Comprehensive NSTX transport simulations with GYRO

R.E. Waltz (work with J. M. Candy)

Supported by the SciDAC Plasma Microturbulence Project (PMP)

NSTX Planning Workshop *PPPL Princeton, NJ* *June 25, 2002*

GENERAL ATOMICS

Gyrokinetic simulations are at the dawn of a new era

- The continuum global gyrokinetic code GYRO is now fully operational after 3 years of development in close conjunction with the GS2 flux tube code.

- We are now able to simulate in physically realistic and comprehensive detail, the turbulent transport energy, plasma, and momentum flows as well as electron-ion energy exchange rates from a given set of experimental core plasma profiles.

  - However the inverse transport problem, i.e. experimental sources or flows generating dynamical plasma profiles, is far into the future.
  - We will continue to need improved simulation based transport code models for many years to come.

- After a period of validation, code comparison, and quantitative match with experiments to verify the coded gyrokinetic equations are adequately comprehensive, "synthetic diagnostics" for the turbulent fields and flows will make direct quantitative experimental data comparison possible, not just qualitative order of magnitude and scaling.

GYRO has comprehensive physics

- Gyrokinetic code GYRO to contains all physics of low frequency (<< ion cyclotron) plasma turbulence assuming only that the ion gyroradius is less than magnetic field gradient length
  - Nonlinear and basic ITG with adiabatic electrons
  - Finite ρ^*
  - Electrons (trapped and passing) electromagnetic and finite-β
  - Collisions
  - Real tokamak geometry
- Continuum (fluid-like) methods in 5-dimensional space ($r, \theta, n, \varepsilon, \lambda$)
- 2-modes of operation:
  - flux-tube with cyclic boundary conditions
    to be compared with the GS2 gyrokinetic flux tude code ..... effectively ρ^* -> 0
  - wedge -tube with non-cyclic BC radial slices or full radius Δn=5-10 ρ^* small but finite
- Why full radius? Shear in the ExB velocity known to have a powerful stabilizing effect. But shear in the diamagnetic velocity can be just as large and cannot be treated at ρ^*= Flux-tube codes at ρ^* -> 0 have only gyroBohm scaling and no nonlocal effects.

GENERAL ATOMICS

NSTX offers a unique opportunity and challenge to GYRO

- Very large ρ^* and large diamagnetically driven ExB and mode velocity shears and possibly large profile and nonlocal effects: the features GYRO was designed for.

- Extreme shaping at low aspect ratio. GYRO has real geometry Miller local equilibria but need more accurate global MHD equilibria.

- GYRO has a growing user base and we expect to develop 'wrappers' or user interfaces with GS2 . We expect GS2 to concentrate on the high-k ETG physics. A global code spanning low-k ITG and high-k ETG physics is far into the future.

- Key problem: ITG runs require a 24hr 128ps run on seaborg.nersc.gov. Full physics electron runs require 5 - 24hr restarts and longer than 10day turn arounds. We need to make the code faster with better processor scaling. Local clusters would be a big help.

Key Questions addressed

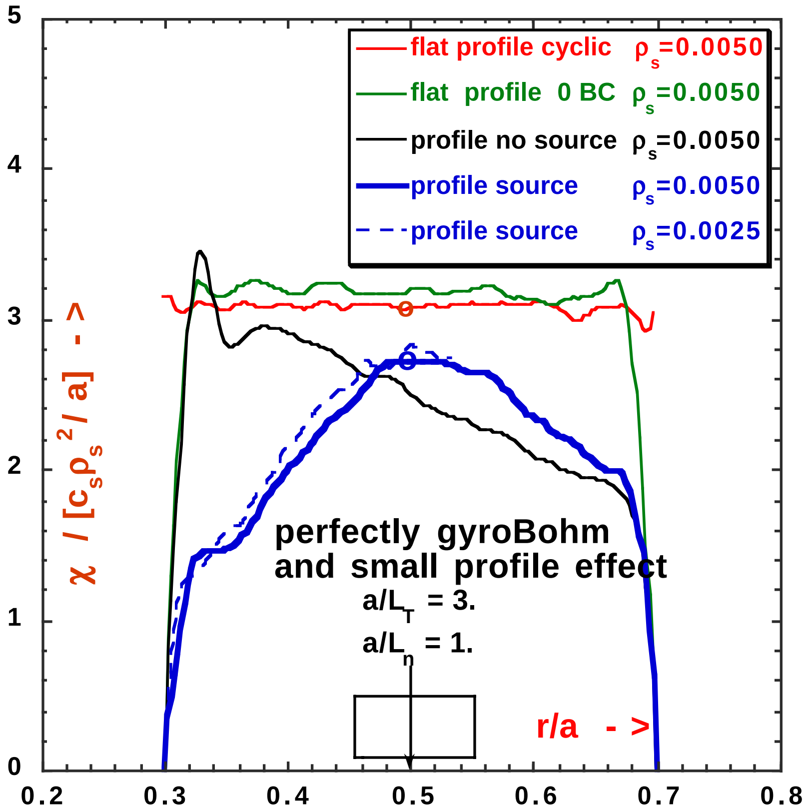
- How and where does shear in the diamagnetic mode phase velocities ($\gamma_{shear} \propto \rho_*$) break gyroBohm scaling to Bohm or worse?
  - Basic paradigm from Garbet and Waltz (APS '95):

