Theses

- The Helimak is a good model of interchange turbulence with magnetic curvature and dimensionless parameters similar to those of the outer region of a tokamak
- The turbulence and radial particle transport can be reduced by application of radial bias
- The bias changes flow velocities, but **turbulence reduction** <u>is not</u> associated with **increased velocity shear**
- A numerical experiment shows the same features
- There is <u>no</u> indication of zonal flows

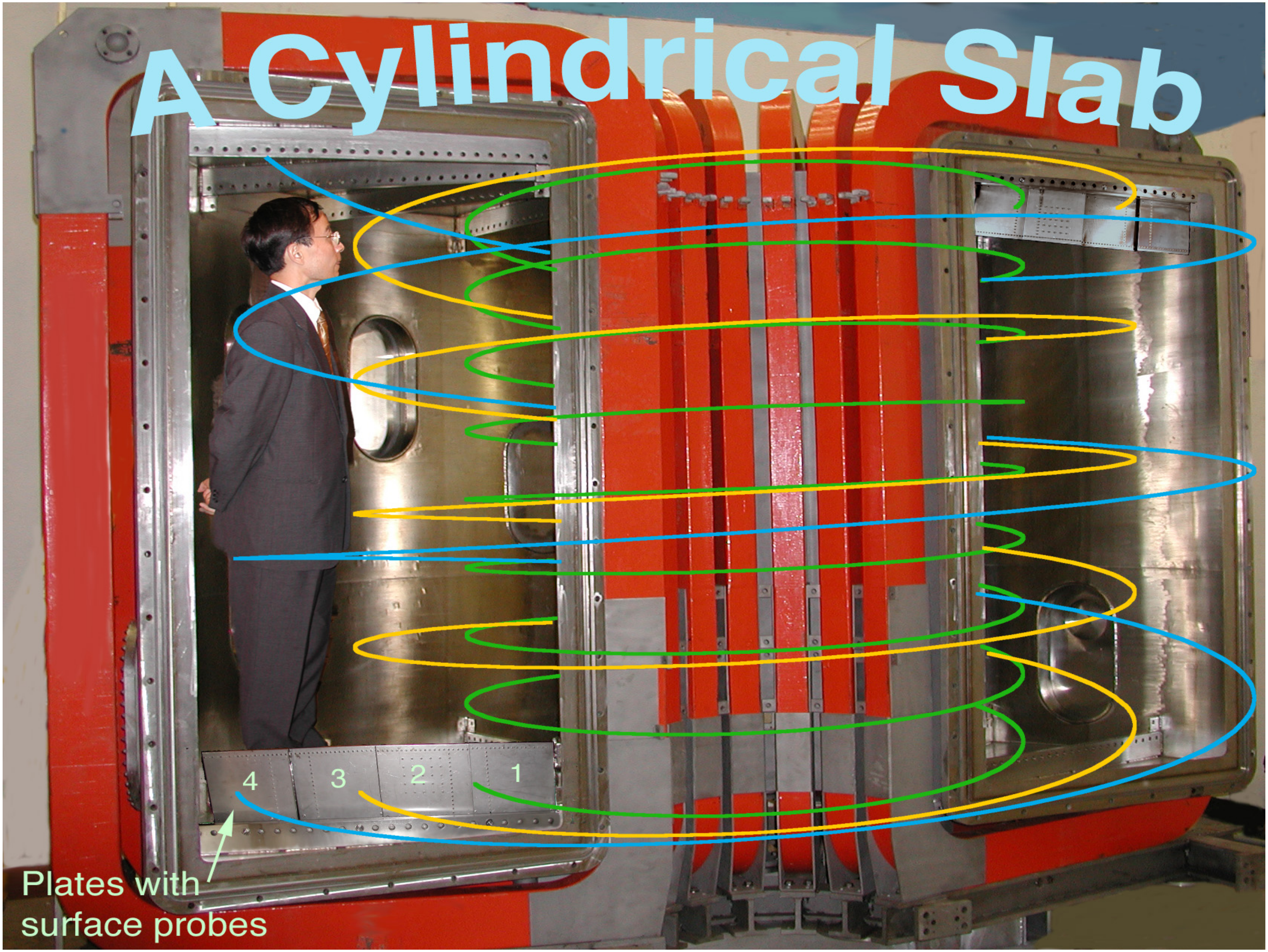
Outline

1. Description of device, plasma parameters, and characteristics of turbulence

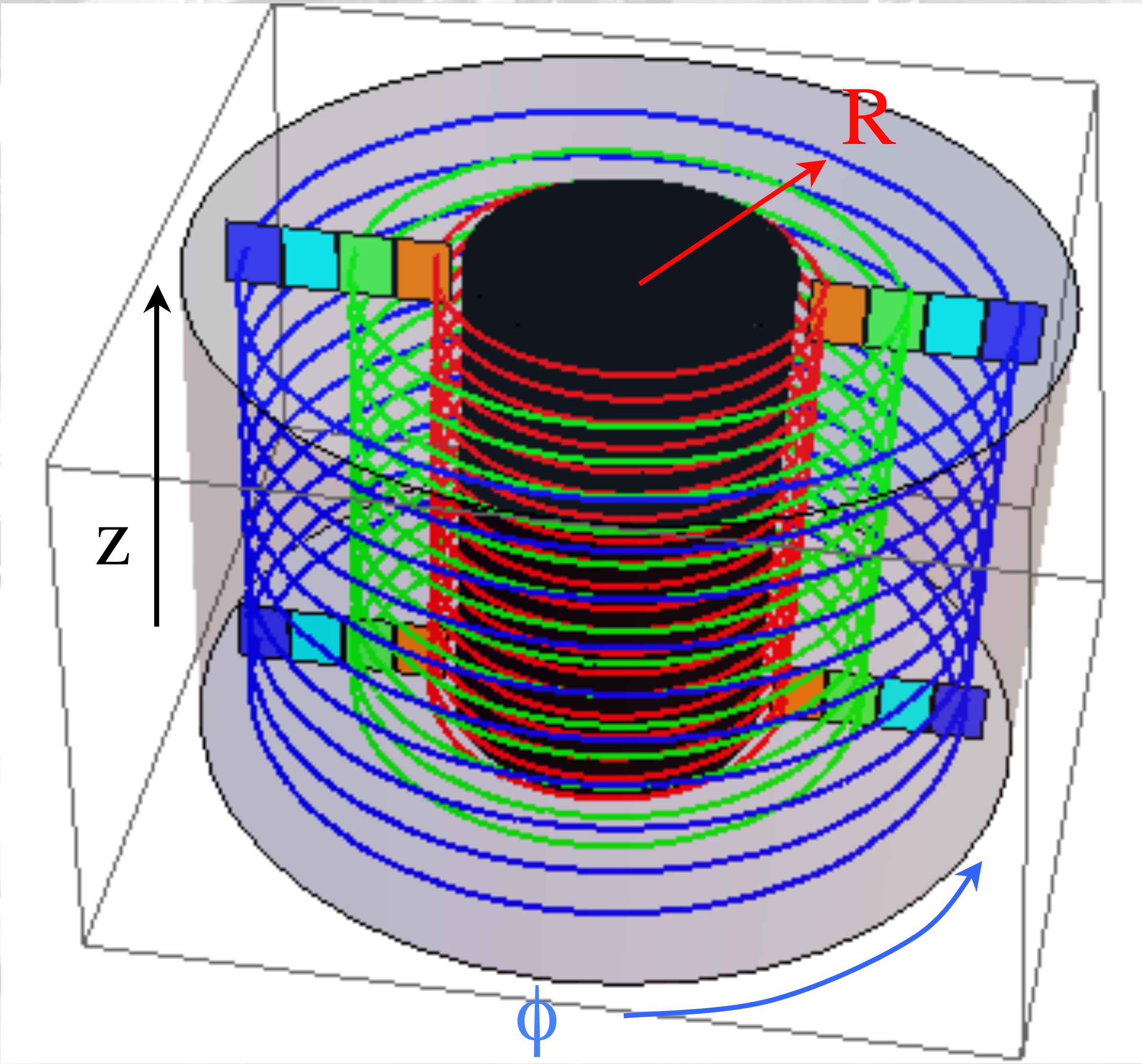
2. Results for reduction of turbulence by biasing

3. Relations between turbulence reduction, velocity shear, radial correlation lengths, and decorrelation rates

4. Comparisons with simulations and tests for zonal flows


A Cylindrical Slab
4
3
2
1
Plates with
surface probes

Helimak Geometry



R = Major radius (Tokamak minor radius)

z = Vertical (Tokamak poloidal direction)

ϕ = Angle (Tokamak toroidal angle)

Helimak Dimensions and Parameters
A Sheared Cylindrical Slab

<R> = 1.1 m $\Delta R = 1$ m   h = 2 m

$B_T = 0.1$ T $B_v \leq 0.01$ T   Pulse $\leq$ 30 s

Plasma source and heating: 6 kW ECH @ 2.45 GHz

$n \leq 10^{17}$ m^{-3} $T_e \sim 10$ eV

Argon, Helium, Neon, Xenon

$c_s = 4 \times 10^4$ m/s (Argon) $V_{drift} = 100$ m/s

$V_{diamagnetic} \sim 10^3$ m/s $\nu_{drift\text{-}wave} \sim 1$ kHz

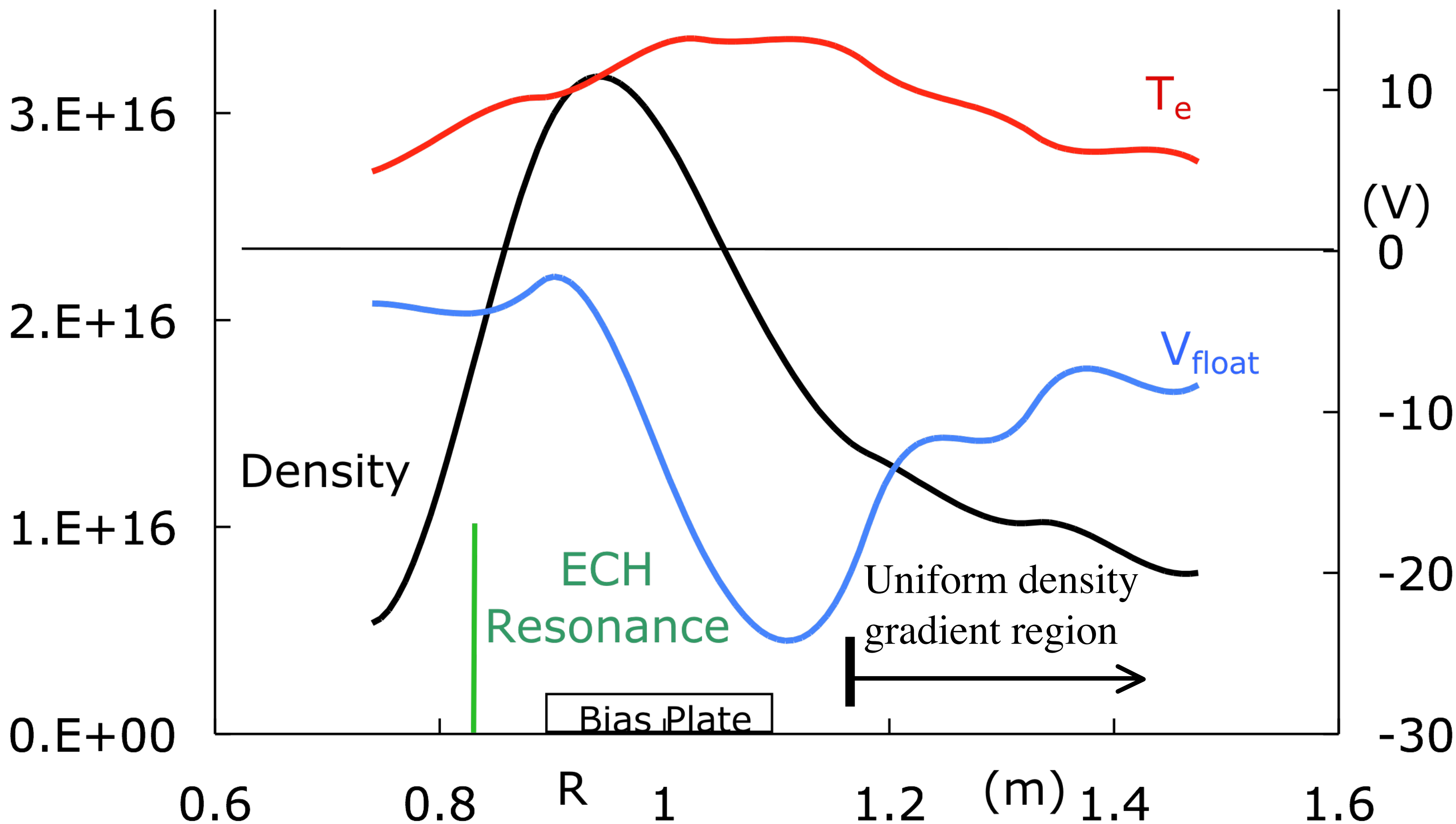
Connection length: 10 m $< L_{||} <$ 2000 m τ_p (parallel loss) > 1 ms

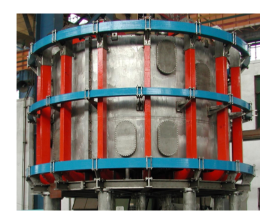
Probe arrays in end plates provide vertical and full radial profiles

Dimensionless Parameters

Transverse scales: ρ_s/L_n	0.2
ρ^* (ρ_s/a)	1/50
L_{corr}/a	0.05
Drift drive v_D/c_s	0.2
β	$6\text{x}10^{-5}$
Collisionality L_c/λ_{ee}	0.1
Turbulence level $\Delta n/n$	0.4
Parallel size L_c (m)	50

Typical Density, Temperature, and Floating Potential Profiles



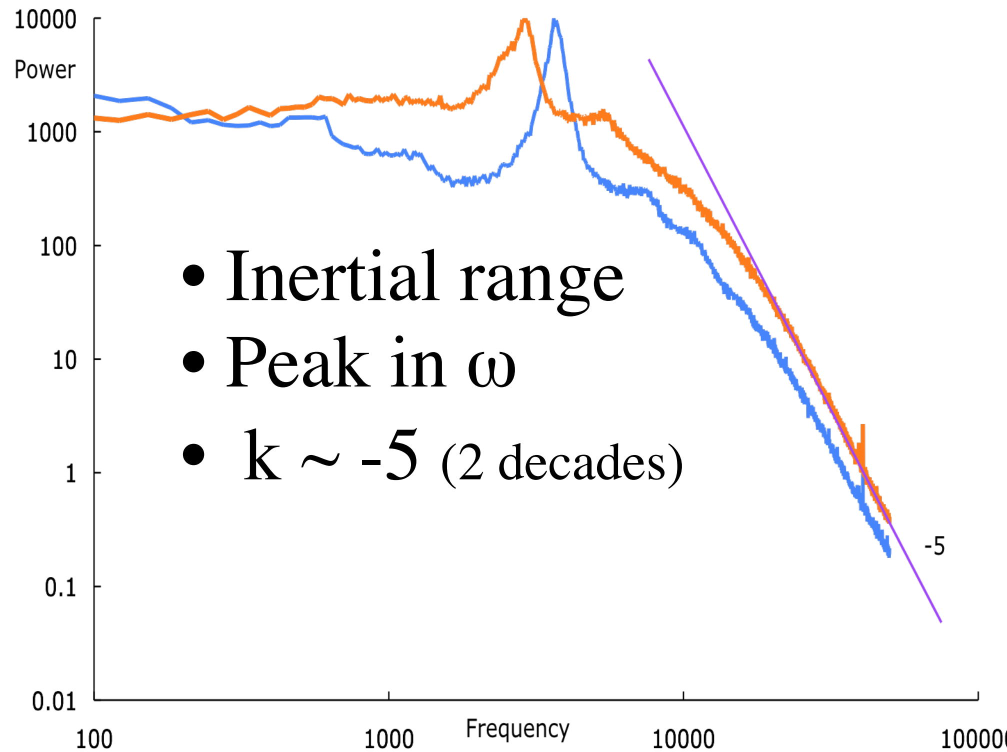


General Features of Power Spectra P(ω)

Based on 100,000+ spectra from all observable conditions

1. At high frequency, $P(\omega) \propto \omega^{-k}$, $2 < k \leq 5$
2. Absolutely nothing else!

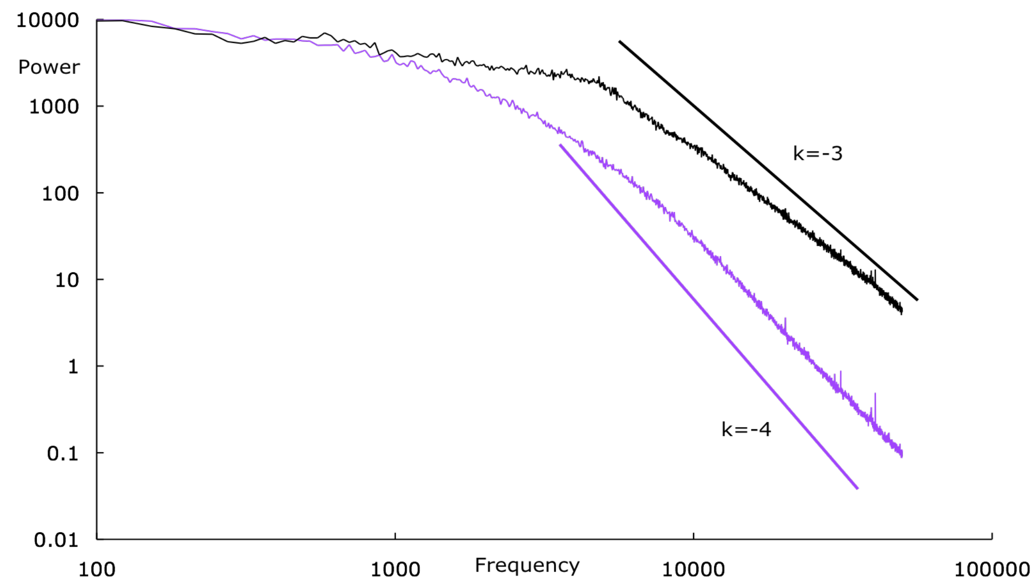
- Examine individual spectra
- Optional inertial range, $P(\omega)$=constant at low ω
- Optional peak at finite ω
- Optional intermediate power law, $P(\omega) \propto \omega^{-s}$, $s < k$
- Great variation in power law exponents
- Never a good fit to an exponential



- Inertial range
- Peak in ω
- $k \sim -5$ (2 decades)

Power Spectra P(ω)

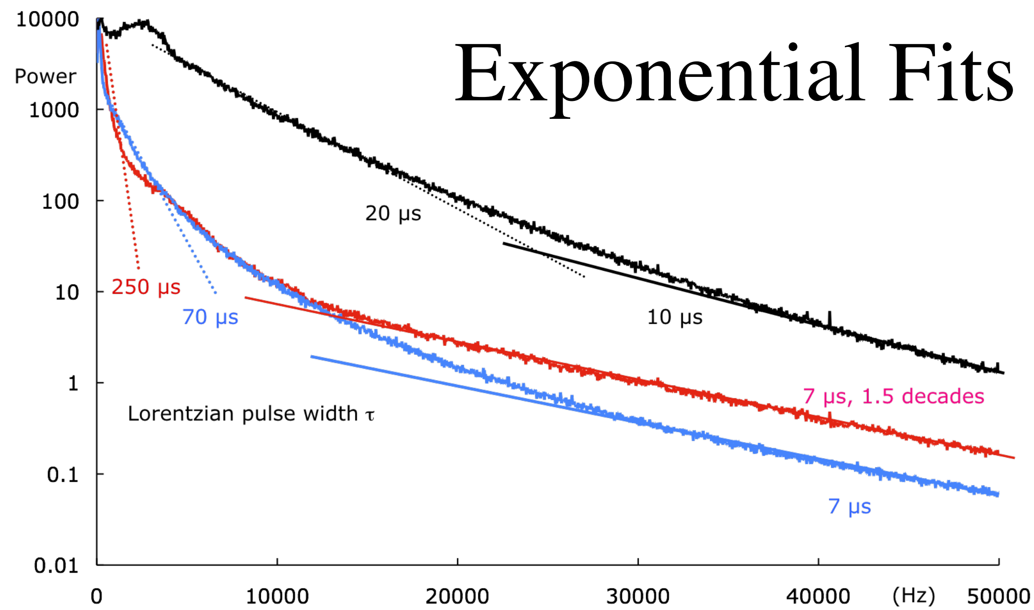
- No inertial range
- No middle range
- Power law,
  2+ decades,
  various k



