Measurements of Reynolds stress flow drive using Langmuir probes in HSX

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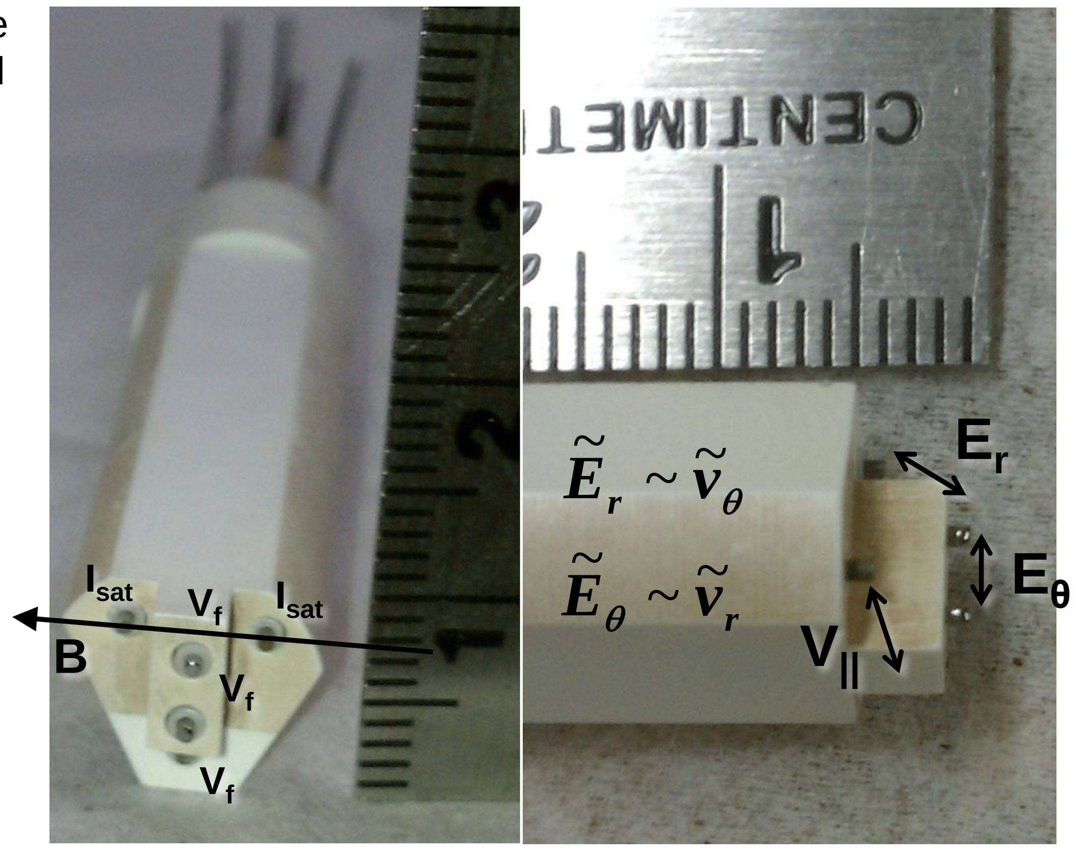
Overview

