# Turbulent Structures 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

# Outline

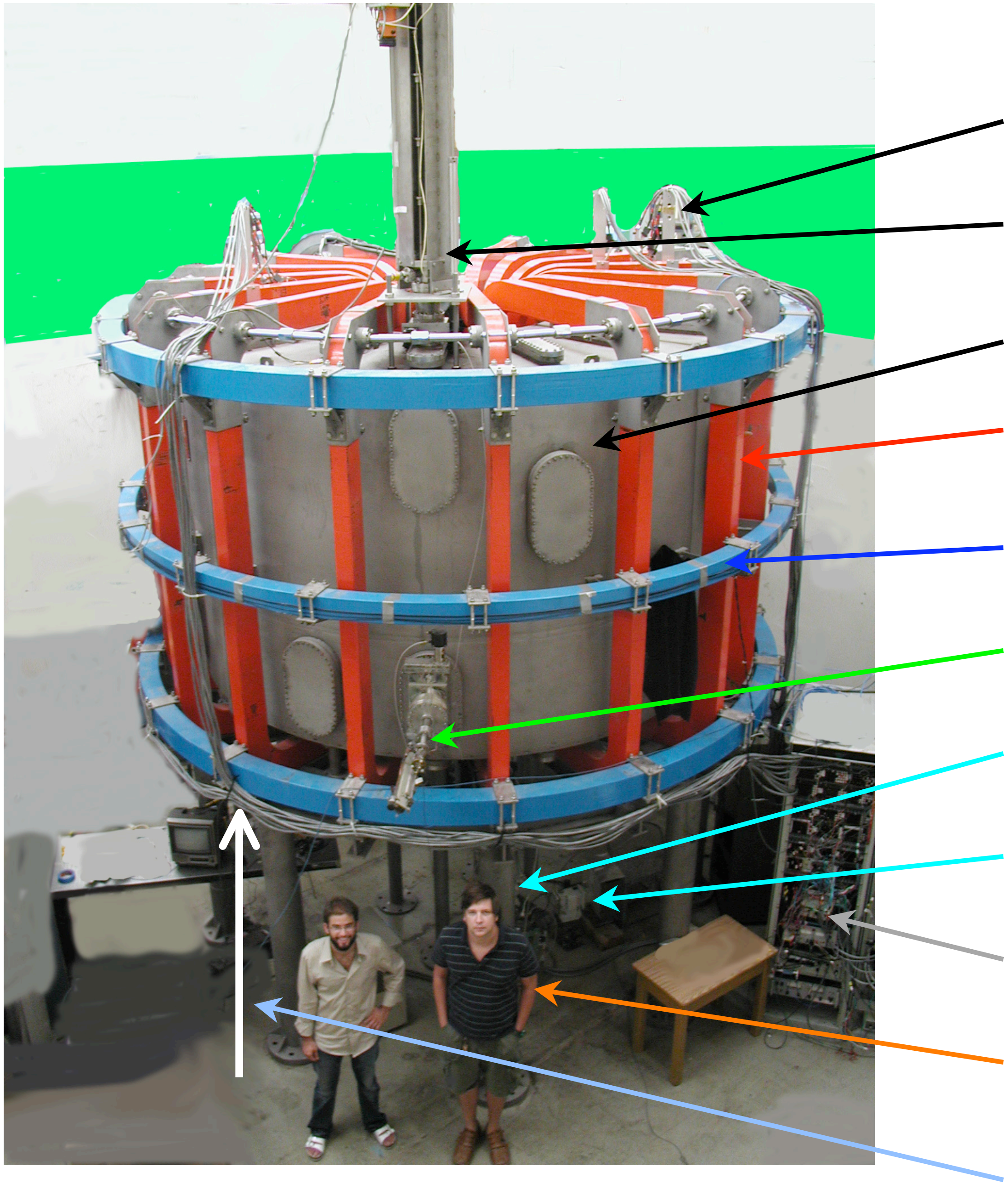
1. Description of device and plasma parameters

2. Results for reduction of turbulence by biasing

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

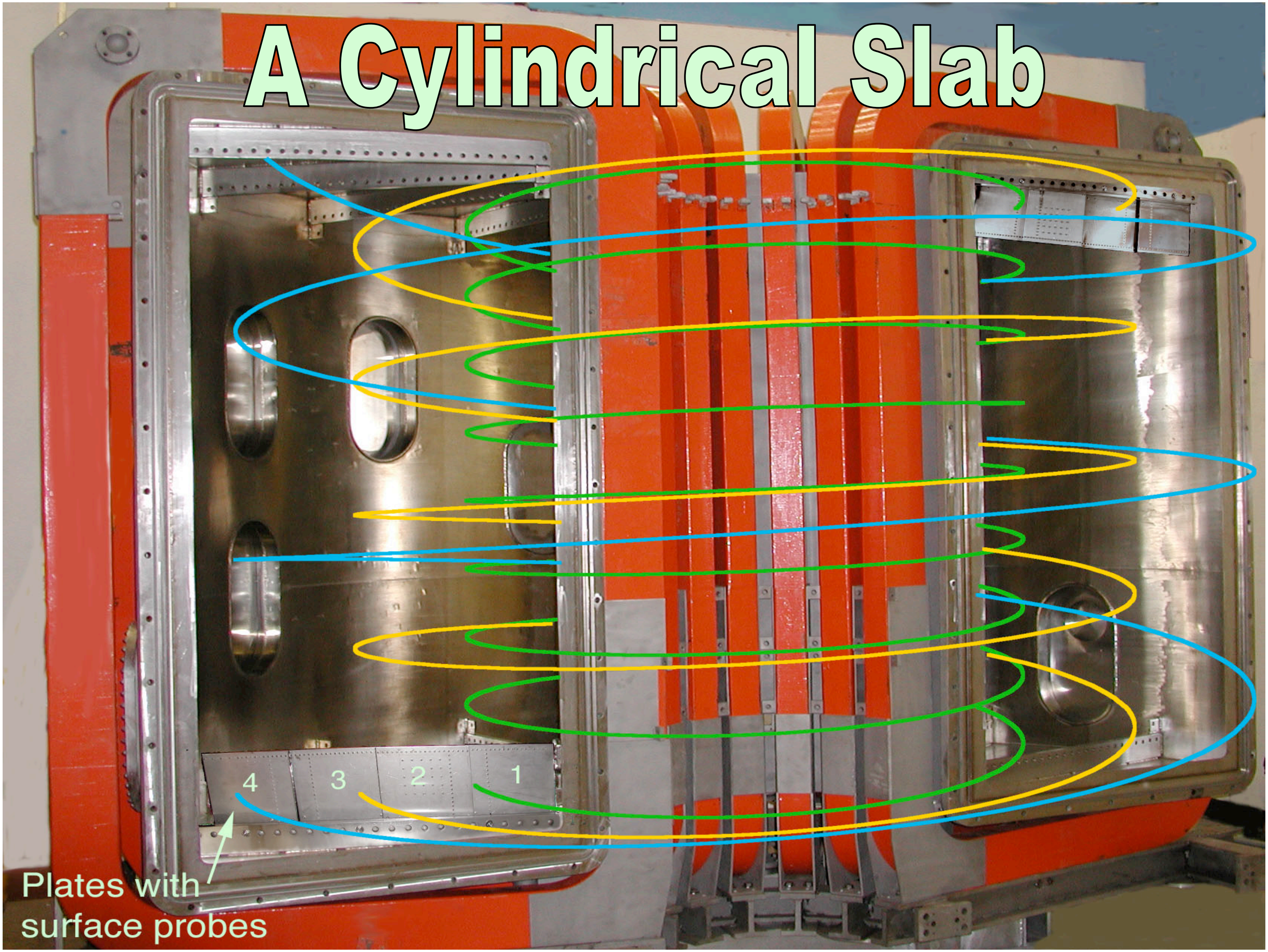
4. Comparisons with simulations and tests for zonal flows

# Helimak

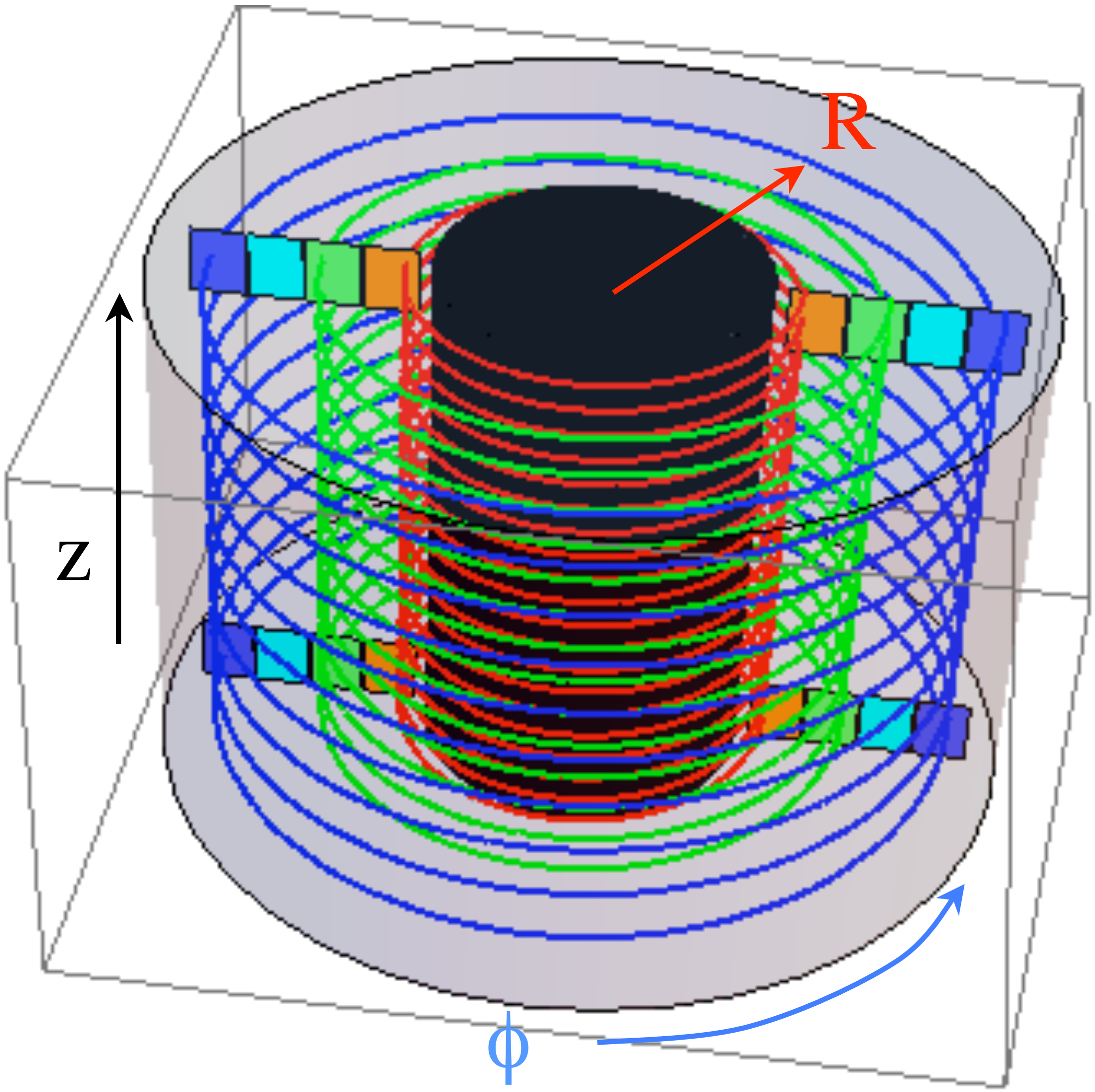


Probe plate connections
Movable probe
Vacuum Vessel
Toroidal field coils
Vertical field coils
Magnetic probe
Microwave feed
Magnetron
Amplifiers and A/D
Scale
Optical Vertical View

