Turbulence and Turbulence Suppression in the Helimak

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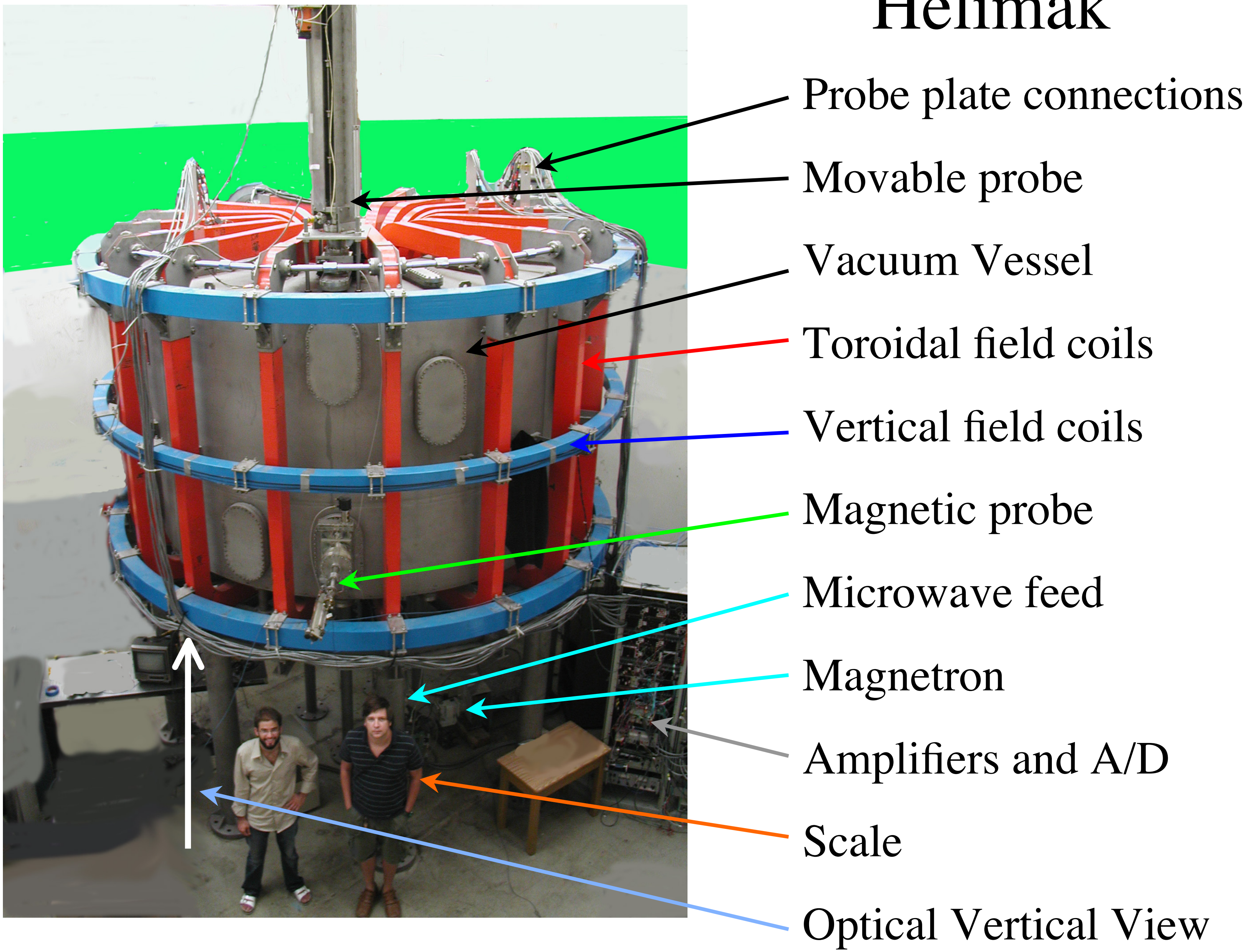
Thesis

- 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** is not associated with **increased velocity shear**
- A numerical experiment shows the same features
- There is no indication of zonal flows

Outline

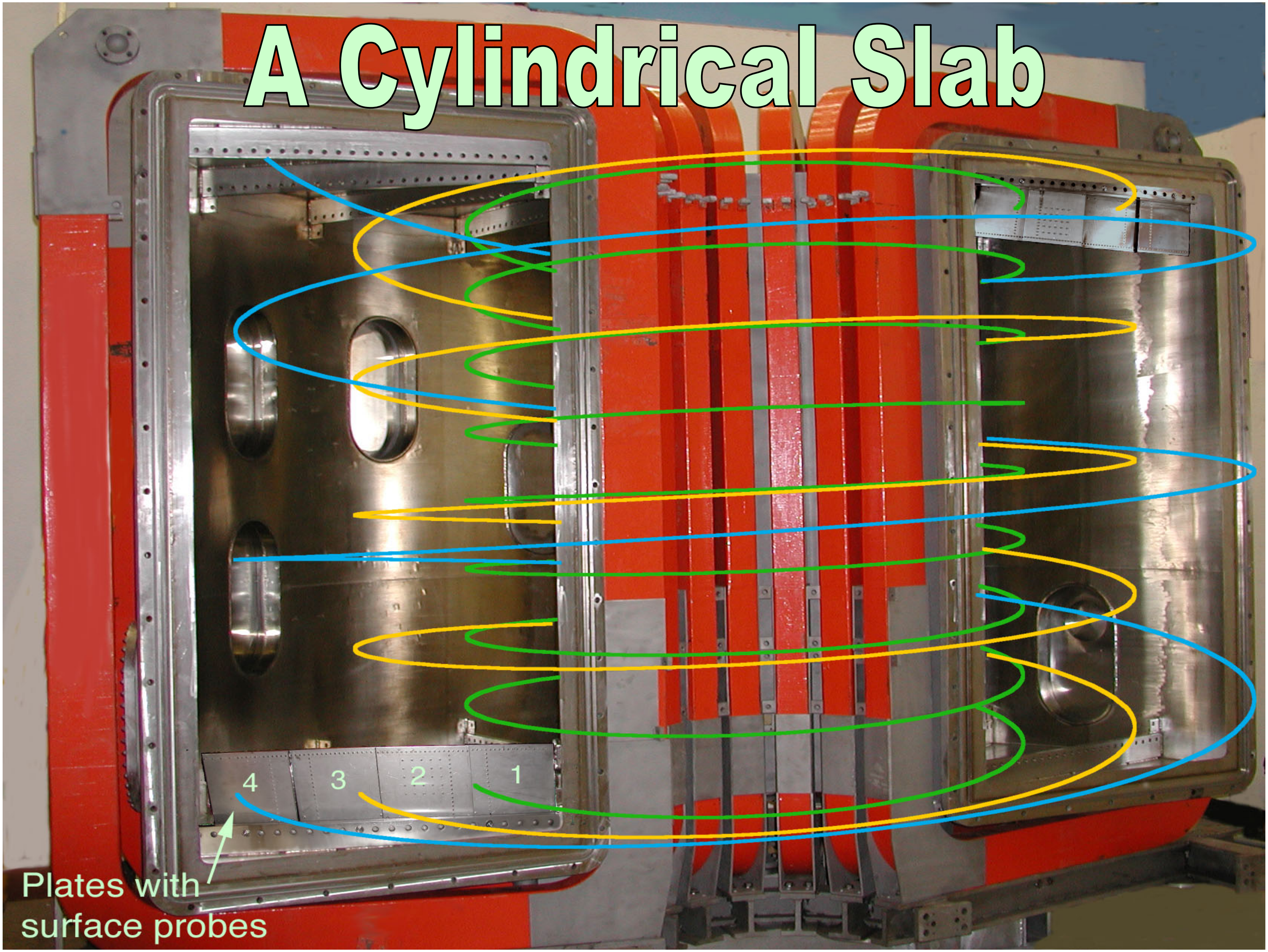
1. Description of device, plasma parameters, and spectral characteristics
2. Results for reduction of turbulence by biasing
3. Relations between turbulence reduction, velocity shear, radial correlation lengths, and decorrelation rates
4. Comparisons with simulations and tests for zonal flows

Helimak

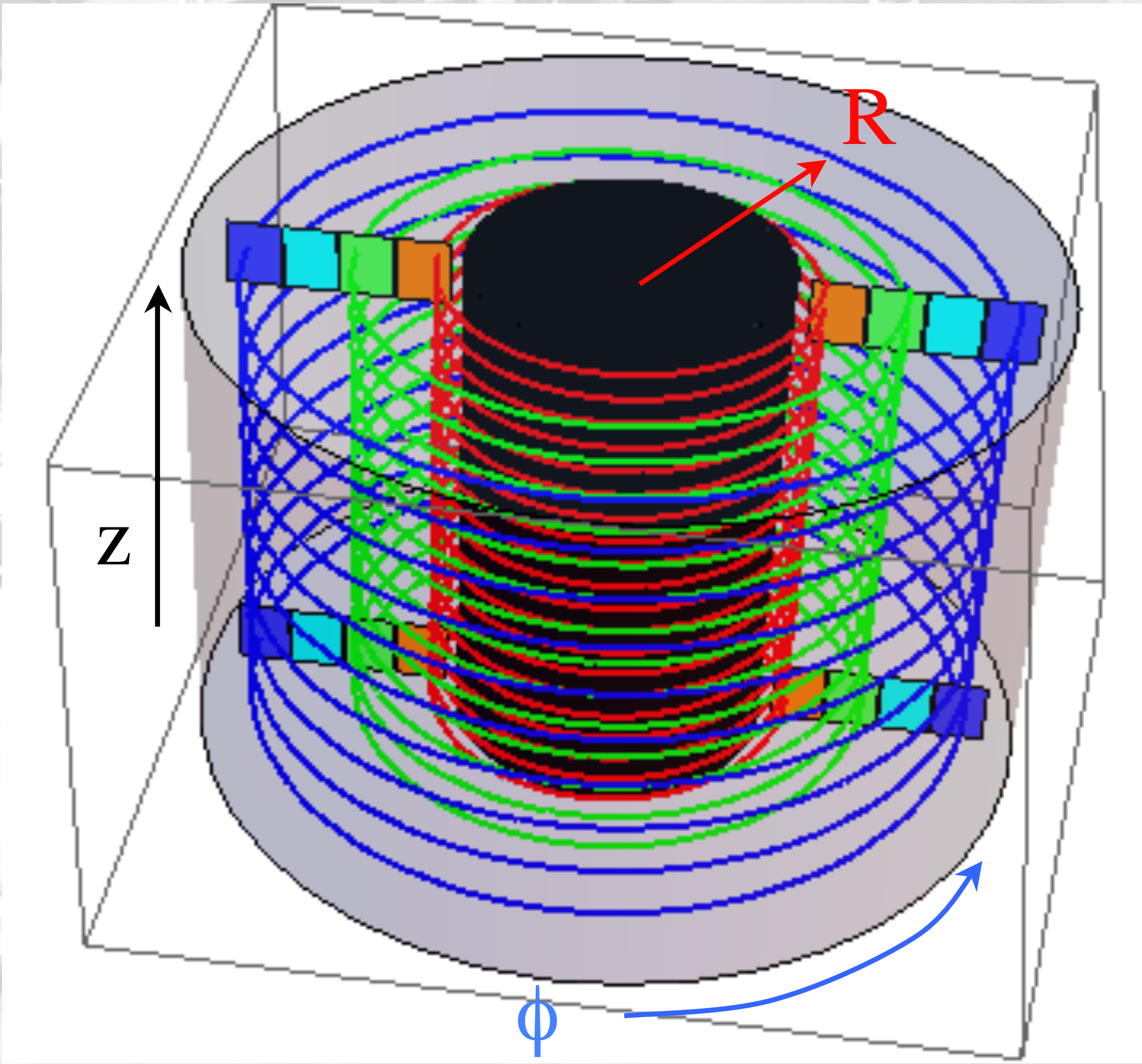


Probe plate connections
Movable probe
Vacuum Vessel
Toroidal field coils
Vertical field coils
Magnetic probe
Microwave feed
Magnetron
Amplifiers and A/D
Scale
Optical Vertical View

A Cylindrical Slab



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

$\langle R \rangle = 1.1$ m　　$\Delta R = 1$ m　　$h = 2$ m

$B_T = 0.1$ T　　$B_v \leq 0.01$ T　　Pulse ≤ 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

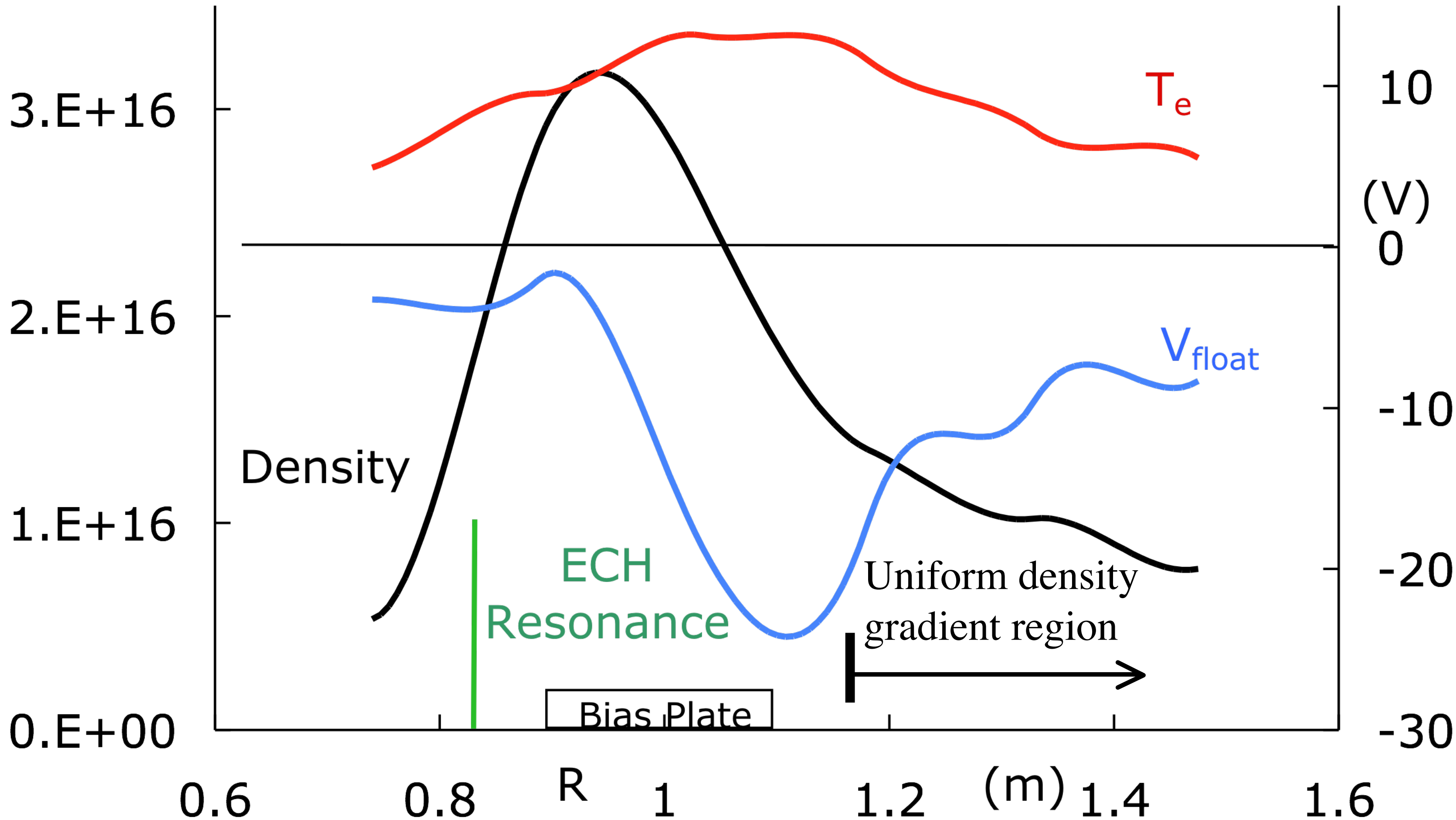
Connection length: $10 \text{ m} < L_{||} < 2000$ m　τ_p (parallel loss) > 1 ms

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	$6\mathrm{x}10^{-5}$
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