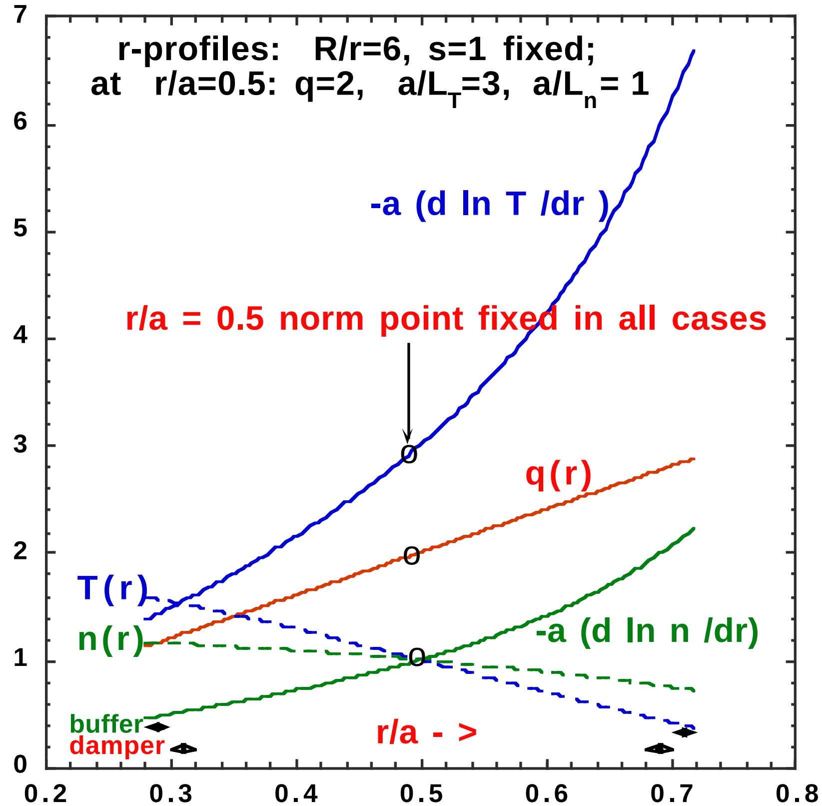
  Velocity shear comparable to linear ballooning mode rate ($\gamma_{shear} > \gamma$) stabilizes, hence expect gyroBohm scaling well above threshold but Bohm or worse near threshold (small γ) with strong shear. There is no single power law in ρ_*.

  $$\chi_{gB} = \rho_* \chi_B \quad \text{and} \quad \chi \propto \chi_{gB} \left(1 - \rho_* / \rho_{*crit} \right) \quad \text{with} \quad \rho_{*crit} = 1 - L_T / L_{Tcrit}$$

  - How do correlation lengths and times scale in a Bohm regime?
- Technical questions:
  - How do flux-tube simulations compare with non-cyclic BC simulations without profile variation, i.e. can we find " benign boundary" conditions ?
  - When adding profile variation, do we need to add sources?
  - How large must the radial simulation slice be to accurately simulate local χ ?
- How "local" is turbulent diffusion? Is there any *"action at a distance"* ?
- See recent paper : Waltz, Candy, and Rosenbluth, Phys. Plasmas 9 (2002) 1938

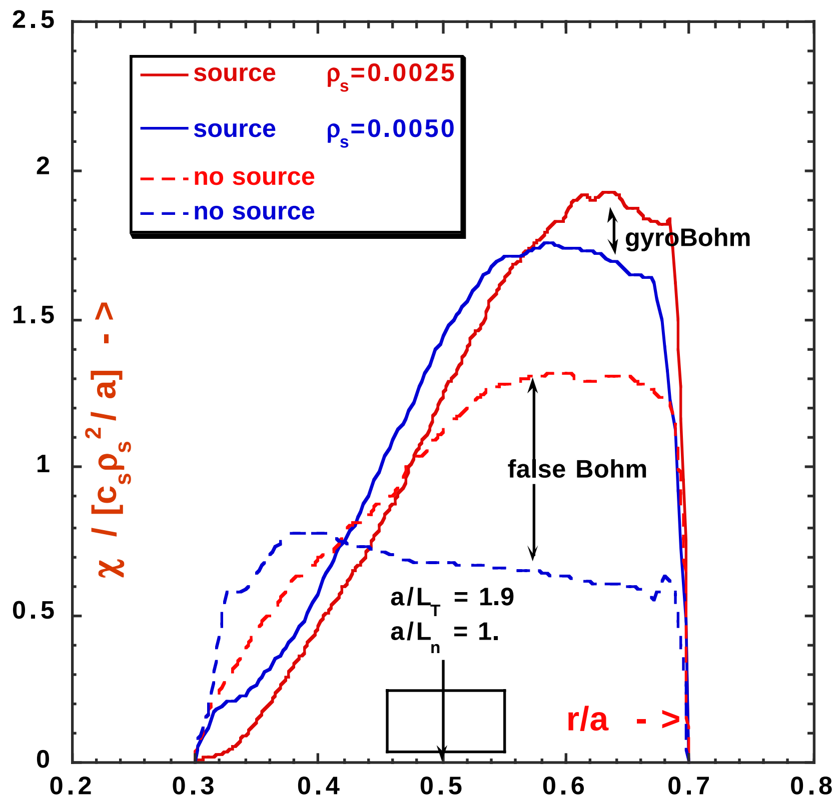
A radial slice with noncyclic BC can reproduce gyroBohm flux tube diffusion at a local radius for weak profile shear well above threshold

