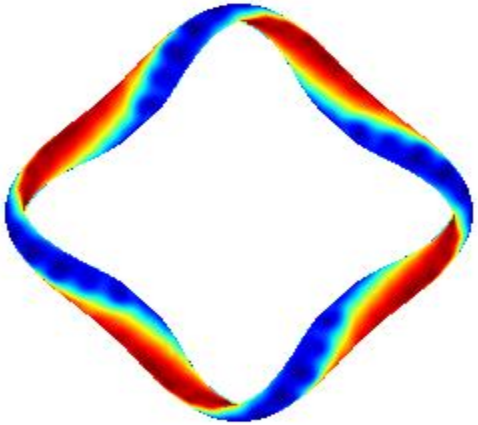
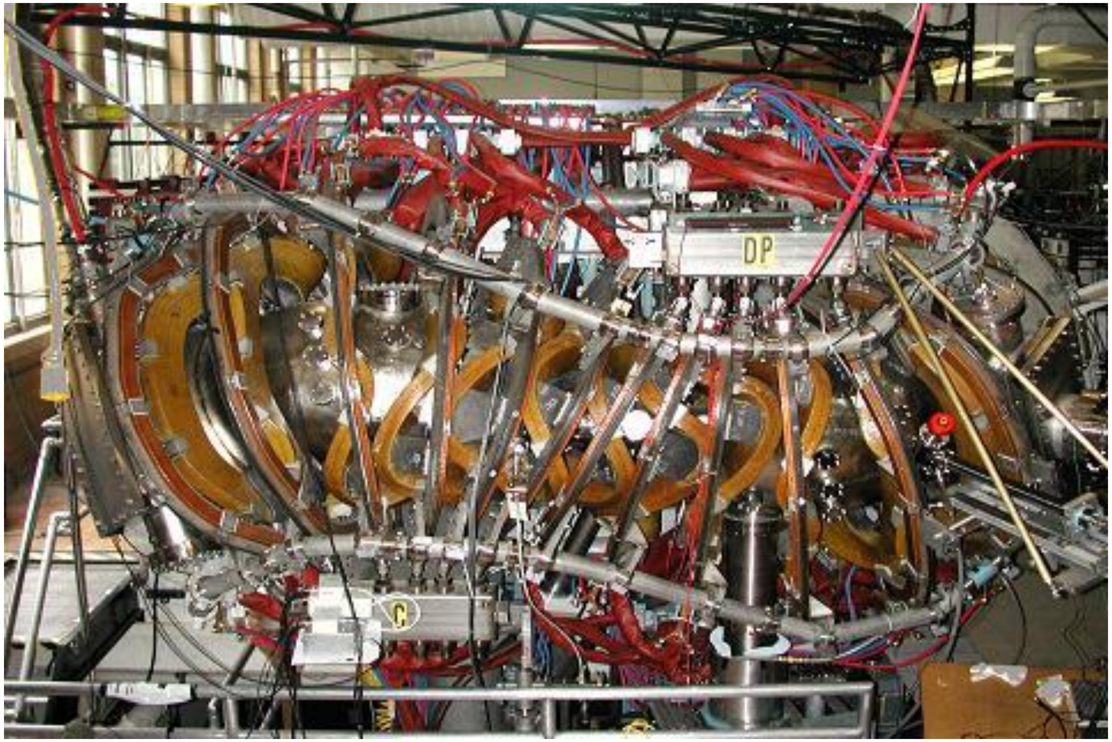
Measurements of the contribution of Reynolds stress to momentum balance in the HSX stellarator





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Thanks to the rest of the HSX team for their contributions to this work

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Outline

- The HSX stellarator
  - Quasi-symmetric optimization
  - Experimental setup: Langmuir probes

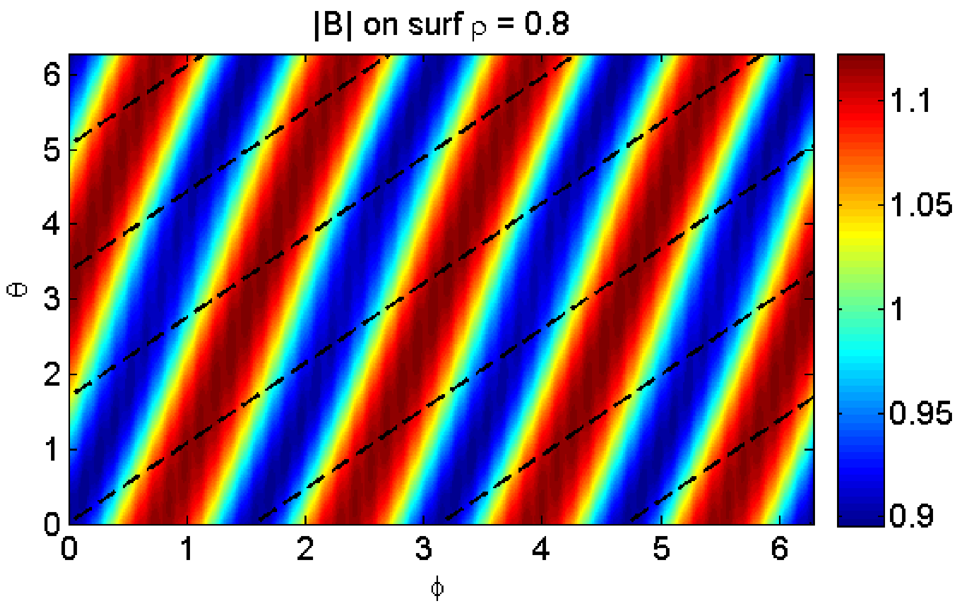
- Measurements of Reynolds stress and E_r
  - Gradient in time-averaged Reynolds stress profile implies relevant macroscopic flow drive
  - Region of measured flow drive corresponds to measured deviation in E_r from neoclassical ambipolarity calculations
  - Fluctuation measurements from multiple probe installations show that Reynolds stress drive changes depending on the local magnetic geometry

