Seeing Turbulence Through a Rippled Reflection

A Tutorial on the Investigation of Turbulent Fluctuations in Fusion Plasmas from the Reflection of Electromagnetic Waves

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Contributions from JAERI, JET, MIT, GA, UCLA, UC Davis and Clemson U.

APS DPP/ICPP Meeting, Quebec, Canada
October 24, 2000

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Acknowledgements

PPPL: E. Valeo, G.J. Kramer, K. Hill, M. Beer, D. Ernst, T.S. Hahm,
H. Park, G. Rewoldt

JAERI: K. Shinohara, S. Ide, T. Fujita, Y. Kishimoto, H. Shirai

UCLA: A. Peebles, T. Rhodes, E. Doyle

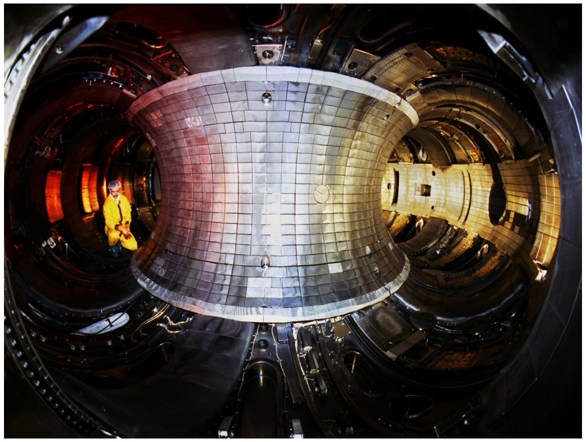
JET: G. Conway

MIT: Y. Lin, J. Irby, E. Marmar

Clemson University: D. Hysell

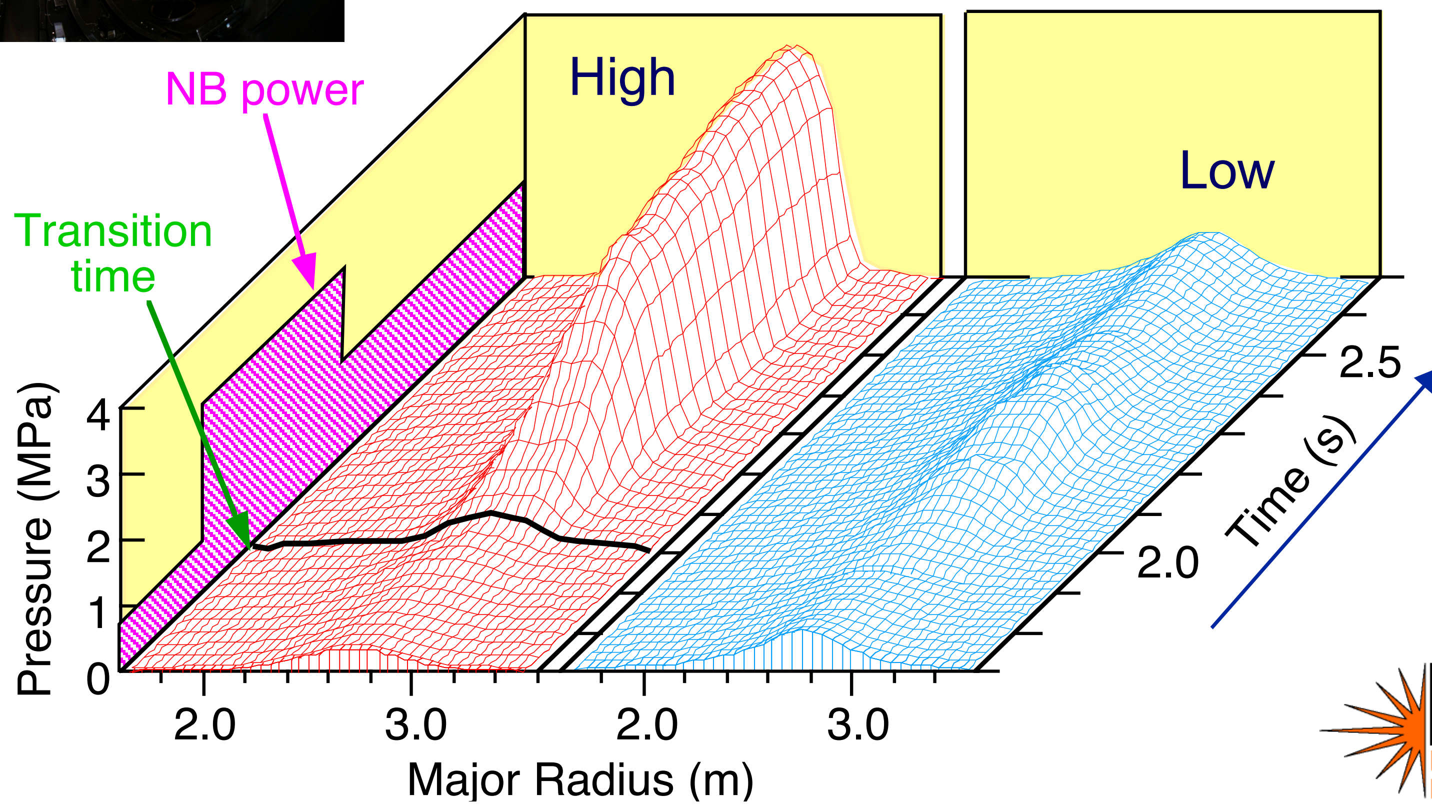
Valuable discussions: D. Farley (Cornell), A. Wong (UCLA)

Fascinating Diversity of Regimes in Fusion Plasmas. What Triggers Change? What Regulates Confinement?



TFTR

- Two regimes with very different confinement for similar initial conditions and neutral beam heating
- Access depends on plasma heating and reducing current density on axis
- Can we attribute a difference in turbulence to these two different confinement regimes?



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A Grand Challenge for Fusion Science is to Understand, Predict and Control Turbulent Transport

Understand:

- structure and dynamics of turbulence and induced transport

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Predict:

- scaling of different confinement regimes

↓

Control:

- plasma equilibrium and confinement, local turbulence control

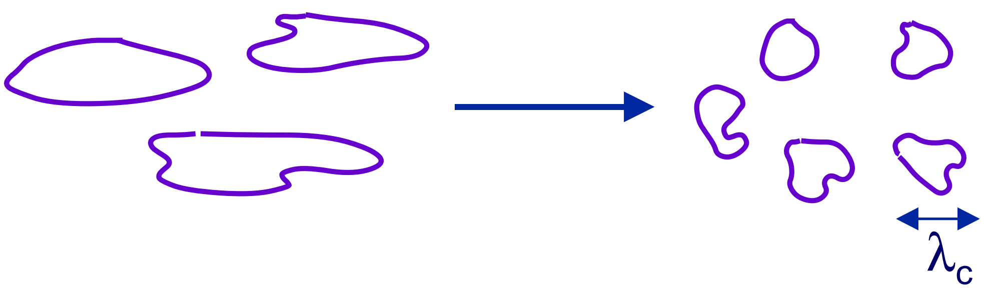
Continued improvement in measurement capability is essential to advance predictive understanding and develop methods for turbulence control

A Major Challenge in Fusion Science is to Measure Turbulent Fluctuations with Good Spatial and Temporal Resolution

- Important turbulence parameters for measurement
  - correlation length λ_c
  - correlation time τ_c
  - density, potential, temperature fluctuation levels
  - velocity fluctuations (self regulation)

- Simple Random Walk Estimate: Diffusivity $D \propto \lambda_c^2 / \tau_c$

Large eddies
High transport



Small eddies
Low transport

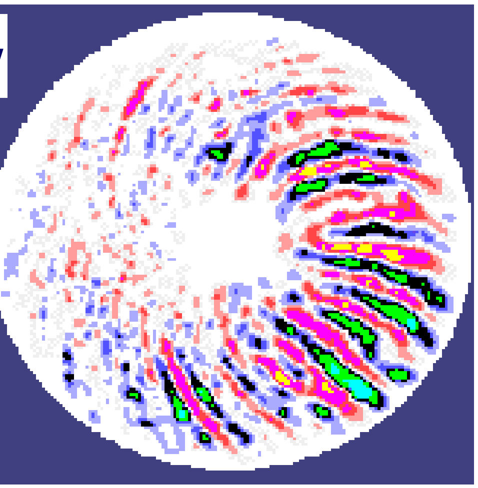
Outstanding questions in fusion science

- Is there a correlation between eddy size, fluctuation level and confinement?
- What controls the turbulent scale length in fusion plasmas?

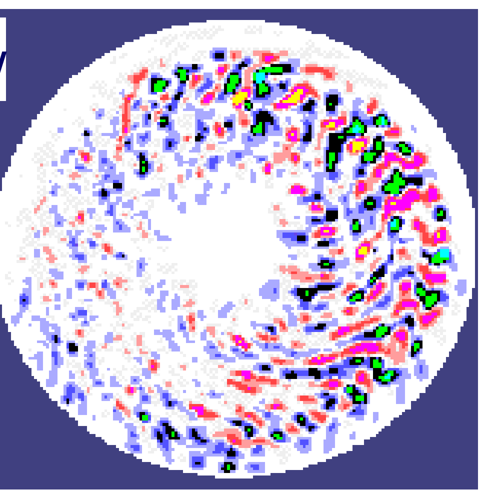
Current Understanding: Sheared ExB Flow Regulates Turbulent Eddy Size and Transport in Fusion Plasmas

Gyrokinetic Simulation: Z. Lin

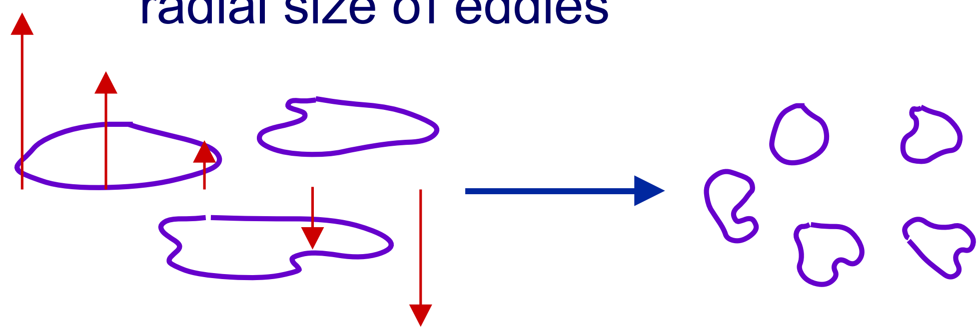
No flow



With flow



- Sheared ExB flow reduces radial size of eddies



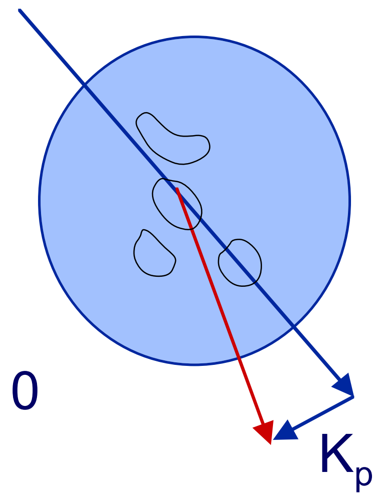
- Breakup of long finger structures suppresses transport

Microwaves can penetrate the core of the plasma and return information on turbulent structures. How?

