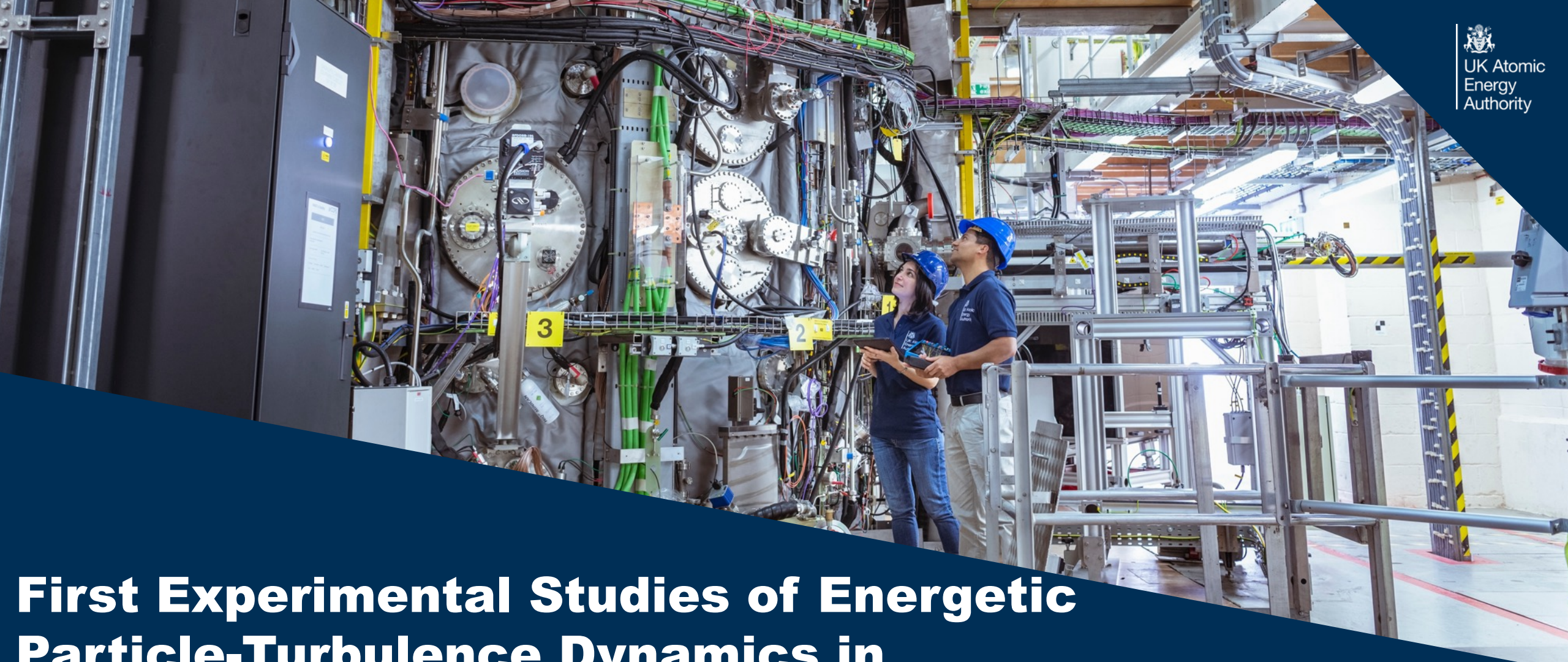




First Experimental Studies of Energetic Particle-Turbulence Dynamics in Spherical Tokamak Plasmas

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Fast Ions can Regulate Microturbulence in Spherical Tokamaks via Many Paths

- STs contain a pronounced fast ion population relative to conventional tokamaks that exhibit different dynamics
- Fast ions can directly/indirectly affect turbulence in STs via:
 1. AE excitation and nonlinear shear suppression [1-2]
 2. NBI induced rotation
 3. Added fast ion pressure/current

[1] X.D. Du et al. PRL 2025
[2] J. Ruiz Ruiz et al. PRL 2025

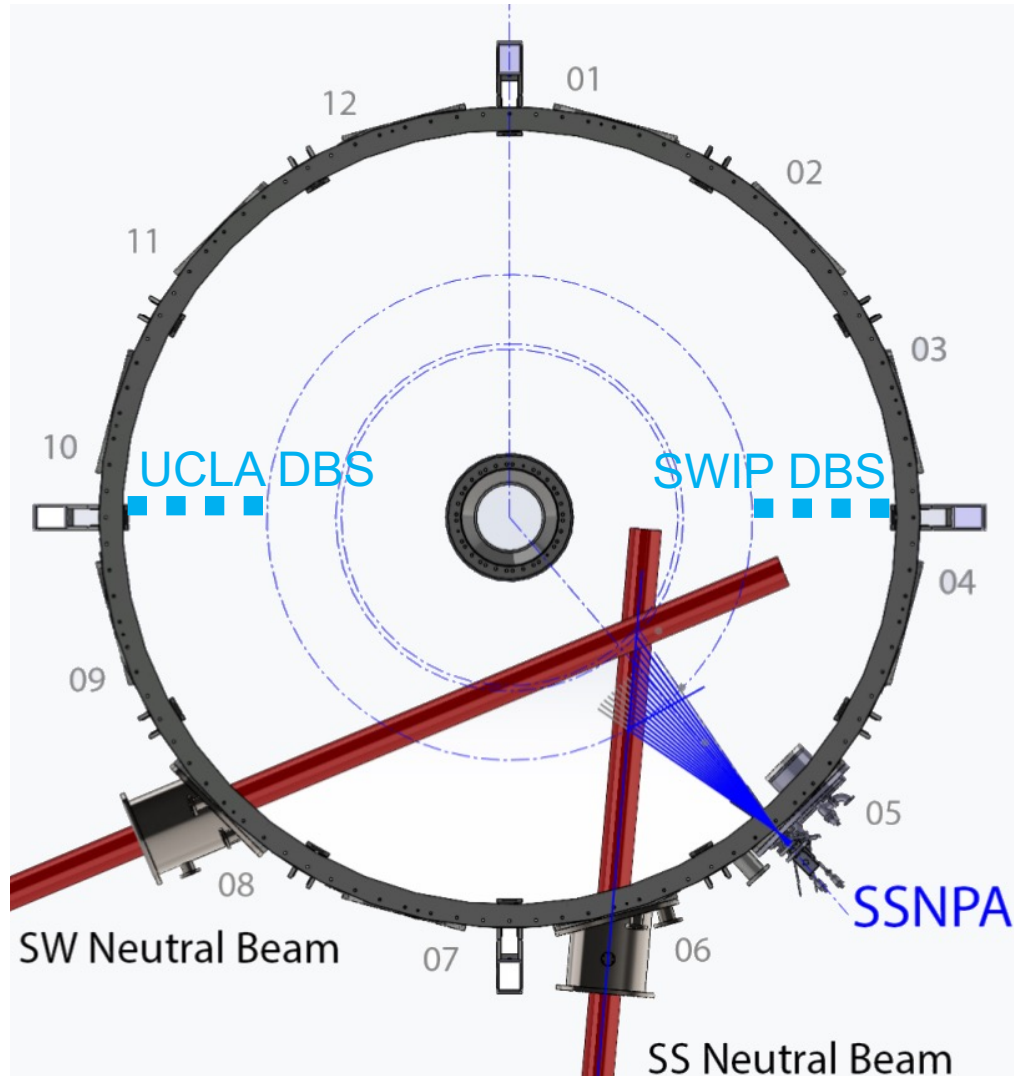
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Which of these effects is strongest?

[1] X.D. Du et al. PRL 2025
[2] J. Ruiz Ruiz et al. PRL 2025

Doppler Backscattering (DBS) Serves as the Primary Turbulence Diagnostic



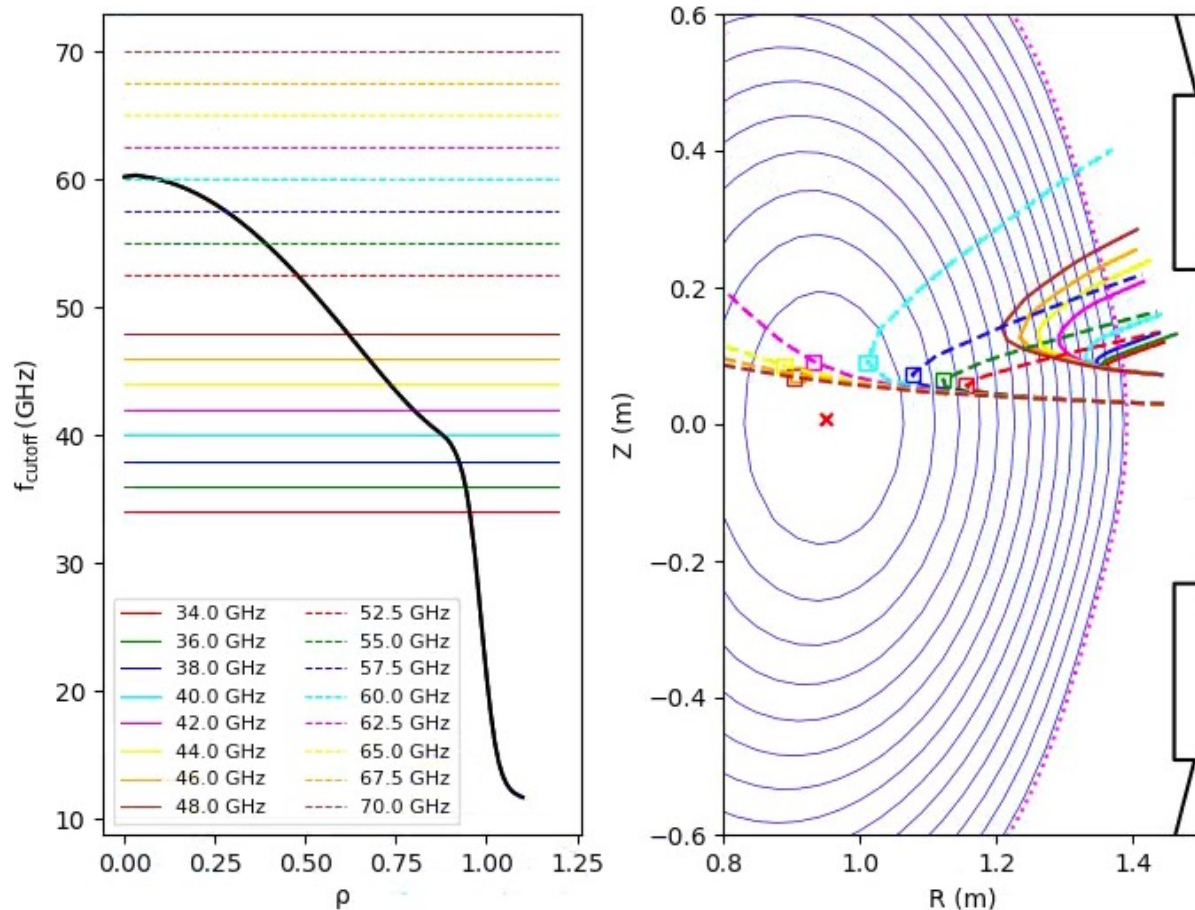
MAST-U

- $R_0 = 0.8$ m, $a = 0.5$ m, $B_\phi = 0.7$ T, $I_p = 1$ MA
- Two NBIs: 75 keV, up to 3.6 MW
 - SS-beam: on-axis
 - SW-beam: off-axis
- Relevant Diagnostics: neutrons, FILD, NPA, FIDA
- **BES unavailable for MU05 Campaign!**

DBS

- 2 systems (UCLA and SWIP) located 180° apart
- Each system has:
 - 8-channel Q-band (edge and outer radii)
 - 8-channel V-band (core and mid-radii)
- One matching channel across systems at 40 GHz

DBS Measures the Backscattered Fluctuation Velocity as a Function of Time and Space (channel)



GENRAY finds cutoff locations and $\vec{k}_{\text{scat}}$

- Received signal is translated as a complex signal of the backscattered electric field:

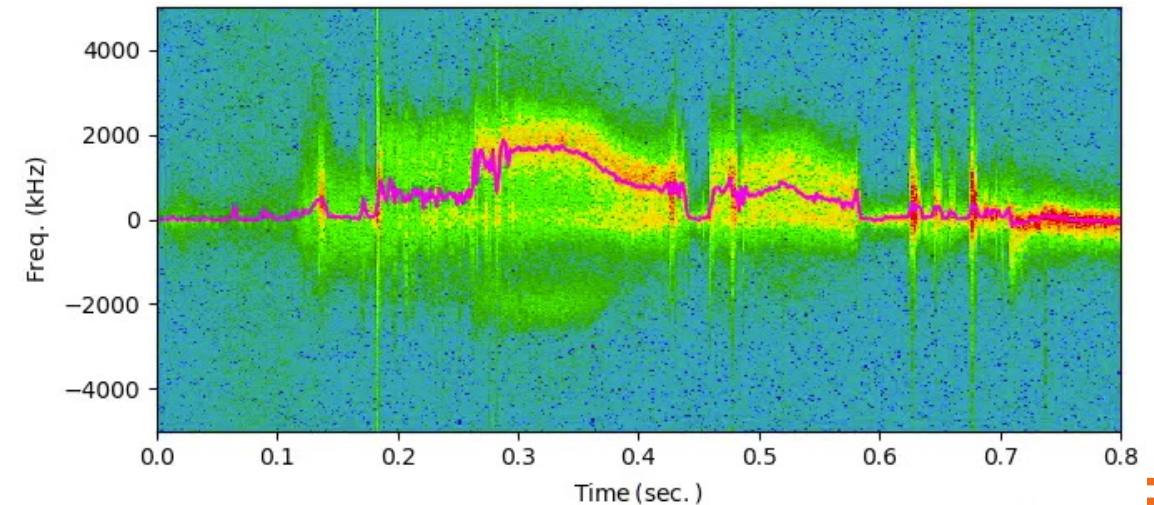
$$E(t) = I(t) + iQ(t)$$

- Power spectrum reveals Doppler frequency:

