Plasma Science Research at PPPL

1991-2001: *A Decade of Scientific Excitement*

R. J. Hawryluk

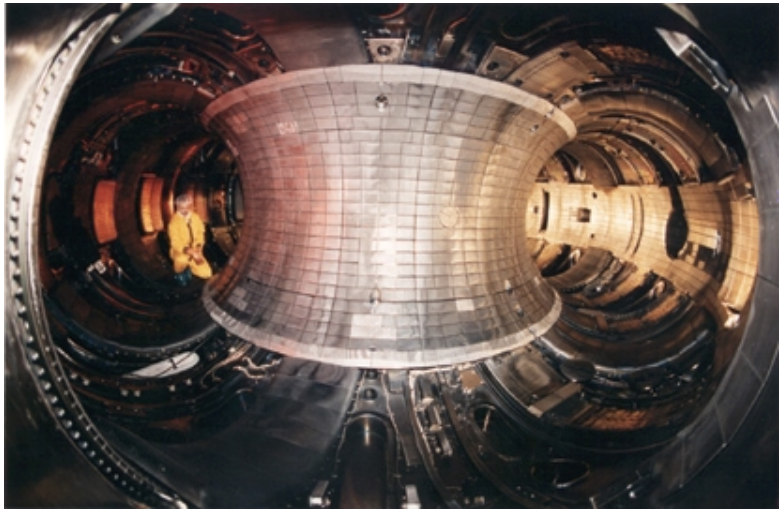
A Celebration of High Temperature Plasma Physics

Princeton Plasma Physics Laboratory

June 5, 2002

Major PPPL Facilities for Scientific Exploration

Tokamak Fusion Test Reactor (TFTR)



High temperature and pressure
High fusion power

National Spherical Torus Experiment (NSTX)

Low aspect ratio, high β

National Compact Stellarator Experiment (NCSX)

3-Dimensional, Low Ripple

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PPPL's Scientific Activities Couple Theory and Experiment

- National Spherical Torus Experiment
- National Compact Stellarator Experiment
- Off-Site Experiments
- Smaller On-Site Experiments
- Inertial Fusion Energy
- Theory and Computation

==> ***Last decade characterized by much stronger interaction between theory and experiment.***

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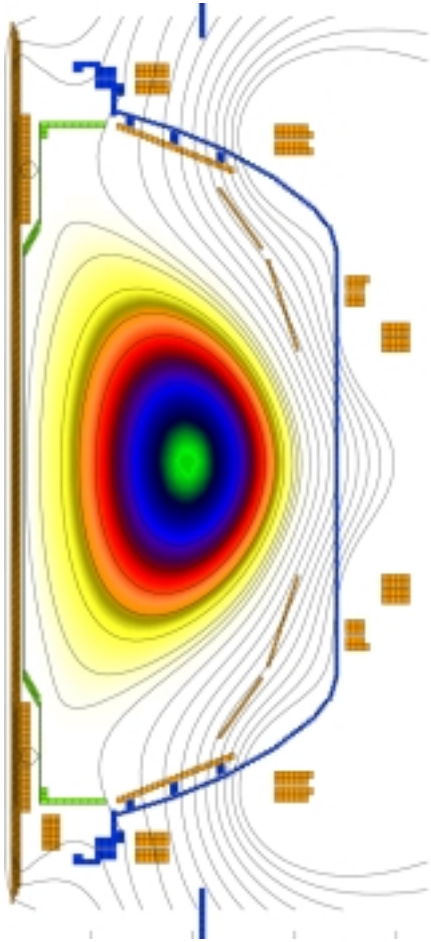
Plasma Science Challenges

Plasma Science Challenges, NRC Plasma Science Committee

- **Macroscopic Stability**
  - **What limits the pressure in plasmas?**
    ⇒ Geomagnetic substorms, Chandra data
- **Wave-particle Interactions**
  - **How do hot particles and plasma waves interact in the nonlinear regime?**
    ⇒ Coronal heating, laser amplification
- **Microturbulence & Transport**
  - **What causes plasma transport?**
    ⇒ Astrophysical accretion disks
- **Plasma-material Interactions**
  - **How can high-temperature plasma and material surfaces co-exist?**
    ⇒ Materials processing



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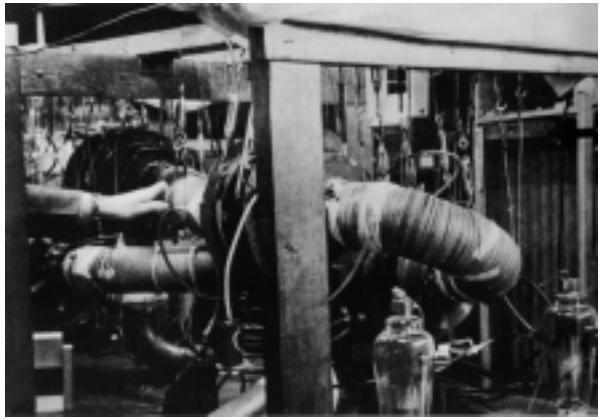
Early Developments in Macrostability

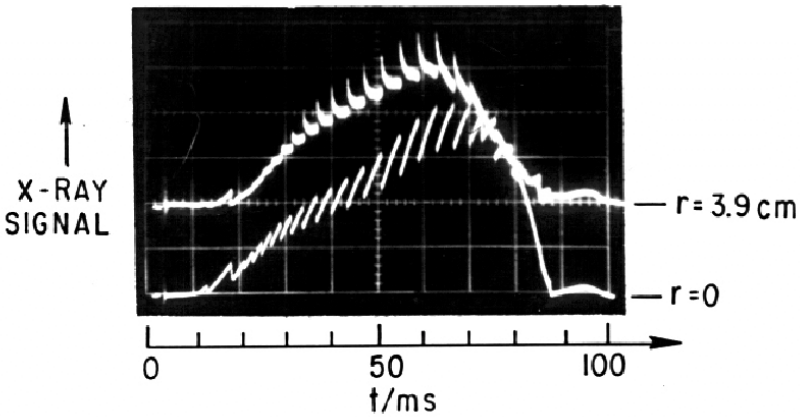
- Closed Magnetic Flux Surfaces '50s
- Equilibrium '50s
- Variational Energy Principle (δW) '57

  Ideal Stability
- Stability

  Resistive
  Kinetic
  Nonlinear
  2D=> 3D systems



Model A Stellarator



Sawtooth Instability on ST

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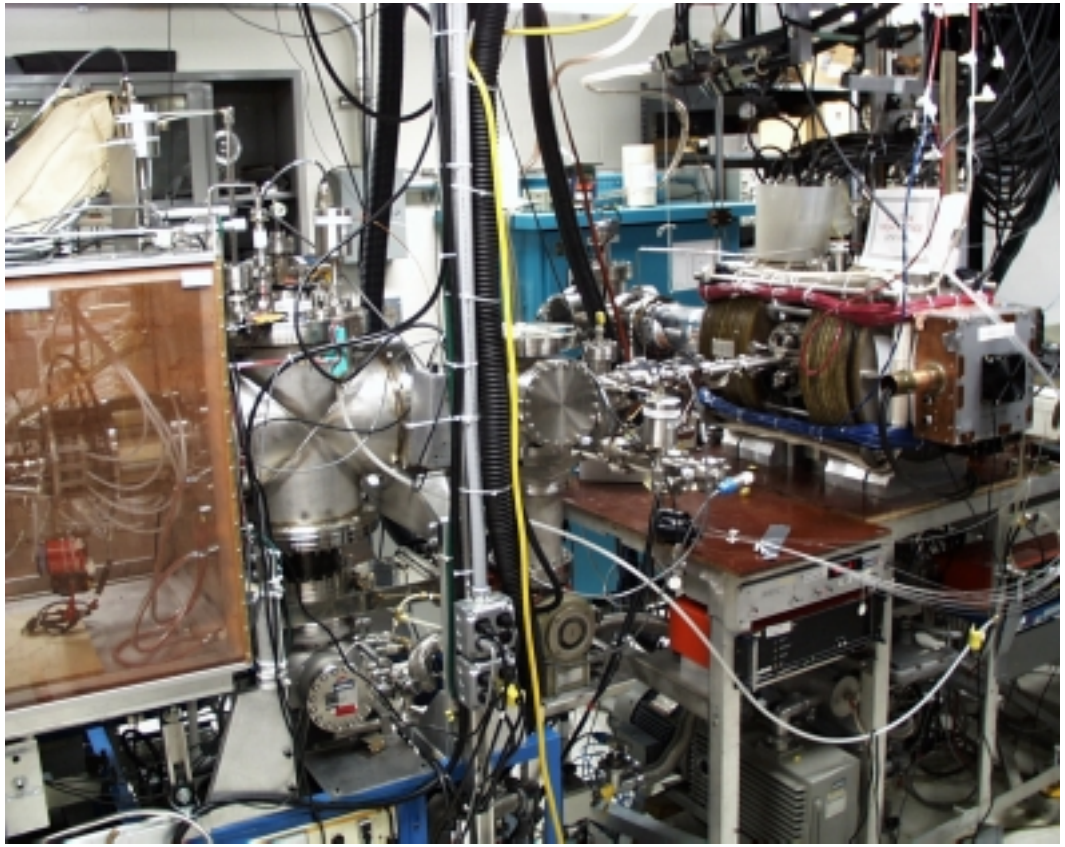
Motional Stark Effect Measurements of Field Angle Revolutionized Stability Studies

- **Motional Stark Effect depends on v x B ⇒ E.**
  - Linear effect in D_0 beam injected into plasma.
- **Allows measurement of B field tilt ⇒ q profile.**
  - Can get E_r and |B| as well as tilt ⇒ rotation & pressure profiles.
- **Developed on PBX-M at PPPL by Nova Photonics; revolutionized stability studies.**
  - Laser induced flourescence being developed for stronger signal in NSTX and other low field/ high β devices.



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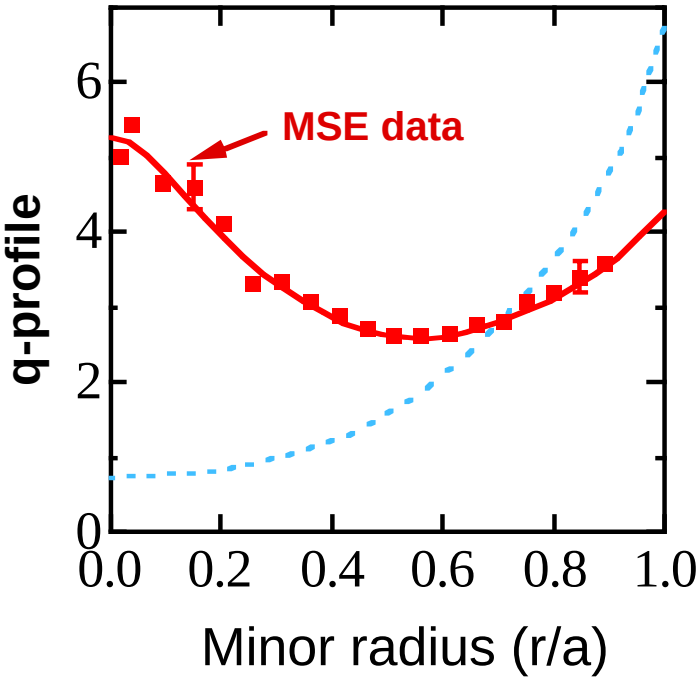
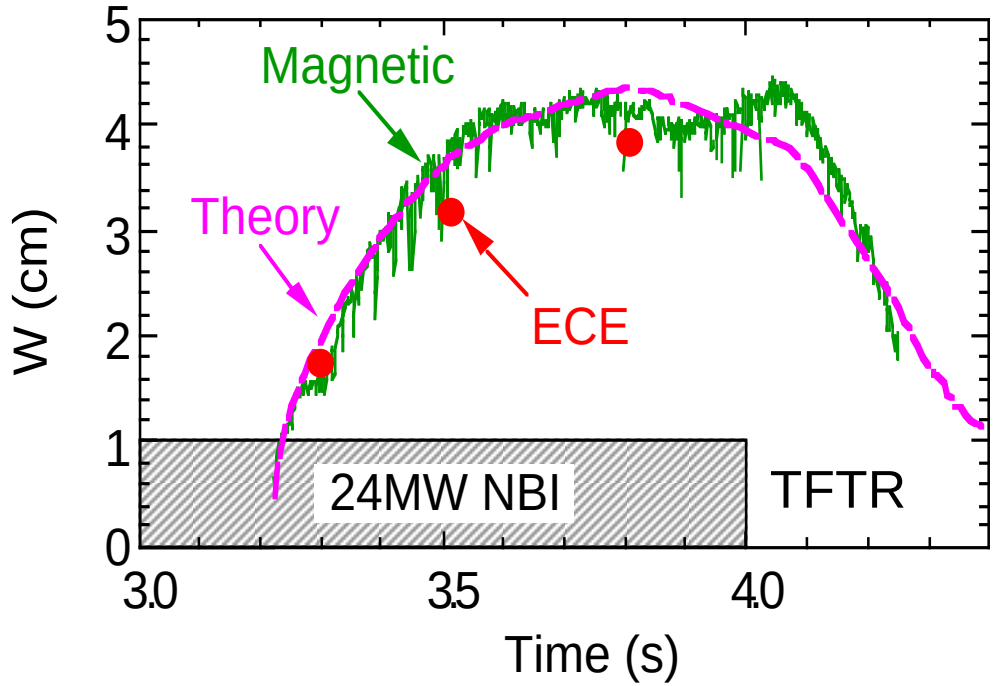
Theory Predicts Observed Amplitudes and Growth Rates for Neoclassical Tearing Modes (NTM)

