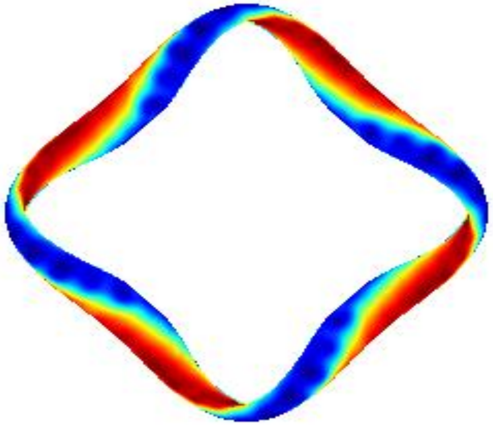
Measurements of Reynolds stress flow drive and radial electric fields in the edge of HSX



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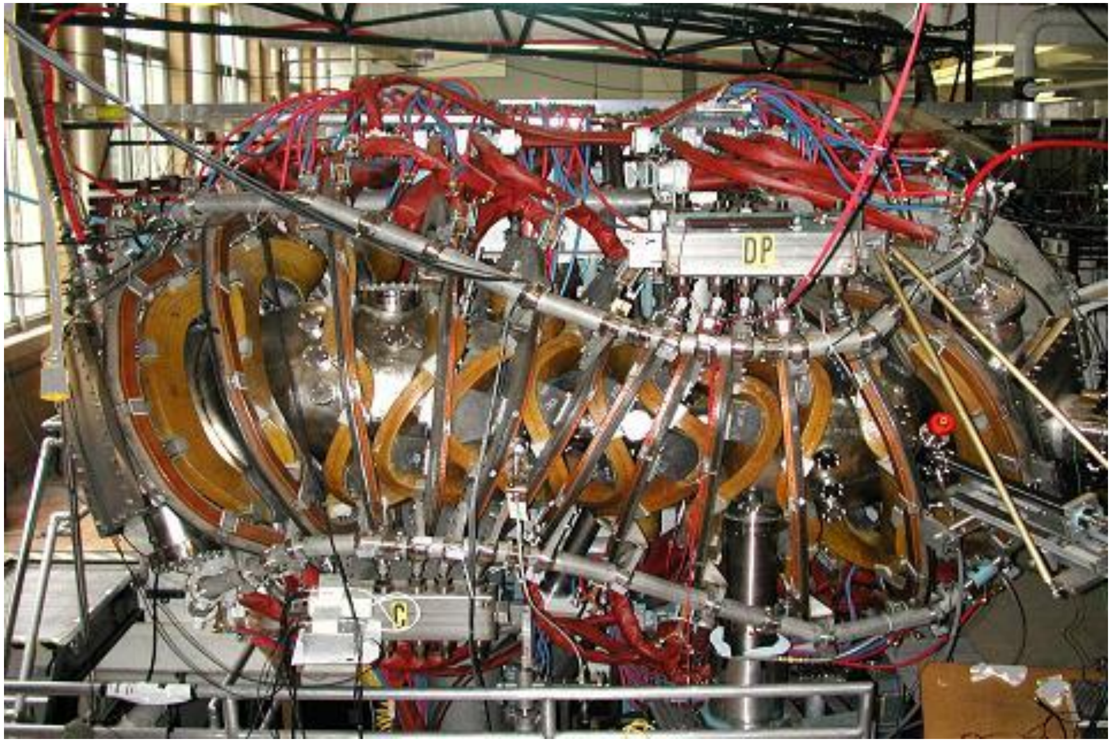


Thanks to the HSX team for their contributions to this work

Outline

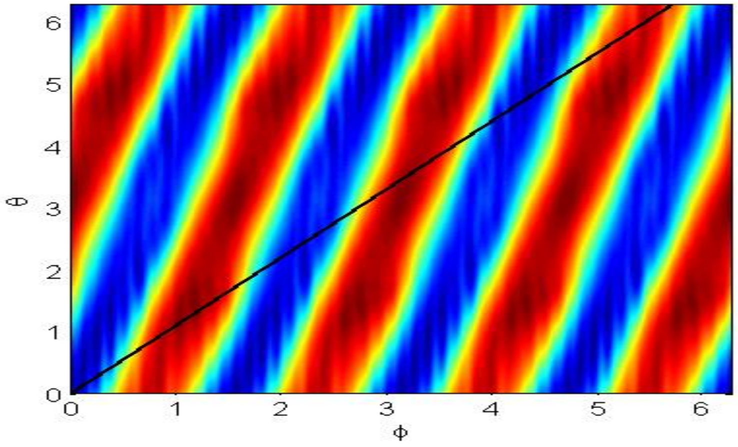
- The HSX stellarator
  - Quasi-symmetric optimization
  - Experimental setup: Langmuir probes
- Measurements of Reynolds stress
  - Gradient in time-averaged Reynolds stress profile implies relevant macroscopic flow drive
  - Region of measured flow drive corresponds to measured deviation in E_r from neoclassical ambipolarity calculations
- Comparison to theory
  - Scalings based on work by Helander and Simakov
- Planned future experiments
  - Additional Reynolds stress probe installation
  - Effective ripple and collisionality scaling

