NSTX

Supported by

U.S. DEPARTMENT OF ENERGY | Office of Science

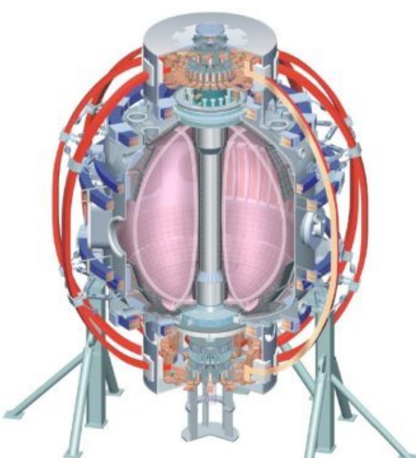
Measurements and gyrokinetic simulations of electron transport in NSTX

(and tokamak turbulence tutorial)

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Greg Hammett, J. Luc Peterson, Howard Yuh
PPPL, Princeton University, Nova Photonics
E. Mazzucato, R. Bell, J. Hosea, S. Kaye, B. LeBlanc, D. Mikkelsen, (PPPL), D. R. Smith (UW Madison), F. Levinton (Nova Photonics), C. W. Domier, N. C. Luhman, Jr., (UC Davis), W. Lee, H. K. Park (POSTECH), J. Candy, R. E. Waltz, E. A. Belli, G. M. Staebler (GA)
and the NSTX Research Team

Newton Institute, July 20, 2010



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Acknowledgements

Many slides and results from Luc Peterson, Howard Yuh, David Smith, & NSTX team.

H. Yuh, APS Invited Talk 08, PoP09, http://link.aip.org/link/PHPAEN/v16/i5/p056120/s1

(My talk has a theorist's view of NSTX results. I borrowed slides from NSTX team members, but this talk has not been reviewed by the NSTX team ☺ .)

SciDAC Center for the Study of Plasma Microturbulence

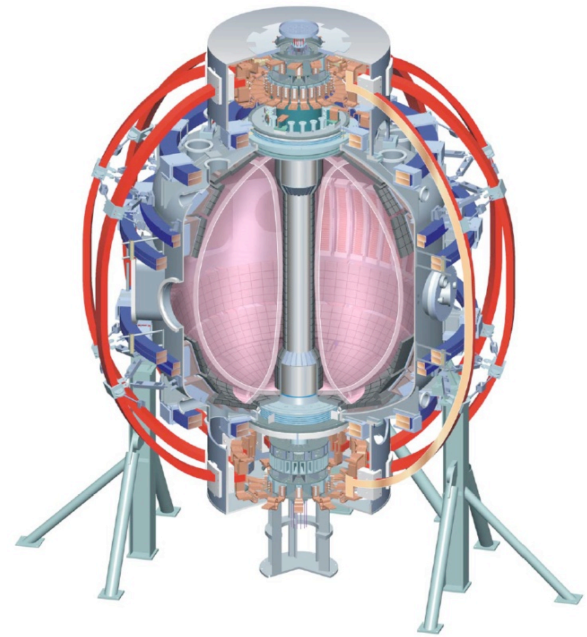
National Center for Computational Sciences at Oak Ridge National Laboratory, DOE DE-AC05-00OR22725

Princeton Plasma Physics Laboratory, Princeton University, DOE DE-AC02-09CH11466

Thanks to the workshop organizers and the Newton Institute.

Motivation to understand confinement

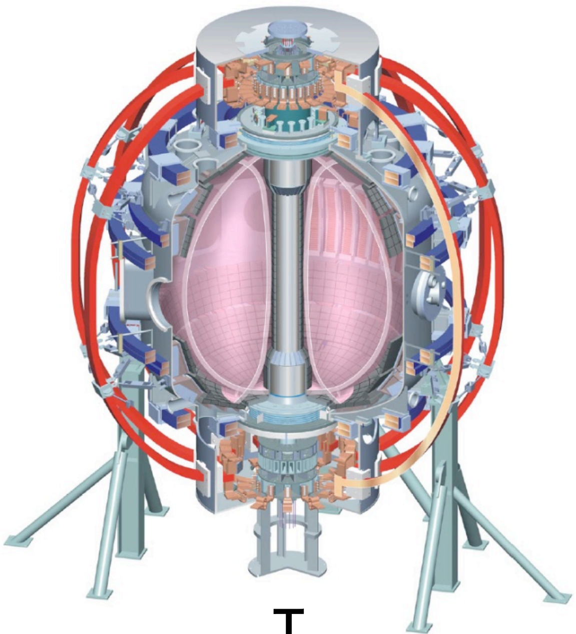
- NSTX is a high performance spherical torus that has achieved very high β
- Ion transport is typically neoclassical in H-modes

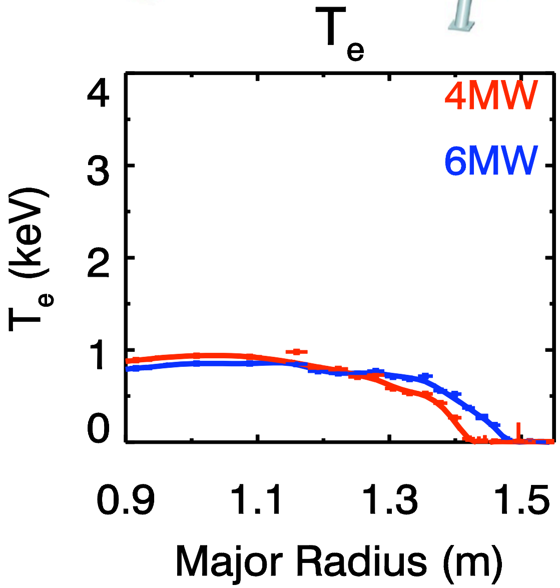


Major radius	0.85 m
Aspect ratio	1.3
Plasma current	1 MA
Toroidal field	0.55 T
Neutral Beams	6 MW
High Harmonic Fast Wave	3 MW
Elongation	2.7
Triangularity	0.8

Motivation to understand confinement

- NSTX is a high performance spherical torus that has achieved very high β
- Ion transport is typically neoclassical in H-modes
- Anomalous electron transport dominates heat loss
- ST fusion reactors must achieve improvements in core electron confinement
- NSTX is well equipped to study electron confinement

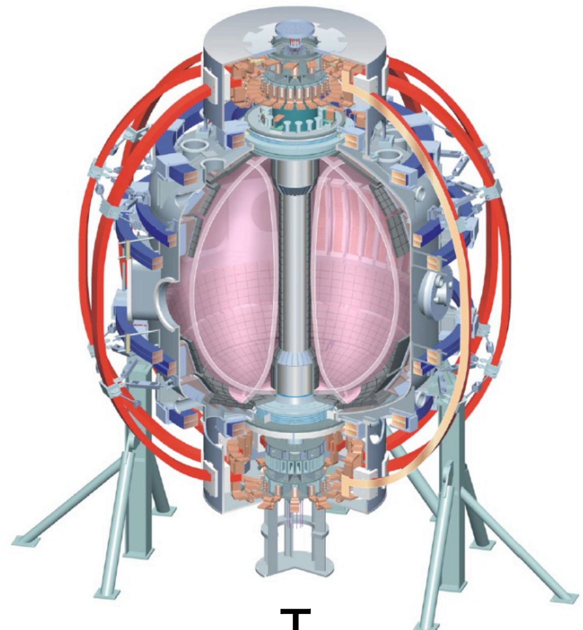


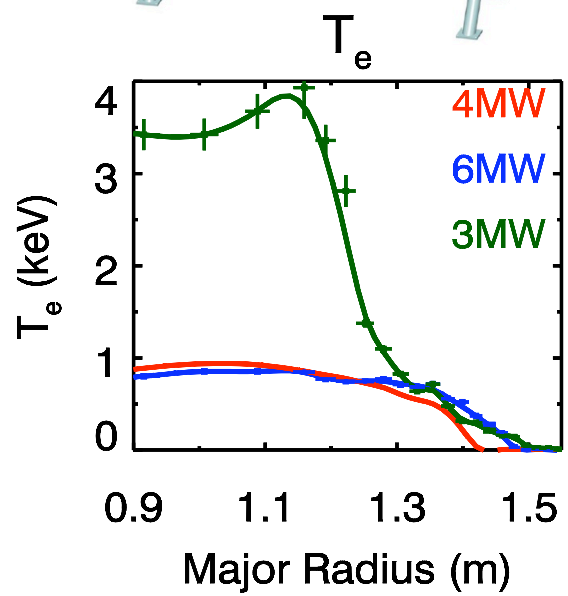


H. Yuh et al. APS Invited Talk 08

Motivation to understand confinement

- NSTX is a high performance spherical torus that has achieved very high β
- Ion transport is typically neoclassical in H-modes
- Anomalous electron transport dominates heat loss
- ST fusion reactors must achieve improvements in core electron confinement
- NSTX is well equipped to study electron confinement
- Internal Transport Barriers (ITBs) lead to dramatic improvements in core electron confinement





H. Yuh et al. APS Invited Talk 08

Summary

- Mini-tutorial on bad-curvature drive of tokamak instabilities
- Why negative magnetic shear is good
- Jenko & Dorland's surprising prediction of significant turbulence driven by Electron Temperature Gradient (ETG)
- Measurements of electron-gyro-scale fluctuations on NSTX and observations of internal transport barriers with negative magnetic shear consistent with ETG expectations. (supports Jenko & Dorland prediction)
- Initial nonlinear GYRO simulations, working toward detailed comparisons with microwave scattering measurements
- Multiple electron transport processes may be important and are being investigated: ETG, TEM (Trapped-Electron Mode), Micro-tearing (Wong PRL07), GAE (high frequency Global Alfven Eigenmode) (Stutman PRL 09). Focus on ETG here.

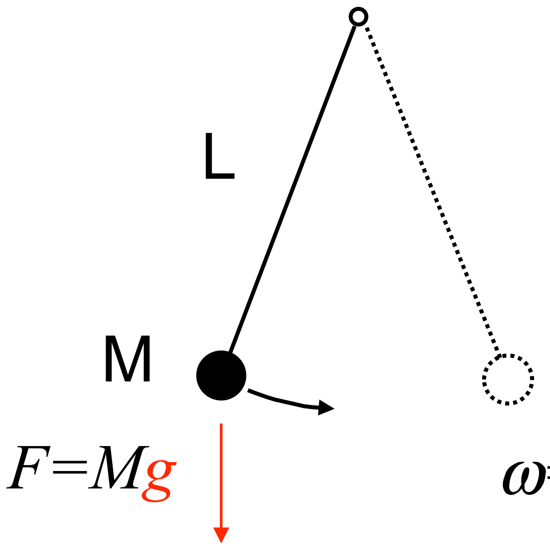
Initial Nonlinear ETG Turbulence Simulations:

- Simulating NSTX electron turbulence is challenging.
- Goal: detailed GYRO simualtions w/ synthetic diagnostic comparisons with high-k microwave scattering measurements
- Global simulations show ETG-driven turbulence in this RF-only discharge:
  - **E**x**B** shearing has little effect (unlike case in Smith et al PRL 2009).
  - Collisions have little effect (unlike case in Roach et al PPCF 2009).
  - Magnetic perturbations have small effect.
  - ETG can account for half of measured heat flux.
- Reversed magnetic shear appears to control turbulence.
- Transport predictions indicate long wavelength (TEM) turbulence may be important.

1. Intuitive pictures of gyrokinetic turbulence, & how to reduce it

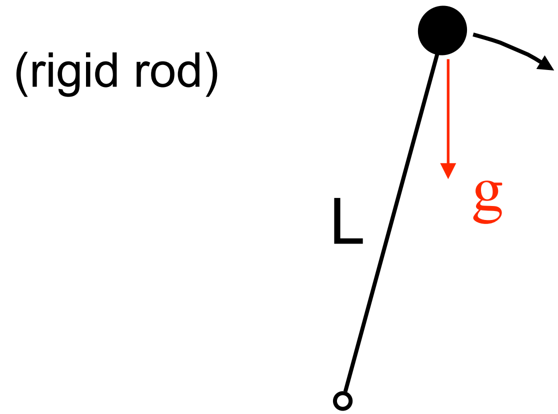
(many of these insights developed with gyrofluid simulations in 1990’s, but gyrokinetics needed for better accuracy.)

Stable Pendulum



$\omega=(g/L)^{1/2}$

Unstable Inverted Pendulum

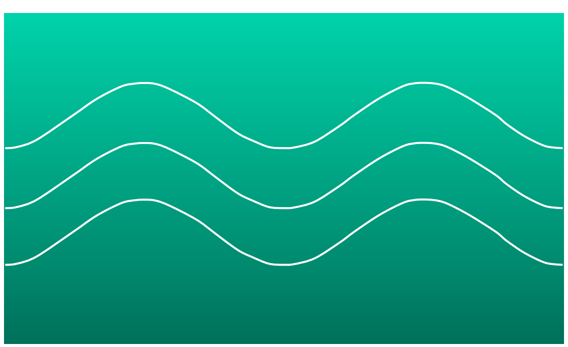


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

$\rho=exp(-y/L)$

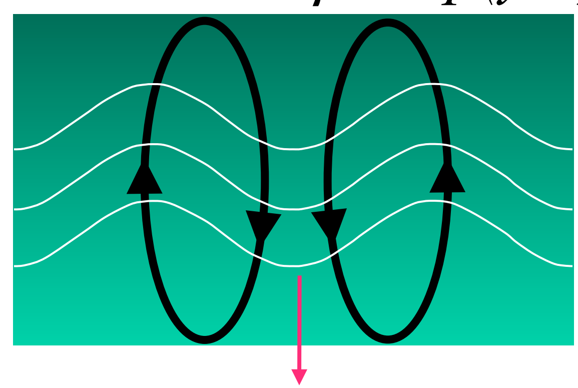


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

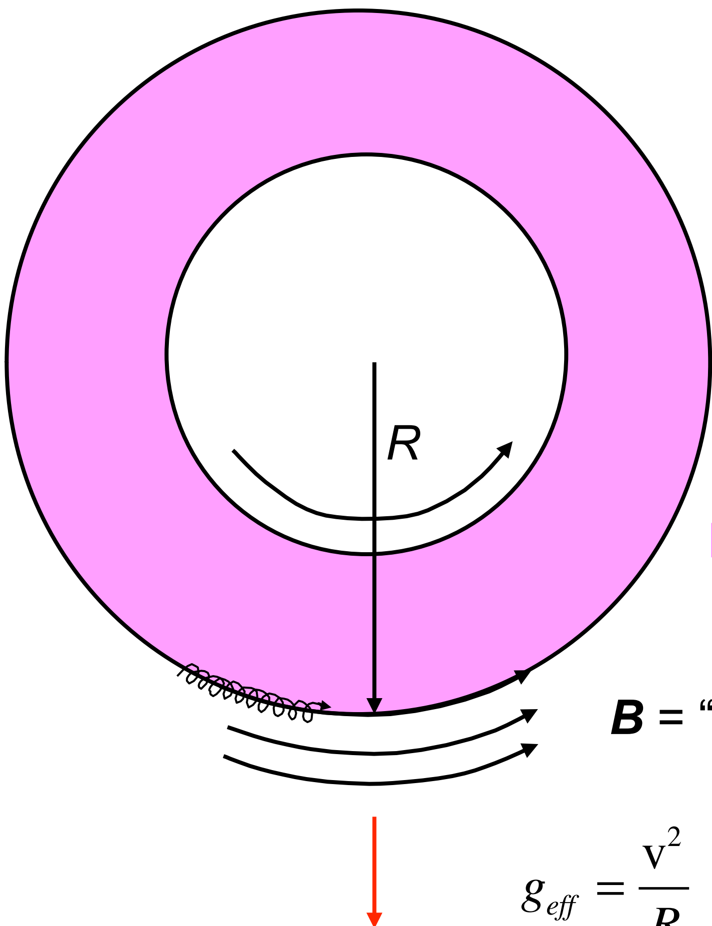
$\rho=exp(y/L)$



Max growth rate $\gamma=(g/L)^{1/2}$

“Bad Curvature” instability in plasmas
⇒ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



plasma = heavy fluid

B = “light fluid”

$$g_{eff} = \frac{\mathrm{v}^2}{R}$$ centrifugal force

Growth rate:

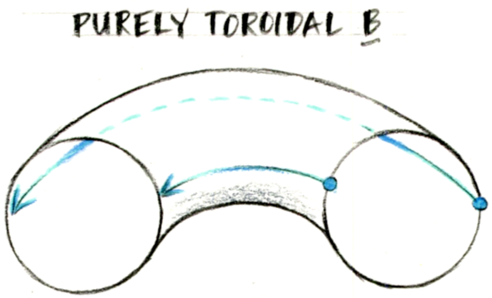
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{\mathrm{v}_t^2}{RL}} = \frac{\mathrm{v}_t}{\sqrt{RL}}$$

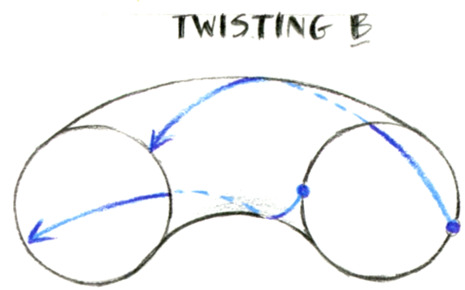
Similar instability mechanism
in MHD & drift/microinstabilities

1/L = ∇p/p in MHD,
∝ combination of ∇n & ∇T
in drift-wave/microinstabilities.