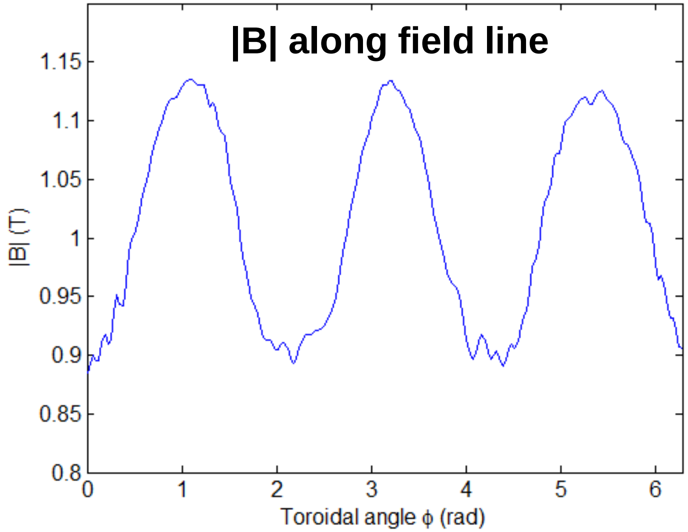
HSX is the first stellarator optimized for quasi-symmetry, designed to minimize neoclassical transport and flow damping

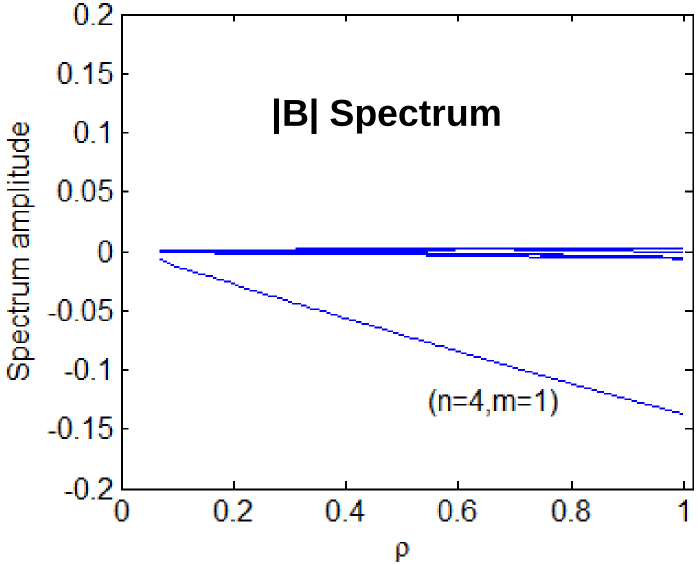
- **HSX is optimized for quasi-helical symmetry: |B| is symmetric in the helical direction (n=4, m=1)**
- **This is designed to give tokamak-like viscosity and neoclassical transport properties**

Tokamak: $B/B_0 = 1 - \varepsilon_t \cos \iota\phi$

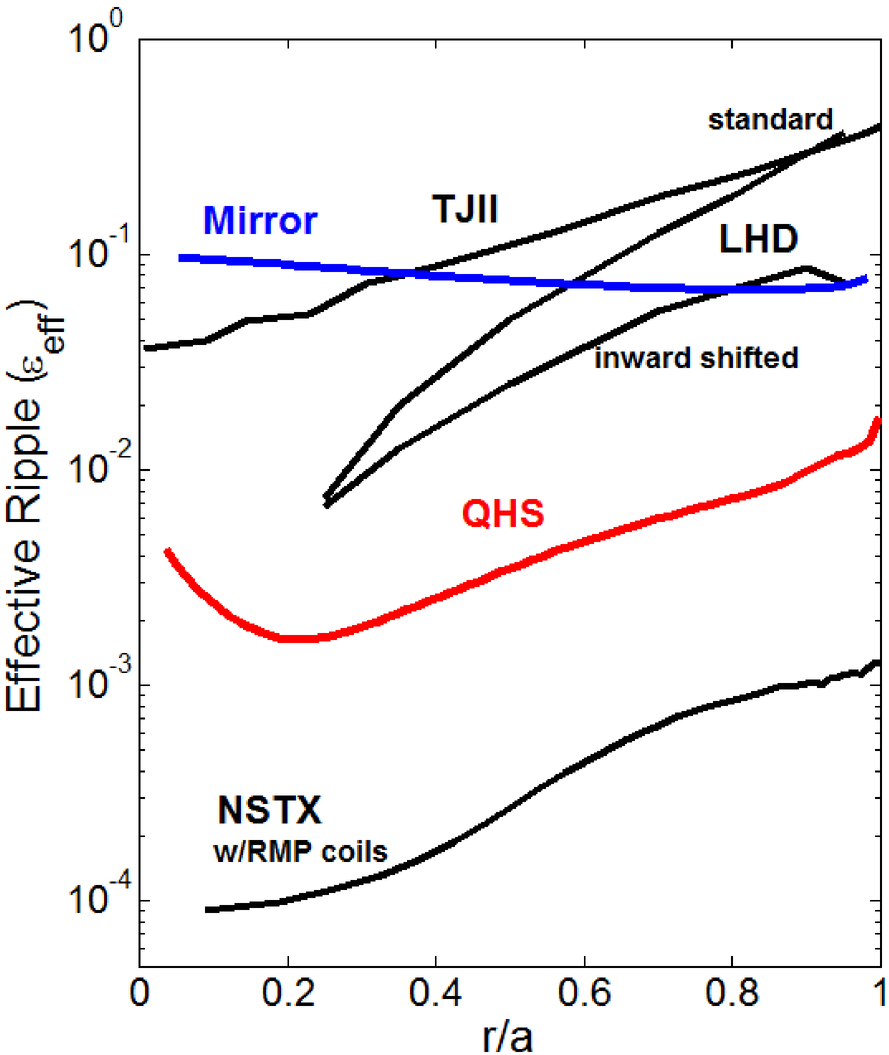
QHS: $B/B_0 = 1 - \varepsilon_h \cos(n - m\iota)\phi$







The level of symmetry breaking in HSX is somewhere between that of a conventional stellarator and a tokamak



