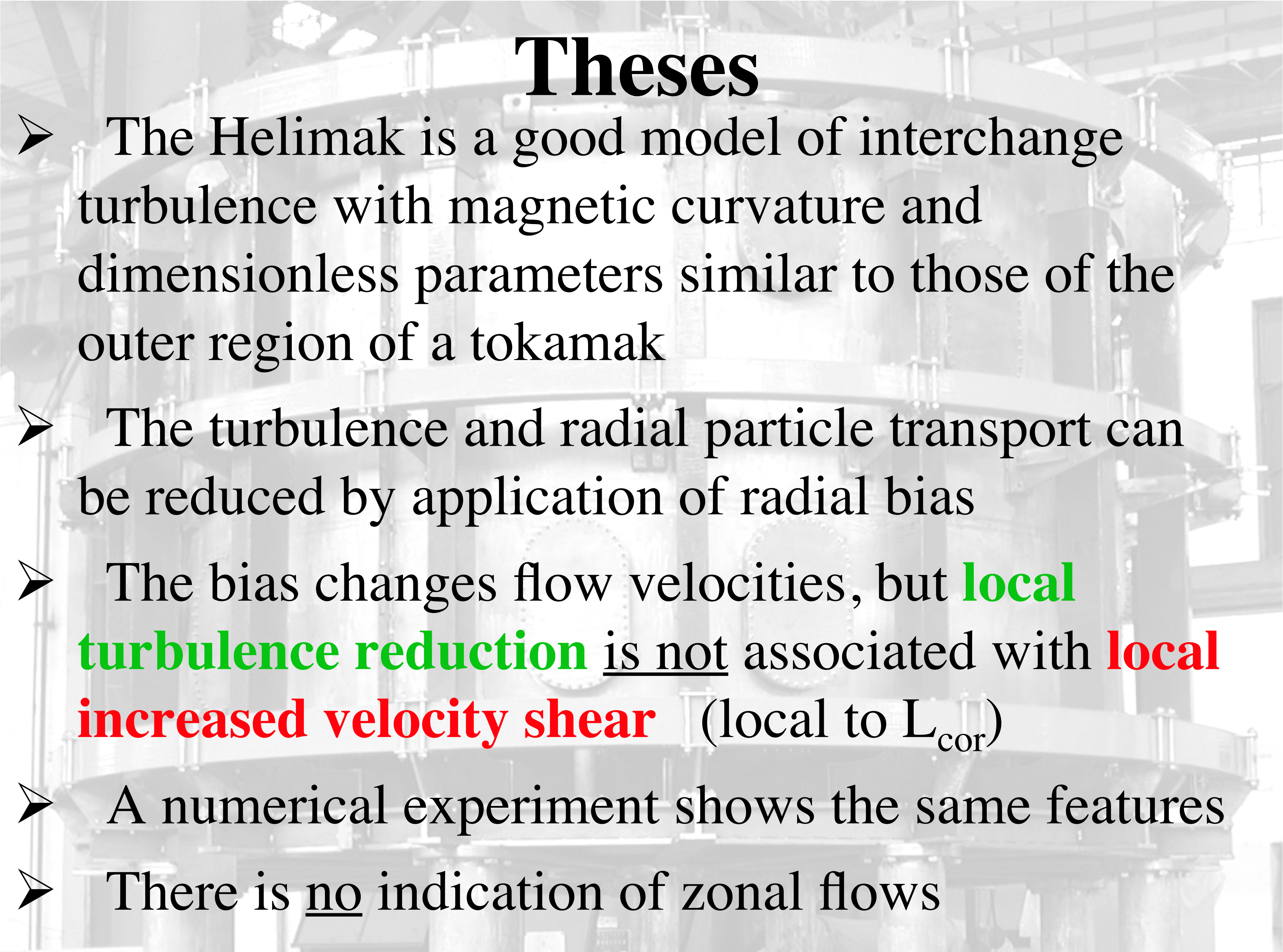
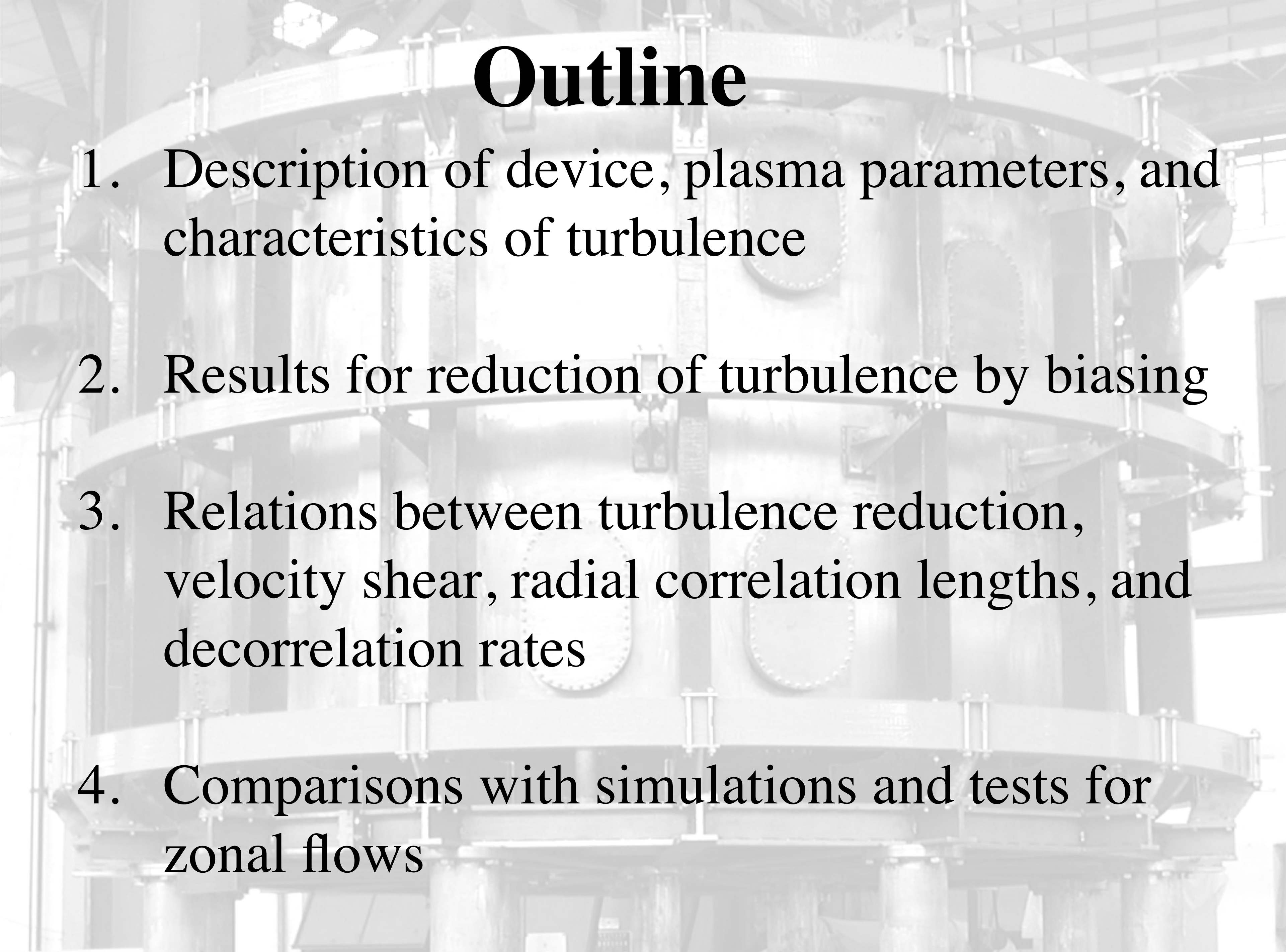


Theses

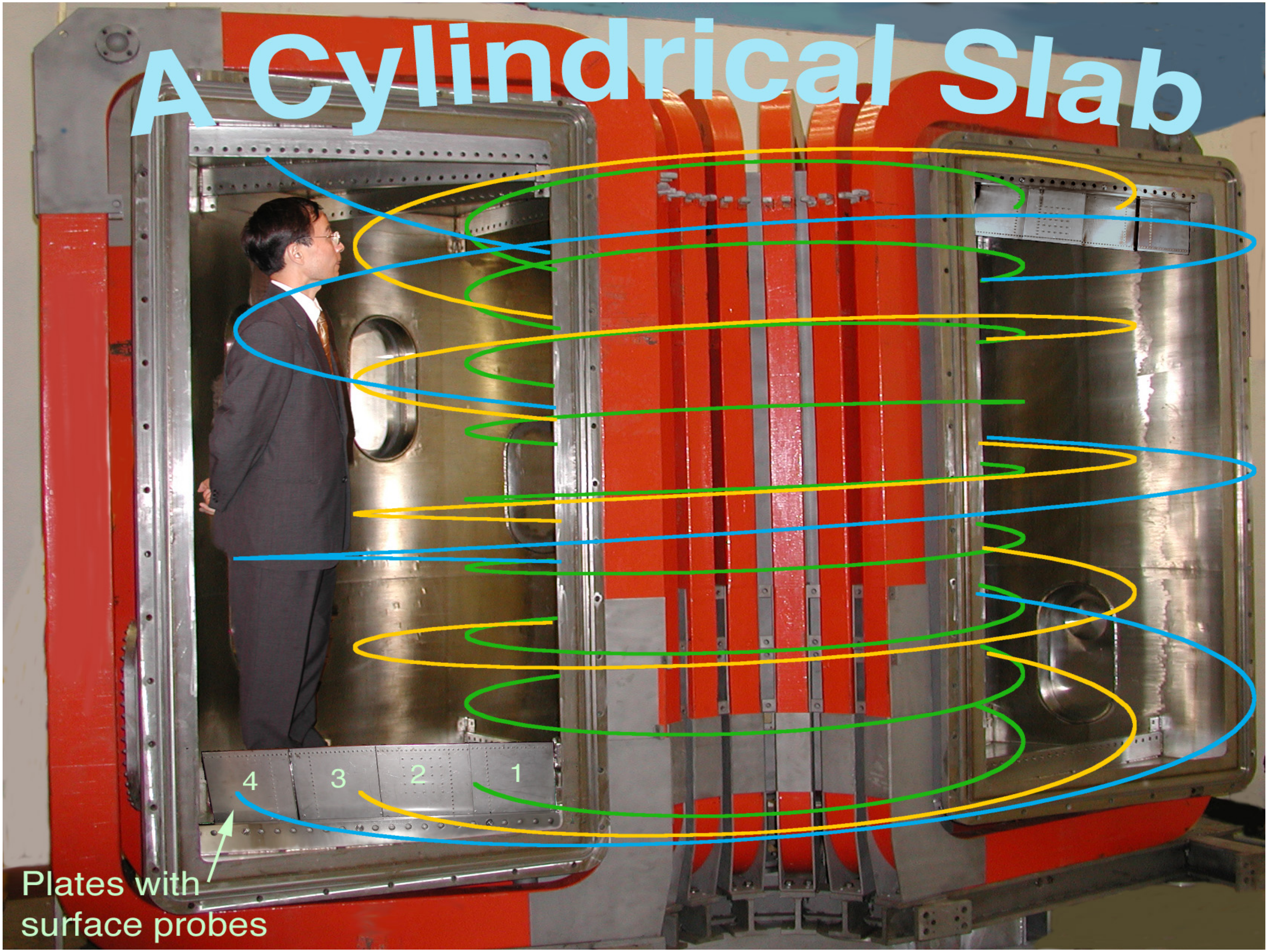
- The Helimak is a good model of interchange turbulence with magnetic curvature and dimensionless parameters similar to those of the outer region of a tokamak
- The turbulence and radial particle transport can be reduced by application of radial bias
- The bias changes flow velocities, but **local turbulence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



Outline

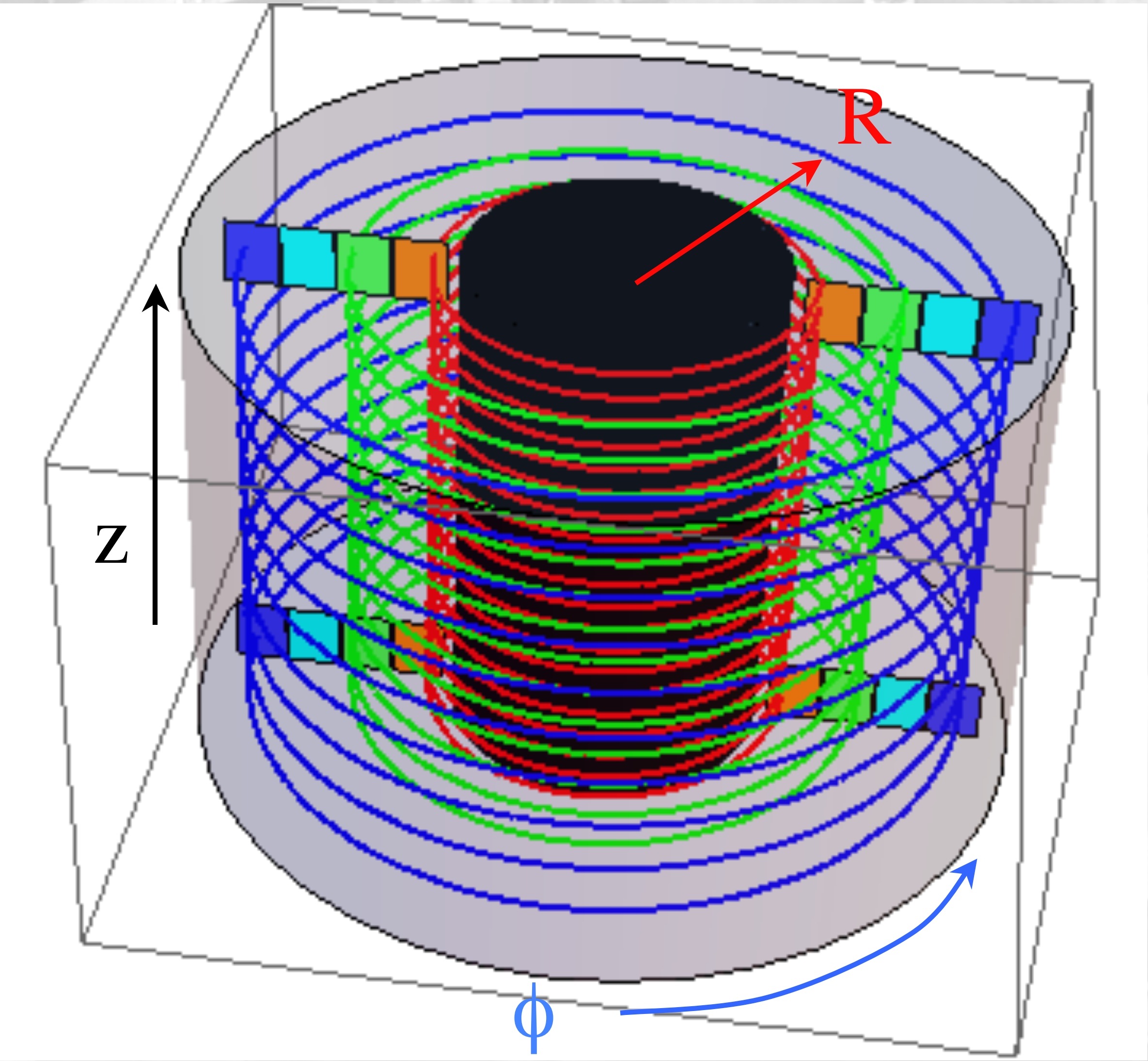
1. Description of device, plasma parameters, and characteristics of turbulence
2. Results for reduction of turbulence by biasing
3. Relations between turbulence reduction, velocity shear, radial correlation lengths, and decorrelation rates
4. Comparisons with simulations and tests for zonal flows

A Cylindrical Slab



Plates with surface probes

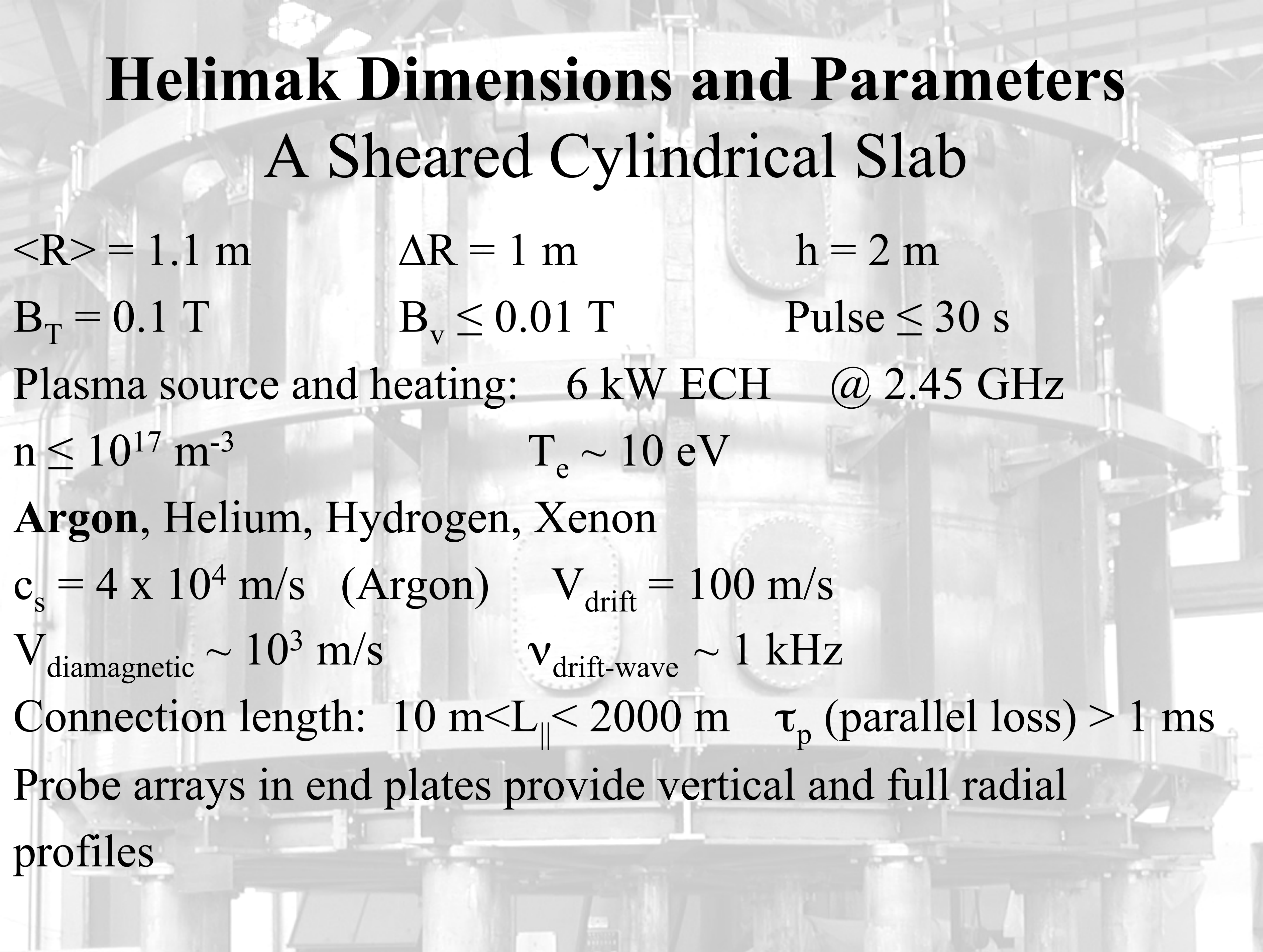
Helimak Geometry



R = Major radius (Tokamak minor radius)

z = Vertical (Tokamak poloidal direction)

ϕ = Angle (Tokamak toroidal angle)



Helimak Dimensions and Parameters

A Sheared Cylindrical Slab

$\langle R \rangle = 1.1$ 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, Hydrogen, Xenon

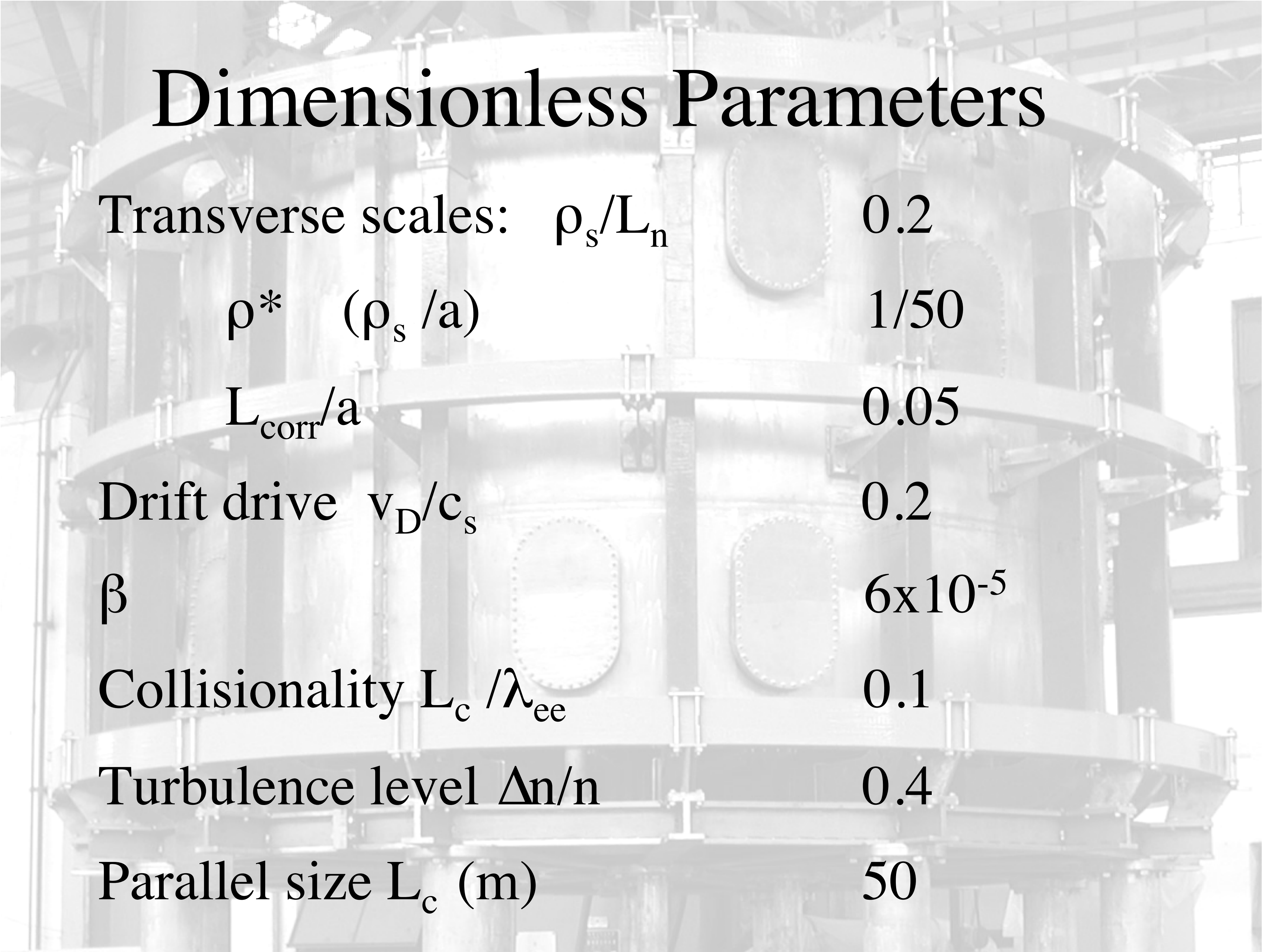
$c_s = 4 \times 10^4$ m/s (Argon) $V_{drift} = 100$ m/s