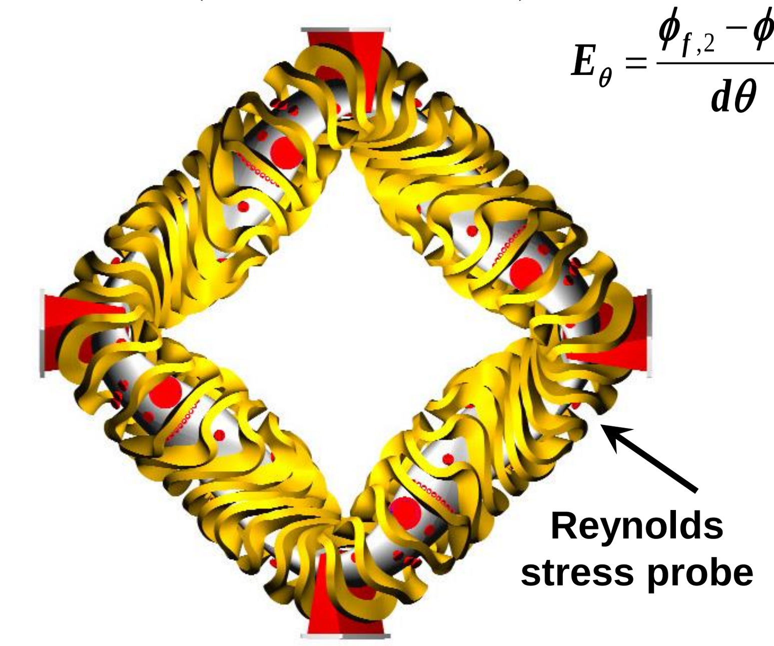
- Indications of zonal flows have been observed in HSX during biasing in previous experiments [1]
- A Langmuir probe configuration designed to measure the Reynolds stress has been designed and implemented to measure the mean and fluctuating values of E_r, E_θ, and $v_{||}$.
- A radial Reynolds stress profile is measured on a shot-to-shot basis using similar discharges
- Neoclassical poloidal viscosity is calculated to estimate the poloidal flow expected from the measured Reynolds stress gradient, and this is compared to the actual measured E_r profile
- The flow drive calculated this way is large enough to drive significant flows, and radial regions of large flow drive correspond with regions where the measured radial electric field deviates significantly from the neoclassically predicted value given by the PENTA code [2].
- When a bias is applied, the fluctuations are reduced by the shearing of the radial electric field and the poloidal flow is simultaneously increased, diminishing the contribution of the Reynolds stress drive to the total poloidal momentum balance relative to the viscous terms
  - No bicoherence above the noise level was observed in any of the discharges studied here

Langmuir Probe Configuration

- 5-pin Langmuir probe configured to measure the Reynolds stress using local floating potential and ion saturation current measurements
- Tungsten probe tips insulated by boron nitride
- Signals sampled at 5 MHz
- Probes scanned radially on a shot-by-shot basis
- Three pins measure floating potential to infer E_r and E_θ for calculation of local plasma ExB velocities
- Two pins measuring ion saturation current are configured as a mach probe and aligned on a field line to measure $V_{||}$.

$$M_{||} = \frac{1}{k}\ln\left(\frac{I_{sat}(upstream\_)}{I_{sat}(downstream\_)}\right) \qquad E_r = \frac{\phi_{f,2}-\phi_{f,1}}{dr} \qquad E_\theta = \frac{\phi_{f,2}-\phi_{f,1}}{d\theta}$$





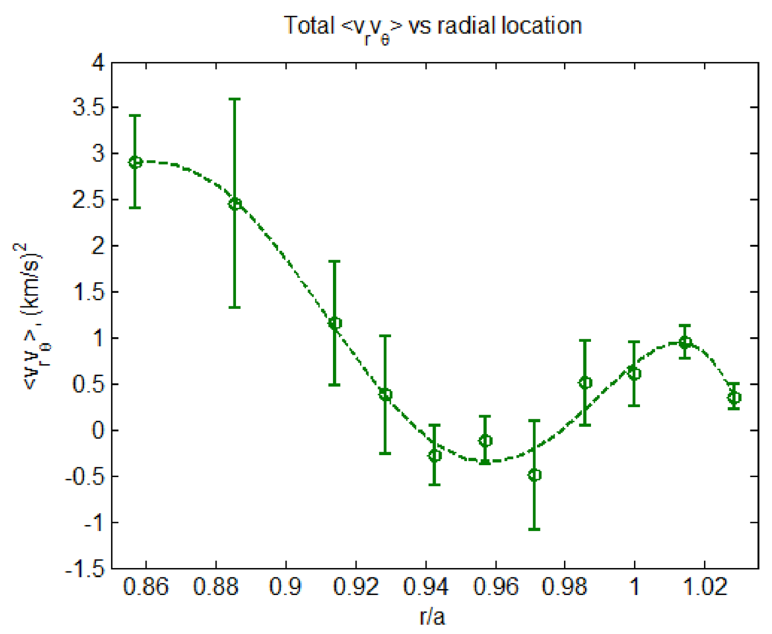
- Probe is located at the outboard midplane of the device, in a region of both low |B| on a magnetic flux surface and "bad" curvature, where fluctuations are expected to be largest
- Flux surfaces are most compressed where probe is scanned, so that the radial derivative of the Reynolds stress may be larger here than at other poloidal locations
- Flow drive calculated here will almost certainly be higher than the flux surface average