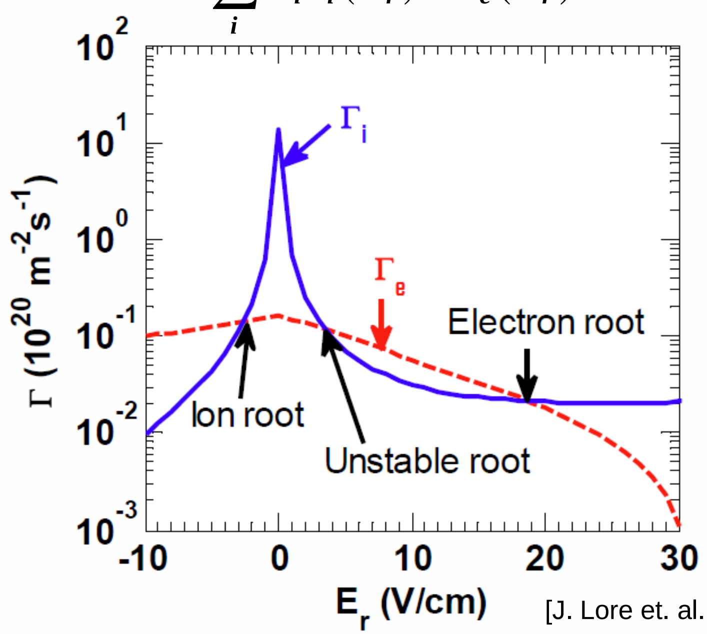
TJII: Seiwald et. Al., JCP 2008
LHD: Okimara, EPS 2012
NSTX calculations courtesy of John Canik, ORNL

- **Effective ripple is a measure of the neoclassical thermal particle losses at low collisionality, and is finite in all real magnetic confinement devices**
  - **Sources like RMP coils, TF ripple, field errors in tokamaks**
- **Particle transport in the low collisionality regime scales like ~** $\varepsilon_{eff}^{3/2}/\nu$
- **Viscosity is similarly in between that of a tokamak and a conventional stellarator**

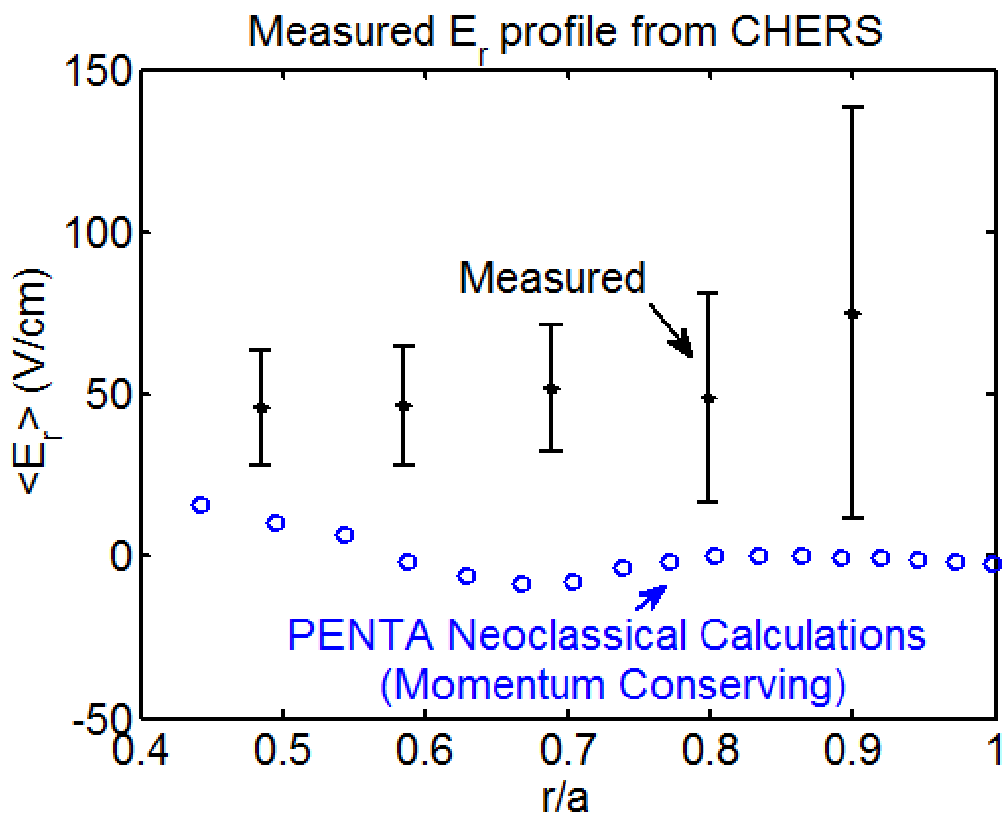
E_r measured in HSX using CHERS does not generally agree well with the values calculated by PENTA

- **DKES and PENTA determine E_r by calculating non-ambipolar particle fluxes as a function of E_r and imposing the ambipolarity condition**

$$\sum_i Z_i \Gamma_i(E_r) = \Gamma_e(E_r)$$



[J. Lore et. al., PoP 2010]



[A. Briesemeister et al, PPCF 2013]