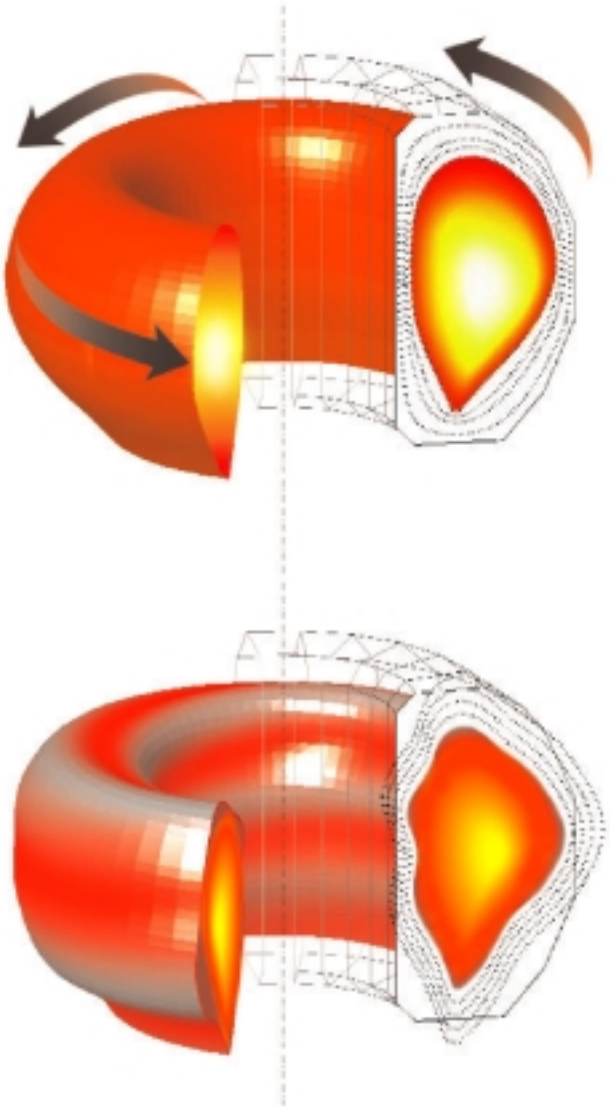




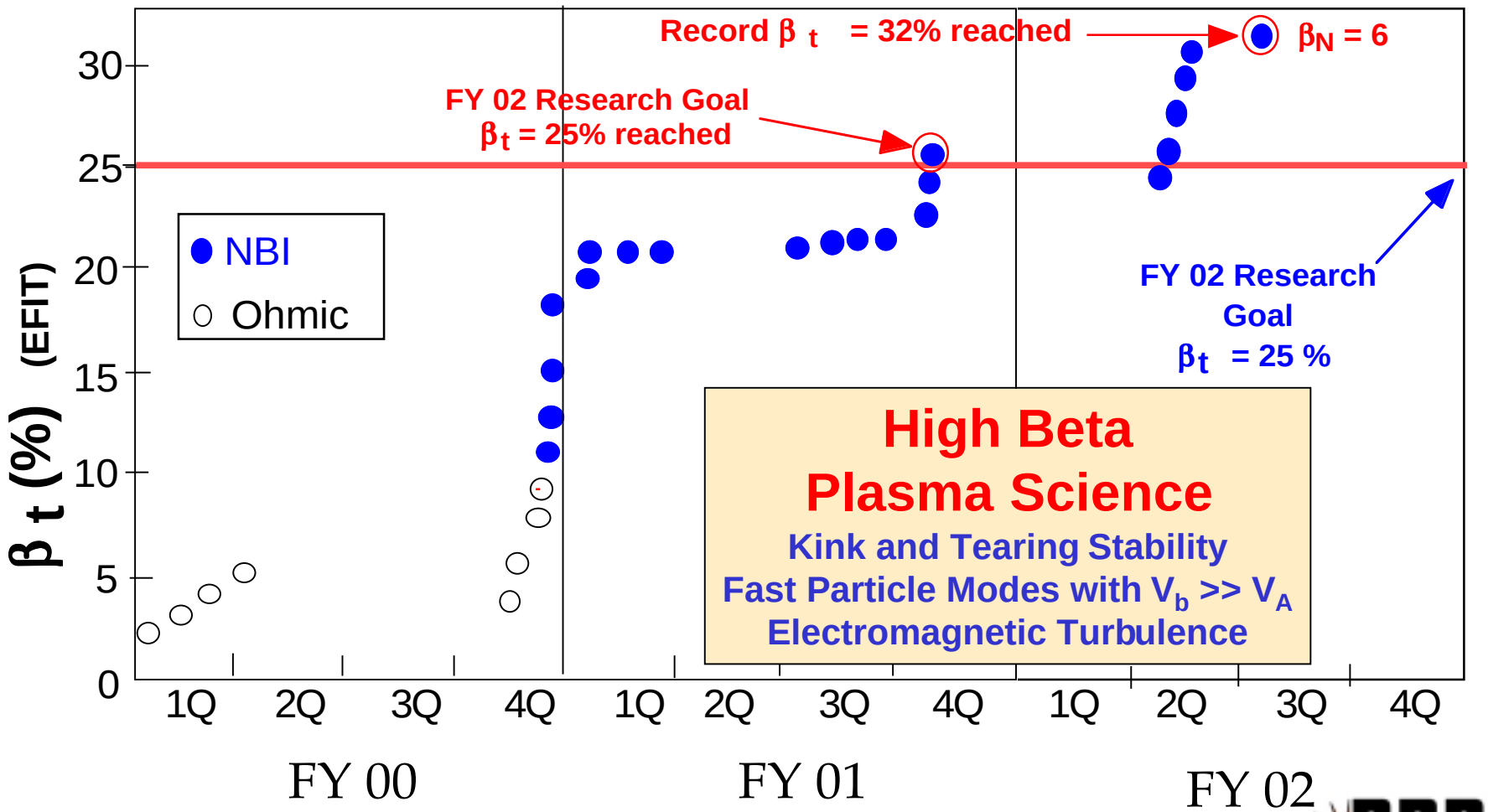
- **Bootstrap current + positive shear destabilizes tearing modes.**
  - **Reversed shear stabilized NTM's on TFTR, as predicted.**
  - **External current drive may allow feedback control.**
- ***NCSX base mode is designed to be stable to NTM's.***

Rotation Stabilizes Kink Modes in DIII-D In the Presence of a Conducting Wall

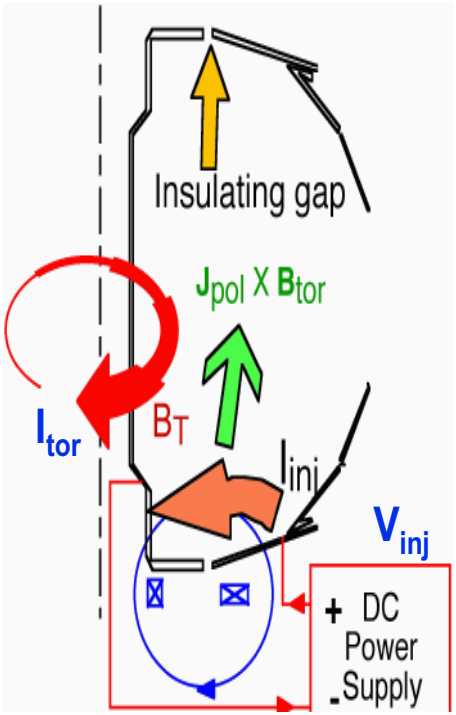
- Strong plasma rotation was predicted to stabilize kink modes up to ideal-wall limit.
- Columbia - Princeton - GA collaboration to test feedback control of kinks.
- Feedback control of field errors allowed rotation to continue, stabilizing kink to 2x higher plasma pressure in special cases.
- Directly transferable to NSTX.
- Feedback not needed for stellarators.

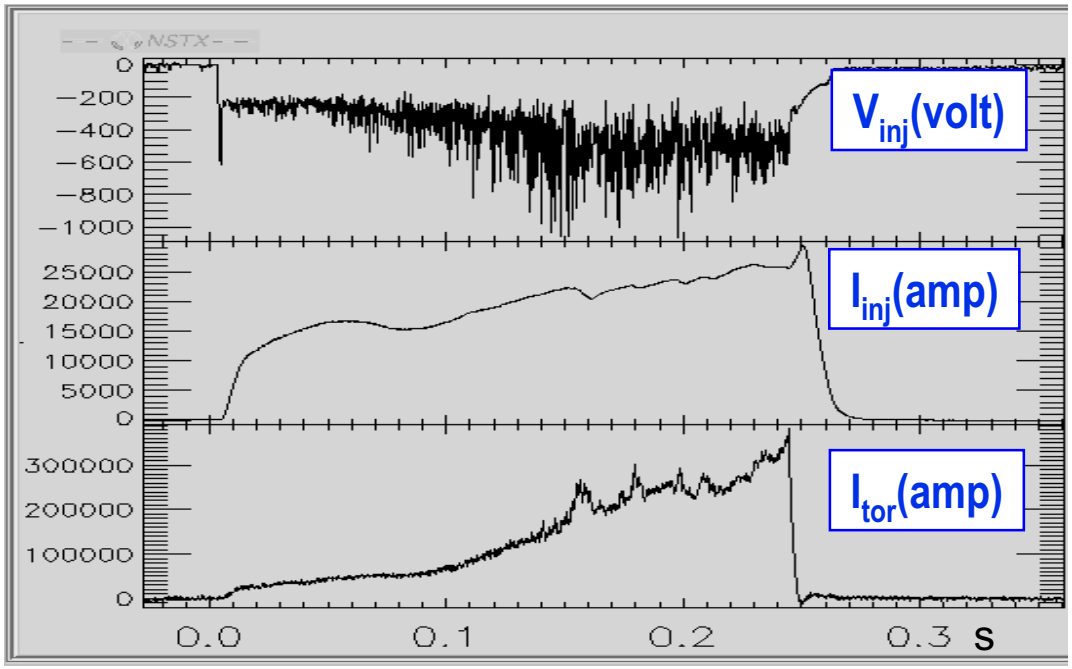


NSTX Achieved High Toroidal Beta Plasmas at High Temperature and Good Confinement!



Coaxial Helicity Injection (CHI) Converts DC Voltage and Current into Large Toroidal Current





- Reached 400 kA toroidal current
- Measured T_e~30 eV, n=1 modes, relaxation behavior

NSTX

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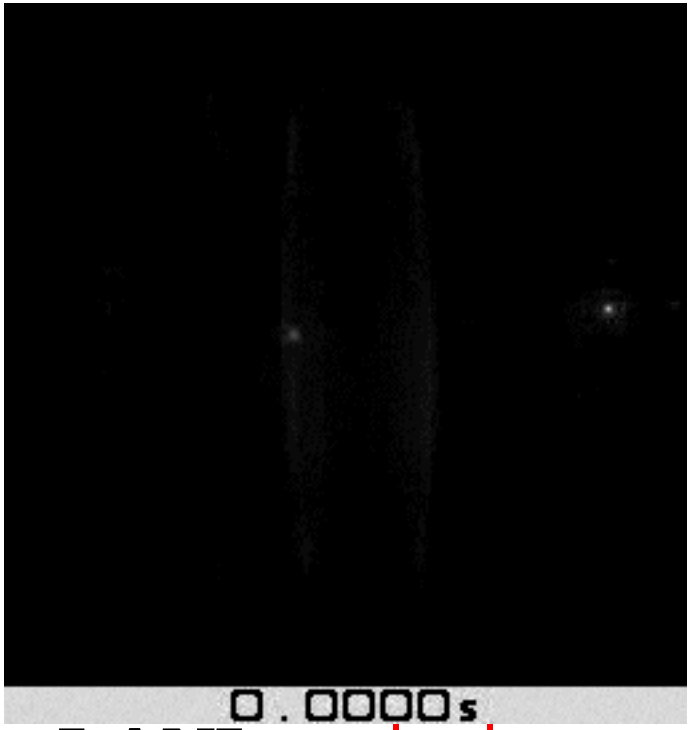
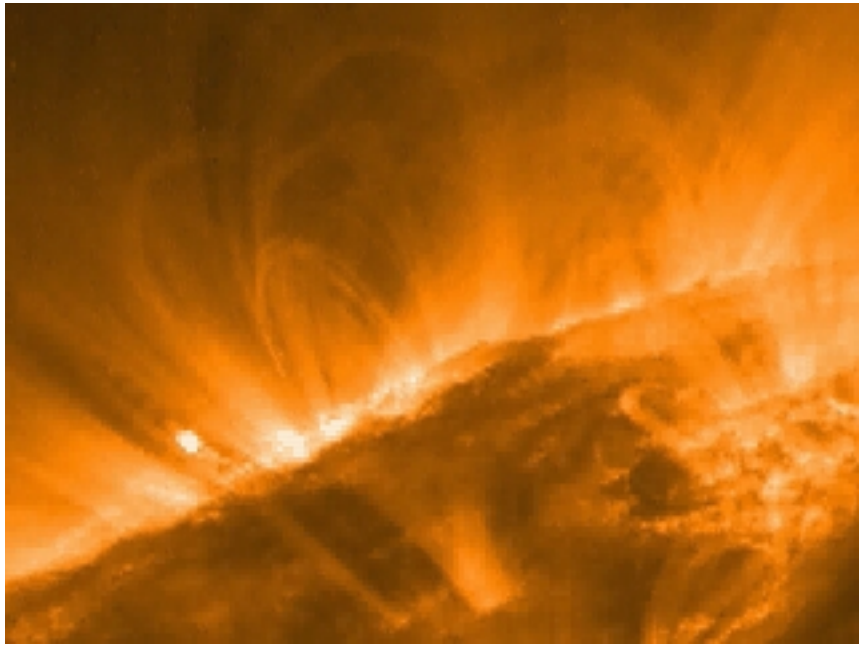
NSTX Coaxial Helicity Injection will Teach us about Magnetic Reconnection