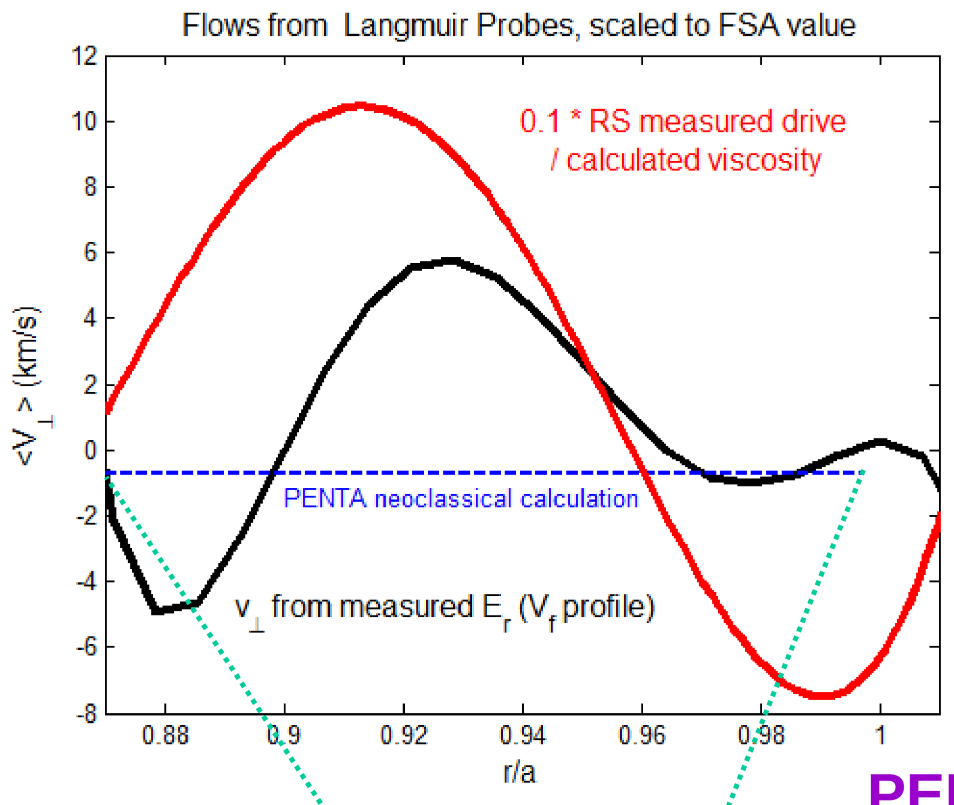
Reynolds Stress and Flow Measurements

- Using a cylindrical approximation, the poloidal momentum evolution equation is given by: [3]

$$\frac{\partial}{\partial t}\langle v_\theta\rangle = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\langle\tilde{v}_r\tilde{v}_\theta\rangle\right) - \mu_\theta\langle v_\theta\rangle - \nu_{in}\langle v_\theta\rangle + \tau_{ext}$$