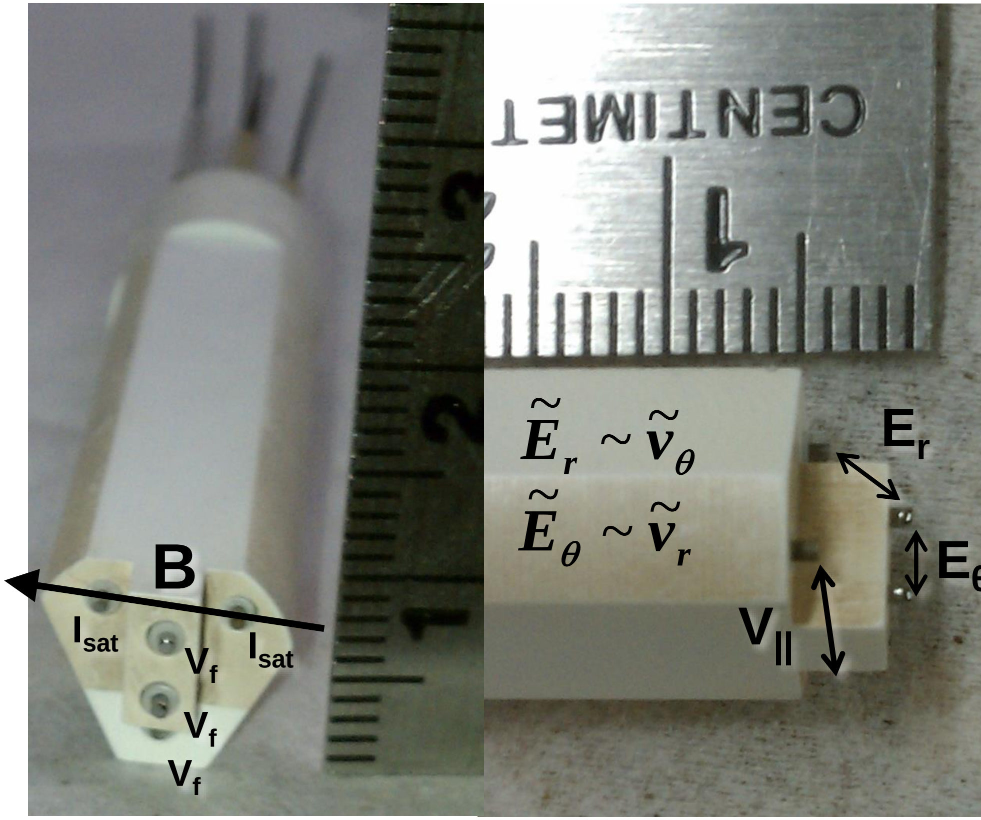
- **CHERS measurements made in similar 50 kW ECRH plasmas doped with CH4 show that E_r differs from neoclassical calculations →**

Investigate turbulent sources for determining E_r

Langmuir probes installed to measure local fluctuating plasma parameters for Reynolds stress studies

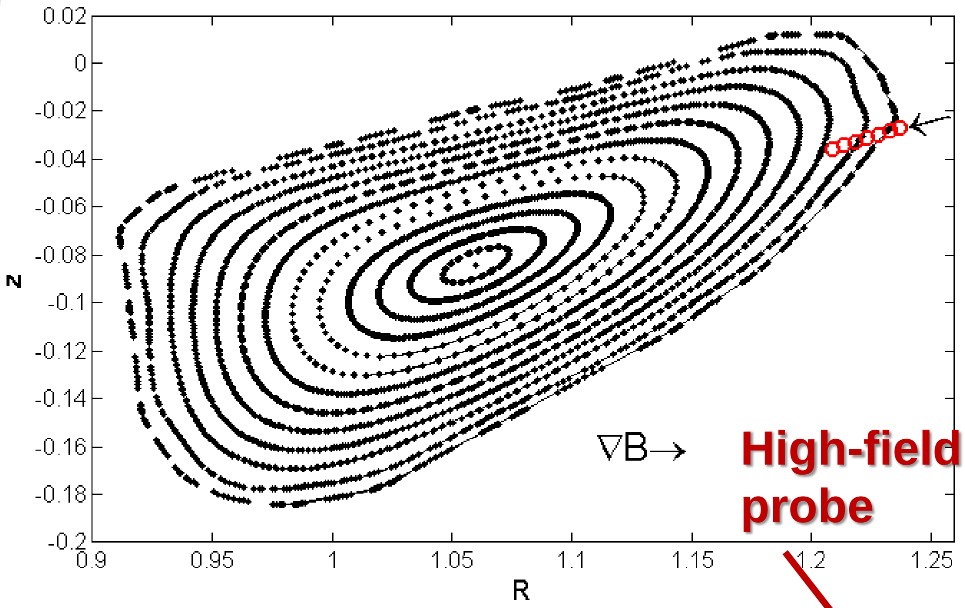
- **Tungsten tips shielded by bulk BN, V_f and I_{sat} signals digitized at 2.5 MHz**
- **Radial profiles taken on a shot-by-shot basis**
  - **Discharges are very repeatable**
- **Differential V_f fluctuations are assumed to be potential fluctuations**
  - **Fluctuating T_e not accounted for**
- **Fluctuating v_r and v_θ quantities for Reynolds stress assumed from measured E_r and E_θ fluctuations, respectively**

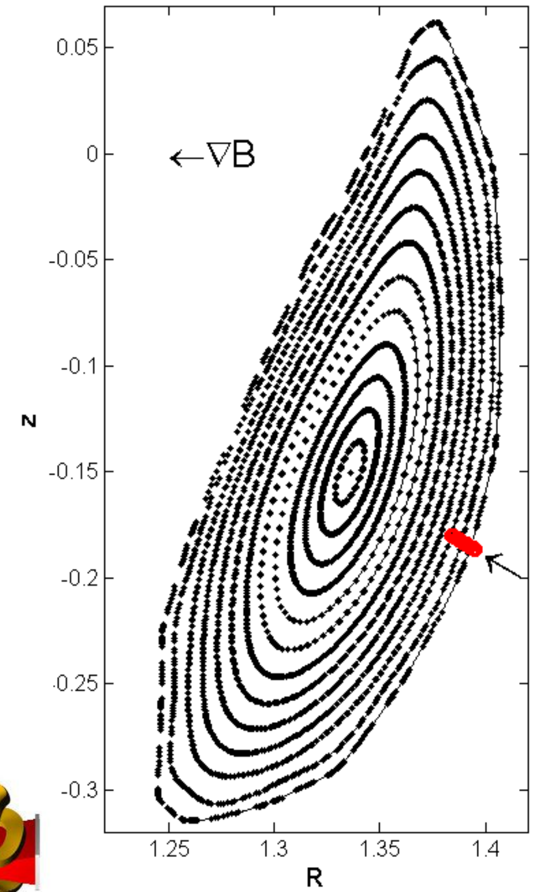
$$\tilde{v}_r \tilde{v}_\theta = -\frac{\tilde{E}_\theta \tilde{E}_r}{B^2}$$