# 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    $B_v \le 0.01$ T    Pulse $\le 30$ s

Plasma source and heating: 6 kW ECH @ 2.45 GHz

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

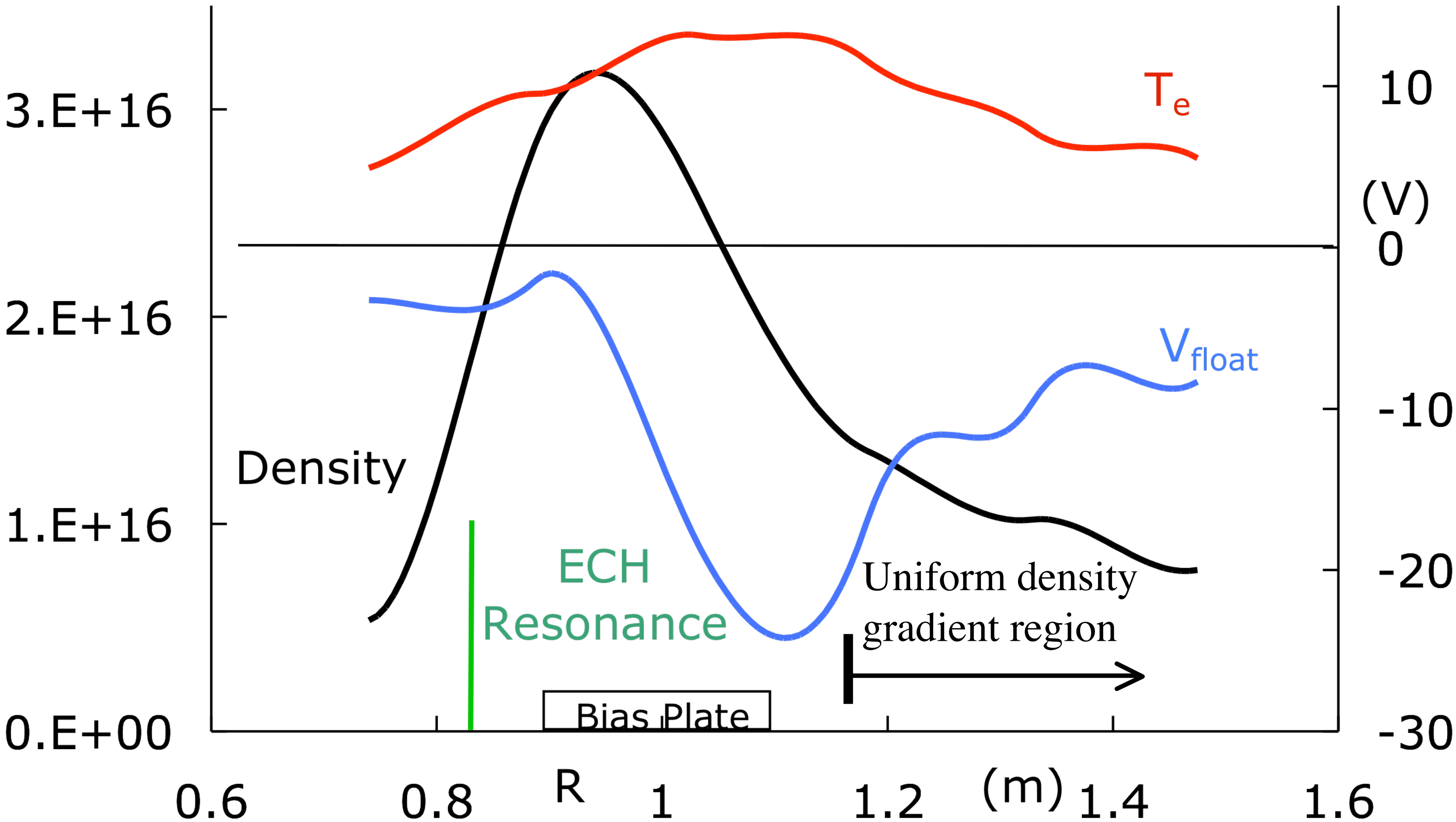
Connection length: $10\ m < L_{\|} < 2000$ m    $\tau_p$ (parallel loss) $> 1$ ms

Probe arrays in end plates provide vertical and full radial profiles

# Dimensionless Parameters

| | |
|---|---|
| Transverse scales: $\rho_s/L_n$ | 0.2 |
| $\rho^*$ $(\rho_s/a)$ | 1/50 |
| $L_{corr}/a$ | 0.05 |
| Drift drive $v_D/c_s$ | 0.2 |
| $\beta$ | $6x10^{-5}$ |
| Collisionality $L_c/\lambda_{ee}$ | 0.1 |
| Turbulence level $\Delta n/n$ | 0.4 |
| Parallel size $L_c$ (m) | 50 |

# Typical Density, Temperature, and Floating Potential Profiles

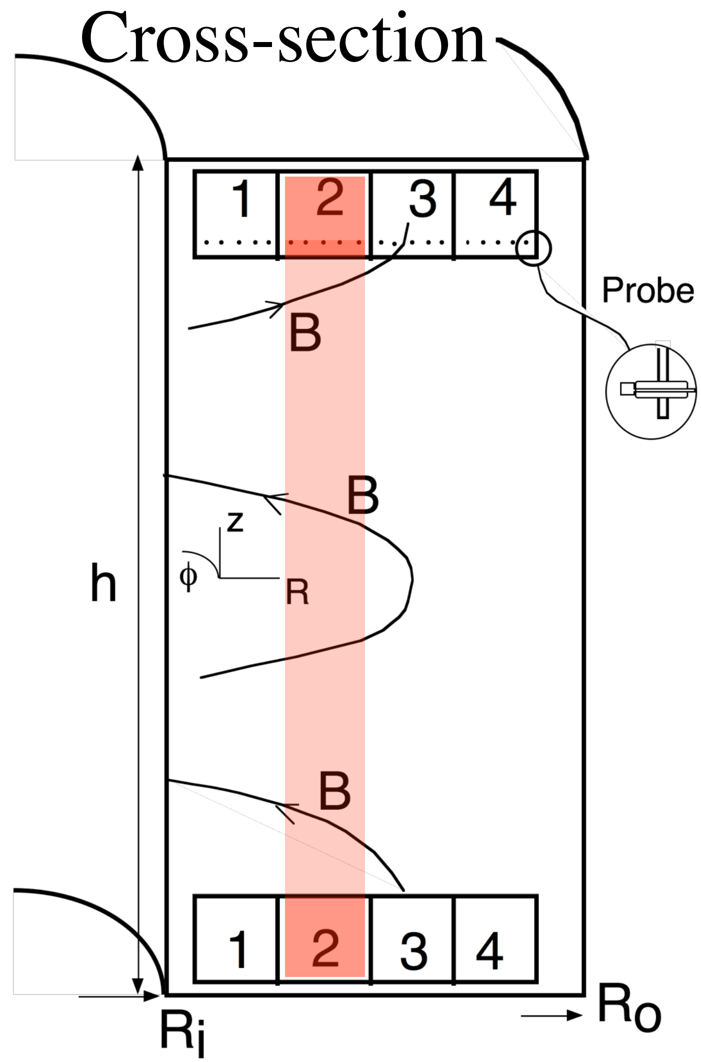



# Application of Bias

➢ 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

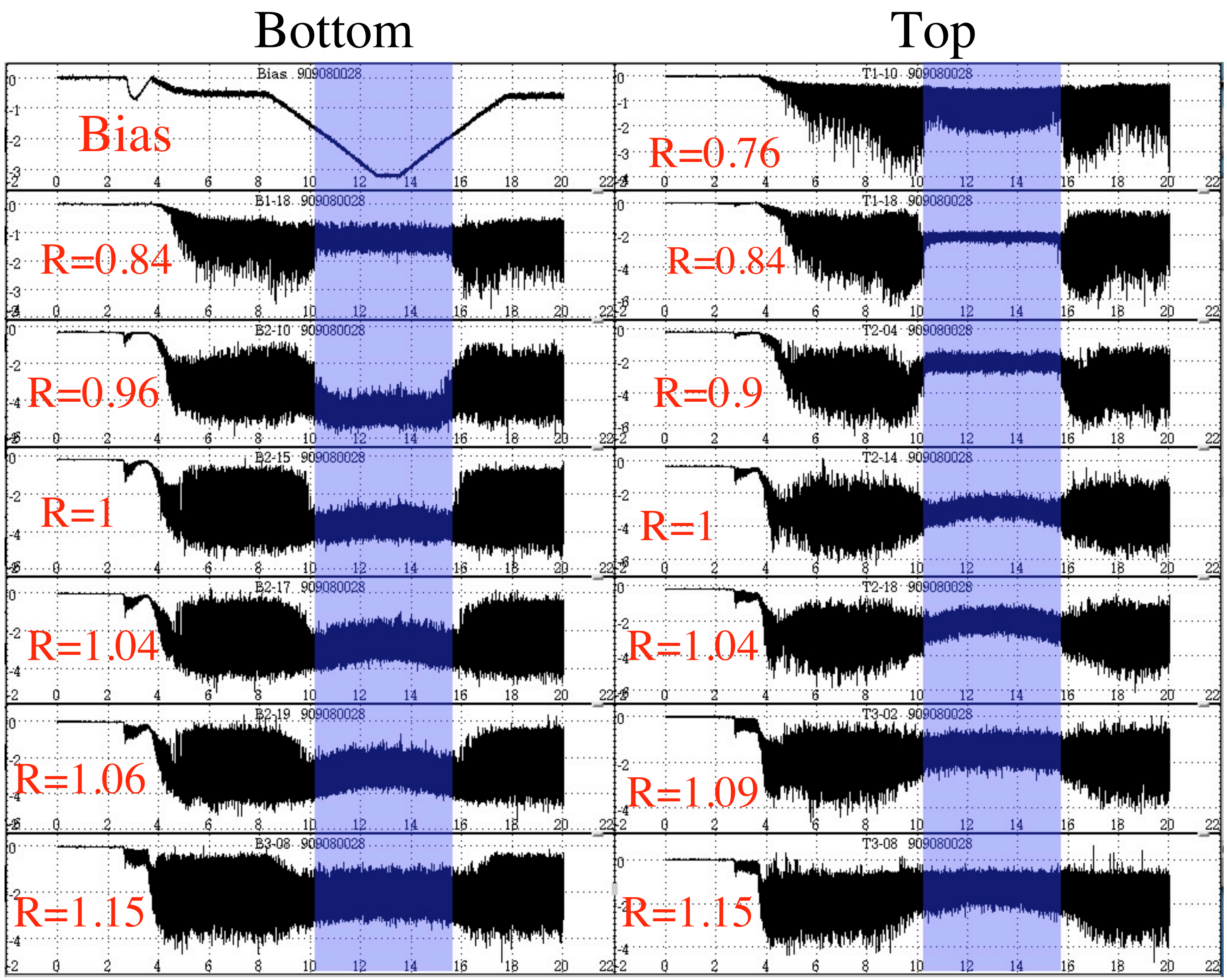
➢ Other plates and vessel grounded



# Simple Phenomenology

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

Negative Bias Transition at ~-20 V



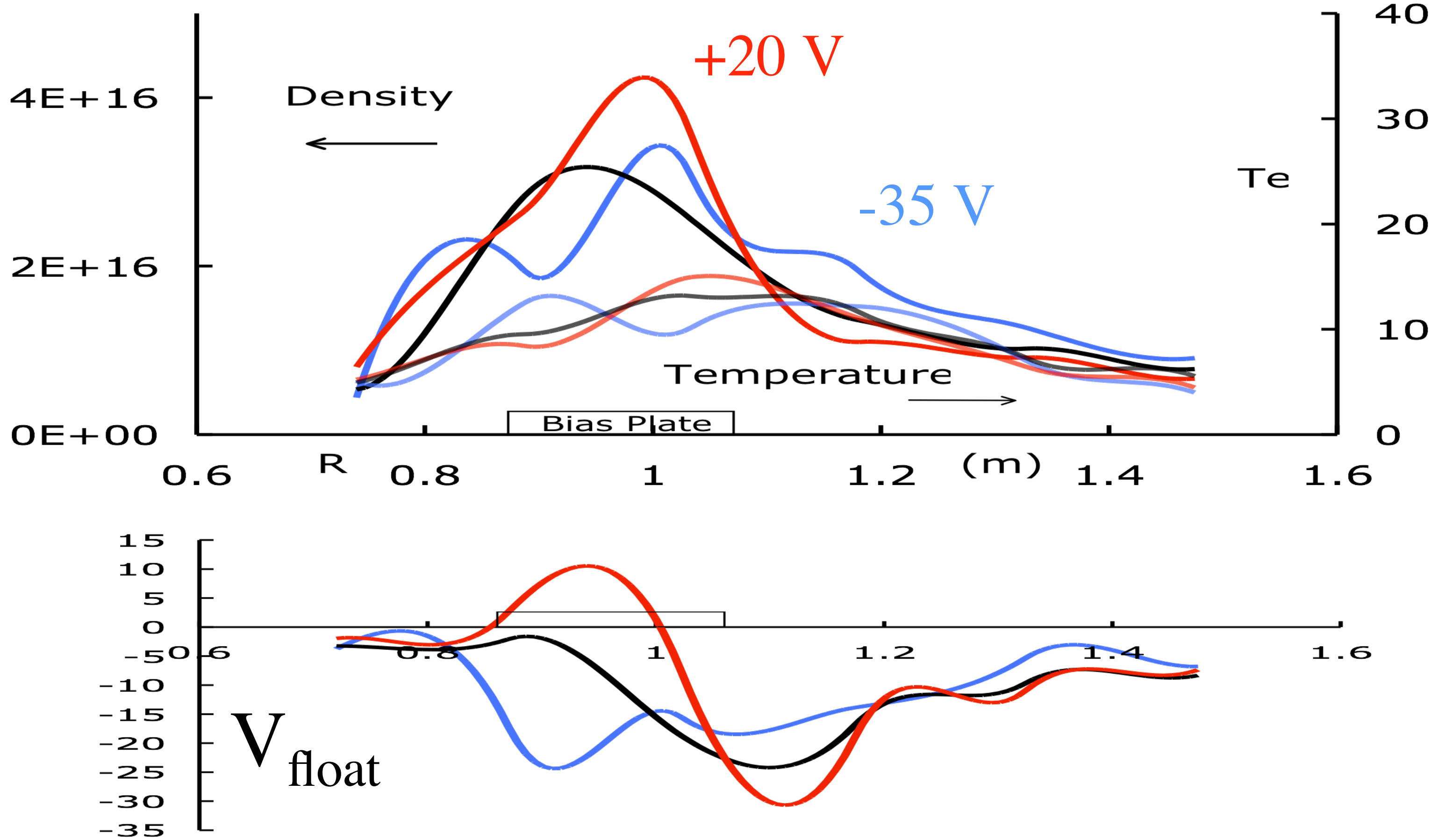
# Bias-Driven Turbulence Reduction

- 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.)