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

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

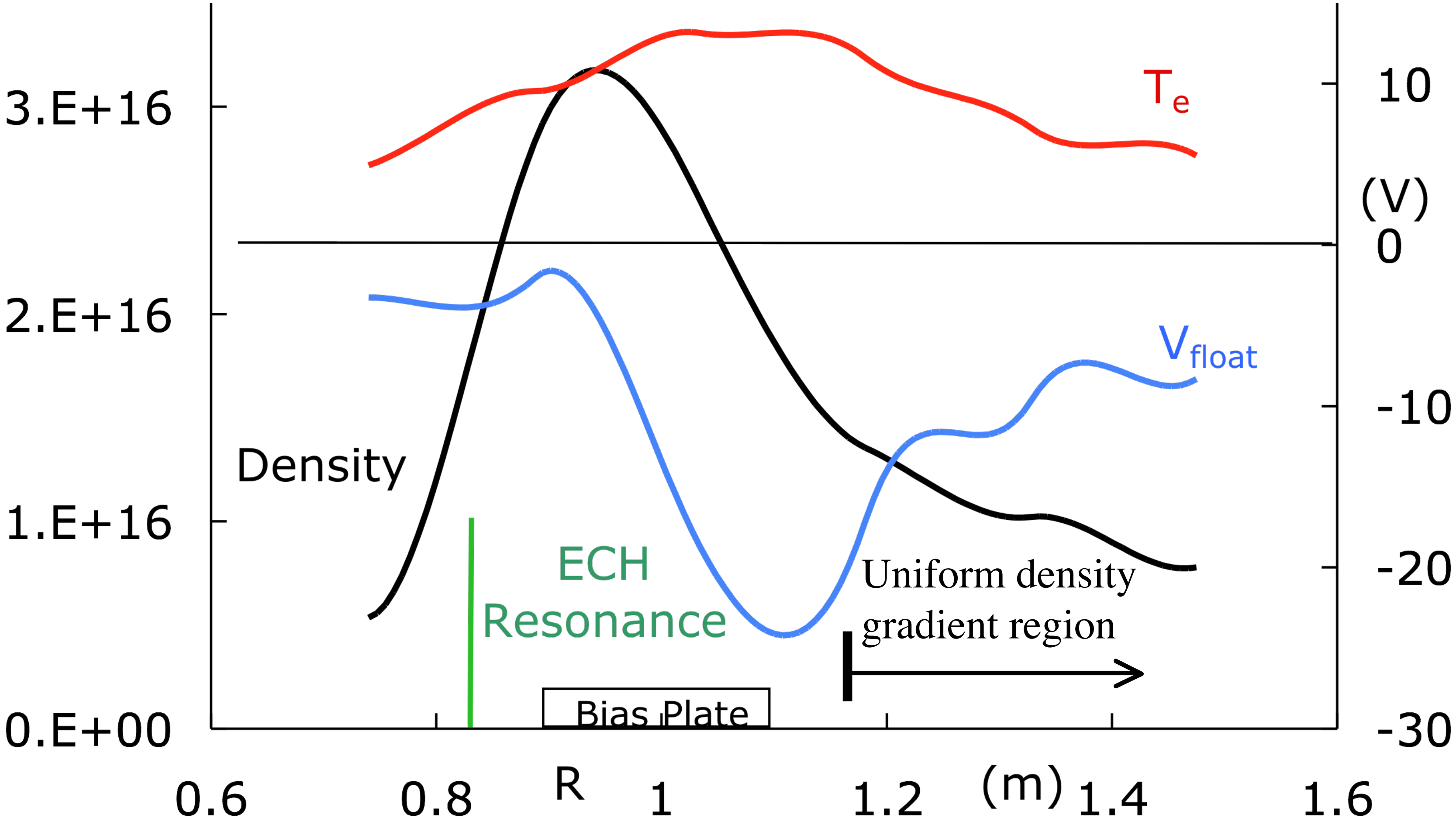
Probe arrays in end plates provide vertical and full radial profiles

Dimensionless Parameters



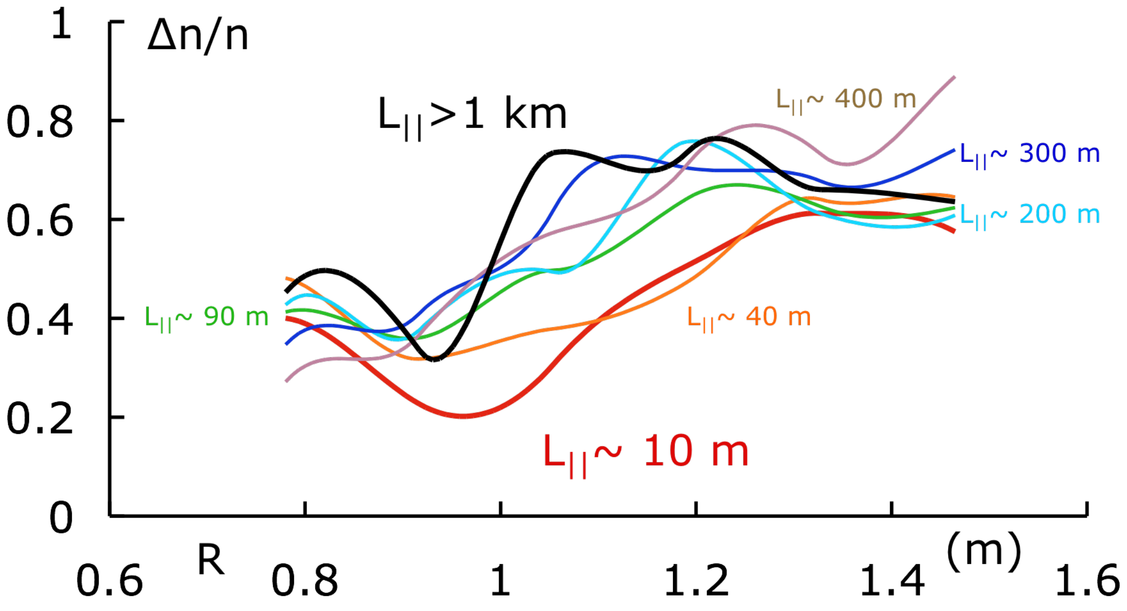
Transverse scales: ρ_s/L_n	0.2
ρ^* (ρ_s /a)	1/50
L_{corr}/a	0.05
Drift drive v_D/c_s	0.2
β	$6x10^{-5}$
Collisionality L_c /λ_{ee}	0.1
Turbulence level $\Delta n/n$	0.4
Parallel size L_c (m)	50

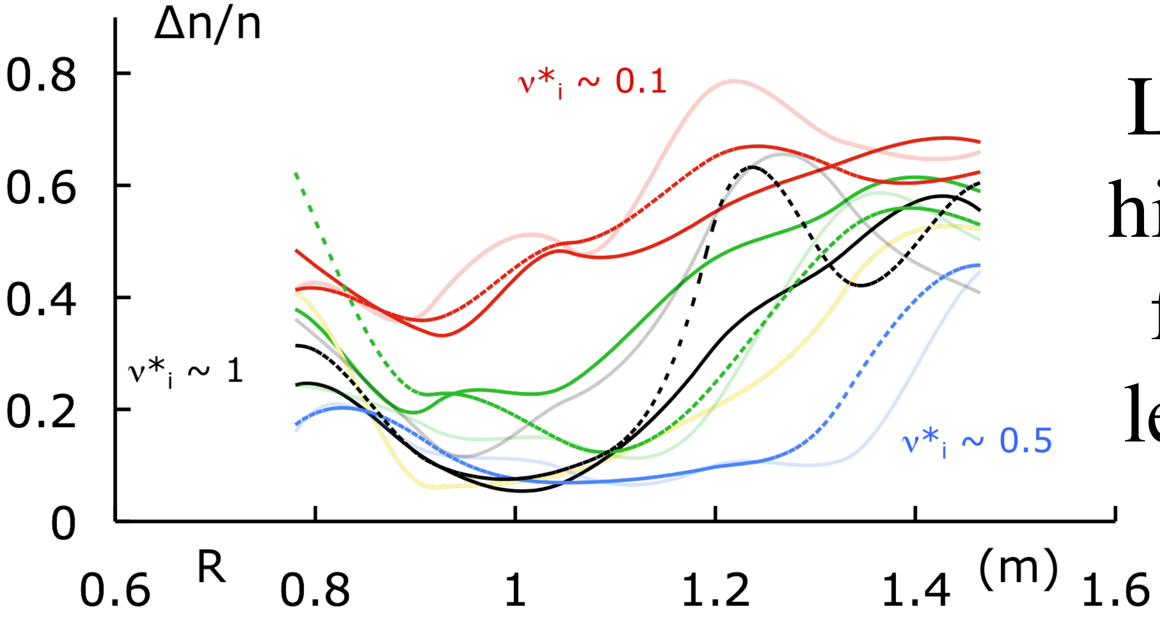
Typical Density, Temperature, and Floating Potential Profiles



Turbulence Levels

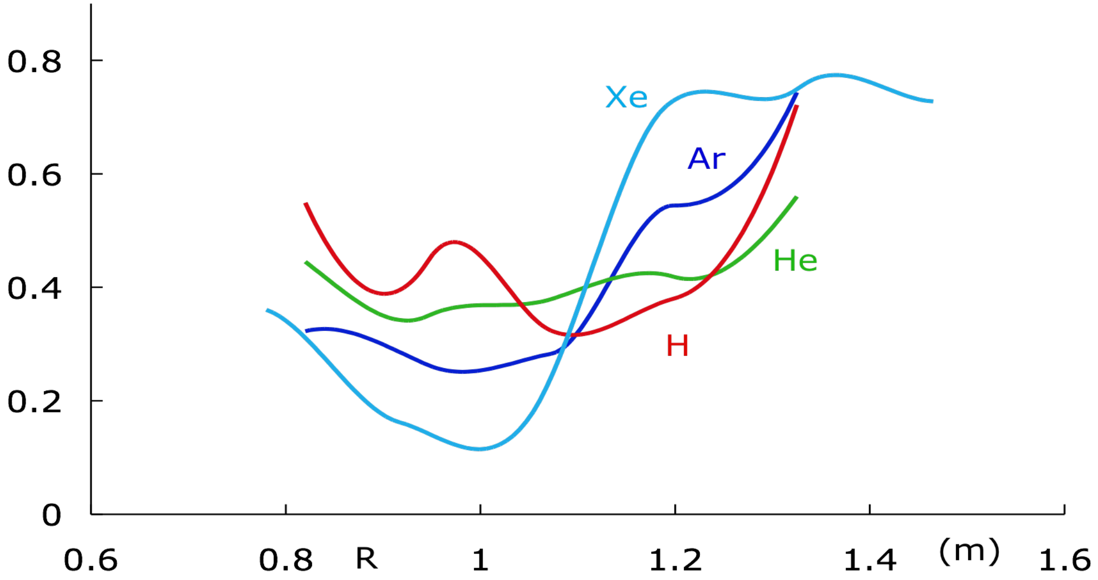
Levels increase slightly with connection length





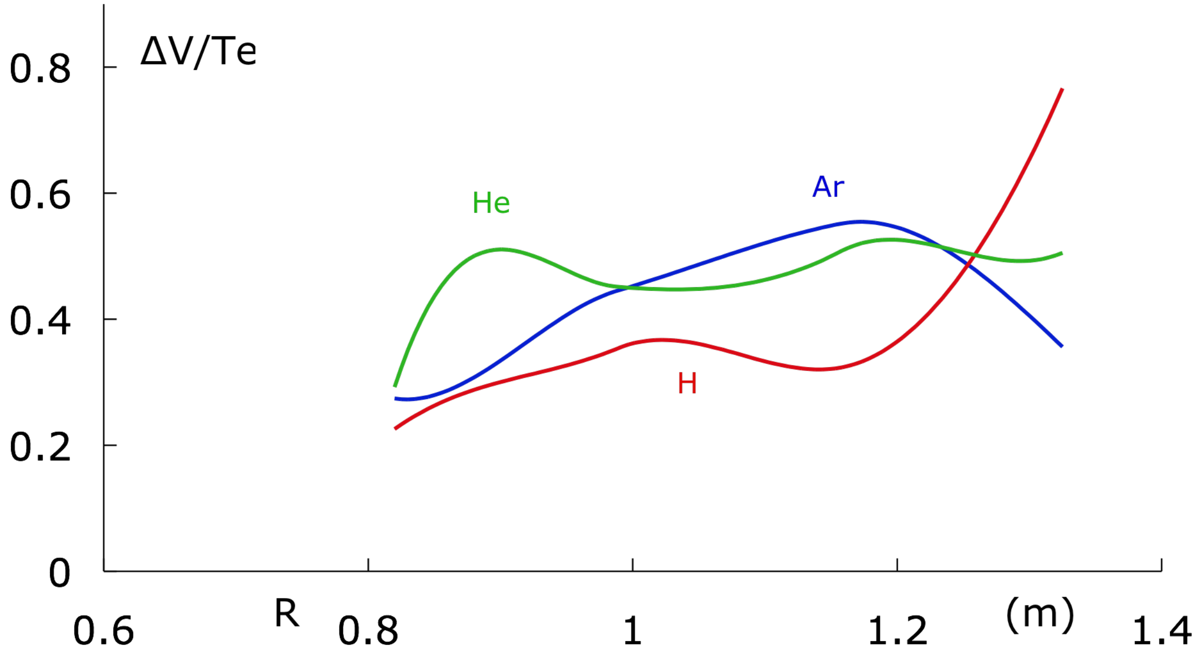
Levels decrease at higher collisionality for all connection lengths (50-200 m)

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

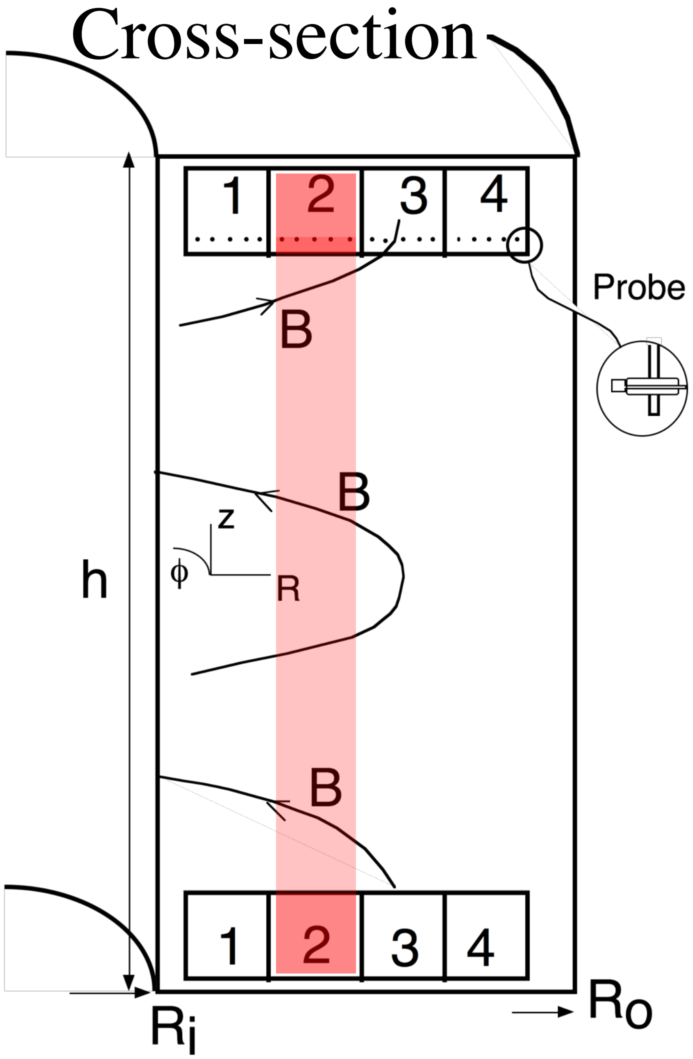


Application of Bias

- ➢ 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

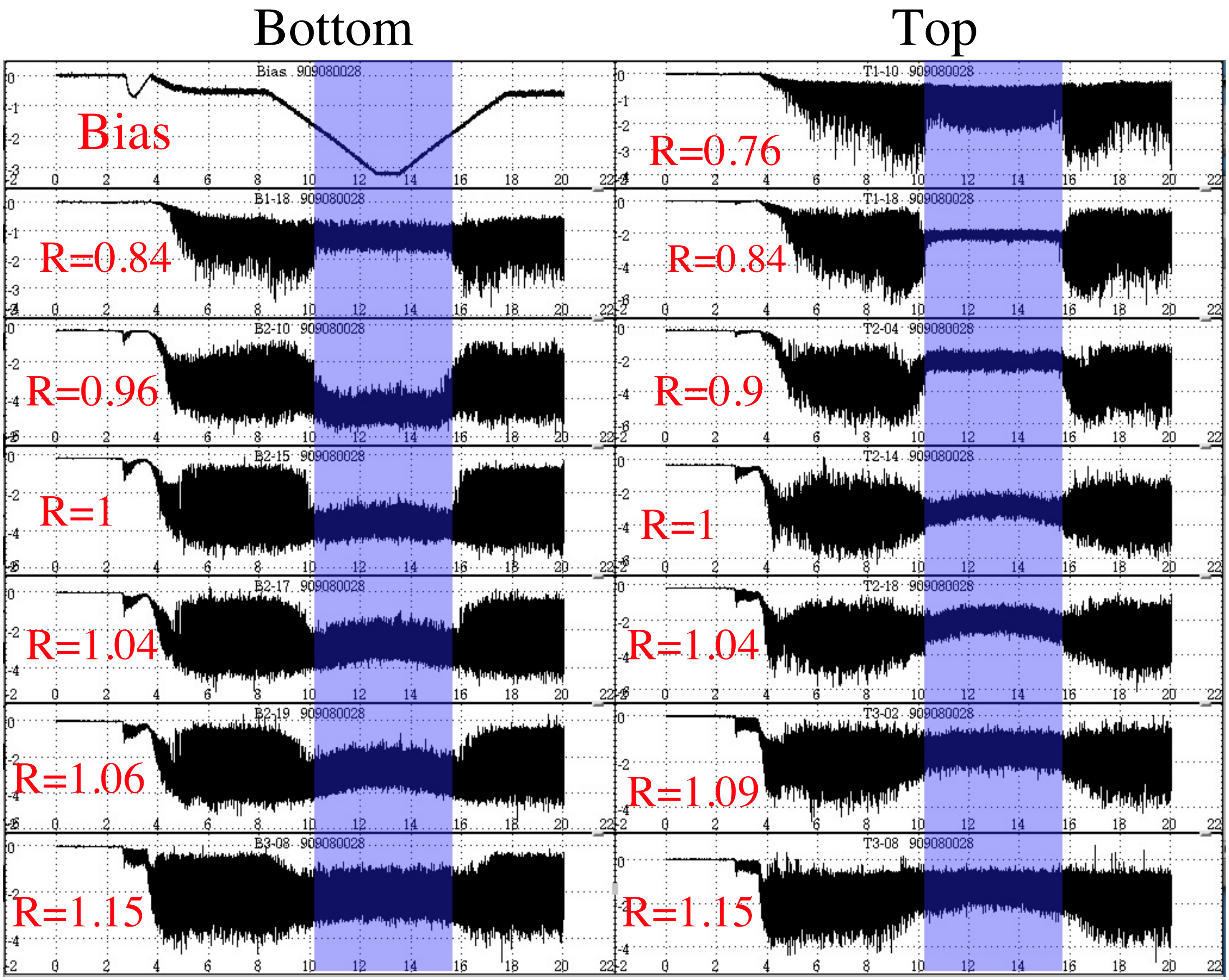
- ➢ Other plates and vessel grounded

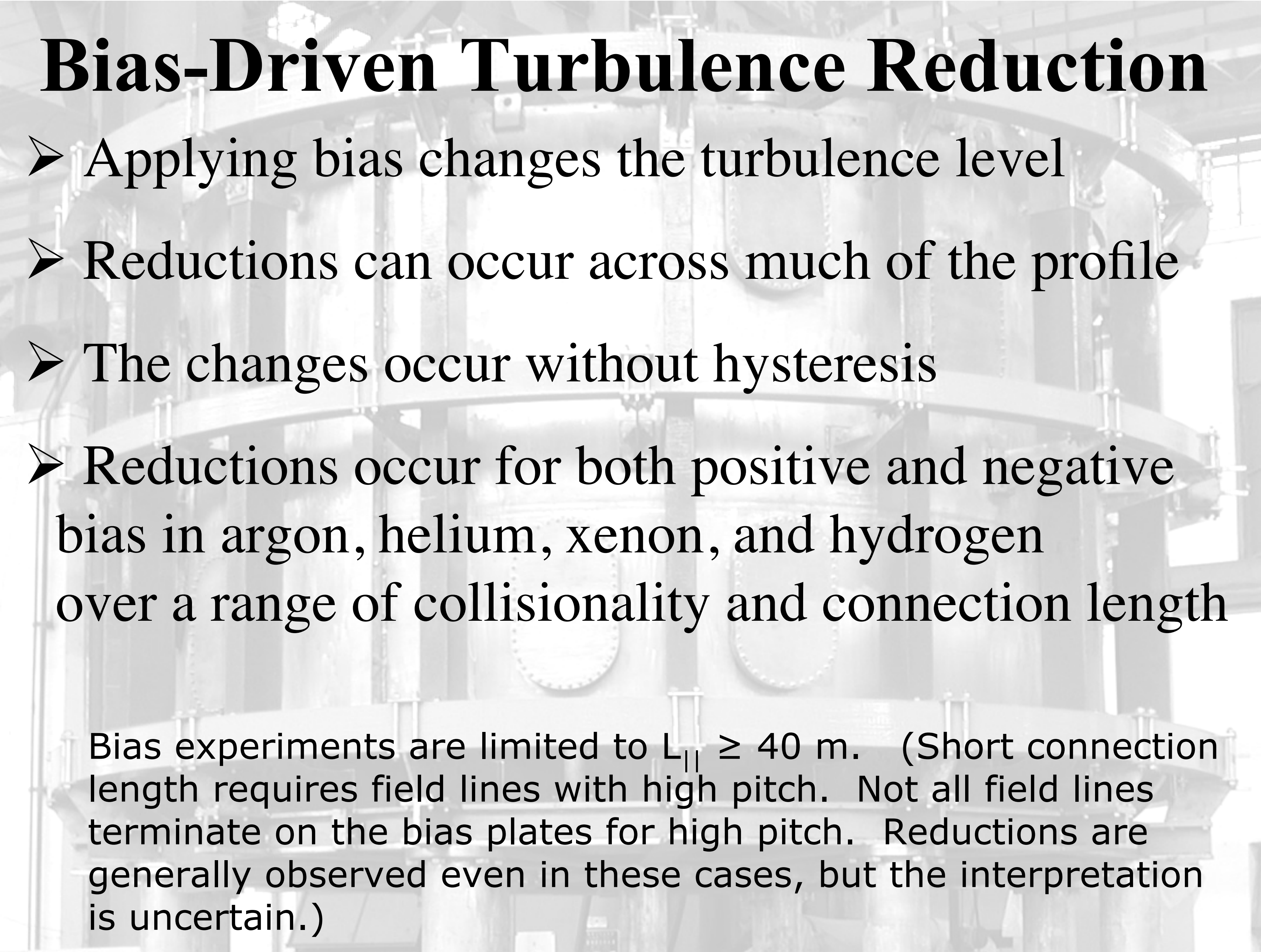


Simple Phenomenology

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

Negative Bias Transition at ~-20 V





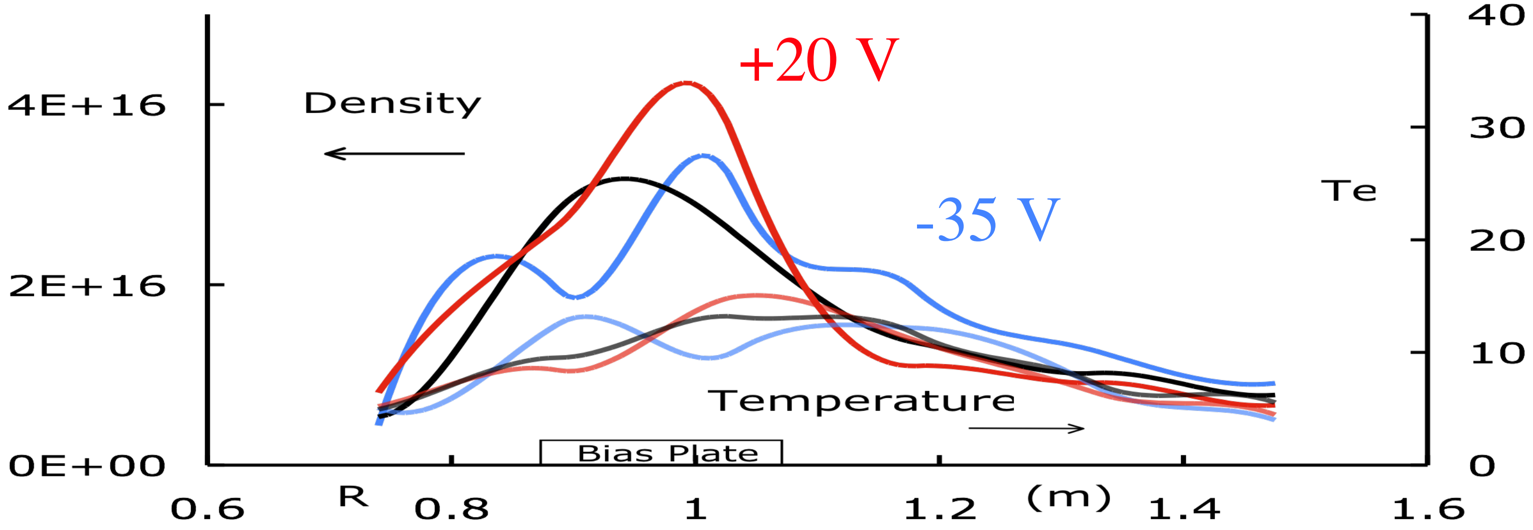
Bias-Driven Turbulence Reduction

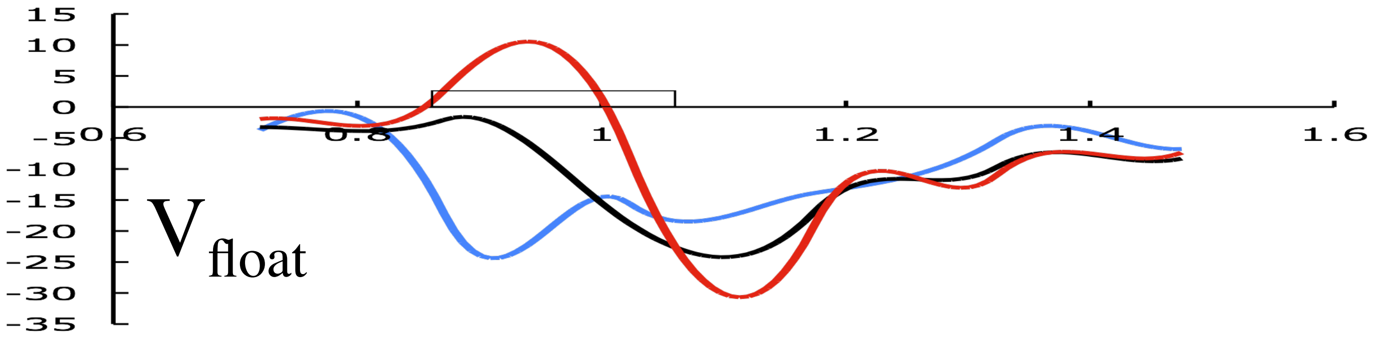
- Applying bias changes the turbulence level
- Reductions can occur across much of the profile
- The changes occur without hysteresis
- Reductions occur for both positive and negative bias in argon, helium, xenon, and hydrogen over a range of collisionality and connection length