High Frequency Waves Probe Refractive Index Fluctuations in a Weakly Absorbing Plasma: Two Different Approaches

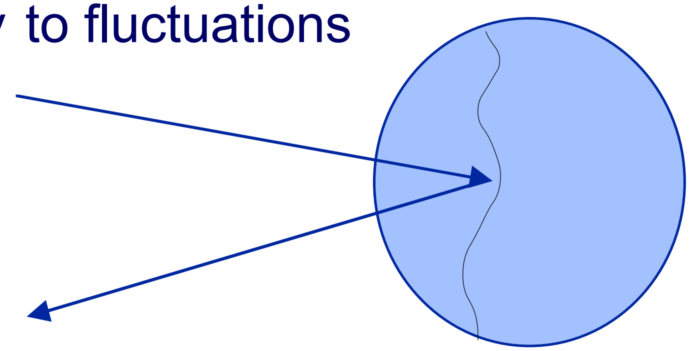
- Sensitivity to refractive index fluctuations: $\frac{\delta E}{E} \propto k_0 L \frac{\delta \mu}{\mu}$

- Collective scattering:
  - frequency usually well above plasma response frequency: $\omega >> \omega_{pe},\omega_{ce}$
  - $\mu \approx 1$, weak refraction
  - weak response (good) and $\propto \delta n$
  - poor spatial resolution for long λ_c



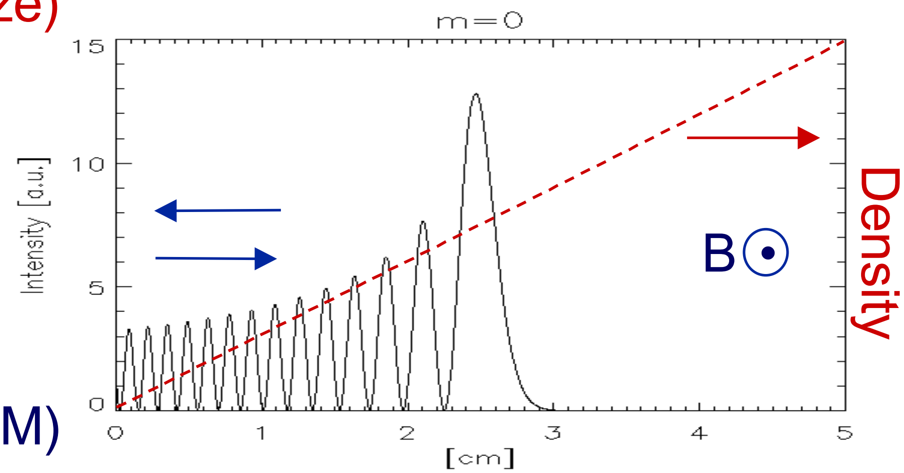
- Reflectometry:
  - as we lower the frequency, waves are cutoff : $\mu = 0$
  - group velocity slows down near cutoff
  - enhanced sensitivity to fluctuations near μ=0

$$\frac{\delta E}{E} \propto \frac{\delta n}{n}$$

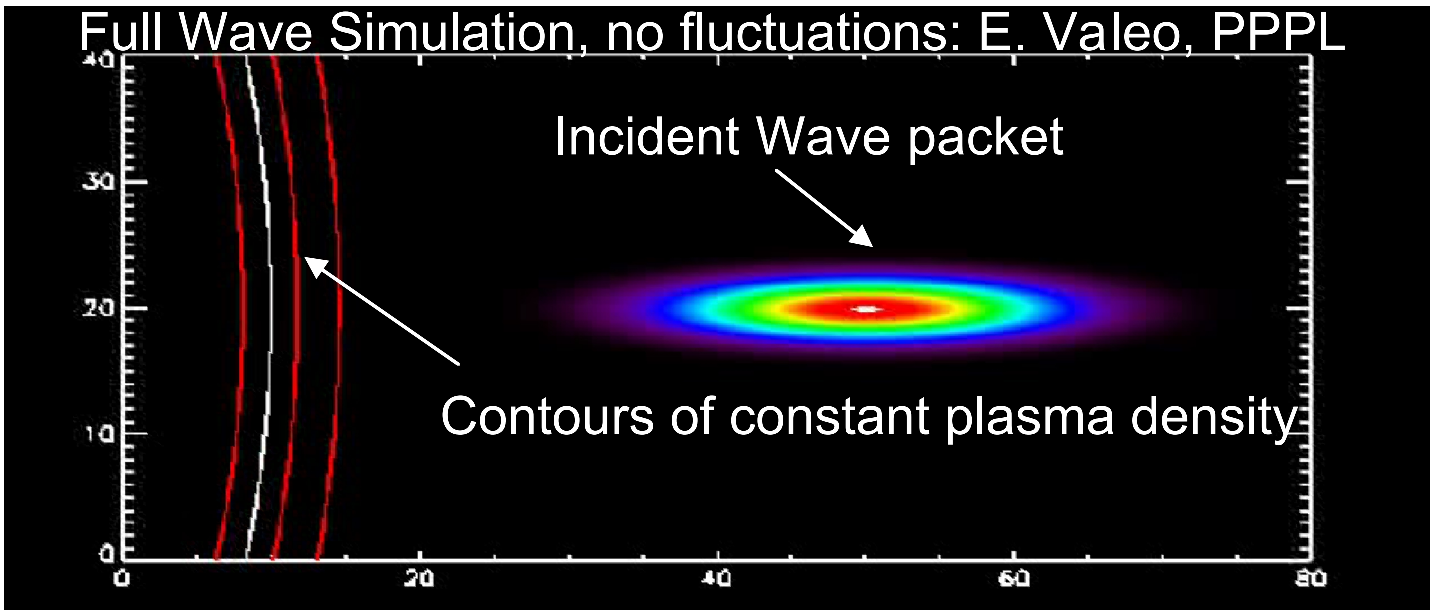


Two Principle Methods of Reflectometry: Steady State Phase Detection vs Short Pulse Group Delay Measurements

• Steady state (pulse length >> system size)
- amplitude swells like waves on a beach
- used for profile and correlation studies (UCLA, GA, PPPL, MIT…)



• pulse length short to system size
- Measure group delay (LLNL, UCSD, FOM)



Ionosonde has a Long History in Ionospheric Research: Discovery and Range Finding Applications

- 1902: First transatlantic wireless communication (Marconi) leads to conjecture (Heaviside) for existence of conducting layer

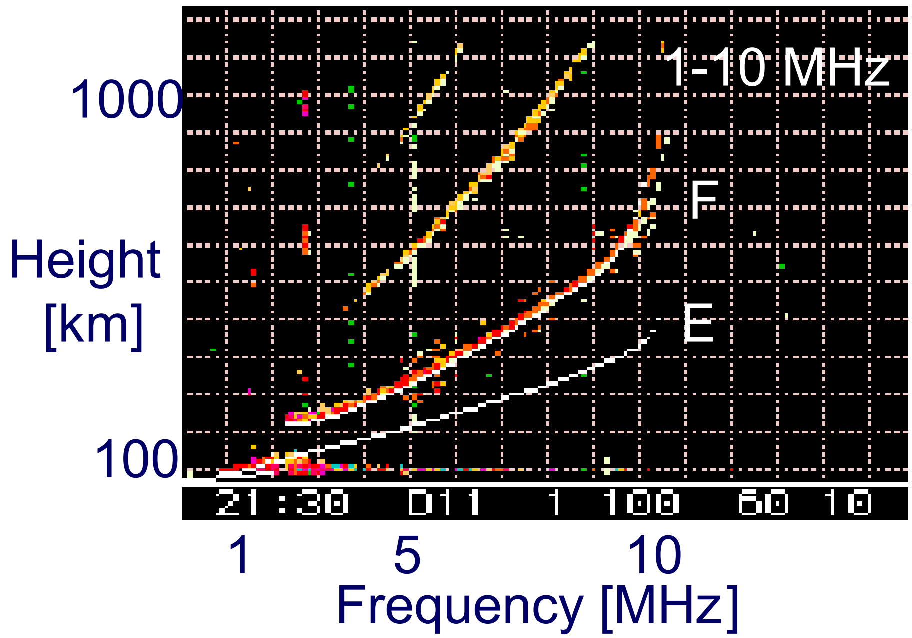
- 1924/25: Electron height distribution from radio wave reflection
  - Pulsed (Breit, USA) radar 1-10 MHz identifies E & F layer
  - Frequency sweep method: (Appleton, UK)

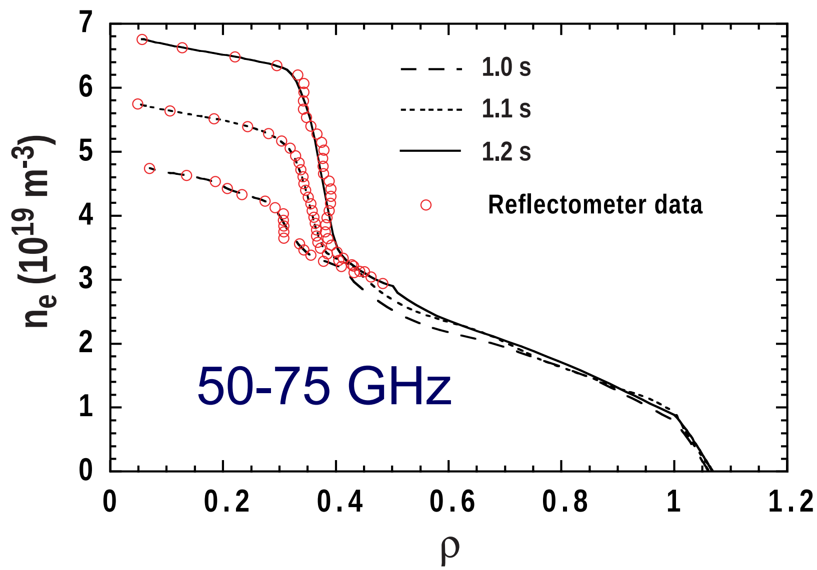
- 1930s: Timely Technology Spin off: Aircraft radar in WWII
  - based on pulsed method

Reflectometry (Ionosonde) is a Principal Tool for Range Finding of Density Layers in Space and Fusion Plasmas

