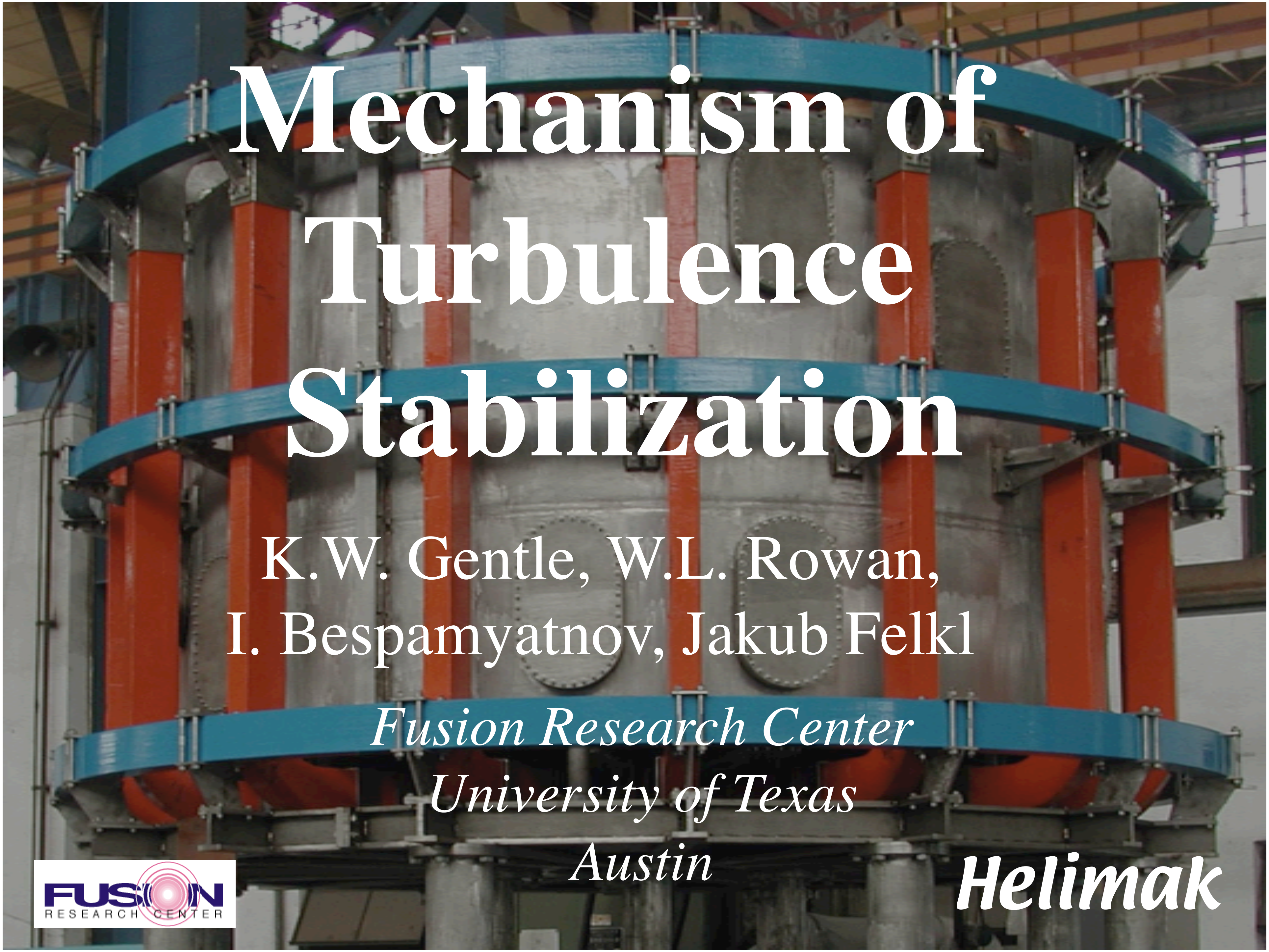

Mechanism of Turbulence Stabilization

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I. Bespamyatnov, Jakub Felkl

Fusion Research Center
University of Texas
Austin

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Helimak

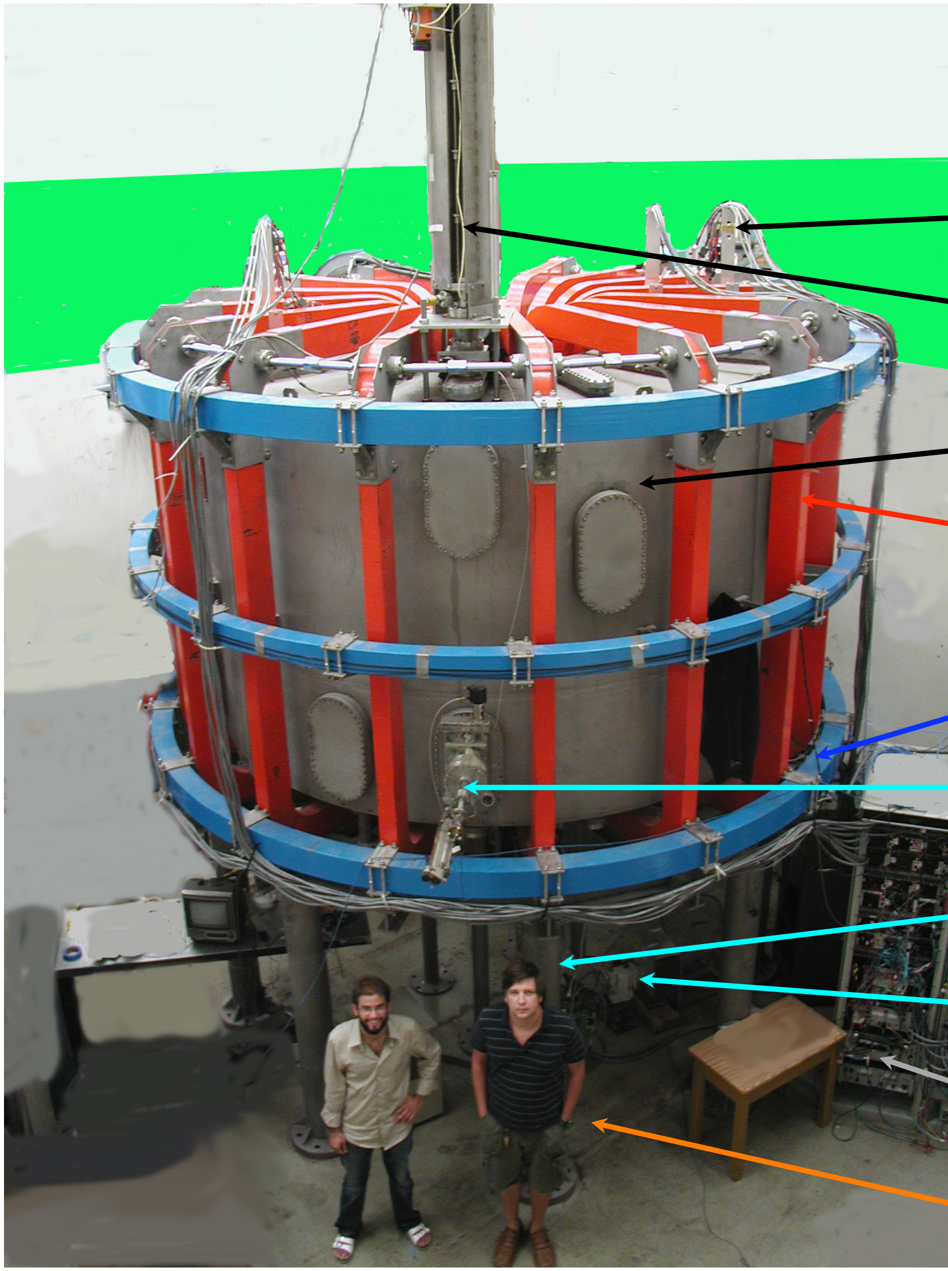
Outline

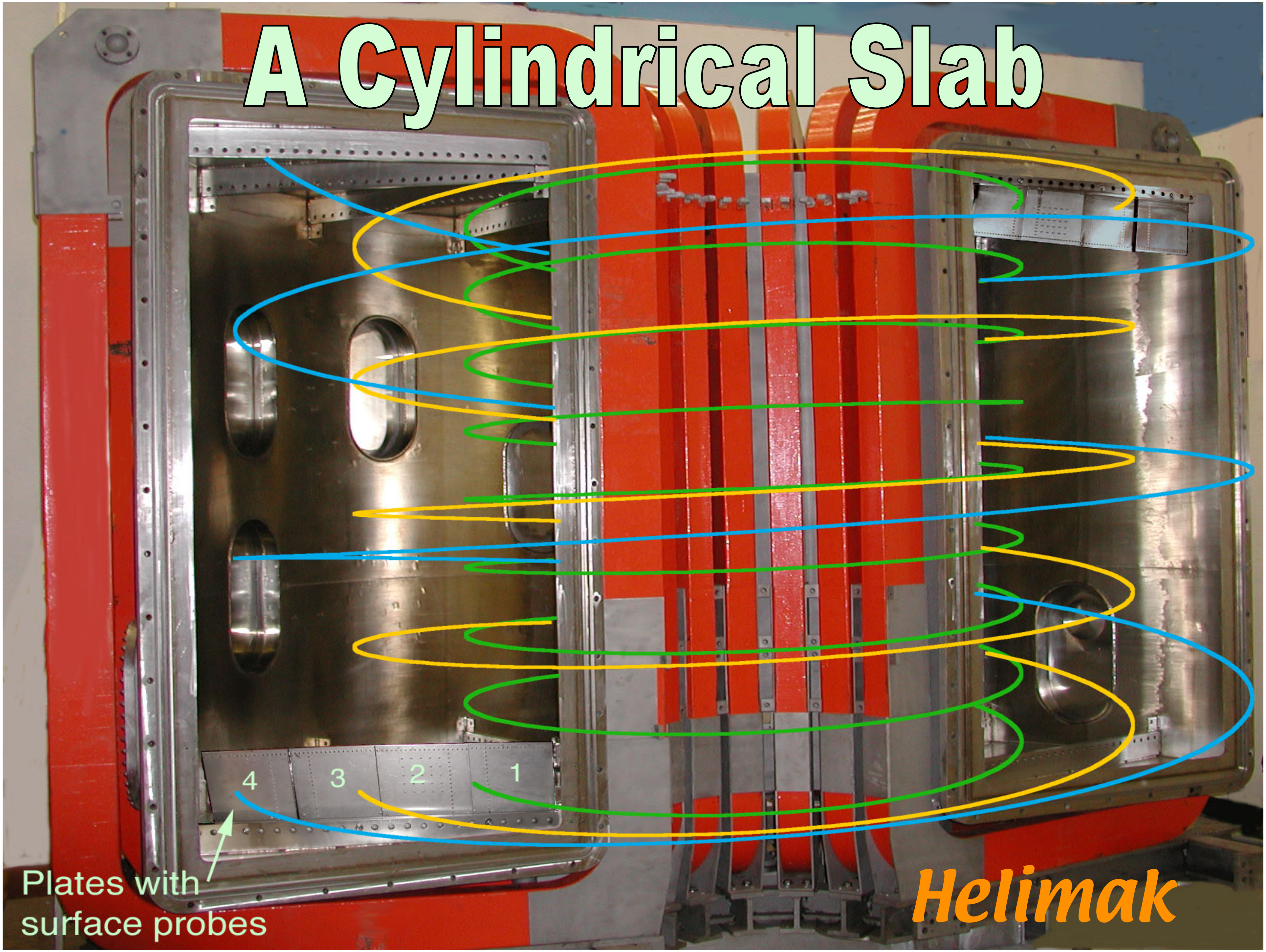
- The Helimak is a good model of drift-wave turbulence with magnetic curvature and shear and dimensionless parameters similar to the outer region of a tokamak
- The turbulence and radial particle transport can be reduced in a bifurcation caused by application of radial bias
- The bias changes flow velocities, but turbulence reduction does not imply increased velocity shear

Abstract

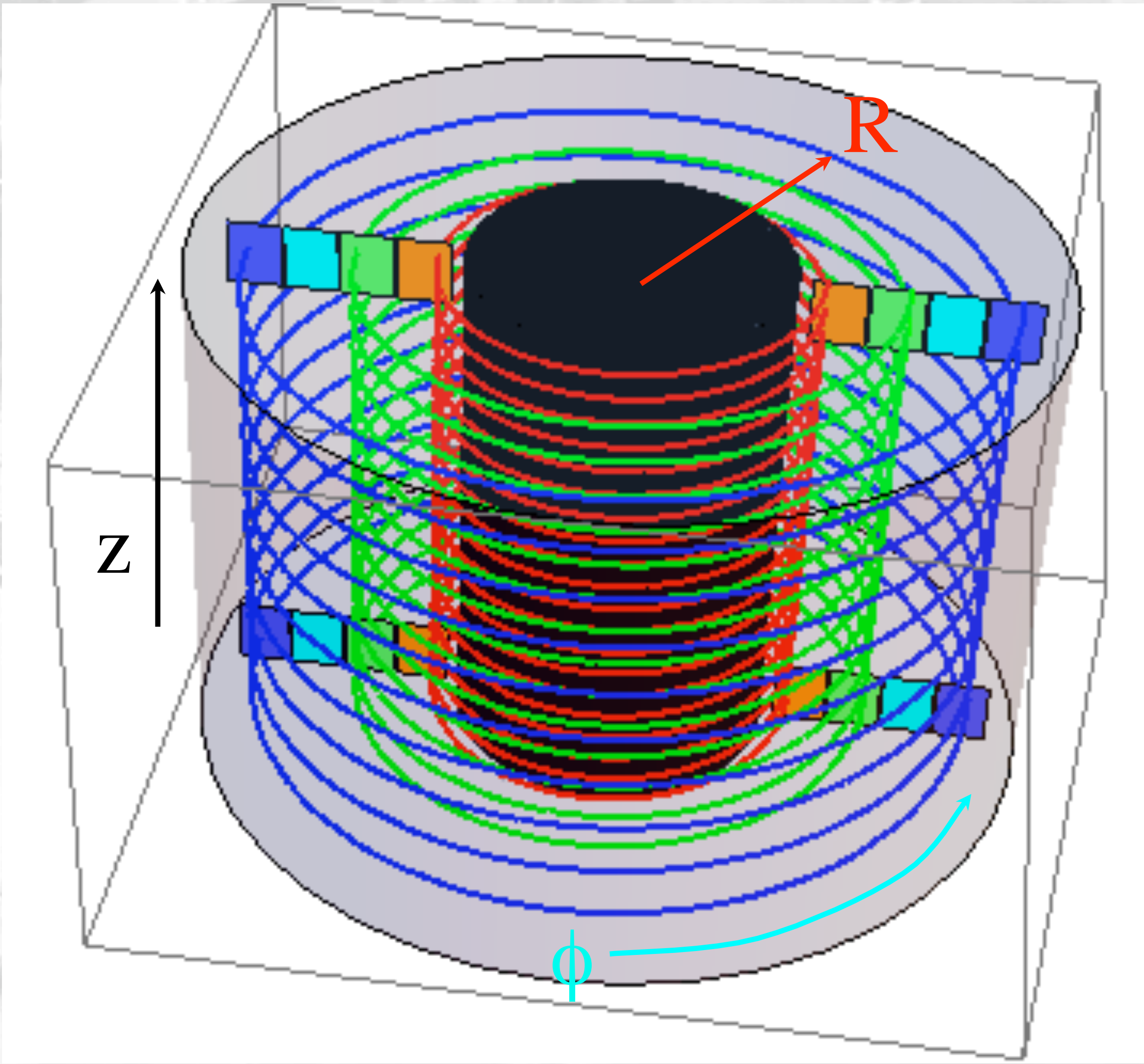
The Helimak is an approximation to the infinite cylindrical slab. Radially segmented isolated end plates allow application of radial electric fields that drive radial currents. Above a sharp threshold in applied voltage (driven current), the fractional turbulent amplitude is greatly reduced, as is the radial turbulent particle transport. The mechanism is rather complex, with density fluctuations, potential fluctuations, and particle flux changing independently in different locations. Contrary to expectation, the radial correlation length is not always reduced by turbulence suppression. Spectroscopic measurements of ion flow velocity profiles do not show increased velocity shear strongly associated with suppression.