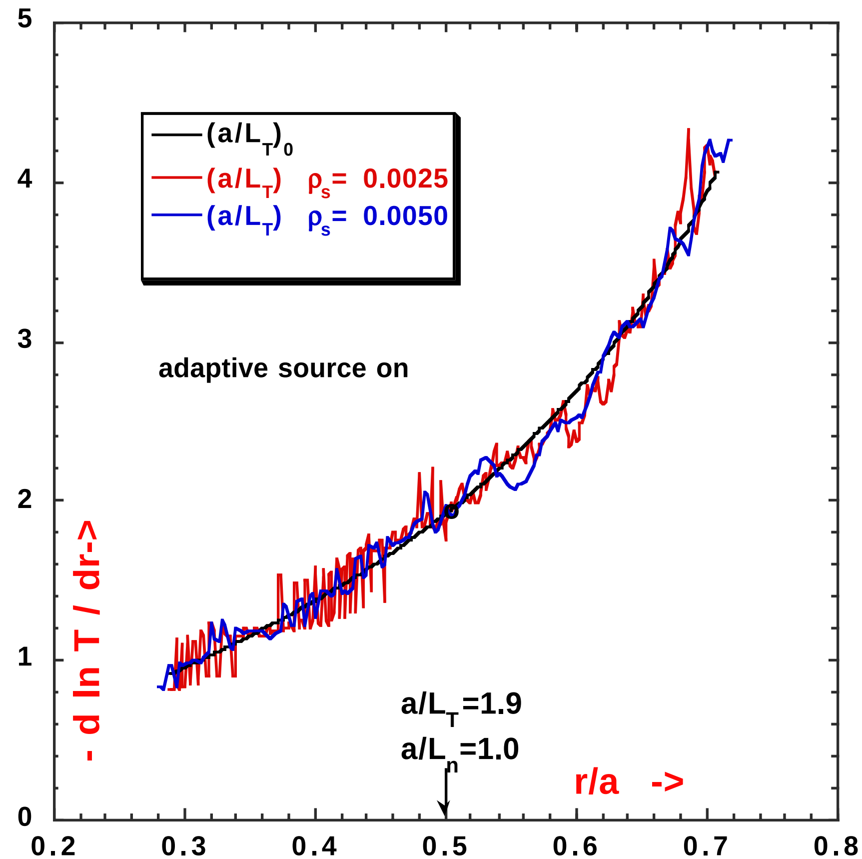




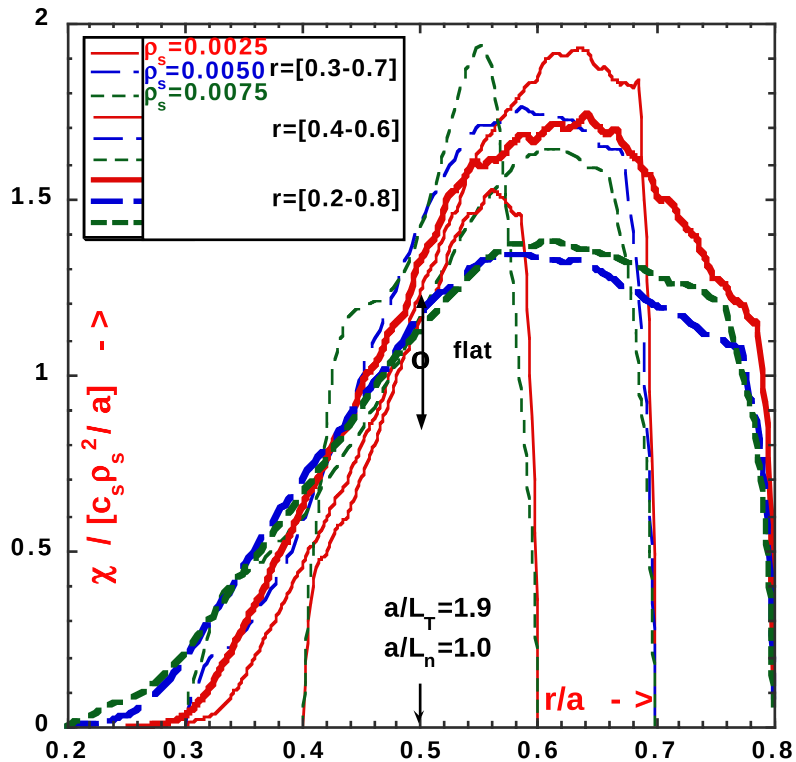
- 80 ρs noncyclic BC radial slice with flat profiles identical to cyclic flux tube gyroBohm result hence zero-value BC with external edge buffer and damper zones are "benign"
- Adding weak profile variation with sources shows only slight profile stabilization and remains gyroBohm at ρs = 0.0050 -> 0.0025 (Typical DIII-D)