Example of range finding using pulse reflectometry in ionosphere

Example of sweep method in fusion: Internal barrier formation in DIII-D





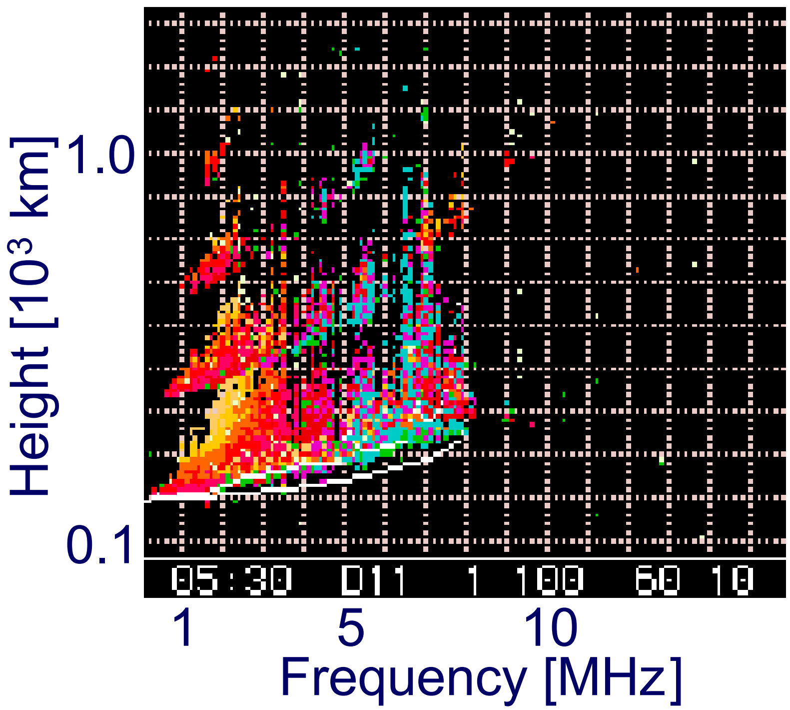
Major issue in early research was to explain the origin of large amplitude and phase fluctuations in reflections

CLEMSON UNIVERSITY SOUTH CAROLINA 1889

UCLA

Combination of Collective Scattering and Reflectometry Used to Investigate Ionospheric Disturbances: Equatorial Spread-F due to Rising Plumes

Disturbed ionosphere
and range spread

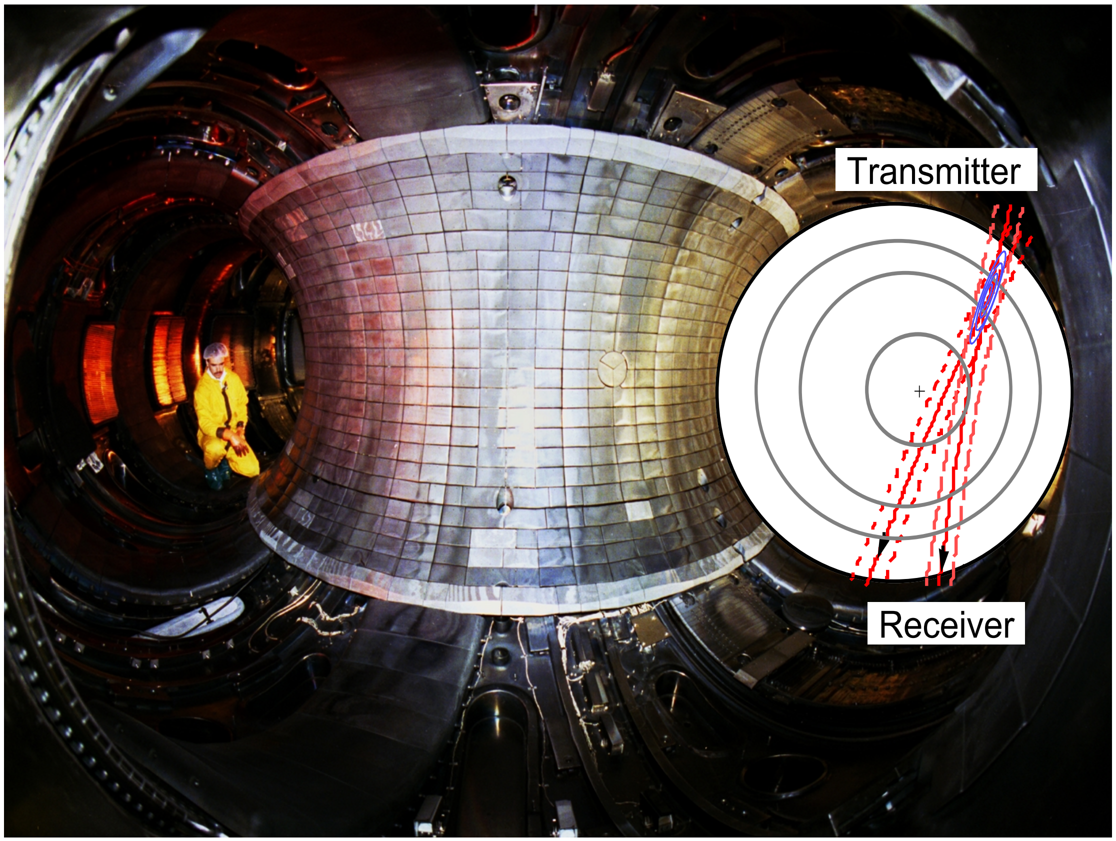


Backscatter "tracer" image of rising plumes
Coherent back scattering

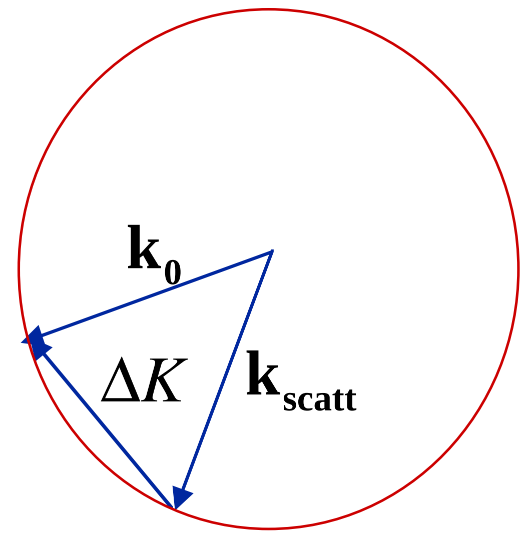
- Collective scattering resolves large scale structures: Bubbles!
- Huge disturbances make interpretation of ionosonde difficult.
  - used as an indicator and for basic height measurements

In Contrast, Collective Scattering Loses Spatial Resolution For Large Scale Eddies in Fusion Plasmas

- Spatial resolution determined by plasma penetration frequency and overlap of receiver and transmitter antenna pattern



Bragg scattering, with $\Delta k << k_0$



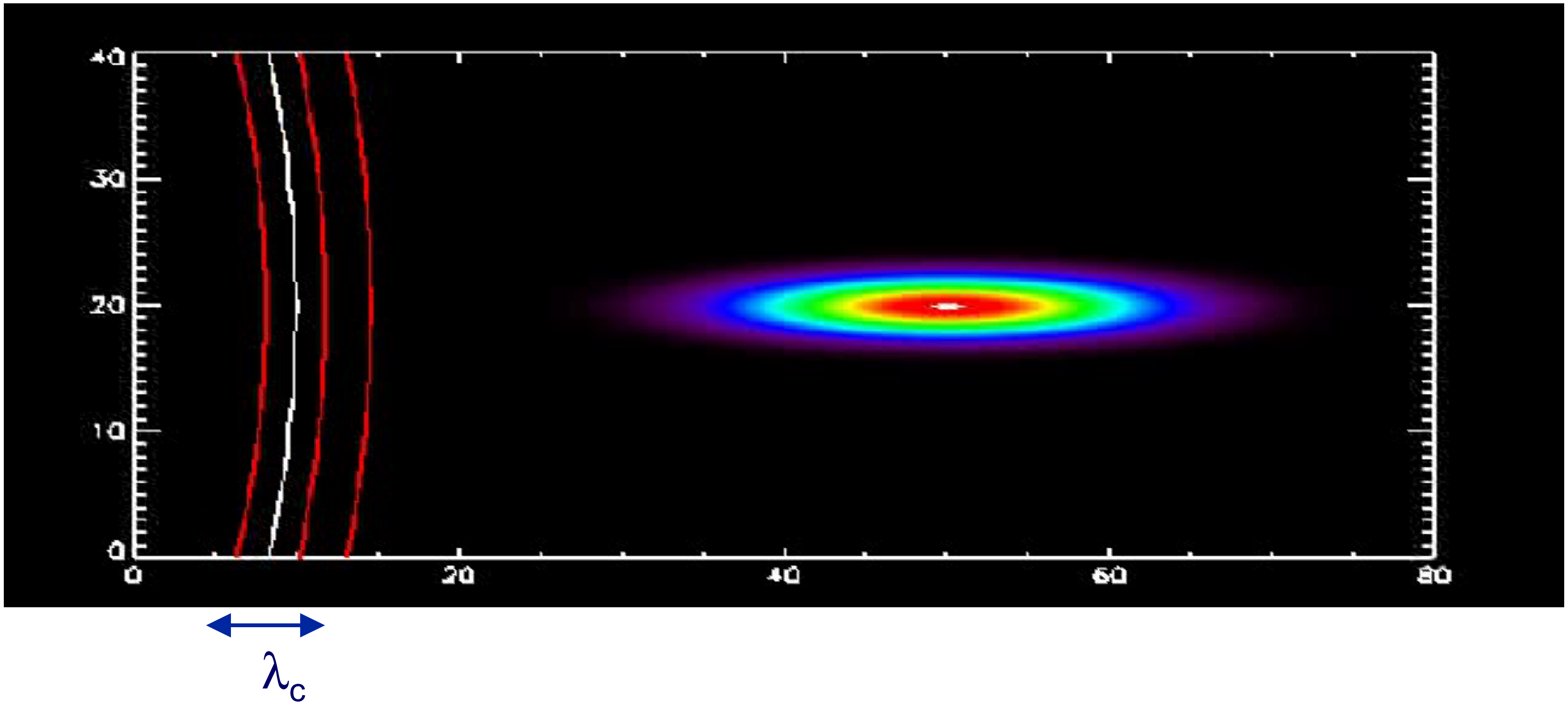
Poor resolution for $k_\perp \rho_i < 0.5$

