Improving Fast-Ion Confinement and Performance by Reducing Alfvén Eigenmodes in the qmin>2, Steady-State Scenario

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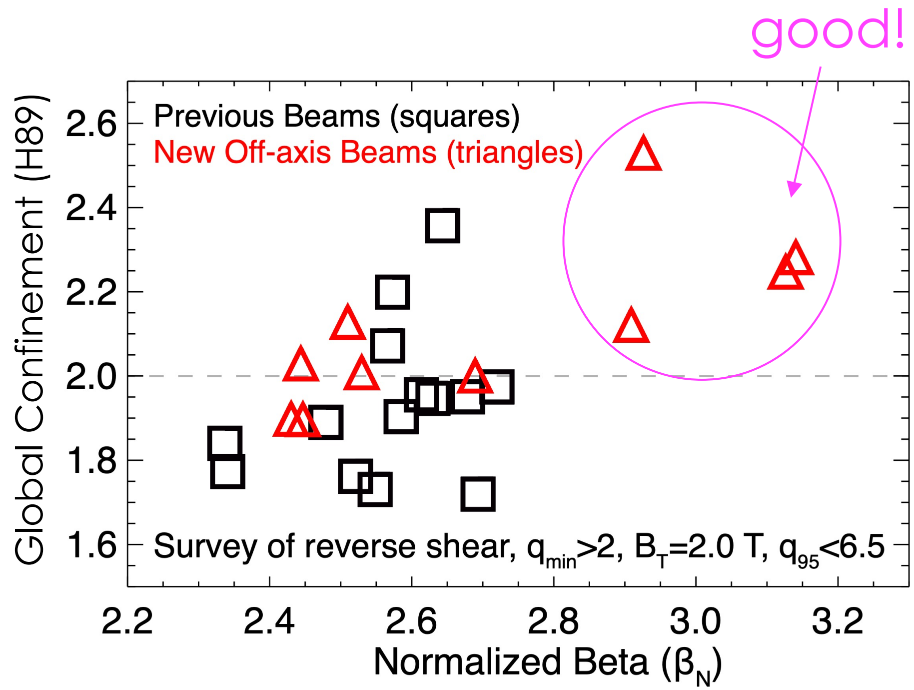

28th IAEA Fusion Energy Conference

May 15, 2021

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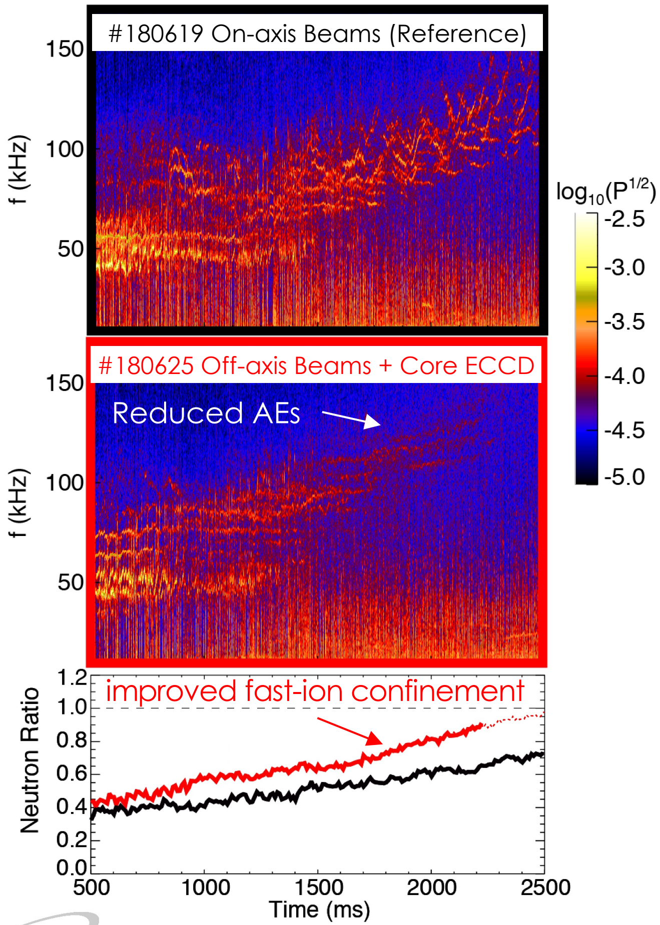
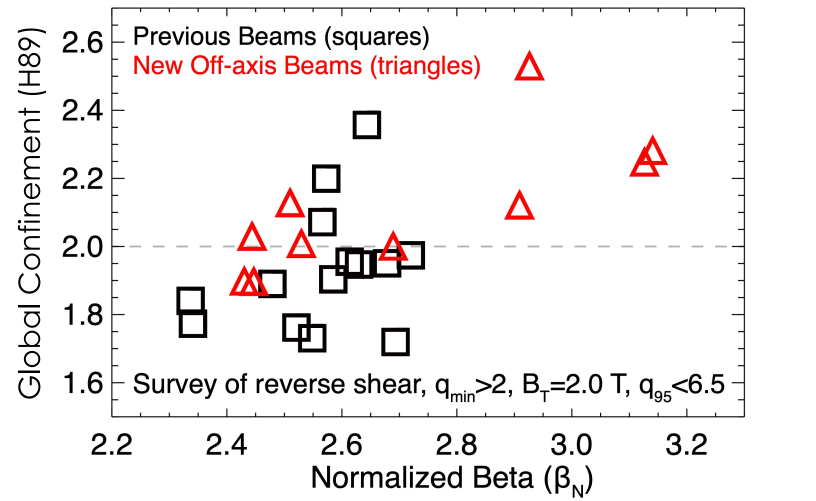
This Talk: Steady-State Scenario Advanced Through Improved AE Control and Fast-ion Transport Modeling

Fast-ion confinement (neutron ratio) improved by ~25%

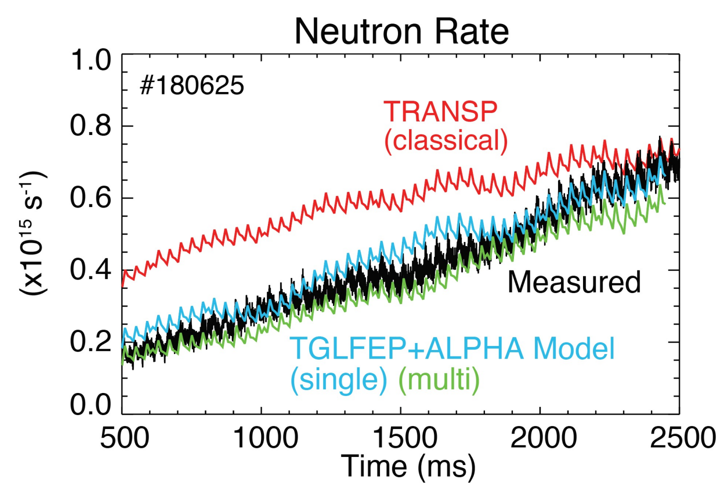
– Key factor is moving ρ_{qmin} towards region of reduced $\nabla\beta_{fast}$



Accessed new regimes with 15% higher β_N



Improved fast-ion transport modeling



AEs Can Cause Performance-Degrading Transport in q_{min}>2, Reverse Shear Steady-State Scenarios

- **ITER has goal to reach Q=5 , q_{95}>5, SS scenario**
- **Reverse shear, q_{min} > 2 scenarios are candidates for fully non-inductive (steady state) tokamak operation**
  - Good for high β_N limit, elevated confinement, and avoidance of low-order tearing modes

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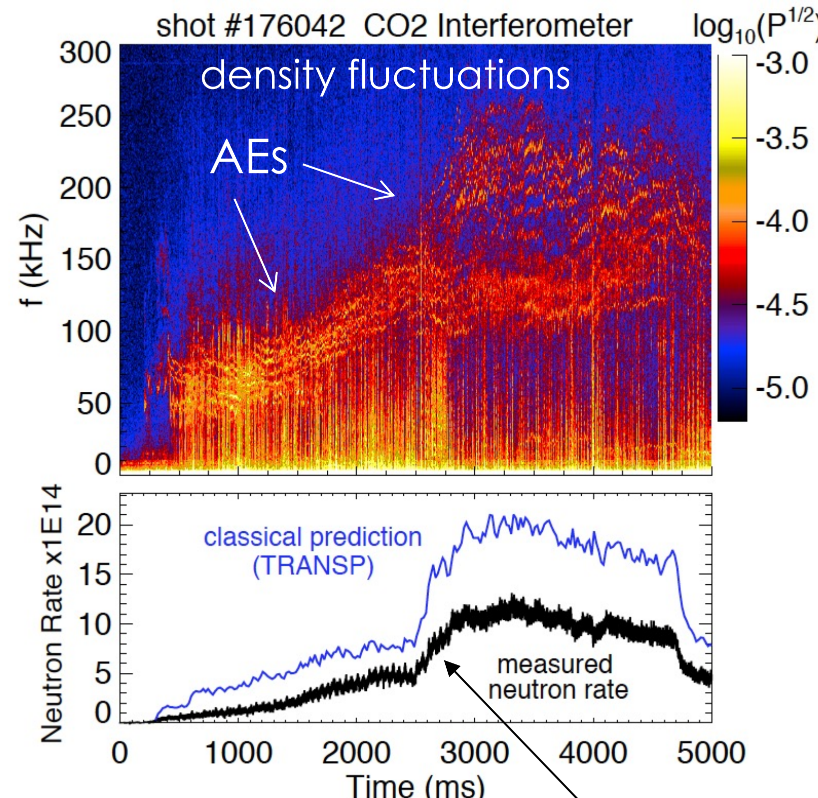
- **In DIII-D, relatively high beam power drives AEs**
  - Observe lower global confinement at higher q_{min}, limits achievable β_N

    [Holcomb, PoP 22 (2015)], [Heidbrink, PPCF 56 (2014)]

Example DIII-D q_{min}>2 SS Scenario



neutrons are volumetric proxy for fast-ion confinement
→deficit due to AE's transporting fast ions

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    [Holcomb, PoP 22 (2015)], [Heidbrink, PPCF 56 (2014)]
- **Multiple AEs cause critical gradient transport**
  - Fast-ion profiles are stiff
  - Any effort to increase the fast-ion gradient results in more transport, losses

    [Collins PRL 116 (2016)] [Heidbrink NF 53 (2013)]
    [Todo, New J. Phys 18 (2016)]