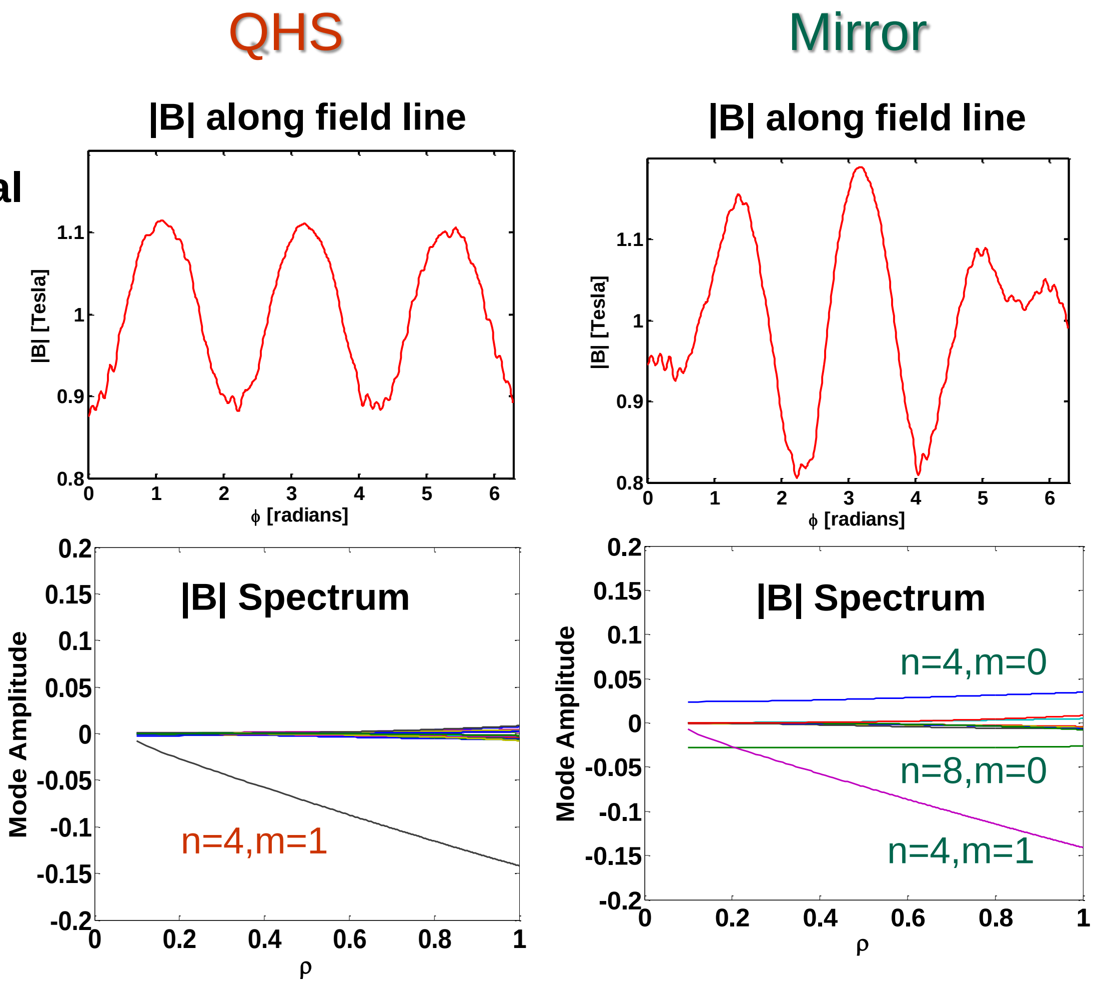
HSX is the first stellarator optimized for quasi-symmetry

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

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

QHS: $B/B_0 = 1 - \varepsilon_h \cos\underbrace{(n - m\iota)}_{\iota_{\text{eff}} \sim 3}\phi$