- Exponential fits limited, ~1 decade
- Wide τ range
- Lorentzian (tail)

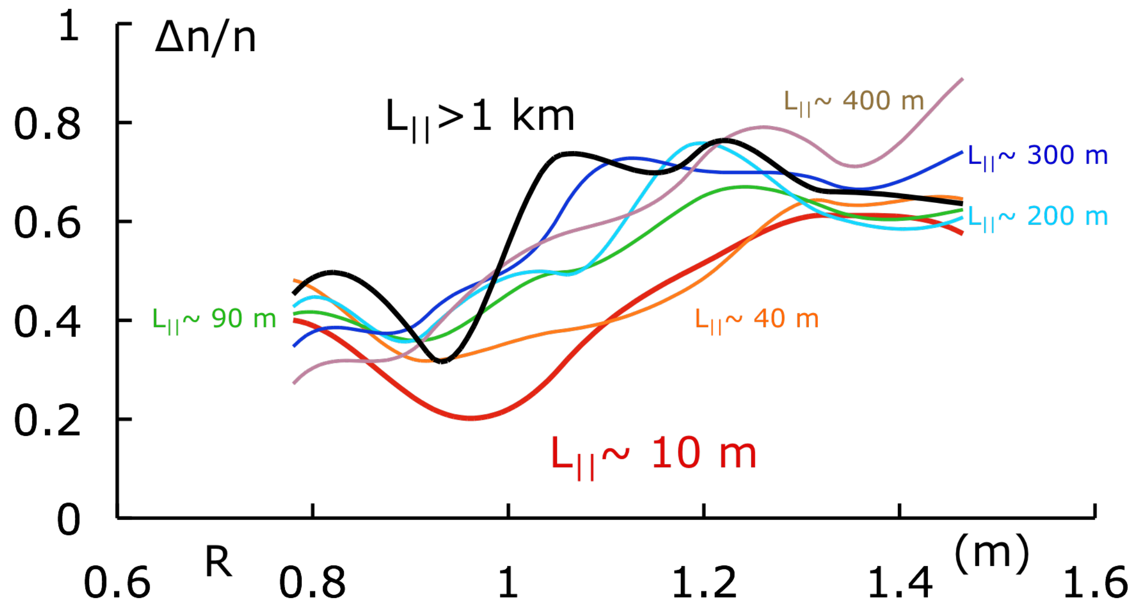
τ << Autocorr τ

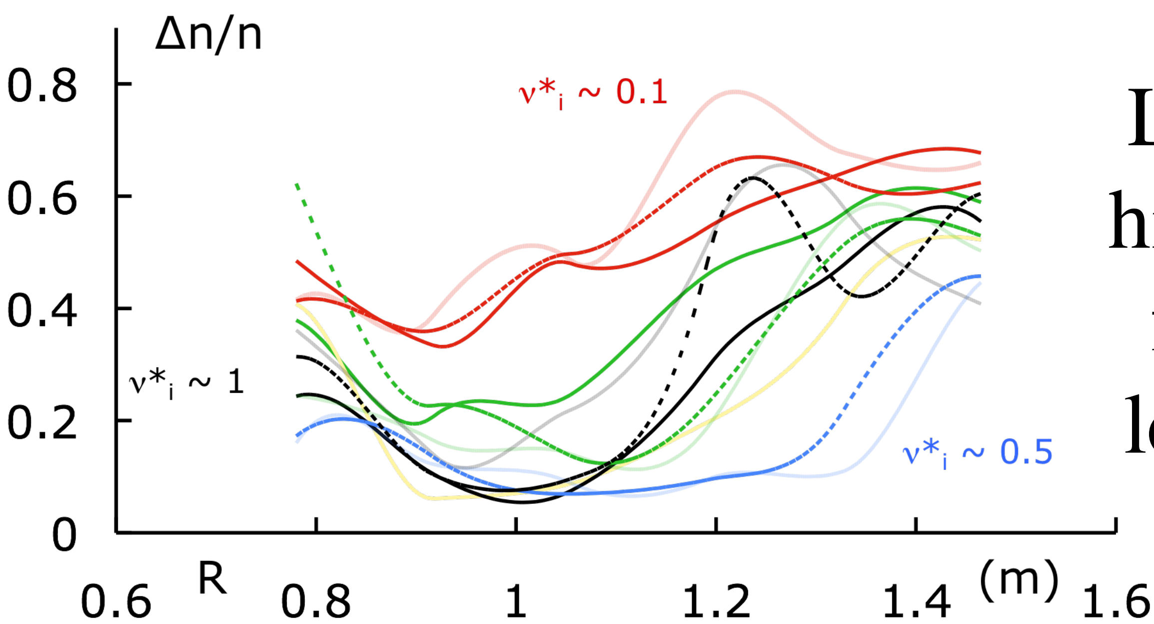
Exponential Fits



Turbulence Levels

Levels increase slightly with connection length

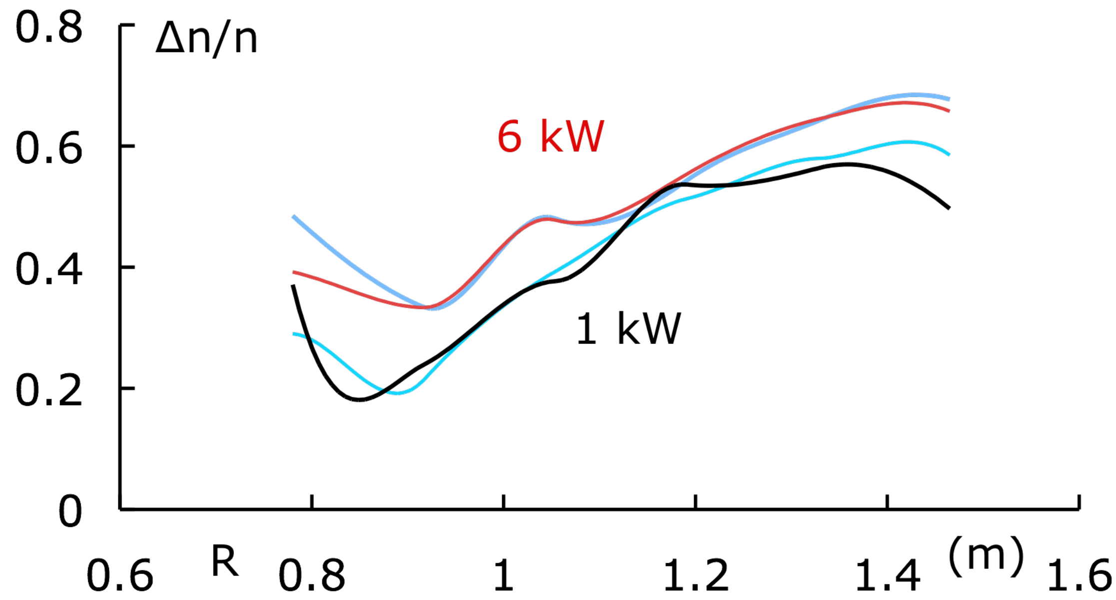


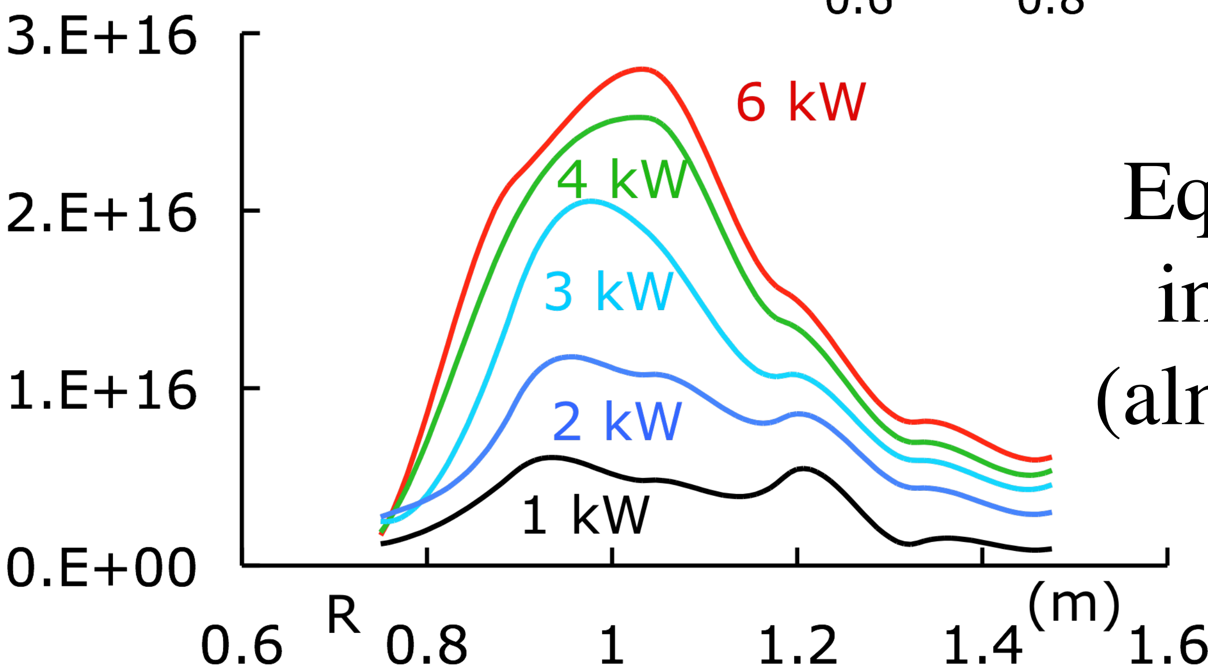


Levels decrease at higher collisionality for all connection lengths (50-200 m)

Turbulence Levels

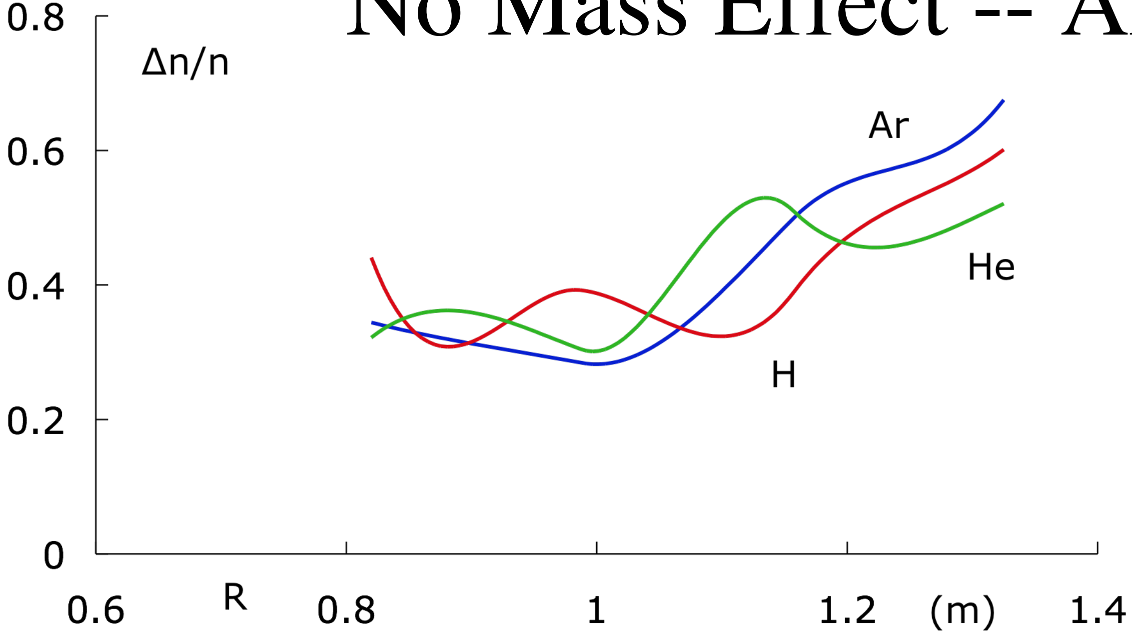
Levels increase slightly with power (density)





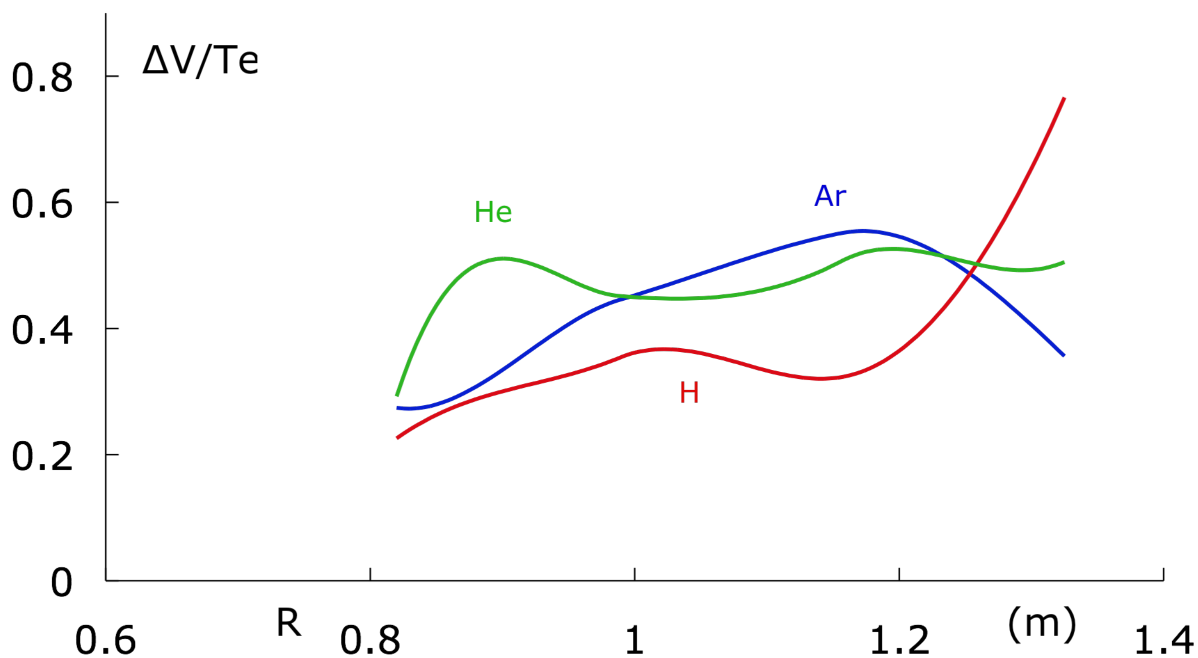
Equilibrium density increases strongly (almost linearly) with power

No Mass Effect -- Ar, He, H similar



Neither density nor floating potential fluctuations vary with ion mass

No ρ* or ρ_s/L_n dependence



V_z (Poloidal) Flows -- Zonal Flows ?

Theory and simulations ⇒ Turbulence "interchange-like": Zero frequency, non-propagating in plasma frame ⇒

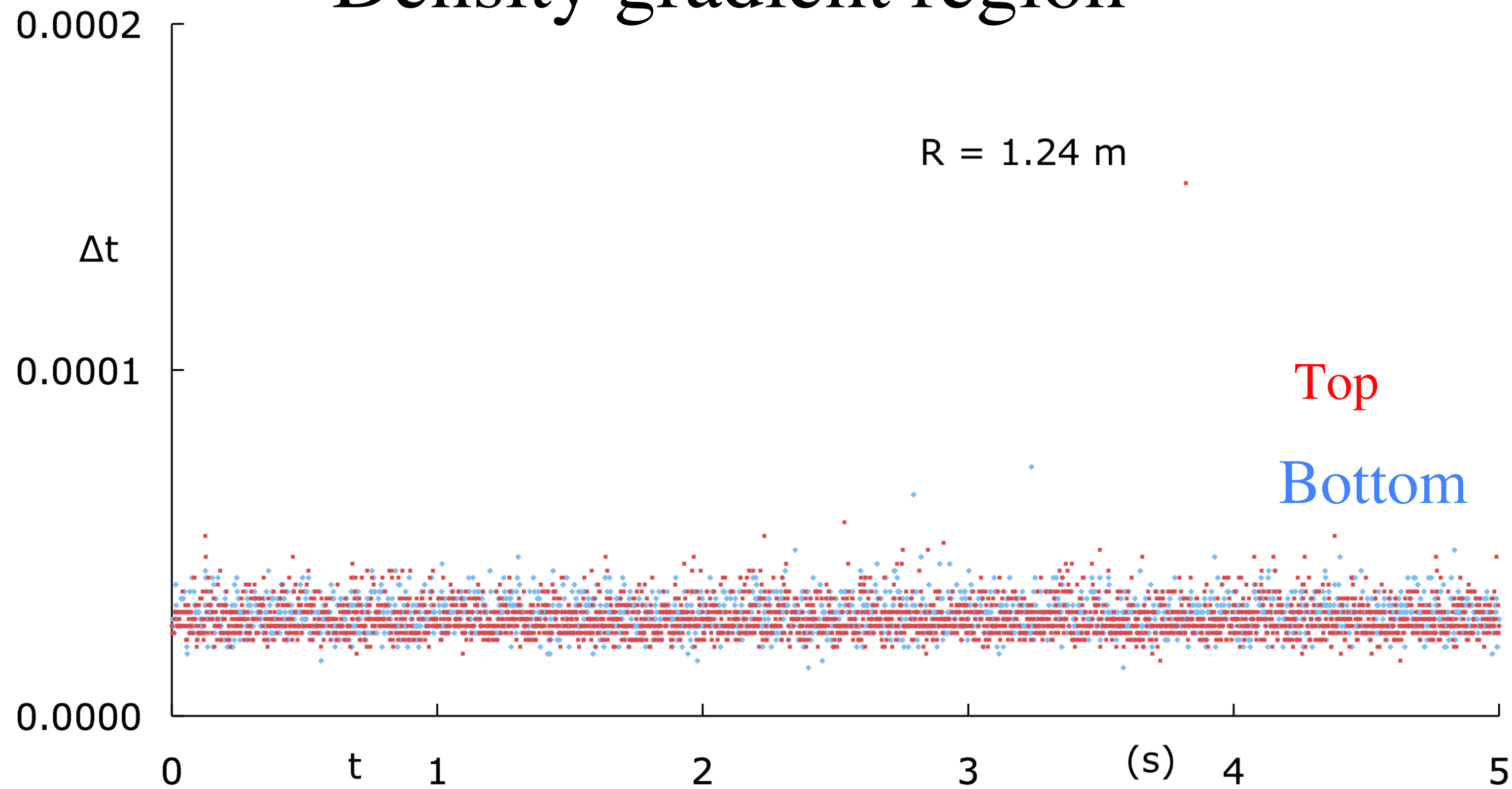
Apparent propagation indication of flow

V_z inferred from density fluctuations at probe pairs Δz= 0.04 m at top and bottom for various R: Cross-correlation and cross-phase over 10s sample, and cross-correlation over sequence of 1 ms sub-samples.