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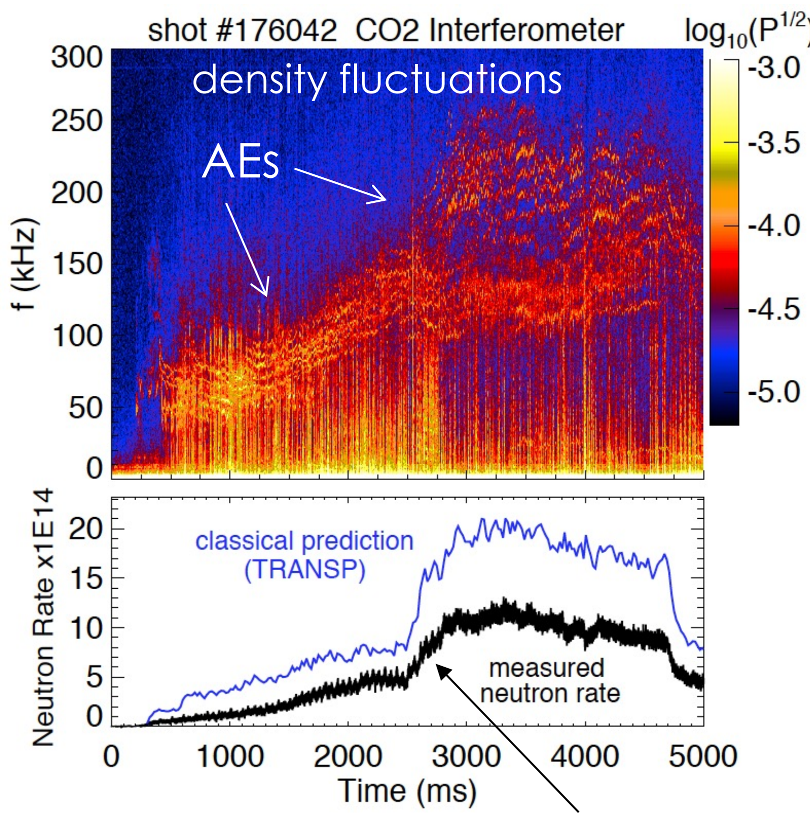

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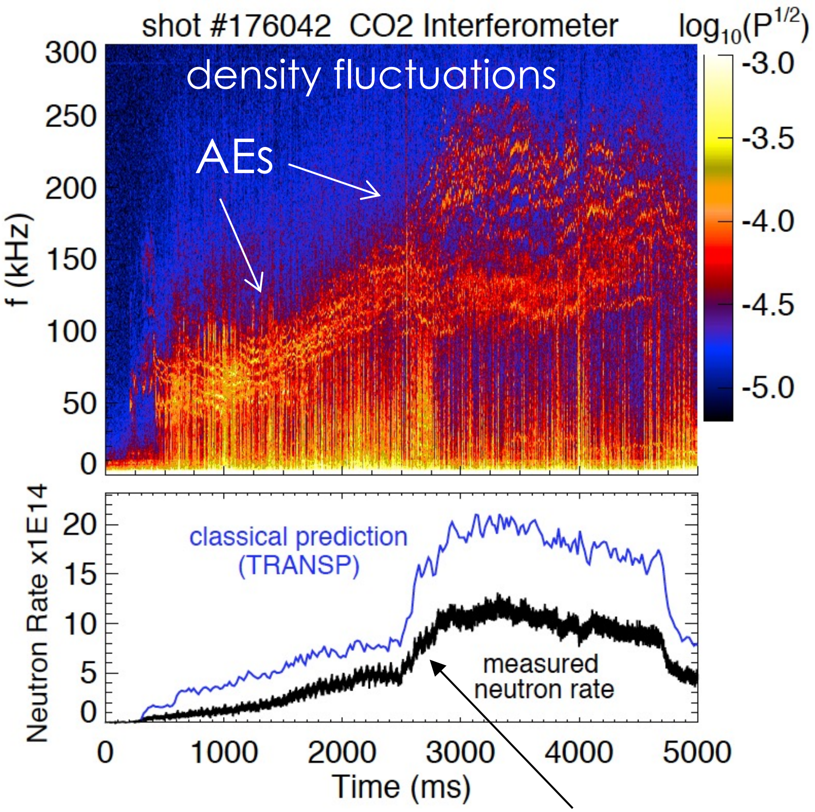

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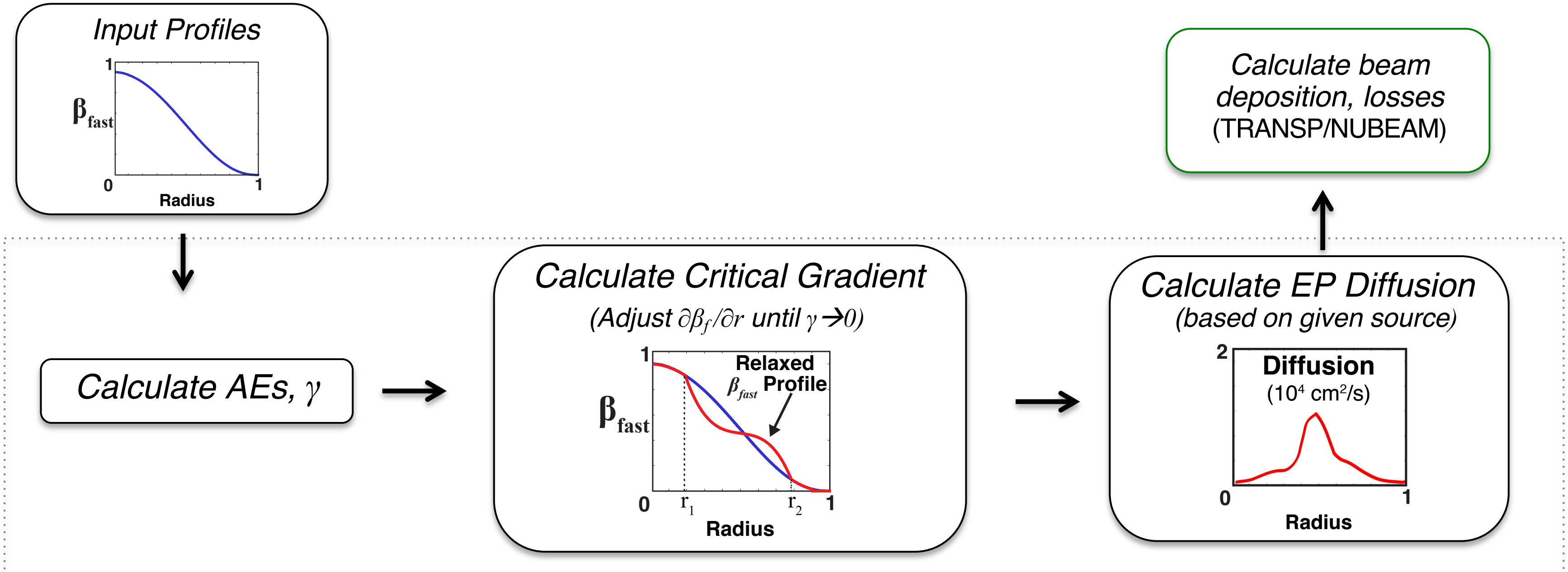
Important questions:
How well do AE control actuators work in varied parameters?
How can we effectively predict EP profiles/losses to optimize scenarios?

Goal: Validate Models in Order to Calculate EP Transport & Optimize Scenarios For Future Fusion Reactors

- **TGLF-EP+Alpha is the simplest, fastest critical gradient EP transport model**
  - -provides fully physics-based calculation of transported EP profile and corresponding EP diffusion
  - -avoids detailed nonlinear calculations of saturated mode amplitudes



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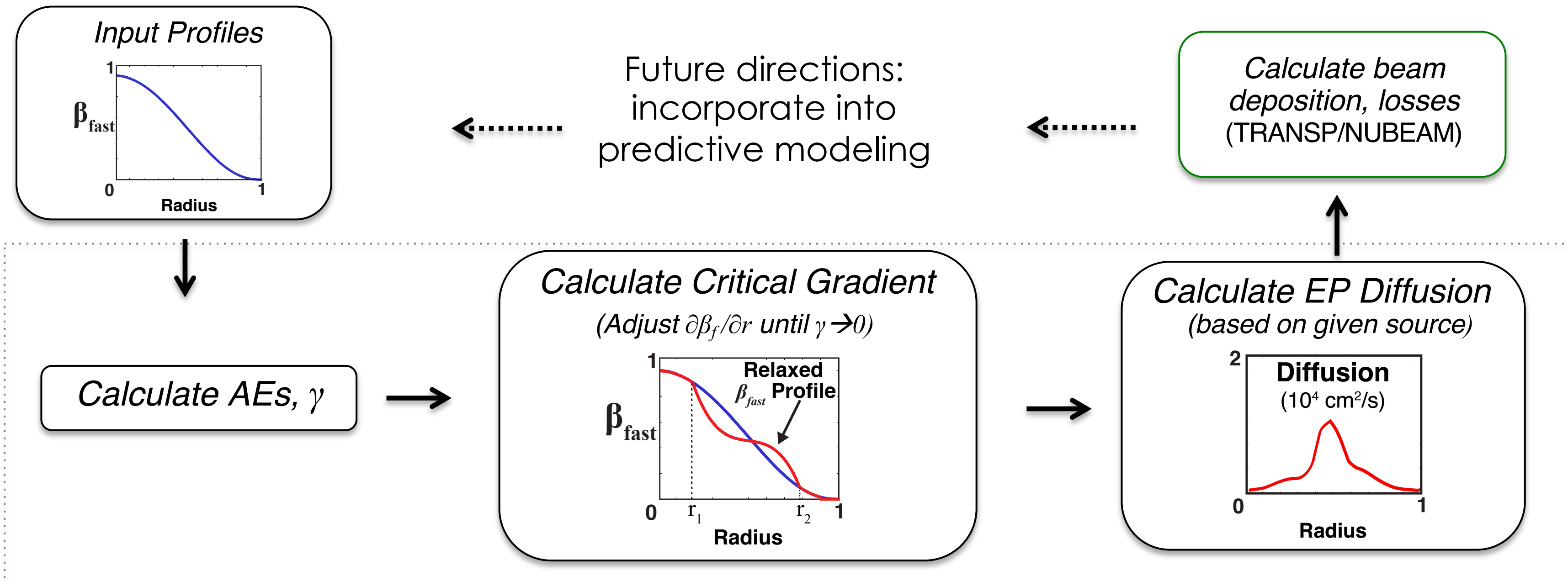