$$f_D \sim \frac{\int f P(f) df}{\int P(f) df} \sim f_{\text{peak}}$$

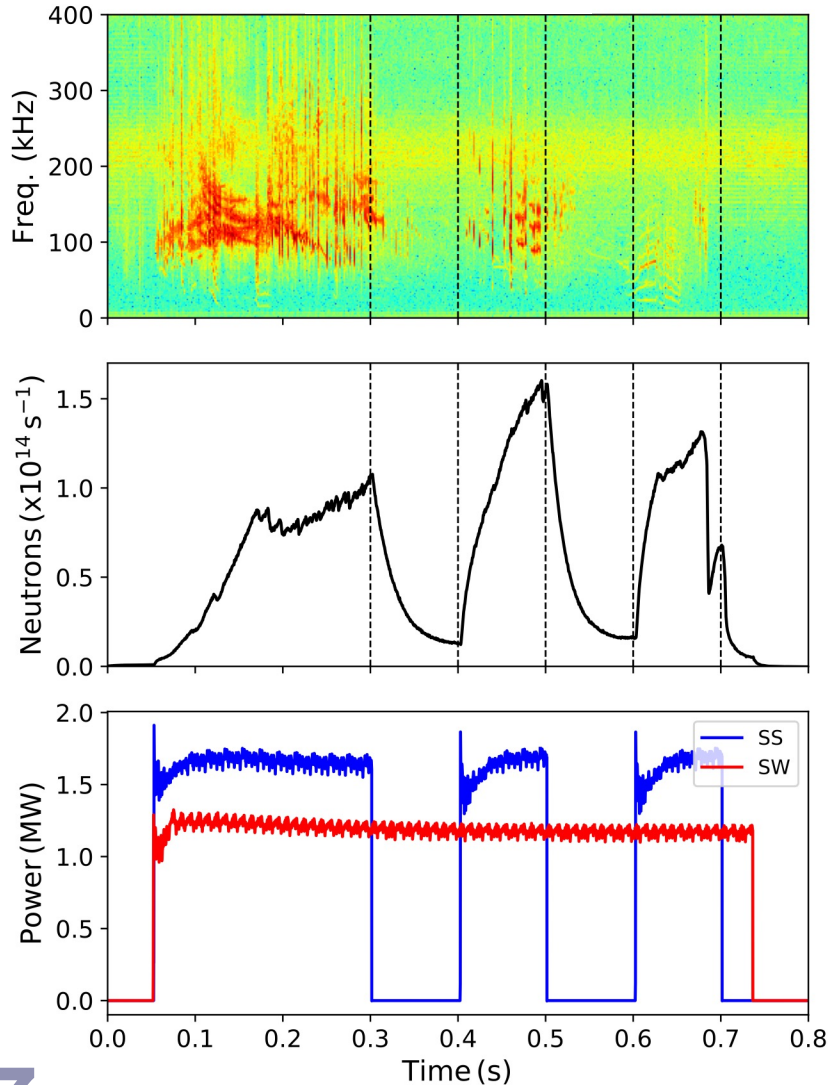
- Solve for v_{ExB} with ray tracing resolved $\vec{k}_{\text{scat}}$

$$f_D = \vec{k}_{\text{scat}} \cdot \vec{v}_{\perp}$$

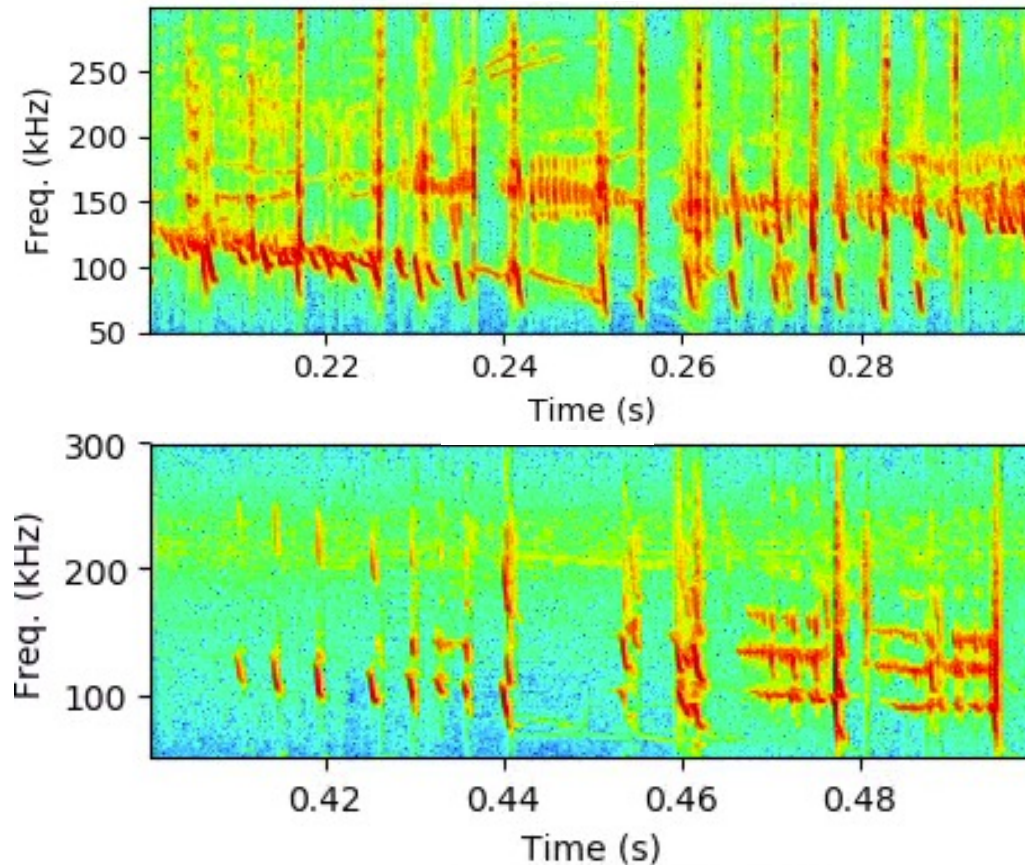


Alternating Periods of Beam-on and Beam-off were used to Probe Fast ion Effects

Shot 53678



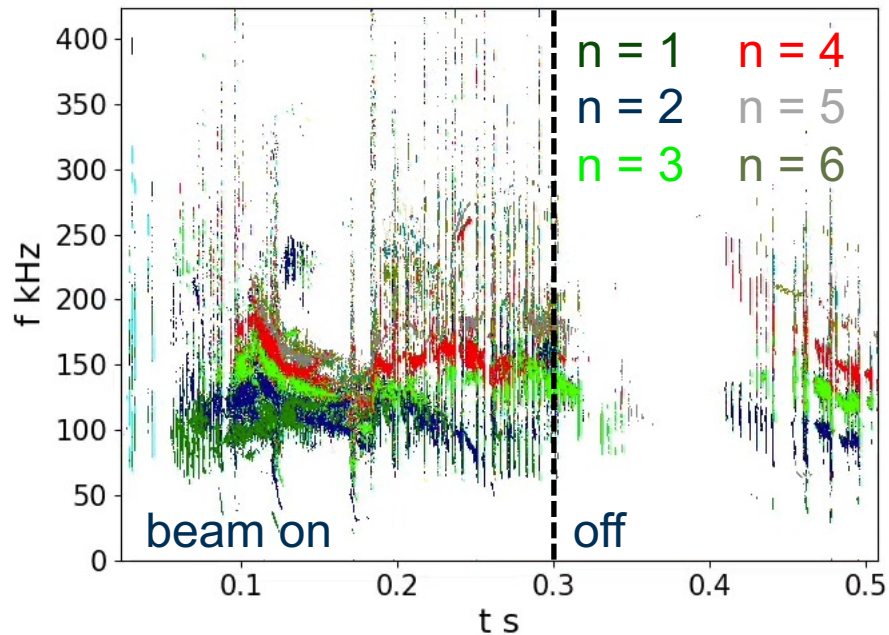
- Observed modes quickly dissipate after beam turn off
- Modes are very bursty and chirp in frequency
 - Commonly observed in STs [1-3]



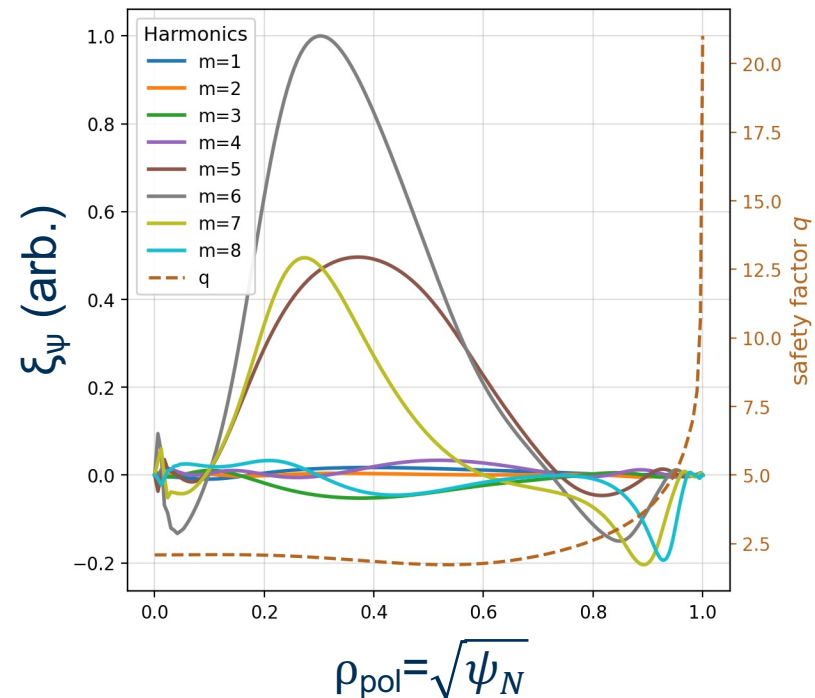
NOVA Computed TAEs Agree with Magnetic Measurements

- $n = 1-4$ TAEs appear during the first two beam-on periods
- Mode structures peak near core to mid radii ($\rho \sim 0.3, 0.4$) and are broad in extent $\Delta\rho \sim 0.5-0.6$ due to low magnetic shear

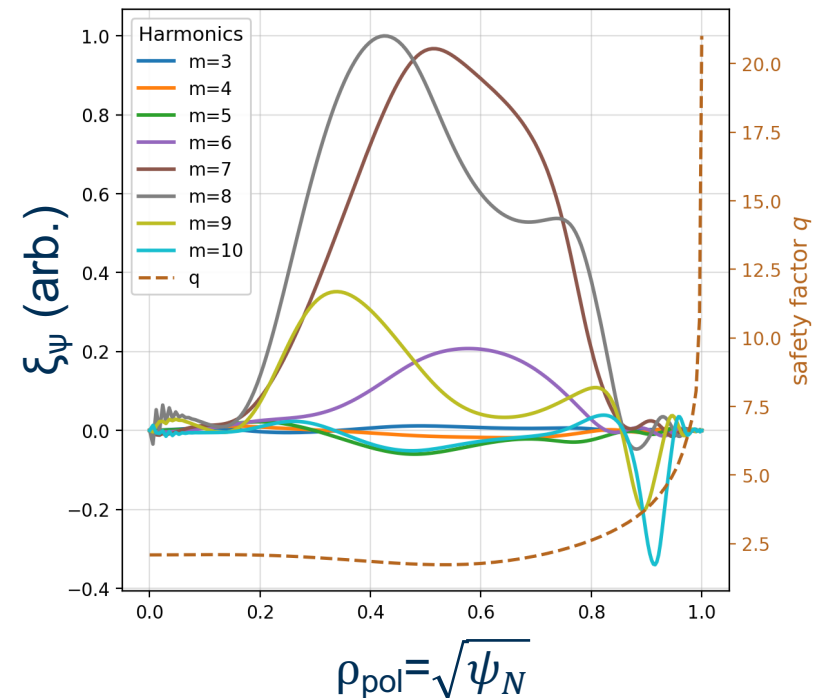
53678 Toroidal Array Decomposition



110 kHz $n=2$ NOVA

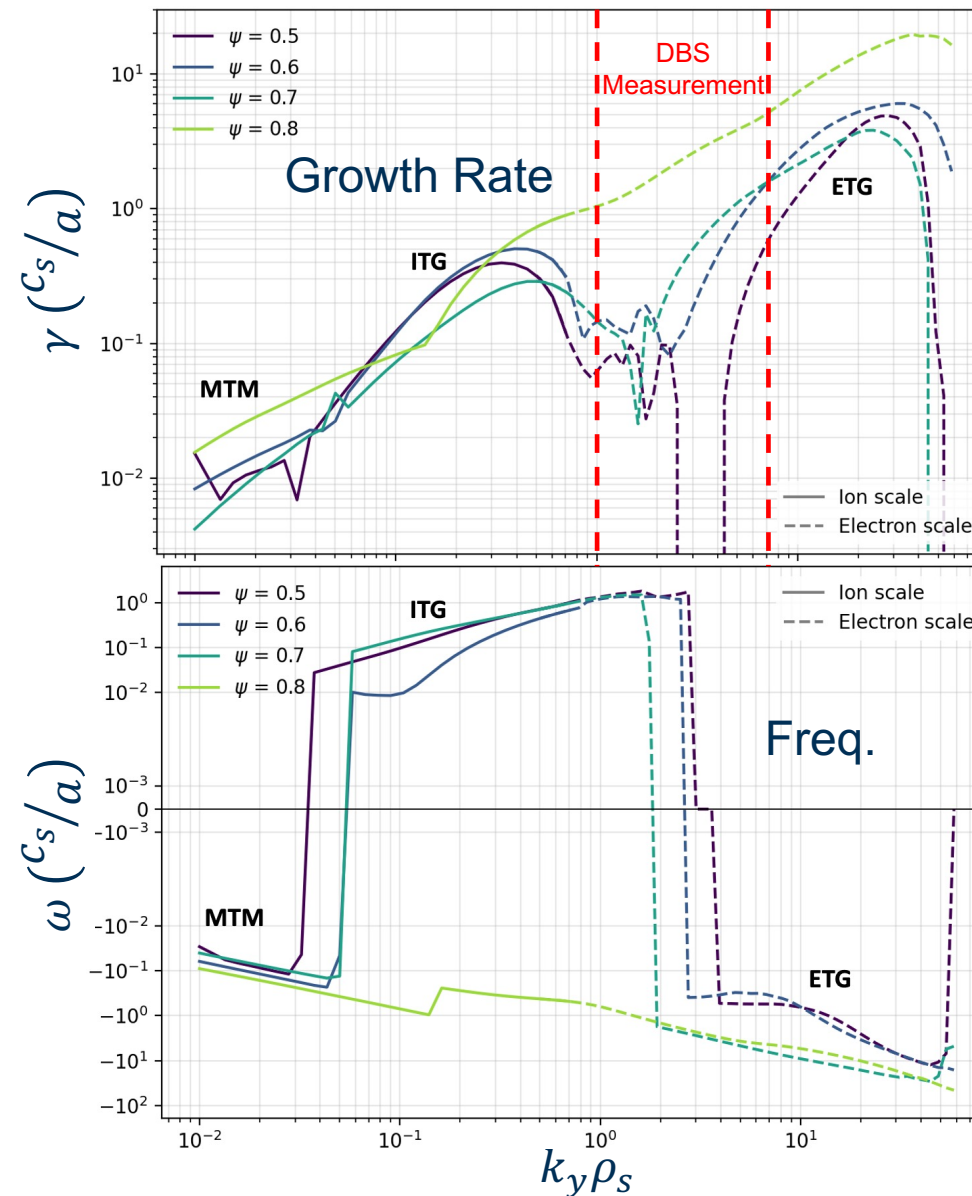


140 kHz $n=3$ NOVA



Linear CGYRO Simulations Point to Electron Channel Dominated Turbulence

- Linear simulations during beam-off period show ETG modes with the highest growth rates
- Initial nonlinear simulations show dominant electron heat flux and negligible ion flux at the neoclassical level [1]
- CGYRO simulations agree with TRANSP calculated fluxes
- See C. Gallaro's poster tomorrow for more details