Helimak


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


A Cylindrical Slab
4
3
2
1
Plates with
surface probes
Helimak

Helimak Geometry



R = Major radius (Tokamak minor radius)

z = Vertical (Tokamak poloidal direction)

ϕ = angle (Tokamak toroidal angle)

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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 ≤ 60 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

$c_s = 3 \times 10^4$ m/s (Argon) $V_{drift} = 100$ m/s

$V_{diamagnetic} = 10^3$ 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

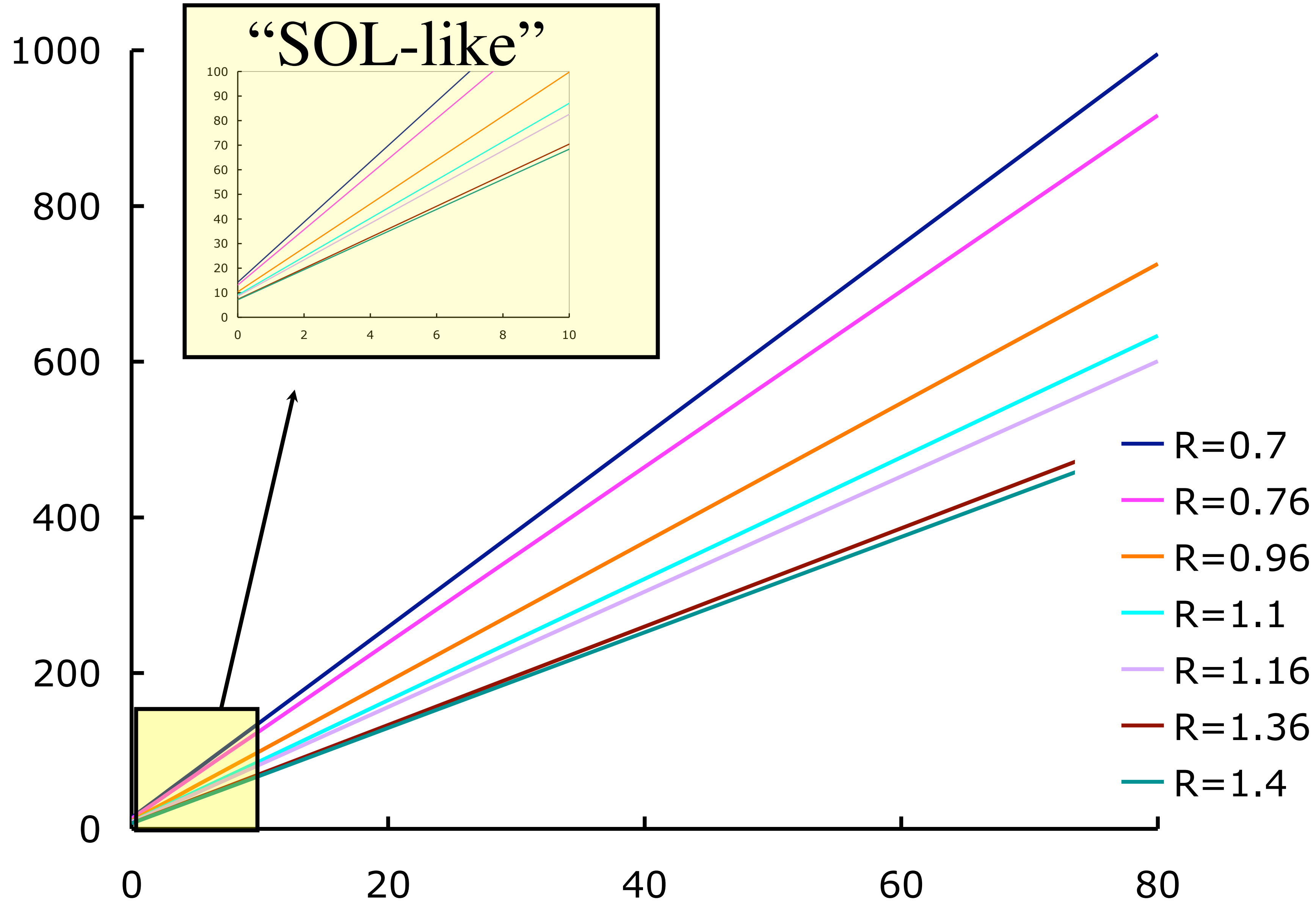
Isolated end plates apply radial electric fields: $V_p \leq \pm 100$ Volts

Helimak

Dimensionless Comparisons

	Helimak	SOL
Transverse size ρ_s/L_n	0.2	0.05
Drift drive v_D/c_s	0.2	0.06
β	$6\text{x}10^{-5}$	$3\text{x}10^{-4}$
Collisionality L_c/λ_{ee}	0.1	0.02
Turbulence level $\Delta n/n$	0.4	0.3
Parallel size L_c (m)	50	40

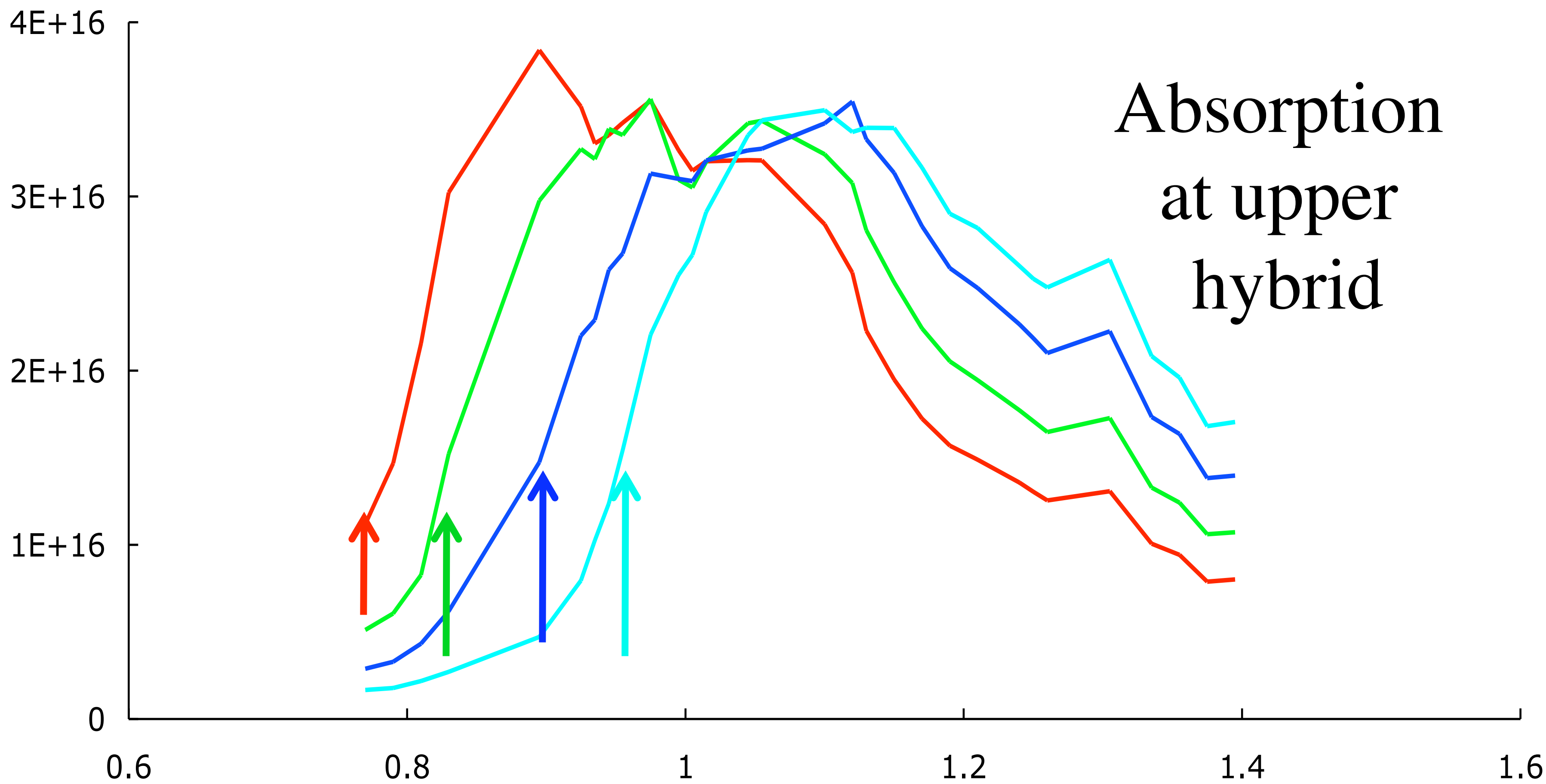
Parallel Connection Length $L_{||}$



Helimak Plasma

Helimak

Density Profiles for various ECH Resonant Radii



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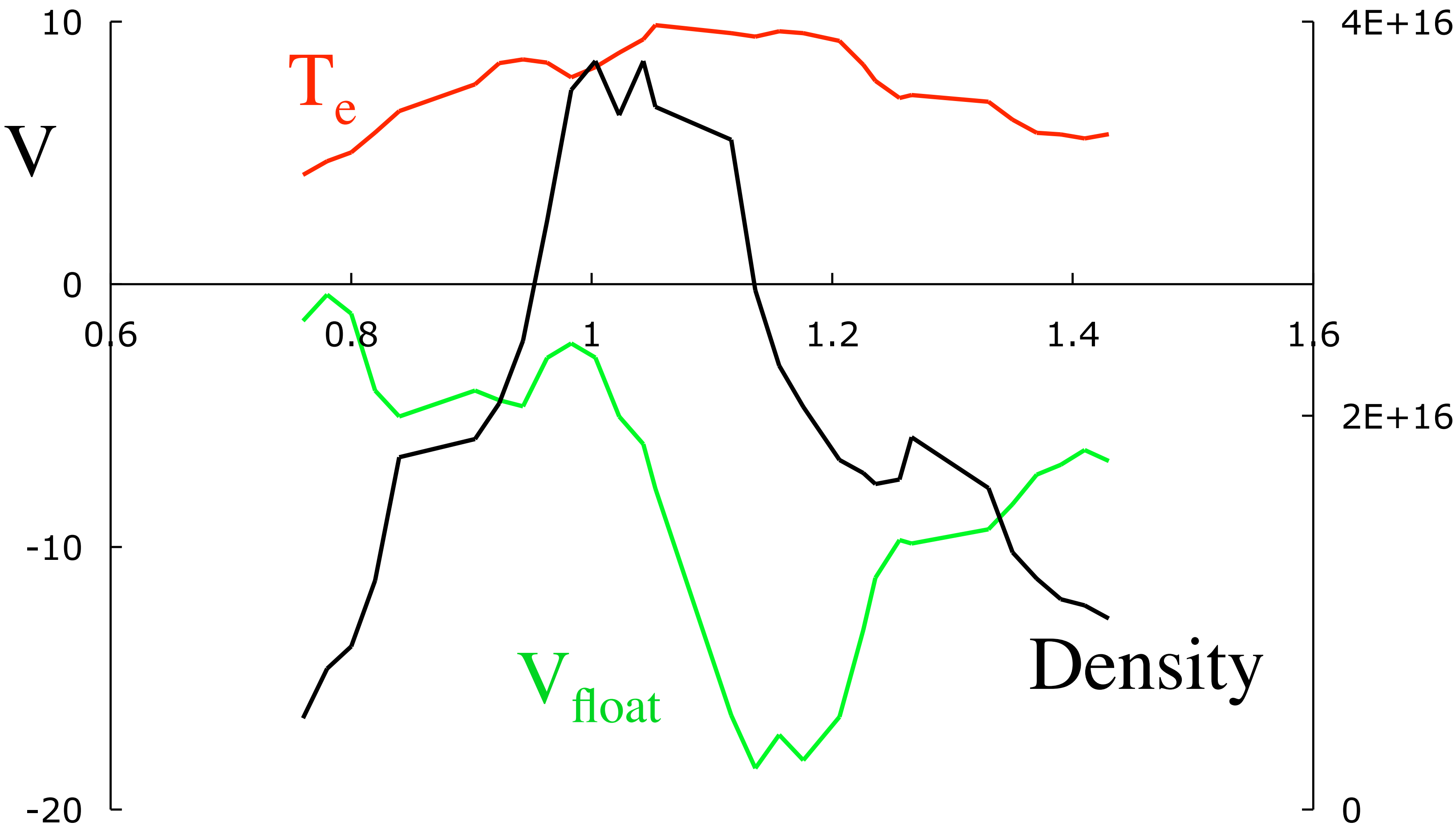
Typical Density, Temperature, and Floating Potential Profiles



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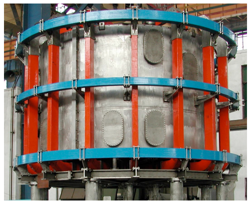

Turbulence in the Helimak

Density fluctuations $\Delta n/n \sim 0.3$,

WITH

A complex phenomenology that depends on the density gradient and connection length

At short connection lengths, $L_{||} < 40$ m, coherent low-frequency modes of order 200 Hz appear around the density peak. On the low field side (unfavorable curvature) in the density gradient region, the turbulence is broad-band over several kHz and propagates vertically with drift-wave characteristics.

At longer connection lengths, $L_{||} > 40$ m, the spectra lose structure and approach 1/f behavior. The fluctuations in the gradient region progressively lose their drift-wave character.

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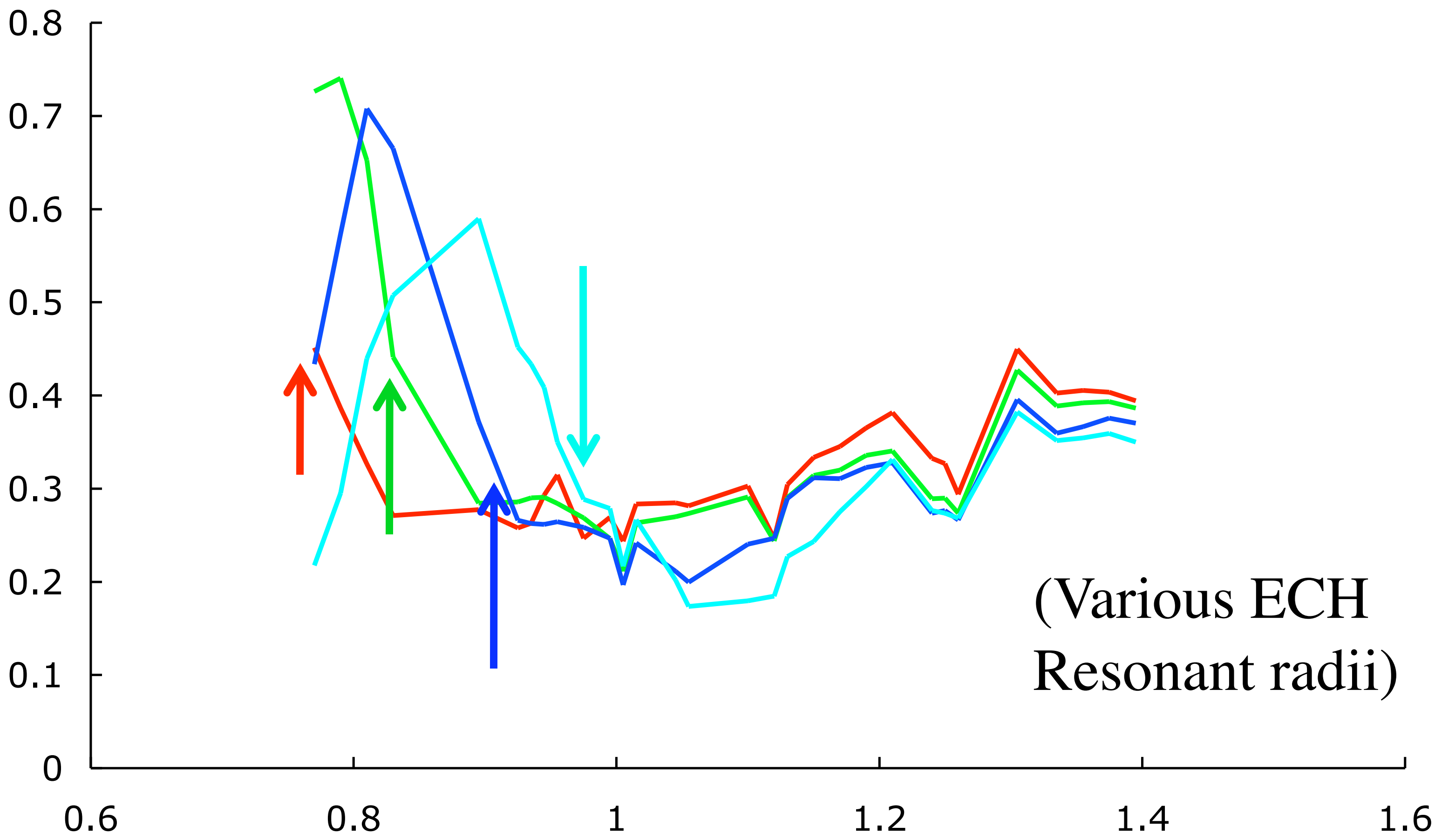
Radial Profiles of Fluctuation Amplitude



