_0^2\rangle}{\tau_c} = \gamma_{lin}(\rho_*)(v_{Ti}/a)\frac{D}{L^2}$$

- E_r set self-consistently by neoclassical



Hatch, Hazeltine, Mahajan, Kotsch
PPCF 2018
Testing model from:
Zhang Mahajan 92,93

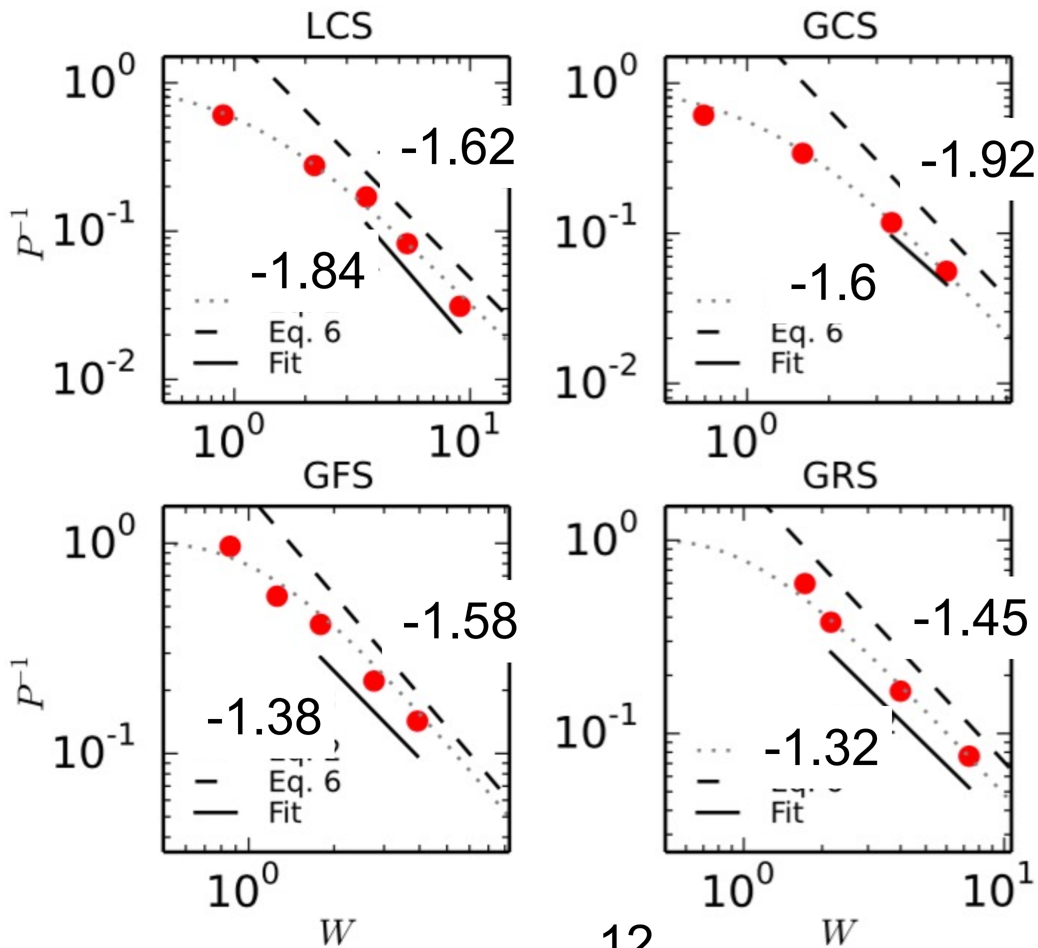
Agreement Also in Asymptotic Limit

Hatch, Hazeltine, Mahajan, Kotsch
PPCF 2018

- Strong shear limit:

$$P^{-1} = (2/3)^{1/(2\alpha-3)} W^{2/(2\alpha-3)}$$

- Scaling strongly dependent on α
  - Strong check on internal consistency: empirical values of α consistent with asymptotic scaling



Implications for Pedestal Transport

Hatch, Hazeltine, Mahajan, Kotsch
PPCF 2018

- Rough translation:

$$Q/Q_{GB} \propto \rho_*^{-2}$$

- ITG pedestal transport is 2 factors of ρ* less favorable than gyroBohm, 1 factor worse than Bohm (i.e. no scaling with gyroradius)

- Needs to be understood and predicted for ITER + SPARC

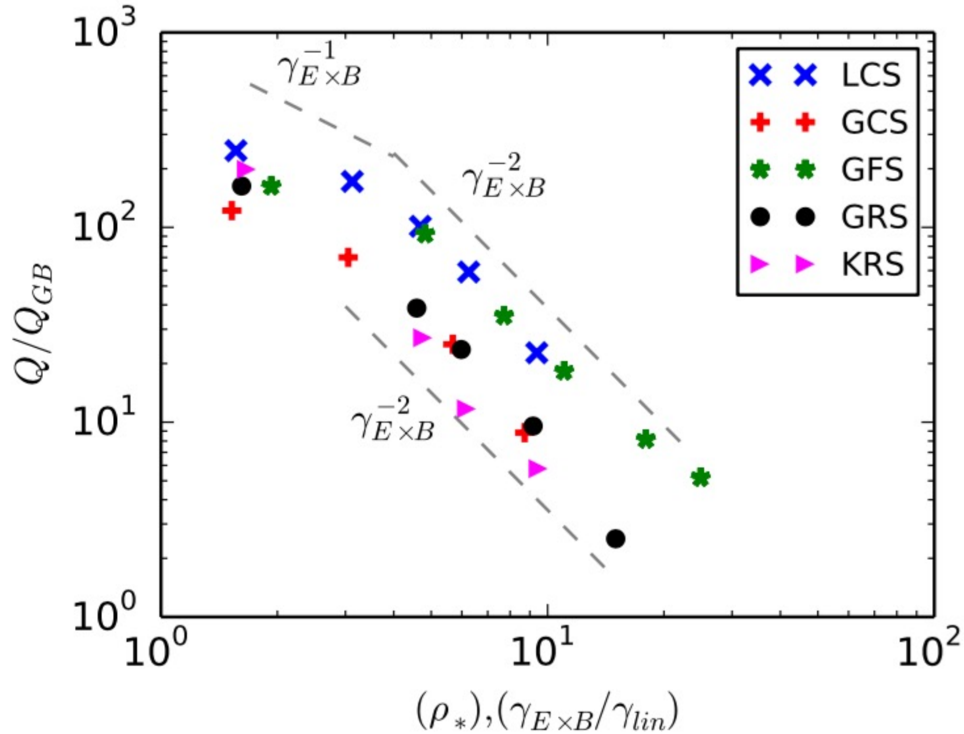


FIG. 4: Plots of gyroBohm normalized heat flux. The LCS, GCS, and GFS cases are plotted against $E \times B$ shear, while the GRS and KRS cases are plotted against ρ_*. The KRS case corresponds the electromagnetic simulations with kinetic electrons described in Ref. [19]

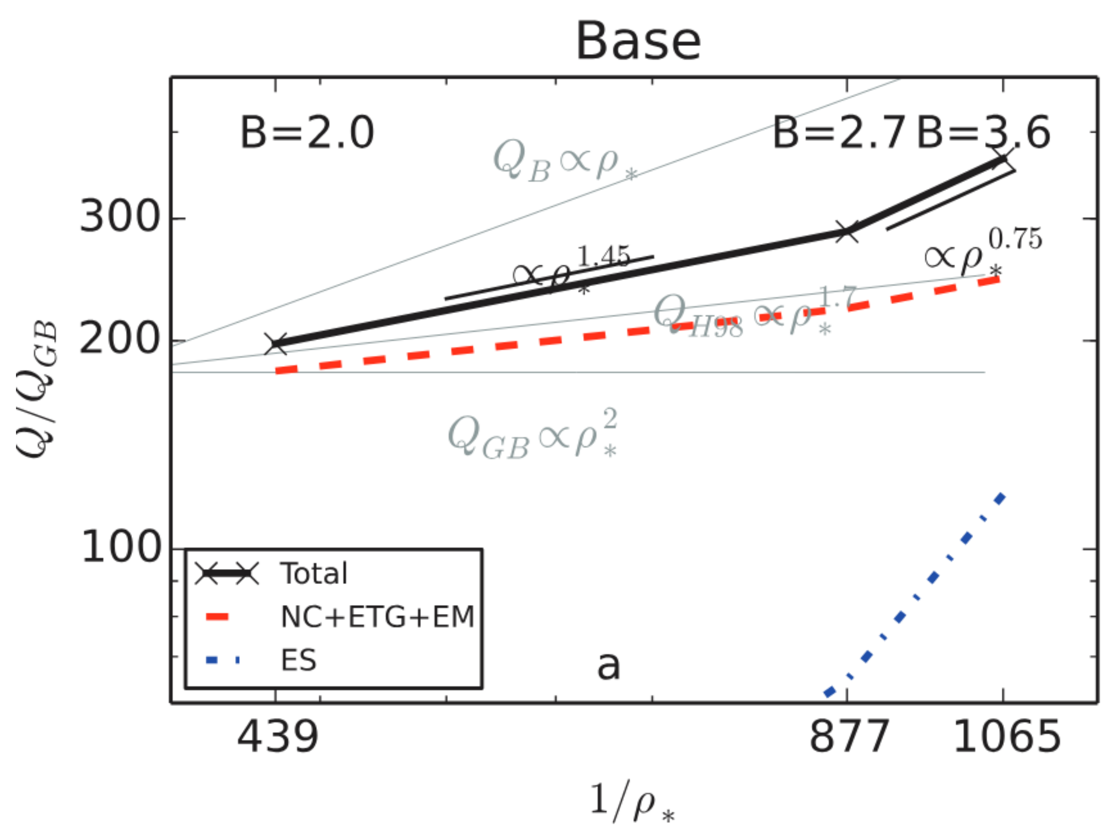
JET-ILW as a Test-Bed for ITER

Gyrokinetic simulations of dimensionless ρ* scan based on JET-ILW scenario.