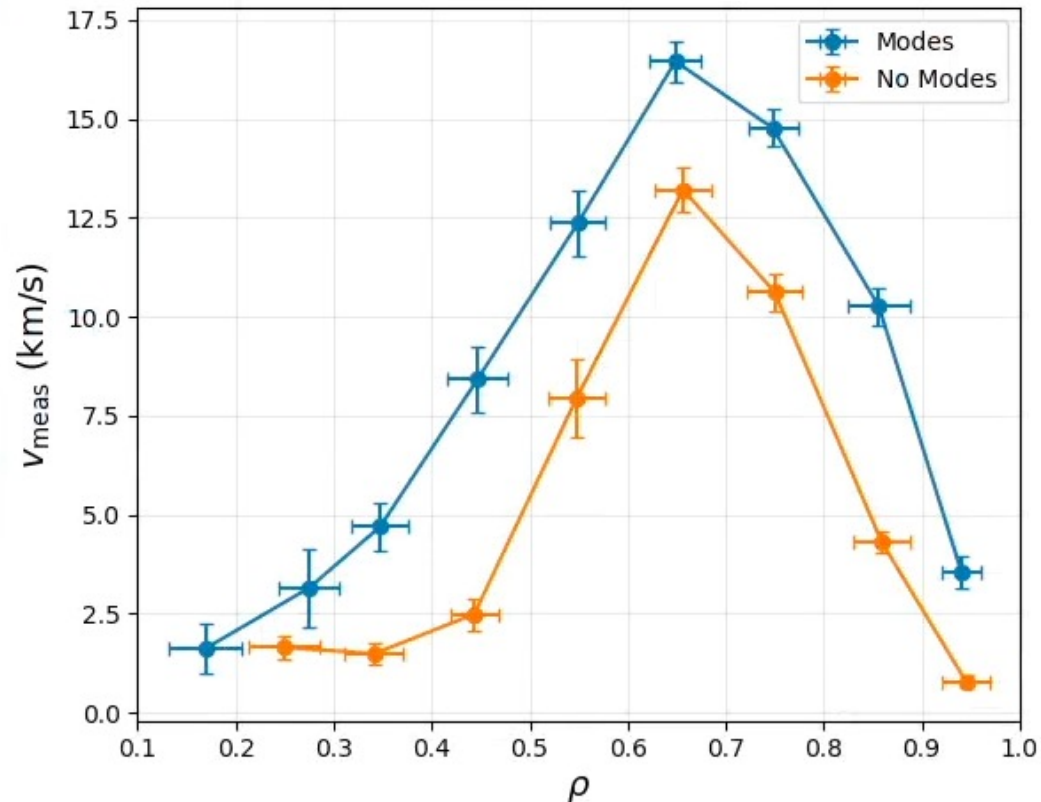


[1] S.M. Kaye et al NF 2007

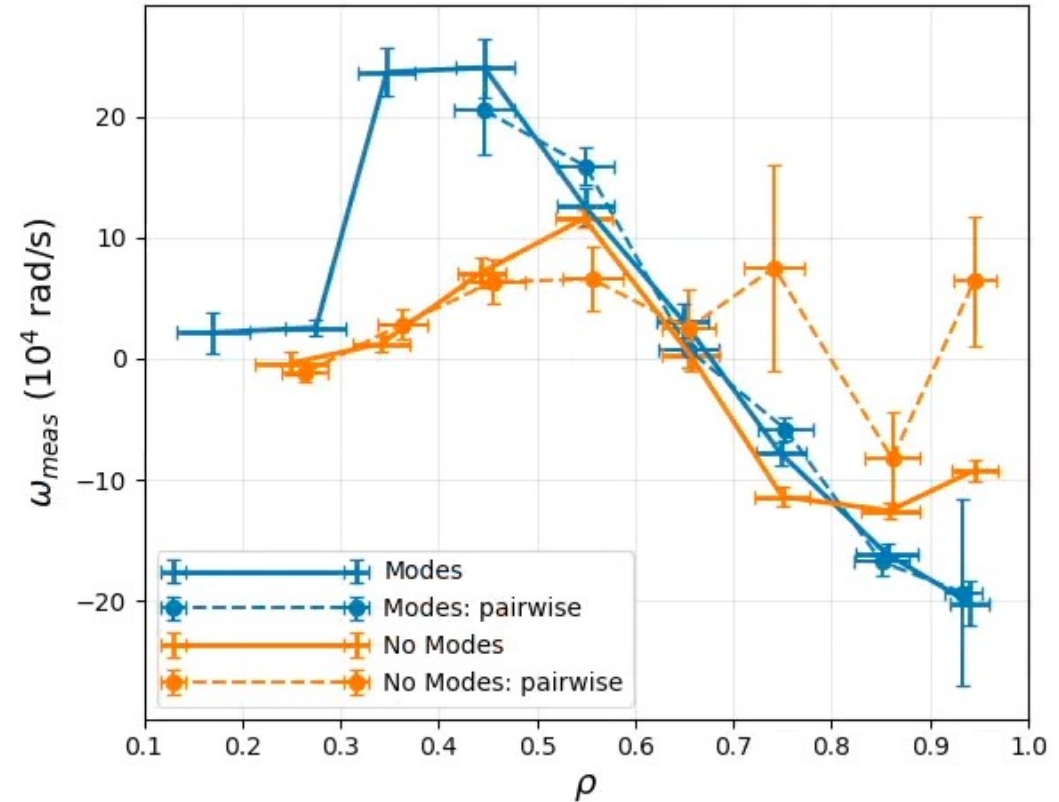
DBS Measures Change in Flow Shear During Active vs. Inactive AE periods

- Measurable increase in flow shear near $\rho \sim 0.3-0.5$ during AEs relative to periods with no modes
- Data is built while NBI is on to avoid effects due beam changes

DBS V_{ExB} Structures



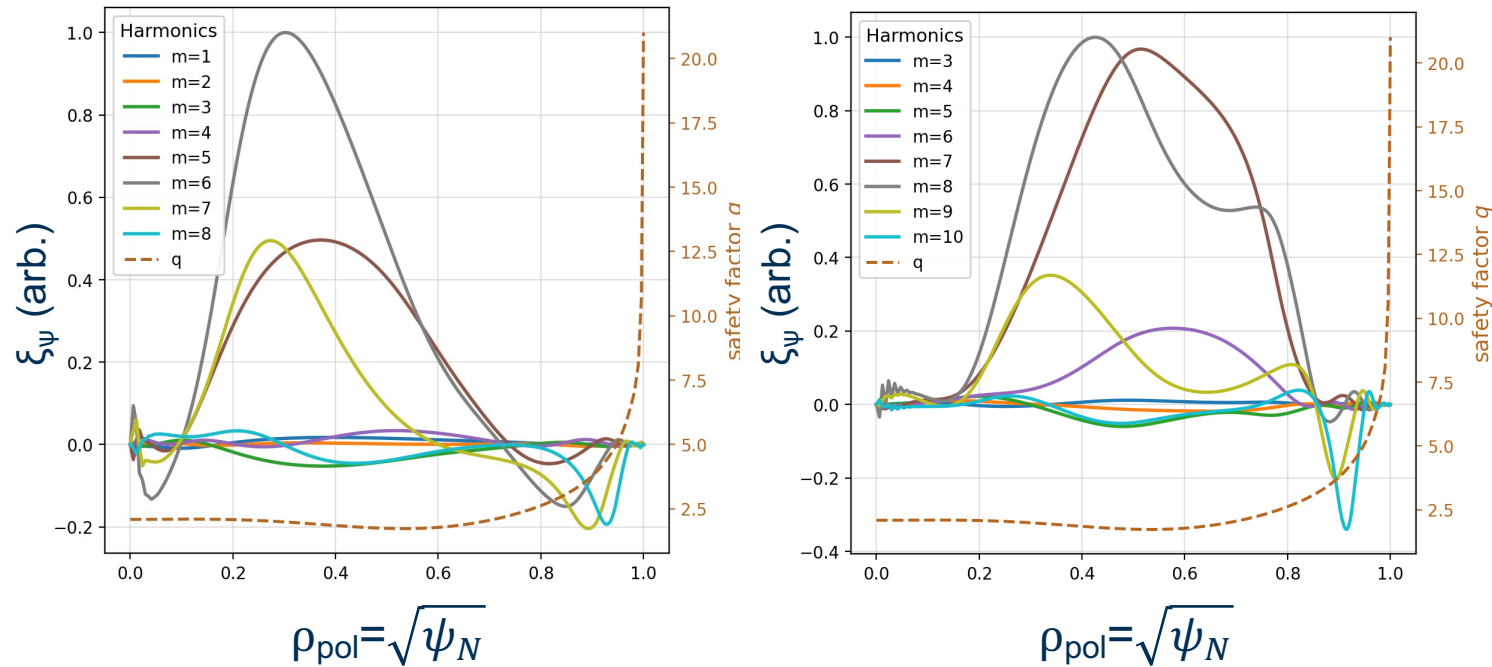
DBS Shear Structures



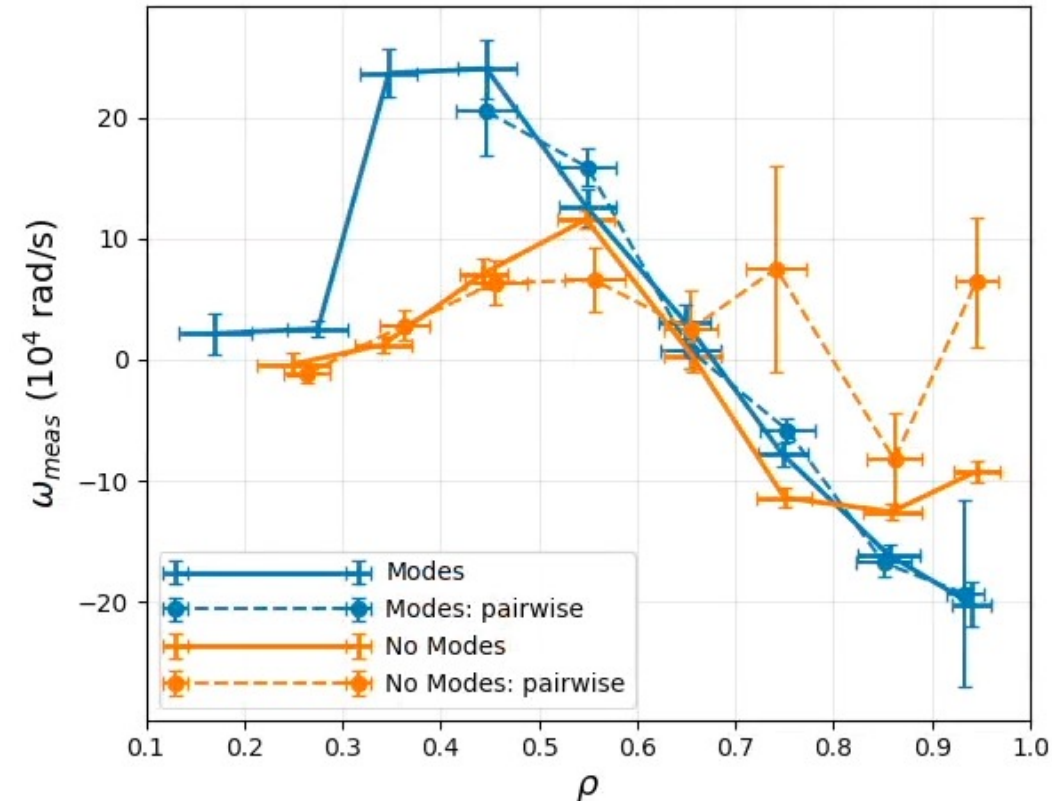
Changes in AE Correlated Flow Shears Qualitatively Agree with TAE Structures

- Very qualitative result because the AE modes are radially broad
- Shear measurements on the right do not distinguish modes – all modes ensembled together