The Secret for Stabilizing Bad-Curvature Instabilities

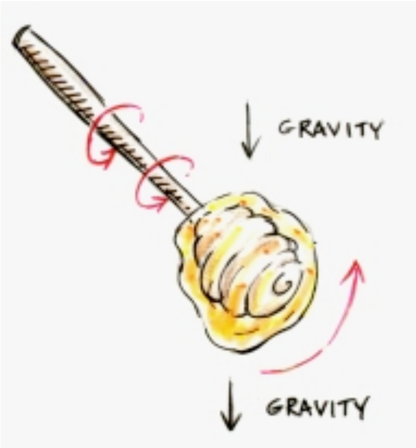
Twist in ***B*** carries plasma from bad curvature region to good curvature region:





Unstable

Stable

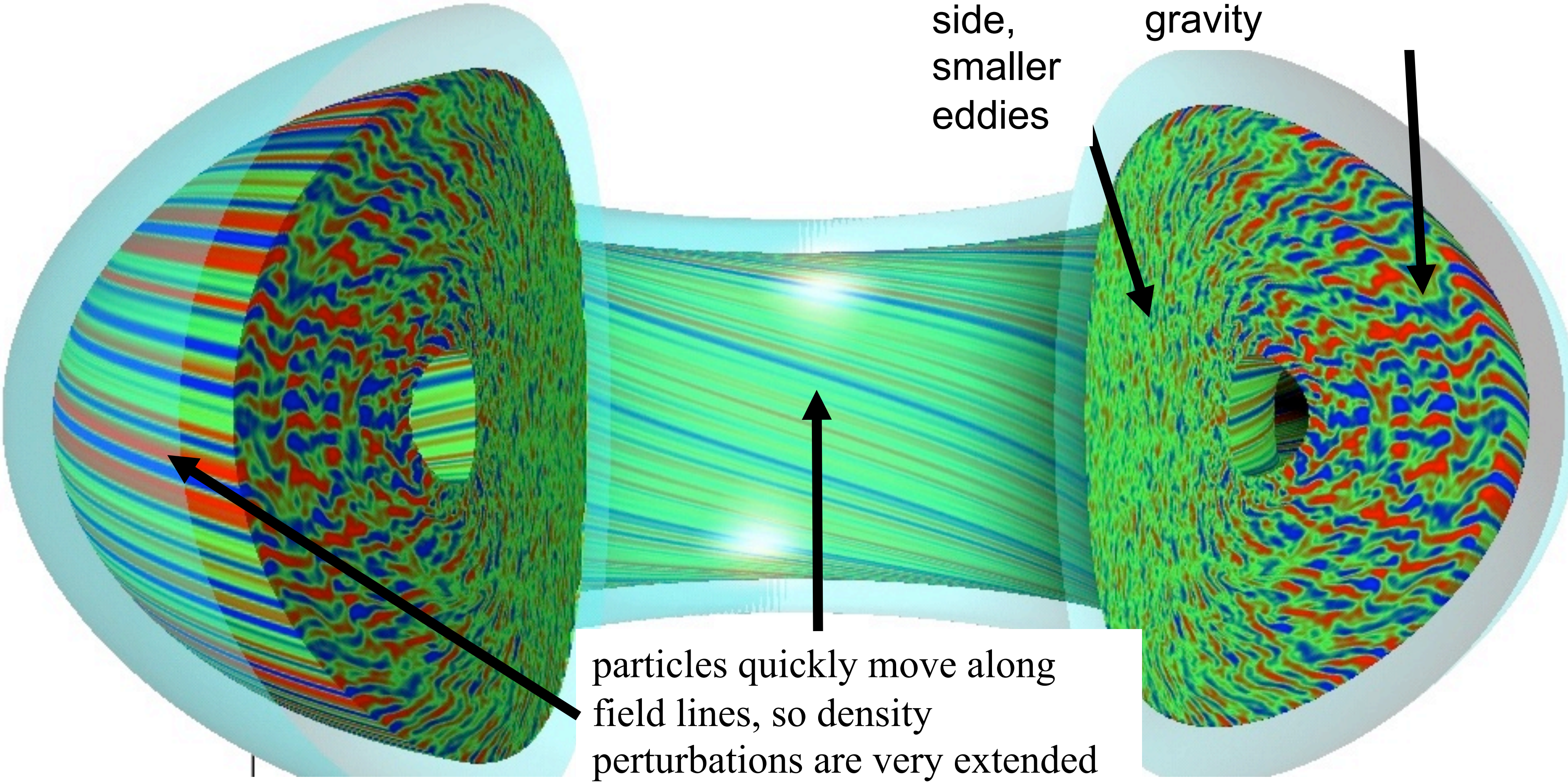


Similar to how twirling a honey dipper can prevent honey from dripping.

These physical mechanisms can be seen in gyrokinetic simulations and movies

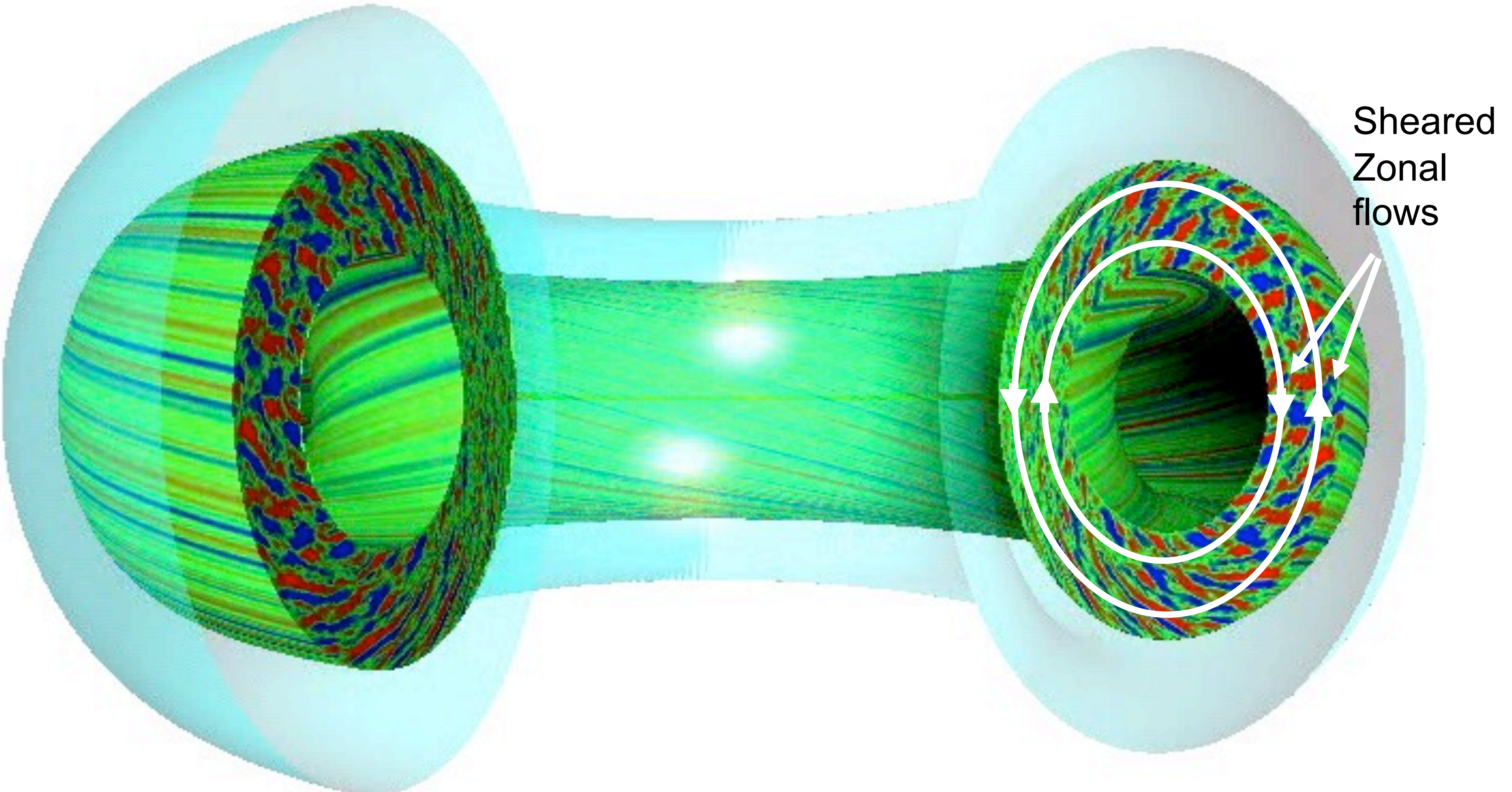
Stable side, smaller eddies

Unstable bad-curvature side, eddies point out, direction of effective gravity



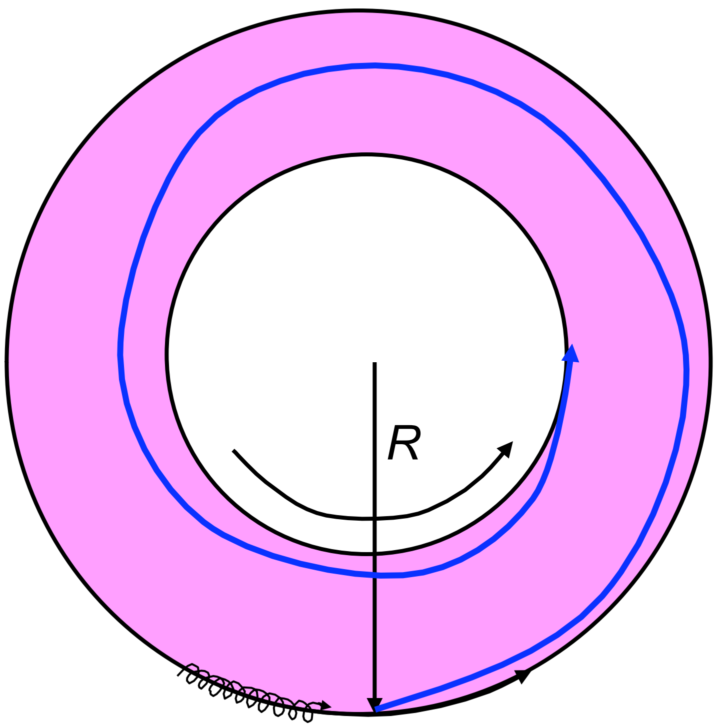
particles quickly move along field lines, so density perturbations are very extended along fields lines, which twist to connect unstable to stable side

Movie http://fusion.gat.com/THEORY/images/3/35/D3d.n16.2x_0.6_fly.mpg from http://fusion.gat.com/theory/Gyromovies shows contour plots of density fluctuations in a cut-away view of a GYRO simulation (Candy & Waltz, GA). This movie illustrates the physical mechanisms described in the last few slides. It also illustrates the important effect of sheared flows in breaking up and limiting the turbulent eddies. Long-wavelength equilibrium sheared flows in this case are driven primarily by external toroidal beam injection. (The movie is made in the frame of reference rotating with the plasma in the middle of the simulation. Barber pole effect makes the dominantly-toroidal rotation appear poloidal..) Short-wavelength,



"Bad Curvature" instability in plasmas
⇒ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



Parallel connection length
to good curvature side
$L_{||} = 2\pi qR$

Growth rate:

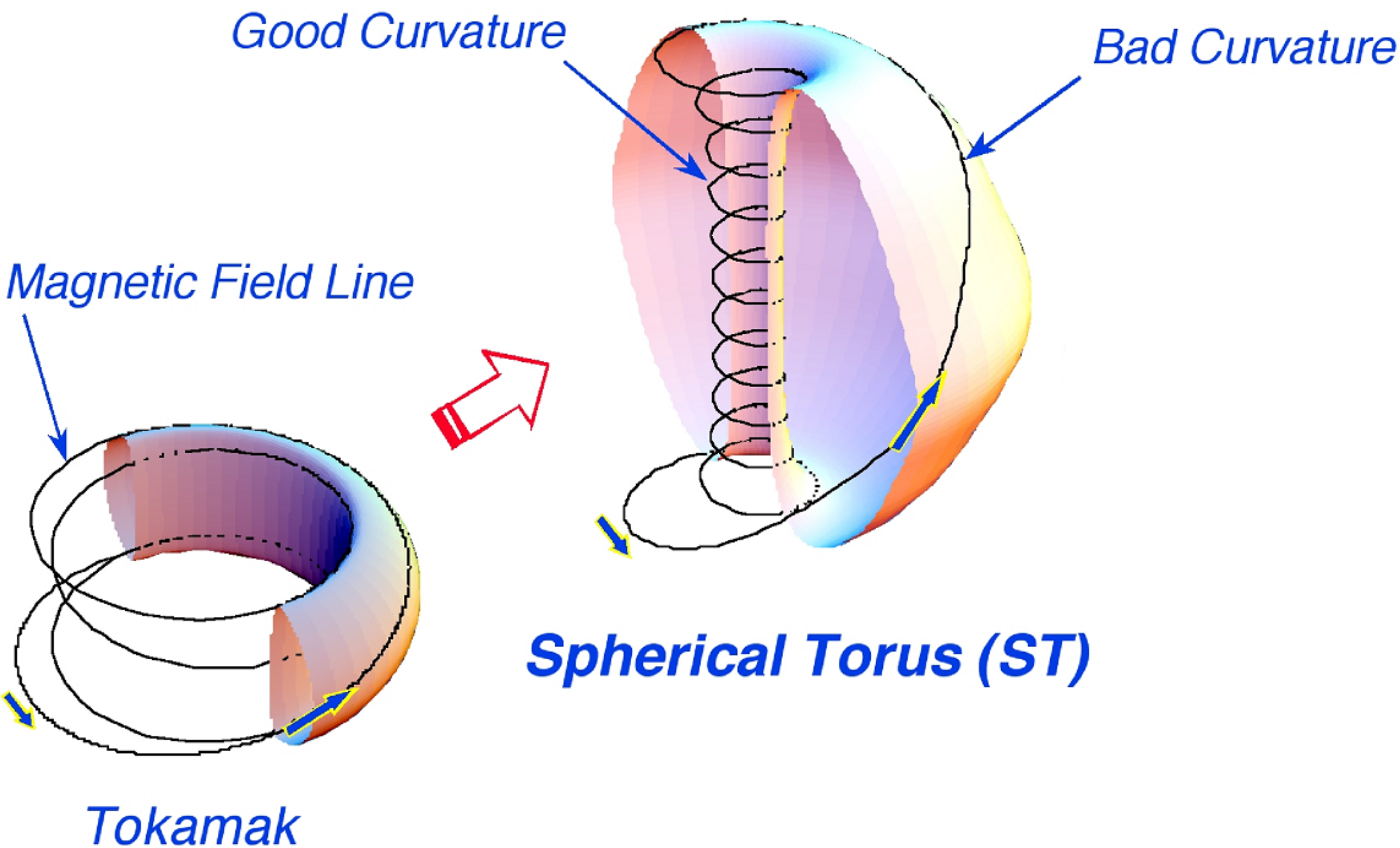
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{V_t^2}{RL}} = \frac{V_t}{\sqrt{RL}}$$