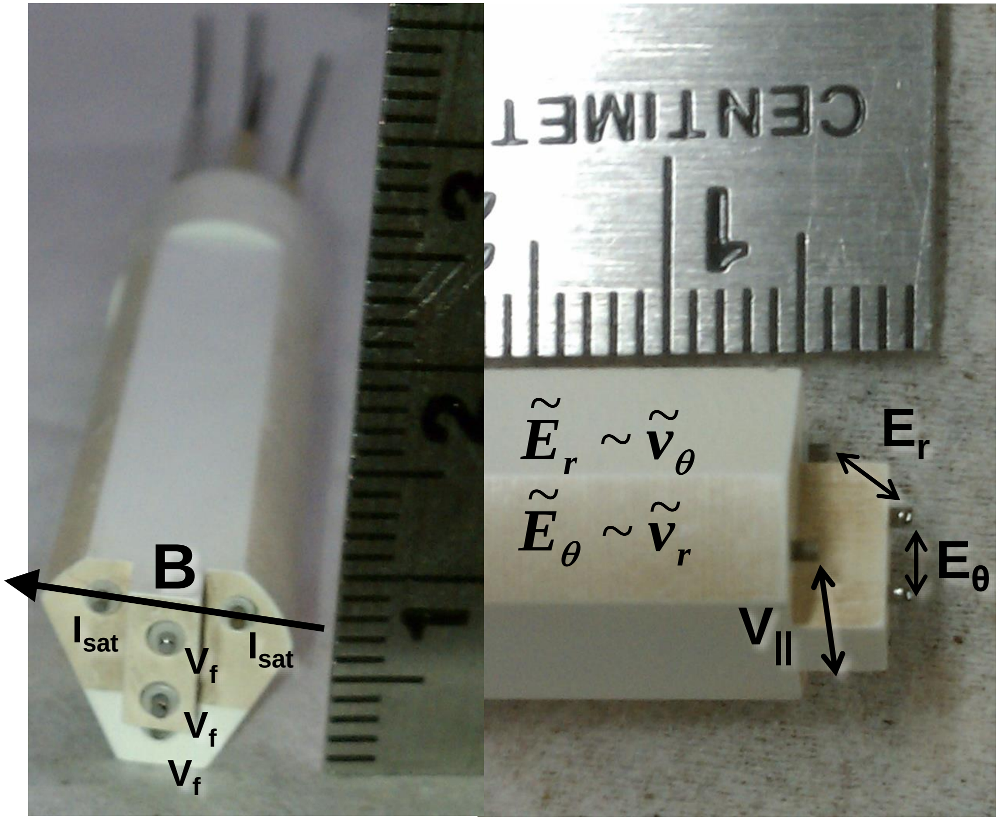




Neoclassical transport can be varied with auxiliary coils

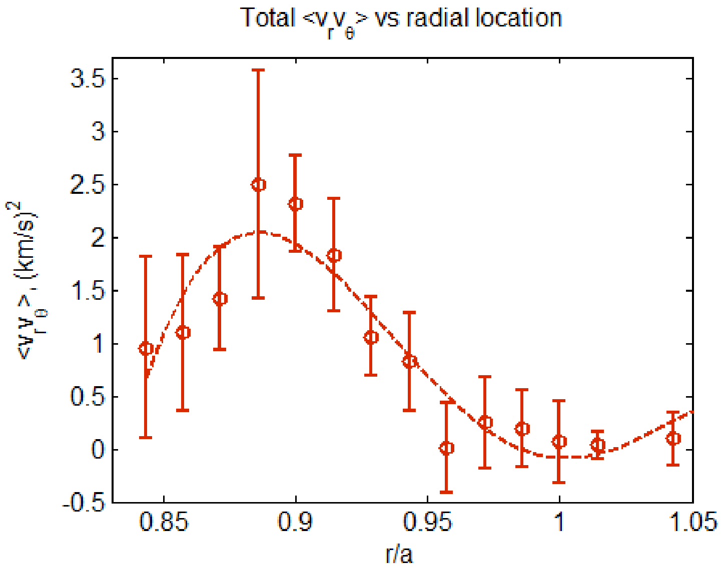
Langmuir probes installed to measure local fluctuating plasma parameters for Reynolds stress studies

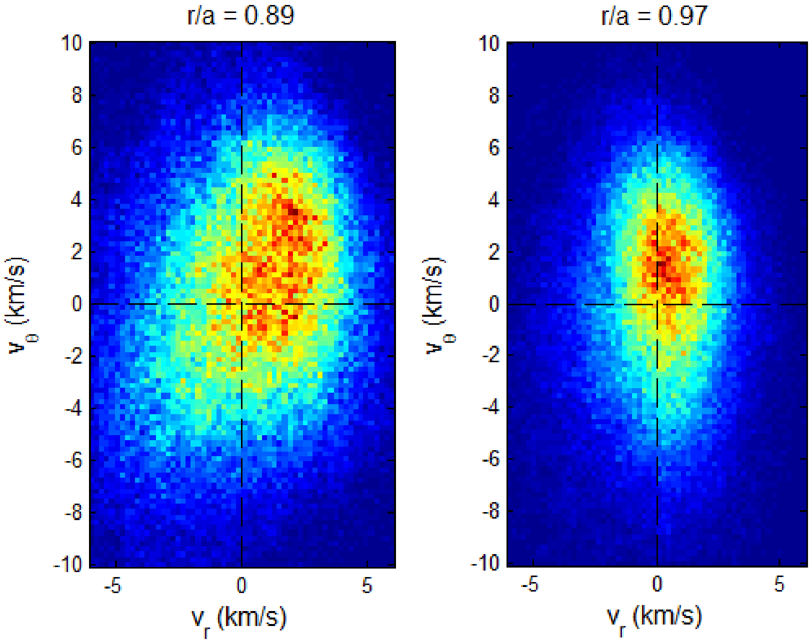
- Tungsten tips shielded by bulk BN, V_f and I_{sat} signals digitized at 5 MHz
- Radial profiles taken on a shot-by-shot basis
- Discharges are very repeatable: n_e consistent to within 1%, probe measurements consistent to within the noise
- For the data shown here, differential V_f fluctuations are assumed to be potential fluctuations
  - Mean T_e difference between pins is accounted for, fluctuating T_e would not be
- Fluctuating v_r and v_θ quantities for Reynolds stress assumed from measured E_r and E_θ fluctuations, respectively



$$\tilde{E}_r = \frac{\tilde{V}_{f,2} - \tilde{V}_{f,3}}{dr} \qquad \tilde{E}_\theta = \frac{\tilde{V}_{f,2} - \tilde{V}_{f,1}}{dx_\theta}$$