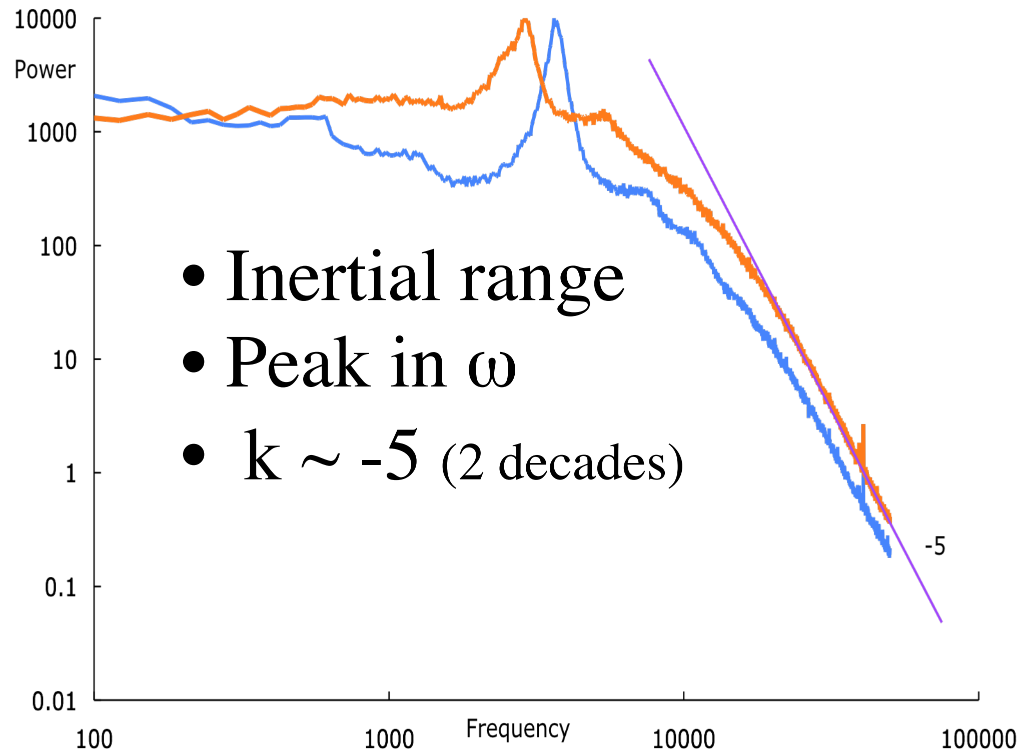


General Features of Power Spectra $P(\omega)$

Based on 100,000+ spectra from all observable conditions

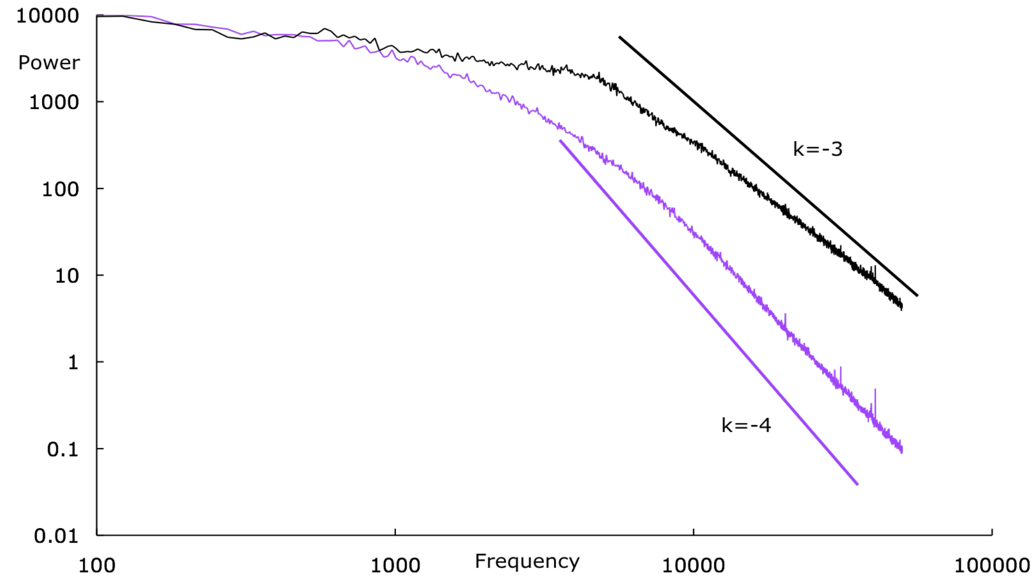
1. At high frequency, $P(\omega) \propto \omega^{-k}$, $2 < k \leq 5$
2. Absolutely nothing else!

- 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



Power Spectra P(ω)

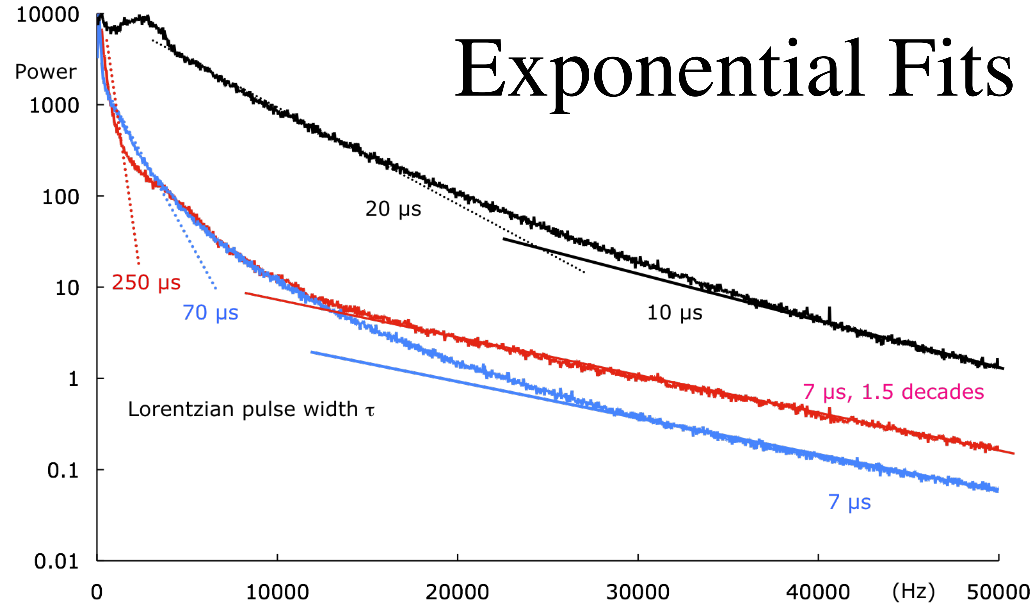
- No inertial range
- No middle range
- Power law,
  2+ decades,
  various k



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

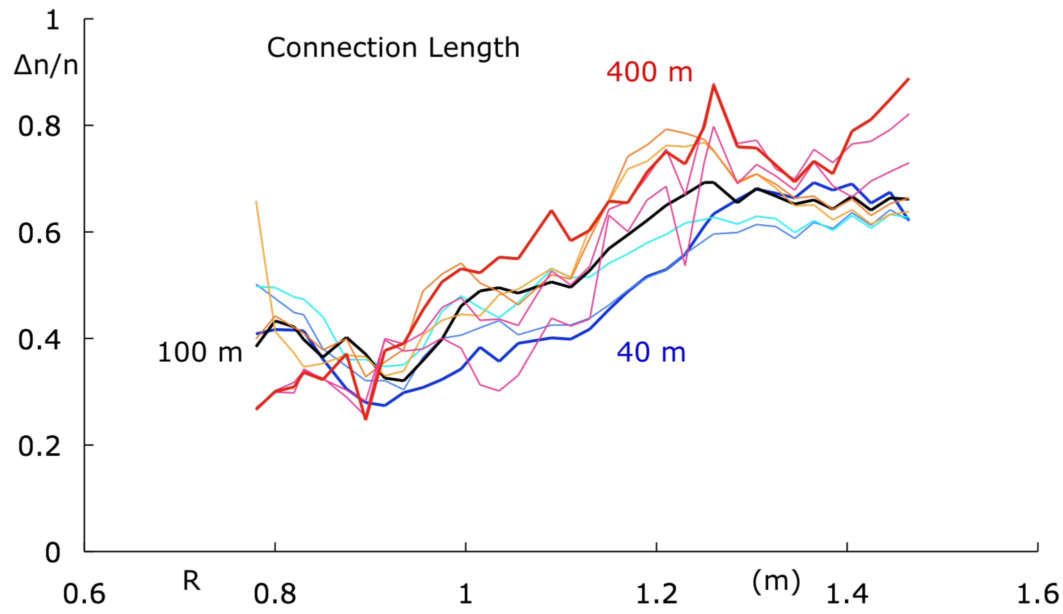
τ << Autocorr τ

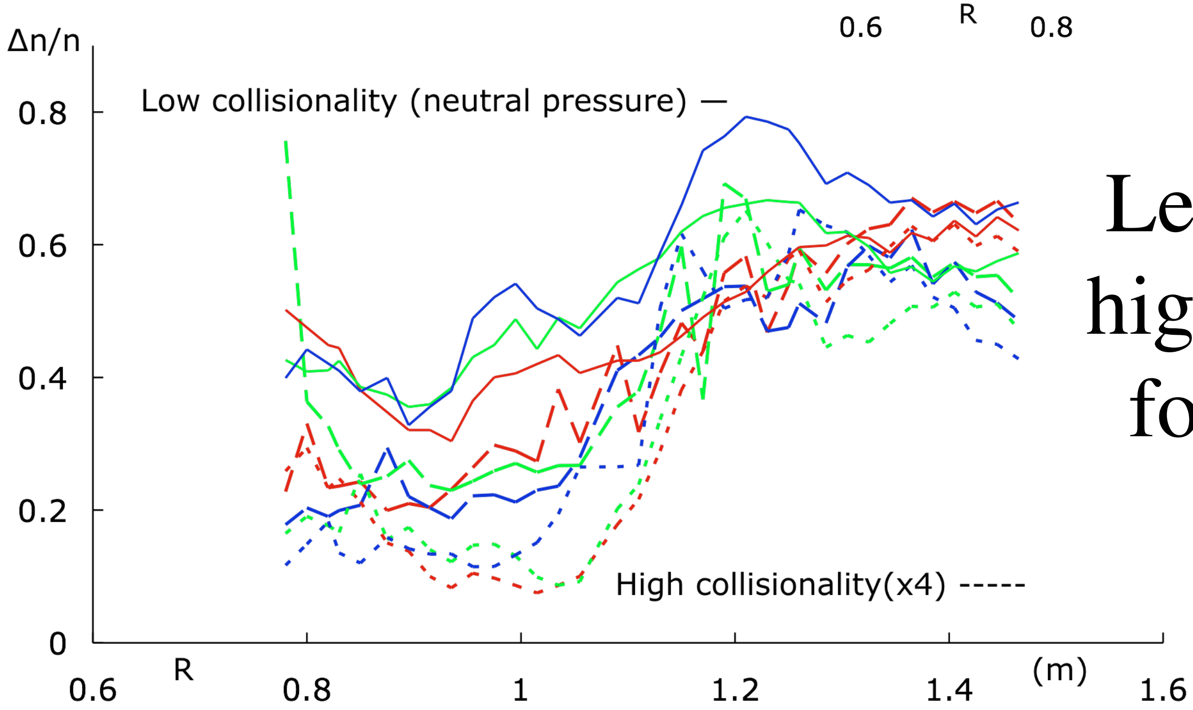
Exponential Fits



Turbulence Levels

Levels increase slightly with connection length

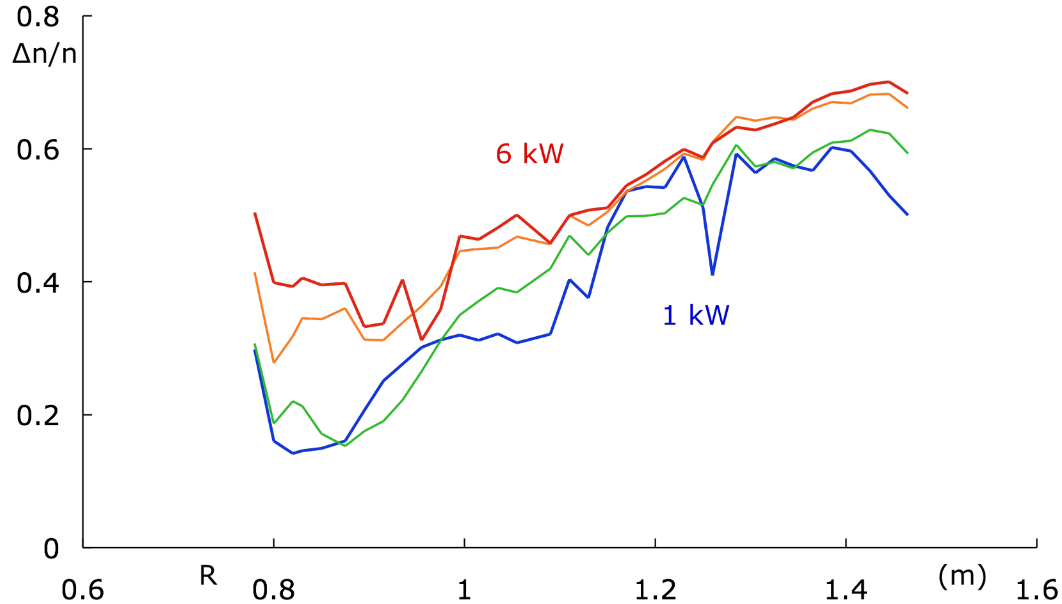


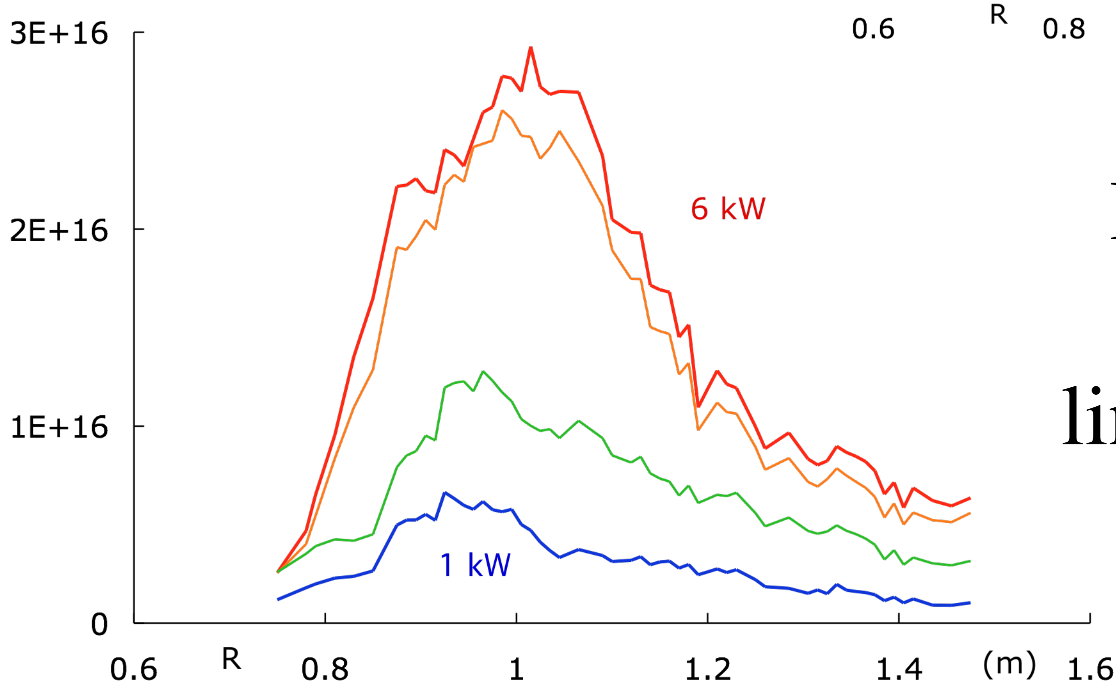


Levels decrease at higher collisionality for all connection lengths

Turbulence Levels

Levels increase slightly with power (density)





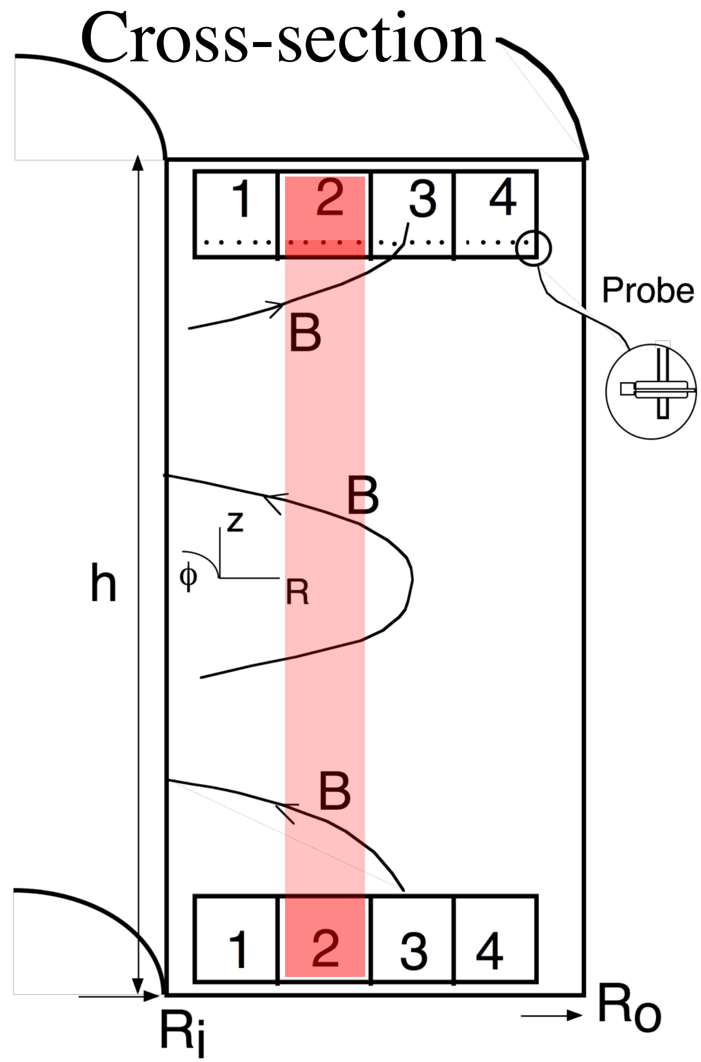
Density increases strongly (almost linearly) with power