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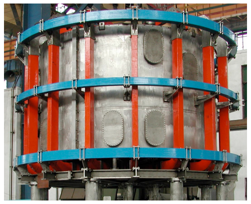
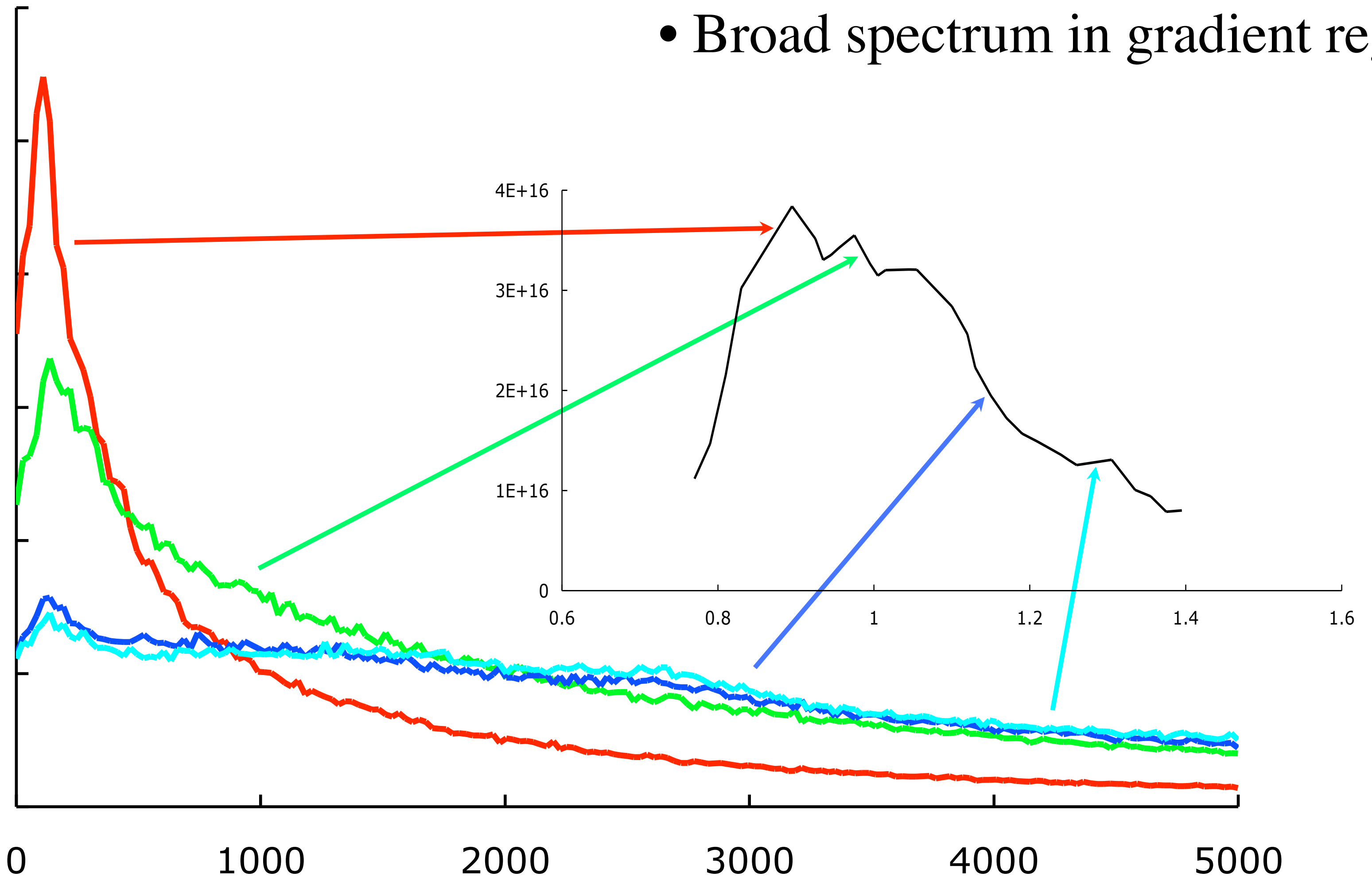


Frequency Spectra

- Coherent mode near density peak
- Broad spectrum in gradient region

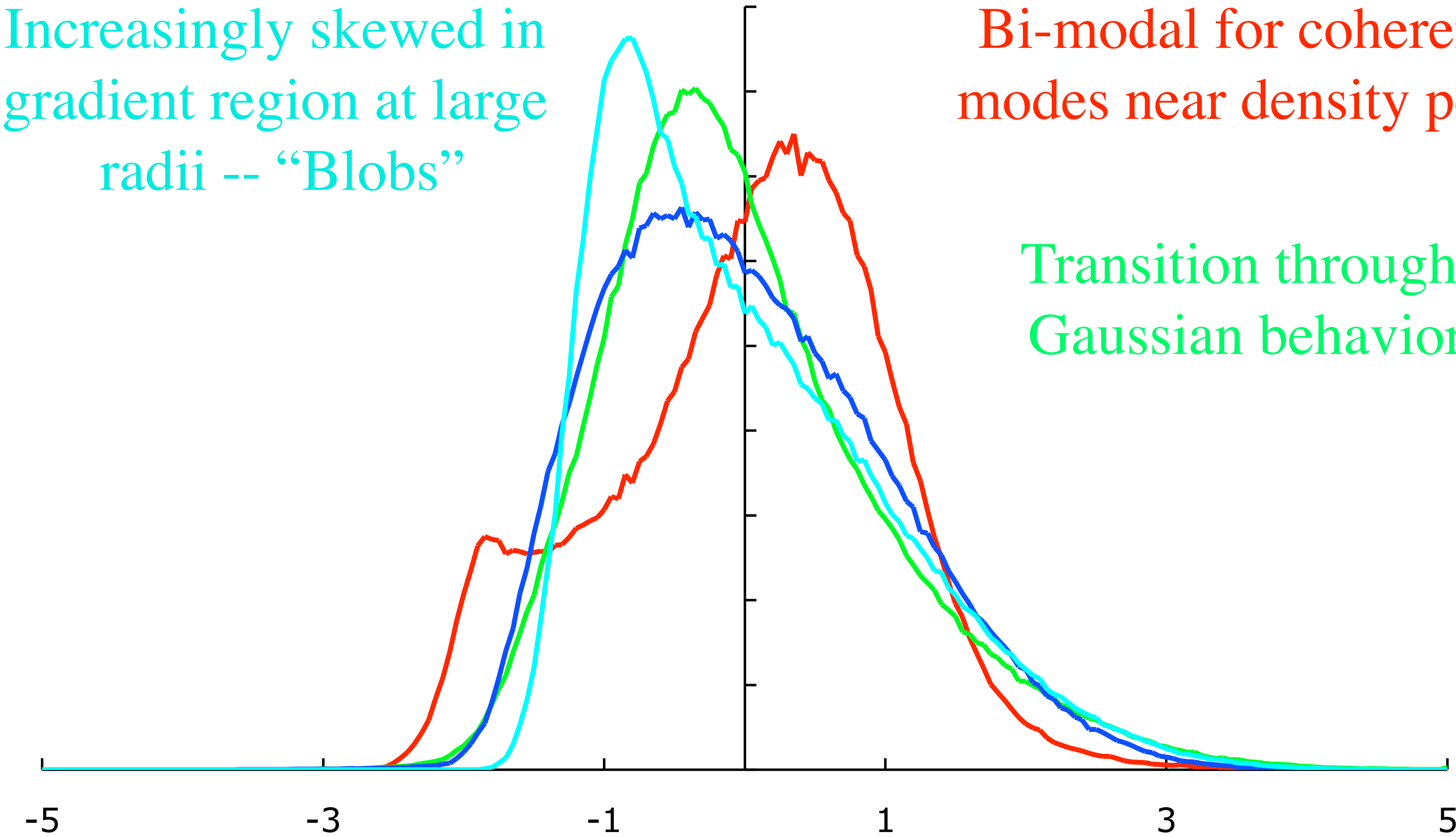


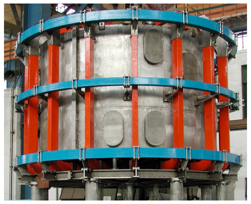
Density PDF

Increasingly skewed in gradient region at large radii -- “Blobs”

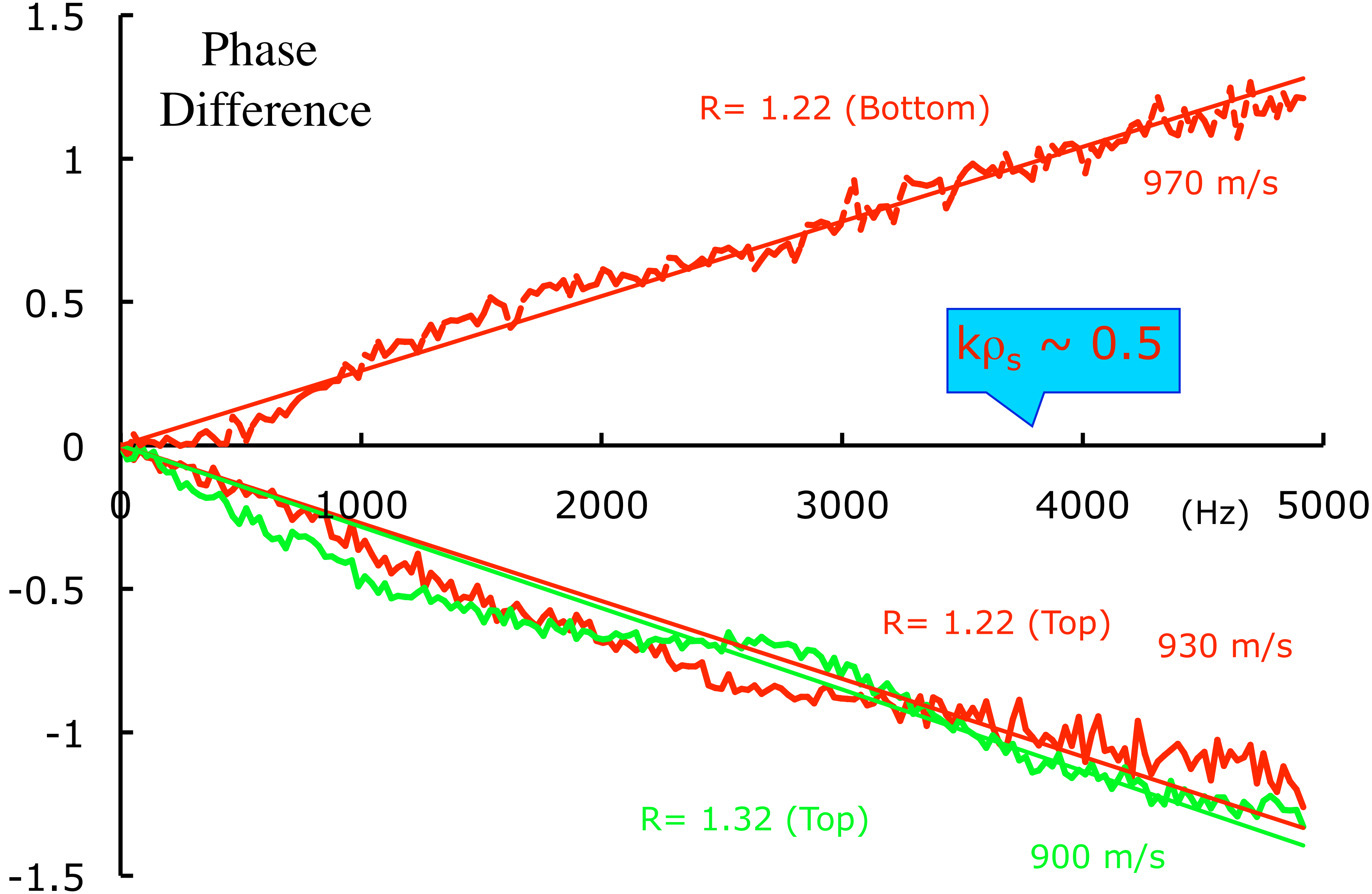
Bi-modal for coherent modes near density peak

Transition through Gaussian behavior





‘Drift-Wave-like’ vertical propagation*



* Propagation upward for all cases

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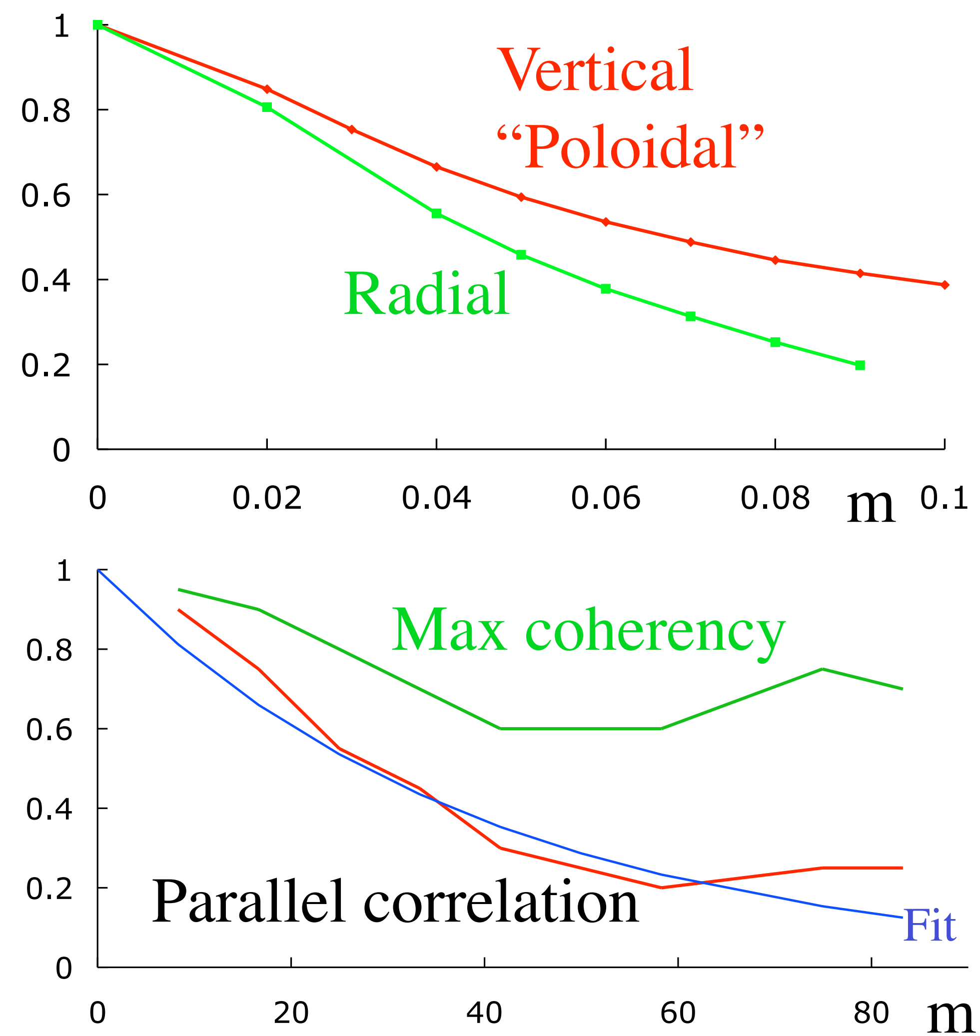
Correlation Lengths