NOVA Structures

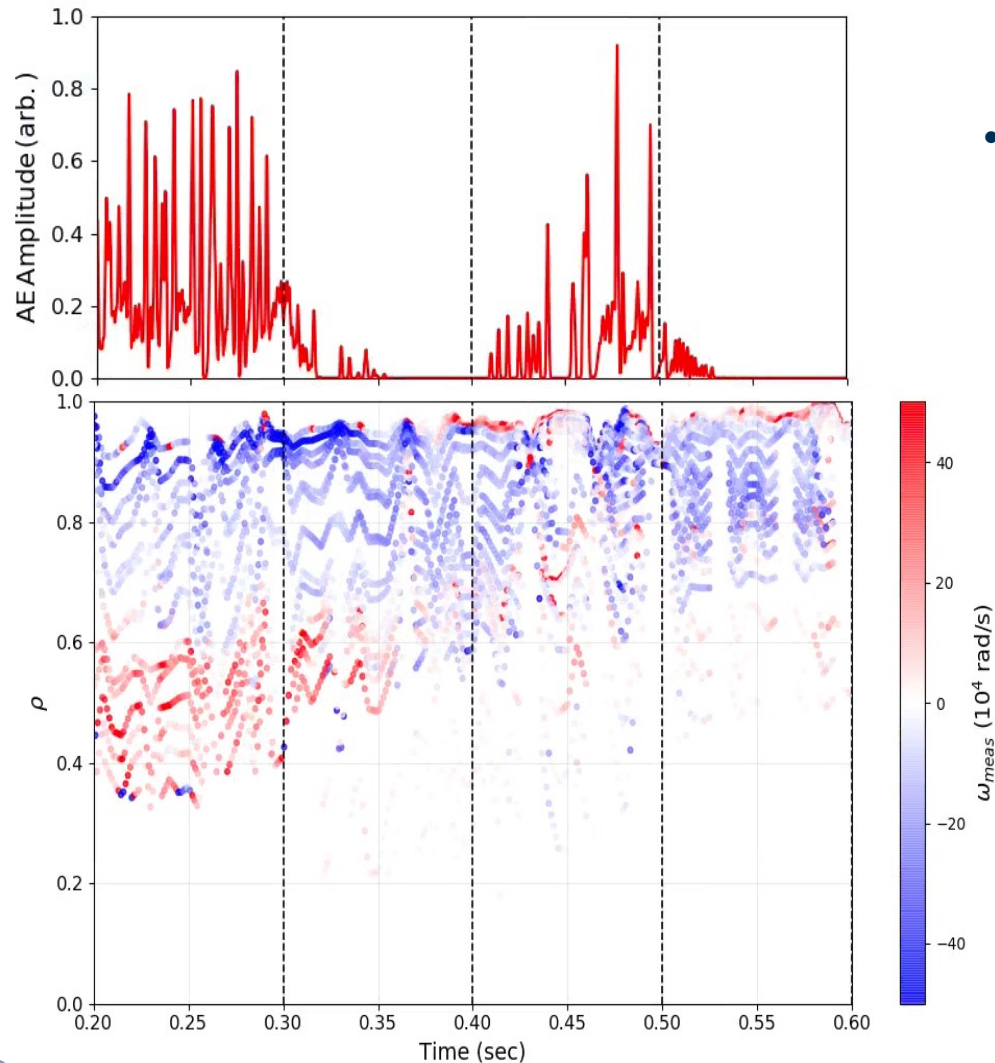


DBS Shear Structures



Each DBS Measurement can be Related to AE Amplitude

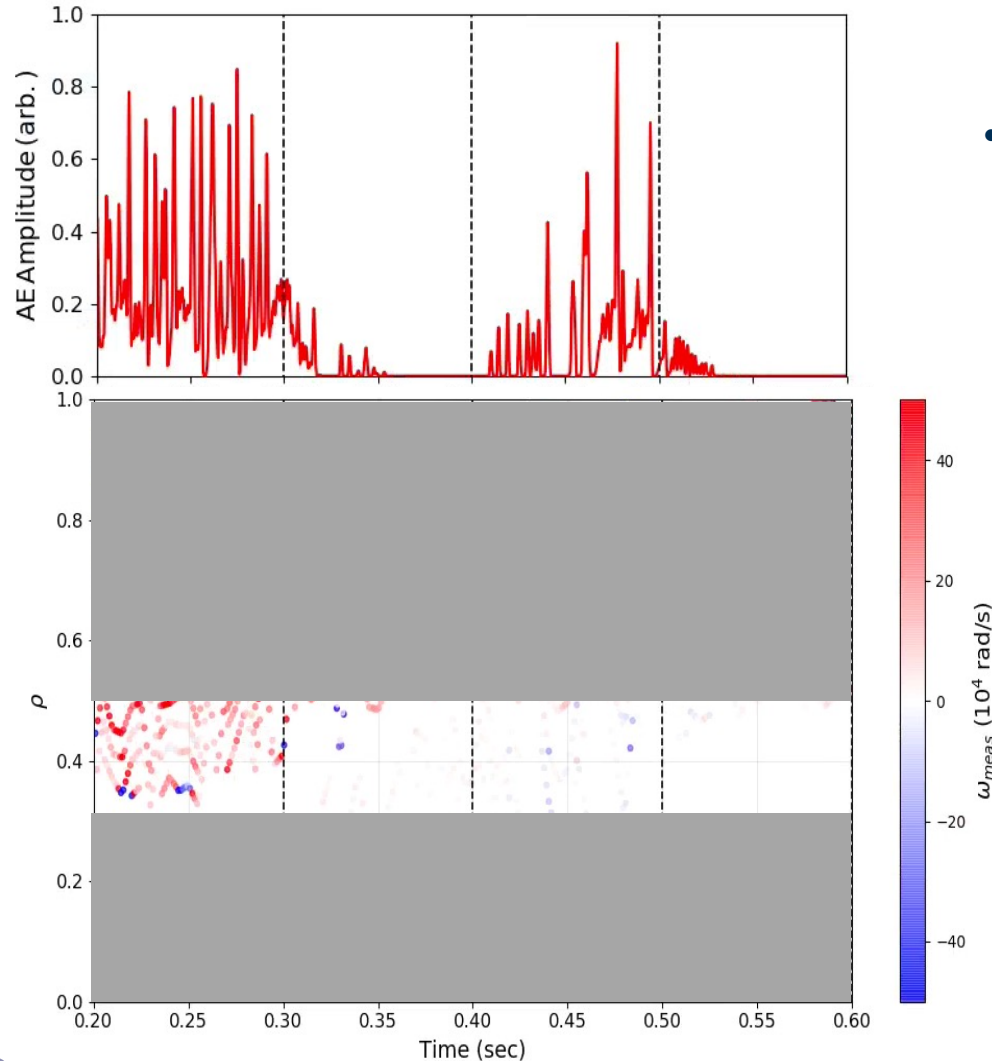
Shot 53678



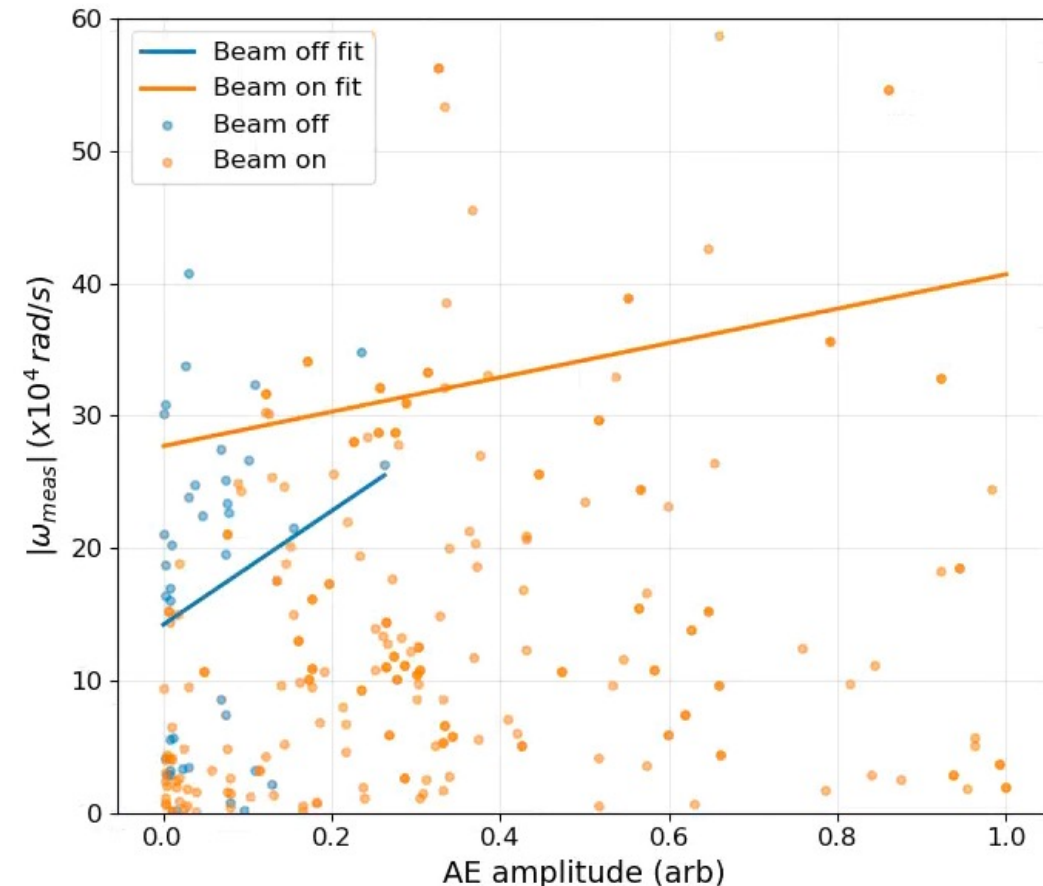
- Relative AE amplitude from edge magnetics considers all modes
- Shear data points are across all available channels

Weak Correlation Exists with AE Amplitude and DBS Measured Shear

Shot 53678



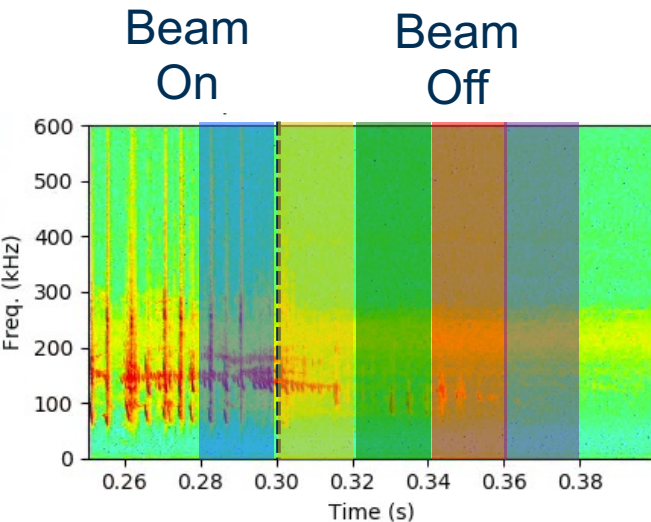
- Very weak correlation among relative AE amplitude and global shearing rate
- Beam off correlation is stronger, indicating AE effects are larger when global beam effects are off/diminishing



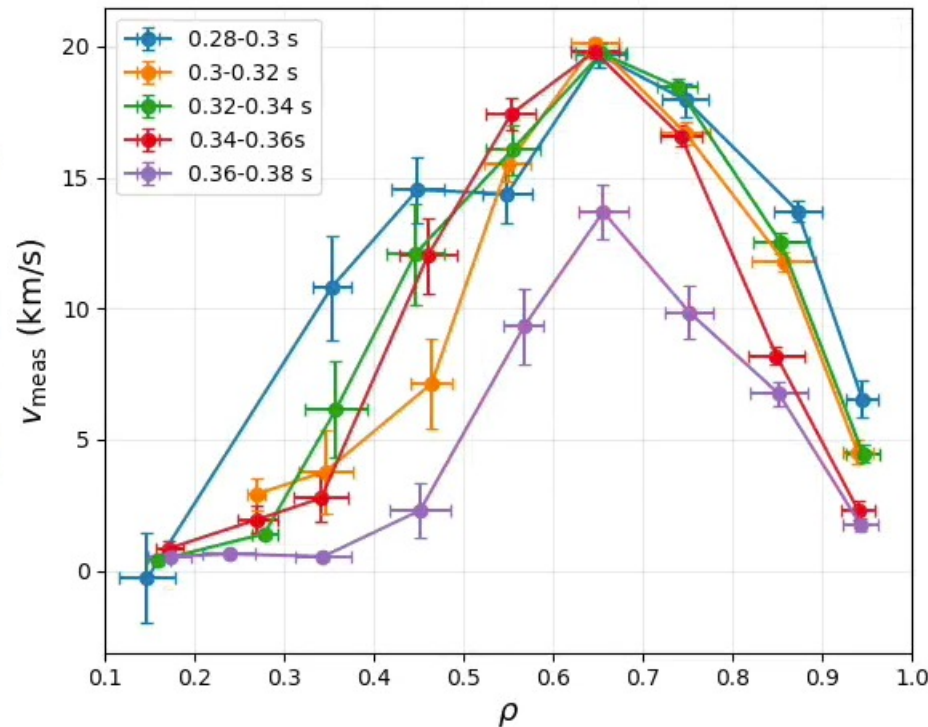
Clear Reduction in Measured Shear Throughout NBI Off Period

- Core flow shear degrades closer to 0 as time progresses post beam cutoff
- Window immediately after cutoff (yellow) sees an increase in shear at mid-radius when modes are still active

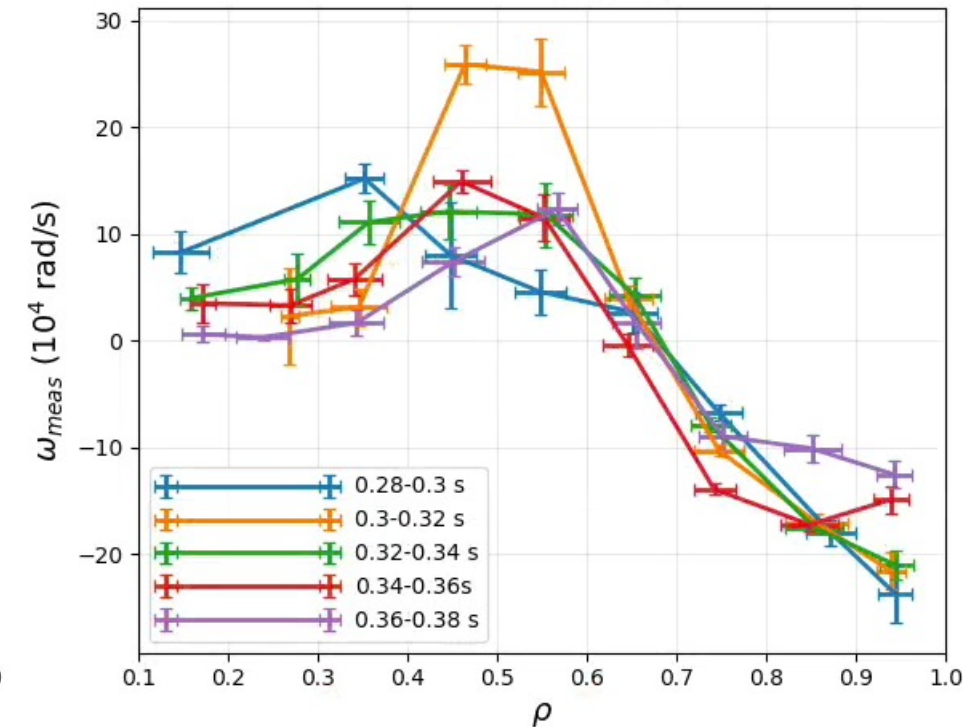
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DBS V_{ExB} Structures



DBS Shear Structures

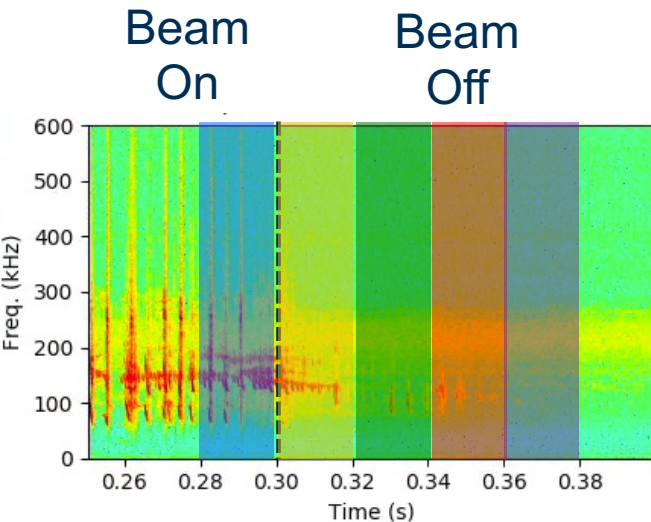


Clear Reduction in Measured Shear Throughout NBI Off Period

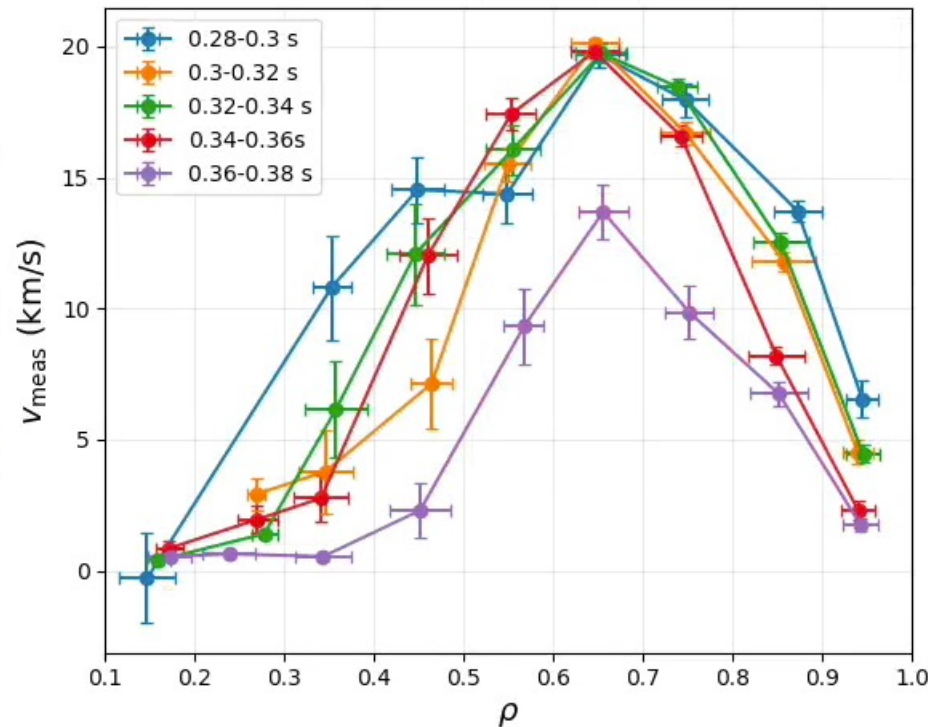
- Core flow shear degrades closer to 0 as time progresses post beam cutoff
- Window immediately after cutoff (yellow) sees an increase in shear at mid-radius when modes are still active

Is there a regime shortly after NBI cutoff where AE effects become stronger?