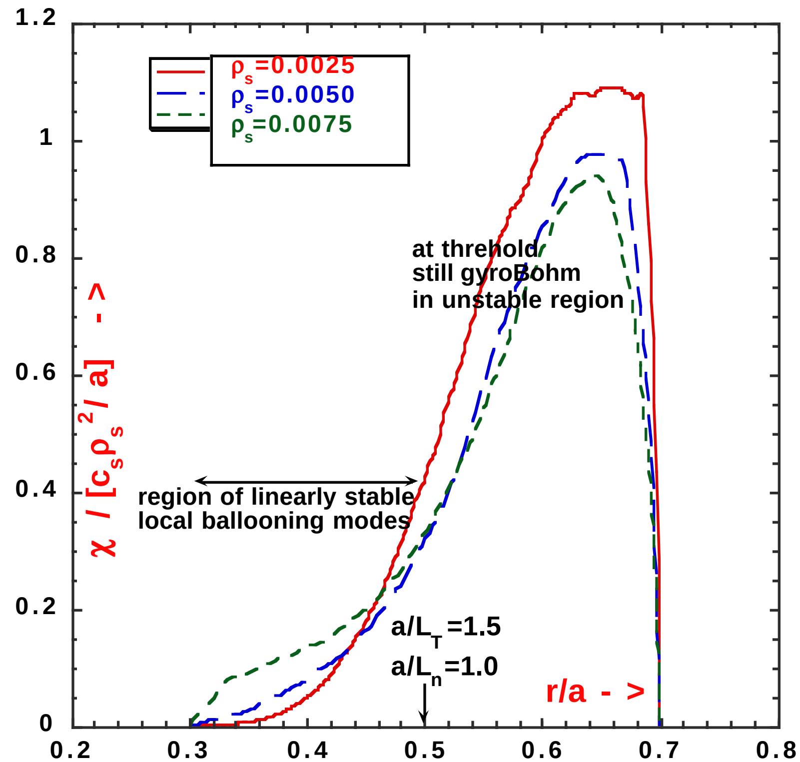
- Small ρ_s scaled deviations from the equilibrium profiles caused by the n=0 perturbations in the absence of sources can cause "false" Bohm scaling nearer threshold.





● In cases without significant profile shear, gyroBohm scaling can persist even close to threshold (a/L $_T$ = 1.9) although we can see a non-local effect at threshold (a/L $_T$ = 1.5)





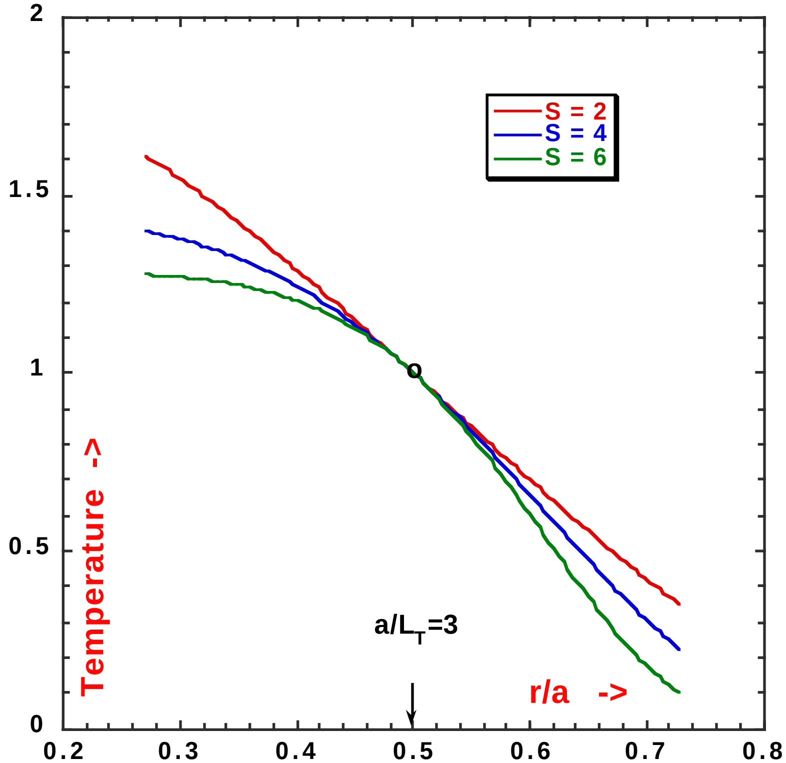
The slice approach appears valid here where χ at the norm pt. is unchanged with box size