ITG Theory predicts lower-k

- Microwave scattering indicates weak core fluctuations: $\delta n/n<1\%$

Low fluctuation levels are ideal for reflectometry

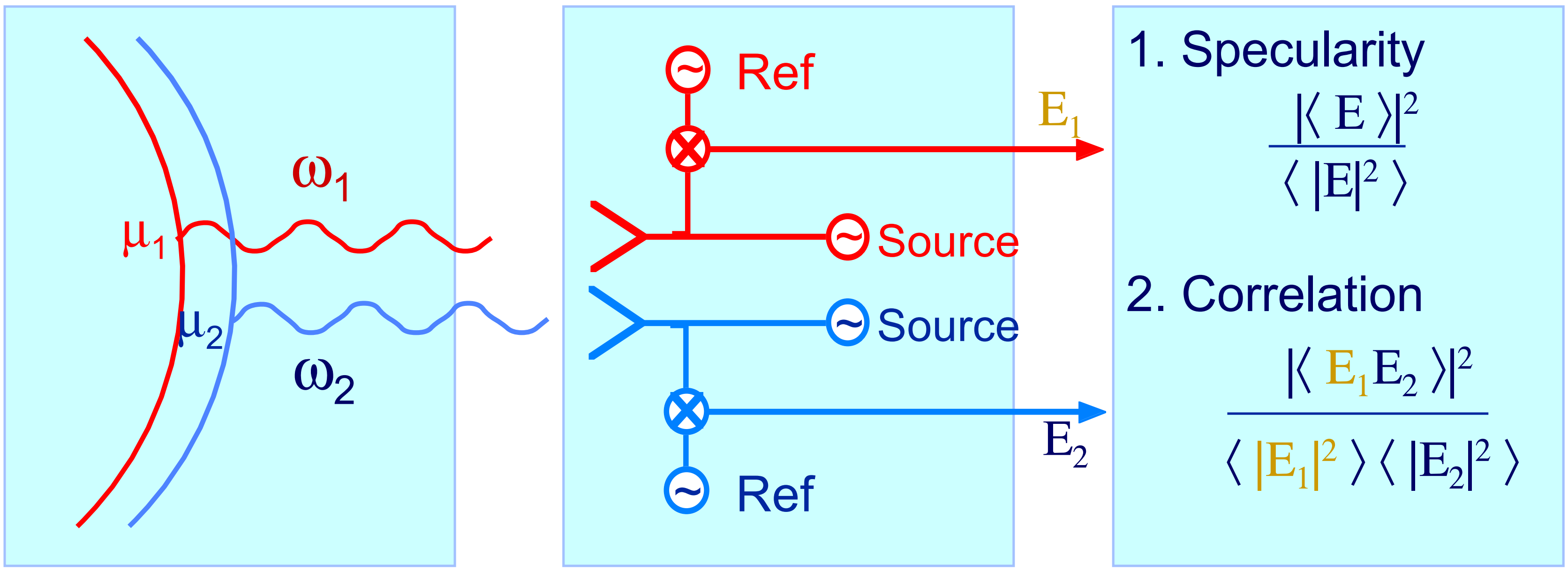
Fluctuations Ripple the Cutoff Layer, Leading to Scintillations (Amplitude Fluctuations) on Scattered Waves



- Each eddy can be considered an irregular lens: λ_c < focal length
- Amplitude fluctuations occur due to focusing away from reflecting region
- Historical note: Intense investigation of scintillations from interplanetary and ionospheric plasma lead to discovery of pulsars c1967: (Hewish, Burnell)

Measurement of Turbulent Fluctuations in Fusion Plasmas: The Method of Correlation Reflectometry

Plasma Cutoff Layers | Hardware Elements | Data Analysis

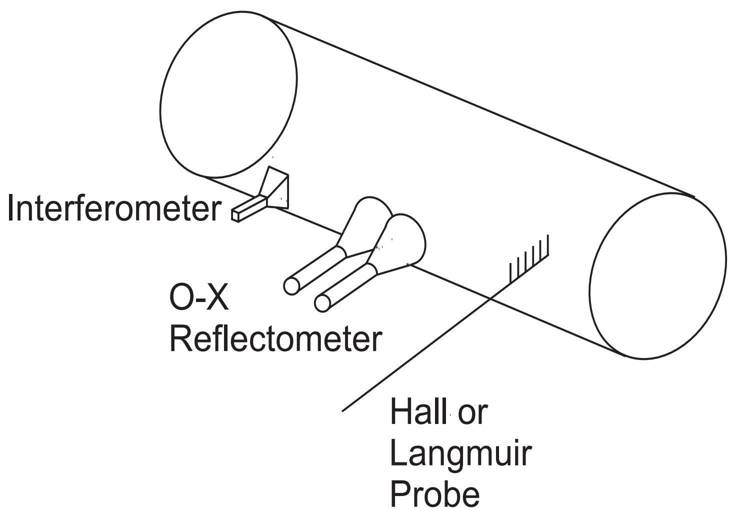


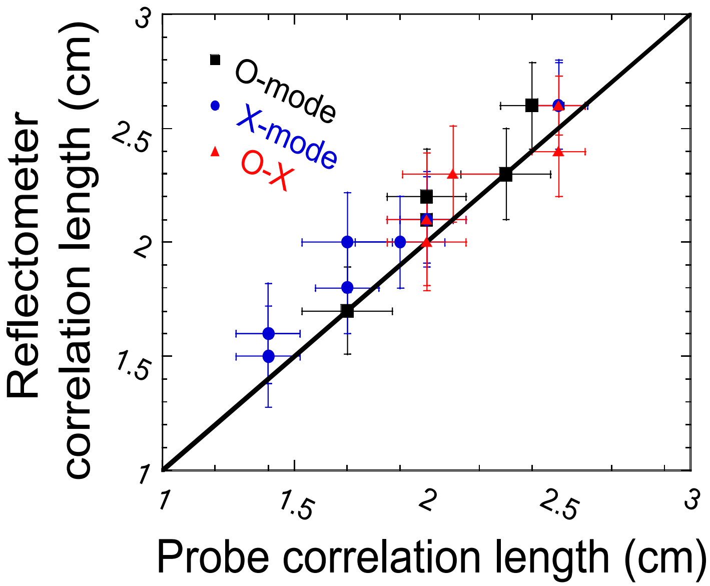
- Tune relative frequency to produce correlation vs cutoff layer separation.
- Compare with simulation using 1-D and 2-D full wave analysis.
  - density fluctuation level
  - radial density correlation length

Reflectometry Used in a World Wide Effort to Understand the Dynamics of Turbulence in Enhanced Confinement Regimes

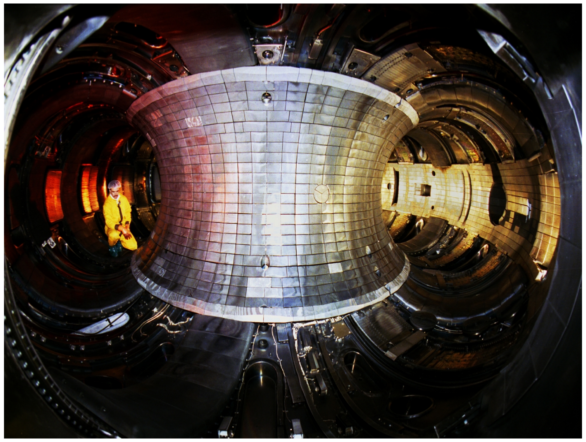
- DIII-D: NCS, QDB regime
- JET: Optimized Shear plasmas
- C-MOD: EDA regime
- JT-60U: ITB plasmas
- TFTR: ERS, Supershot
- ASDEX, TEXTOR (imaging),...

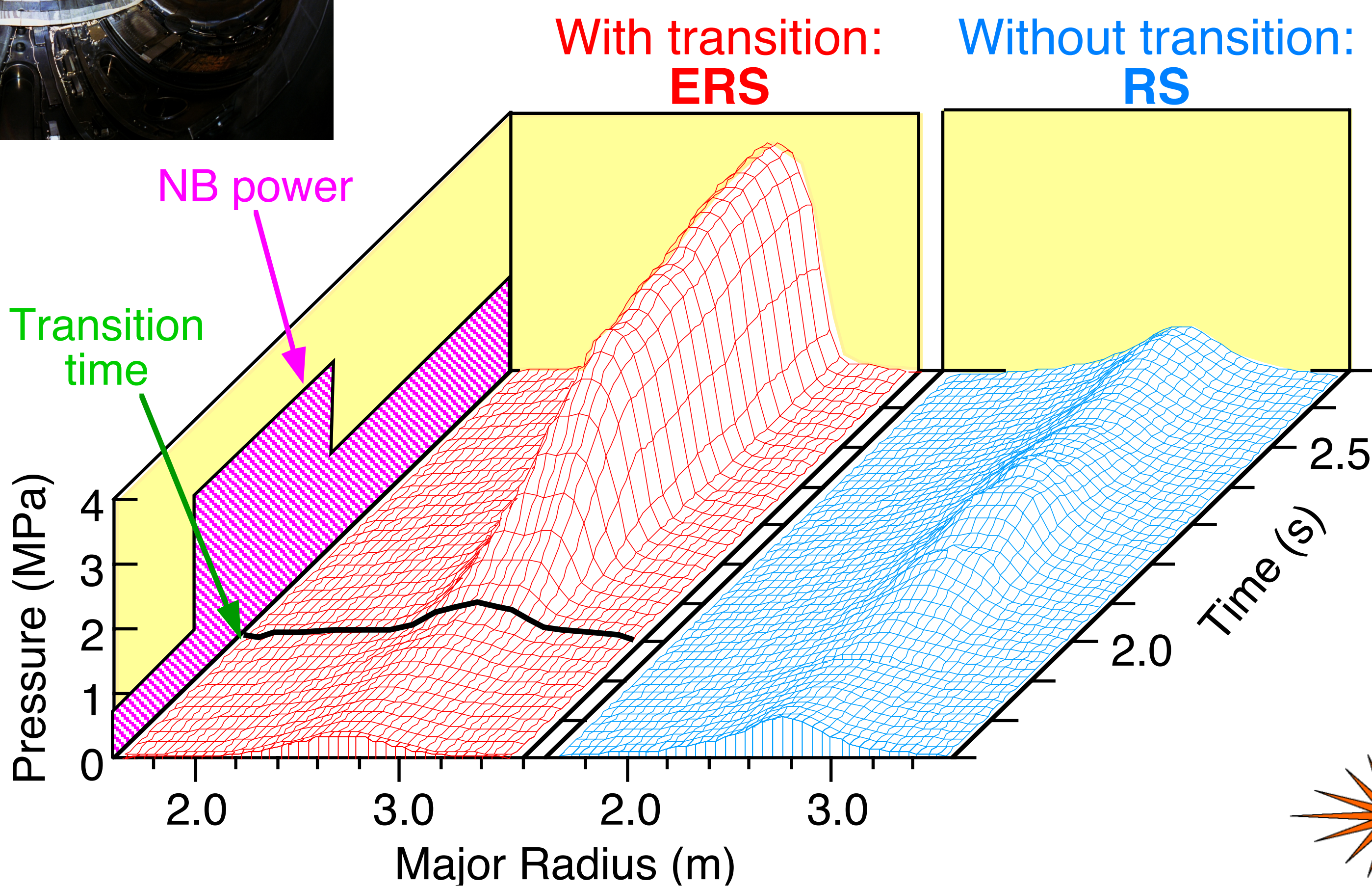
- Basic plasma experiments in correlation reflectometry and comparison to Langmuir probe measurements in LAPD/UCLA





Enhanced Reverse Shear Regime of TFTR. What Happens at the Time of the Transition to Enhanced Confinement?





