Unraveling the Nature and Impact of Quasi-2D Turbulence on Transport in Magnetized Plasmas:

Utilizing the DIII-D Tokamak to Explore Frontier Plasma Science

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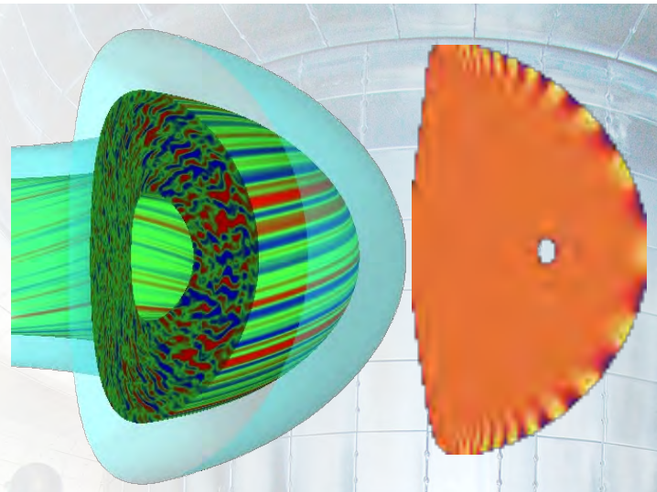

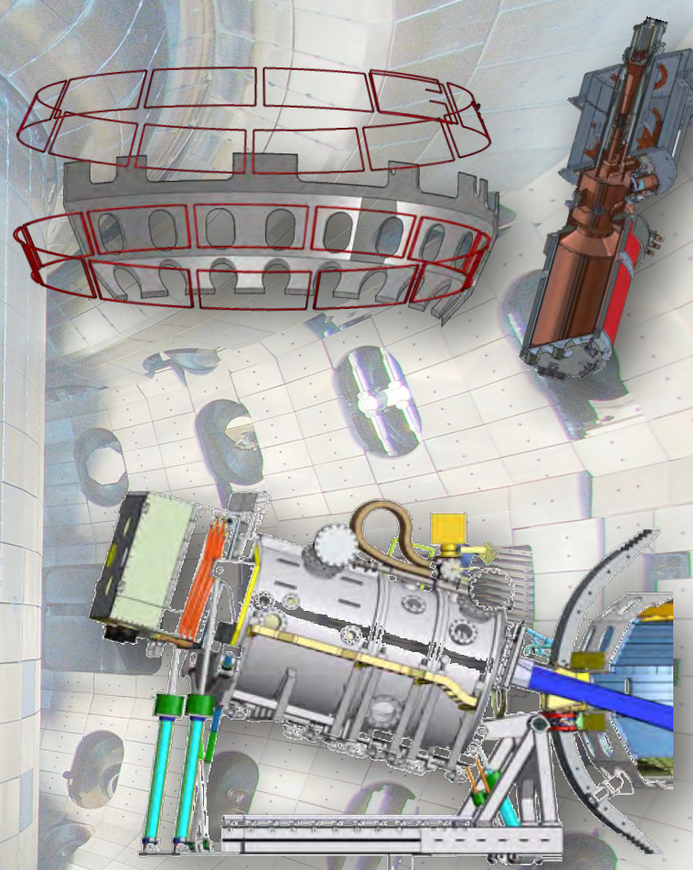

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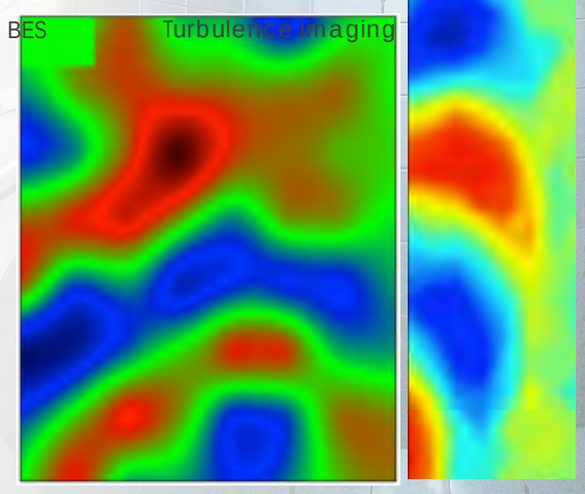
Workshop-Town Hall Meeting

Bethesda, Maryland
June 30-July 1, 2015



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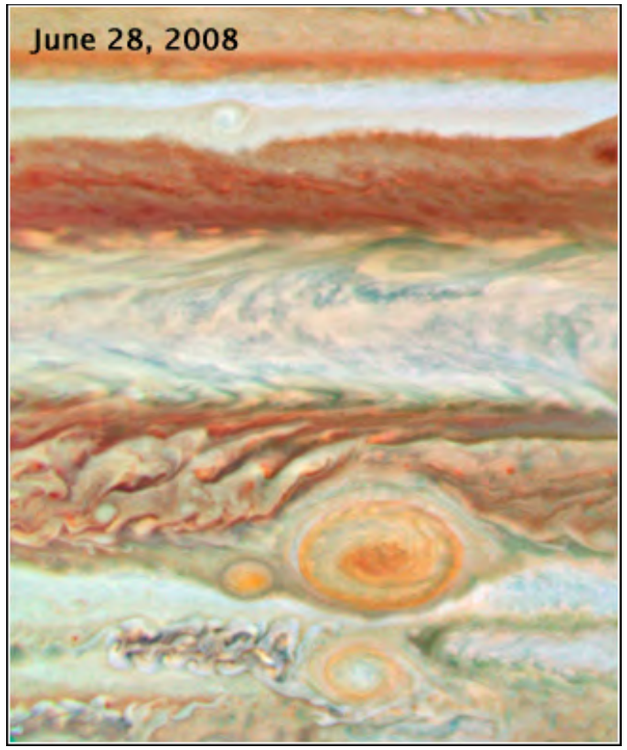
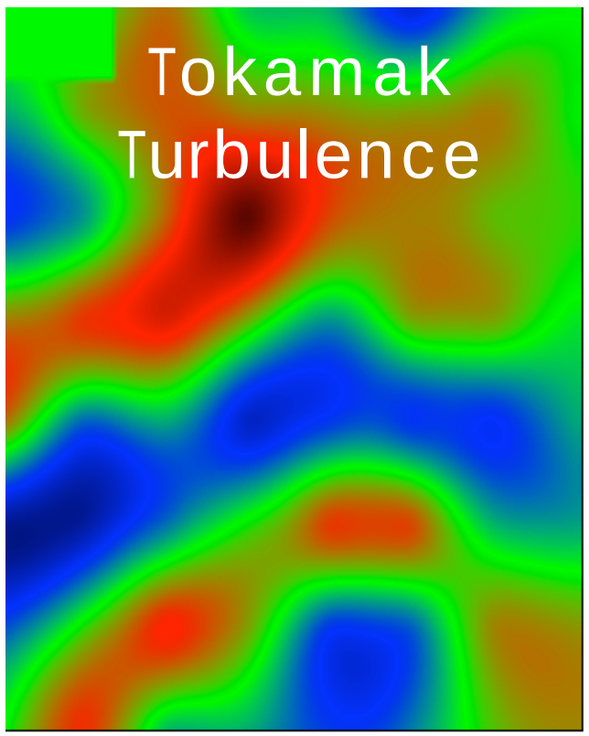
Plasma Turbulence is a Compelling Scientific Problem and a Challenge for the Development of Fusion Energy

