Validation of the TGLF-EP+Alpha critical-gradient model of energetic particle transport in DIII-D scenarios for ITER

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UCSD

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Computations performed at NERSC

GENERAL ATOMICS

Outline

I. Introduction

II. TGLF-EP+Alpha local critical-gradient model of Alfvén eigenmode (AE)-driven energetic particle (EP) transport

III. Validation against discharges from four scenarios in DIII-D discharges

IV. Summary

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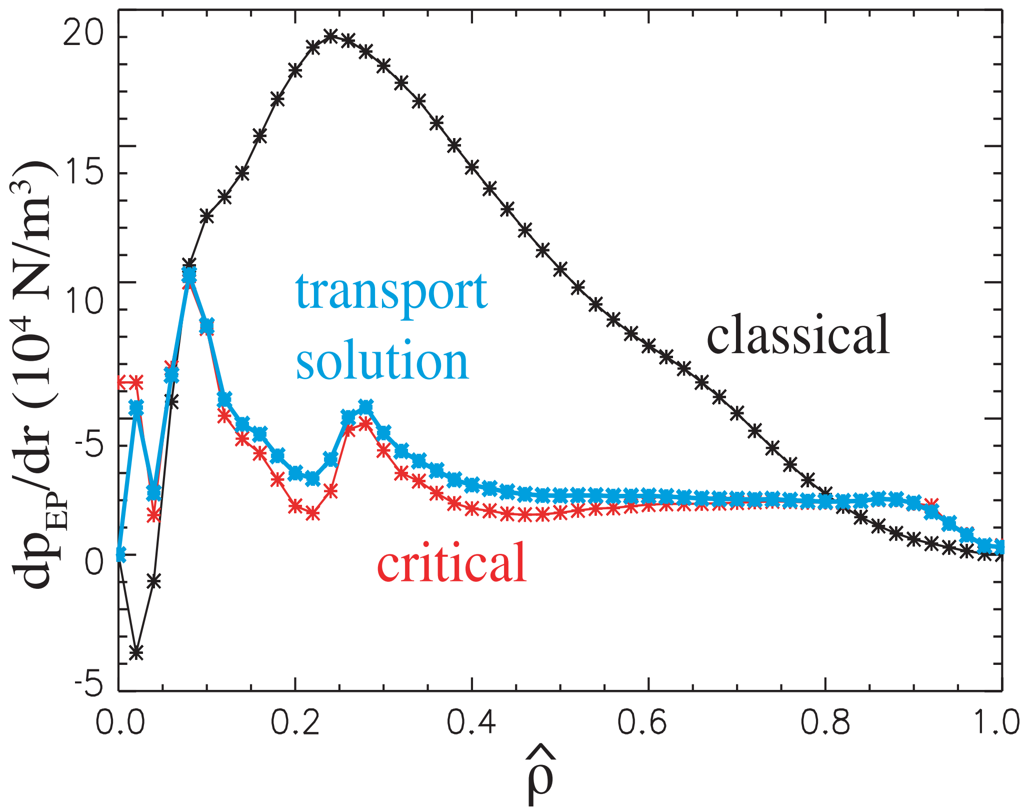
TGLF-EP+Alpha is the simplest, fastest EP transport model available → extensive validation possible and necessary



Stiff transport forces the gradient to not (much) exceed a "critical gradient" of AE transport (essentially the linear stability threshold).

TGLF-EP+Alpha is a local 1D critical-gradient model (CGM) using gyro-fluid stability calculations and a stiff AE-EP transport assumption.

Model features:

- Highly reduced → inexpensive
- Increasingly automated, minimal human judgment required
- **Fully physics-based!** No "fudge factors" or AE inputs from experiment.
- Solves for EP profile and diffusion coefficient (usable in TRANSP)

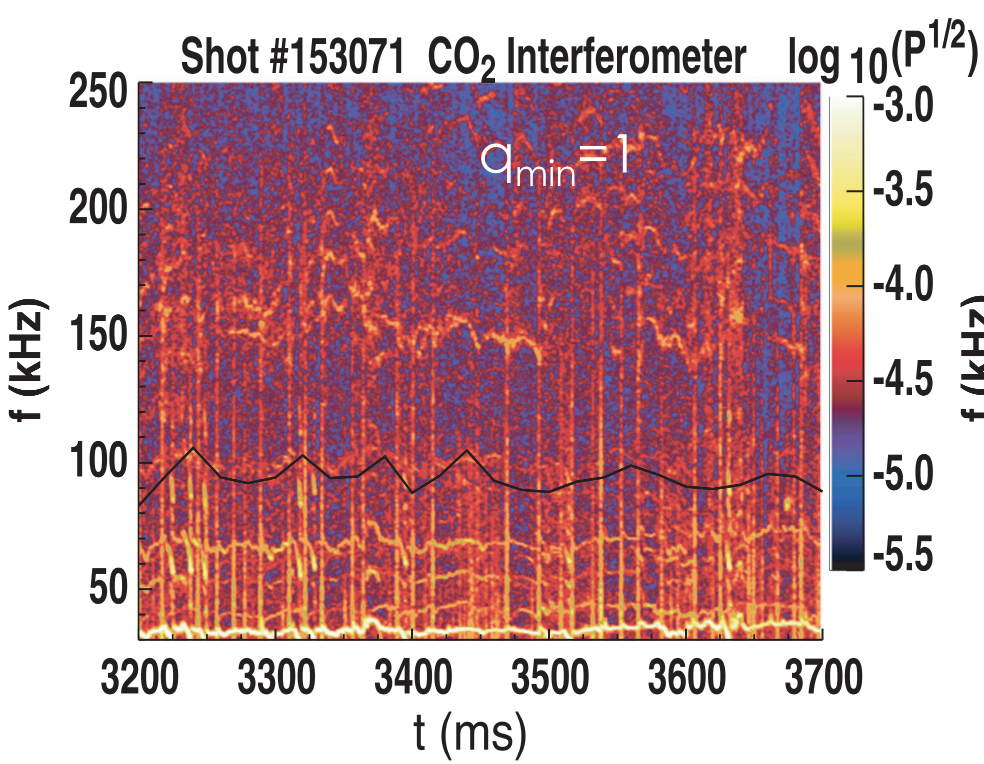
Simplifying assumptions (Maxwellian EPs; stiff, local transport; no velocity-space dependence; etc.) make **validation** especially necessary to **map applicability**.

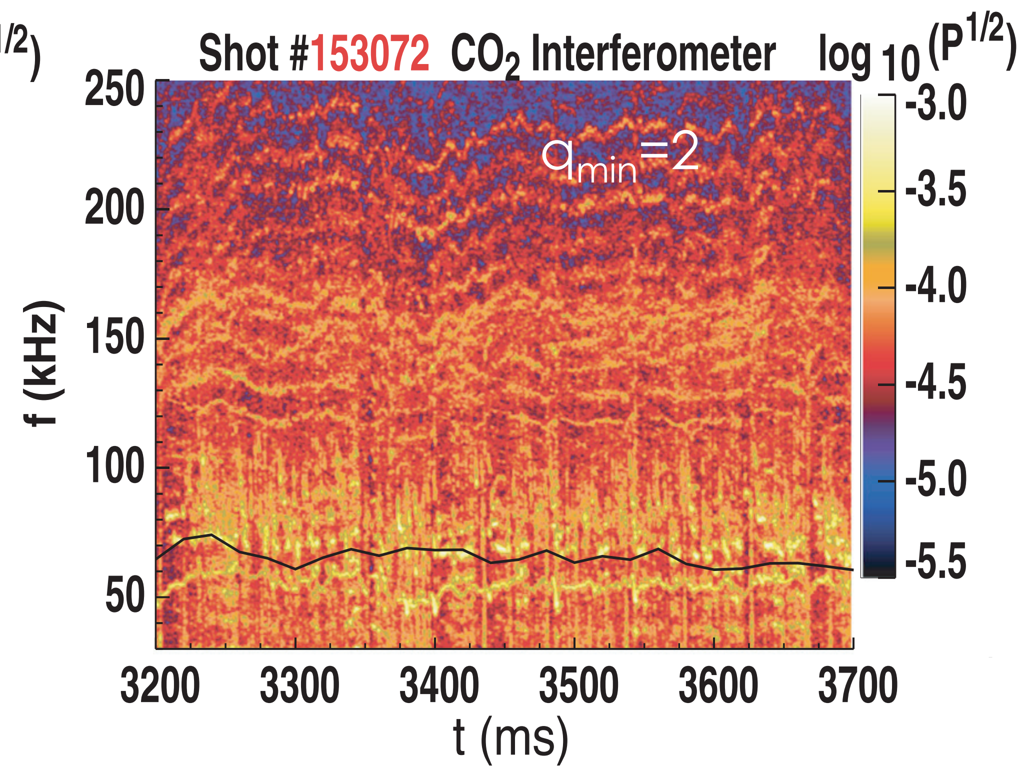
Four DIII-D cases test TGLF-EP+Alpha validity across regimes

TGLF-EP+Alpha is increasingly integrated into the GACODE workflow, enabling rapid turnaround of cases. Here we examine four H-mode cases.

I. **q_{min}=1**: Shot 153071. Beam heated discharge, monotonic q with q_{min}=1 at axis. Low central shear. Minimal EP flattening by AEs

II. **q_{min}=2**: Shot 153072. Similar to Case I, but with q_{min}=2 and 40% lower thermal beta. Much greater EP flattening.





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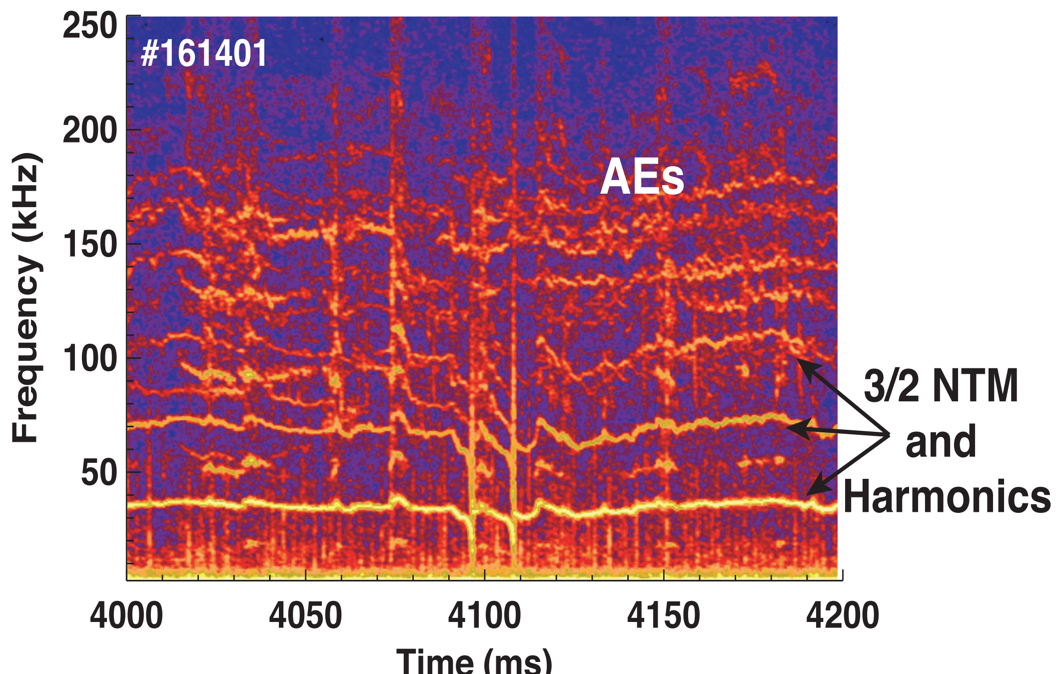
III. **hybrid**: Shot 161401. ITER steady-state-relevant scenario with strong EP flattening driven by AEs and a 3/2 tearing mode.



