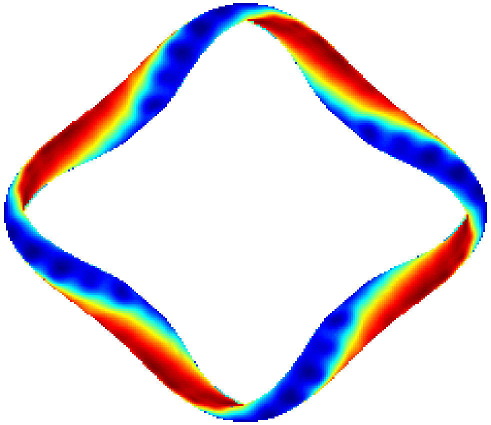
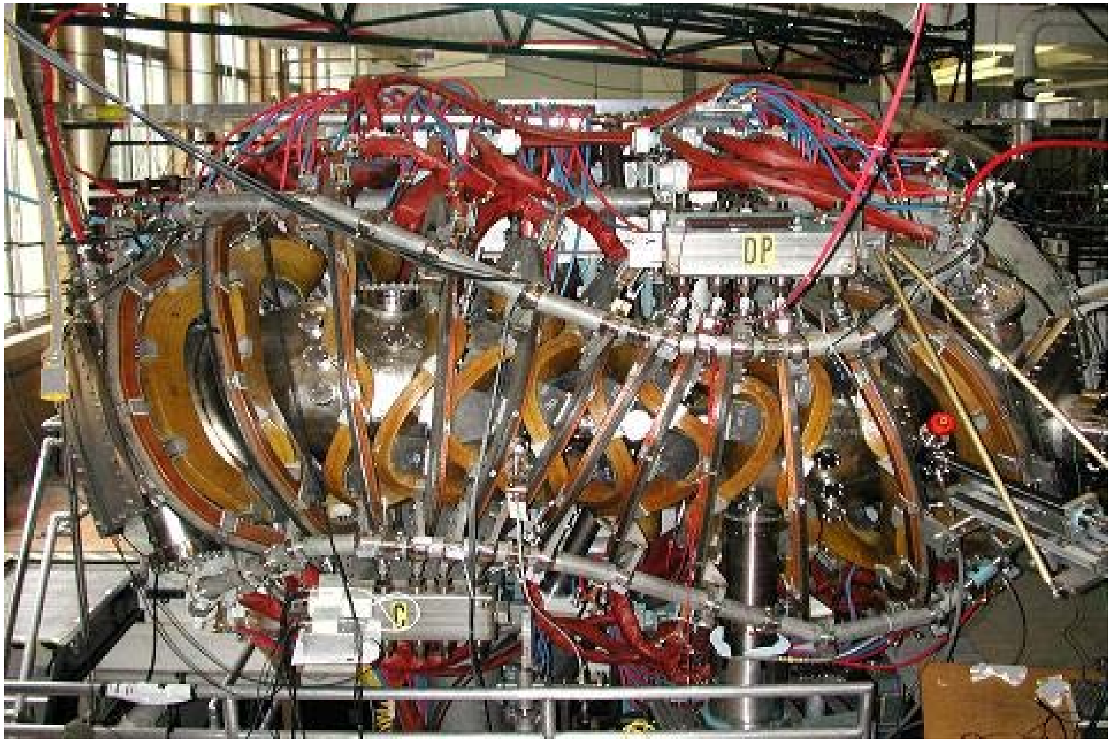
Measurements of Reynolds stress flow drive and radial electric fields in the edge of HSX





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Thanks to the HSX team for their contributions to this work

Outline

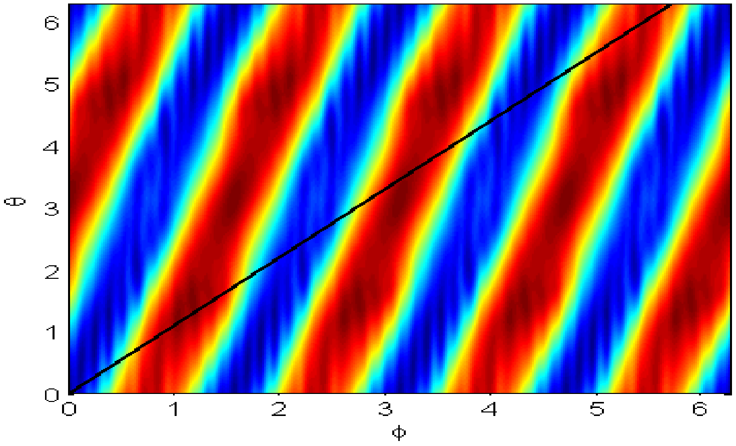
- The HSX stellarator
  - Quasi-symmetric optimization
  - Experimental setup: Langmuir probes
- Measurements of Reynolds stress
  - Gradient in time-averaged Reynolds stress profile implies relevant macroscopic flow drive
  - Region of measured flow drive corresponds to measured deviation in E_r from 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**