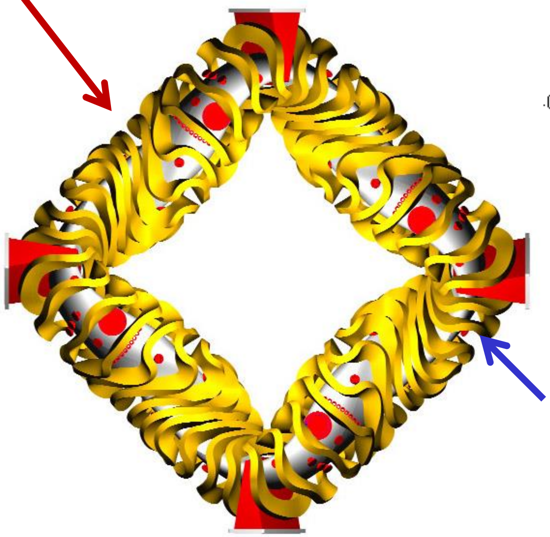
$$\tilde{E}_r = \frac{\tilde{V}_{f,2} - \tilde{V}_{f,3}}{\Delta r} \qquad \tilde{E}_\theta = \frac{\tilde{V}_{f,2} - \tilde{V}_{f,1}}{\Delta x_\theta}$$

Two probe installations to provide better estimate of flux-surface averaged Reynolds stress from local measurements





High-field side probe

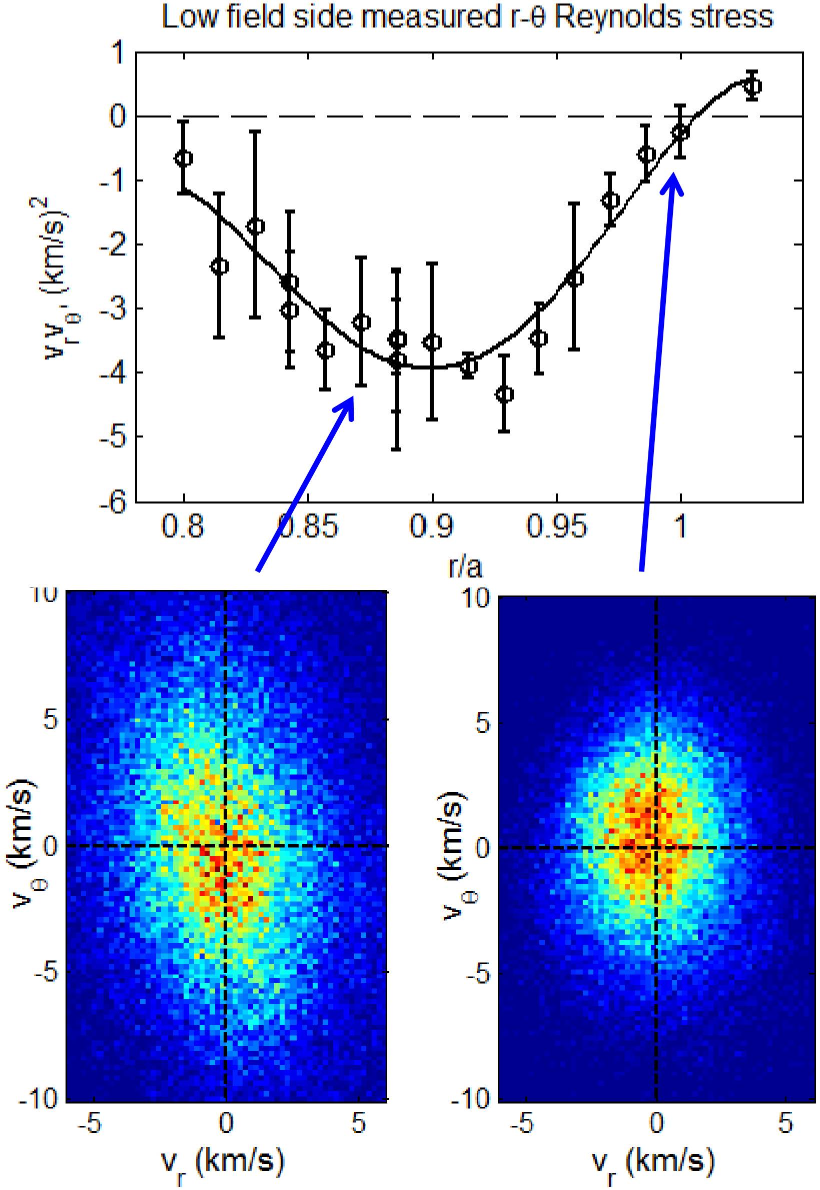


Low-field side probe

- **Probes located in regions near limits of magnetic field strength, curvature, and flux expansion on a flux surface**

- **Compare measurements at two locations with different local magnetic geometries**

Clear radial gradient exists in time-averaged Reynolds stress profiles



- **Reynolds stress flow drive is proportional to**

$$\frac{\partial}{\partial r}\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle$$

- **PDF of velocity fluctuations (inferred from V_f measurements) show negative correlation between instantaneous v_r and v_θ fluctuations inside the confined plasma**
  - **Fluctuations are more isotropic near the last closed flux surface**

- **Measurement needs to be compared to some estimate of the poloidal viscosity to calculate resulting poloidal rotation and E_r**

Estimate of neoclassical poloidal viscosity is calculated to find contribution of measured Reynolds stress to flows and E_r

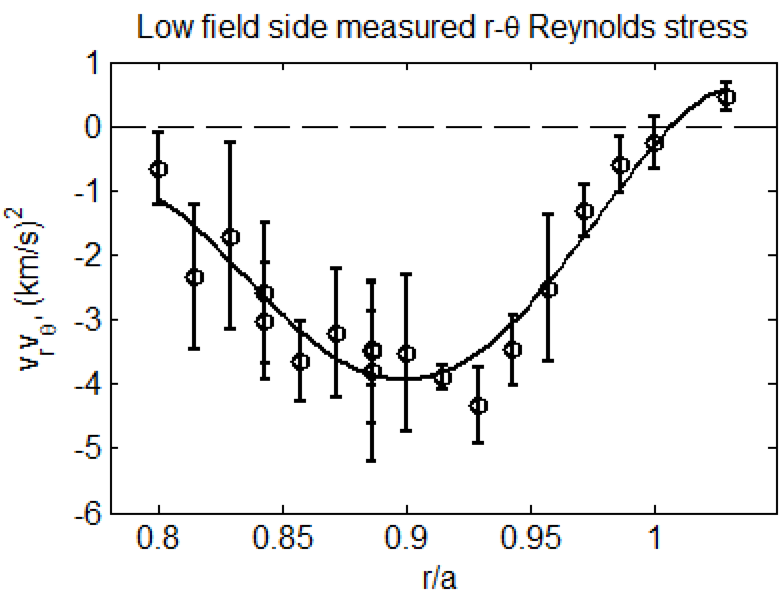
$$\frac{\partial}{\partial t}\langle v_\theta\rangle = 0 = -\frac{\partial}{\partial r}\left(\langle \tilde{v}_r \tilde{v}_\theta\rangle\right) - \mu_\theta\langle v_\theta\rangle - \nu_{in}\langle v_\theta\rangle + \tau_{ext}$$