D. Lin talk yesterday

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IV. **Super H-mode**: Shot 171322. A high-confinement H-mode with relatively little EP transport.

Agreement with experiment is mixed, but extremely encouraging for a such a reduced model. **Big differences from experiment tend to show too little AE transport.**

C. T. Holcomb et al., PoP **22**, 055904 (2015)
W.. W. Heidbrink et al., PPCF **56**, 095030 (2014)
N. N. Gorelenkov et al., NF **56**, 112015 (2016)

G. J. Kramer et al., NF **57**, 056024 (2017)
Zhen-Zhen Ren et al., PoP **25**, 122504 (2018)
C.C. Petty et al., NF **57**, 116057 (2017)

D. Liu talk yesterday

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The 1D Alpha EP density transport code uses the stiff critical gradient model based on local nonlinear 2010 GYRO simulations[1]

"Alpha" transport EP continuity equation

$$\frac{\partial n_{EP}}{\partial t} = S\left(1 - \frac{n_{EP}}{n_{SD}}\right) - \nabla \cdot \Gamma_{EP} \rightarrow 0$$

fusion or beam source

slowing-down sink (plasma heating)

Diffusive EP flux:

$$\Gamma_{EP} = -\left(D_{\text{micro}} + D_{\text{AE}}\right)\nabla_r n_{EP}$$

For present DIII-D cases, D_{micro} is effectively shut off.

Critical gradient as a function of r determined by TGLF-EP, the **crucial input**.

Boundary condition: Edge n_{EP} is set to zero (pessimistic edge loss estimate).

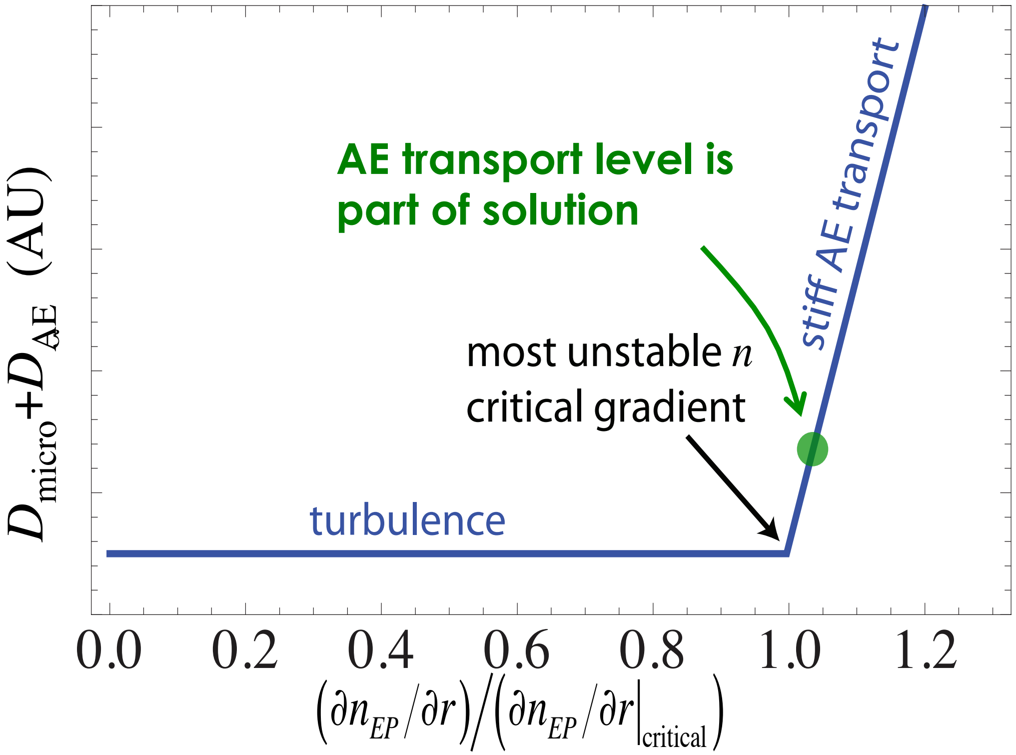
$$S = n_D n_T \langle \sigma v \rangle_{DT}$$

fusion source

$$n_{SD} = \int_0^{\infty} \frac{S\tau_s}{2} \frac{\Theta(E_\alpha - E)}{E_c^{3/2} + E^{3/2}} E^{1/2} dE$$

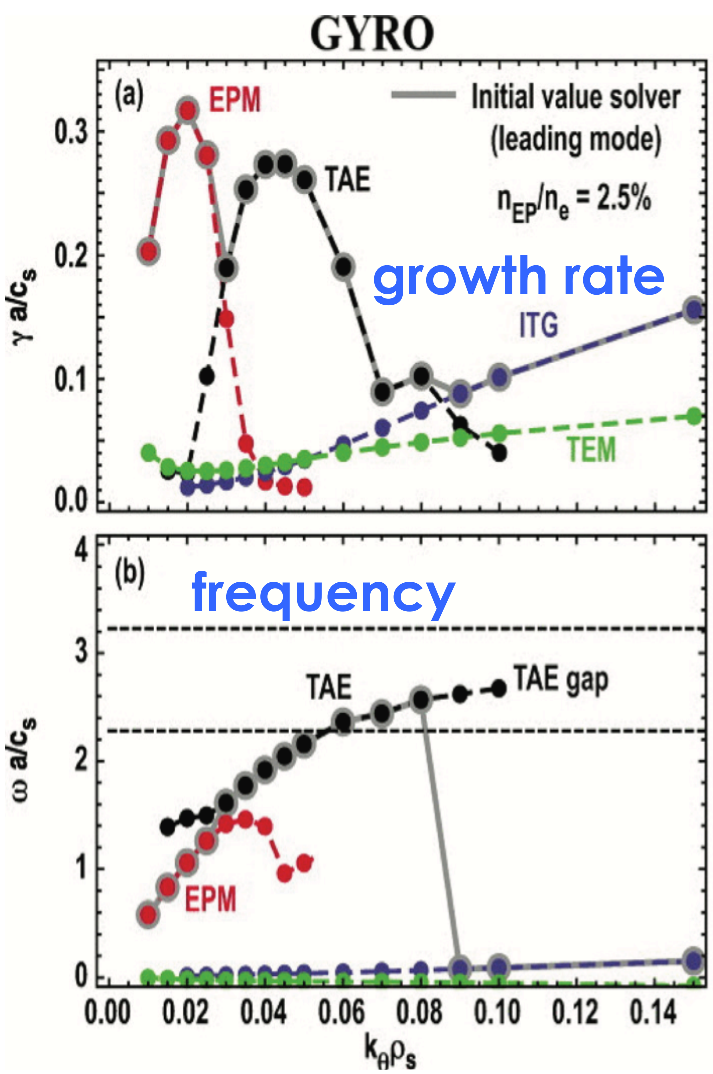
classical slowing-down density

Gaffey 1976



[1]E.M. Bass and R.E. Waltz, PoP **17** 112319 (2010)
[2]Angioni and Peters, PoP **15** 052307 (2008)

TGLF-EP code uses the gyro-Landau fluid TGLF model to find the AE-EP critical gradient where $\gamma_{AE} \to 0$



A local linear stability analysis is required to find the local critical gradient. **We can use GYRO (gyrokinetic), but it's expensive and time consuming.**

Benchmark GYRO simulations in ITER-like conditions track two main AE branches (with Maxwellian EPs).

Specially tuned, TGLF (gyro-Landau fluid) matches GYRO (gyrokinetic) AE spectrum well, but is **>100 times cheaper**.

TGLF-EP[1]**:** A parallelized, automated wrapper that searches across mode number and drive strength for the critical gradient.

[1]He Sheng, R.E. Waltz, and G.M. Staebler, PoP **24**, 072305 (2017)

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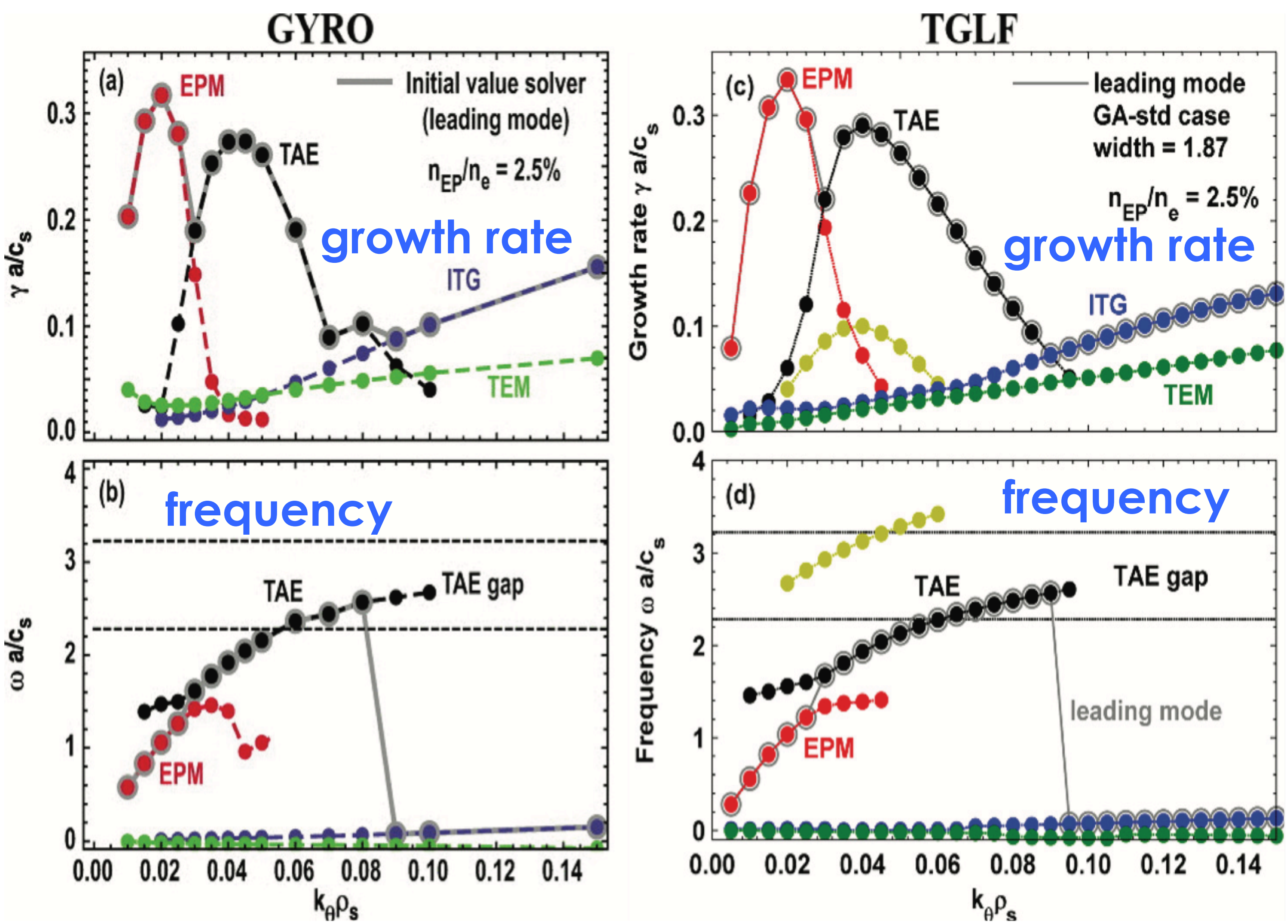