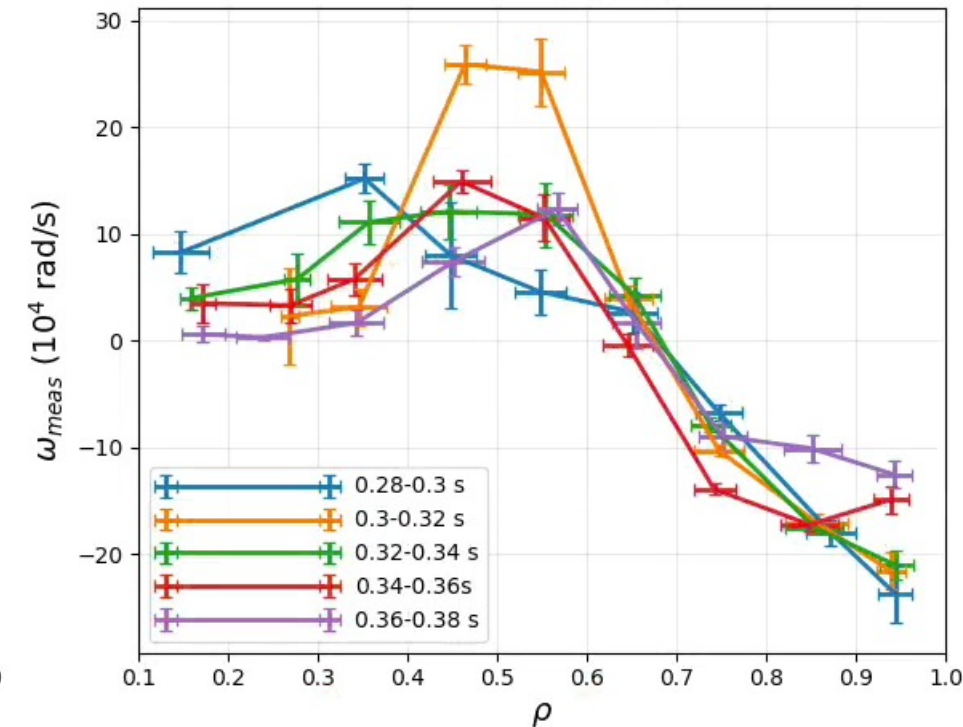
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DBS V_{ExB} Structures



DBS Shear Structures



Equilibrium Shear Effects are Investigated with TRANSP

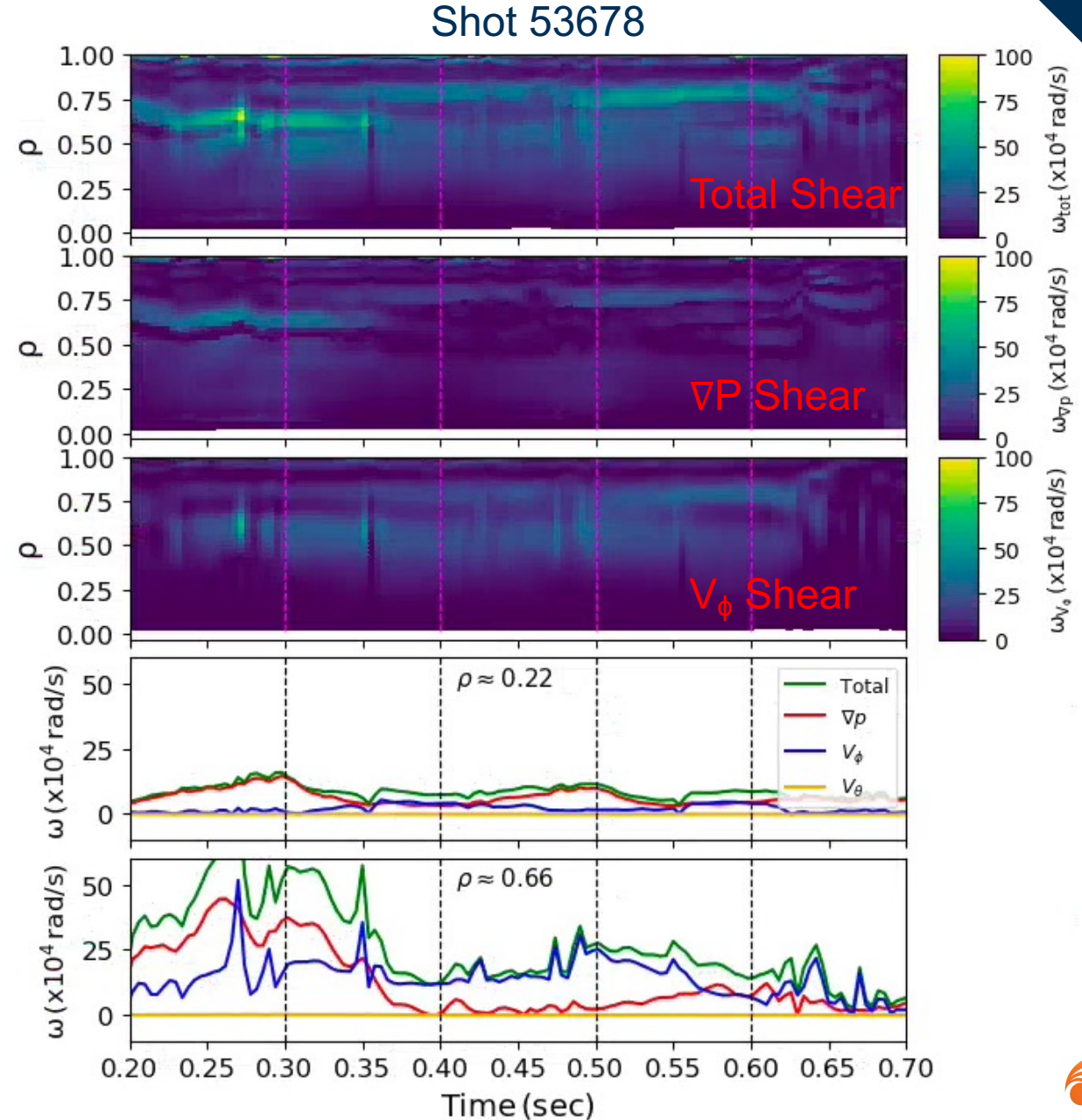
- Radial force balance gives:

$$E_r \sim \frac{\partial p}{\partial r} - v_\phi B_\theta + v_\theta B_\phi$$

- Calculate V_{ExB} and take radial shear:

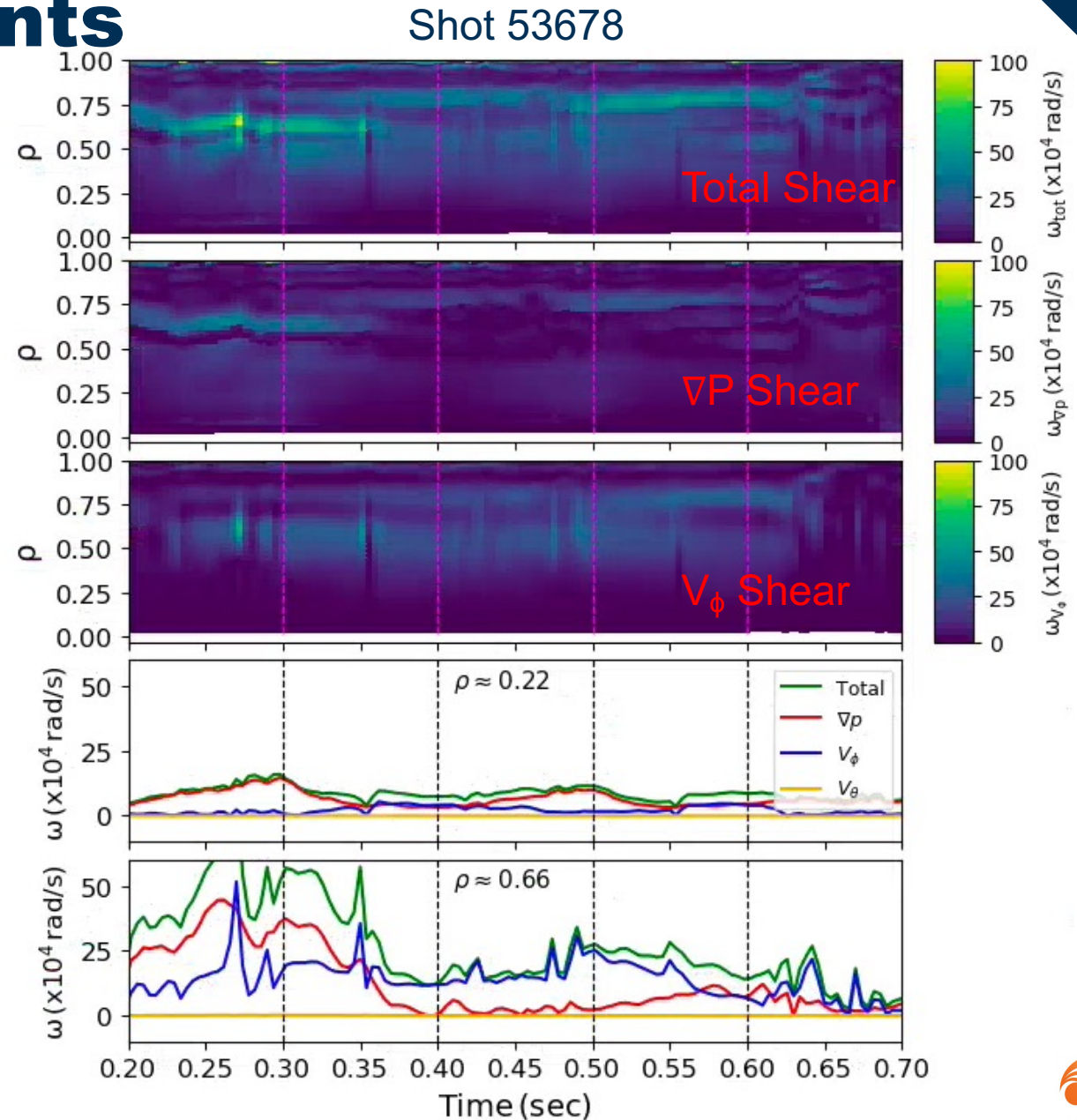
$$\omega_{ExB} \sim \frac{\partial V_{ExB}}{\partial r} \sim \frac{\partial}{\partial r} \left(\frac{E_r}{B} \right)$$

- TRANSP computed ExB shear is split into three main components: ∇P , V_ϕ , V_θ
- CX measurements (V_ϕ) are interpolated between beam-blips



Distinct Features are Observable Between ∇P and V_ϕ Shear Components

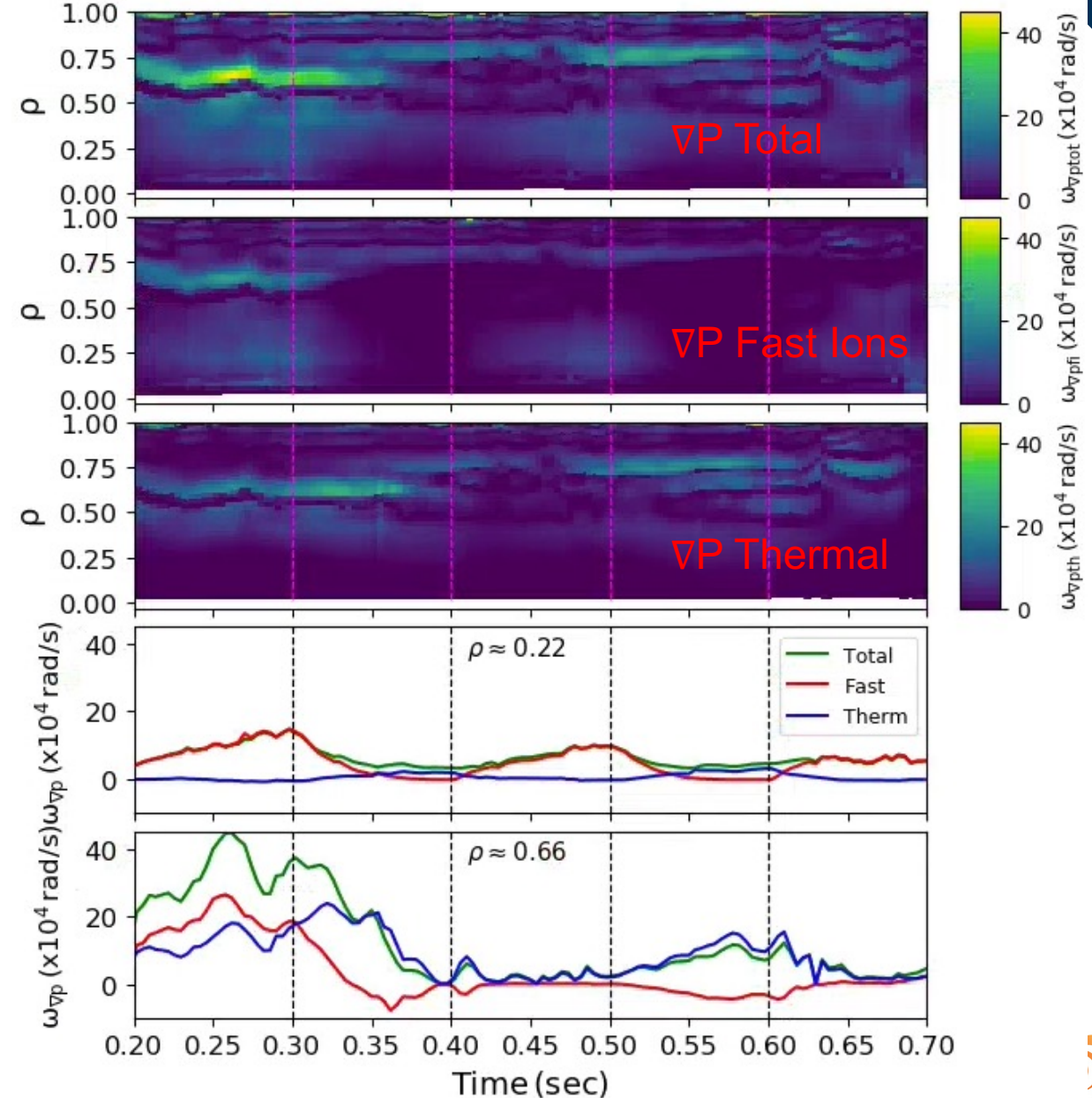
- ExB shear near the core is dominated by ∇P -component, while the V_ϕ -component becomes comparable at larger radii
- Pressure driven shear follows beam-blips while toroidal rotation shear is rather constant in time
- V_θ contribution is ignorable
- In general agreement with DBS measured shear values (20-50 $\times 10^4$ rad/s)