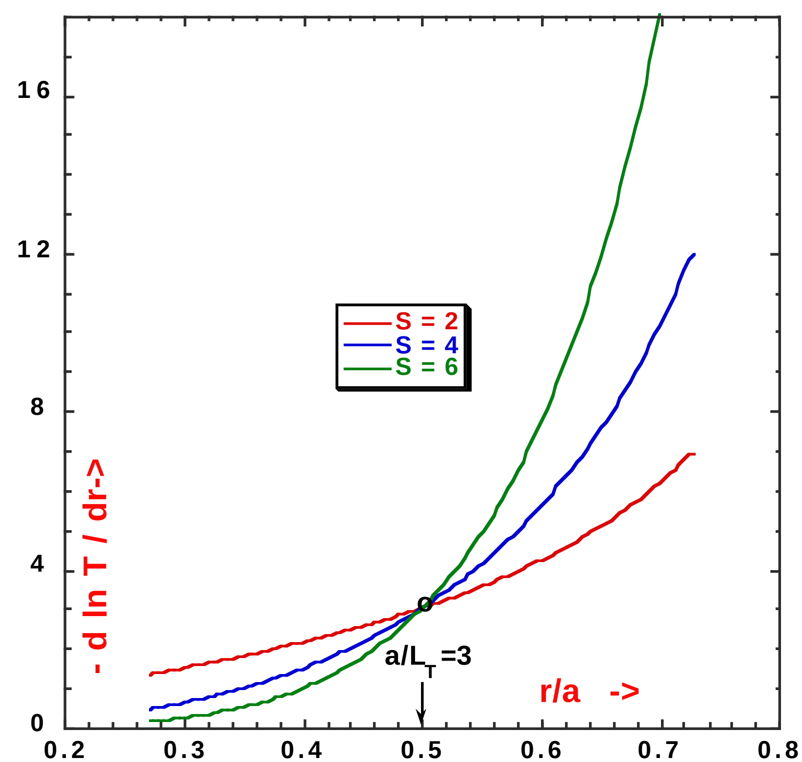
GENERAL ATOMICS

- To find Bohm scaling, we increase the density gradient lowering γ_{max}, increasing diamagnetic ExB shear, and increasing the profile shearing S from 2 to 4 and 6

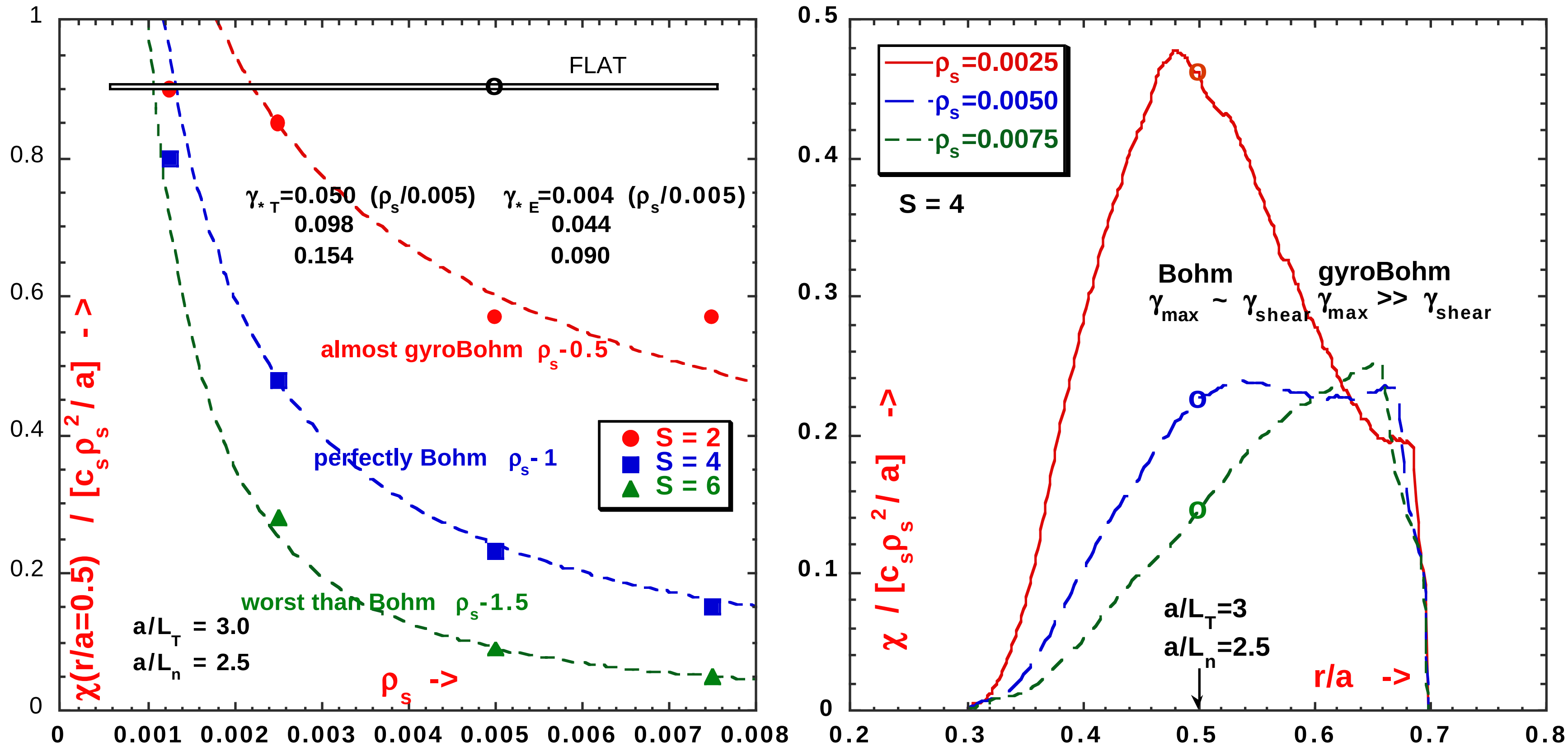
$T(r)=T_0(1 - r/a^{S})^{\alpha_T}$, $n(r)=T_0(1 - r/a^{S})^{\alpha_n}$ keeping a/L_T and a/L_n fixed at r/a =0.5