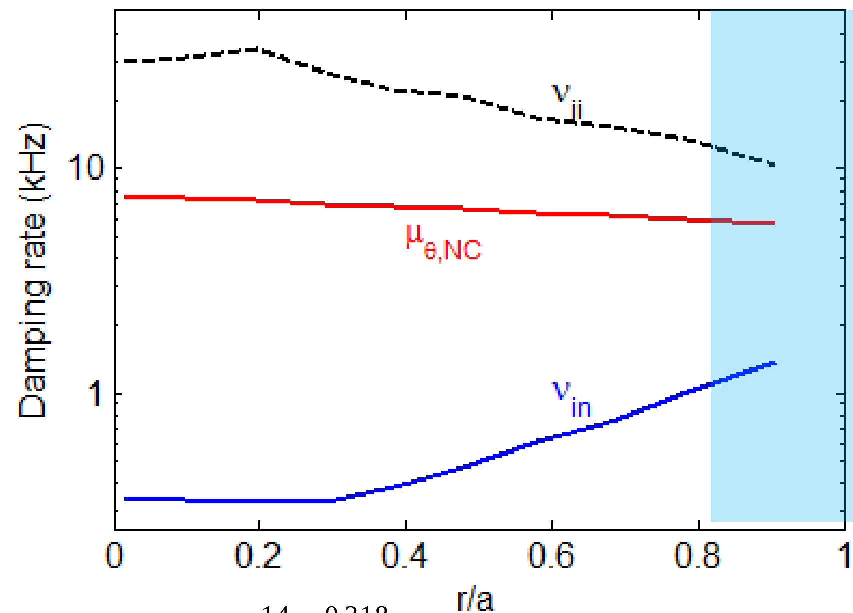
$$\langle v_\theta\rangle_{RS} = -\left(\frac{1}{\mu_\theta+\nu_{in}}\right)\frac{\partial}{\partial r}\left(\langle \tilde{v}_r\tilde{v}_\theta\rangle\right)$$

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

[M. Coronado and H. Wobig, *Phys. Fluids B 29* (1986) 527]

- **Estimate the purely poloidal component of neoclassical viscosity for poloidal momentum balance**
- **Neutral density based on measurements from H-alpha arrays and calculations from DEGAS neutral gas code**

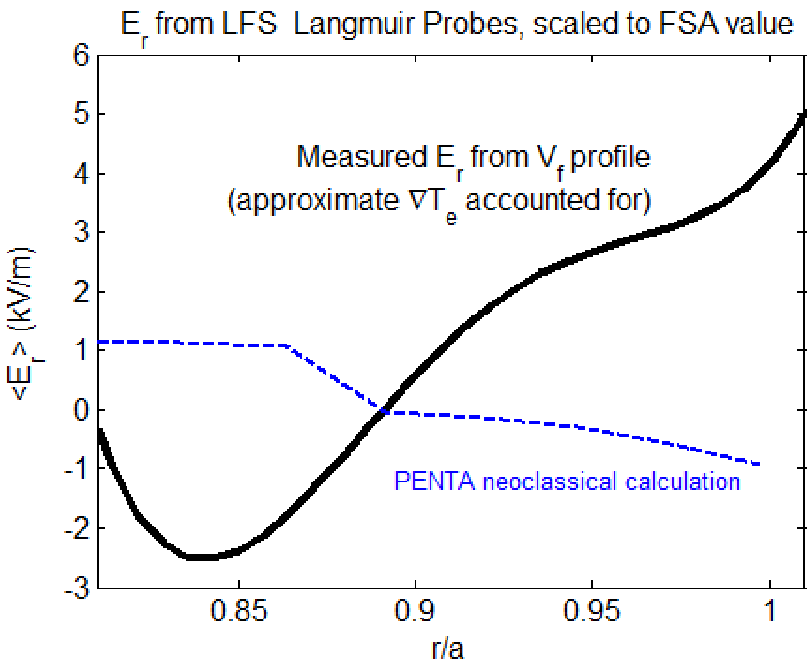


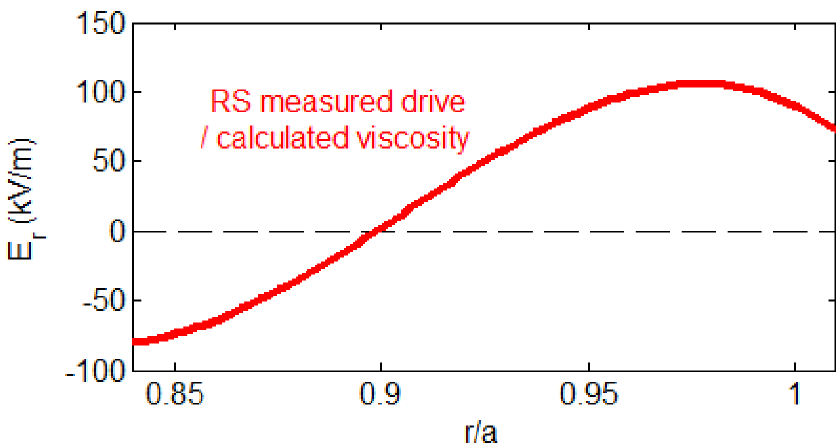


$$\upsilon_{in}\approx N_n 10^{-14} T_i^{0.318}$$

- **Neutral damping is small but non-negligible at the edge where probe measurements are made**