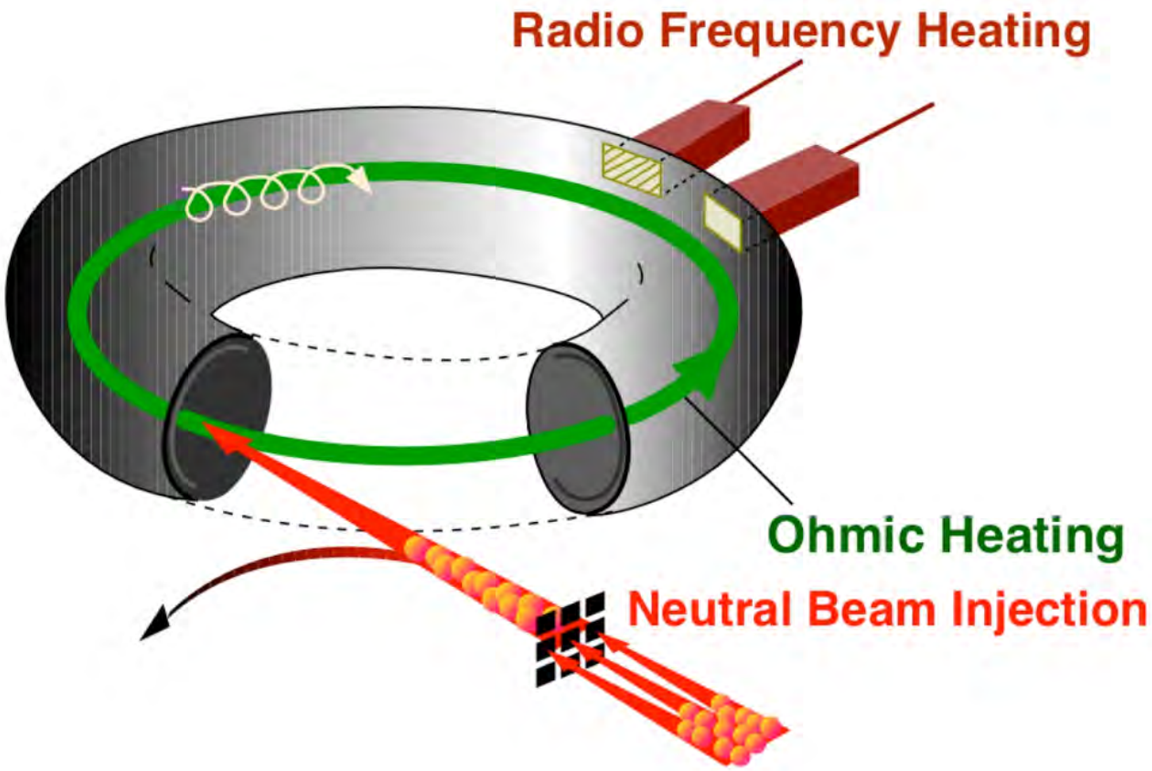
- Nonlinear dynamics across multiple scales
  - Strong connection to related research fields
    - *Fluid dynamics, geo/planetary fluids, astrophysics*
- Understanding turbulence and turbulent transport is critical to fusion energy:
  - Drives transport of energy, particles & momentum
  - Sets global energy confinement time
  - Determines size of fusion reactors
- Goal: Explore opportunities to advance frontier plasma science on DIII-D
  - Advance fundamental plasma research
  - Complement plasma physics for fusion sciences
  - Applies to other fusion plasma facilities: NSTX-U, C-MOD
    - Topologically similar; different parameters

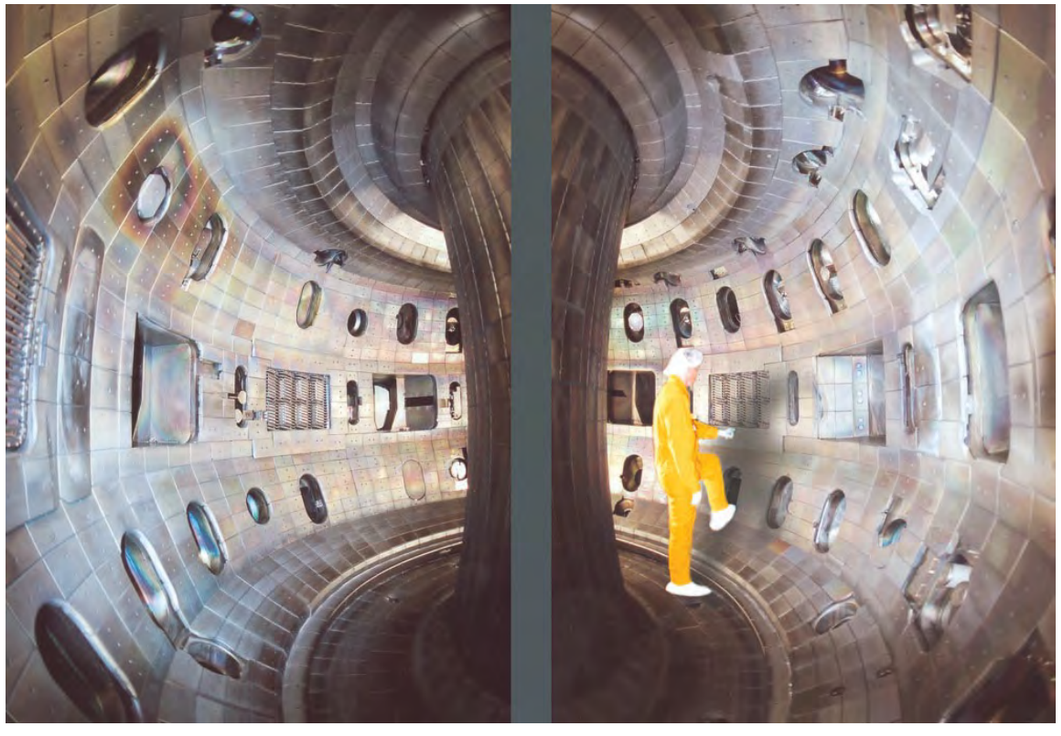




The DIII-D Tokamak Advances Plasma Science Through Implementation of Advanced Capabilities, Heating Systems