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

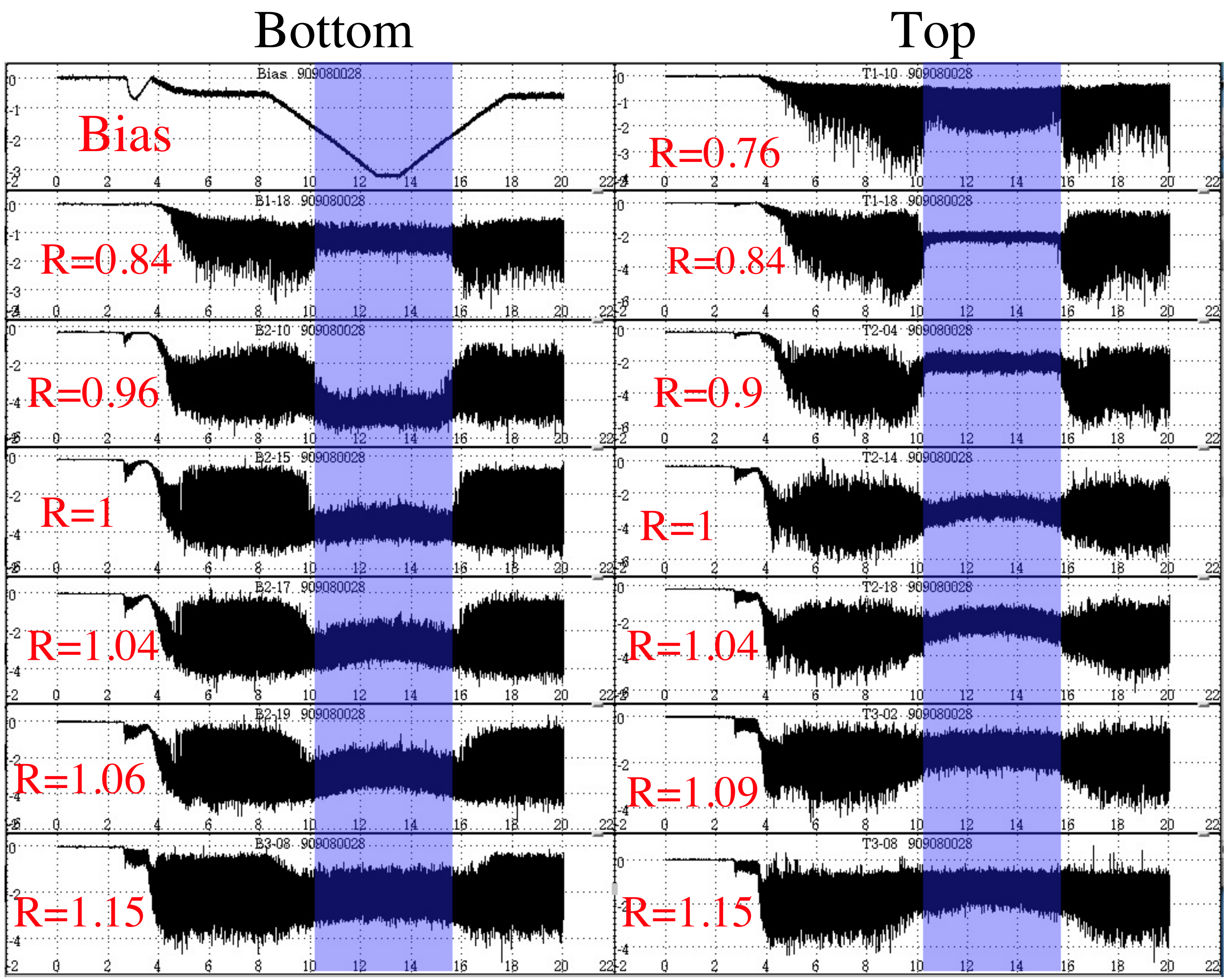
- Other plates and vessel grounded



Simple Phenomenology

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

Negative Bias Transition at ~-20 V



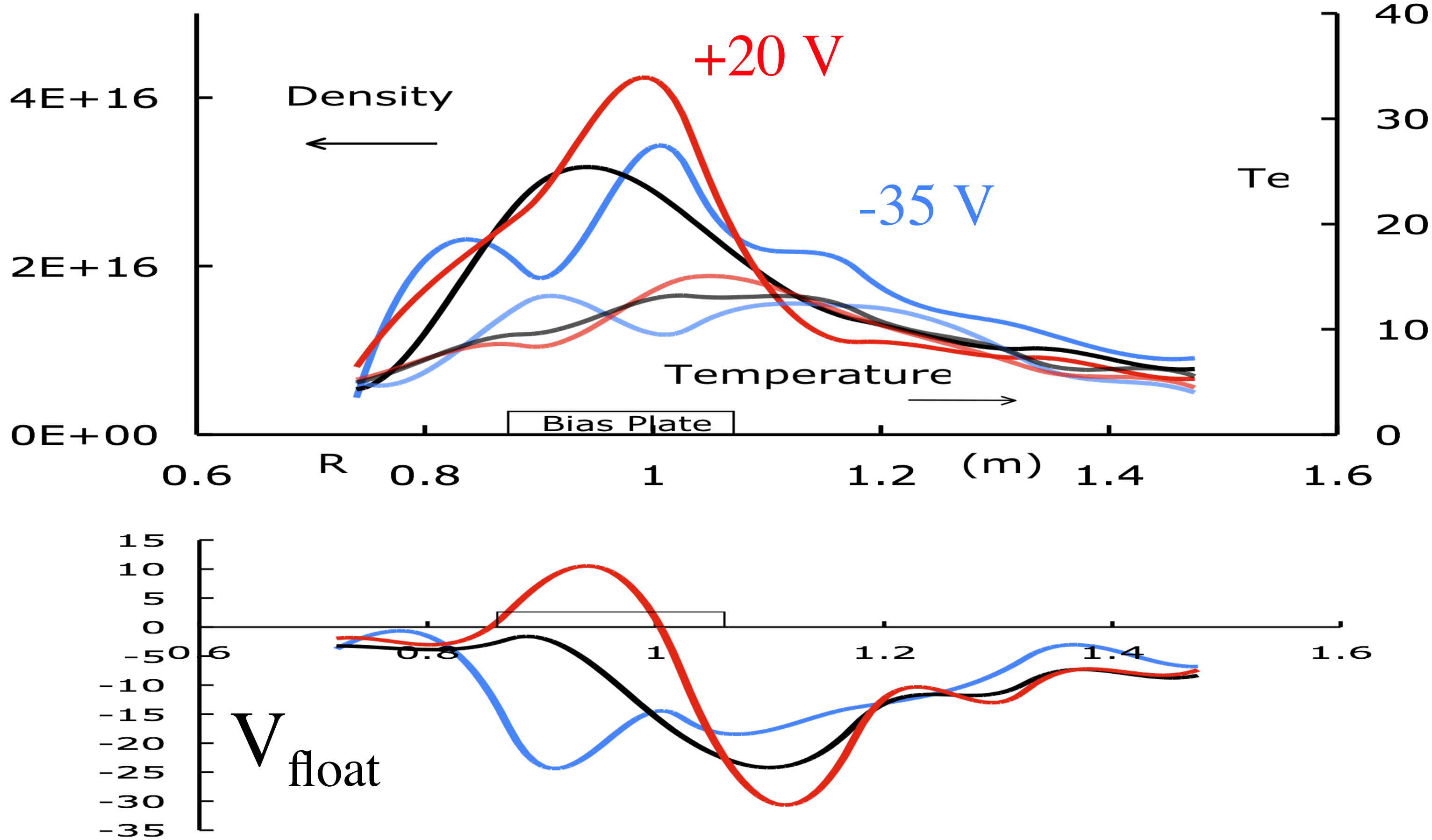
Bias-Driven Turbulence Reduction

- Applying bias above a threshold reduces the turbulence level
- The reduction occurs across much of the profile
- The transition occurs without hysteresis
- Reductions occur for both positive and negative bias in argon and helium over a broad range of control parameters

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.)

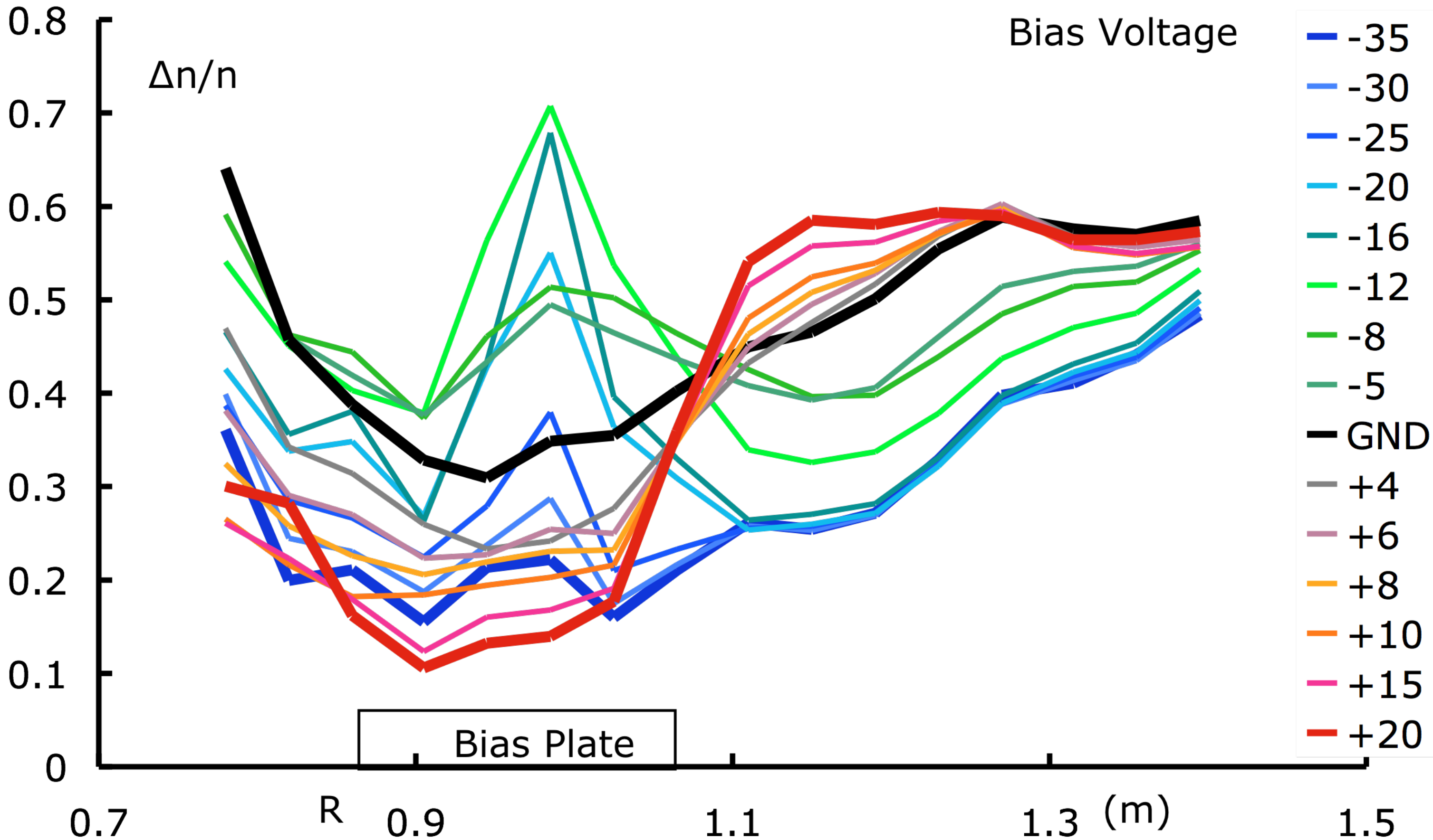
Profile Changes with Bias

Positive, Negative, Zero Bias

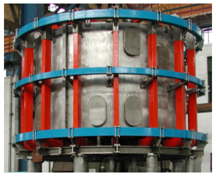


- Temperature ~ constant; density changes modest
- Potential change at plate as expected
- Effects extend outward from plate, esp. negative bias