Clear radial gradient exists in time-averaged Reynolds stress profile





- **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 positive correlation between instantaneous v_r and v_θ fluctuations**

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

Neoclassical poloidal viscosity is calculated roughly to find contribution of measured Reynolds stress to flows and E_r

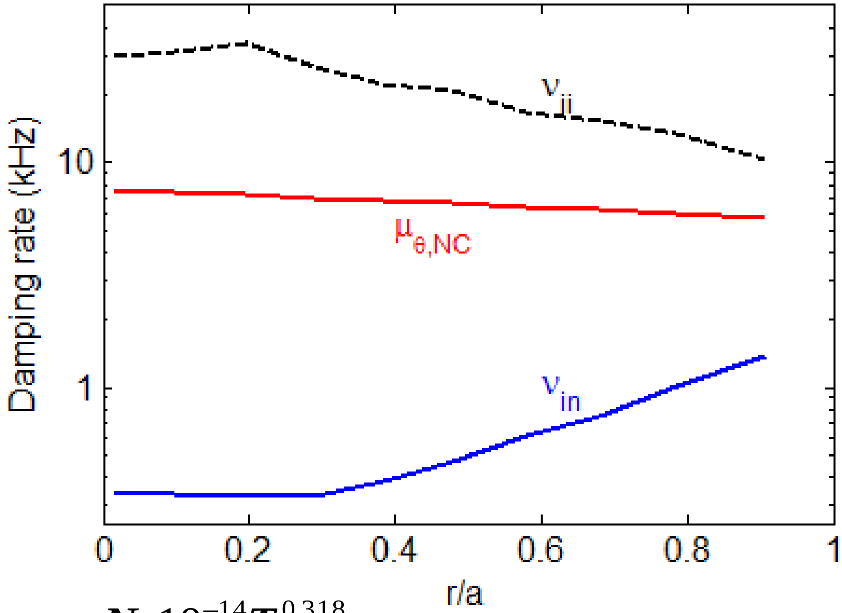
$$\frac{\partial}{\partial t}\langle v_\theta\rangle = 0 = -\frac{\partial}{\partial r}\left(\langle \tilde{v}_r \tilde{v}_\theta\rangle\right) - \mu_\theta\langle v_\theta\rangle - \nu_{in}\langle v_\theta\rangle + \tau_{ext}$$

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

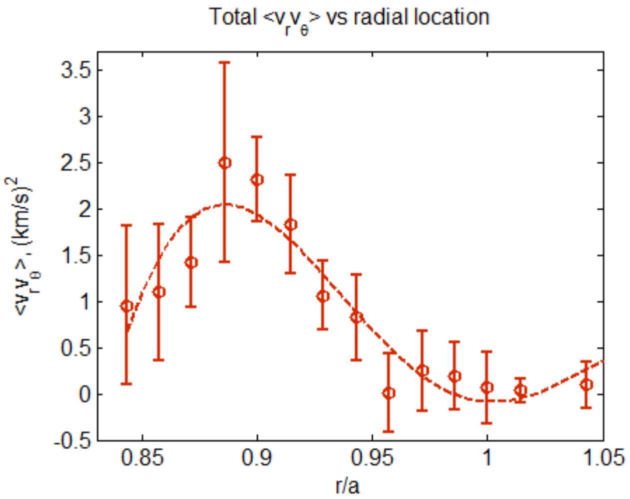
$$\mu_\theta = \frac{1}{4\pi^{1/2}}\frac{v_{ti}R_0}{r^2}\sum_{n,m}\frac{m^2 b_{n,m}}{|n-\iota m|}$$

