Alfvén eigenmodes (AE) degrade fast-ion confinement in high β_N, steady-state scenarios

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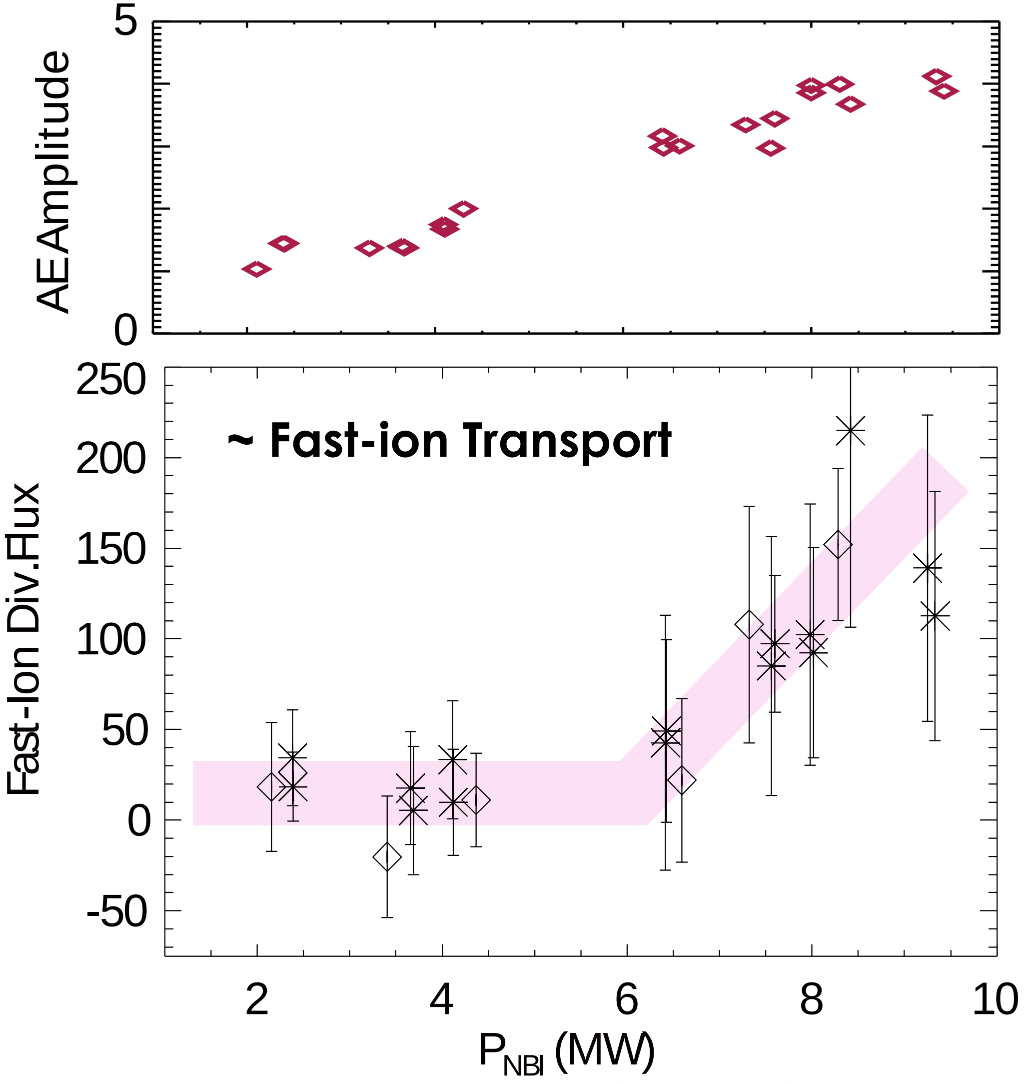
[5]Institute of Plasma Physics Chinese Academy of Science
[6]Princeton Plasma Physics Laboratory
[7]Oak Ridge National Laboratory



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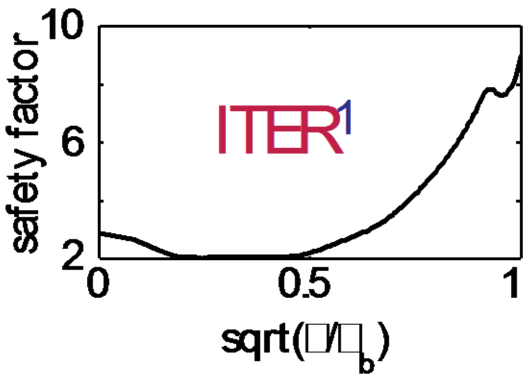
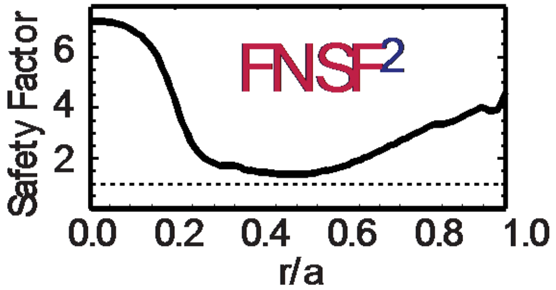
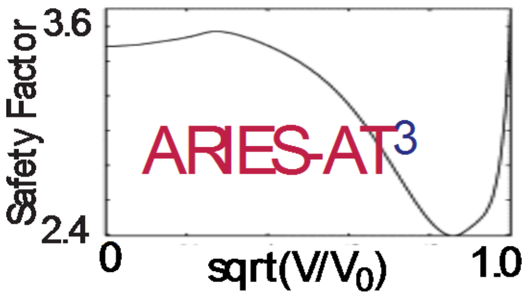
UCIrvine University of California, Irvine

Steady-state Advanced Tokamak (AT) scenarios often have elevated values of safety factor q

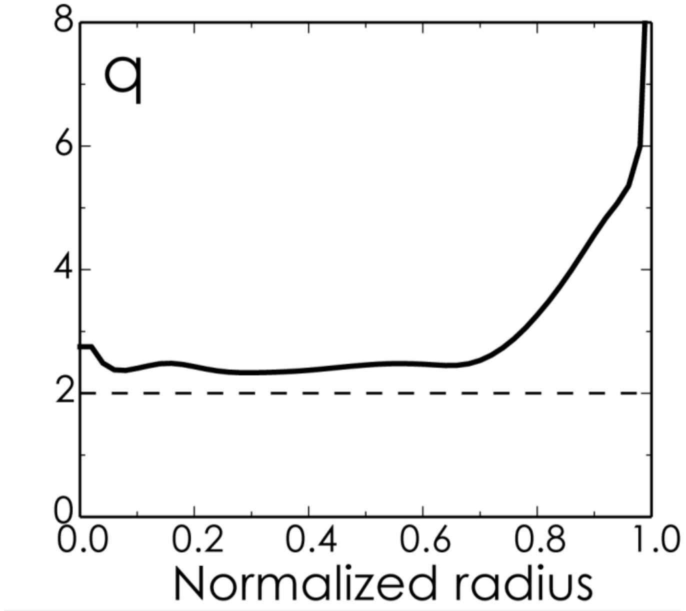






1) Poli, NF **54** (2014)
2) Garofalo, NF **54** (2014)
3) Kessel, FED **80** (2006)

- **Projections predict a stable β_N=5 steady-state scenario in DIII-D with increased ECCD and off-axis NBI**

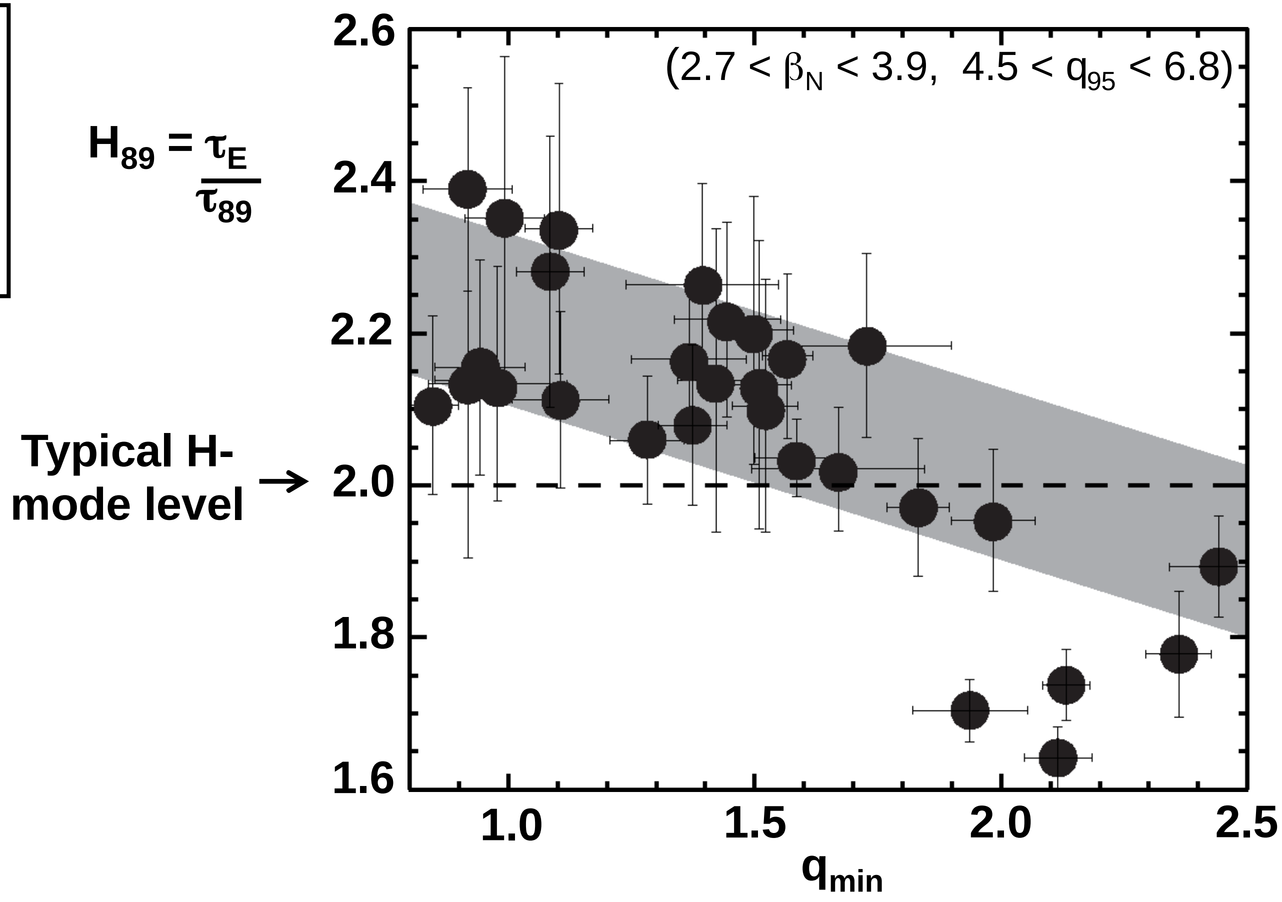


J.M. Park, APS (2013)

Many DIII-D discharges with q_{min}>2 have poor global confinement

Is degraded fast-ion confinement the culprit?