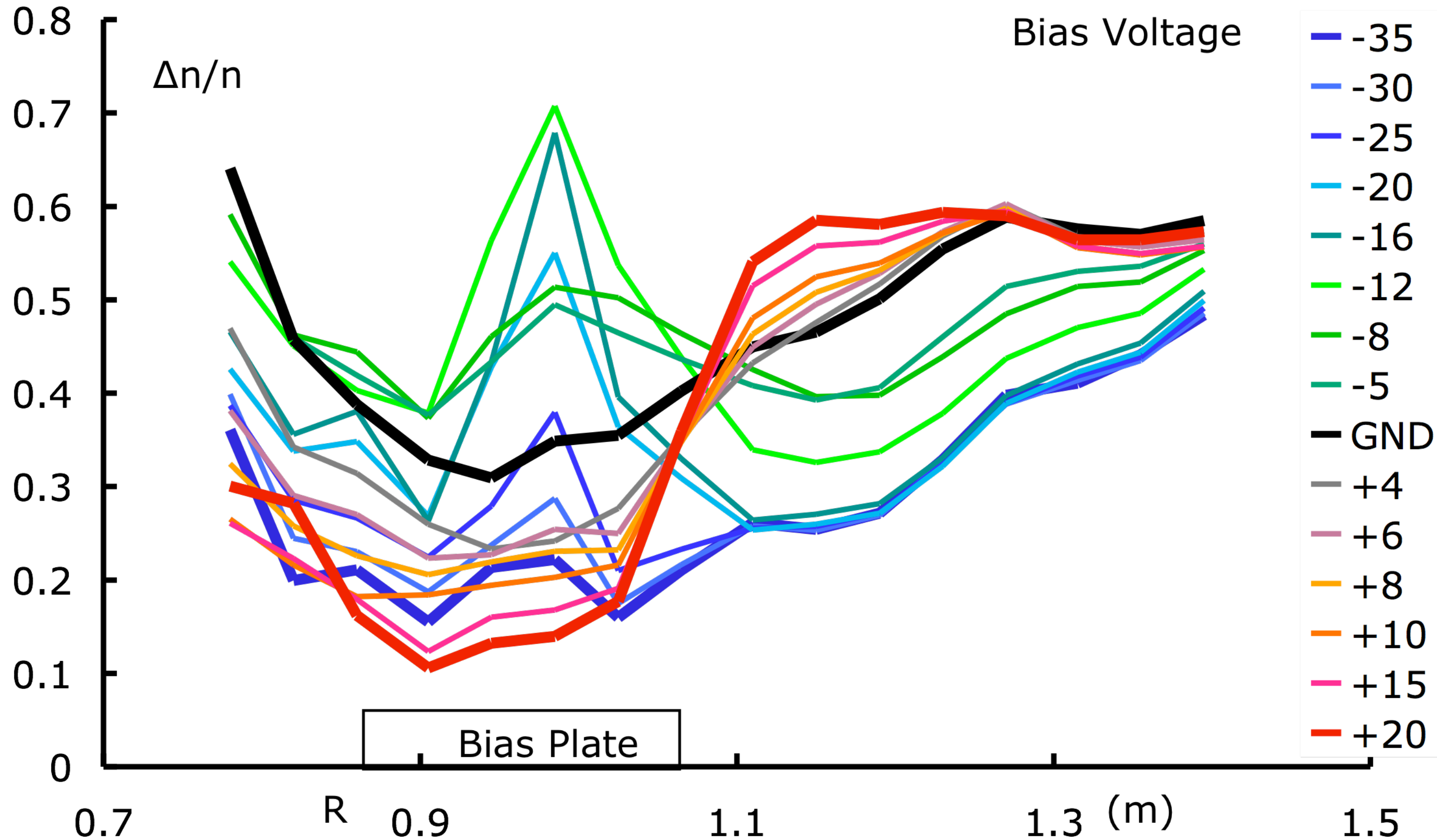
# Profile Changes with Bias

## Positive, Negative, Zero Bias




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

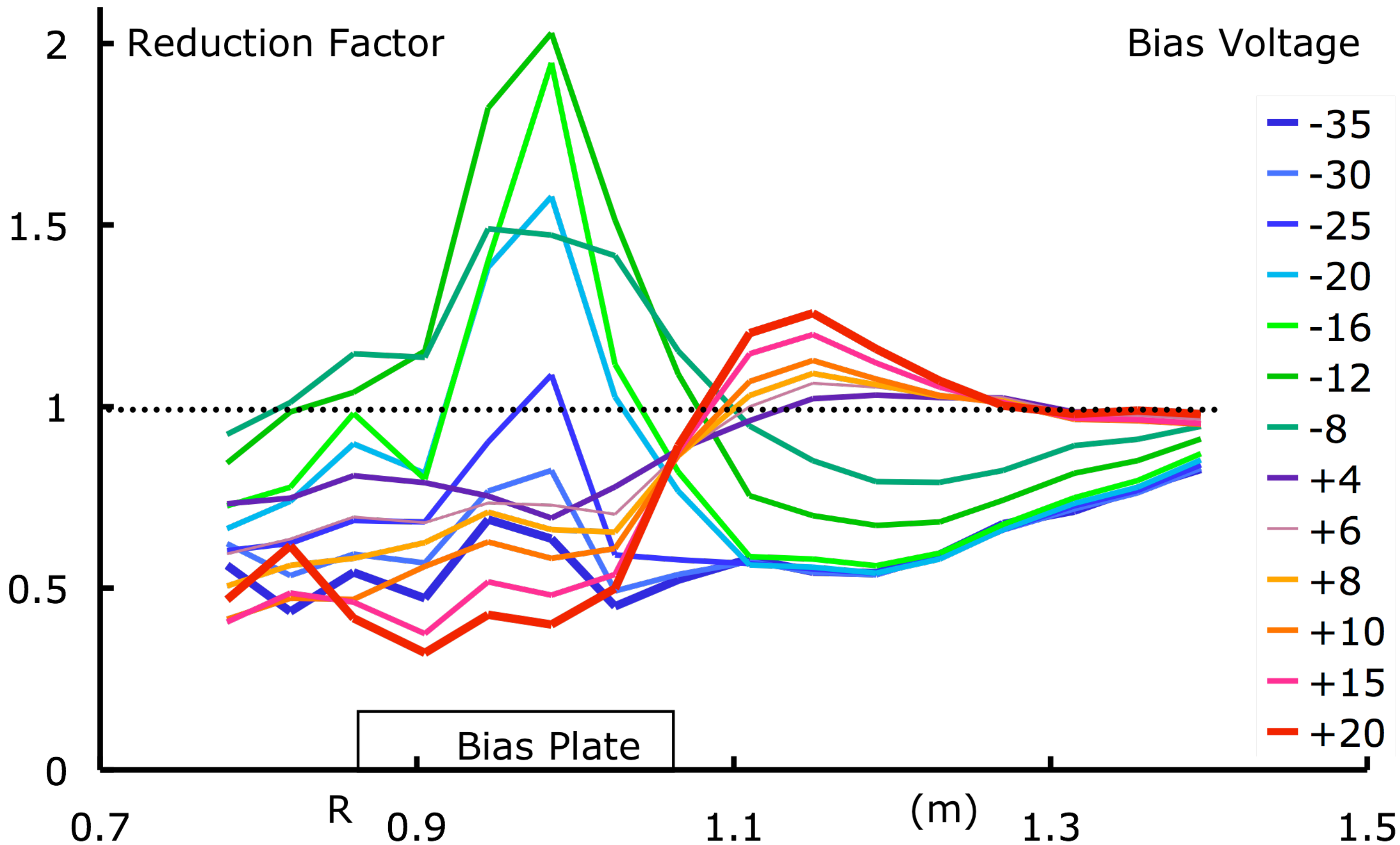
# Density Fluctuations




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

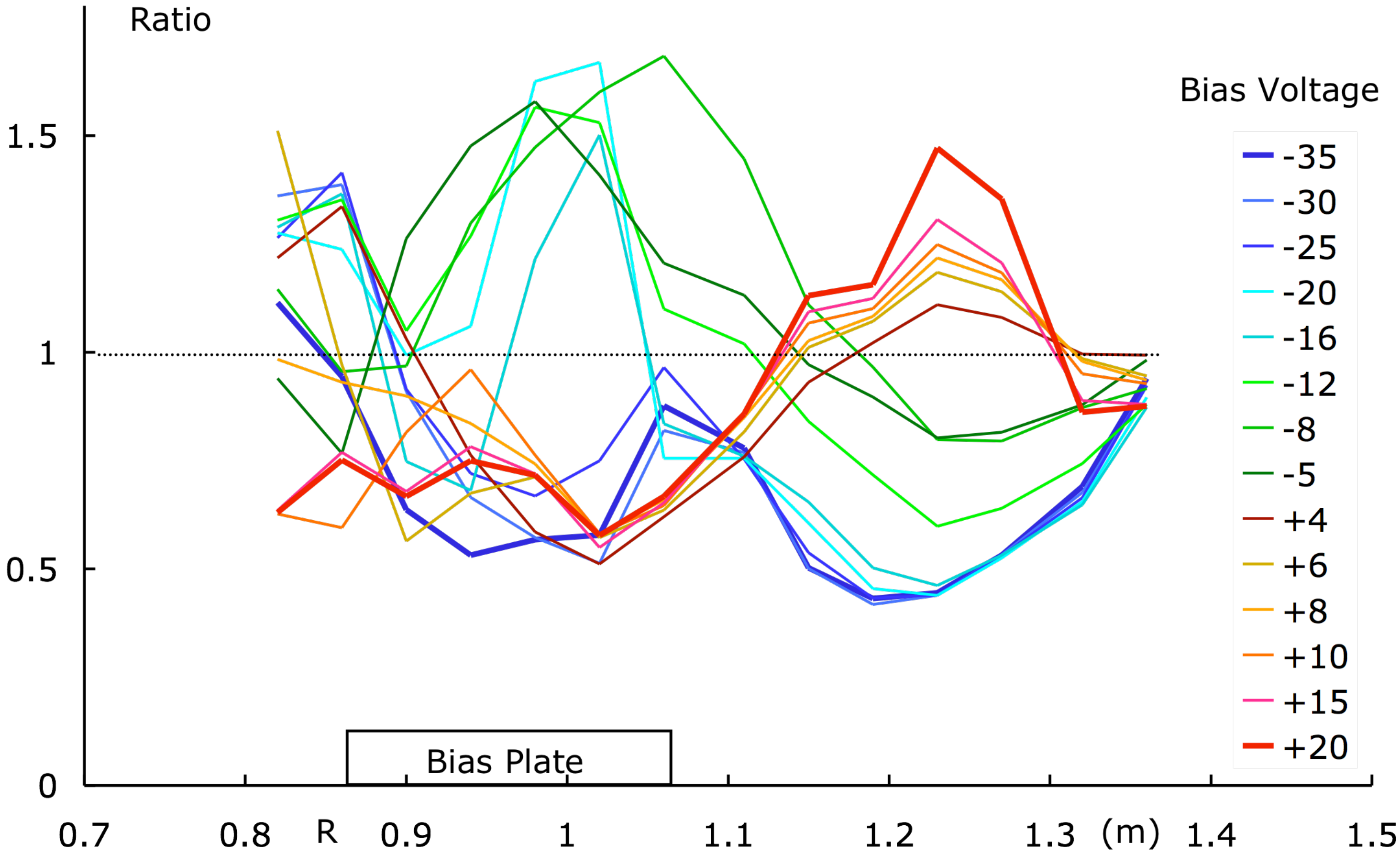
# Turbulence Reduction -- Density

## Reduction = Δn/n(Bias)/Δn/n(Grnd)




Suppression largely completed by -25 V

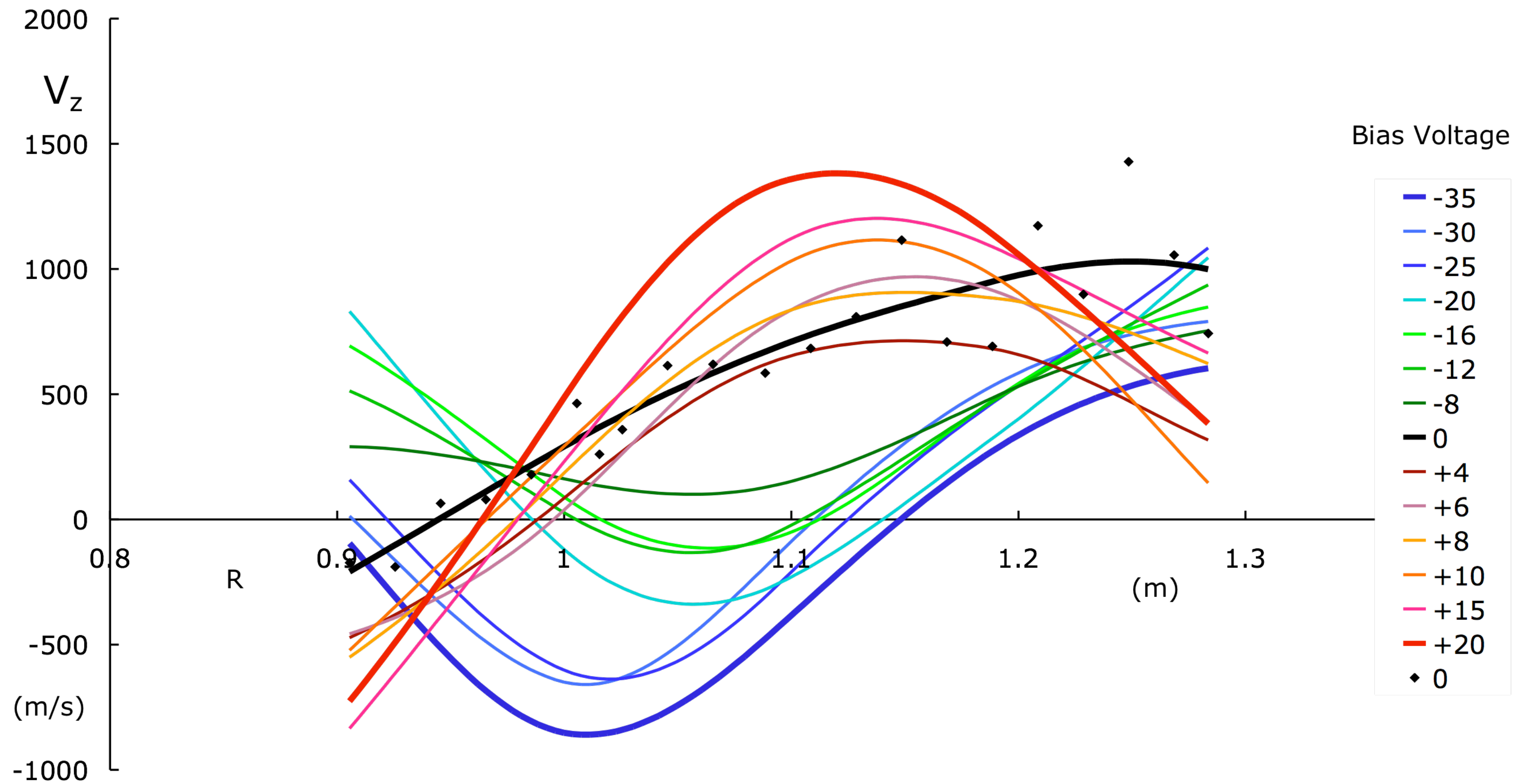
# Change in Radial Correlation Length




Change in radial correlation length generally follows change in turbulence level

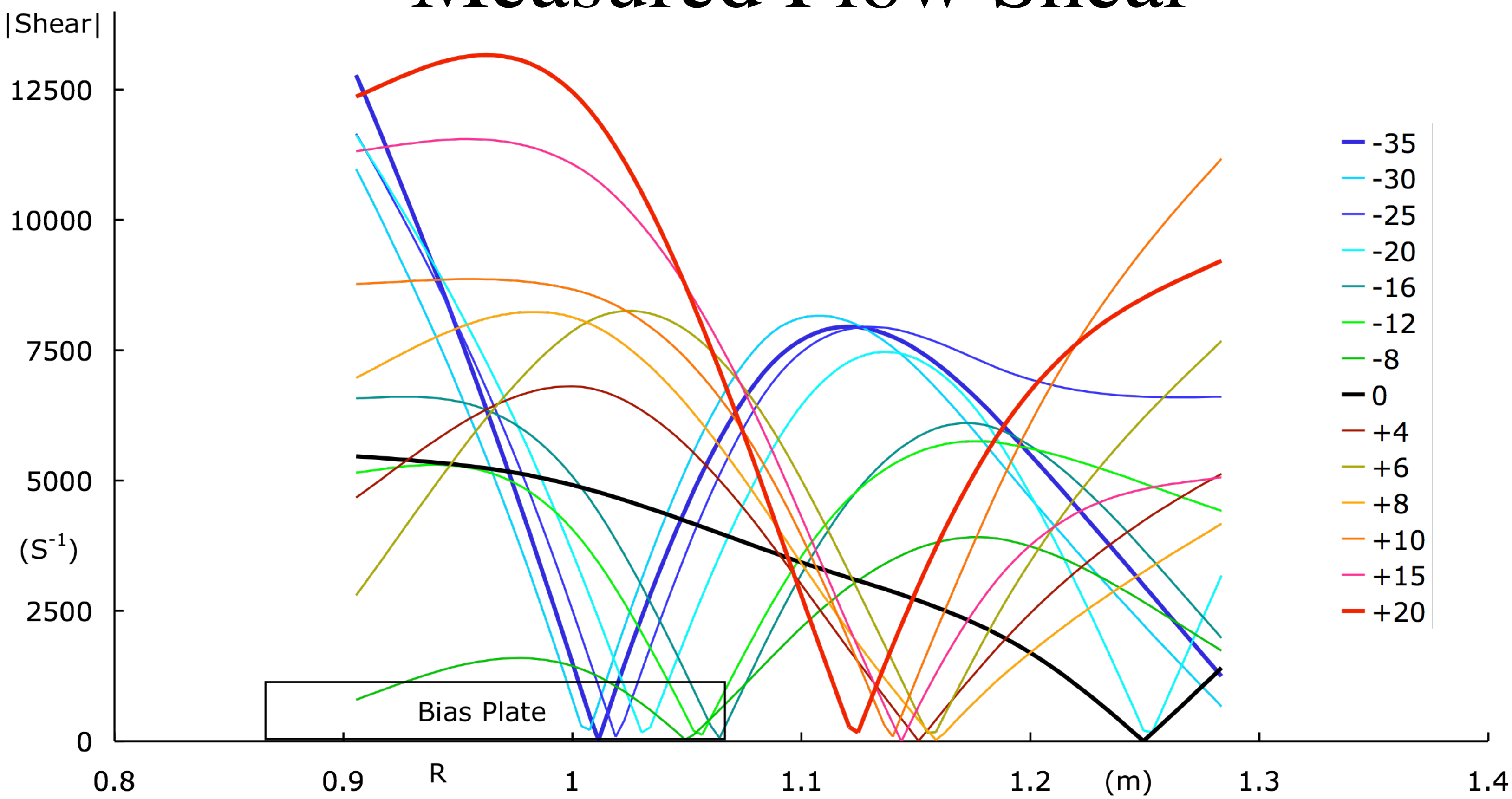