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

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



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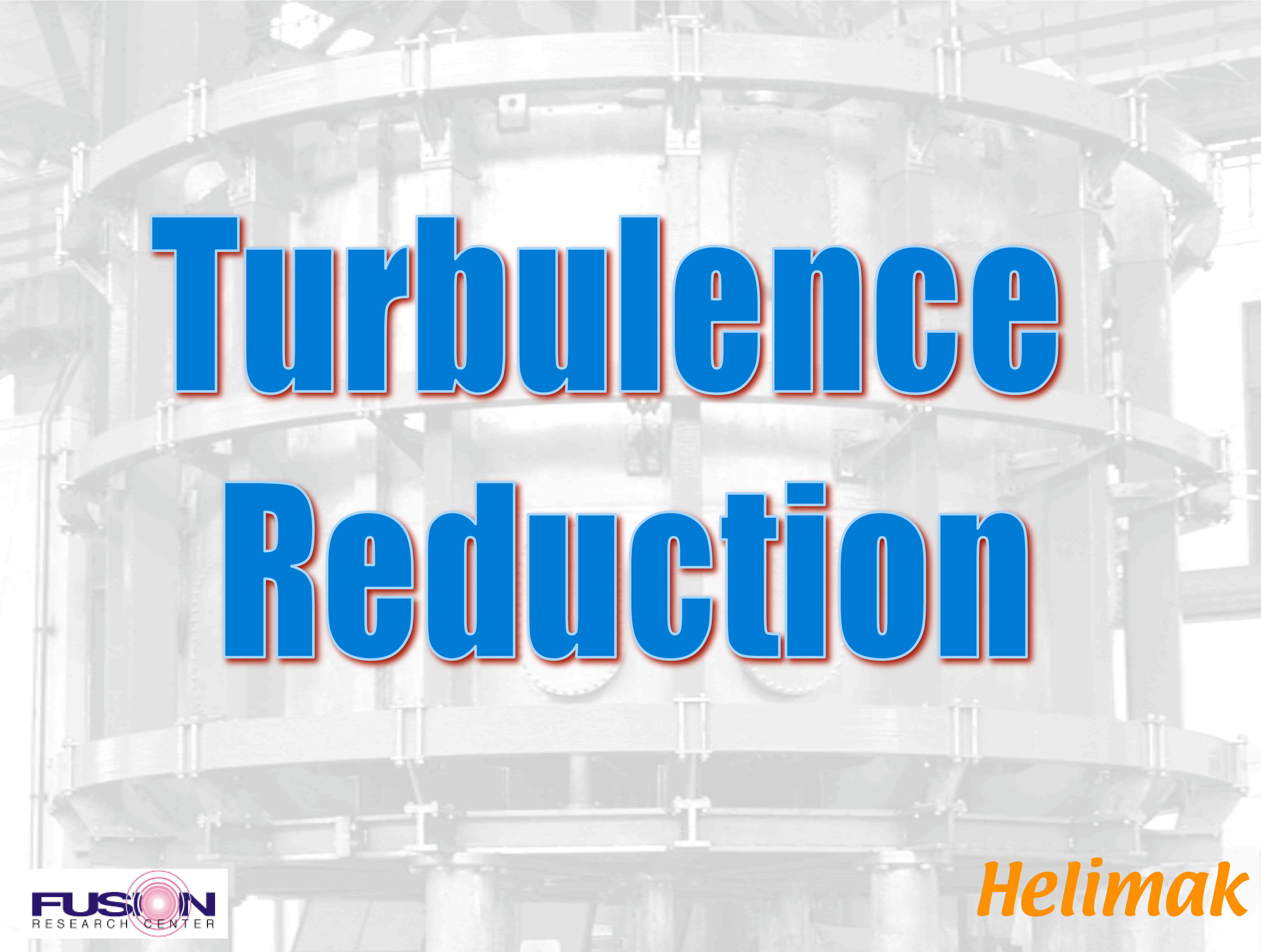

Turbulence Reduction

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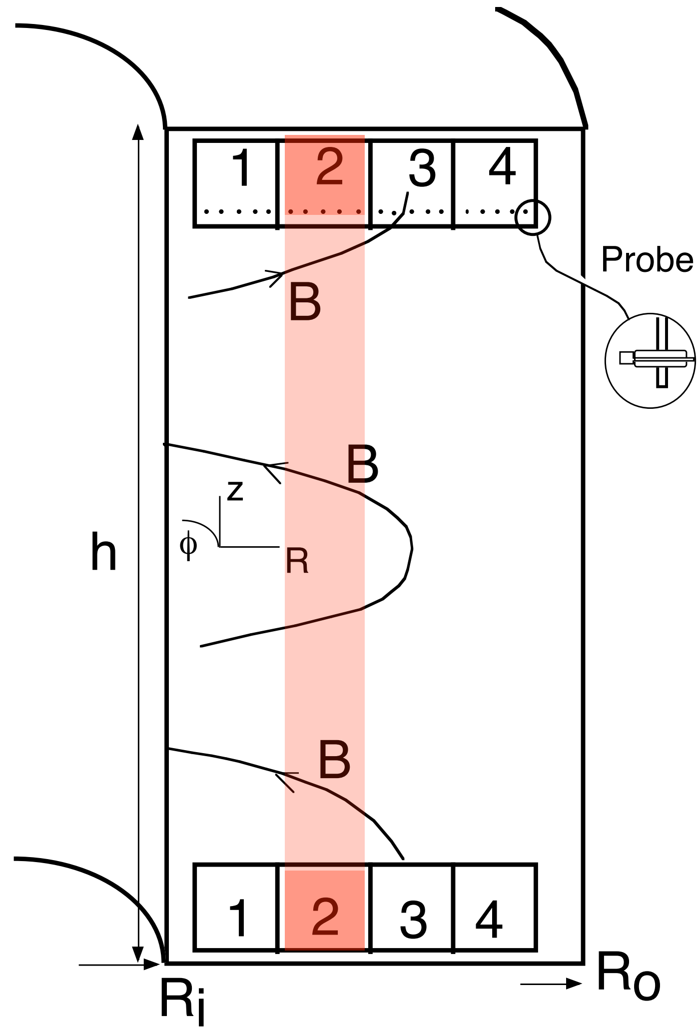
Cross-section

➢ Field lines terminate on isolated end plates

➢ Biasing one set (set 2 for data shown) with respect to others imposes radial electric field, current

➢ Other plates and vessel grounded



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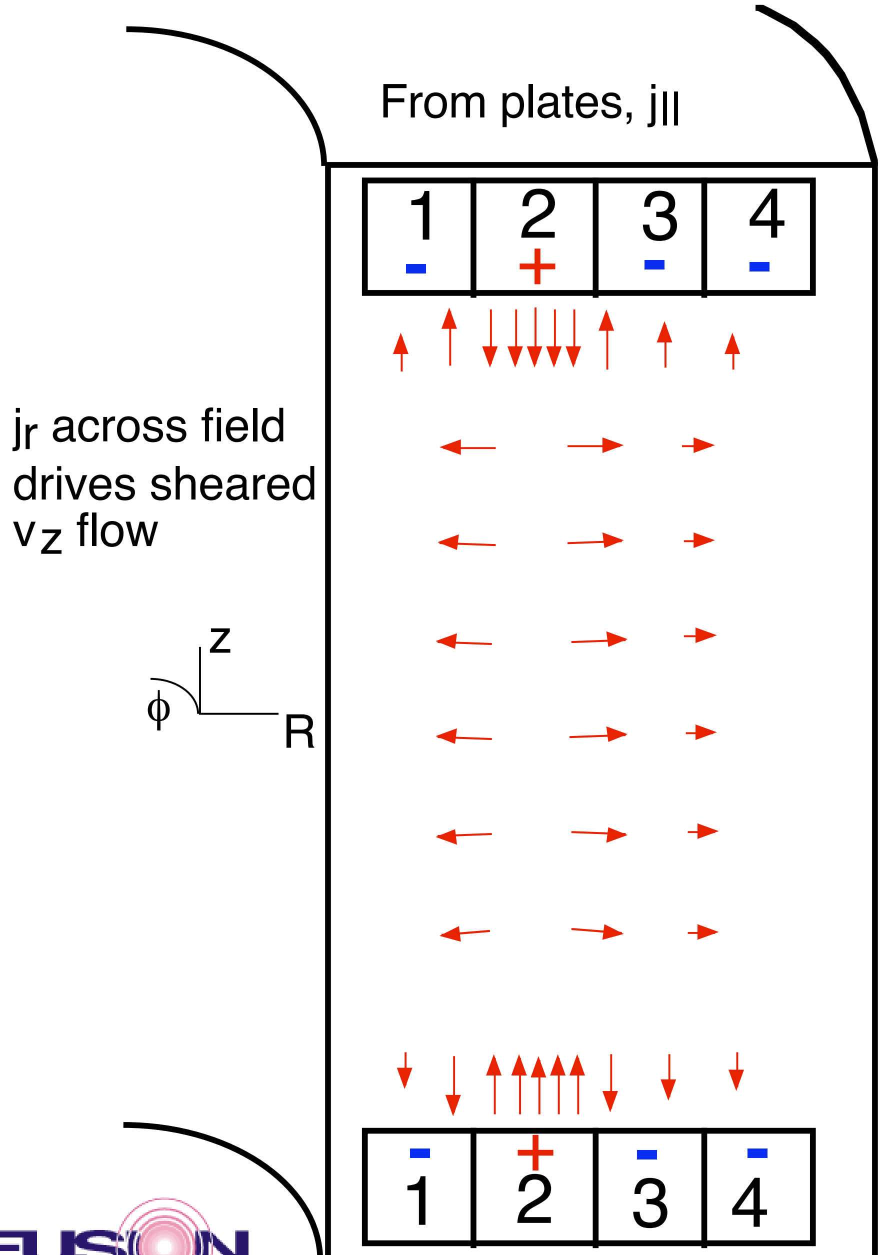
Flow of Bias Current



Biasing drives current from + plates into plasma along field lines and out across the field lines. Some returns back out along field lines to the - plates; most flows to vessel walls.

For typical threshold currents, $\langle j_r \rangle \sim 0.1\ A/m^2$

$j \times B = dp/dt \sim p/\tau_p$

$p = mnV_z$

For $\tau_p \sim 1$ ms, $V_{zmax} \sim 2$ km/s

Shear, $\partial v_z/\partial r \sim 10^4\ s^{-1}$

Bias-Driven Turbulence Reduction

➢ Applying bias above a threshold drives a bifurcation to a state of reduced $\Delta n/n$

➢ The reduction occurs across much of the profile

➢ The transition occurs without hysteresis in hundreds of milliseconds

➢ Transitions occur for both positive and negative bias in helium and argon over a broad range

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.)

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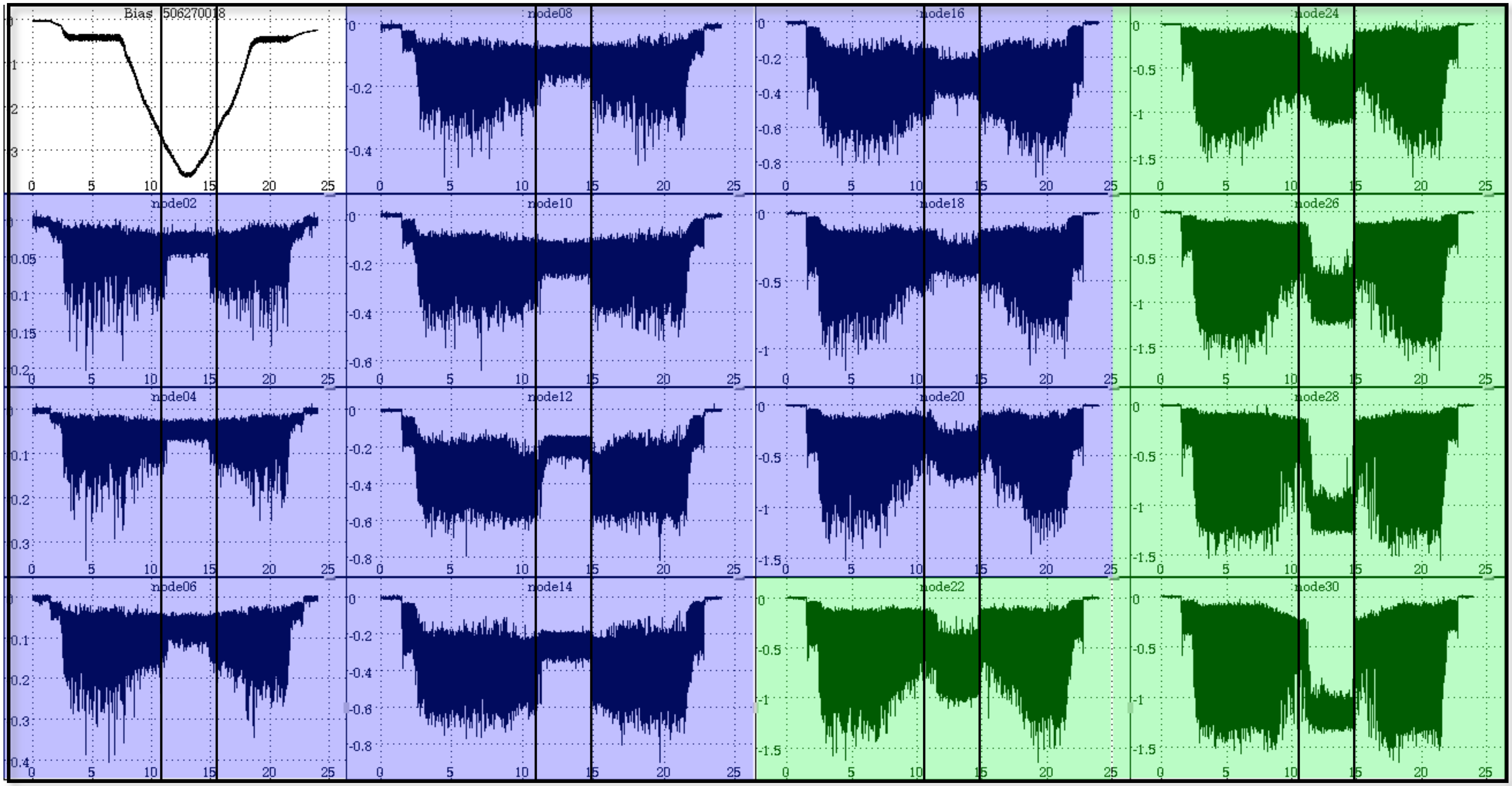
Response to Negative Bias