∇P -ExB Shear is Dominated by Fast Ion Pressure

Shot 53678

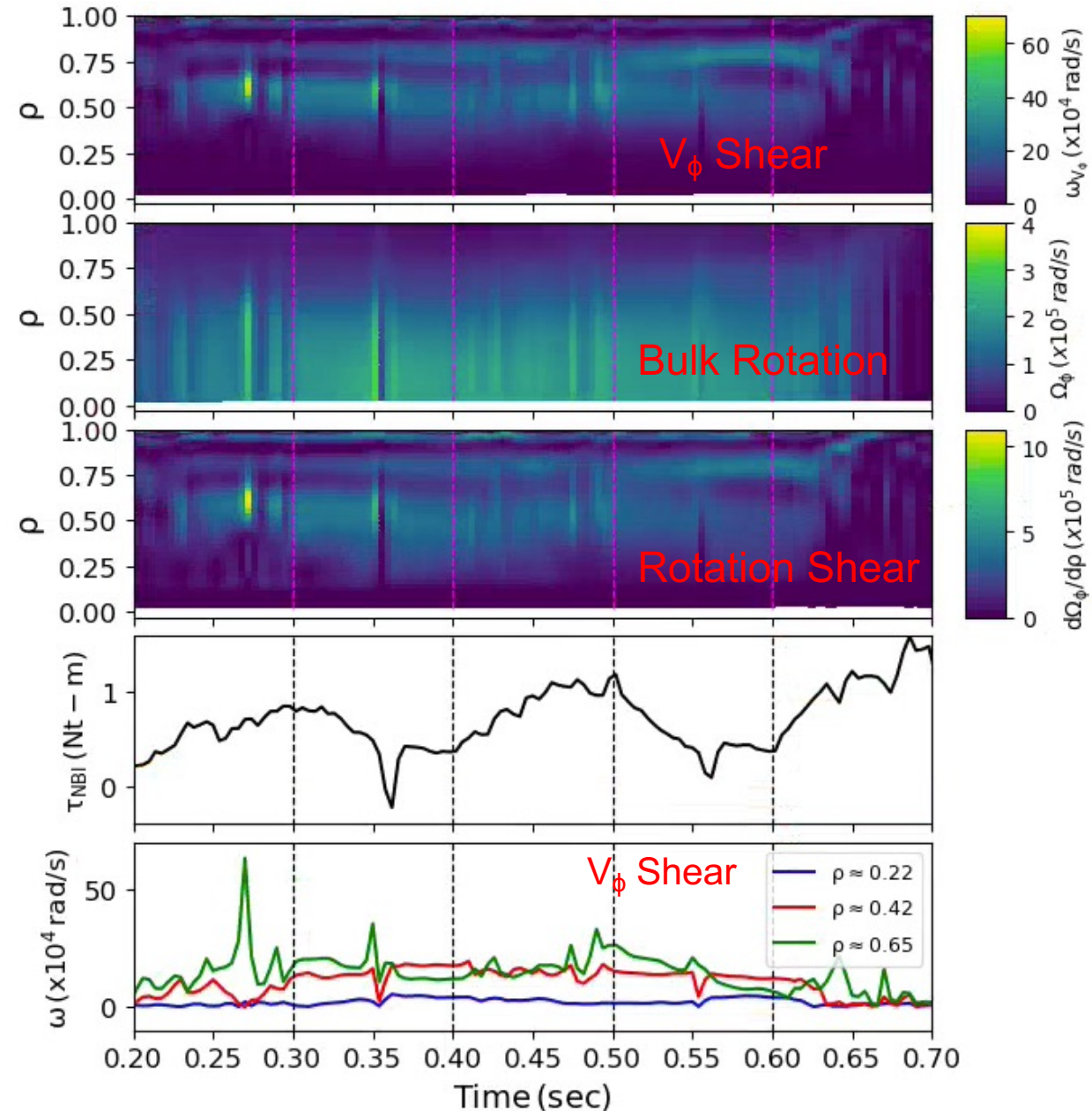
- Previous slide: Core shear is dominated by ∇P -component
- Near the core, the pressure is dominated by fast ions, while radially outward the thermal pressure becomes more comparable
- Core ExB shear is strongly induced by fast ion pressure gradient



V_ϕ -ExB Shear Becomes Important at Larger Radii

Shot 53678

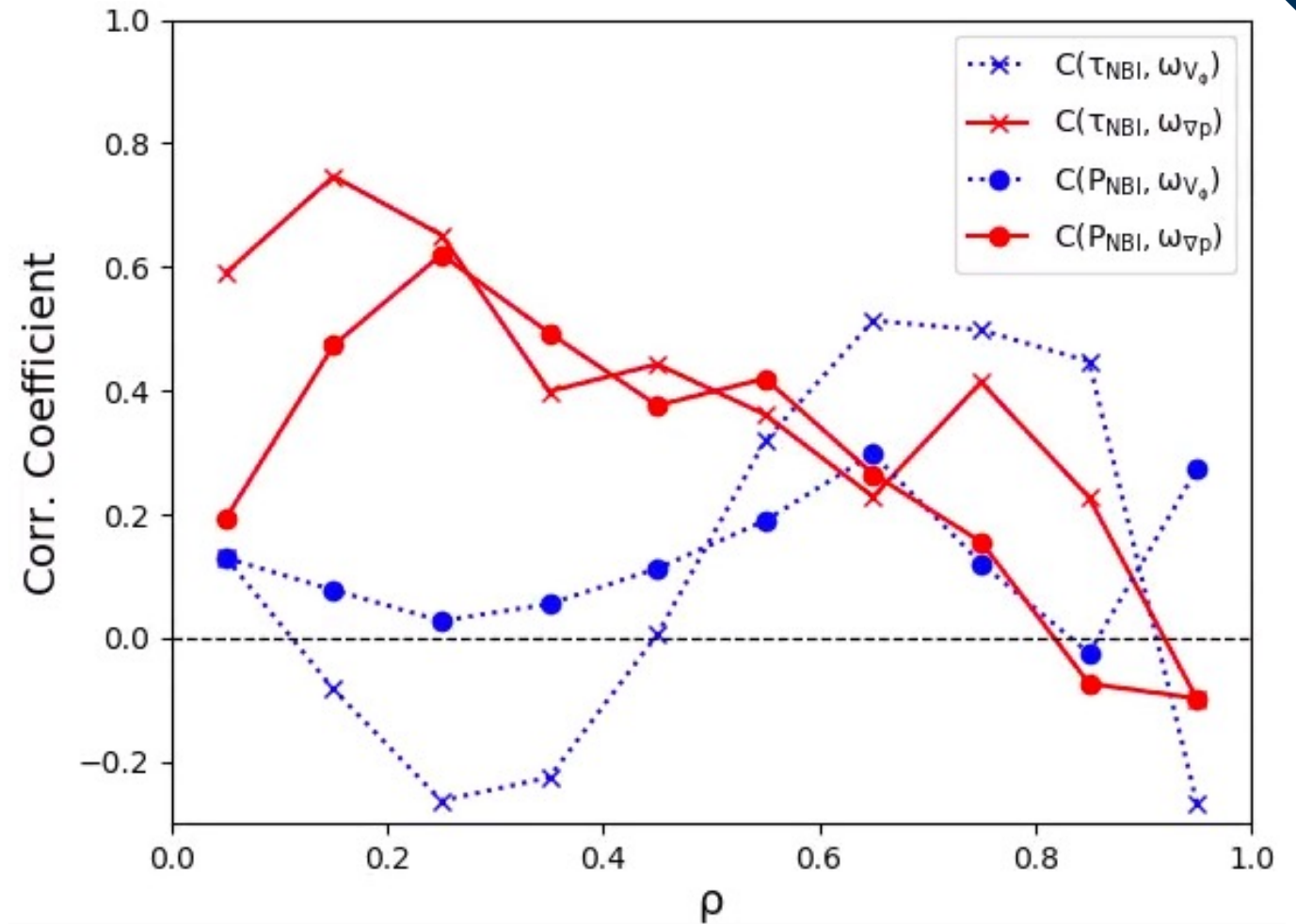
- V_ϕ -component follows the bulk rotation shear closely
- Relatively constant as a function of time across beam-blips
- Becomes comparable to, or larger than, ∇P -component at outer radii
- Not an obvious correlation with NBI induced torque (next slide)



∇P and V_ϕ Shear Components can be Attributed to NBI

- ∇P -component observes strong correlations in the core and decreases with radii
- V_ϕ -component shows weak correlations in the core but increases at outer radii to comparable levels to the ∇P term
- TRANSP shows a regime where equilibrium ∇P and V_ϕ induced ExB shear are primarily fast ion driven and each term varies with radius

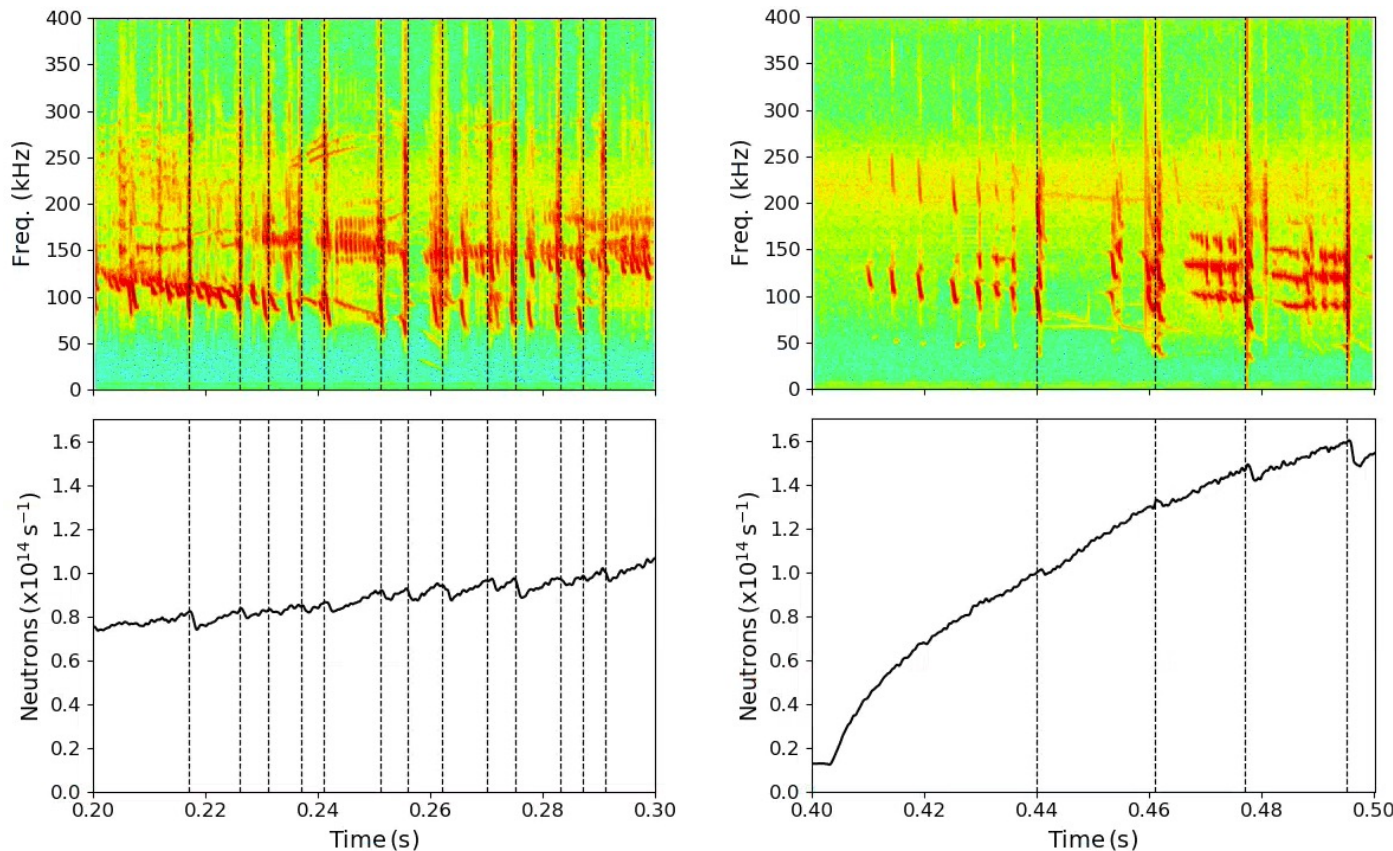
Shear Correlations with NBI



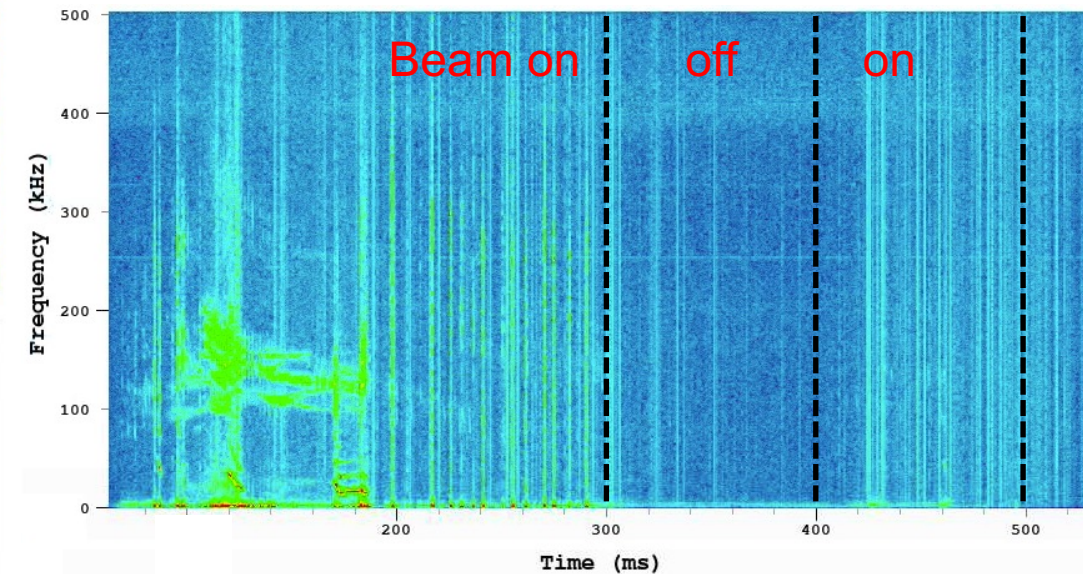
FILD and Neutron Measurements Show Weak Fast Ion Losses Due to AEs

- FILD shows no coherent losses with times of interest
- AEs build to “mini-avalanches” [1] correlated with small drops in the neutron rate (<5%)

53678 Magnetic Spectra and Neutron Drops



53678 FILD Signal



Ongoing Work

- Adding more DBS measurements to the database:
 - Varied launch angle ($\vec{k}_{scat}$)
 - Increase statistics
 - Sensitivity analysis, multivariate regression
- Removing DBS instrumental effects with the Scotty code
- Distinguish AEs (i.e. n-number)
- TRANSP turbulent transport models: TGLF, MMM
- More CGYRO simulations
- ssNPA and FIDA transport analysis

Conclusions

- Overall, we observe strong fast ion+turbulence effects that are characteristic of STs that greatly differ from that of conventional tokamaks and are distinct in active vs. inactive NBI periods
- DBS-resolved measurements show weak global AE–turbulence correlations, but AE-active periods exhibit distinct local flow/shear states
- AEs may contribute to localized shear and turbulence regulation, but NBI-driven pressure, rotation, and E_r modifications are substantial and must be treated as competing or coupled mechanisms
- Do the AEs themselves regulate turbulence, or are they a signature of the same fast-ion-driven plasma response that produces enhanced shear?
 - **The data favor a coupled EP/equilibrium/turbulence picture, in which AEs may be both an actuator and a marker of the fast-ion-driven state. AEs, fast-ion pressure, and NBI torque/rotation are all coupled parts of the same EP-rich state that modify plasma turbulence.**