# Measured Flow Velocity

## Argon Ion Doppler




Spline fits with data points for 0 bias case

# 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*

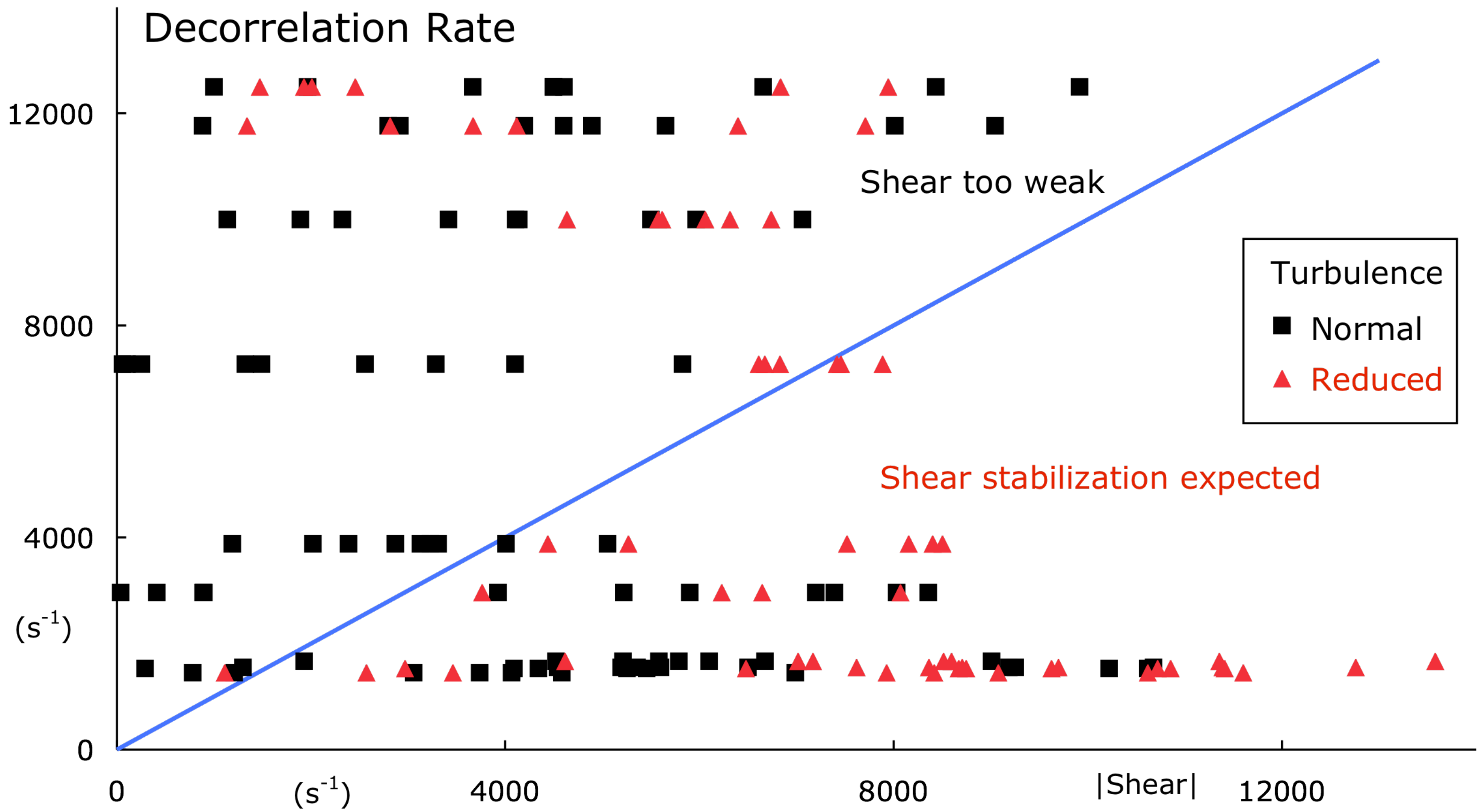
Flow shear will stabilize fluid turbulence under minimal, very general conditions, which are met in these experiments. Mechanism is local and can be tested at all locations in the plasma.

- 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.
- 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)



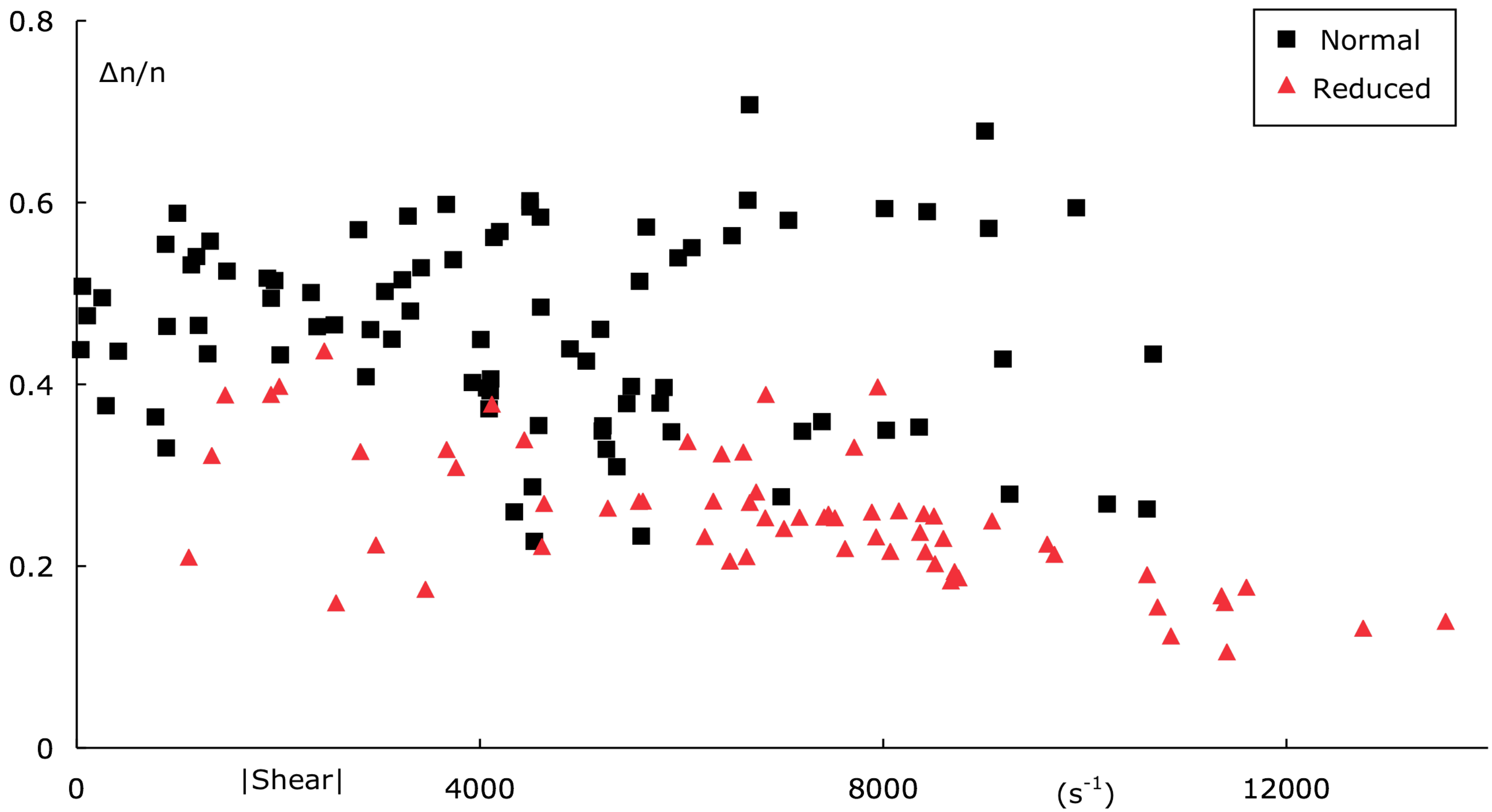

Shear often sufficient to stabilize turbulence in theory, but all combinations actually observed