Probe n(t) across radial profile

Bias Reduced Δn Reduced Δn; increased <n>



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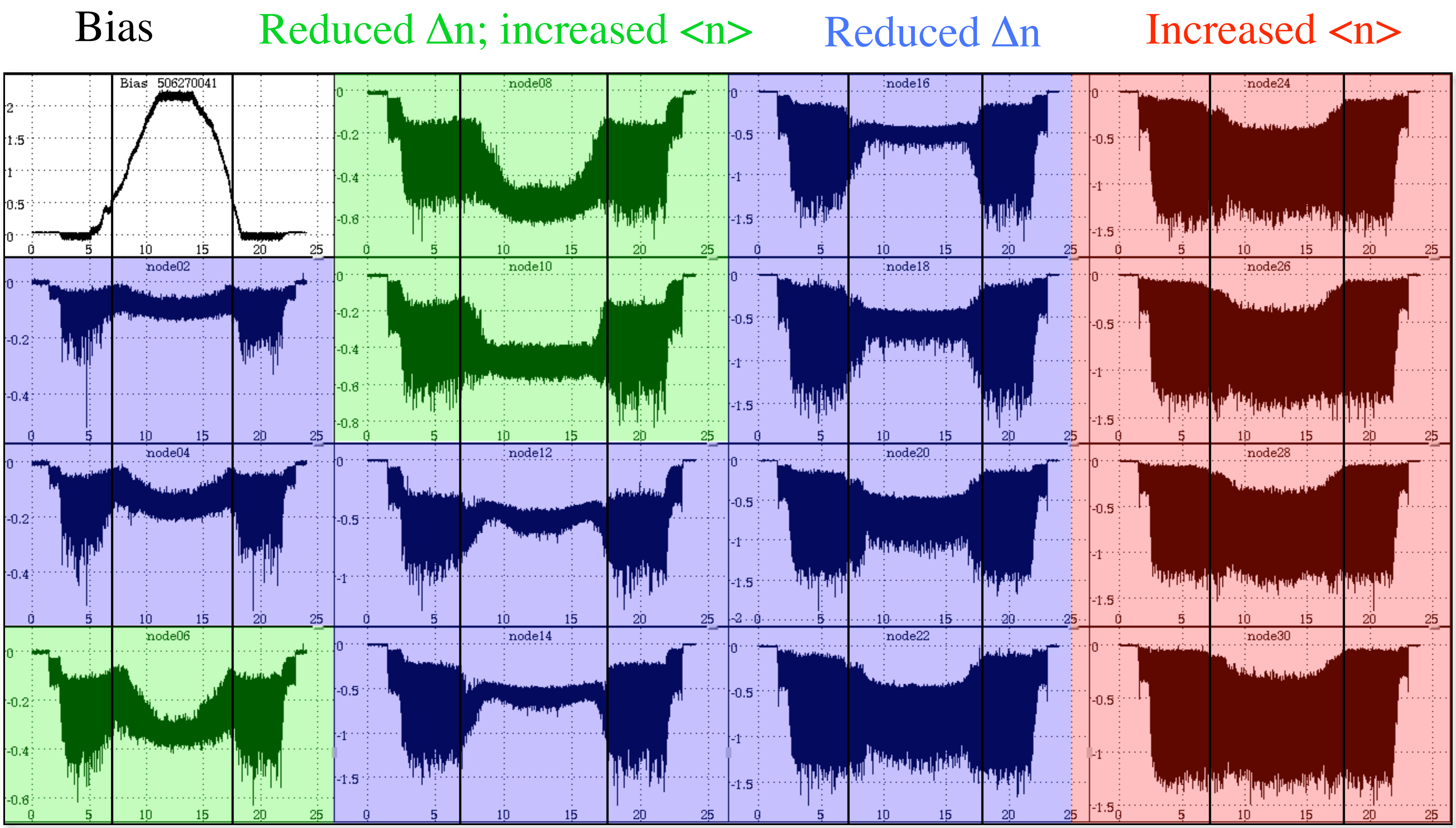
Response to Positive Bias

Probe n(t) across radial profile



Response to Negative Bias

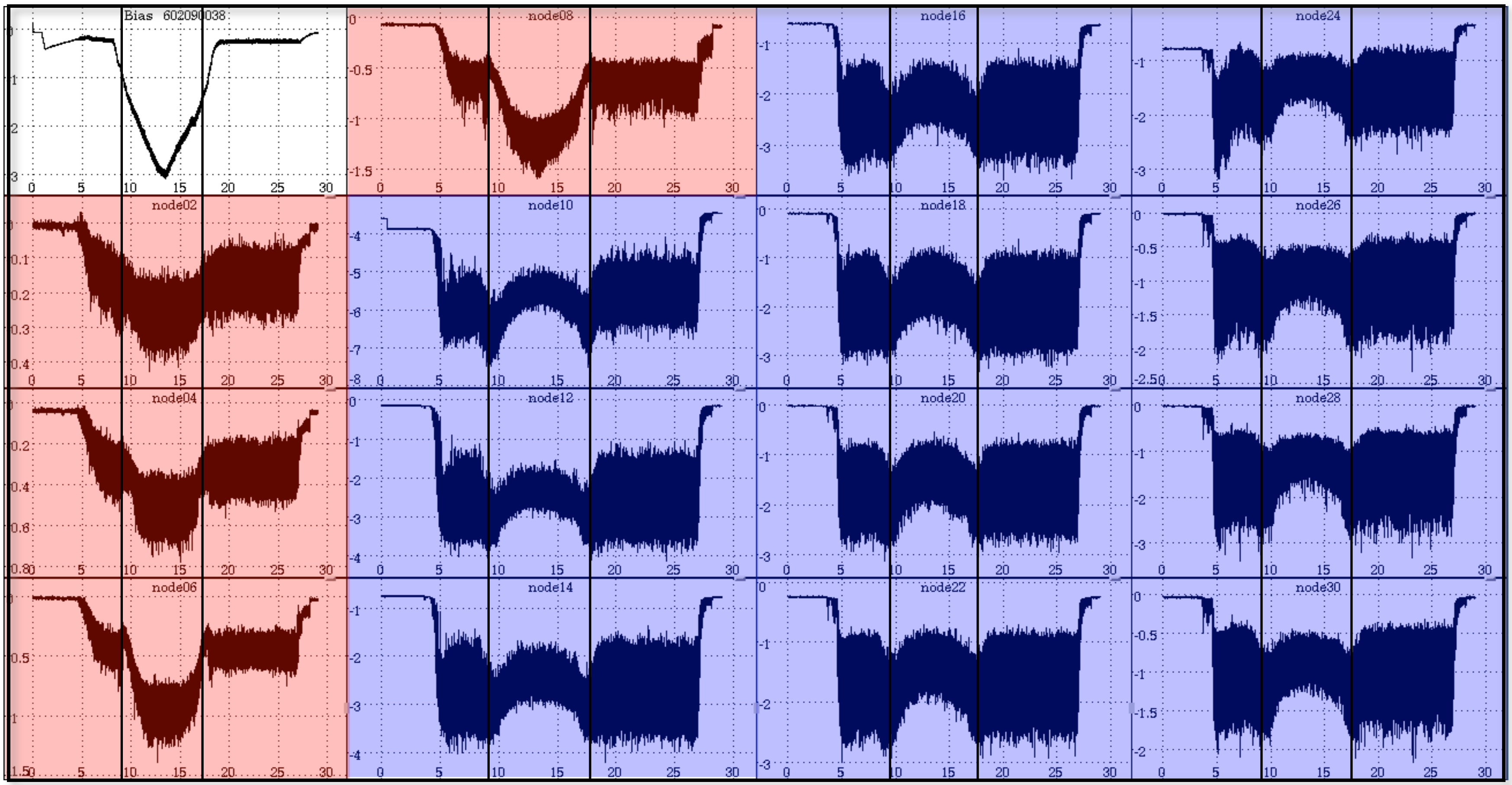
Probe n(t) across radial profile

Helium

Bias

Increased <n>

Reduced Δn



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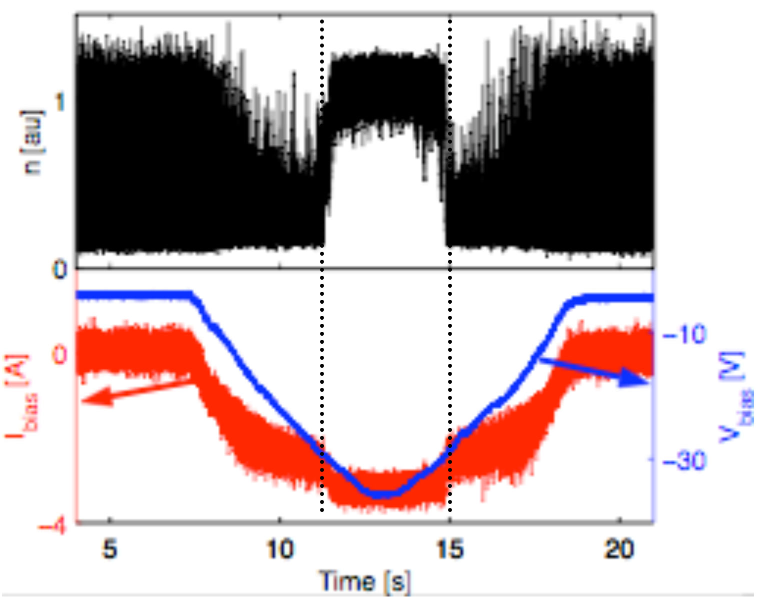
Time History of a Bifurcation