LANL,
U. Washington

Injecting Voltage



TRACE Solar Image

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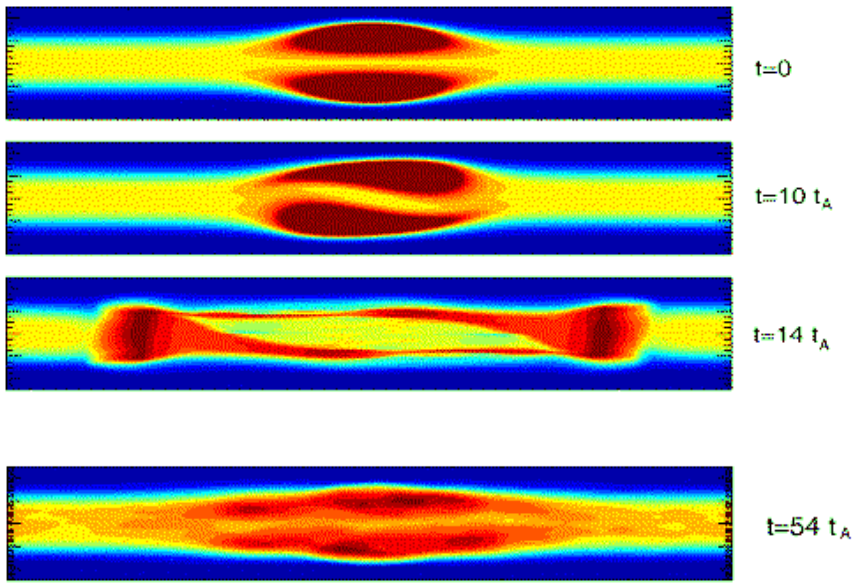
Hybrid (fluid/kinetic) Simulations Demonstrate Nonlinear Kinetic Stabilization of FRC

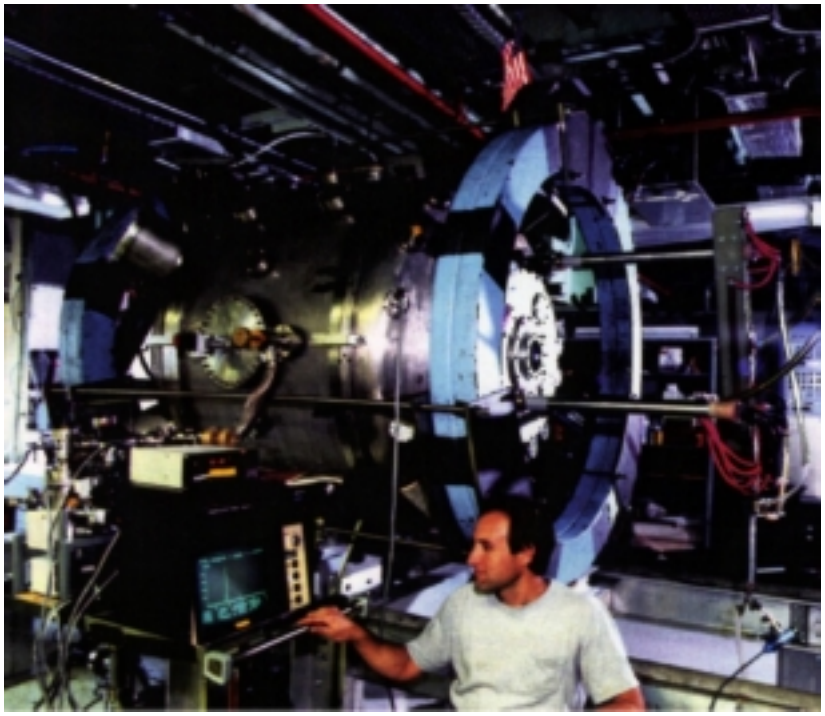


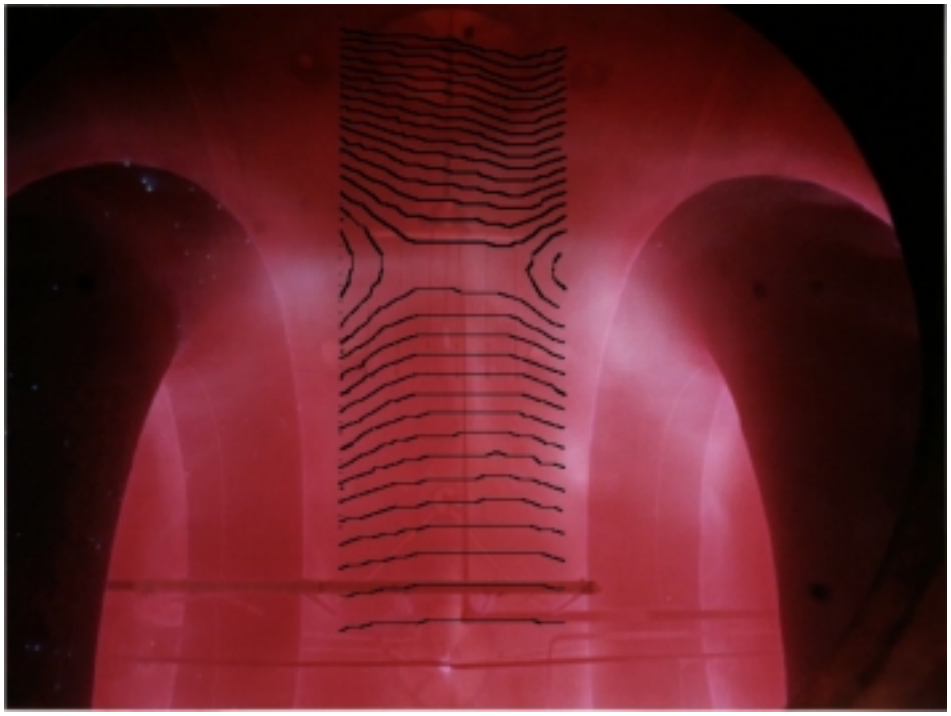
Comprehensive analysis of FRC stability includes:

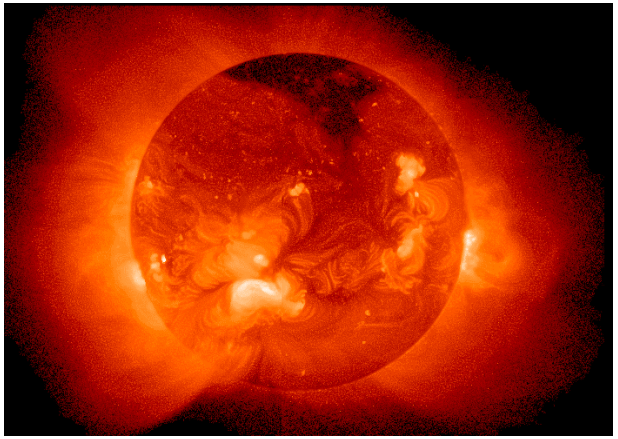
***- full ion kinetic effects*:**

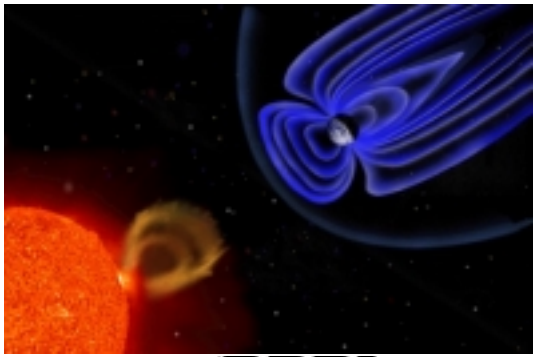
- **Resonant particle effect on linear stability and nonlinear saturation of the n=1 tilt mode**
- **FLR effect on MHD modes**
  - **plasma rotation**
  - **close-fitting conductors**

Magnetic Reconnection Experiment









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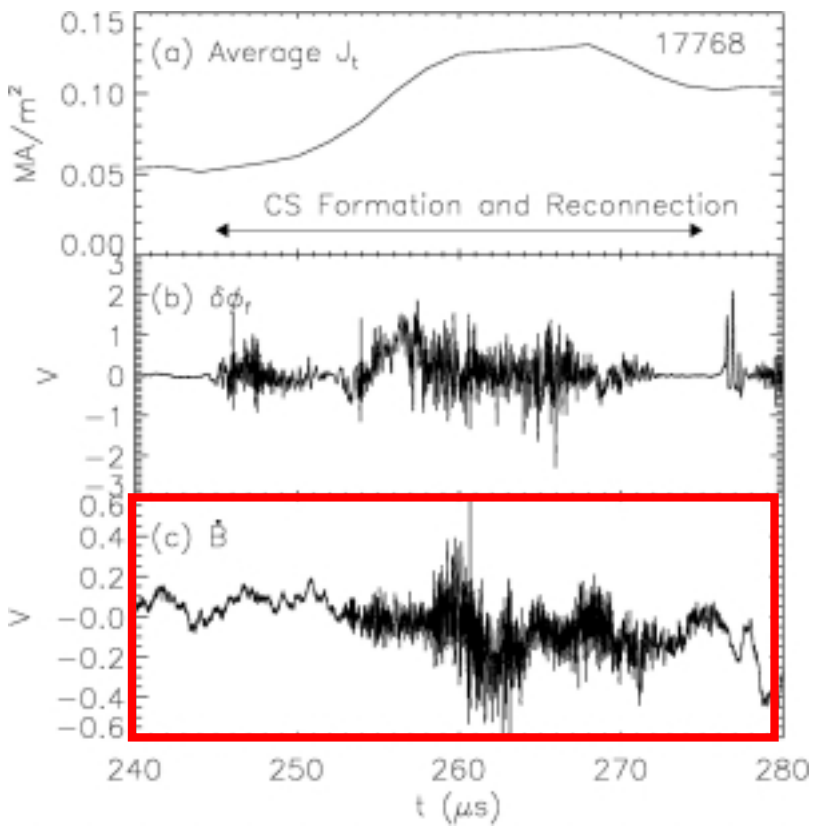
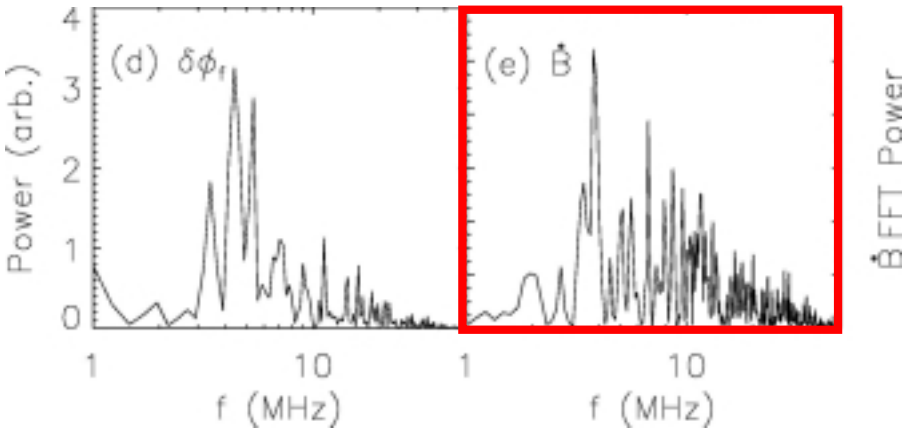
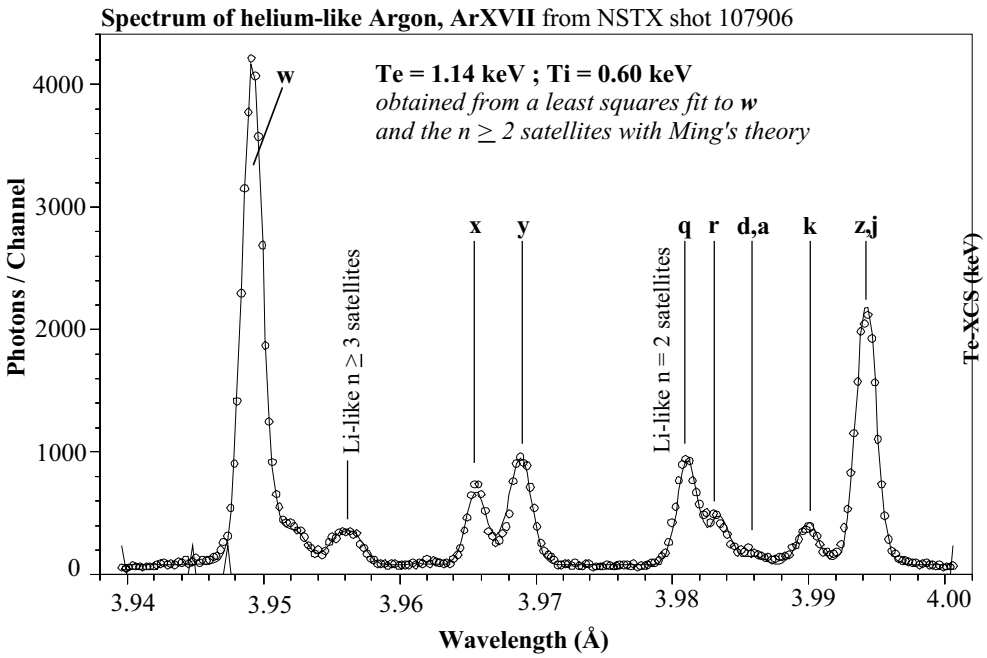
Fast Fluctuations Identified as Lower Hybrid Drift Waves

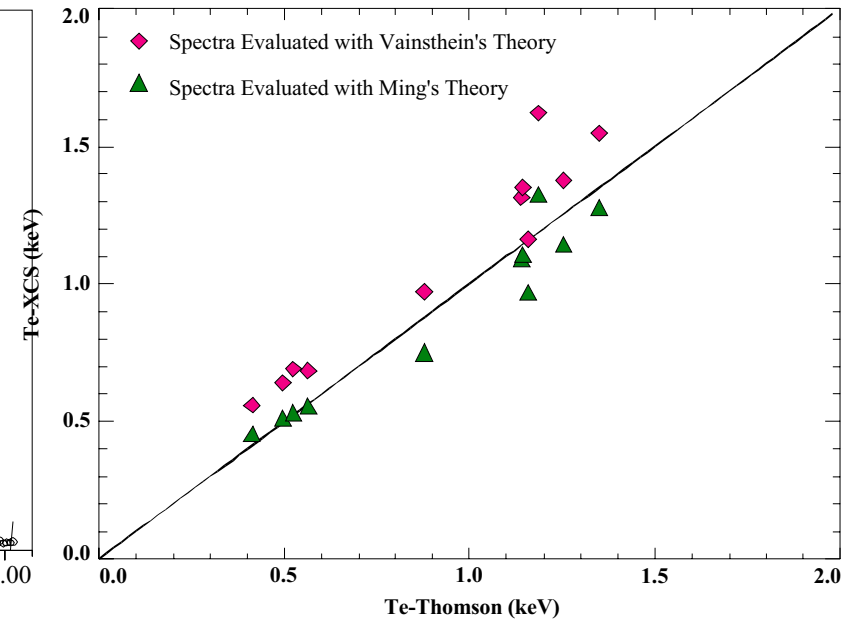




Not sure yet if this is the culprit!