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

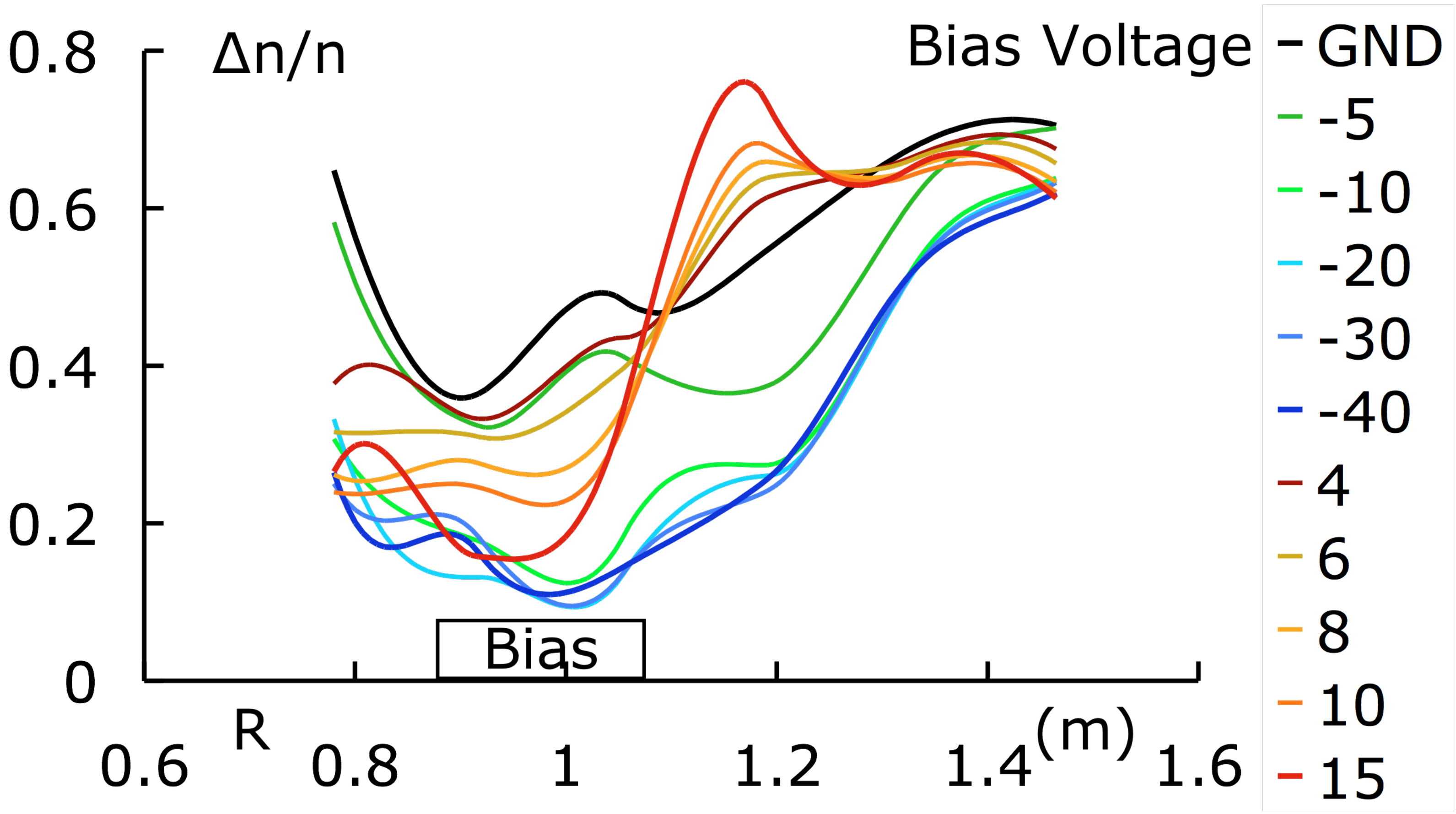
Positive, Negative, Zero Bias



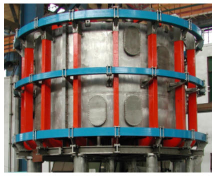


- Temperature ~ constant; density changes modest
- Potential change at plate as expected
- Effects extend outward from plate, esp. negative bias

Density Fluctuations

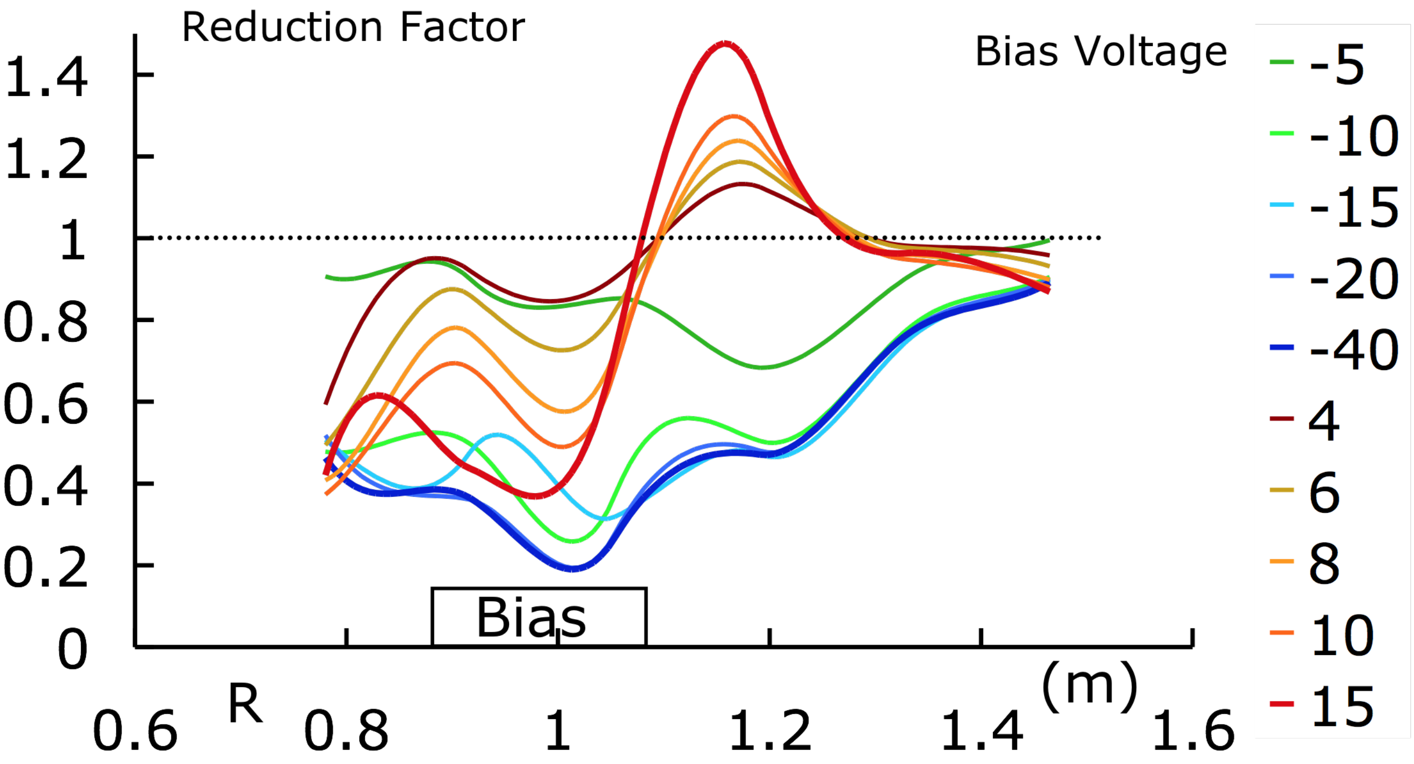


- Reduced across plate
- Effect extends outward for negative bias



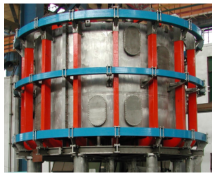
Turbulence Reduction -- Density

Reduction = Δn/n(Bias)/Δn/n(Grnd)



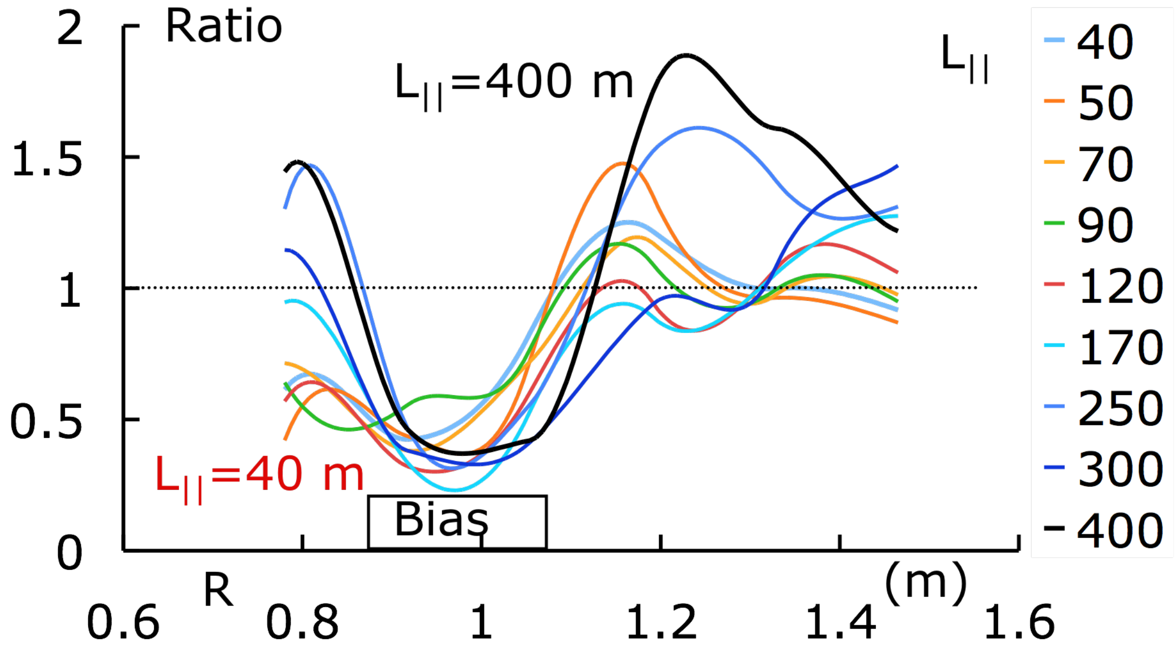
Suppression completed by -20 V

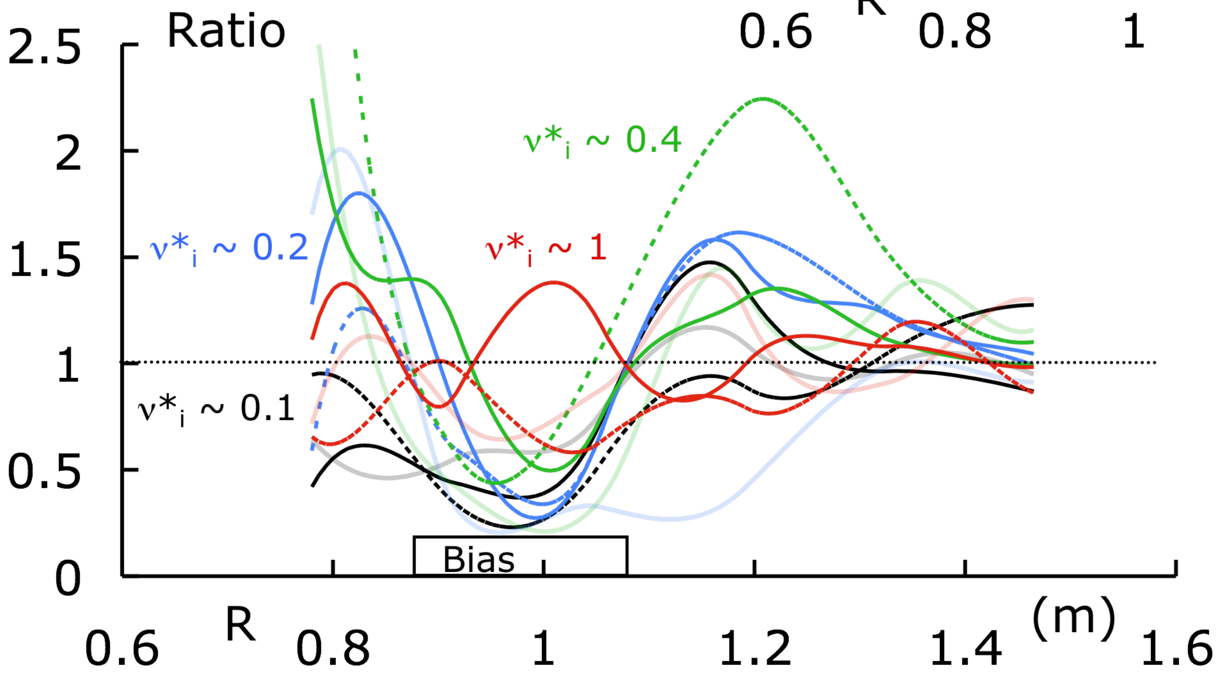
$L_{||} = 50$ m



Turbulence Reduction: Positive Bias

Weak dependence on connection length

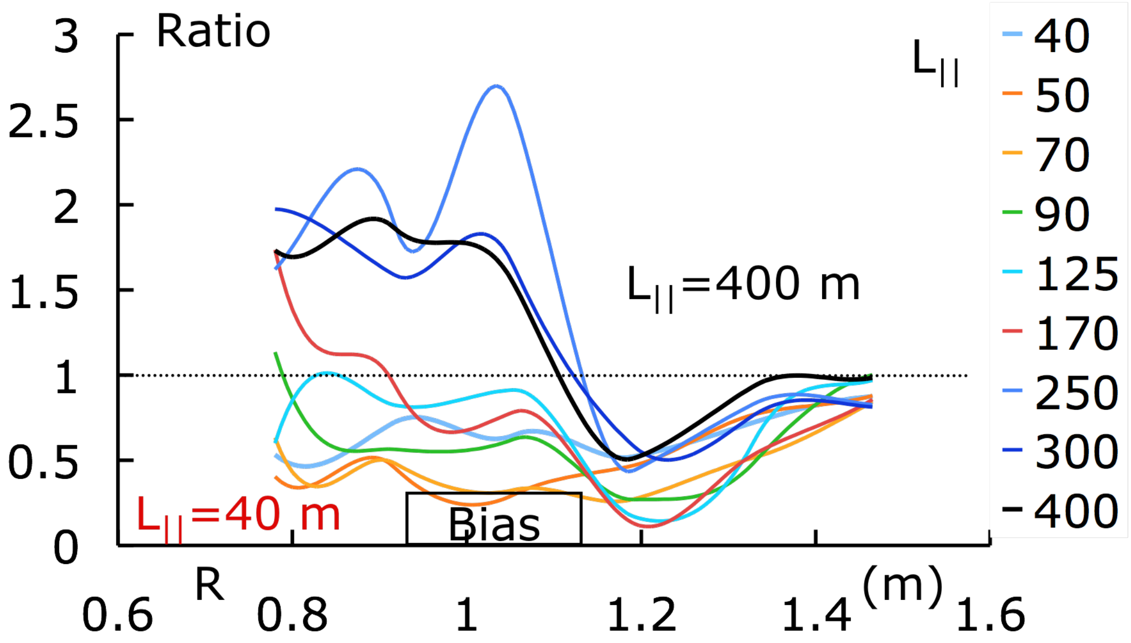


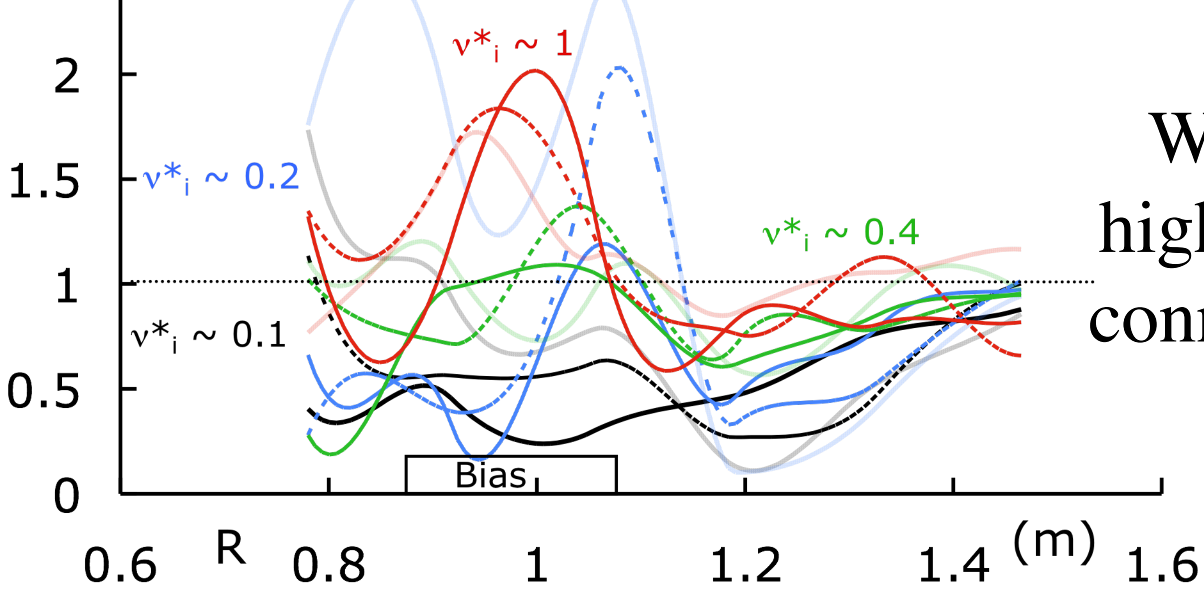


Reductions weaker at highest collisionality, otherwise little effect

Turbulence Reduction: Negative Bias

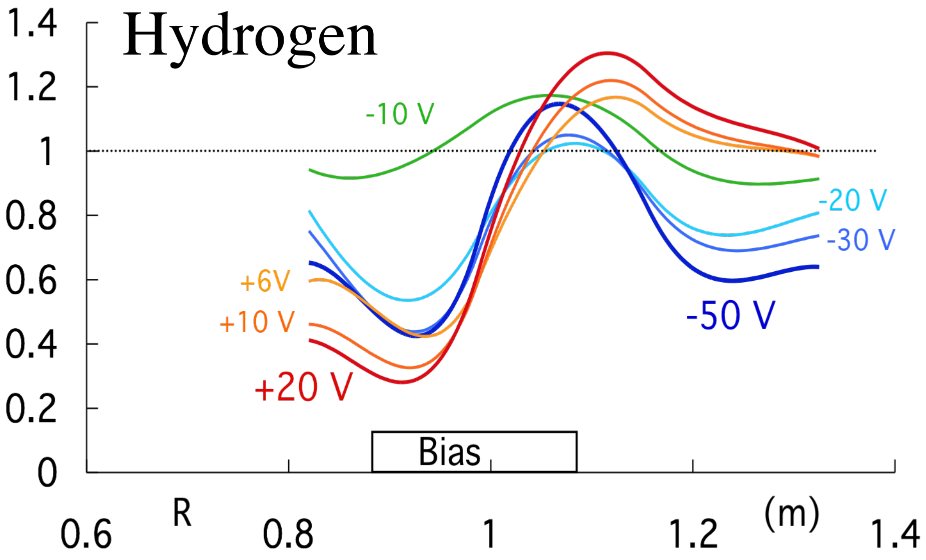
Less reduction for long connection lengths, $L_{||} \geq 200$ m. Optimum depends on location.