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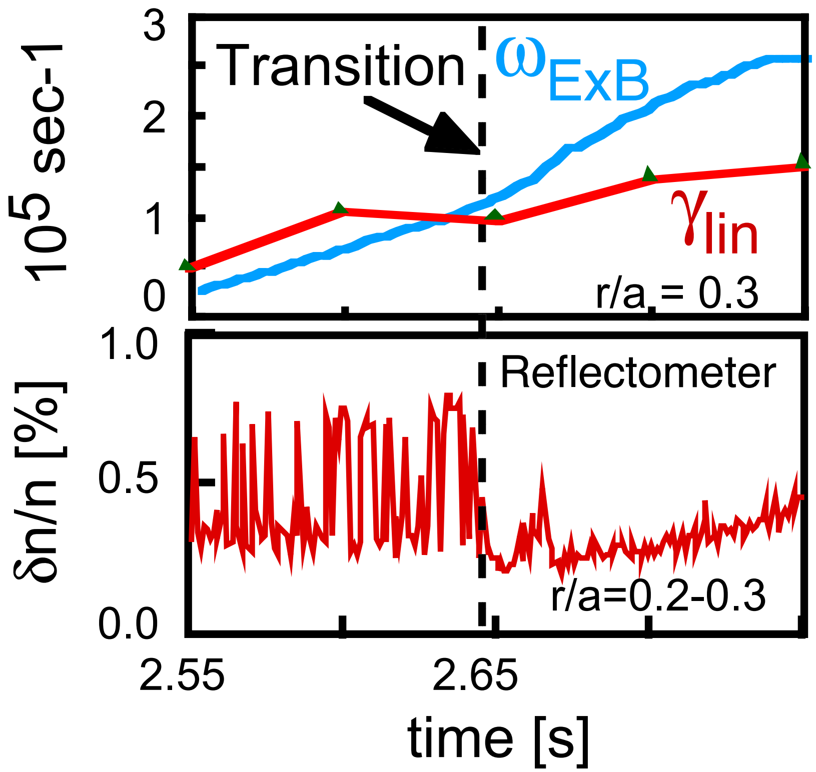
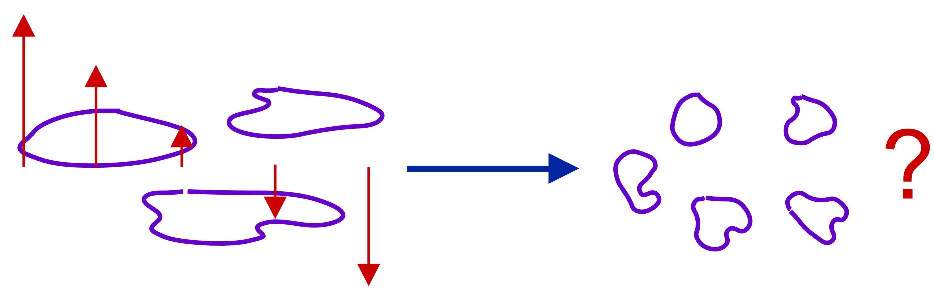
Transition to Enhanced Confinement Regime is Correlated with Suppression of Core Fluctuations in TFTR



- Theory predicts fluctuation suppression when rate of shearing (ω_{ExB}) exceeds rate of growth (γ_{lin})

- Outstanding issue:
  Is suppression accompanied by radial decorrelation?



- Similar suppression observed on JET (X-mode reflectometer) and DIII-D (FIR Scattering)

Hahm, Burrell, Phys. Plas. 1995, E. Mazzucato et al., PRL 1996.

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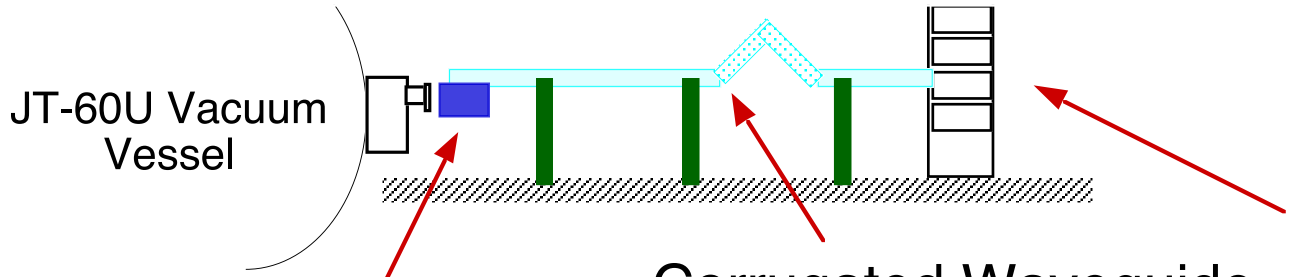
PPPL/JAERI Reflectometer Collaboration for Continuous Correlation Measurements in Transport Barriers on JT-60U

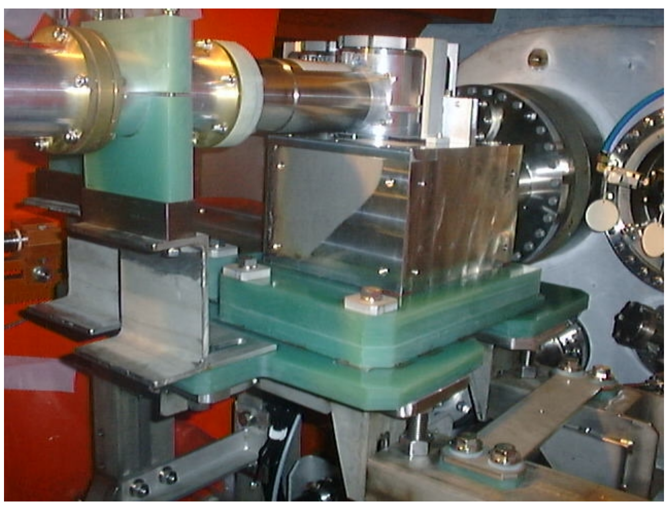
- Main element of a reflectometer system



Mirror System: GA

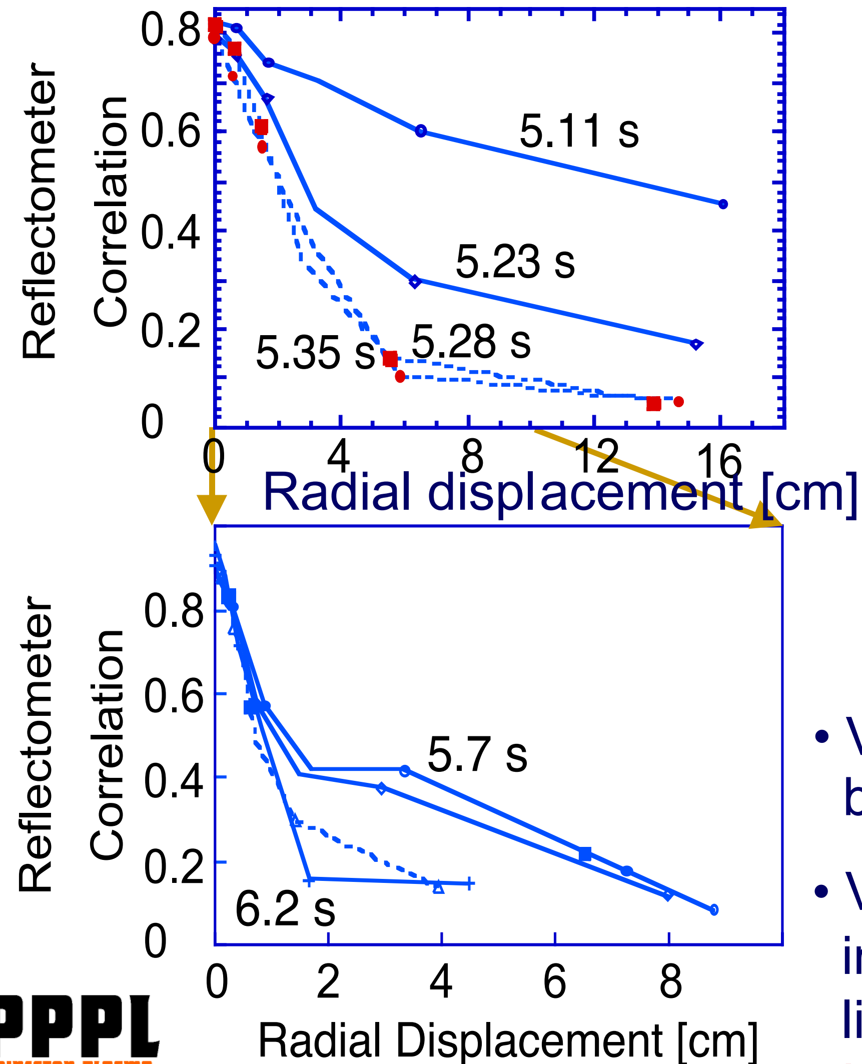
Corrugated Waveguide & Shield Box

Microwave sources

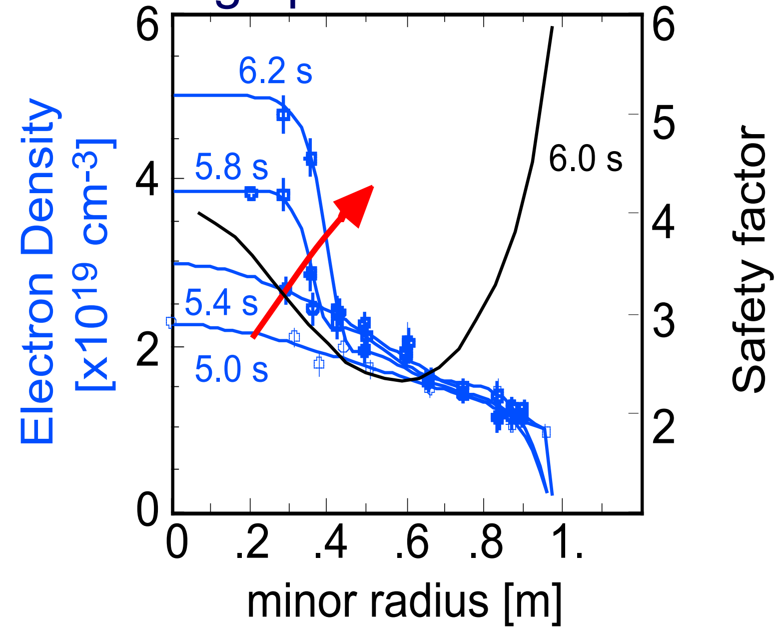


- Range: 105-140 GHz measures up to magnetic axis:
- Frequency scanning channel allows a radial correlation scan every 60 ms

Dramatic Reduction of Radial Correlation Length in ITB of JT-60U: Are We at The Limit of Our Spatial Resolution?