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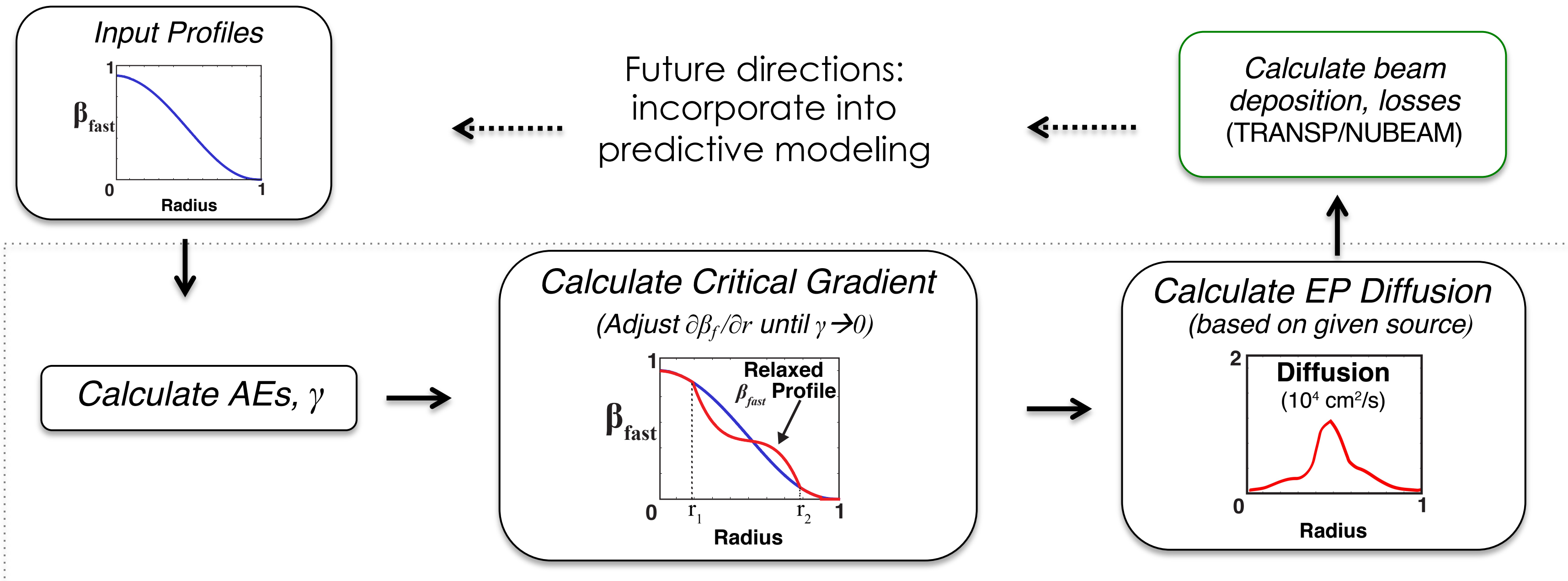
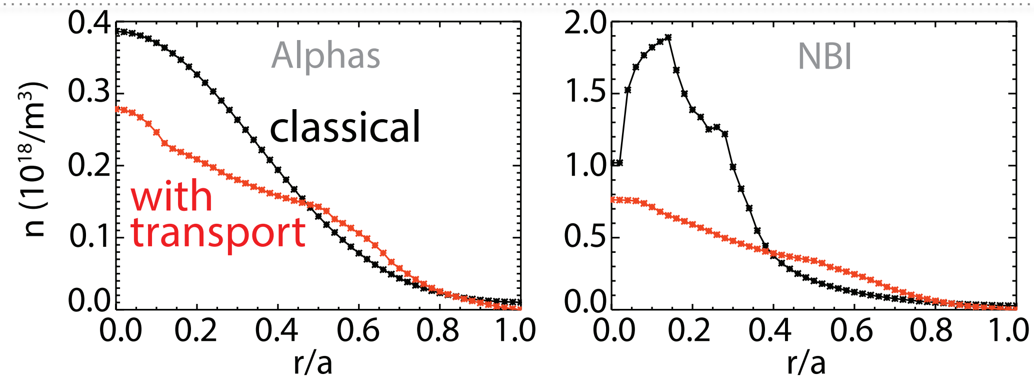


TGLF-EP predicts fast-ion redistribution by AEs in ITER baseline scenario
[Bass, NF 60 016032 (2020)]



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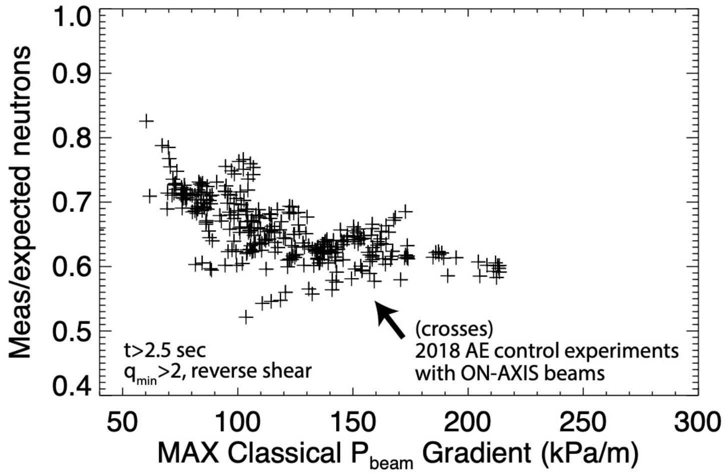
Outline

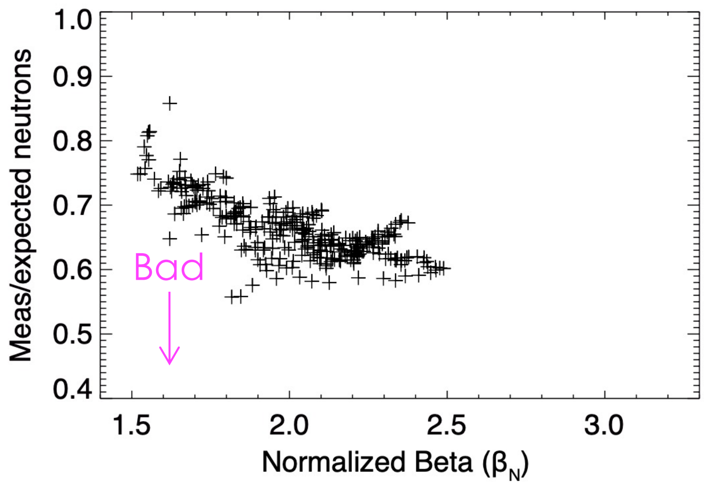
- **DIII-D experiments with AE control in SS scenario**
- **Broad fast-ion profiles reduce core EP transport**
  - Further improvement by tuning q-profile with ECCD
- **Progress with TGLF-EP+Alpha model validation**

DIII-D's Beam Upgrade Enabled Improved Fast-Ion Confinement While Maintaining Scenario

- **In 2018 experiments with 2 off-axis NBI sources, AEs were reduced and neutron ratio increased by decreasing $\nabla\beta_{fast}$** (using higher plasma density)
  - However, β_N decreased ($\beta_N \rightarrow 1.5$)
  - q-profile had less shear, confinement decreased

Neutron Ratio (Goal=1)





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  - However, β_N decreased ($\beta_N \rightarrow 1.5$)
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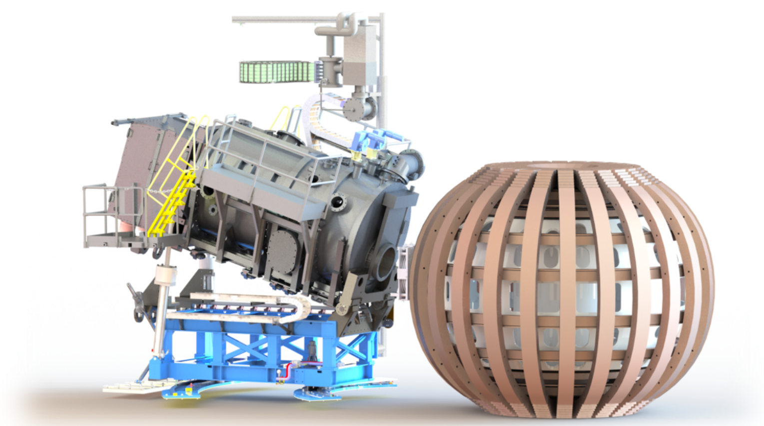
- **Recent experiments using 4 off-axis NBI further decreased $\nabla\beta_{fast}$, improved neutron ratio ~25% while maintaining scenario and β_N**



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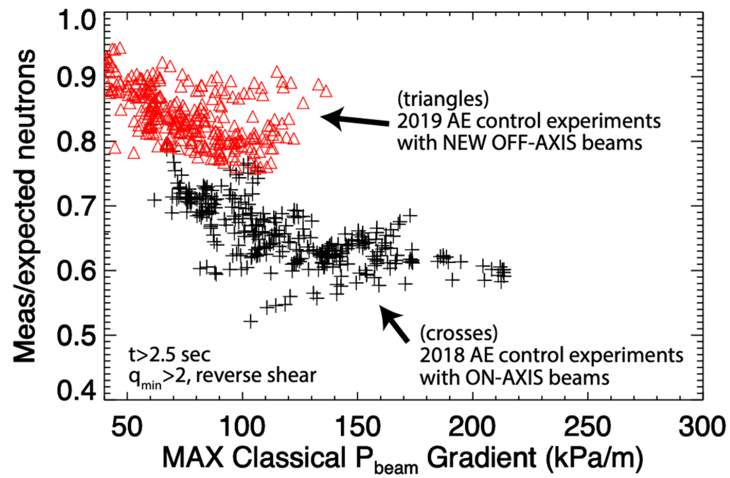

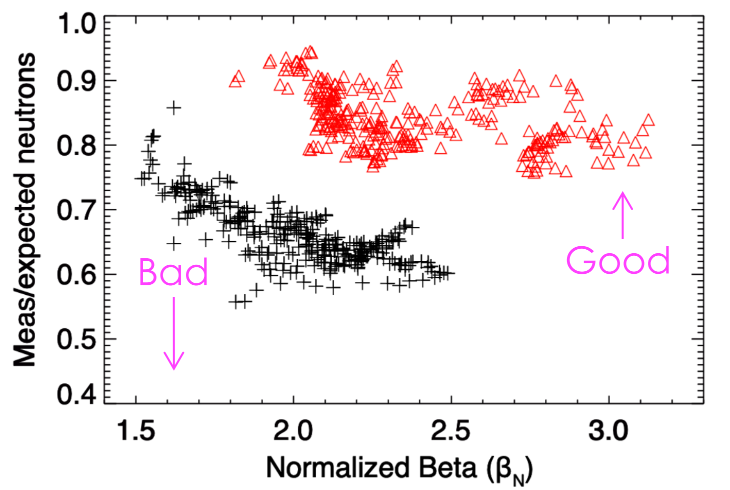

See also:
Victor, 662. *Global stability of elevated-q_{min}, SS scenario plasmas on DIII-D*
Park, 1009. *Off-axis Neutral Beam Current Drive for Advanced Tokamak*
Grierson, 744. *Testing the DIII-D Co/Counter Off-axis Neutral Beam …*