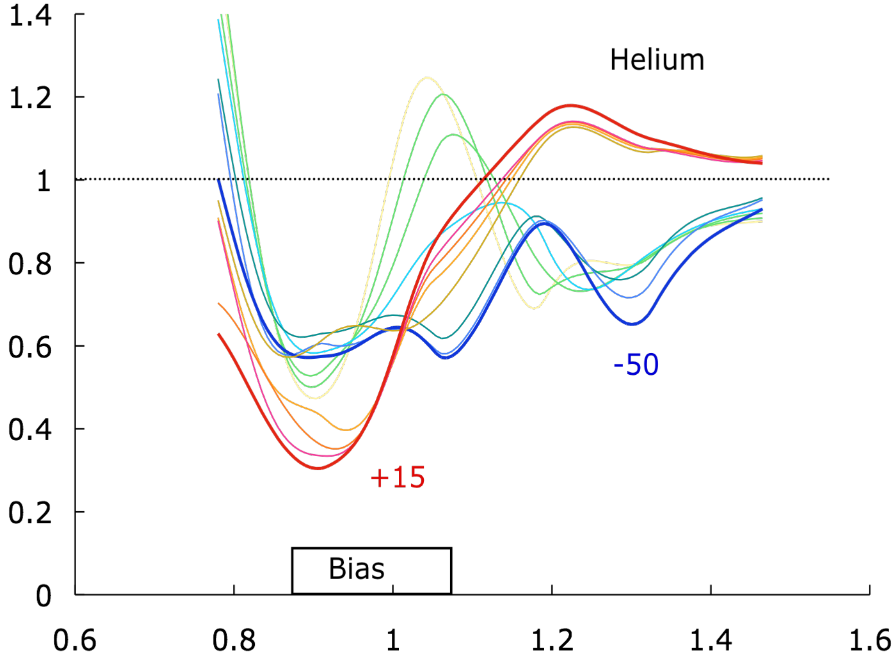


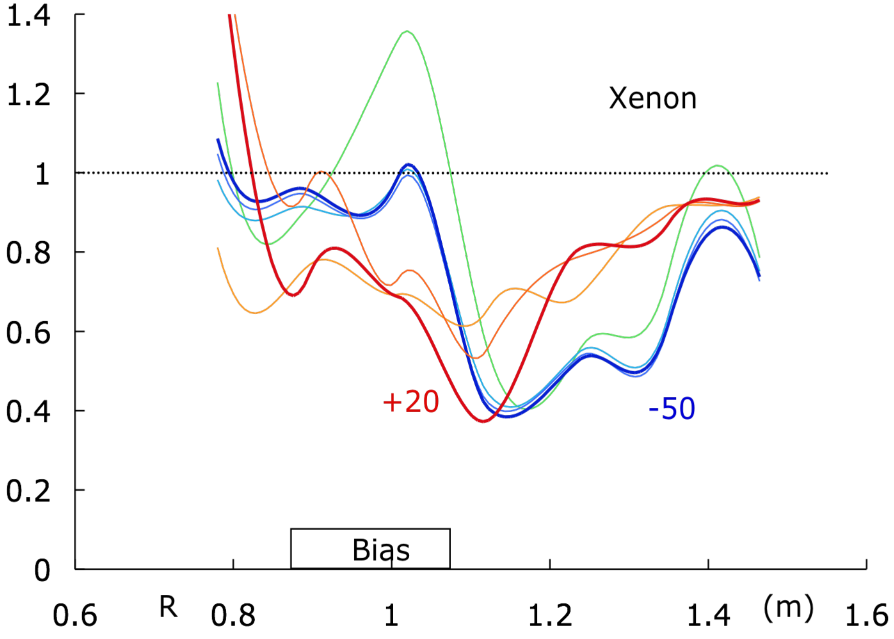


Weaker reduction at higher collisionality for connection lengths from 50-200 m

Similar Turbulence Reductions in H, He, and Xe

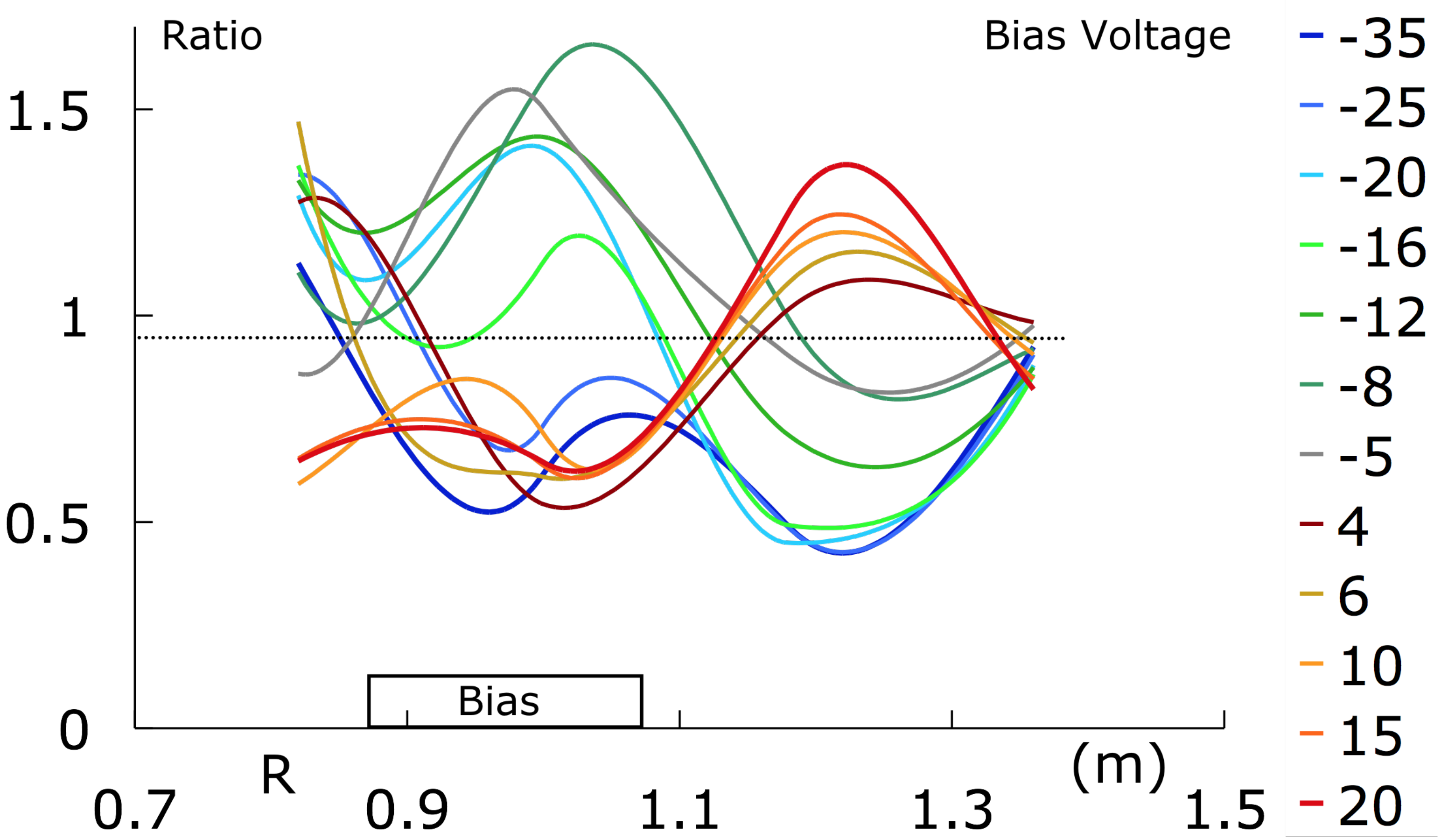






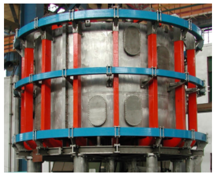
Similar reductions are seen in all gases, but the specific radial patterns vary with gas, $L_{||}$, and collisionality.

Change in Radial Correlation Length



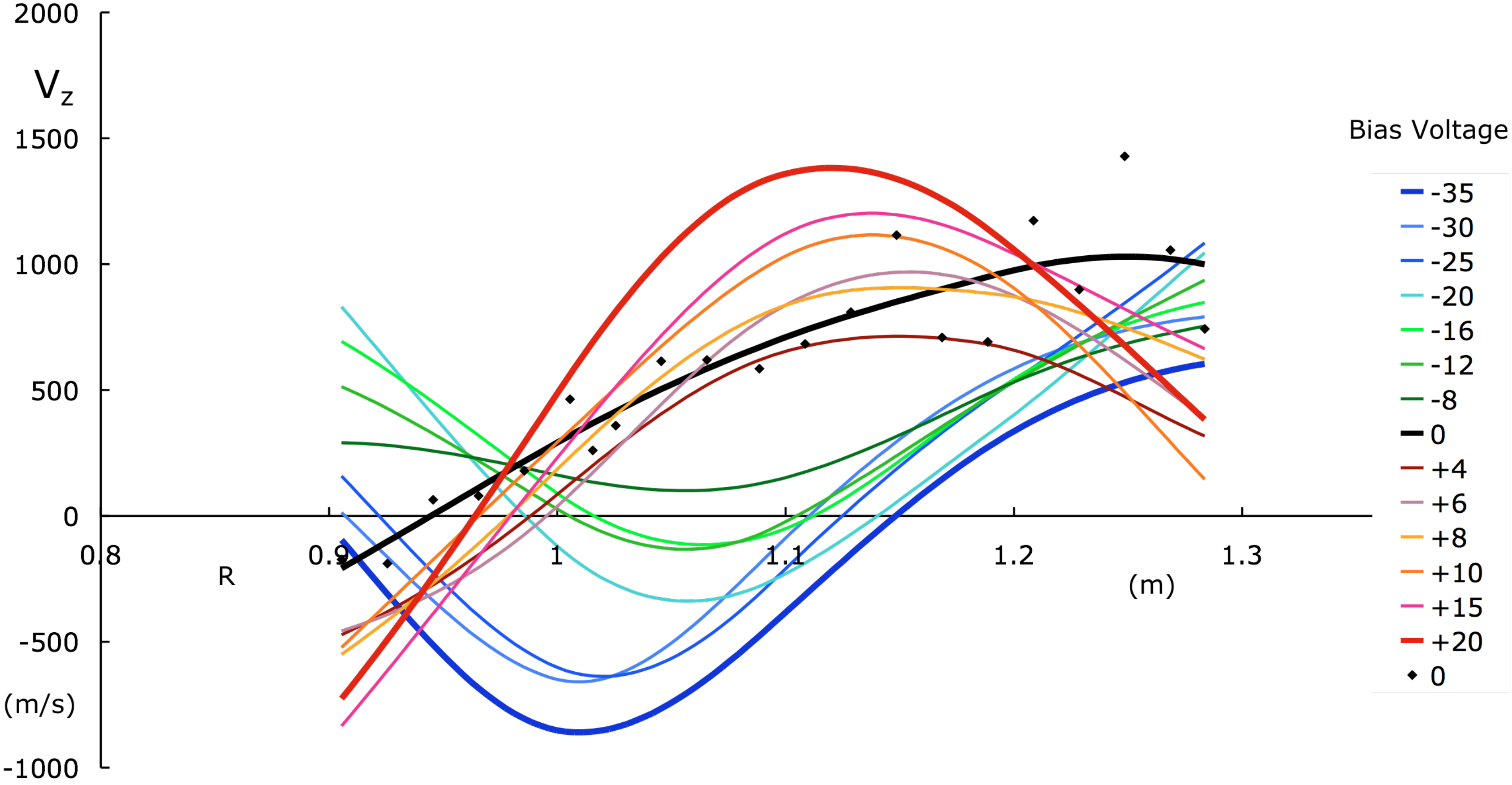
Change in radial correlation length generally follows change in turbulence level

Argon $L_{||} = 40$ m



Measured Flow Velocity

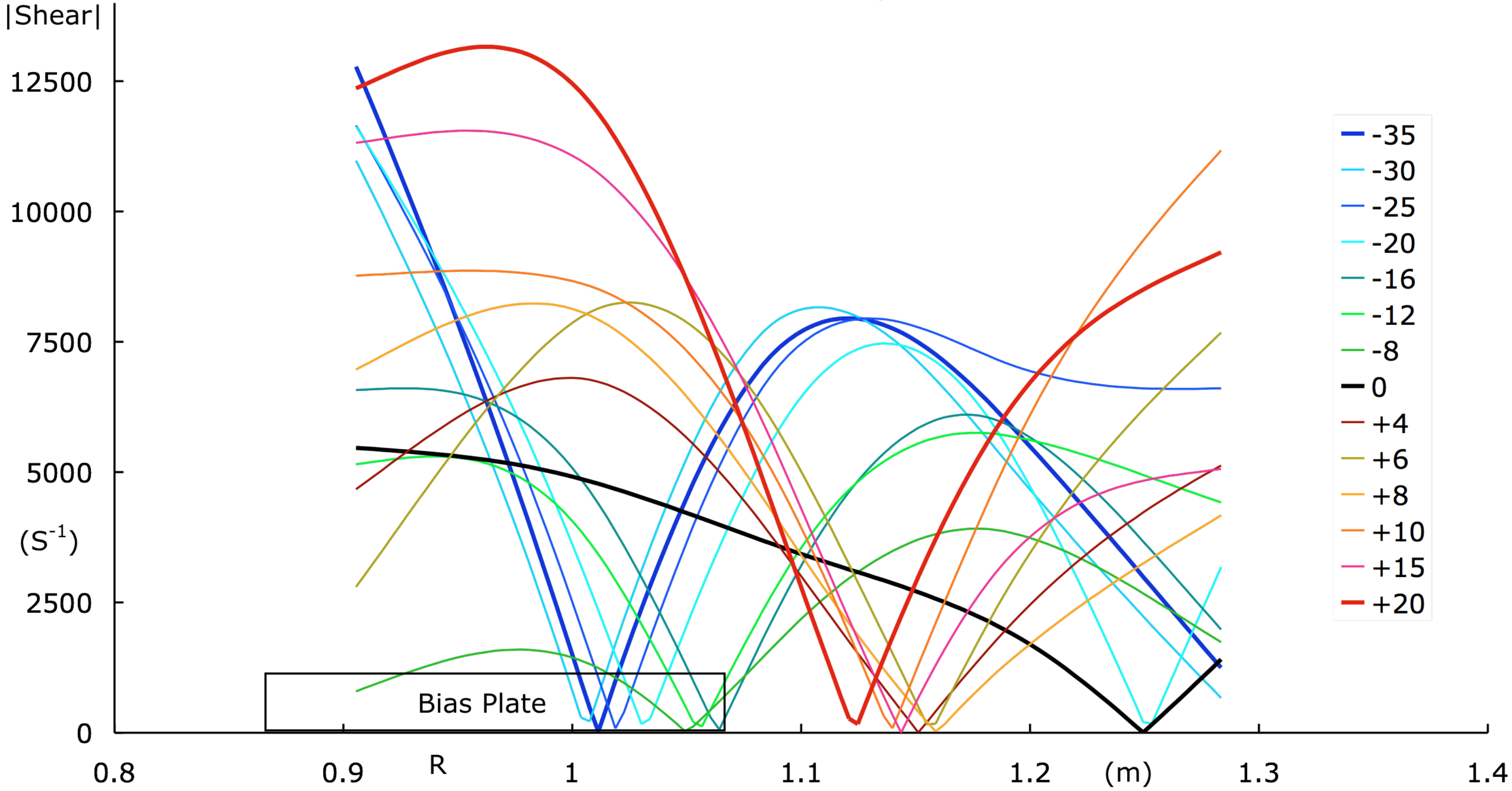
Ion Doppler Velocity for Argon -- The Plasma Ion



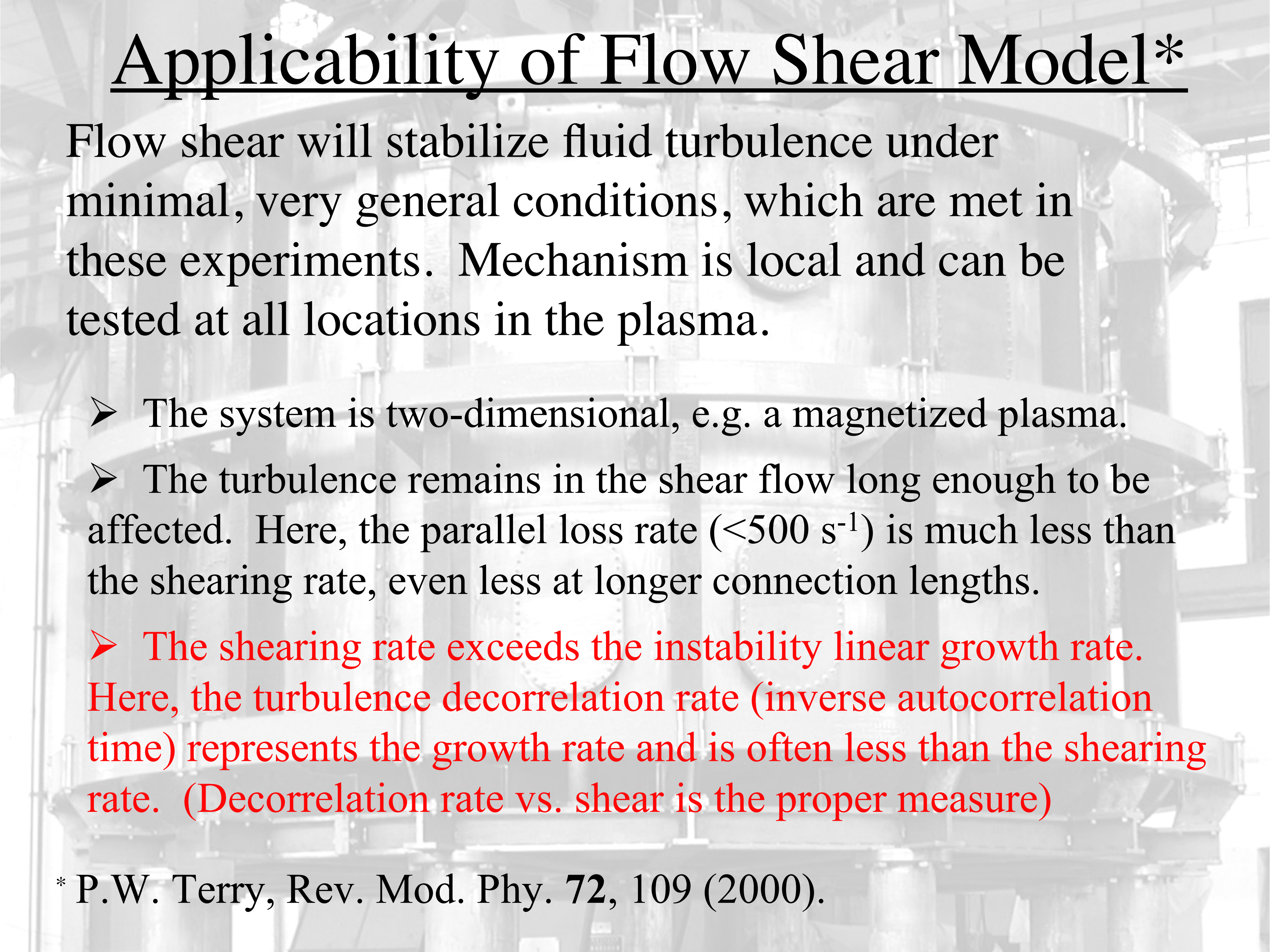
Spline fits -- data points for 0 bias case only

$L_{||} = 40$ 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[*]

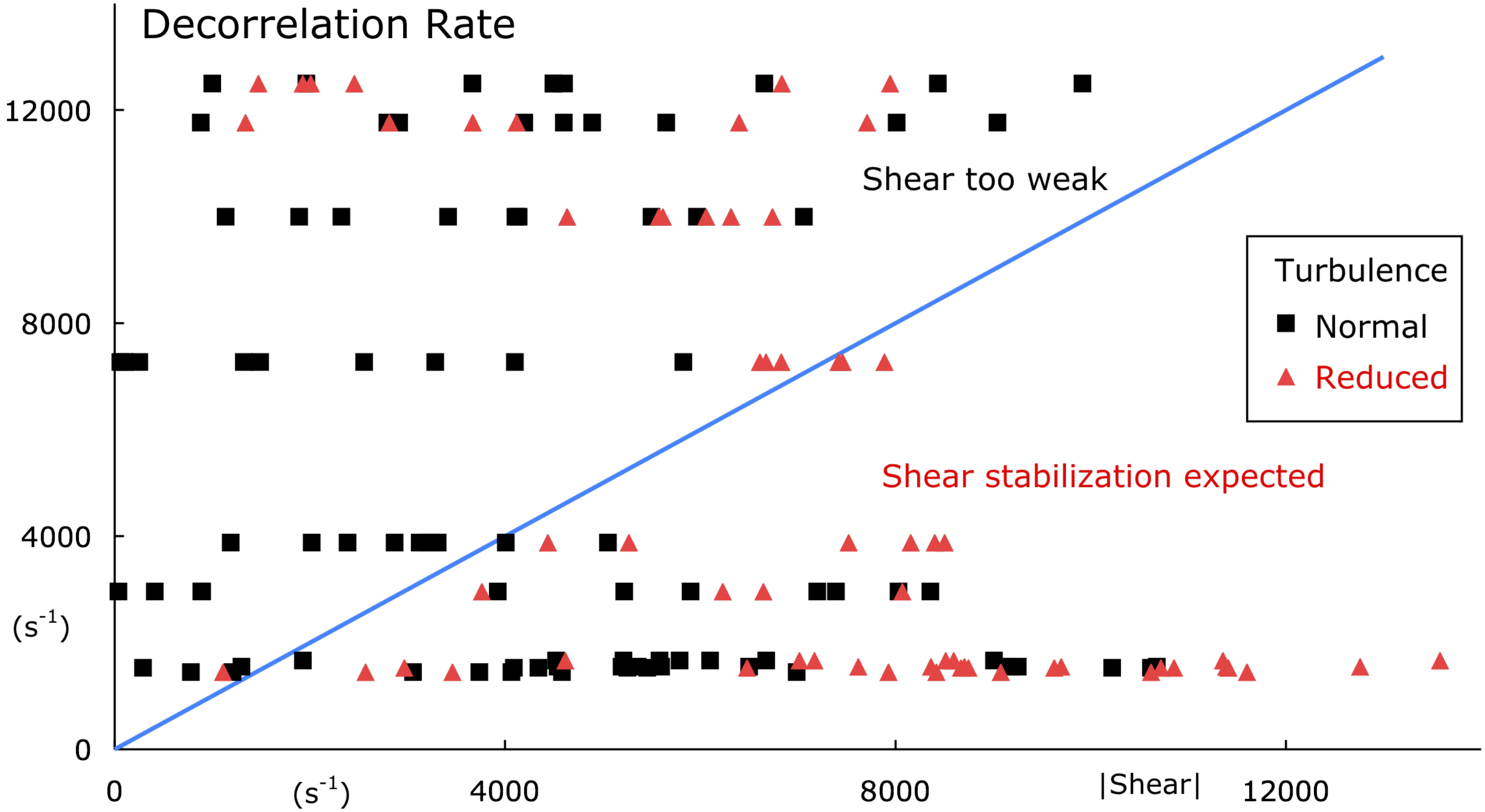
Flow shear will stabilize fluid turbulence under minimal, very general conditions, which are met in these experiments. Mechanism is local and can be tested at all locations in the plasma.