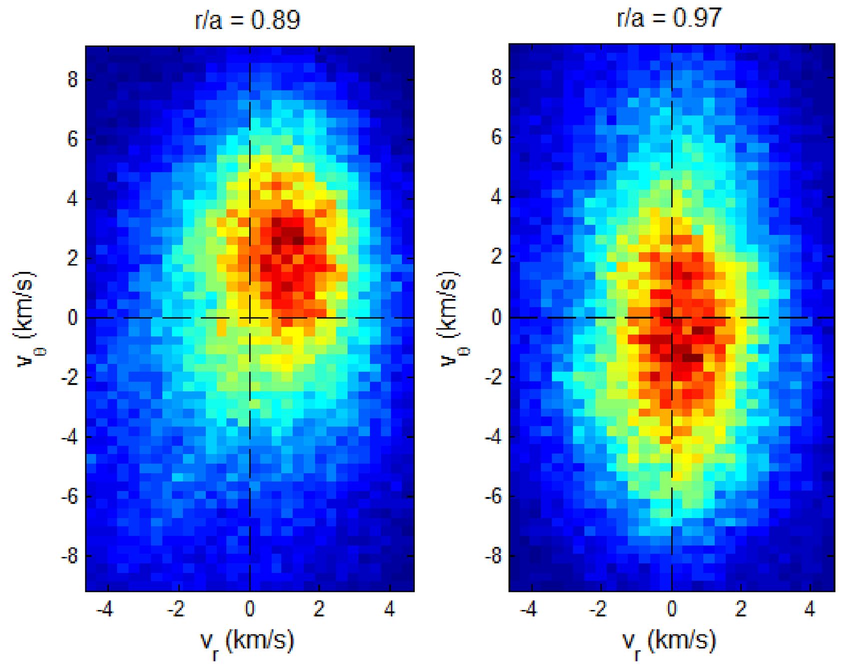
  - at steady state before a bias is applied, Reynolds stress term is balanced by poloidal viscosity (μ_θ) and neutral damping (ν_{in})
- A polynomial fit is applied to the shot-by-shot Reynolds stress profile, shown in green on the right, and the appropriate spatial derivative is taken to determine the approximate flow drive
- This flow drive is divided by the total damping ($\mu_\theta+\nu_{in}$) to get an estimate of the expected poloidal flow due to the RS if it were constant everywhere on the flux surface
- A fit of the shot-by-shot V_f profile is used to estimate the local E_r profile, plotted below in black
  - T_e gradient in this region is unknown, but will lead to small changes in E_r
- The regions where there is significant deviation of the measured E_r from the value predicted neoclassically from PENTA correspond to the regions of high measured Reynolds stress flow drive



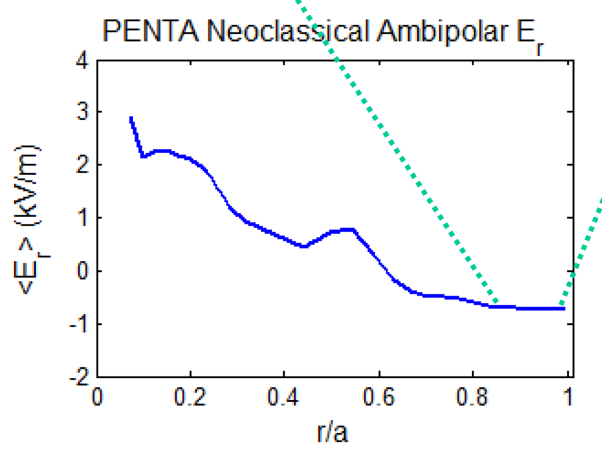


- The Reynolds stress flow drive is measured where fluctuations and spatial gradients of fluctuations should be highest
- Local RS flow drive measurements are scaled down to compare to characteristics of the measured perpendicular flow profile
- Proper flux surface average of the Reynolds stress profile is impractical to measure in complex geometry