Zonal Flows -- Essential Characteristics

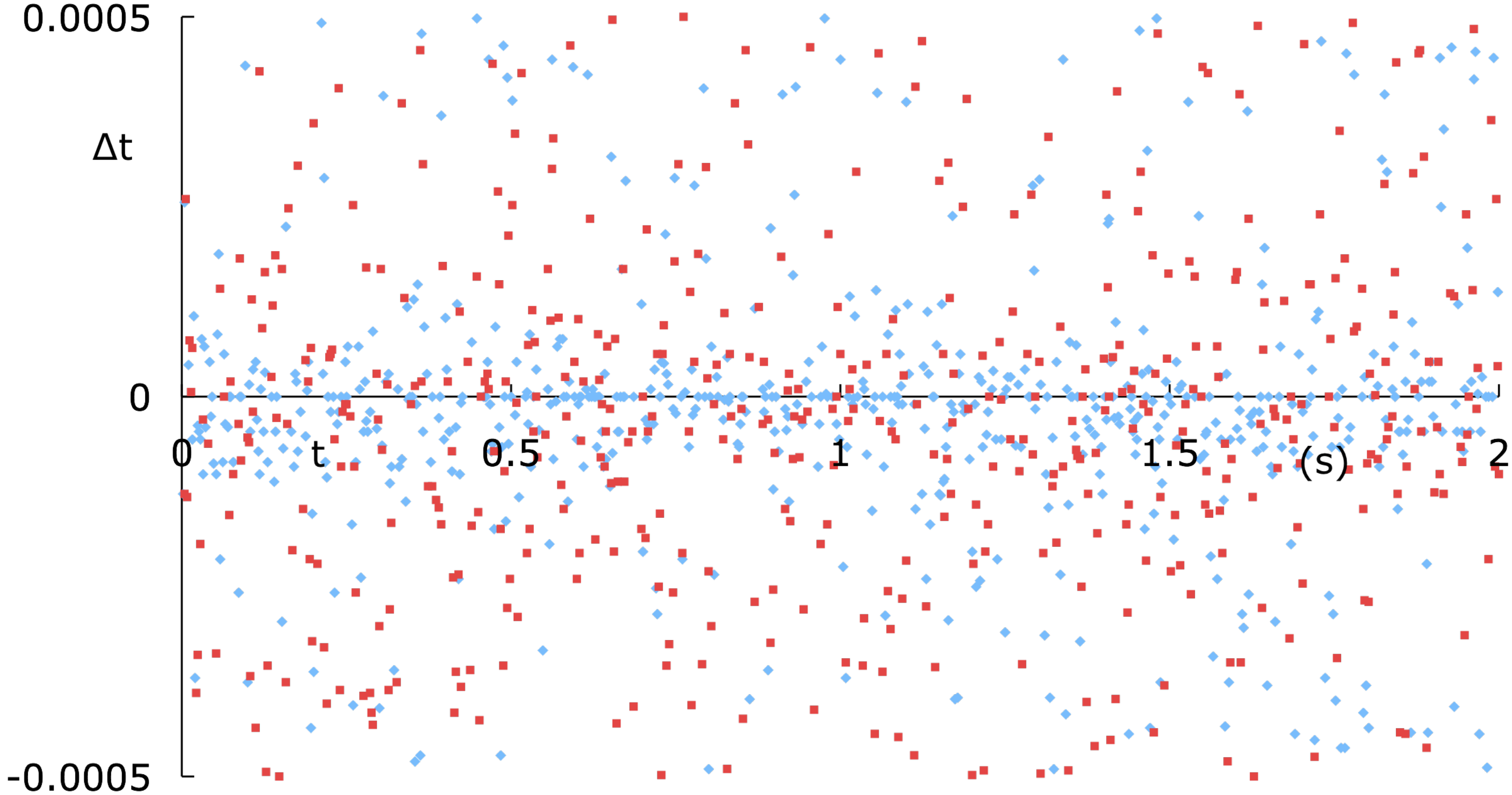
- Flow "m=0; ω=0" Same at top and bottom
- May vanish over 10s ($\sim 10^5\ \tau_{decorrelation}$)
- Should be clear and slowly varying in sequence of 1 ms subsamples ($\sim 10\ \tau_{decorrelation}$)

Density gradient region



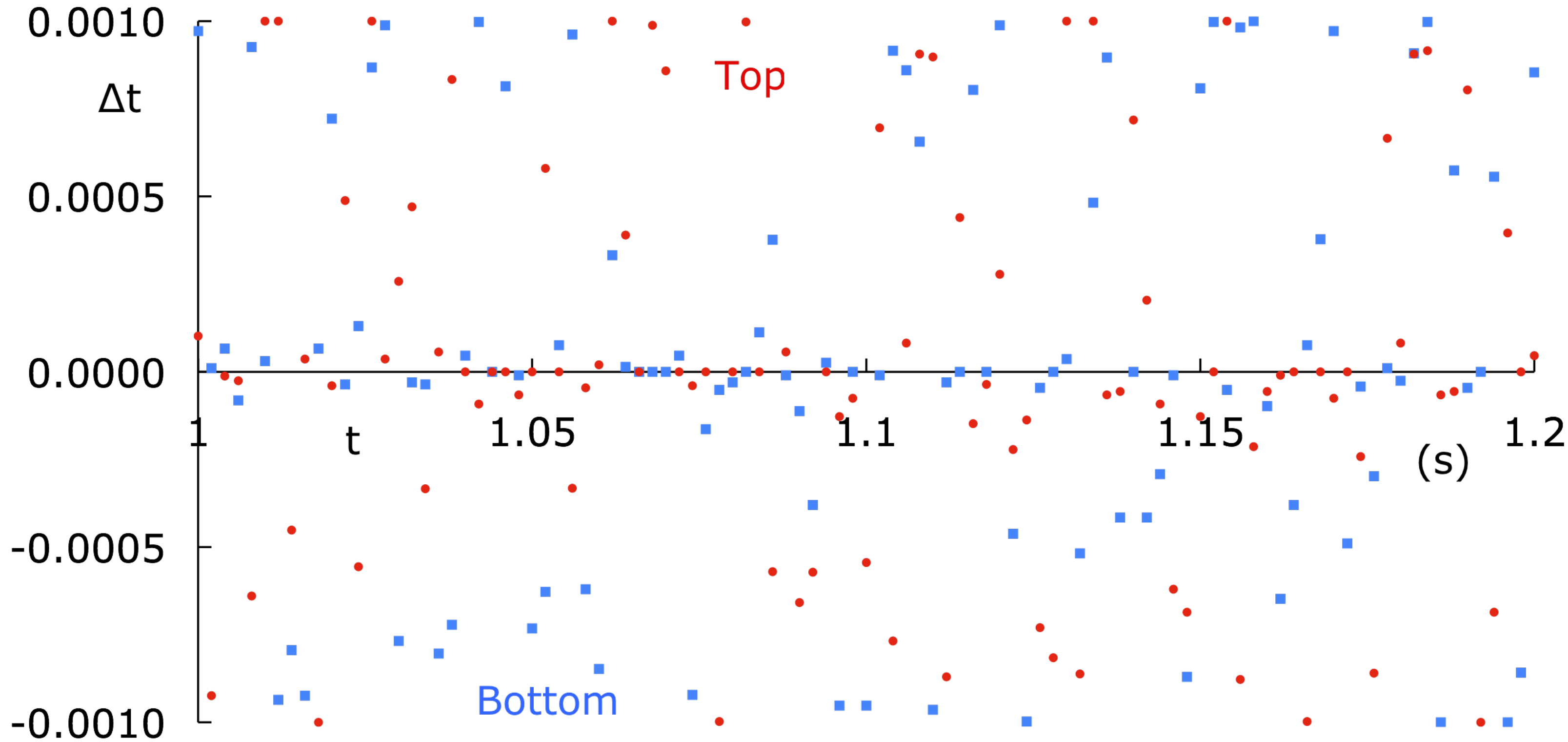
- Clear mean flow -- well-defined delay time Δt, consistent top/bottom
- No secular variation
- Small, fast random variations about mean -- local turbulence

Near Density Peak (R = 1 m)



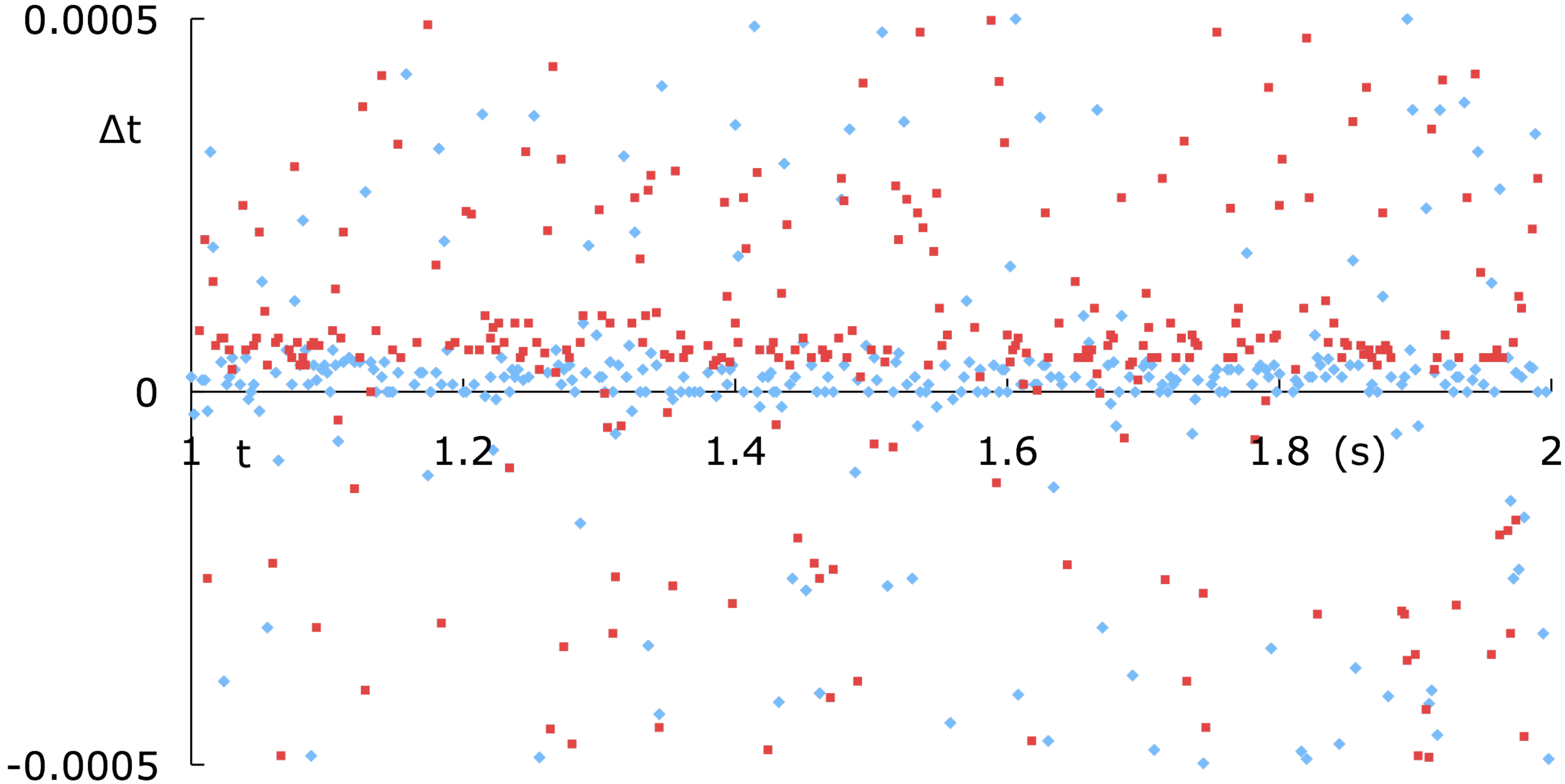
No mean flow; only local turbulent fluctuations. Fast, random variations in delay times; top and bottom independent.

Near Density Peak (R = 0.9 m)



Some clustering at $\Delta t=0$ ($V_z \sim 0$), but mostly fast-changing, random turbulent variations with top and bottom independent.

Near Density Peak (R = 0.9 m, + Bias)



Some clustering at $V_z \sim 1000$ m/s, but methods and top/bottom differ somewhat, and substantial fast, random scatter.

➡ Strong <u>turbulent</u> modification of mean flow.

General Flow Characteristics

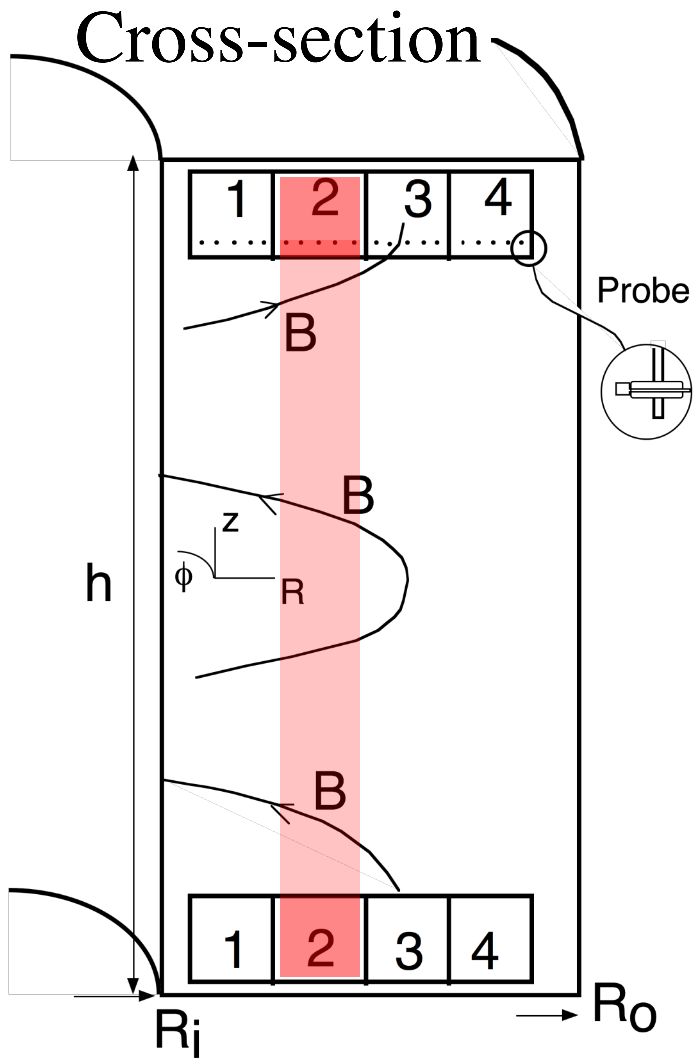
- In the density gradient region ($R \geq 1.2$ m), well-defined mean bulk flows $<V_z(R)> \sim 1000$ m/s, consistent top/bottom by all measures with no secular or shot-to-shot variation and small, fast random variations about mean in the sub-samples.
- Near the density maximum ($R < 1.2$ m), flows less well-defined. Most often, no mean flow, no top-bottom consistency, and random fast variation in sub-sample times -- flows are local turbulent motion.
- <u>Never</u> a characteristic zonal flow -- a clear flow but with secular or shot-to-shot variation. <u>All flows are mean equilibrium bulk flows.</u>

Application of Bias

- Field lines terminate on isolated end plates

- Biasing one set (set 2 for data shown) with respect to others biases annulus of field lines, imposes radial electric field, current