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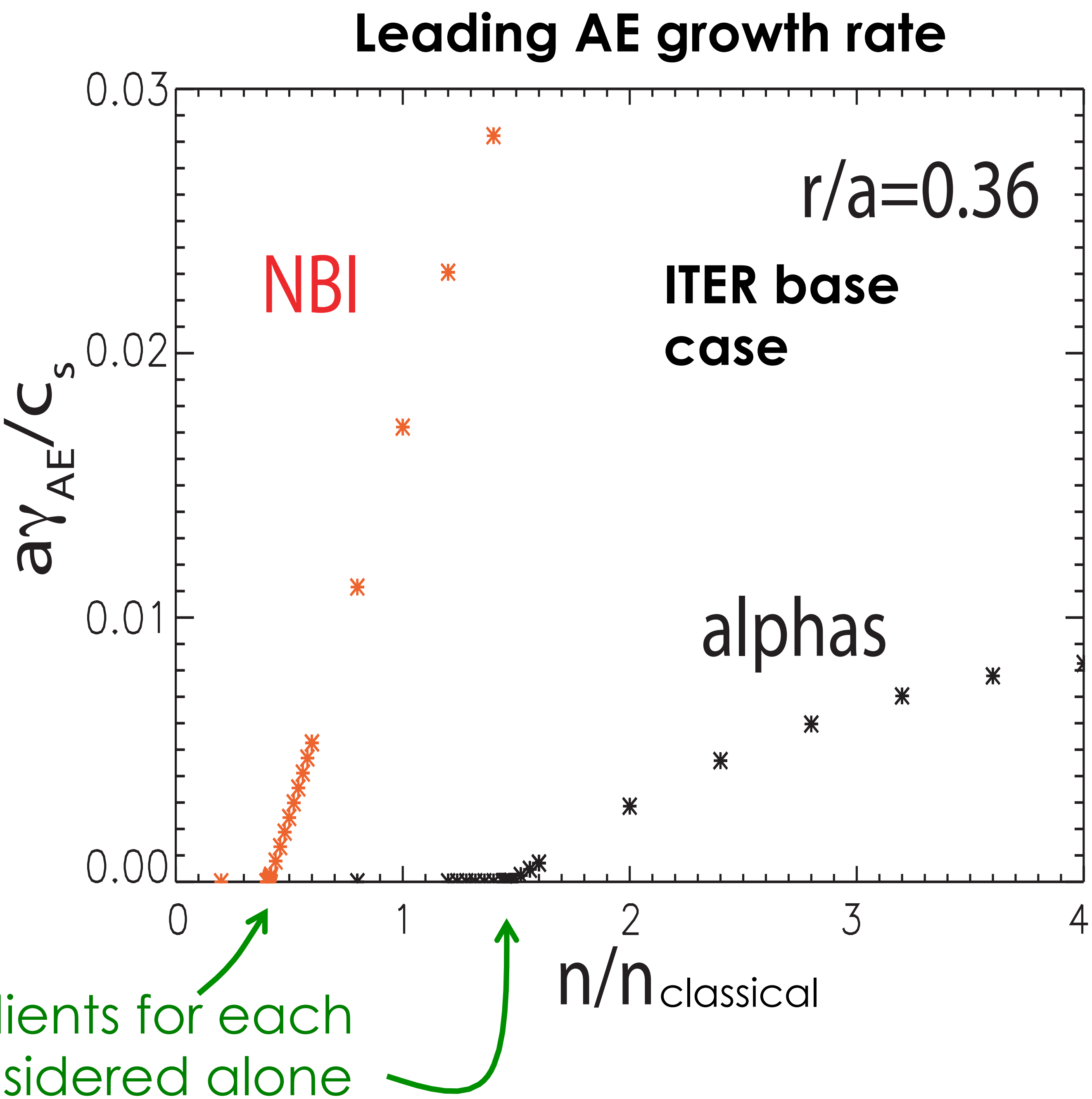
TGLF-EP automatically finds the most-unstable AE critical gradient at each radius

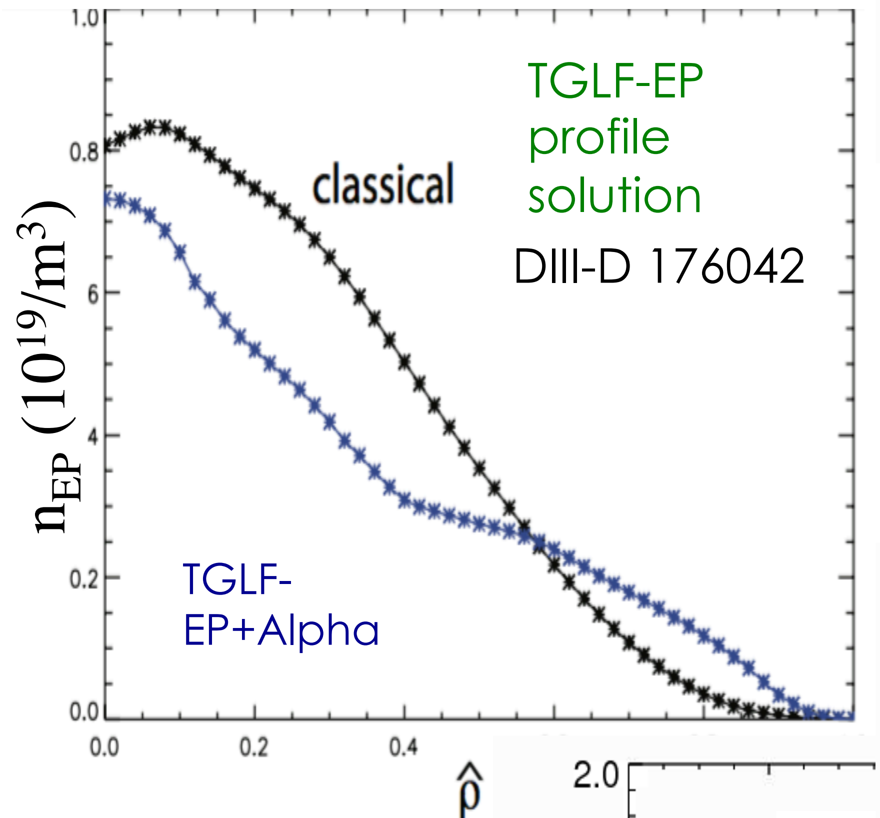
The TGLF-EP automated algorithm filters by frequency and eigenfunction (no tearing parity) to select only EP-driven AEs.

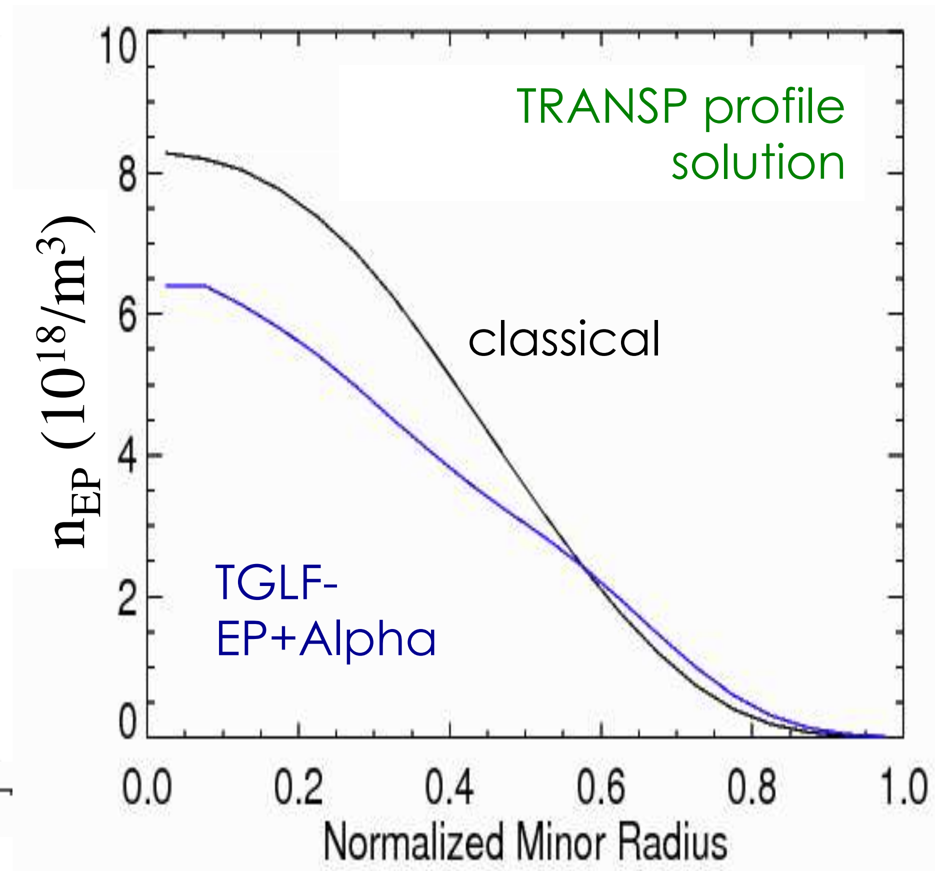
A range of toroidal n (actually $k_\theta \rho_{EP}$) tested and lowest critical gradient (earliest unstable) selected.

The present DIII-D cases have only one driving EP species: NBI ions.



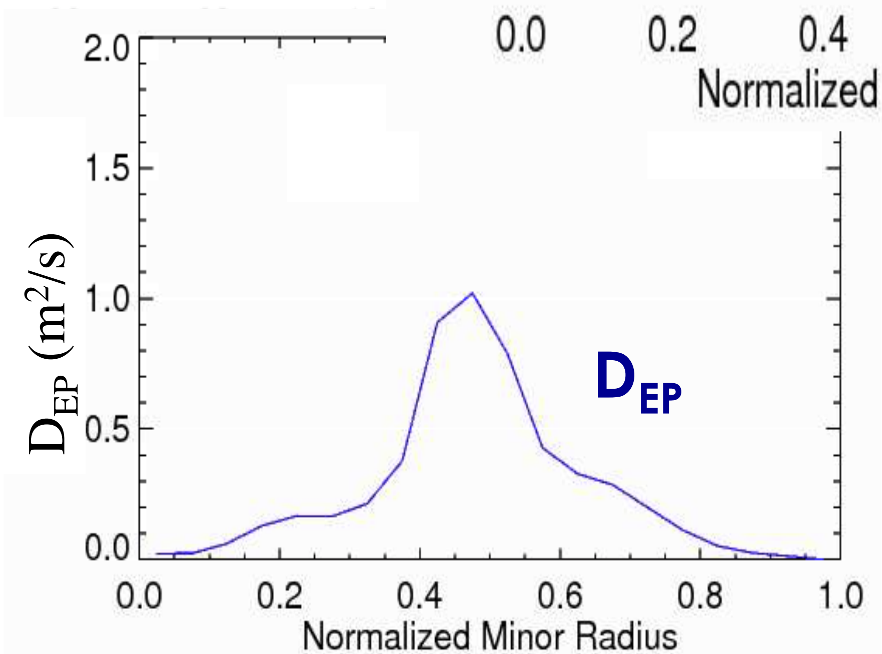
The TGLF-EP+Alpha validation workflow feeds the predicted EP diffusion coefficient back into TRANSP





TRANSP profile has "smearing" from finite orbits → more center drop.

TGLF-EP+Alpha gives both profile and D_{EP}.