Uses Thermal + Fast Ion Stored Energy

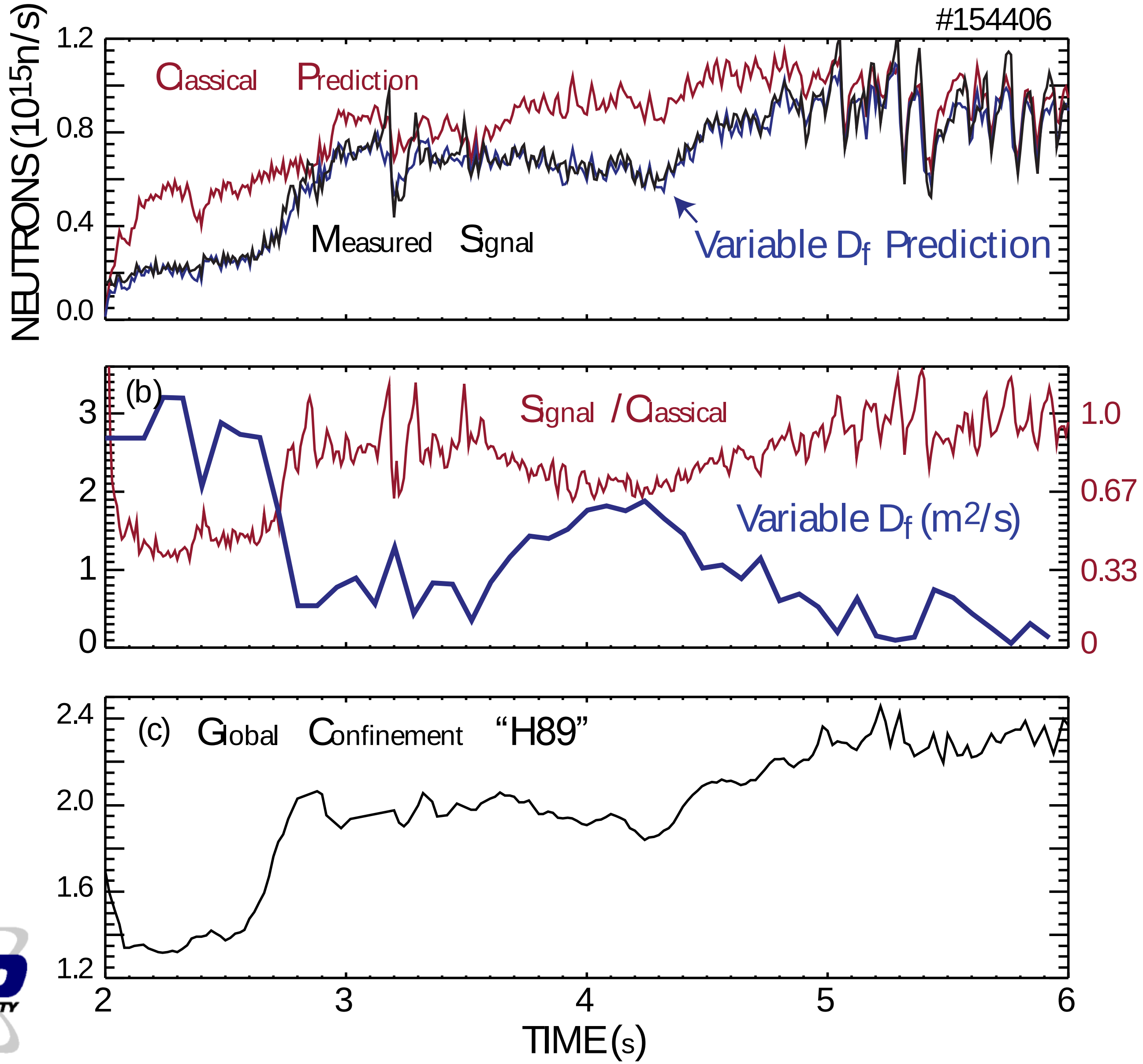


Ferron, PoP **20** (2013) 092504

Outline

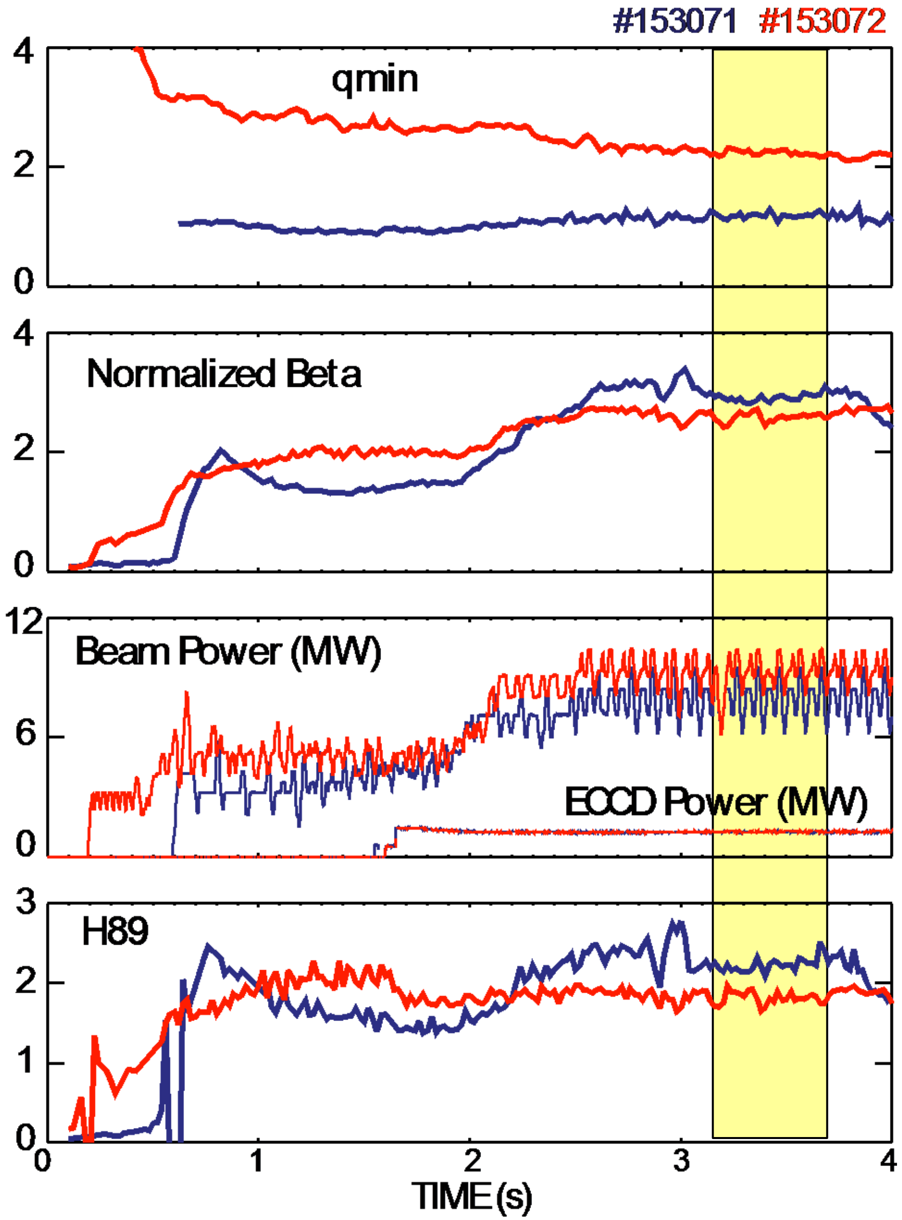
1. AEs degrade fast-ion confinement in many steady-state scenario discharges
2. Degradation of fast-ion confinement can account for the overall degradation in global confinement
3. Physical mechanism of fast-ion transport: critical gradient behavior due to many wave-particle resonances
4. Outlook

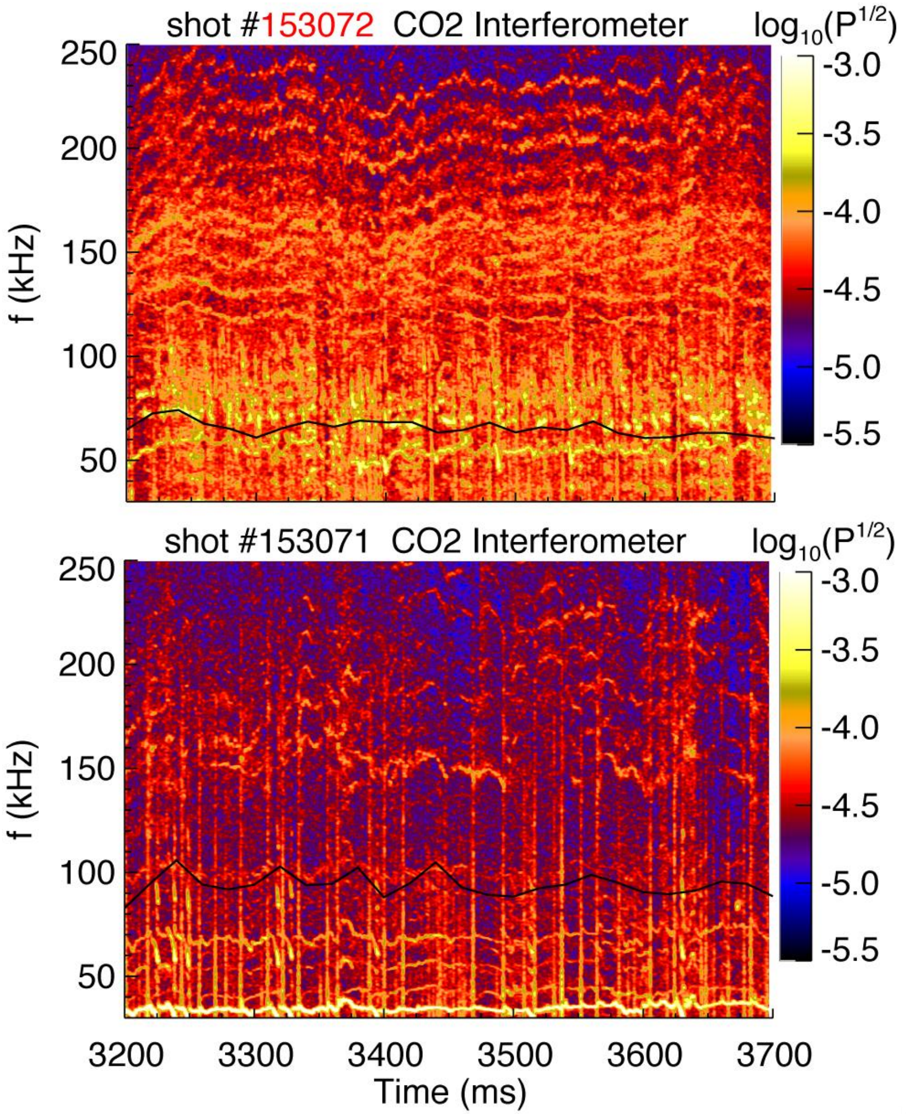
Use TRANSP to quantify the degradation in fast-ion signals



- **Use spatially uniform *ad hoc* fast-ion diffusion D_f in TRANSP as an empirical measure of degraded fast-ion confinement**
- **Alternatively, use ratio of signal to "classical" prediction**
- **Global confinement varies with fast-ion confinement**

The qmin~2 discharge has more AEs and worse confinement than the qmin~1 discharge





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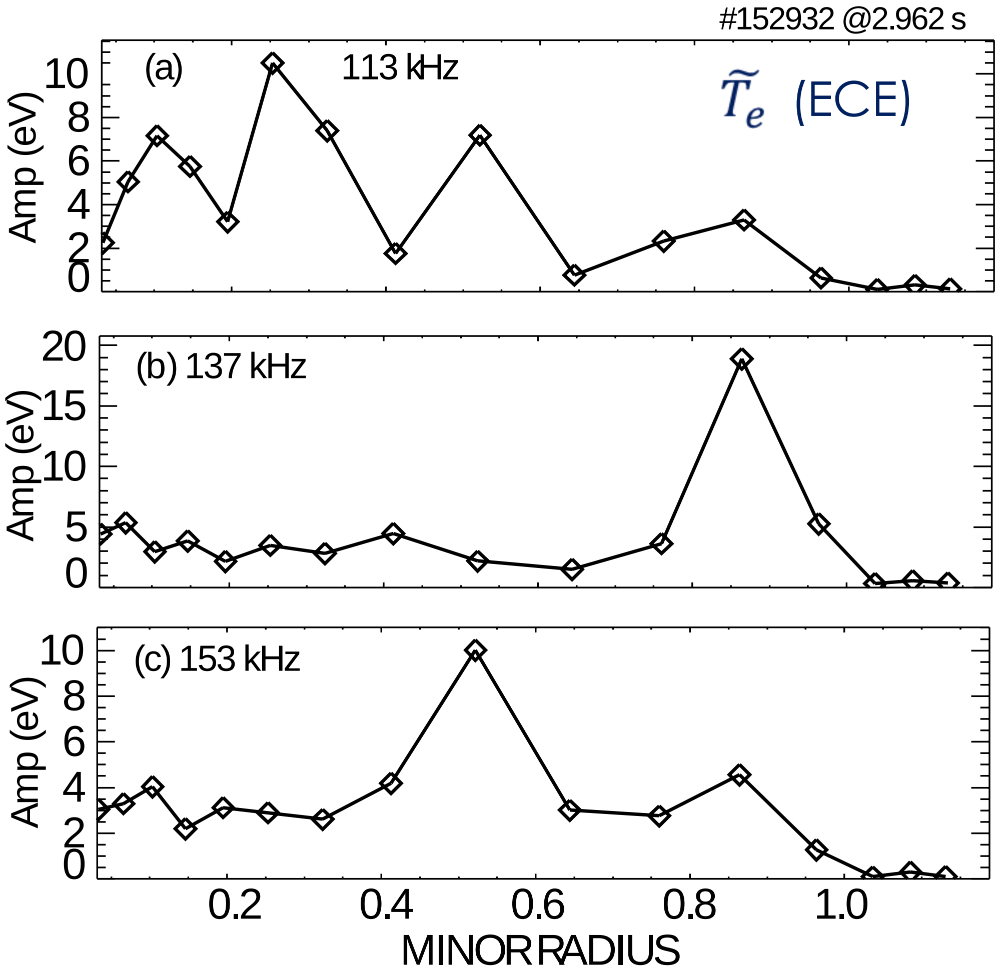
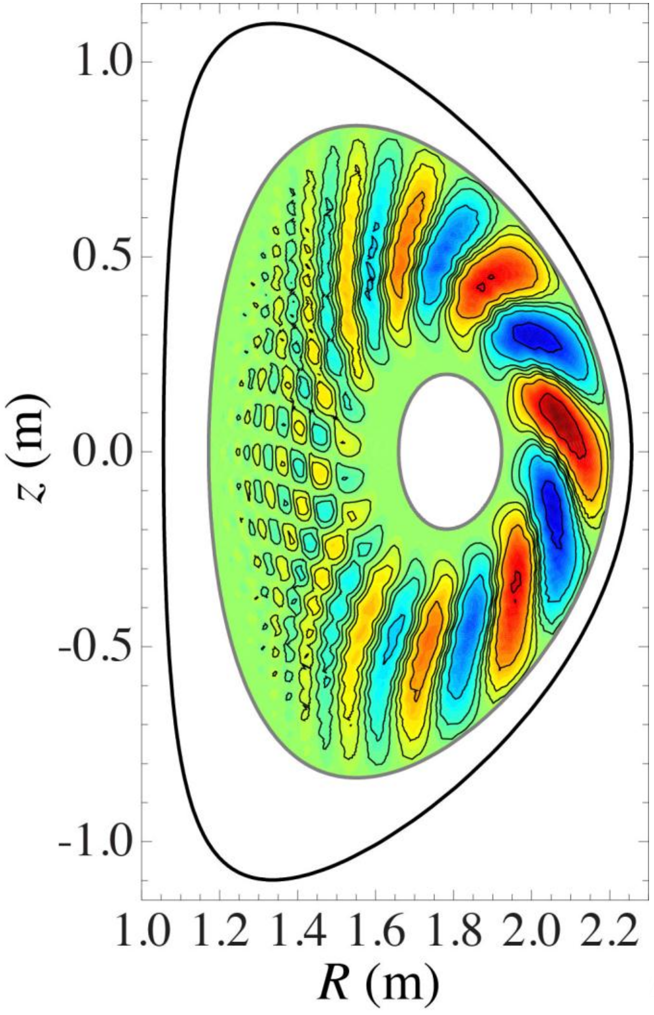
Many Alfvén Eigenmodes are Observed & Expected