- Other plates and vessel grounded

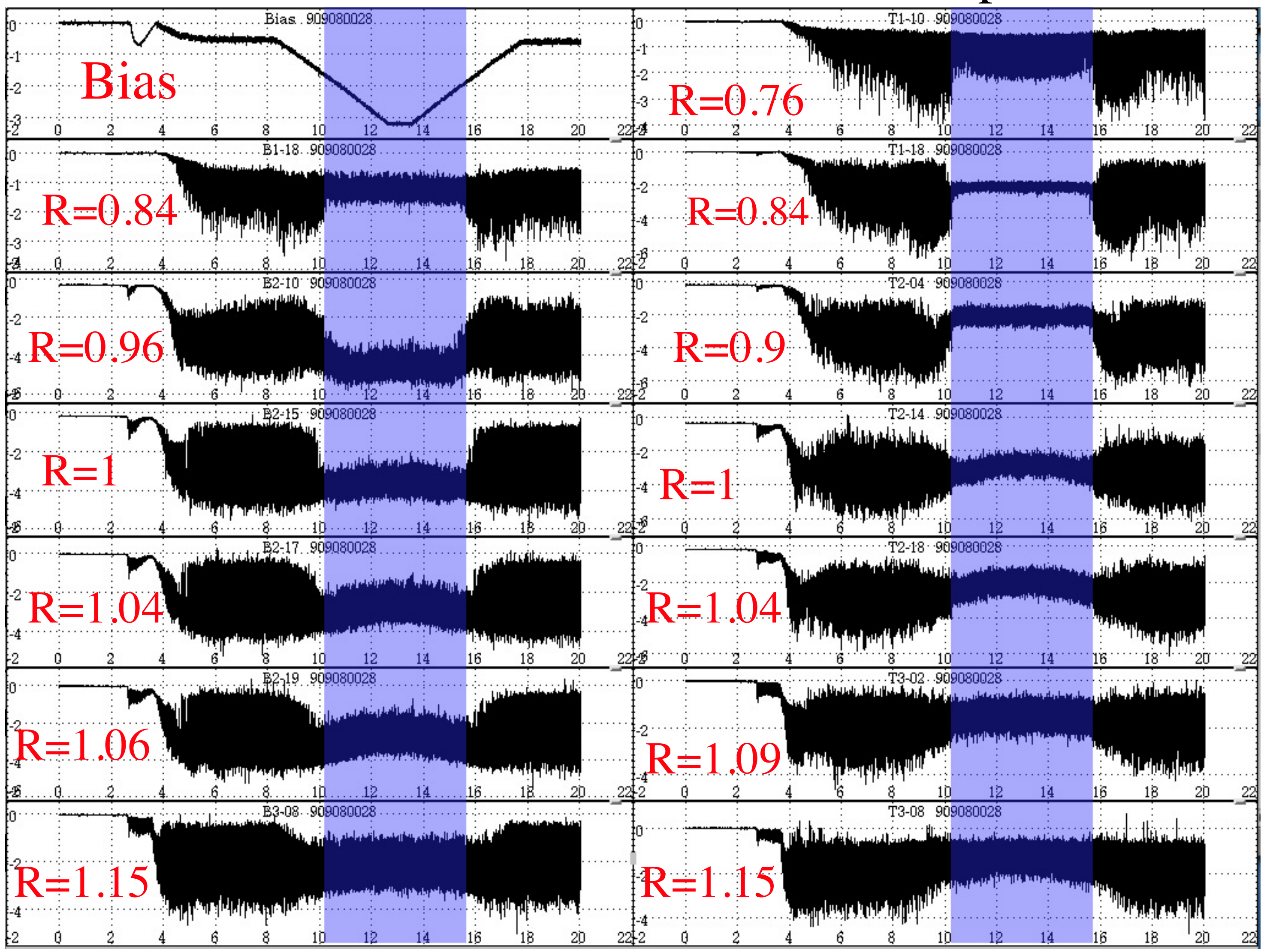


Simple Phenomenology

$I_{sat}(t)$ -- $\propto n(t)$ -- from probes across radial profile

Negative Bias Transition at ~-20 V

Bottom　　　　Top



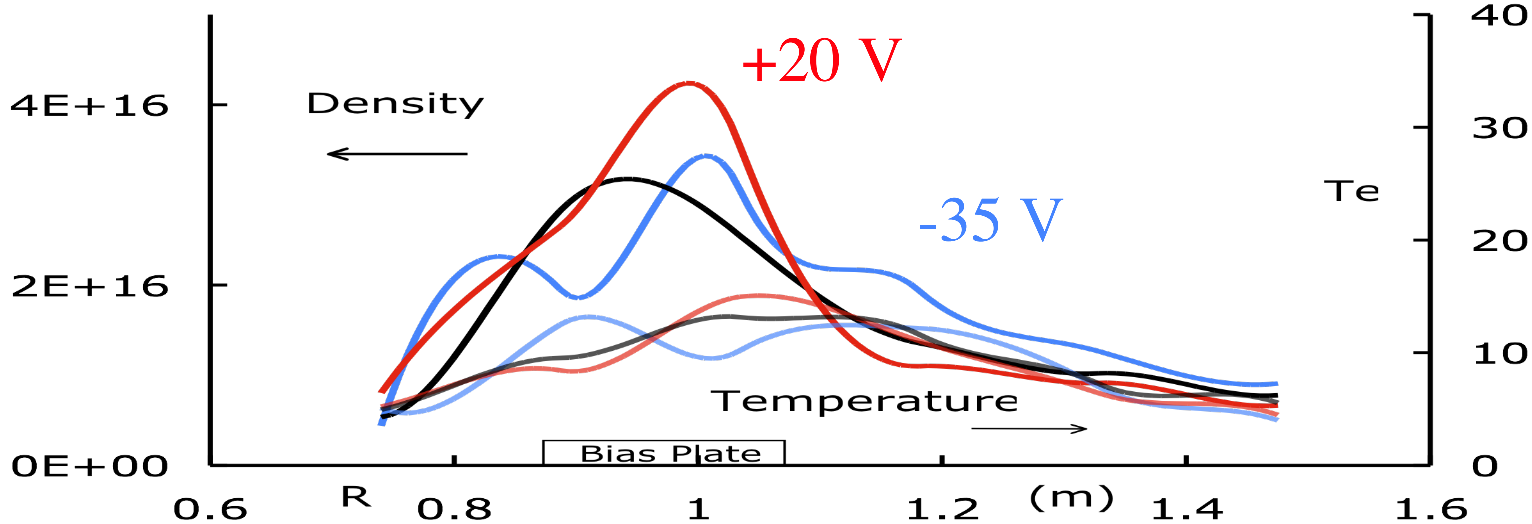
Bias-Driven Turbulence Reduction

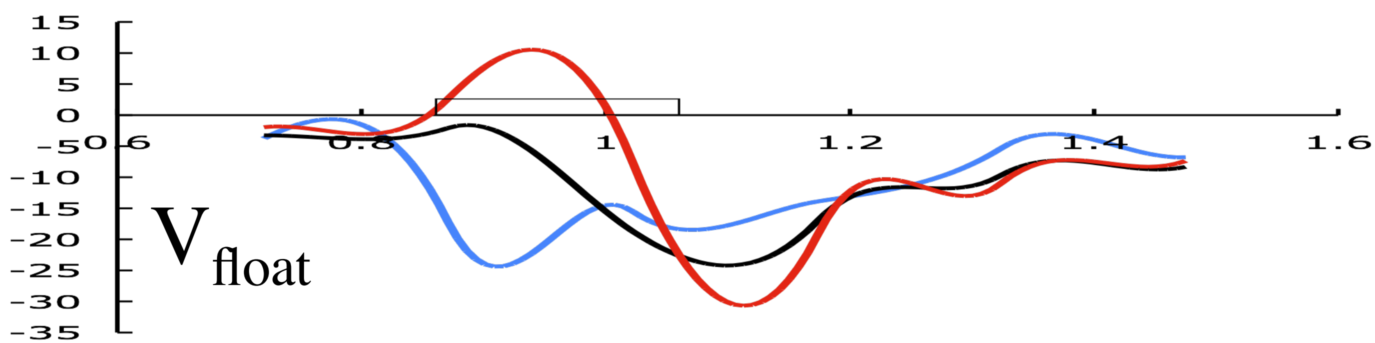
- Applying bias above a threshold reduces the turbulence level
- The reductions occur across much of the profile
- The changes occur without hysteresis
- Reductions occur for both positive and negative bias in argon, helium, and hydrogen over a range of collisionality and connection length

Bias experiments are limited to $L_{||} \geq 40$ m.   (Short connection length requires field lines with high pitch. Not all field lines terminate on the bias plates for high pitch. Reductions are generally observed even in these cases, but the interpretation is uncertain.)

Profile Changes with Bias

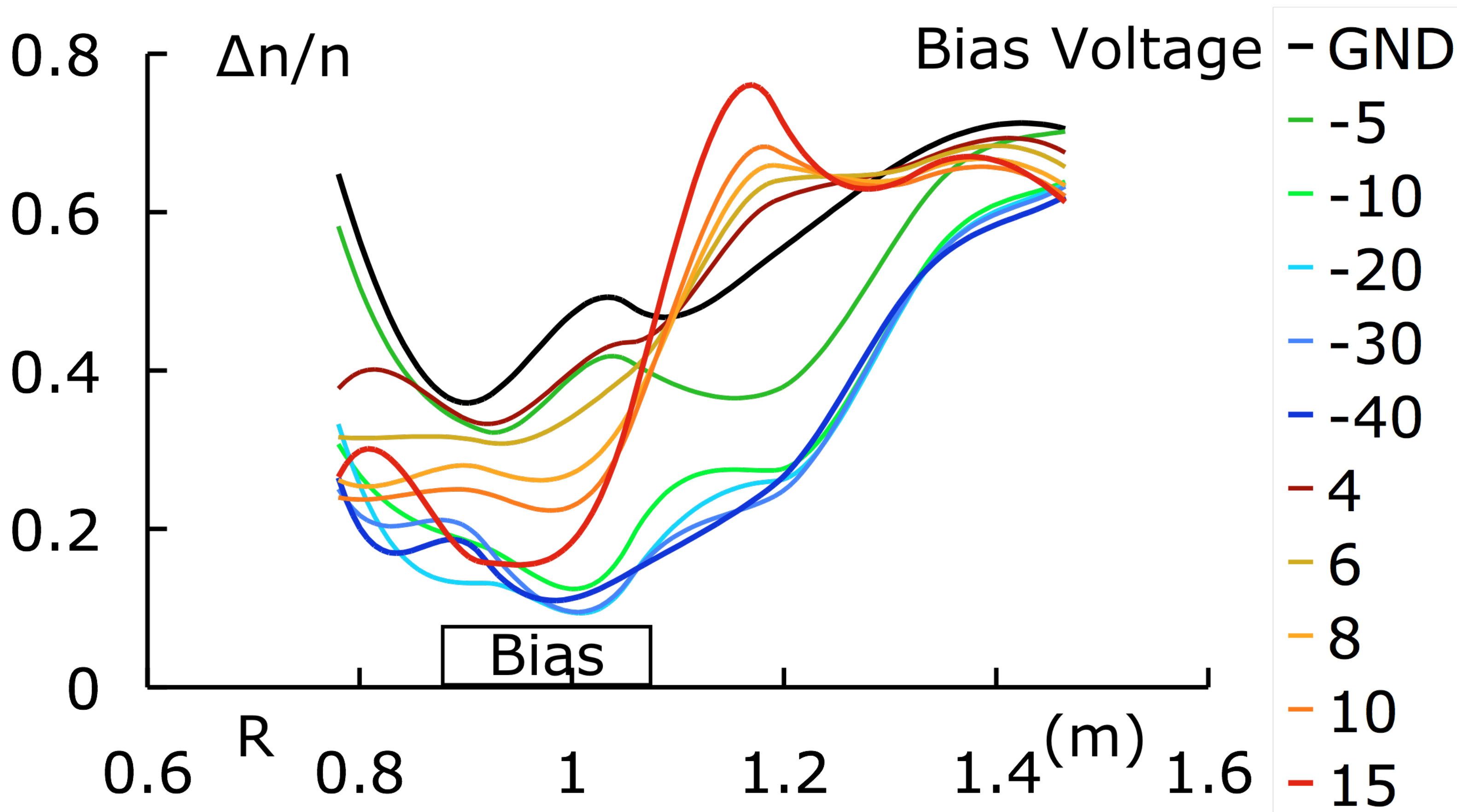
Positive, Negative, Zero Bias



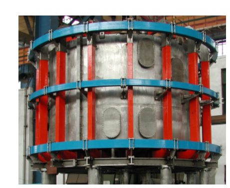


- Temperature ~ constant; density changes modest
- Potential change at plate as expected
- Effects extend outward from plate, esp. negative bias

Density Fluctuations

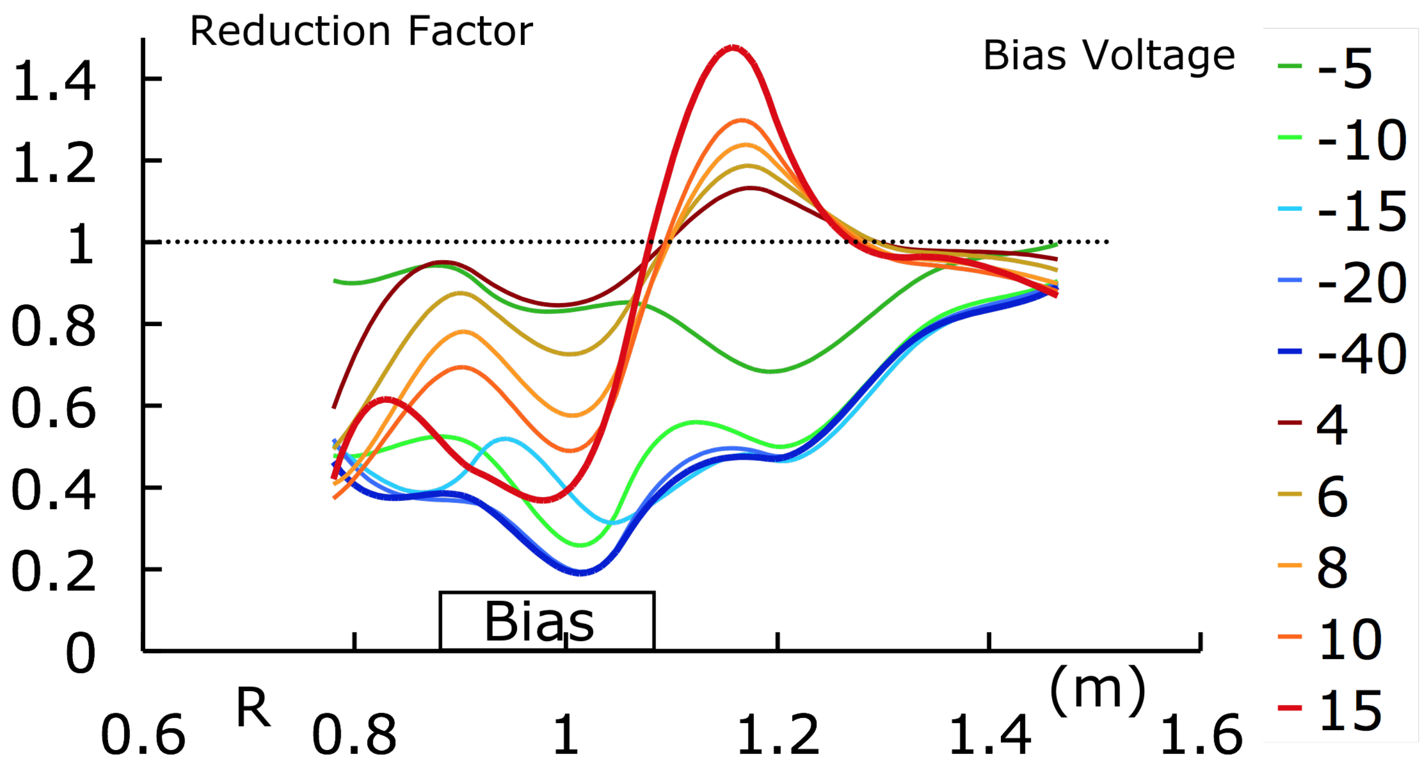


- Reduced across plate
- Effect extends outward for negative bias



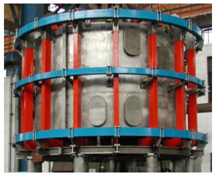
Turbulence Reduction -- Density

Reduction = Δn/n(Bias)/Δn/n(Grnd)



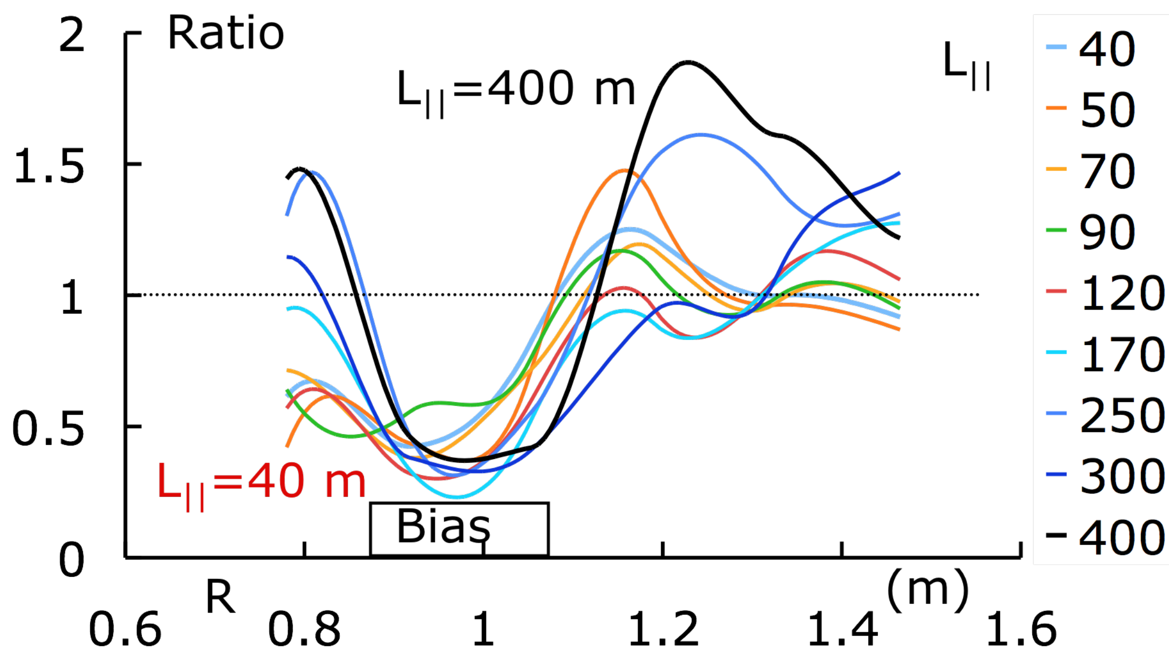
Suppression completed by -20 V

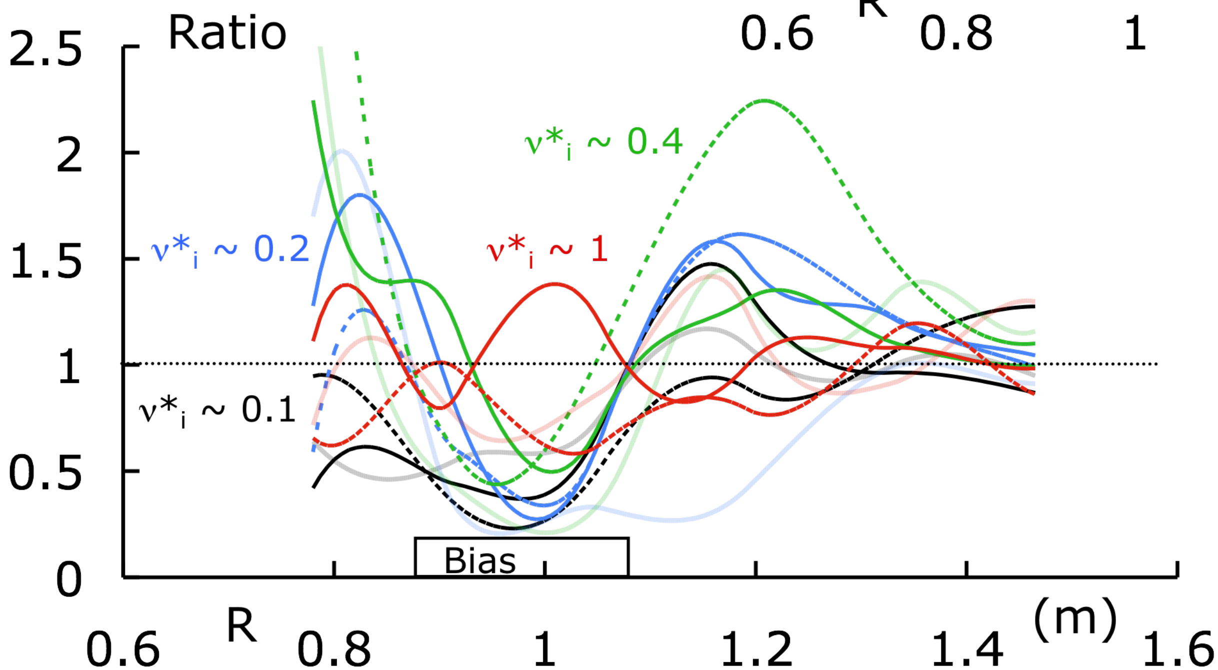
$L_{||}$ = 50 m



Turbulence Reduction: Positive Bias

Weak dependence on connection length

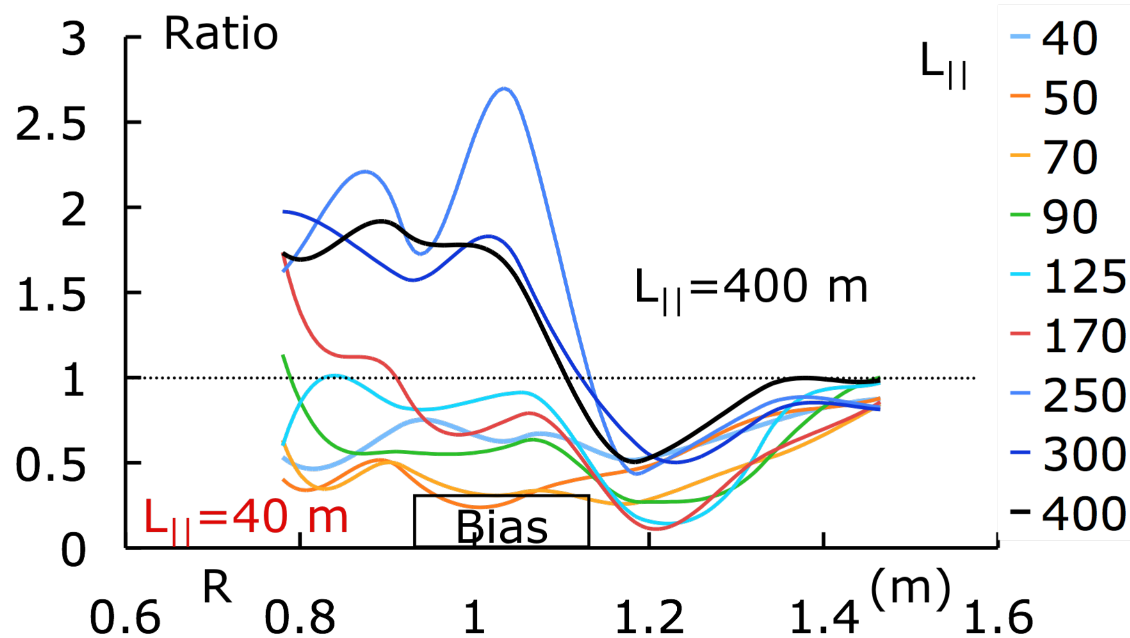


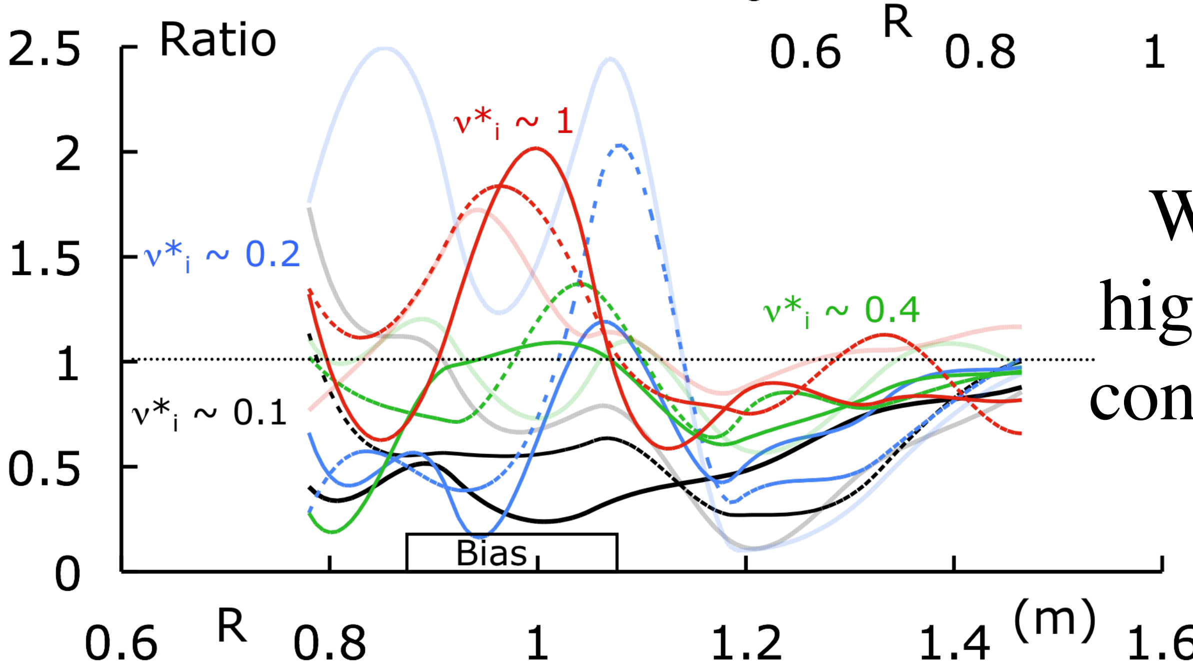


Reductions weaker at highest collisionality, otherwise little effect

Turbulence Reduction: Negative Bias

Less reduction for long connection lengths, $L_{||} \geq 200$ m. Optimum depends on location.