# 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:

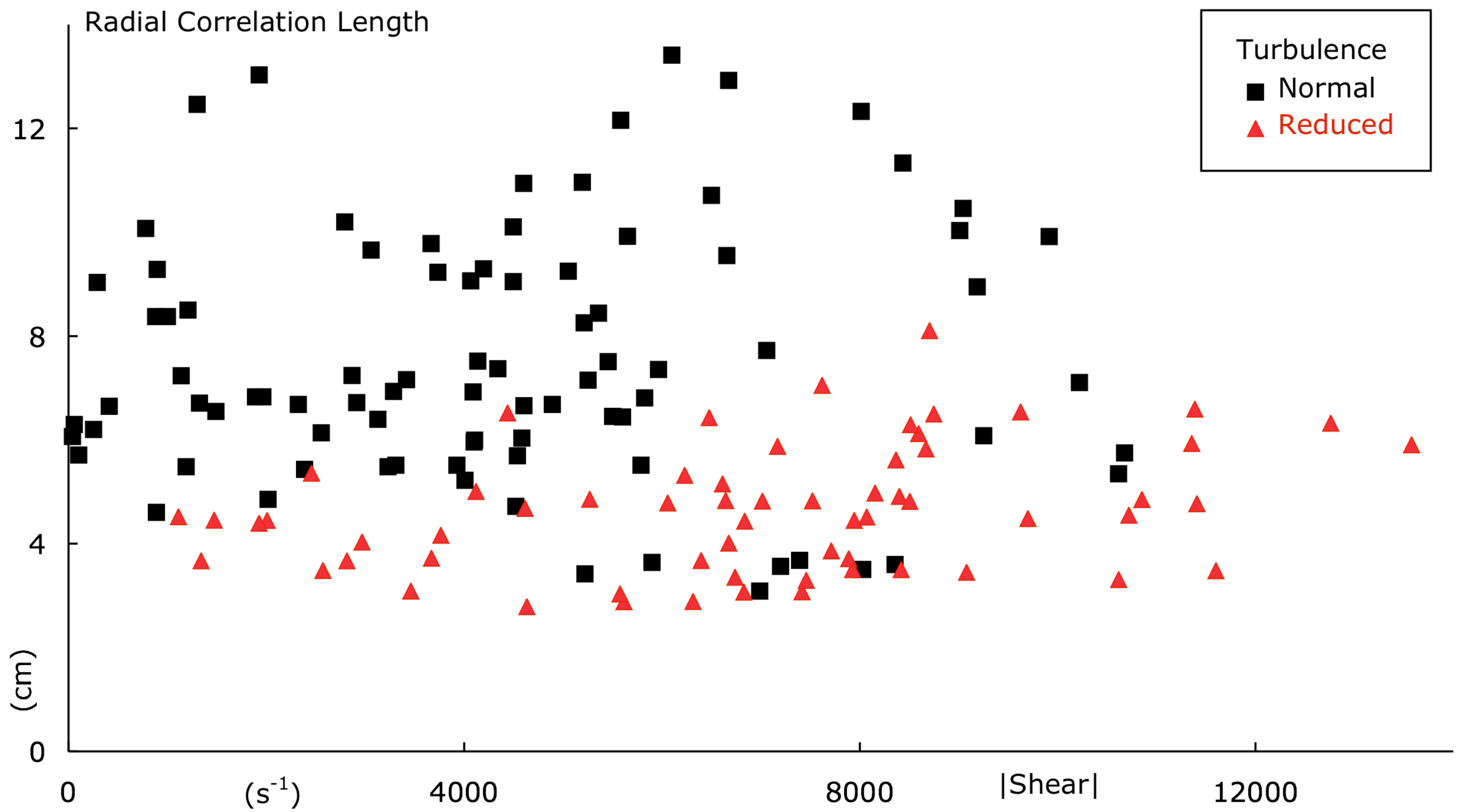
- Shear vs. Turbulent amplitude
- Shear vs. Correlation length
- Turbulent amplitude vs. Correlation length
- Amplitude reduction vs. Change in length

# Shear Magnitude vs. Density Fluctuations



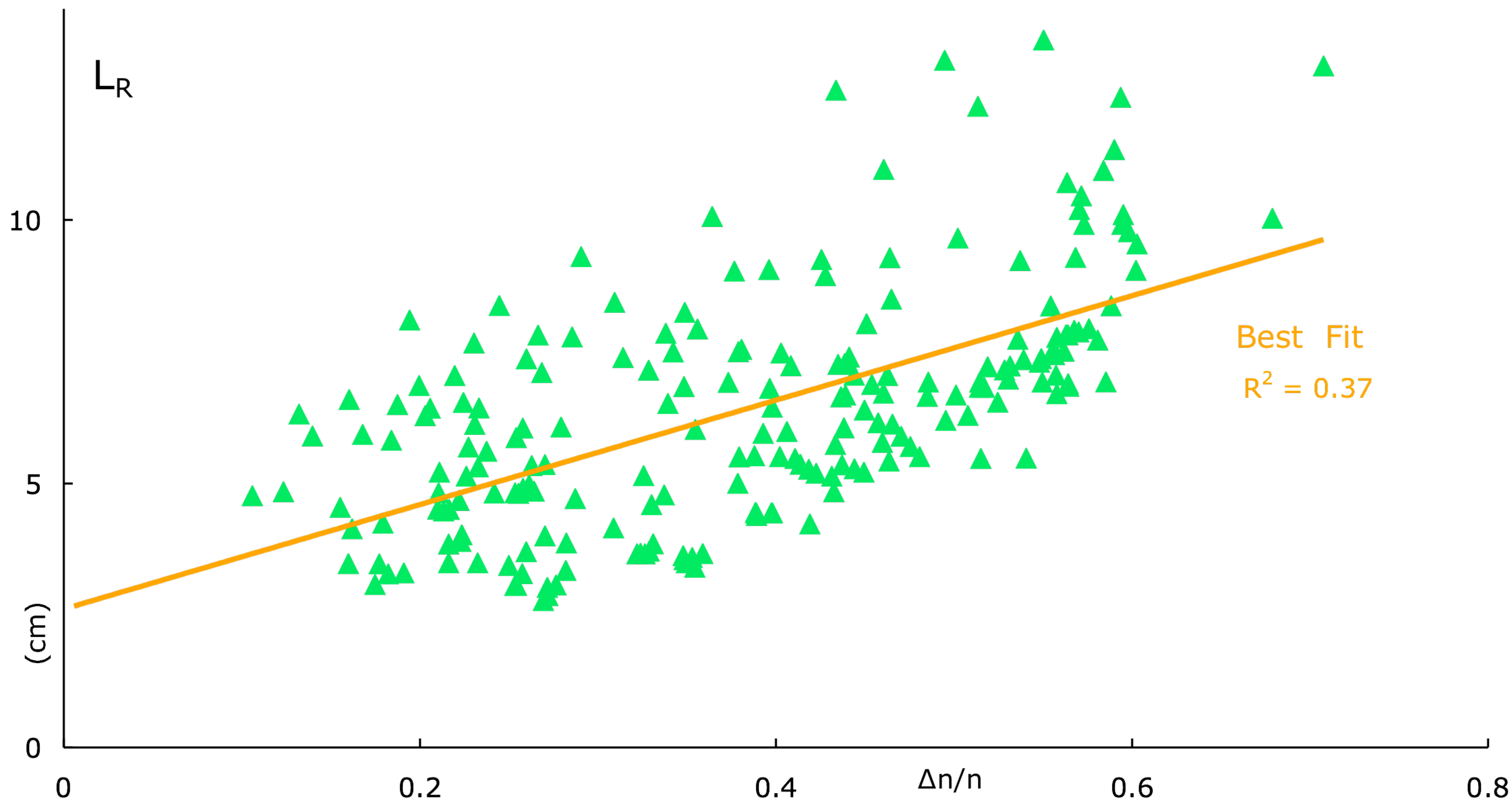

- No evidence for a general physical relation
- Turbulence reductions even at low shear
- High turbulence may persist at high shear