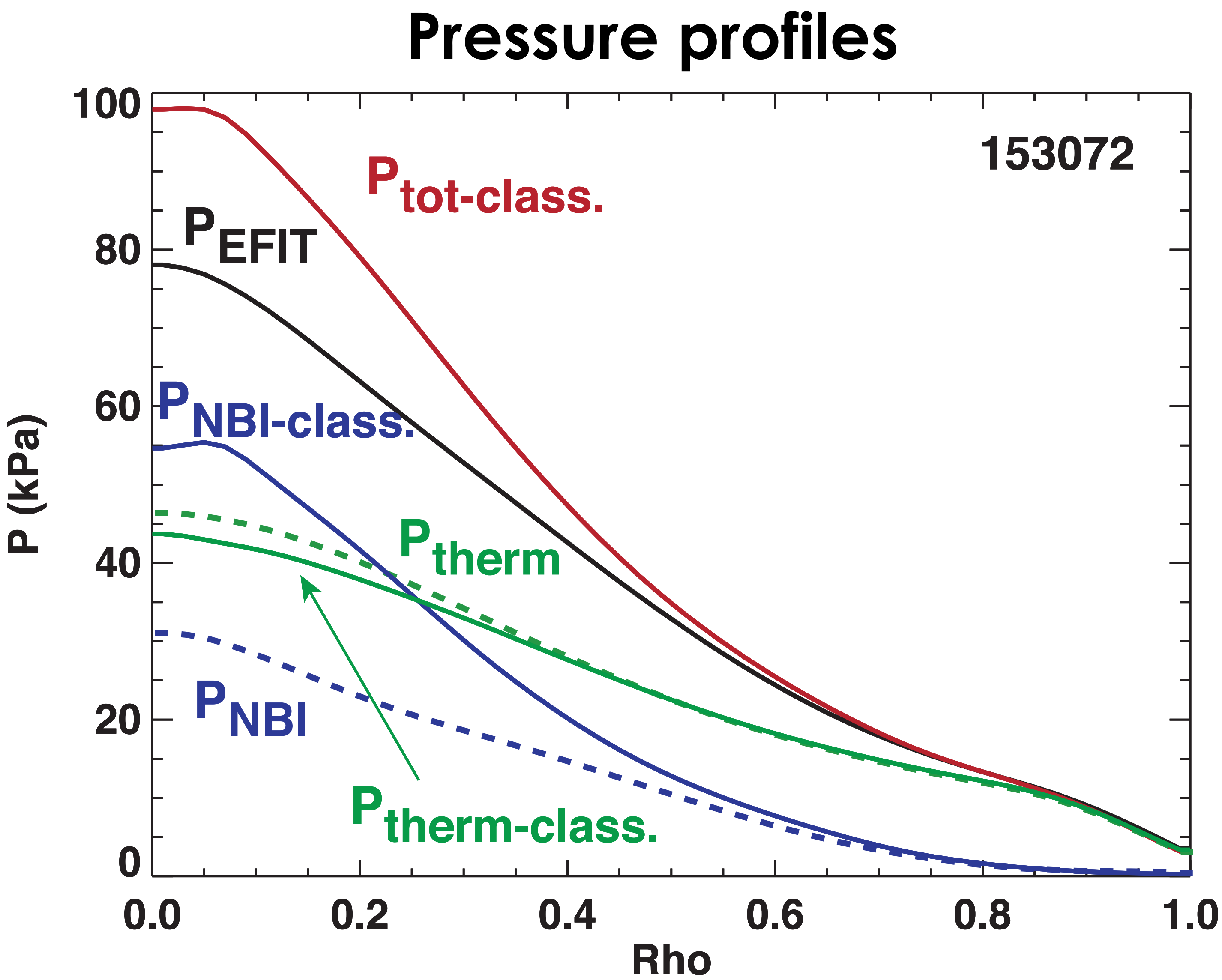


Feed D_{EP} back to TRANSP.

TRANSP enables "easy" calculation of neutron rate and FIDA signal.

Neutrons:
class/expt. ≈ 1.8
TGLF-EP/expt. ≈ 1.5

The experimental EP pressure profile is determined as the difference between EFIT total pressure and thermal pressure



EFIT finds a Grad-Shafronov pressure solution below the classical value.

The experimental NBI (beam EP) pressure is the **EFIT pressure minus thermal pressure**, with a small quasineutrality correction in the thermal pressure.

We will compare the TGLF-EP+Alpha+TRANSP pressure profile with this experimental beam EP pressure.

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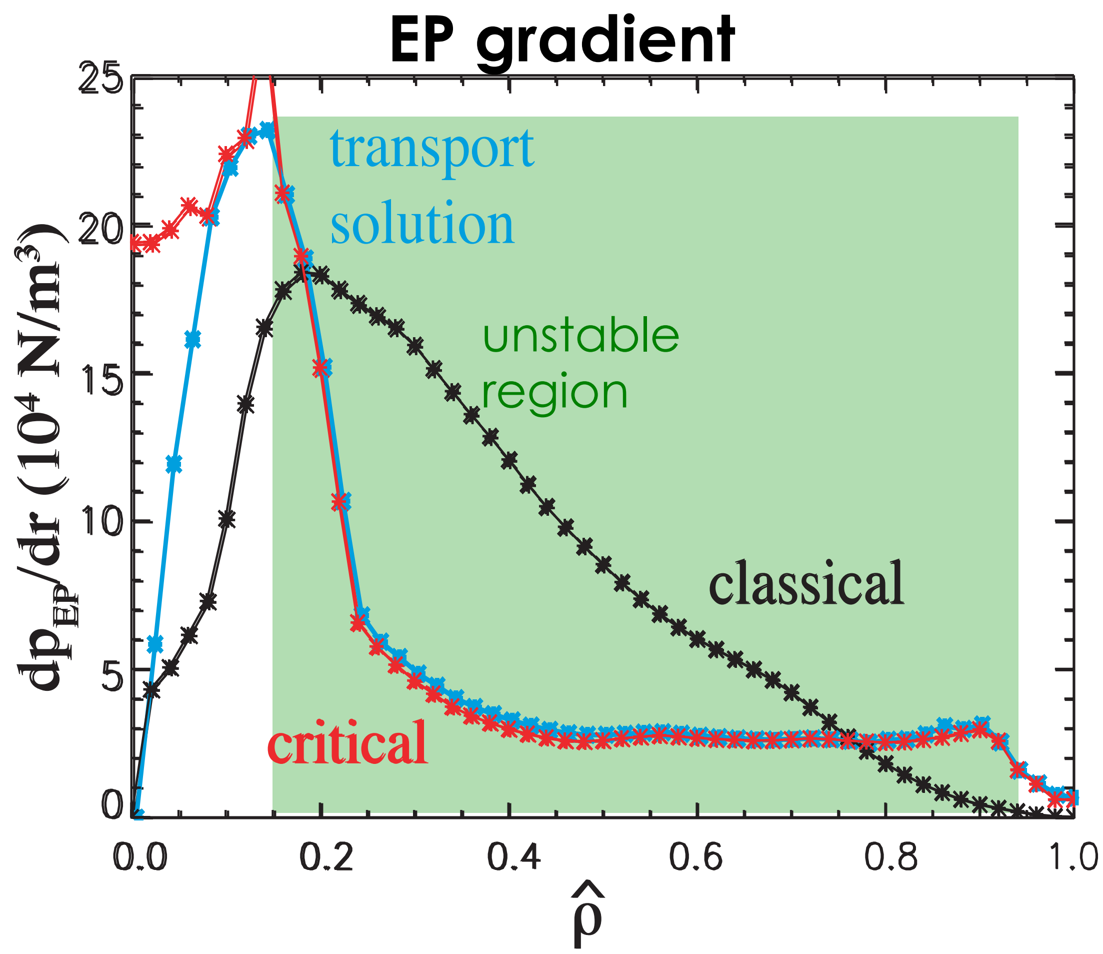
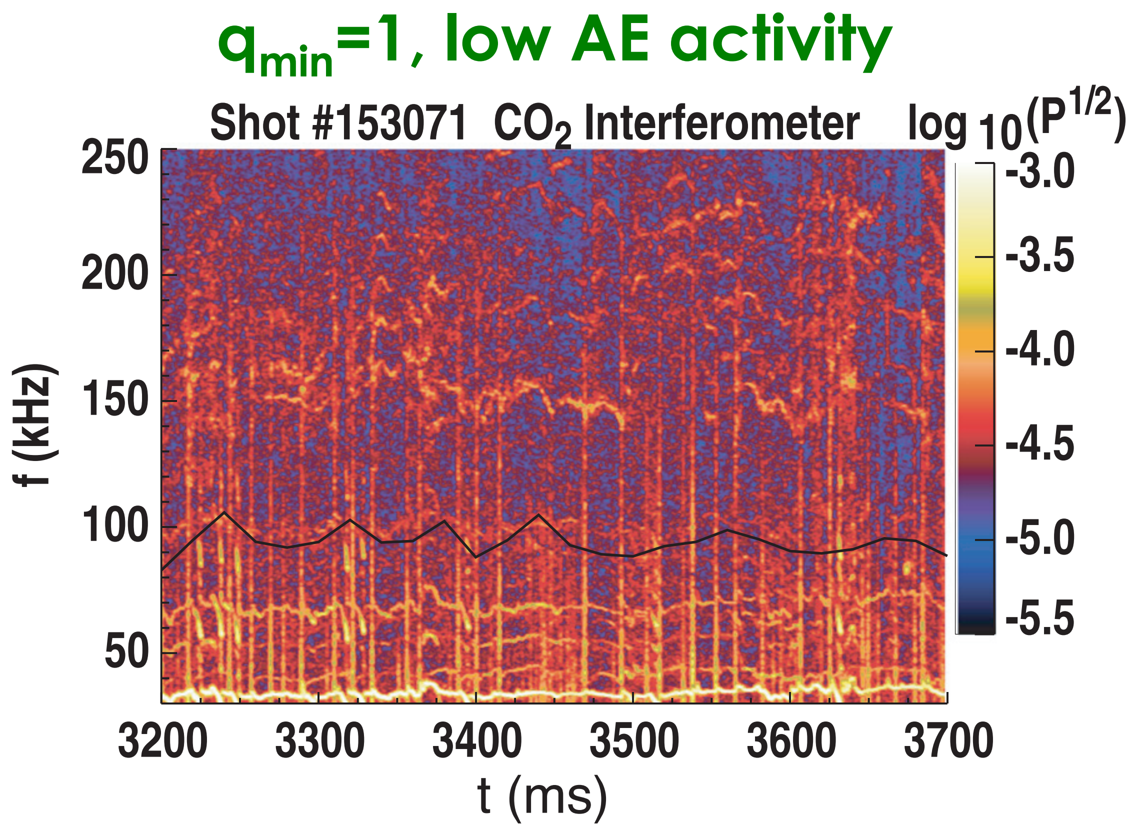
The q_{min}=1 case has finite but small transport