Measured Simultaneous Modes



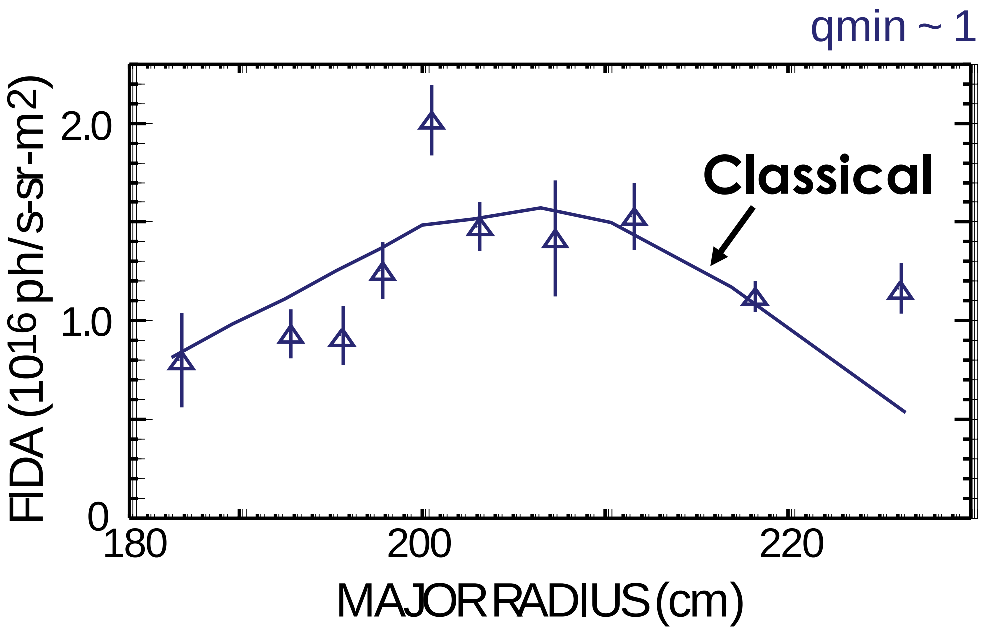
Typical toroidal mode numbers: 2-5

Calculated Unstable TAE



GYRO

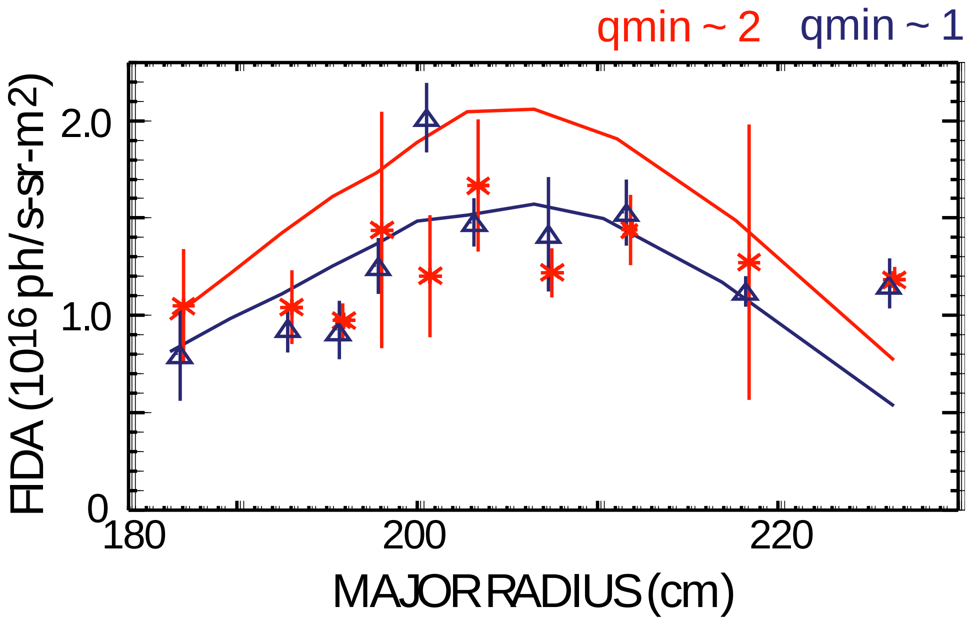
q_{min}~1 data agree with predicted fast-ion signals



Ratio of signal to calculated predictions

	Classical △
Neutrons	89%
W_{fast}	100%

q_{min}~1 data agree with predicted fast-ion signals but q_{min}~2 data do not



Ratio of signal to calculated predictions

	Classical △	Classical ∗
Neutrons	89%	61%
W_{fast}	100%	72%

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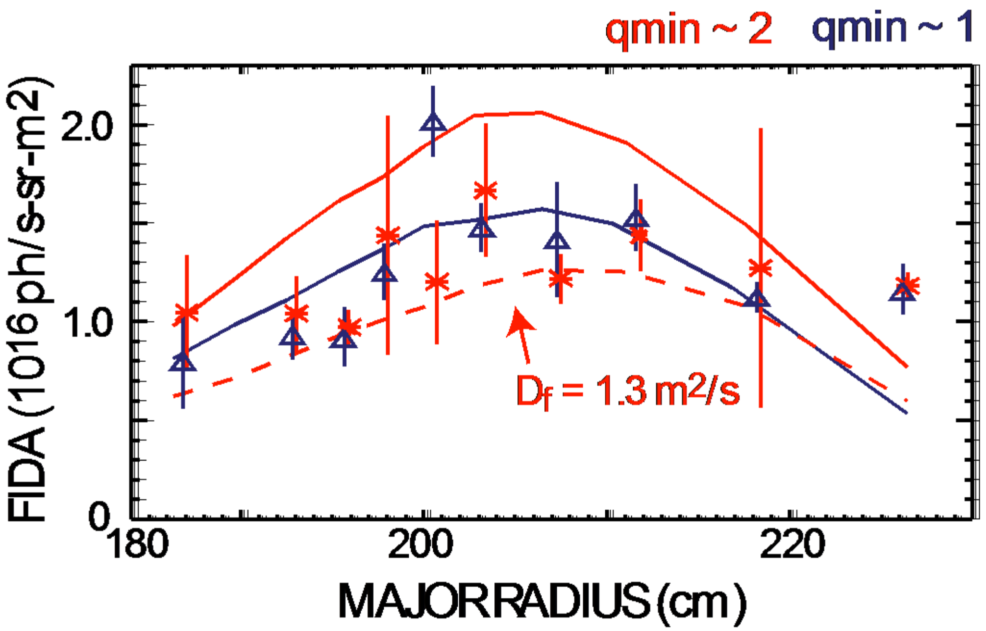
Assuming fast-ion diffusion of 1.3 m^2/s gives approximate agreement with qmin~2 data

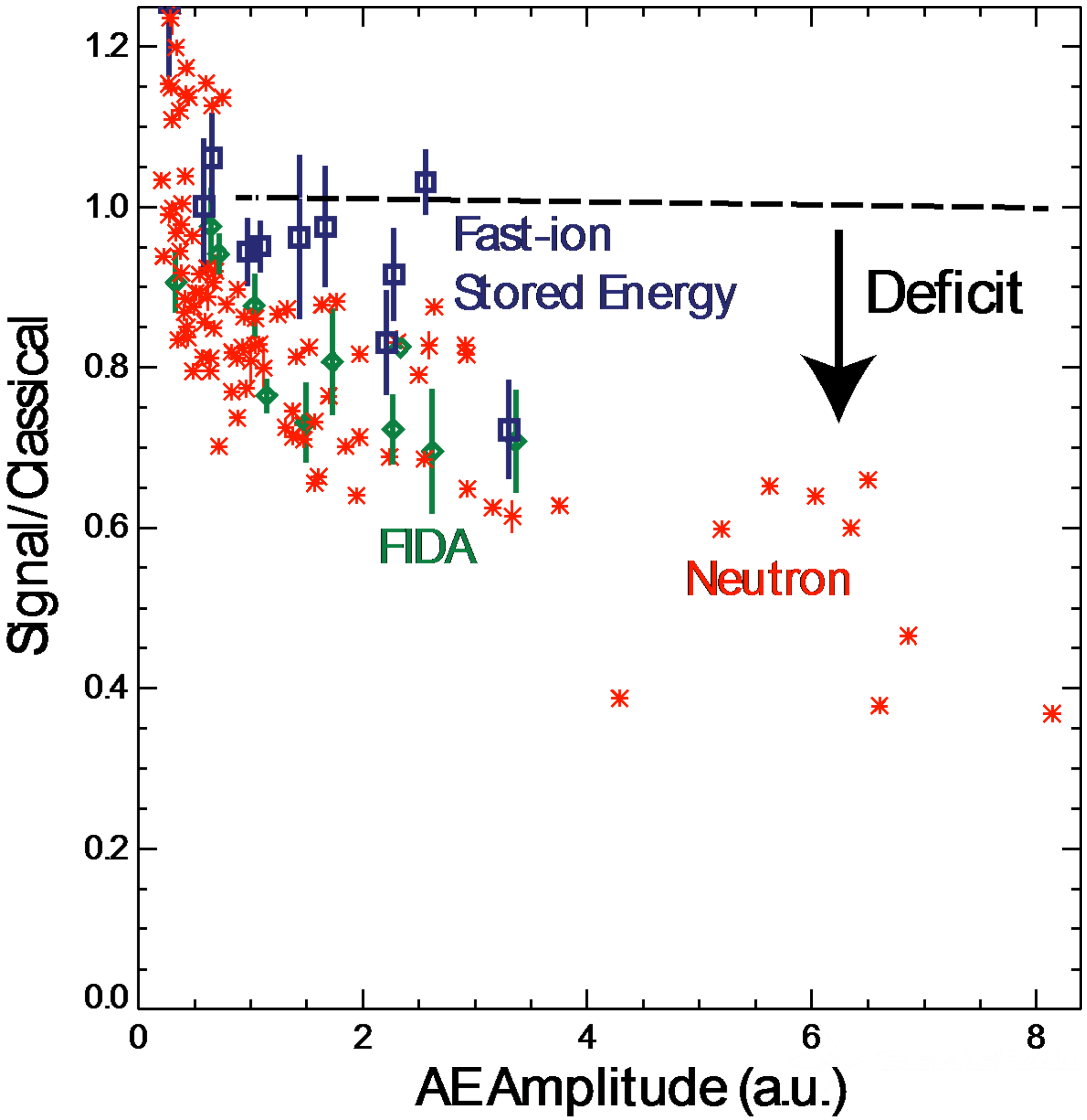


Ratio of signal to calculated predictions

	Classical △	Classical	D_f *
Neutrons	89%	61%	91%
W_{fast}	100%	72%	108%

Degraded fast-ion signals correlate with increasing Alfvén eigenmode activity

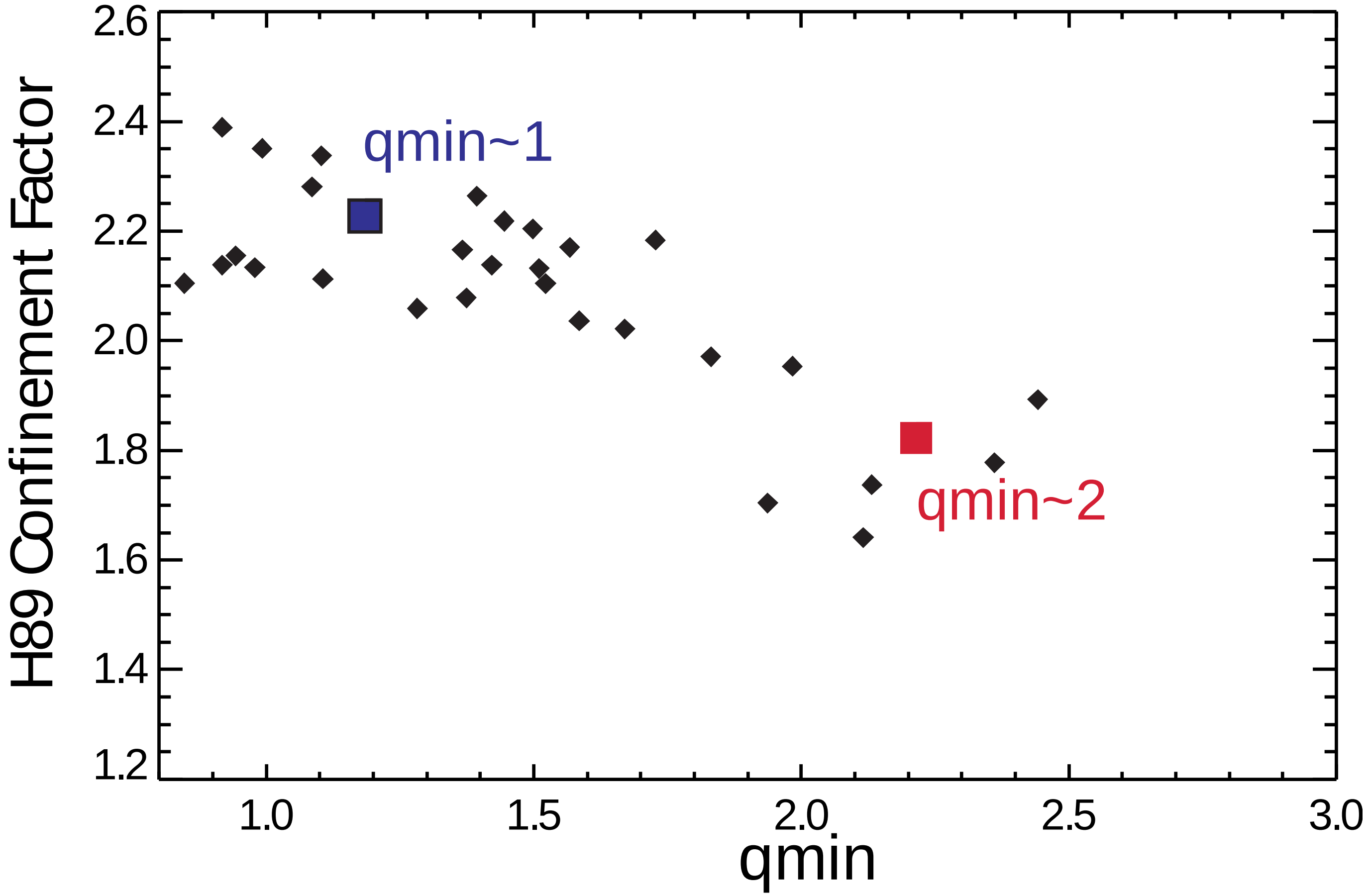
- Every diagnostic that is sensitive to co-passing fast ions measures reductions
- The "AE Amplitude" is the average amplitude of coherent modes in the TAE band (from interferometer signals)
- Data from quasi-stationary portion of steady-state scenario discharges