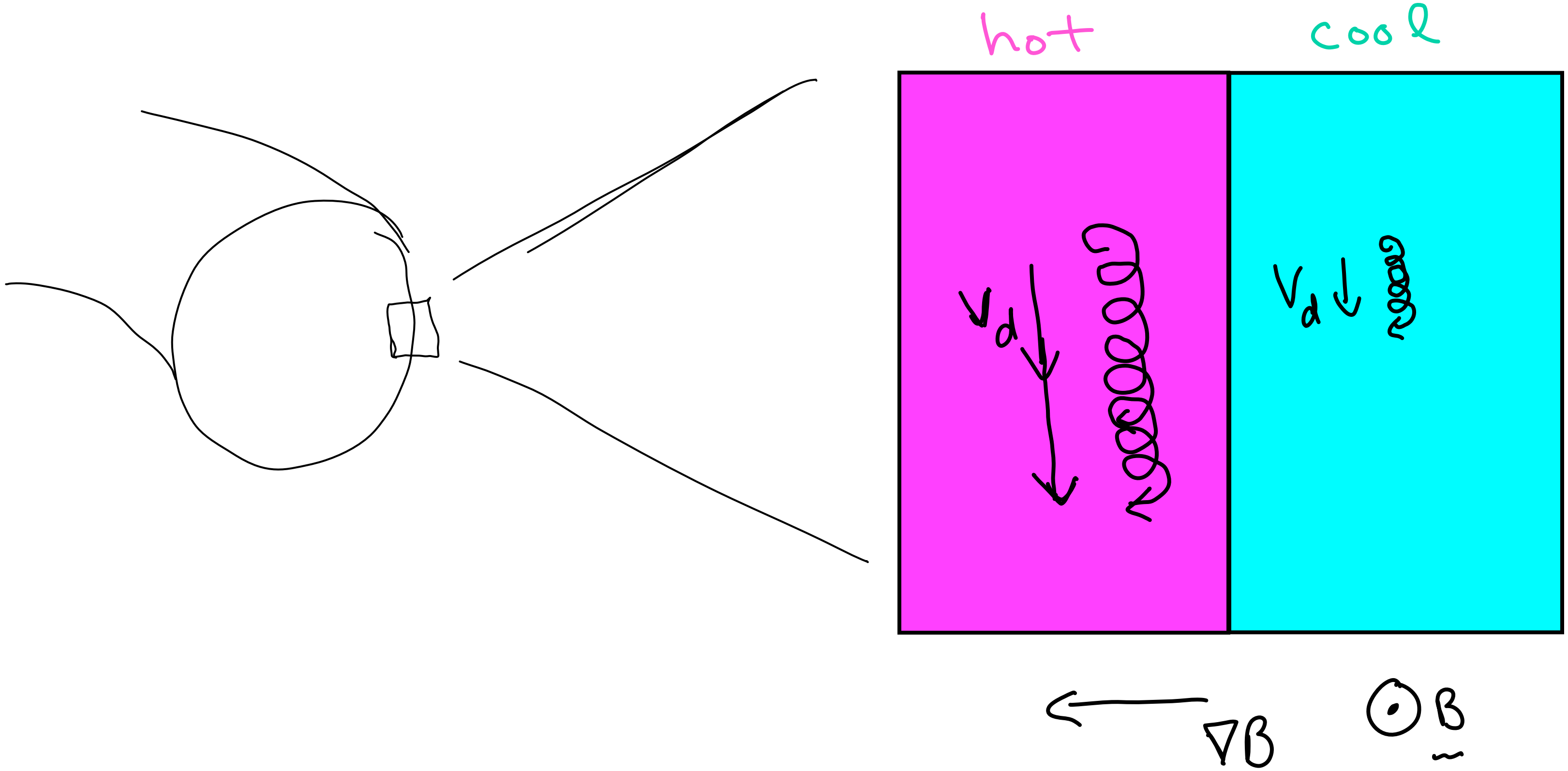
Similar instability mechanism
in MHD & drift/microinstabilities

$1/L = \nabla p/p$ in MHD,
$\propto$ combination of ∇n & ∇T
in drift-wave/microinstabilities.

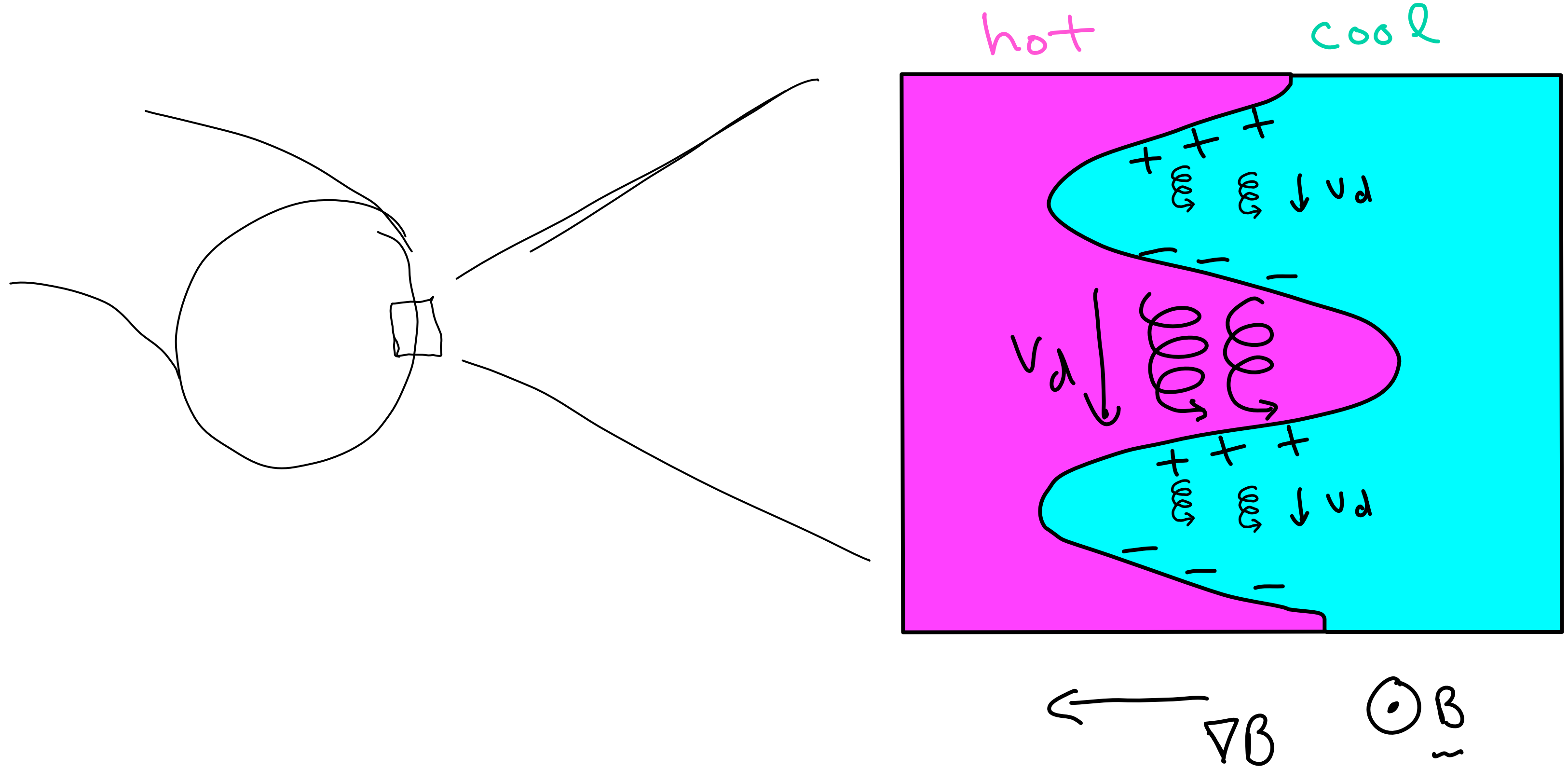
Local growth rate > Alfven rate
to good curvature ~ $v_A / L_{||}$
→MHD ballooning $\alpha = R\, q^2\, d\beta/dr$

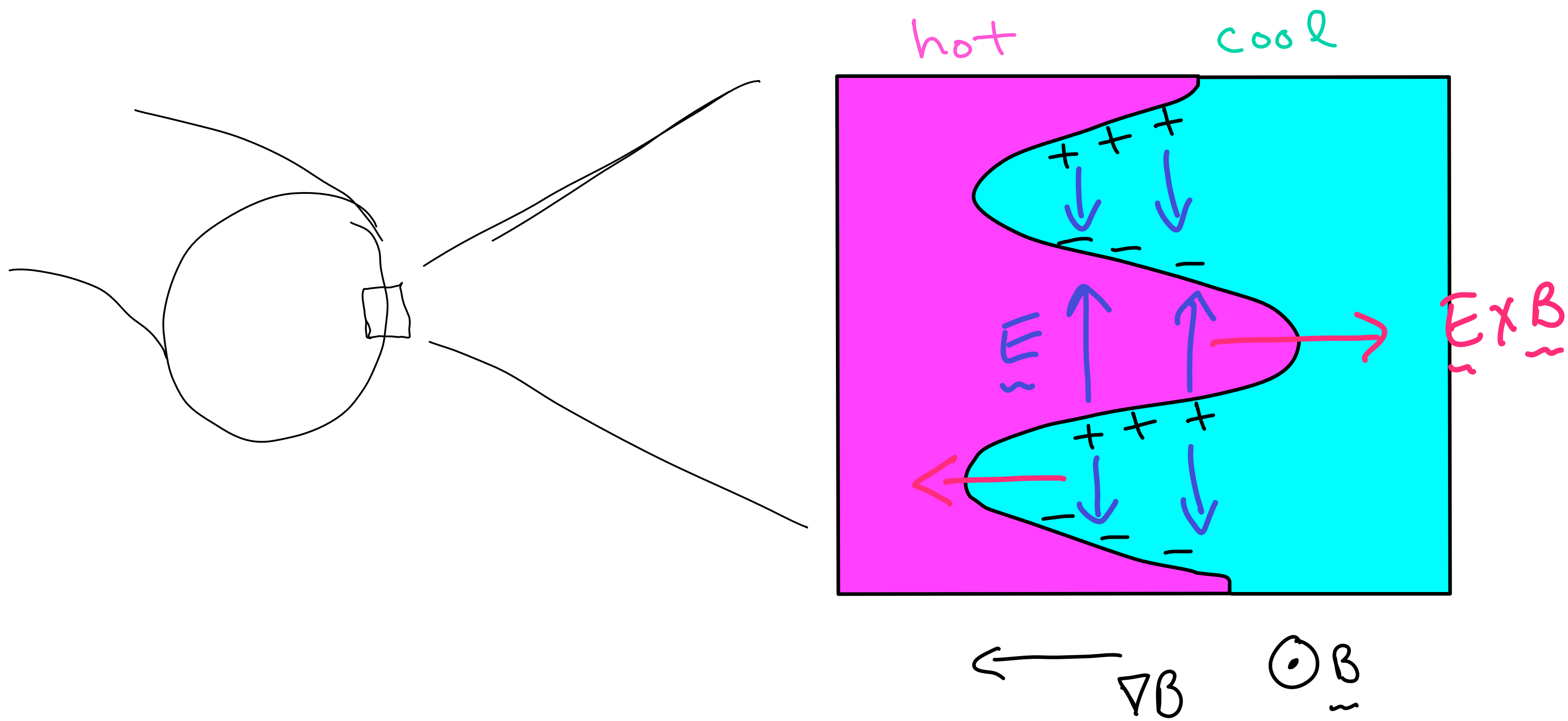
Spherical Torus has improved confinement and pressure limits (but less room in center for coils)