Transition from gyroBohm-like to Bohm-like: less favorable

Cf Verdoolaege NF 2021: "Notable differences with IPB98(y, 2) are the weaker scaling with normalized gyroradius (Bohm-type scaling)"

Hatch et al. NF 2017



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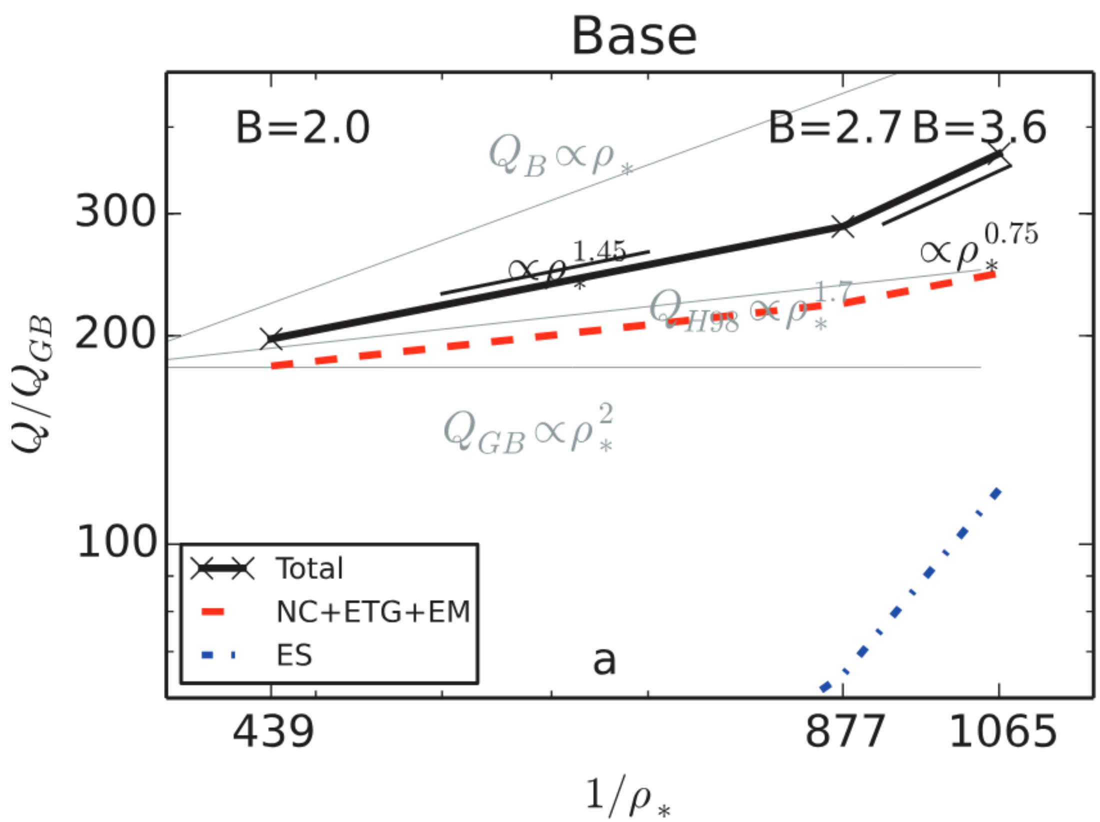
Conclusion: Performance for next-step devices (ITER, SPARC) depends on interplay between shear suppression (ρ*) as well as SOL boundary.

Hatch et al. NF 2017



Transport Barriers that Don’t Rely on ExB Shear?

Two Gyrokinetic Constraints

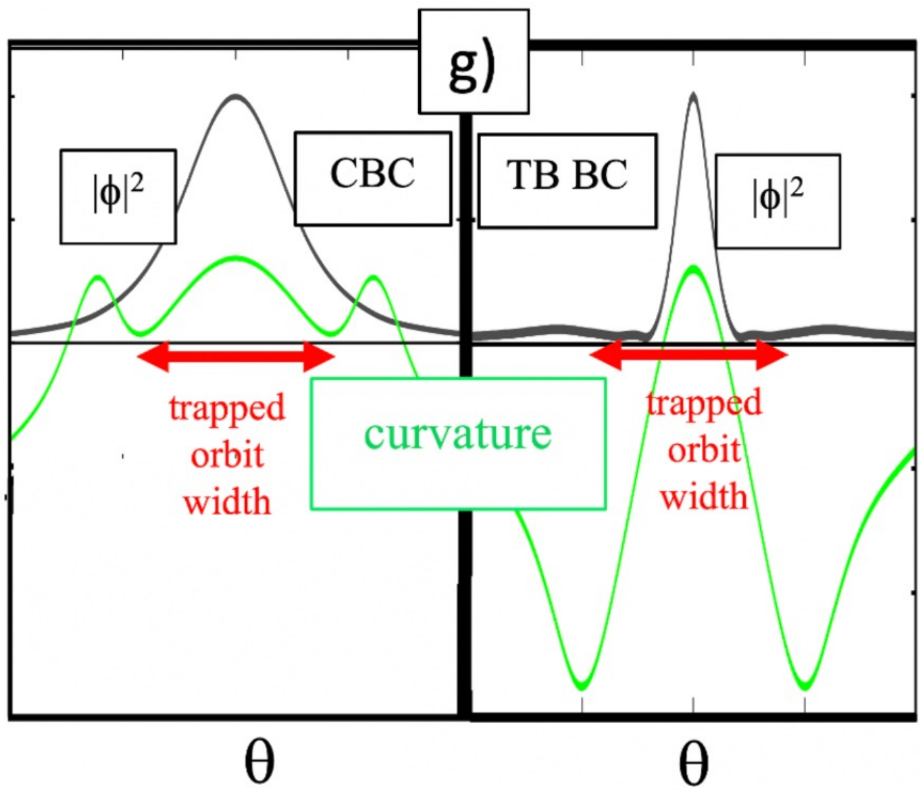
(1)
$$\frac{\partial}{\partial t}\sum_s\left[\frac{T_s}{2}\int d\boldsymbol{x}d\boldsymbol{v}\frac{\delta f_s^2}{F_M}+\frac{\boldsymbol{m}_s\boldsymbol{n}_s\delta V_{E\times B}^2}{2}+\frac{\delta E^2}{8\pi}\right]=$$
$$\sum_s\left[\boldsymbol{n}_s(\boldsymbol{Q}_s\frac{1}{T_s}\frac{dT_s}{dx}+\Gamma_s\frac{T_s}{n_s}\frac{dn_s}{dx})\right]-\sum_s\int d\boldsymbol{x}d\boldsymbol{v}\frac{\delta f_s}{F_M}\boldsymbol{C}(\delta f_s)$$

$$Re(i\omega D(\omega))=0$$

(2)
$$\sum_s q_s\Gamma_{rs}=0,$$

$$Im(D(\omega))=0$$

Two Ingredients for a Transport Barrier without ExB Shear:
(1) The right magnetic geometry
(2) Density gradients



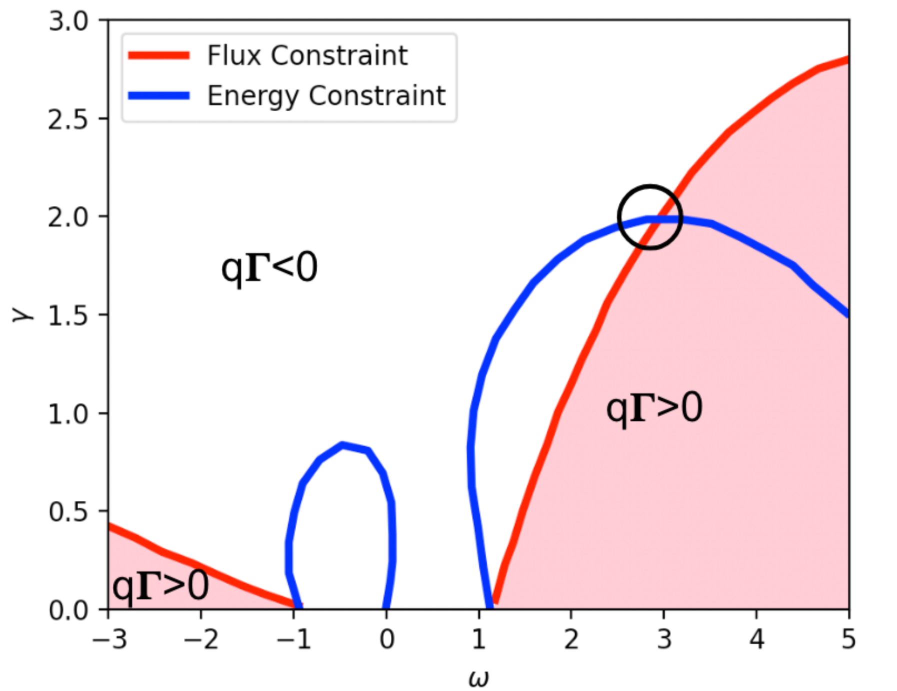
Low magnetic shear
High Shafranov shift (alpha)

Weak density gradient

Transport Barrier Geometry (low shear, high alpha):

Small trapped electron contribution

Weak density gradient ⇒ large growth rates

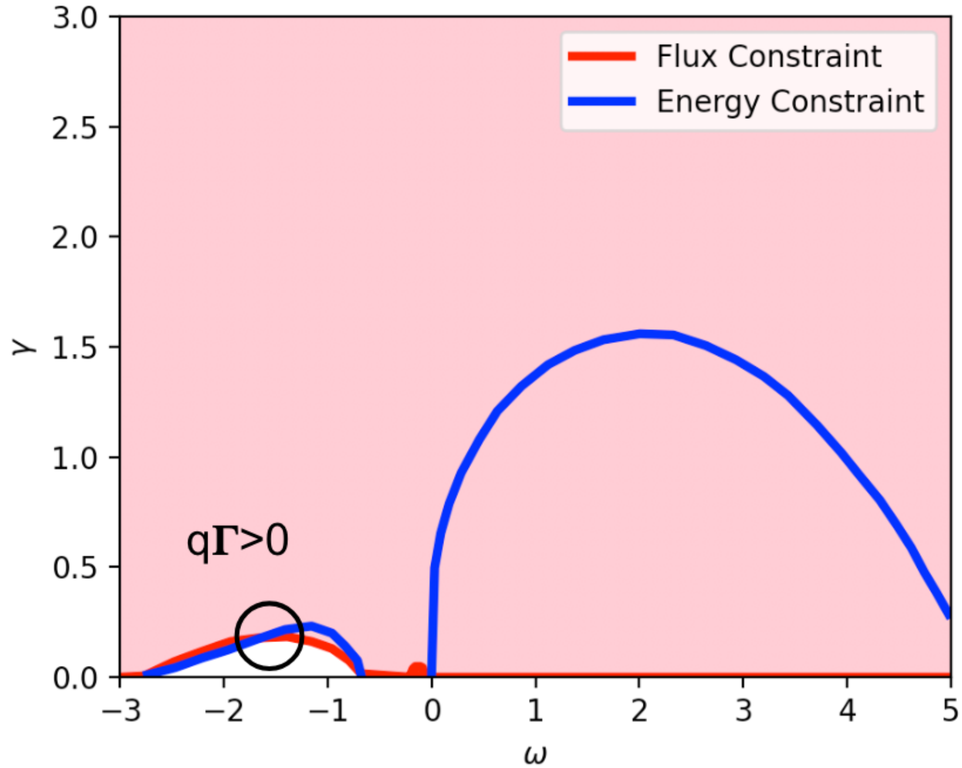


Strong density gradient

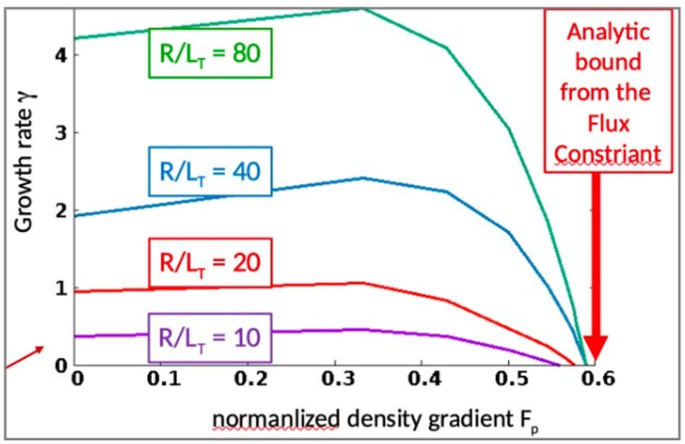
Transport Barrier Geometry (low shear, high alpha):