Density Fluctuations

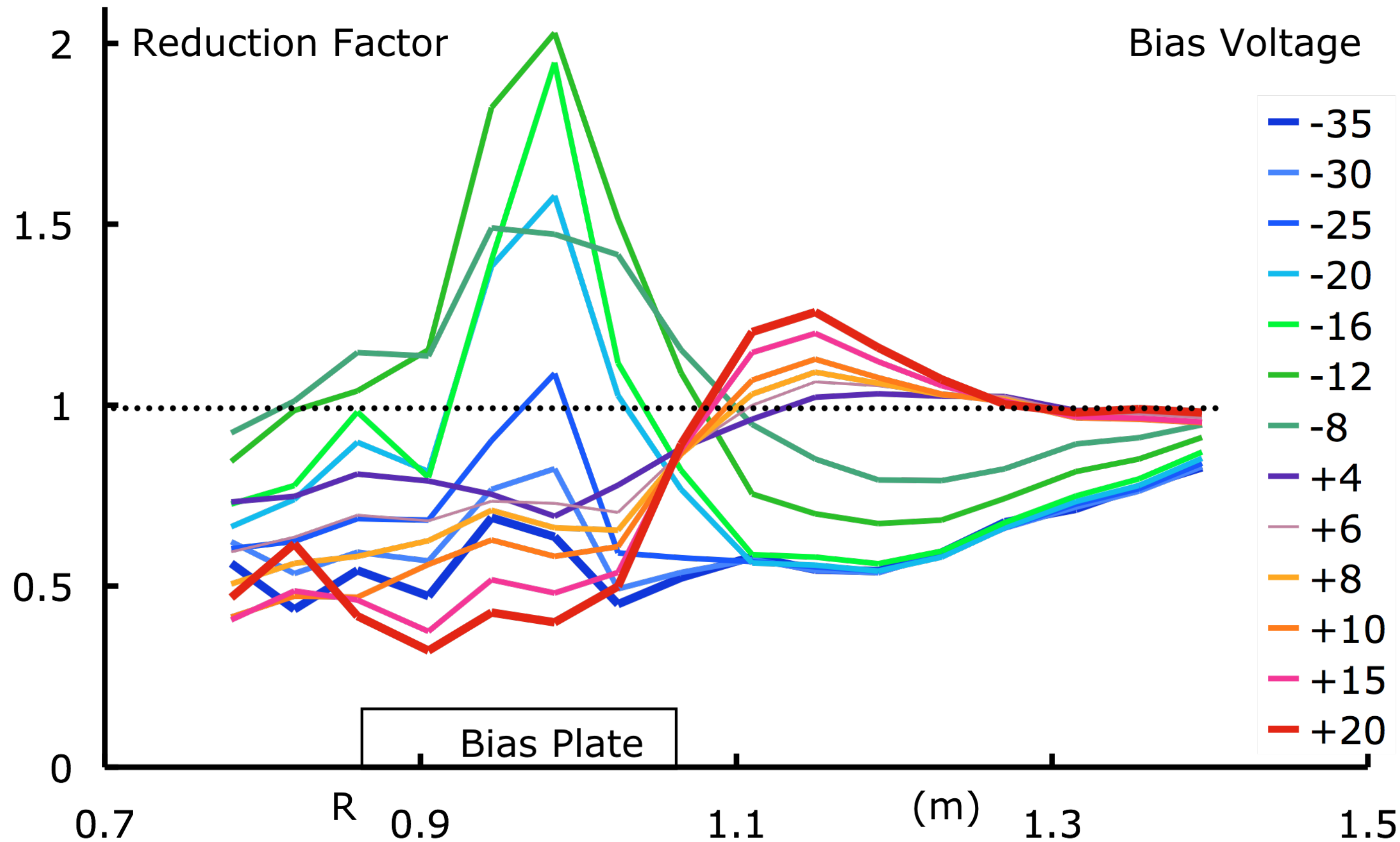


- Reduced across plate
- Effect extends outward,
  strongly for negative bias



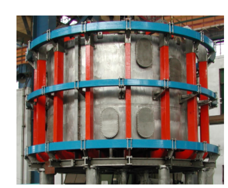
Turbulence Reduction -- Density

Reduction = $\Delta n/n(\text{Bias})/\Delta n/n(\text{Grnd})$



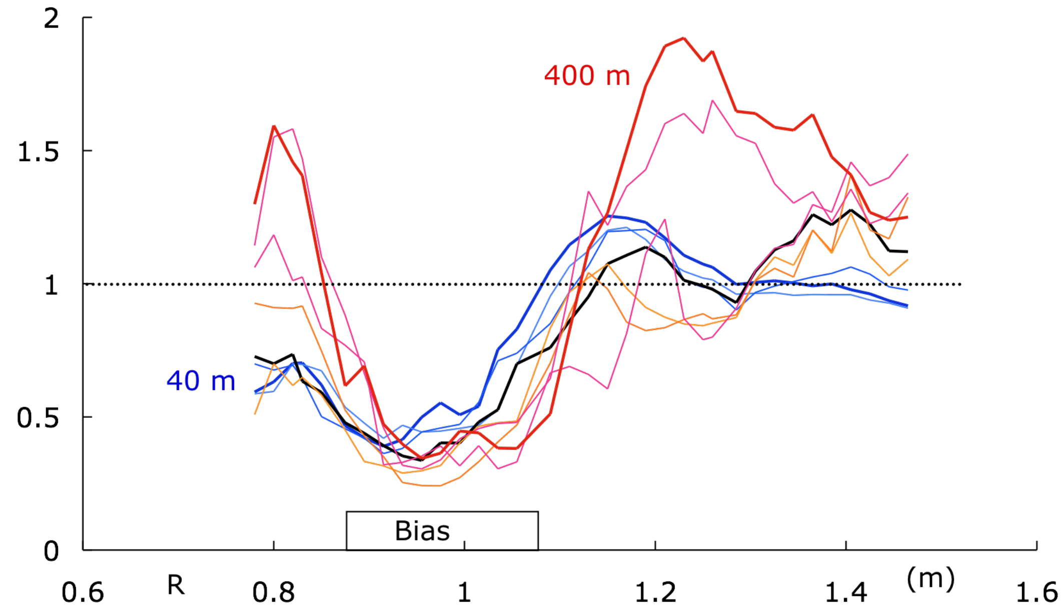
Suppression largely completed by -25 V

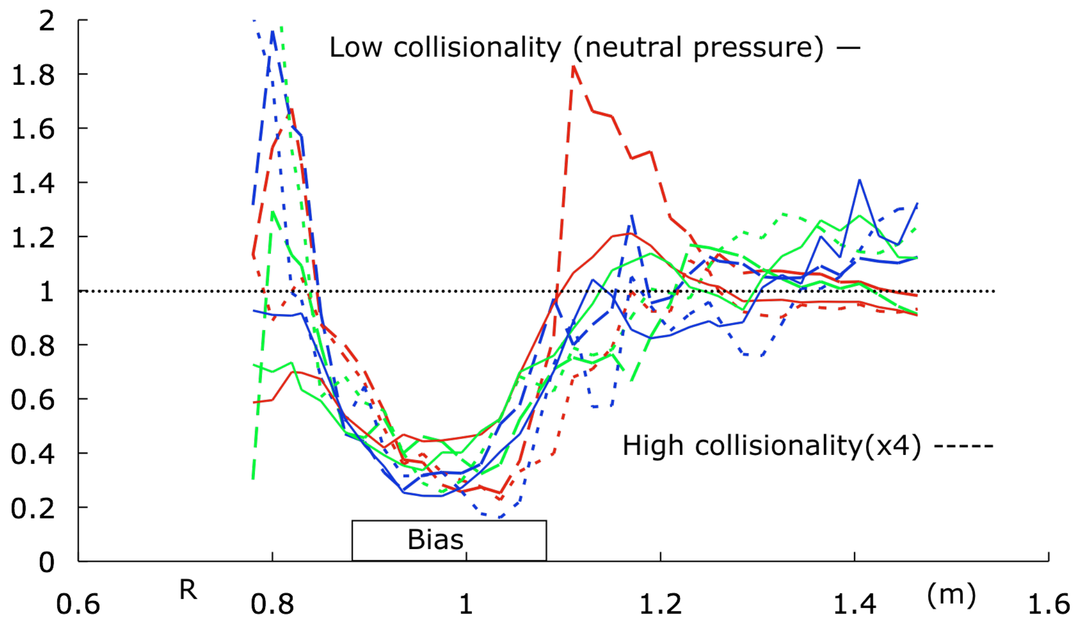
$L_{||} = 40$ m



Turbulence Reduction: Positive Bias

Weak dependence on connection length

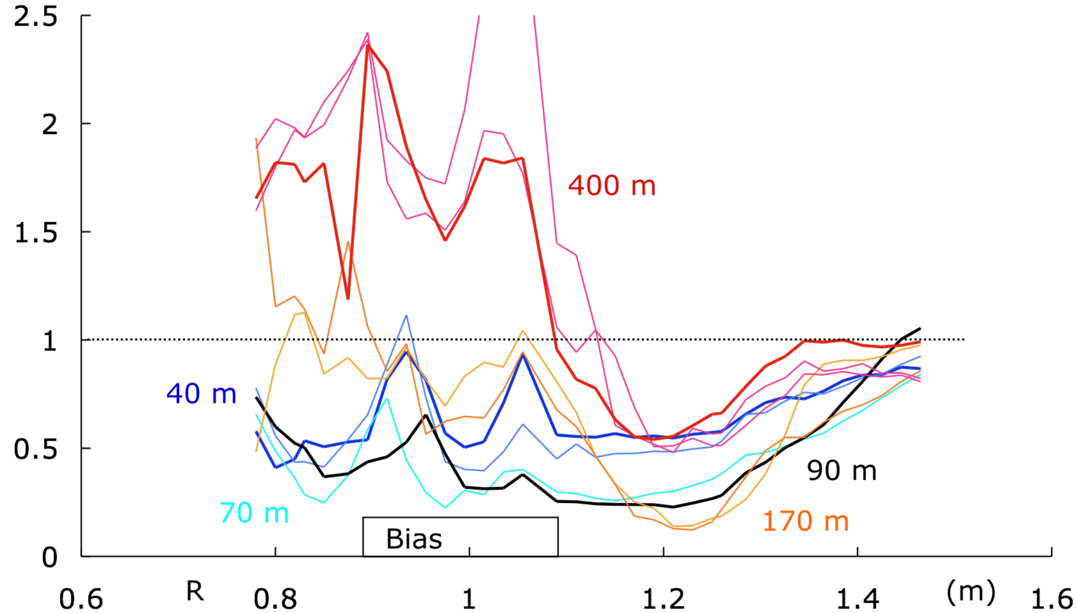


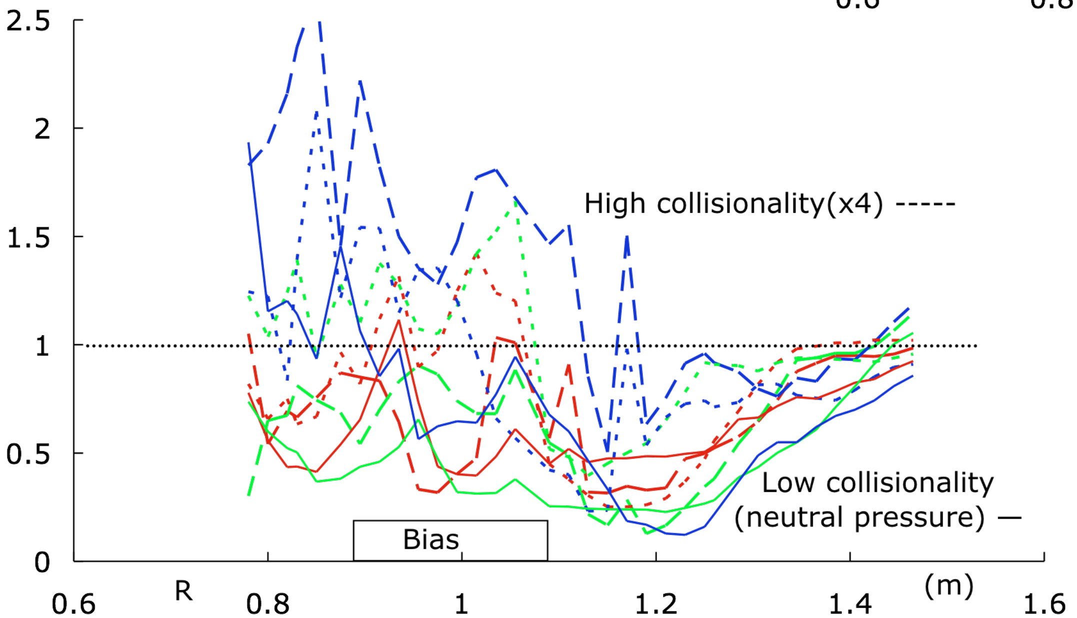


Weak dependence on collisionality

Turbulence Reduction: Negative Bias

Less for long connection lengths. $L_{||} \leq 200$ m optimum, depending on location

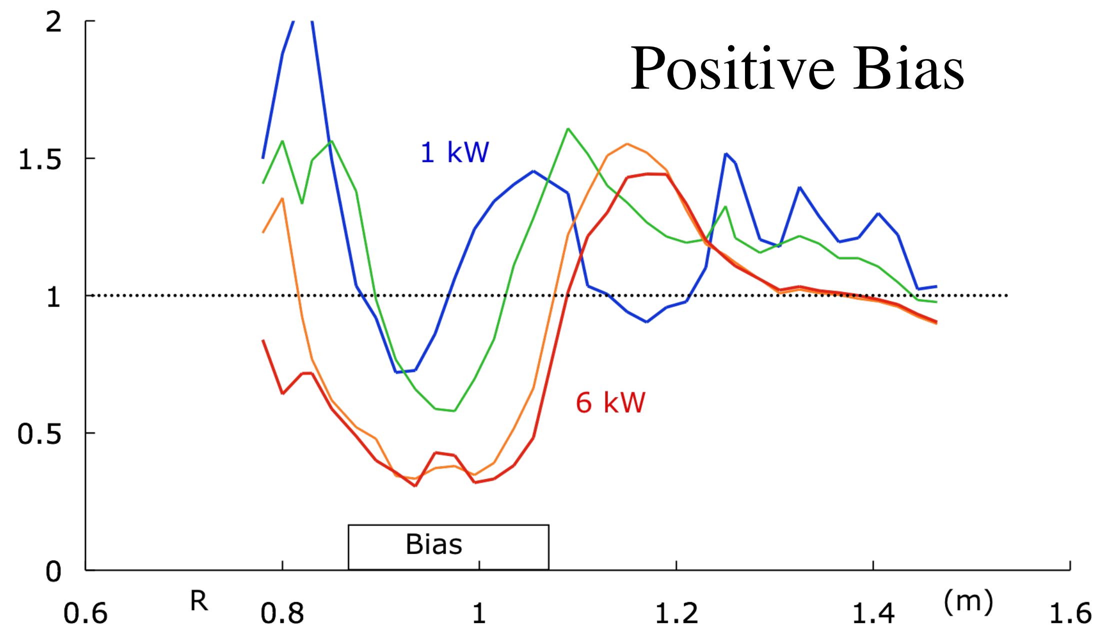


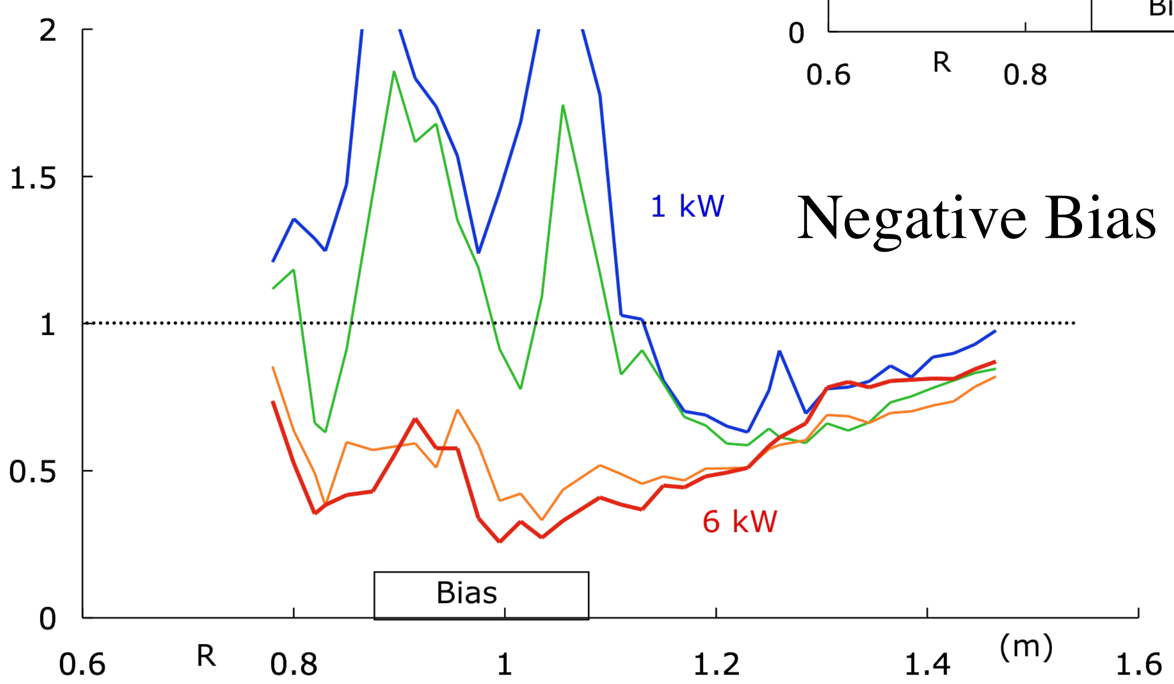


Weaker reduction at higher collisionality for all connection lengths

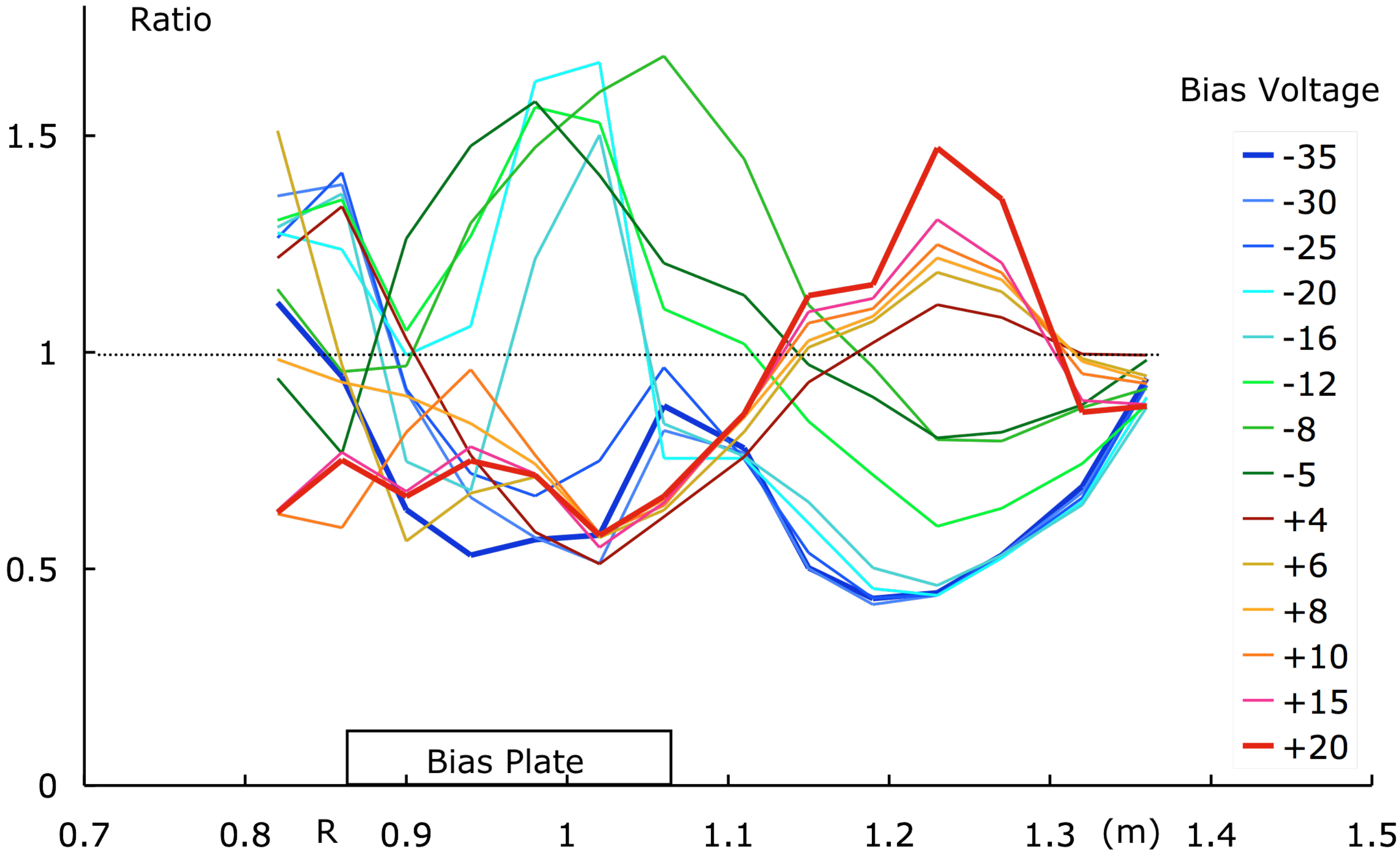
Turbulence Reduction: Power

Effect disappears at low power (density)