Outline

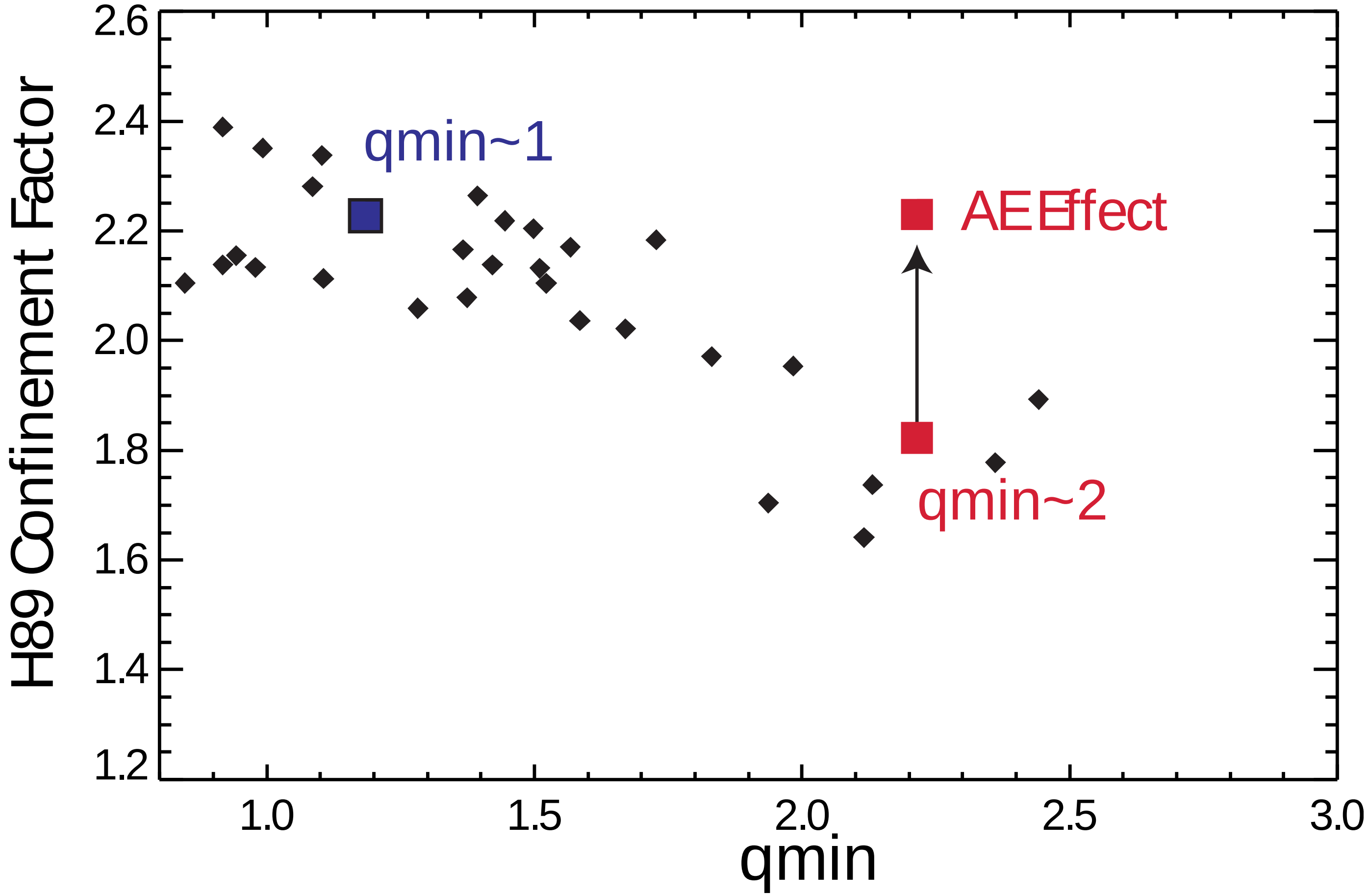
1. AEs degrade fast-ion confinement in steady-state scenario discharges
2. Degradation of fast-ion confinement can account for the overall degradation in global confinement
3. Physical mechanism of fast-ion transport: critical gradient behavior due to many wave-particle resonances
4. Outlook

Enhanced fast-ion transport can explain the apparent reduction in thermal confinement at high qmin



- **Compare two matched discharges: qmin ~ 1 & qmin ~ 2**

Enhanced fast-ion transport can explain the apparent reduction in thermal confinement at high qmin



- Compare power balance in **qmin ~ 2 shot**: Classical vs. D_f=1.3 m^2/s
- Reduced fast-ion stored energy
- Less power delivered to thermal plasma

→ Thermal diffusivities like qmin ~1 discharge

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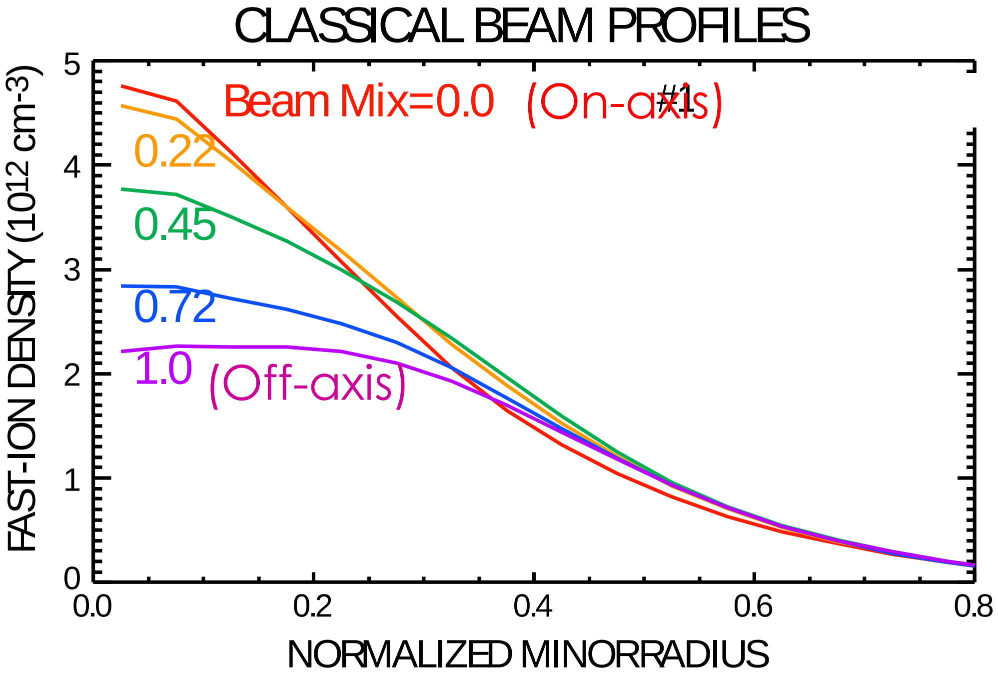
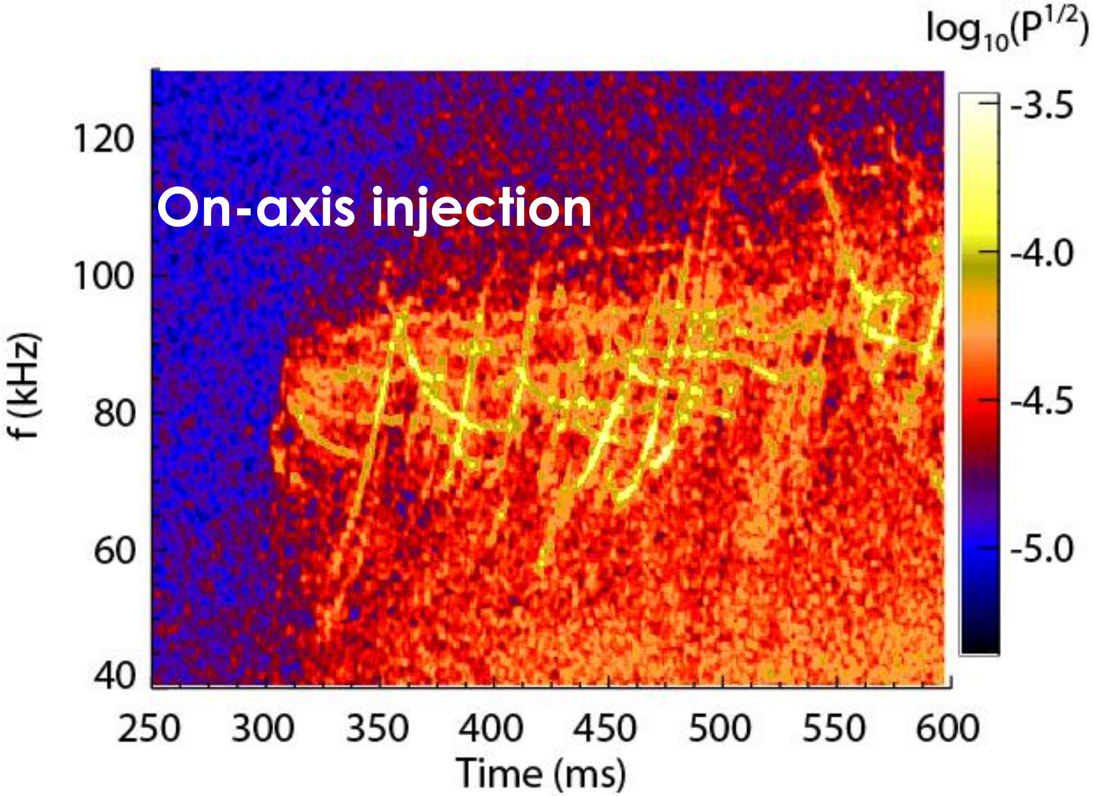
Different combinations of on-axis & off-axis beams vary the fast-ion gradient that drives AEs