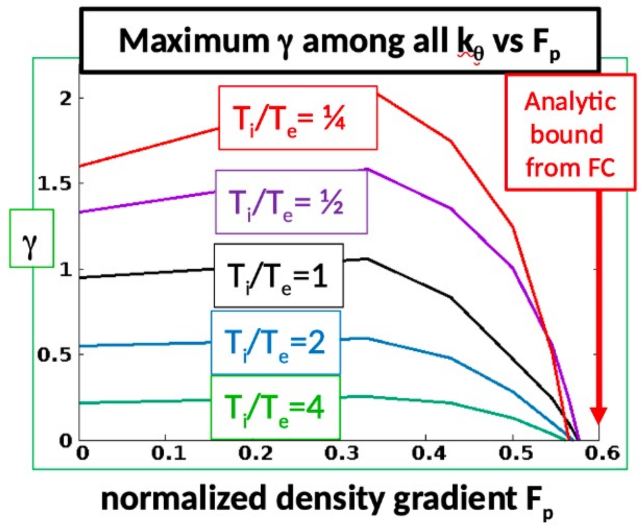
Small trapped electron contribution

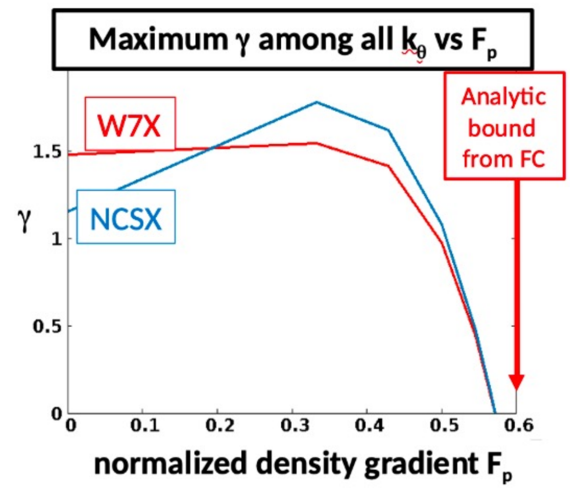
Large density gradient ⇒ small growth rates



Many Gyrokinetic Demonstrations of Density Gradient Stabilization

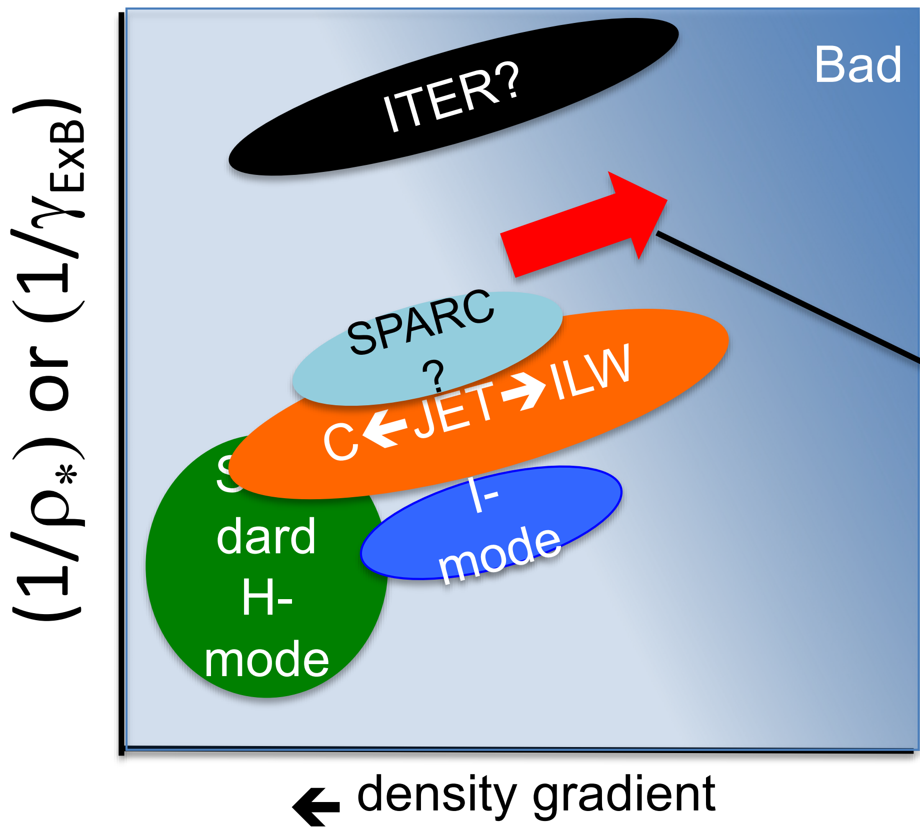






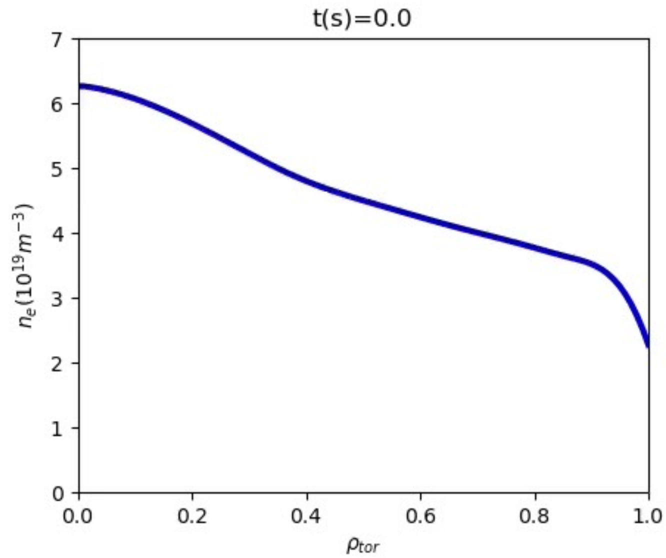
Kotsch, Mahajan, Liu, Hatch Merlo, NF 2024

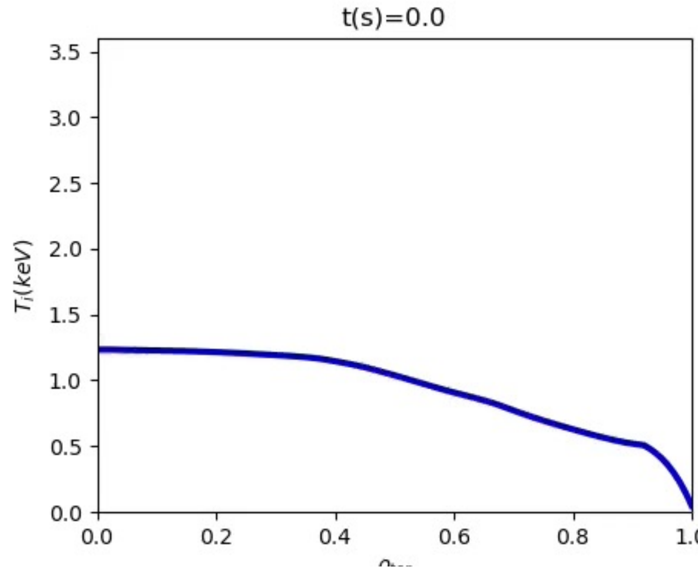
Fate of the Pedestal?



Divertor constraints, gas puffing, metal walls, low ρ_*….

Use an Impurity Pellet to Trigger an Internal Transport Barrier



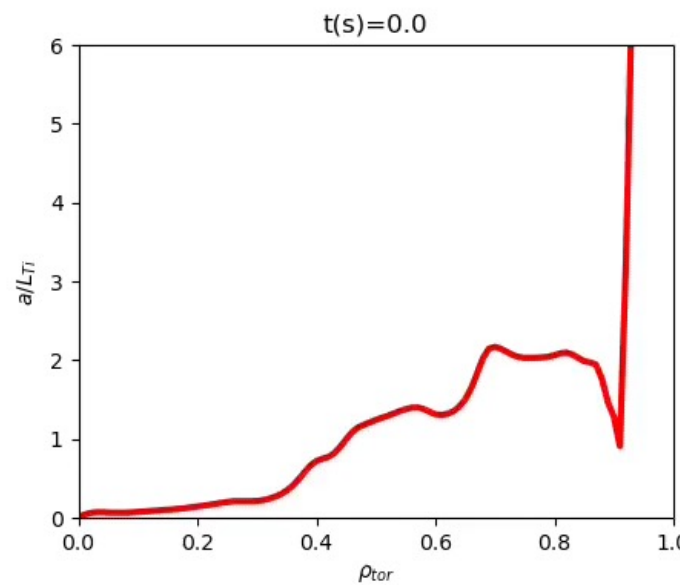


Collaboration with EAST + GA

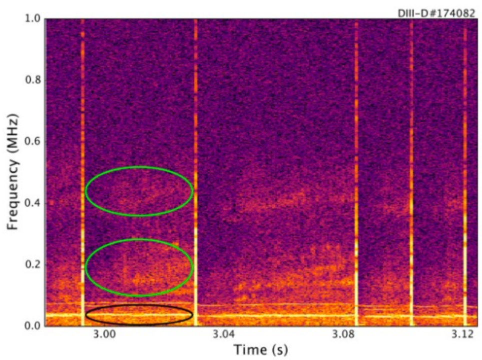
TGLF + IPS-FASTRAN

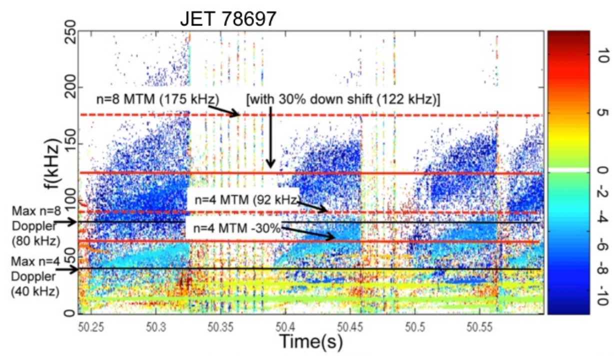
Current ramp

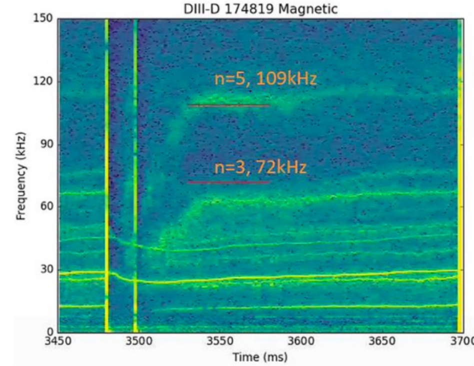
Impurity pellet at ρ_t=0.75

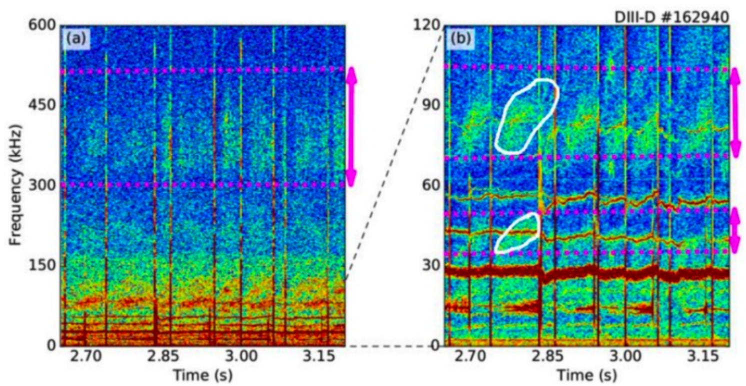


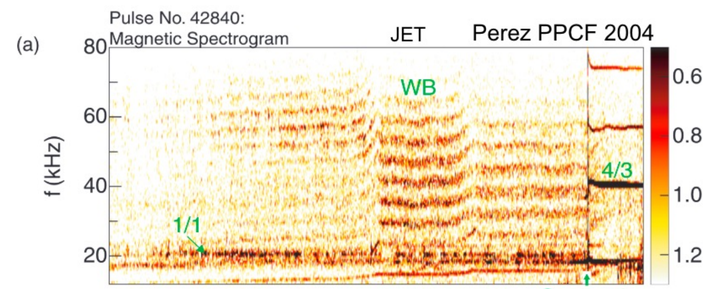
Interpreting Fluctuations in the Pedestal