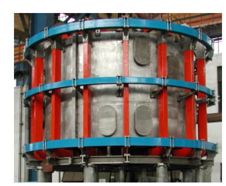


Change in Radial Correlation Length



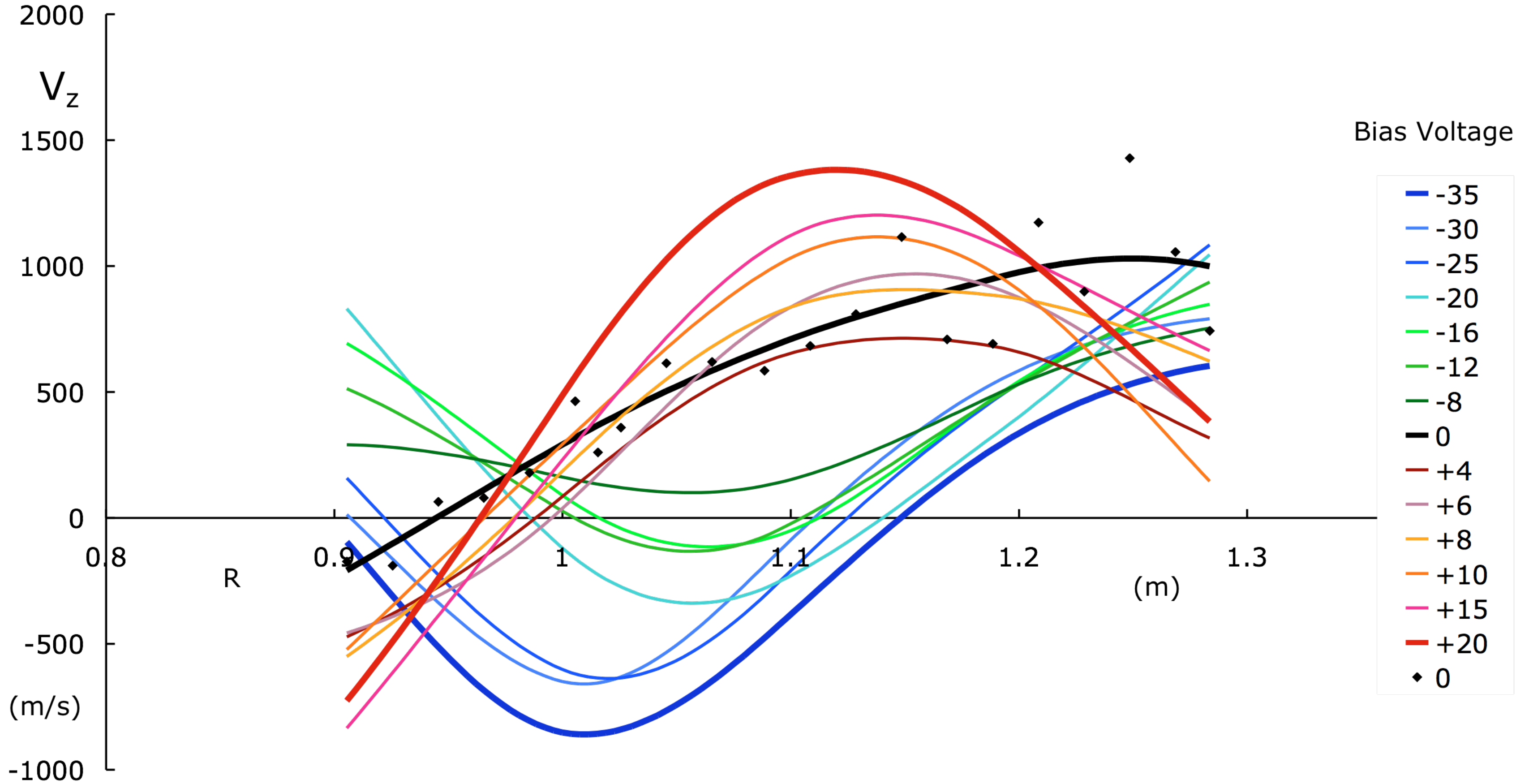
Change in radial correlation length generally follows change in turbulence level

$L_{||} = 40$ m



Measured Flow Velocity

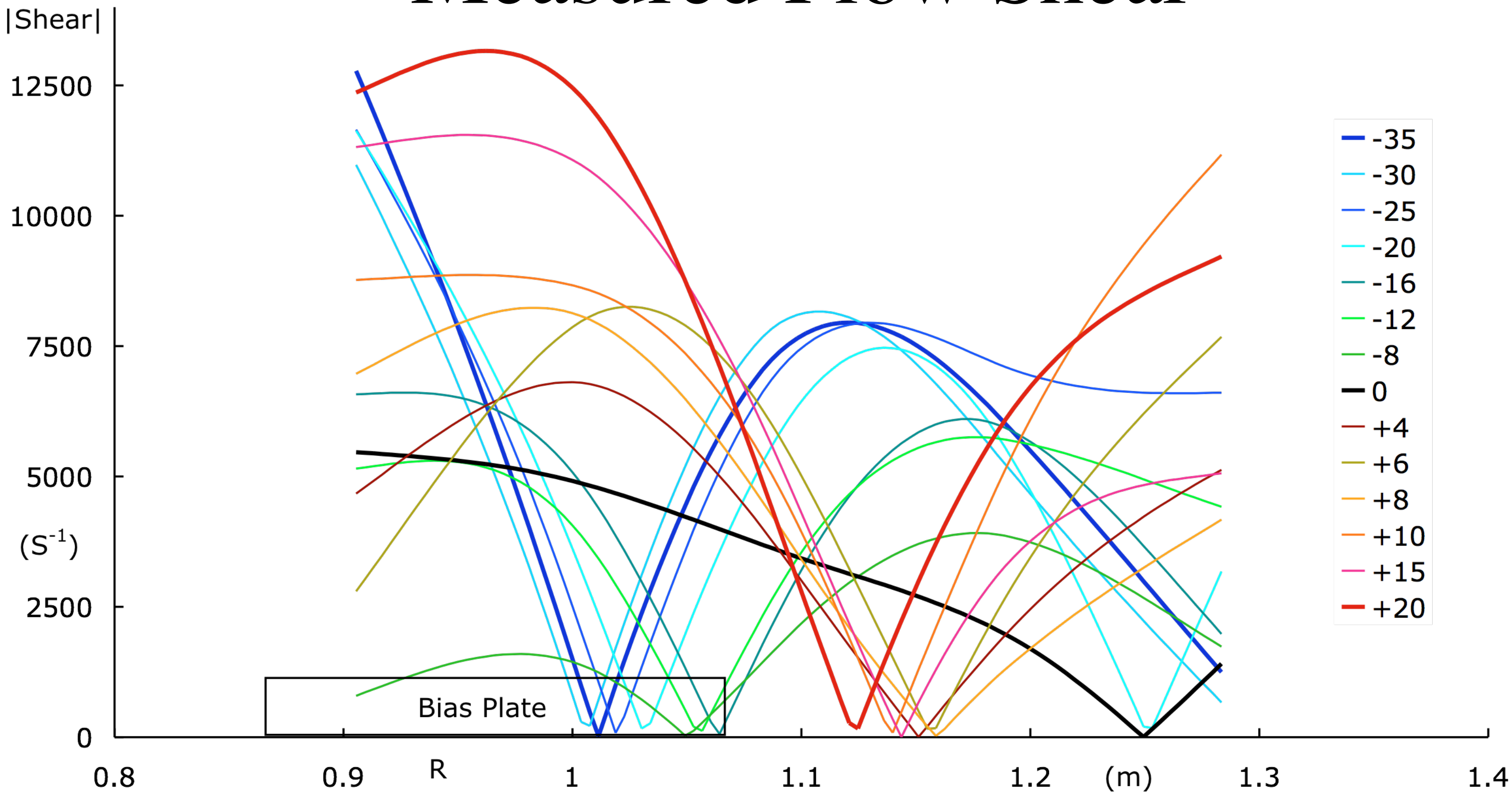
Argon Ion Doppler



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*

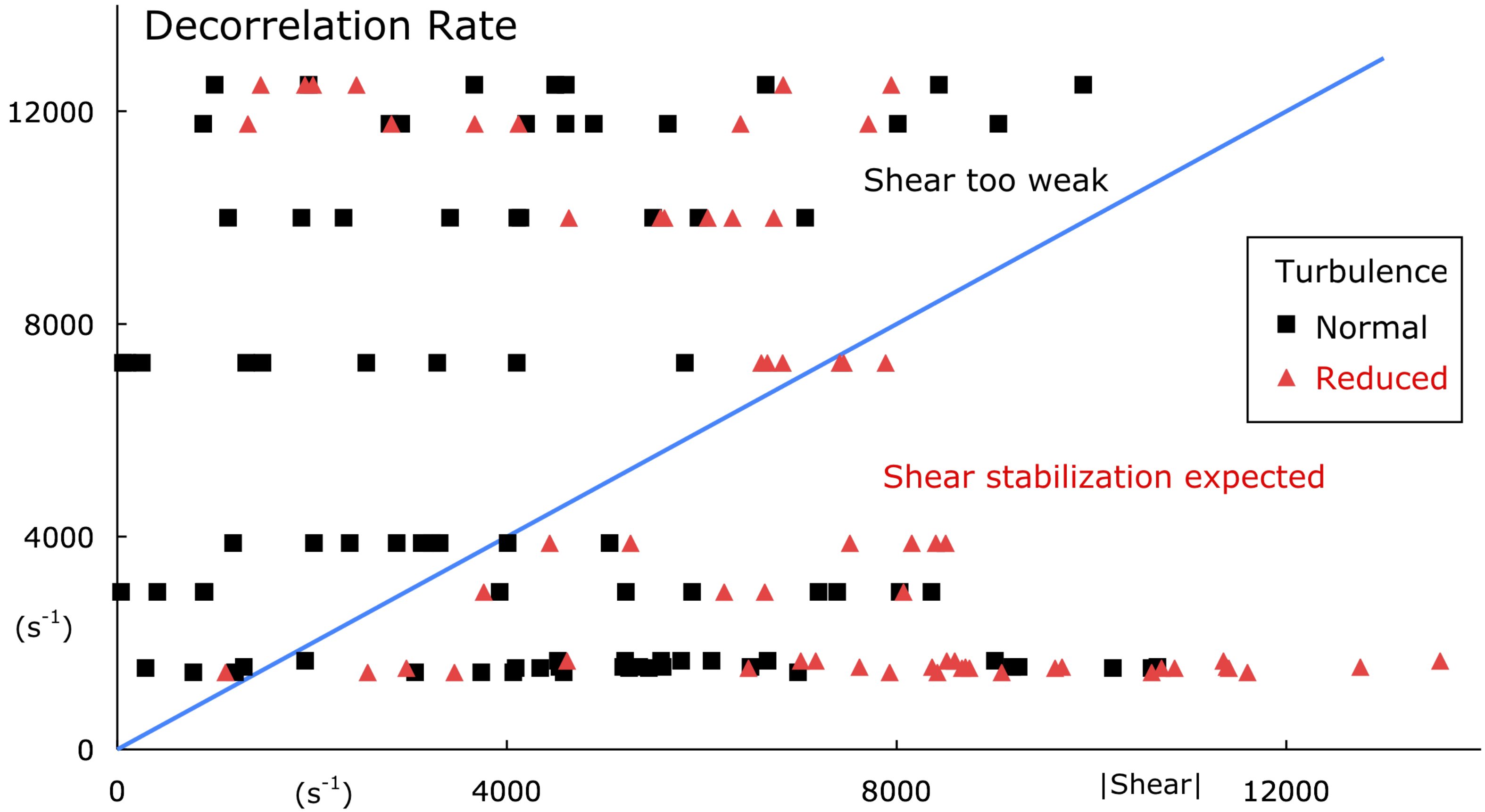
Flow shear will stabilize fluid turbulence under minimal, very general conditions, which are met in these experiments. Mechanism is local and can be tested at all locations in the plasma.

- 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)



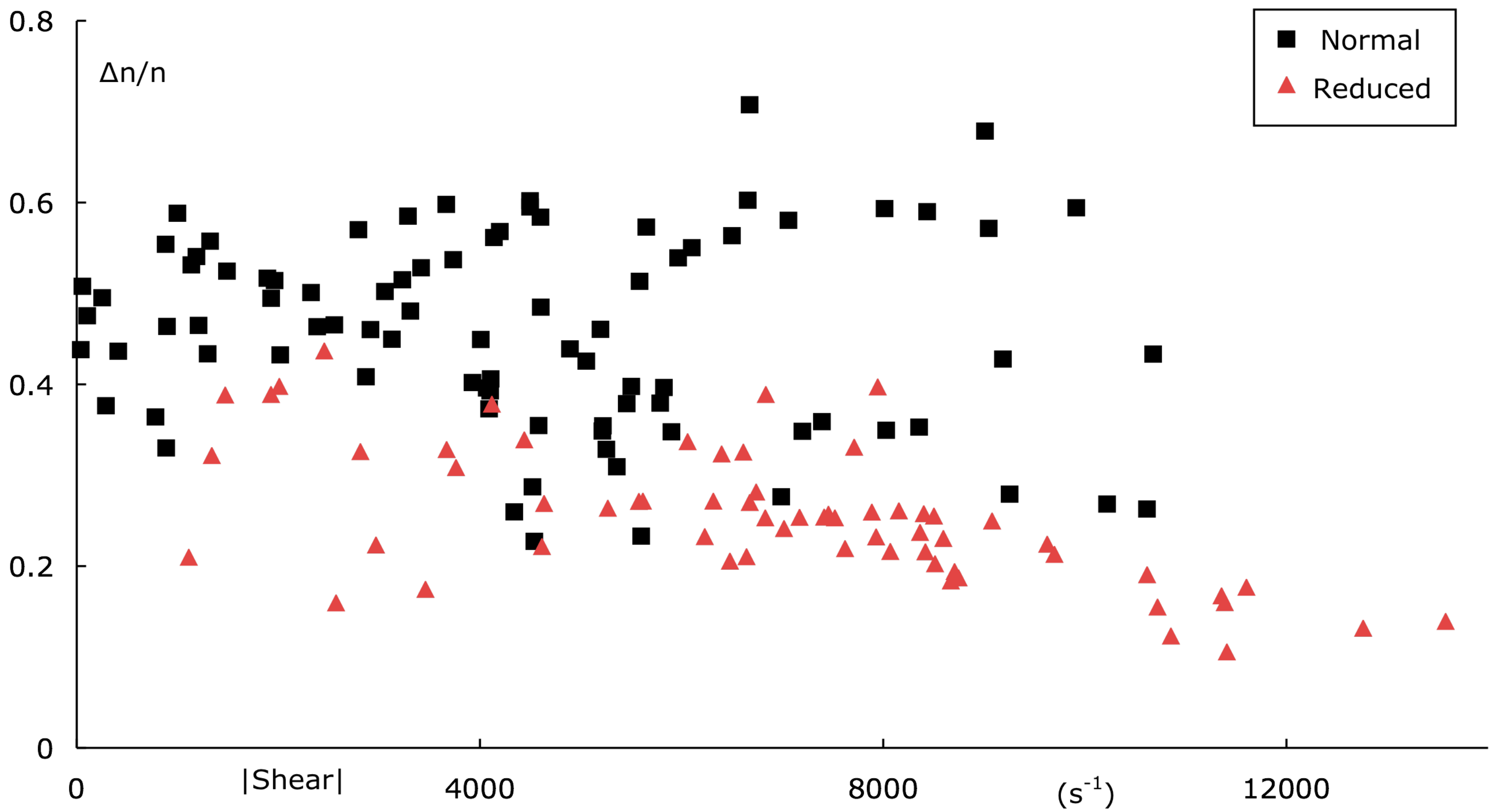
Shear often sufficient to stabilize turbulence in theory, but all combinations actually observed

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:

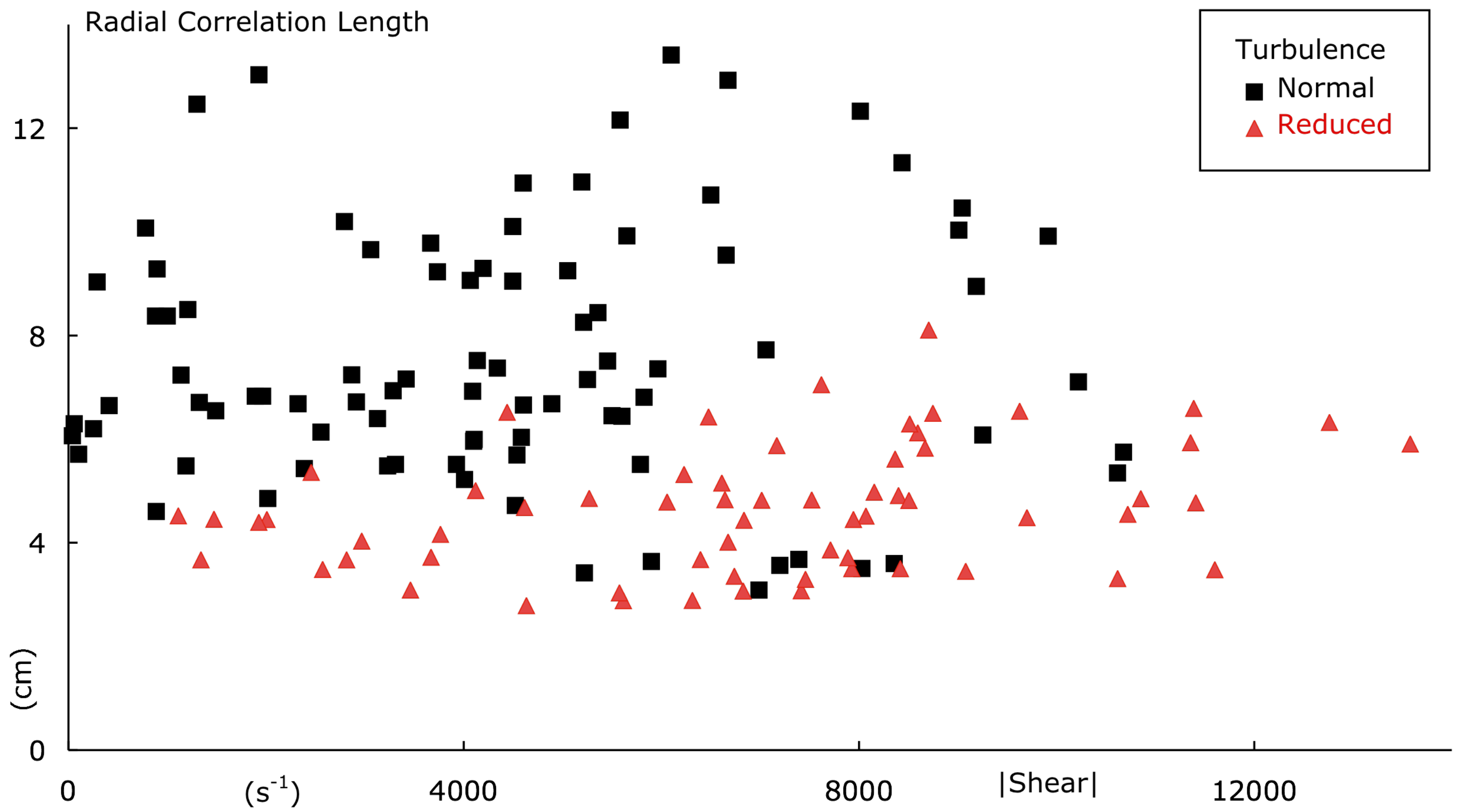
- Shear vs. Turbulent amplitude
- Shear vs. Correlation length
- Turbulent amplitude vs. Correlation length
- Amplitude reduction vs. Change in length

Shear Magnitude vs. Density Fluctuations



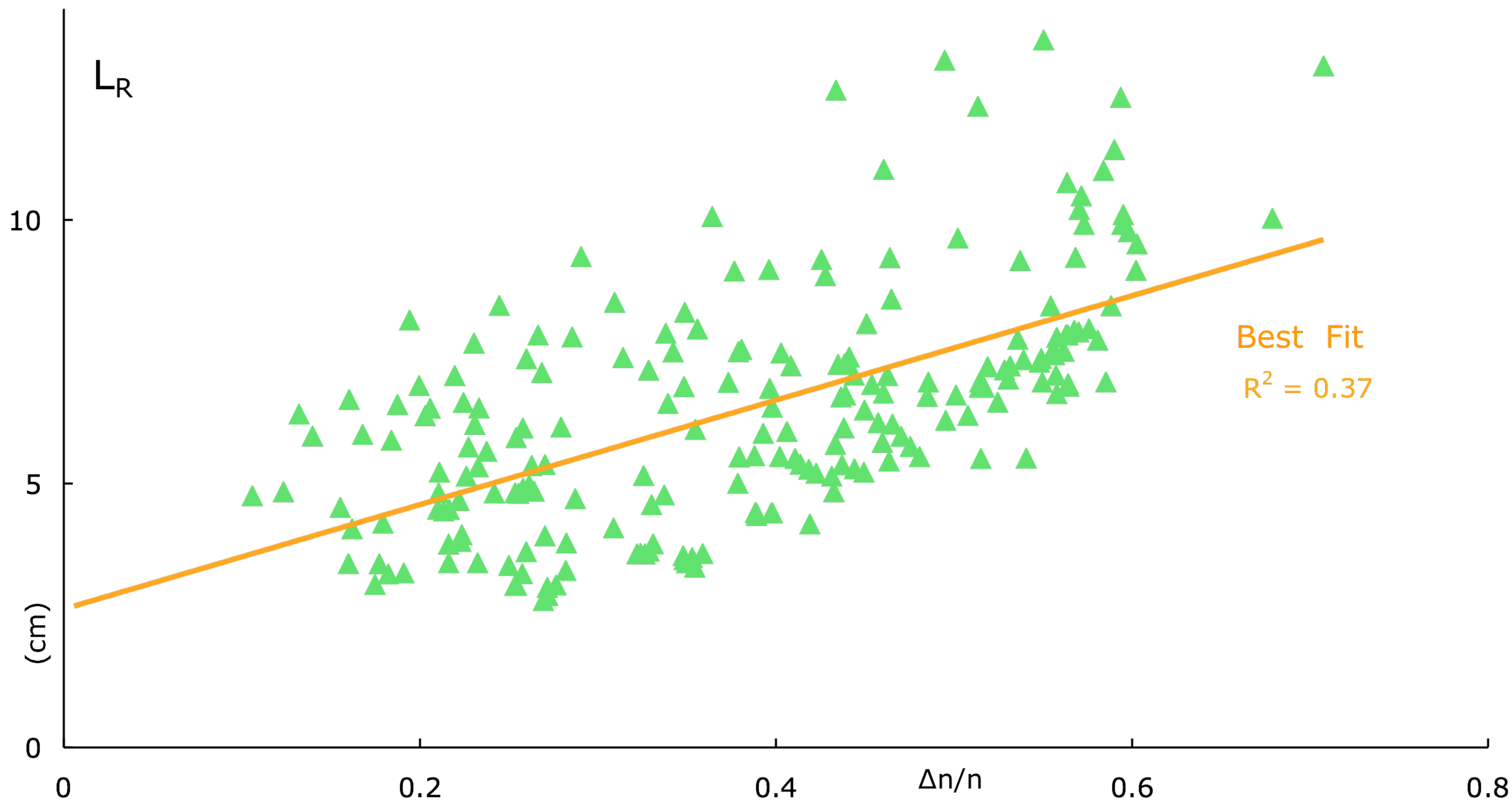
- **No evidence for a general physical relation**
- **Turbulence reductions even at low shear**
- **High turbulence may persist at high shear**

Shear vs. Radial Correlation Length



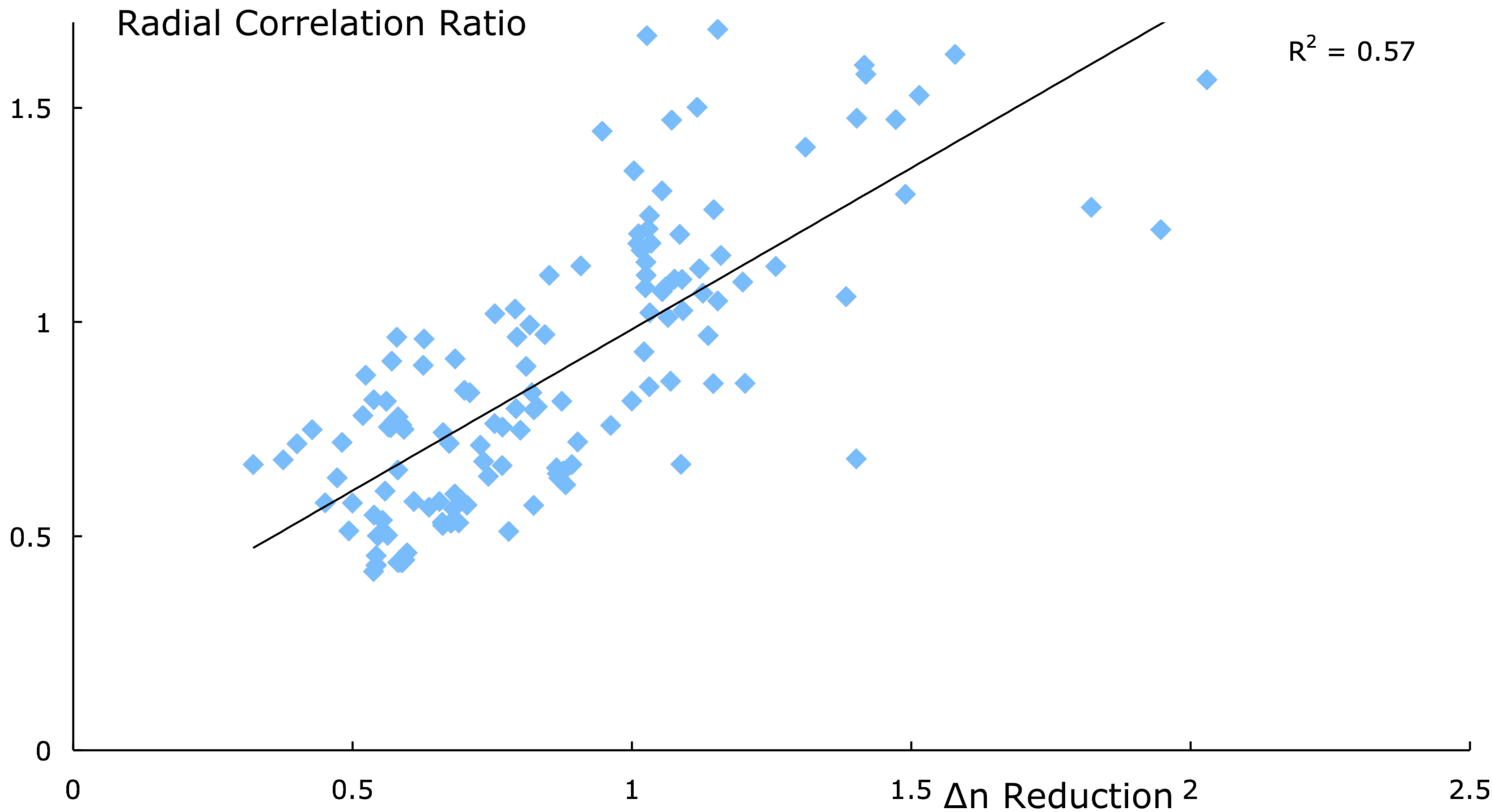
- **No evidence for a physical relation**
- **No trace of inverse trend**

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 roughly correlated with change in turbulence level

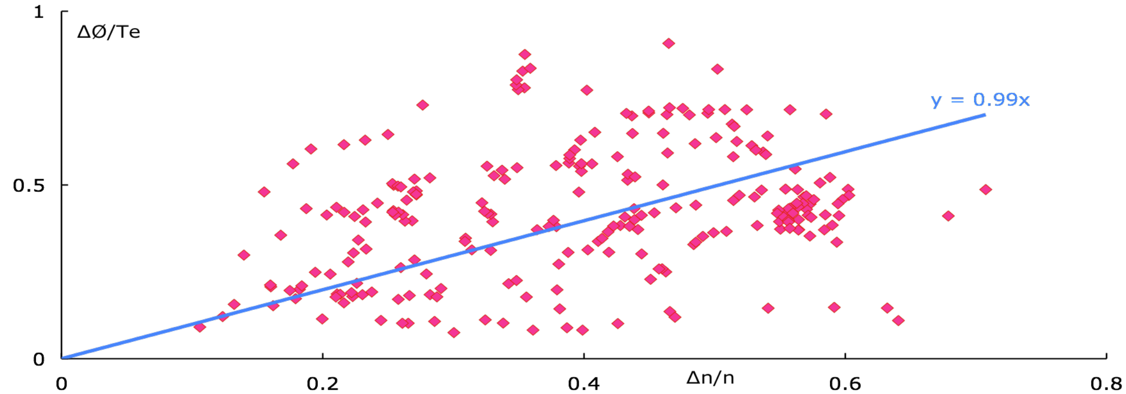
Why is the Helimak Different?

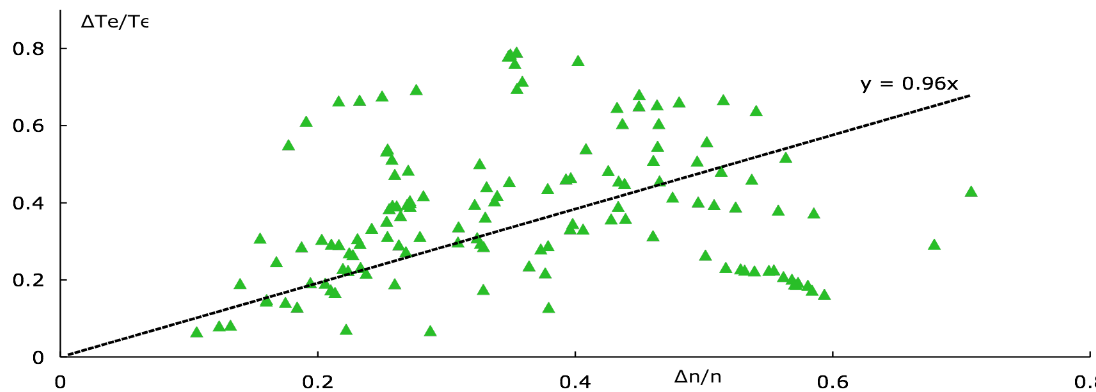
- Flow shear is a "self-fulfilling prophesy" in a tokamak -- a "flux-driven" system. The high thermal flux coupled with turbulence suppression → steep gradients → high flow shear.

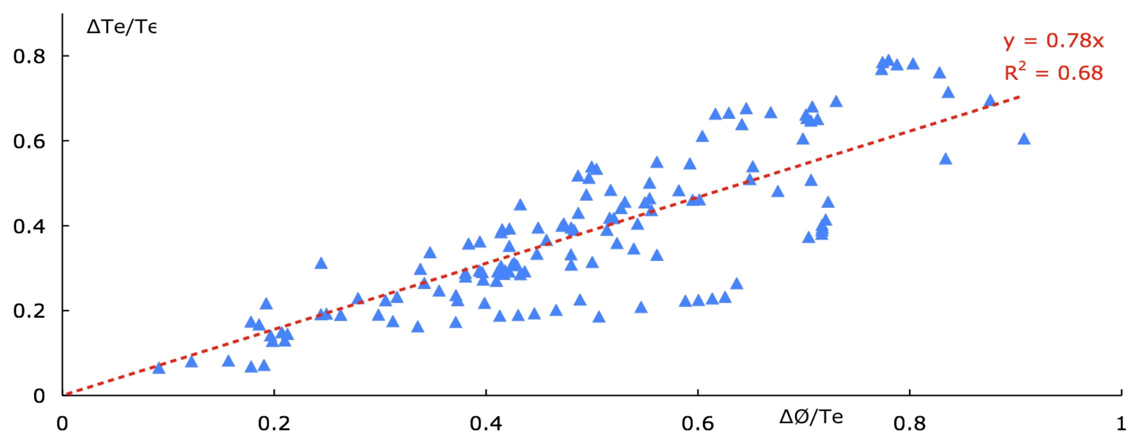
- The Helimak is not (radial) "flux-driven." Turbulence and radial transport can vary independently across the profile to give a clear test of the relation to flow shear for a range of conditions.

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.







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.