- 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 ($<500\ \mathrm{s}^{-1}$) 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. (Decorrelation rate vs. shear is the proper measure)

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

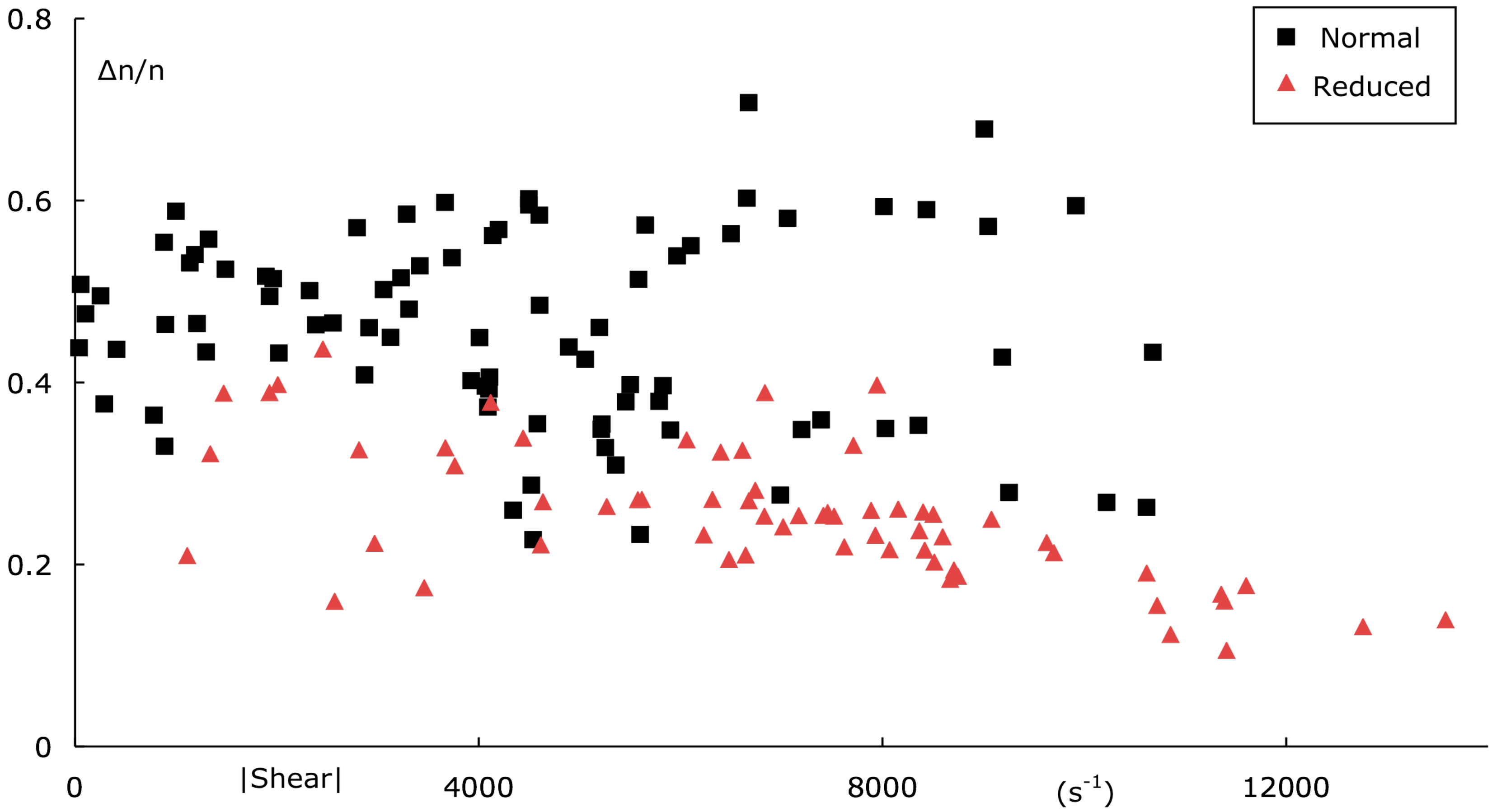
Decorrelation Rate vs. Shearing Rate

(All radii, all bias voltages)



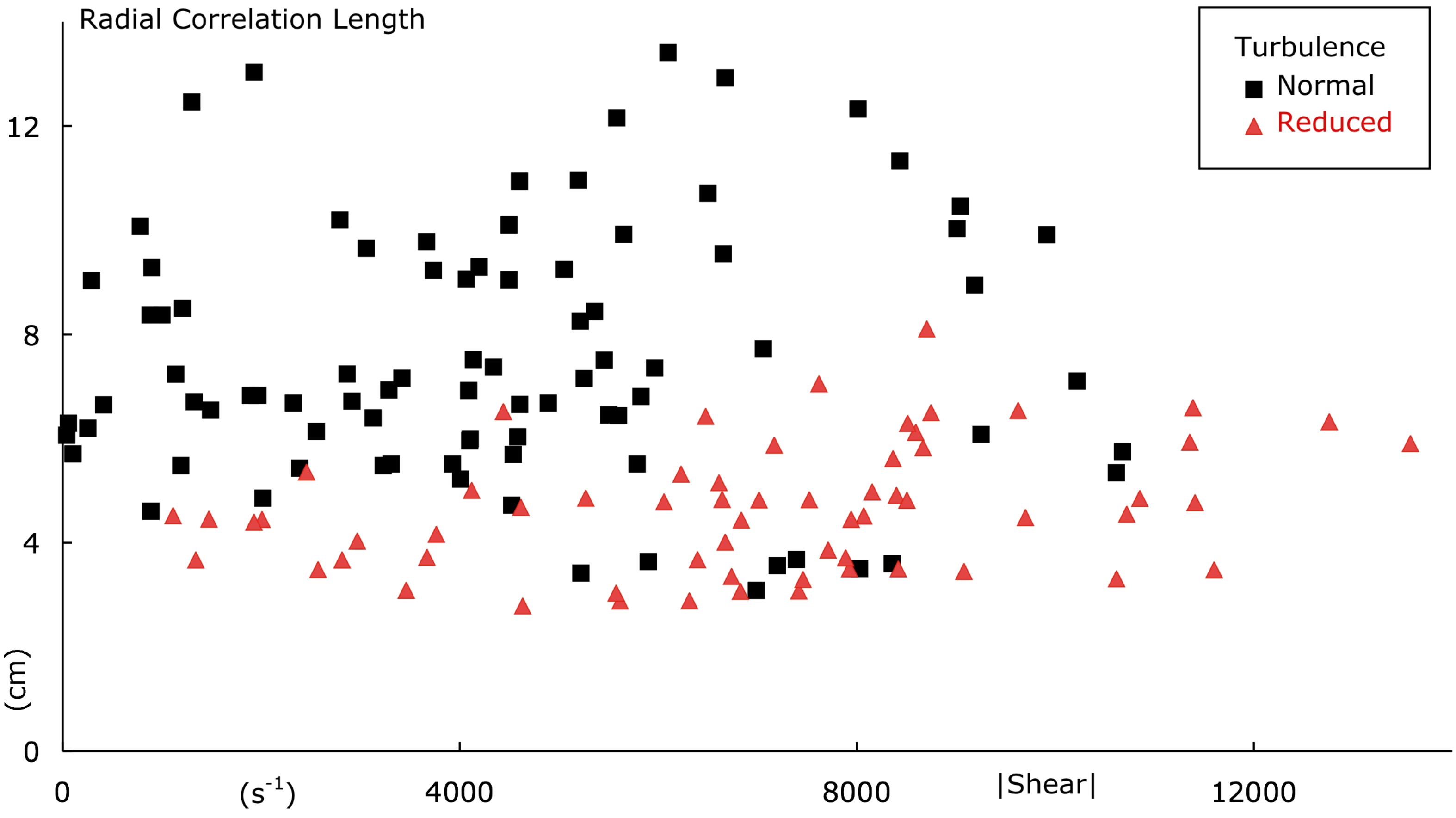
Shear often sufficient to stabilize turbulence in theory, but all combinations actually observed

Shear Magnitude vs. Density Fluctuations



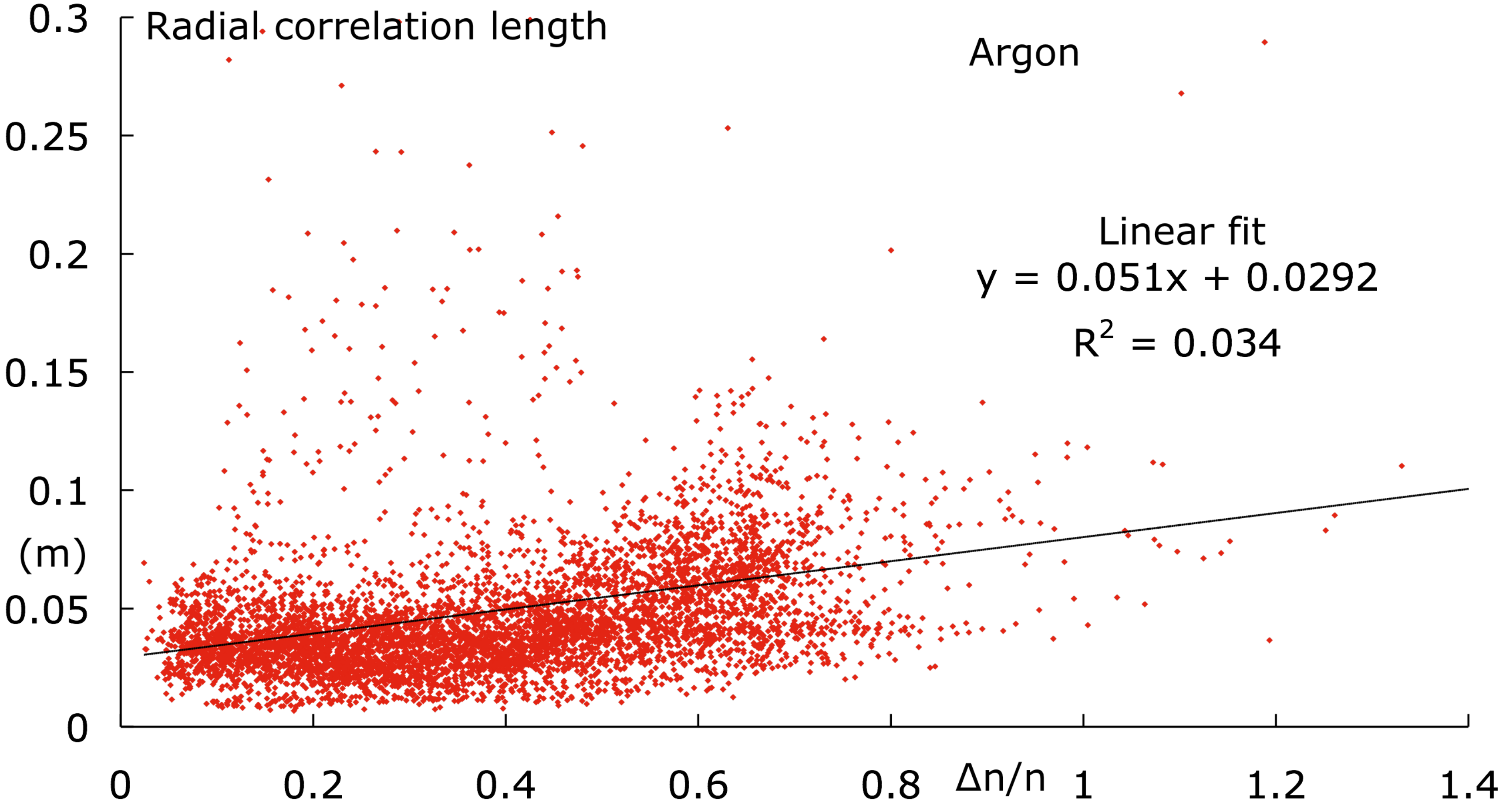
- **No evidence for a general physical relation**
- **Turbulence reductions even at low shear**
- **High turbulence may persist at high shear**

Shear vs. Radial Correlation Length



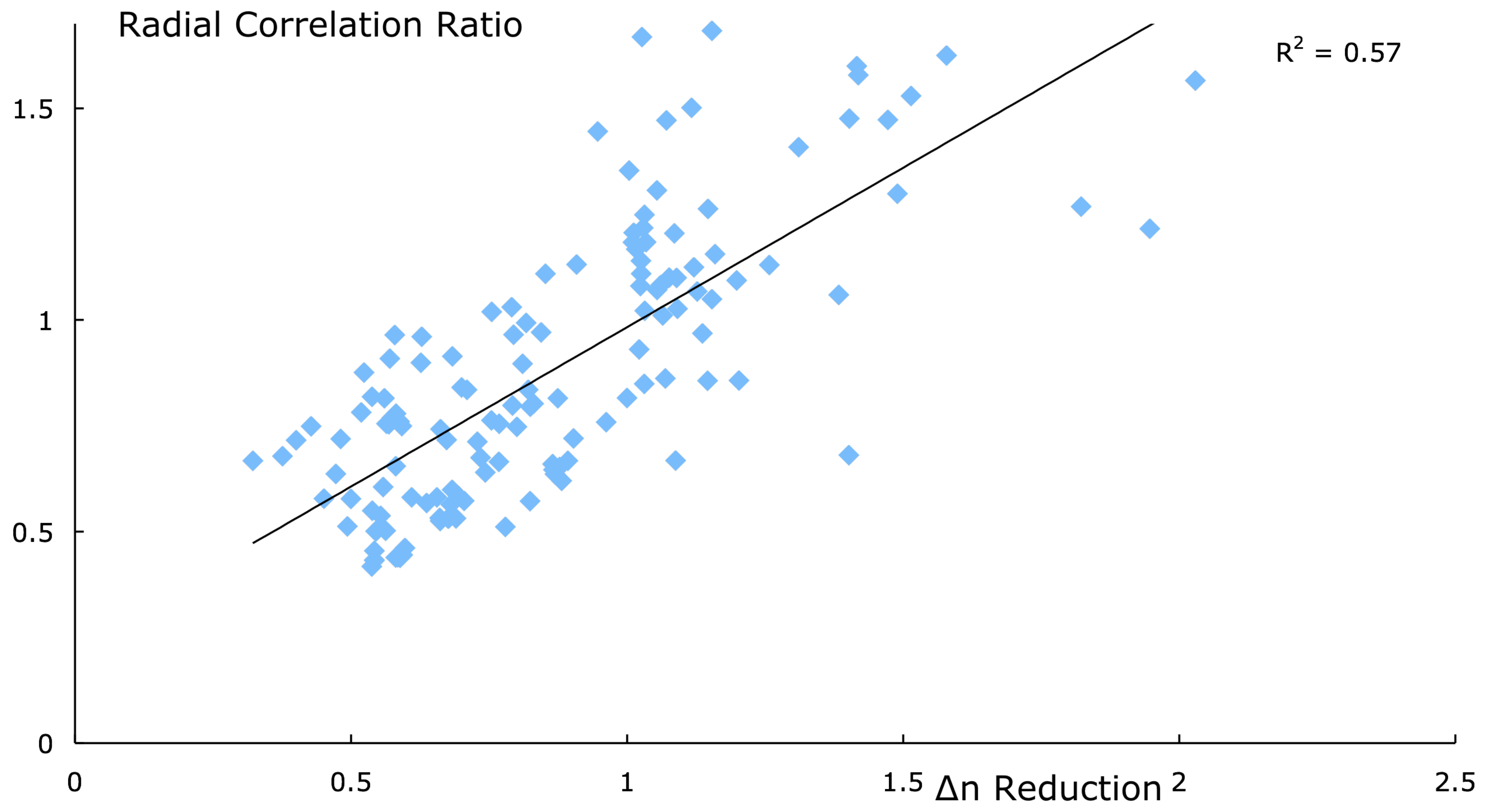
- No evidence for a physical relation
- No trace of inverse trend

Density Fluctuations vs. Radial Correlation Length

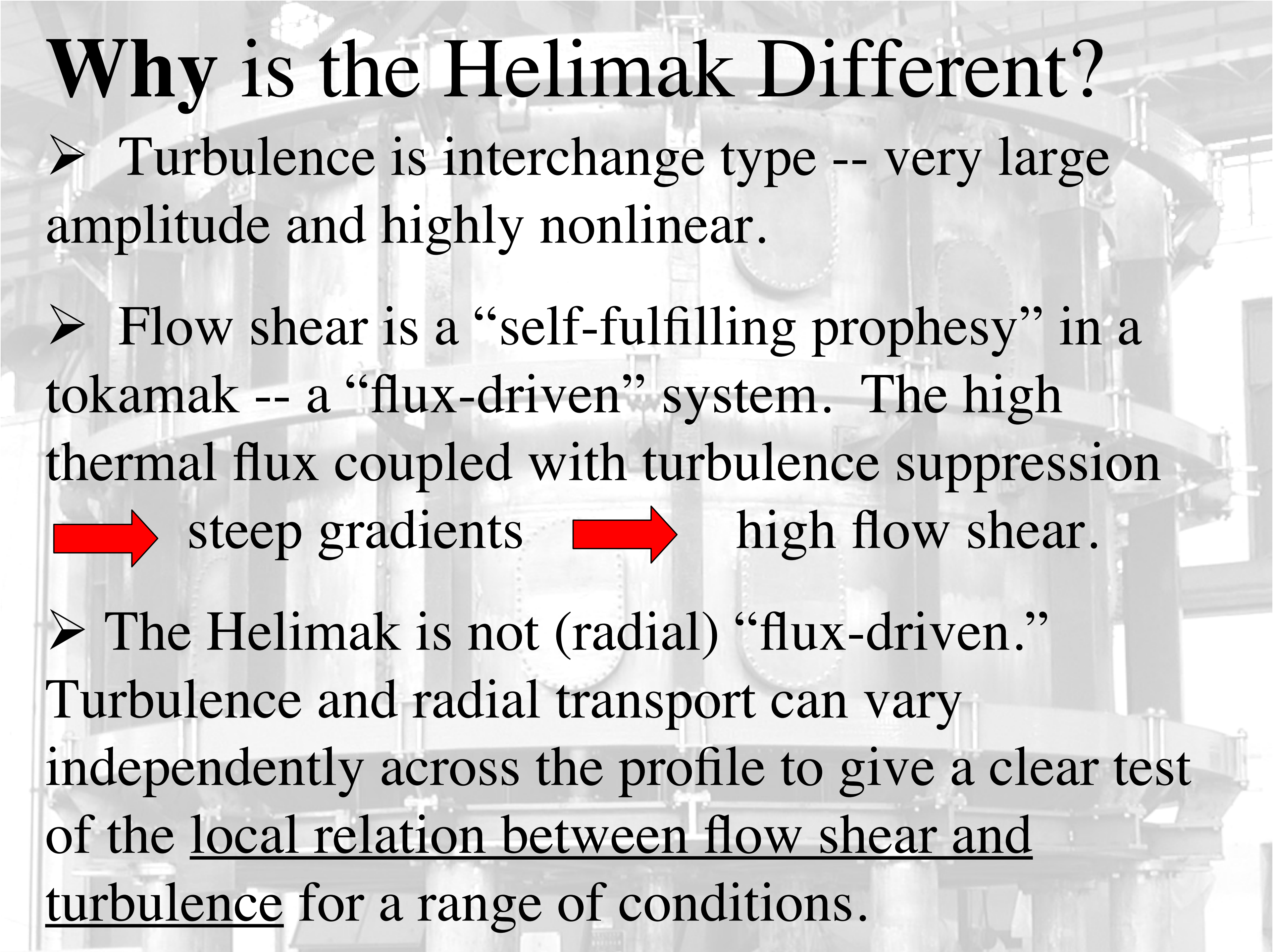


Correct tendency, but very large scatter and offset with marginal significance

Turbulence Reduction vs. Change in Length



Change in radial correlation length roughly correlated with change in turbulence level



Why is the Helimak Different?

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

- 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 <u>local relation between flow shear and turbulence</u> for a range of conditions.

V_z (Poloidal) Flows -- Zonal Flows ?

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

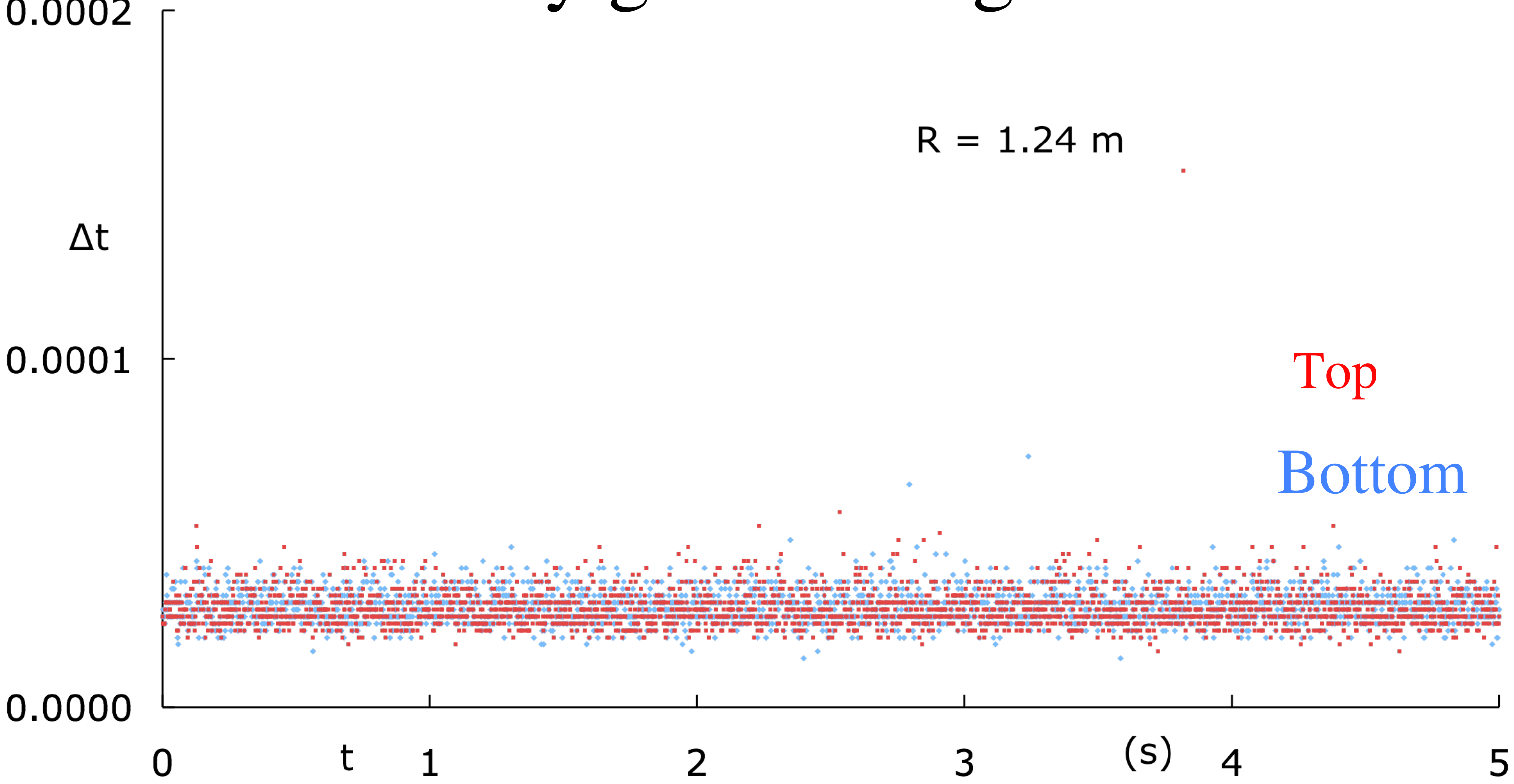
Apparent propagation indication of flow

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 -- Essential Characteristics

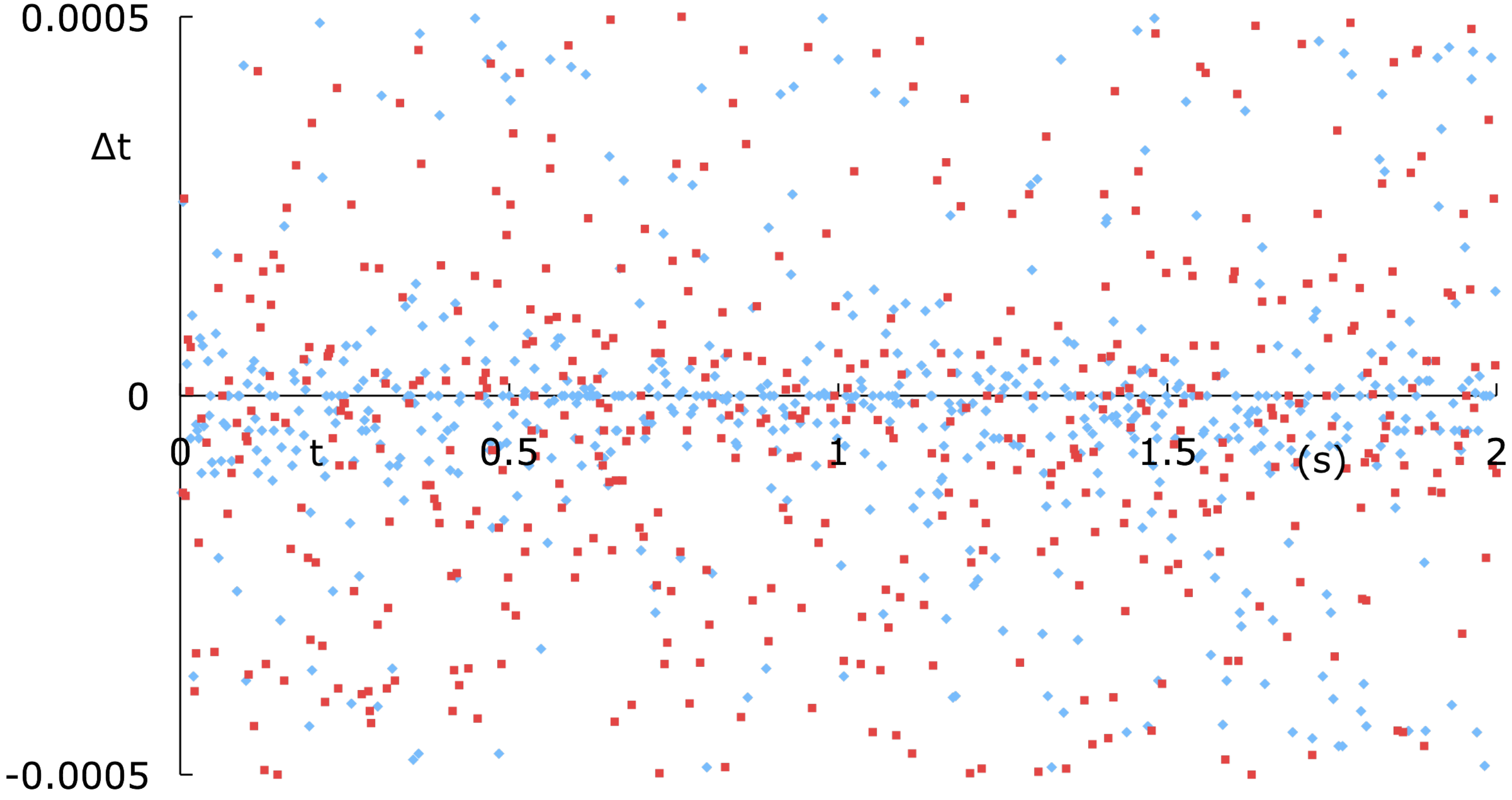
- Flow "m=0; ω=0" <u>Same</u> at top and bottom
- May vanish over 10s ($\sim 10^5\ \tau_{decorrelation}$)
- Should be clear and slowly varying in sequence of 1 ms subsamples ($\sim 10\ \tau_{decorrelation}$)