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

- **Crudely 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**

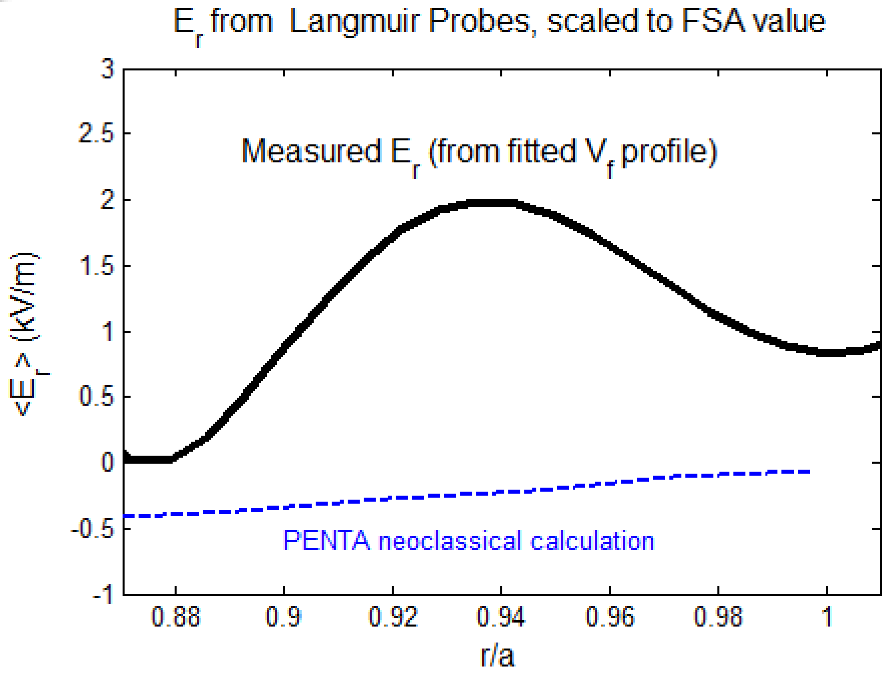


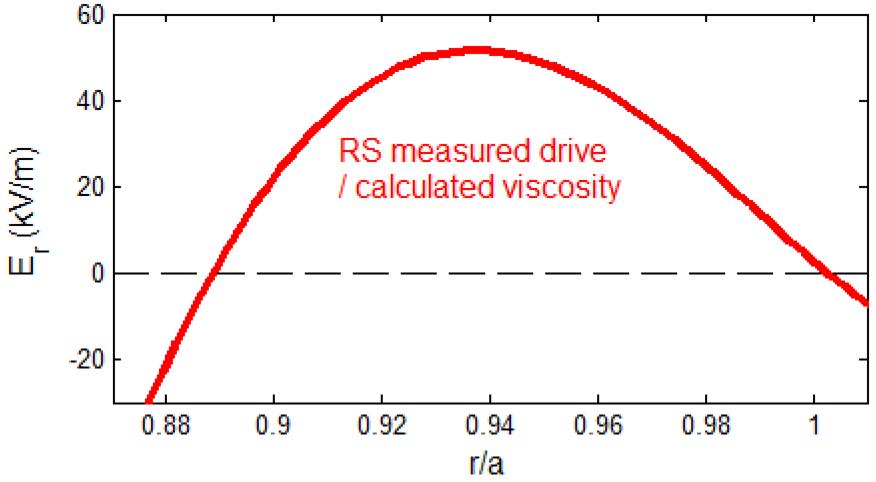
$$\upsilon_{in} \approx N_n 10^{-14} T_i^{0.318}$$


Total $\langle v_r v_\theta\rangle$ vs radial location

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

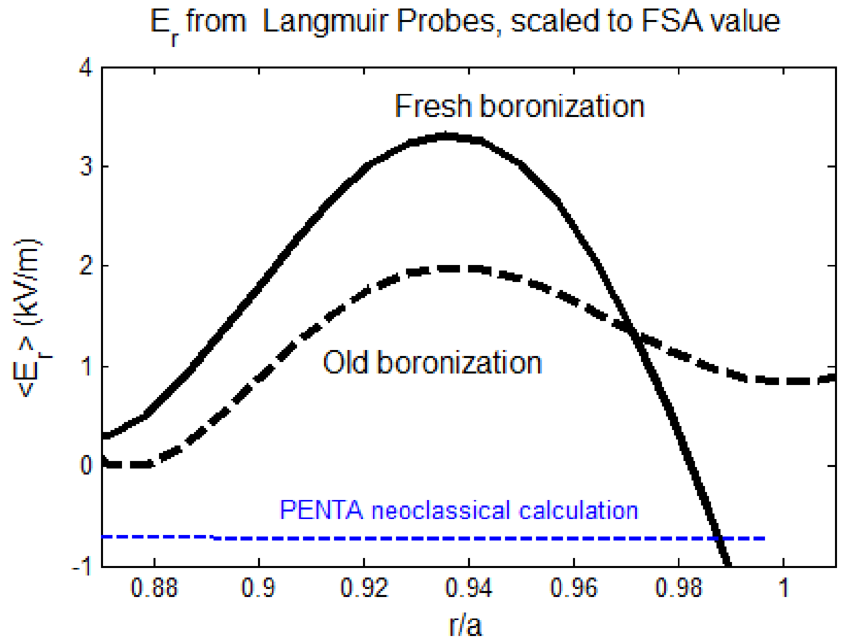
Measured Reynolds stress flow drive agrees qualitatively with deviation of E_r from neoclassical ambipolarity calculation