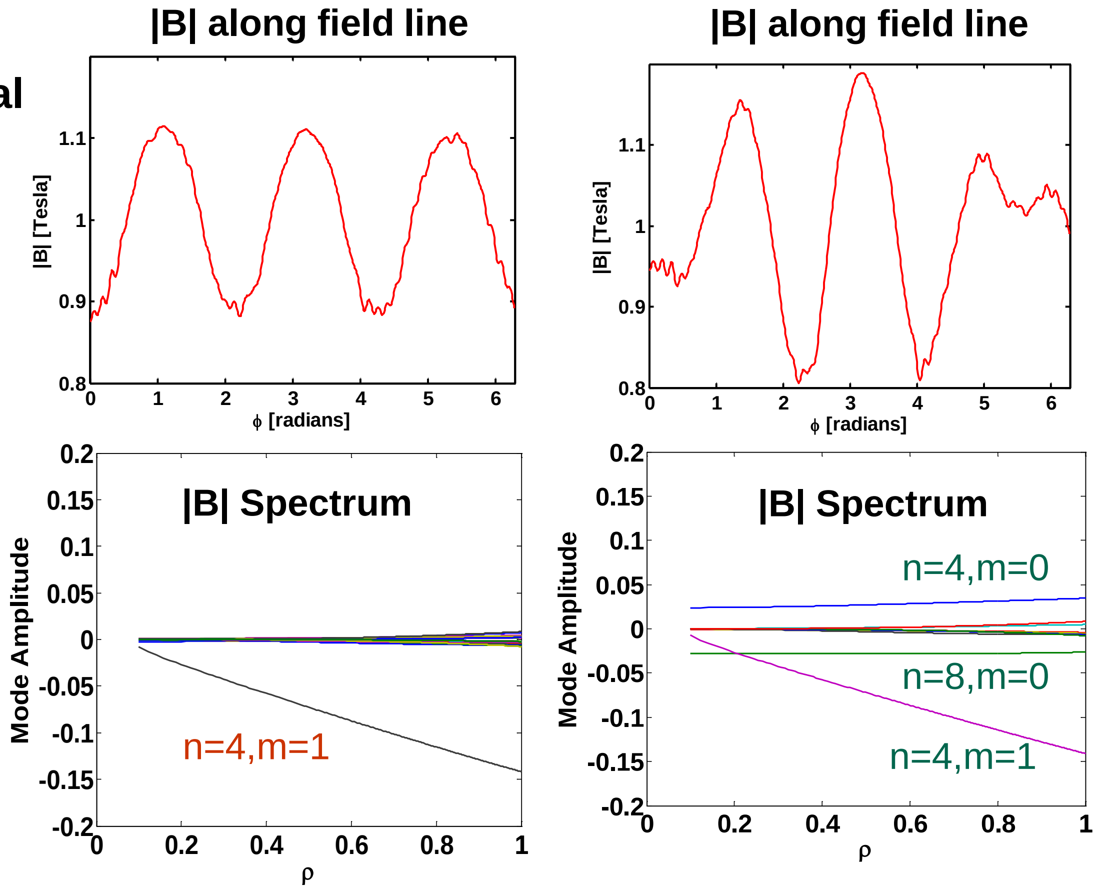
Tokamak: $B/B_0 = 1 - \varepsilon_t \cos \iota\phi$