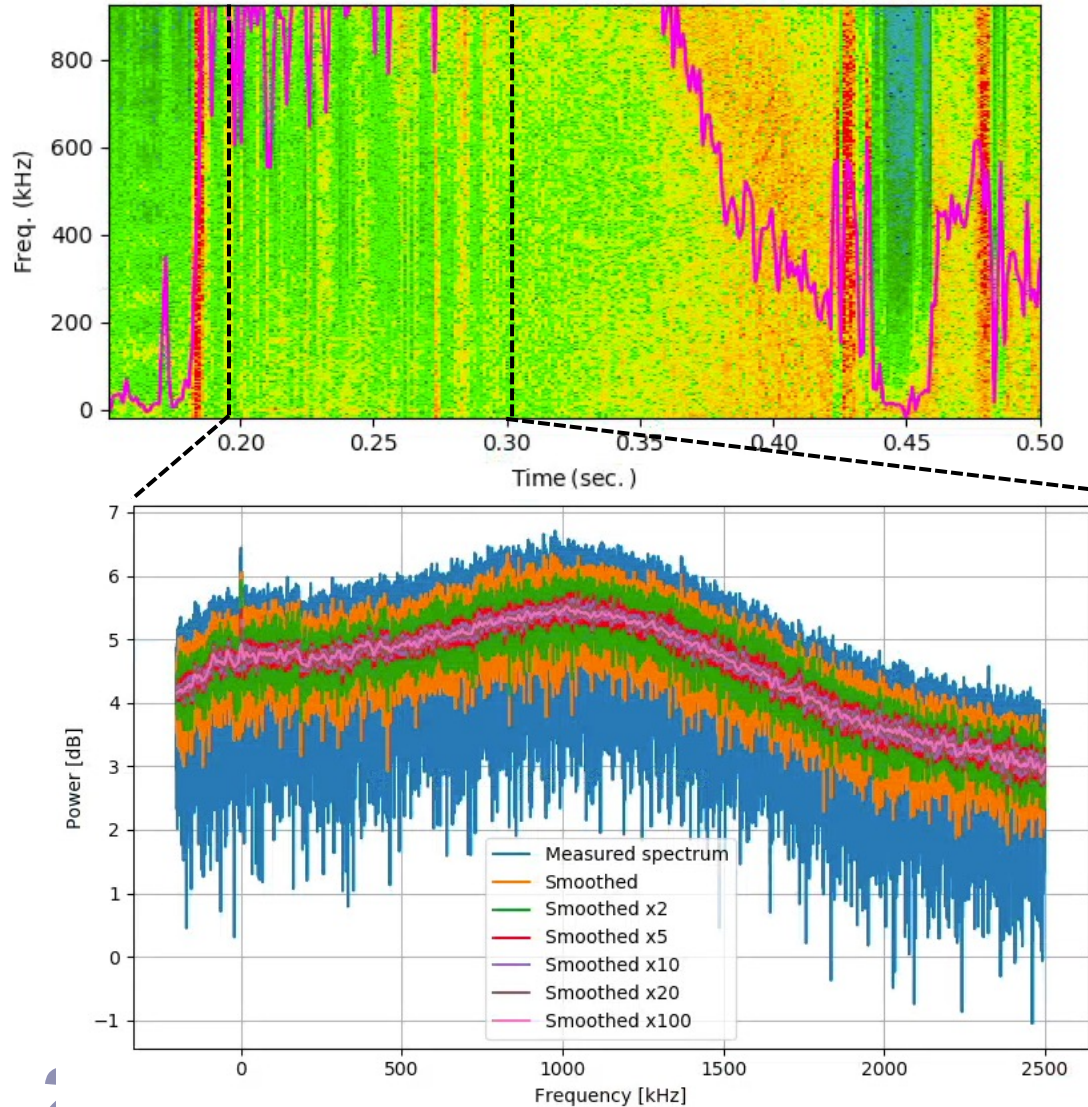
Looking Forward to Future STs

- **How universal are these findings for strongly rotating ST plasmas with high fast ion fraction/beta?**
-
- For high rotation and pressure STs, ion modes may be generally stabilized such that we need only focus on the electron channel
 - **Can we find an actuator to reliably control ETG?**
 - Fusion pilot plants will favor RF-only regimes which will greatly change the fast ion distribution and resulting effects
 - **Without beams, will the fast ion-turbulence dynamics behave the same as reported here? (probably not... see P. Oyola talk this morning)**
 - NSTX-U will resume operations next year and reach new ST/fast ion regimes
 - **How will our picture change in these new regimes?**
 - **How can we leverage NSTX-U experiments? (multiple beam sources, hopefully RF...)**

Backup

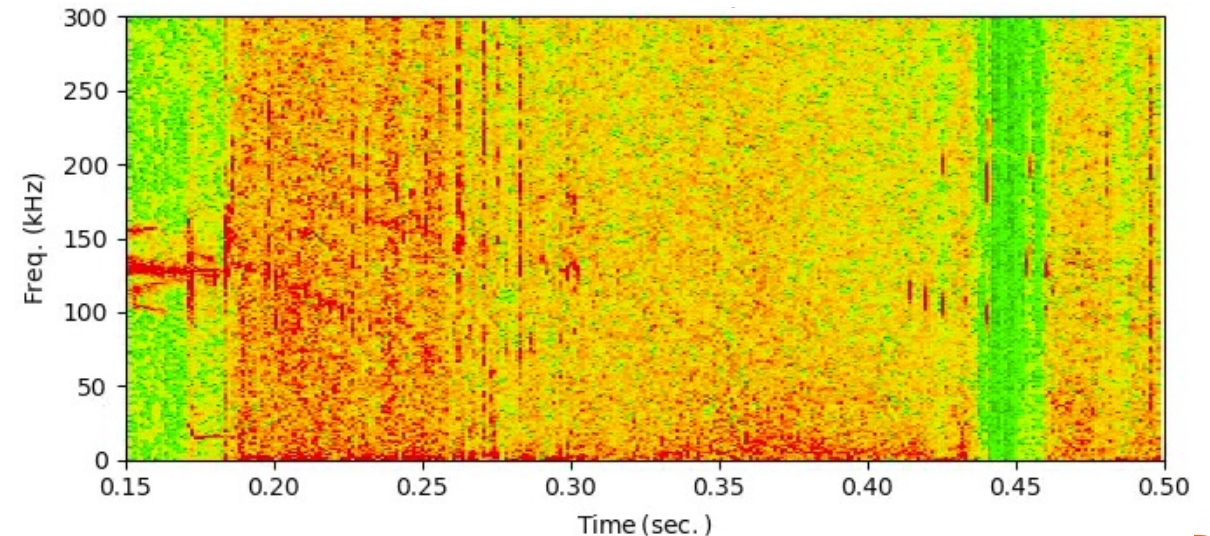
AEs are Not Visible in the DBS Power Spectrum

Power Spectra



- AE signatures do not appear in DBS power spectra regardless of smoothing or denoising (true for all channels)
- Modes appear in the $d\phi/dt$ spectra
 - Weakly beyond 0.2 s
 - Spurious during mode bursting 0.4– 0.47 s
- AEs do not alter the scattered power (i.e. density fluctuations) but weakly modulate the scattered phase velocity

$d\phi/dt$ Spectra



40 GHz Channel Velocity Decomposition

- 40 GHz channel is the only identical channel across UCLA and SWIP systems
- GENRAY shows $\vec{k}$ is nearly perpendicular w.r.t. to B-field, assume velocity is also only in the perpendicular direction
- Solve for $\vec{v}$ and can translate to (ψ, Θ, ϕ) -coordinates

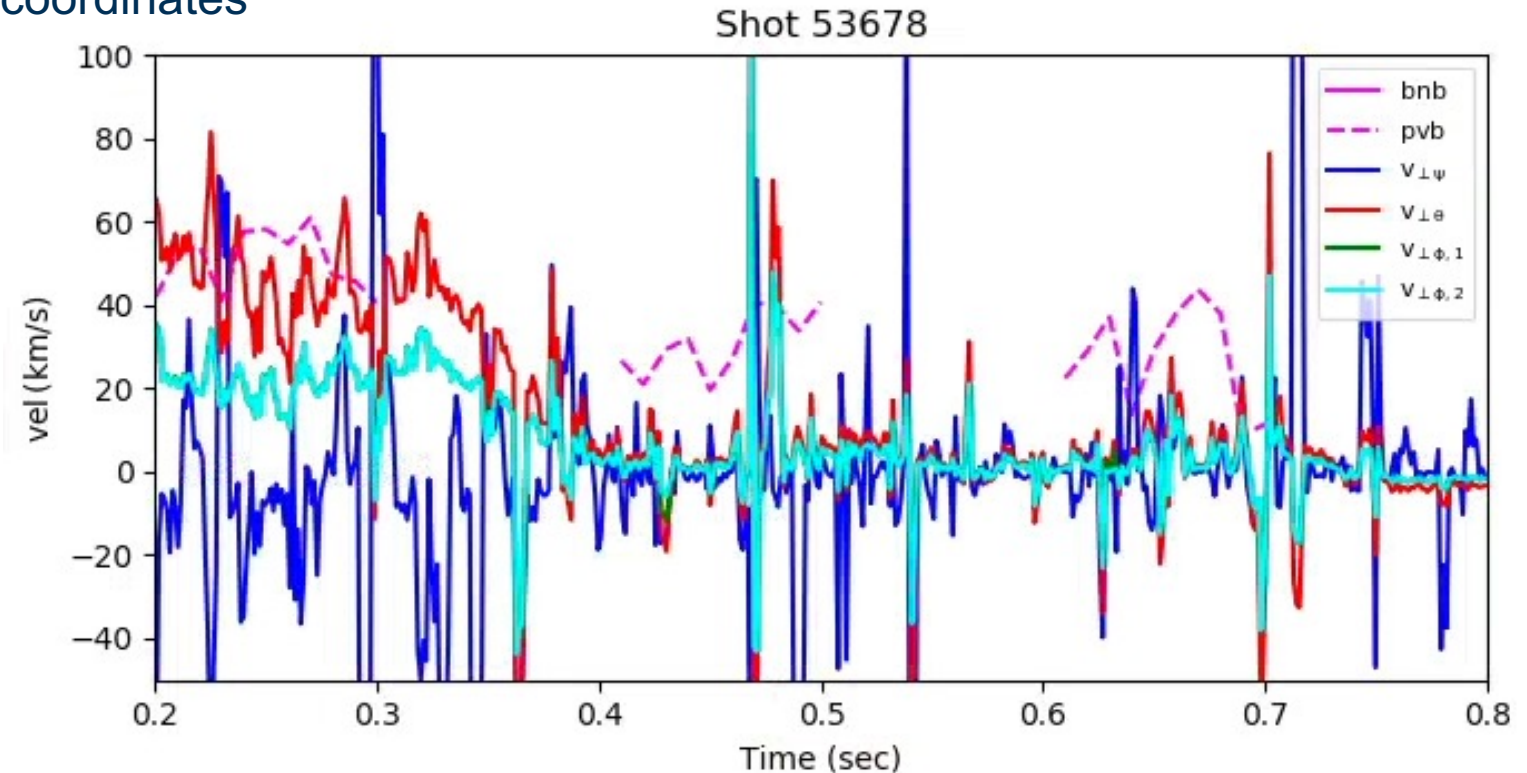
$$f_{UCLA} = \vec{k}_{\perp} \cdot \vec{v}_{\perp}$$

$$f_{SWIP} = \vec{k}_{\perp} \cdot \vec{v}_{\perp}$$

$$0 = \vec{v}_{\perp} \cdot \vec{B}$$

- Ψ -component is zero as it should be
- ϕ -component is noticeably below the measured CX bulk rotation
 - Implies a noticeable parallel component that is presumably due to the NBI

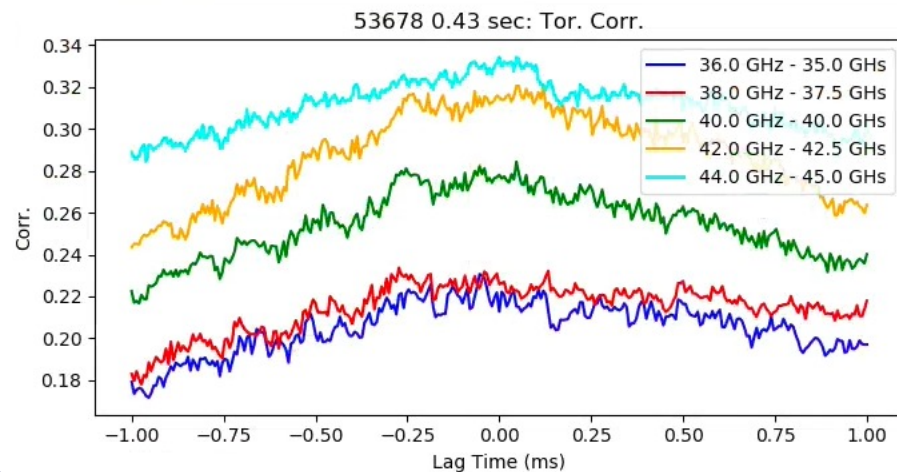
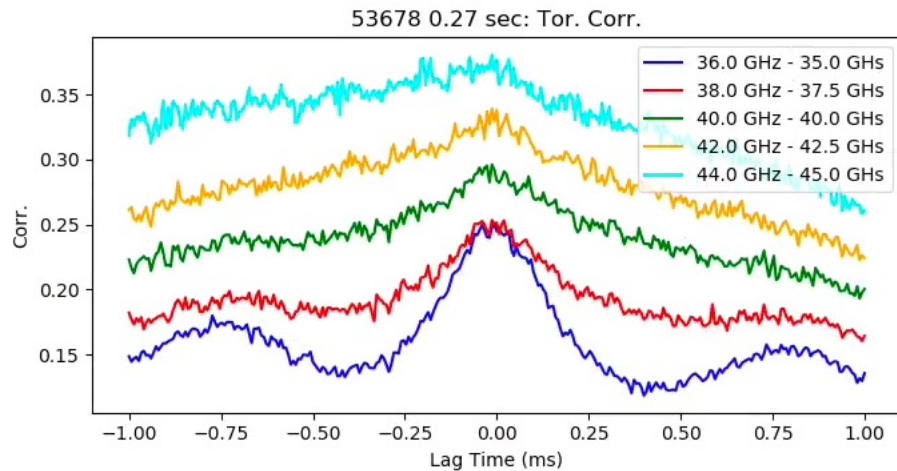
$$v_{\phi} = v_{\phi, \perp} + v_{\parallel} \frac{B_{\phi}}{B}$$



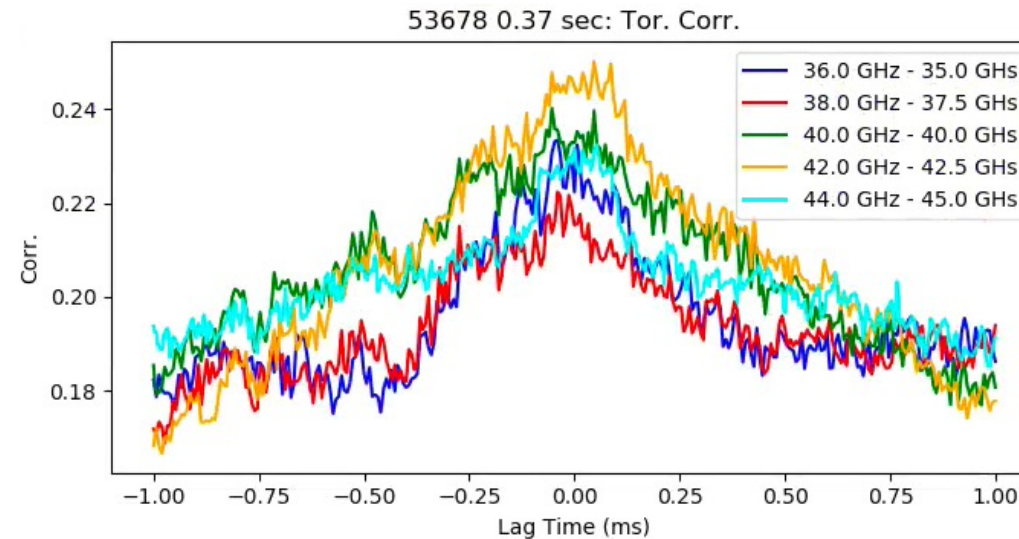
Toroidal Correlations

- $n=0$ structure in beam-on and beam-off periods
- Possible indication of $n=0$ zonal flows?