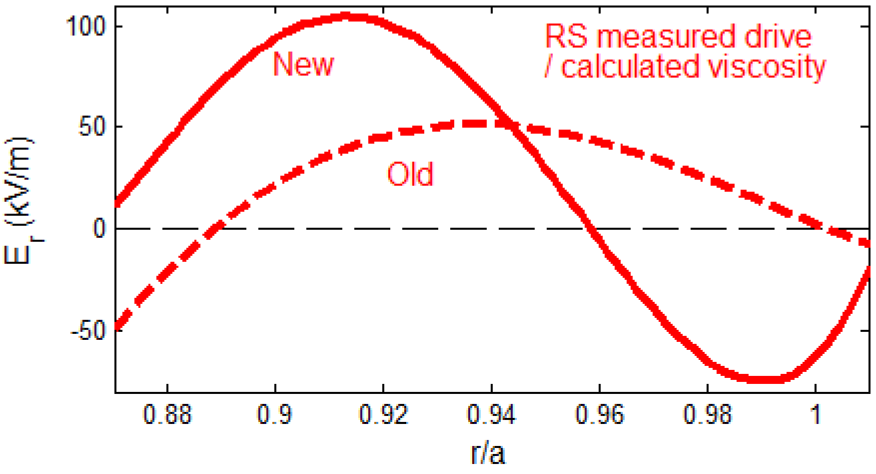




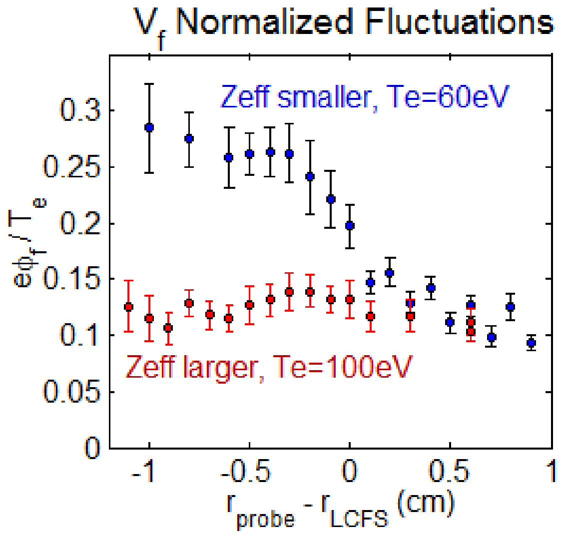
- **PENTA code calculates neoclassical ambipolarity condition based on non-ambipolar particle fluxes as a function of E_r**
  - **Neoclassical particle transport is small for optimized QHS configuration**
  - **More on PENTA calculations from A. Briesemeister tomorrow**
- **Unknown T_e gradient is ignored, but would make E_r more positive if present**
  - **Anywhere between ~0-5 kV/m, depending on where local T_e drops off beyond the last Thomson scattering point**
- **Reynolds stress measurements imply extremely large flow drive, but this is a single point measurement in a region where fluctuations are expected to be large (low field, bad curvature)**

Measured deviation from neoclassical E_r prediction scales with Reynolds stress flow drive measurements when conditions change





- **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**

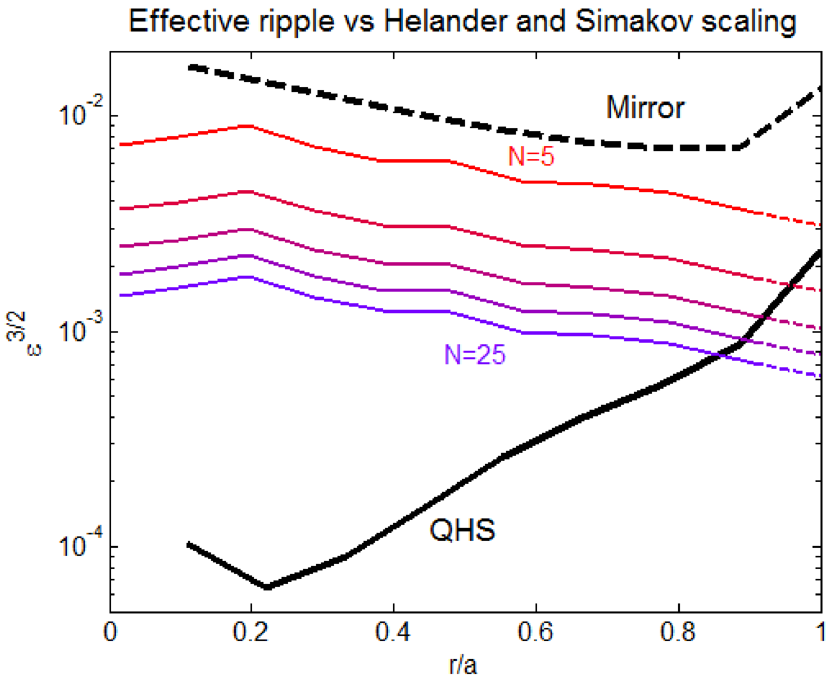


Helander and Simakov scaling finds that collisionless HSX should be free to rotate in core, constrained to neoclassical value at edge

- **How much symmetry breaking is tolerable before neoclassical non-ambipolar transport dominates turbulence-driven Reynolds stress?**
- **For collisionless plasma with ions in 1/ν regime, a deviation from neoclassical ambipolarity can be maintained over a radial distance of N ion gyroradii if**