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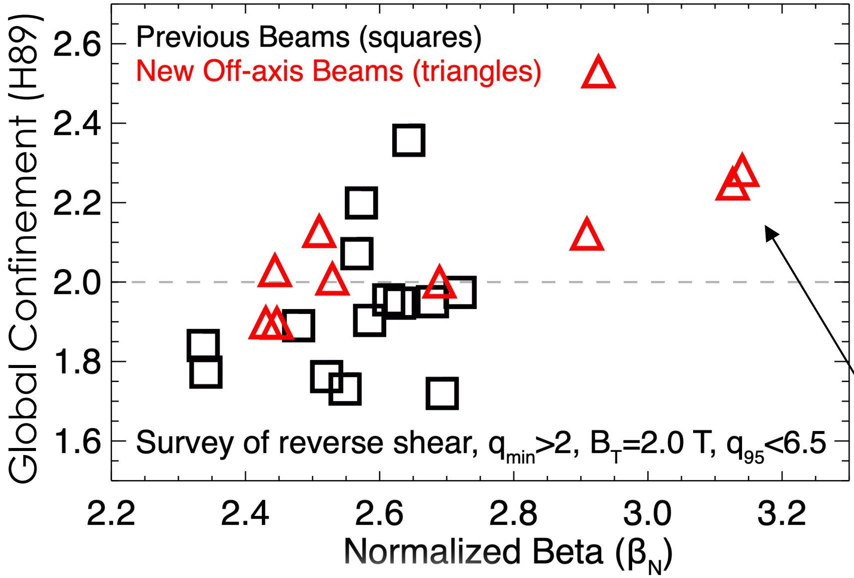
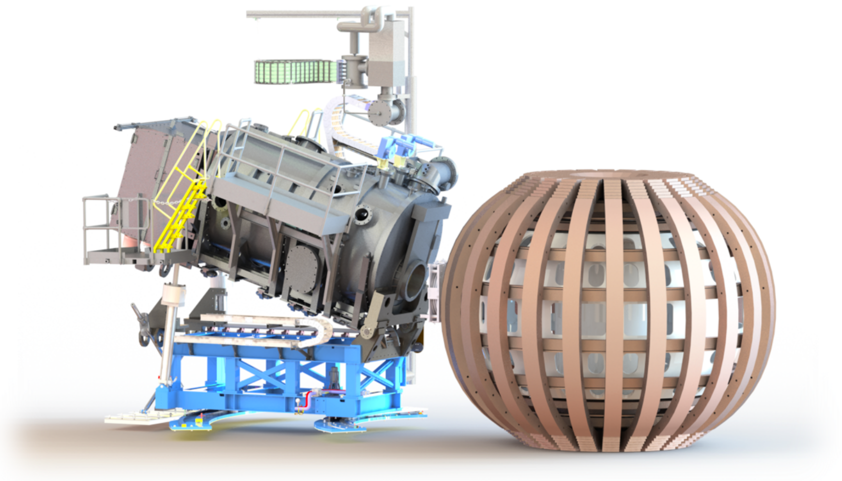
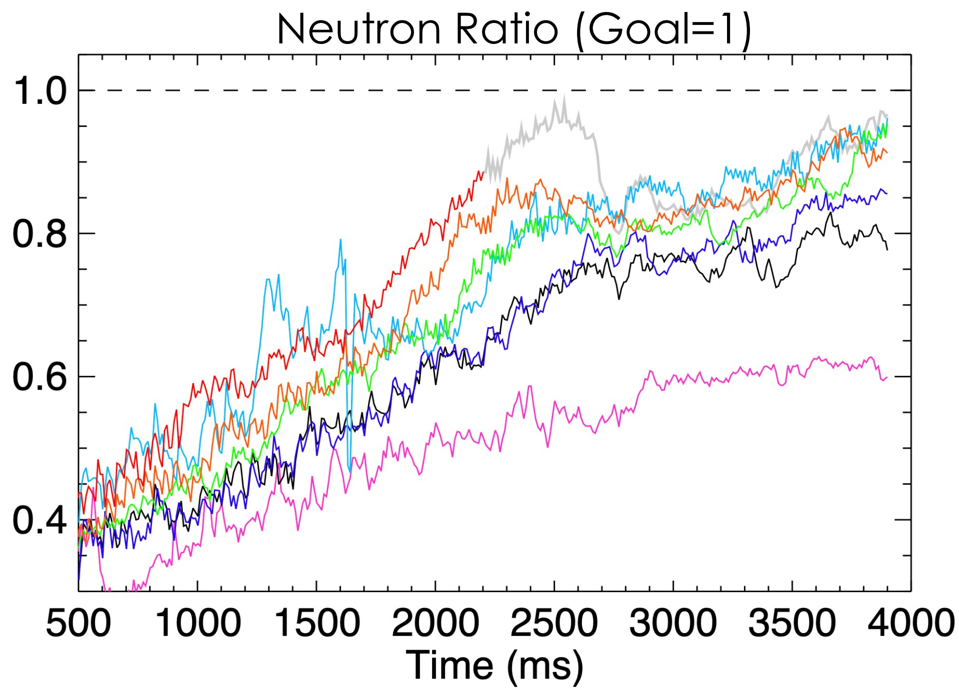




In a database survey comparing all previous years, additional off-axis beam power in 2019 enabled 15% increase in β_N

Neutron Ratio Improved with AE Control Techniques

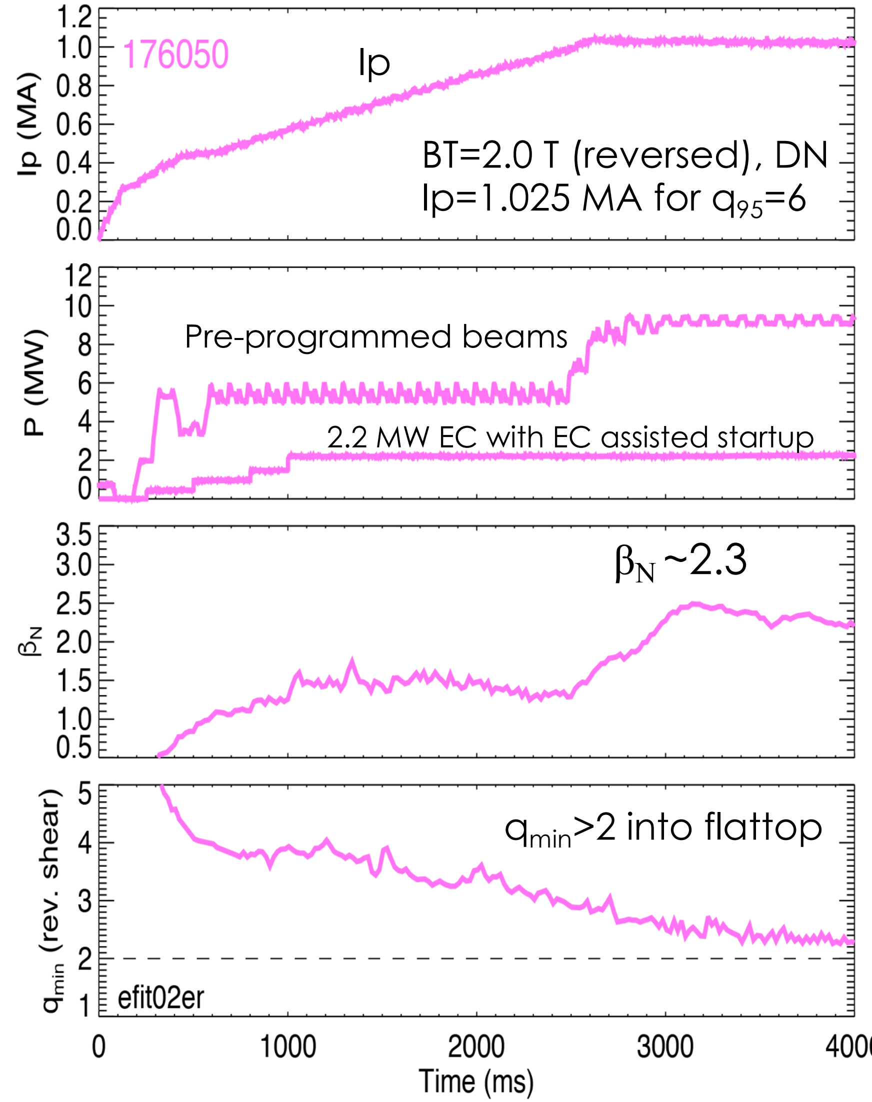
- **AEs can be suppressed by**
  - Manipulating equilibrium profiles
  - Increasing the mode damping
  - Decreasing the fast-ion drive
- **In practice, actuators affect multiple mechanisms**
  - Manipulating NBI heating can change beam profile, q profile, plasma pressure
  - ECCD can affect q profile, plasma pressure, …



shot	% off-axis NBI (ramp/flattop)	Control Method
176050	25/32	old reference
180619	26/30	new reference
180620	26/72	off-axis NB (flattop only)
180622	36/63	spread beam voltage
180623	71/72	off-axis NBI
180624	83/71	max off-axis NBI
180625	83/72	max off-axis NBI + ECCD on-axis

Control Case: Representative High-q_{min} Plasma Was Prepared to Test Various AE Control Methods

- **Established sustained reverse shear (q_0>q_{min}) with q_{min}>2 using early heating**
  - Preprogrammed beam timing was same for every shot (no β_N feedback)
  - Off-axis ECCD helped broaden current profile and prevent tearing modes



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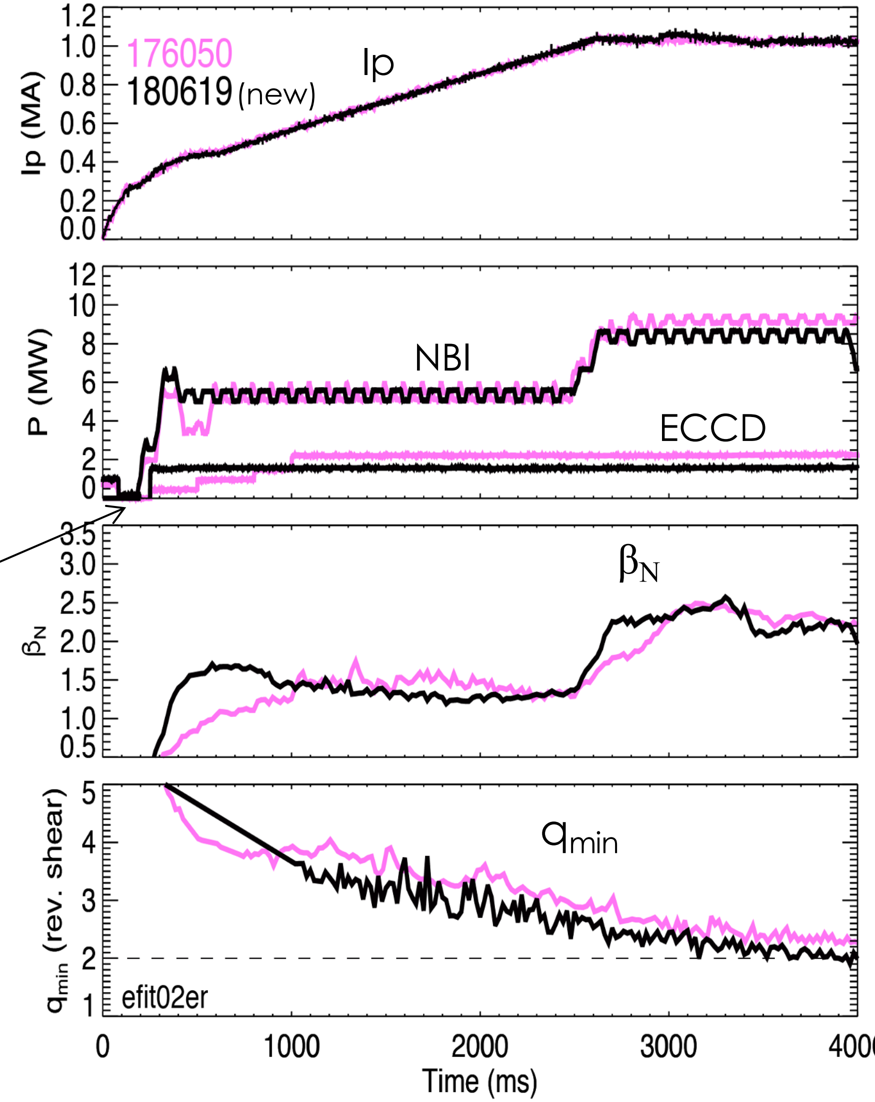
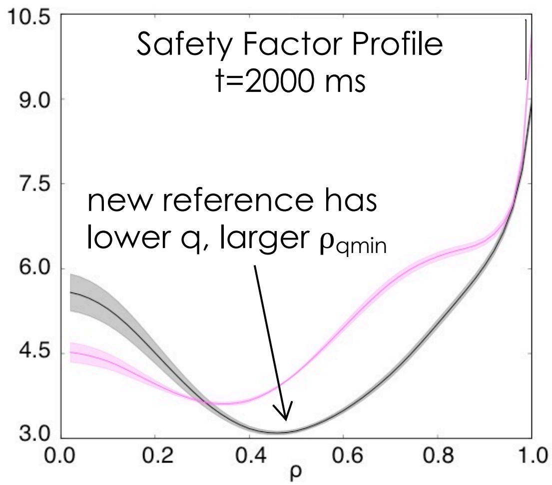
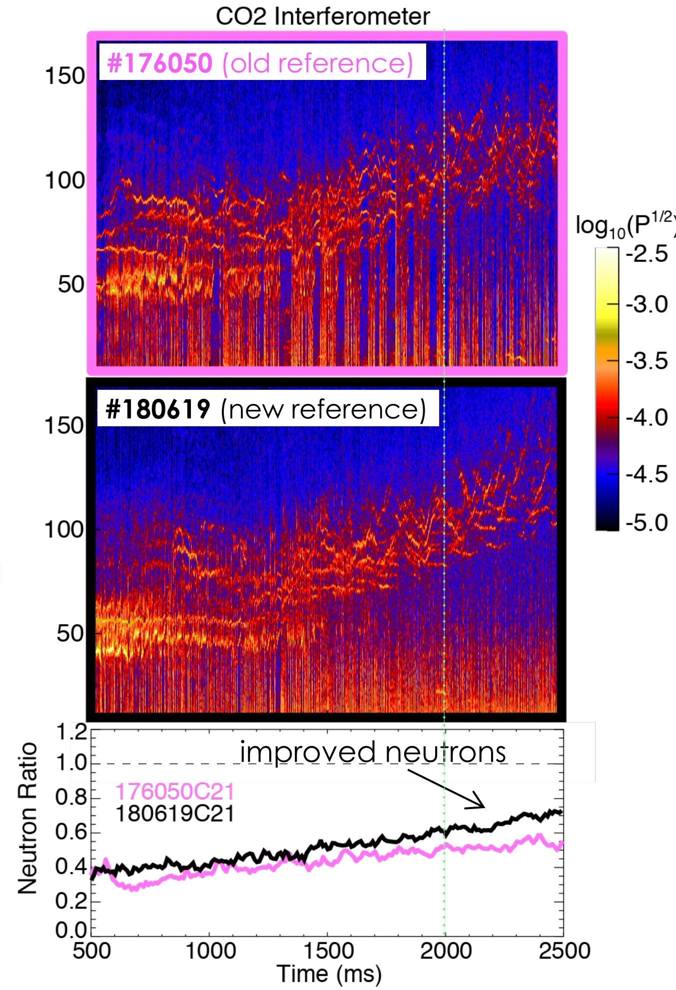
- **First step: Early heating timing was varied to improve q-profile evolution**