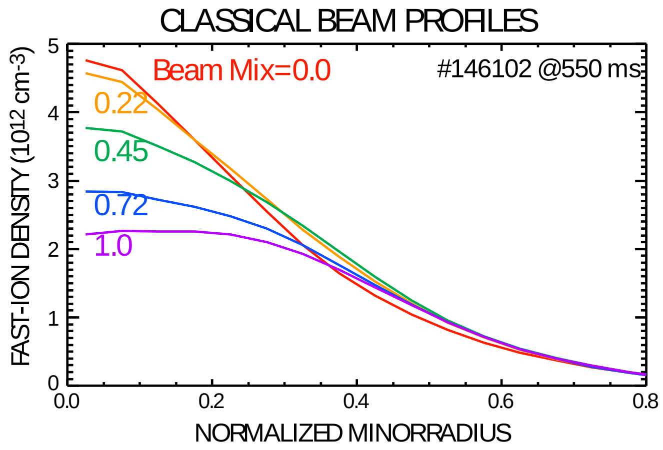


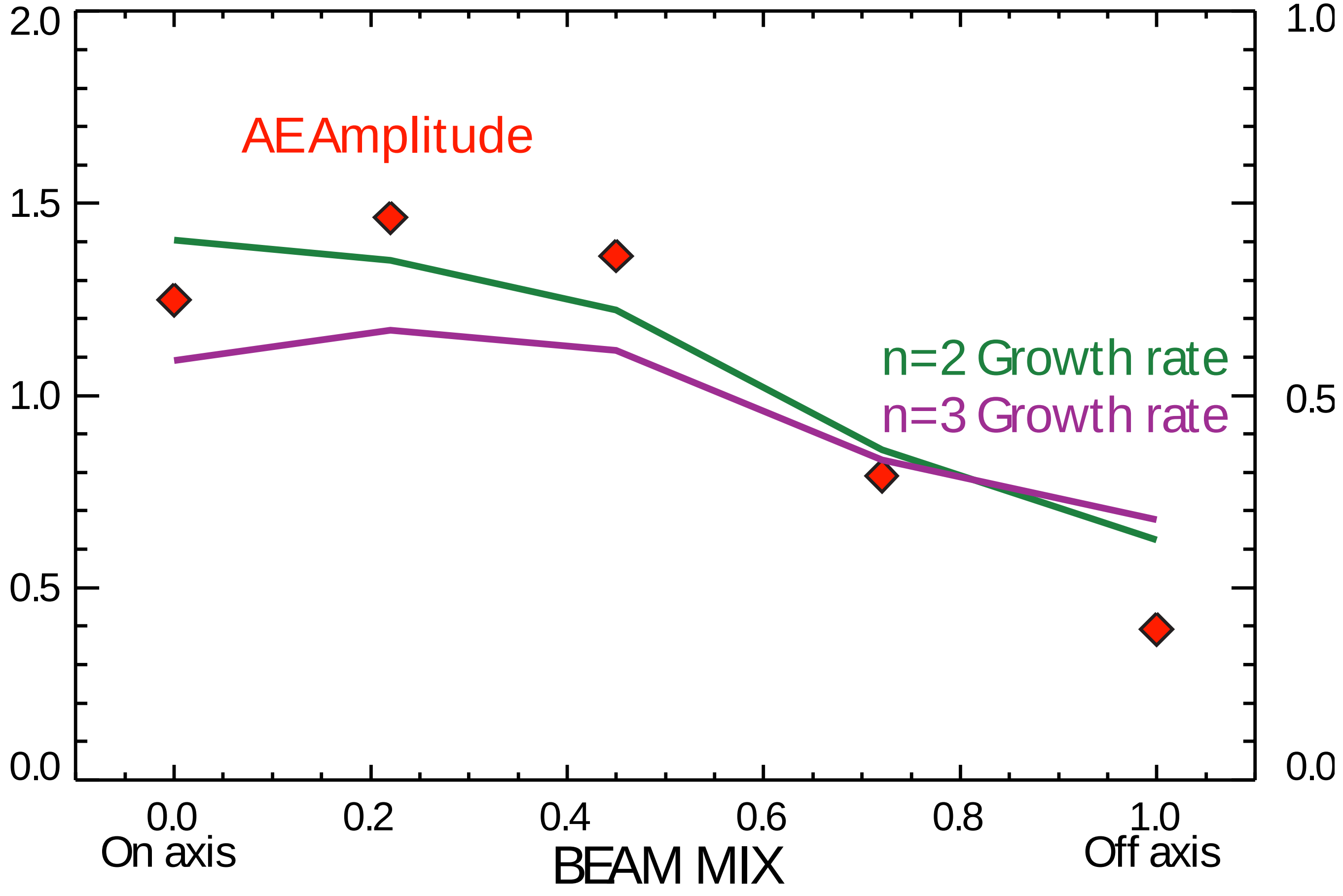
Use L-mode plasma in current ramp:

- **Low AE threshold**
- **Well diagnosed**



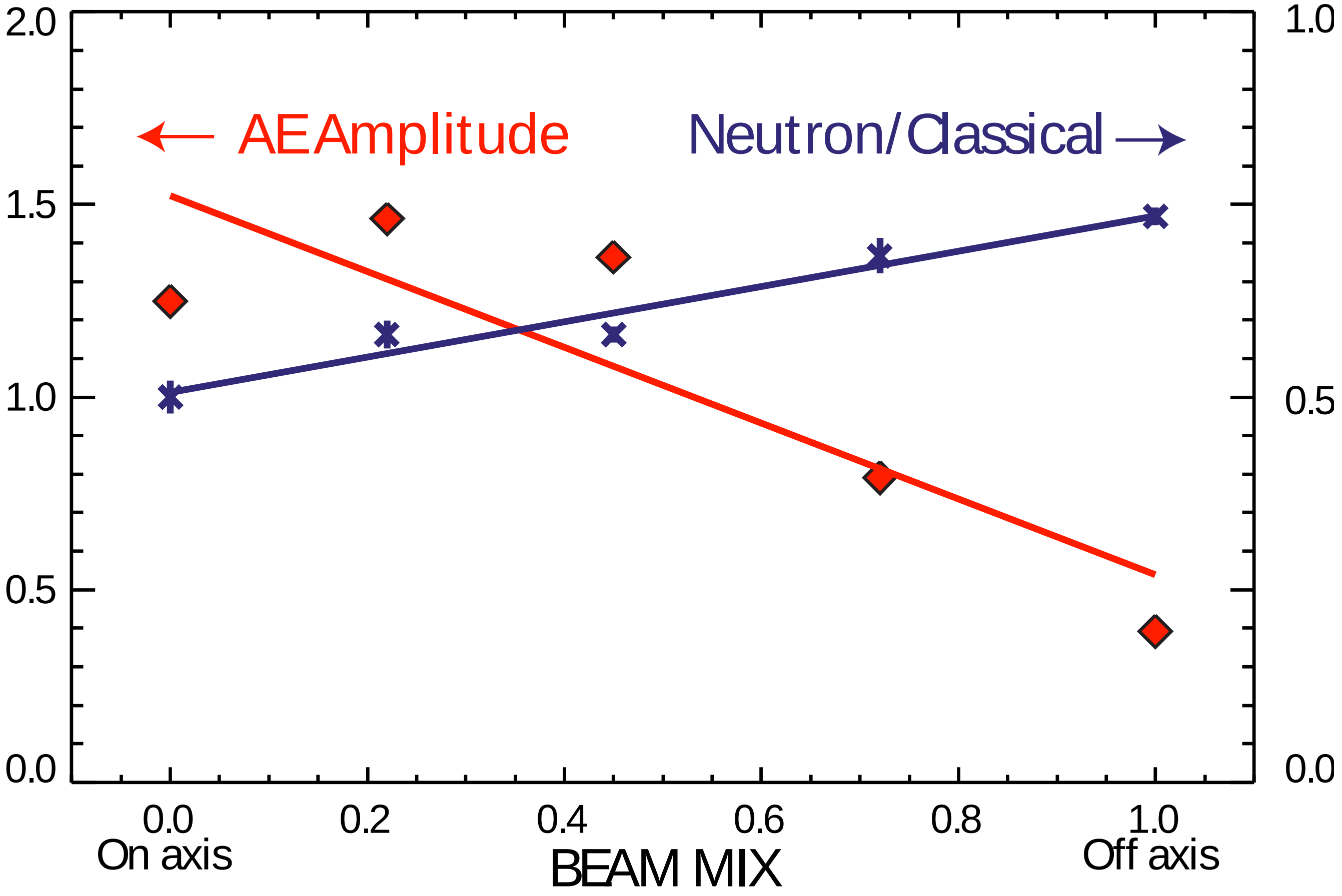
As predicted by linear AE stability theory, a steeper gradient drives more AE activity

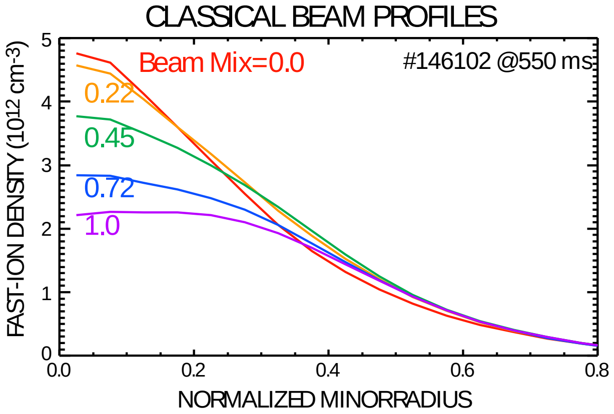




- **Growth rate from TAEFL gyrofluid code**
- **GYRO gyrokinetic code gives similar results**

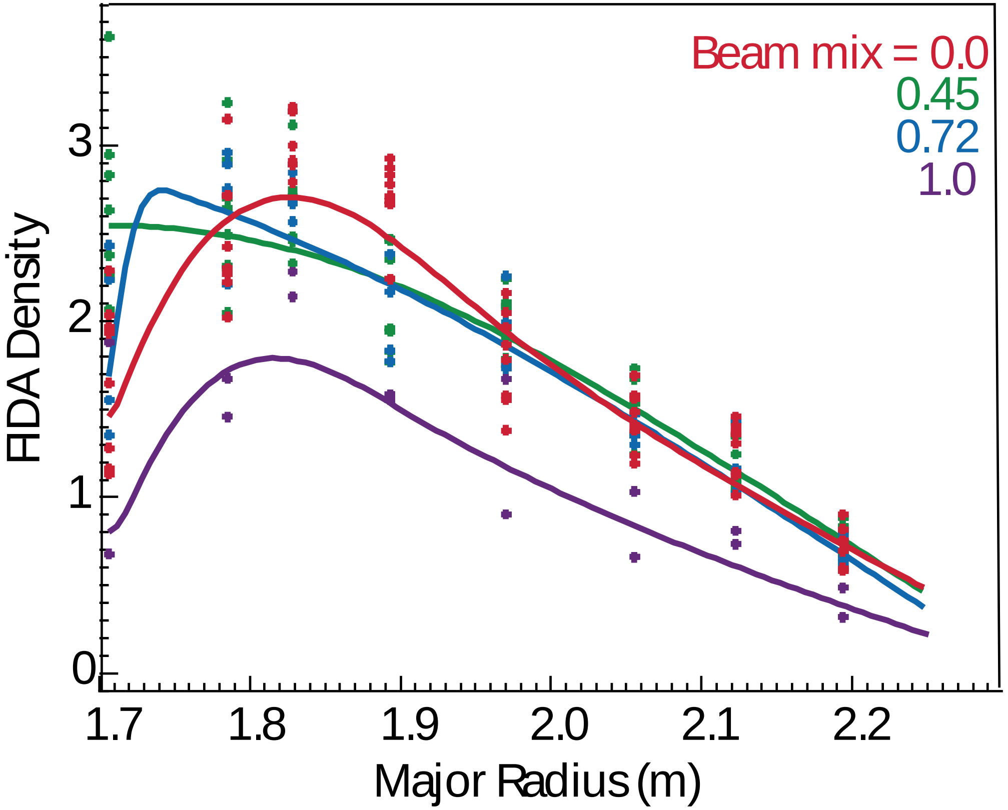
Stronger AE activity causes a larger fast-ion deficit

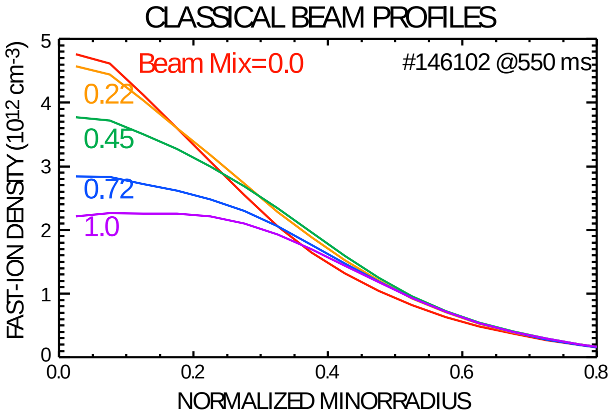




- **The measured neutron rate approaches the classical prediction for off-axis injection**

The measured fast-ion profile is nearly the same for all angles of injection!

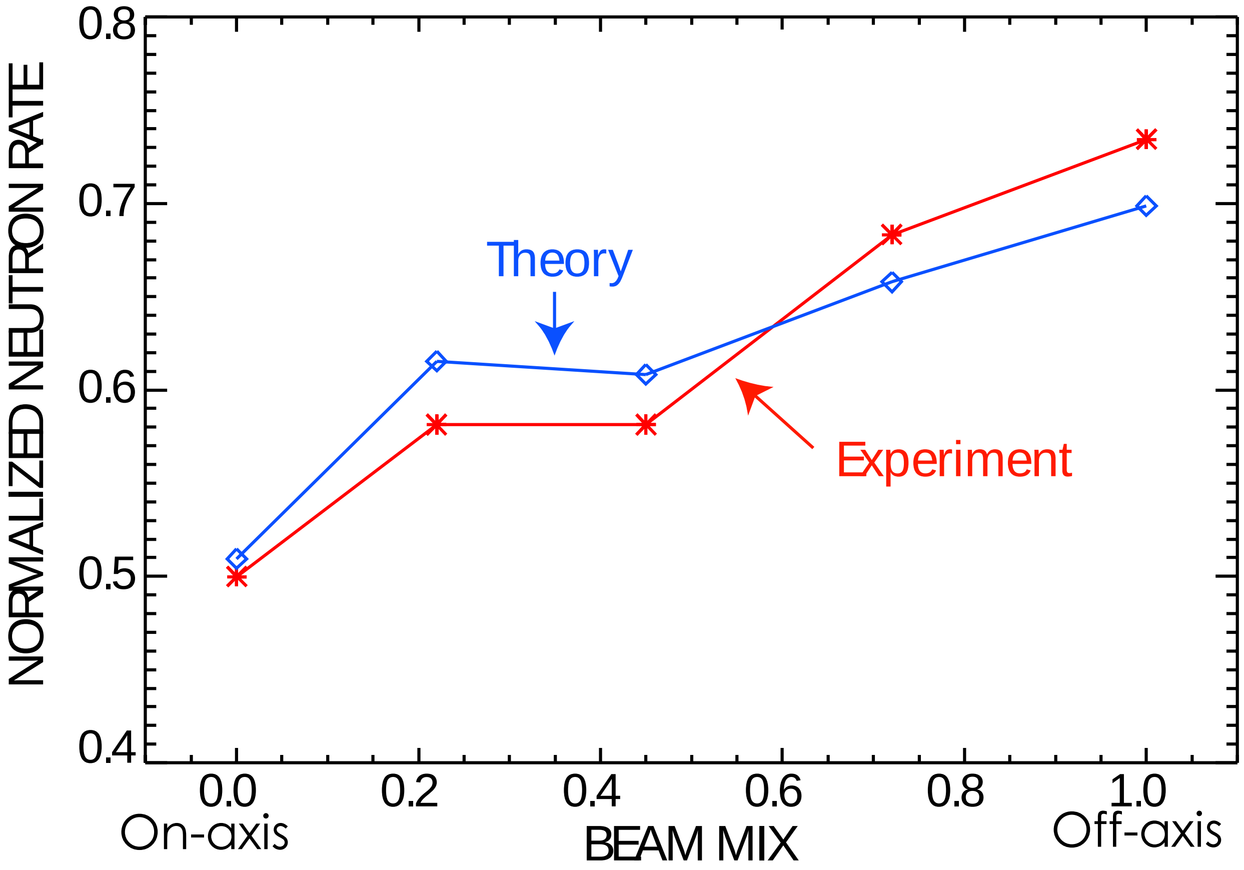


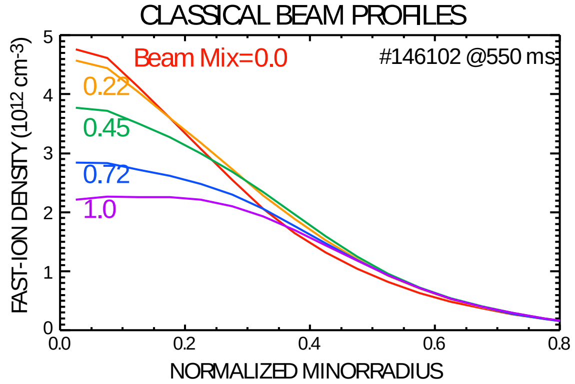


- **Suggests the fast-ion transport is “stiff”**
- **The linear stability threshold acts (approximately) as a “critical gradient”**

Of course, in quiet plasmas, the profiles differ.