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)

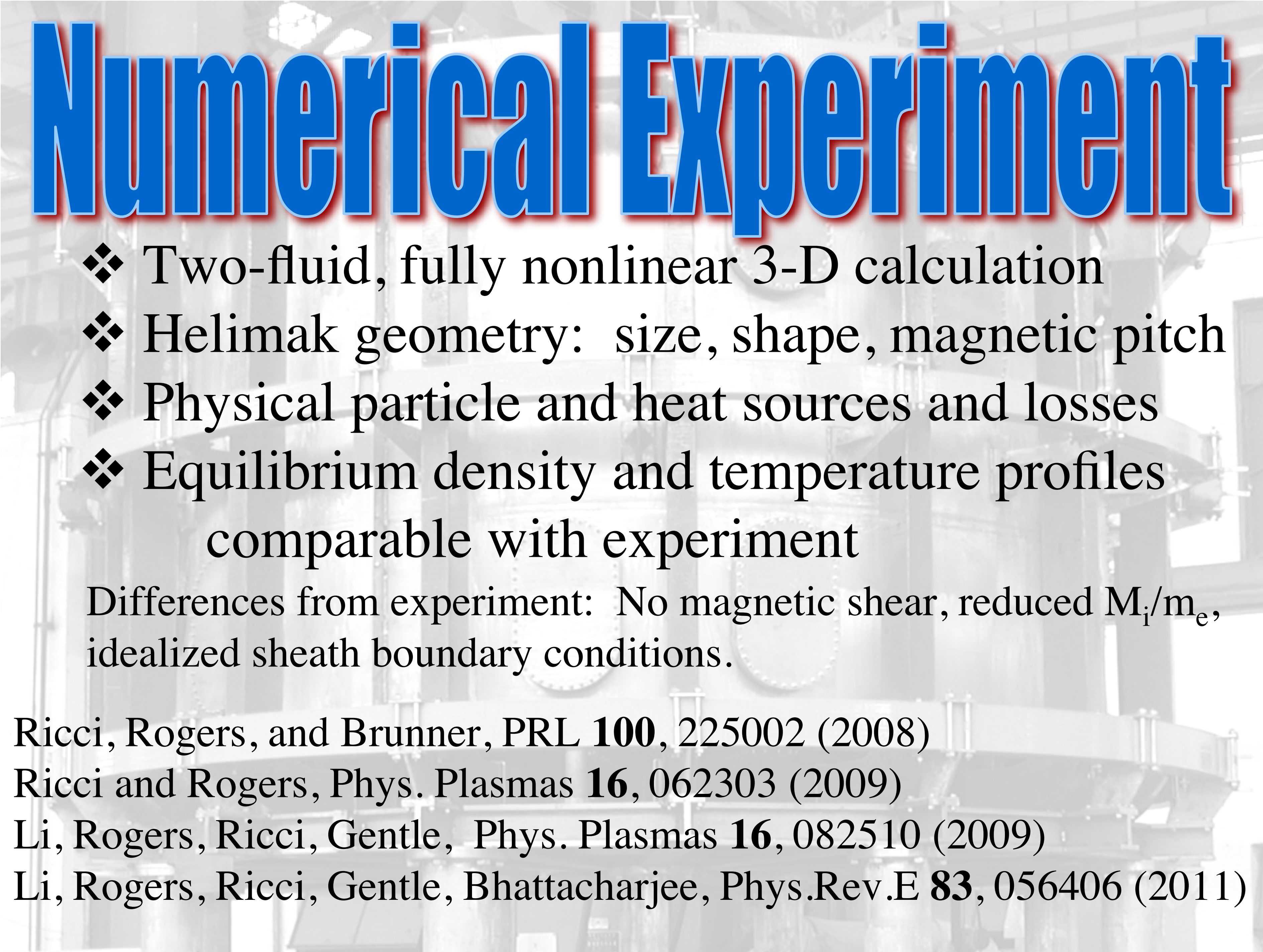


No mean flow; only local turbulent fluctuations. Fast, random variations in delay times; top and bottom independent.

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 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>

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.

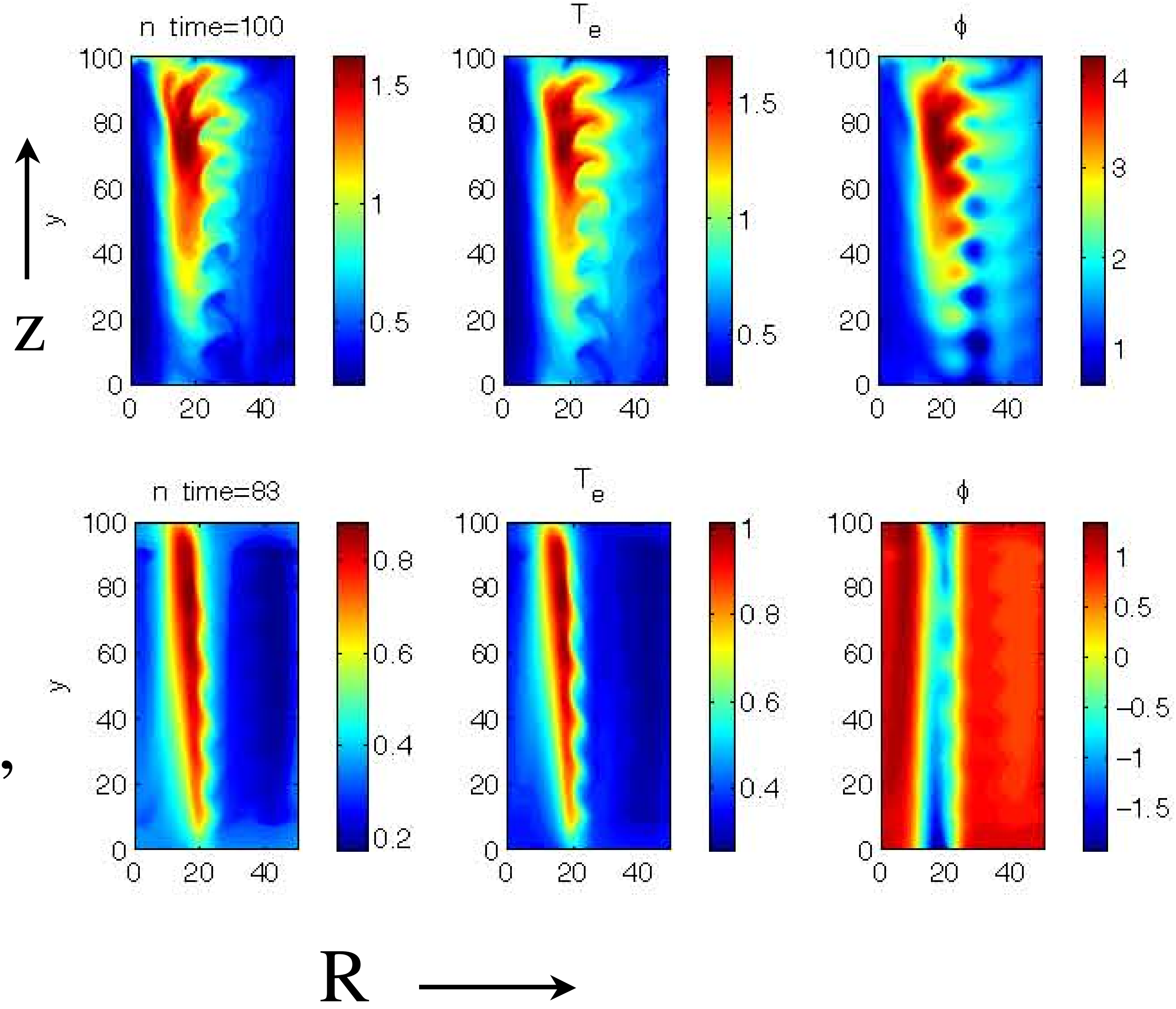
Ricci, Rogers, and Brunner, PRL **100**, 225002 (2008)
Ricci and Rogers, Phys. Plasmas **16**, 062303 (2009)
Li, Rogers, Ricci, Gentle, Phys. Plasmas **16**, 082510 (2009)
Li, Rogers, Ricci, Gentle, Bhattacharjee, Phys.Rev.E **83**, 056406 (2011)

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



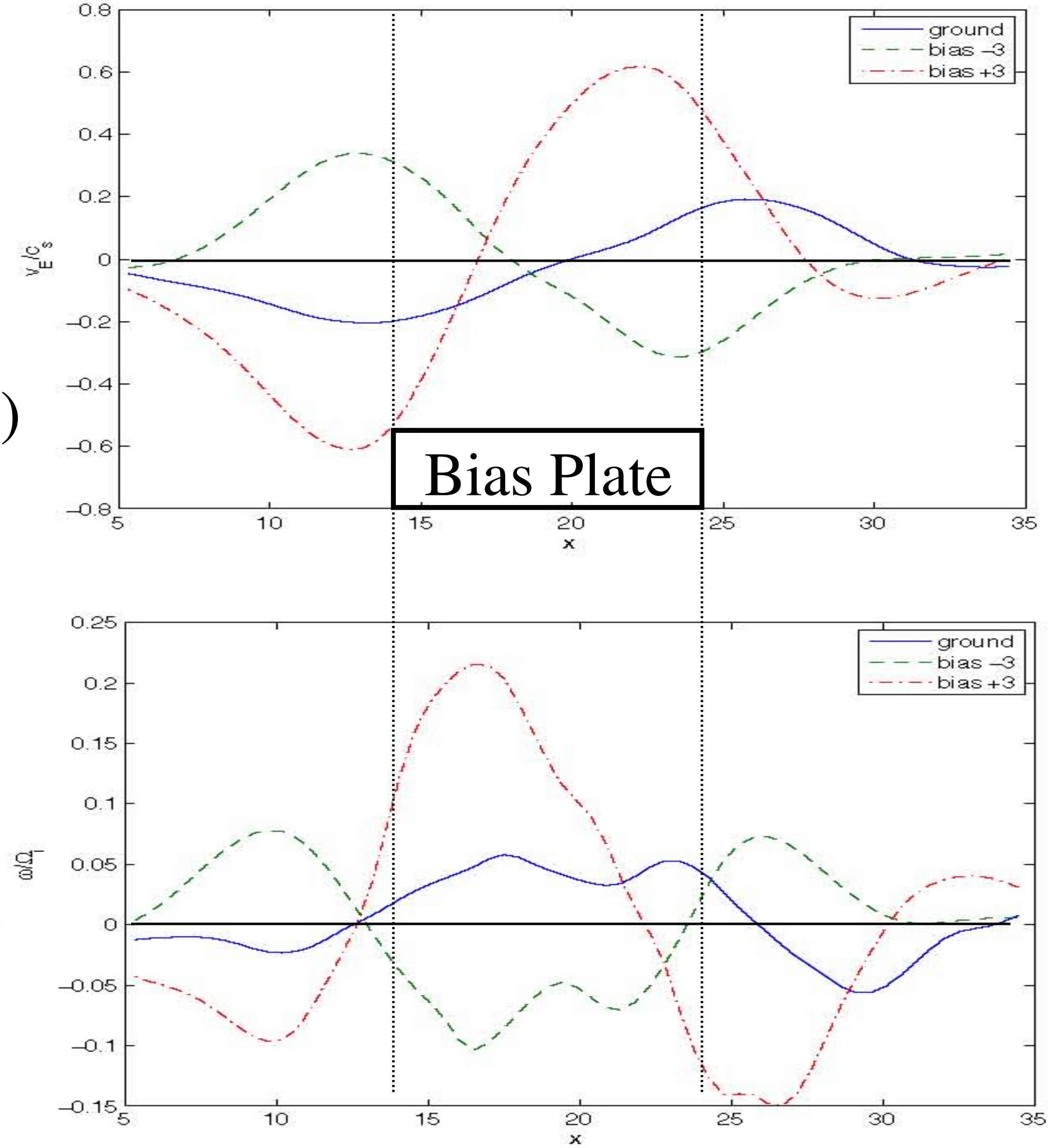
Flow and Flow Shear -- Normal, ±Bias

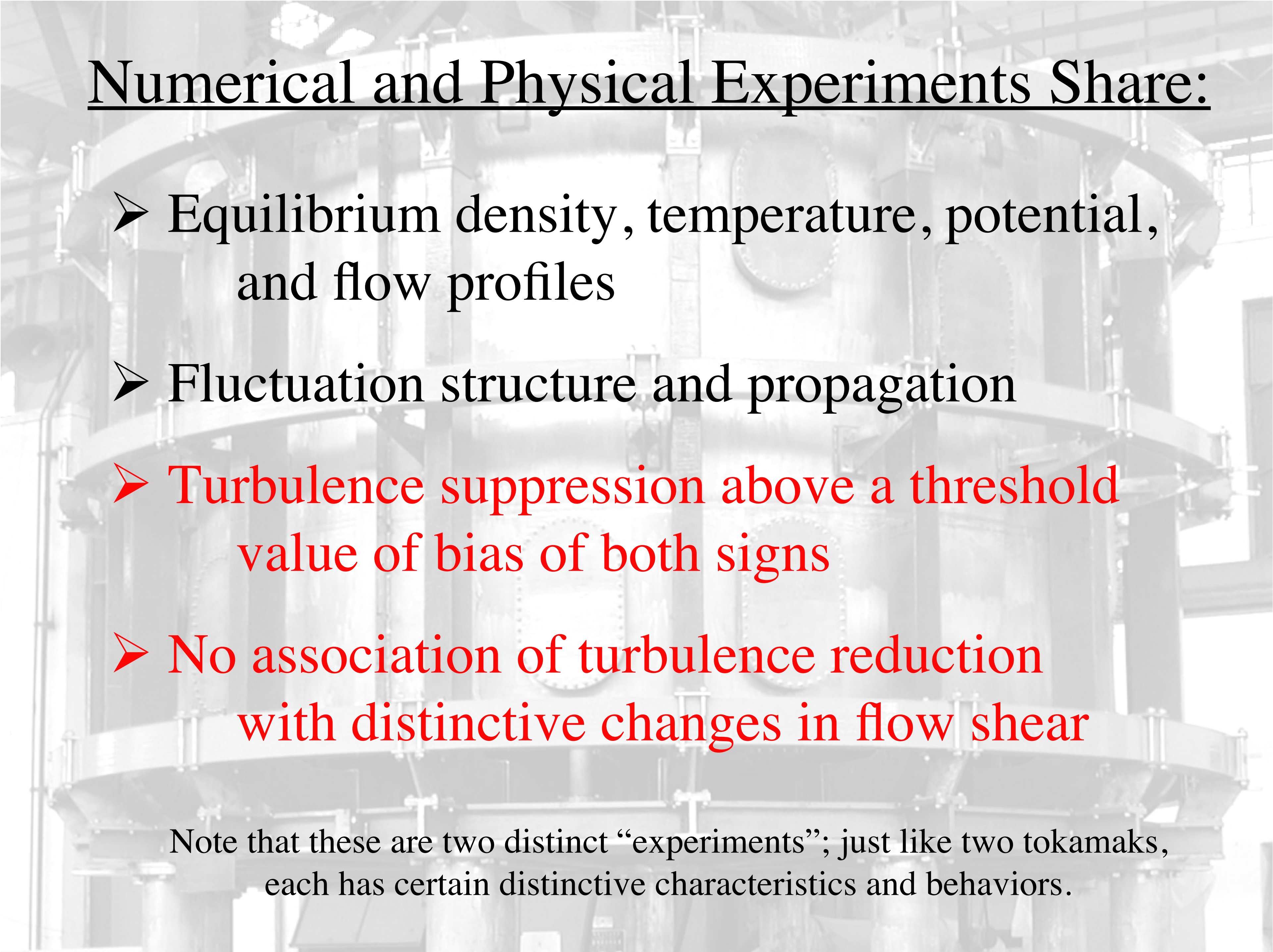
Flow (V_z)

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

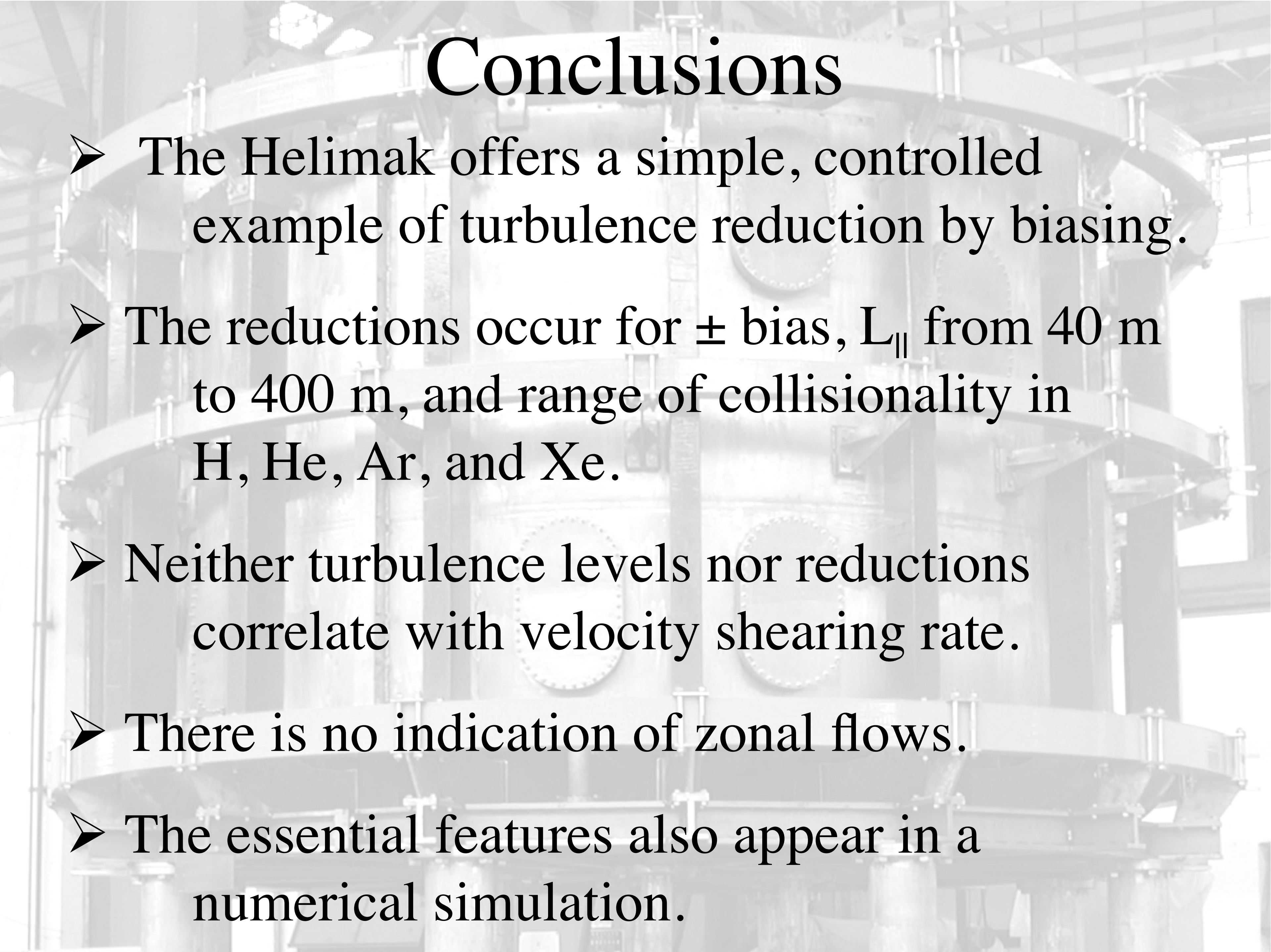




Numerical and Physical Experiments Share:

- 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.

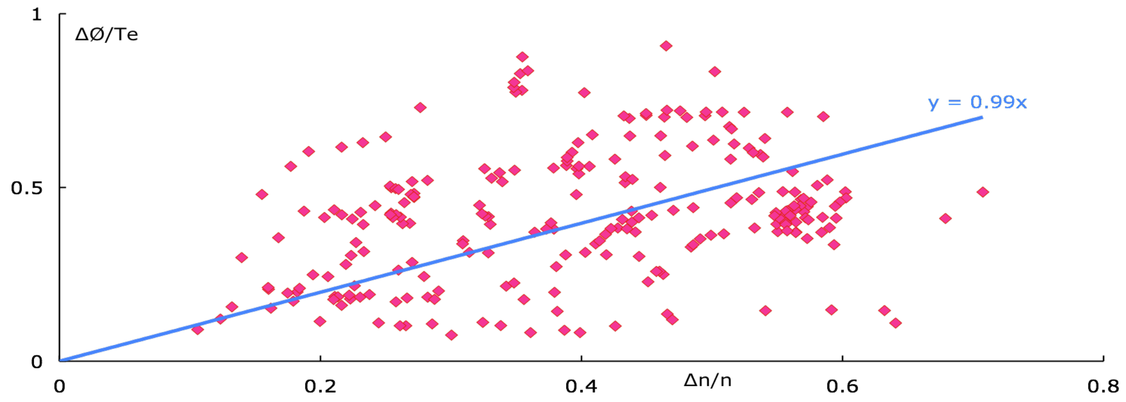


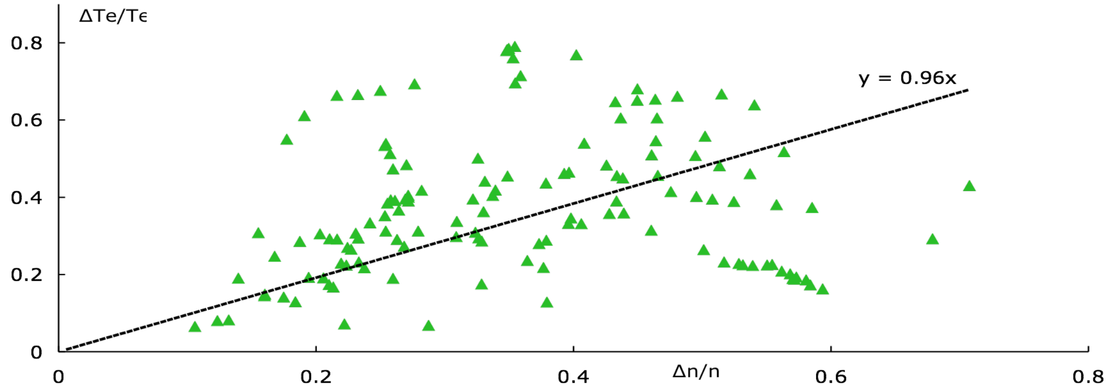
Conclusions

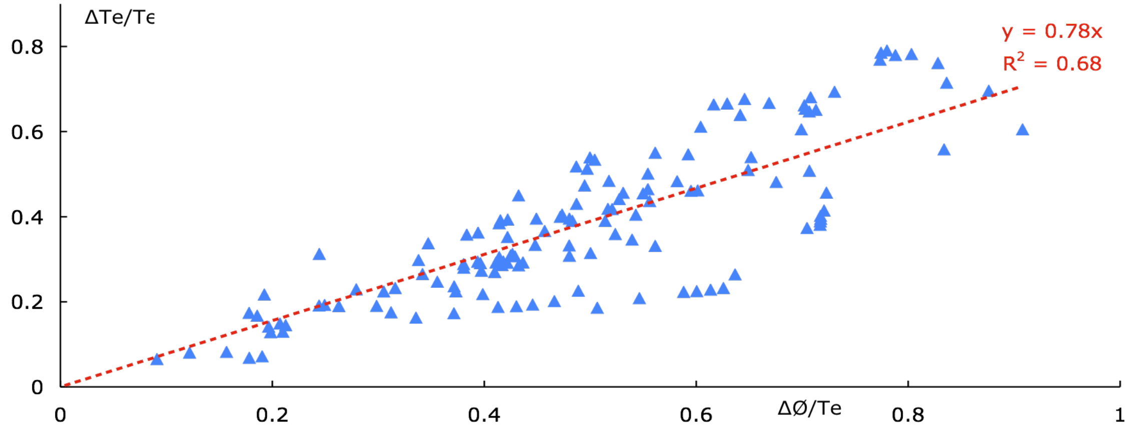
- The Helimak offers a simple, controlled example of turbulence reduction by biasing.
- The reductions occur for ± bias, $L_{||}$ from 40 m to 400 m, and range of collisionality in H, He, Ar, and Xe.
- Neither turbulence levels nor reductions correlate with velocity shearing rate.
- There is no indication 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.