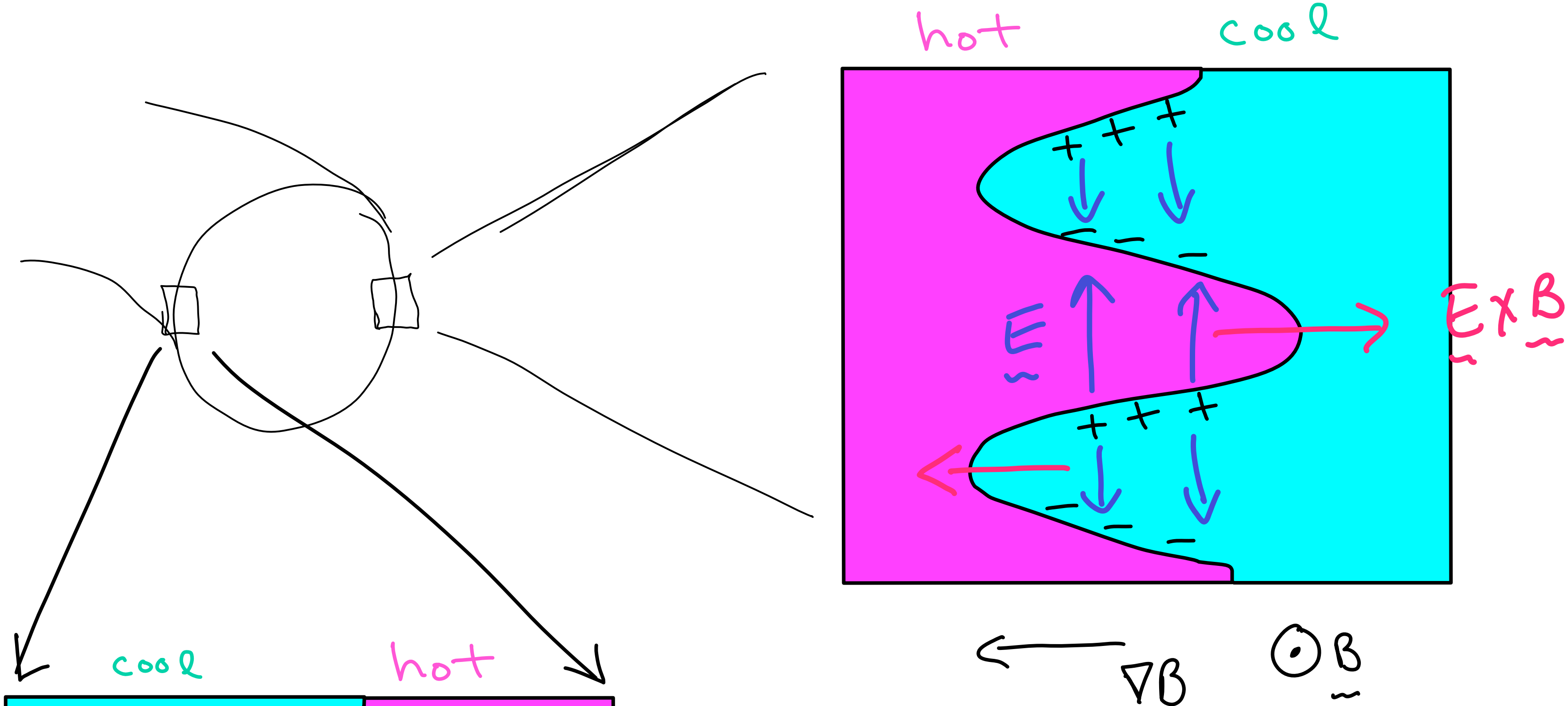
hot
cool
V_d
V_d
∇B
$\underset{\sim}{B}$


hot
cool
v_d
v_d
v_d
+ + +
− − −
∇B
$\odot \underset{\sim}{B}$



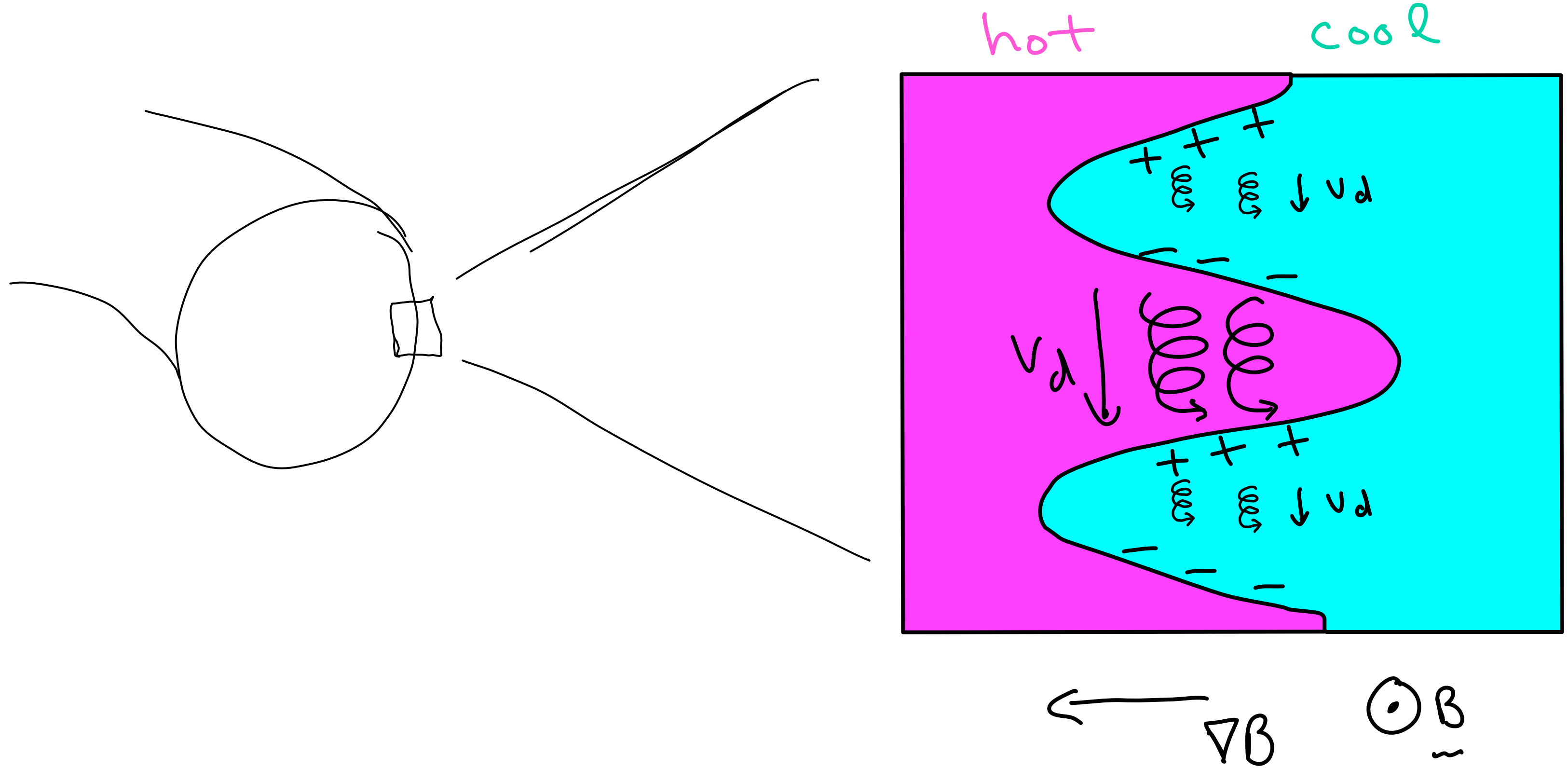
Higher energy particles ∇B drift faster, creates charge separation & thus E field, causes E×B flow that further accentuates perturbation. Positive feedback ⇒ instability.

Rosenbluth-Longmire picture



Can repeat this analysis on the good curvature side & find it is stable. (Leave as exercise.)

Rosenbluth-Longmire picture



Even if MHD stable, can drive drift waves ("microinstabilities") at small scales by including FLR effects (electron pressure) in Ohm's law, which allow plasma to slip through magnetic field

$$\gamma_{local} \sim (k_y \rho)\, v_t / (R\, L)^{1/2}$$

Including Landau-damping / phase-mixing from perpendicular drifts:

$$\gamma_{net} \sim \gamma_{local} - C\, k_y\, v_{drift}$$

Gives instability if R/L > O(1)

Simple picture of reducing turbulence by negative magnetic shear

Particles that produce an eddy tend to follow field lines.

Reversed magnetic shear twists eddy in a short distance to point in the ``good curvature direction''.

Locally reversed magnetic shear naturally produced by squeezing magnetic fields at high plasma pressure: ``Second stability'' Advanced Tokamak or Spherical Torus.

Shaping plasma (elongation and triangularity) can change local shear

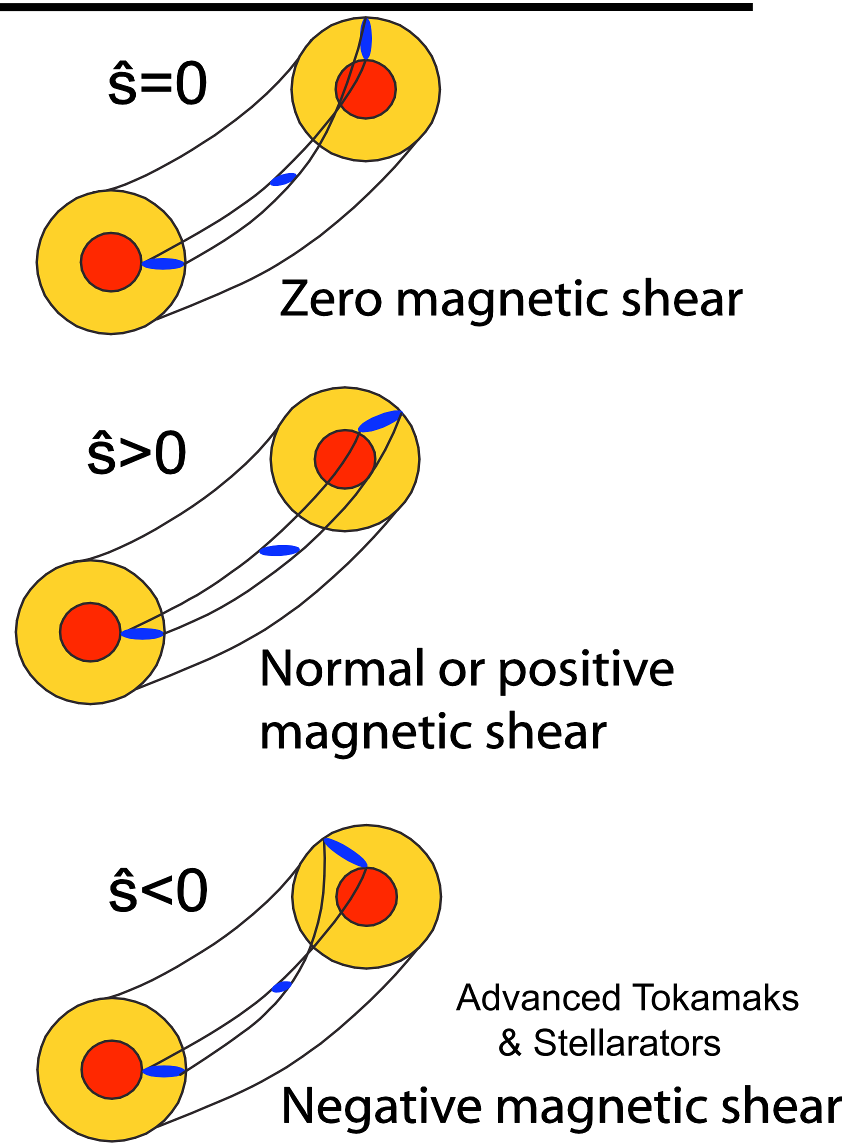
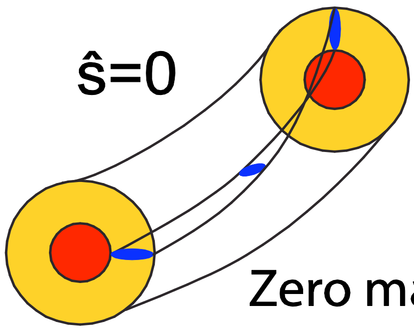


Fig. from Antonsen, Drake, Guzdar et al. Phys. Plasmas 96
Kessel, Manickam, Rewoldt, Tang Phys. Rev. Lett. 94

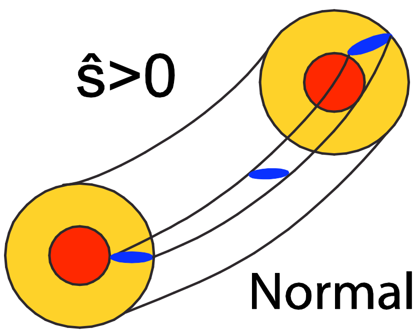
Negative magnetic shear twists radial eddies away from curvature drive

$\hat{s}=0$



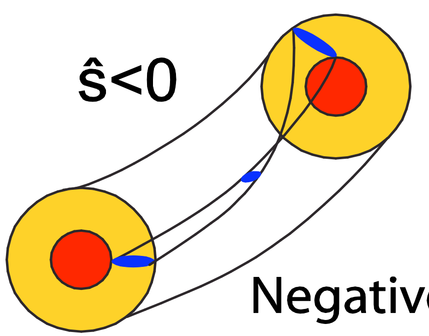
Zero magnetic shear

$\hat{s}>0$



Normal or positive magnetic shear

$\hat{s}<0$

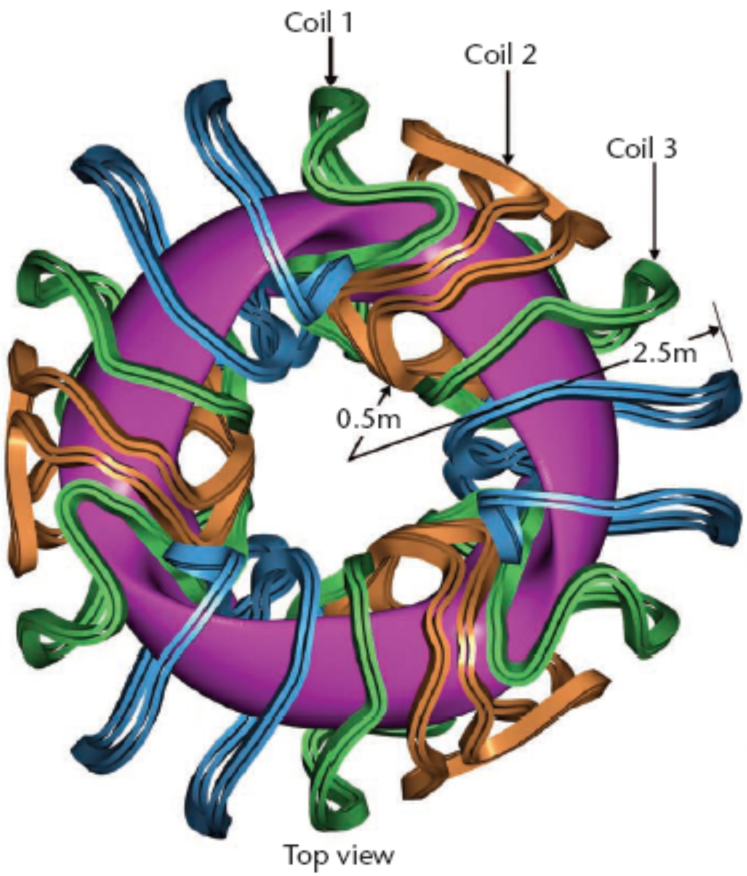


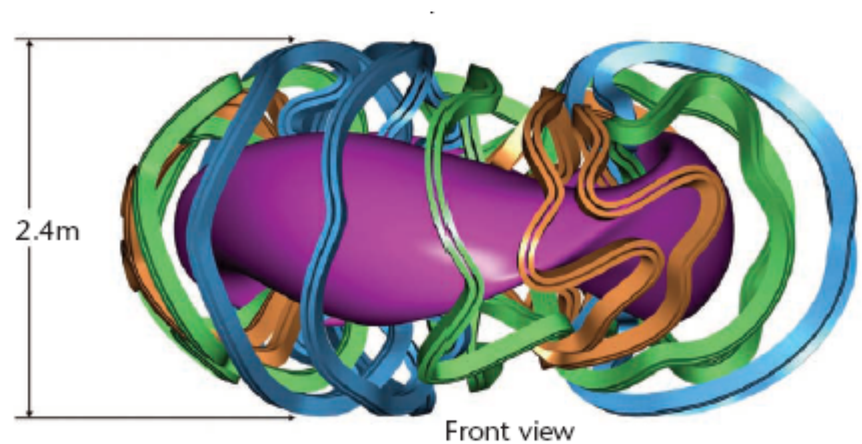
Negative magnetic shear

- $\hat{s}=r/q\ (dq/dr)$
- Antonsen [PoP **3**,2221,(1996)] showed pictorially how negative magnetic shear stabilizes ballooning type modes and simulation results showing the breaking up of radially extended streamer structures
- Negative shear rotates radially extended streamers such that they are no longer aligned with the curvature drive

Improved Stellarators Being Studied

- Naturally has stabilizing effect of negative magnetic shear.
- Magnetic field twist and shear provided by external coils, not plasma currents. More stable?
- Computer optimized designs much better than 1950-60 slide rules?
- Quasi-toroidal symmetry allows plasma to spin toroidally: shear flow stabilization as good as a tokamak?