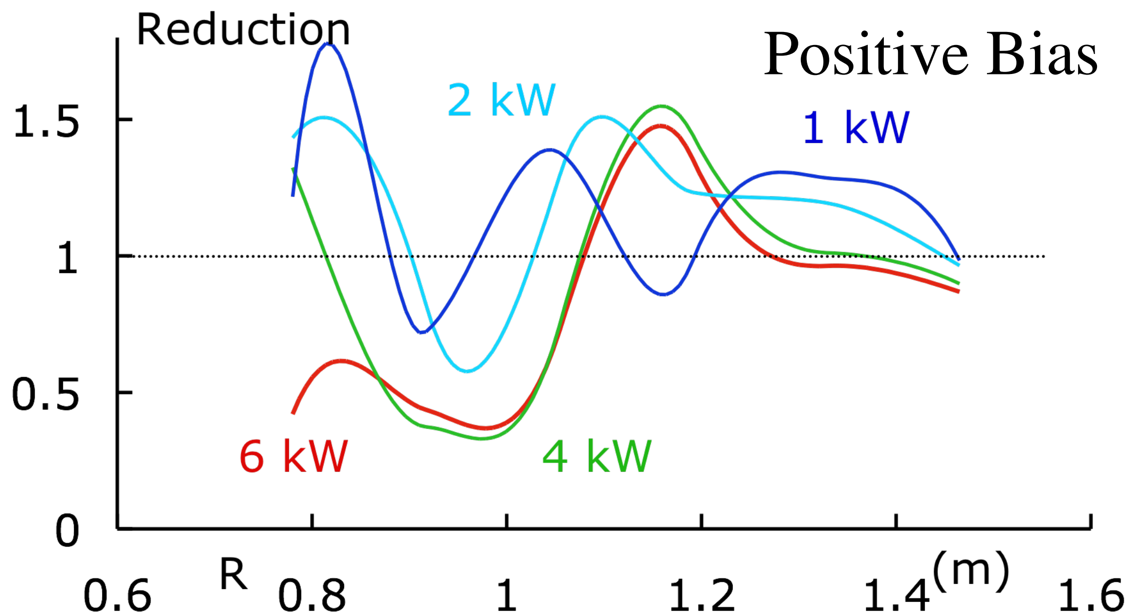


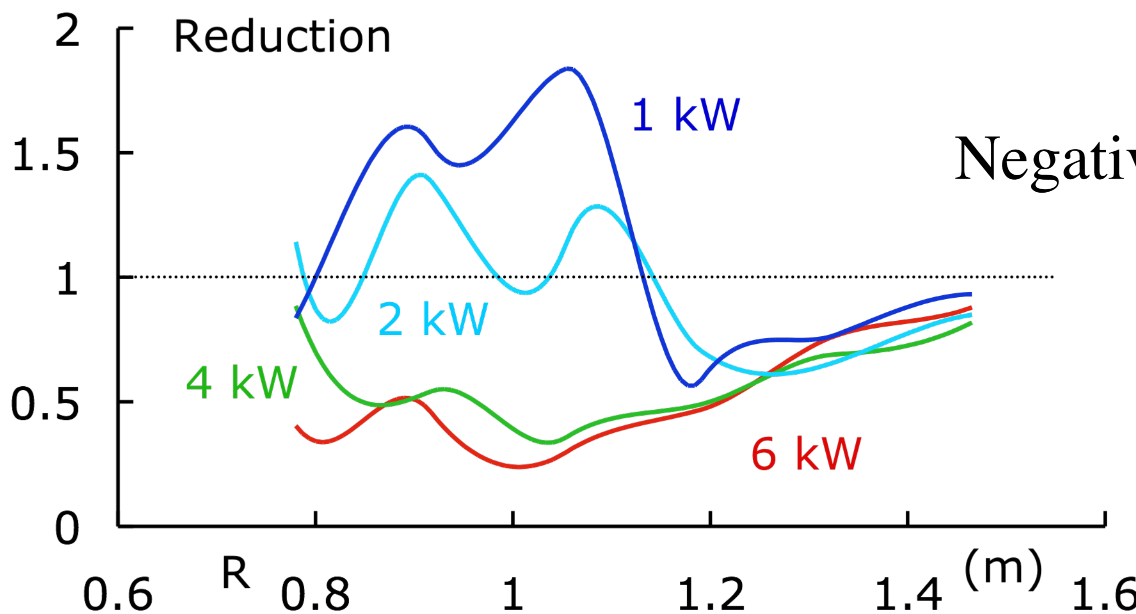


Weaker reduction at higher collisionality for connection lengths from 50-200 m

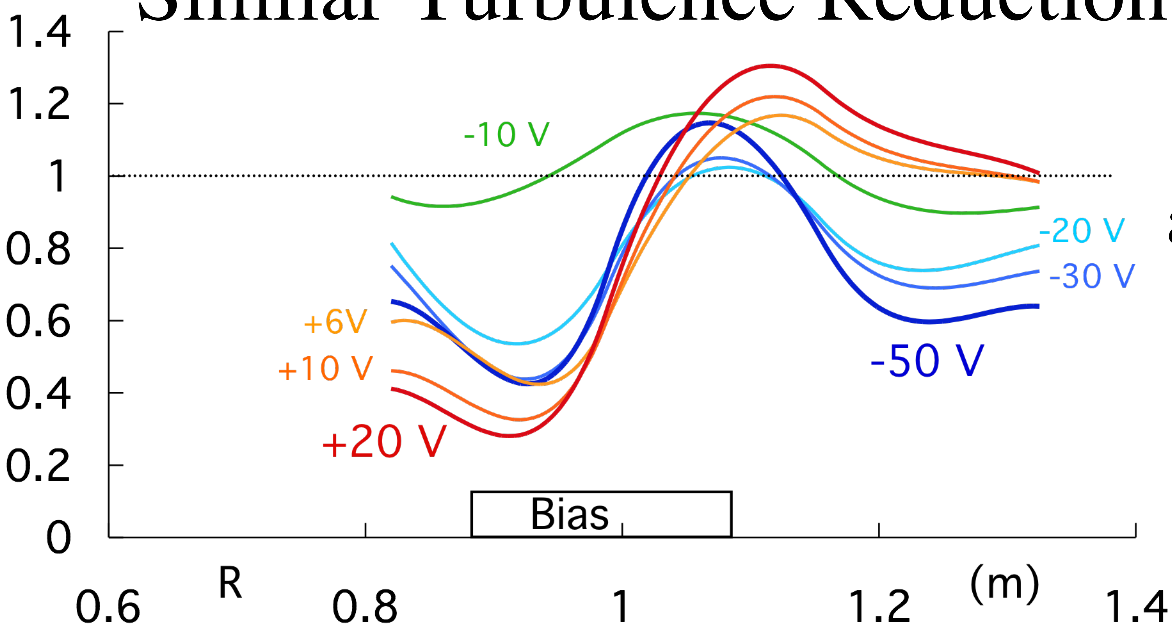
Turbulence Reduction: Power

Effect disappears at low power (density)



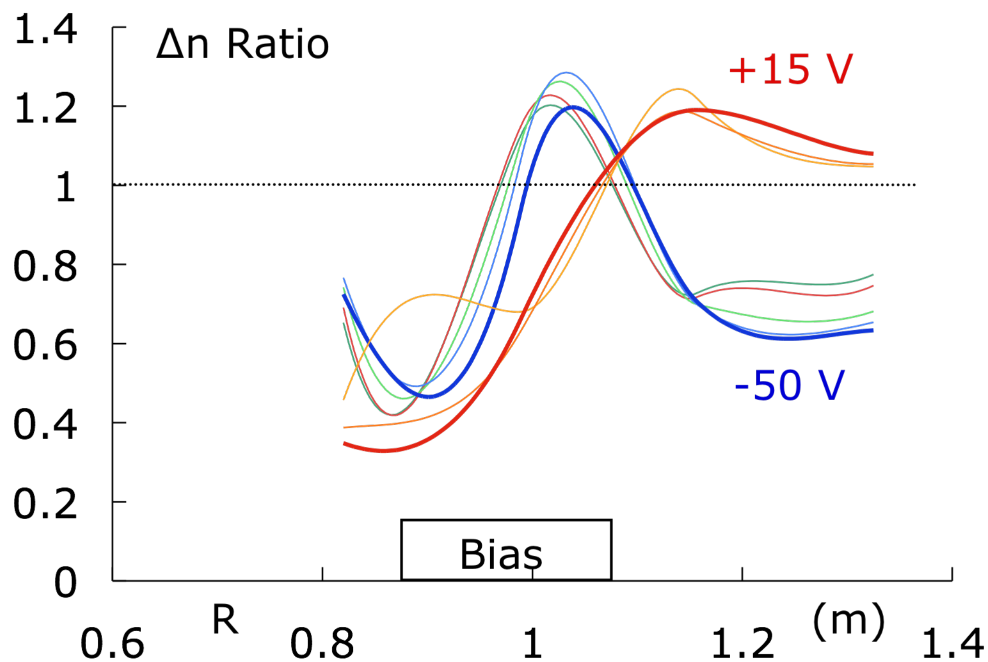


Similar Turbulence Reductions in H and He

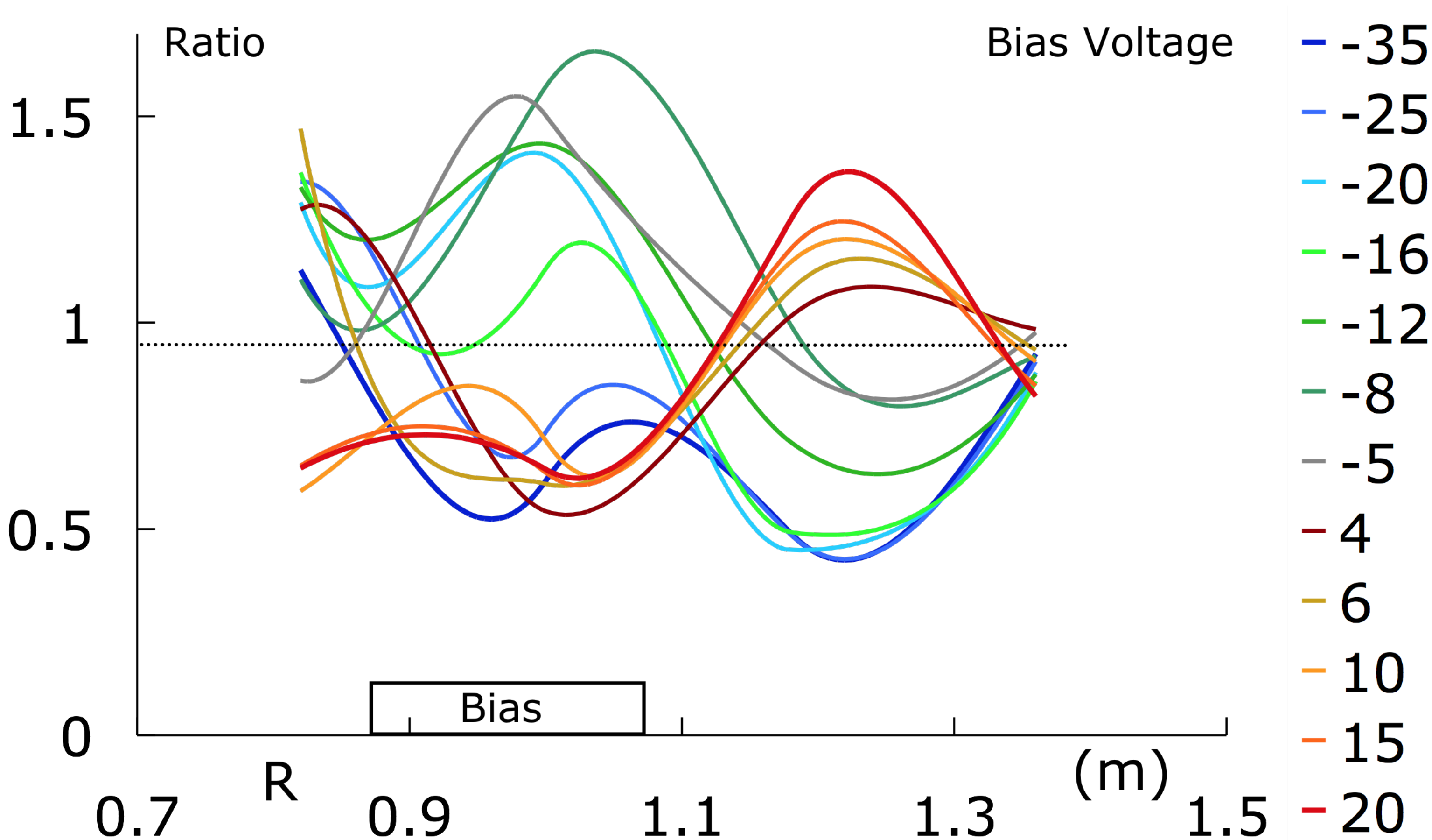


Hydrogen at short $L_{||}$ and low collisionality similar to Argon, but parameter range limited

Helium at short $L_{||}$ and low collisionality similar to Argon, but parameter range of effect more limited

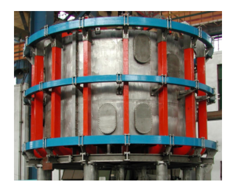


Change in Radial Correlation Length



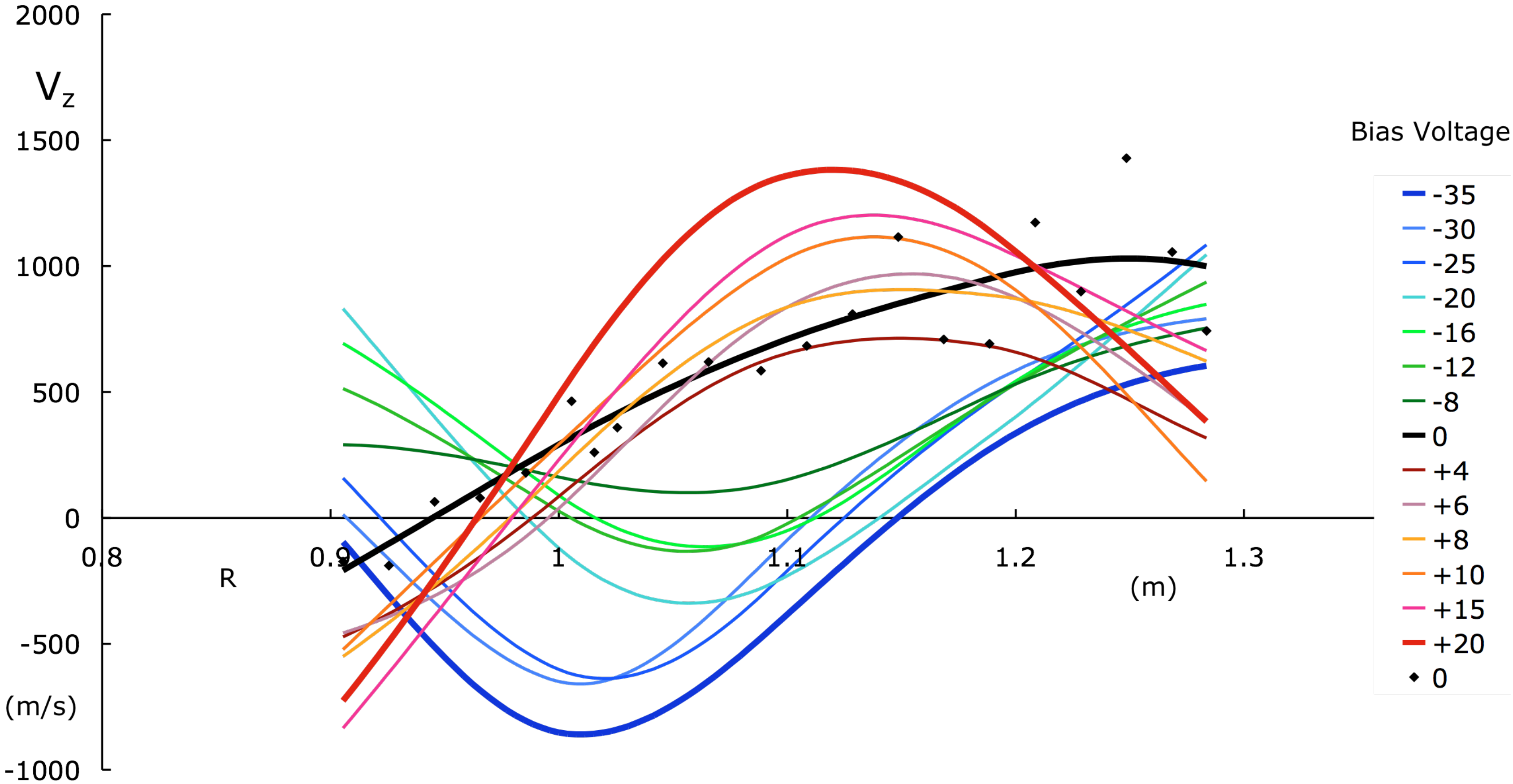
Change in radial correlation length generally follows change in turbulence level