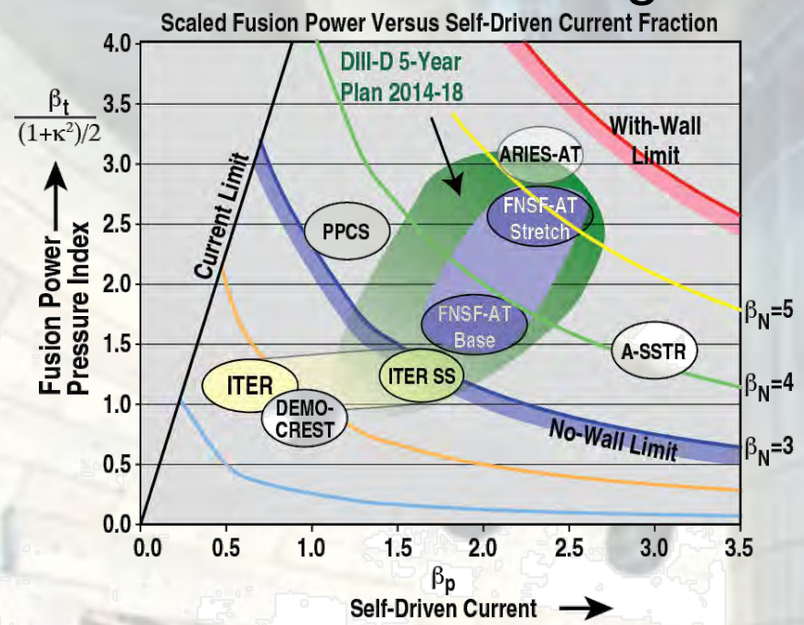
- Toroidal magnetic confinement system:
  - Deuterium, hydrogen, helium
  - Applied toroidal magnetic field: 2.1 T
  - Ohmic current: 1.6 MA (B_θ~0.4 T)
  - Neutral Beam (Ion) Heating: 20 MW
  - Electron Cyclotron Heat: 4 MW/110 GHz
  - Flexible shaping via external coils
  - R_{MAJOR}~1.7 m, R_{MINOR}~0.6 m
  - Carbon/graphite first walls
- Fusion-relevant plasma parameters:
  - T_i~10 keV, T_e~ 5 keV, n_e~5x10^{19} m^{-3}
- Burning Plasma Physics Topical Area
  - Turbulence and Transport
  - Energetic particles & instabilities

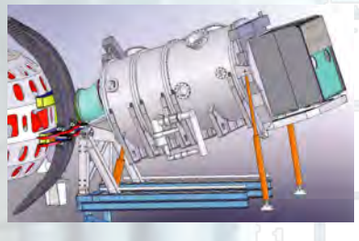




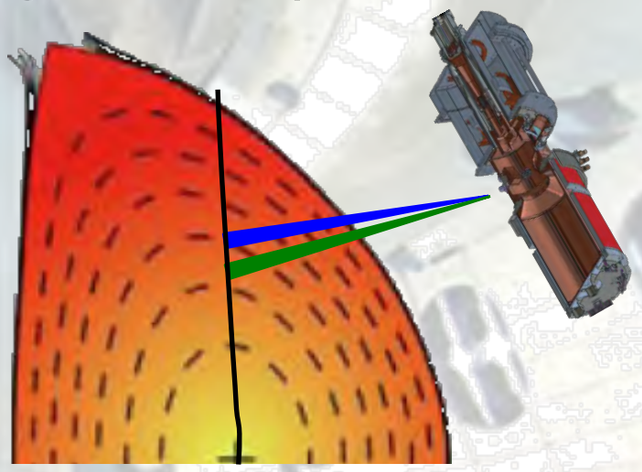
DIII-D Research Motivated by Challenge to Advance the Science of High-Temperature Fusion Plasmas