National Compact Stellarator eXpt. (NCSX)

Jenko & Dorland found ETG turbulence >> ITG turbulence (in Gyro-Bohm units)

Conventional wisdom had been
$\chi_e / \chi_{gyroBohm,e} \sim \chi_i / \chi_{gyroBohm,i}$

Which would cause
$\chi_e << \chi_i$

$$\chi_{\text{gyroBohm}} \approx \frac{\text{v}_t}{\text{L}} \rho^2$$
$$\approx \frac{cT}{eB} \frac{\rho}{L}$$

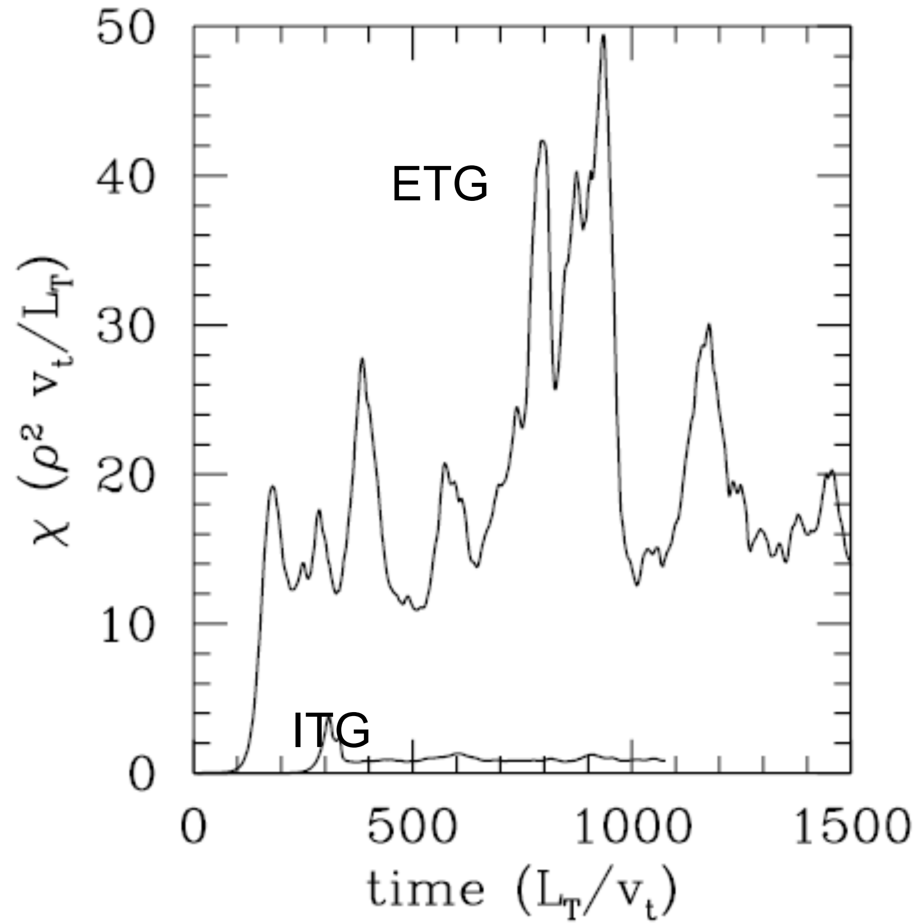


FIG. 1. χ_e^{ETG} (upper curve) and χ_i^{ITG} (lower curve) for similar parameters.

(Dorland & Jenko 2000, see also Jenko & Dorland 2002: with larger box, Lx=512 ρ, report C_e = 13)

ETG eddies are radially extended streamers

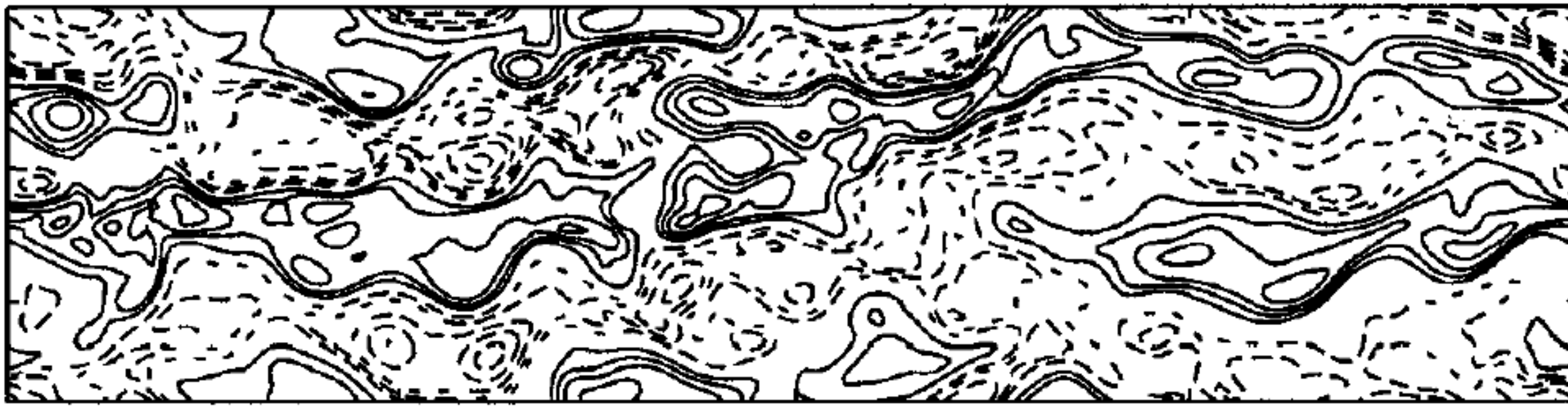


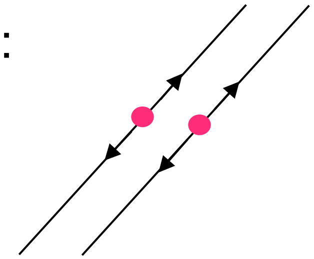
FIG. 2. Characteristic ϕ contours in the outboard x-y plane. This snapshot was taken at the end of the ETG run shown in Fig. 1. The figure is $256\rho_e \times 64\rho_e$.

High ETG transport relative to ITG transport theoretically understood as due to difference in adiabatic response for ions vs. electrons ==> reduces ETG zonal flows ==> ETG streamers get to higher velocity and are more elongated. (Rogers & Dorland, Jenko & Dorland 2000, 2002, etc.)

(Jenko & Dorland 2000)

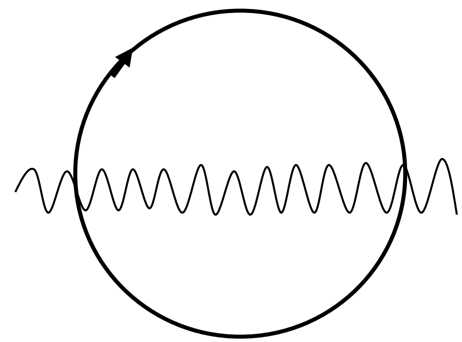
Key ITG/ETG Difference: different adiabatic response to zonal flows

ITG turbulence, adiabatic electron response:



electrons ***don't*** respond to zonal flows ($k_{||}$=0, pure E_r).
since electrons are adiabatic because $k_{||}v_{te}$ >> w

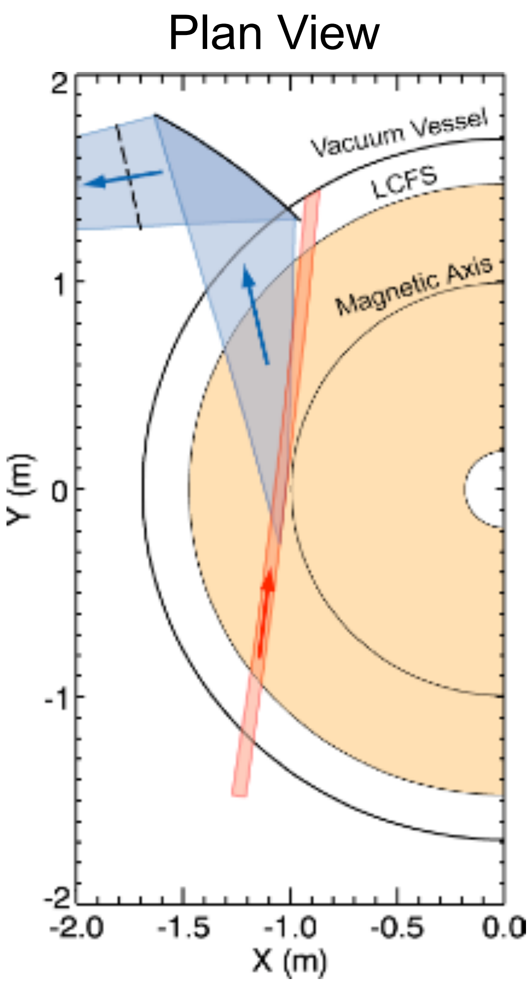
ETG turbulence, adiabatic ion response:

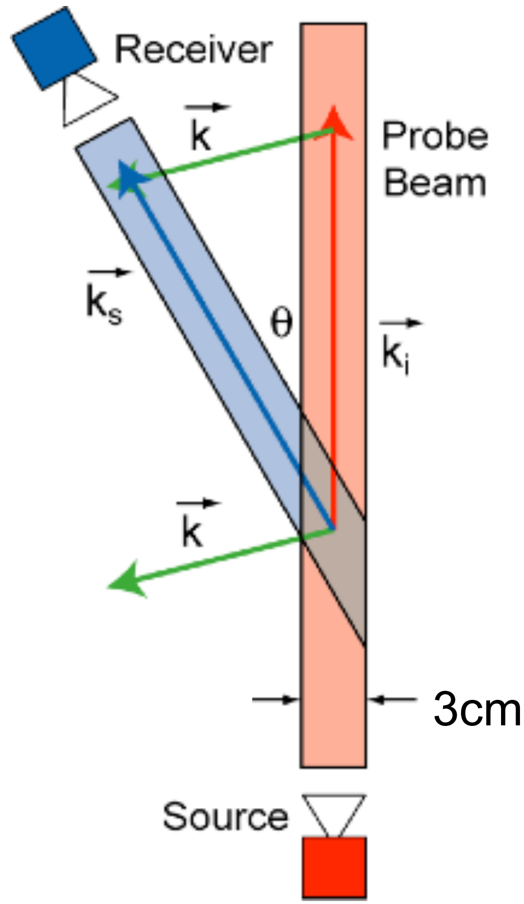


Ions do shield zonal flows for ETG
Since ions are adiabiatic because $k_\perp \rho_i >> 1$.
↓ zonal flows --> streamers elongate --> transport ↑

Detailed secondary/tertiary instability analysis includes this, explains ITG/ETG saturation level differences, scalings (Rogers, Dorland, Jenko papers)

High-k microwave scattering diagnostic measures n_e fluctuations at electron scale wavenumbers

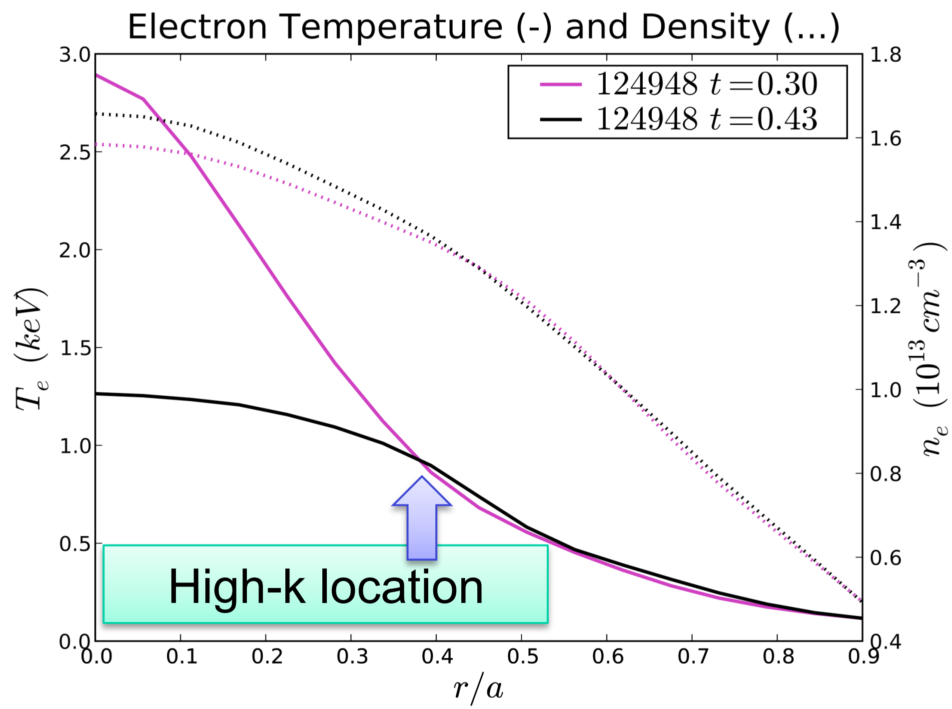


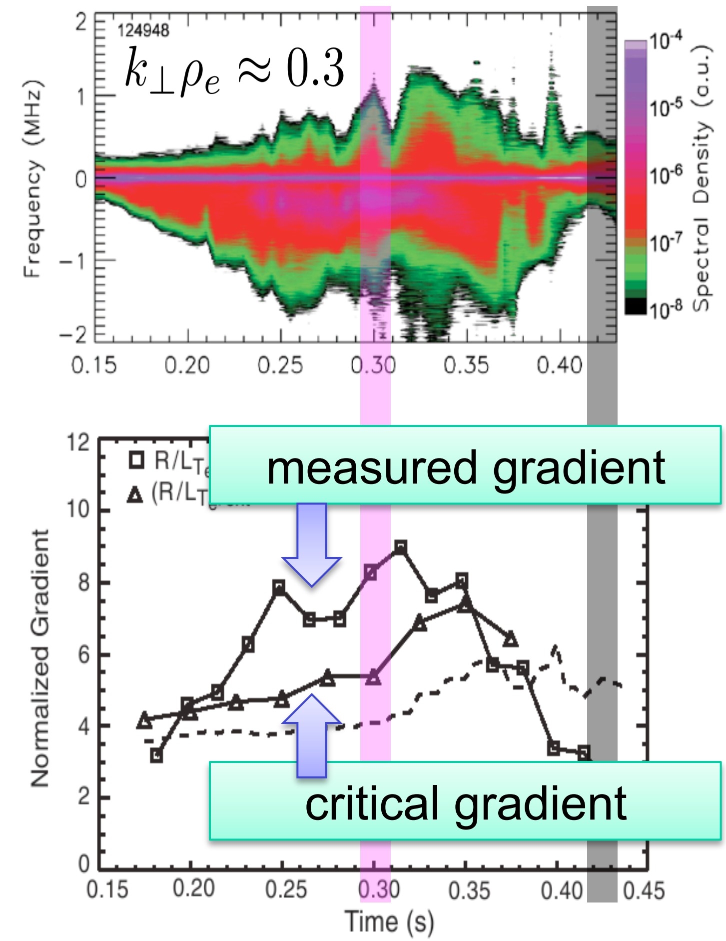


- $k_\perp \rho_e \leq 0.6$ can be measured
- Multiple detection channels can measure fluctuations at multiples k values simultaneously
- Localized scattering volume, radial resolution ~3cm