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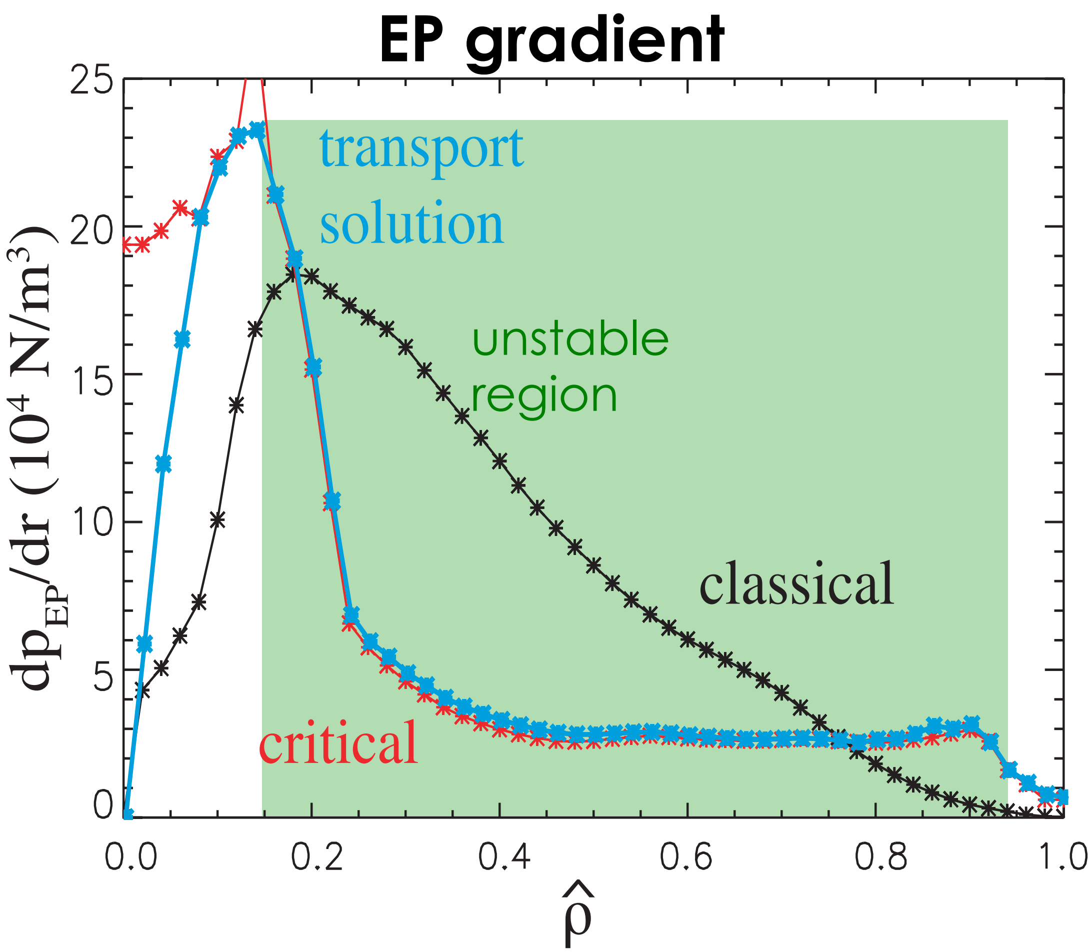
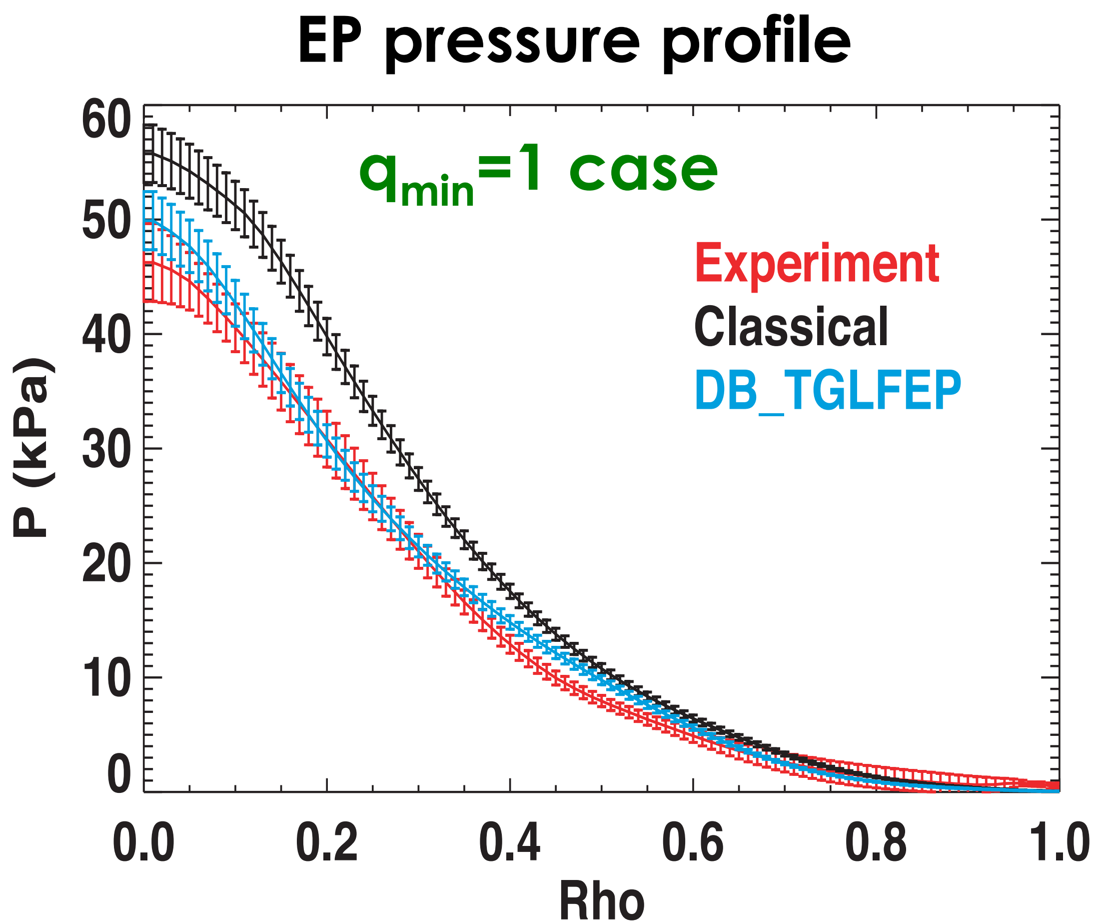




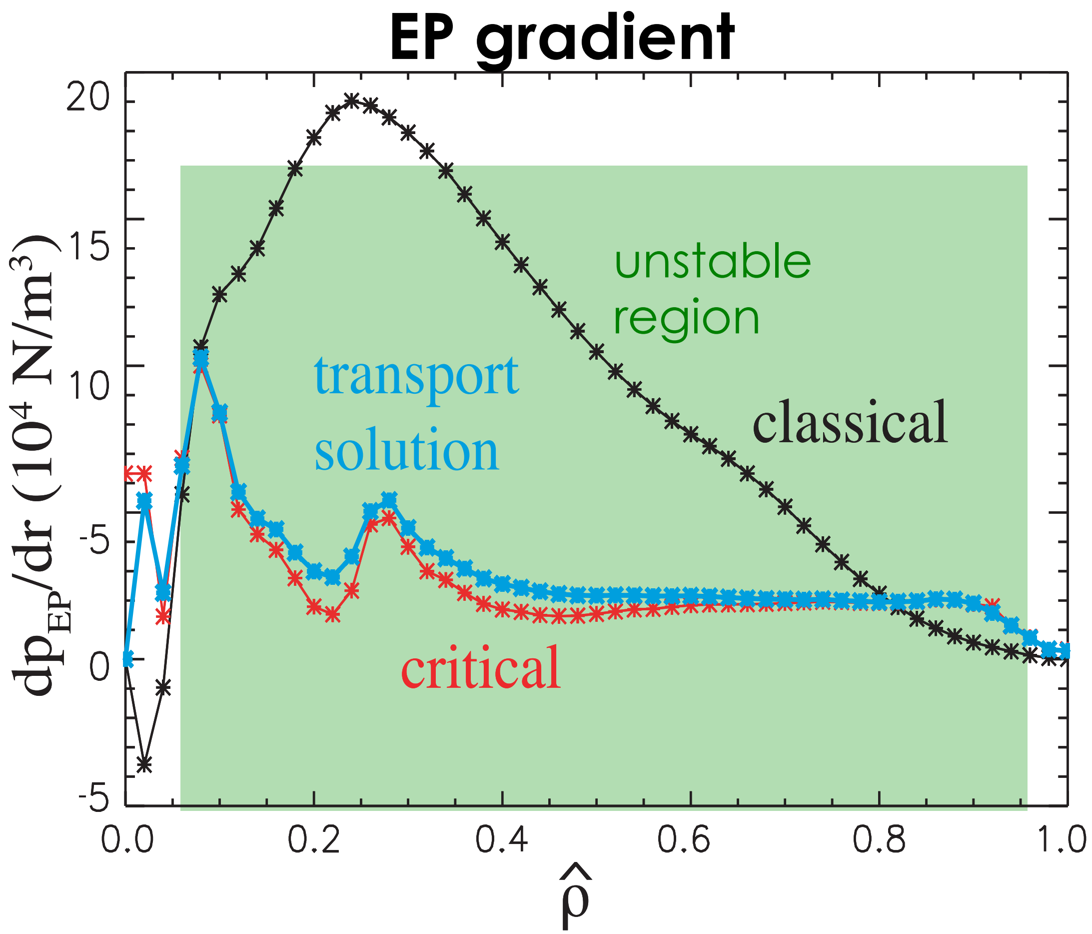
Neutrons:

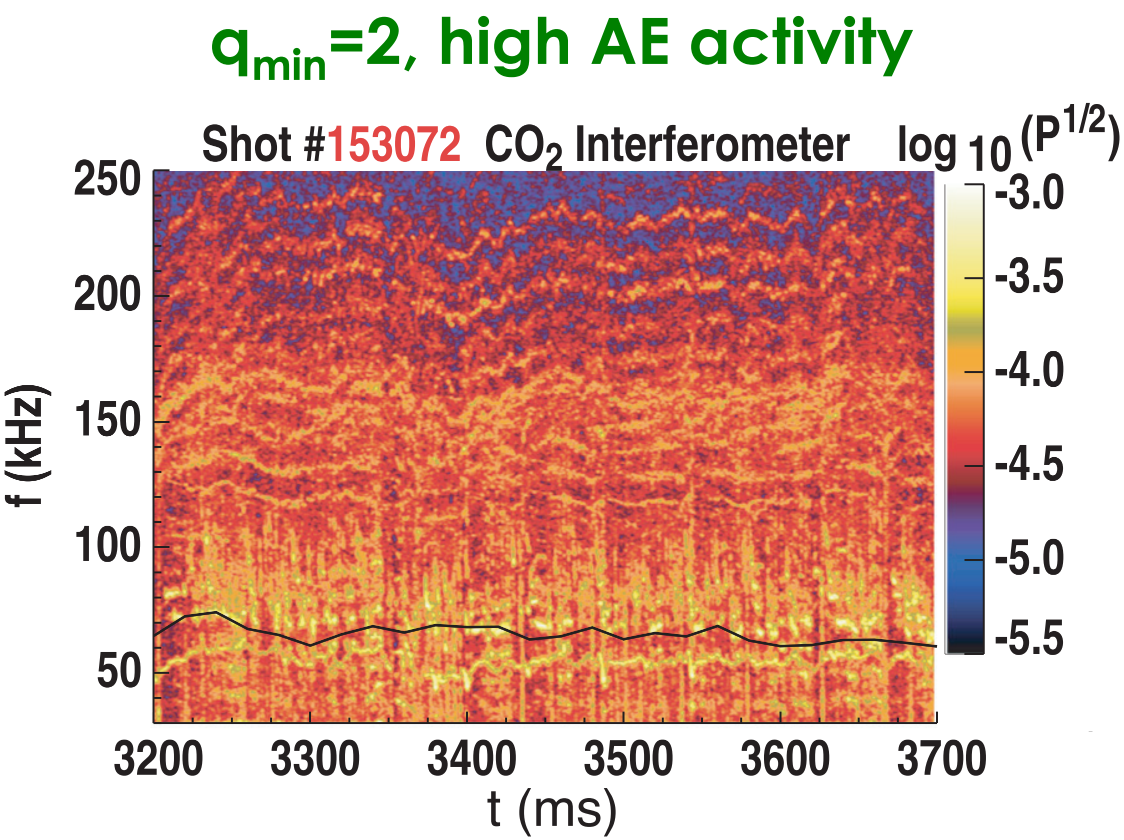
Classical/expt.: 1.23 ± 0.02

TGLF-EP+Alpha/expt.: 1.024 ± 0.02

Only very slight over-prediction of EP pressure and neutrons, **solid agreement**.