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



QHS

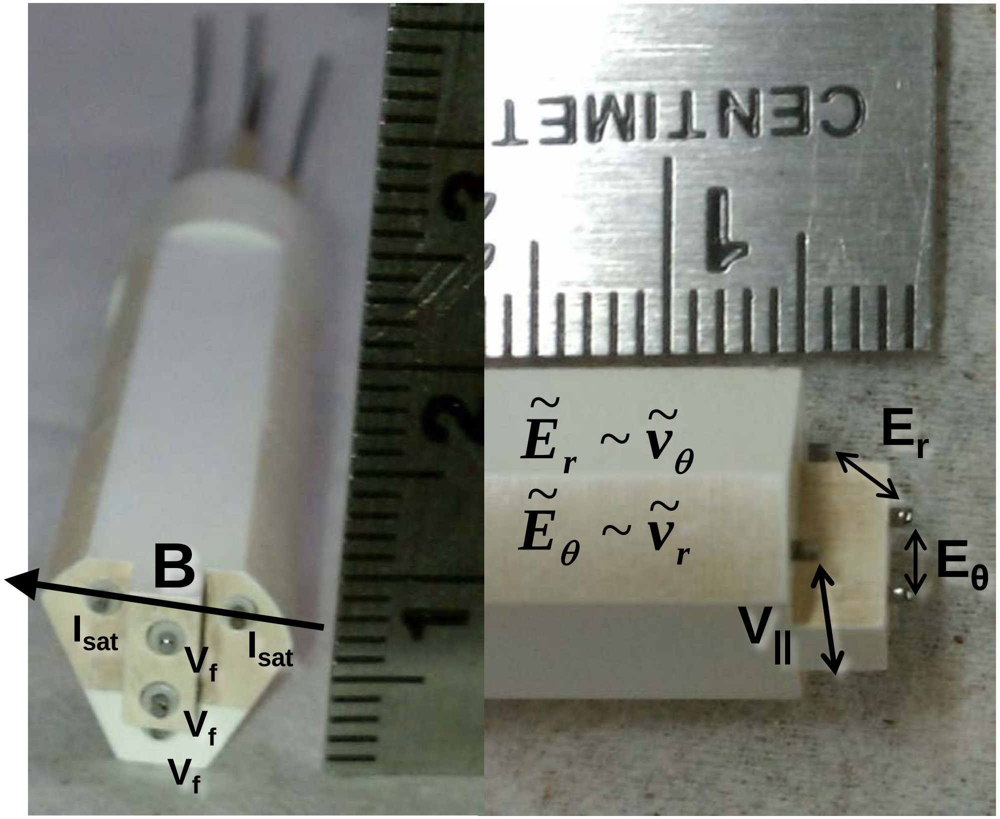
Mirror



Neoclassical transport can be varied with auxiliary coils

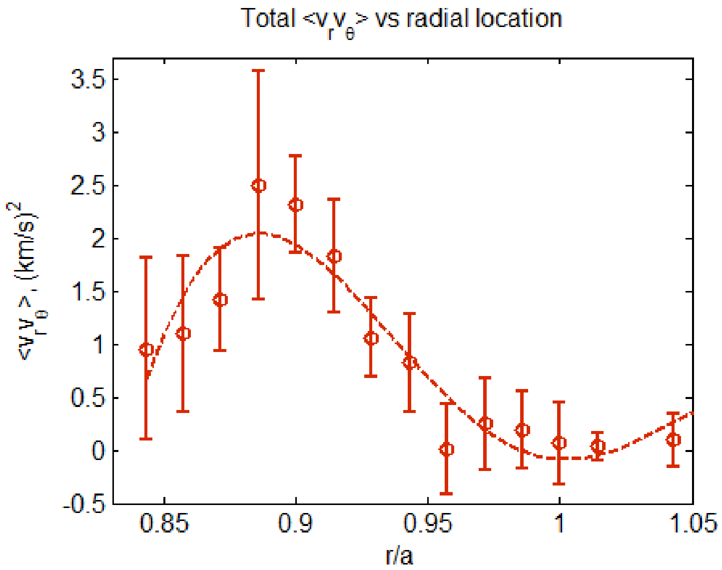
Langmuir probes installed to measure local fluctuating plasma parameters for Reynolds stress studies

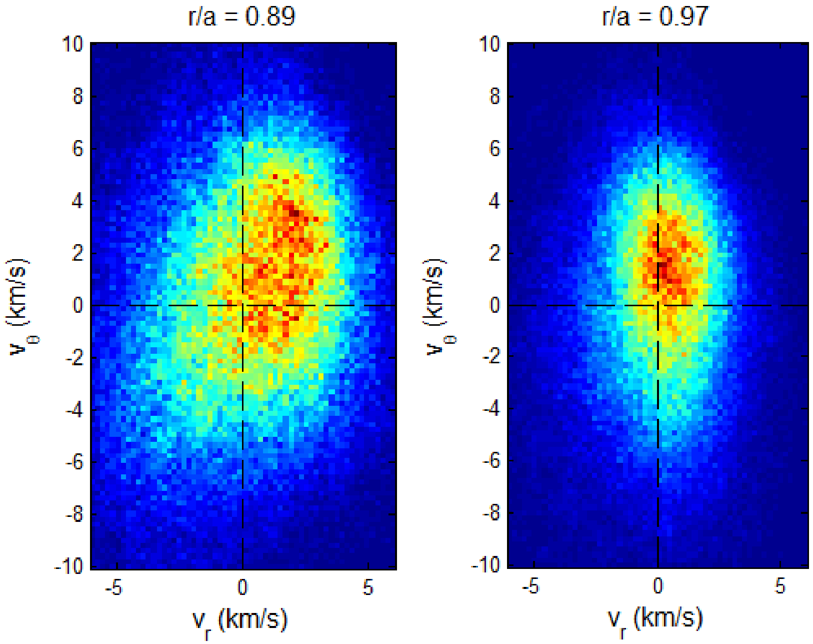
- Tungsten tips shielded by bulk BN, V_f and I_{sat} signals digitized at 5 MHz
- Radial profiles taken on a shot-by-shot basis
- Discharges are very repeatable: n_e consistent to within 1%, probe measurements consistent to within the noise
- For the data shown here, differential V_f fluctuations are 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**