Mazzucato 08, D.R. Smith 09 PRLs

Electron-scale fluctuations in NSTX appear when linearly unstable to ETG

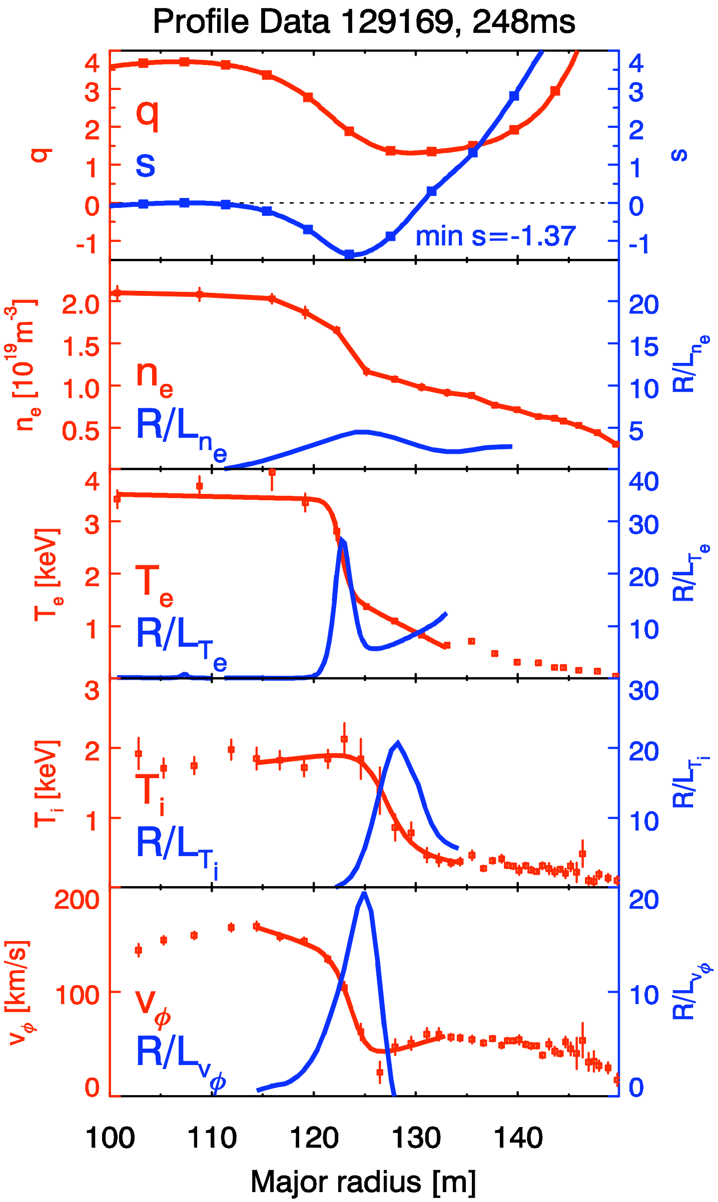




$$\left(\frac{a}{L_{T_e}}\right)_{crit} (t = 0.3\ s) \approx 3.3$$

Mazzucato et al PRL (2008)

Internal transport barriers form when magnetic shear is negative

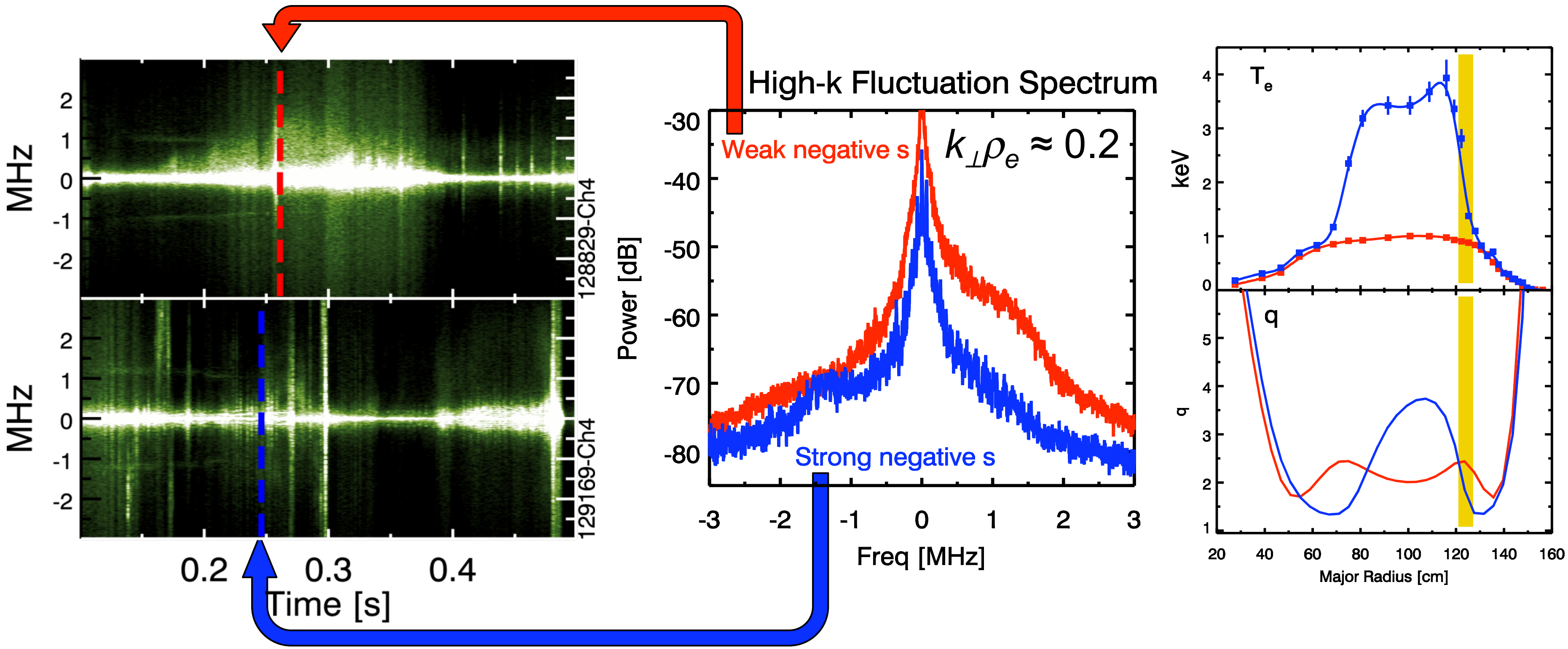


- Peaked core gradients in electron and ion temperatures, and toroidal velocity
- Electron density gradient does not show much change with ITB
- NSTX profile diagnostics
  - 51 channel CHarge Exchange Recombination Spectroscopy (CHERS) measures T_i,v_f
  - 30 channel Thomson scattering measures T_e, n_e
  - 16 channel MSE

ITB's not correlated w/ qmin or rational q.

H. Yuh et al. APS Invited Talk 08

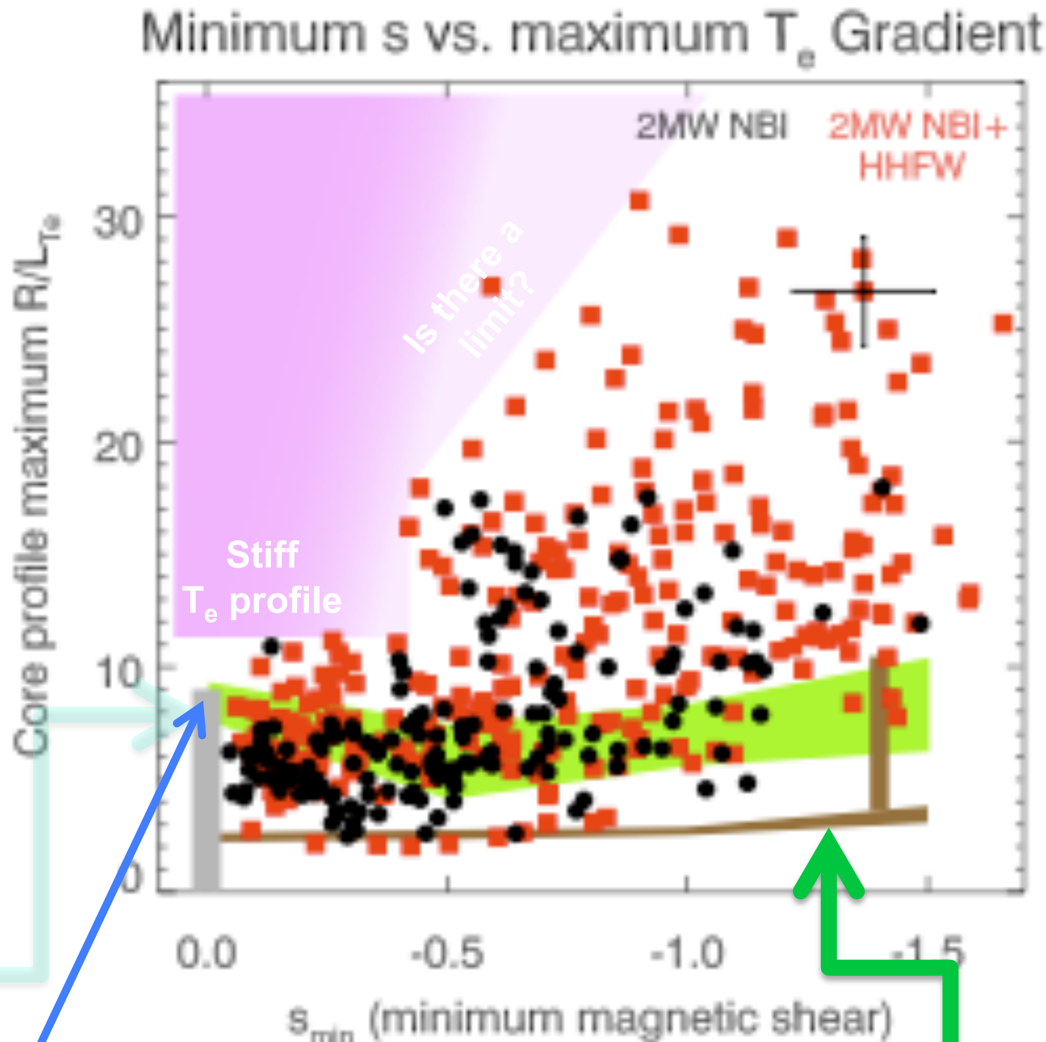
High-k scattering fluctuations are reduced inside e-ITB



- Low high-k fluctuation amplitude seen in strongly reversed shear e-ITB
- Weak negative shear shows higher high-k fluctuations despite lower T_e gradients

Measured gradients well above predicted ETG critical gradient

- GS2 and GYRO linear simulations performed across profile range
- Critical gradients for ETG instability greatly exceeded in e-ITBs
- Low high-k fluctuation power measured in ITB
- Can negative magnetic shear suppressing transport caused by ETG ?



GS2 critical gradients

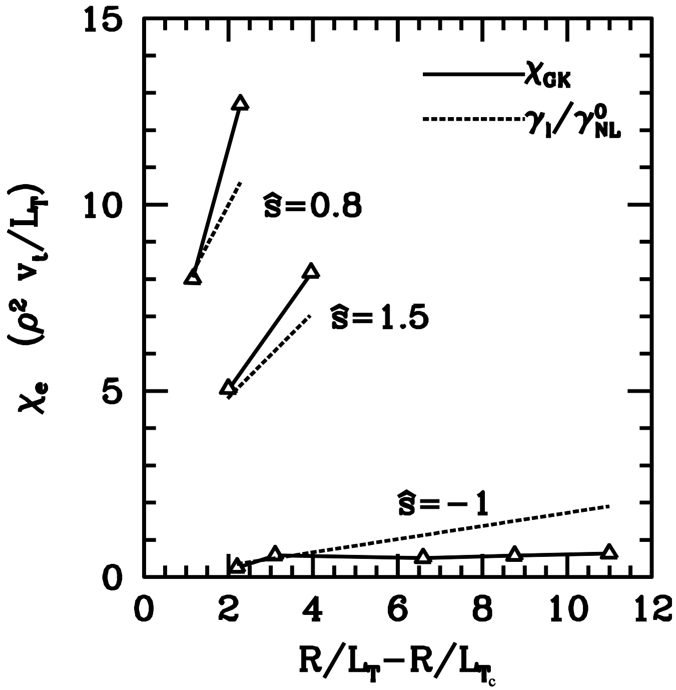
6MH H-modes w/ s~0 stuck at $R/L_{Te} < 9$

GYRO critical gradients: single profile, s & Zeff(T_e/T_i) variation

H. Yuh et al. APS Invited Talk 08

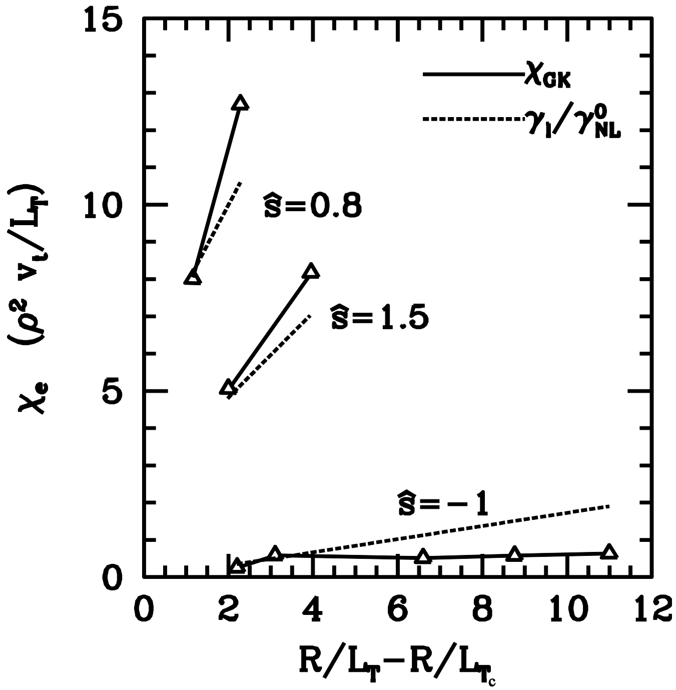
Previous non-linear simulations has shown negative magnetic shear can reduce transport by ETG