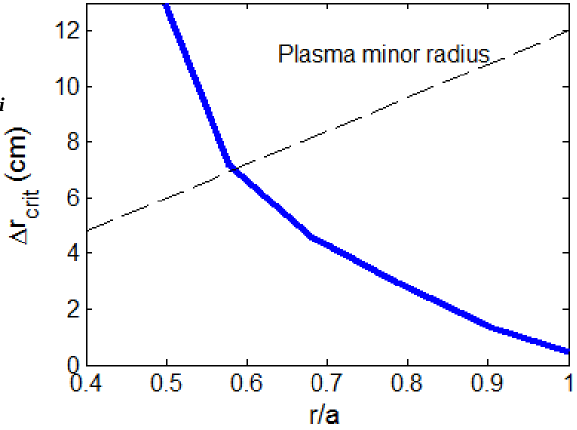
$$\varepsilon_h^{3/2} < \frac{L}{N\lambda_{MFP}}$$

- **This prediction finds that HSX should be "free to rotate" at inner radii, constrained to neoclassical rotation at edge**
- **Assumes 1/ν ions, which doesn't apply to these HSX plasmas (measured ion temperatures put H ions squarely in plateau regime)**
  - **Model represents an upper bound on allowable ripple for HSX**



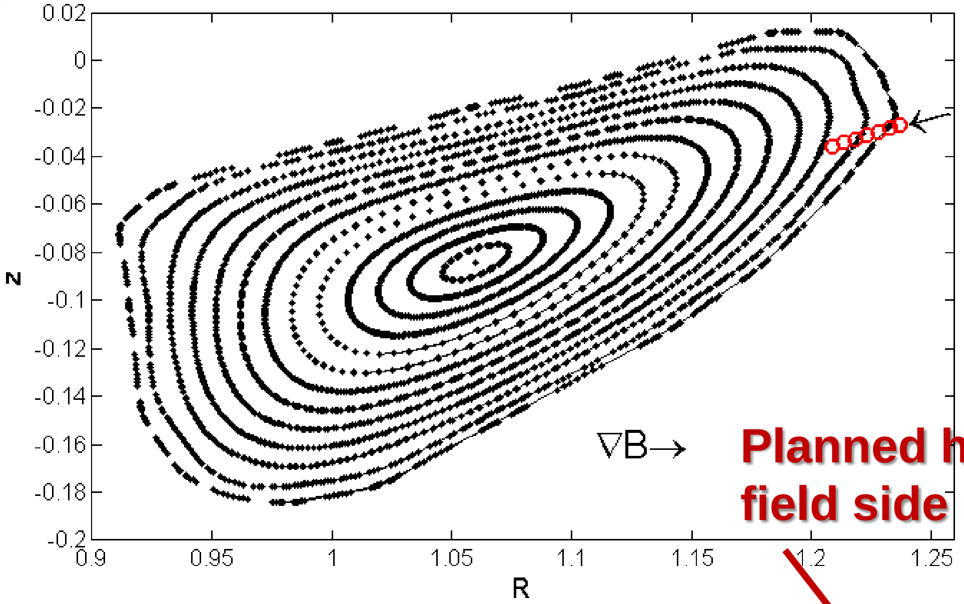
$$r_{crit} = N_{crit}\rho_i$$

$$r_{crit} = \frac{L}{\varepsilon_h^{3/2}\lambda_{MFP}}\rho_i$$

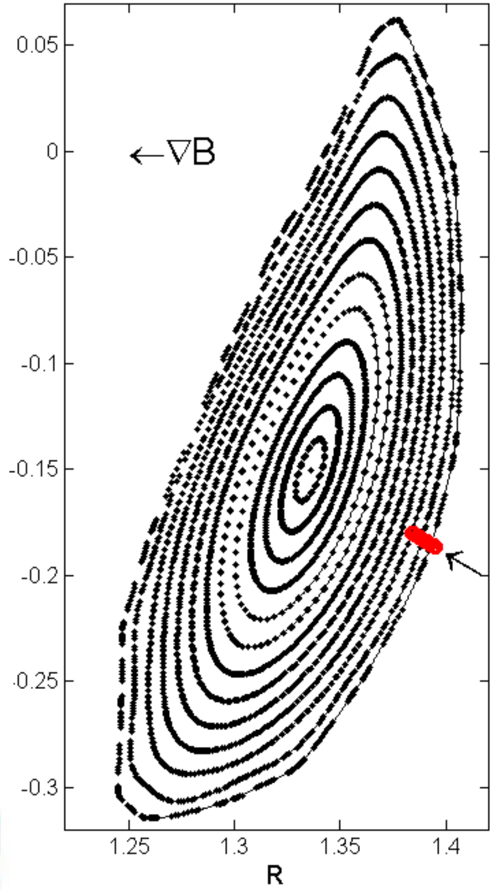


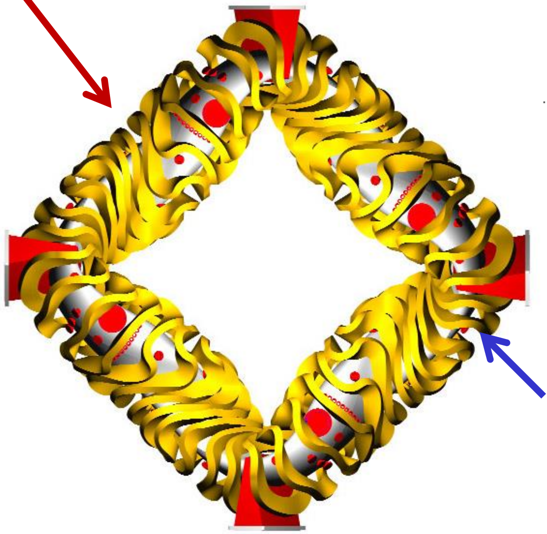
[P. Helander and A.N. Simakov, *Phys. Rev. Lett.* 101 (2008) 145003]

Second probe installation planned in high-field region for better estimate of flux-surface averaged Reynolds stress



Planned high-field side probe

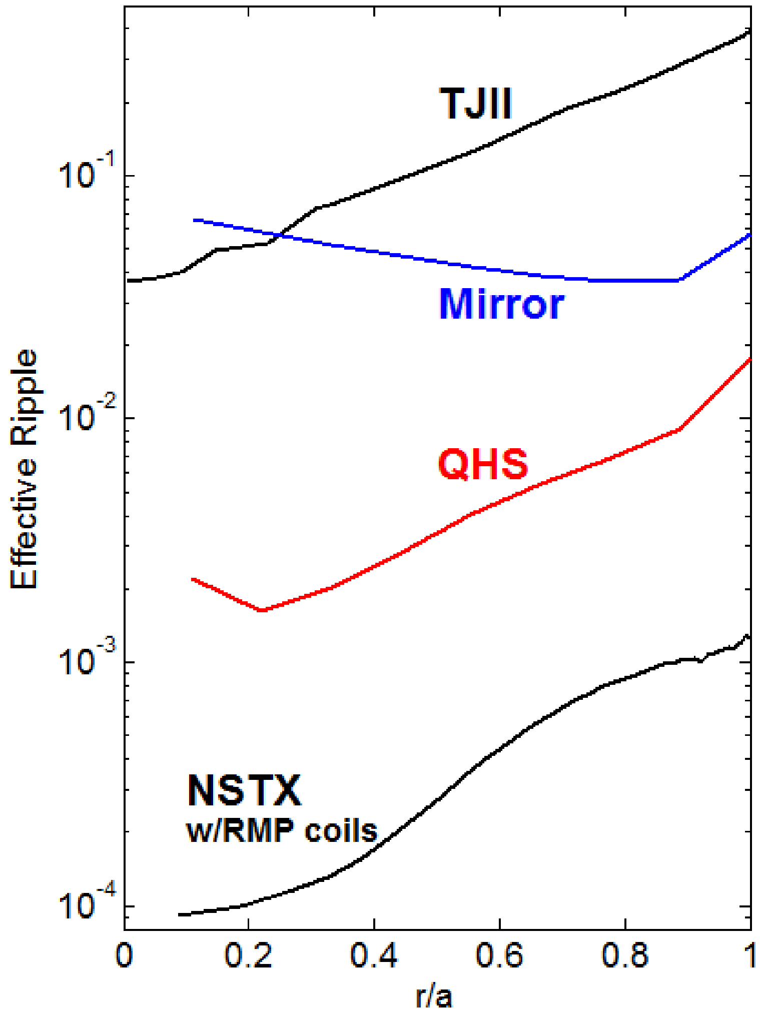




Existing low-field side probe

- **Existing probe is in region of low field, bad curvature**
- **Additional probe will be in region of high field, good curvature (still on outboard side)**
- **Approximate limits of RS value on a flux surface**
- **Possibly interpolate to find flux surface average value**

Effective ripple can be changed to examine the role of symmetry breaking in E_r determination



TJII ε_{eff}: Seiwald et. al, JCP 2008
NSTX ε_{eff} calculations courtesy of John Canik, ORNL

- **Effective ripple (ε_{eff}) is a measure of the neoclassical optimization, and is finite in all real magnetic confinement devices**
  - **Sources like RMP coils, TF ripple, field errors in tokamaks**
- **Experiments planned for Mirror configuration to find scaling of E_r deviation from neoclassical calculation with increased ripple**
  - **ε_{eff} at the edge where probes measure can be increased by a factor of ~5**
- **Collisionality scan can also be performed by adjusting heating power, line-averaged density**

Summary

- Regions where the Reynolds stress flow drive is measured to be large correspond to regions where E_r deviates significantly from the predicted ambipolar value calculated by PENTA
- Scalings suggest that quasi-symmetric configuration may be close to critical value of ε_{eff} where neoclassical non-ambipolar transport processes dominate to determine E_r
- Future experimental plans to test scaling
  - Additional probe installation to more accurately measure flux-surface average value of Reynolds stress
  - Scan edge effective ripple by breaking optimization
  - Scan collisionality by adjusting ECH heating power, density