ITB Density Evolution:
High power NBI: 5.05s



- Very long correlation lengths before ITB formation: $L_r/\rho_i >> 1$!
- Very short correlation lengths inside ITB: close to resolution limit?
- Weak change in fluctuation level

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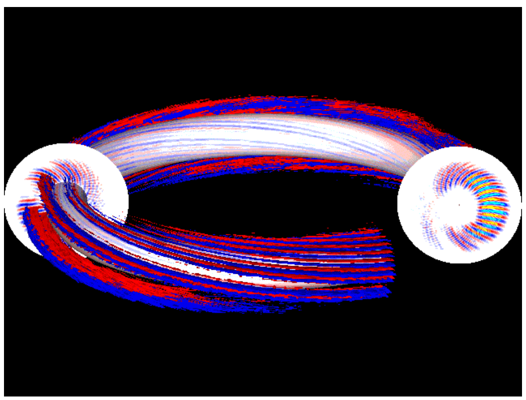
To Make Progress in Quantitative Analysis, Need Advanced Simulation *and* Visualization: Further Integration of Theory and Experiment is Essential

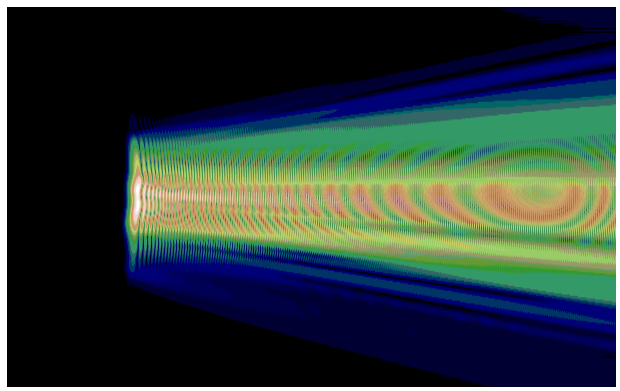
Turbulence simulation in realistic geometry: Gyrokinetic and Gyrofluid codes



Z. Lin, M. Beer

+

Full wave simulation of reflectometry in real geometry



E. Valeo, G.J. Kramer

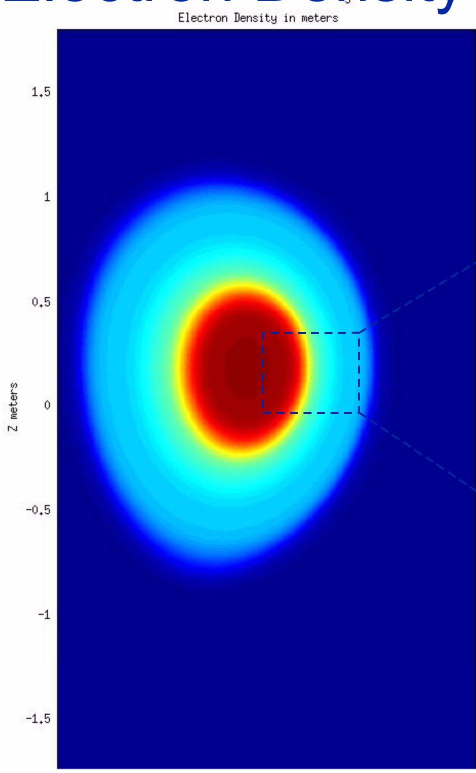
→ Major advance in quantitative analysis

→ New possibilities for experimental design

- PPPL is part of a broad effort to simulate experiment:
  - MIT (Issue of super resolution with curved wave fronts)
  - LLNL (Interpretation of pulse reflectometry with fluctuations)

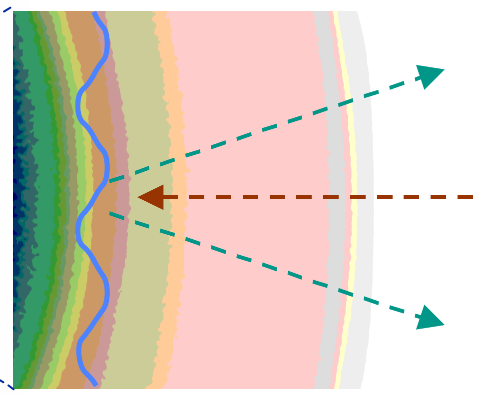
Full Wave Simulation of Reflectometry in JT-60U: Importance of Angular Spread and the Need for Antenna Modeling

JT-60U ITB Electron Density



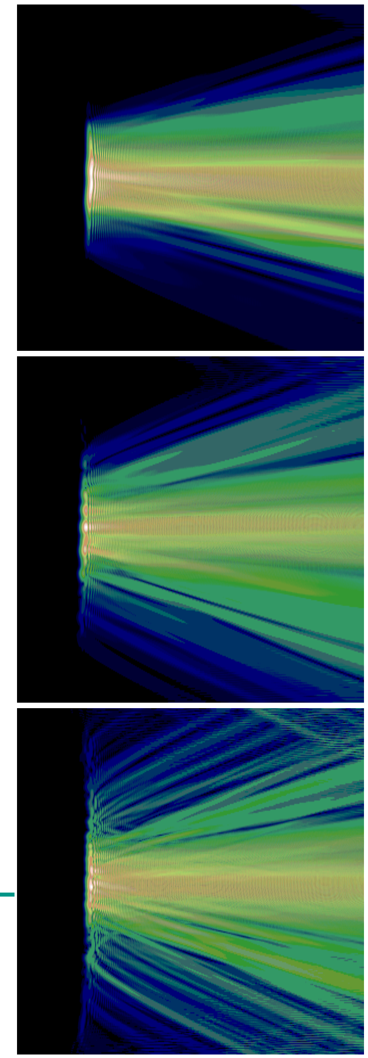
Simulation Box 40 cm (H) x80 cm (W)

$$\tilde{n}/n = 0.6\%$$



Waves scatter out of receiver aperture with increasing K_θ

Scattered Waves



$K_\theta = 1\ cm^{-1}$

receiver

$K_\theta = 2\ cm^{-1}$

$K_\theta = 4\ cm^{-1}$

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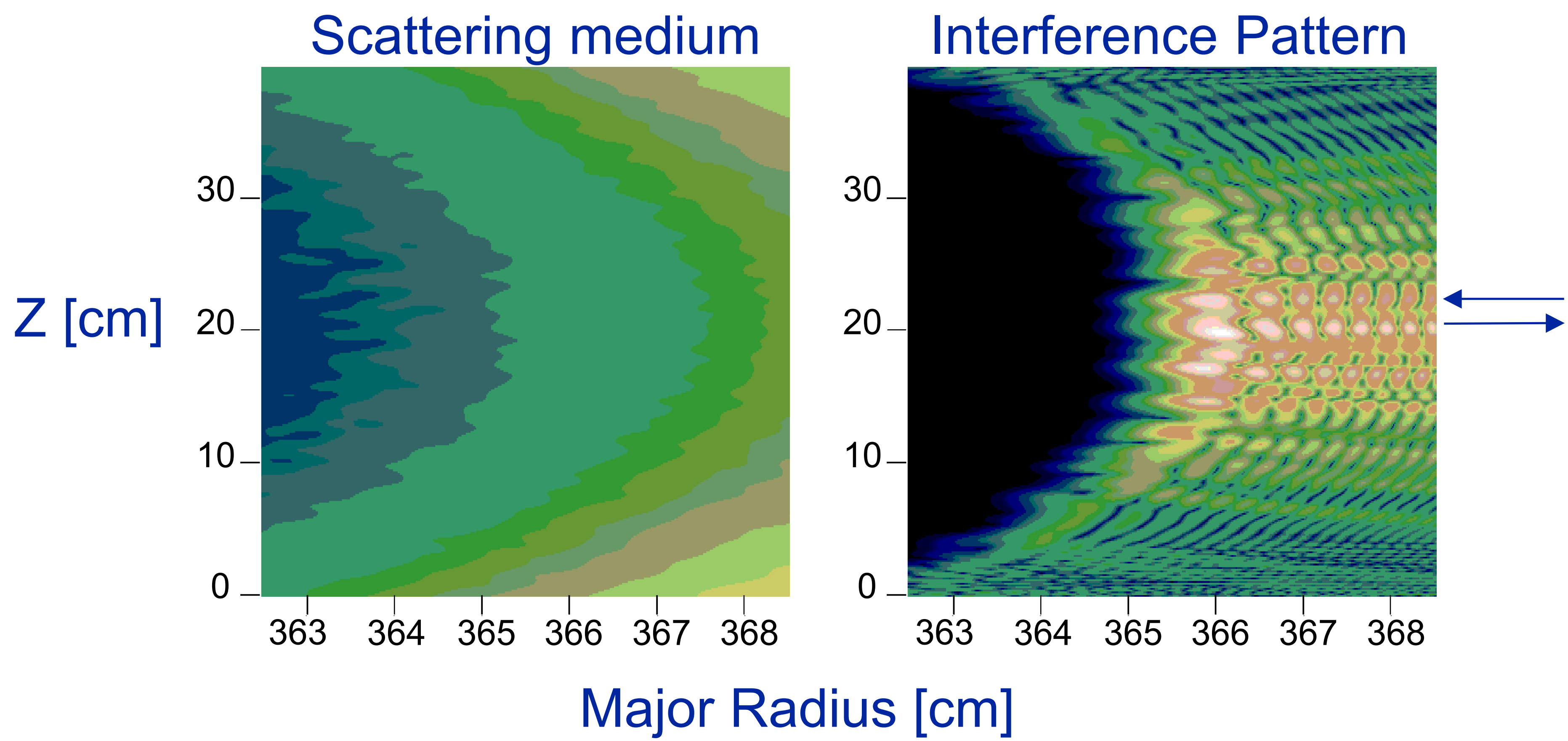
Visualization of Wave Intensity Near the Cutoff Layer: Plasma Curvature and Ripples Revealed in Reflection