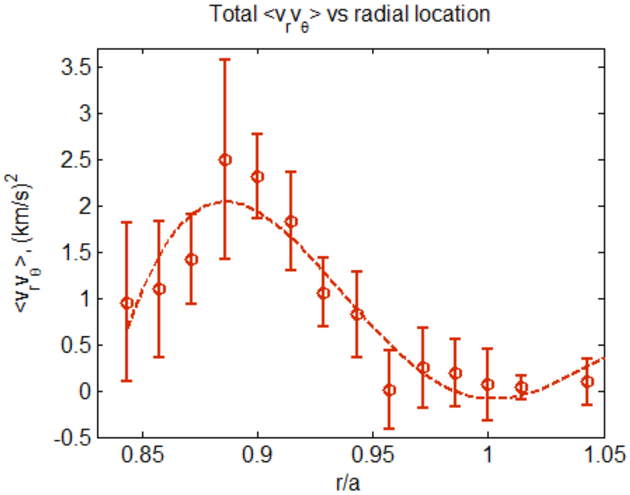
- **Measurement needs to be compared to some rough estimate of the poloidal viscosity to calculate resulting poloidal rotation and E_r**

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

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

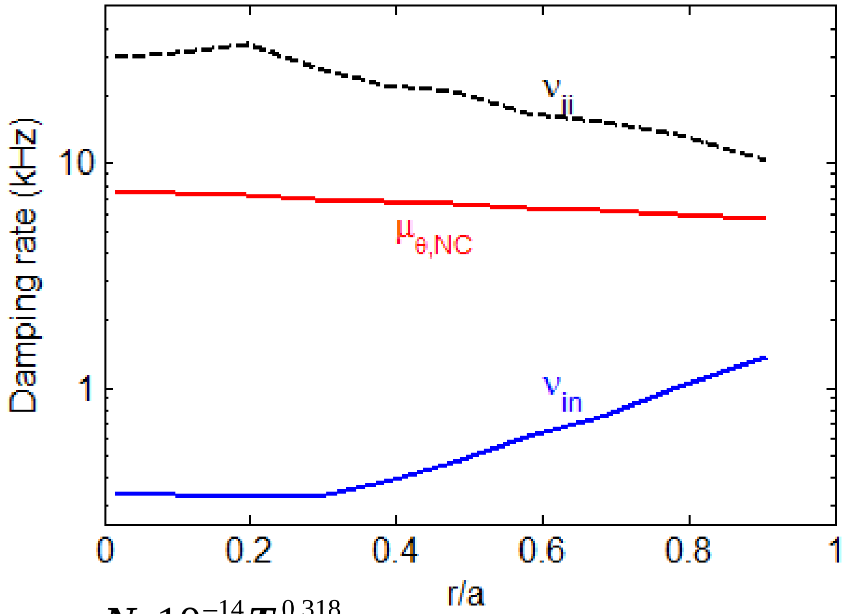
$$\langle v_\theta\rangle_{RS} = -\left(\frac{1}{\mu_\theta + \nu_{in}}\right)\frac{\partial}{\partial r}\left(\langle \tilde{v}_r \tilde{v}_\theta\rangle\right)$$