The q_{min}=2 case has much stronger AE transport





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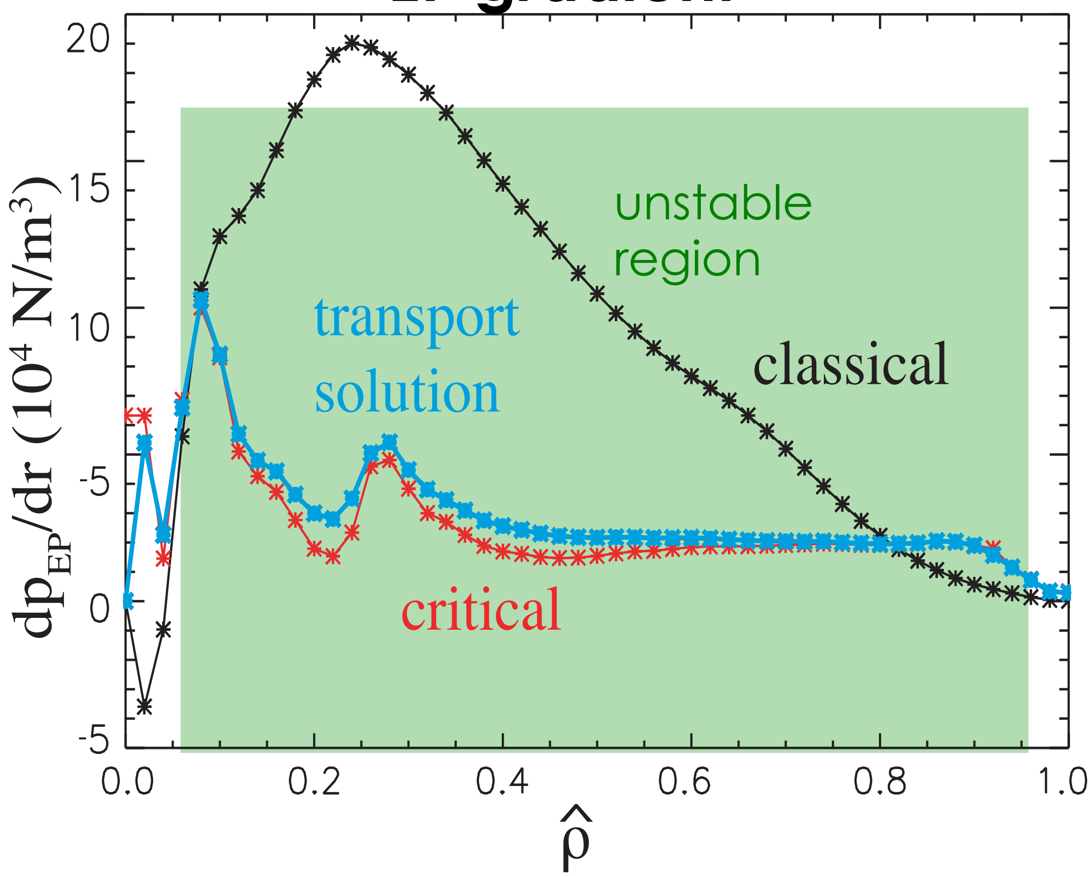
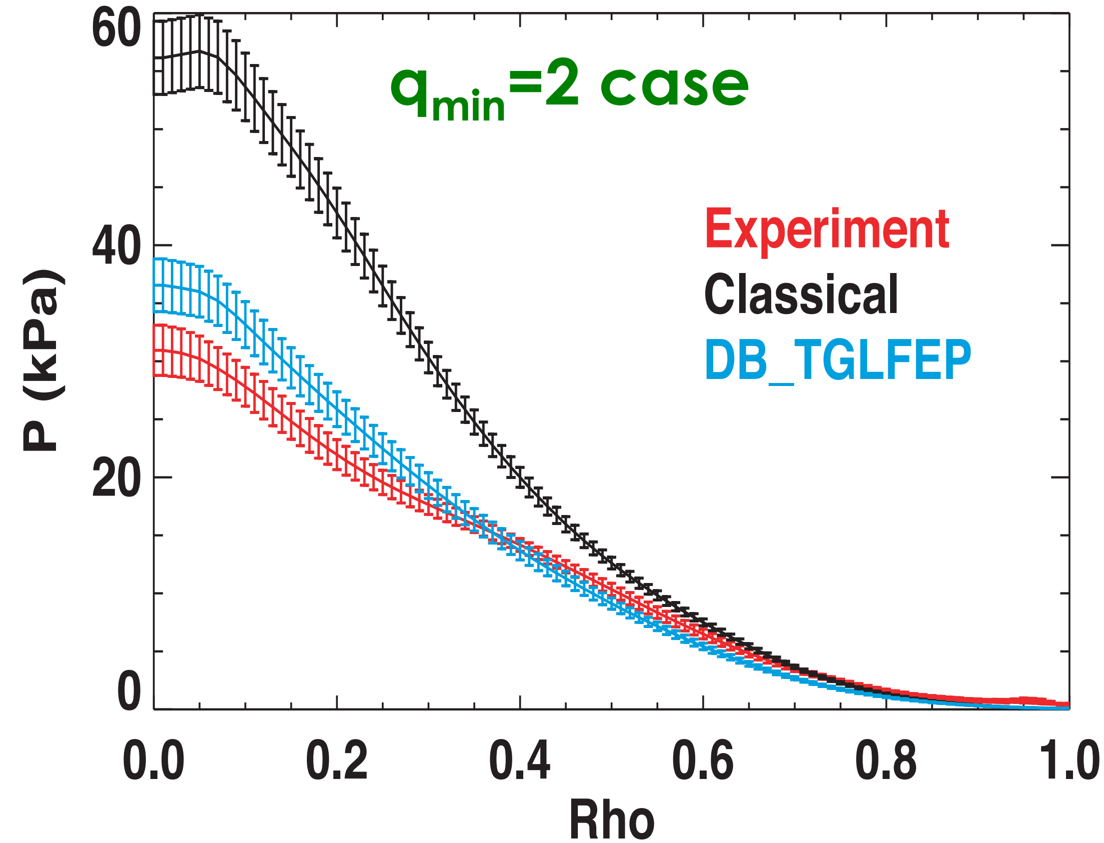
EP gradient



EP pressure profile



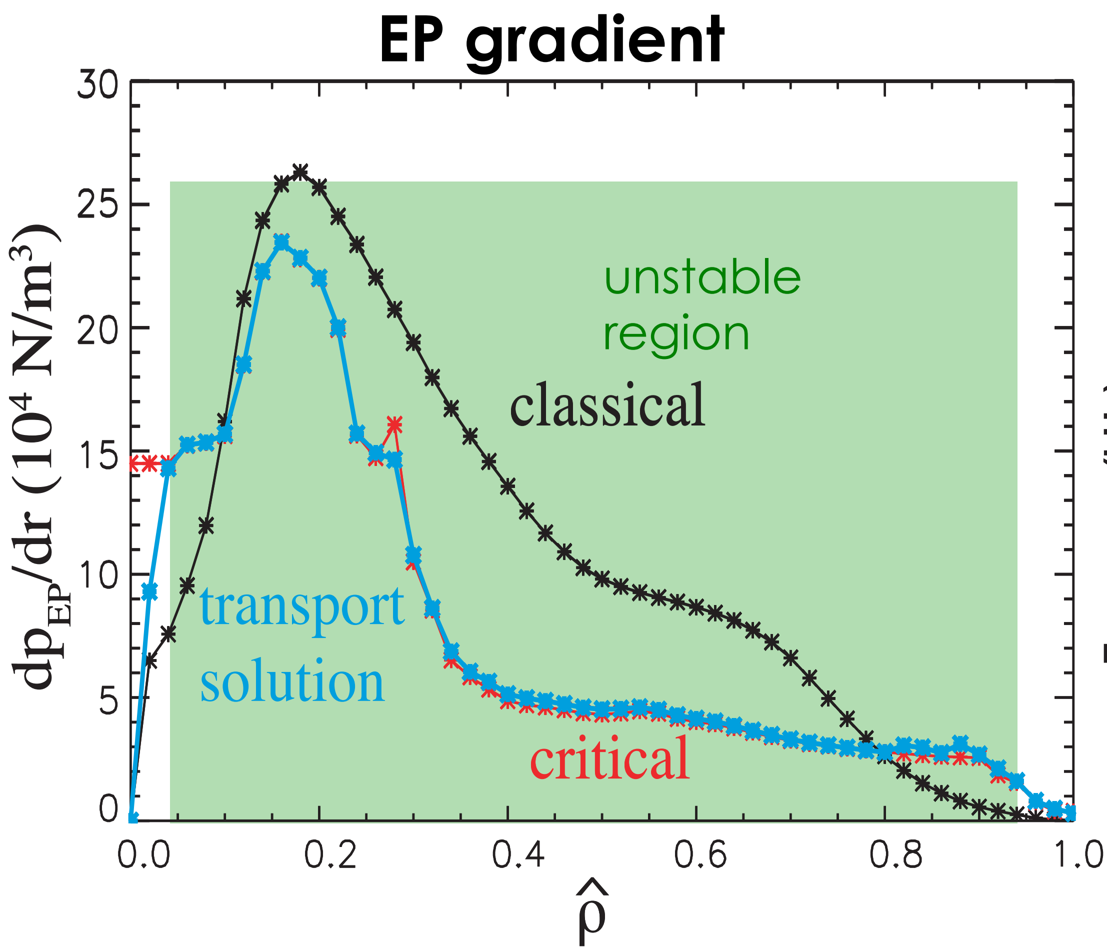
Neutrons:

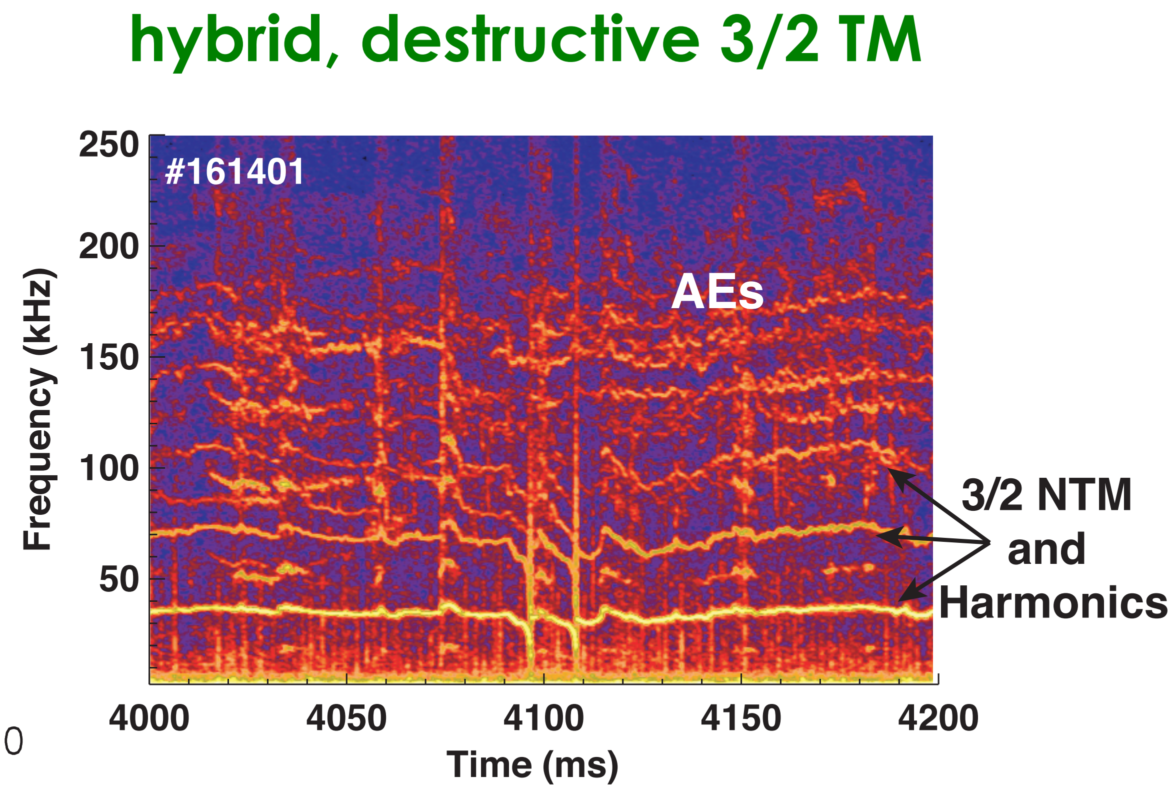
Classical/expt.: 1.79 ± 0.10

TGLF-EP+Alpha/expt. : 1.21 ± 0.06

Roughly 20% over-predicition of EP pressure and neutrons, but **trend (increase q → increase transport) clearly captured.**