PDF of velocity fluctuations



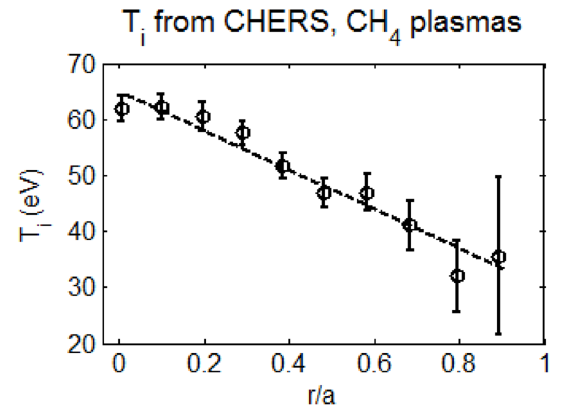
- Probability density functions of the fluctuating portions of v_r and v_θ demonstrate how anisotropy changes with minor radius



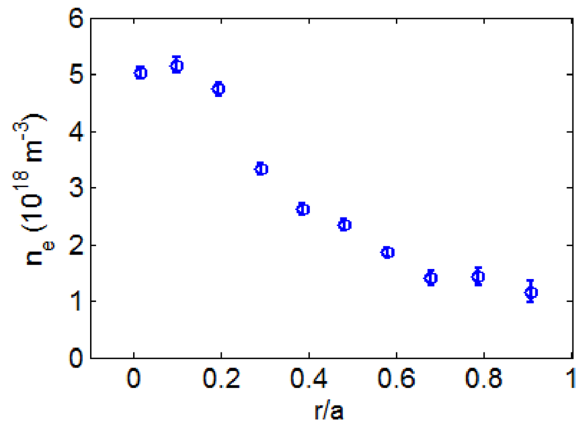
- "Ion root" solution exists at all positions across the minor radius, so "electron root" solutions in the core are not plotted here

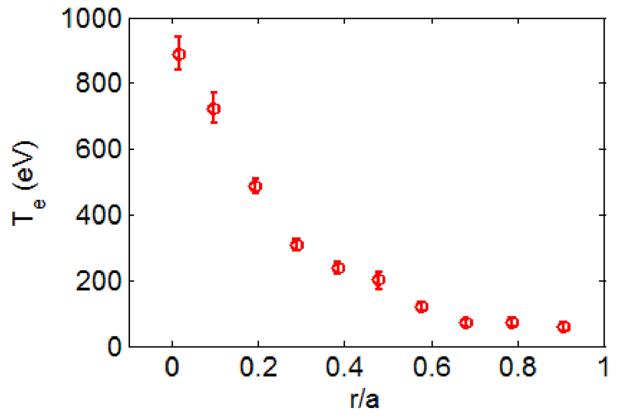
PENTA Neoclassical E_r Predictions

- PENTA code [2] calculates the neoclassical particle fluxes for a set of plasma parameters in a given magnetic configuration, then finds the ambipolar radial electric field
- These calculations do not account for ECRH driven flux, but this is expected to be small towards the edge



- Ion temperature from CHERS measurements in a methane discharge
- T_i input into calculations is scaled down to account for removal of C ion species from plasma





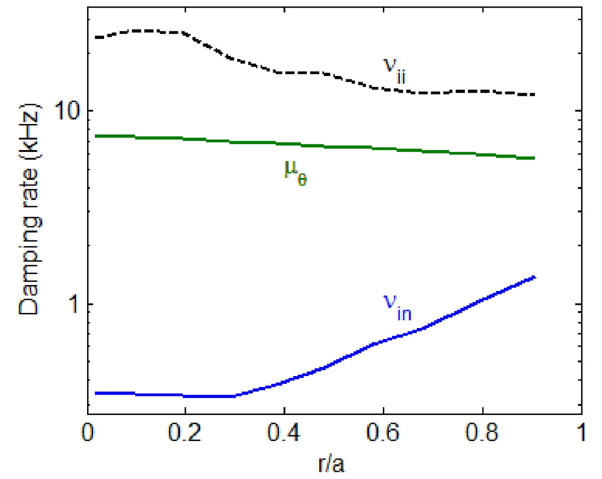
Viscosity calculations

- Neoclassical poloidal viscosity (μ_θ) is calculated approximately by using the purely poloidal term of the expression for an arbitrary stellarator configuration [4]