A critical gradient model* reproduces the observed trend



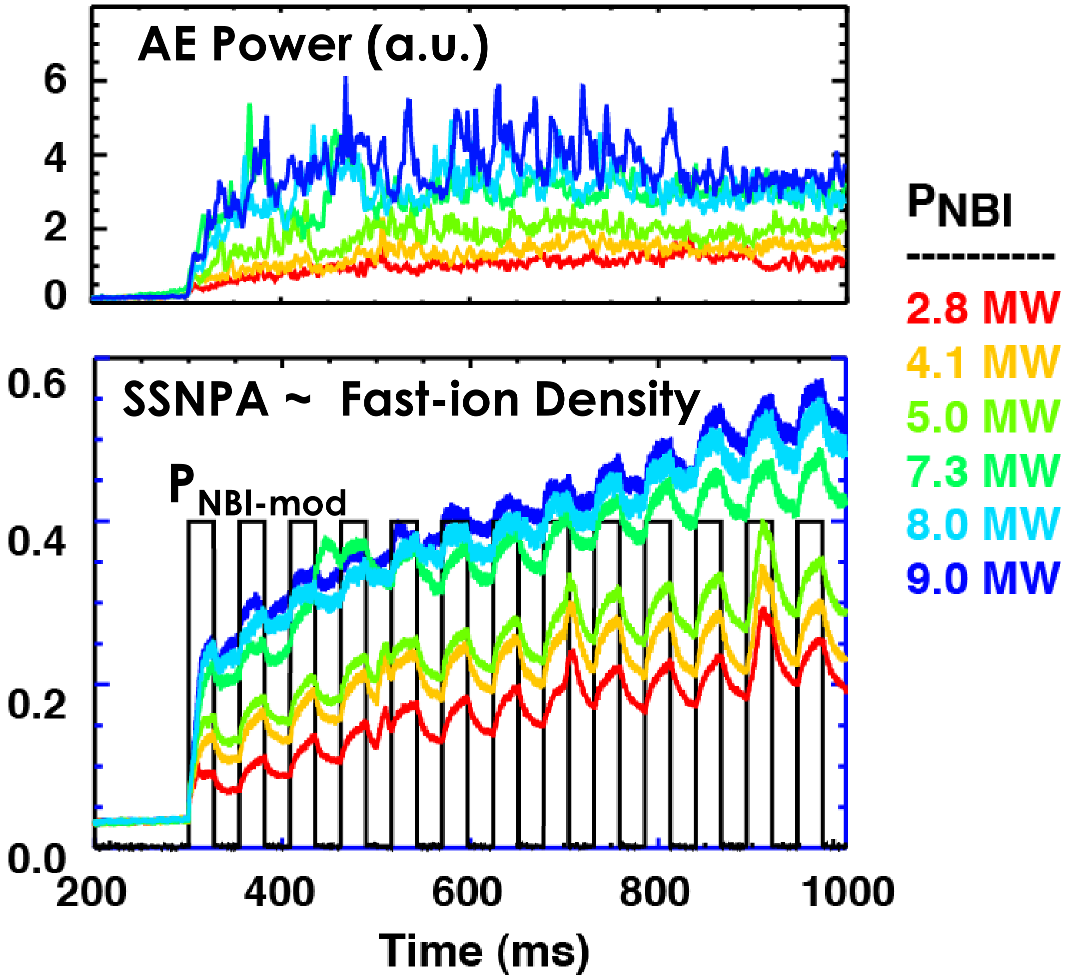


Ghantous, Phys. Pl.* ***19* *(2012) 092511.*

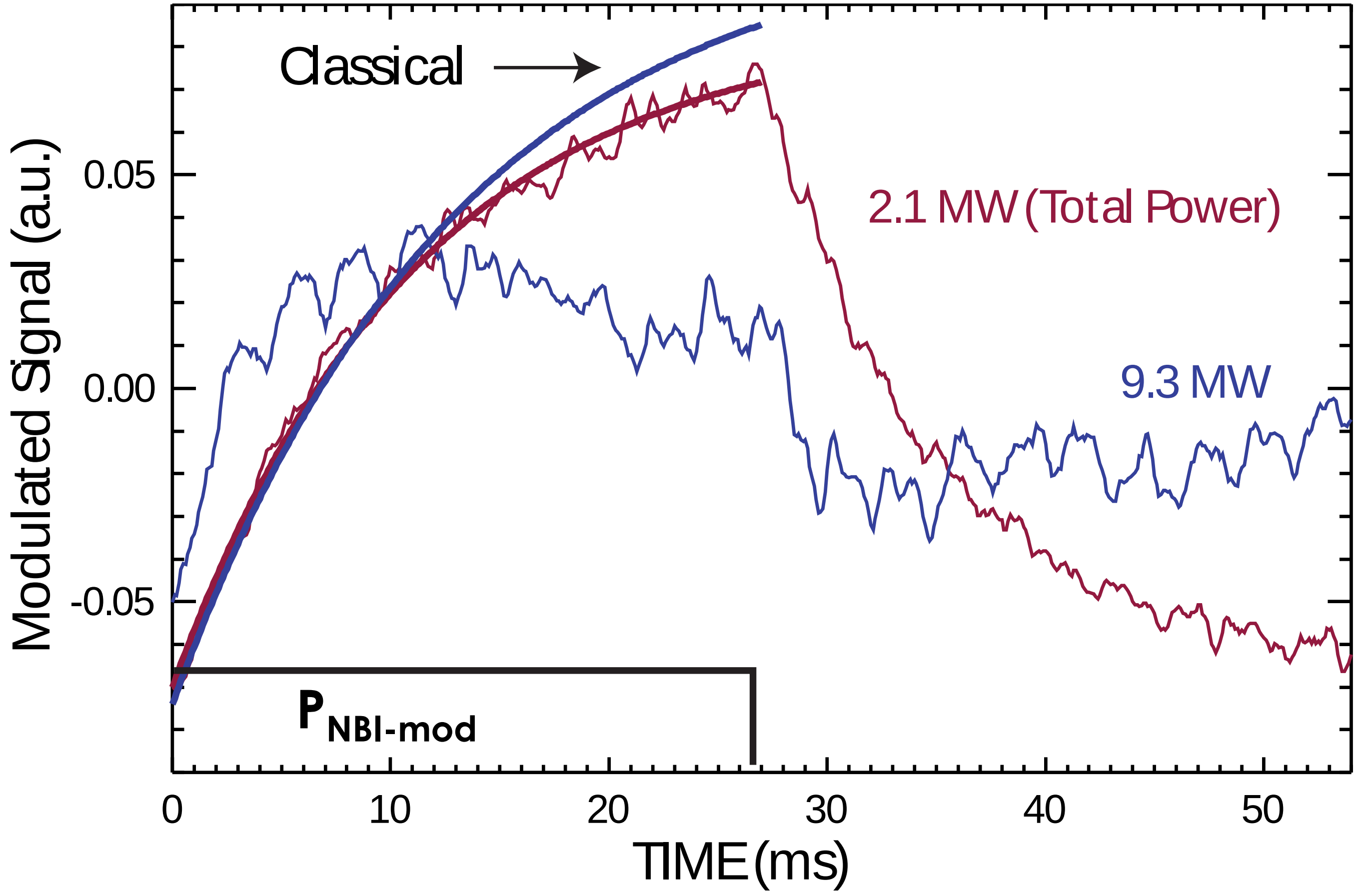
Gorelenkov TH/P1-2

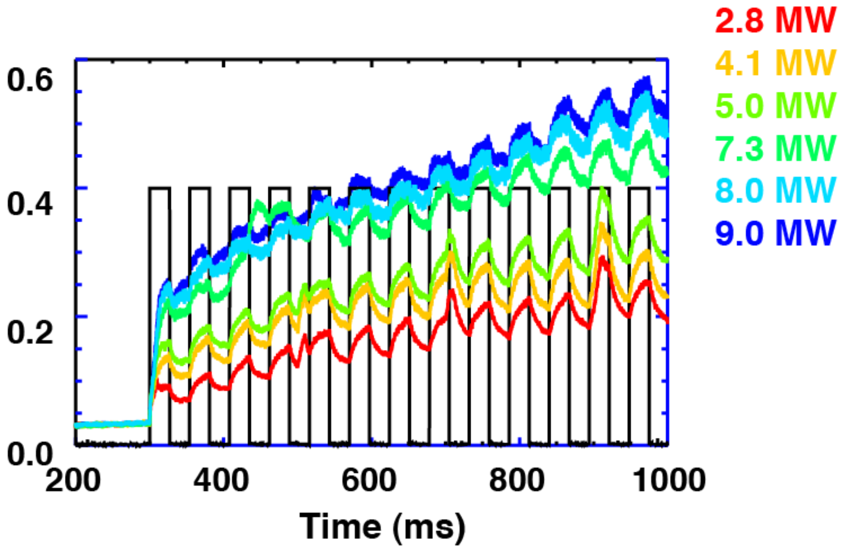
Recent Data Supports Critical Gradient Model of Alfven Eigenmode (AE) Induced Fast Ion Transport

- **Beam power scan varies AE amplitude**
- **Modulated off-axis beam allows measurement of incremental fast-ion flux**
- **Local fast-ion density ceases to rise above certain input power/ AE amplitudes**
  - SSNPA Neutral particle analyzer -> fast-ion density localized in phase space



Above threshold, the modulated signal is strongly distorted by AE transport





- Conditionally average the modulated signal
- At low power, the signal agrees well with a classical model
- Classically, the amplitude of the modulated signal should increase at high power

Infer the fast-ion transport from a continuity equation for the measured “density”

- Define a “density” that incorporates the phase-space sensitivity W in its definition

Weight Function

$$n = \int FW \, d\vec{v},$$

Distribution Function

- Multiply the kinetic equation by $\int W \, d\vec{v}$ to derive a fluid equation. Here, S is the beam source and n/τ is the thermalization sink

$$\frac{\partial n}{\partial t} + \nabla \cdot \Gamma = S - \frac{n}{\tau}.$$

“Flux”

- Linearize. Obtain a continuity equation for 1st order (modulated) quantities

$$\frac{\partial \tilde{n}}{\partial t} + \nabla \cdot \tilde{\Gamma} = \tilde{S} - \frac{\tilde{n}}{\tau}.$$