- Interference fringes due to superposition of forward and backward going waves

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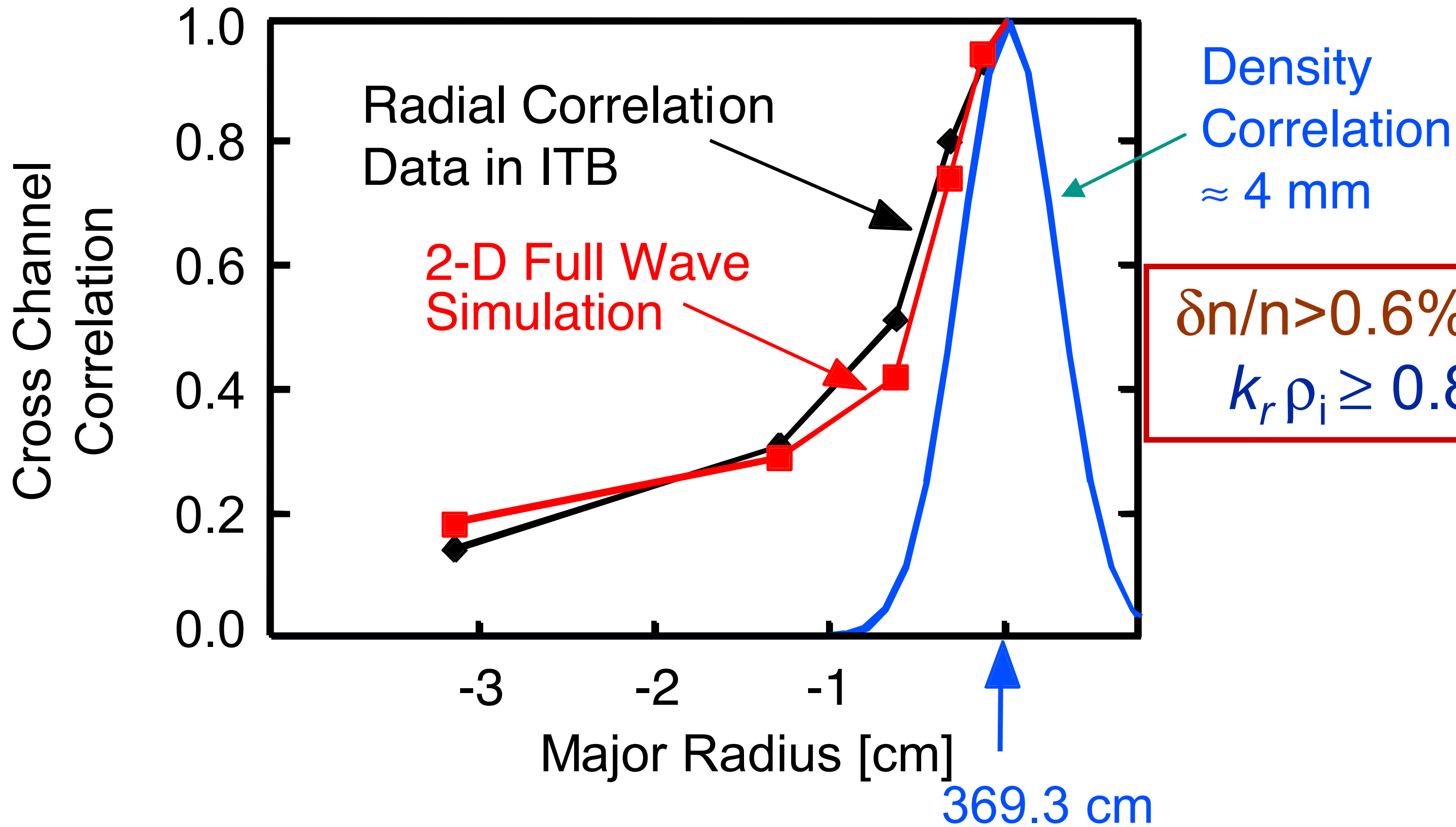
Bottom Line: 2-D Simulation of Correlation Reflectometry inside ITB Reproduces Experimental Data



$\delta n/n > 0.6\%$, $k_r > 5$: $k_r \rho_i \geq 0.8\text{-}1.0$

- Gaussian spectrum of model fluctuations, ensemble of 30 runs per correlation
- Higher k_r produce similar result

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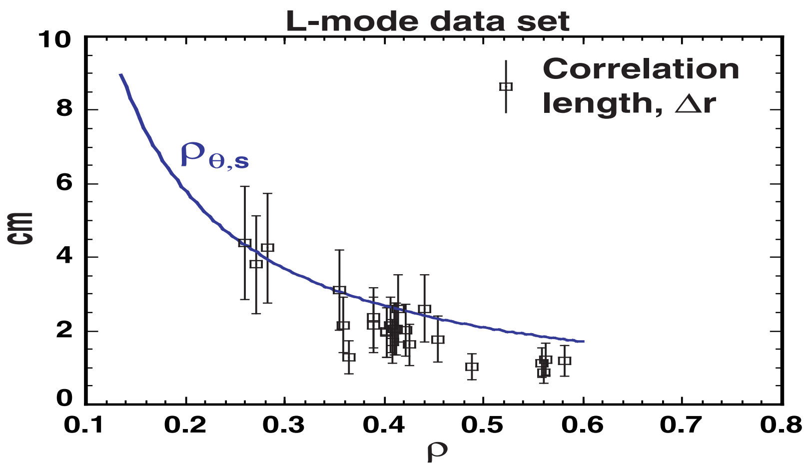
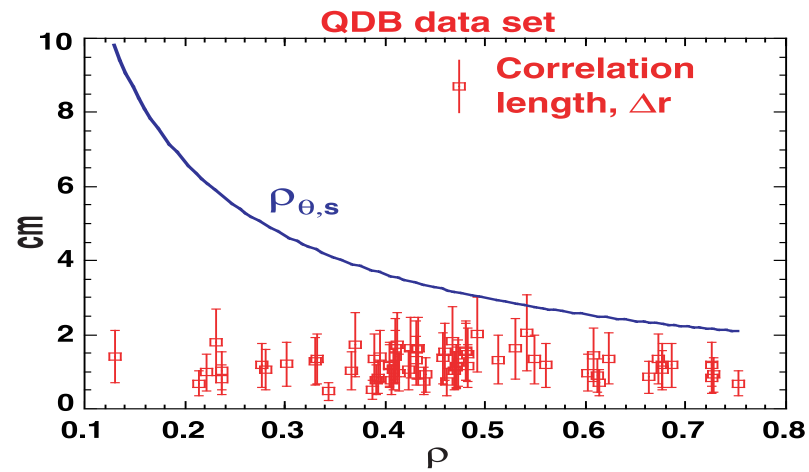
measurement at spatial resolution limit

JAERI

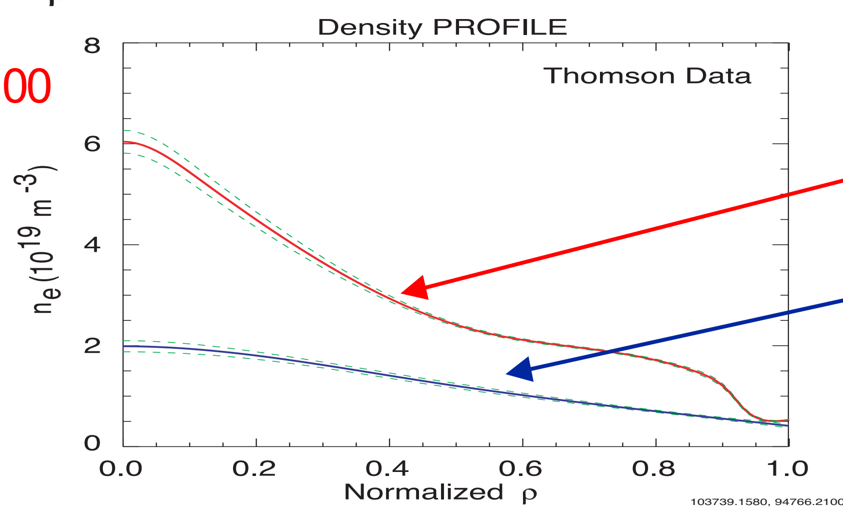
Reflectometry Provides Strong Evidence for Role of Radial Turbulence Decorrelation in Enhanced Confinement on DIII-D

- **In L-mode, correlation lengths Δr are observed to scale approx. as $\rho_{\theta,s}$ (or 5-8ρ_s).**
- **In QDB plasmas, central correlation lengths Δr is reduced.**





Doyle et al., IAEA 2000



$n_e(r)$ Quiescent Double Barrier

$n_e(r)$ L-mode

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Reflectometry Has Been Highly Successful in Measuring Fluctuation Characteristics in Transport Barriers

New measurements and advanced simulation provide new insights & challenges:

- detailed investigation of ExB shear and turbulent decorrelation

Outstanding issues:

- Role of zonal (turbulence induced) flow shear on correlation length (can we measure it with reflectometry?)
- What is the trigger for transition to enhanced confinement? (can we tell by looking at turbulence?)

Measurement issue:

- What are the potential benefits of multiple receivers?
- What more can be resolved?

Can we Perform Imaging with Reflectometry? New Insights can be Gained from Detailed Understanding of Turbulent Structures

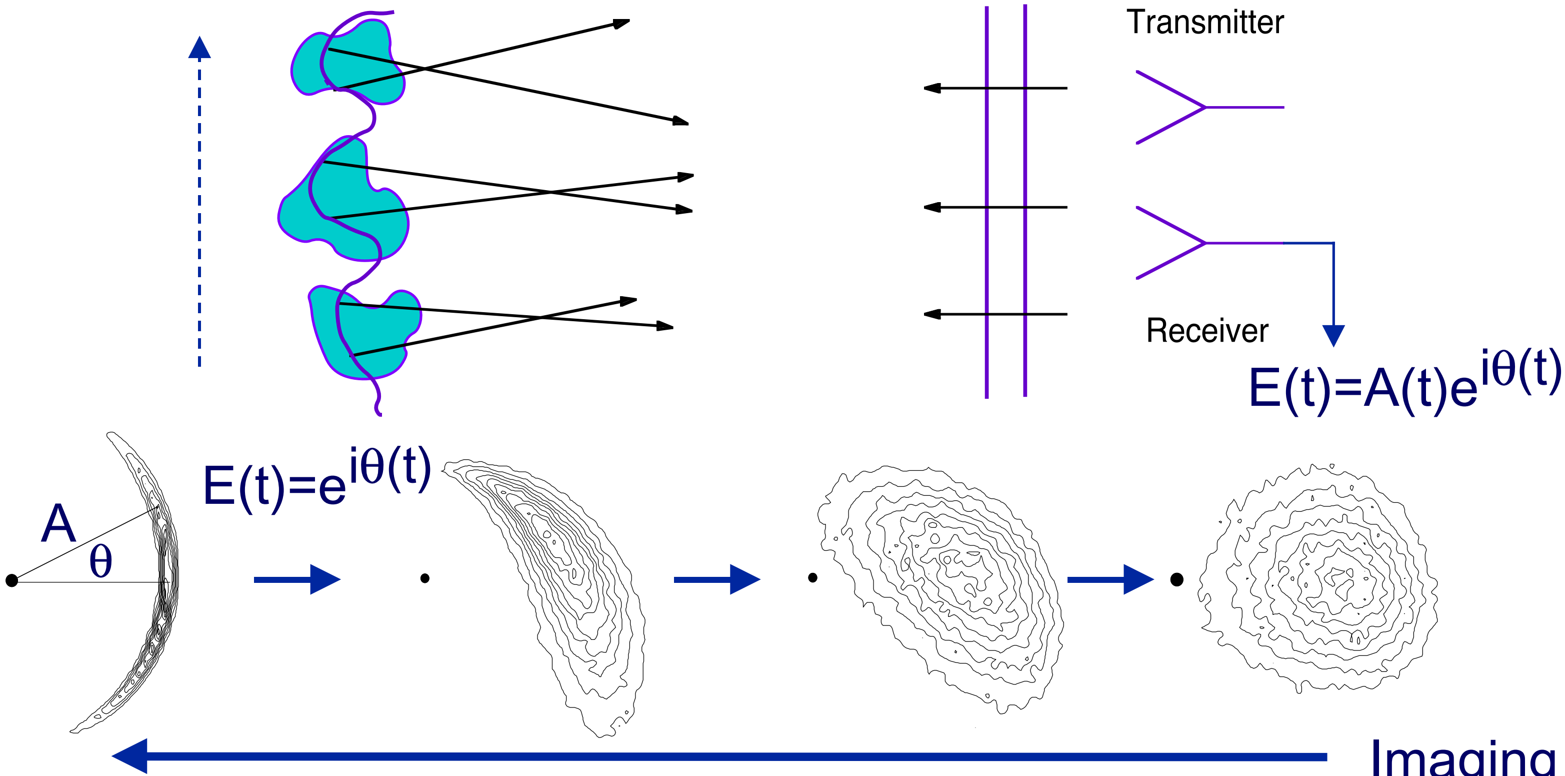
David Hysell
Equatorial Bubbles

- Example of backscatter image of Ionospheric instability F-Layer.
- Evidence for rising plumes (plasma bubbles) consistent with simulations of Rayleigh Taylor instability.