Early Heating Increases ρ_{qmin} , Reducing EP Transport

- **Early heating drives off-axis inductive current and larger ρ_{qmin}**
  - Plasma and beam pressure profiles similar
  - Similar AE activity, but neutron ratio improved





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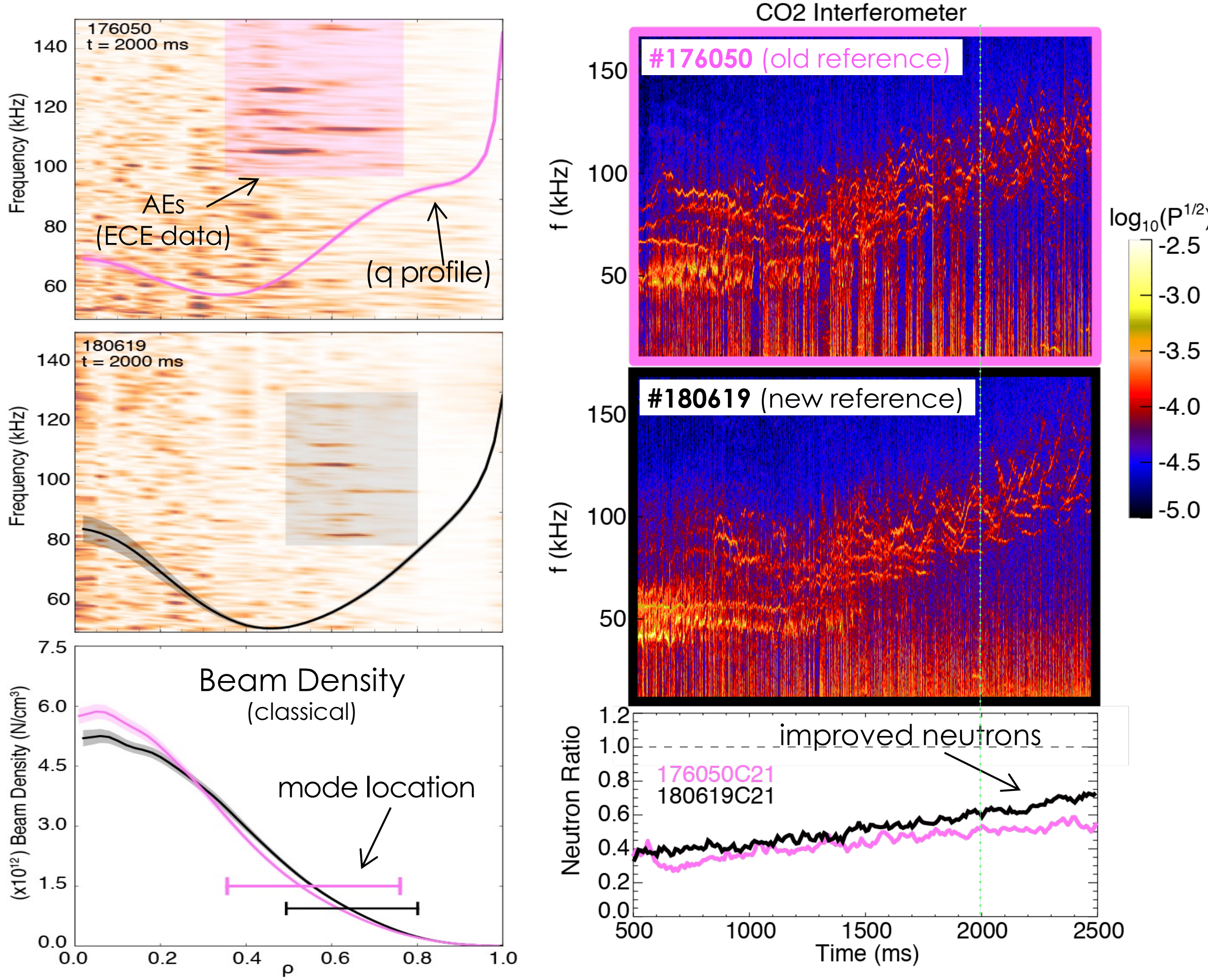

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  - Plasma and beam pressure profiles similar
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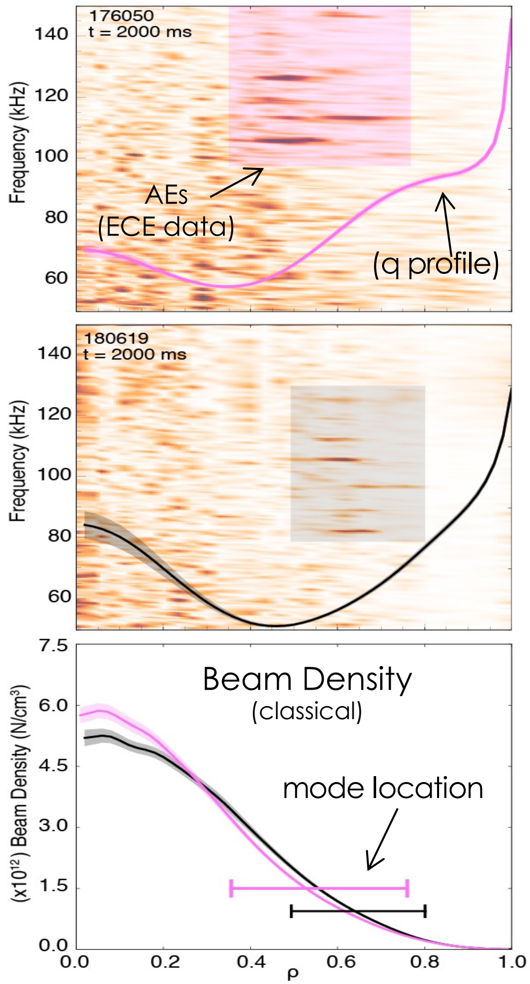
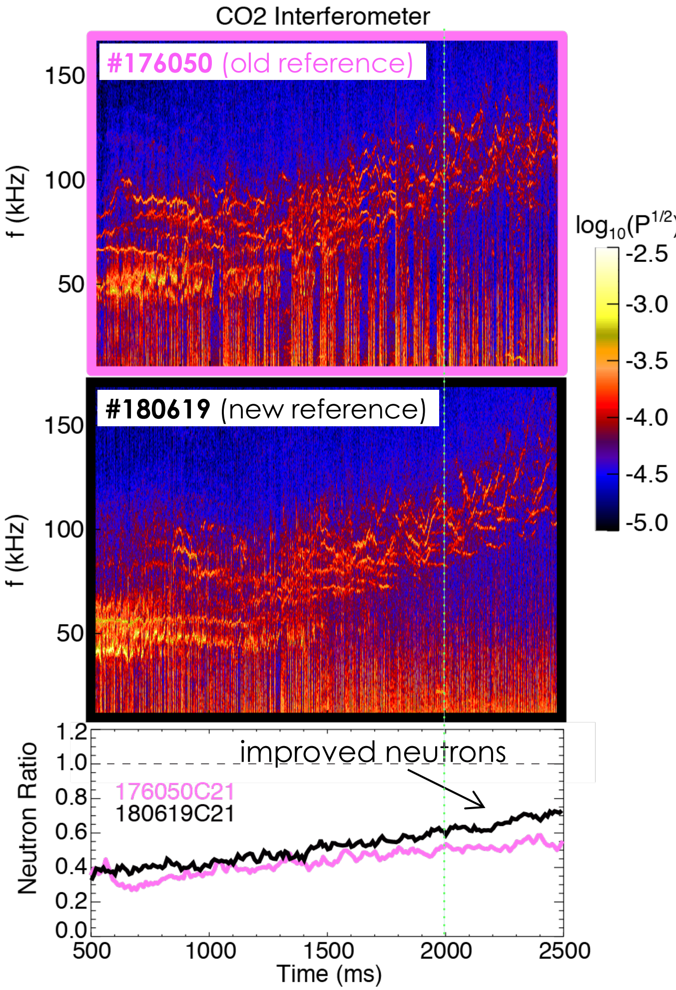
- **AE mode location moves outward to region of lower beam density**
- **→Improvement in neutron ratio because modes transport fewer core EPs**