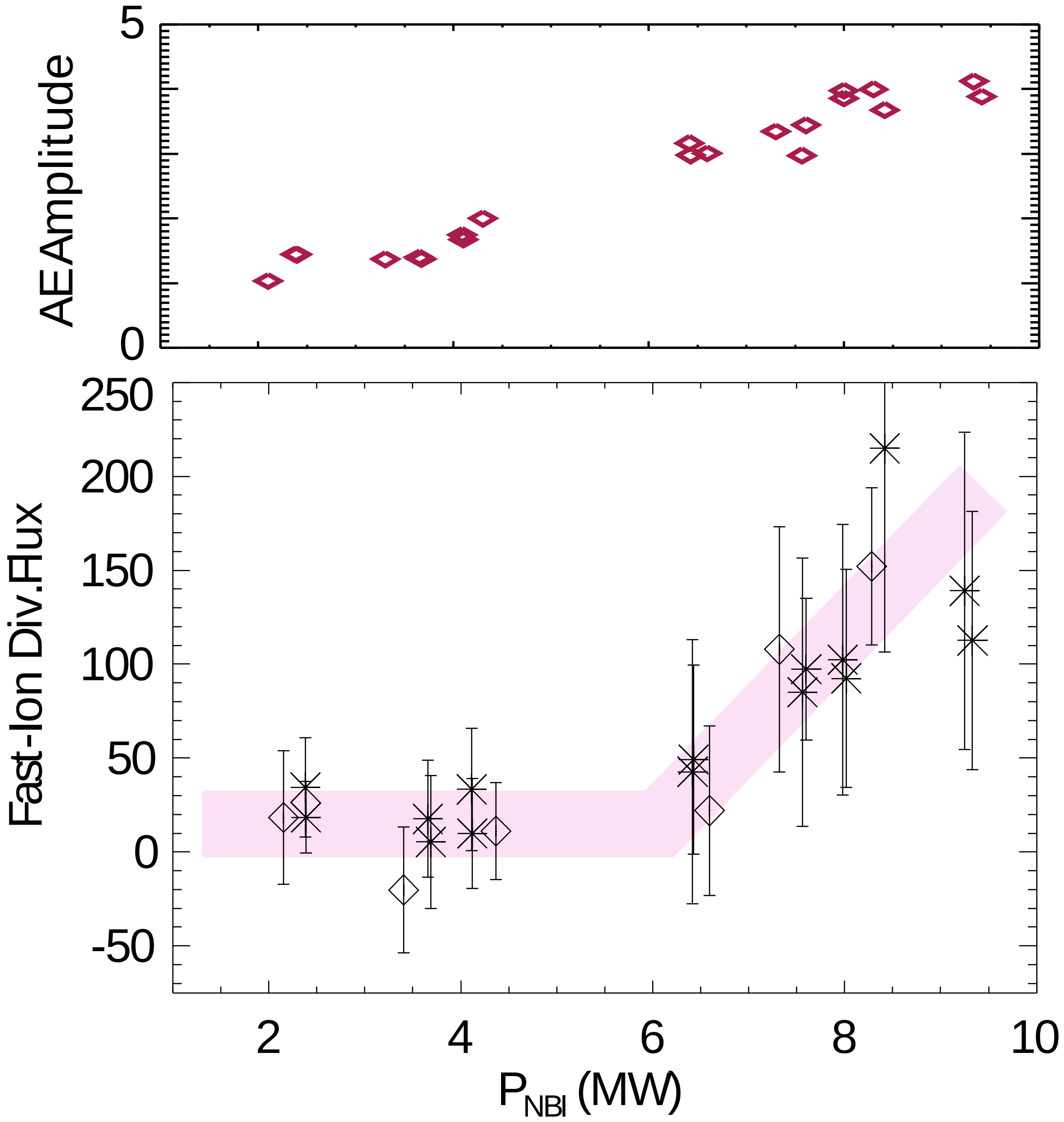
- When the AEs are absent, the transport term is negligible → measure source in a low-power shot

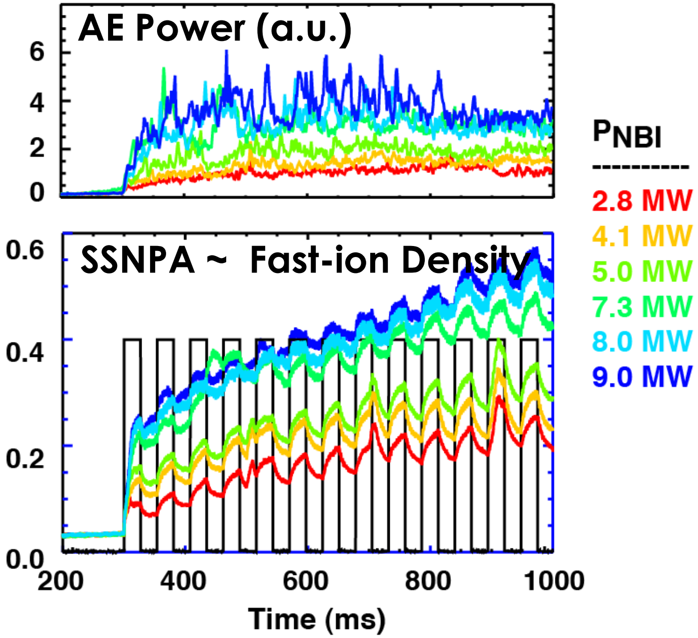
$$\tilde{S} = \frac{\tilde{n}}{\tau} + \frac{\partial \tilde{n}}{\partial t}.$$

- With AEs, use the measured n to infer the divergence of the fast-ion flux

$$\nabla \cdot \tilde{\Gamma} = \tilde{S} - \frac{\tilde{n}}{\tau} - \frac{\partial \tilde{n}}{\partial t},$$

Divergence of fast-ion flux abruptly increases above an AE threshold → critical gradient behavior





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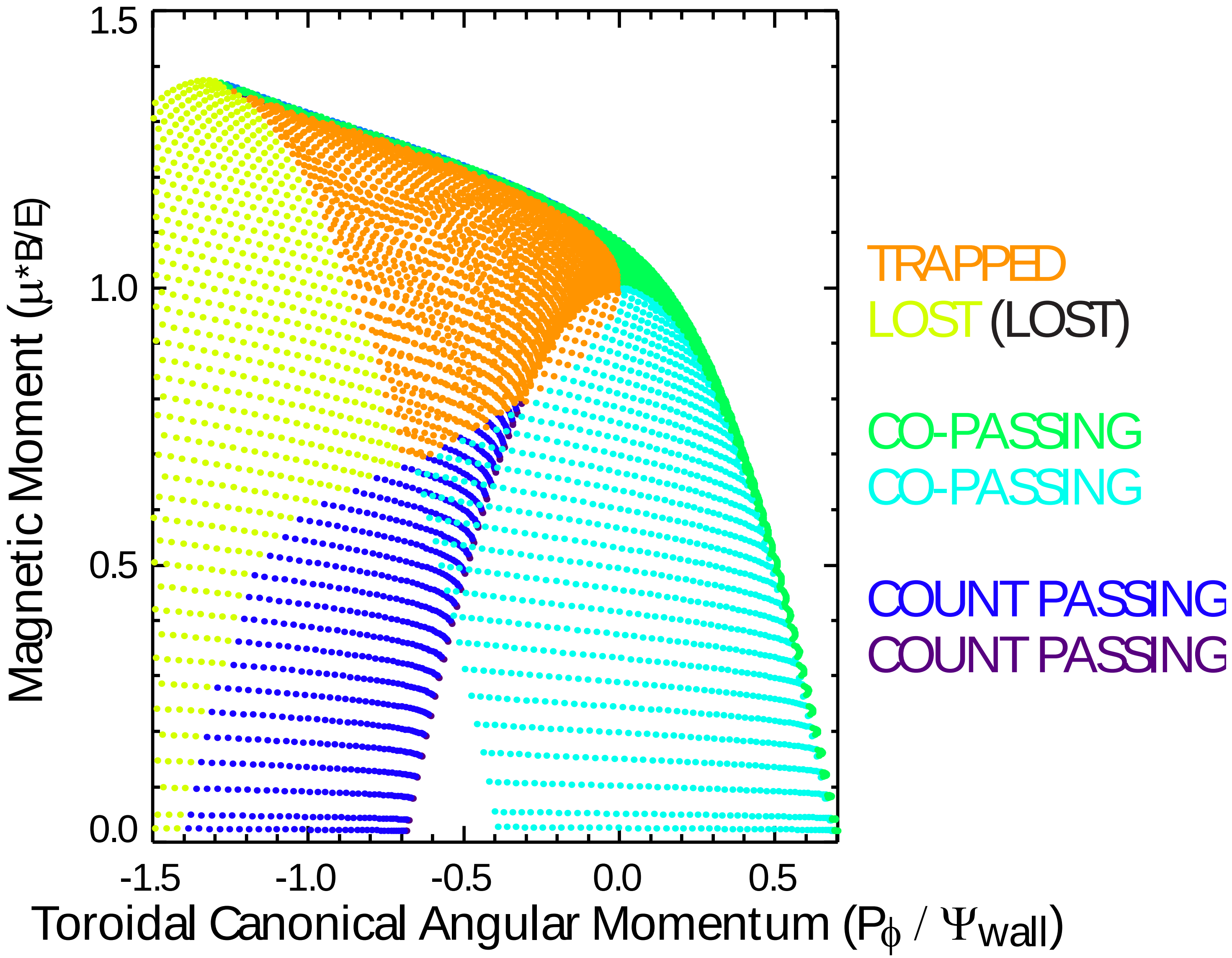
Many small-amplitude resonances → “stiff” transport



- **Use constants-of-motion to describe complex Energetic Particle orbits**

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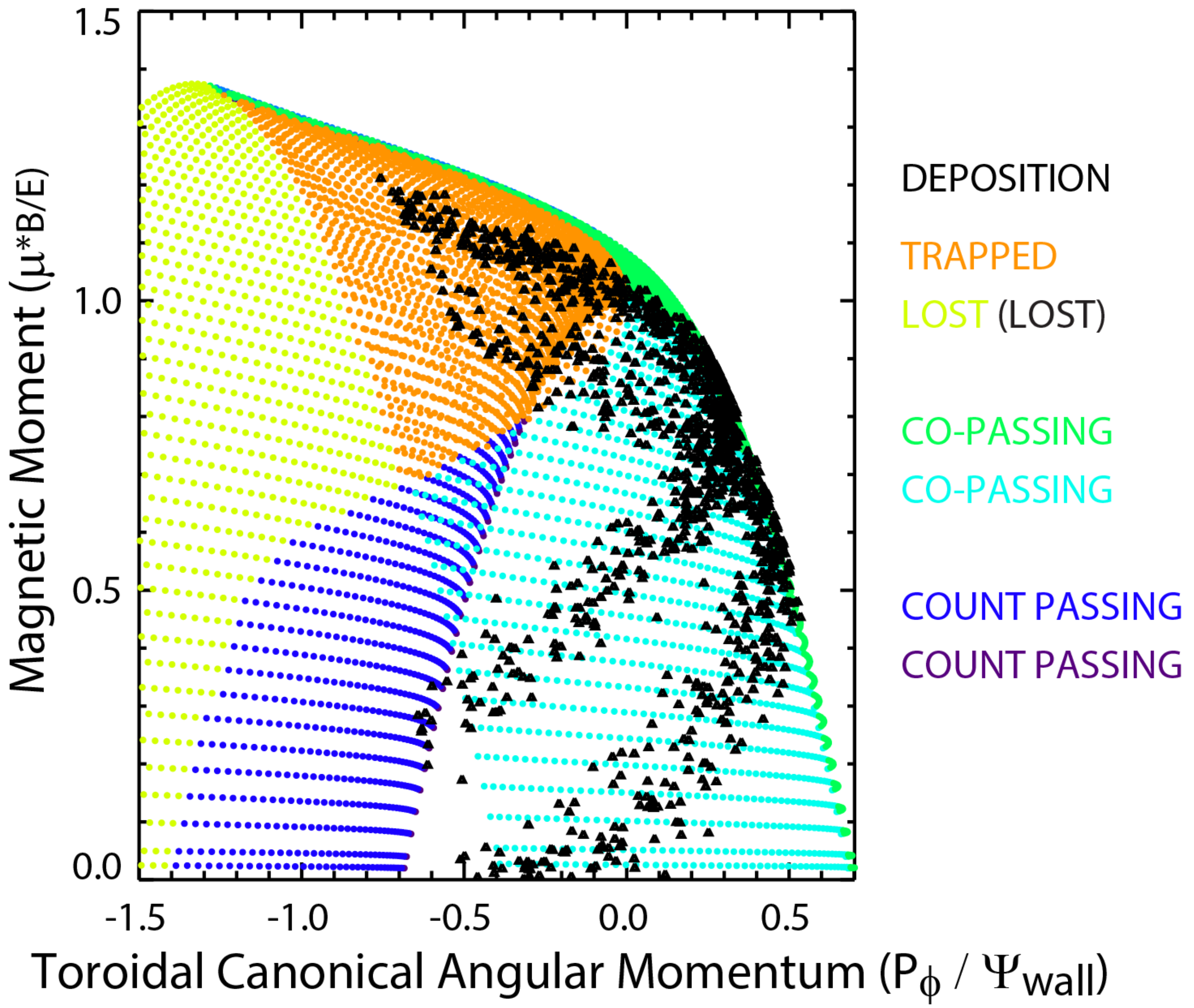
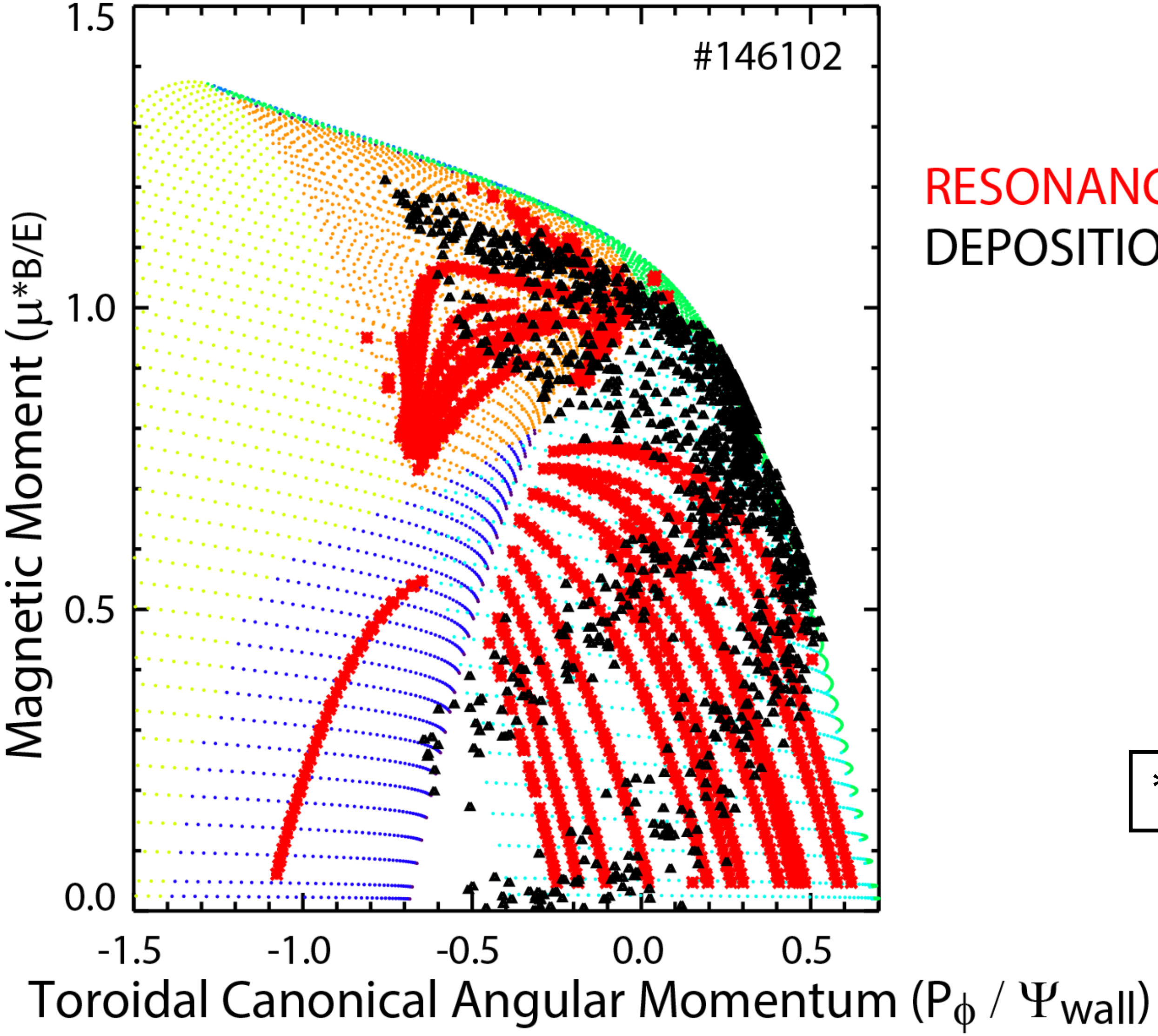
Many small-amplitude resonances → "stiff" transport