- **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**



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

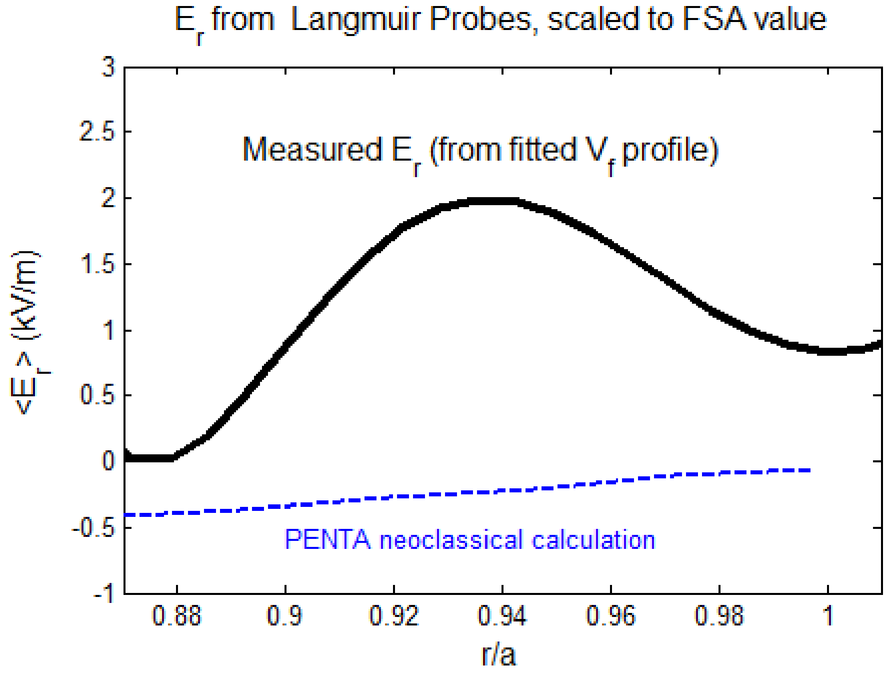
[M. Coronado and H. Wobig, *Phys. Fluids B 29* (1986) 527]

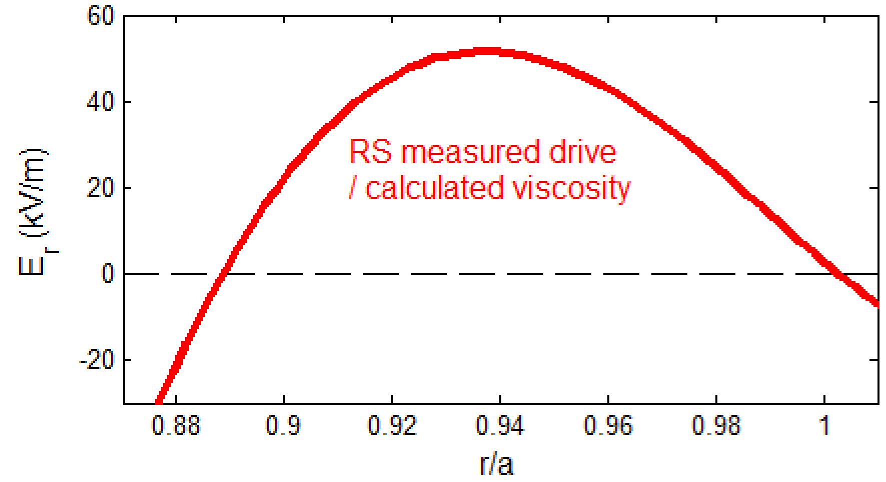


$$\upsilon_{in} \approx N_n 10^{-14} T_i^{0.318}$$

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

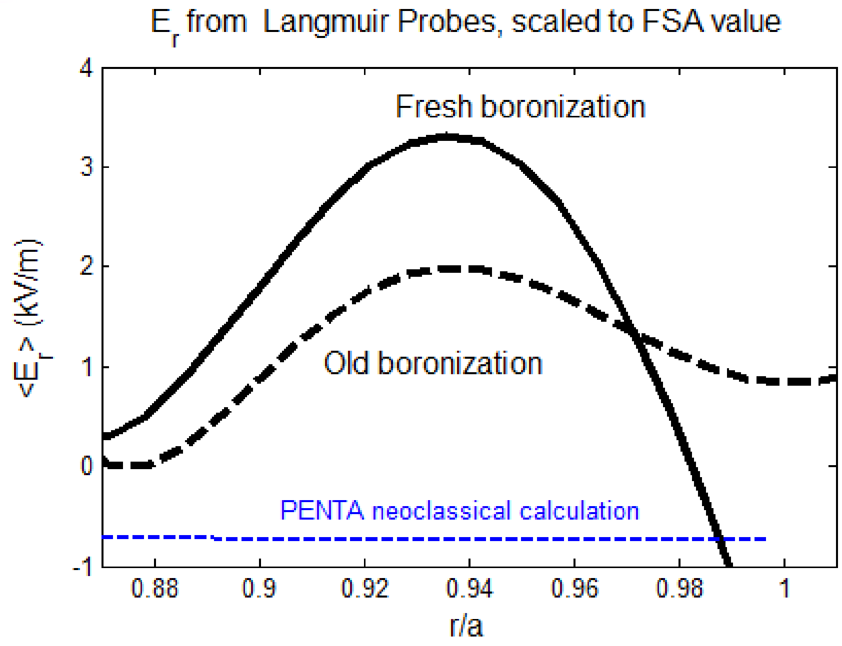
Measured Reynolds stress flow drive agrees qualitatively with deviation of E_r from neoclassical ambipolarity calculation