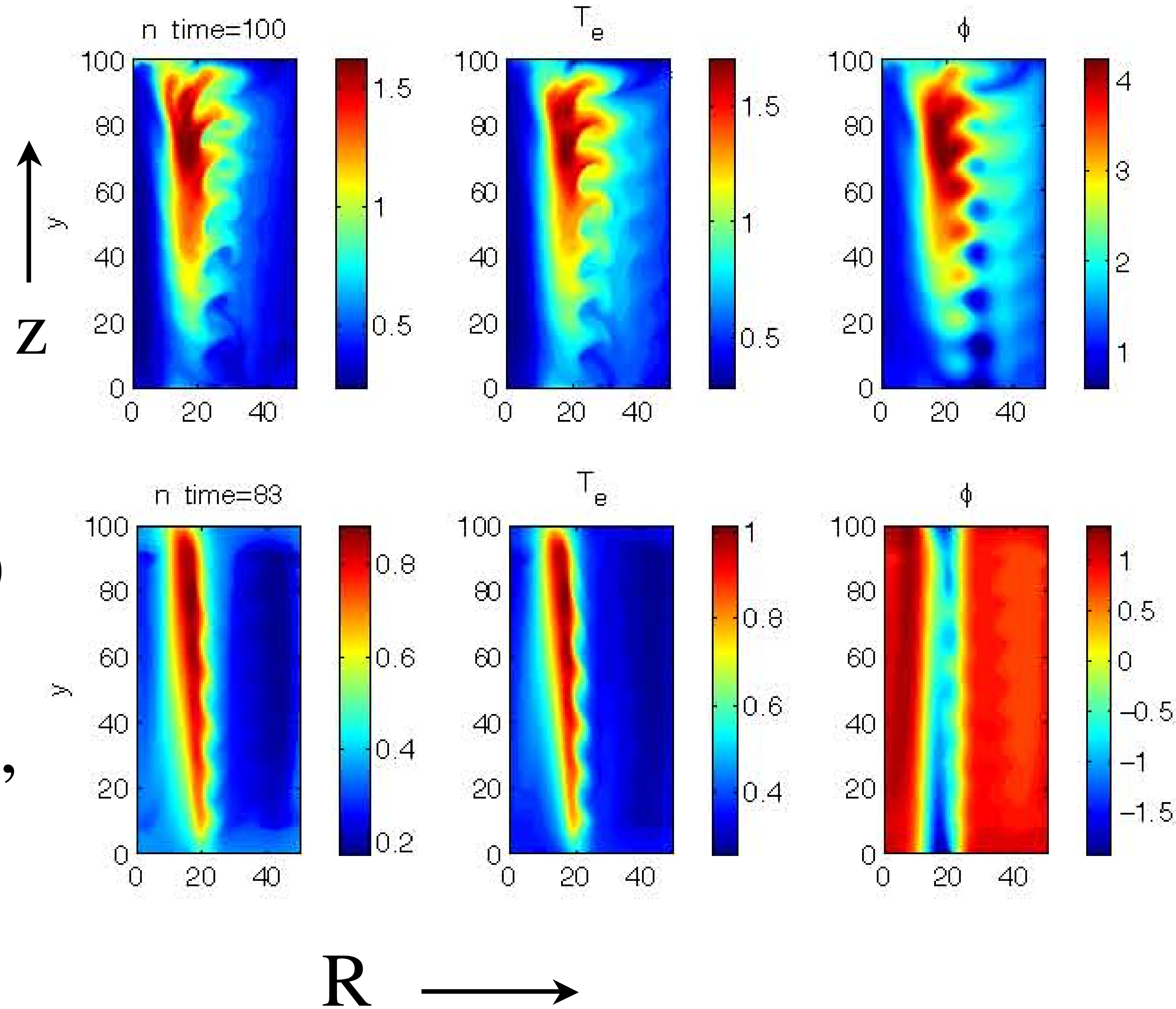
Ricci, Rogers, and Brunner, PRL **100**, 225002 (2008)
Ricci and Rogers, Phys. Plasmas **16**, 062303 (2009)
Li, Rogers, Ricci, Gentle, Phys. Plasmas **16**, 082510 (2009)
Li, Rogers, Ricci, Gentle, Bhattacharjee, Phys.Rev.E **83**, 056406 (2011)

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



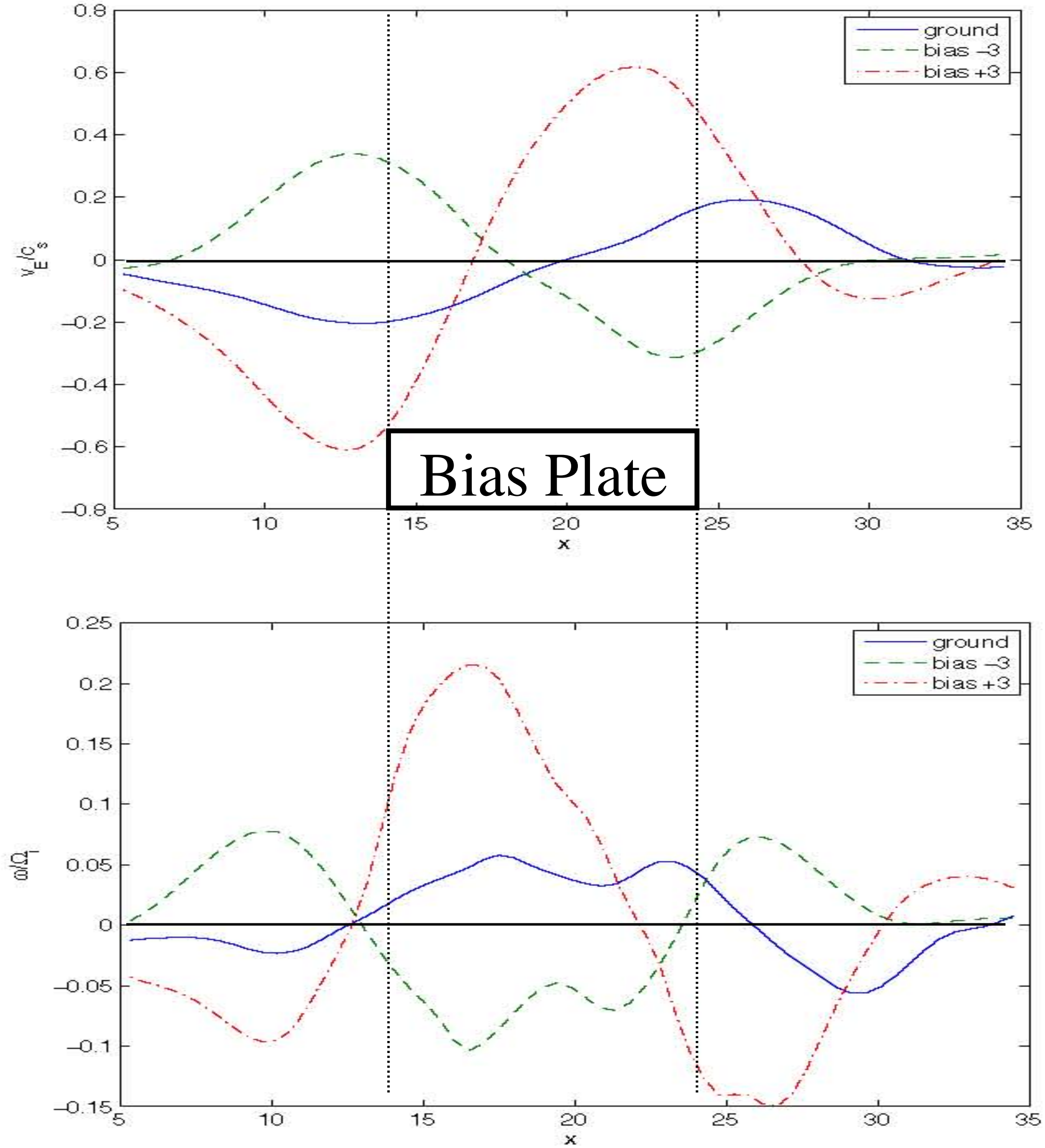
Flow and Flow Shear -- Normal, ±Bias

Flow (V_z)

Flows modified, especially near plate boundary

Flow Shear

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



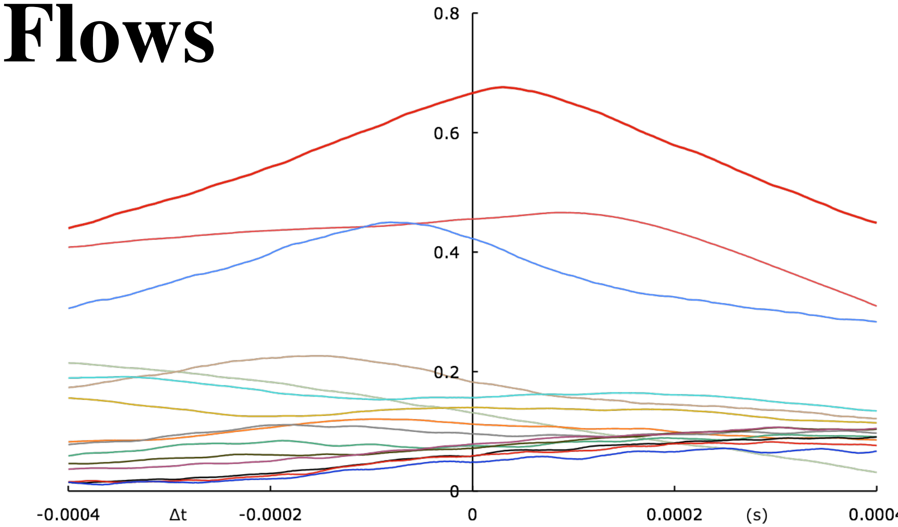
Numerical and Physical Experiments Share:

- 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.

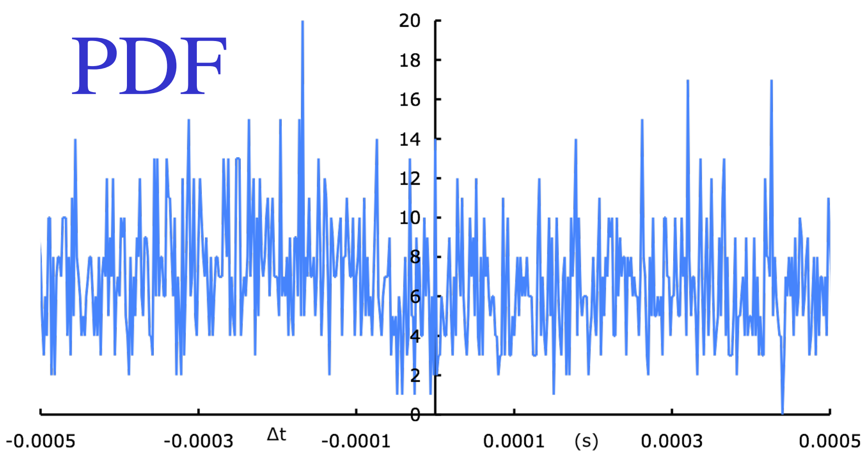
Radial Flows

Radial Cross-correlations:
No indication of mean flows

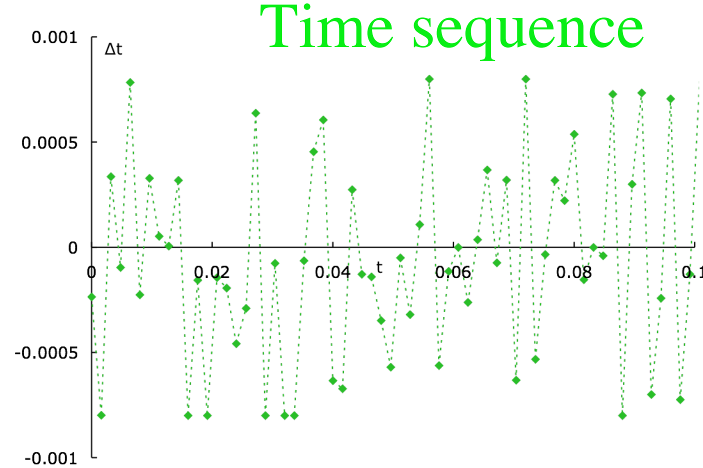


Time delays from 1 ms sub-samples

PDF



Time sequence



Uniform distribution, random sequence ⇒No flows

V_z (Poloidal) Flows -- Zonal Flows

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

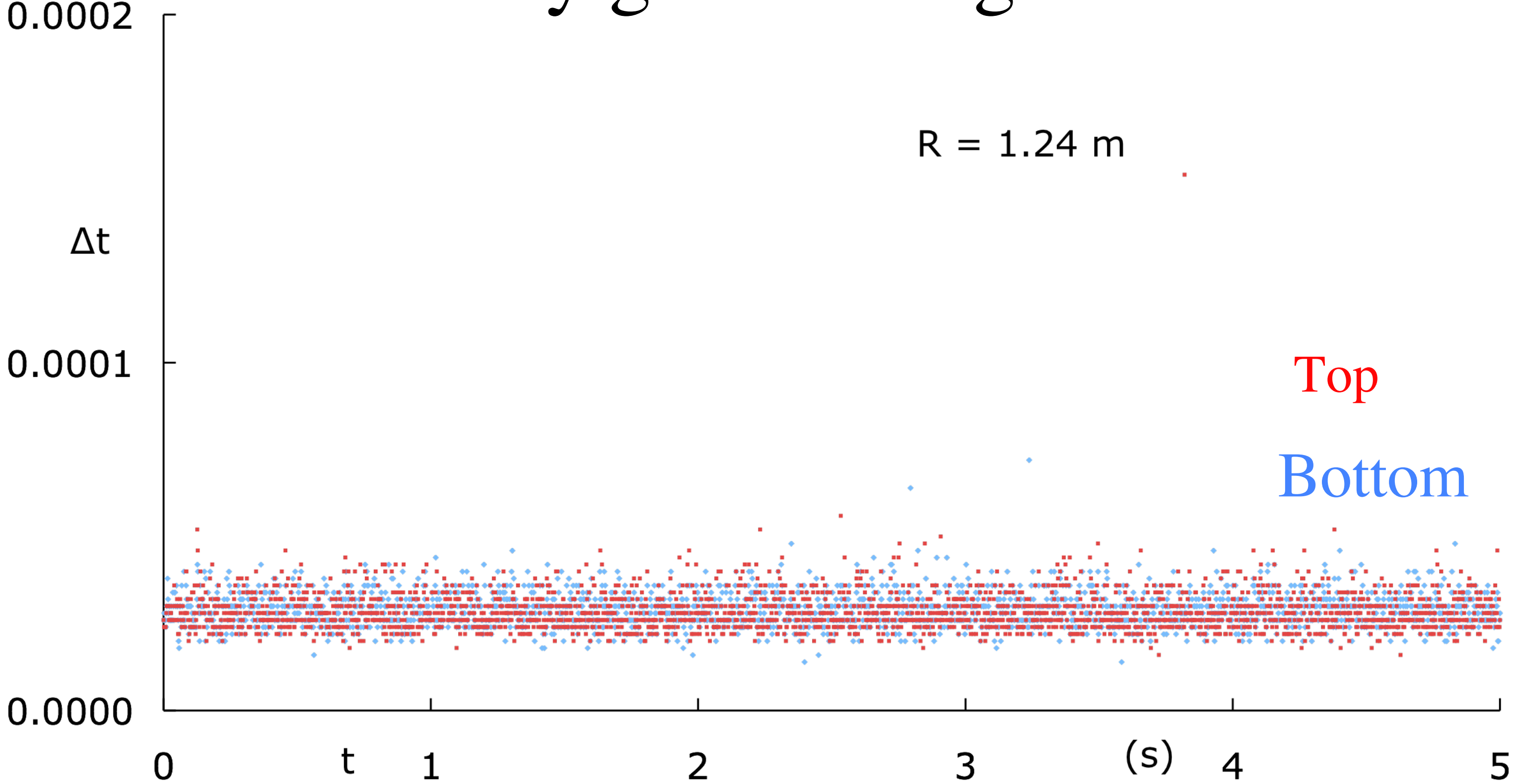
Apparent propagation indication of flow

V_z inferred from density fluctuations at probe pairs $\Delta z=$ 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