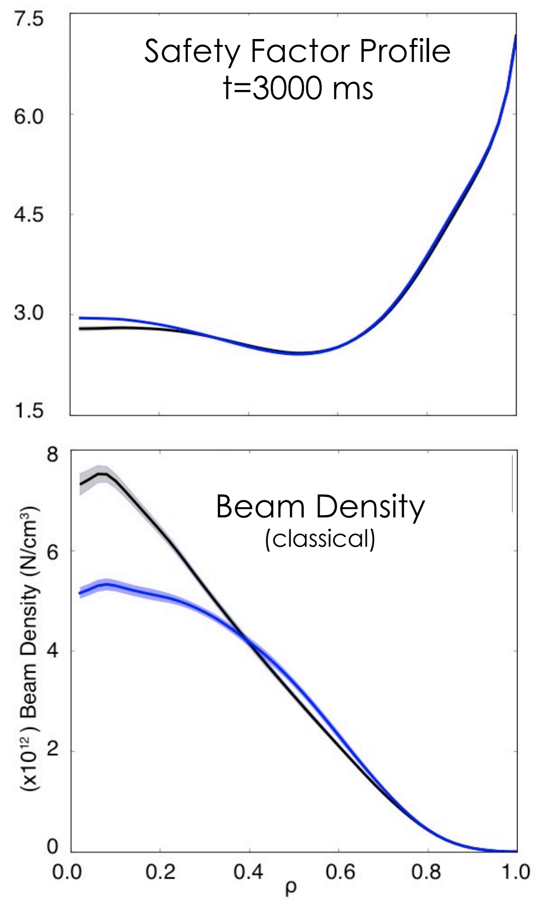
[Kramer, NF 57, 056024 (2017)]

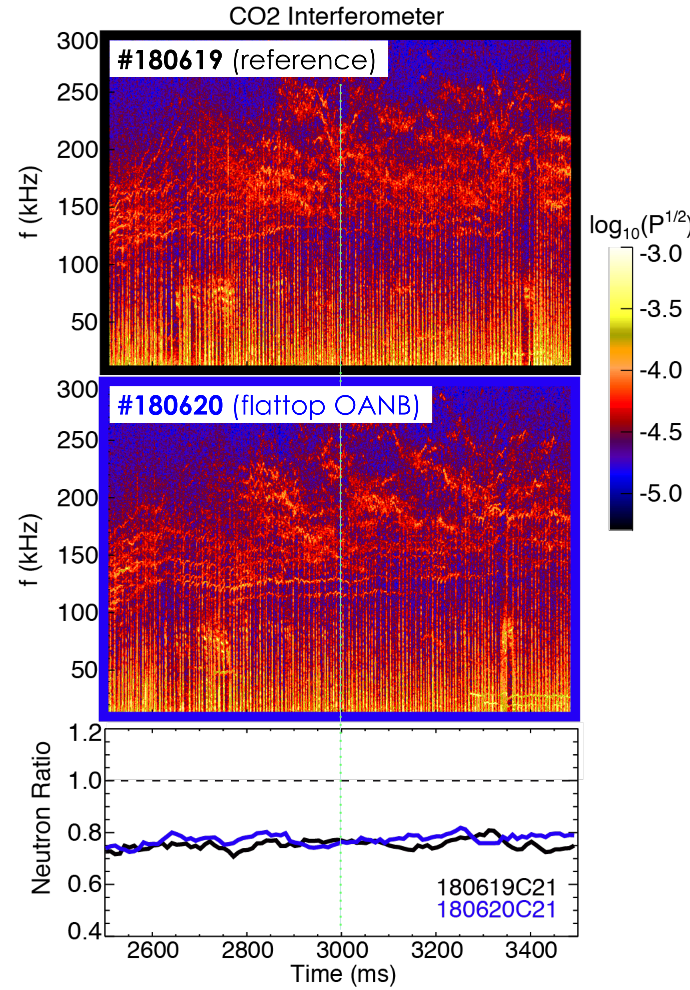




Experiment: Replace 4 MW of On-Axis with Off-Axis Beams in Flattop
Result: Little Difference in AE Activity, Neutron Ratio

- **Plasma profiles (q, T_e, n_e) nearly identical**
- **→Little improvement because little change in $\nabla\beta_{fast}$ at ρ_{qmin} where modes are driven**

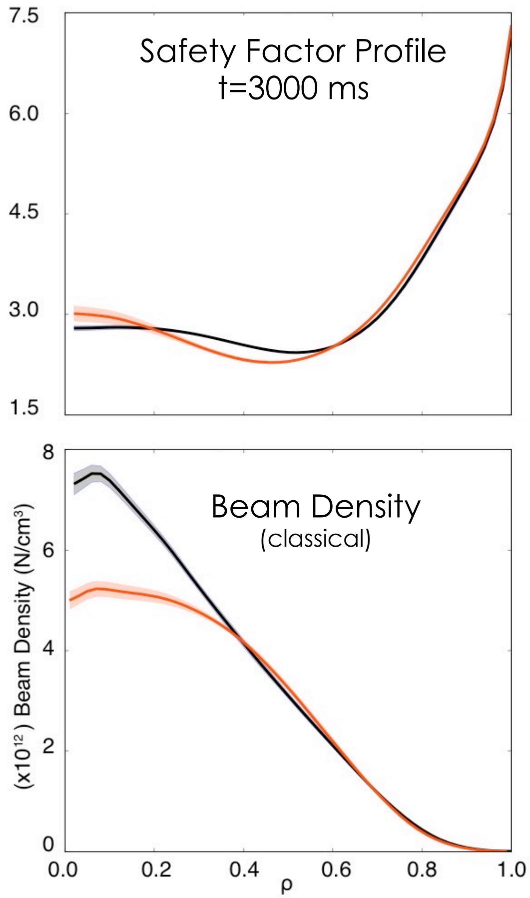


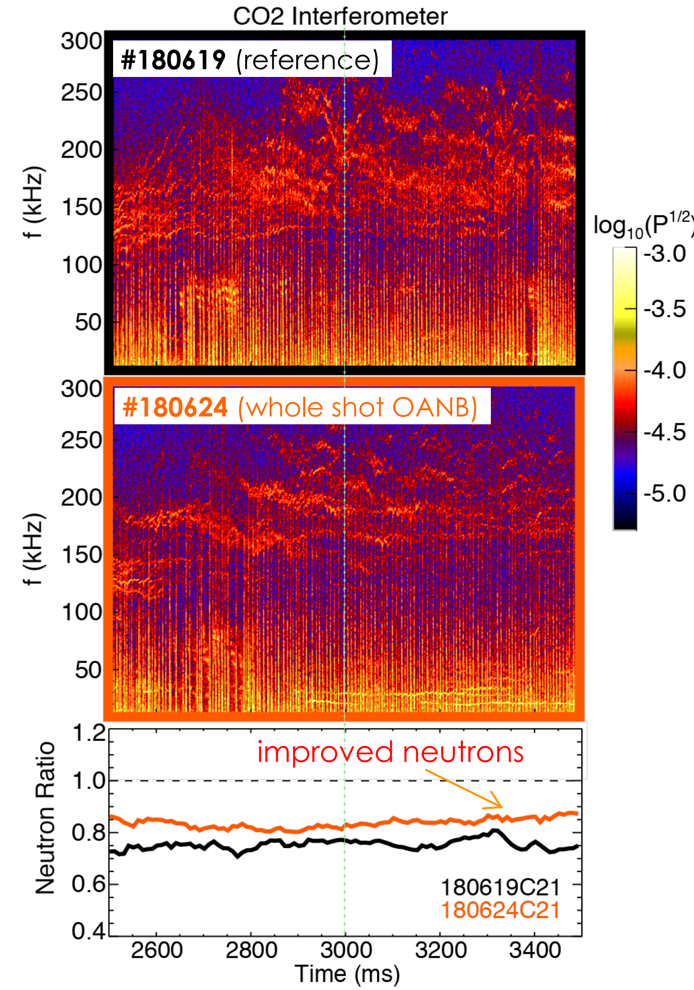


Experiment: Swap in Off-Axis Beams for Whole Shot
Result: Reduced AE Activity, Neutron Ratio Improved 10% in Flattop

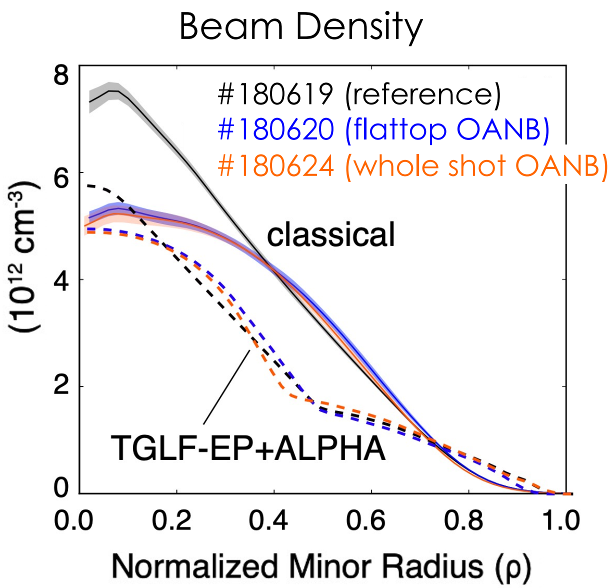
- **ρ_{qmin} moved inward**
  - thermal profiles similar

- **→Improvement due to reducing AE drive by moving ρ_{qmin} towards reduced $\nabla\beta_{fast}$**





TGLF-EP Model and FIDA Measurements Show Broader Beam Pressure Profile Reduced Core Transport of Fast Ions



- **AEs cause fast-ion profile to relax to similar gradient**

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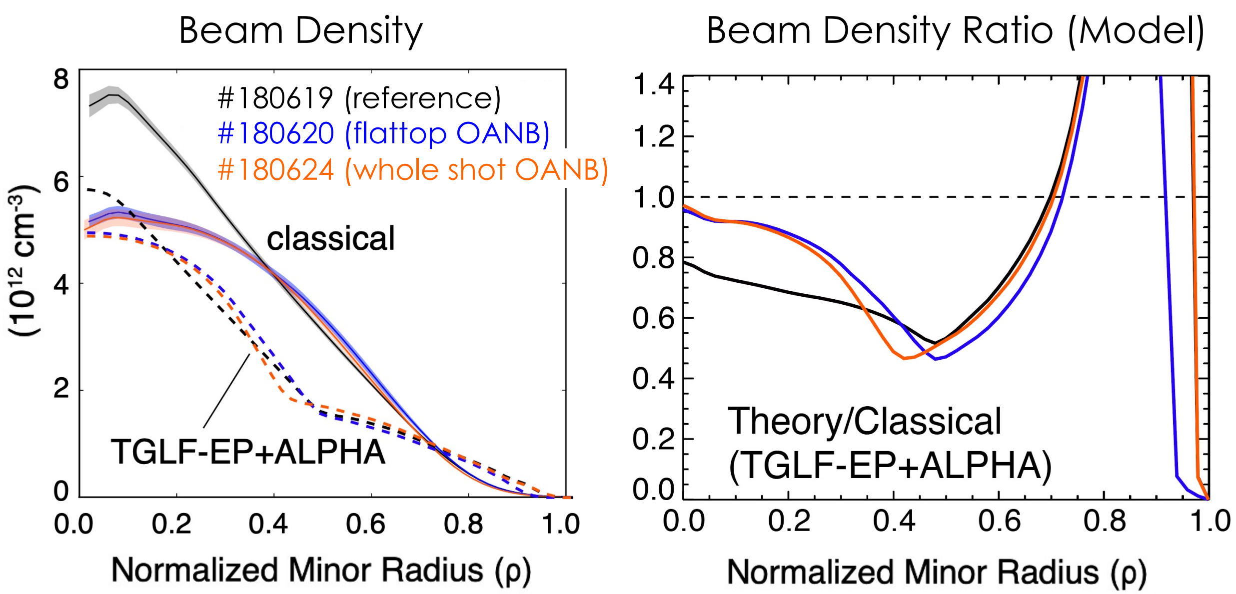