$L_{||} = 40$ m



Measured Flow Velocity

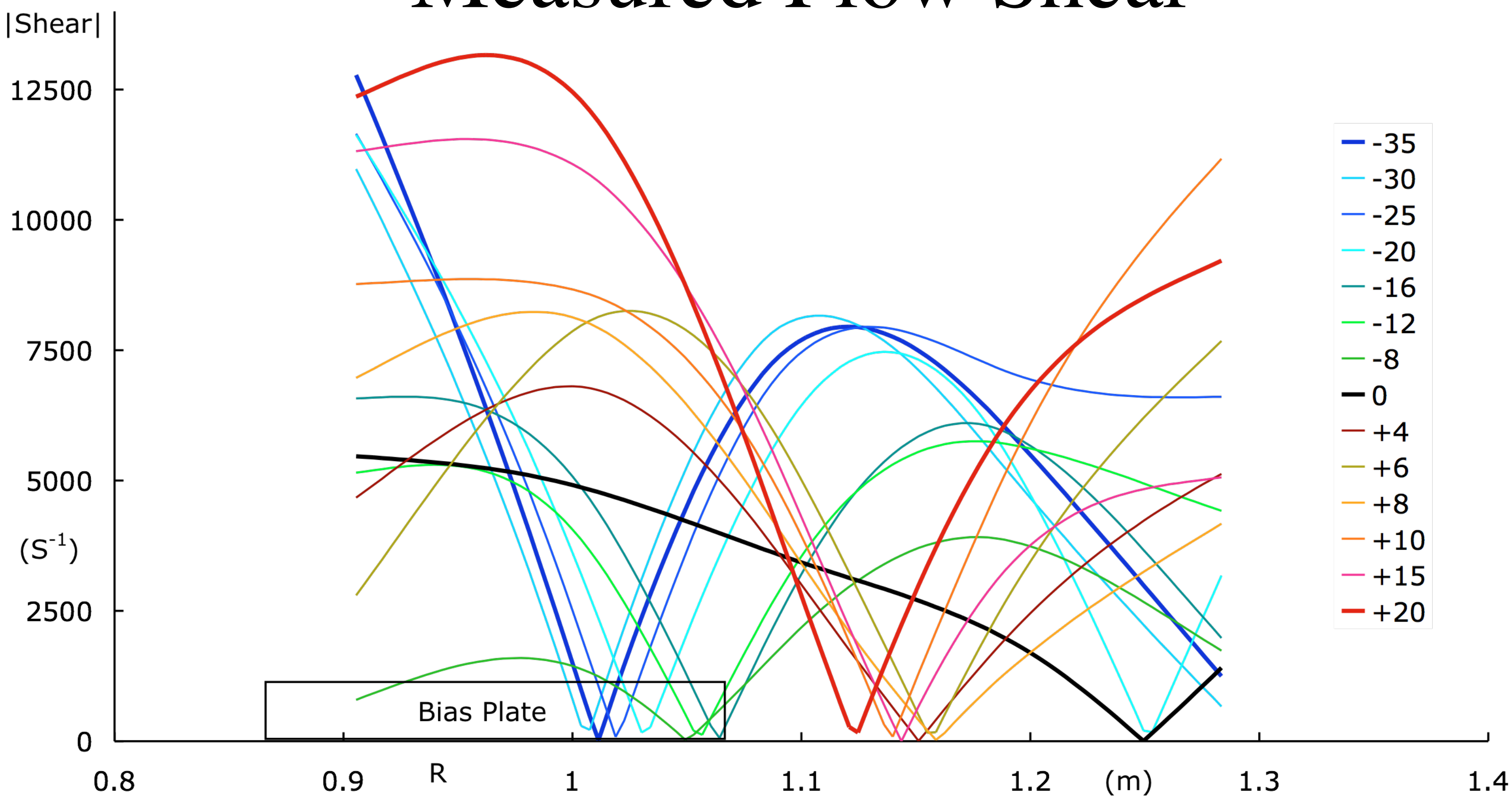
Ion Doppler Velocity for Argon -- The Plasma Ion



Spline fits with data points for 0 bias case

$L_{||} = 40$ m

Measured Flow Shear



- Shear increases greatest for + bias > +10 V
- Shear not greatly increased for - bias until -20 V
- Shear often not at locations needed

Applicability of Flow Shear Model*

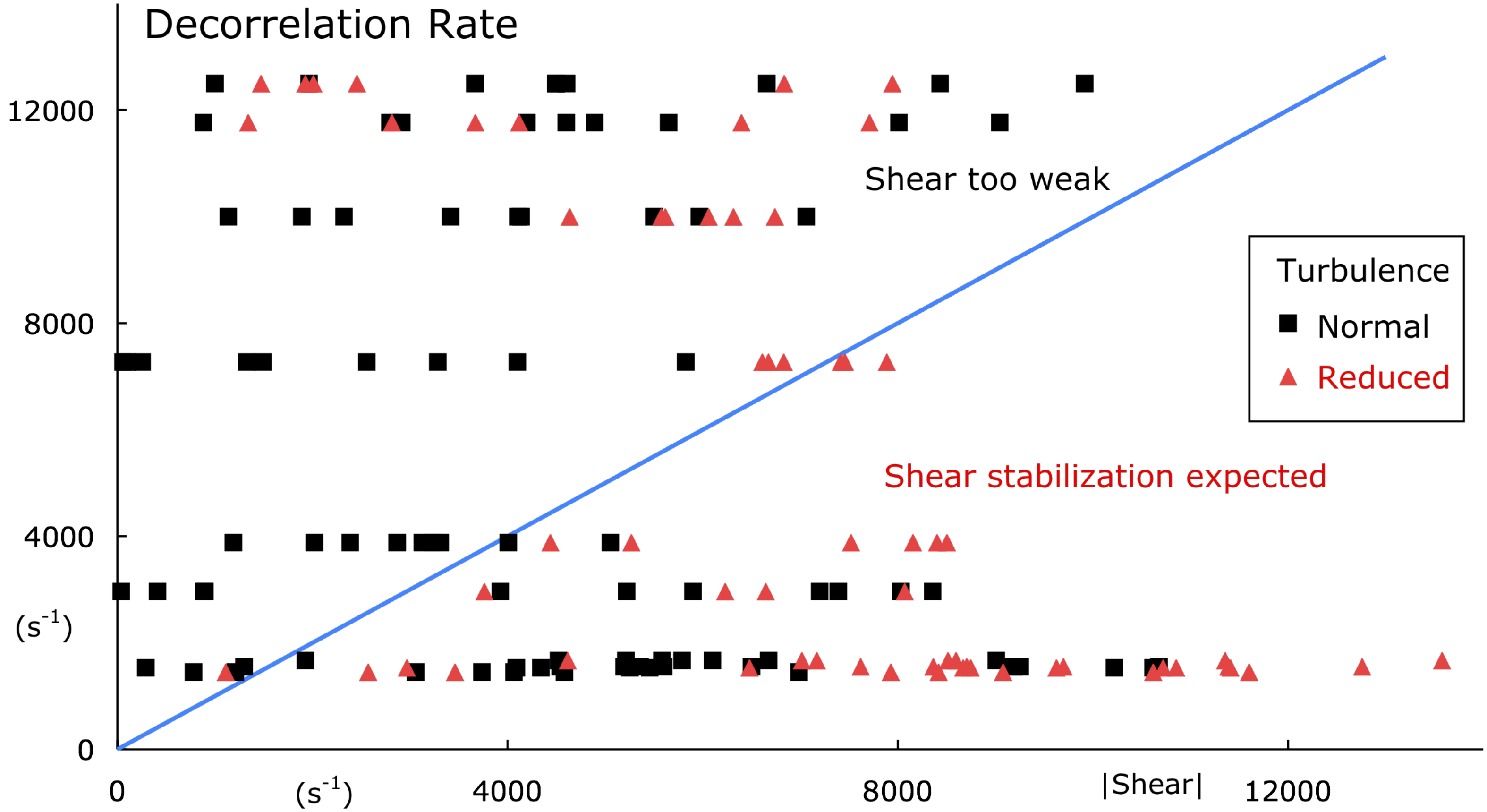
Flow shear will stabilize fluid turbulence under minimal, very general conditions, which are met in these experiments. Mechanism is local and can be tested at all locations in the plasma.

- The system is two-dimensional, e.g. a magnetized plasma.
- The turbulence remains in the shear flow long enough to be affected. Here, the parallel loss rate (<500 s^{-1}) is much less than the shearing rate, even less at longer connection lengths.
- The shearing rate exceeds the instability linear growth rate. Here, the turbulence decorrelation rate (inverse autocorrelation time) represents the growth rate and is often less than the shearing rate.

* P.W. Terry, Rev. Mod. Phy. **72**, 109 (2000).

Decorrelation Rate vs. Shearing Rate

(All radii, all bias voltages)



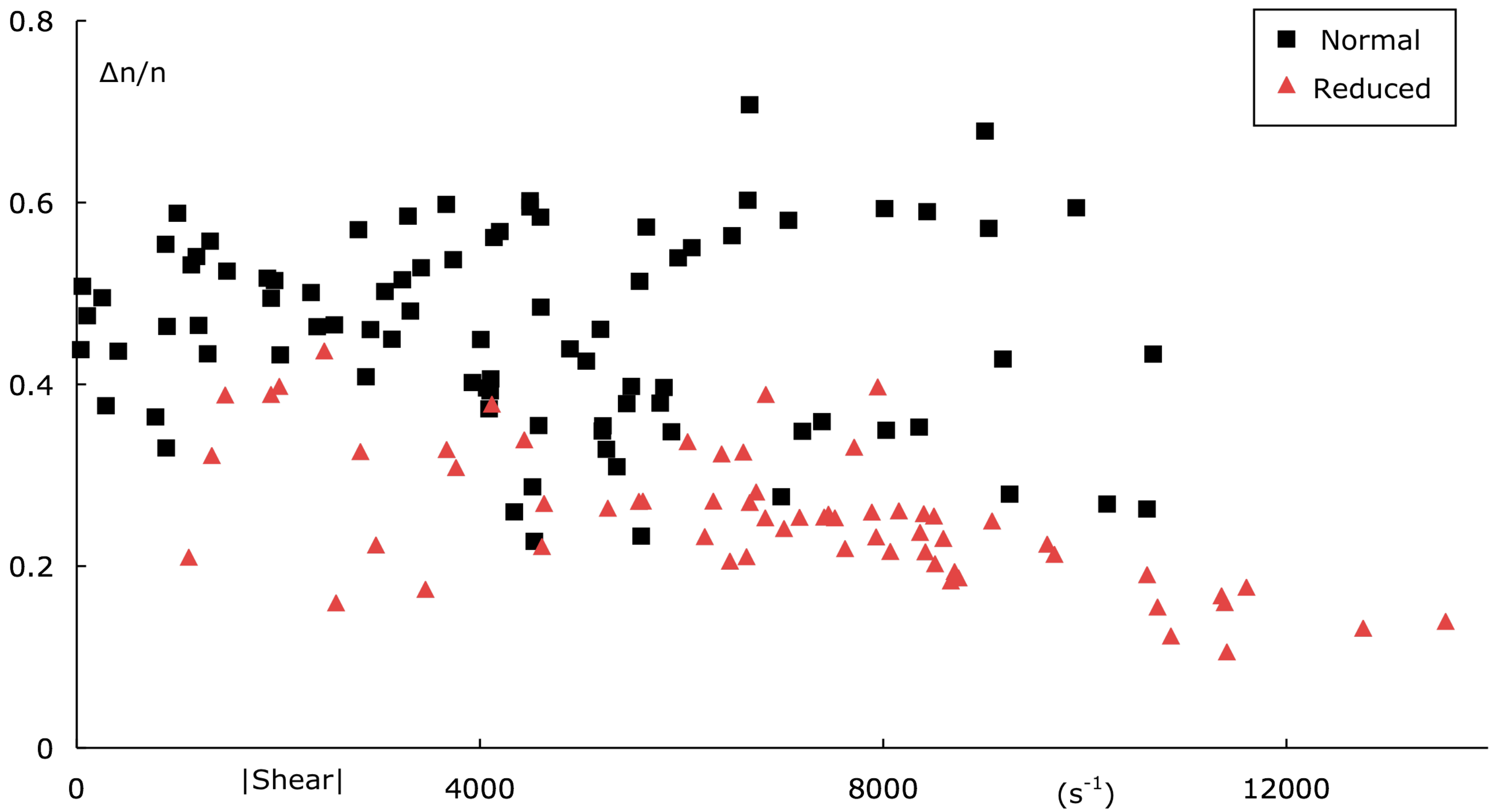
Shear often sufficient to stabilize turbulence in theory, but all combinations actually observed

Test of Turbulence Reduction by Flow Shear

A local model that links flow shear, radial correlation length, and fluctuation amplitude at each position: shear shortens correlation length, which reduces drive available. Experimentally, each linkage pair can be examined separately.   In theory, all couplings logically connected, but experimentally, the observations are independent (and subject to independent errors)! Couplings examined:

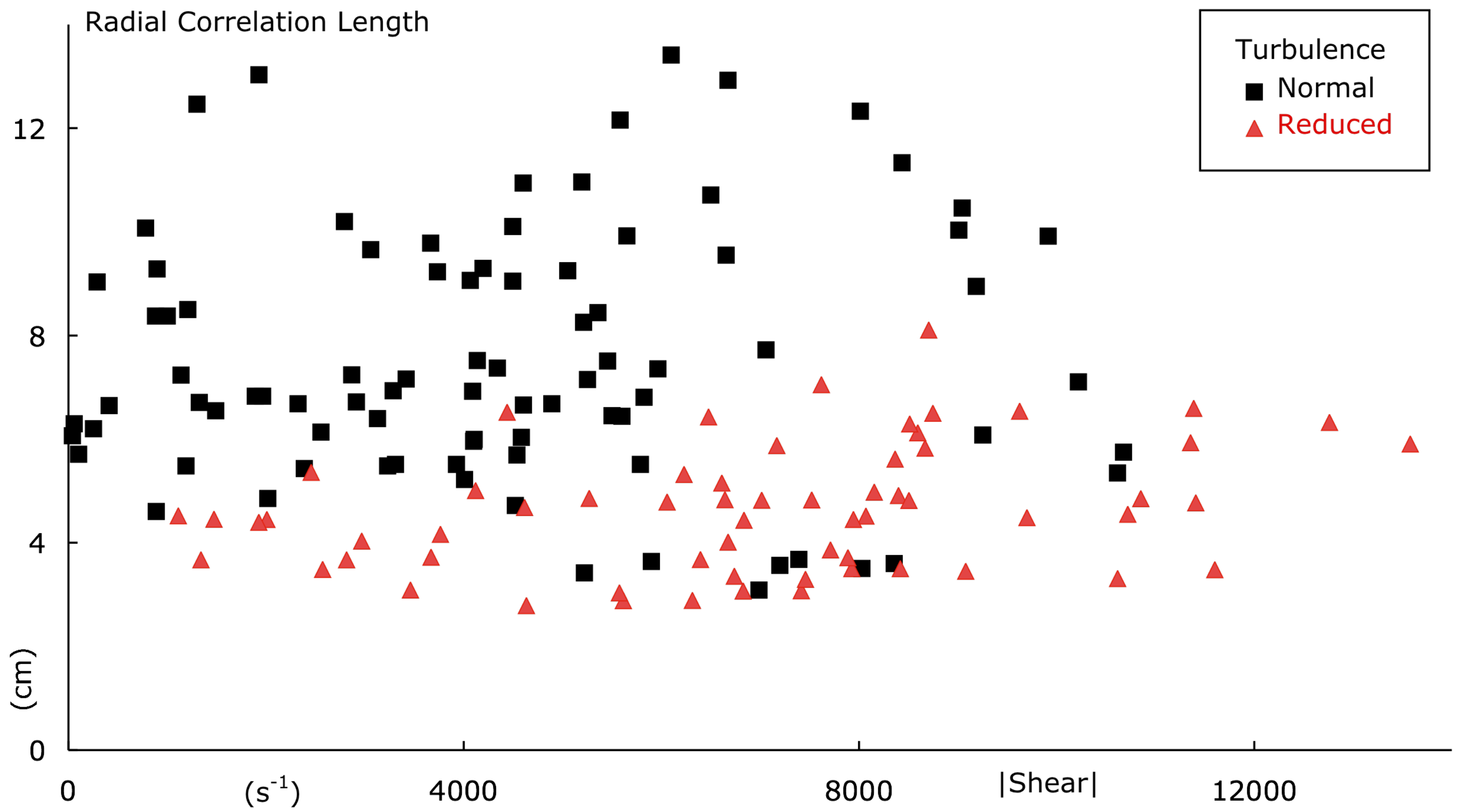
- Shear vs. Turbulent amplitude
- Shear vs. Correlation length
- Turbulent amplitude vs. Correlation length
- Amplitude reduction vs. Change in length

Shear Magnitude vs. Density Fluctuations



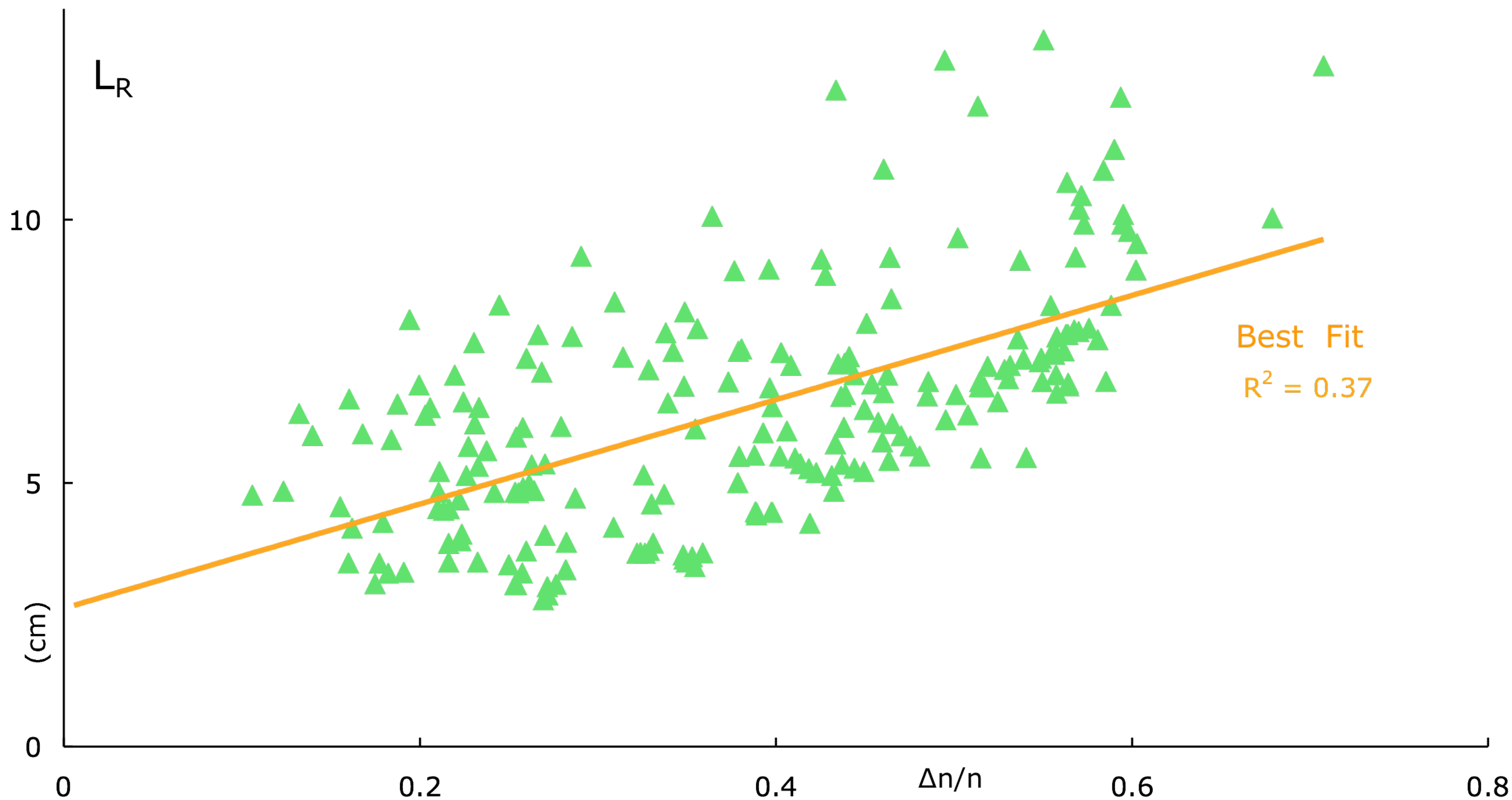
- No evidence for a general physical relation
- Turbulence reductions even at low shear
- High turbulence may persist at high shear