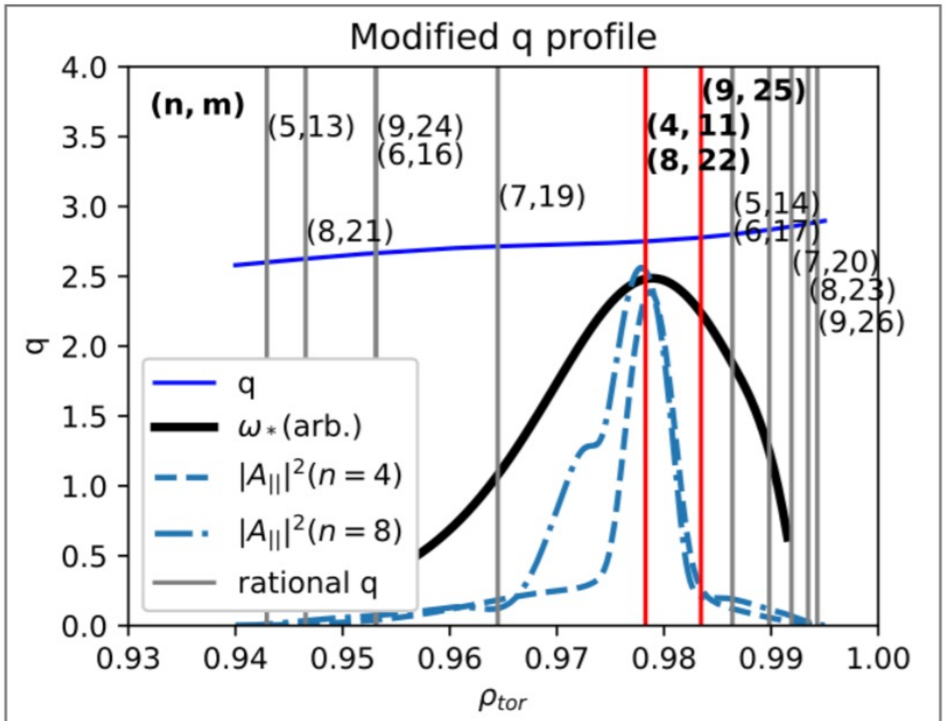




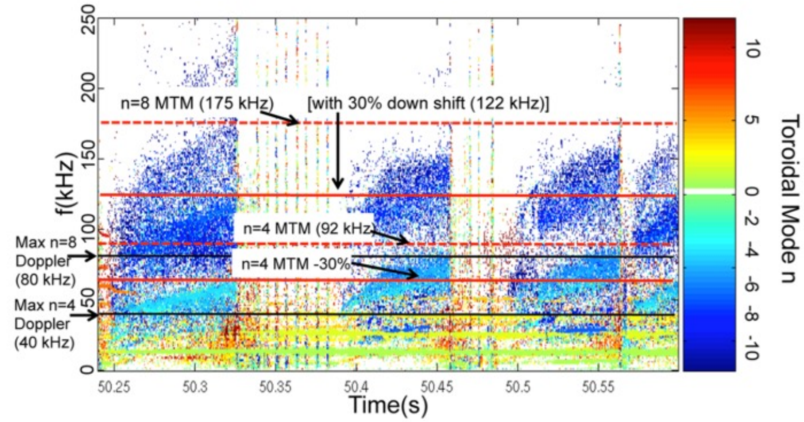


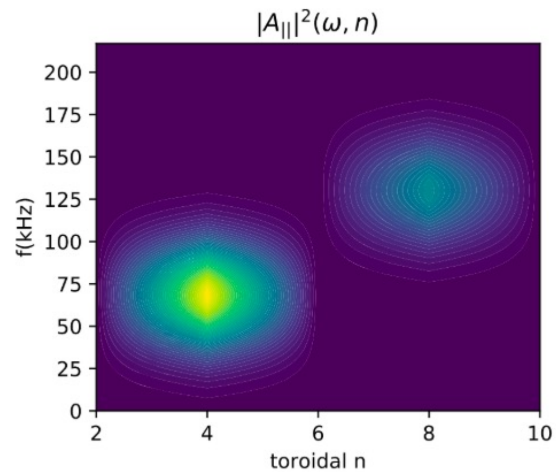


Microtearing modes:
Alignment of Rational Surfaces with ω^* Controls Stability

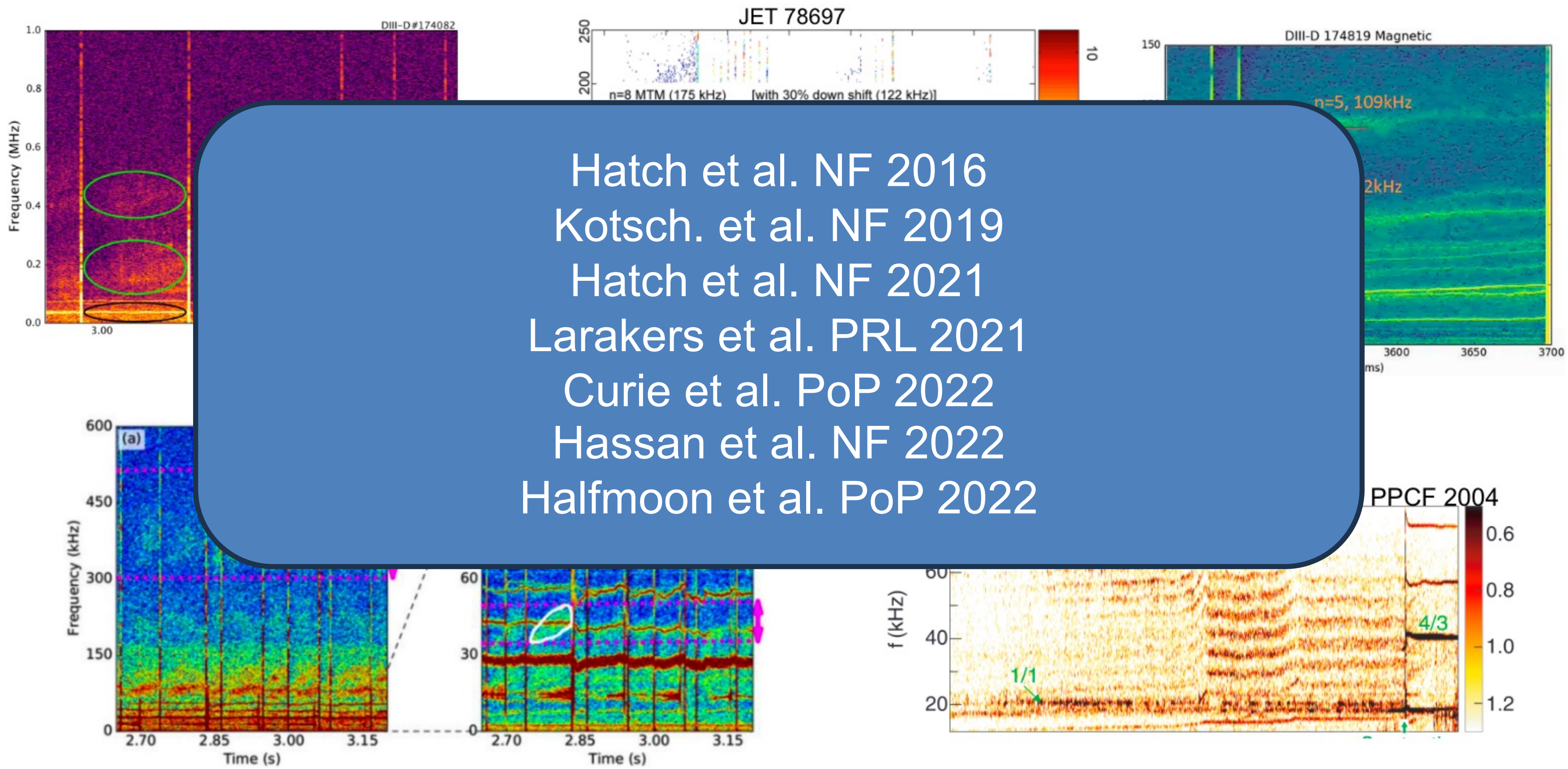


Hatch et al NF 2021



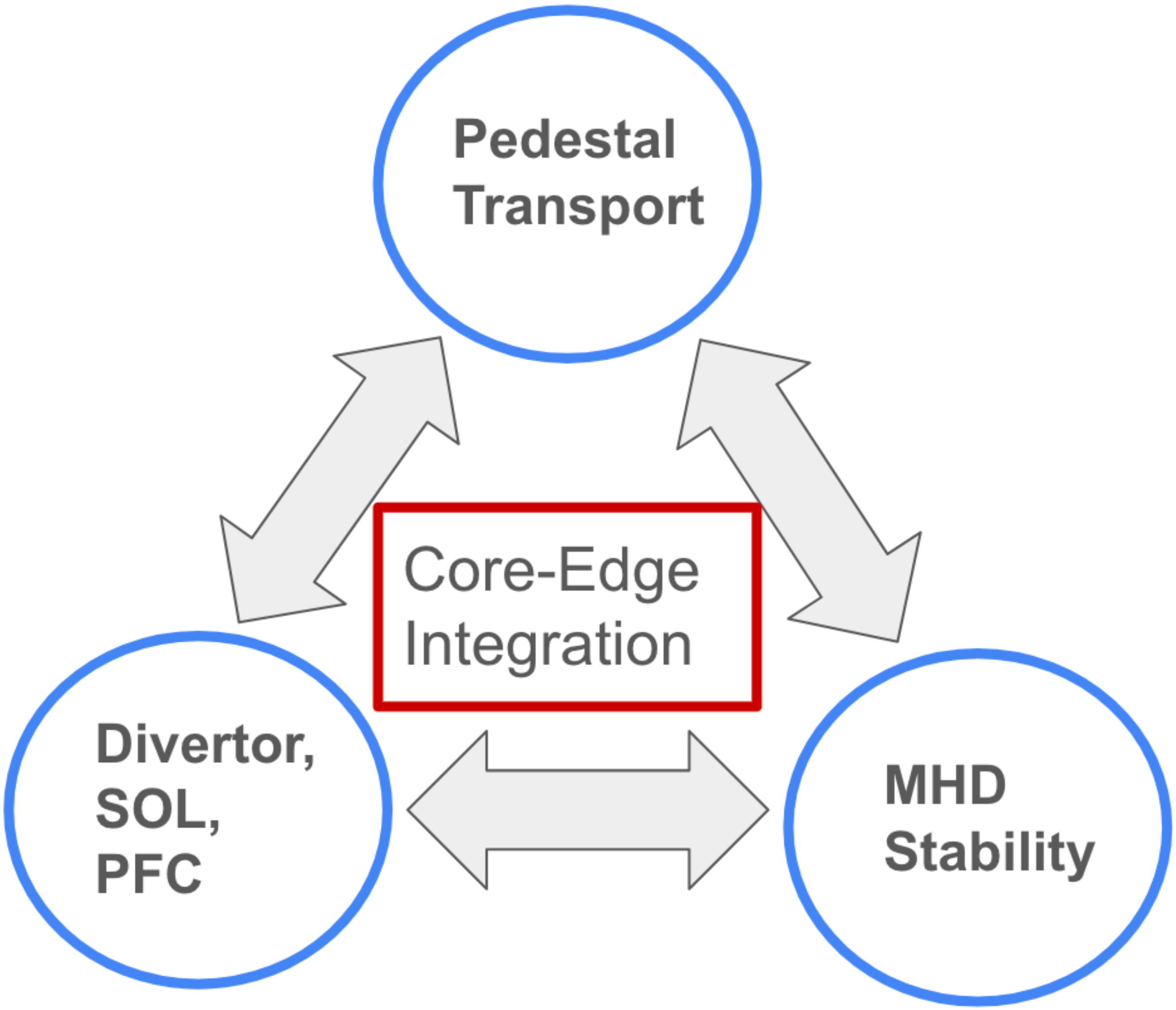


1. Explanation of Underlying mechanism
2. Near Quantitative reproduction of frequencies
3. Disparate Frequency Bands vs Contiguous