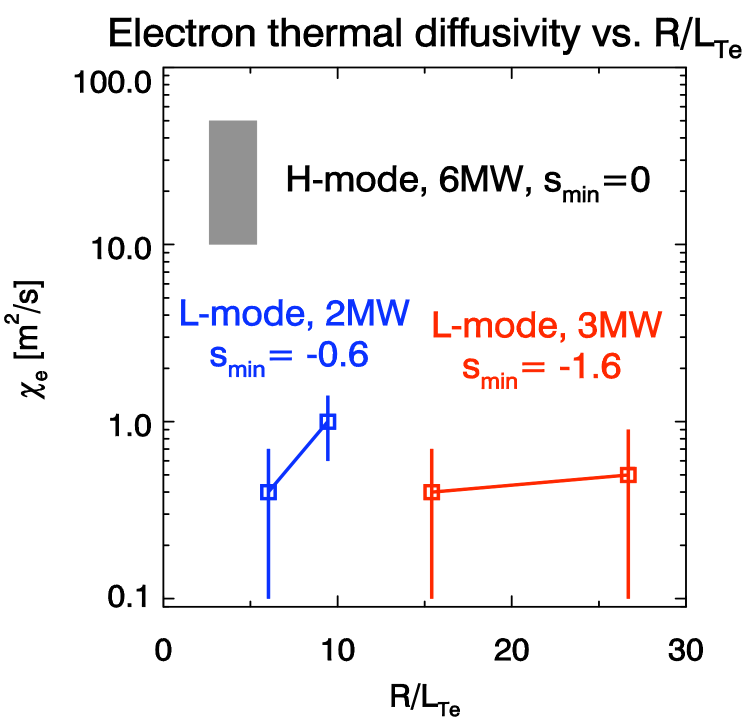
- Negative magnetic shear suppression of ETG transport has been predicted by Jenko, Dorland [PRL **89**, 225001 (2002)]
- Nonlinear gyrokinetic simulations showed negative magnetic shear effective at reducing ETG turbulence



Previous non-linear simulations has shown negative magnetic shear can reduce transport by ETG

- Negative magnetic shear suppression of ETG transport has been predicted by Jenko, Dorland [PRL **89**, 225001 (2002)]
- Nonlinear gyrokinetic simulations showed negative magnetic shear effective at reducing ETG turbulence

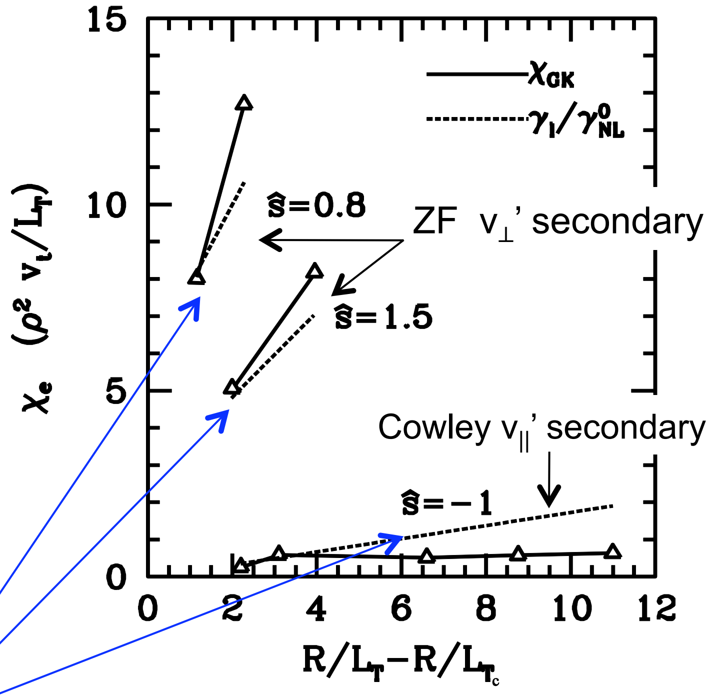




- Experimental data shows a similar reduction in χ_e with low sensitivity to increasing temperature gradients

Previous non-linear simulations has shown negative magnetic shear can reduce transport by ETG

- Negative magnetic shear suppression of ETG transport has been predicted by Jenko, Dorland [PRL **89**, 225001 (2002)]
- Nonlinear gyrokinetic simulations showed negative magnetic shear effective at reducing ETG turbulence



Dotted lines: theoretical prediction of turbulent flux based on balancing:

Primary instability growth rate
~ secondary instability growth rate (∝mode amplitude)

Rogers' $v_\perp$' ZF secondary suppressed by perpendicular adiabatic ion response, Cowley secondary unaffected

Some physical parameters for NSTX 124948 @ 300 ms

r_0/a	0.373
R_0/a	1.502
κ	1.859
δ	0.129
q	3.113
$\hat{s}$	-0.127
ρ_*	0.007
n_i/n_e	1.0
T_i/T_e	0.833

Z_{eff}	2.50
$\gamma_E(a/c_s)$	-5.6×10^{-3}
λ_D/a	9.4×10^{-5}
$\nu_{ei}(a/c_s)$	0.087
$\nu_{ii}(a/c_s)$	0
a/L_n	0.628
a/L_{T_i}	1.302
a/L_{T_e}	4.71
$\beta_{e,unit}$	6.1×10^{-3}

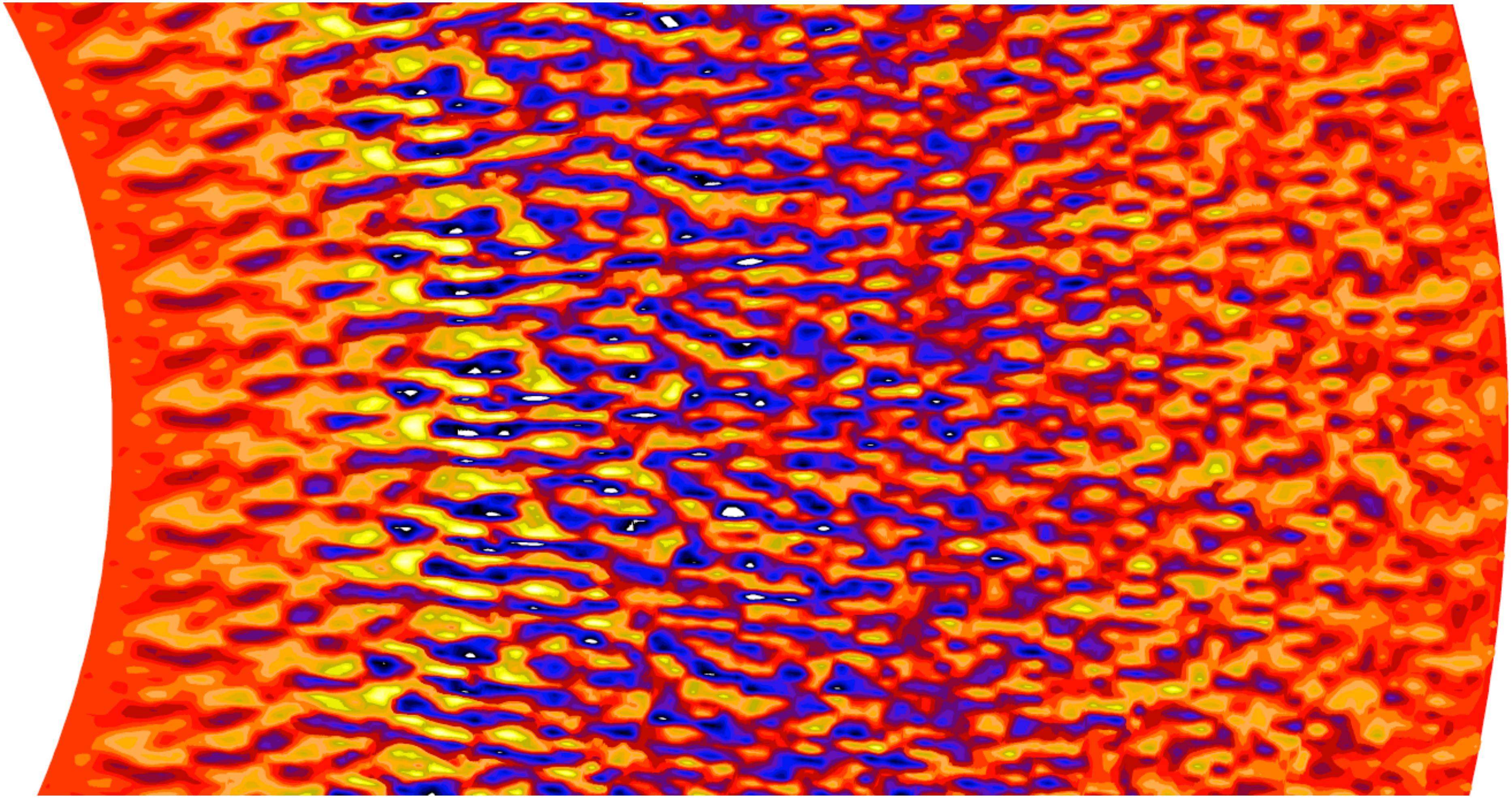
Data from TRANSP/TORIC analysis of RF shot with NBI blips

NSTX ETG simulations are tough.

- TGYRO/GYRO/NEO/TGLF pull data from TRANSP
  - Radial variation in profiles
- Higher resolution necessary for convergence
  - Resolve electron gyroradius
  - Small time step to get electron dynamics
  - Increase velocity space, poloidal resolutions from standard
  - Reduced mass ratio $\sqrt{m_i/m_e} = 20$
- Gyrokinetic electrons; gyrokinetic (or adiabatic) ions
- Electrostatic or Electromagnetic
  - (no parallel magnetic compressions yet)
- 52 million distribution points
- 60,000 – 150,000 CPU hours each at ORNL's Jaguar

Poloidal cross-section shows elongated streamers.

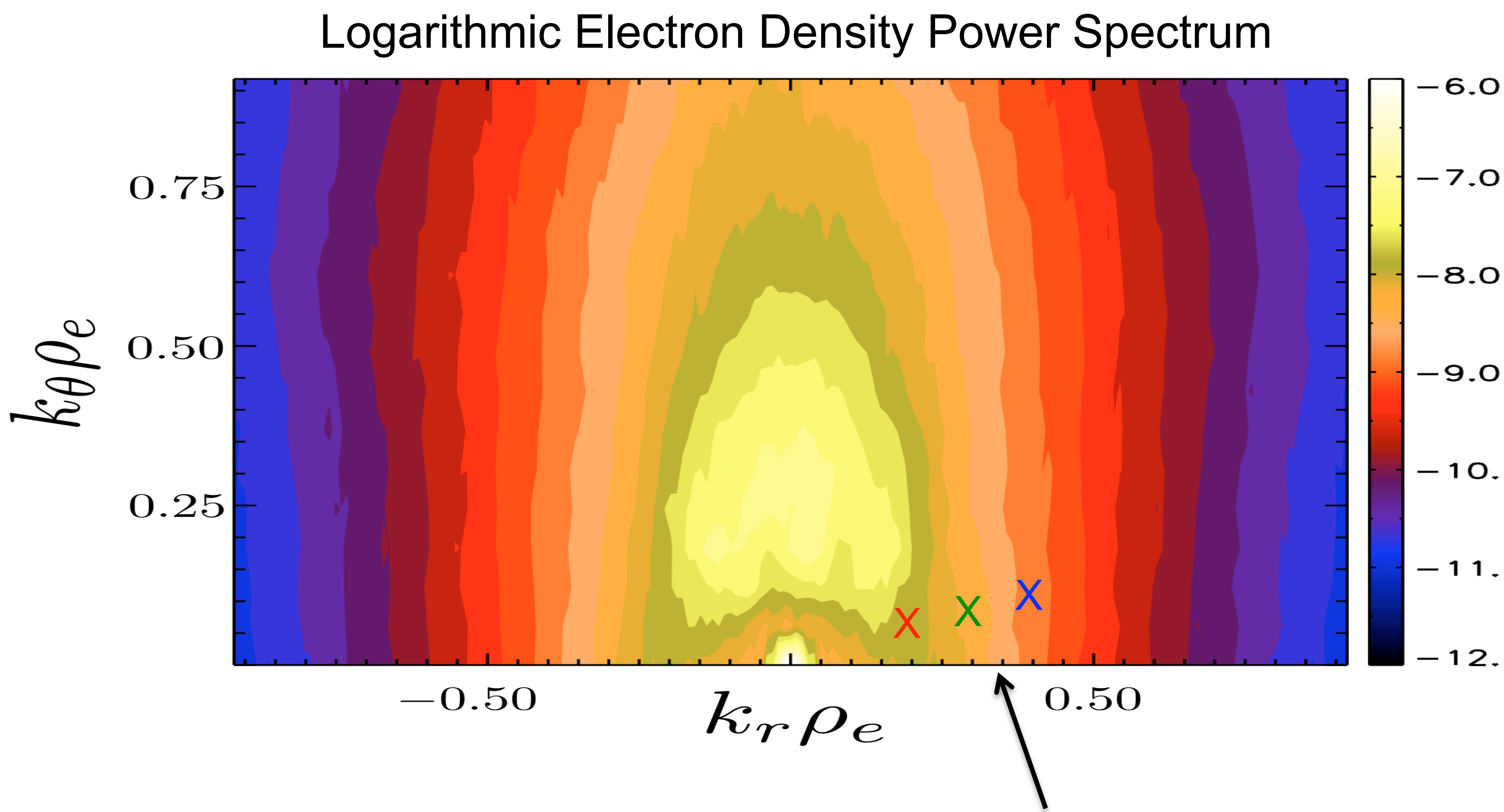
$\rho_i/\rho_e \approx 20$ (streamers will be smaller at real mass ra



$640\rho_e$

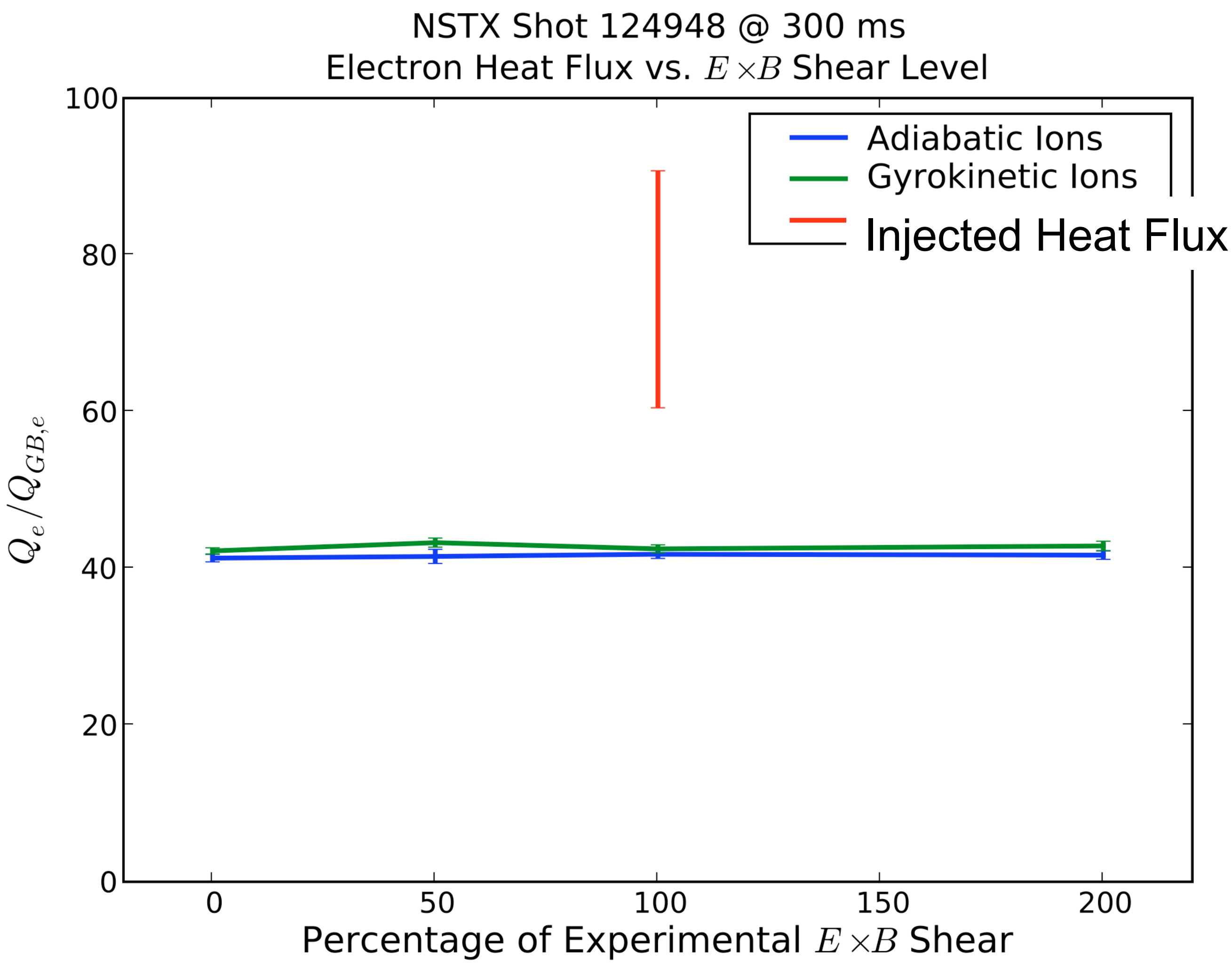
r/a=0.26 Radial direction (ignore outer ¼ buffer regions) r/a=0.49

Anisotropic electron density power spectrum may have implications for experimental comparison.