Shear vs. Radial Correlation Length



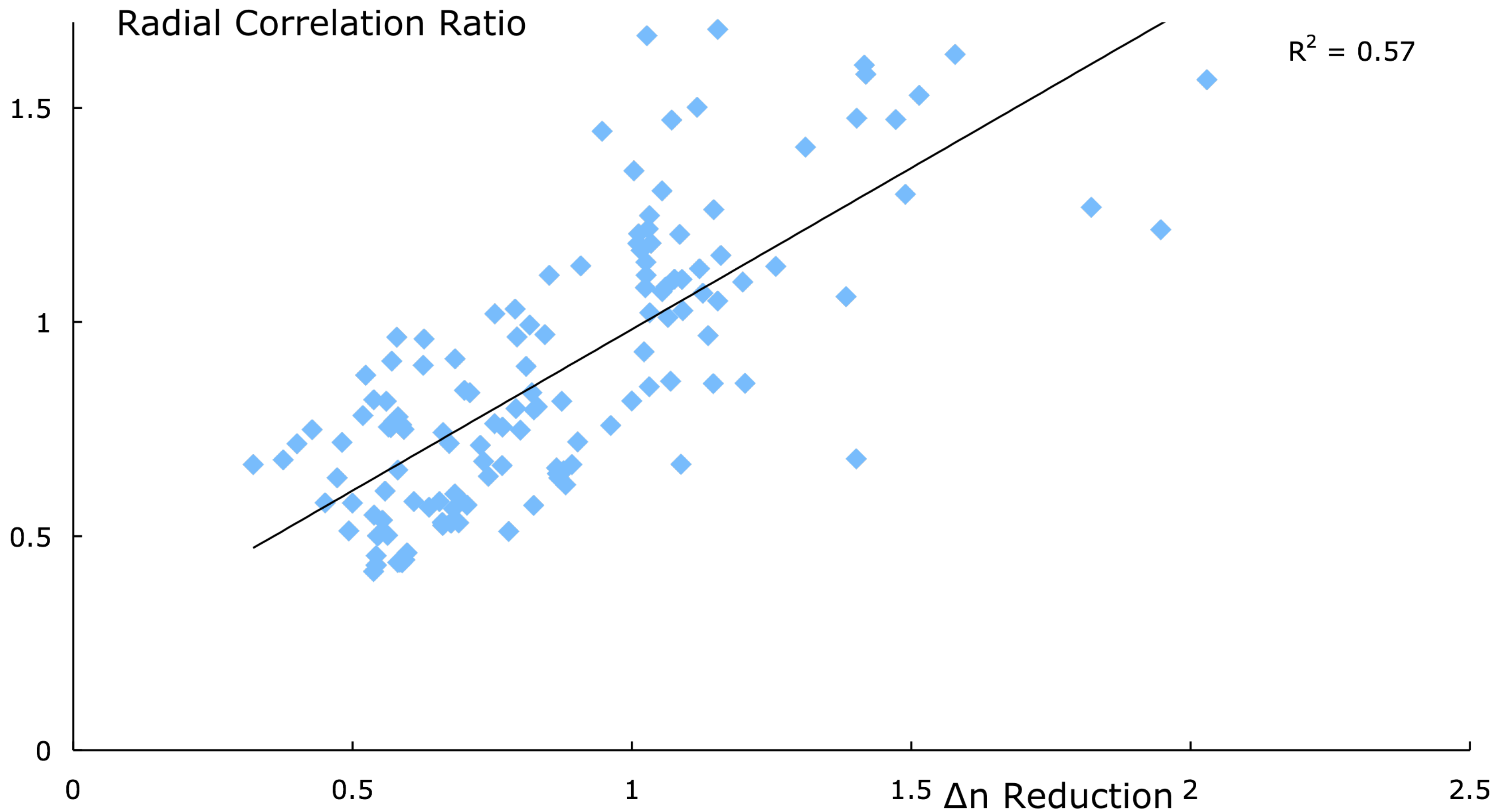
- No evidence for a physical relation
- No trace of inverse trend

Density Fluctuations vs. Radial Correlation Length



Trend correct, but large scatter and modest significance

Turbulence Reduction vs. Change in Length



Change in radial correlation length <u>roughly</u> correlated with change in turbulence level

Why is the Helimak Different?

- Turbulence is interchange type -- very large amplitude and strongly nonlinear.

- Flow shear is a “self-fulfilling prophesy” in a tokamak -- a “flux-driven” system. The high thermal flux coupled with turbulence suppression $\Rightarrow$ steep gradients $\Rightarrow$ high flow shear.

- The Helimak is not (radial) “flux-driven.” Turbulence and radial transport can vary independently across the profile to give a clear test of the <u>local relation between flow shear and turbulence</u> for a range of conditions.

Numerical Experiment

- ❖ Two-fluid, fully nonlinear 3-D calculation
- ❖ Helimak geometry: size, shape, magnetic pitch
- ❖ Physical particle and heat sources and losses
- ❖ Equilibrium density and temperature profiles comparable with experiment

Differences from experiment: No magnetic shear, reduced M_i/m_e, idealized sheath boundary conditions.

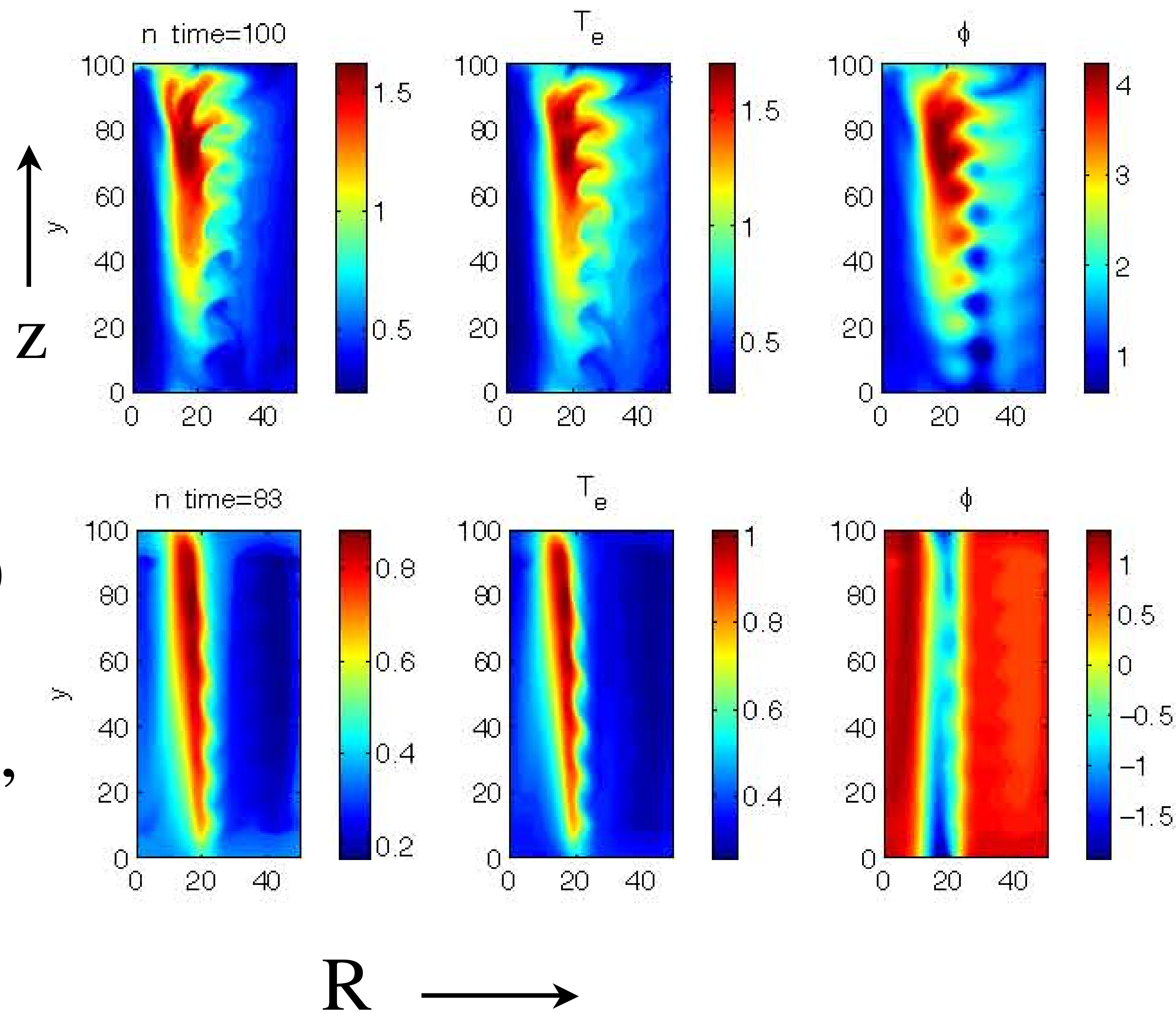
Ricci, Rogers, and Brunner, PRL **100**, 225002 (2008)
Ricci and Rogers, Phys. Plasmas **16**, 062303 (2009)
Li, Rogers, Ricci, Gentle, Phys. Plasmas **16**, 082510 (2009)
Li, Rogers, Ricci, Gentle, Bhattacharjee, Phys.Rev.E **83**, 056406 (2011)

Fields from 3-D Calculation

1 m X 2 m cross-section

Normal case
Strong z variations in n, T_e, ϕ

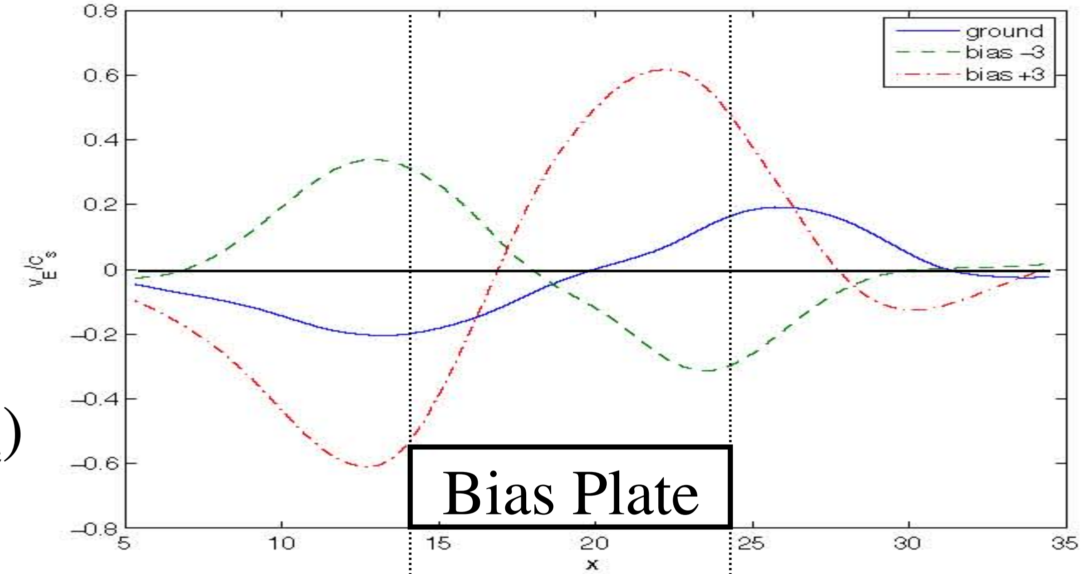
Bias case (-V)
Weak z variations in n, T_e, ϕ



Flow and Flow Shear -- Normal, ±Bias

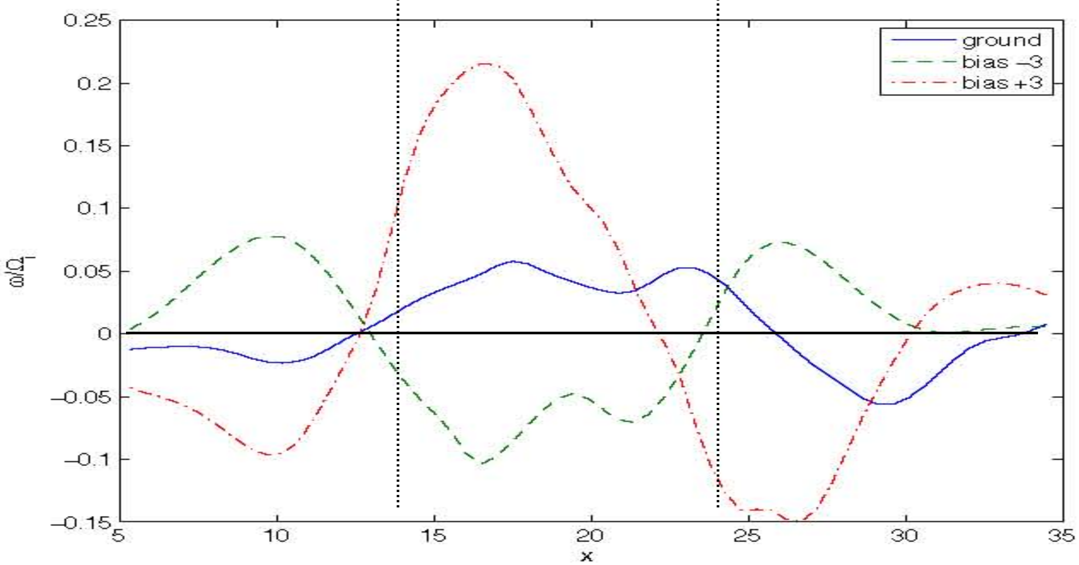
Flow (V_z)

Flows modified, especially near plate boundary
(Bias values scaled to T_e)



Flow Shear

Shapes change, but significant increase only for + bias, the case of weaker suppression



Numerical and Physical Experiments Share:

- Equilibrium density, temperature, potential and flow profiles
- Fluctuation structure and propagation
- Turbulence suppression above a threshold value of bias of both signs
- No association of turbulence reduction with distinctive changes in flow shear

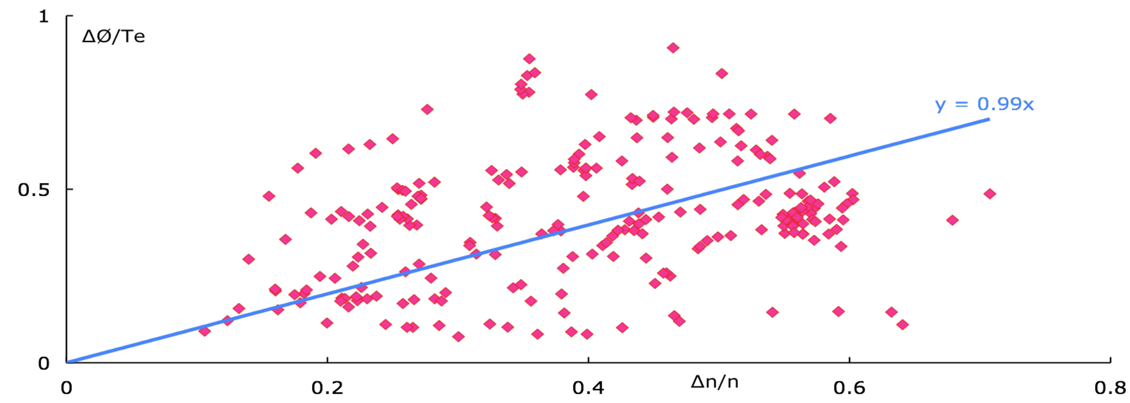
Note that these are two distinct "experiments"; just like two tokamaks, each has certain distinctive characteristics and behaviors.

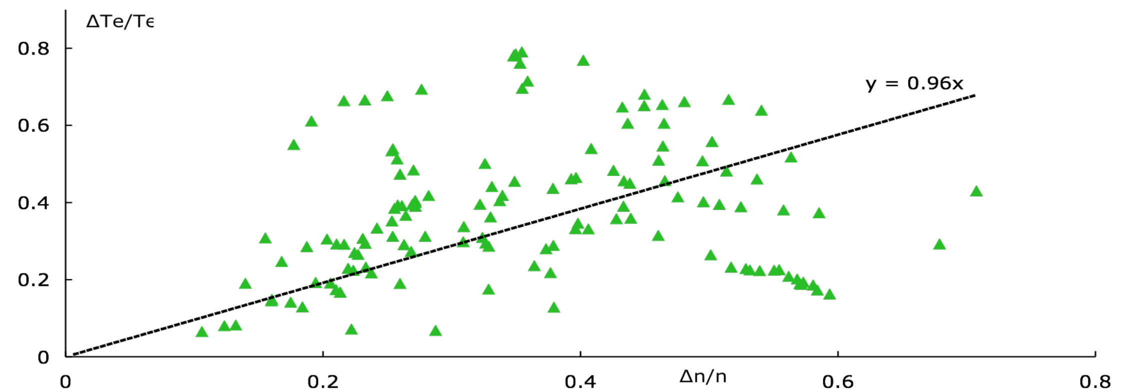
Conclusions

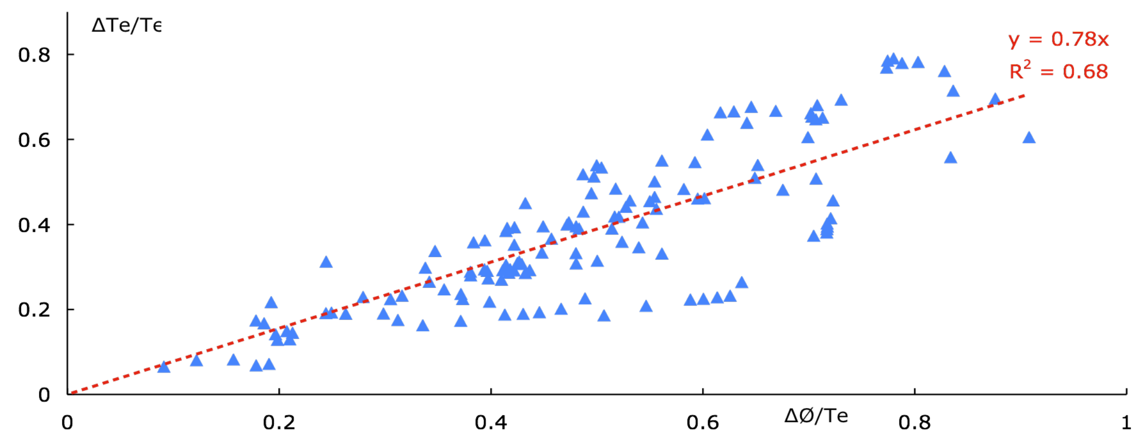
- The Helimak offers a simple, controlled example of turbulence reduction by biasing.
- The reductions occur for both positive and negative bias for parallel connection lengths from 40 m to 400 m.
- Neither turbulence levels nor reductions correlate with velocity shearing rate.
- There is no indication of zonal flows.
- The essential features also appear in a numerical simulation.

Relations Between Turbulent Fields

- No strict covariance, as in a simple linear theory, but all levels comparable.
- Density fluctuations "independent" of others.
- Temperature and potential most closely related, but temporal cross-correlation negative.