Hatch et al. NF 2016
Kotsch. et al. NF 2019
Hatch et al. NF 2021
Larakers et al. PRL 2021
Curie et al. PoP 2022
Hassan et al. NF 2022
Halfmoon et al. PoP 2022

Core-Edge Integration



Sensitive Connection between Confinement and Separatrix Parameters

Edge + Confinement

Latest ITPA confinement database [G. Verdoolaege *et al* 2021 *Nucl. Fusion*]

Includes **wall material** and n_{sep} (AUG+JET)

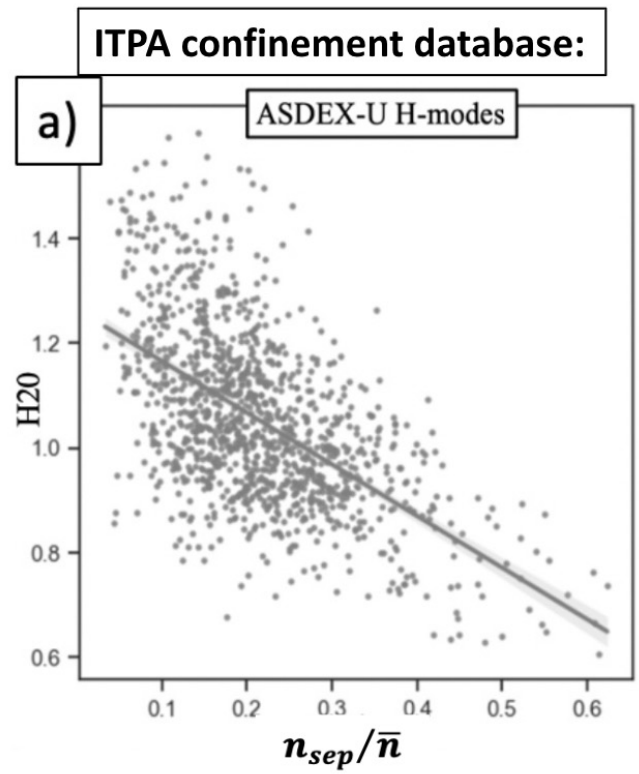
Following slides: confinement dependence on n_{sep}/n

Proxy for n_{sep}/n_{ped} (not available)

But n_{sep}/n is a good proxy since there is little variation in density peaking in this dataset

No 'hybrids' and no ITBs

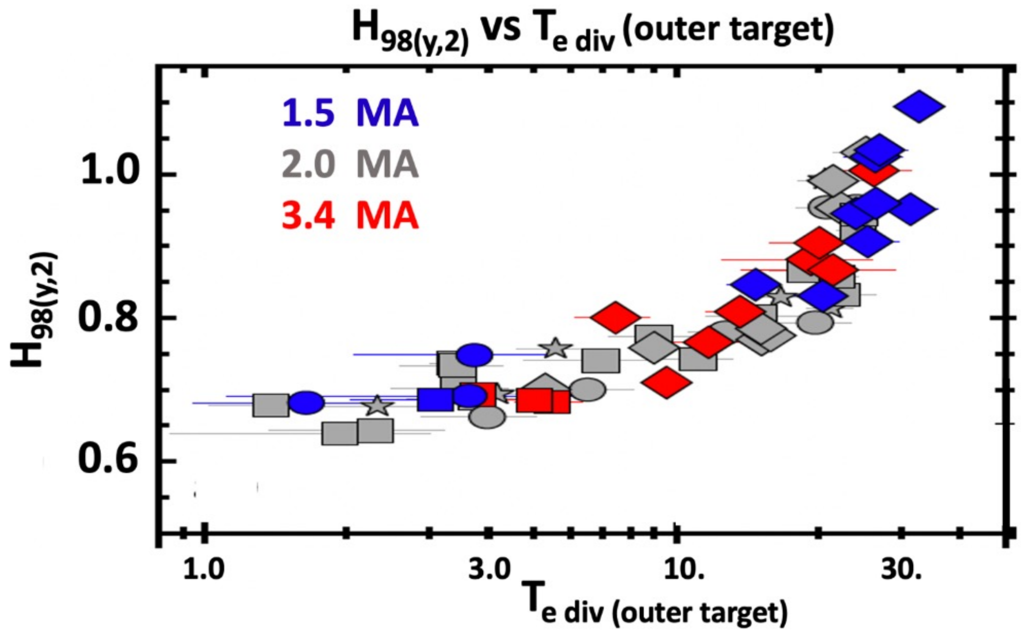
⇒**Although this is a 0D database, it offers a good view into pedestal properties**



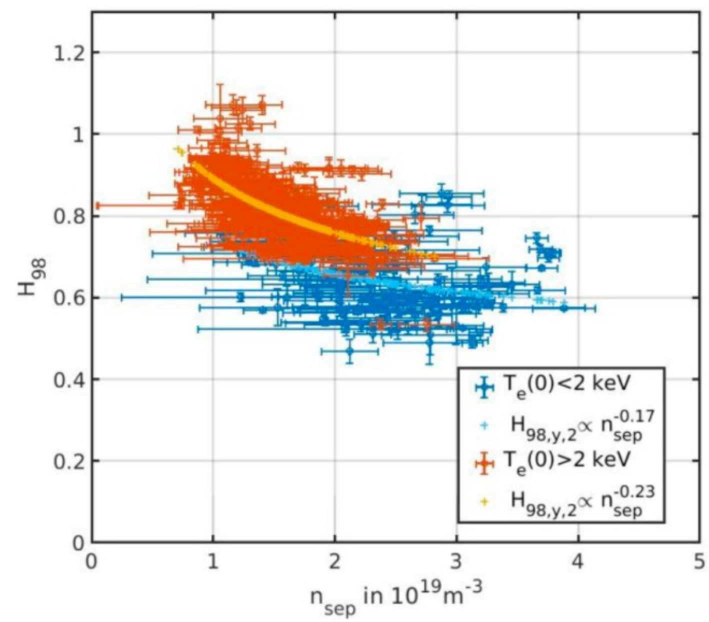
Kotsch. Et al. arxiv

Sensitive Connection between Confinement and Separatrix Parameters

Many Similar Results beyond ITPA Database



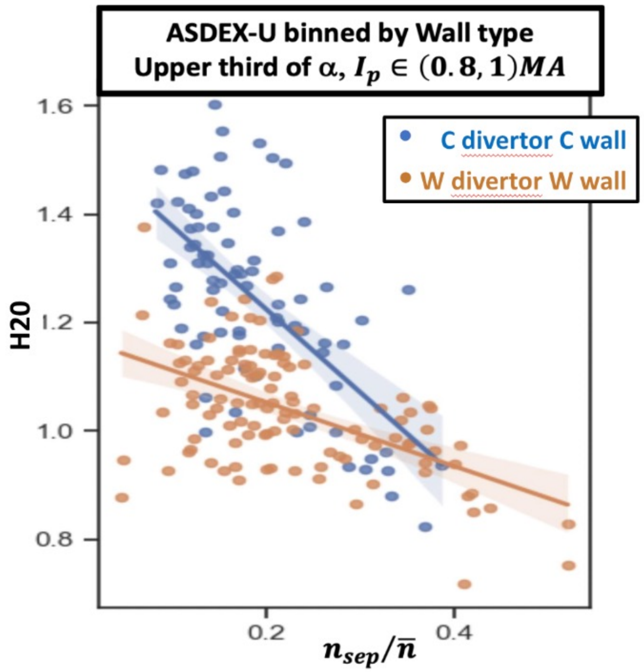
Lomanowski NF 2022



Bourdelle NF 2023

Sensitive Dependence on Wall Material

Same trend for C or W but much stronger for C



Viability in FPP requires: (1) low-Z sputtering, and (2) compatible with high SOL T (erosion, etc.) ⇒ liquid metal PFC solutions

Kotsch. Et al. arxiv

Mechanism: Transport not MHD

Modest increase in β_N ⇒ some beneficial effect on MHD stability

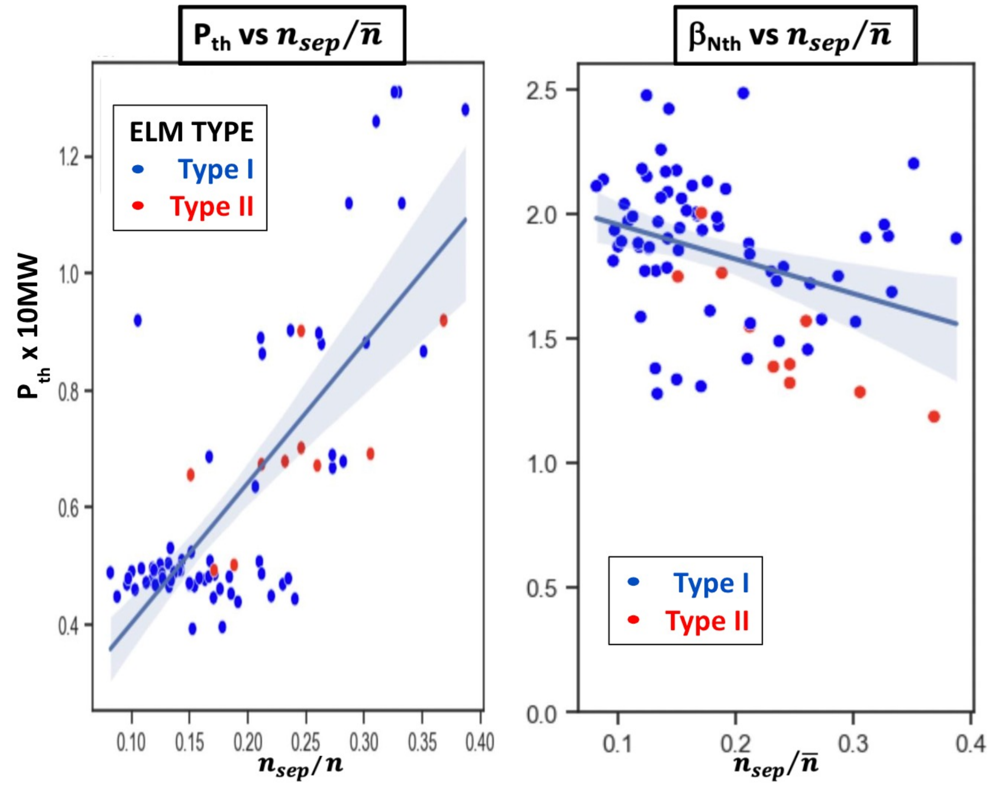
Less heating power required to drive the pedestal pressure gradient to the MHD stability ⇒ A transport effect