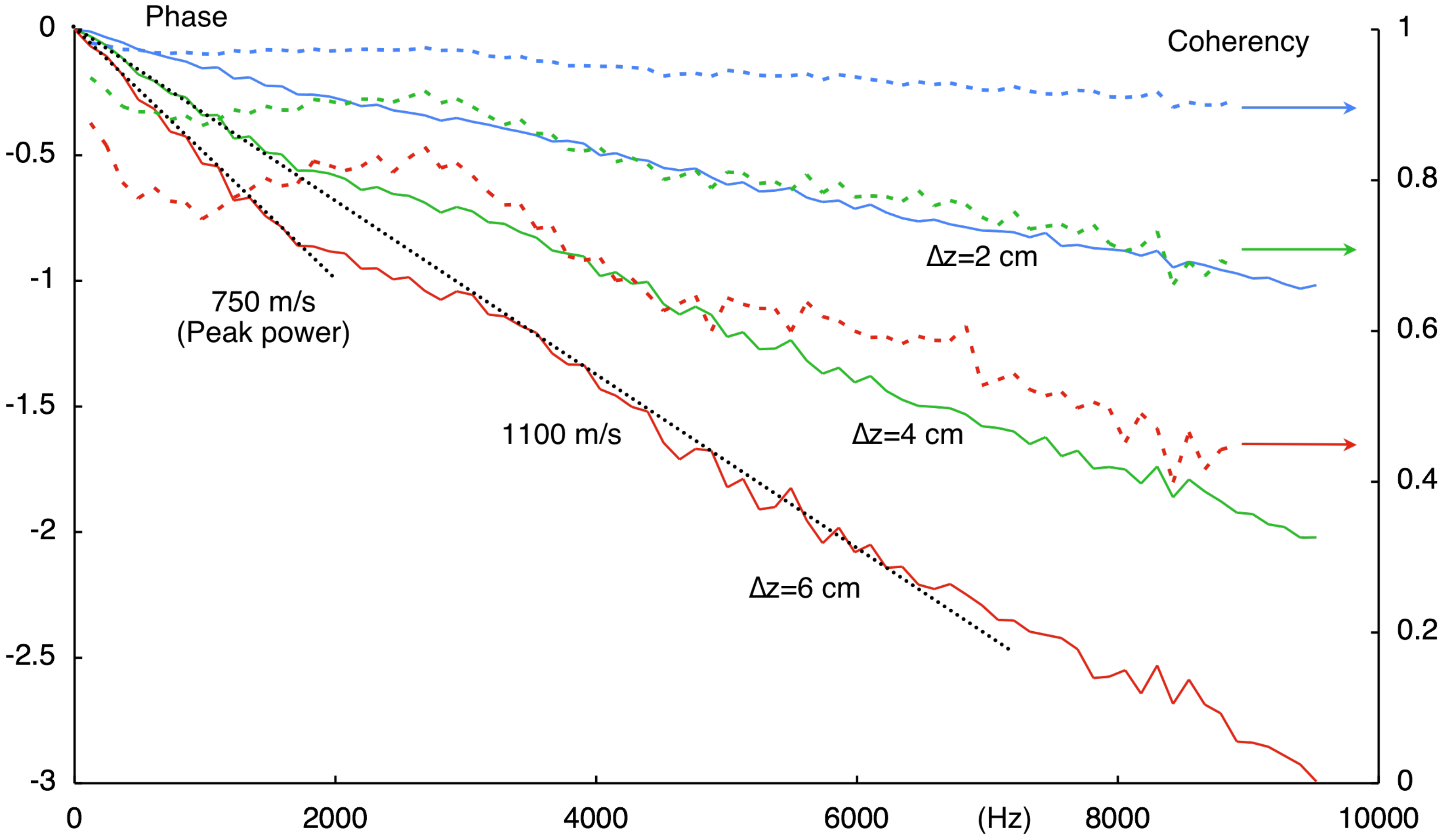


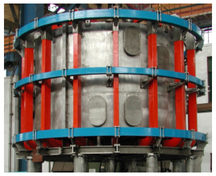




Gradient Region

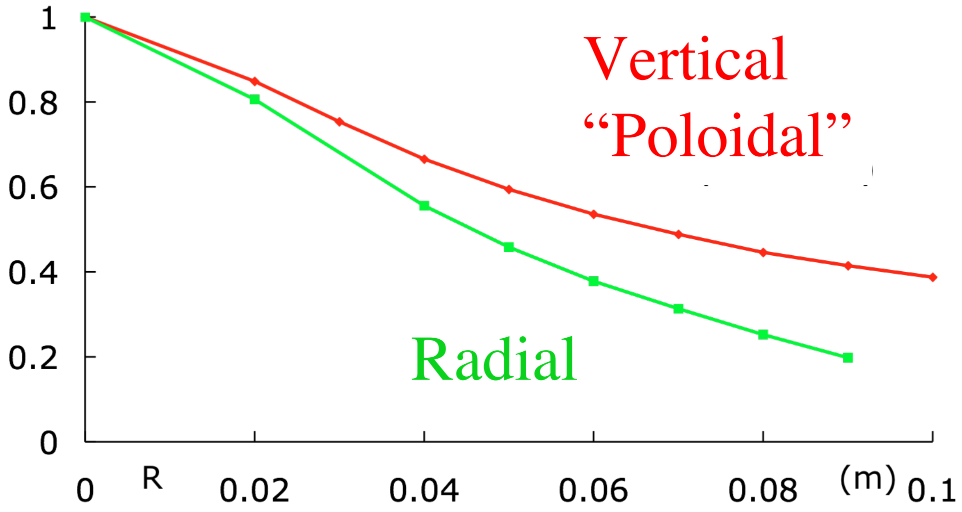
Propagation with high coherency



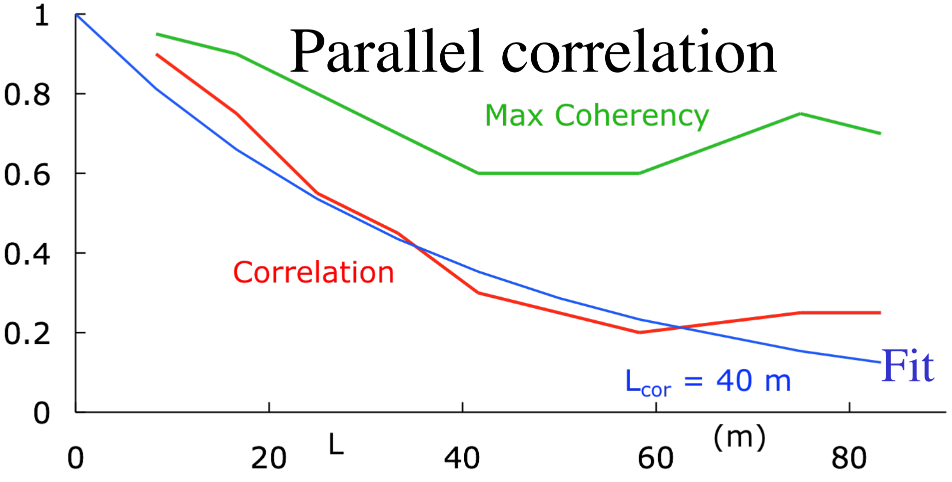


Correlation Lengths

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



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

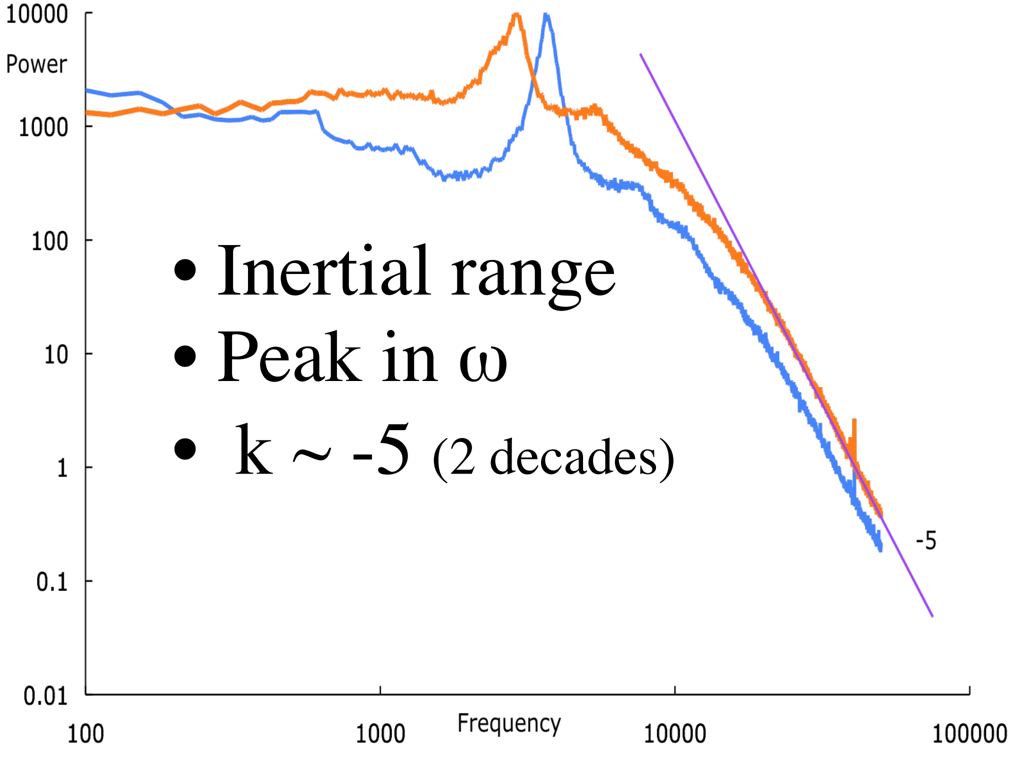


General Features of Power Spectra P(ω)

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!

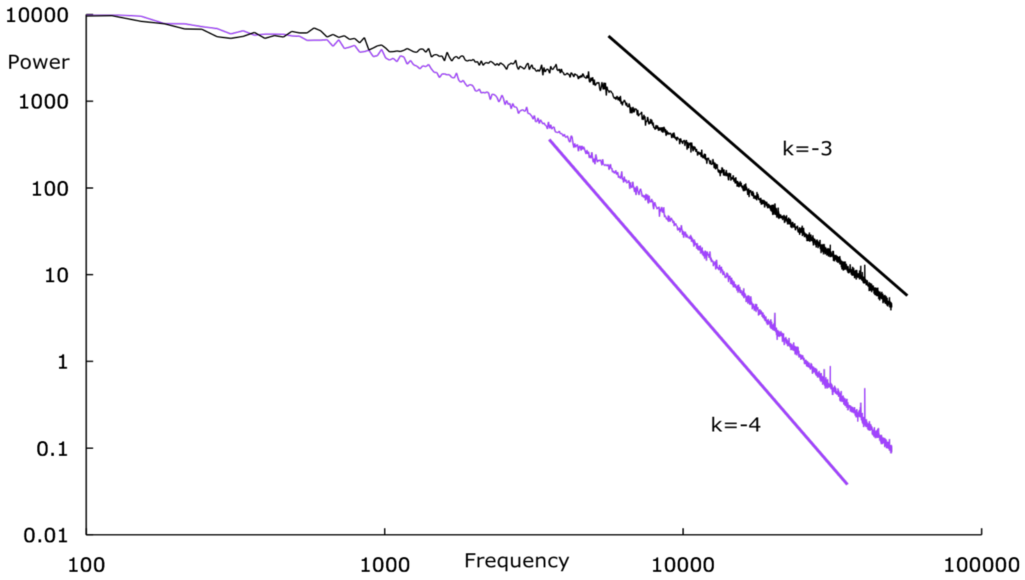
- Examine individual spectra
- Optional inertial range, P(ω)=constant at low ω
- Optional peak at finite ω
- Optional intermediate power law, $P(\omega) \propto \omega^{-s}$, $s < k$
- Great variation in power law exponents
- Never a good fit to an exponential



- Inertial range
- Peak in ω
- k ~ -5 (2 decades)

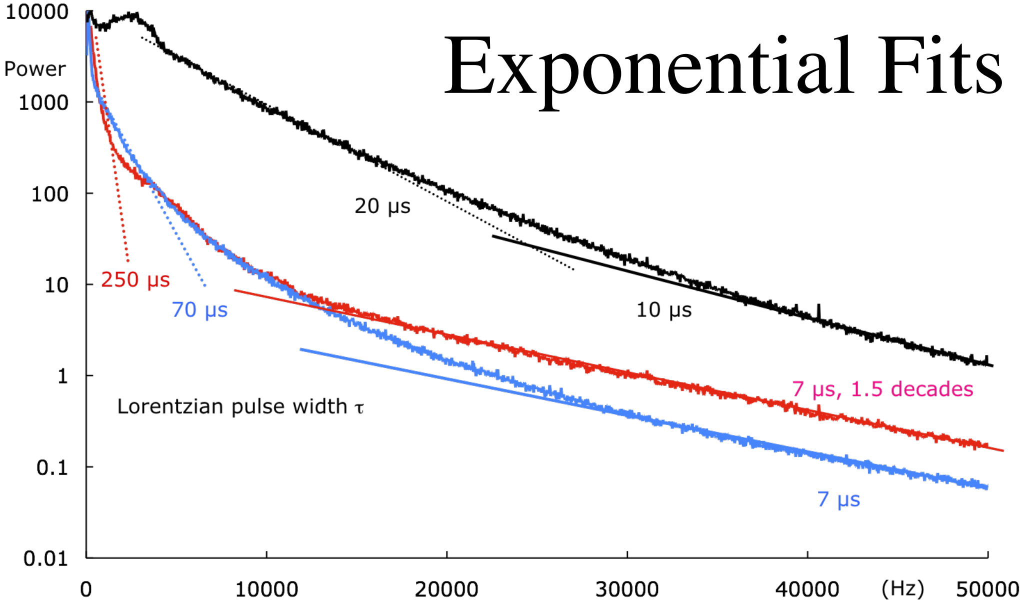
Power Spectra P(ω)

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

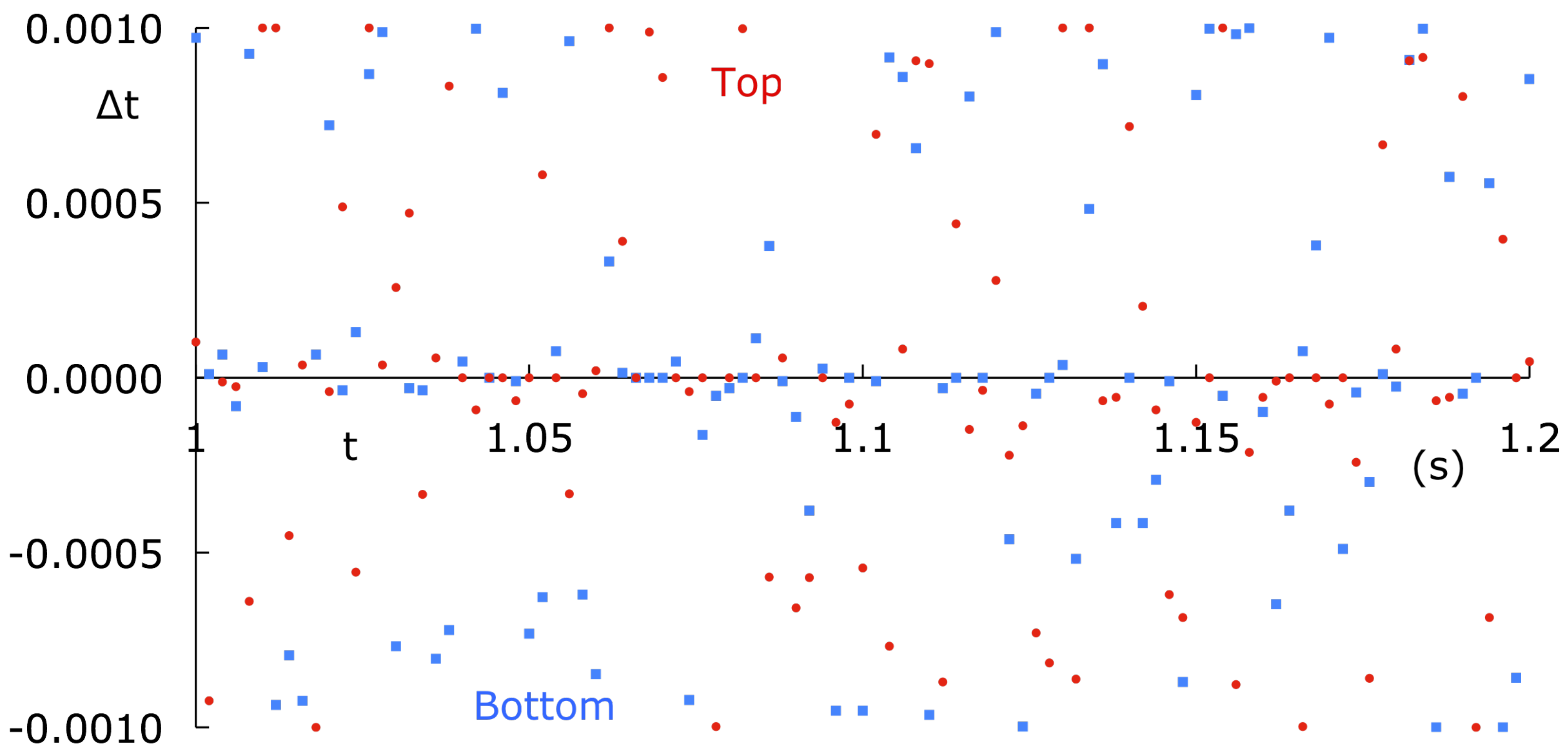


- Exponential fits limited, ~1 decade
- Wide τ range
- Lorentzian (tail)

τ << Autocorr τ

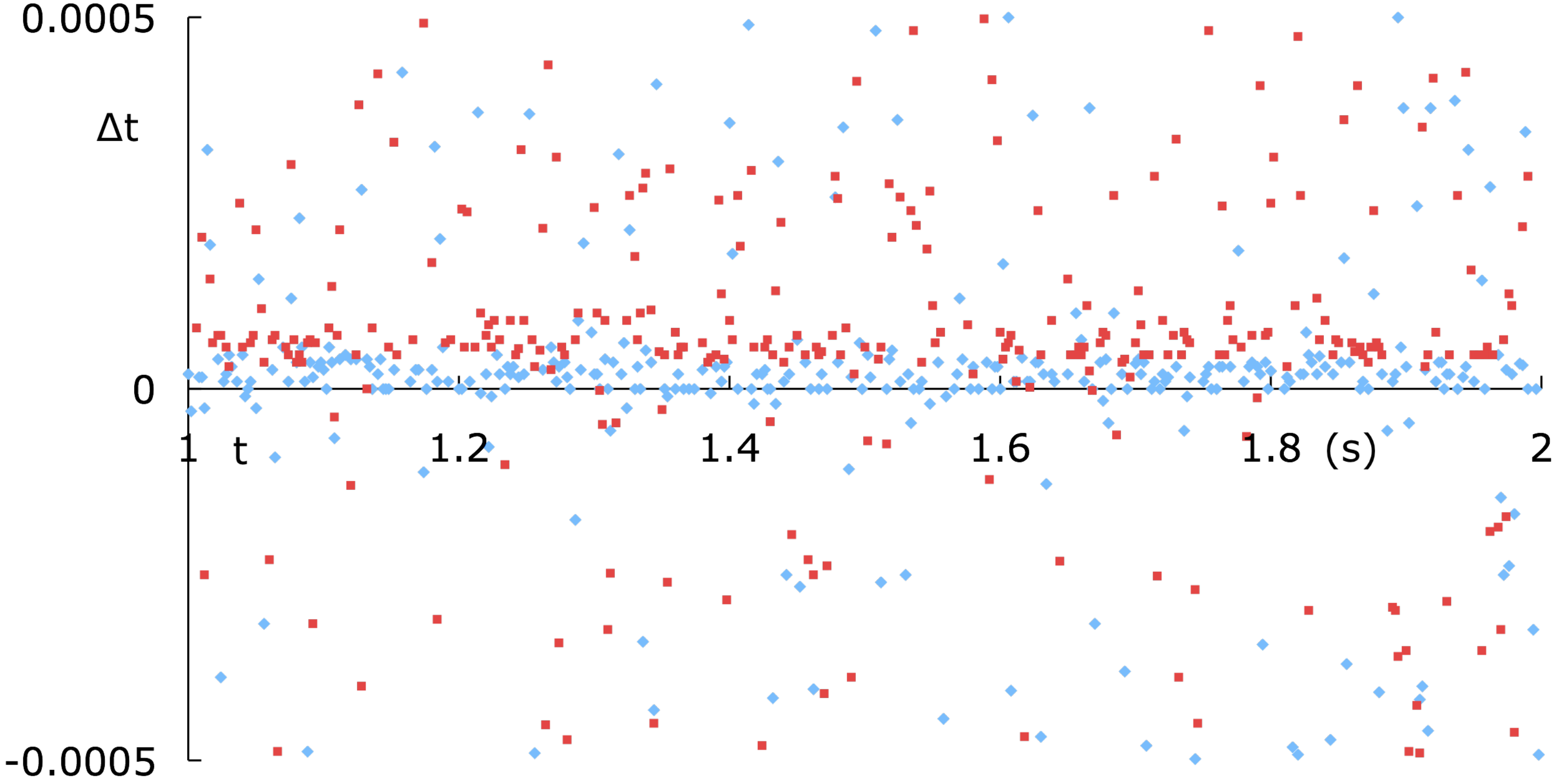


Near Density Peak (R = 0.9 m)



Some clustering at Δt=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)

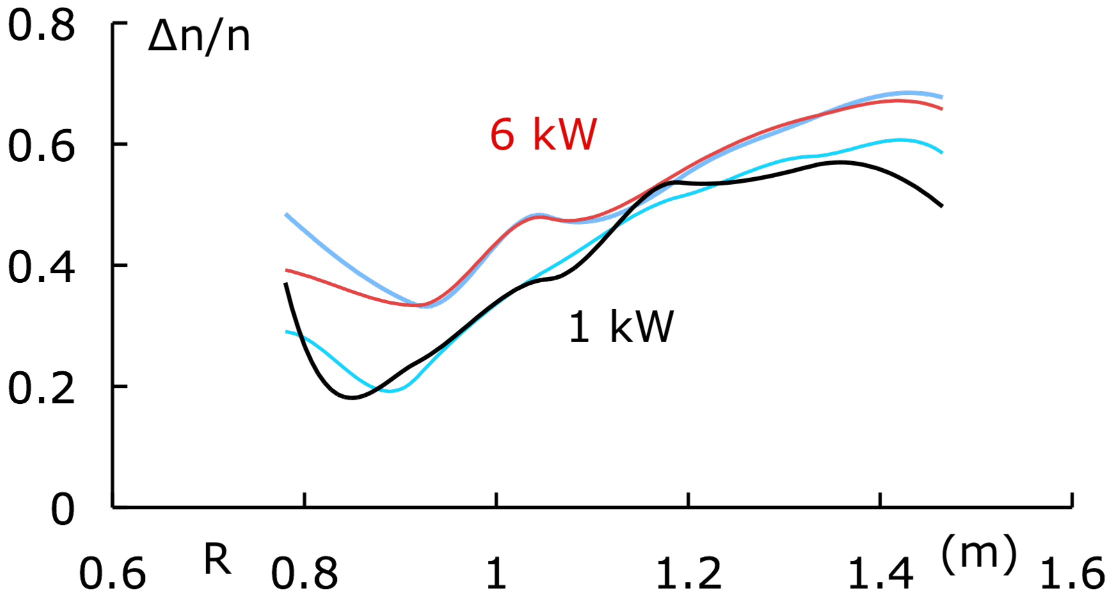


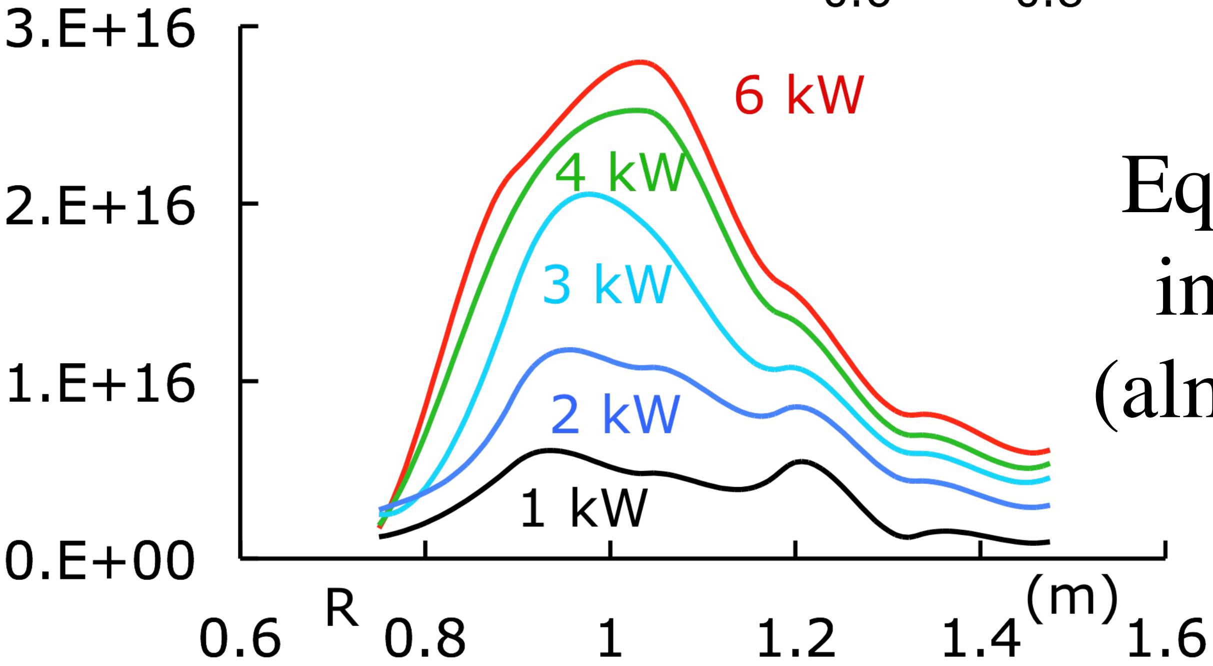
Some clustering at V_z ~ 1000 m/s, but methods and top/bottom differ somewhat, and substantial fast, random scatter.