Negative Bias



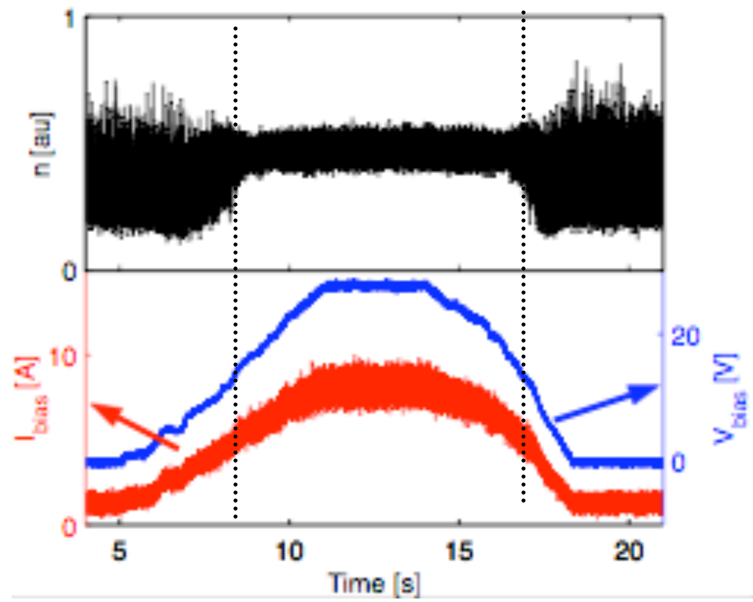
$I_{sat}(t)$

Bias

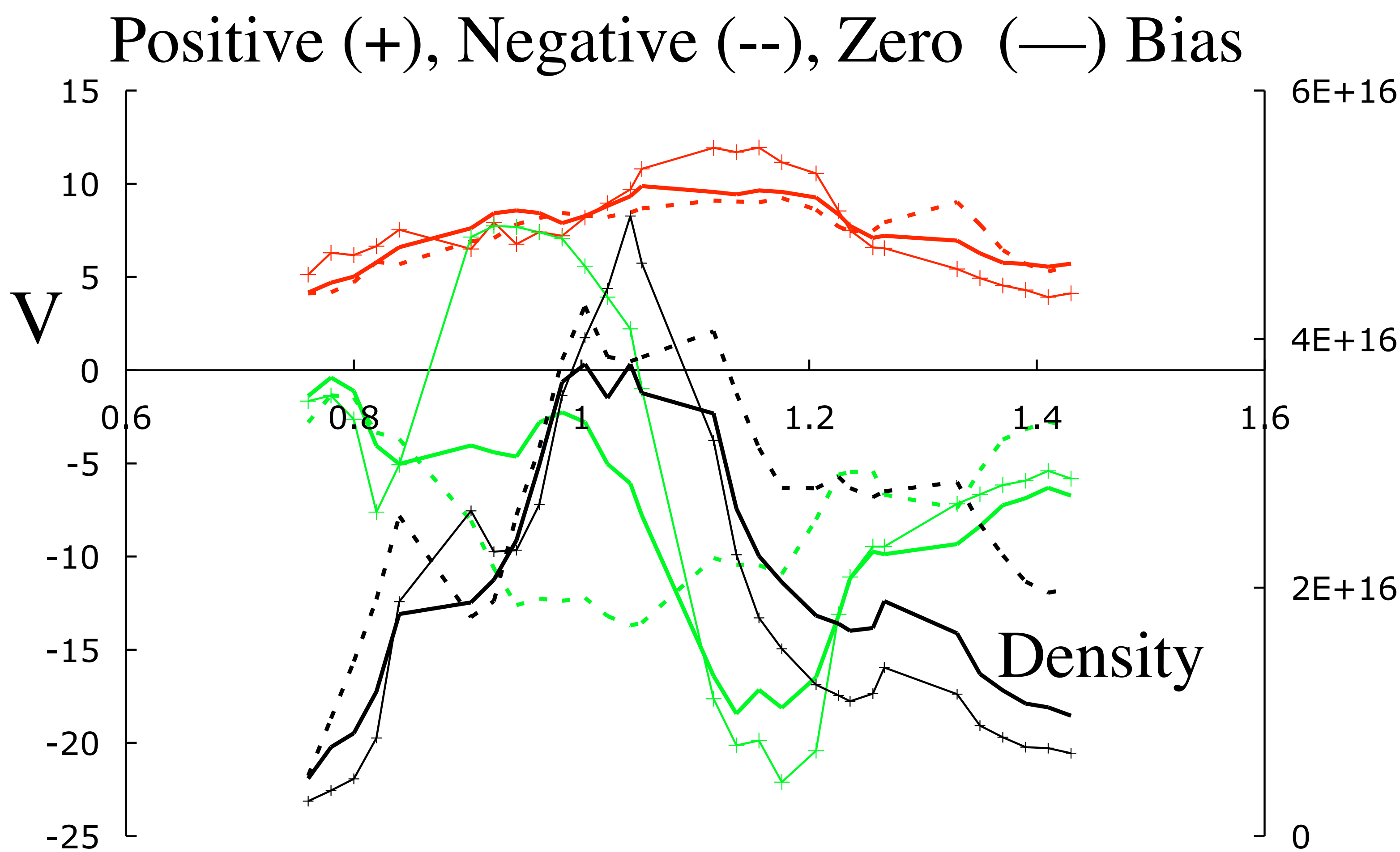
Voltage

Current

Positive Bias

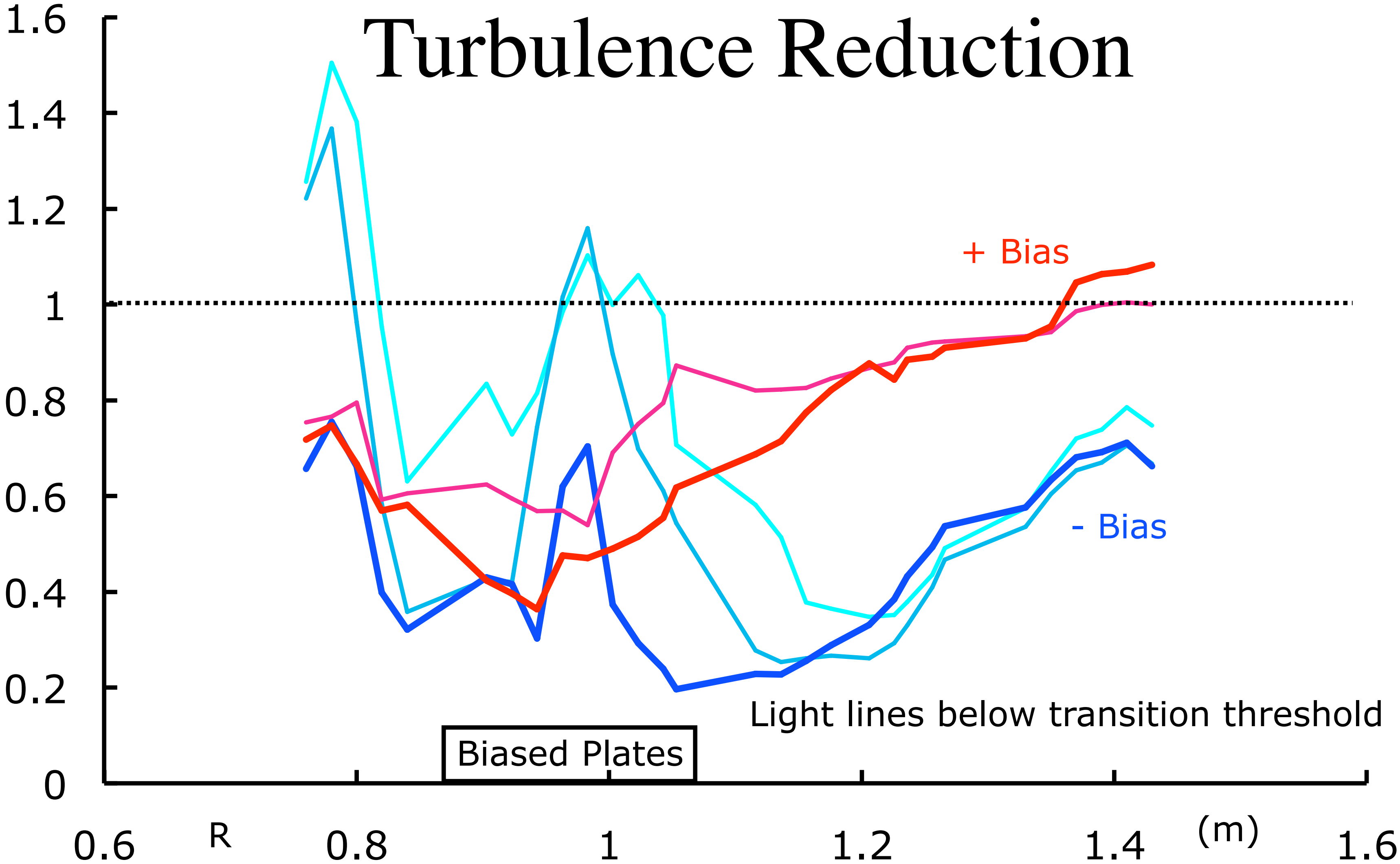


Profile Changes at Bifurcation



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

Turbulence Reduction



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

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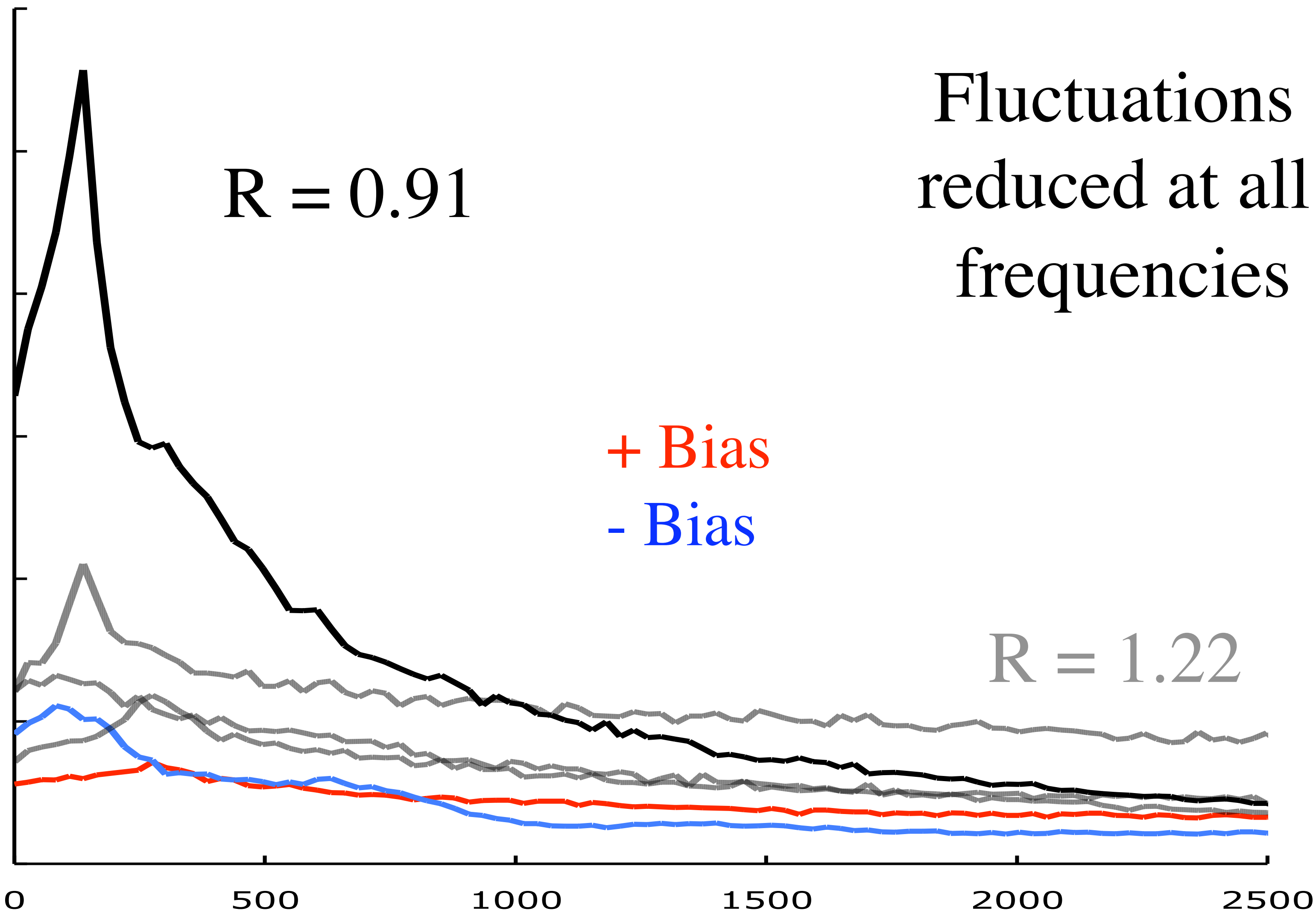
Changes in Frequency Spectra



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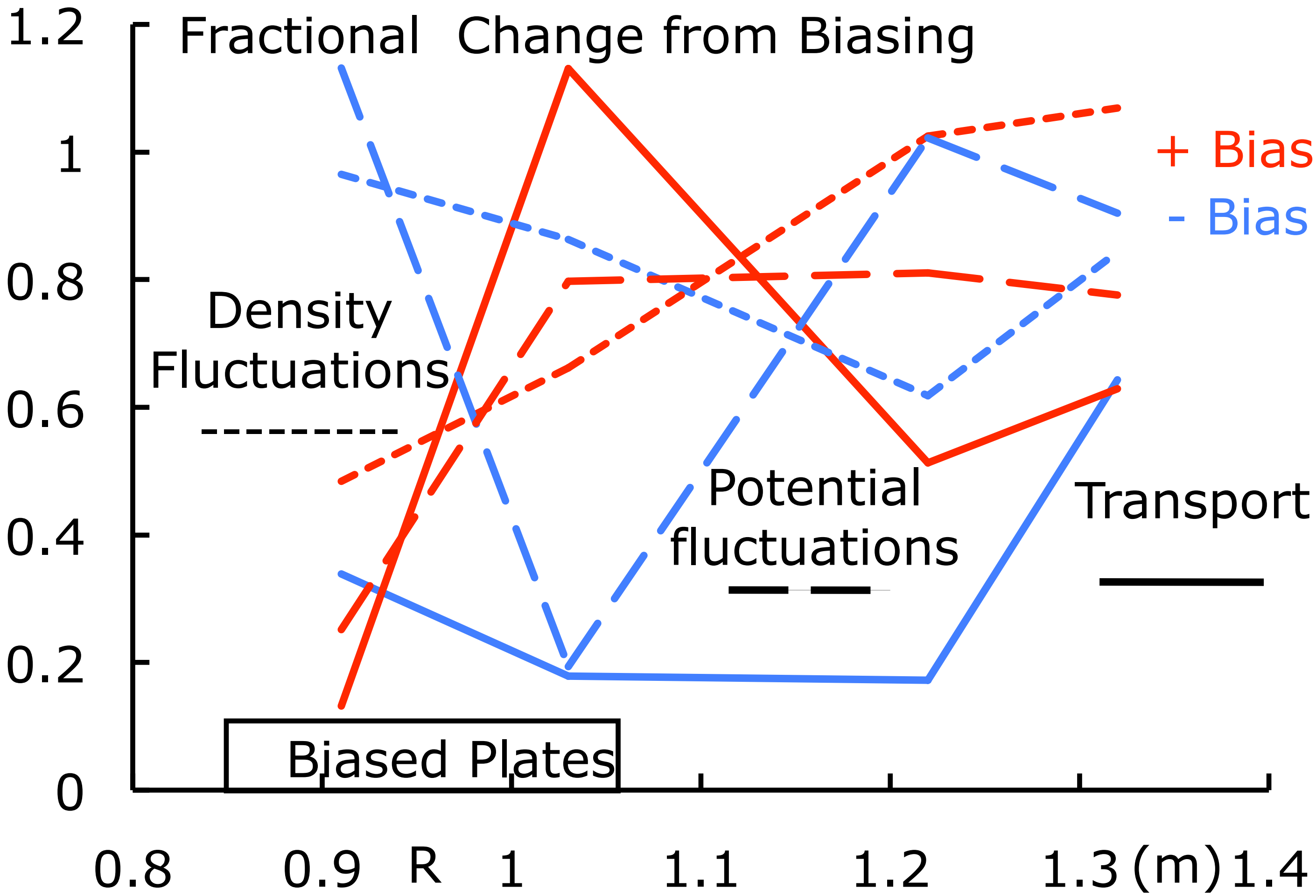
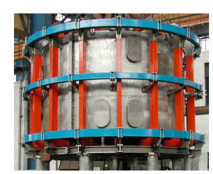
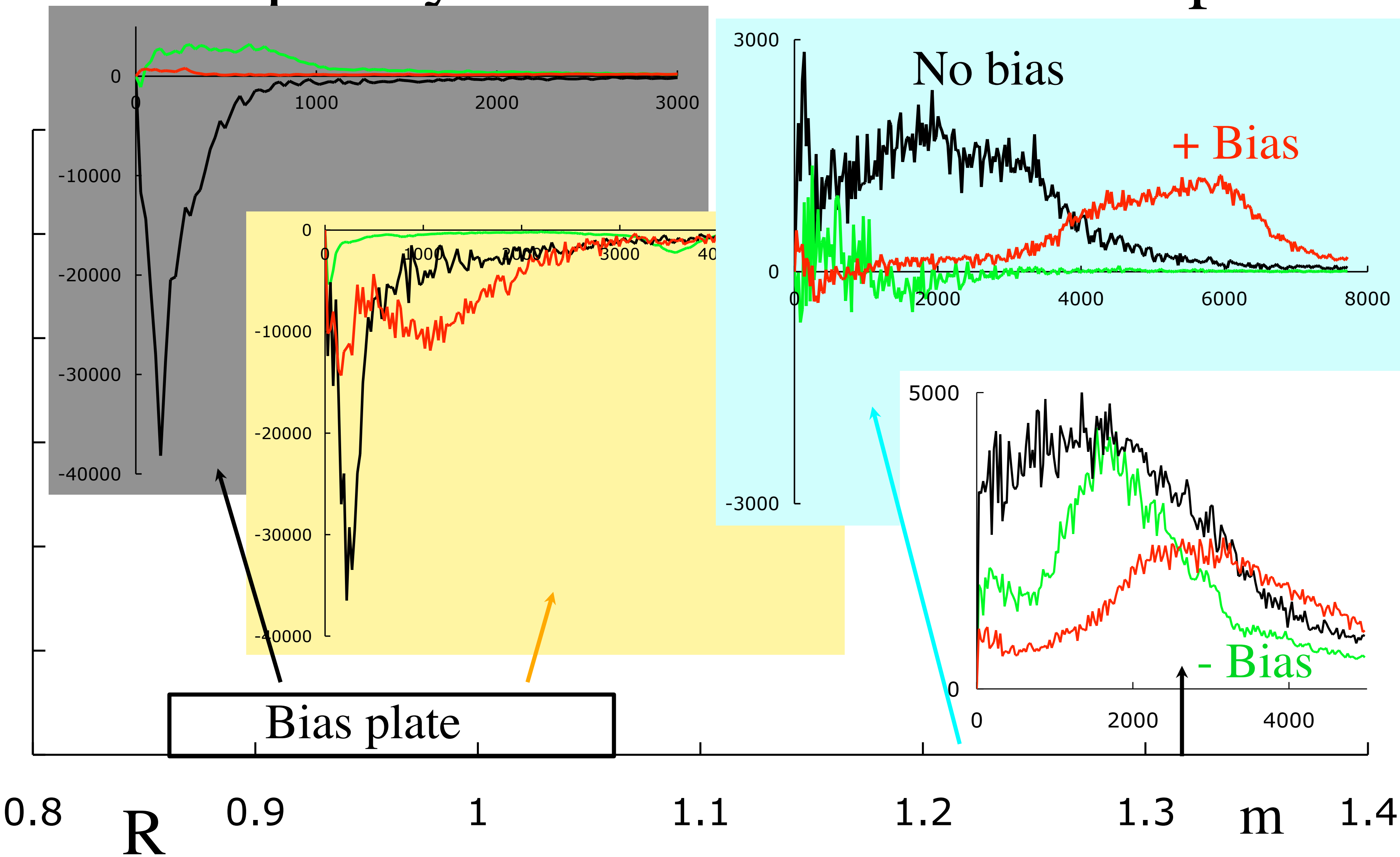
Change in Transport, Density, and Potential Fluctuations

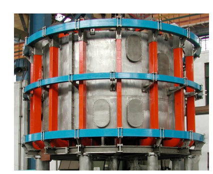


All quantities reduced, but no simple proportionality

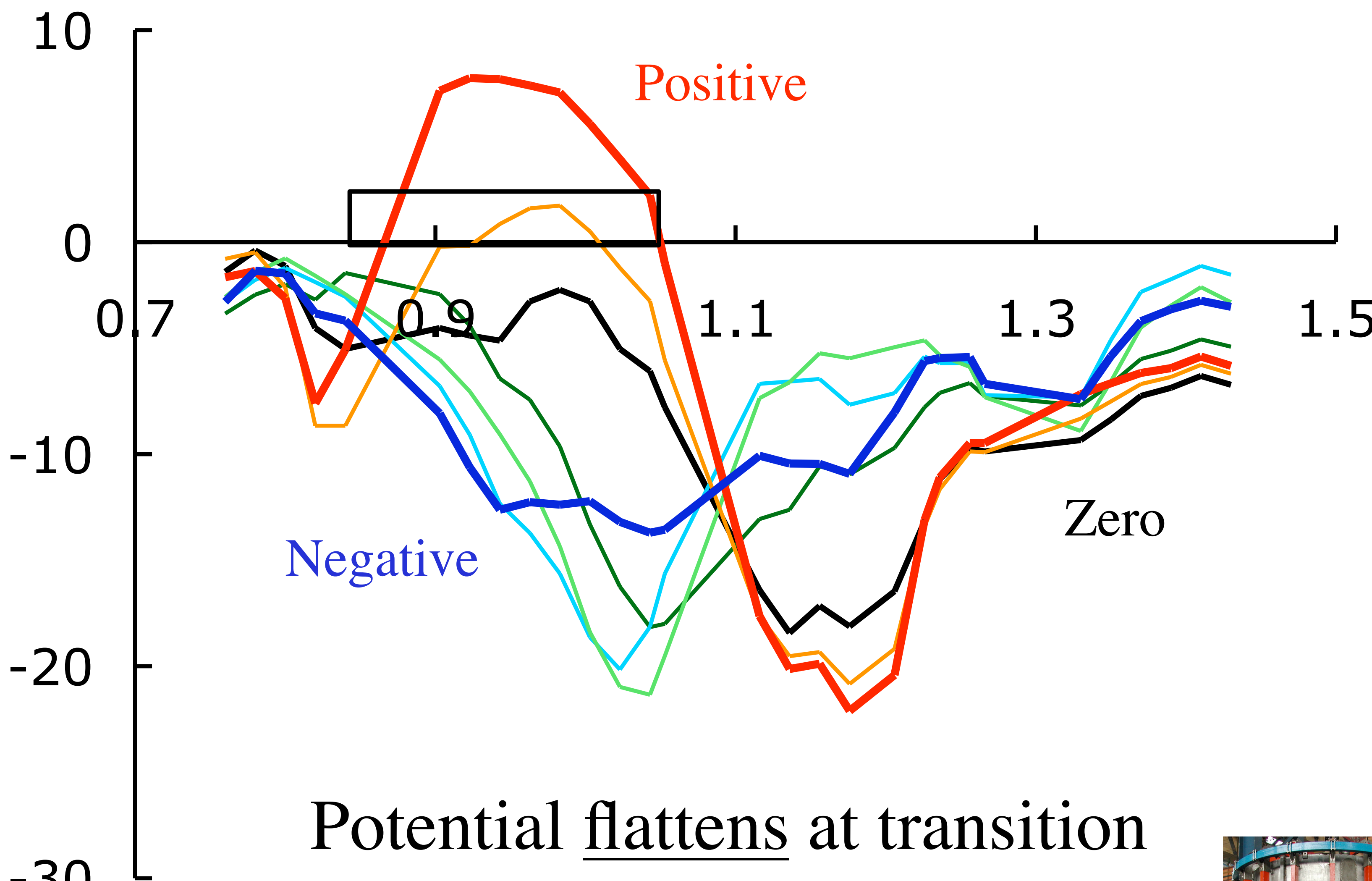


Frequency-Resolved Particle Transport

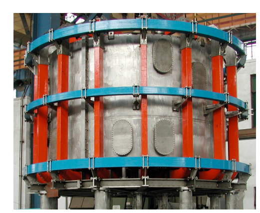




Floating Potential Profiles



Potential <u>flattens</u> at transition
for negative bias



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Comparison With Flow Shear Model