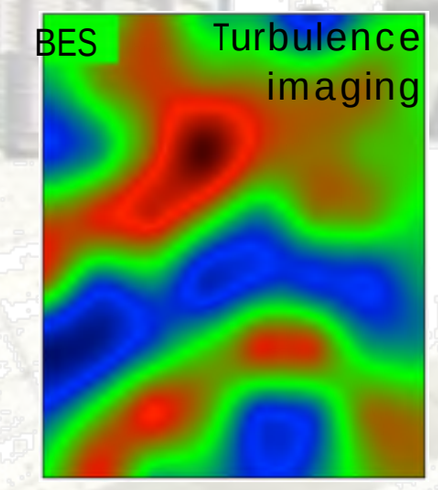
- Access relevant regimes & physics



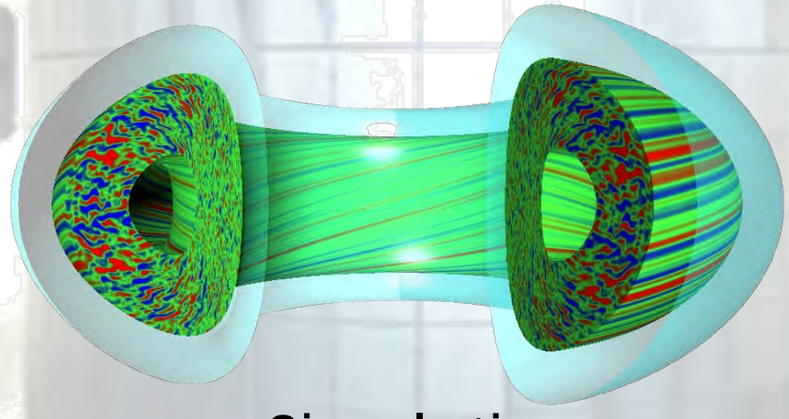


- Vary parameters to test physics & optimize behavior

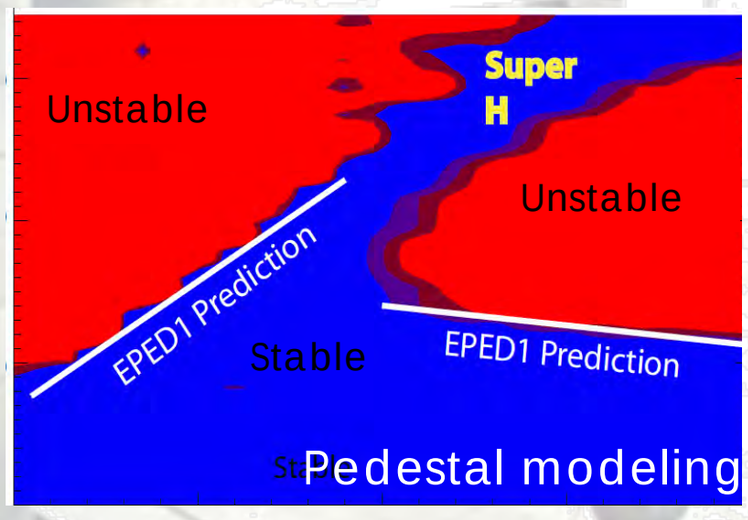




- Innovative diagnosis



- Simulation



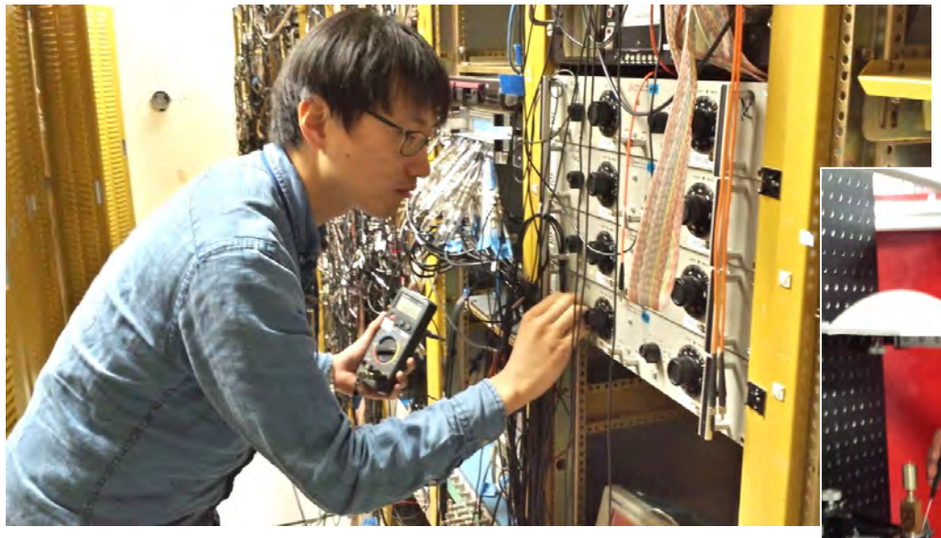
- Pedestal modeling

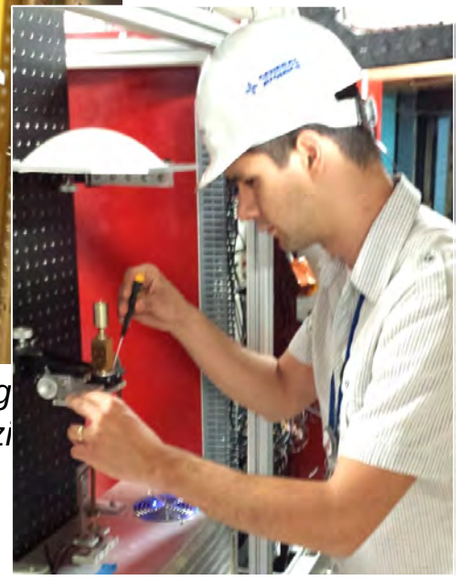
- Exploration

Provide confidence to project solutions to future devices

DIII-D Provides a Vibrant Research Environment & Opportunities for University Collaboration: Students, PostDocs

- Training of PhDs on projects that enable leading edge contributions
- Experimental run-time to support student theses
  - Annual Research Opportunity Forum
  - Student seminar series
- Publications, Invited talks





UCLA Postdoc, Choongki Sung & PhD student Lazlo Bardoczi

University Collaborations at DIII-D

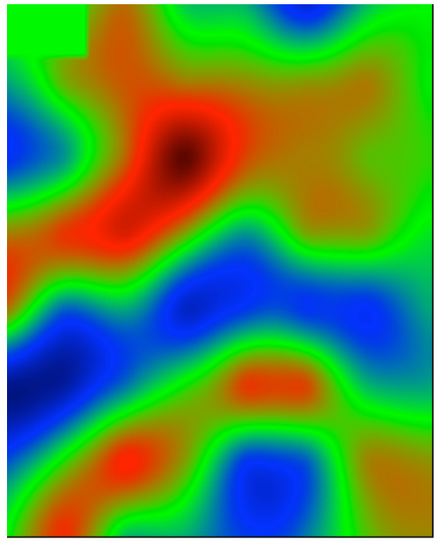
Columbia	Resistive Wall Mode control, High Pressure plasma scenarios
MIT	Fluctuation Diagnostics: Phase Contrast Imaging
UC Davis	Microwave Imaging and Electron Cyclotron Emission Imaging
UC-Irvine	3D turbulence: Gyrokinetic sims Energetic Particle Diagnostics and Research
UCLA	Fluctuation Diagnostics: CECE, DBS, CPS, Profile Reflectometry
UCSD	Probe, fast camera diagnostics, L-H transition, disruption physics
U. Texas	Electron Cyclotron Emission, Te diagnostic, Transport studies
U Toronto	Boundary Physics, Swing Probe, Materials code
U Wisconsin	Fluctuation Diagnostics and Turbulence Research: Beam Emission Spectroscopy & UF-CHERS

Goals for Plasma Turbulence Research in Magnetized Plasmas

- Understand the behavior, properties and dynamics of turbulence in magnetically confined plasmas
  - What is the nature of fully saturated turbulence?
  - How does it affect plasma behavior and performance?
  - Can we control turbulence?
- Develop experimentally validated turbulent transport simulations
  - Essential to extrapolating our understanding to fusion energy systems