$(a/L_T=3, a/L_n=1) \rightarrow (a/L_T=3, a/L_n=2.5)$ lowing η_i from3 to 1.3 & γ_{max} from 0.13 to 0.06





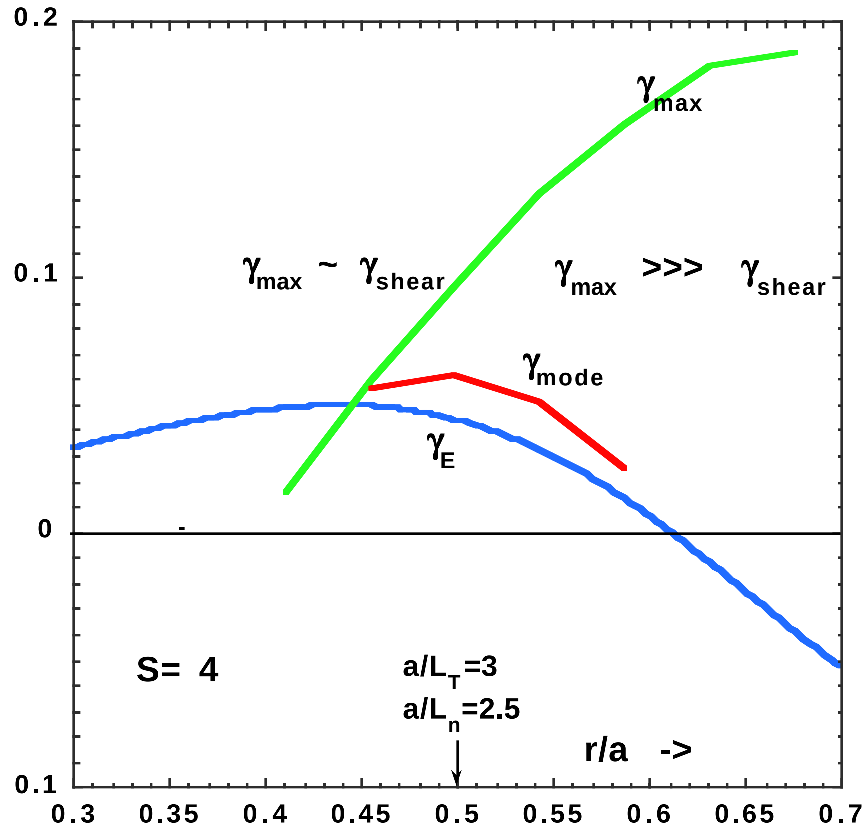
- Bohm scaling or worse results at the norm point r/a= 0.5 with increased shearing S =4 ->6
- At weaker shear and small ρ_s, approach gyroBohm scaled "flat"(no profile) results
- GyroBohm scaling still results where profile shearing rates are weak $\gamma_{shear} < \gamma_{max}$