The hybrid case has large EP loss from AEs and a tearing mode missed by TGLF-EP





D. Liu talk yesterday

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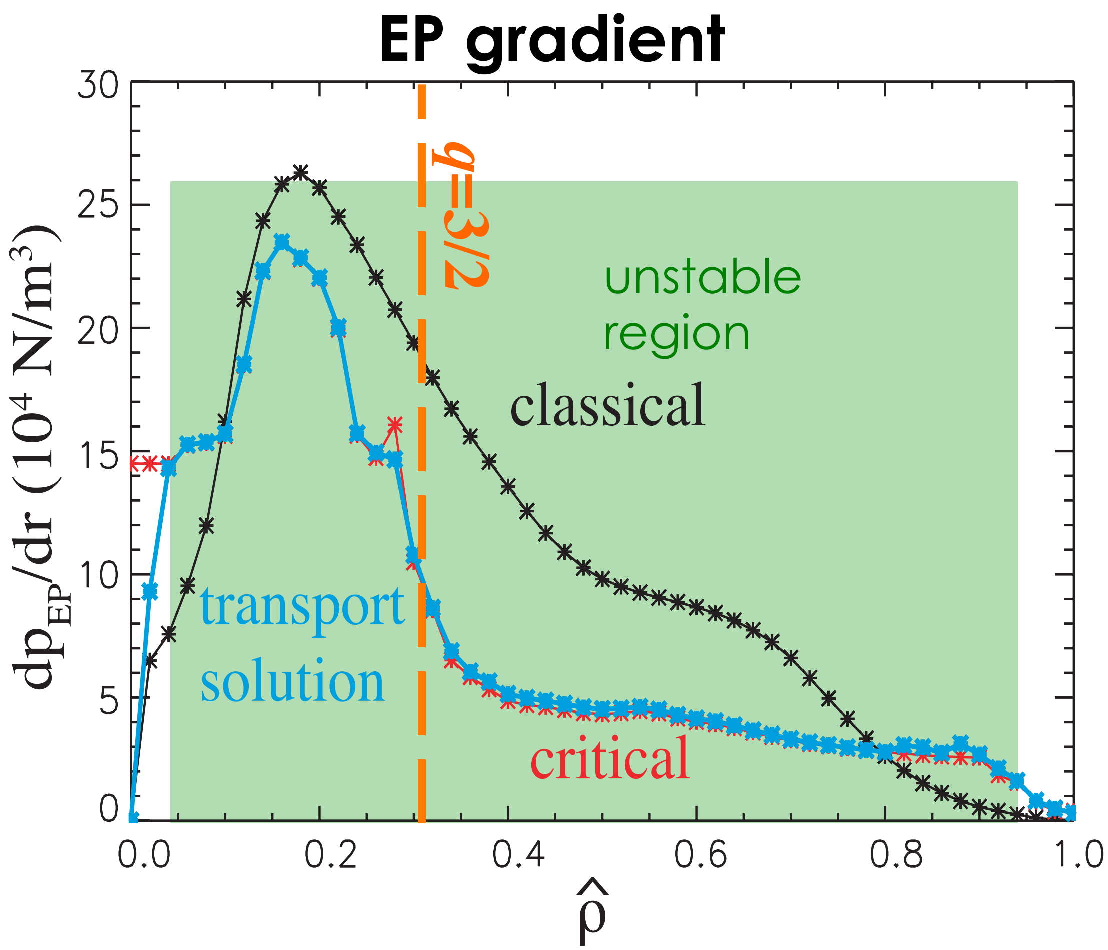
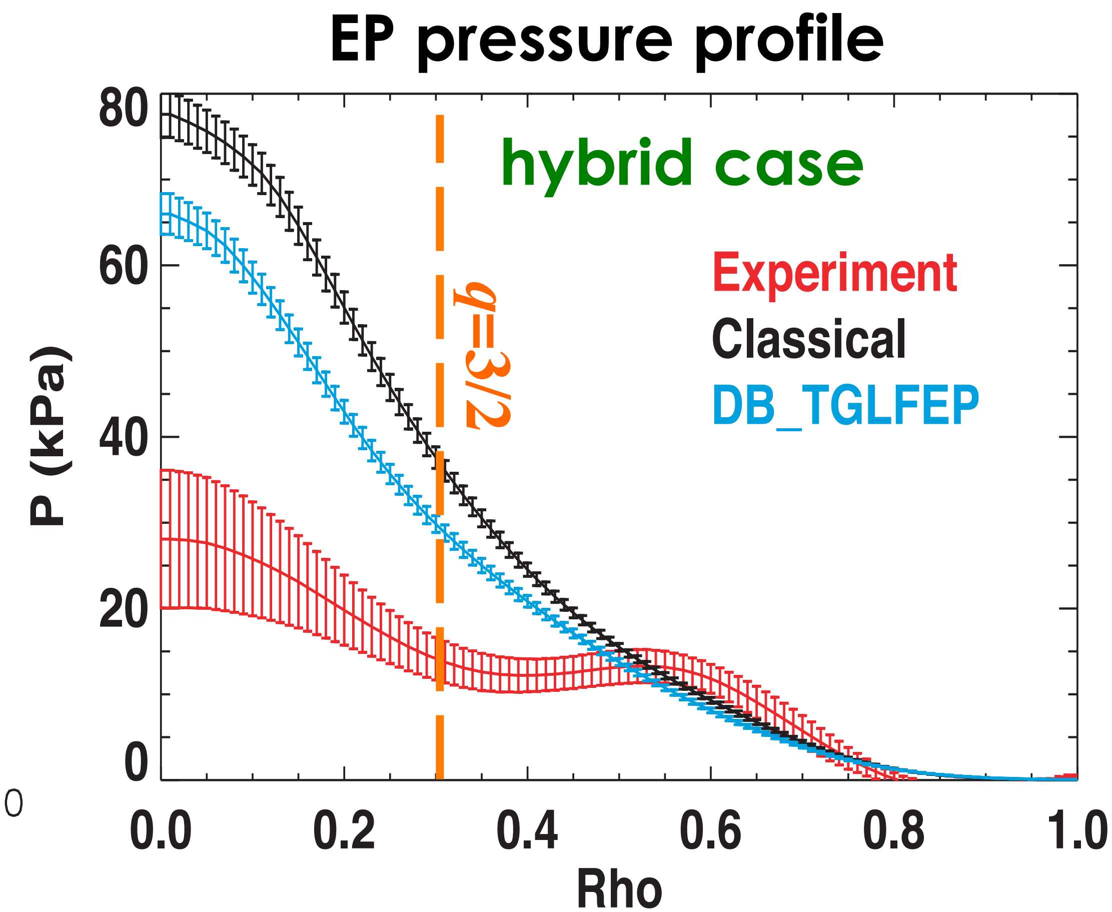




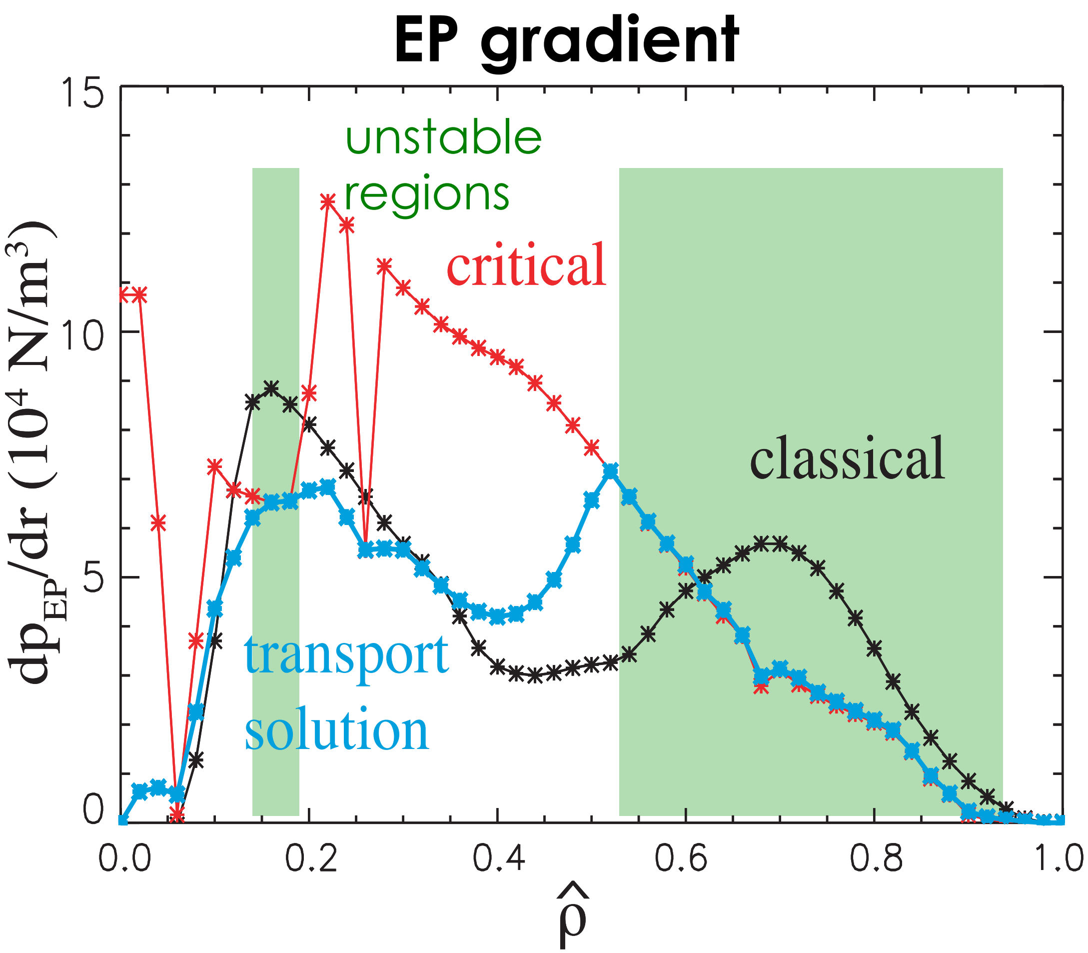
Neutrons:

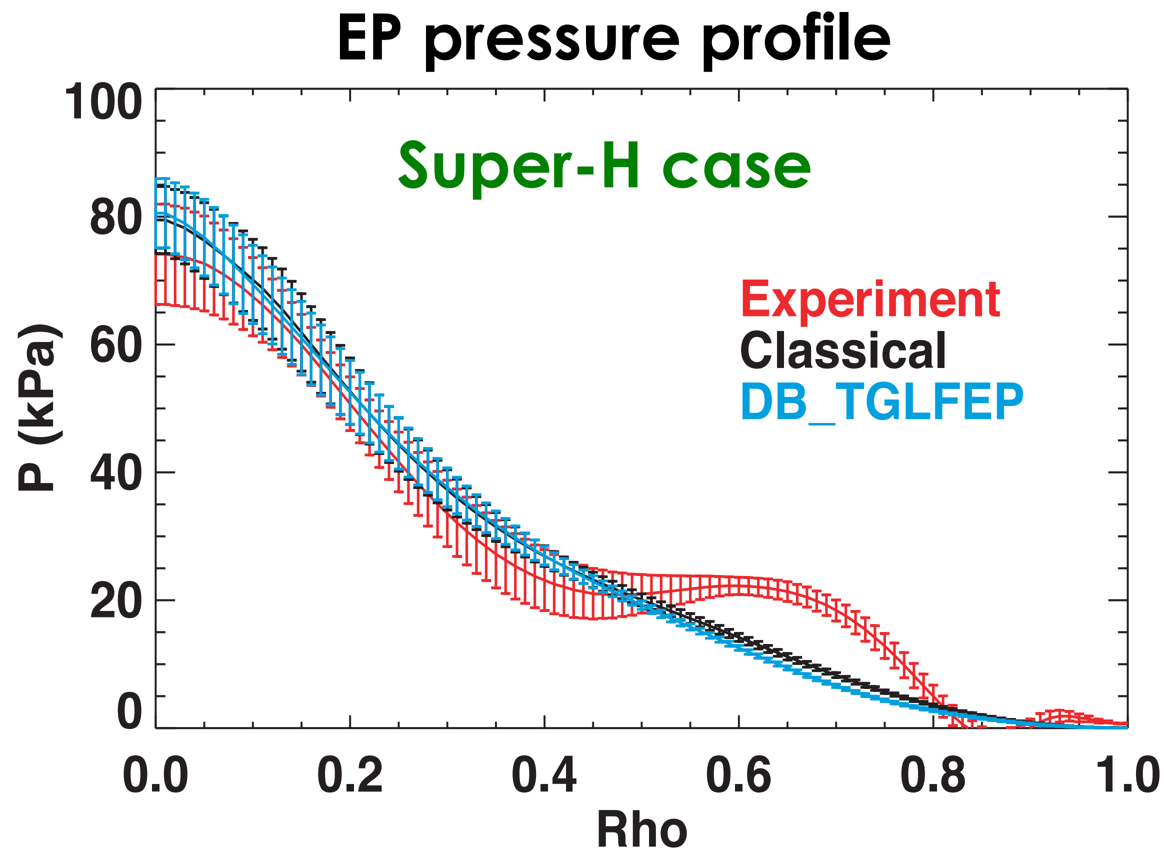
Classical/expt.: 1.66 ± 0.10

TGLF-EP+Alpha/expt.: 1.44 ± 0.09

Most experimental EP deficit unaccounted for. The observed **3/2 tearing mode** (missing in TGLF-EP) is the likely cause.