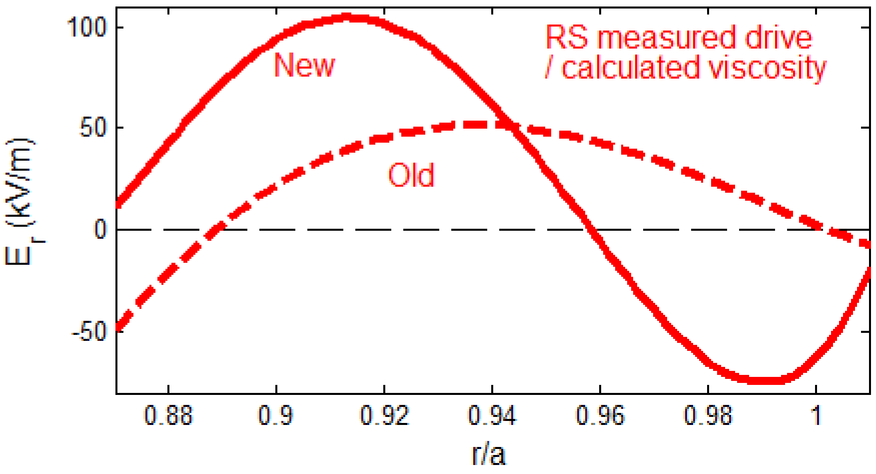


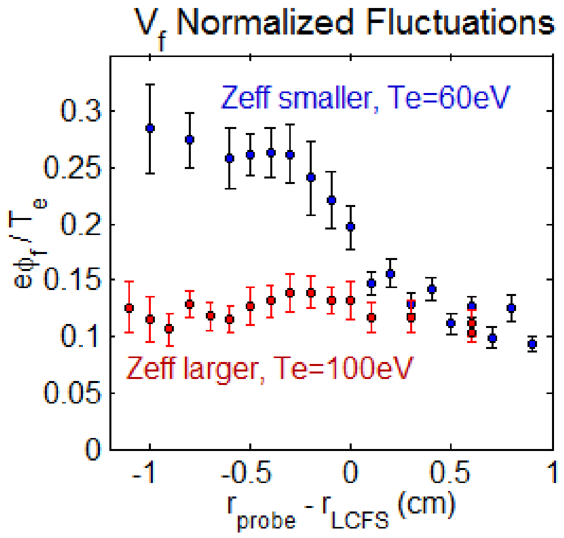
- **PENTA code calculates neoclassical ambipolarity condition based on non-ambipolar particle fluxes as a function of E_r**
  - **Neoclassical particle transport is small for optimized QHS configuration**
  - **More on PENTA calculations from A. Briesemeister tomorrow**
- **Unknown T_e gradient is ignored, 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