# Shear vs. Radial Correlation Length



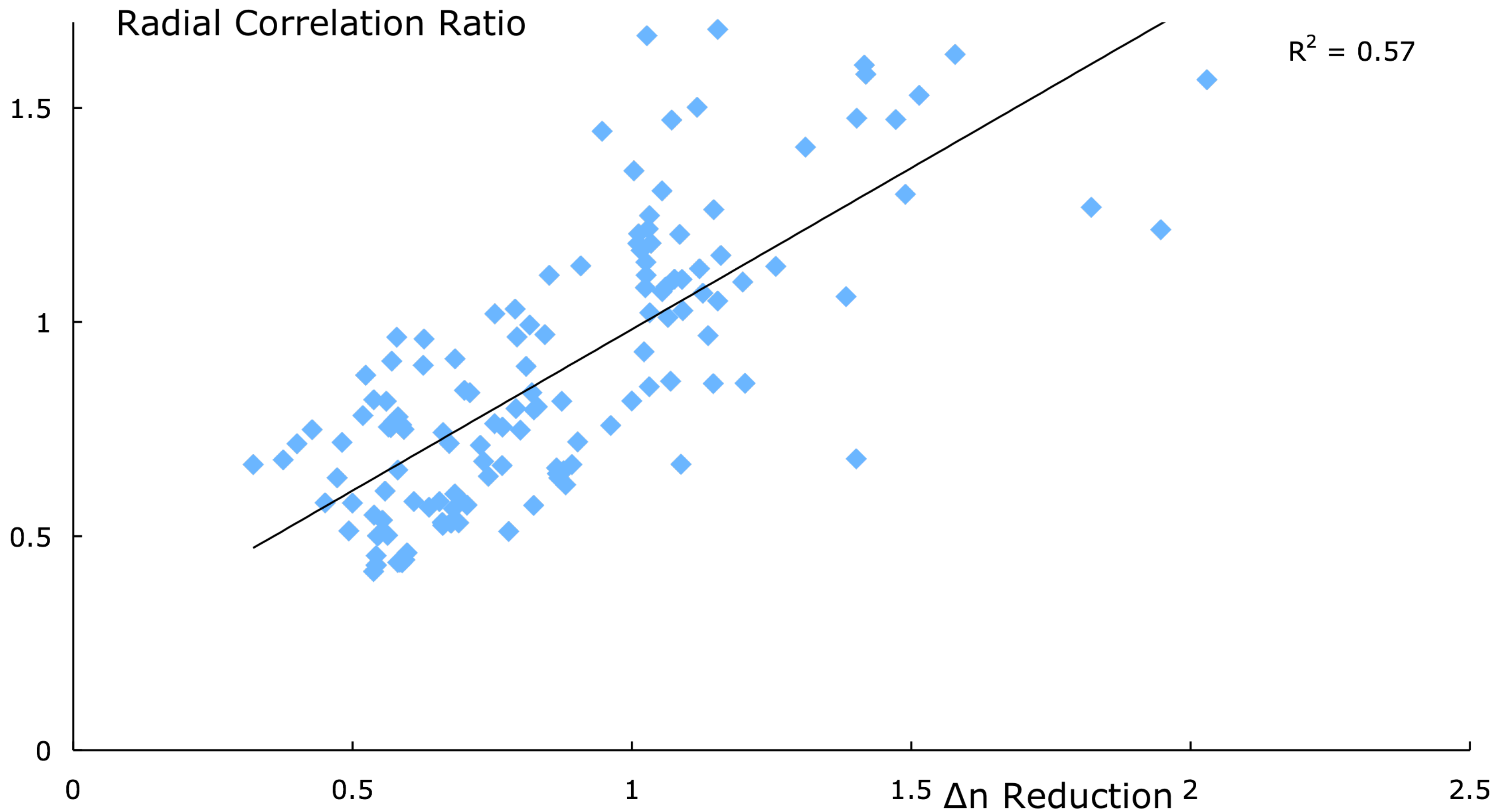

- ➢ **No evidence for a physical relation**
- ➢ **No trace of inverse trend**

# 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

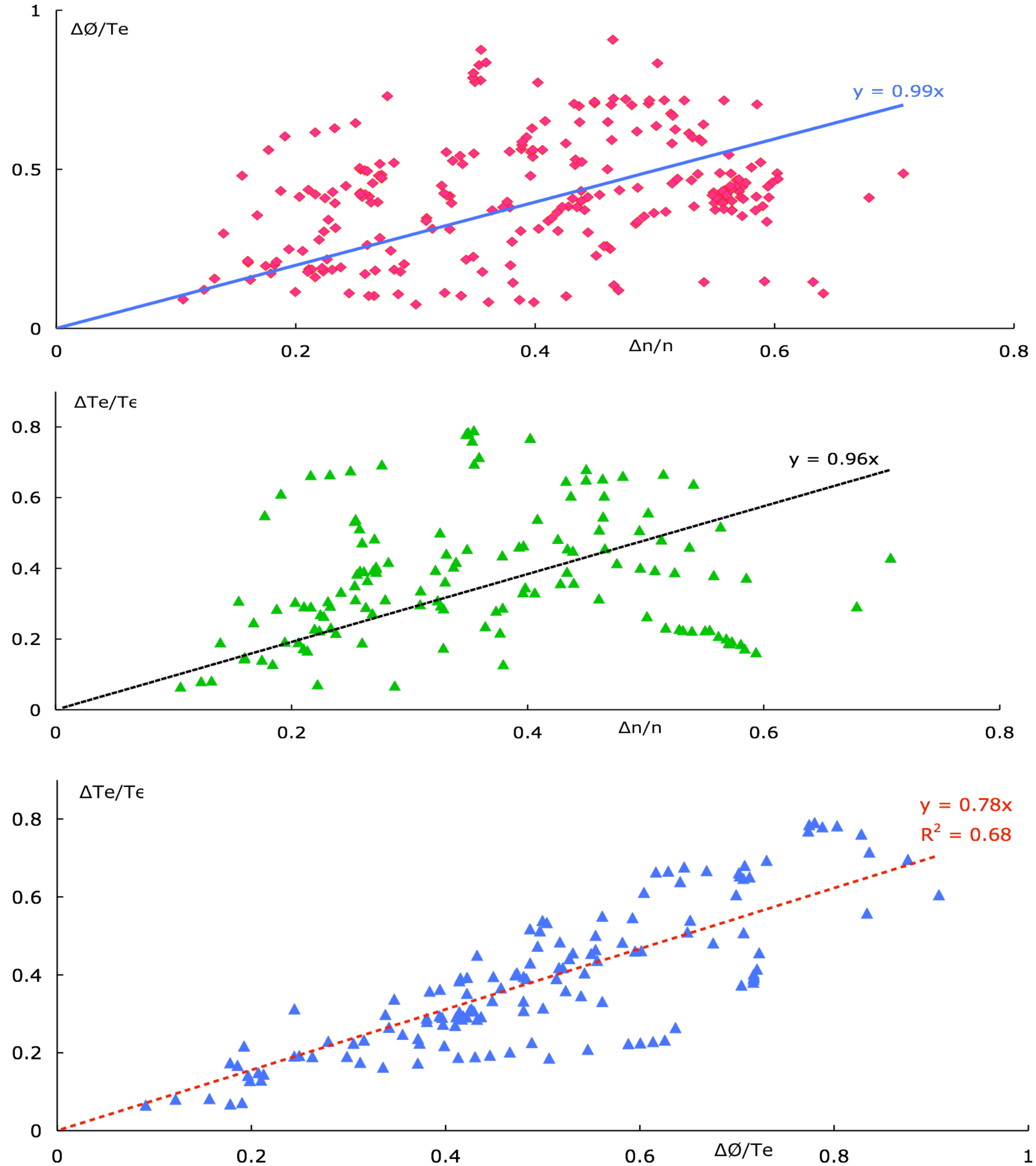
# **Why** is the Helimak Different?

- 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 clean 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

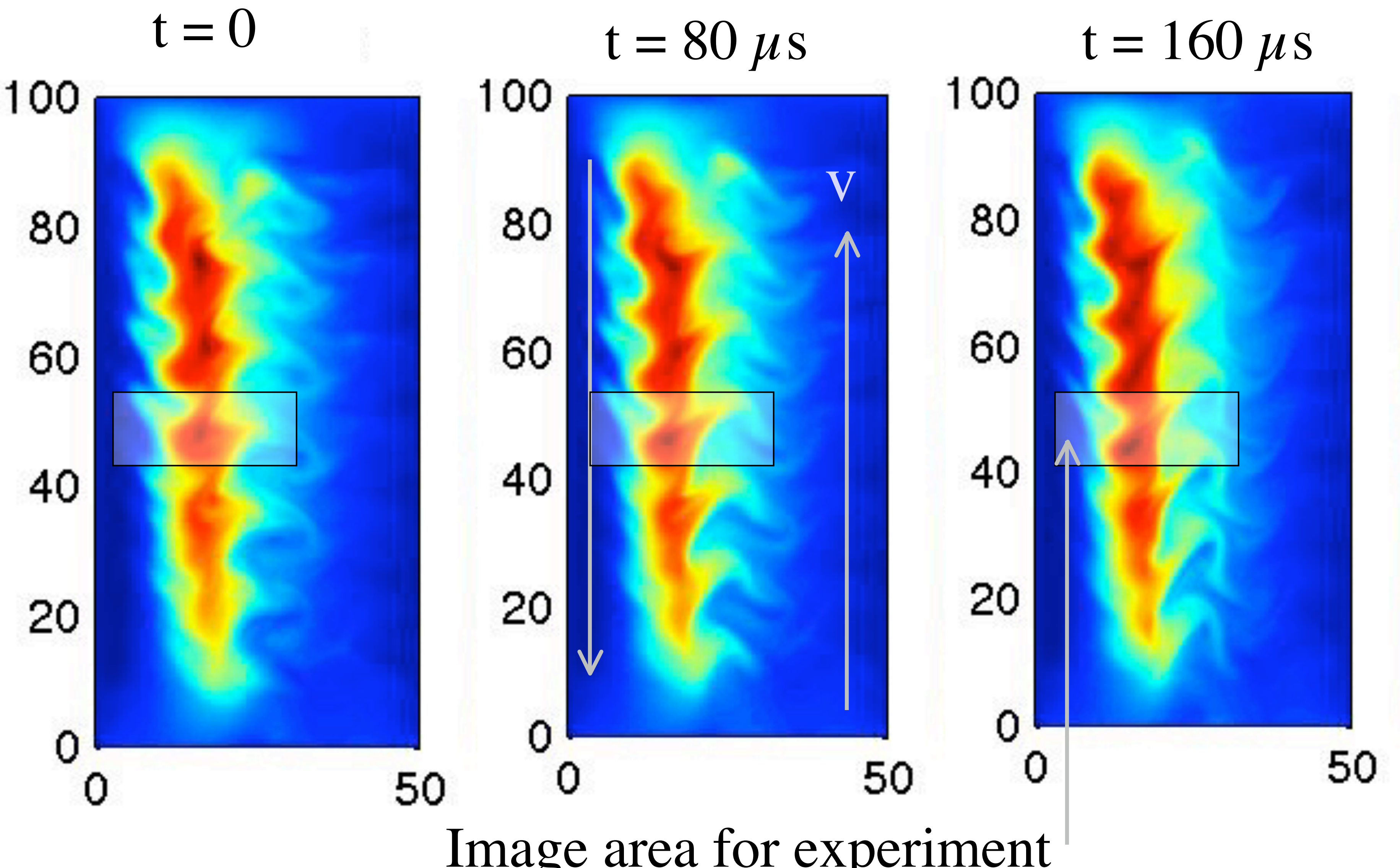
- Two-fluid, fully nonlinear calculation
- Helimak geometry:  size, shape, magnetic pitch
- Physical particle and heat sources and losses
- Equilibrium density and temperature profiles comparable with experiment

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)

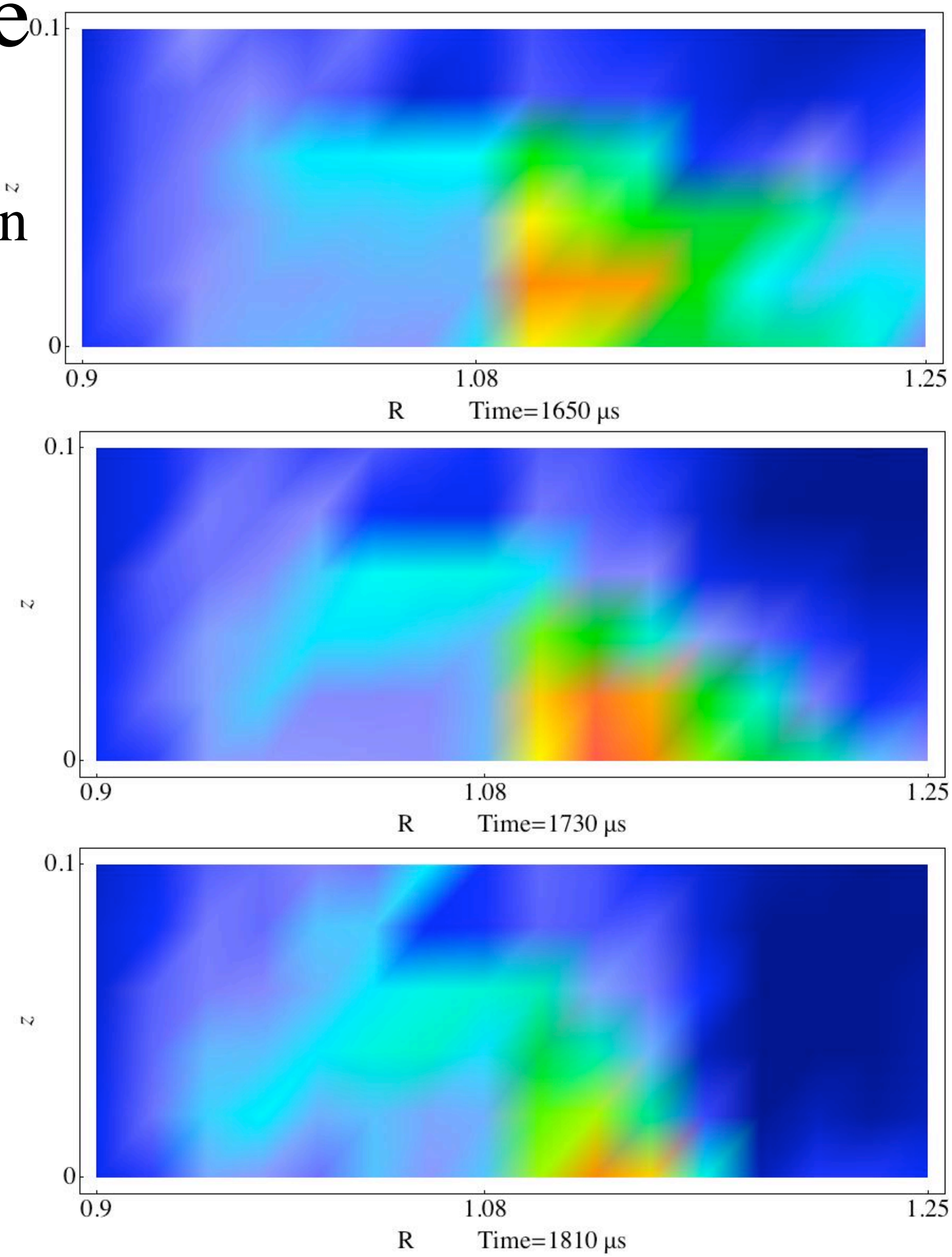
# Density

1 m X 2 m cross-section



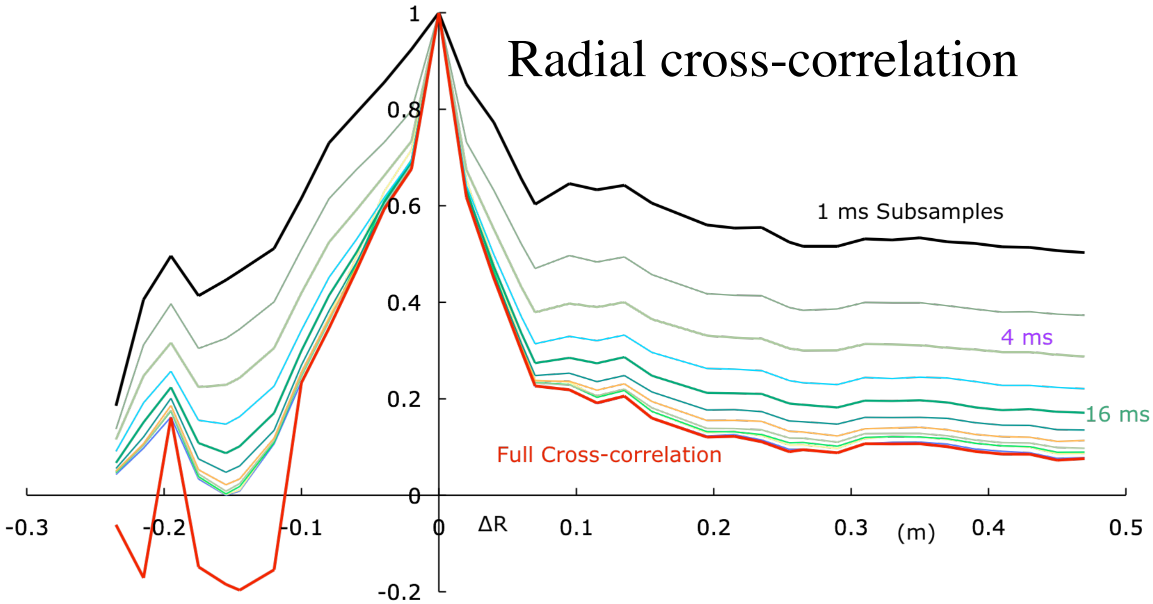
# Density from Probe Array

0.1 m X 0.35 m cross-section

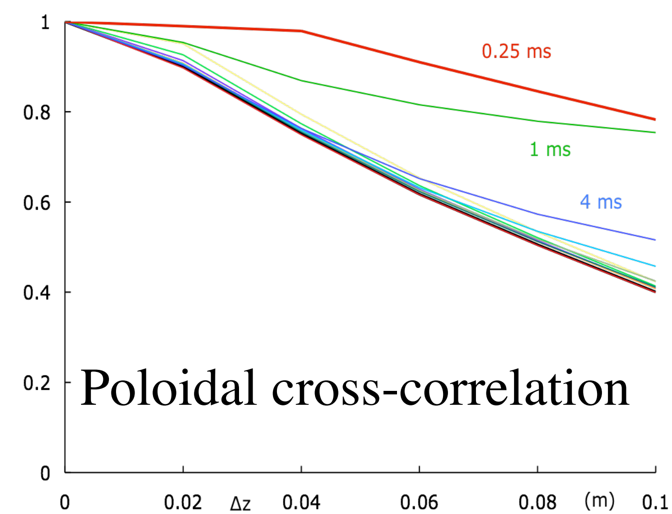



Fluctuation amplitude larger and more chaotic than in numerical experiment, but sizes, time scales, and motion of structures similar