High Resolution X-Ray Spectroscopy Yields Ion and Electron Temperatures





Development on NSTX enables application in space!

- **Collaboration with Chandra group on atomic physics.**

Plasma Science Challenges

Plasma Science Challenges, NRC Plasma Science Committee

- **Macroscopic Stability**
  - What limits the pressure in plasmas?
    ⇒ Geomagnetic substorms, Chandra data
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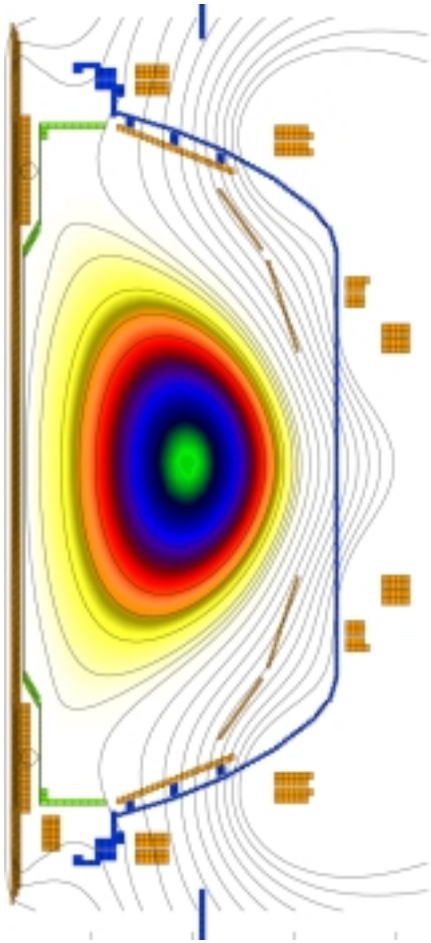

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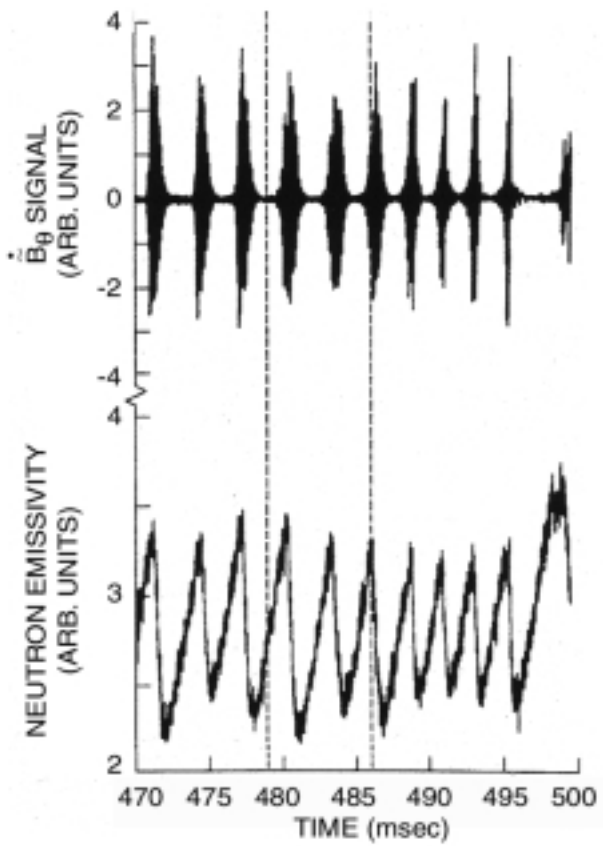
Early Developments in Wave-particle Interactions

- **Heating and Current Drive by Waves and Energetic Particles**
  - ICRF '50s
  - LH '70s
  - Neutral Beams '70s
  - Alpha Particles '90s
- **Instabilities Driven by Energetic Particles**
  - Fishbones '80s
  - TAE modes '90s



PDX

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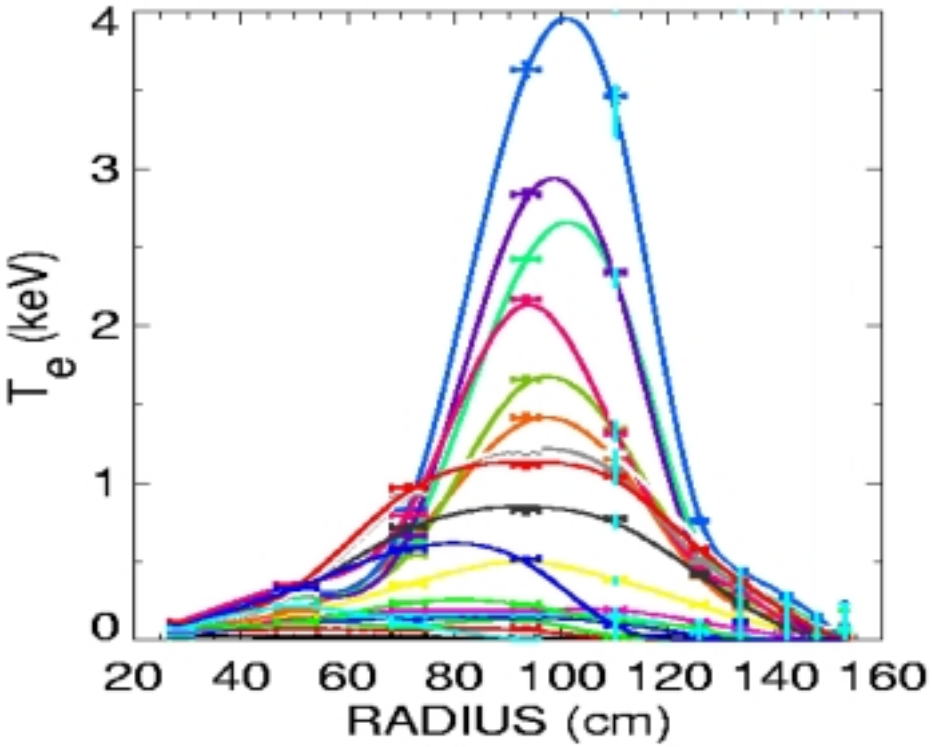
Good Electron Heating with High Harmonic Fast Wave Observed on NSTX

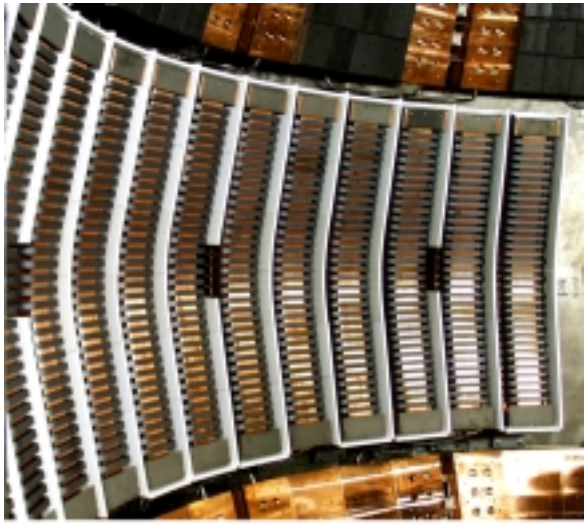


Very high accuracy Thomson scattering

M. Ono (1995): Fast wave decay (absorption) rate:

$$k_{\perp im} \sim n_e / B^3 \sim \varepsilon / B,$$

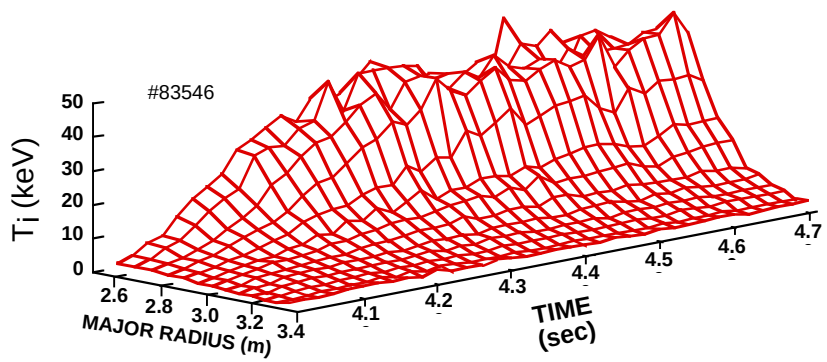
$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$



12-Strap Antenna
- capable of current drive

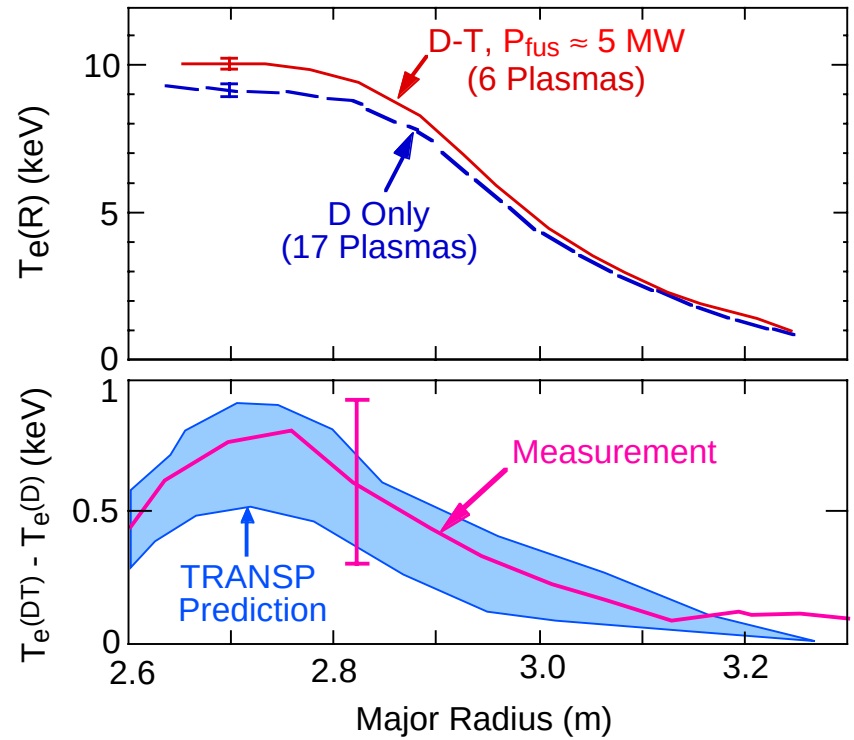
Energetic Particles are Routinely Used to Heat Plasmas to High Temperatures

- **Neutral Beam Heating**
  - **Well understood**
  - **Achieved Record T_i**



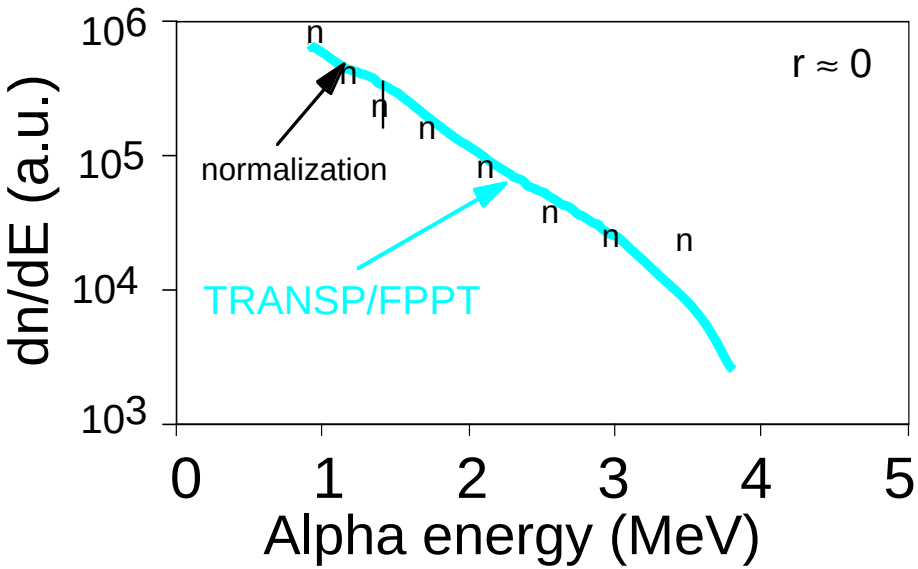
TFTR

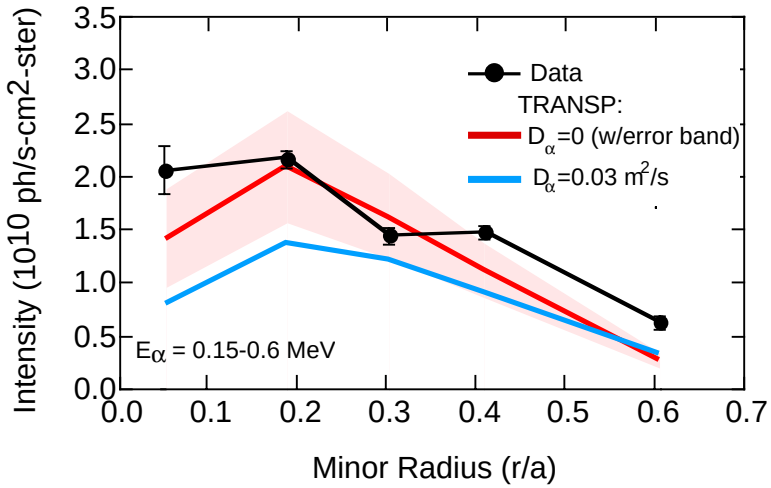
Initial Evidence for Alpha Heating



Comprehensive study of alpha heating requires $P_\alpha > P_{aux}$.