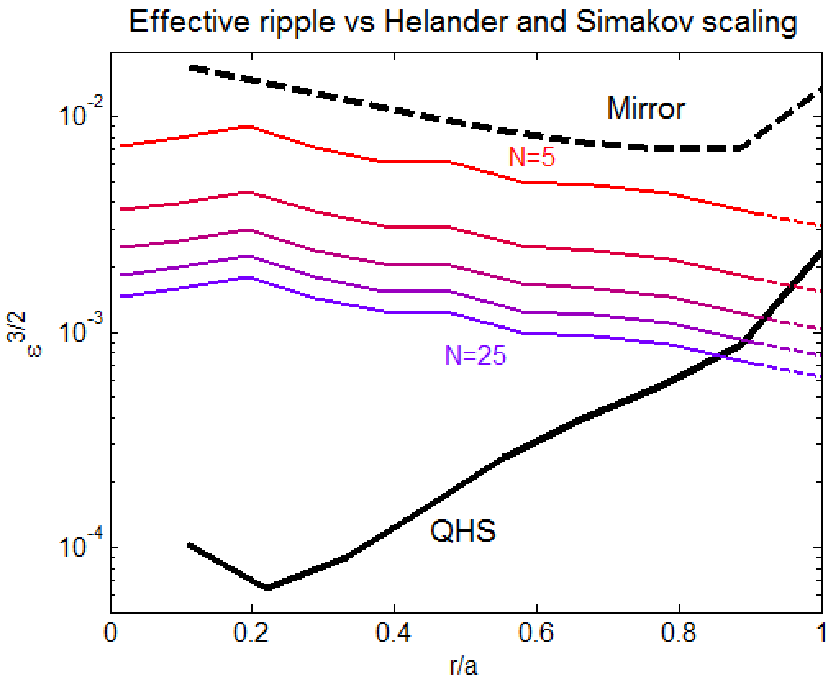


Helander and Simakov scaling finds that collisionless HSX should be free to rotate in core, constrained to neoclassical value at edge

- **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**

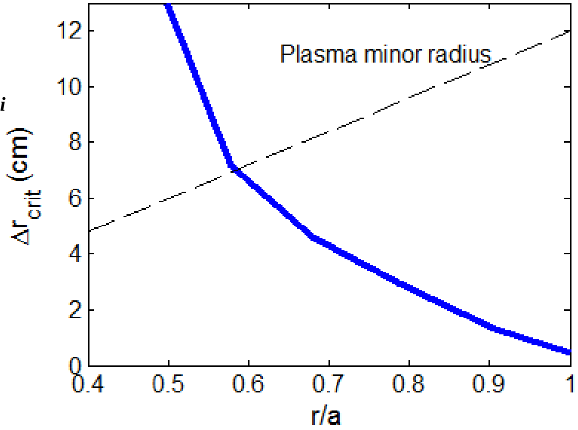
$$\varepsilon_h^{3/2} < \frac{L}{N\lambda_{MFP}}$$

- **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**



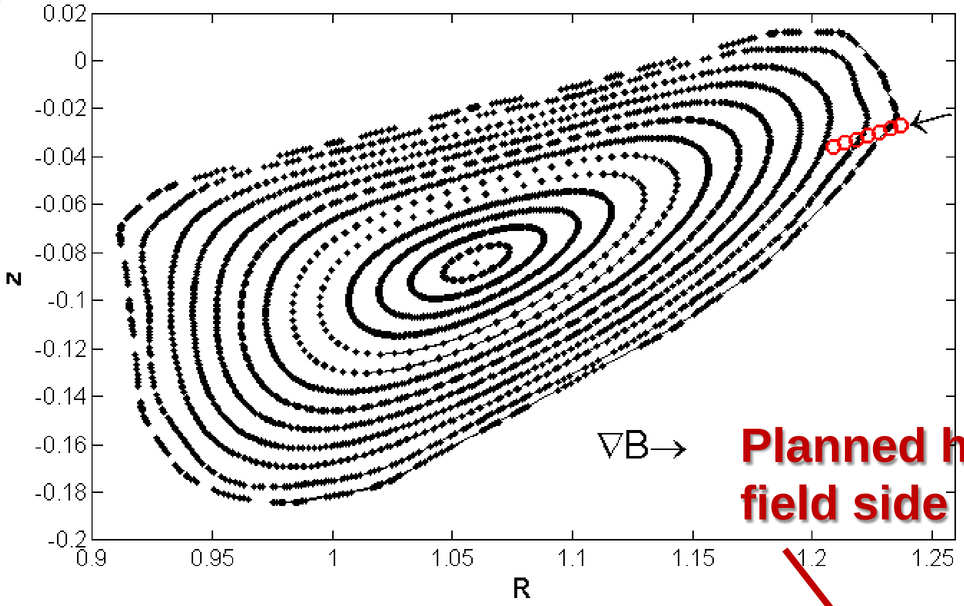
$$r_{crit} = N_{crit}\rho_i$$

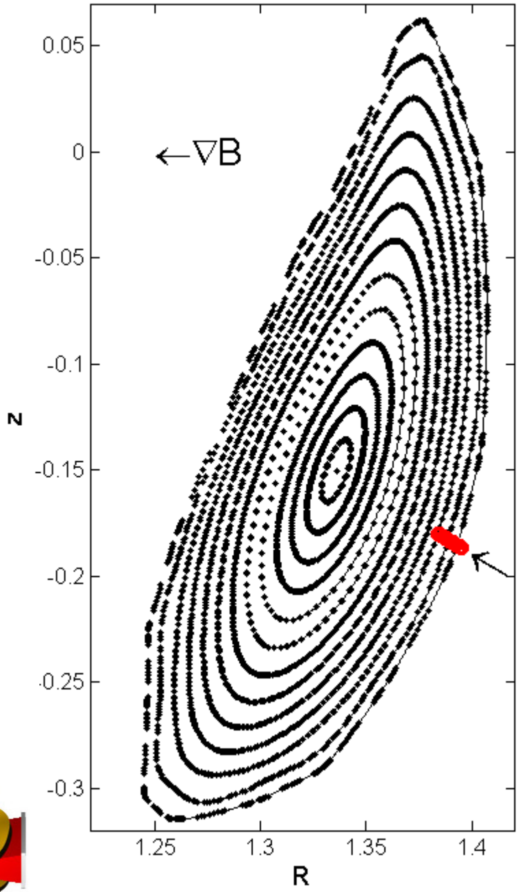
$$r_{crit} = \frac{L}{\varepsilon_h^{3/2}\lambda_{MFP}}\rho_i$$