Two point correlation analysis performed up till now is only a first step towards detailed understanding

Is Imaging Possible in Fusion Plasmas? Need to Look for Evidence of a Thin Scattering Region Near Cutoff Layer

- A narrow scattering region is equivalent to a thin phase changing screen
- Problem! How can we tell if the scattering comes from a thin layer?



- Key insight (first investigated in ionosphere, Mercier, Phil. Mag. 1959):
  - Look for pattern of amplitude spread from a thin phase screen

Analysis of Reflectometer Data on TFTR Suggests Imaging May Be Possible!

- Analysis: Project signal back into plasma and search for a plane with reduced amplitude fluctuation

- Numerical procedure

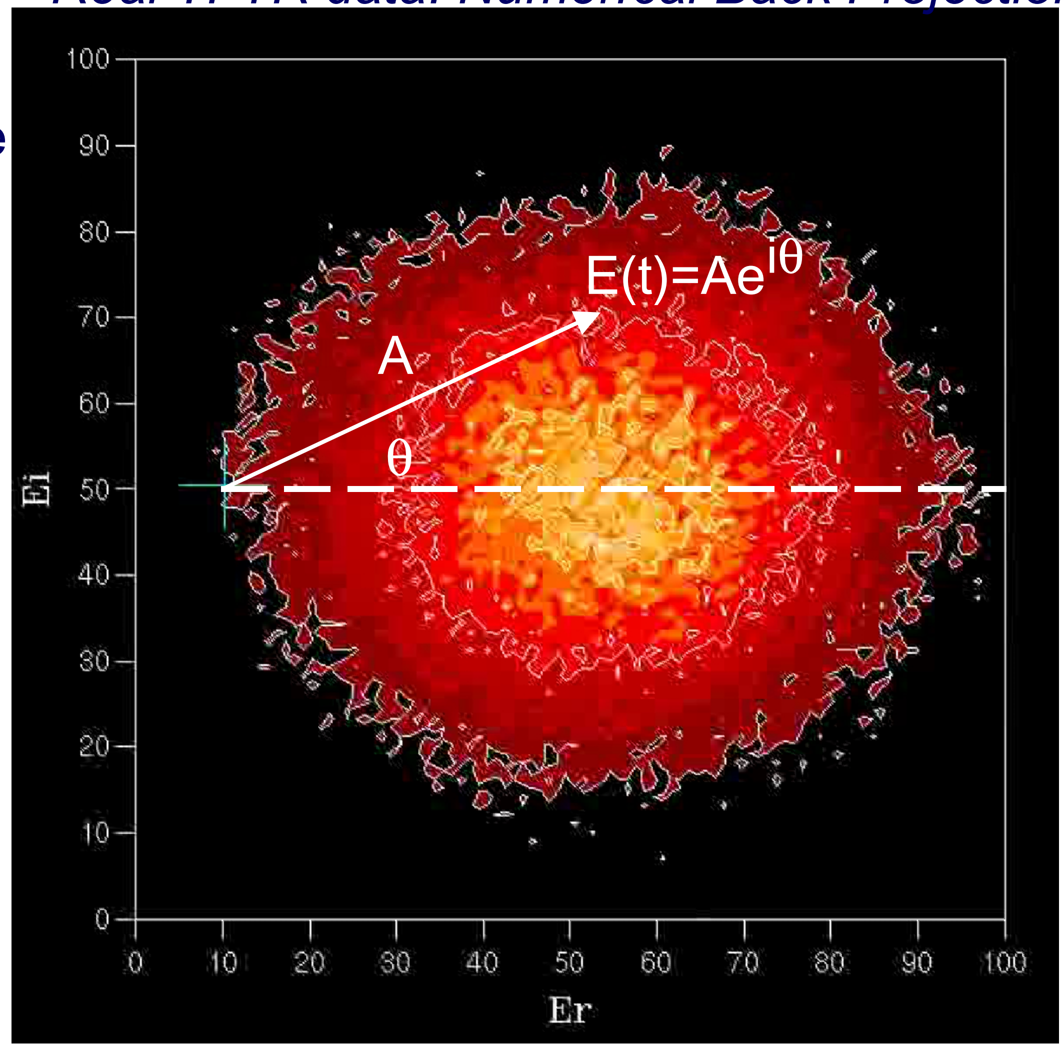
1) Assume $\omega \propto k_\theta$

2) Add phase dispersion $\exp(i\beta\omega^2)$ - (Lens)

3) Recompute amplitudes and phases

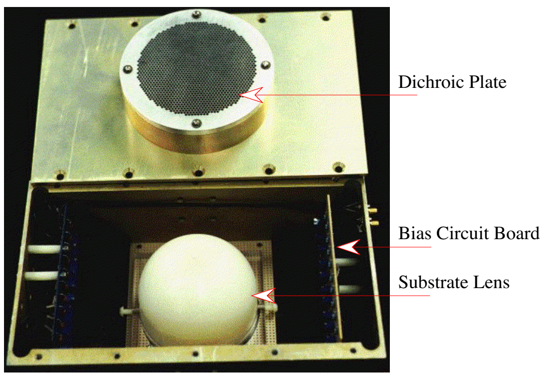
4) Plot field distribution →

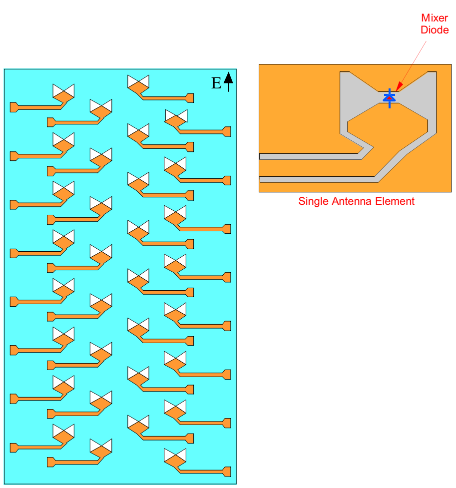
Real TFTR data: Numerical Back Projection

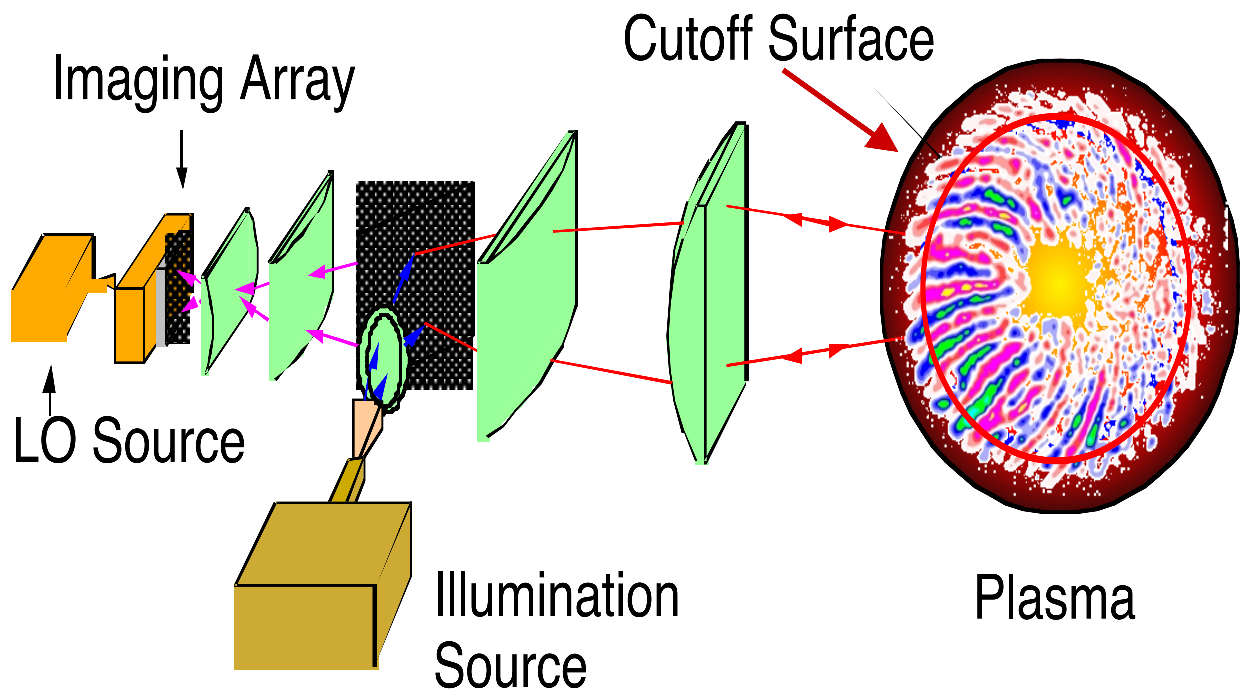


New System Now Under Development on TEXTOR to Explore the Feasibility of Imaging

- Array of receivers







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Summary and Future Directions

- The recent progress in reflectometry exemplifies the excitement of science when experiment and theory combine to push the limits of what is possible

- New observations of turbulent decorrelation in internal transport barriers challenge theory and experiment

    - need systematic analysis of ExB shear, decorrelation
    - need to identify trigger for transition
    - need comparison to simulations

- Key to future success is the integration of experiment and theory through advanced scientific simulation and visualization

    - drives quantitative interpretation of measurements
    - drives innovation in diagnostic ideas (imaging,…)
    - drives non-linear simulation of turbulence, new theory insight