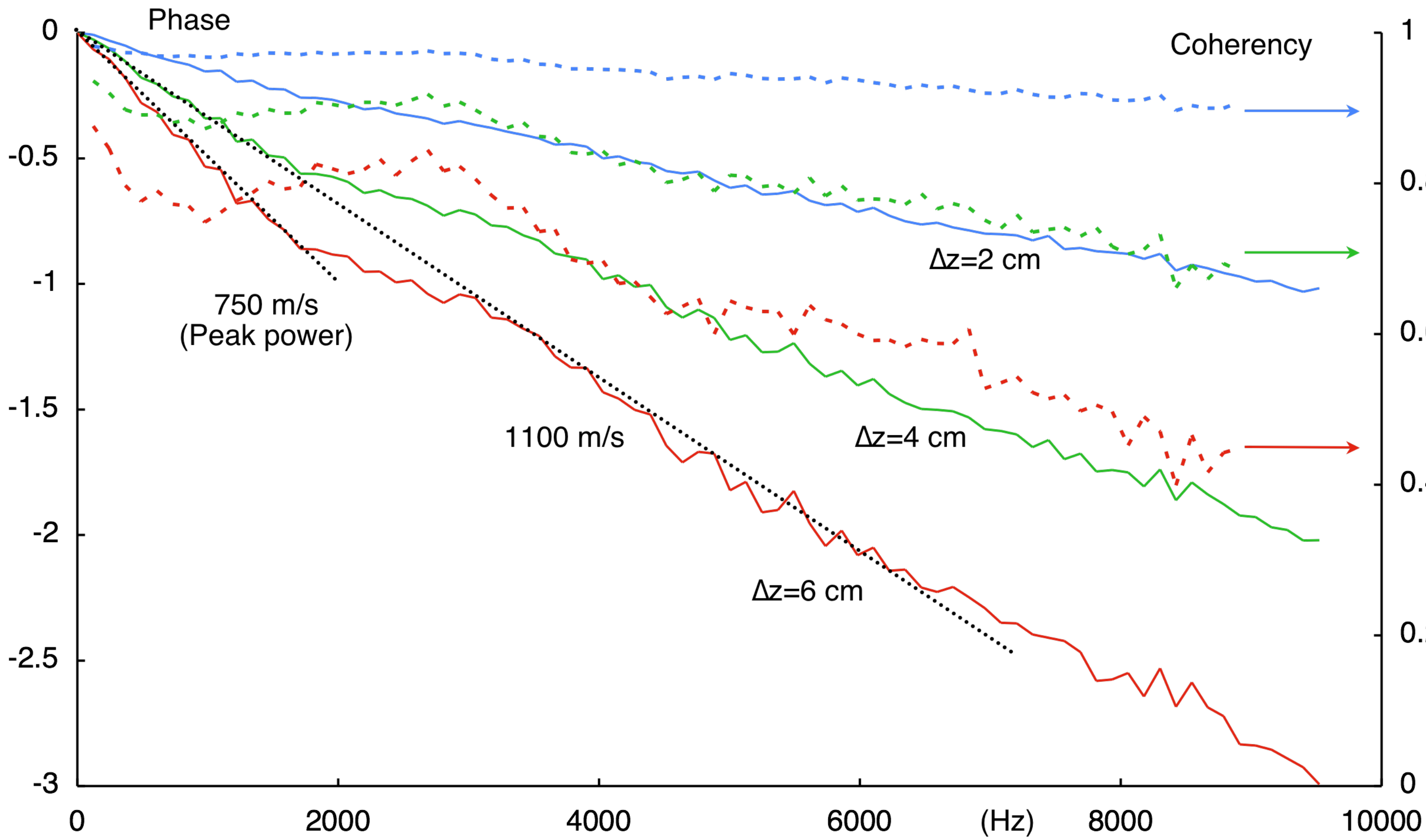


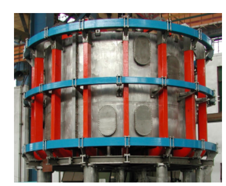




Gradient Region

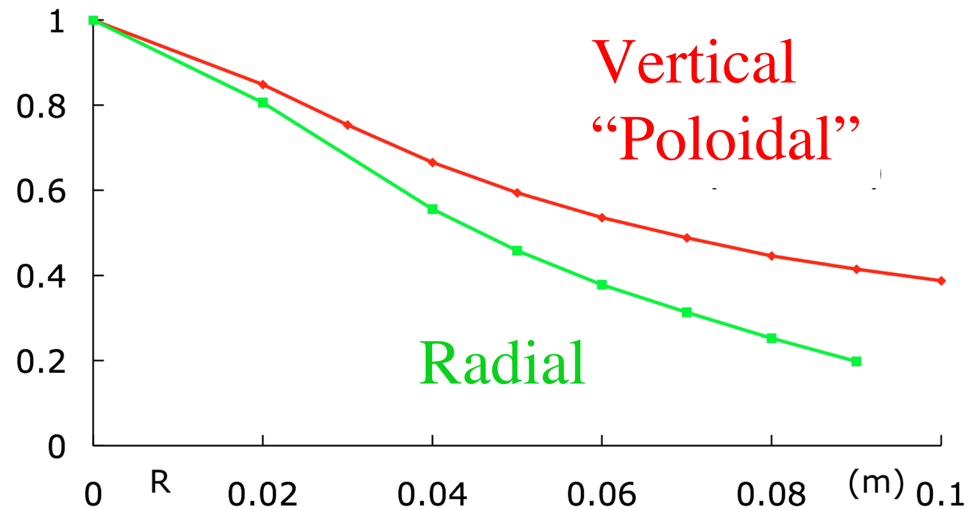
Propagation with high coherency



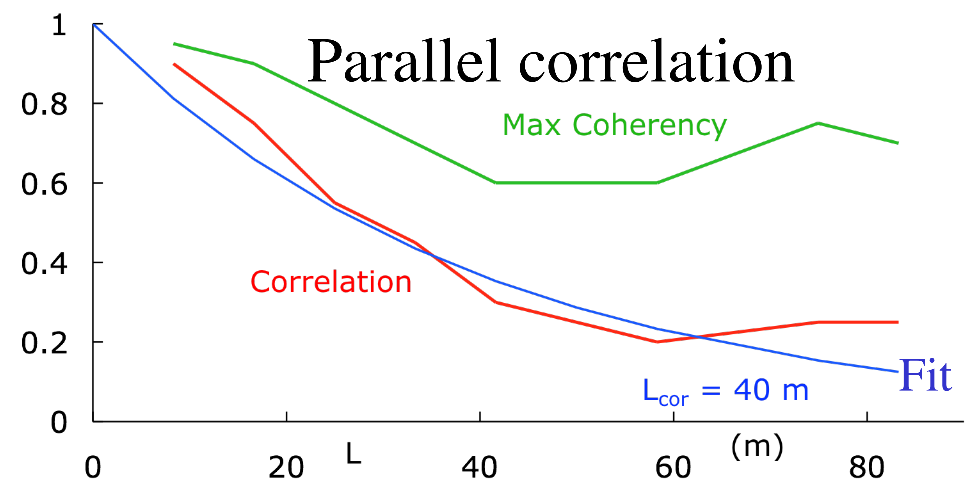


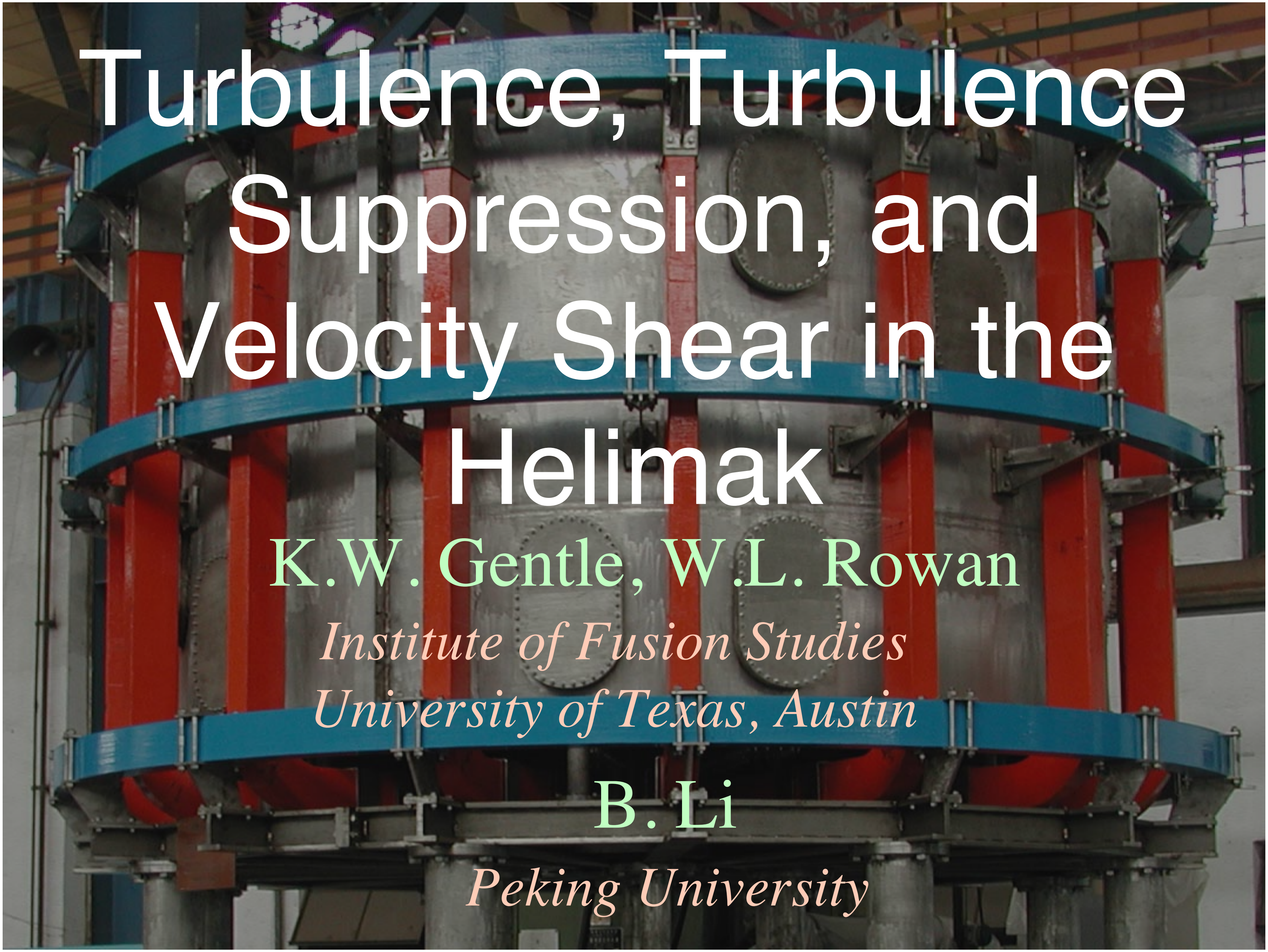
Correlation Lengths

Perpendicular correlation lengths comparable with scale lengths; small compared with plasma size



Parallel correlation length comparable with connection lengths; waves coherent over $L_{||}$





Turbulence, Turbulence Suppression, and Velocity Shear in the Helimak

K.W. Gentle, W.L. Rowan

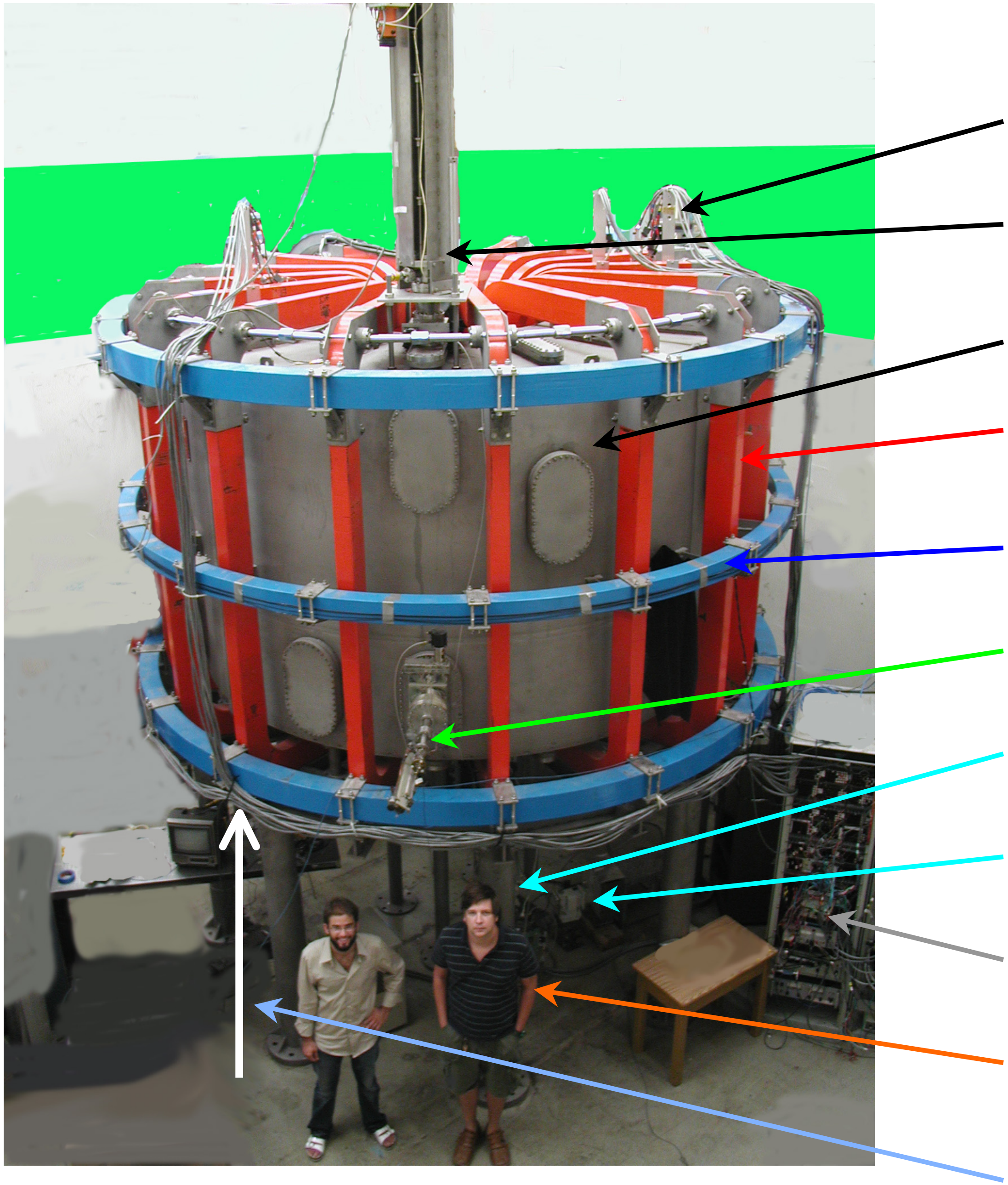
Institute of Fusion Studies

University of Texas, Austin

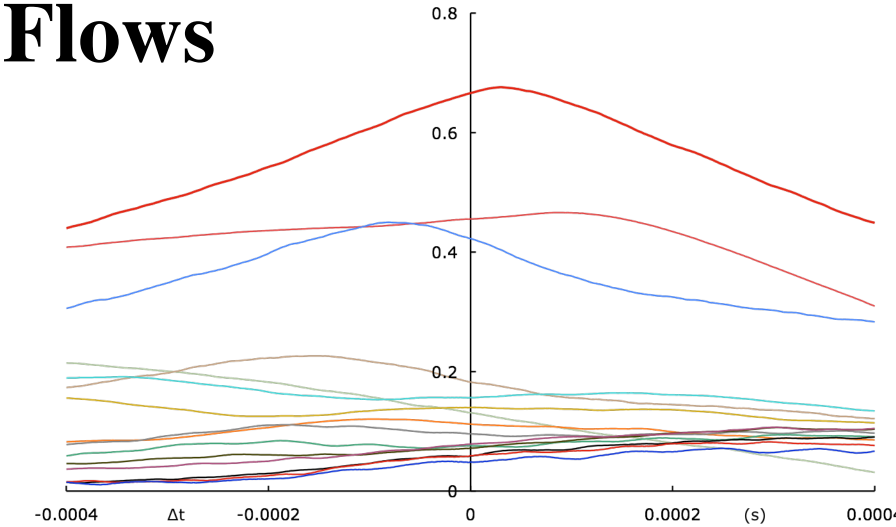
B. Li

Peking University

Helimak


Probe plate connections
Movable probe
Vacuum Vessel
Toroidal field coils
Vertical field coils
Magnetic probe
Microwave feed
Magnetron
Amplifiers and A/D
Scale
Optical Vertical View

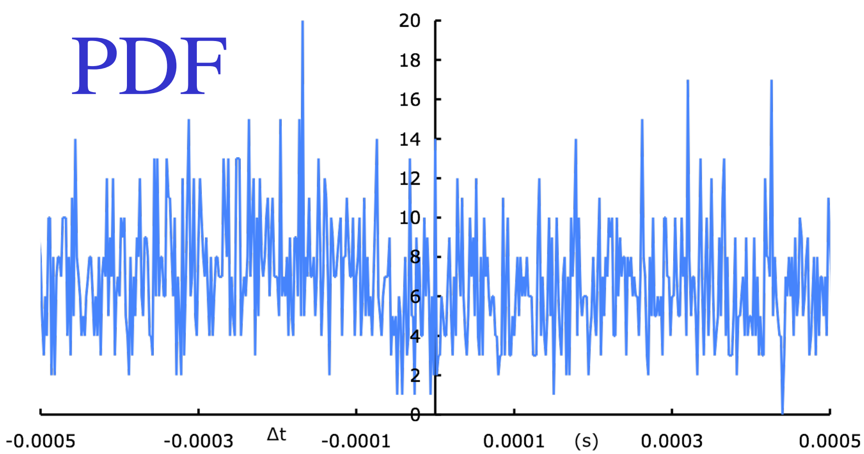
Radial Flows



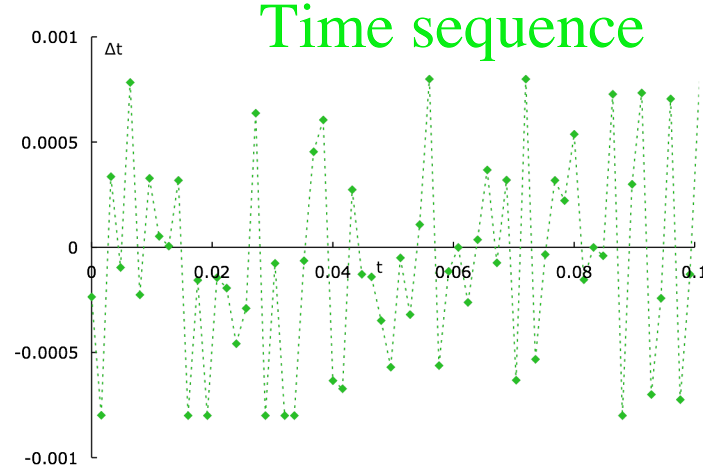
Radial Cross-correlations:
No indication of mean flows

Time delays from 1 ms sub-samples

PDF



Time sequence



Uniform distribution, random sequence ⇒No flows

Turbulence, Turbulence Suppression, and Velocity Shear in the Helimak

K.W. Gentle, W.L. Rowan, University of Texas at Austin
B. Li, Peking University

The Helimak is an approximation to the infinite cylindrical slab with a size large compared with turbulence transverse scale lengths, but with open field lines of finite length. Radially-segmented isolated end plates allow application of radial electric fields that drive radial currents. Above a threshold in applied voltage (driven current), the fractional turbulent amplitude is greatly reduced. Reductions are observed for both positive and negative bias over a broad range of collisionality and parallel connection length. Concurrent measurements of the ion flow velocity profile are made by Doppler spectroscopy of the argon plasma ion. Turbulence reductions are broadly correlated with reductions in radial correlation length, but not with velocity flow shear. No evidence of zonal flows has been found. The turbulence -- density, potential, and temperature fluctuations, is compared with simulations from a two-fluid model for this geometry, which also show reduced turbulence with bias. Work supported by the Department of Energy OFES DE-FG02-04ER54766.

Type: Experimental
Category 5.1.0

Limit: 1300 characters

session BP8, (Poster Session I: Non-Neutral, Dusty, and Strongly Coupled Plasmas I; Non Linear Phenomena and Turbulence Experiment; Plasma Waves; Stellarator, General Tokamak, Transport and Turbulence Theory)
which will begin at 09:30 AM on Monday, 10/29/12 in room: Hall BC. BP8.00168

Poster board 8 ft W X 4 ft H (96" X 48") 8 Slides wide by 5.6 high
or 40 - 48 slides This presentation 4x5 + 4x6 = 44.