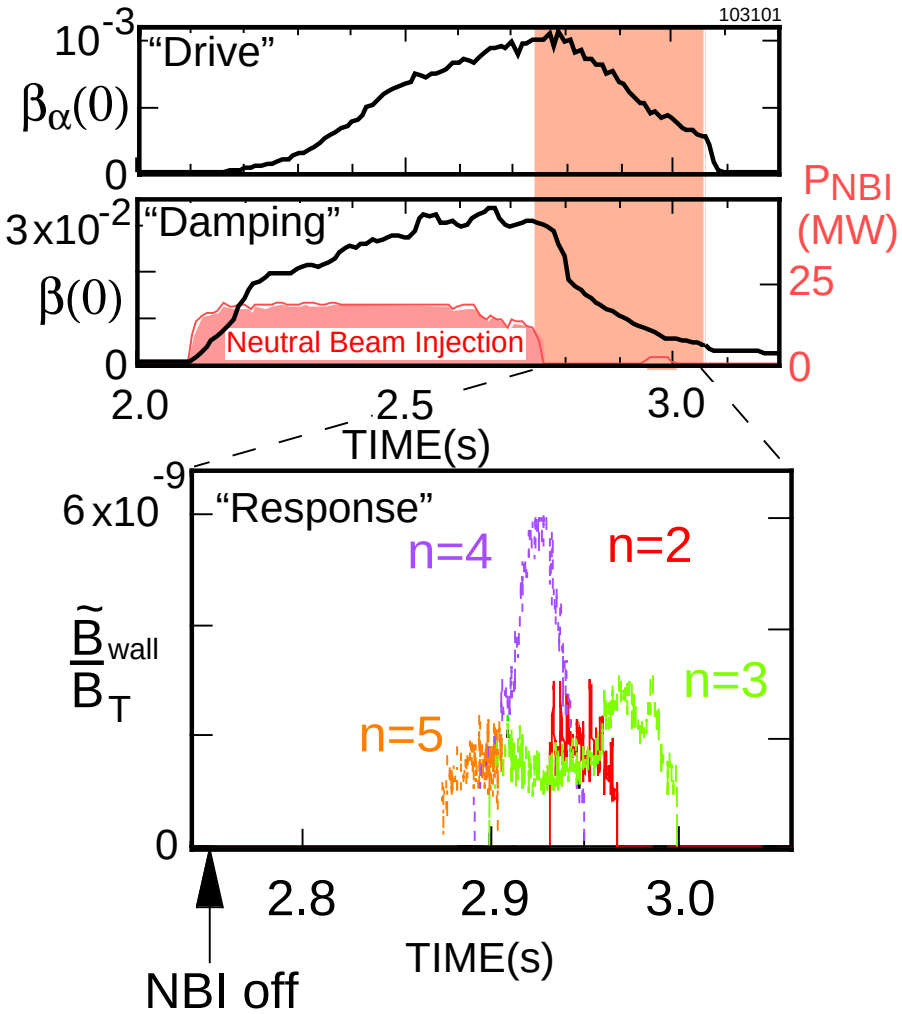
Alpha Particles Well Confined in TFTR

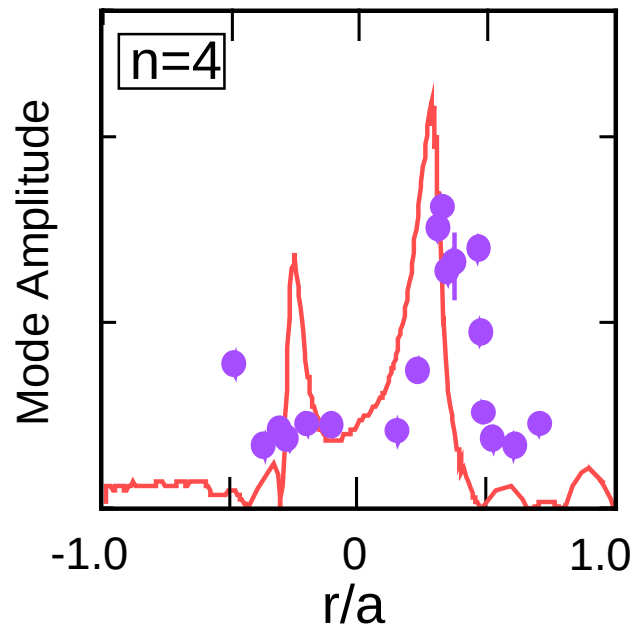




- **Confined alphas in the plasma core show classical slowing down spectrum.**
- **$0<D_\alpha<0.03 m^2/s$**

Observation of Instability Driven by Fusion Alphas – TFTR

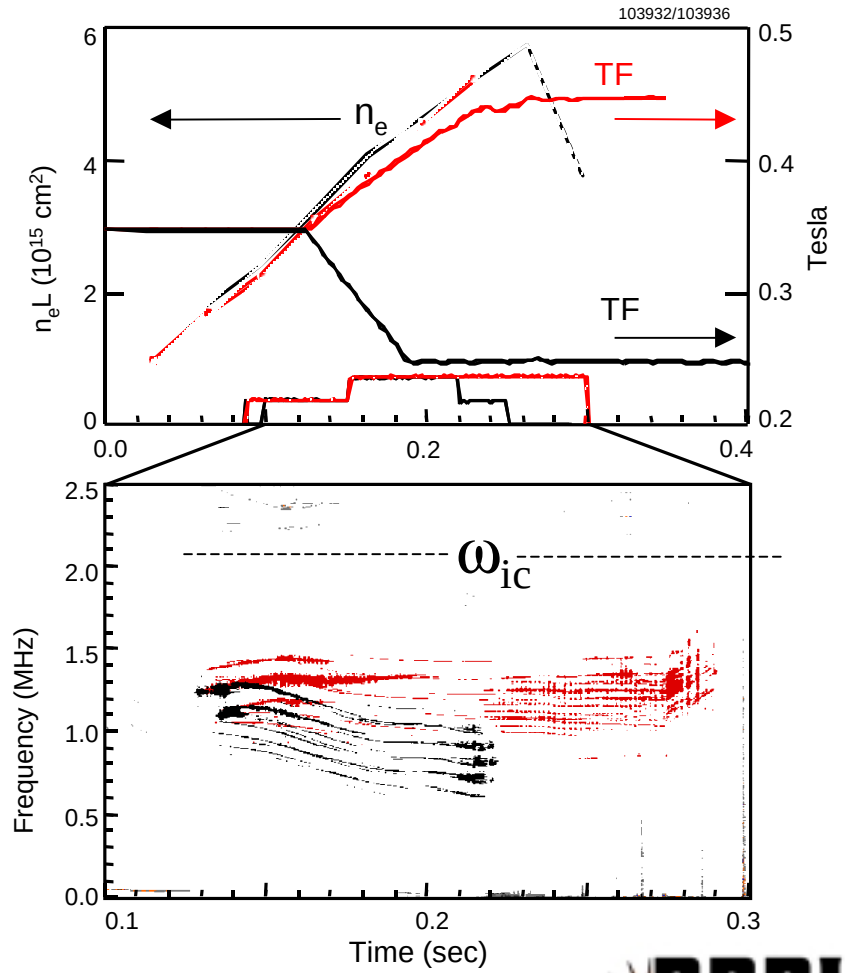




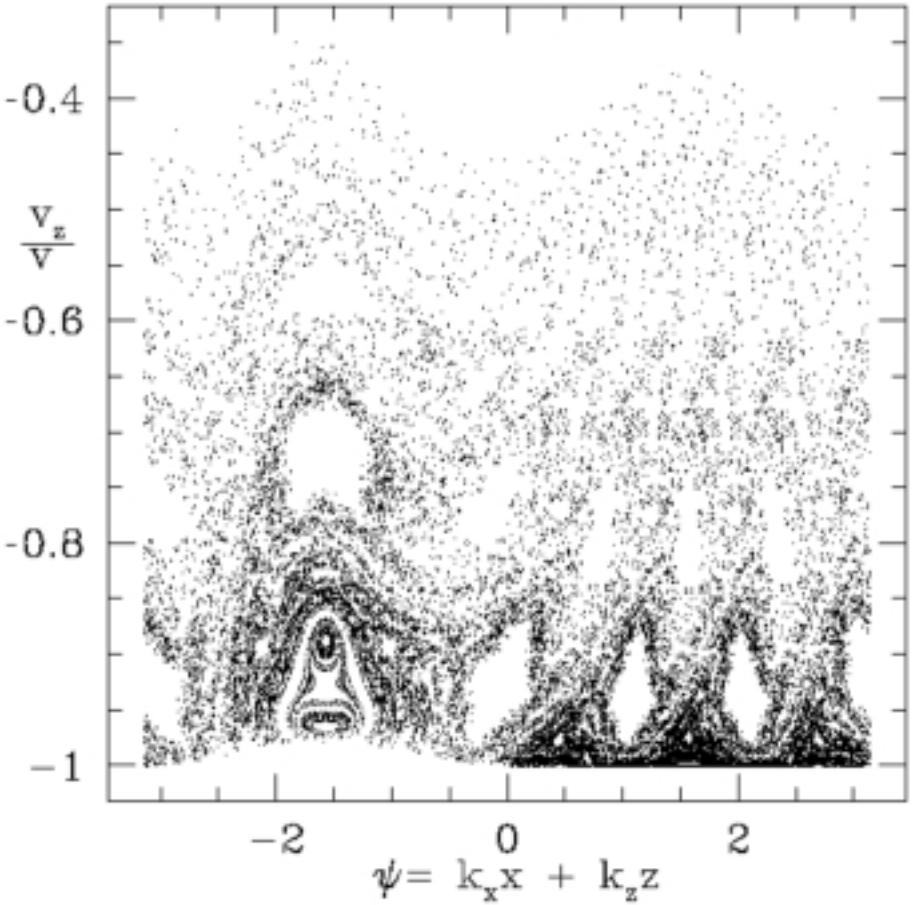
Radial mode structure via microwave reflectometry.

Compressional Alfvén Modes Identified – Predicted for High Beta NSTX Plasmas

- **New physics regime**
  - $V_{beam} >> V_{Alfven}$
  - $V_{th} \sim V_{Alfven}$ at high beta
  - Relevant to astrophysics
- **Possible effects**
  - Direct ion heating?
  - Fast ion loss?



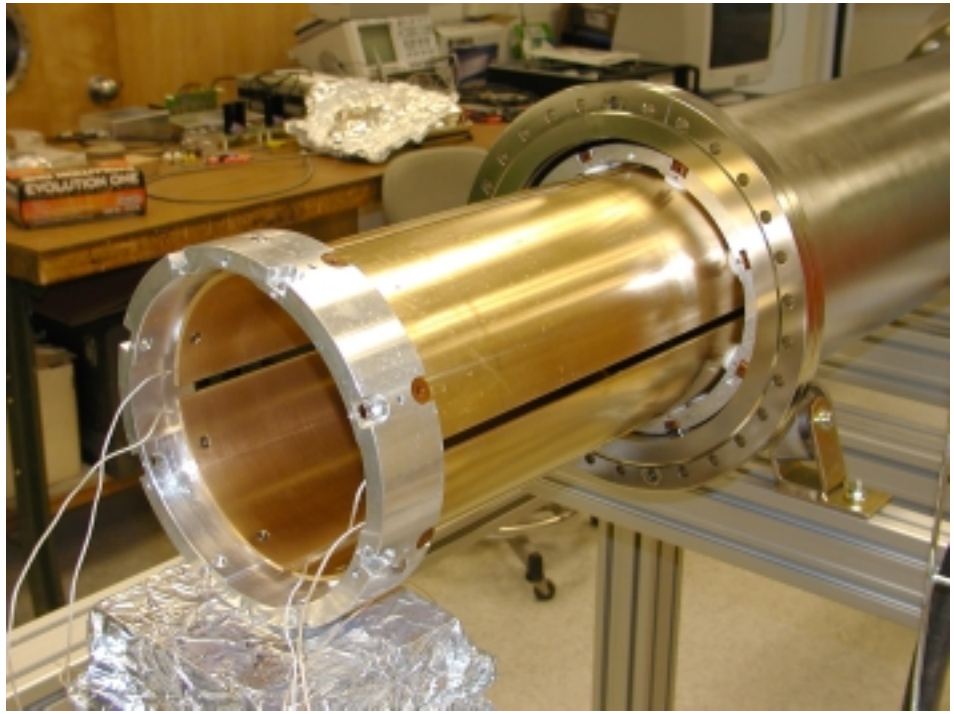
Stochastic Heating by a Single Alfvén Wave – Nonlinear Dynamics



- Large amplitude Alfvén wave with $\omega < \Omega$ can produce stochastic ion motion – may explain heating of solar corona.
- Stochastic threshold much lower for many waves – NSTX?

Paul Trap Experiment to Simulate Particle Beam Propagation

- Simulate transverse vxB forces on the beam charge bunch by oscillating electric fields in the lab frame.
- Study beam instabilities and collective wave excitation.