# Can the large spatial structures in the simulation be seen in the experiment?




Radial and poloidal (Δz) correlations both large for 1 ms subsamples

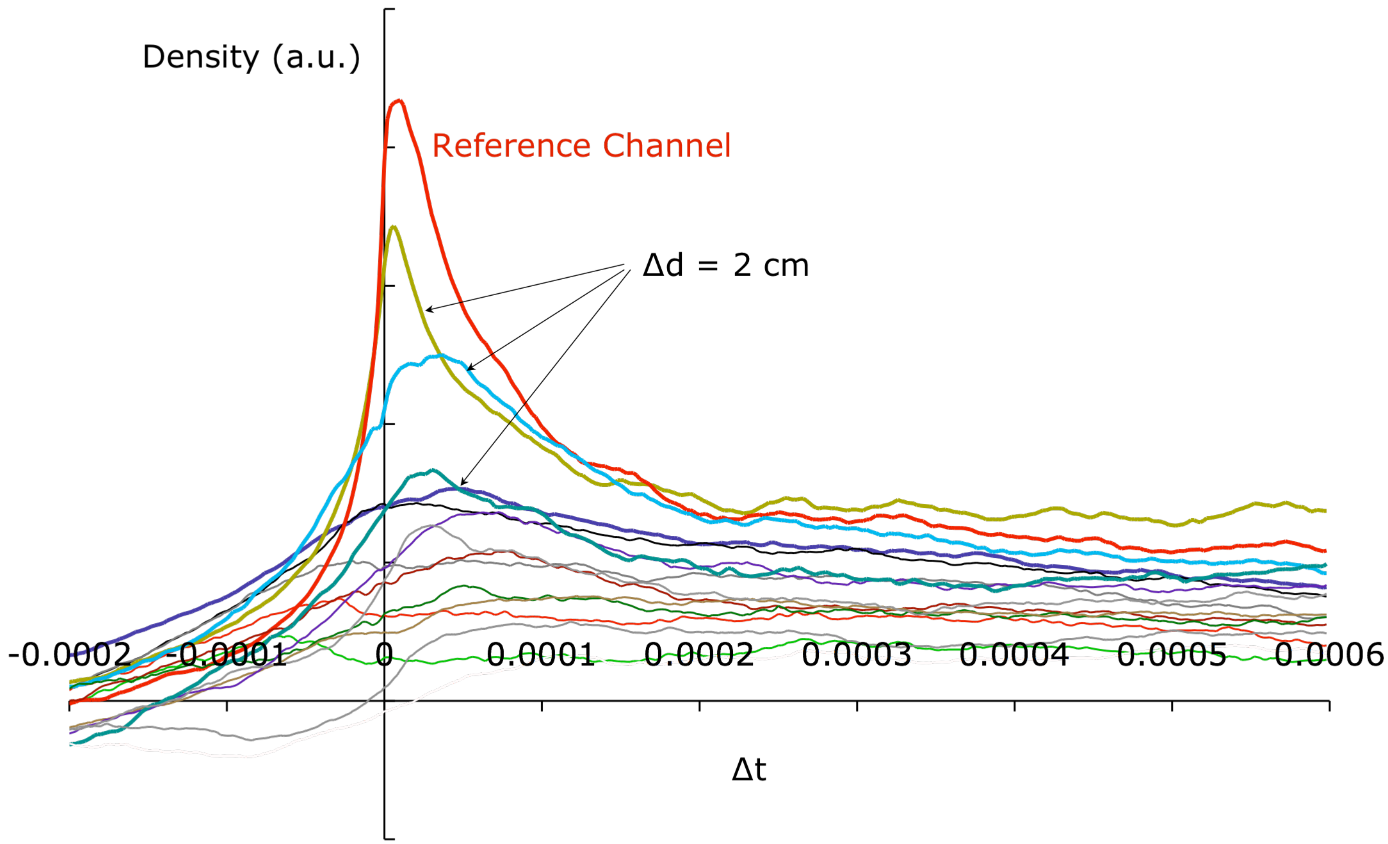



YES

But they persist only for ~ 1 ms and are seen only in short subsamples

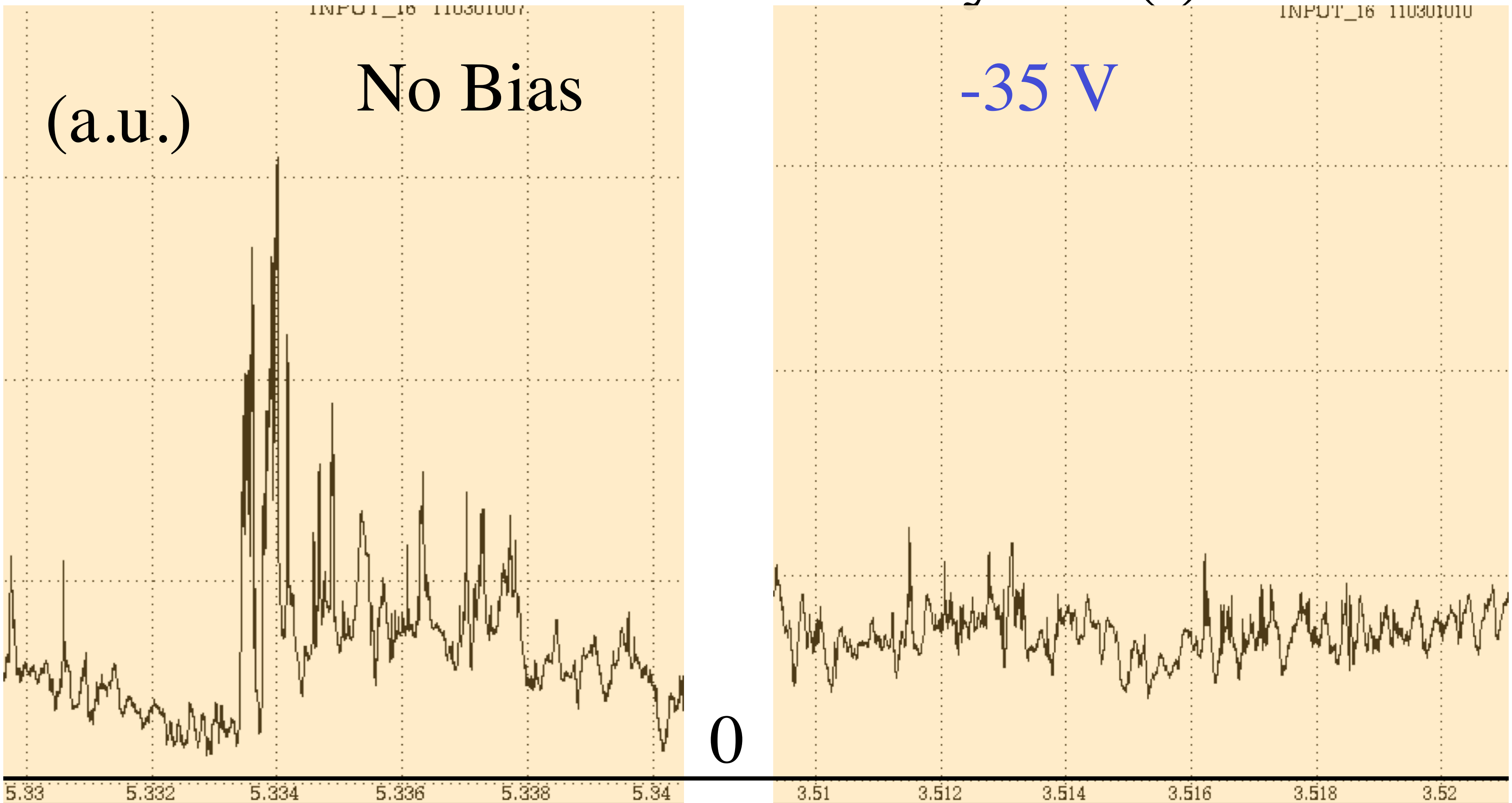
Each structure is different and the result "washes out" in usual cross-correlation

# Structures not in conditional average




Density peaks decay rapidly in time (<100 $\mu$s)
and in all spatial directions

# Effect of Bias on Density -- n(t)




Bias reduces fluctuation amplitude (rms), intermittency, and extrema

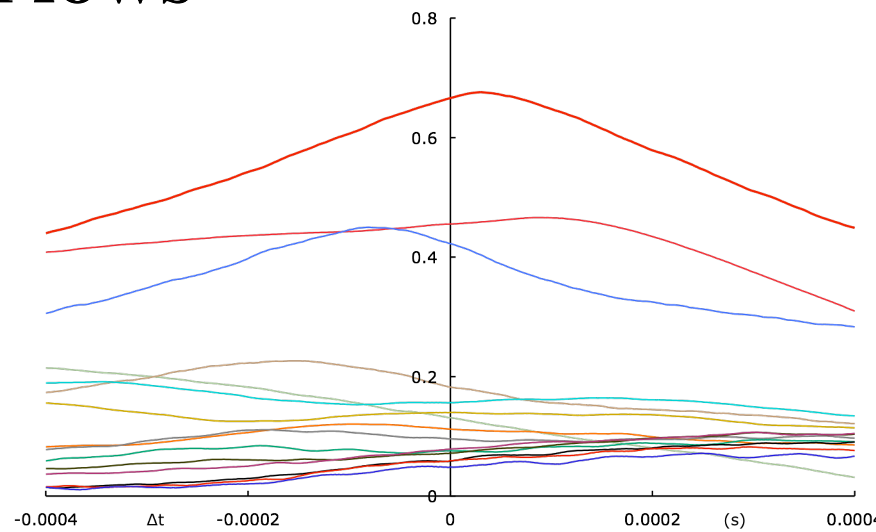
# Numerical and Physical Experiments Share:

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

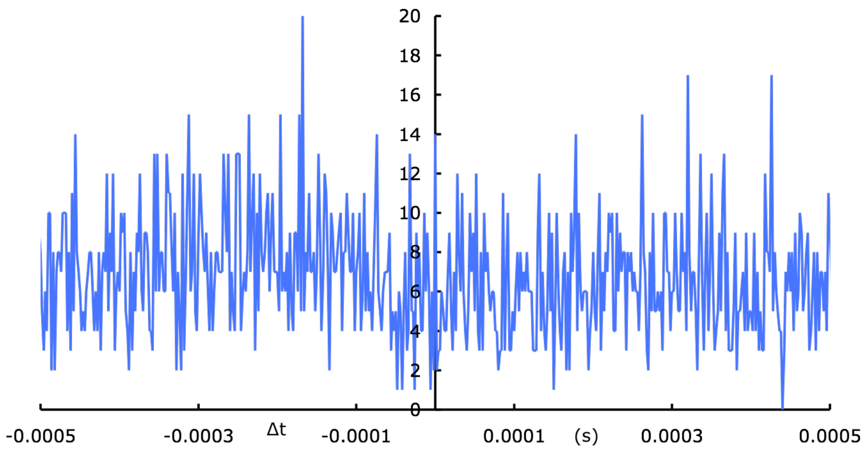
Note that these are two distinct "experiments"; just like two tokamaks, each has certain distinctive characteristics and behaviors.