Low nsep is beneficial for both MHD limits and transport

~1.25X increase in β_N
~3X decrease in power

⇒ The main effect is on pedestal transport

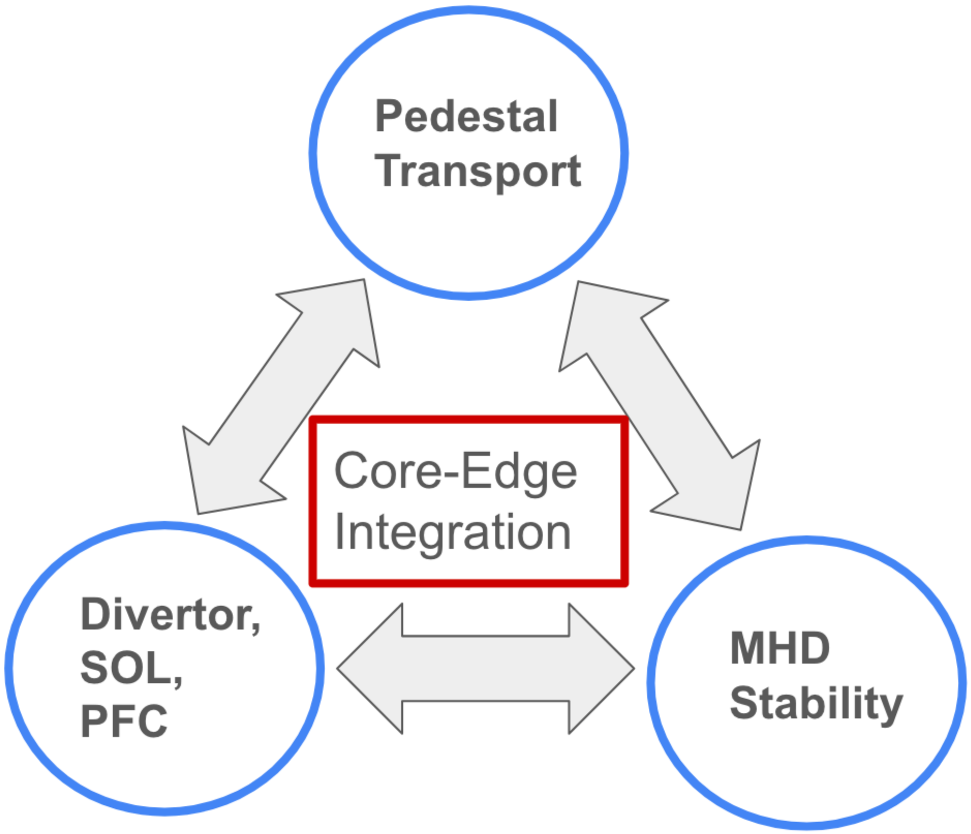
Note: JET-ILW appears to have more *parity* between transport and MHD



Kotsch. Et al. arxiv

Reduced Transport Models for Pedestal Prediction

Core-Edge Integration



Simple Model for Slab ETG in the Pedestal

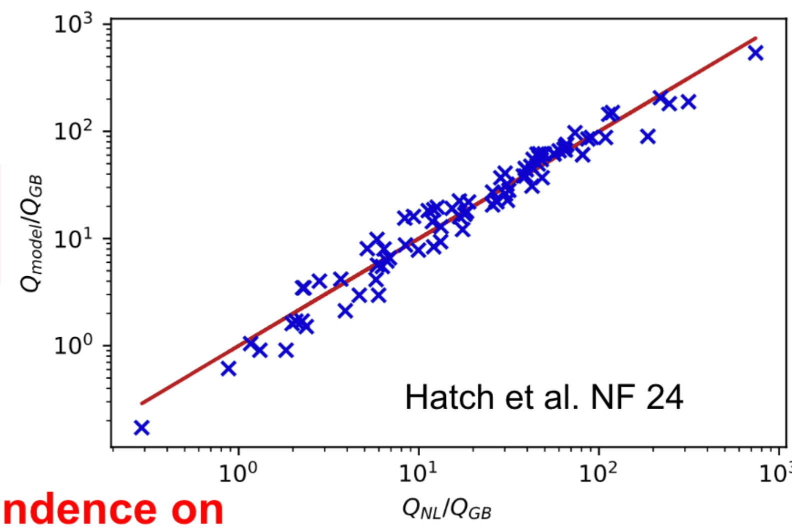
Accurate Algebraic Expressions for Pedestal ETG Transport: Strong Dependence on Electron Temperature Gradient (expected) and $\eta_e = \omega_{Te}/\omega_{ne}$

From extensive database of nonlinear GK simulations

$$Q_e/Q_{GB} = a_0\sqrt{m_e/m_i}\omega_{Te}^2(\eta_e - 1)\eta_e^{b_0}\tau^{c_0}$$

$$a_0 = 0.1 \qquad b_0 = 1.54 \qquad c_0 = -0.5$$

Hatch et al. NF 22
Hatch et al. NF 24



Extremely strong dependence on gradients: a/L_{Te} (destabilizing), a/L_n (stabilizing)

Reduced 'Quasilinear' Models for Pedestal Transport

Quasilinear mixing length model for ion-scale transport

Growth rates and eigenmodes from linear GENE simulations

This presentation: local

Global is also possible

Two free parameters:

Saturation rule: a_0

Width: radial smoothing or Gaussian envelope

All other dependencies from linear GK

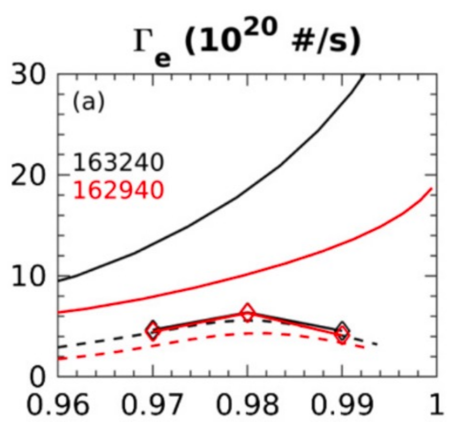
From GENE

$$Q_e = a_0 Q_{GB} \omega_{Te} \left(\frac{\gamma}{< k_\perp >^2} \right)$$

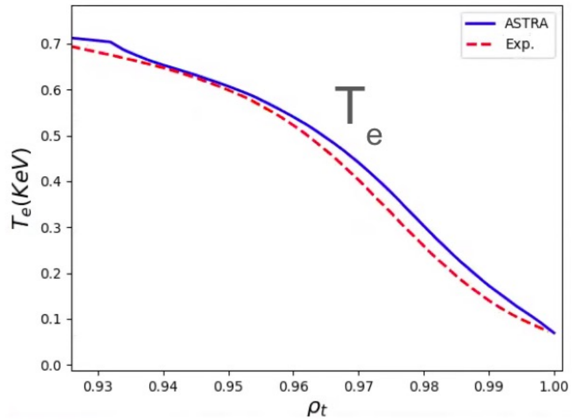
\+ Radial smoothing or radial envelope

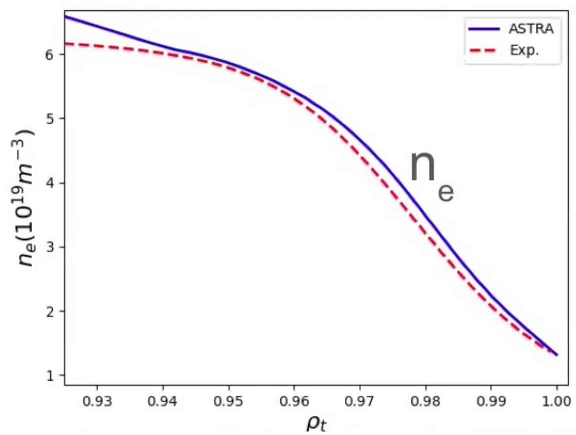
First Test on DIII-D

Evolving T_e and n_e with ETG and KBM/MTM



Particle source from SOLPS interpretive analysis [Guttenfelder NF 2021]





Can simultaneously match Te and ne

Two free parameters set to match both nonlinear simulation and experiment

Correct ratio of D/chi, correct pedestal width, consistent with nonlinear GK.

Hatch et al. submitted to PoP

Physics Discoveries

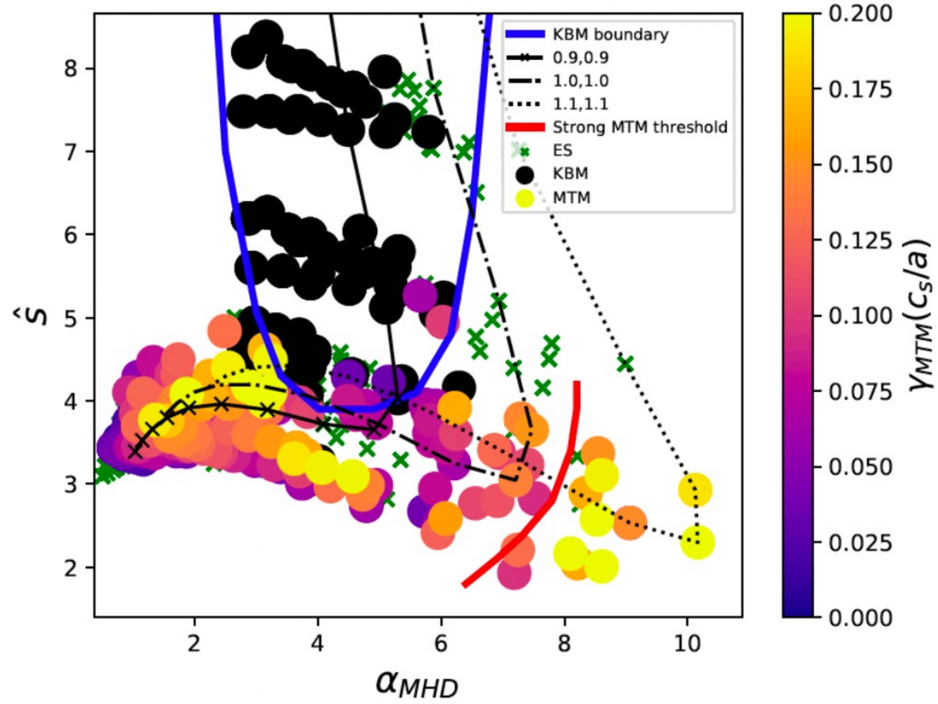
Interplay between KBM and MTM

DIII-D 162940

Pre-ELM state is in second stability for KBM

MTM matches experimental frequencies.