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

Turbulence Levels

Levels increase slightly with power (density)

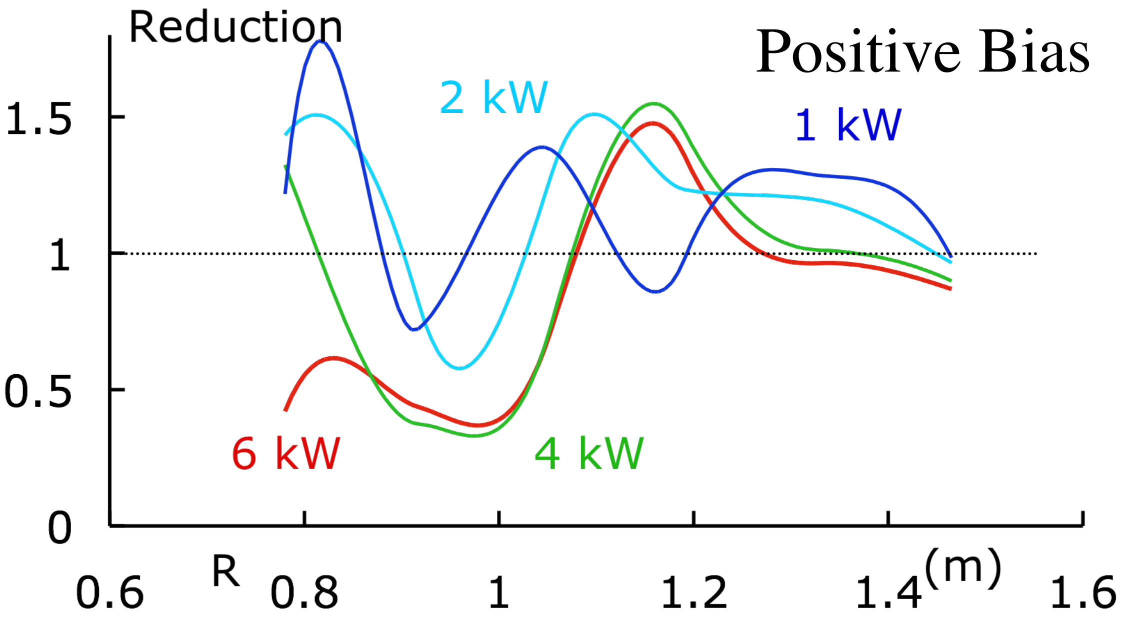


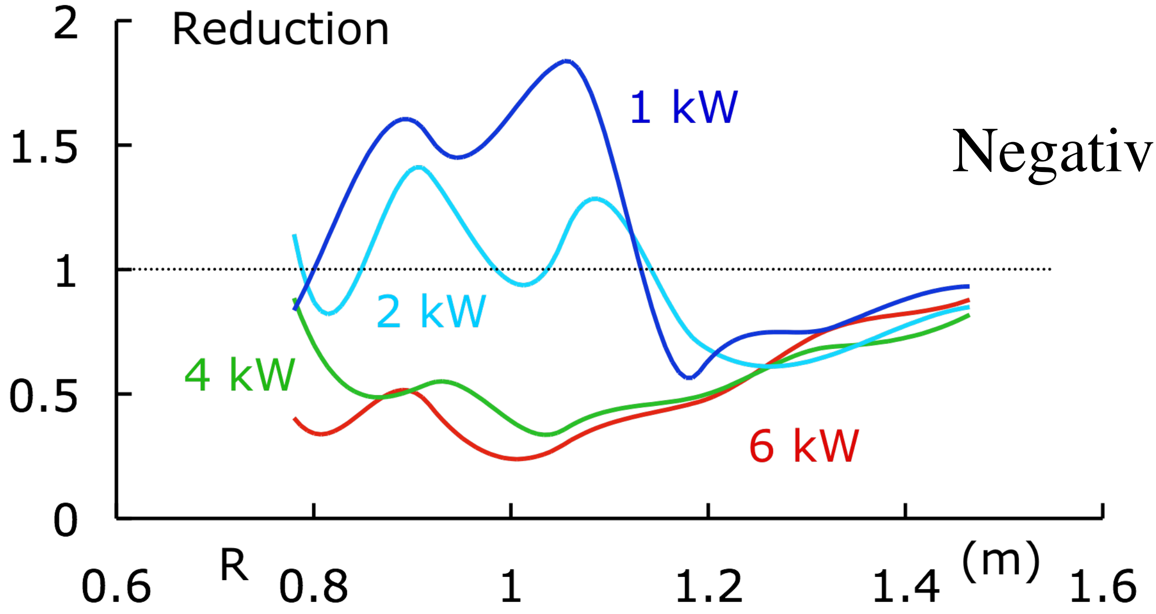


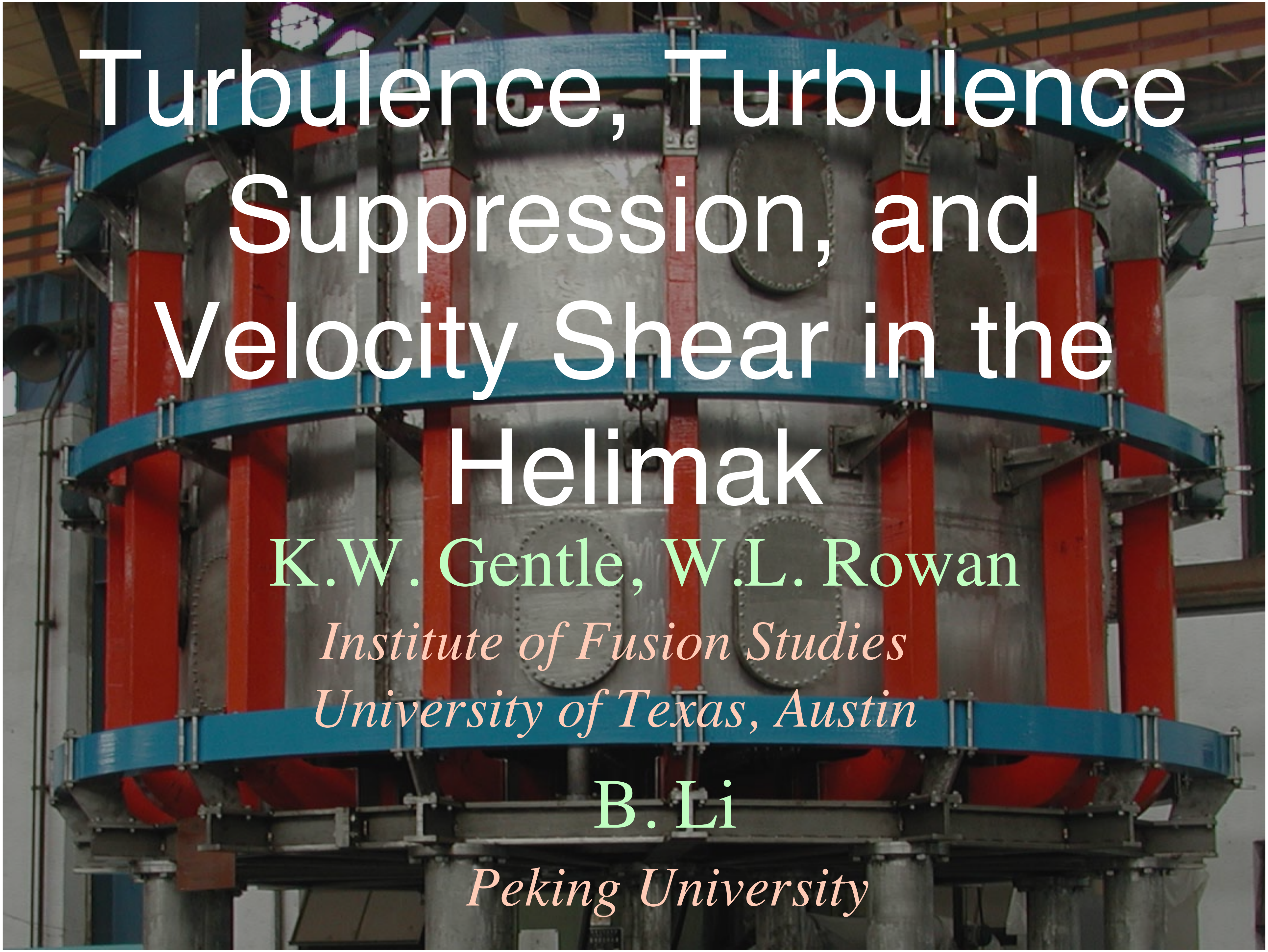
Equilibrium density increases strongly (almost linearly) with power

Turbulence Reduction: Power

Effect disappears
at low power
(density)


Positive Bias


Negative Bias



Turbulence, Turbulence Suppression, and Velocity Shear in the Helimak

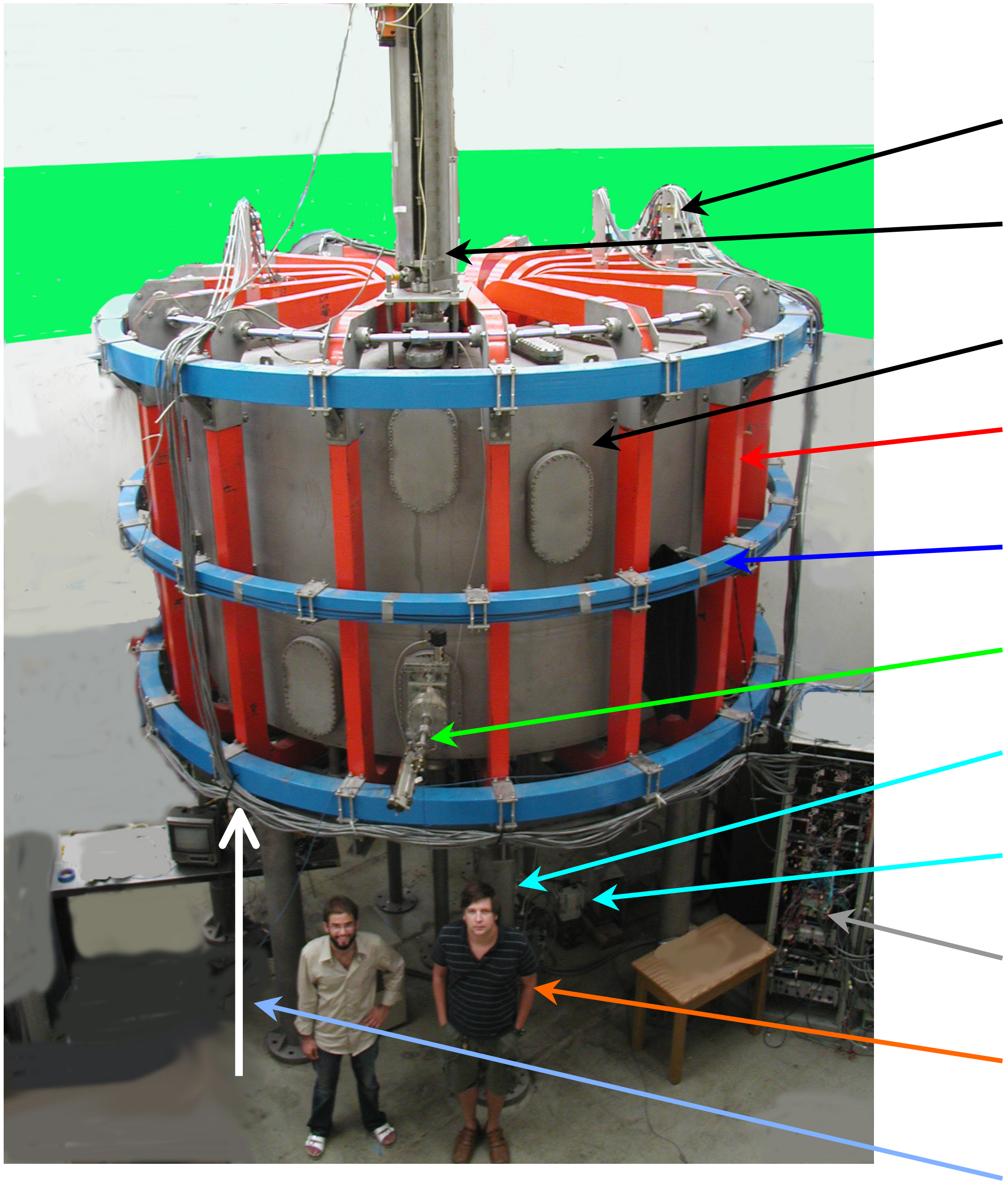
K.W. Gentle, W.L. Rowan

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

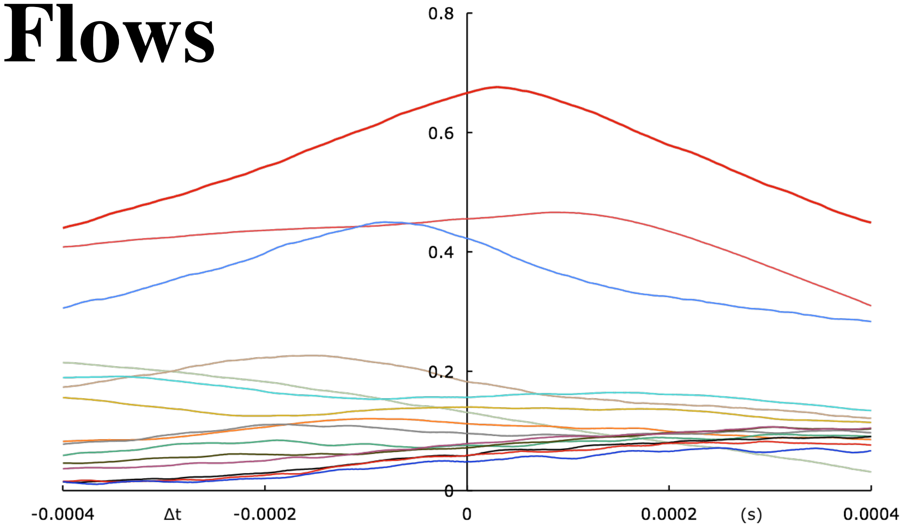
Amplifiers and A/D

Scale

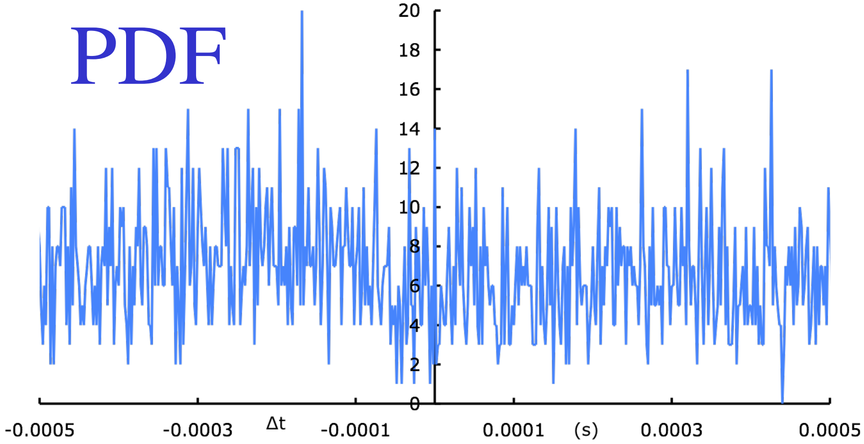
Optical Vertical View

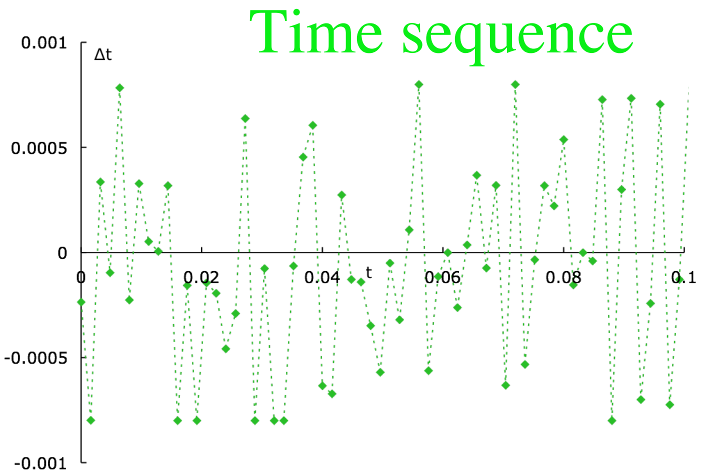
Radial Flows

Radial Cross-correlations:
No indication of mean
flows



Time delays from 1 ms sub-samples





Uniform distribution, random sequence ⇒No flows

Relation of Turbulence Reduction to Velocity Shear in Interchange Turbulence

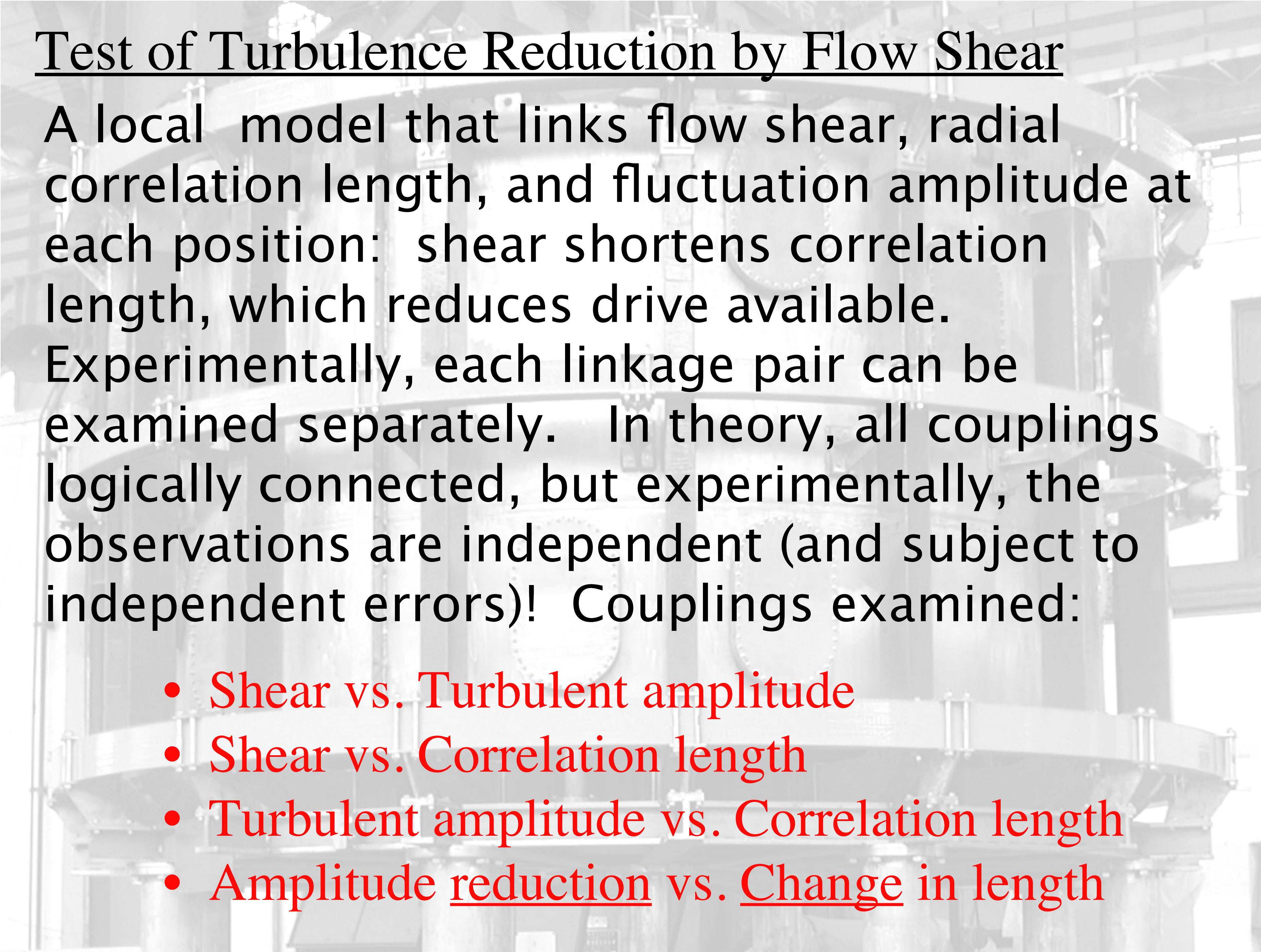
K.W. Gentle, W.L. Rowan, University of Texas at Austin
B. Li, Peking University

Shear in the flow velocity transverse to the magnetic field is a very general mechanism for stabilizing turbulence in a magnetized plasma, and most cases of turbulence suppression, from H-mode to internal transport barriers, are attributed to this mechanism. The Helimak allows a controlled study of the relation between flow shear and turbulence in a simple geometry with good diagnostics. The Helimak is an experimental approximation to the infinite cylindrical slab or Simple Magnetized Torus. The magnetic geometry is similar to the tokamak SOL at the outer midplane, turbulence levels are similar, and simulations show the instabilities are dominantly interchange-like. The device is large compared with scale and correlation lengths. Since the open field lines terminate on the ends of the finite cylinder, radially-segmented isolated end plates may be biased to allow application of radial electric fields. A plasma flow is thereby driven in the axial ("poloidal") direction. Above a threshold in applied voltage, the fractional turbulent amplitude is greatly reduced. The experiment is uniquely simple because the equilibrium is largely determined by end loss -- suppressing the turbulence does not lead to inexorable strong changes in the equilibrium. Turbulence reductions occur for both positive and negative bias and without hysteresis in the control voltage. Concurrent measurements of the ion flow velocity are made by Doppler spectroscopy. The argon plasma produced by ECH has cold ions that give no diamagnetic contribution to the measured ion velocity.

The observations are compared with the results of a two-fluid, 3-D nonlinear simulation of the SMT that shows the basic features of the normal turbulence – a high level of interchange-like modes -- as well as turbulence suppression at sufficient bias. Although large changes in turbulence, turbulent structures, flows, and flow shear are seen in both experiment and simulation, the suppression is not associated with a simple increase in local flow shear as one might expect. Zonal flows are never observed experimentally. Although there is no general correlation between turbulence level and radial correlation length, the local change in turbulence level with bias is roughly correlated with the local change in correlation length.

Work supported by the Department of Energy OFES DE-FG02-04ER54766.

Poster I, Board 32 Wed 3:30-5:30 (40 slides)



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