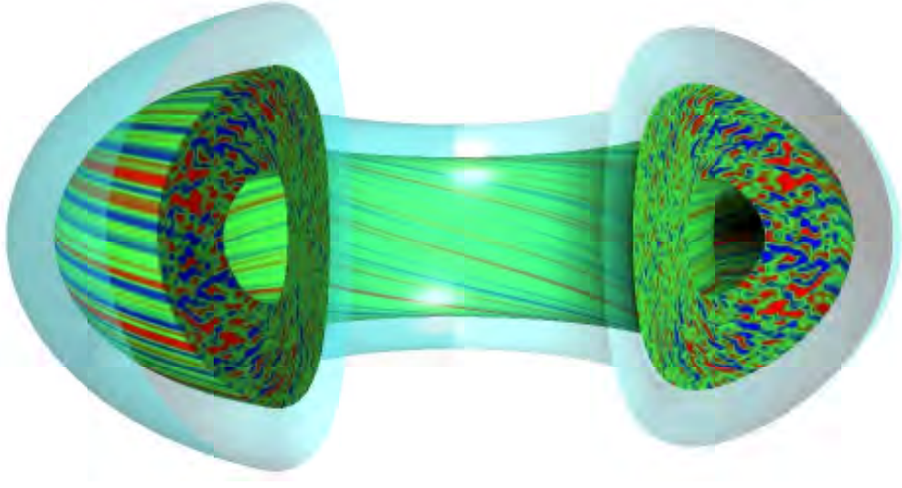
Analytic Theory

$$\frac{\partial \bar{f}}{\partial t} + \left(v_{\parallel}\hat{\mathrm{b}} + \mathrm{v}_E + \mathrm{v}_d\right)\cdot\nabla\bar{f} + \left(\frac{q}{m}E_{\parallel} - \mu\nabla_{\parallel}B + v_{\parallel}\left(\hat{\mathrm{b}}\cdot\nabla\hat{\mathrm{b}}\right)\cdot\mathrm{v}_E\right)\frac{\partial \bar{f}}{\partial v_{\parallel}} = 0$$



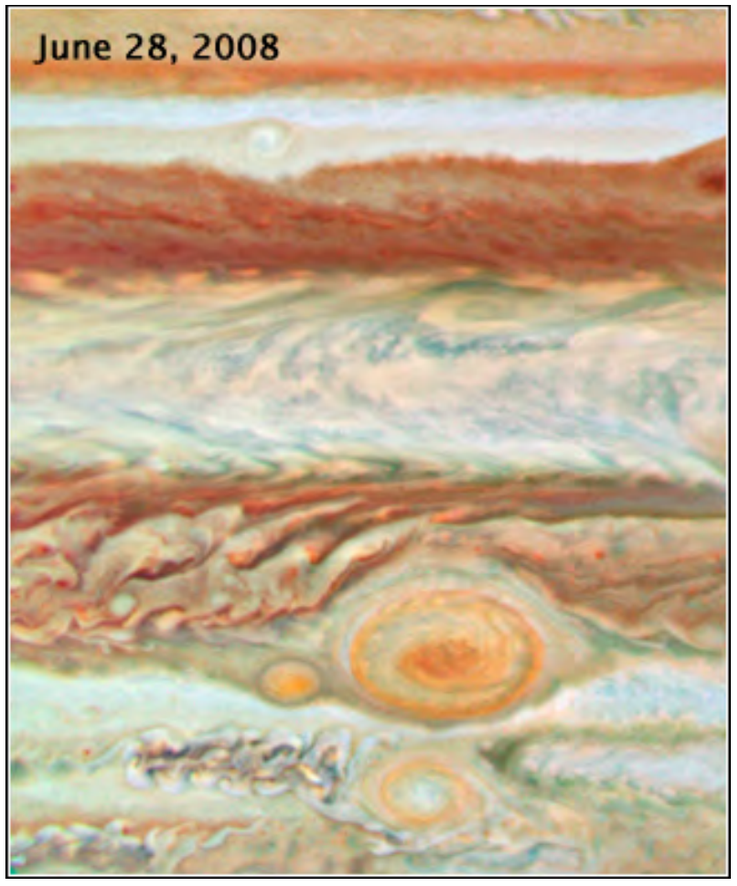
Experiment

Nonlinear Simulation



Turbulence in Geophysical Fluids and Magnetized Plasmas Exhibit Many Common Physical Features

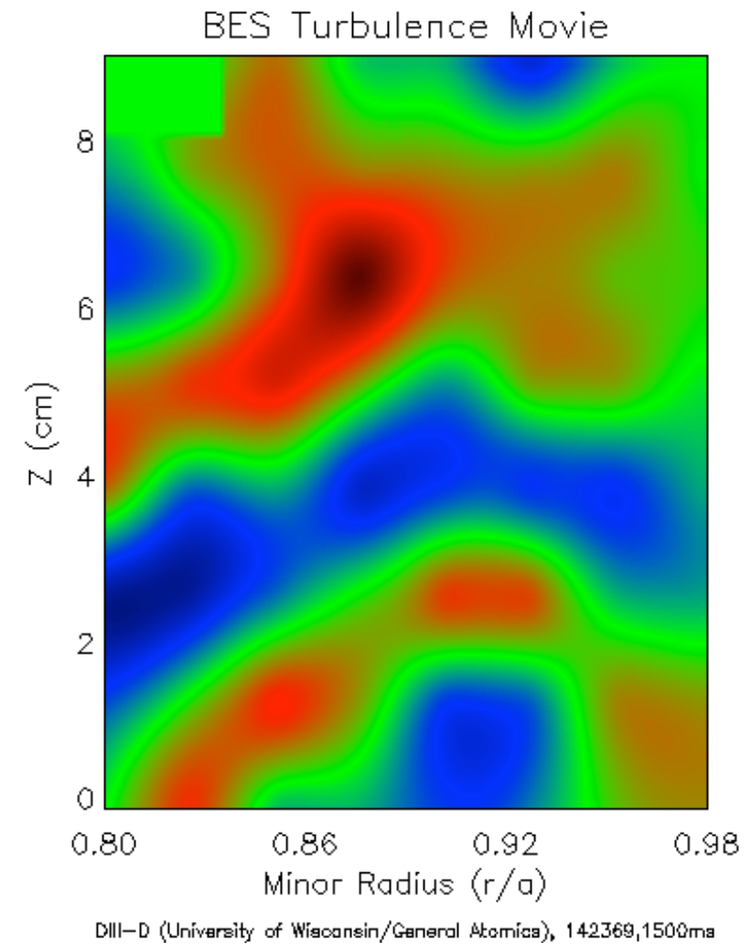
Planetary Atmosphere



2-Dimensional
∇P-driven turbulence

Inverse Energy
Cascades

Plasma Turbulence



Coriolis Force ⟷	Rotation Source ⟷	Lorentz (vxB)
Equatorial (Solar) ⟷	Energy Source ⟷	Central (Ohmic, NB, Fusion)
Polar Regions ⟷	Energy Sink ⟷	Pedestal to Divertor
Charney-Okukhov ⟷	Equations ⟷	Hasegawa-Mima
Rossby Waves ⟷	Waves ⟷	Drift Waves
Jet Stream ⟷	Meso-Scale Flows ⟷	Zonal Flows