R.E. Waltz NSTX Workshop June 2002

GENERAL ATOMICS

- Shearing rate approached growth rate only near norm point r/a= 0.5



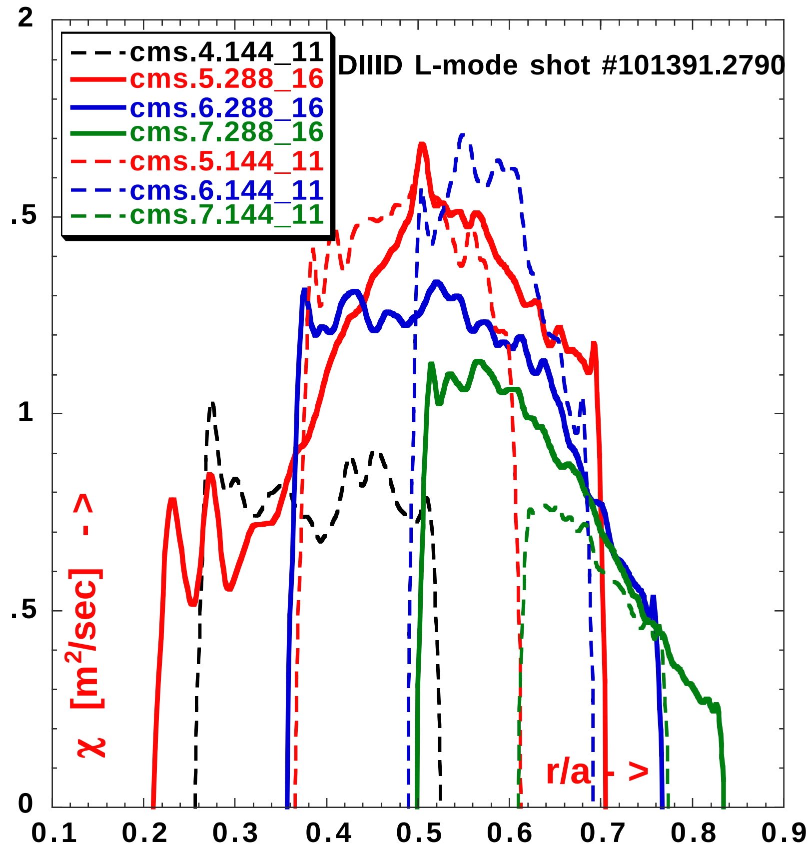
$$\gamma_{shear} \sim \gamma_{mode} \equiv r/q \ \partial \left(q/r \ V_{mode\ phase}\right) / \partial r$$

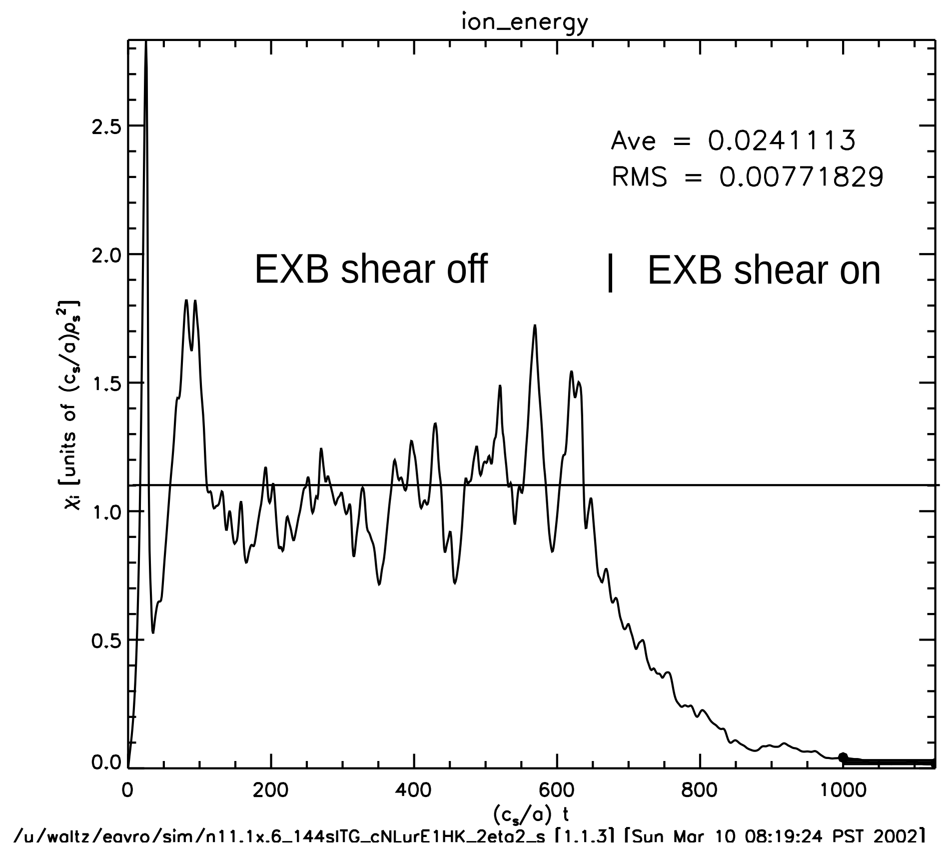
DIIID simulations with comprehensive physics

- Since previous study with ITG adiabatic electrons in s-a circular geometry, we are now treating actual DIIID profiles form the L-mode rho-star scaling experiments with full physics capability of GYRO.
- In particular we have
  - Electrons (trapped and passing), electromagnetic and finite β with collisions.
  - Real tokamak geometry with Miiller local equilibria input from experiment.
  - Toroidal velocity profiles for parallel shear driving Kelvin-Helmholtz ITG
  - Computed toroidal viscosity η_ϕ and e- i energy exchange rate (x a ^{2}) as well as energy and particle diffusivities χ_i χ_e D_i D_e
  - Experimental profiles E_r used to compute the very important equilibriumExB