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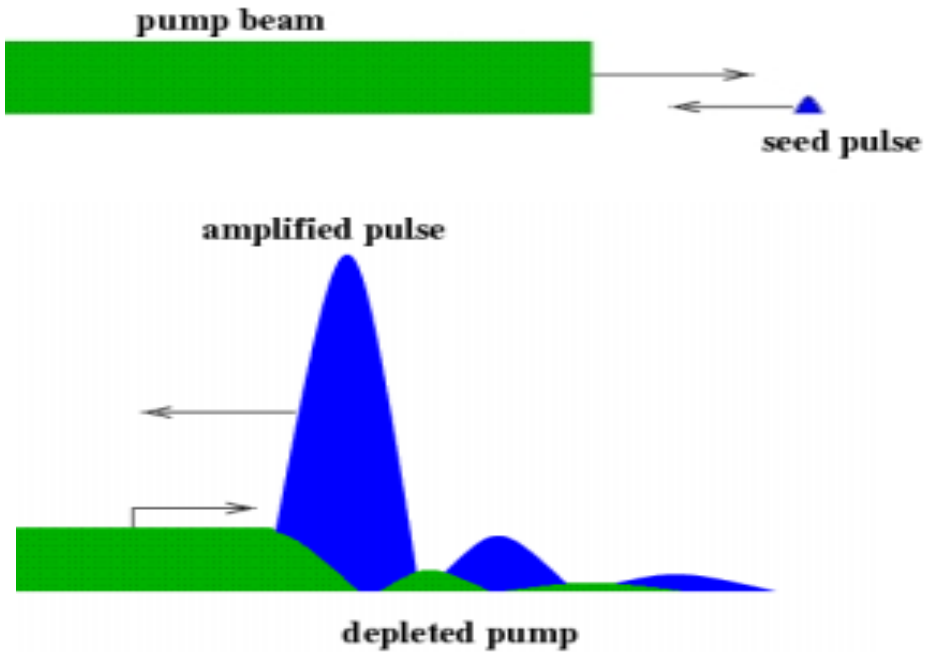
Wave Physics Contributions in Related Fields



Laser Pulse Compression:

Can nonlinear plasma effects be used to develop extra-ordinarily high power lasers?

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Plasma Science Challenges, NRC Plasma Science Committee

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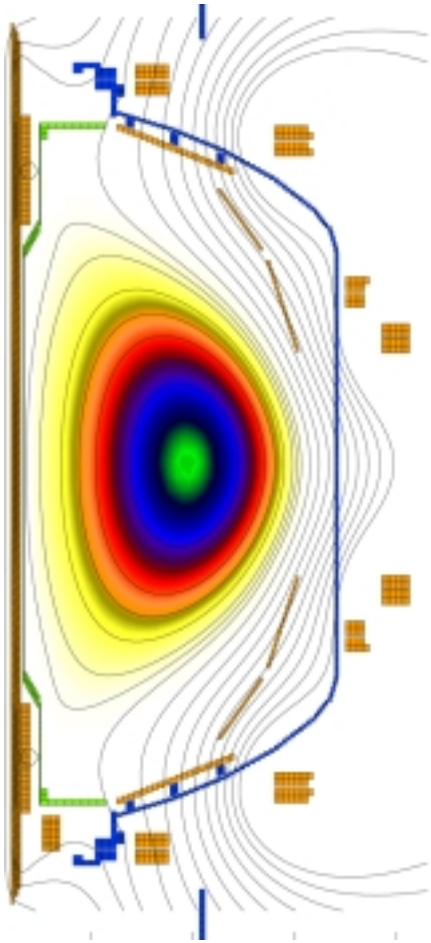

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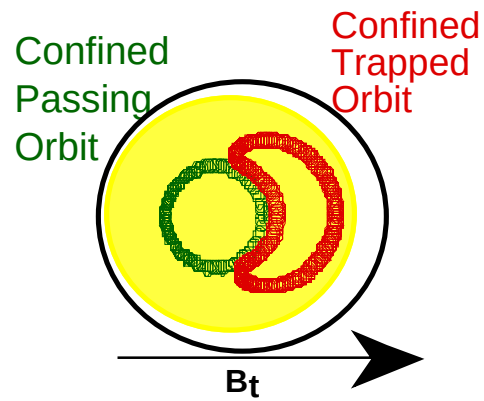
Early Developments in Microturbulence and Transport

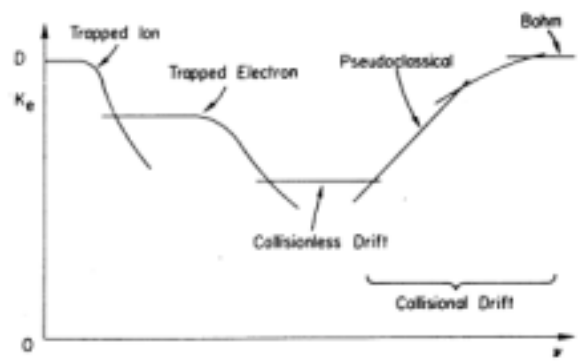
Neoclassical Transport ('70s)

- Variation of B causes some particles to mirror
  - $\Delta r \propto \rho\, B_T/B_p$
  - $D_\perp^{neo} \sim (a/R)^{0.5} (B_T/B_p)^2 D_\perp^{cl}$



Experimentally:

- Transport rates much larger than neoclassical ('60s)
- Empirical Scaling relations were developed ('80s)



Theoretically:

- Turbulent processes were identified:
- Linear growth rates==> diffusion coefficients ('70s)
- Simulations of the turbulence ('90s)

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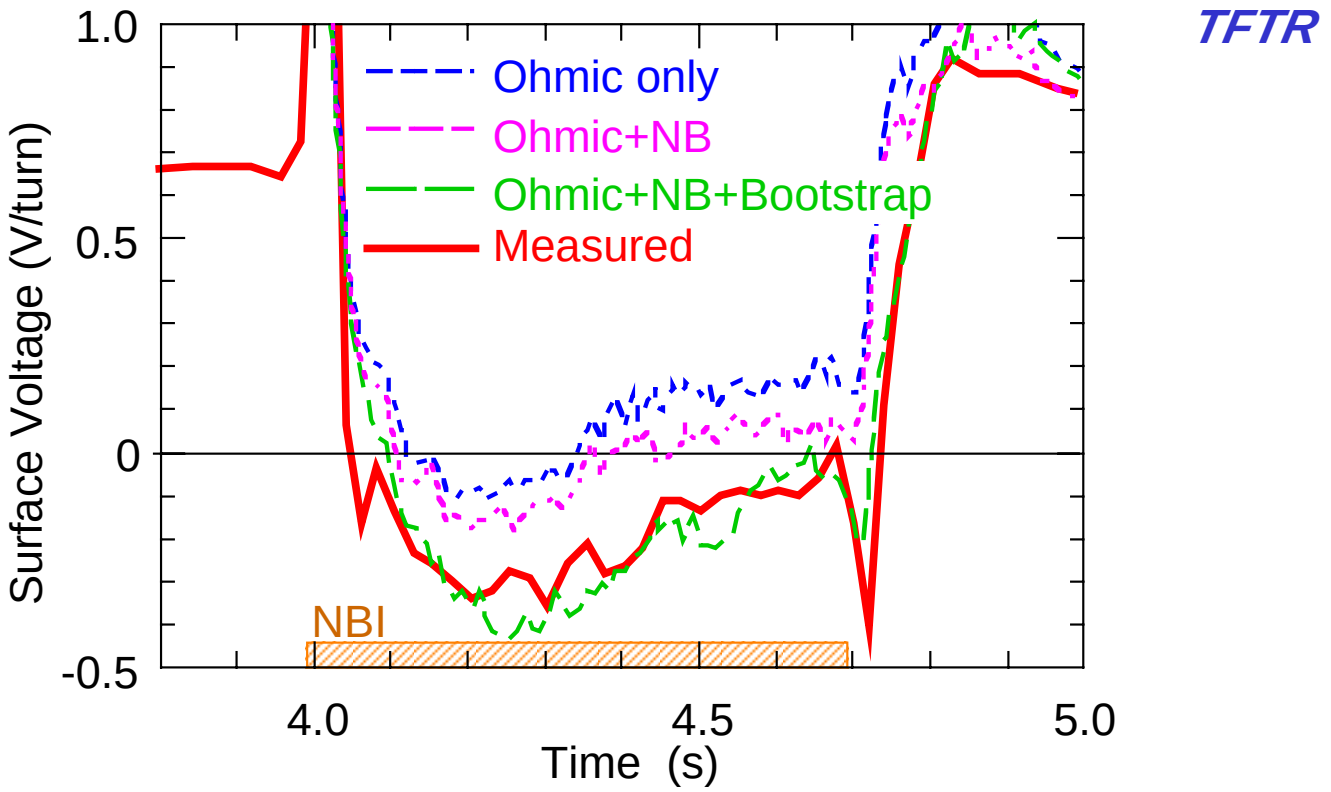
Neoclassical Theory Predictions of Bootstrap Current Confirmed

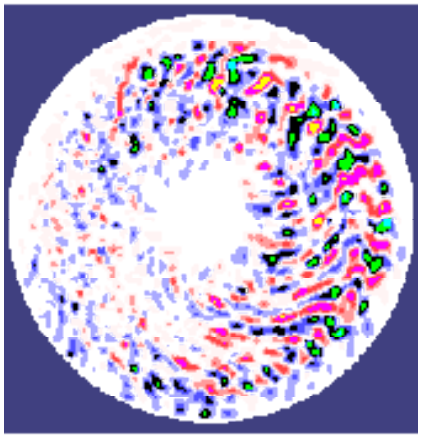


- **Parallel resistivity in accord with neoclassical predictions.**
- **Major impact on the design of steady state Advanced Tokamak, Spherical Torus, and Stellarator devices.**

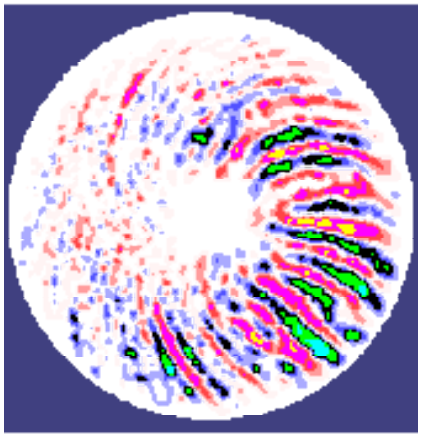
Turbulent Fluctuations Suppressed When Flow Shearing Rate Exceeds Maximum Linear Growth Rate of Instabilities

Simulations show turbulent eddies disrupted by strongly sheared plasma flow

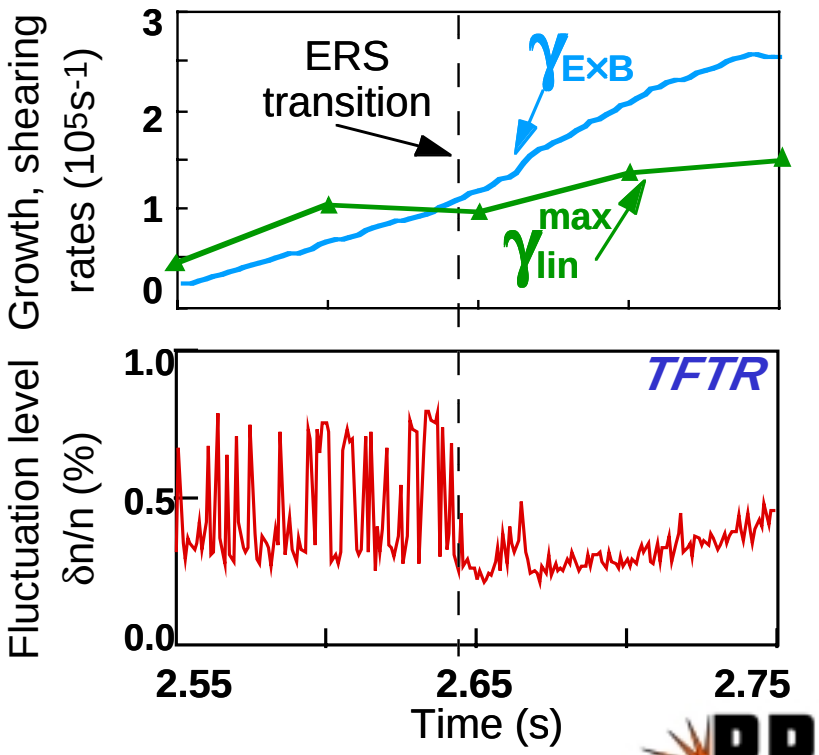
With Flow



Without Flow



Turbulent fluctuations are suppressed when shearing rate exceeds growth rate of most unstable mode