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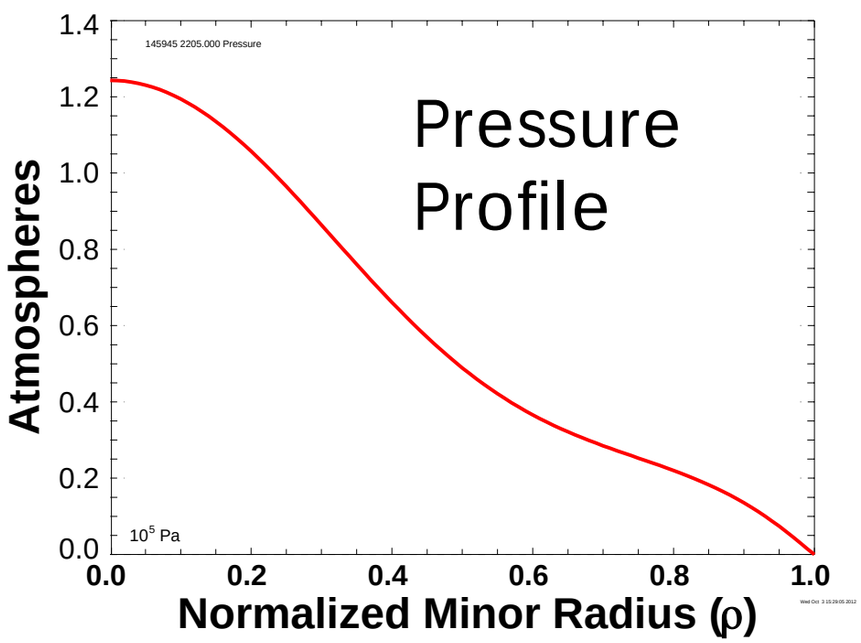
∇P-Driven Turbulence Drives Cross-Field Transport of Particles, Energy, and Momentum in Magnetically-Confined Plasmas

Free Energy Source:

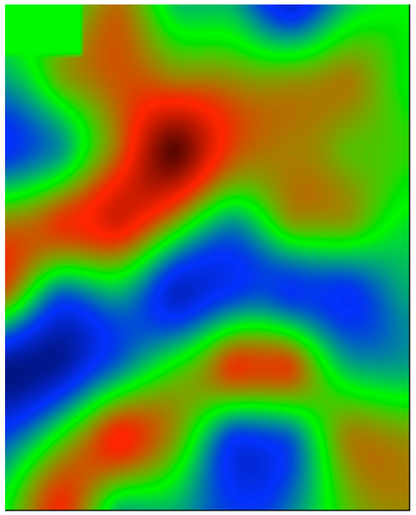
$$\nabla n, \nabla T_{i,e}, \nabla U$$

Turbulence

$$\tilde{n}, \tilde{T}, \tilde{\phi}, \tilde{B}$$



Transport



Particle Flux: $\Gamma = \langle \tilde{n}\tilde{v}_r \rangle - \dfrac{\langle \tilde{J}_{\parallel}\tilde{B}_r \rangle}{eB_\phi}$

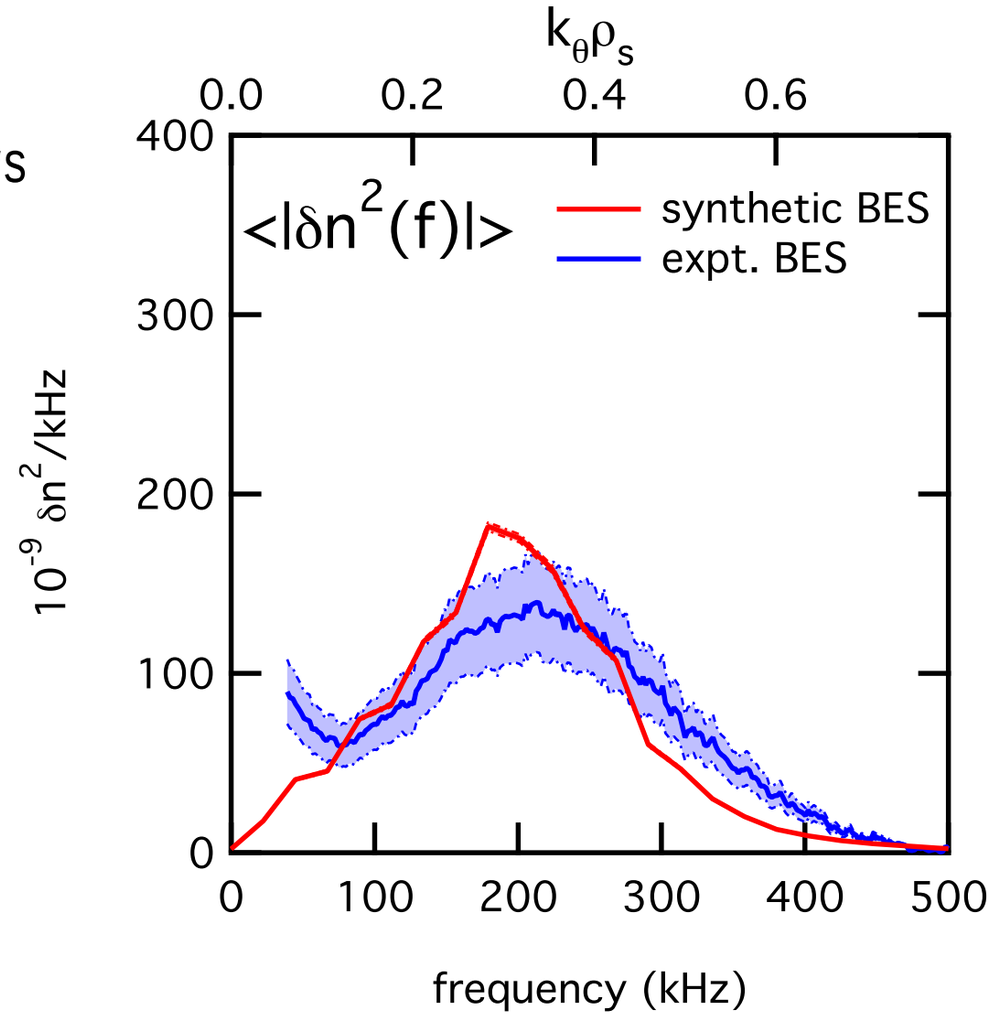
Heat Flux: $Q = n\langle \tilde{v}_r\tilde{T} \rangle + T\langle \tilde{n}\tilde{v}_r \rangle + \dfrac{\langle \tilde{Q}_{\parallel}\tilde{B}_r \rangle}{B_\phi}$