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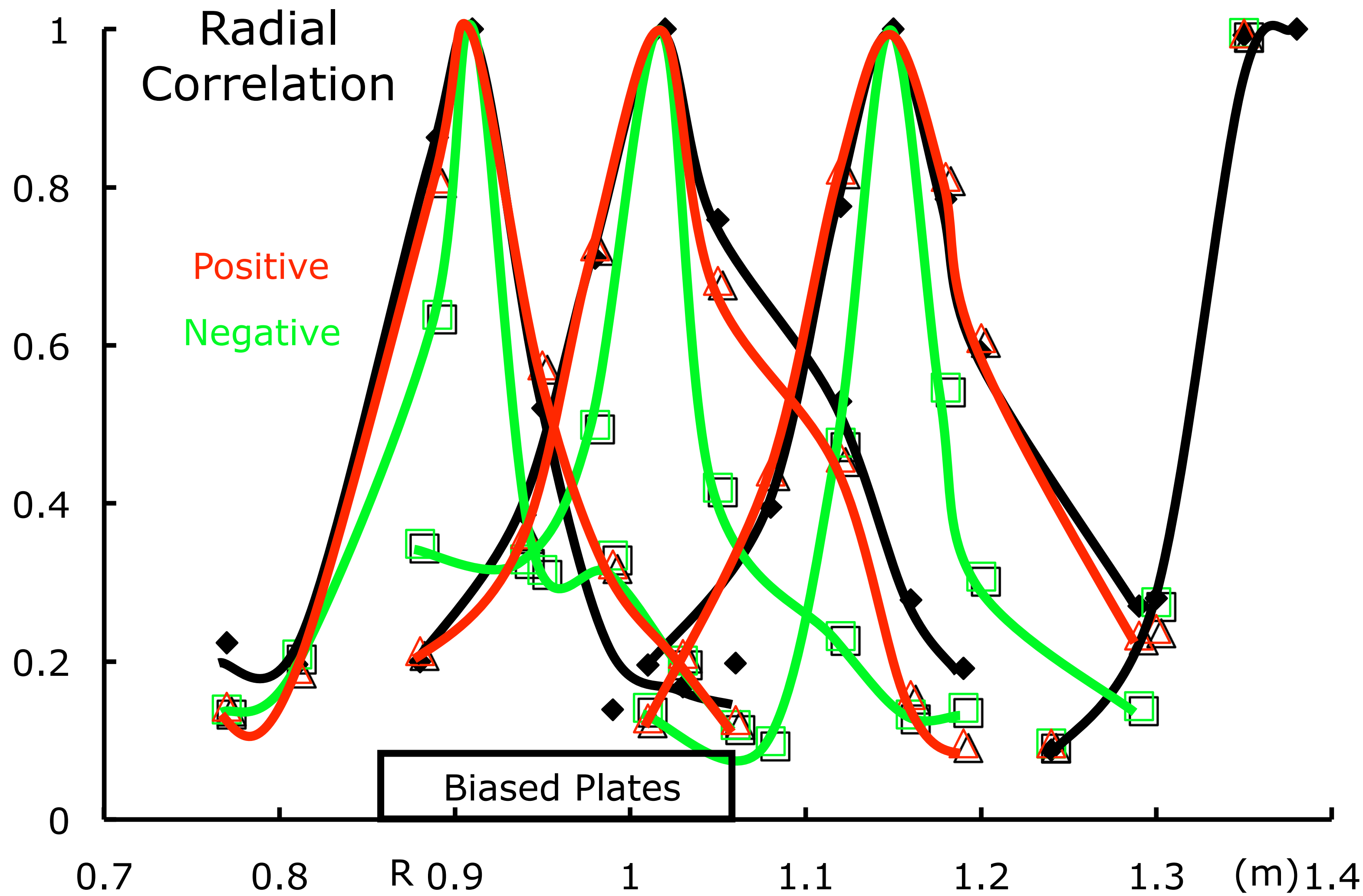
Effect of Bias on Radial Cross-Correlation



Negative bias reduces correlation length

Positive bias does not

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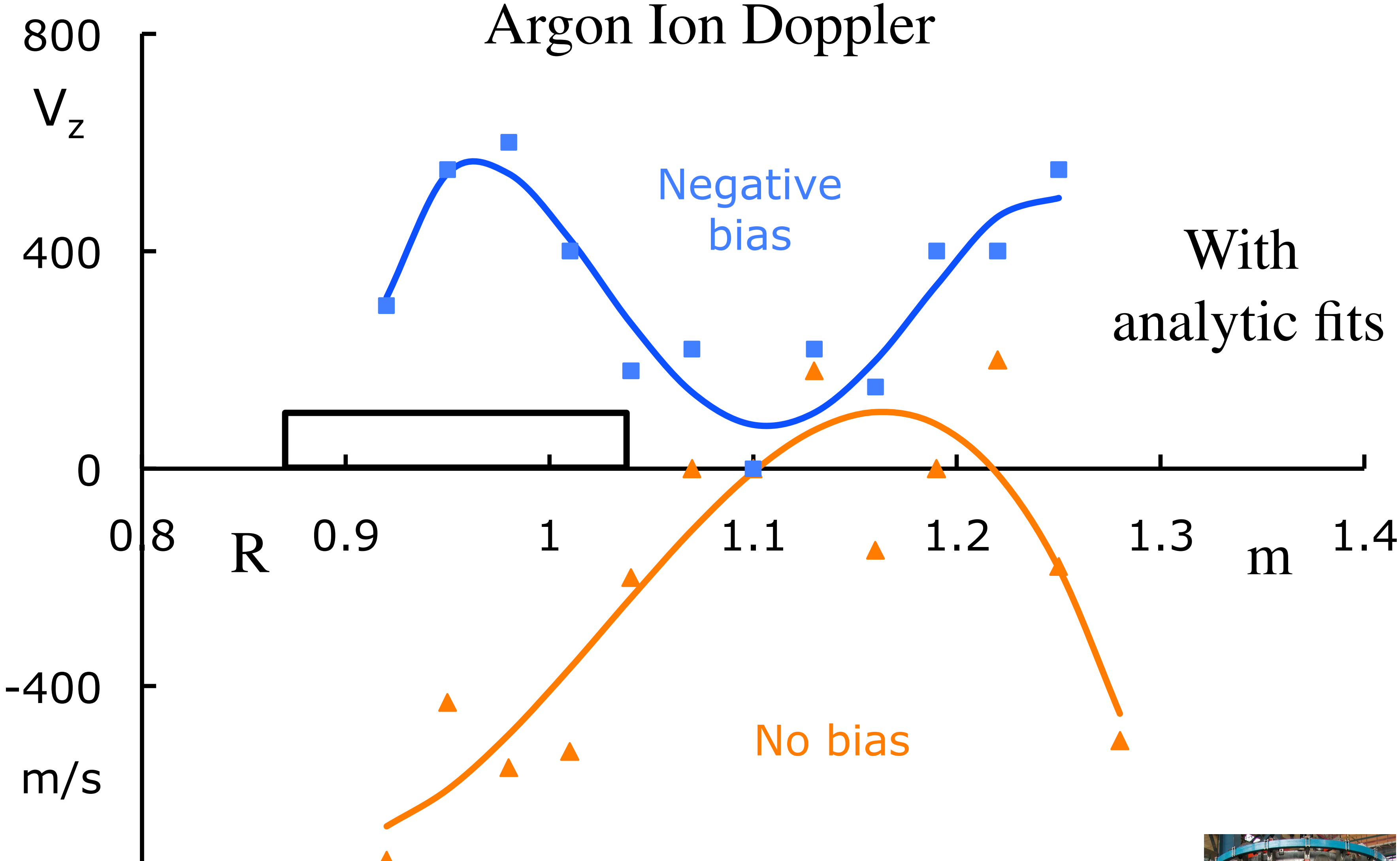
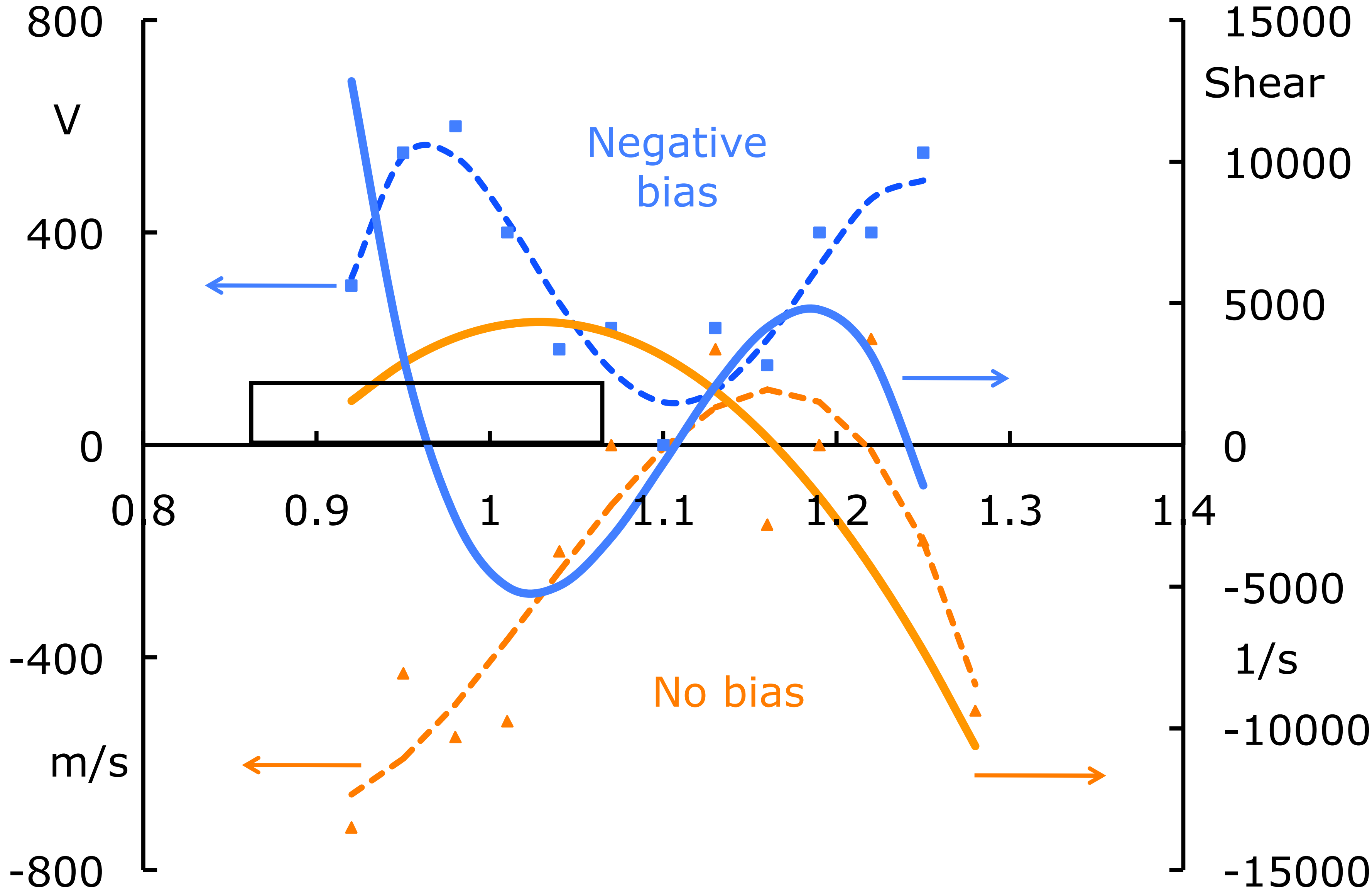
Measured Flow Velocity

Argon Ion Doppler



Measured Flow and Flow Shear



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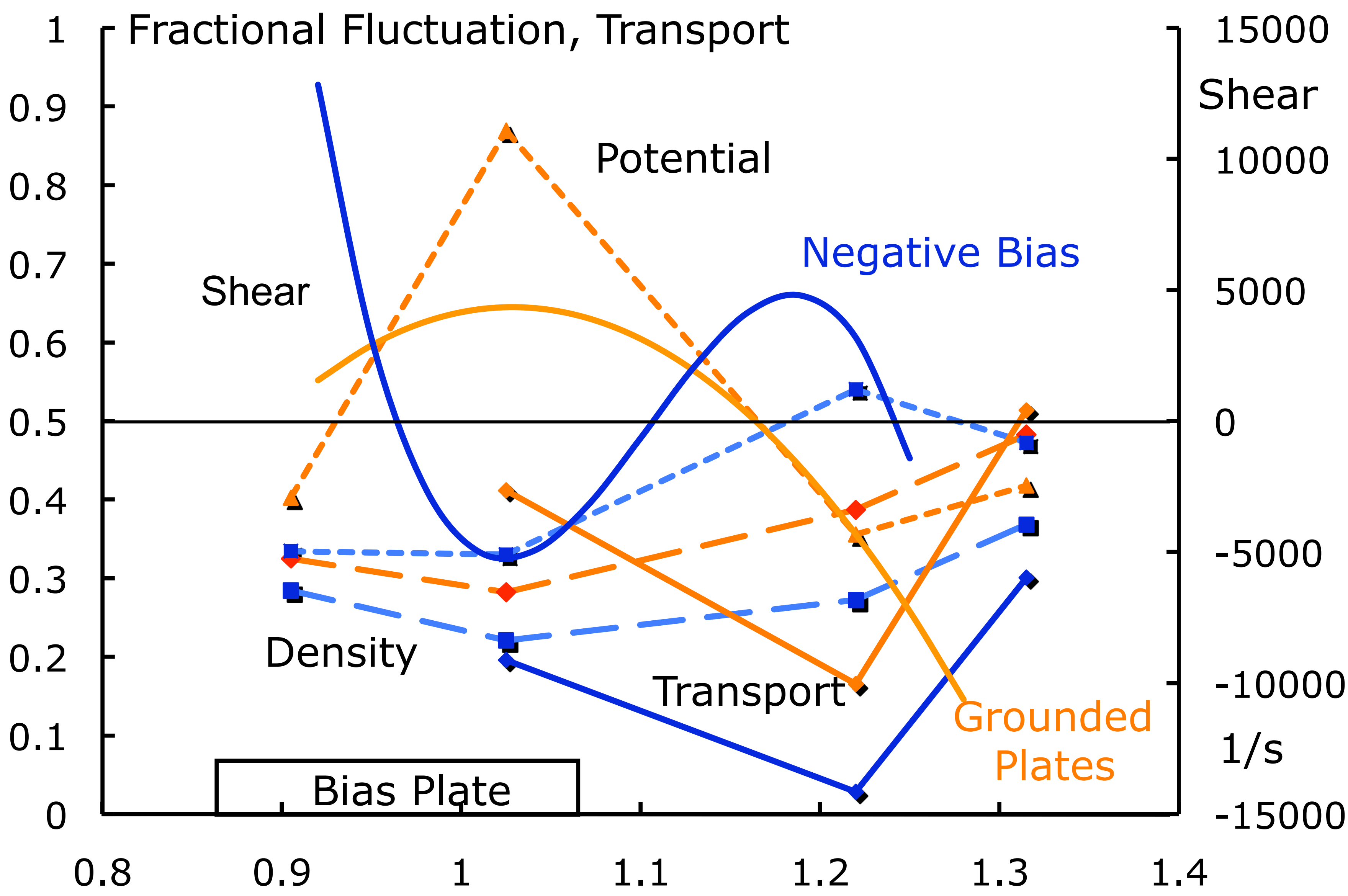
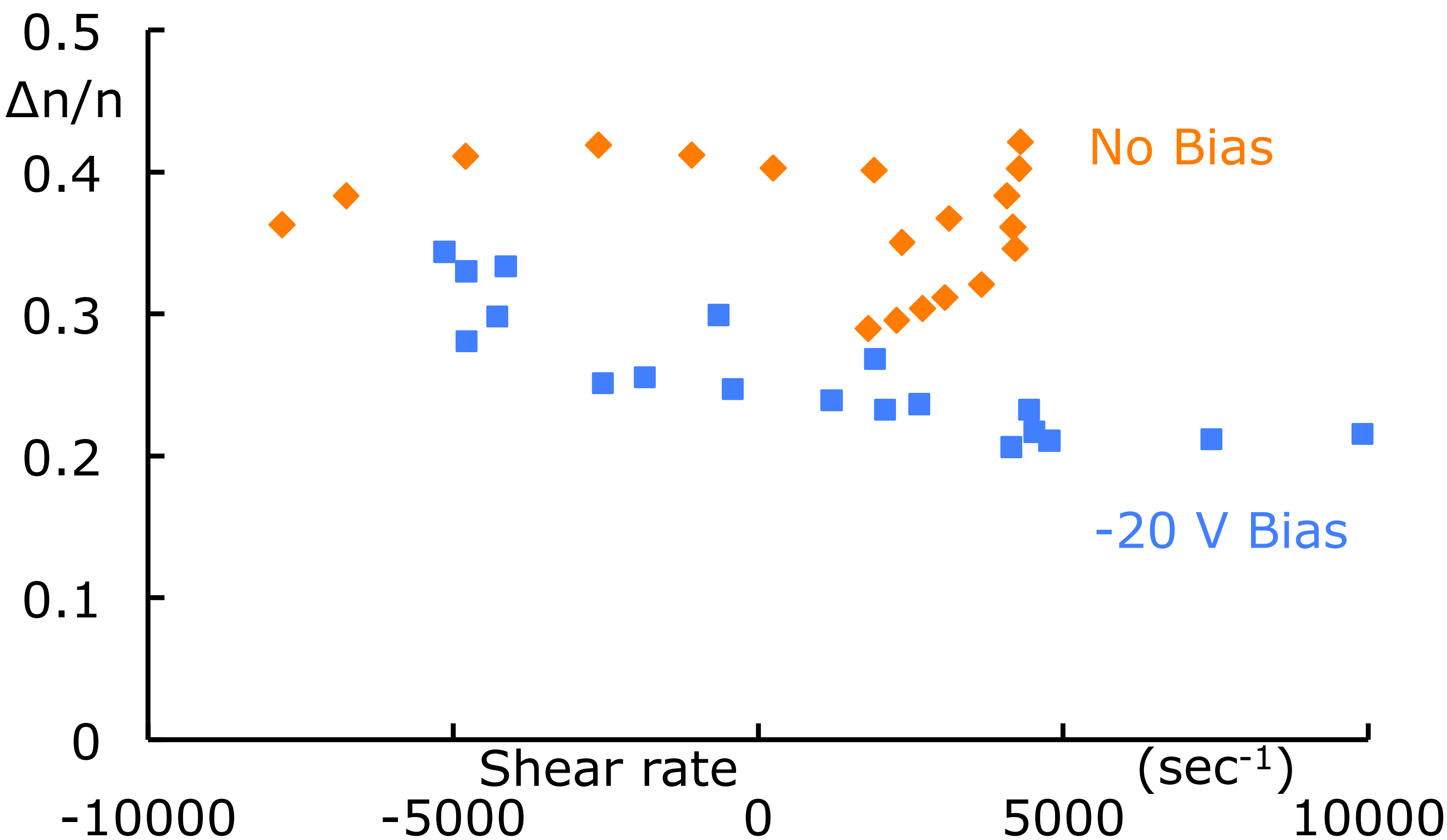
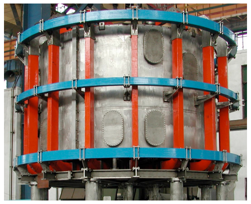
Comparison of Shear with Turbulence Suppression