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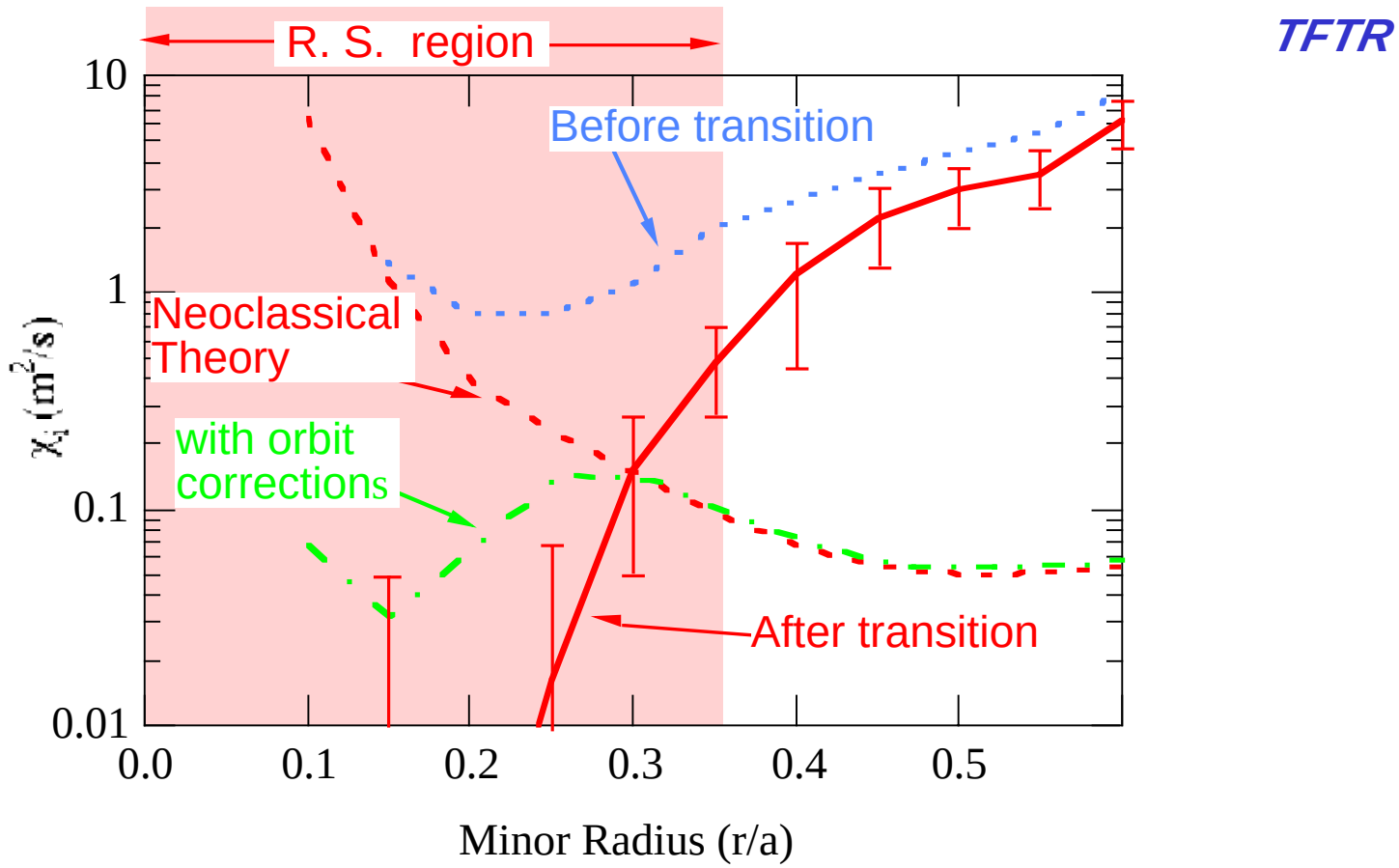
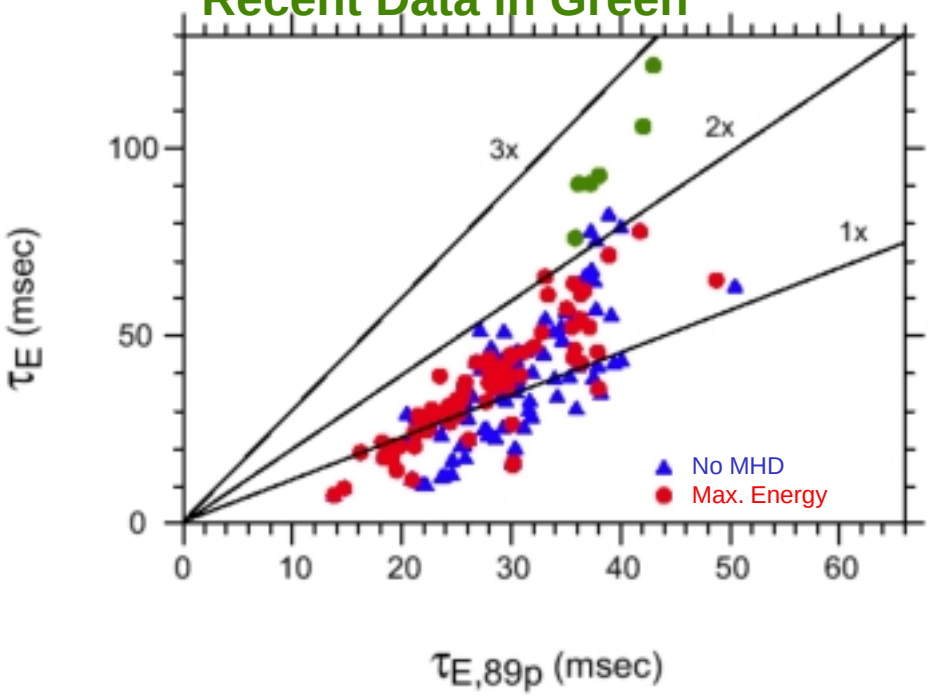
Ion Thermal Conductivity is Drastically Reduced in Core of Enhanced Reversed Shear Mode



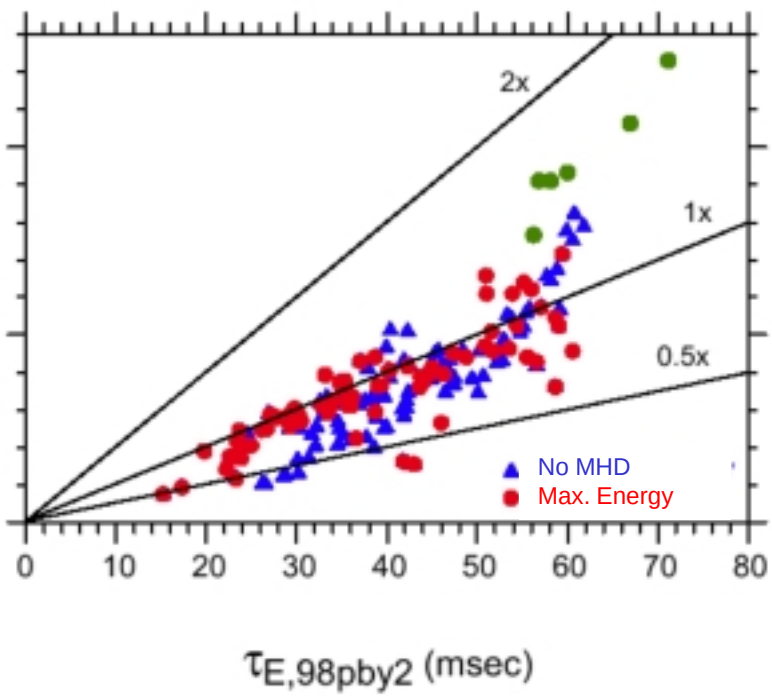
- D_e reduced by factor of 10-50 approaching D_e^{neo}
- χ_e increased!

Plasma Confinement in NSTX Exceeds Empirical-Scaling Expectations

Recent Data in Green



L-mode Scaling



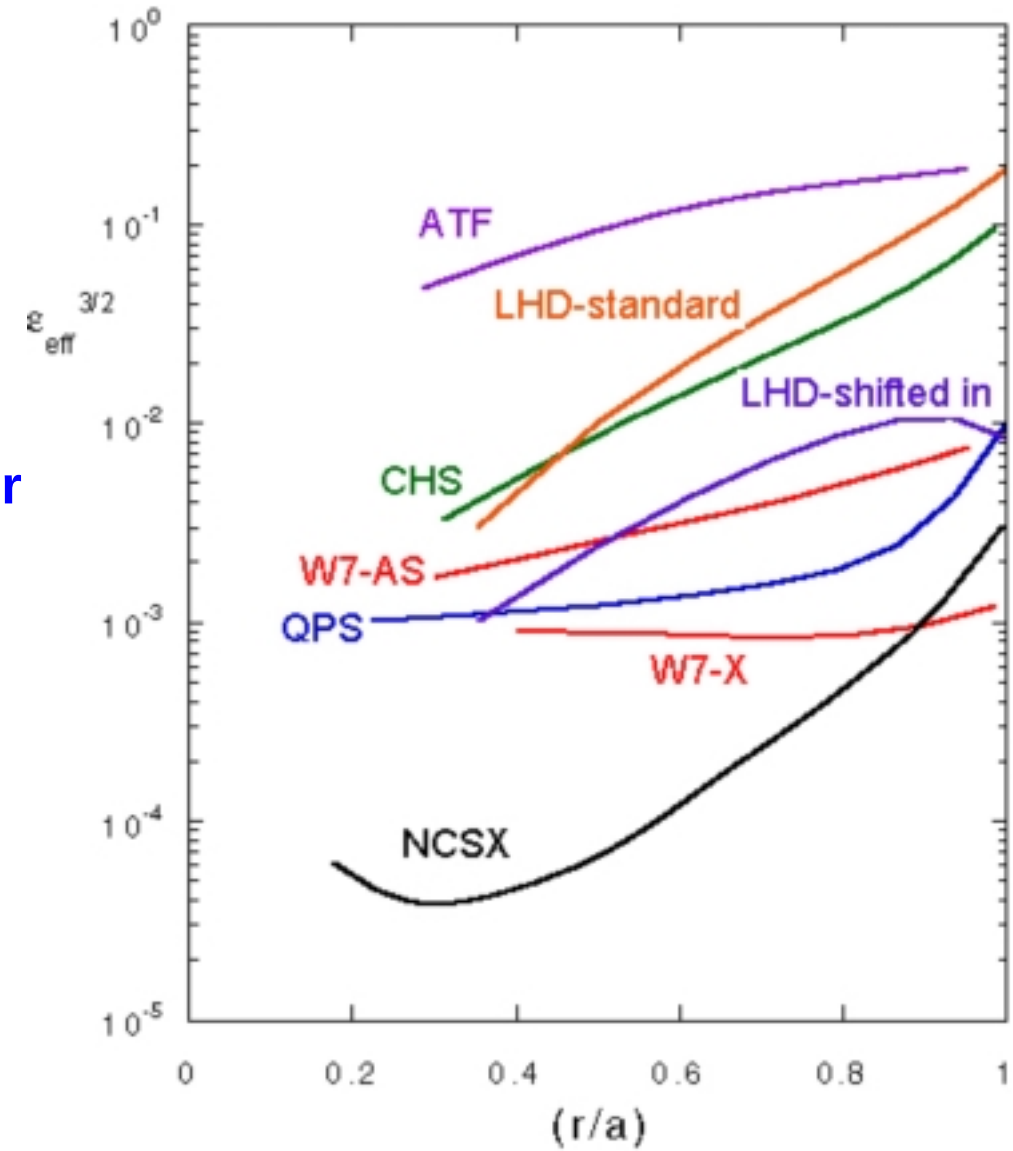
H-mode Scaling

Improved confinement was predicted theoretically for NSTX!

Advanced Computing Enables Design of Systems with Good Confinement, Flow Shear and Passive Stabilization

- **Asymmetrical neoclassical transport**
  - scales as $\varepsilon_{eff}^{3/2}$

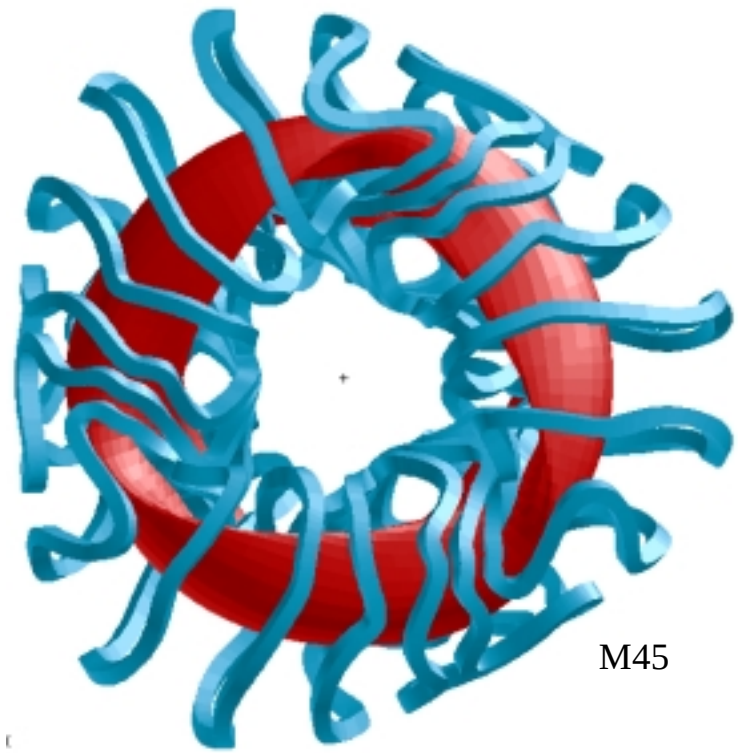
- **Low (adjustable) flow-damping**
  - manipulation of flows for flow-shear stabilization
  - zonal flows like in tokamaks, but can be turned on and off.