Electrostatic

Electromagnetic

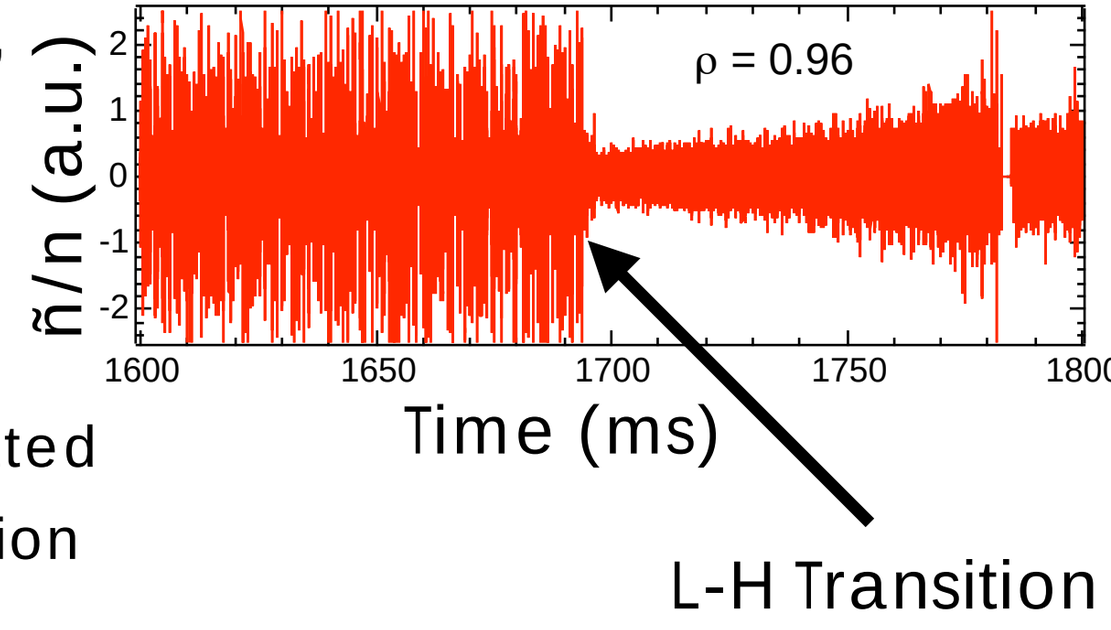
Numerous Outstanding Research Topics in Turbulence and Transport in Magnetized Toroidal Plasmas

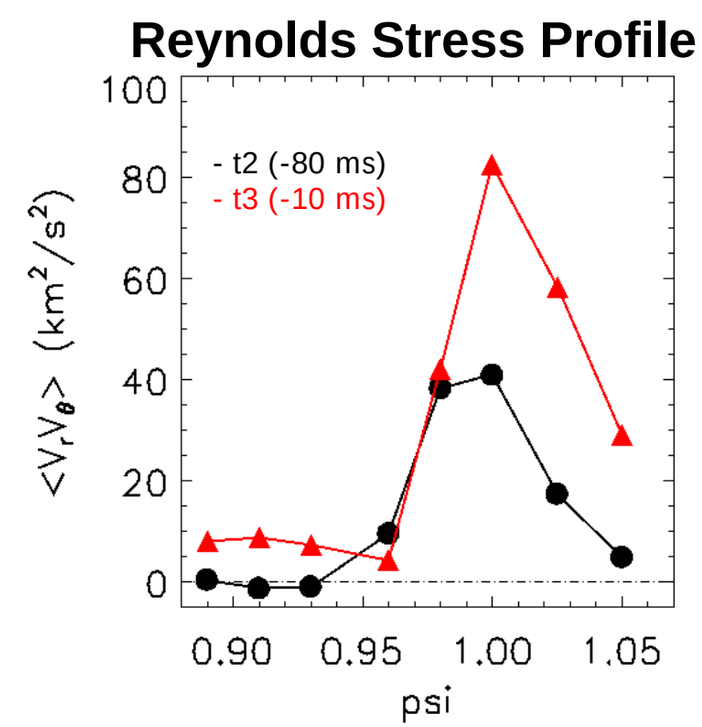
- Driving mechanisms, underlying instabilities, saturation processes
  - Strongly nonlinear system; saturation via turbulence driven zonal flows
- Interplay of Turbulence<—>Transport <—> Current Drive <—> Stability
  - Practical for optimizing plasma pressure for a given magnetic field
- Validating nonlinear simulations of turbulent transport
  - Build confidence in predictive capability: extrapolate to burning plasmas
- Multi-scale Interactions
  - Ion to electron gyroscale; mesoscale zonal flows
  - Magnetohydrodynamics; Alfven Eigenmodes
- 3D Physics (non-axisymmetric)
  - Suppression of damaging edge instabilities
  - Increases turbulence, transport
- Neutral-plasma interaction: collisions
- Bifurcation Dynamics
  - Low to High-Confinement Transitions
  - Internal Transport Barriers



Example: Understanding the Beneficial Bifurcation from Low-Confinement to High-Confinement as Heat Flux *Increases*

- Increase Heat Flux to a "Power Threshold"
  - Drives Turbulence
  - Increasing Reynolds Stress
  - Energy transfer from turbulence to shear flow
  - Stabilizing radially sheared zonal flows generated
  - Flow shearing exceeds turbulence decorrelation
  - Turbulence suppressed at edge
  - Transition from "L" to "H" occurs: Confinement inc. 2-3*
- Fusion energy systems depend on "H-mode" to achieve performance goals
- Empirical scaling laws relate P_{LH} to:
  - Toroidal field, density, size
- Can we determine *how* underlying edge dynamics at L-H transition yield global parameter scaling?