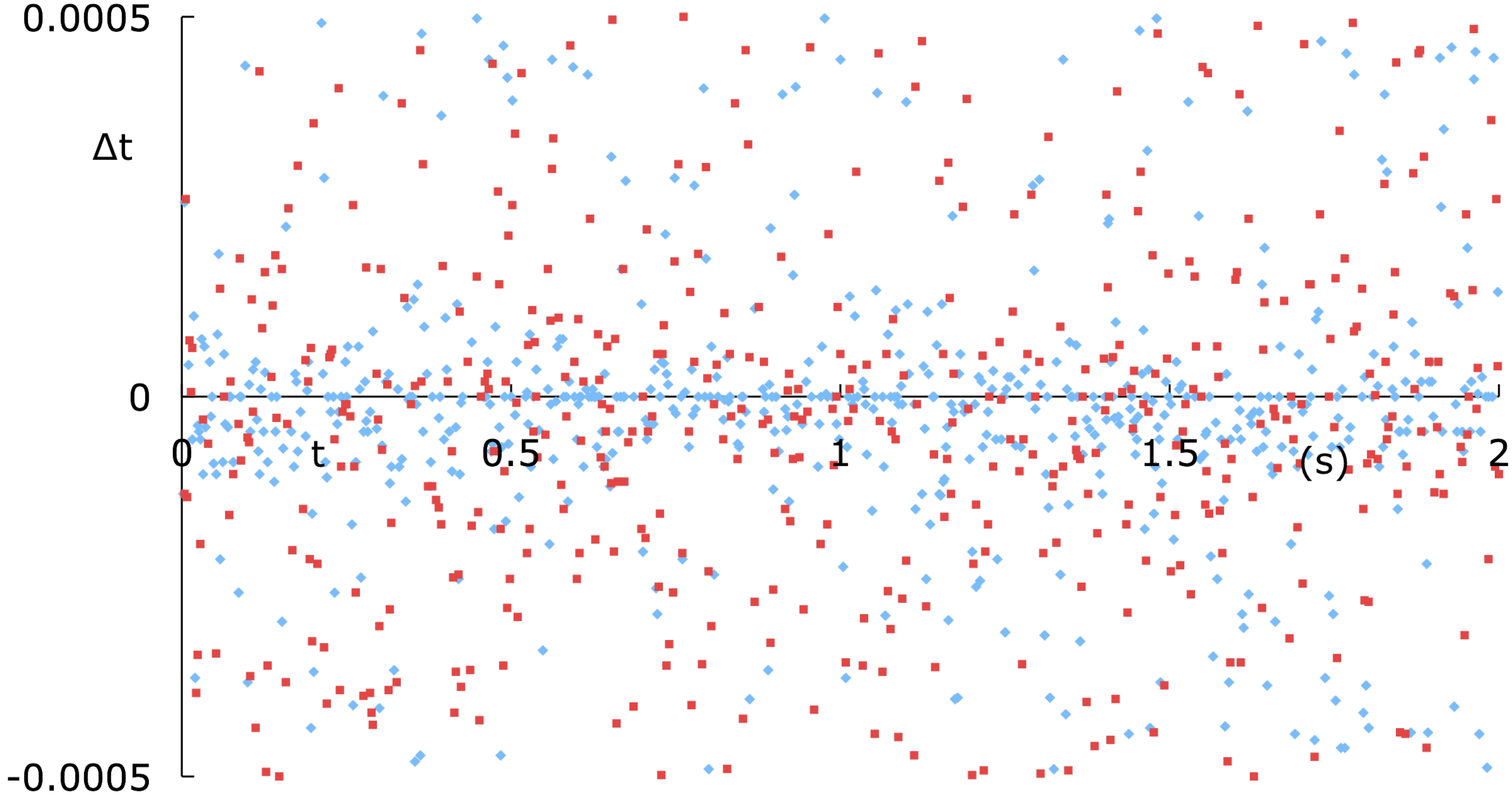
- Flow "m=0; ω=0" Same at top and bottom
- May vanish over 10s ($\sim 10^4\ \tau_{decorrelation}$)
- Should be clear and slowly varying in sequence of 1 ms subsamples

Density gradient region



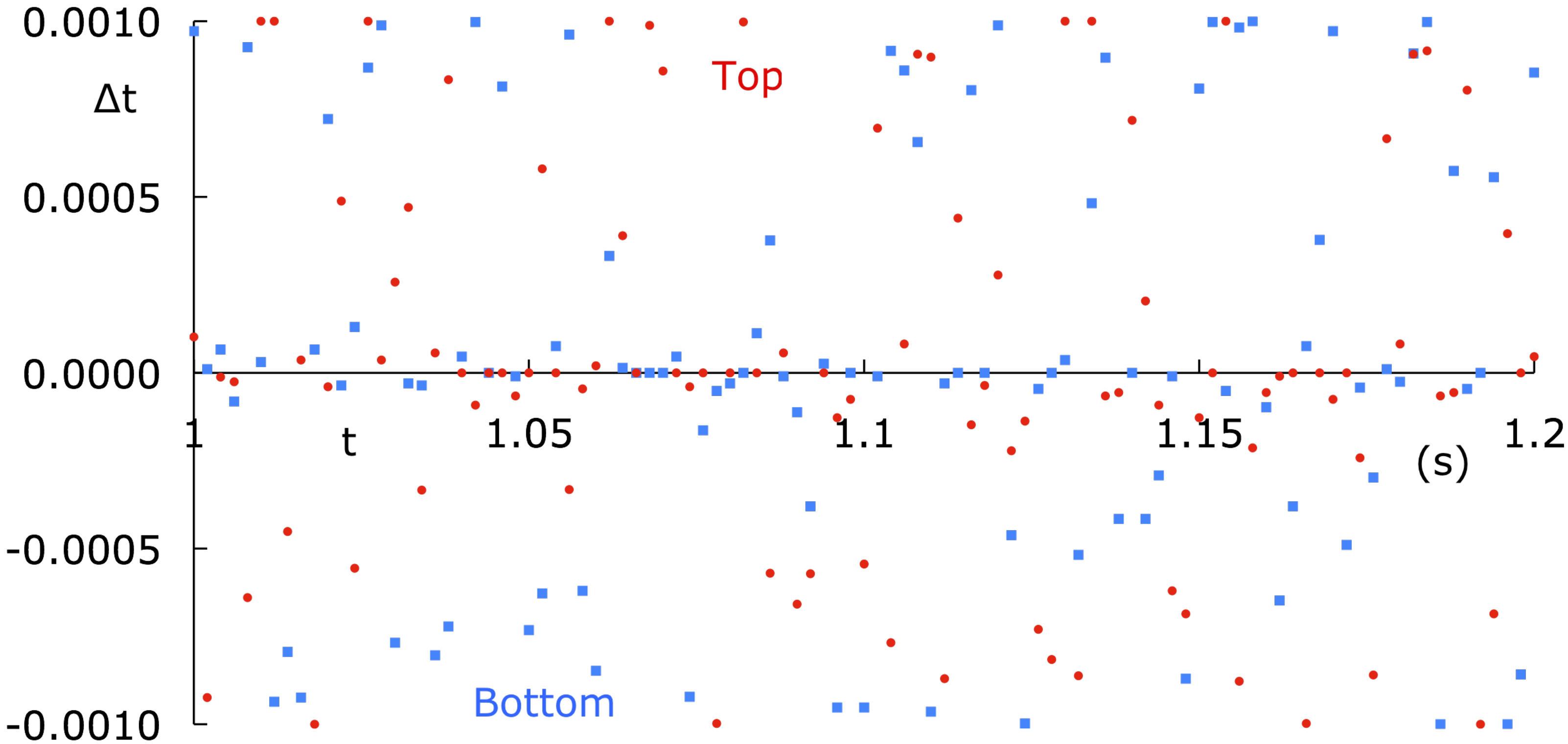
- Clear mean flow -- well-defined delay time Δt, consistent top/bottom
- No secular variation
- Small, fast random variations about mean -- local turbulence

Near Density Peak (R = 1 m)



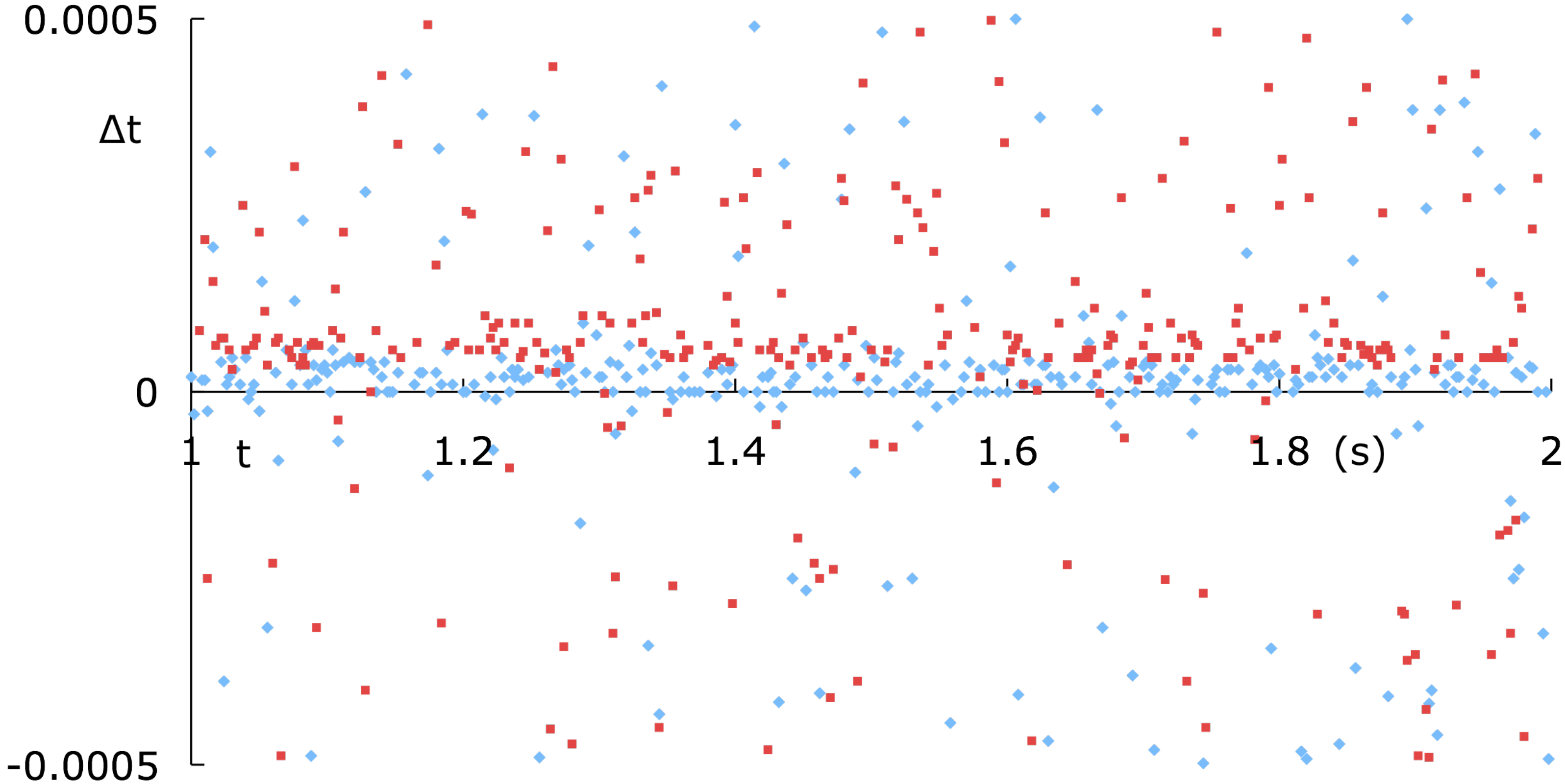
No mean flow; only local turbulent fluctuations. Fast, random variations in delay times; top and bottom independent.

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 turbulent modification of mean flow.

General Flow Characteristics

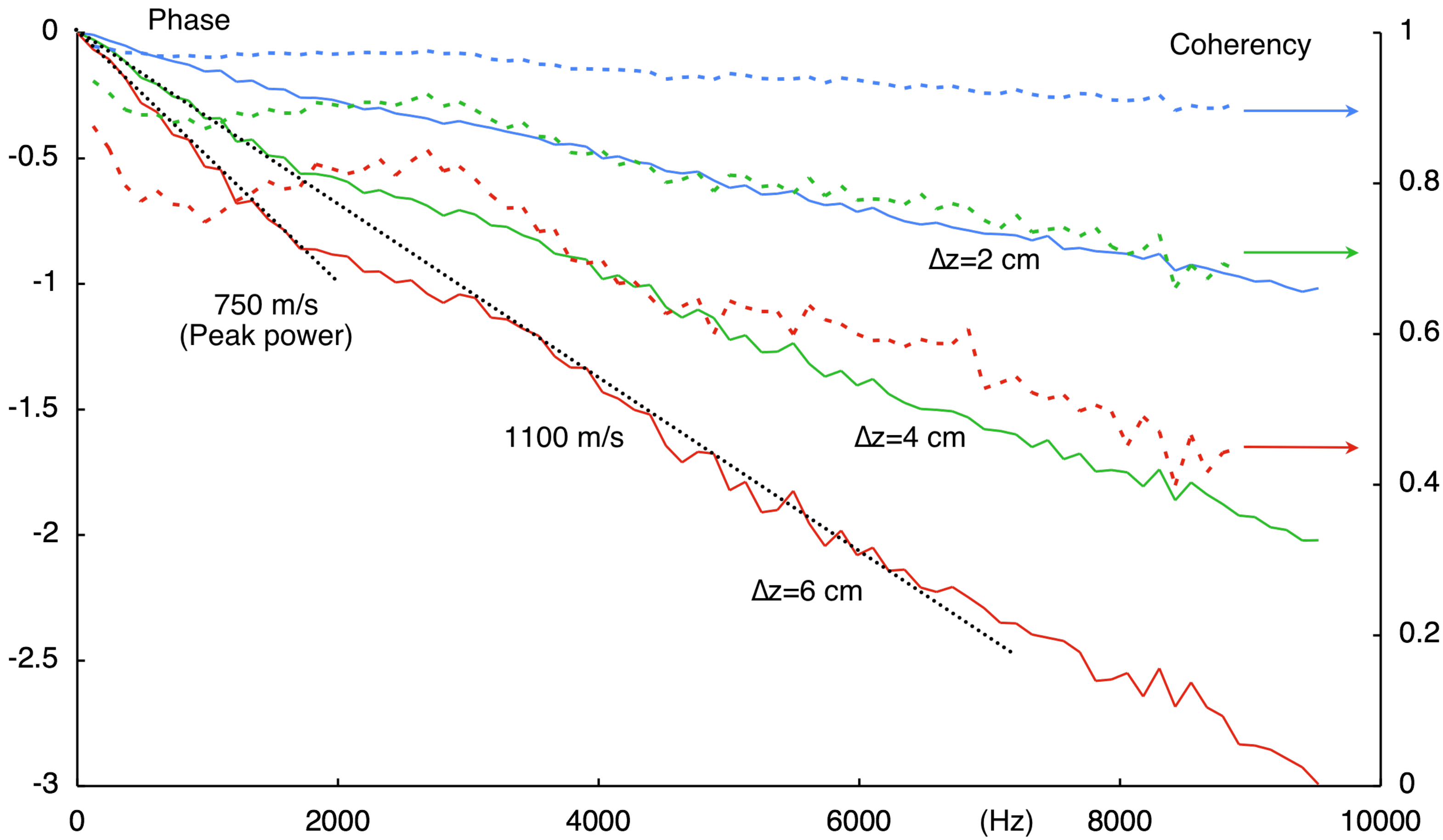
- In the density gradient region ($R \geq 1.2$ m), well-defined mean bulk flows $\langle V_z(R) \rangle \sim 1000$ m/s, consistent top/bottom by all measures with no secular or shot-to-shot variation and small, fast random variations about mean in the sub-samples.
- Near the density maximum ($R < 1.2$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

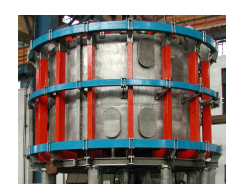
Conclusions

- 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.

Gradient Region

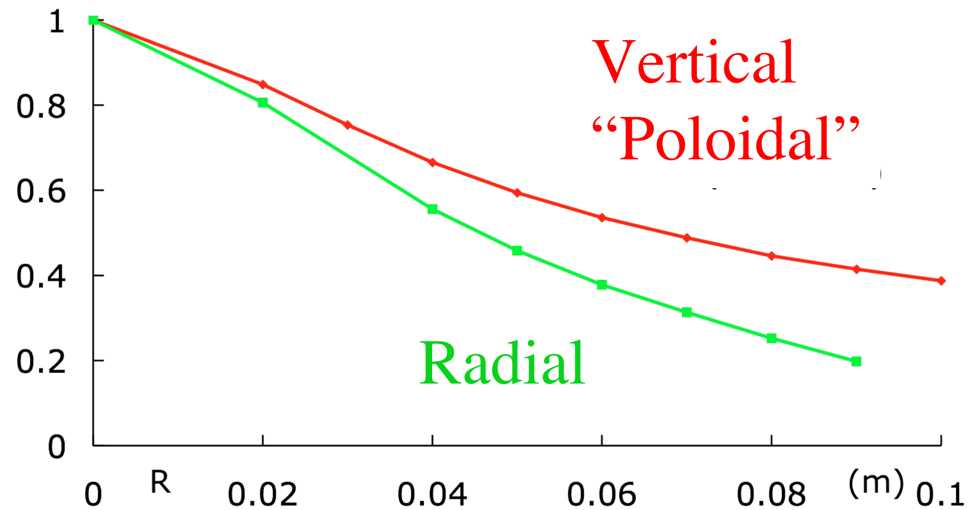
Propagation with high coherency





Correlation Lengths

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



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