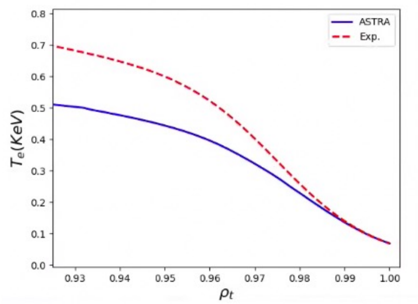
Novel characteristics of MTM: (1) Partial density gradient drive; (2) Substantial particle transport. MTM as inter-ELM ***pressure*** constraint. [Hatch et al. arxiv 2026]

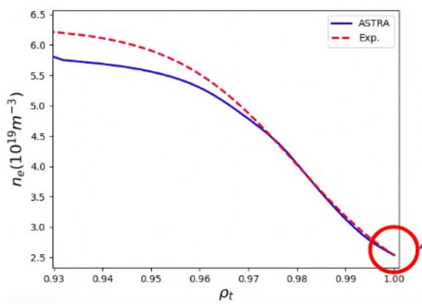


Hatch et al. submitted to PoP

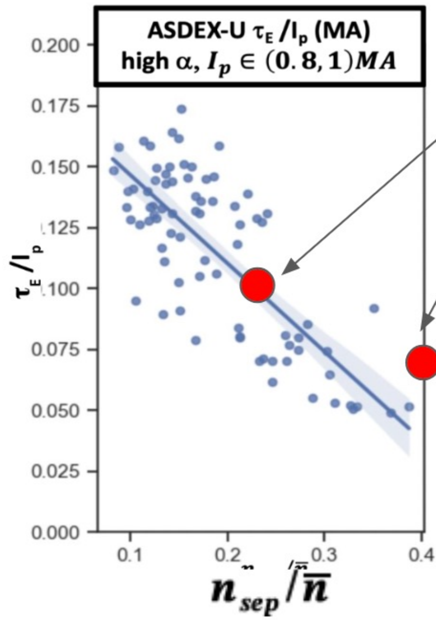
Initial Probe of Core-Edge Connections

Confinement degrades as n_{sep} increases





High n_{sep} Boundary condition



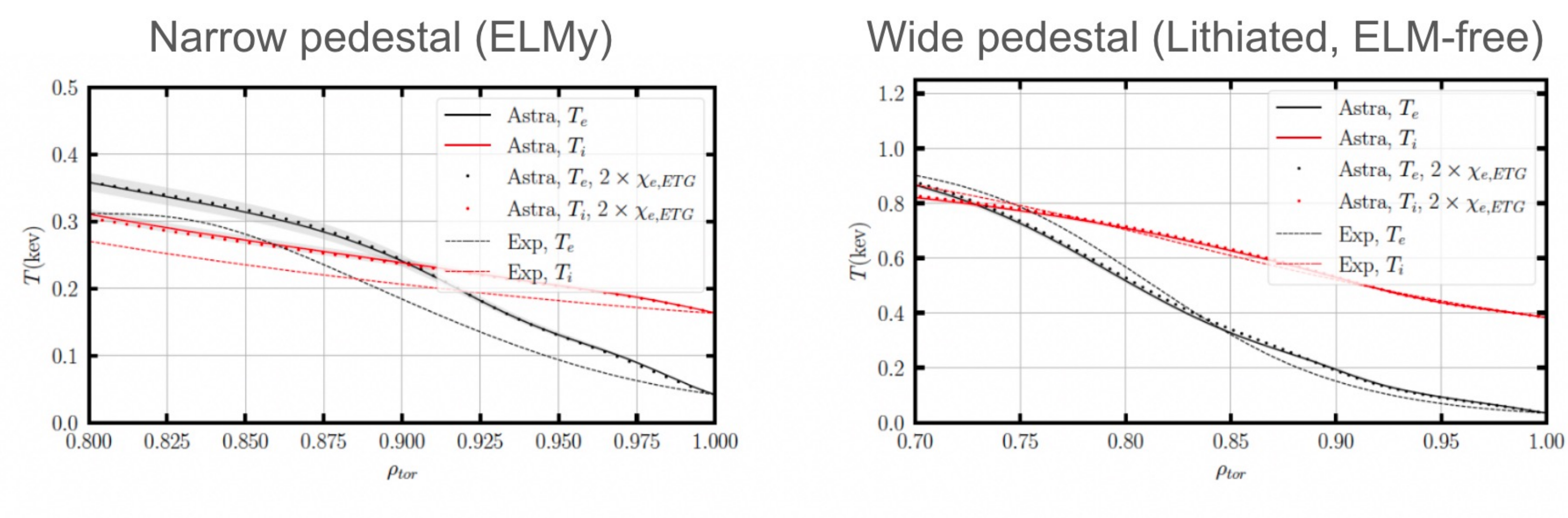
"Pedestal confinement time" (different scale)

P_{ped}/P_{th}

Strong decrease in T_{ped}, moderate decrease in n_{ped}

Successful Demonstration for NSTX

NSTX results: *One* free parameter: good match for *two* transport channels (Te and Ti) for *two* (very different) discharges

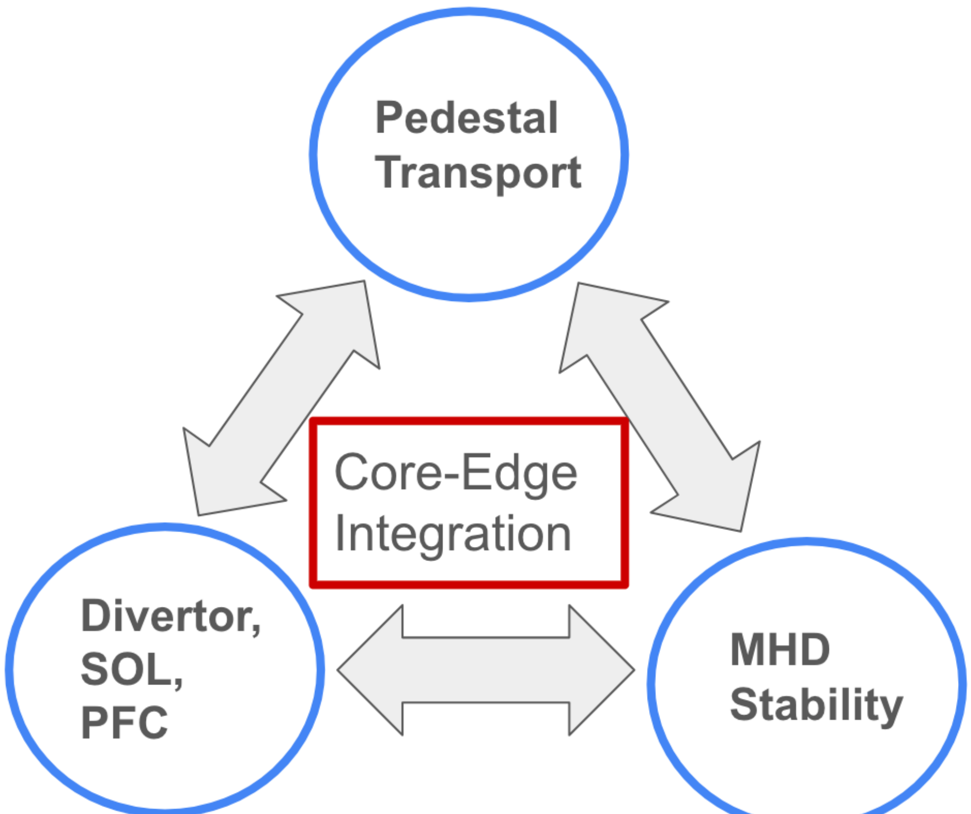


(a) 132543 (b) 132588

Ping-Yu Li et al., https://arxiv.org/abs/2603.20502

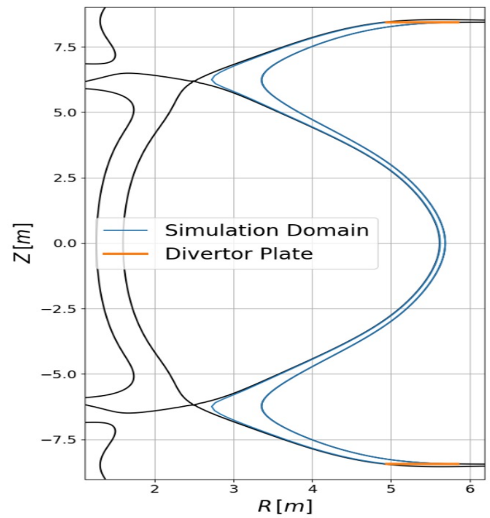
Divertor Innovations

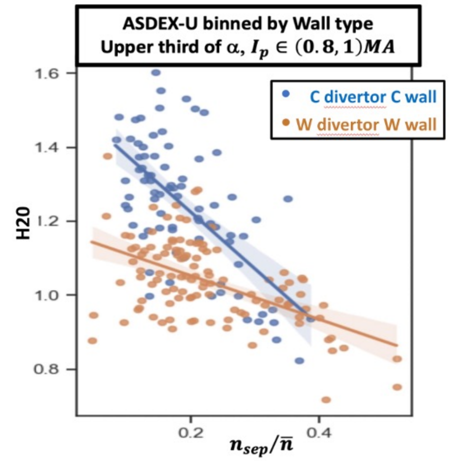
Core-Edge Integration



Controlling Edge Particle Source to Optimize Fusion

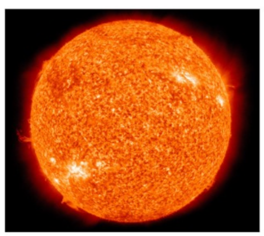
High vs Low Recycling





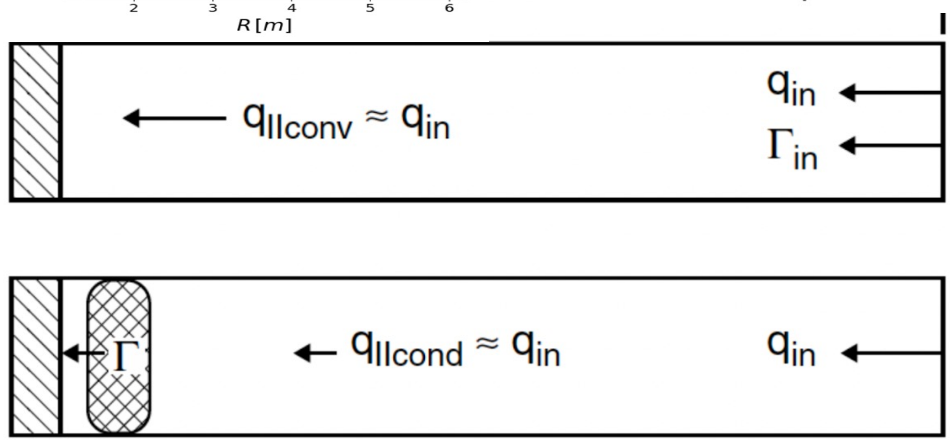
1 keV

~a few eV



a)

b)



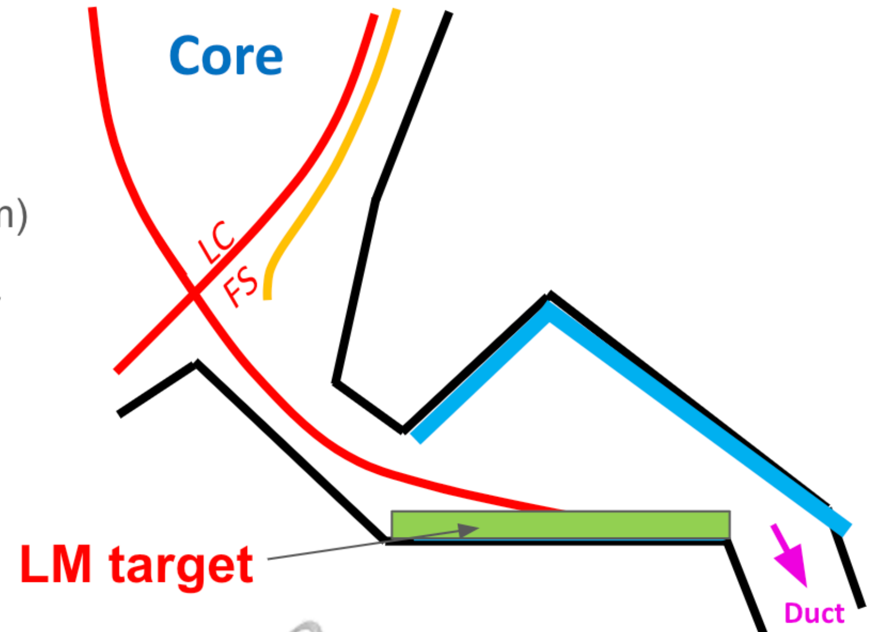
Stangeby

Super-XT Divertor: Enable Low Recycling Parameter Space

Integrated solution to:

- Sputtering/erosion: novel liquid metal alloys (not lithium)
- Impurities: manipulation of divertor magnetic geometry
- Low-recycling: absorbing boundary
- Heat exhaust
- Alpha pumping

Spanning low and high recycling regimes



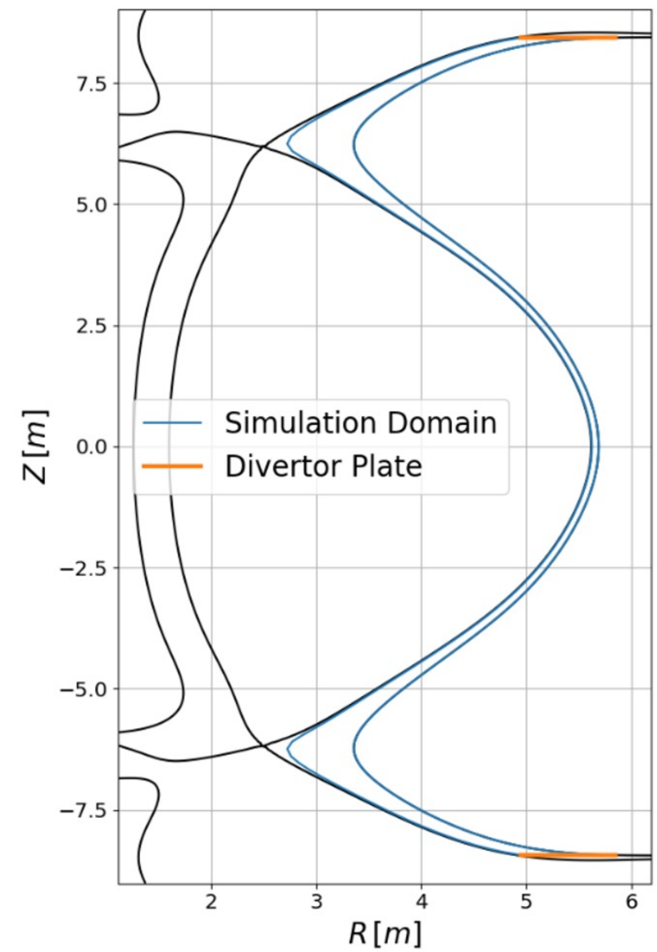
Gyrokinetic Simulations of SOL to test Low Recycling

Testing super-XT divertor using edge gyrokinetic simulations (Gkeyll code)

Need **kinetic** simulations due to high T, low n (low collisionality)

Testing for spherical tokamak STEP geometry (UK fusion pilot plant)

(Recent graduate A. Shukla)



Kinetic Effects are Important

Non-Maxwellian distribution functions develop

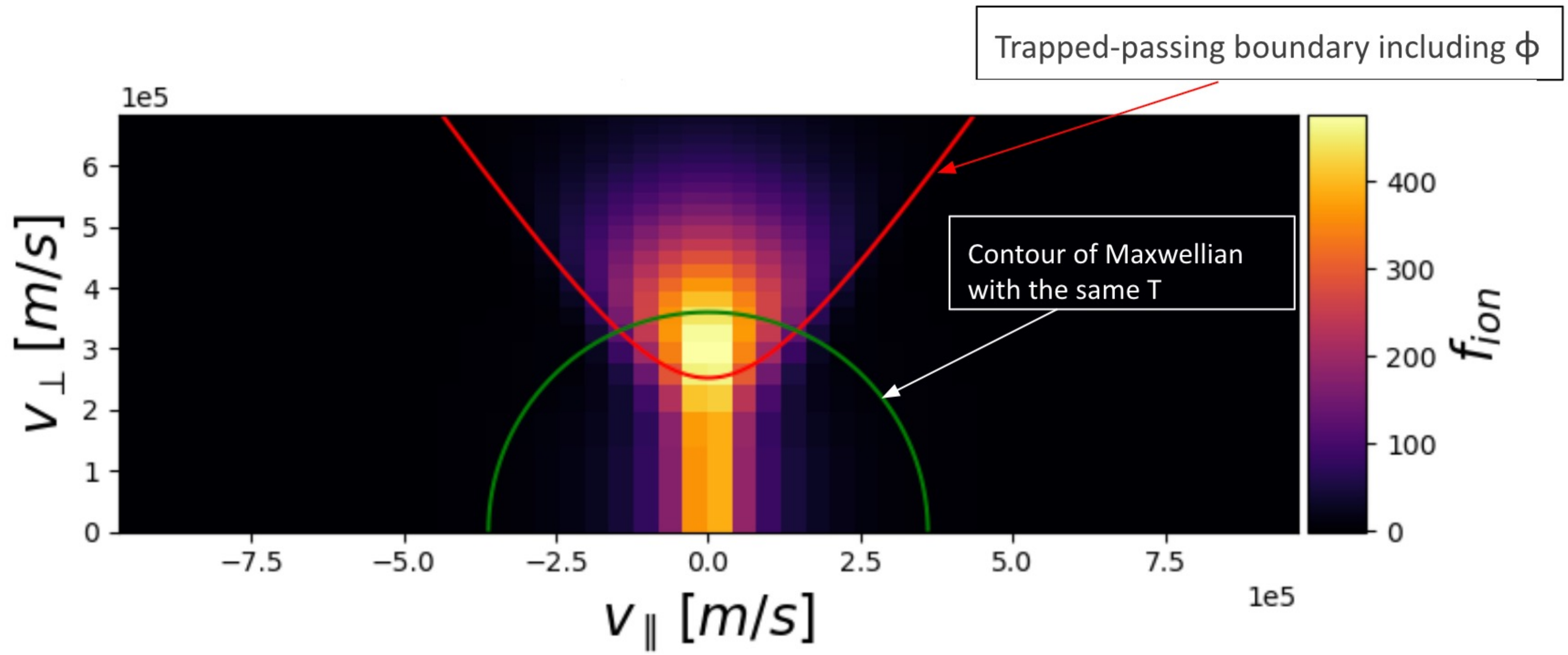


Figure 4: Ion distribution upstream at midplane **2mm away from radial center**. Depleted at large $v_{||}$

Shukla et al. AIPA 2025

Kinetic Effects: Improved Impurity Shielding

Gkeyll: kinetic effects produce much better impurity shielding

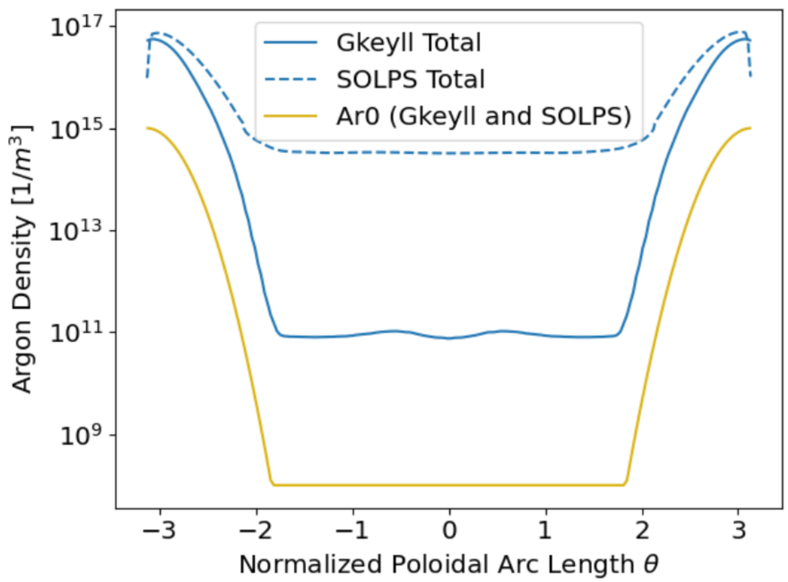


Figure 10: Neutral and Total (summed over charge states 1-4) Argon density along the field line

- Upstream Argon density is much lower in Gkeyll due to the low temperature and enhanced potential drop
- Only High Z are hot enough to make it upstream, but high Z particles come from low Z which are shielded
- **The kinetic regime may allow us to increase impurity concentration downstream while avoiding core contamination**

Shukla et al. AIPA 2025

Materials: Plasma Facing Component

W: Tungsten
L: Lithium
LMA: Liquid metal alloys

	W	L	LMA
Can Handle High Heat Flux	✅	?	✅
High Operating Temperature	✅	❌	✅
Resilient to Transients	❌	✅	✅
Benign Sputtering	❌	✅	✅
Compatible with High Confinement	?	✅	✅
Demonstrated Tokamak Operation	✅	❌	❌

Innovations in PFC Materials: Novel Liquid Metal Alloys

Alloys that can operate at much higher temperature can accept high heat flux
WHILE HAVING LOW Z SPUTTERING:

- Bulk metal:
  Sn, Ga, In

- Minority low Z component:
  Li, Be, Mg, Al, Si, Ca

- Non-metal added (in very small concentration)

to induce segregation of low Z:

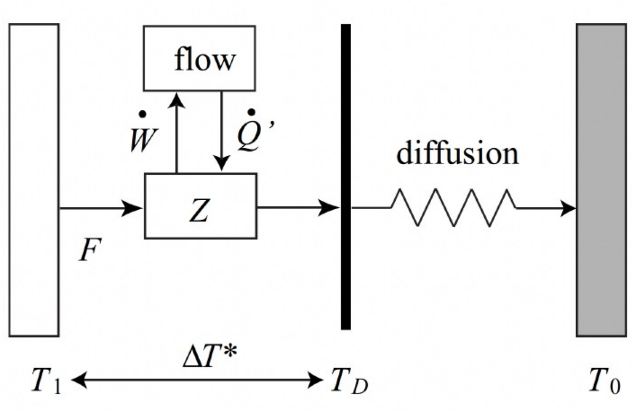
O, N, F, S, P, Cl – in metallurgy, these are also observed to segregate to the surface of LMs, and can bind preferentially to low Z elements

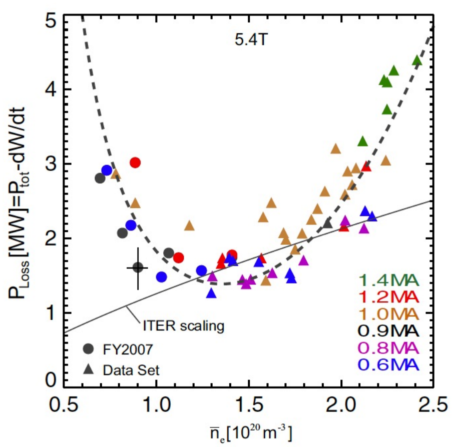
- Rough estimate of the segregation energy indicates that it can be strong enough to give surface coverage even for very low % of low Z component and non-metal

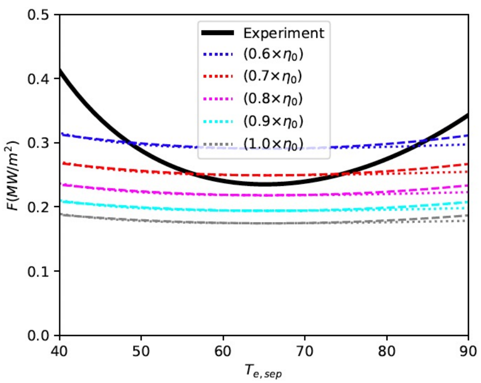
Three DOE grants: interdisciplinary team investigating properties of these alloys

Thermodynamic Model of Transport Barriers

Ma et al. NF 2012







Mahajan et al. submitted to NF; arXiv:2603.26919