- **Injected beams populate the co-passing & trapped portions of phase space**

Many small-amplitude resonances → "stiff" transport

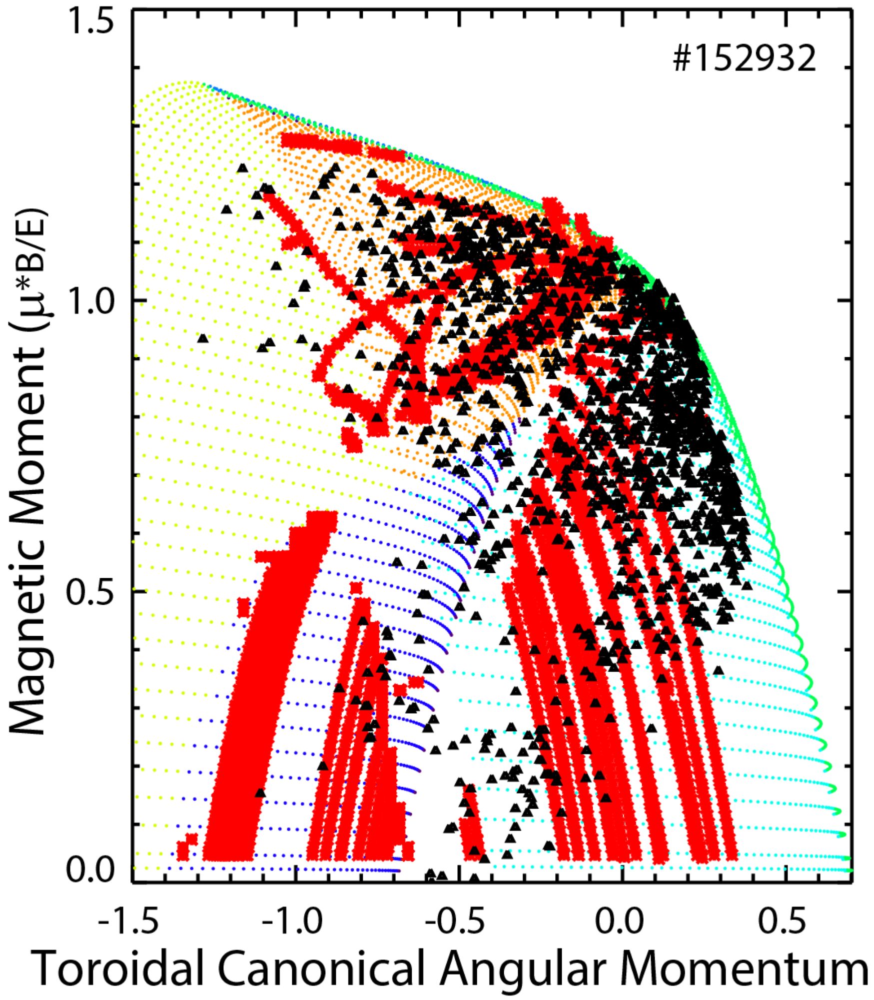


- Use measured modes to compute orbits that satisfy a resonance condition
- Many resonances cause stochastic overlap in phase space*

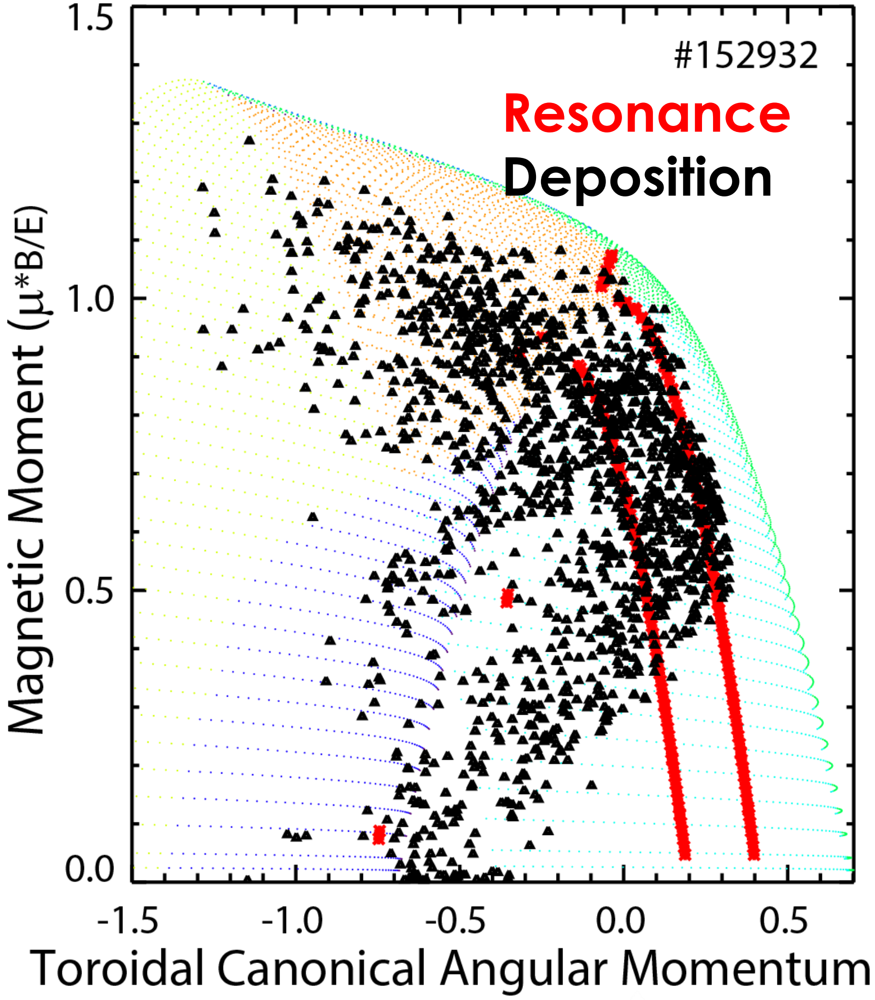
*White, PPCF **52** (2010) 045012*

The high qmin steady-state scenario plasmas also have many resonances

qmin ~ 2



qmin ~ 1



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New strategies are needed to overcome critical gradient behavior

Above AE stability threshold, additional on-axis beam power is ineffective

- More off-axis beam power (broader beam profile) *Nucl. Fusion 53 (2013) 093006*
- Better thermal confinement (less auxiliary power for same β_N) *PPC/P2-31, EX/P2-39*
- Replace beam-driven current with RF *TH/P2-38*
- Modify AE stability *Nucl. Fusion 49 (2009) 065003*

Conclusions

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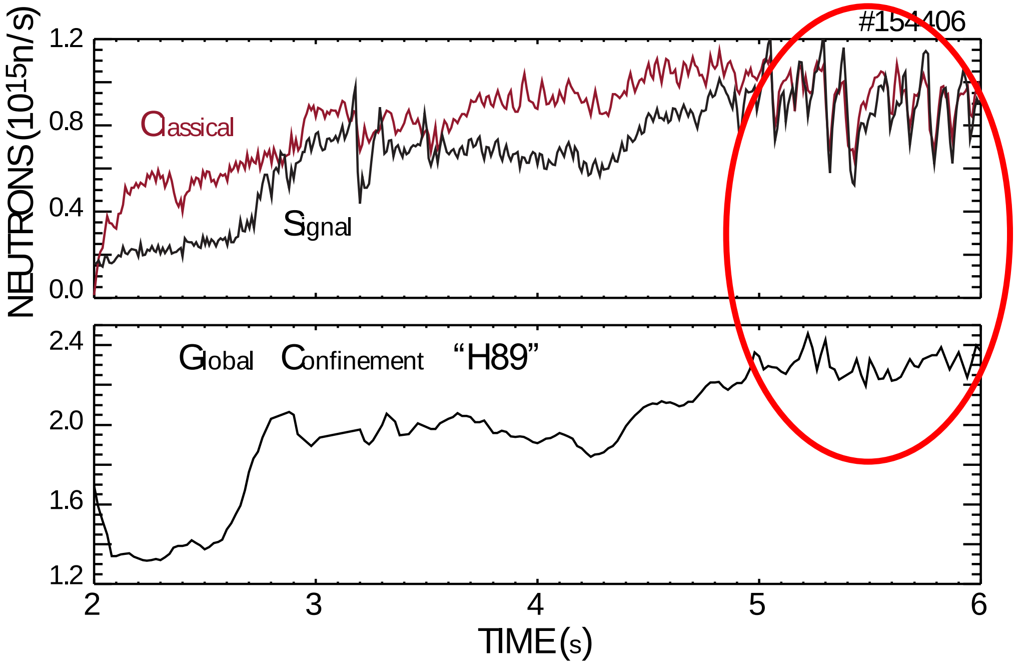
Backup Slides

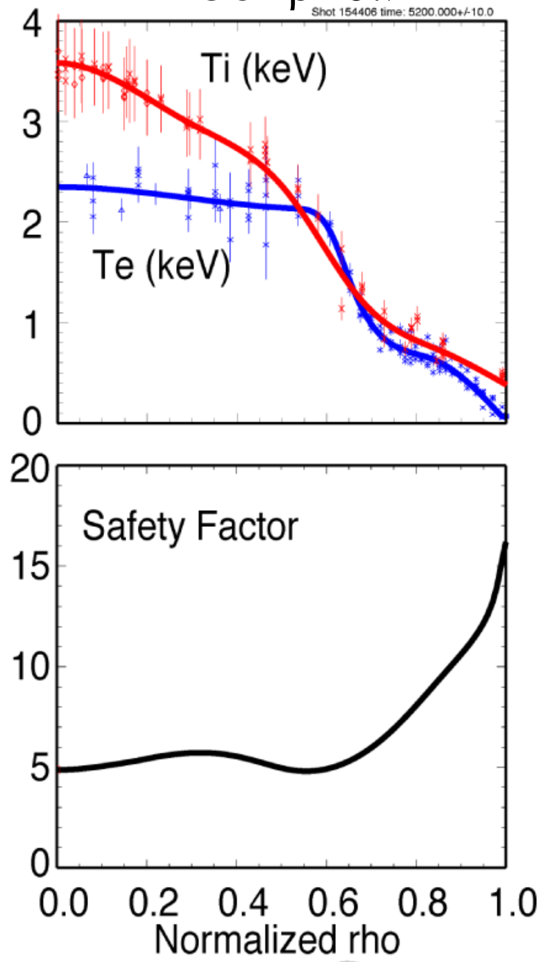
Implications for ITER

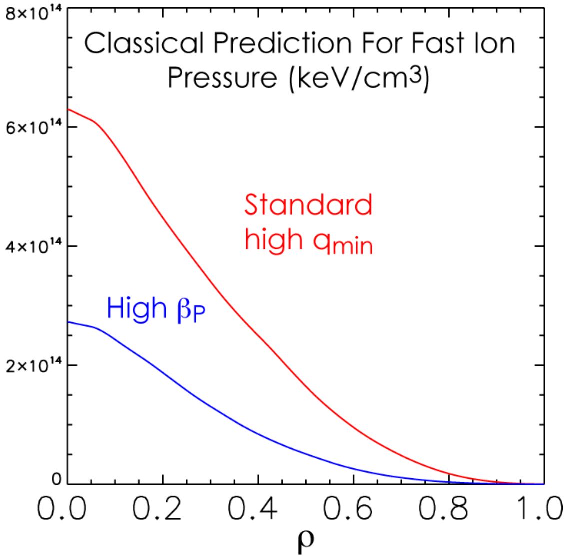
- ITER steady-state scenario is predicted to have unstable AEs
- Multiple modes with many resonances are likely → critical gradient fast-ion transport regime
- Not strongly driven past threshold
- Critical gradient calculation predicts modest effect

High β_N, high q_{min} discharges with good fast-ion confinement are observed



Transport barrier near ρ=0.7





- **Less Beam Power**
- **Higher Density**

→ Weaker AE Drive