53678 Beam-on



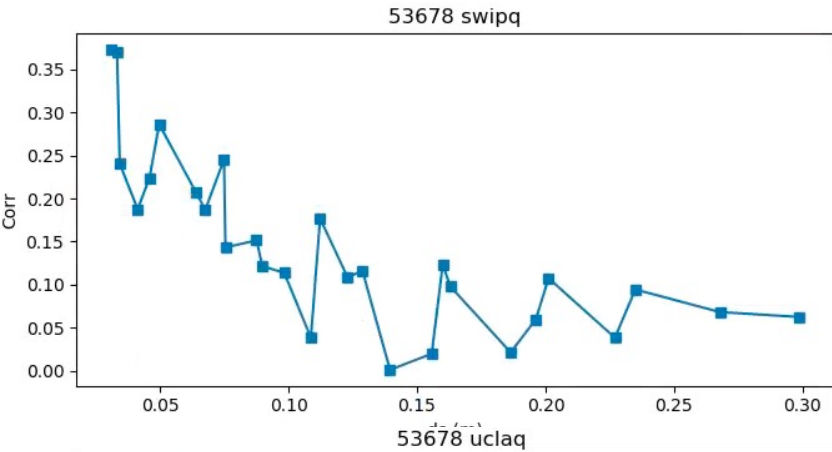
53678 Beam-off



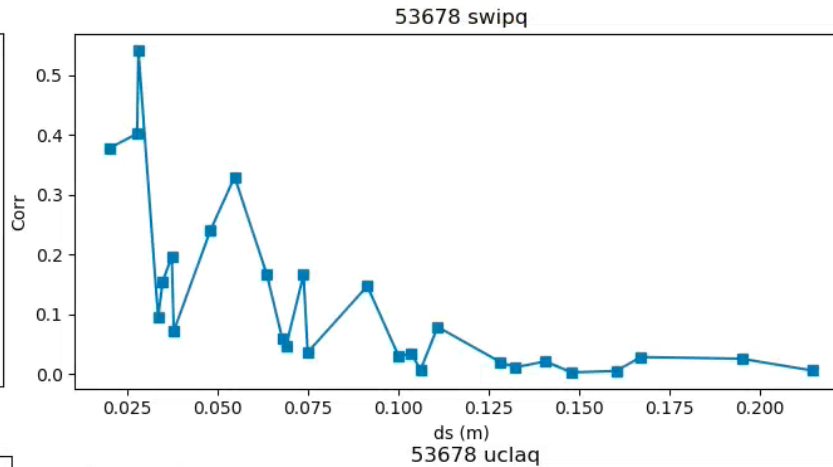
Radial Correlations

- Exponential fits show slightly smaller radial correlation length in beam-on (0.17 m) vs beam-off (0.2 m)
 - Smaller radial correlation = smaller eddy size = **reduced turbulence?**
- Best method to fit correlations length: exp, double-exp, gaussian?
- Can quantify error by averaging multiple times together

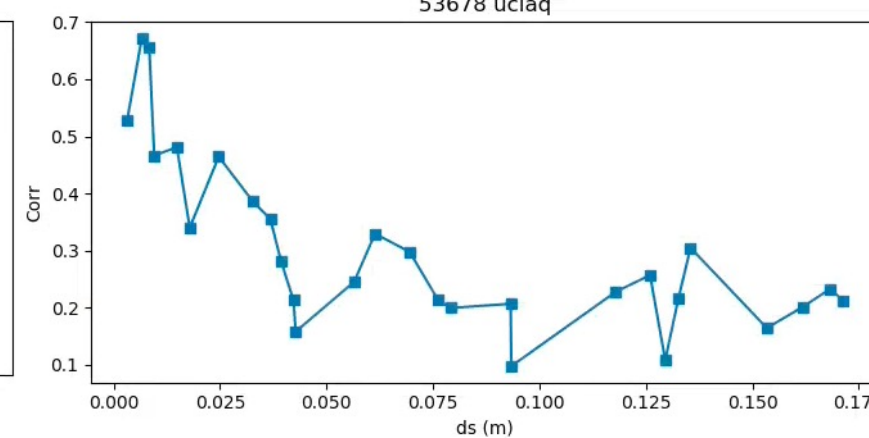
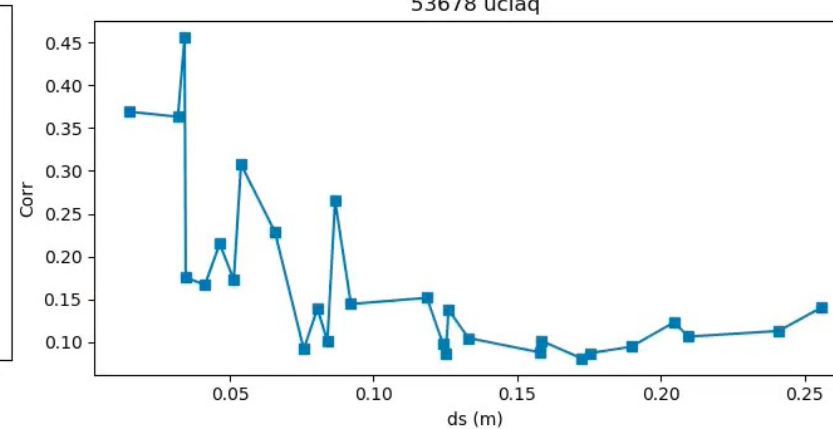
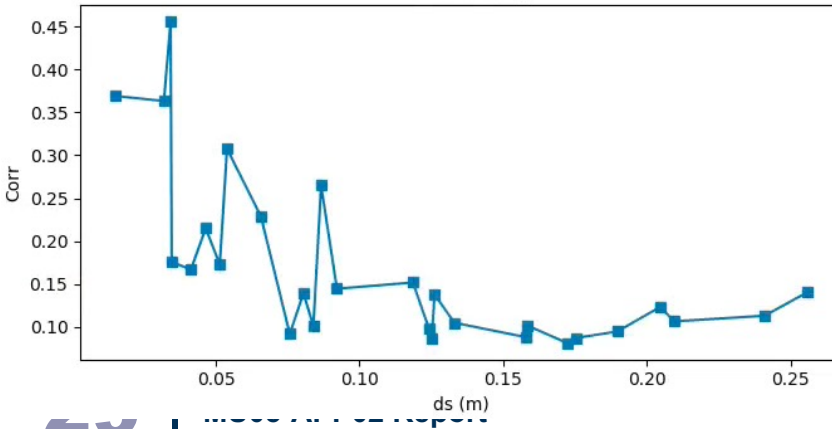
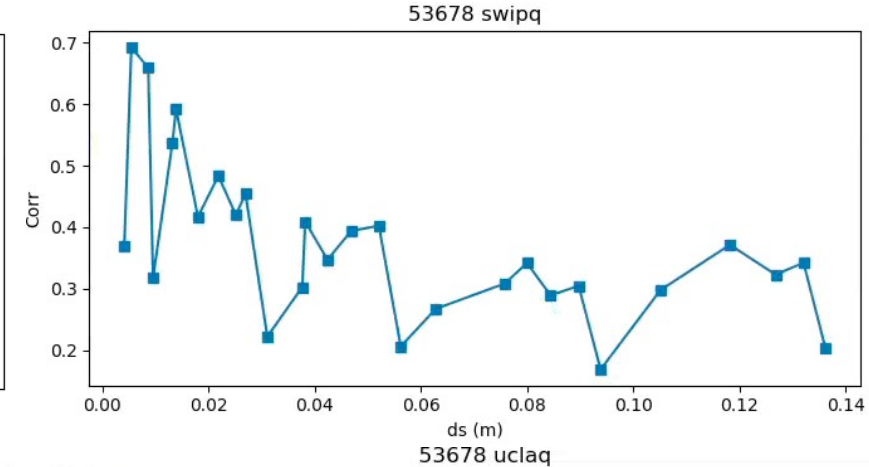
53678 Beam-on 0.27 s



53678 Beam-off 0.38 s



53678 Beam-on 0.44 s

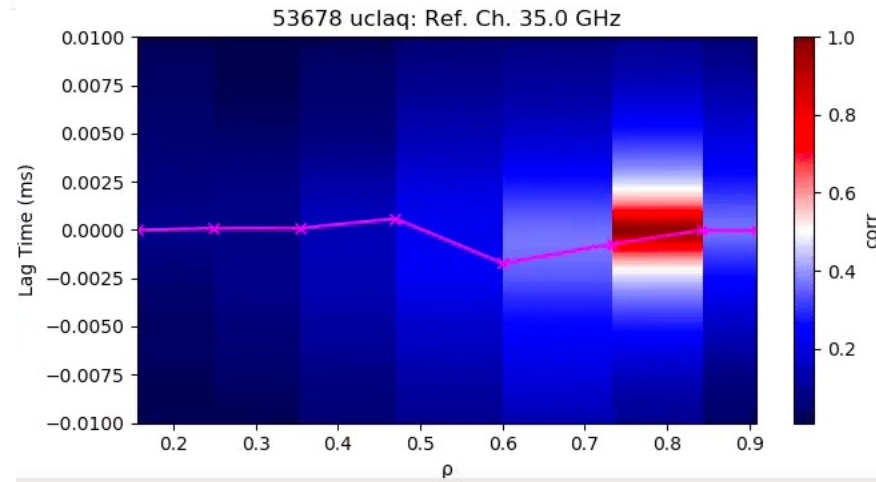
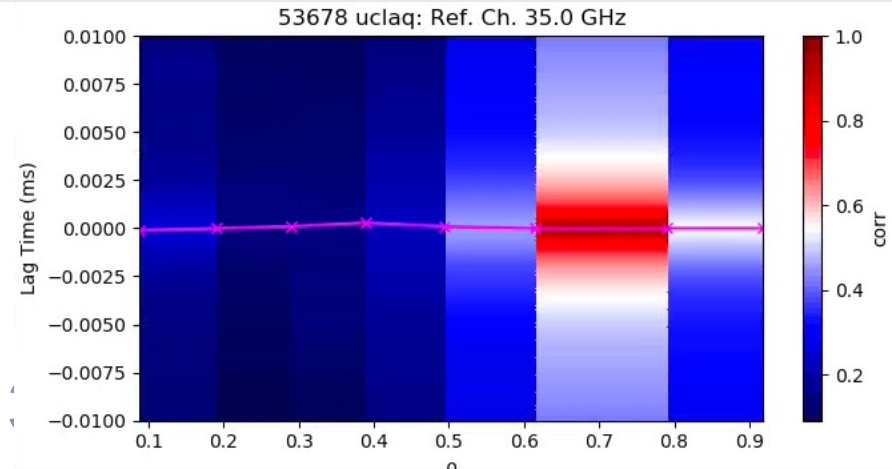
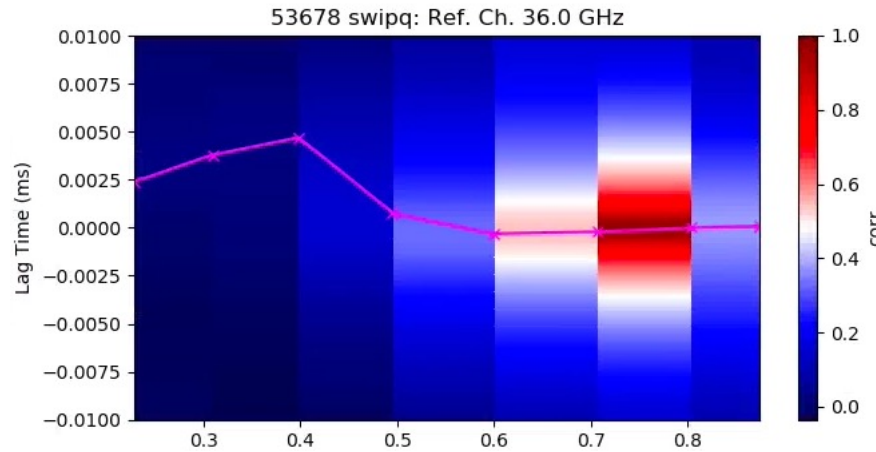
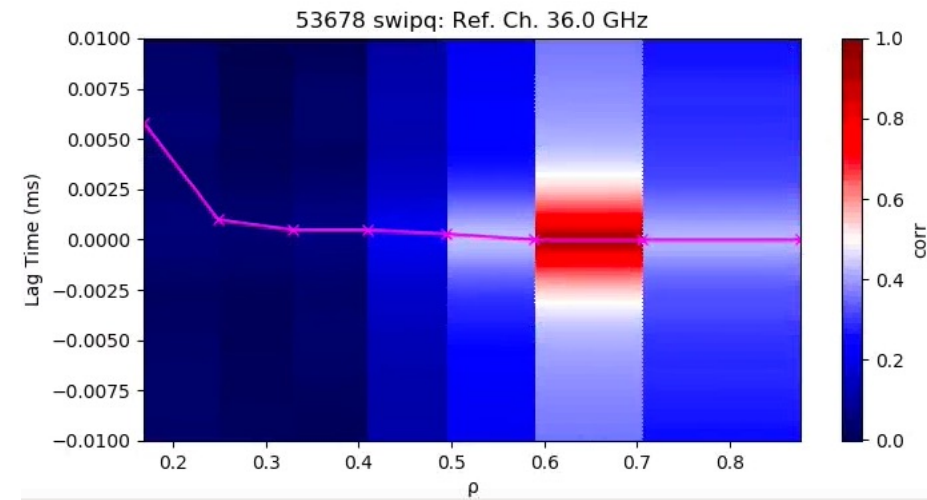


Radial/Temporal Correlations Cont.

- Reduction in lag vs. radius visible?
 - Hard to interpret or see; need to ensemble with many other time points
- Reduced lag would correspond to reduced ExB velocity shear. If the the lag time is low (close to 0), it indicates that turbulent scattering is dominating

53678 Beam-on 0.26 s

53678 Beam-off 0.38 s



ssNPA Measurements Show Very Strong Fast Ion Redistribution

- ssNPA data was reconstructed via FIDASIM with the fast ion distribution provided via TRANSP
- Simulated signal greatly overpredicts the ssNPA measurements, suggesting massive redistribution
 - Difference is larger for lower energies
 - Redistribution/transport may simply be out of the ssNPA line of sight
- Lower energy ions are not as easily resolvable on the FILD