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- **Model profile is closer to classical in core (less transport) in off-axis NBI cases**

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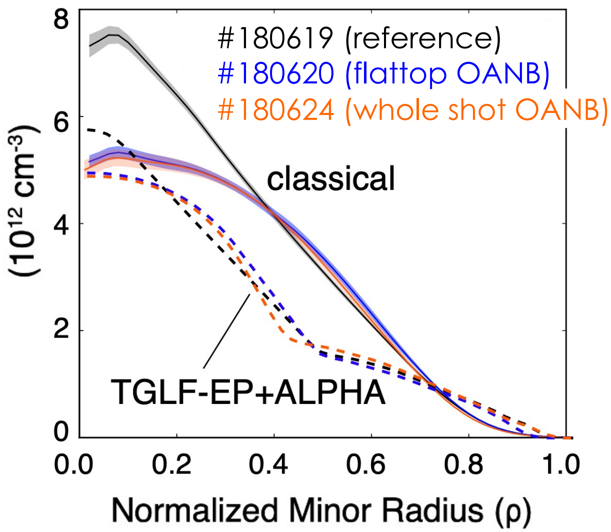
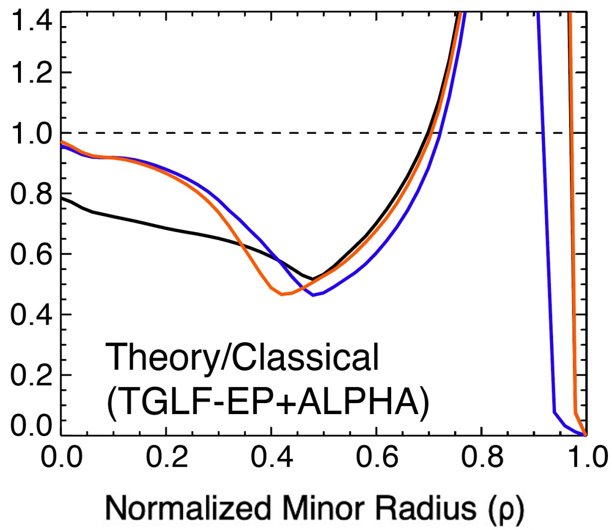
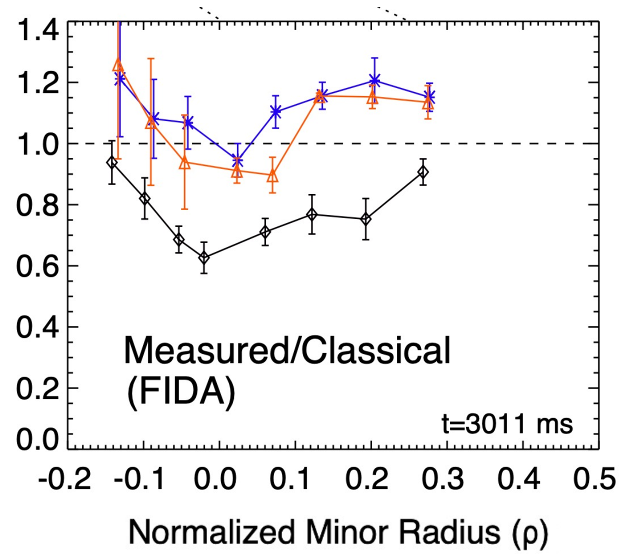
Beam Density



Beam Density Ratio (Model)



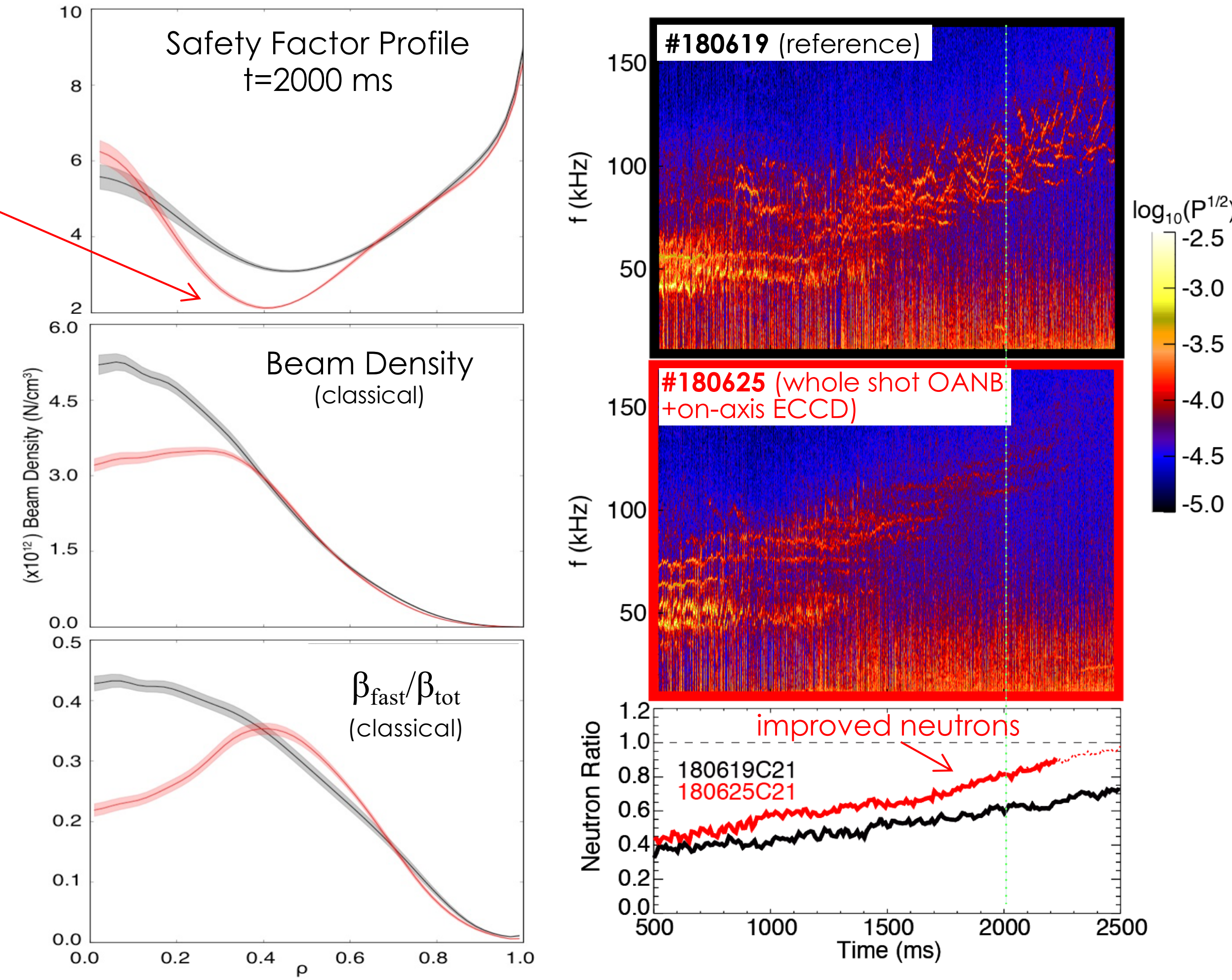
Fast-Ion Profile Ratio (Measured)



- **AEs cause fast-ion profile to relax to similar gradient**
- **Model profile is closer to classical in core (less transport) in off-axis NBI cases**
- **FIDA measurement also indicates less core transport in off-axis NBI cases**

Experiment: OANB + Core ECCD (but q_{min}>2 in Current Ramp Only)
Result: Reduced AEs, Neutron Ratio Improved ~35%

- **q profile: increased shear, lower q_{min}, ρ_{qmin} inward**



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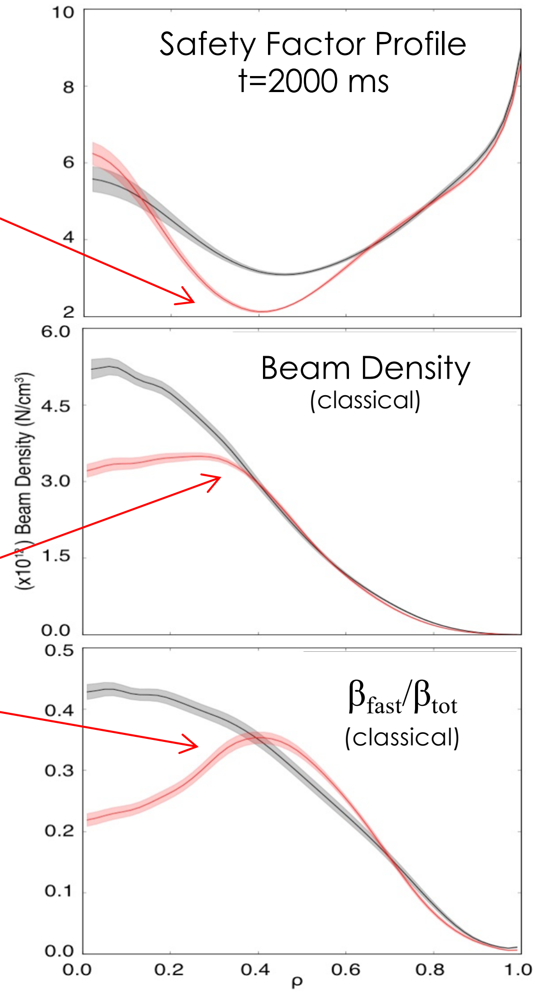
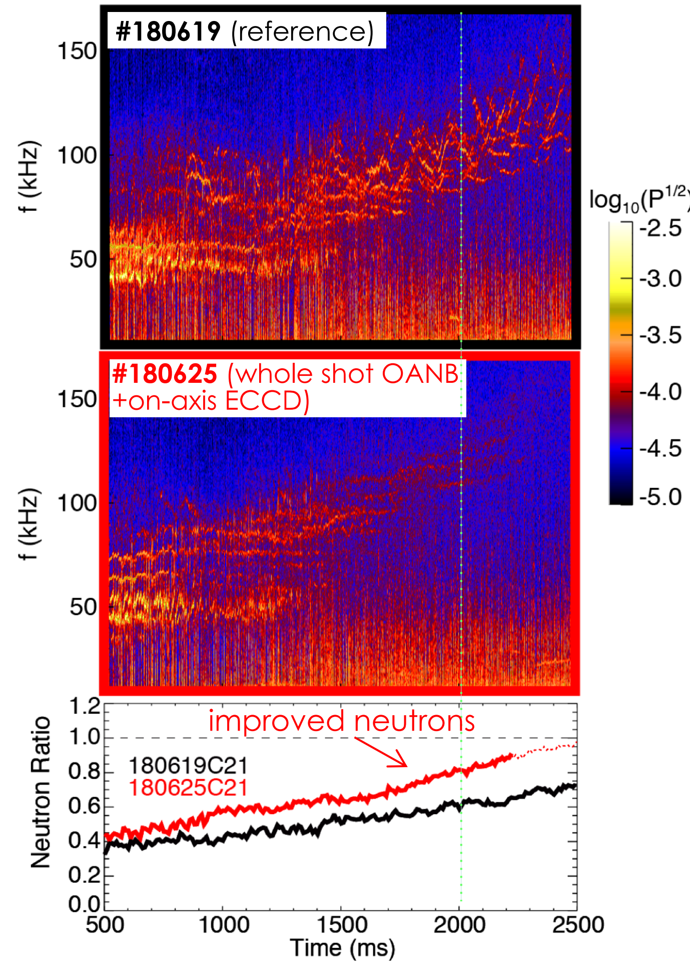
- **q profile: increased shear, lower q_{min}, ρ_{qmin} inward**