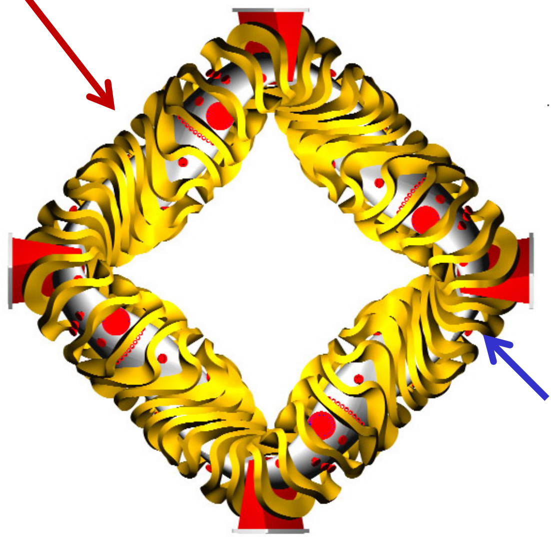
[P. Helander and A.N. Simakov, *Phys. Rev. Lett.* 101 (2008) 145003]

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





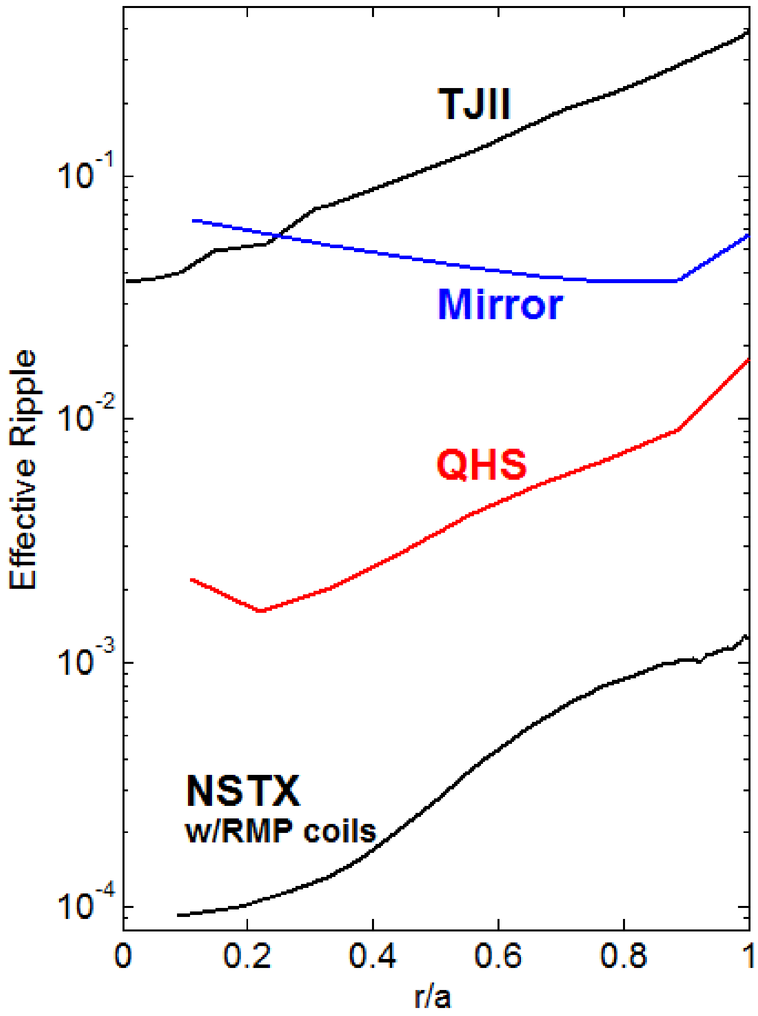
Planned high-field side probe



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



- 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

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

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