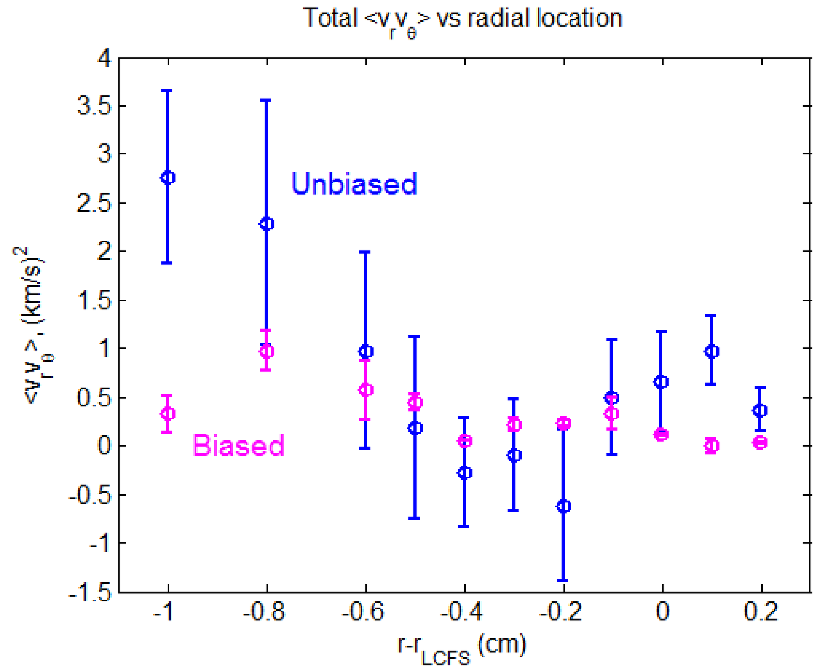
$$\mu_\theta = \frac{1}{4\pi^{1/2}}\frac{v_{ti}R_0}{r^2}\sum_{n,m}\frac{m^2 b_{n,m}}{|n-\iota m|}$$

- Same experimental profiles used here as for neoclassical E_r predictions
- Neutral density profile from DEGAS neutral gas code
- Neutral damping is small compared to neoclassical term, but not negligible at the edge where probe measurements are taken

$$\nu_{in} \approx N_n 10^{-14} T_i^{0.318}$$



Biased discharges



- No bicoherence was detected above the noise level on any fluctuating signals during this set of experiments, including when a bias was applied
- When a large bias is applied, E_r shear may reduce turbulence to a level too low to drive zonal flows
- External torque applied by the bias probe becomes the dominant forcing term in the momentum balance equation rather than Reynolds stress

Summary

- Reynolds stress flow drive measured with the probe is large compared to the calculated neoclassical poloidal viscosity and measured E_r profile
- Radial regions of large flow drive correspond to regions where the measured E_r deviates significantly from neoclassical predictions
- Future work will investigate the relationship between the Reynolds stress flow drive, edge radial electric field, and parallel flows
- Reduce levels of biasing to re-introduce low frequency zonal flow signatures and measure the corresponding Reynolds stress

References

1) R. S. Wilcox et al., *Nucl. Fusion* 51 (2011) 083048.
2) D.A. Spong, *Phys. Plasmas* 12 (2005) 056114.
3) G. Tynan et al., *Plasma Phys. Control. Fusion* 48 (2006) S51.
4) M. Coronado and H. Wobig, *Phys. Fluids B 29* (1986) 527.

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