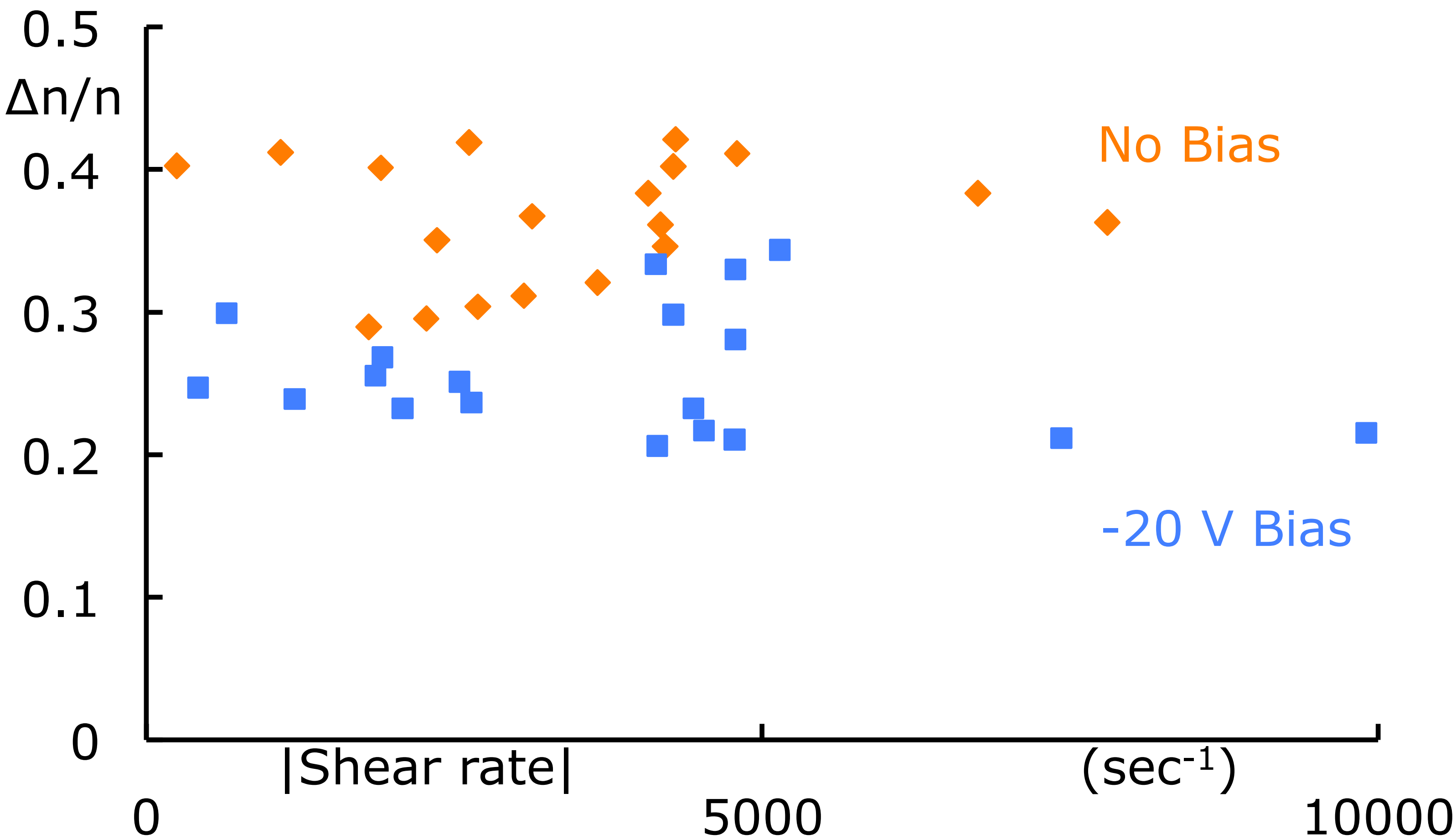
Density Fluctuations vs. Shear



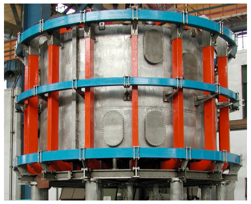
Reduction with bias not related to shearing rate



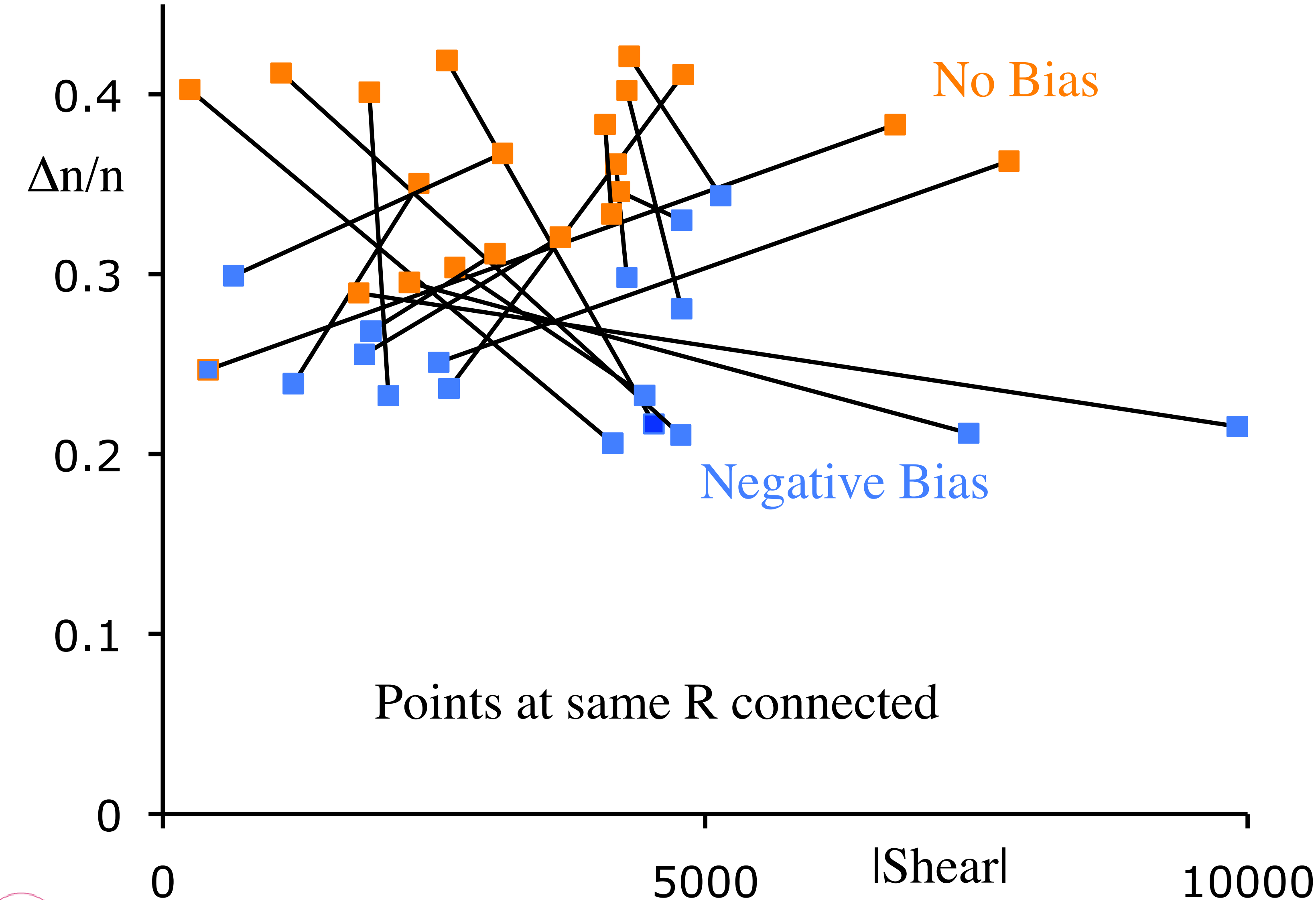
Density Fluctuations vs. Shear Magnitude



Neither reduction with bias
nor turbulence level
related to shearing rate

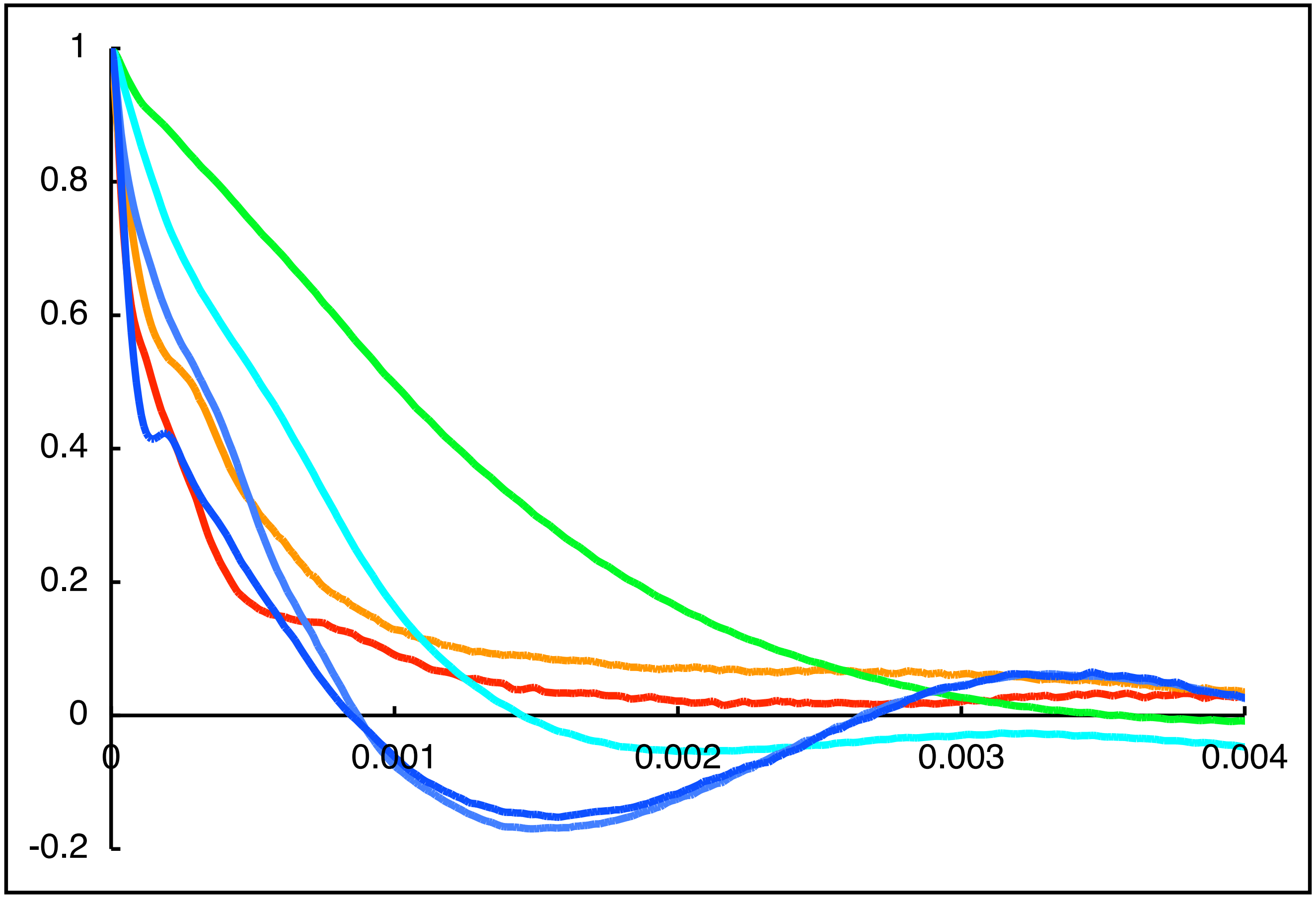


Density Fluctuations vs. Shear Magnitude



Auto-correlation times (~ growth rate)

Velocity shear $\sim 10^4\ s^{-1}$ shorter than turbulence autocorrelation times ~ 0.5 ms ($\gamma \sim 2 \times 10^3\ s^{-1}$)



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Scorecard for Flow-Shear Model

	- Bias	+ Bias
Reduced radial correlation length	**YES**	**NO**
Turbulence reduction associated with increased flow shear	**NO**	**--**
Turbulence level decreases with increased flow shear*	**NO**	**--**
Density fluctuations, potential fluctuations, and transport decrease together*	**NO**	**NO**

* Coupled with quasi-linear theory

Conclusions

- The Helimak offers a simple, controlled example of shear-flow suppression of turbulence and transport.
- The reductions in density fluctuations, potential fluctuations and transport are not closely related to one another
- Neither turbulence reductions nor levels correlate closely with velocity shearing rate

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