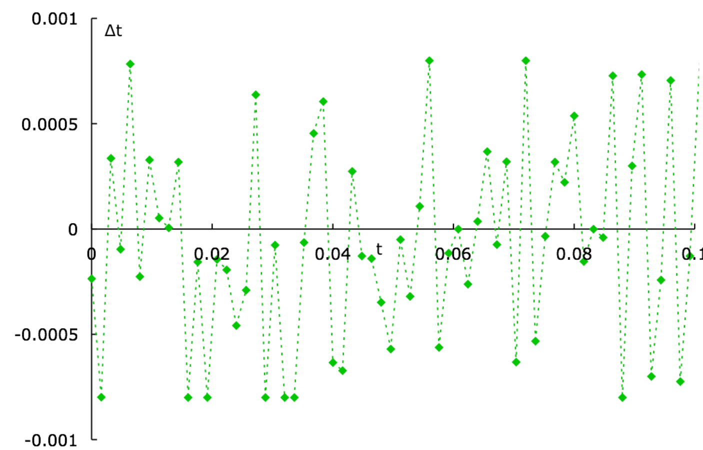
# Radial Flows

Radial Cross-correlations: No indication of mean flows




PDF    Time delays from 1 ms samples    Sequence

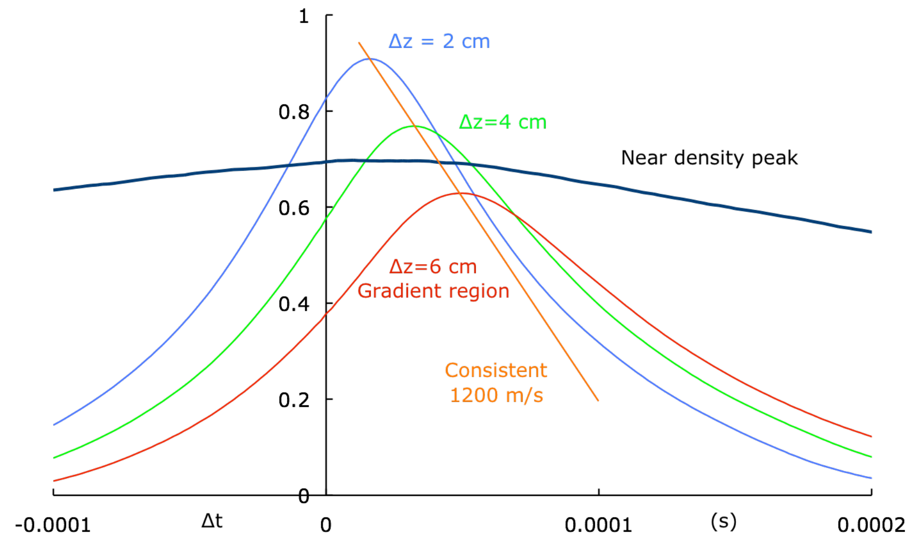


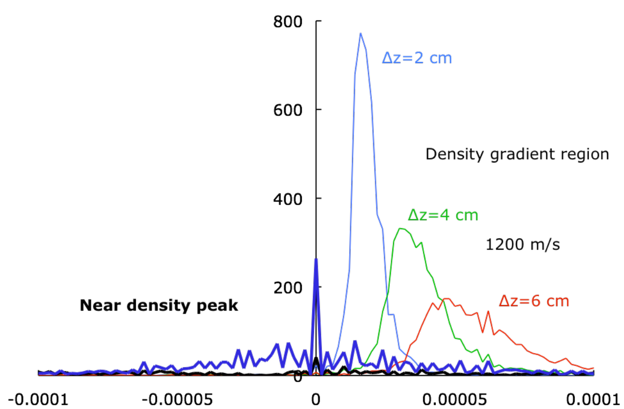

Uniform distribution, random sequence ⇒No flows

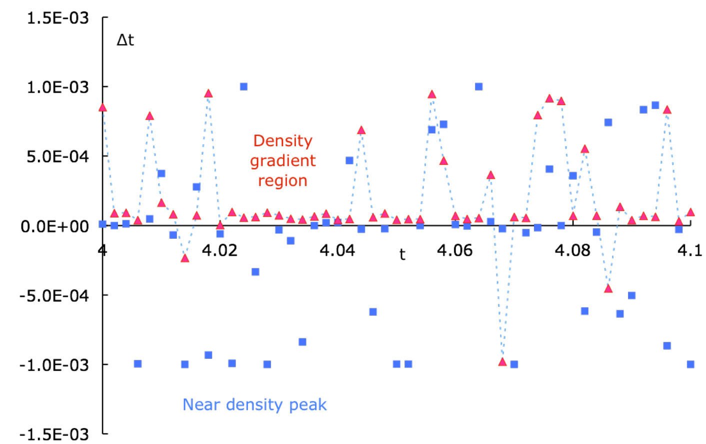
# Poloidal (z) Flows

Poloidal (Δz) Cross-correlations:
No mean flows near the density peak, clear mean flow in gradient region




PDF Time delays from 1 ms samples Sequence



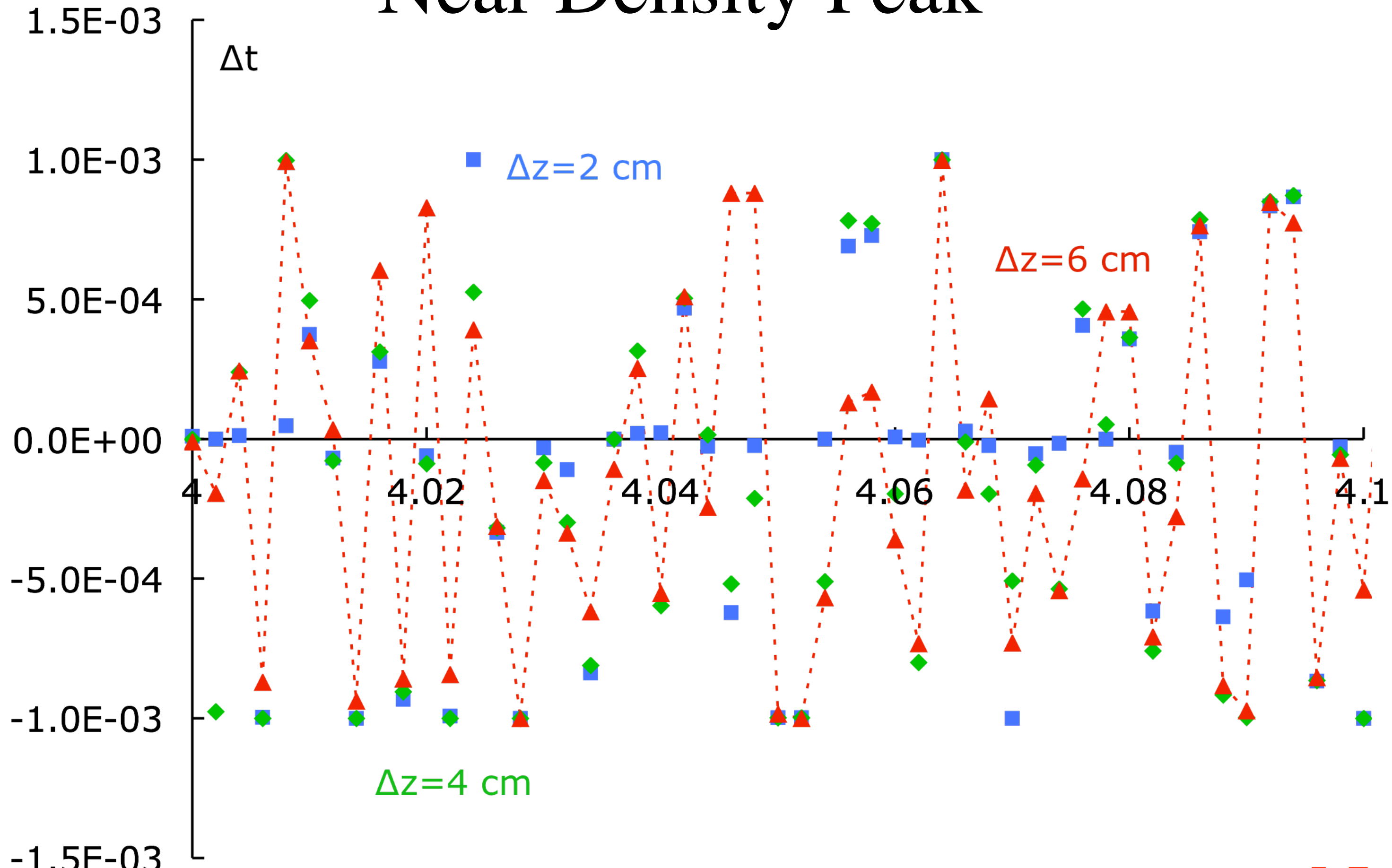

No flow near density peak Mean flow in gradient region

# Zonal Flows?

Flows in the poloidal (z) direction varying slowly on turbulence time scale ($\tau_{cor}$~0.5 ms; $T_{FFT}$~5ms), varying with R (to generate flow shear), but probably having zero mean on 10 s scale of experiment

Experimental approach: Analyze sequence of 1 ms samples. At each radius, test cross-correlations at $\Delta z$ = 2, 4, 6 cm for consistent indication of flow. Examine flows for slow time variations and spatial scale.

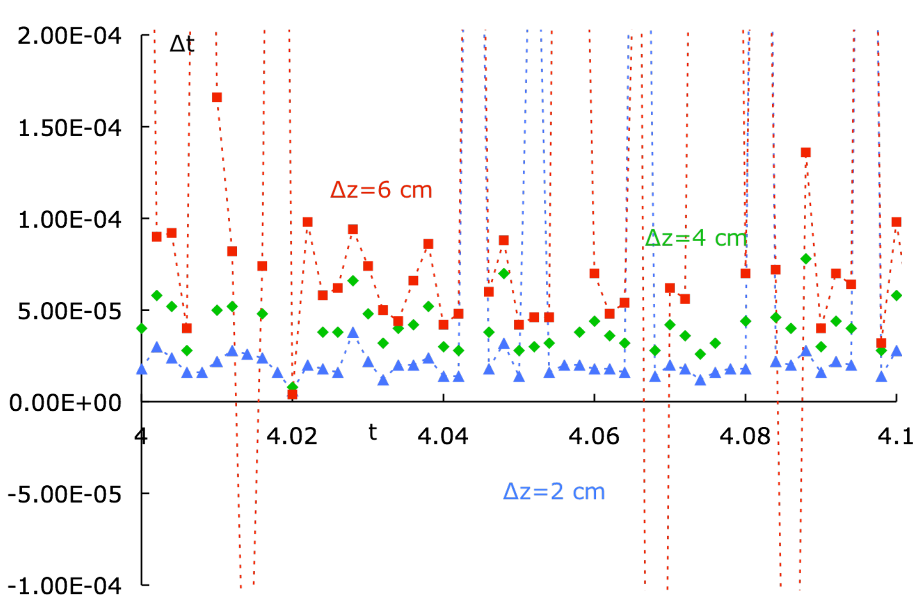
# Near Density Peak

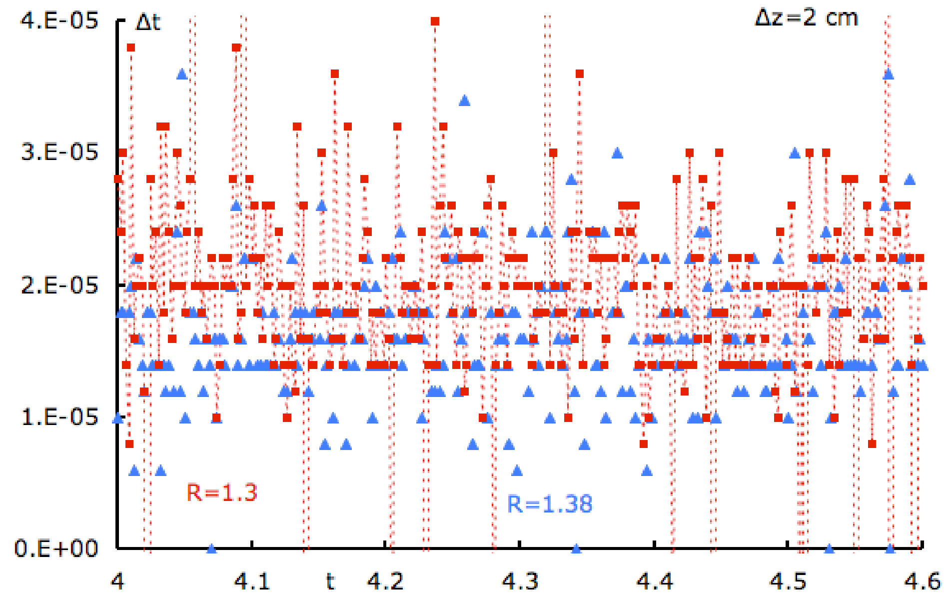



- Delay times not proportional to Δz
- Values vary rapidly

No Flows!

# Density gradient region




- Clear, consistent mean flow
- No secular variation (on slow time scale)
- Spread is a fast stochastic variation
- No systematic variation with radius (shear)

No Zonal Flows

# Conclusions

- The Helimak offers a simple, controlled example of turbulence reduction by biasing.
- Neither turbulence levels nor reductions correlate with velocity shearing rate.
- There is no indication of zonal flows.
- The reductions in density, potential, and temperature fluctuations are not simply related to one another.
- The essential features also appear in a numerical experiment.