TGLF-EP shows very little AE activity in the super H-mode





Neutrons:

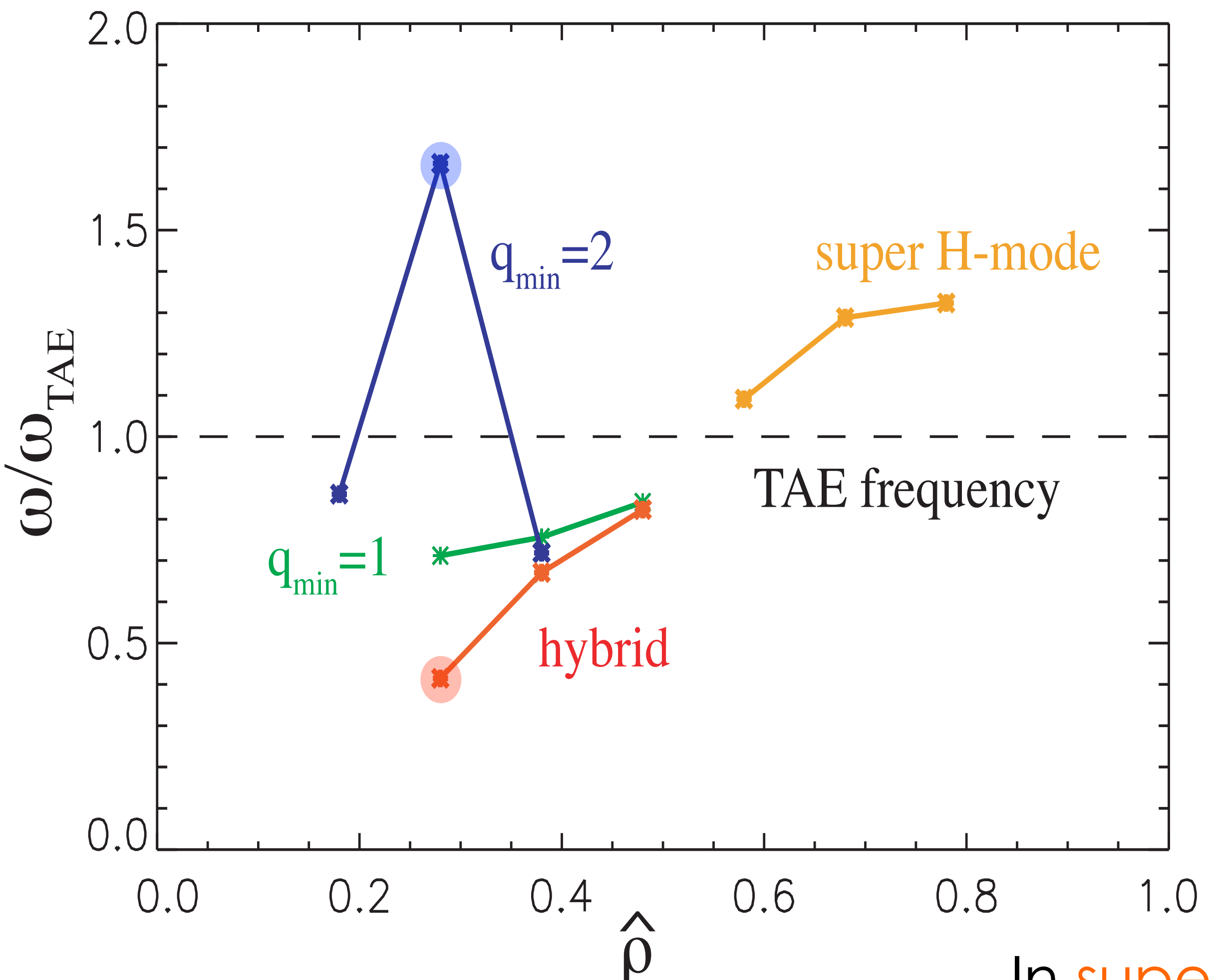
Classical/expt.: 0.99 ± 0.15

TGLF-EP+Alpha/expt. : 0.97± 0.15

Within fit error, neutrons and the **experiment and TGLF-EP+Alpha** EP pressure **are basically classical.**

Leading local mode frequencies span AE range, possibly BAEs or EAEs are present

Frequencies at radii near instability peak (most unstable $k_\theta \rho_{EP}$)



Frequency jumps across domain are uncommon, but sometimes occur.

Structure of $q_{min}=1$, $q_{min}=2$, and hybrid cases generally TAE-like: wide or double-peaked in ballooning angle.

Low frequencies in hybrid case might be BAEs (seen in M3D-K[1]).

In super H-mode case, most unstable modes are narrow in ballooning-space (low k_r). Possibly EAEs.

[1]Zhen-Zhen Ren et al., PoP **25**, 122504 (2018)

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Summary

- The TGLF-EP+Alpha critical gradient model of AE-EP transport has been validated across a wide range of DIII-D H-mode cases.

- TGLF-EP+Alpha agrees quite well with measurement even with the considerable simplifiations used (Maxwellian EPs; critical-gradient, 1D transport; local stability and transport)

- Significant disagreement is found in the hybrid case, where a non-AE mode (a 3/2 tearing mode) likely drives additional EP transport.

Improvements for the future:

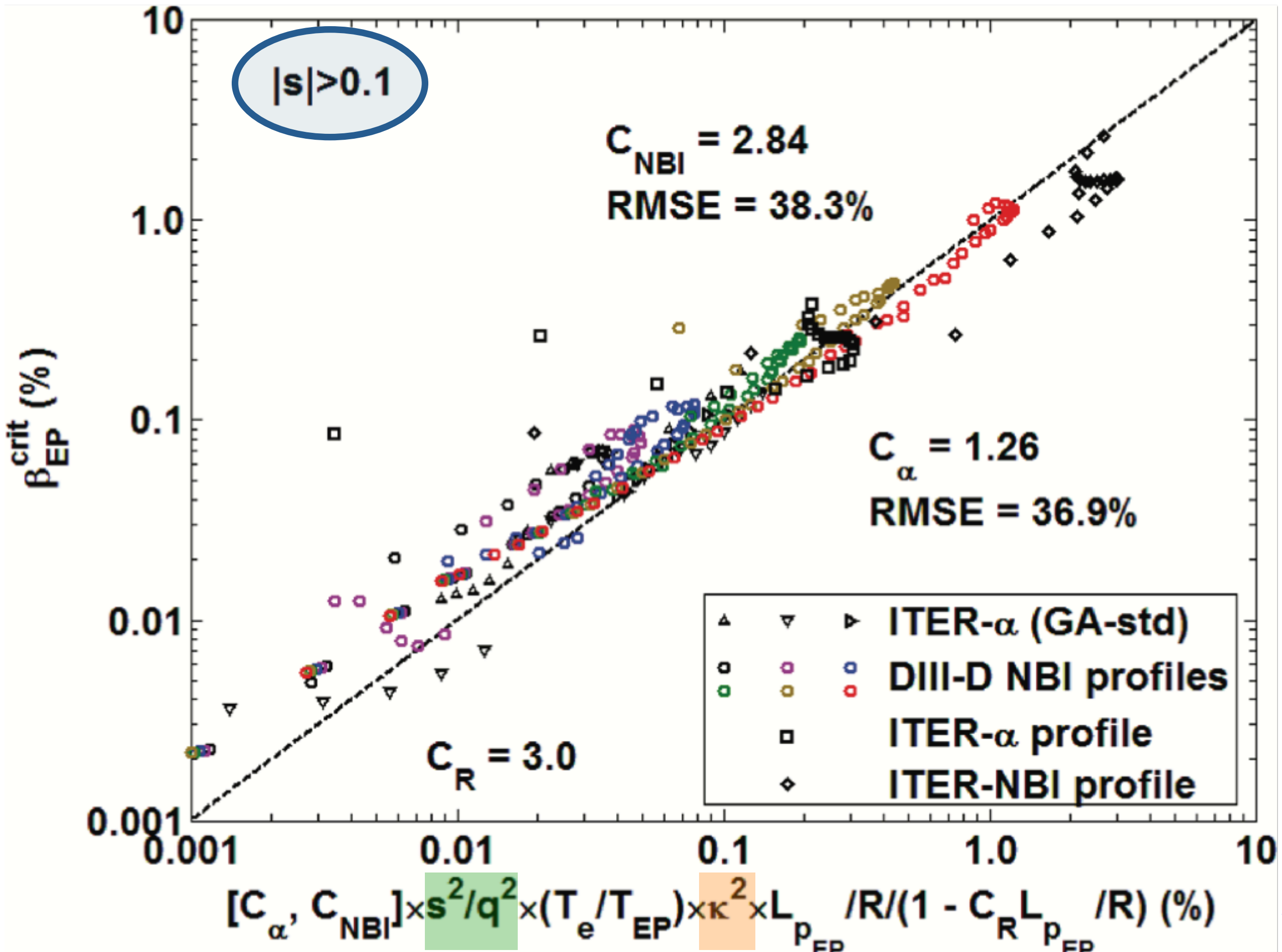
- Add energy dependence in D_{EP} from analytic model.
- Continue to streamline the workflow and make it accessible through OMFIT.
- Possibly add additional EP transport mechanisms (e.g., non-EP driven MHD).
- Pitch-angle dependence of transport (for torque and current drive modeling).
- Non-Maxwellian stability effects?

Table of plasma parameters

All values reported on axis. For q_{min}, the lowest q is always on or very near axis (ρ=0 discarded).

	β_e (%)	β_i (%)	β_{EP} (%)	q_{min}	B_t (T)	v_A/c_s
q_{min}=1	2.88	3.97	4.61	1.00	1.66	8.34
q_{min}=2	2.16	2.77	5.03	2.05	1.62	9.62
hybrid	2.54	3.93	5.72	1.24	1.80	8.87
super H-mode	5.13	8.02	1.78	1.24	2.03	6.25

Inexpensive, automated TGLF-EP confirms shear and elongation are stabilizing, higher *q* is destabilizing



The linear stability threshold (synonymous with the critical gradient absent thermal drive) spans at least three orders of magnitude for experimentally relevant parameters.

Empirical scaling of the critical EP gradient[1].

q profile dependence

Stronger elongation is also generally stabilizing.

But… Most transport occurs at very low shear, where *q* scaling is much weaker.

We will see that the *q* profile matters surprisingly little in practice.

[1]He Sheng et al., PoP **24**, 072305 (2017)