DIIID L-mode rho-star scaling shots

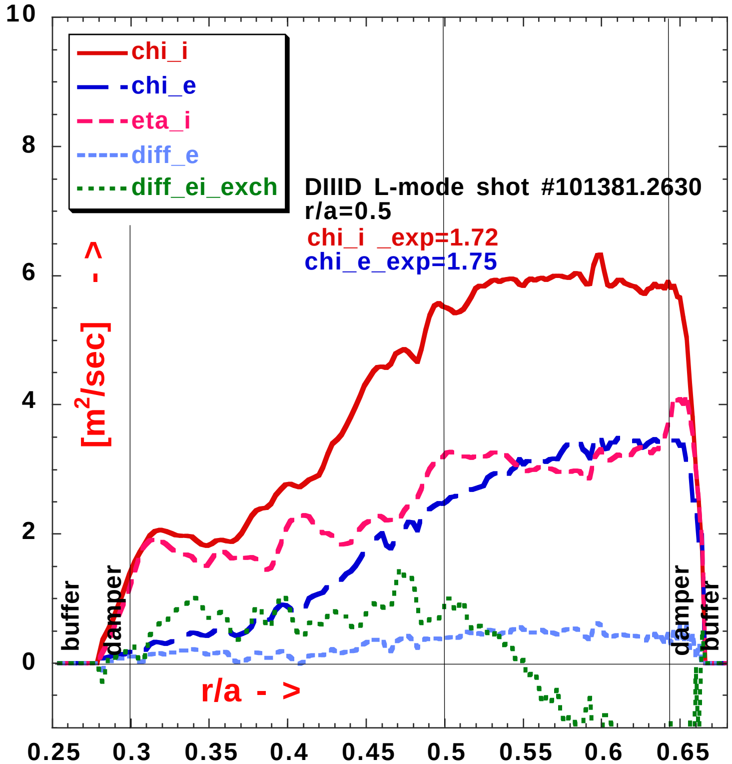
- B=2 .1T low rho_star shot. ITG adiabatic-e with no v_ϕ or ExB shear
  - -Smaller low-resolution boxes compare well with larger high-resolution boxes.
  - -Boxes centered at different r/a have good overlap.
  - -With ExB shear (and dv_ϕ/dr Kelvin- Helmholtz), ITG needs electrons to get transport

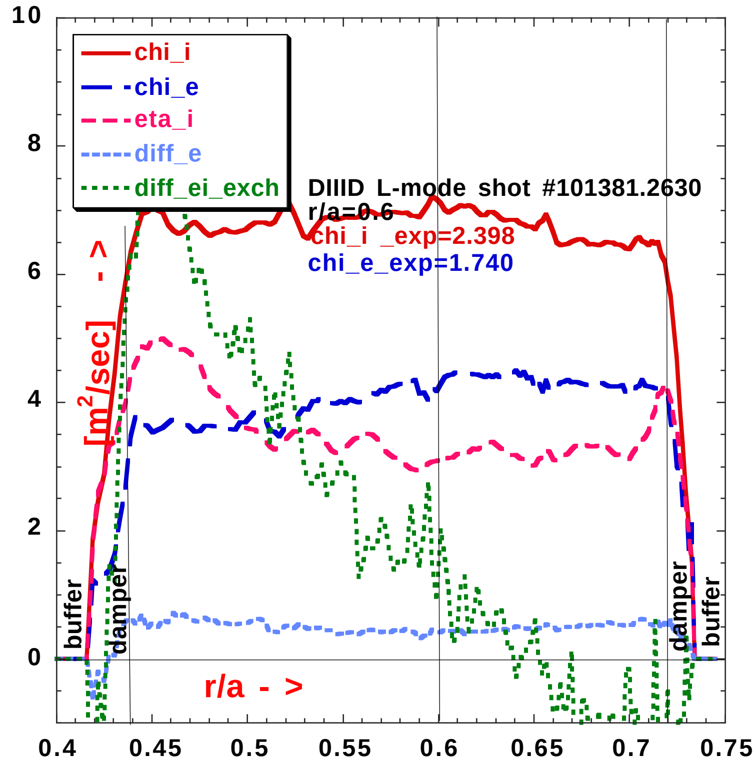




DIIID L-mode rho-star scaling shots (cont'd)

- B=1.050 high rho-star shot. All physics (save collisions)





DIIID L-mode rho-star scaling shots: some results to date

- at r/a = .6 both GRYO runs and experiment have the Bohm scaling ratios

B_t T	χ_{gB} m/sec^2 $(c_s / a)\rho_s^2$	ρ_s / a	χ^i/χ_{gB} GYRO	χ^i/χ_{gB} exp
2.1	1.018	0.00257	8.1* 6.0 # 3.9	2.34
1.05	1.934	0.00400	7.7* 3.6 # 2.7	1.24
0.5	0.56	$1/\rho$ 0.64	0.60	0.55

- χ_{gB} ratio near 0.5 means near perfect experiment
- χ^i/χ_{gB} ratio $1/\rho$ ratio means nearly perfect Bohm
- χ^i/χ_{gB} in GYRO < 2 X larger than experiment. (* = flux tube # = no collisions)

We need a sensitivity studie to determine χ^i/χ_{gB} changes with errors in profile. Typically profiles are 10% but gradient lengths are 30%. Very likely 30% lower temperature gradients and 30% higher shear rates will compensate.

Visit the GYRO web site http://web.gat.com/comp/parallel/ for literature and movies.