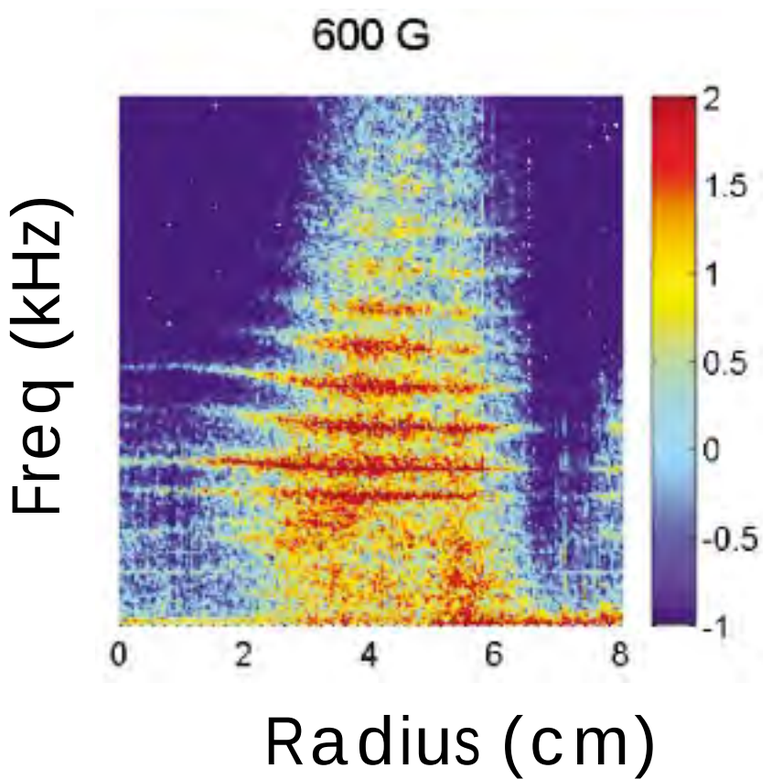
G. Tynan, Nucl. Fusion (2013)

Z. Yan, Phys. Rev. Lett. (2014)

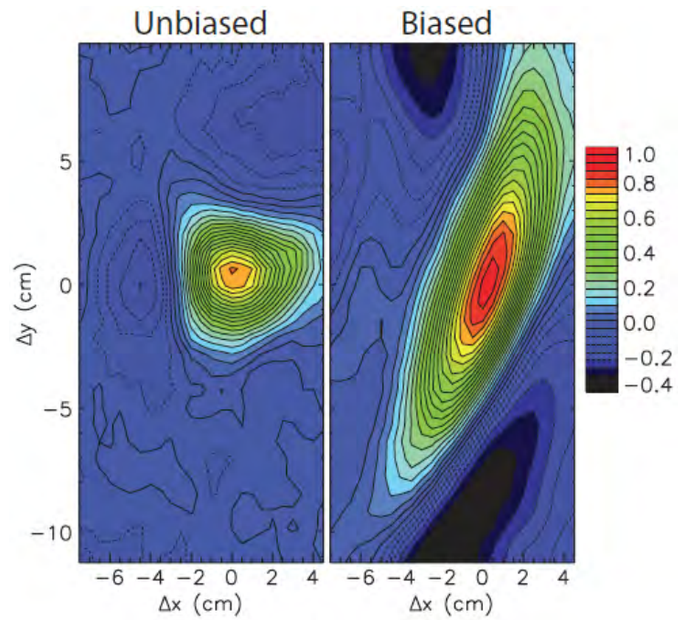
Seek Research Synergies Between Focused Plasma Experiments and Toroidal Fusion Experiments like DIII-D

- Excellent turbulence physics research at universities:
  - CSDX at UC-San Diego: drift-wave, zonal flow physics, detailed measurements
  - LAPD at UC-Los Angeles: linear plasma device, axial field
- Relate to behavior observed in fusion experiments:
  - Toroidal system: Turbulence-Zonal Flow-Equilibrium Shear
  - Rotational shear: control turbulence and improve confinement

CSDX

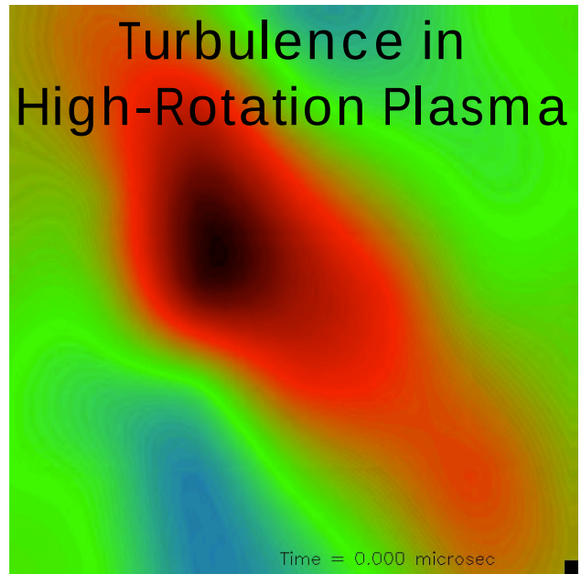


LAPD



DIII-D

9 cm



7 cm

Linear instability—> Developed turbulence—> Shear Flow Stabiliztion

M. Burin, Phys. Plasmas (2005); D. Schaffner, Phys. Rev. Lett. (2012)

DIII-D Welcomes Opportunities to Pursue Fundamental Plasma Physics Research in a Toroidal Magnetized Plasma

- Seek to explore avenues for increasing collaborations
  - Universities and National Laboratories
- Identify areas were DIII-D facility provides unique capabilities to advance frontier scientific questions
  - Heating, shaping flexibility, 3D perturbations
  - Comprehensive diagnostics: potential for further additions
- Progress can be made in several FPS topical areas
  - Turbulence and Transport* (emphasized here)
  - Plasma and wave interactions; energetic particle-driven modes (xAE)
  - Self-organization
  - Atomic physics, spectroscopy via high T_e: high-Z materials
- DIII-D program supports outreach to plasma physics community
  - Seek opportunities to advance plasma physics & fusion energy sciences

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