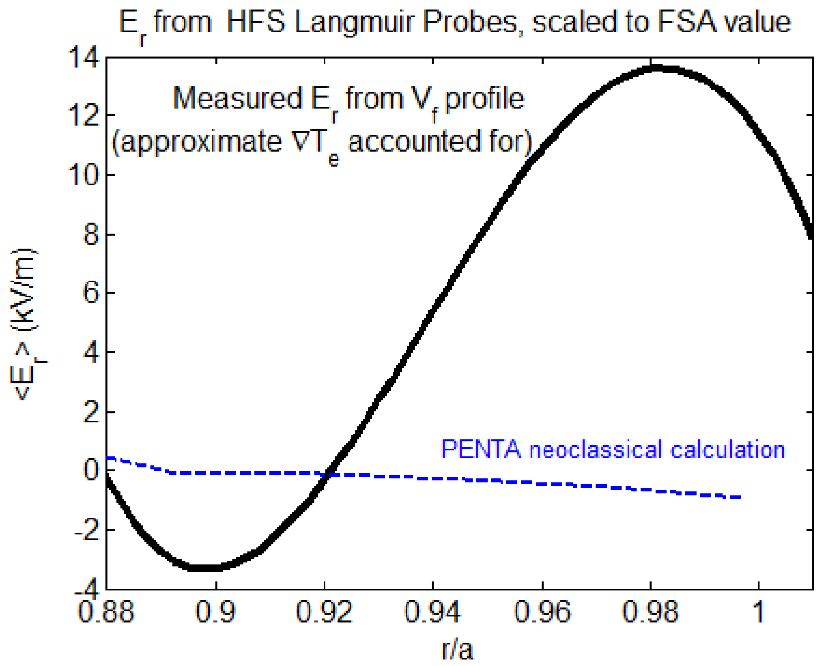
Measured Reynolds stress flow drive agrees qualitatively with deviation of E_r from neoclassical ambipolarity calculation

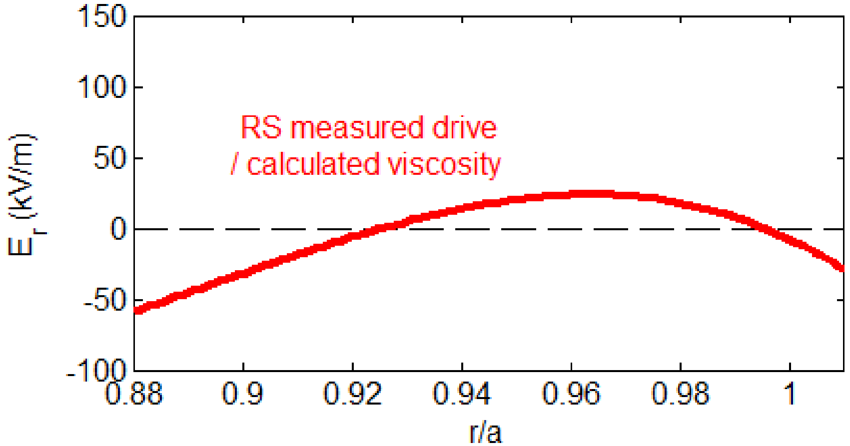




- E_r calculated from shot-by-shot floating potential profiles
- T_e gradient is estimated from Thomson scattering and accounted for
  - $T_e(\rho=0.9) \approx 60$ eV
- Based on sensitivity studies, neoclassical calculations have small errorbars relative to measured deviations
- Reynolds stress measurements imply unphysically large flow drive
  - Single point measurement where microinstabilities are expected to be most unstable (low field, bad curvature)
  - T_e fluctuations observed through V_f may lead to over-estimation of fluctuating φ [Gennrich & Kendl, PPCF 2012]
  - Viscosity may be underestimated

High field side probe measures qualitatively similar E_r profile, with lower-amplitude Reynolds stress drive than low-field side





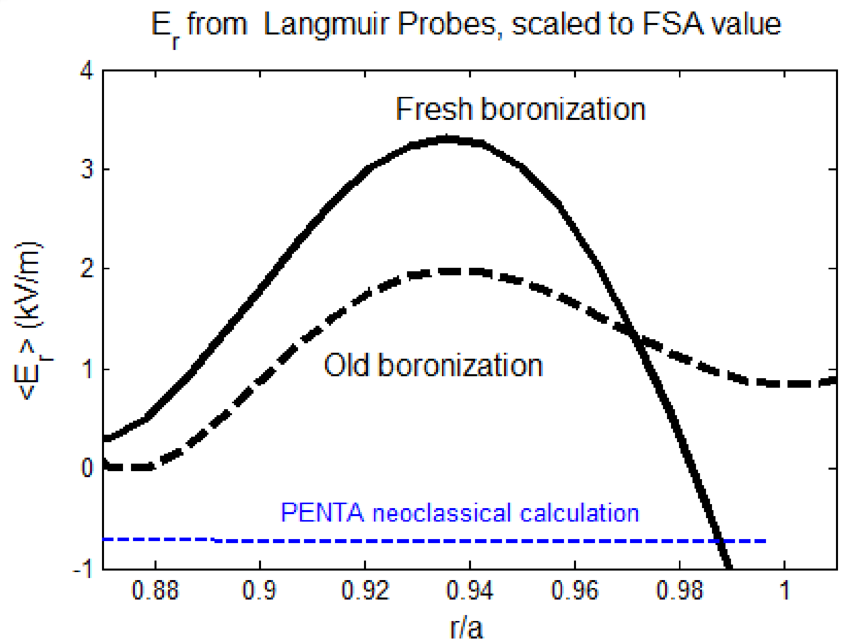
- E_r profile at HFS probe is similar
- Reynolds stress drive measured on high-field side is generally smaller magnitude, but still larger than the observed deviation from the neoclassical calculation
- How to interpolate the flux surface average Reynolds stress from 2 measured locations on a surface remains an open question