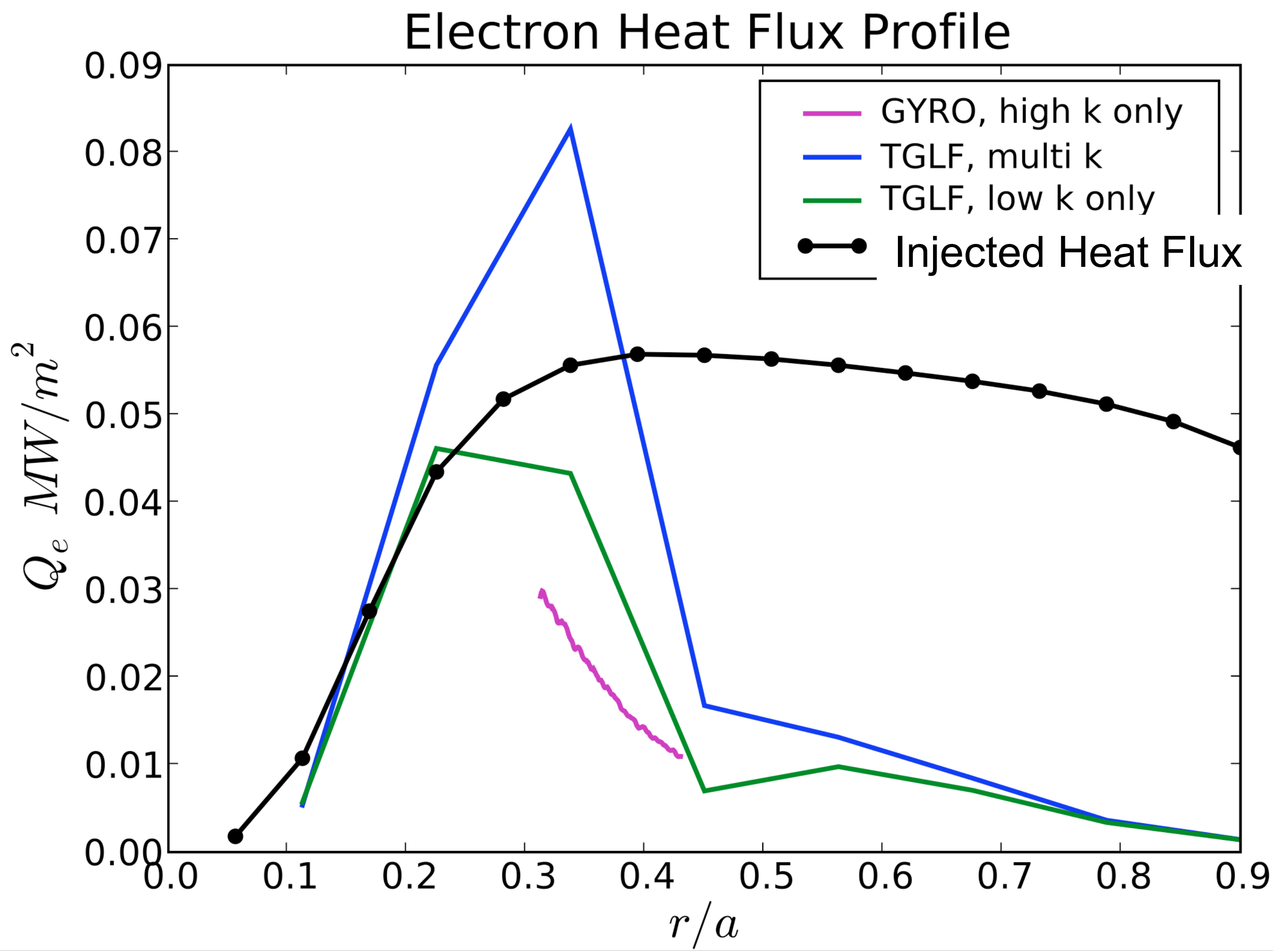


Approx. high k locations:
Ch. 3 Ch. 4 Ch. 5

Good agreement with models at experimental ExB shear level.

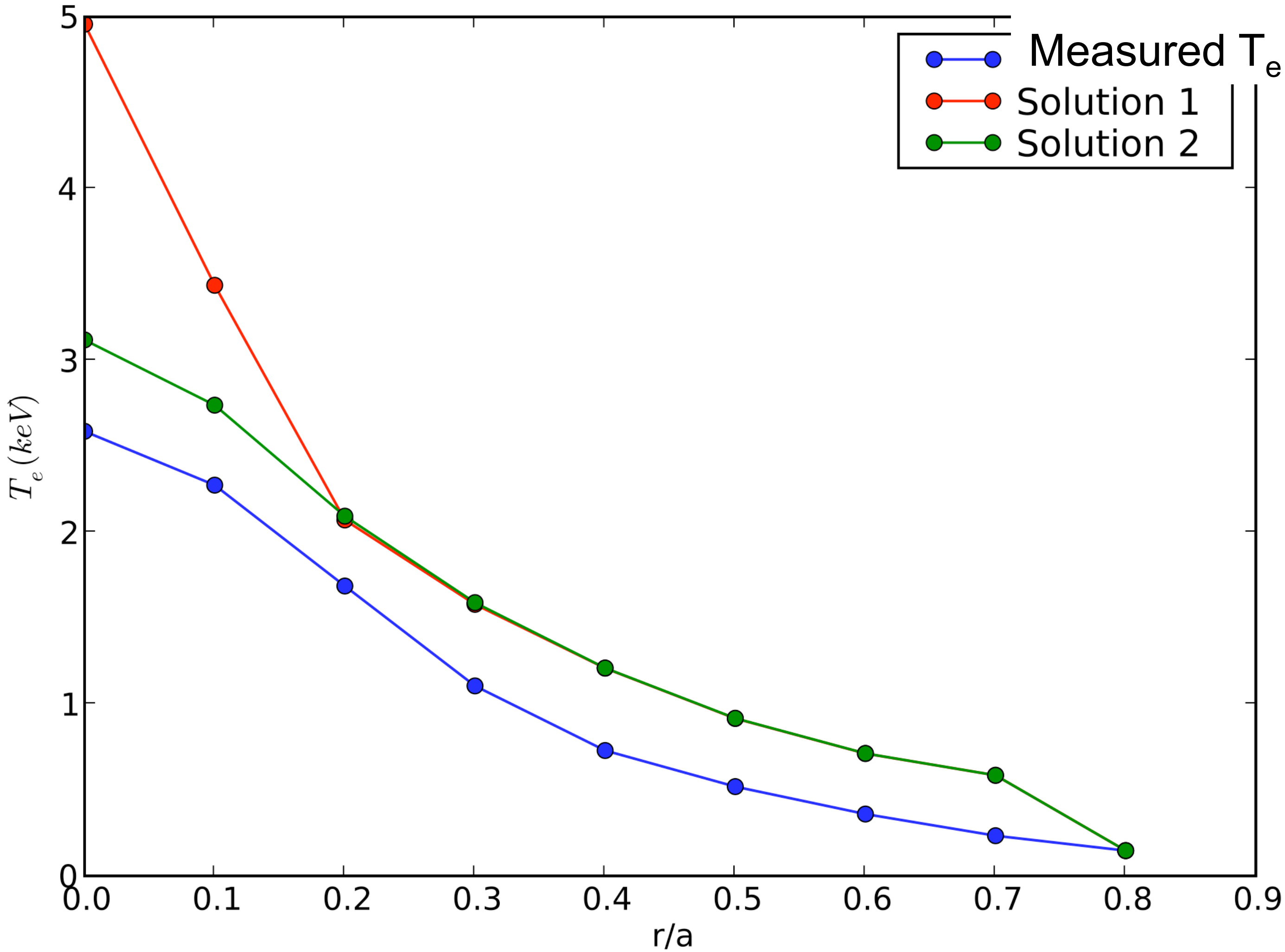


Great radial variation in heat flux predicted by GYRO and TGLF.

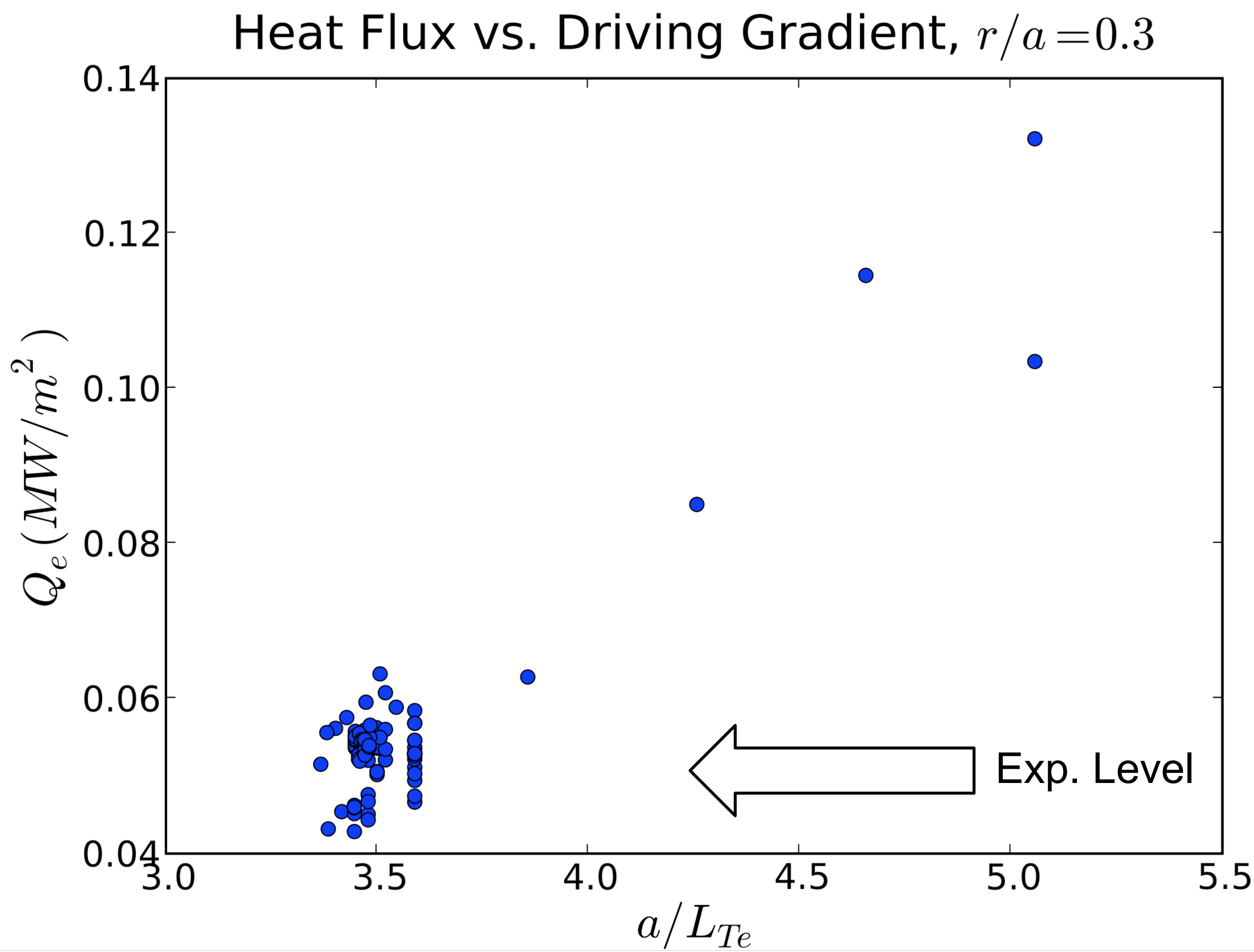


TGYRO/TGLF can predict profiles fairly well (appear to be 2 bifurcated solutions possible)

Using variation of Newton algorithm to solve nonlinear transport equations in a stable way:



Small changes in temperature gradients lead to electron flux agreement.



Key Point: ETG may not be the only player.

- Nonlinear simulations of NSTX show ETG-driven turbulence.
  - Can account for half of electron heat flux with experimental gradients.
- Reversed magnetic shear is important.
  - Model saturation and overall transport levels
- TGLF suggests longer wavelength (TEM) may contribute.
  - TEM linearly unstable above shearing rate for this RF shot.
- Small changes in gradients can lead to large changes in flux, at this moderate shear s = -0.14
  - TGYRO/TGLF (with TEM and ETG) converges to experimental flux.

Open Questions

- Can uncertainty account for electron heat flux?
  - Mass ratio, ion dynamics, compressional magnetic perturbations
  - Temperature, density, impurity concentration
- What is the role of long wavelength (TEM) turbulence?
  - Can it make up the balance of electron heat flux?
  - Does it alter the properties of the ETG turbulence?

We need to simulate steady-state shots diagnosed at multiple wavelengths.

BES System Coming FY2010-12

Summary

- Mini-tutorial on bad-curvature drive of tokamak instabilities
- Why negative magnetic shear is good
- Jenko & Dorland's surprising prediction of significant turbulence driven by Electron Temperature Gradient (ETG)
- Measurements of electron-gyro-scale fluctuations on NSTX and observations of internal transport barriers with negative magnetic shear consistent with ETG expectations. (supports Jenko & Dorland prediction)
- Initial nonlinear GYRO simulations, working toward detailed comparisons with microwave scattering measurements
- Multiple electron transport processes may be important and are being investigated: ETG, TEM (Trapped-Electron Mode), Micro-tearing (Wong PRL07), GAE (high frequency Global Alfven Eigenmode) (Stutman PRL 09). Focus on ETG here.

Initial Nonlinear ETG Turbulence Simulations:

- Simulating NSTX electron turbulence is challenging.
- Goal: detailed GYRO simualtions w/ synthetic diagnostic comparisons with high-k microwave scattering measurements
- Global simulations show ETG-driven turbulence in this RF-only discharge:
  - **E**x**B** shearing has little effect (unlike case in Smith et al PRL 2009).
  - Collisions have little effect (unlike case in Roach et al PPCF 2009).
  - Magnetic perturbations have small effect.
  - ETG can account for half of measured heat flux.
- Reversed magnetic shear appears to control turbulence.
- Transport predictions indicate long wavelength (TEM) turbulence may be important.