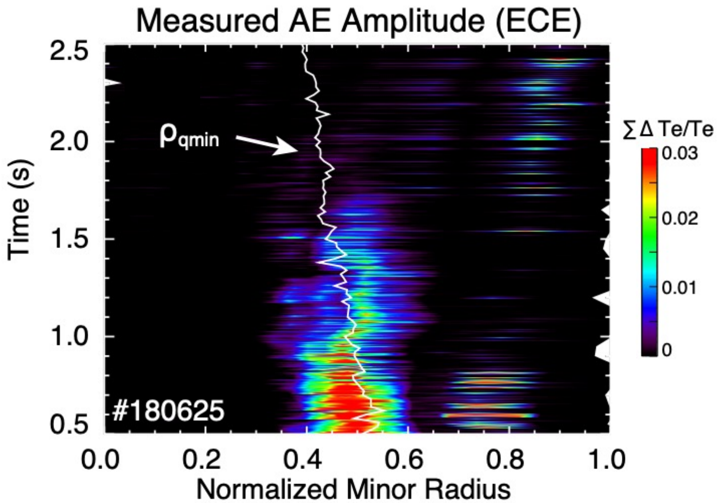
- **→Improvement in neutron ratio may be due to:**
  - lower q
  - moving ρ_{qmin} towards region of reduced $\nabla\beta_{fast}$
  - moving ρ_{qmin} towards region of reduced fast ion fraction

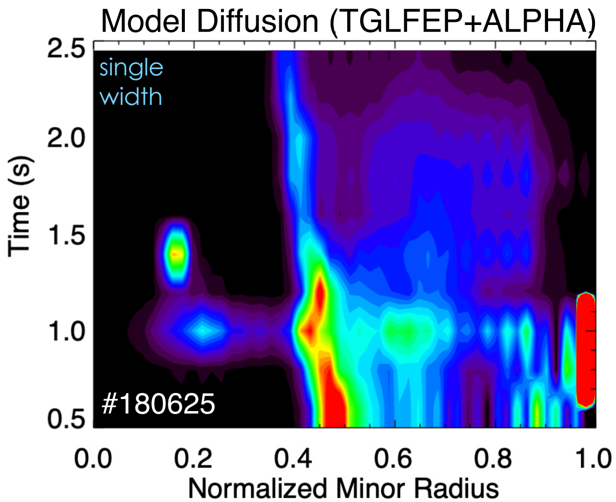




AE-Induced Fast-Ion Diffusion Calculated by TGLF-EP+Alpha is Within 12% of Measurement

- TGLF-EP+ALPHA is used to calculate EP diffusion (radial, time dep.)





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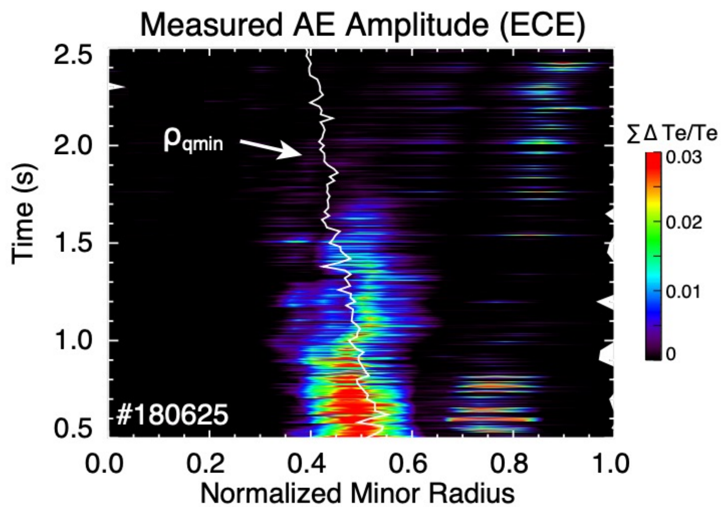
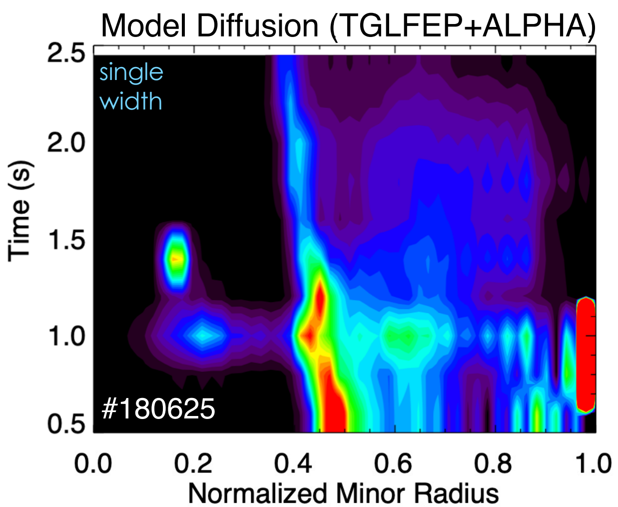
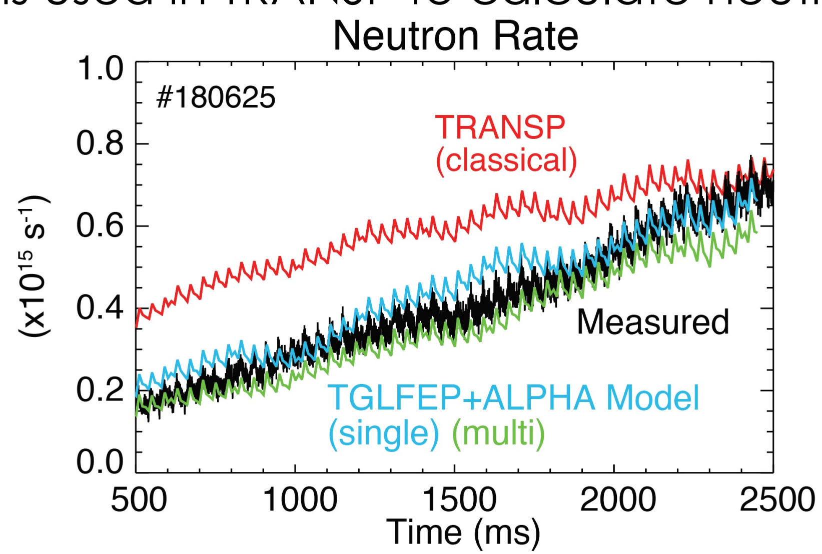




- Diffusion is used in TRANSP to calculate neutron rate



- TGLF-EP model overpredicts by 10% or underpredicts by 12% depending on treatment of free parameter (basis function width)
- TRANSP (classical) with no transport overpredicts by 50%

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Next Steps: Incorporate EP Transport Models Into Integrated Modeling

- **Questions to answer in determining how to achieve SS:**
  - What is the optimal q profile?
  - How much do EP instabilities affect performance, H&CD efficiency?
  - How to create the scenario?

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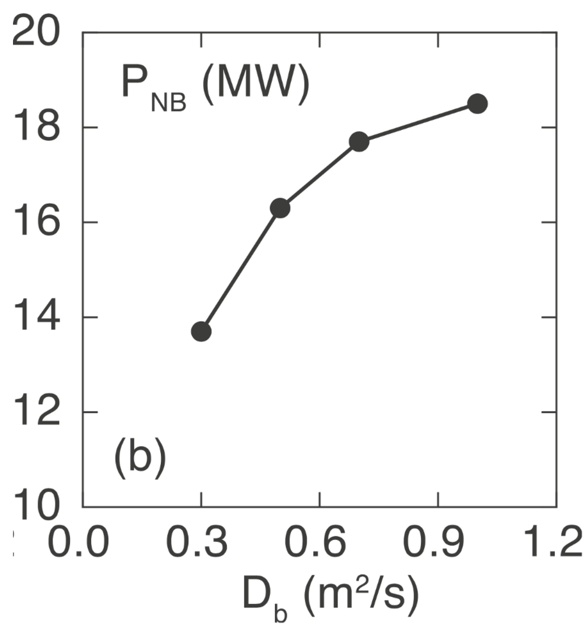
Sensitivity of integrated modeling predictions to fast-ion transport

NBI Power Required to Reach β_N ~4.6



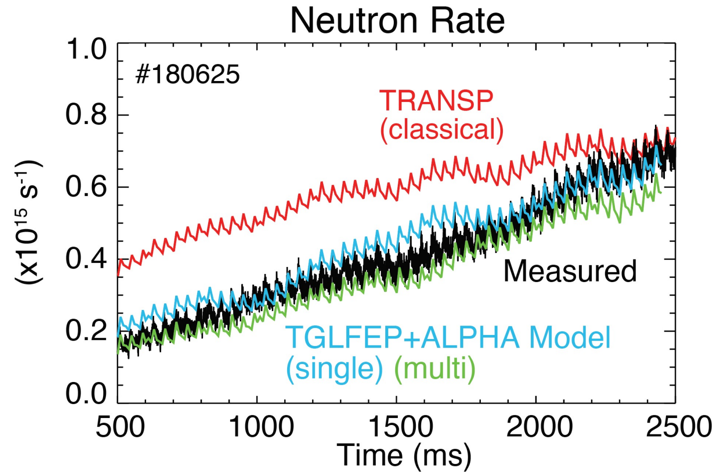
Assumed Anomalous Fast-Ion Diffusion

[Park PoP 25 012506 (2018)]

Summary

- **Broadened EP profile enables better control of AEs in steady-state scenarios**
  - Key factor is moving ρ_{qmin} towards region of reduced $\nabla\beta_{fast}$
  - Neutron ratio improved by ~25% in flattop
  - Accessed new regimes with 15% higher β_N

- **TGLF-EP+ALPHA critical gradient model reproduces EP transport trends**
  - Model-based diffusion matches measured neutron rate within 12%



- **This work provides a basis for understanding how to avoid AE-induced EP transport in ITER and future advanced tokamak scenarios.**