Summary and future work

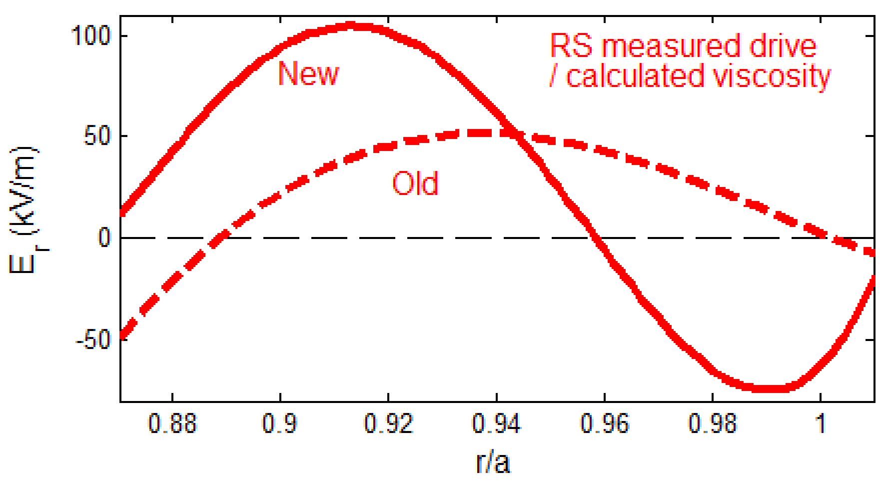
- **Reynolds stress flow drive is measured to be large in the same radial regions where E_r deviates significantly from the predicted ambipolar value calculated by PENTA**
- **Locally measured Reynolds stress drive can change depending on local magnetic geometry**
  - **No clear way to extract a flux surface averaged value of the Reynolds stress from 2 spatial locations**
- **Upcoming measurements in configuration with the symmetry intentionally spoiled will hopefully shed light on the dependence of intrinsic flows on quasisymmetry**

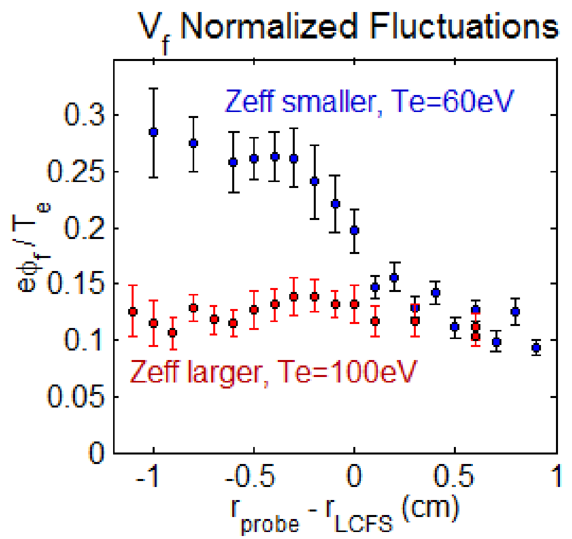
Extra Slides

Additional datasets show positive definite Er even before compensating for the temperature gradient

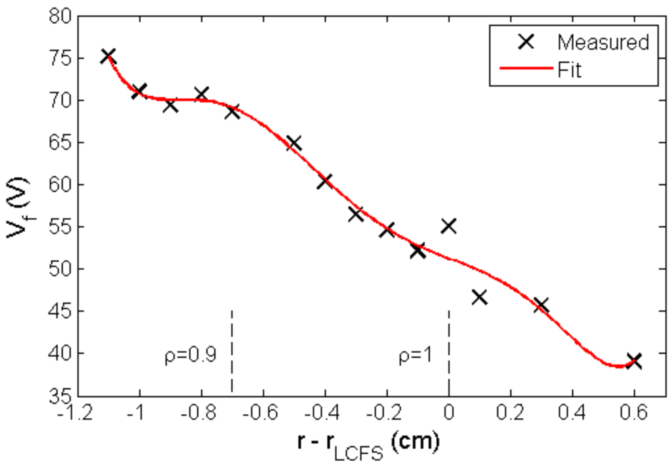


- **When wall conditioning changes (fresh boronization), edge T_e is reduced, and fluctuation levels are increased, along with the measured deviation from neoclassical E_r prediction**
- **E_r deviation from neoclassical prediction and Reynolds stress measurements qualitatively scale together in amplitude and radial location**





E_r measured by radial scan of floating potential signal, which also has electron temperature dependence



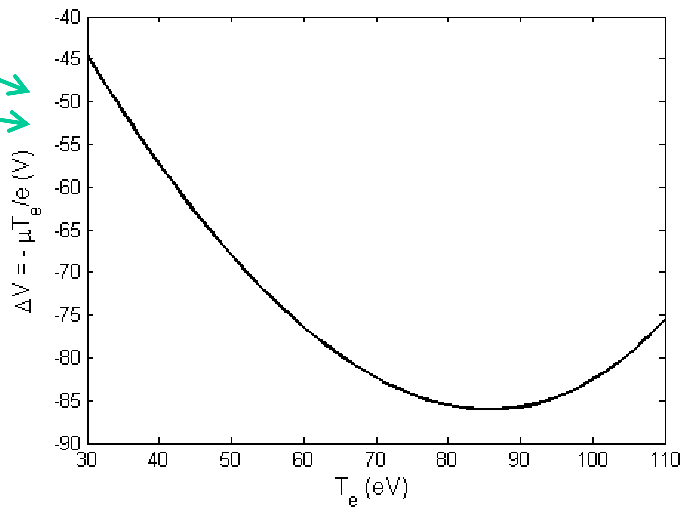
- **E_r measured using fit of shot-by-shot Langmuir probe V_{fl} profile**
  - **Attempt to account for local T_e gradient in measured E_r plots**
- **For low T_e, physical ∇T_e results in more-positive E_r, larger deviation from NC ambipolarity**
- **Non-linearity above ~80 eV due to secondary electron emission, γ_e**
- **E_r measurements from probe may not be reliable above T_e~100 eV without local T_e measurements**

$$\Phi_{fl} = \Phi_p - \mu \frac{T_e}{e}$$

$$\mu = \ln\left(\frac{(1-\gamma_e)}{(1+\gamma_i)} \frac{A_e}{A_i} \sqrt{\frac{T_e}{T_e + T_i}} \sqrt{\frac{m_i}{2\pi m_e}} \right)$$

$$E_r = -\nabla\left(\Phi_{fl} + \mu \frac{T_e}{e} \right)$$

Contribution of T_e to V_{fl} measurement



From ~70-100 eV, offset has small effect on E_r measurement (gradient small)