NCSX Plasma Configuration Has Attractive Physics

- Low helical ripple transport, low flow damping
- Passively stable at β=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes; without conducting walls or feedback systems.
- Steady state without current-drive
- Coils meet engineering criteria:

  Bend radii & Coil-coil separation distance



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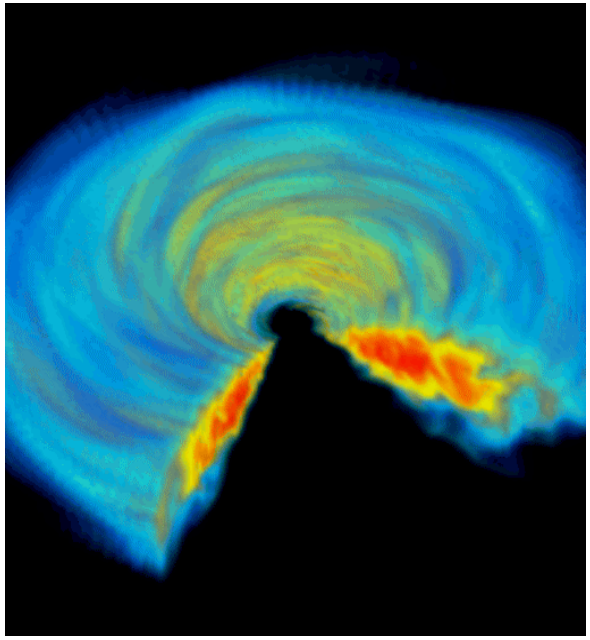
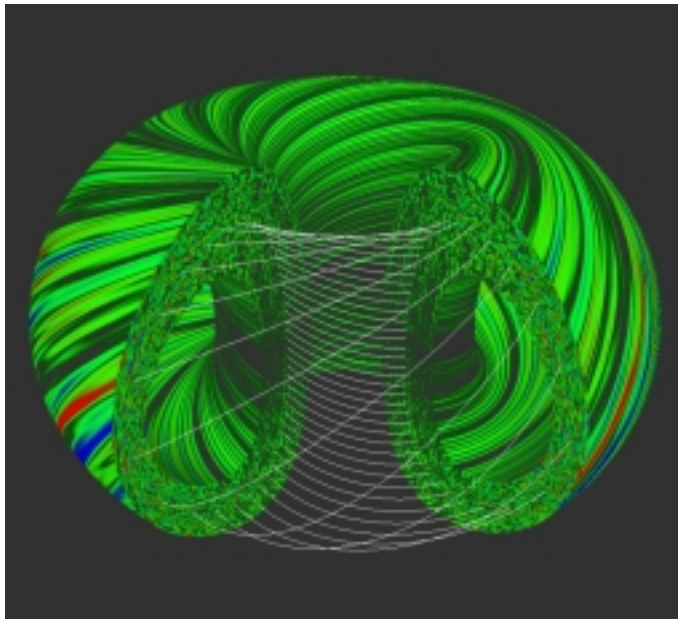
Opportunity: Physics link with Astrophysics via High β Turbulence

Accretion Disk Simulation



Hawley, Balbus, Univ. Virginia

NSTX Simulation

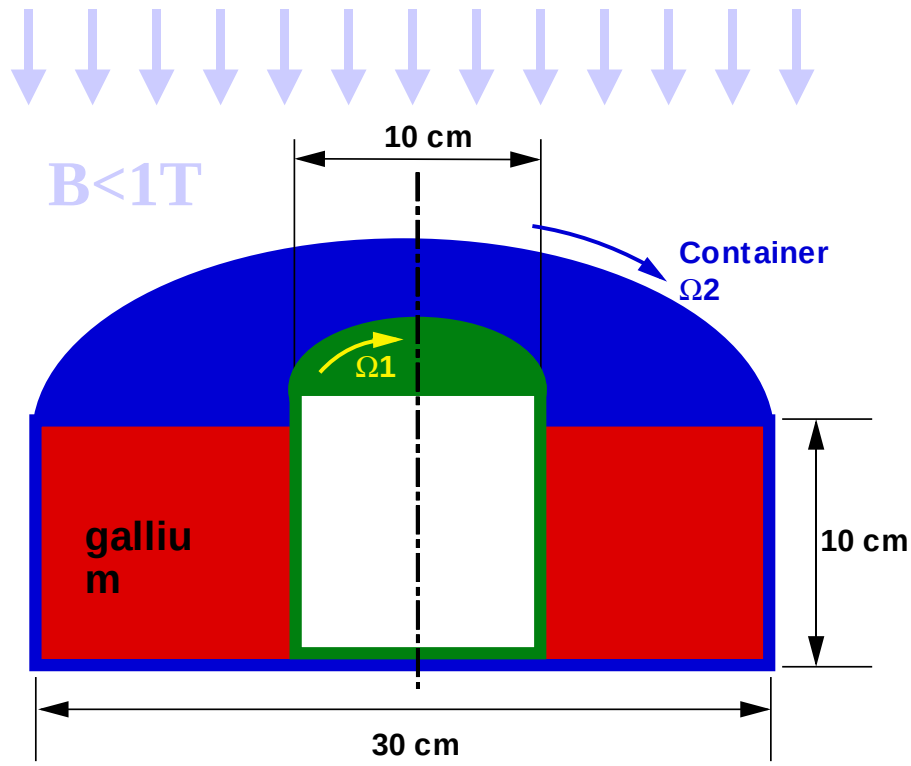


- **Turbulent momentum transport is needed to fuel black holes.**
- **Turbulence cascades to small eddies that heat electrons and/or ions.**
- **Benchmark codes for small-scale turbulence in NSTX high beta plasmas.**
  - **Requires advance in plasma simulations and measurements.**

Rotating Gallium Disk Experiment

- **Magnetorotational instability (MRI) is a candidate mechanism for momentum transport but never studied in laboratory.**

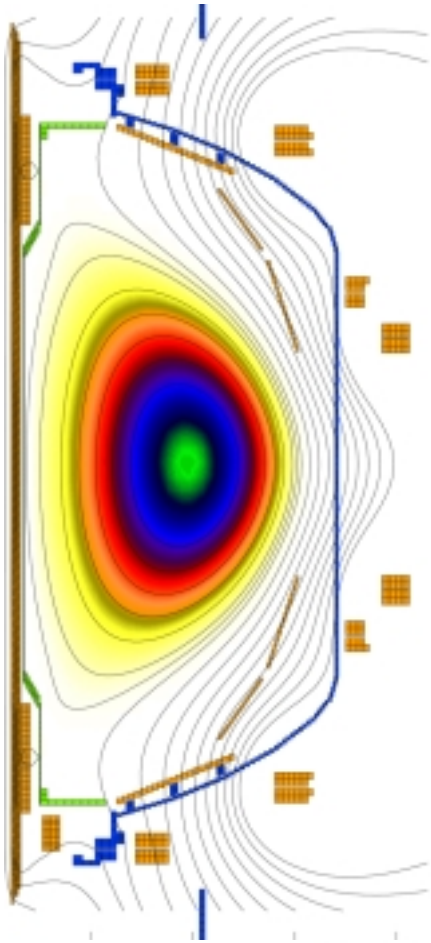
- **A table-top experiment has been proposed to study MRI:**
  - **Centrifugal force is balanced by pressure force, simulating gravity force in accretion disks**
  - **MRI can be destabilized with appropriate Ω_1, Ω_2 and B_z.**



Plasma Science Challenges

Plasma Science Challenges, NRC Plasma Science Committee

- **Macroscopic Stability**
  - What limits the pressure in plasmas?
    ⇒ Geomagnetic substorms, Chandra data
- **Wave-particle Interactions**
  - How do hot particles and plasma waves interact in the nonlinear regime?
    ⇒ Coronal heating, laser amplification
- **Microturbulence & Transport**
  - What causes plasma transport?
    ⇒ Astrophysical accretion disks
- **Plasma-material Interactions**
  - How can high-temperature plasma and material surfaces co-exist?
    ⇒ Materials processing



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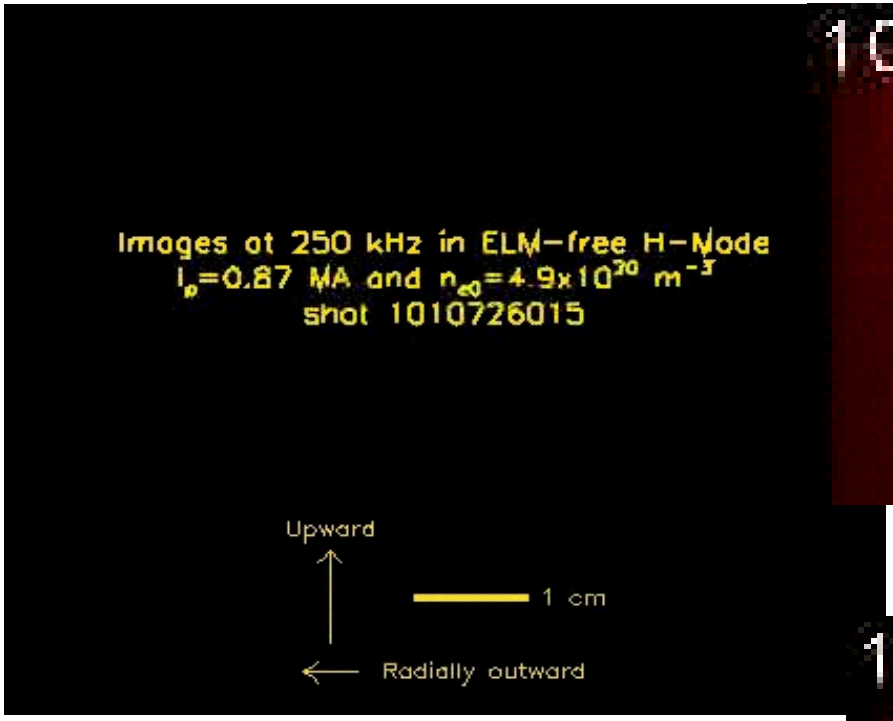
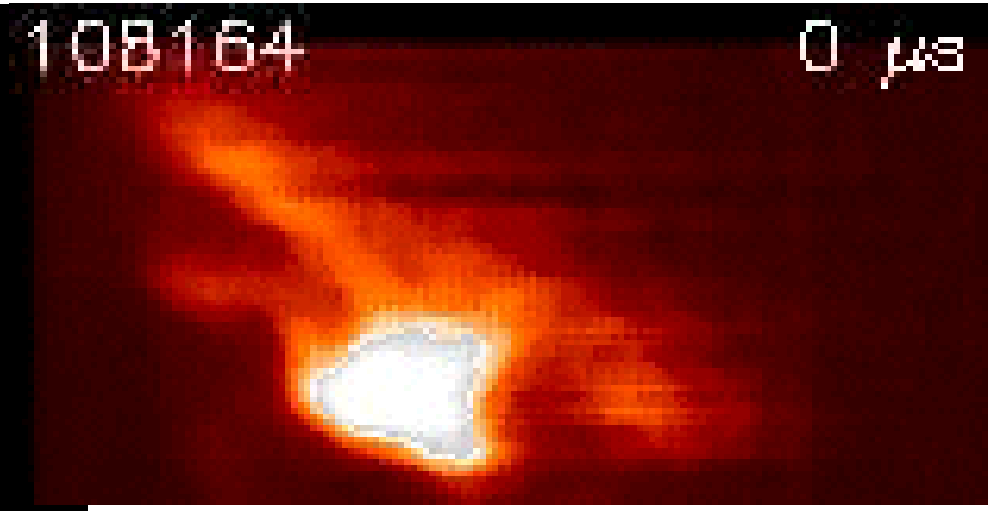
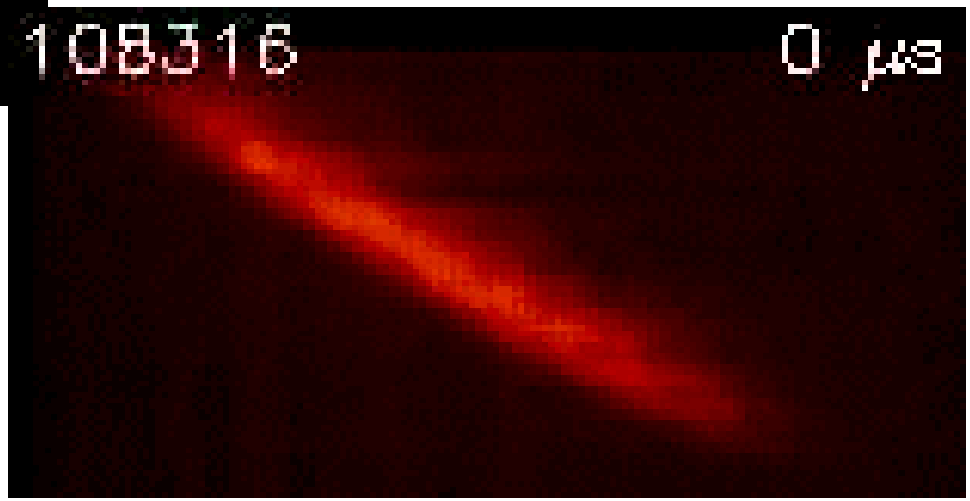
Edge Turbulence Observed to Scale with Magnetic Field



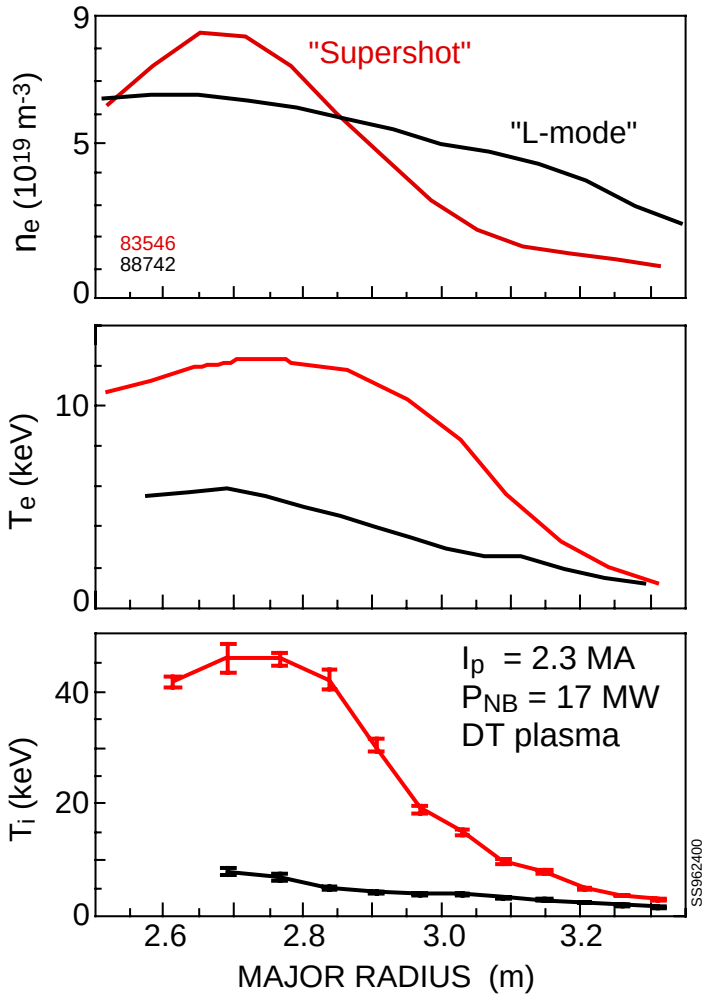
- **C-Mod: L_B~1cm, $k_\perp\rho_s$~0.1**



- **NSTX: L_B~5cm, $k_\perp\rho_s$~0.2**



Lithium Wall Conditioning Techniques Dramatically Improved Performance in TFTR



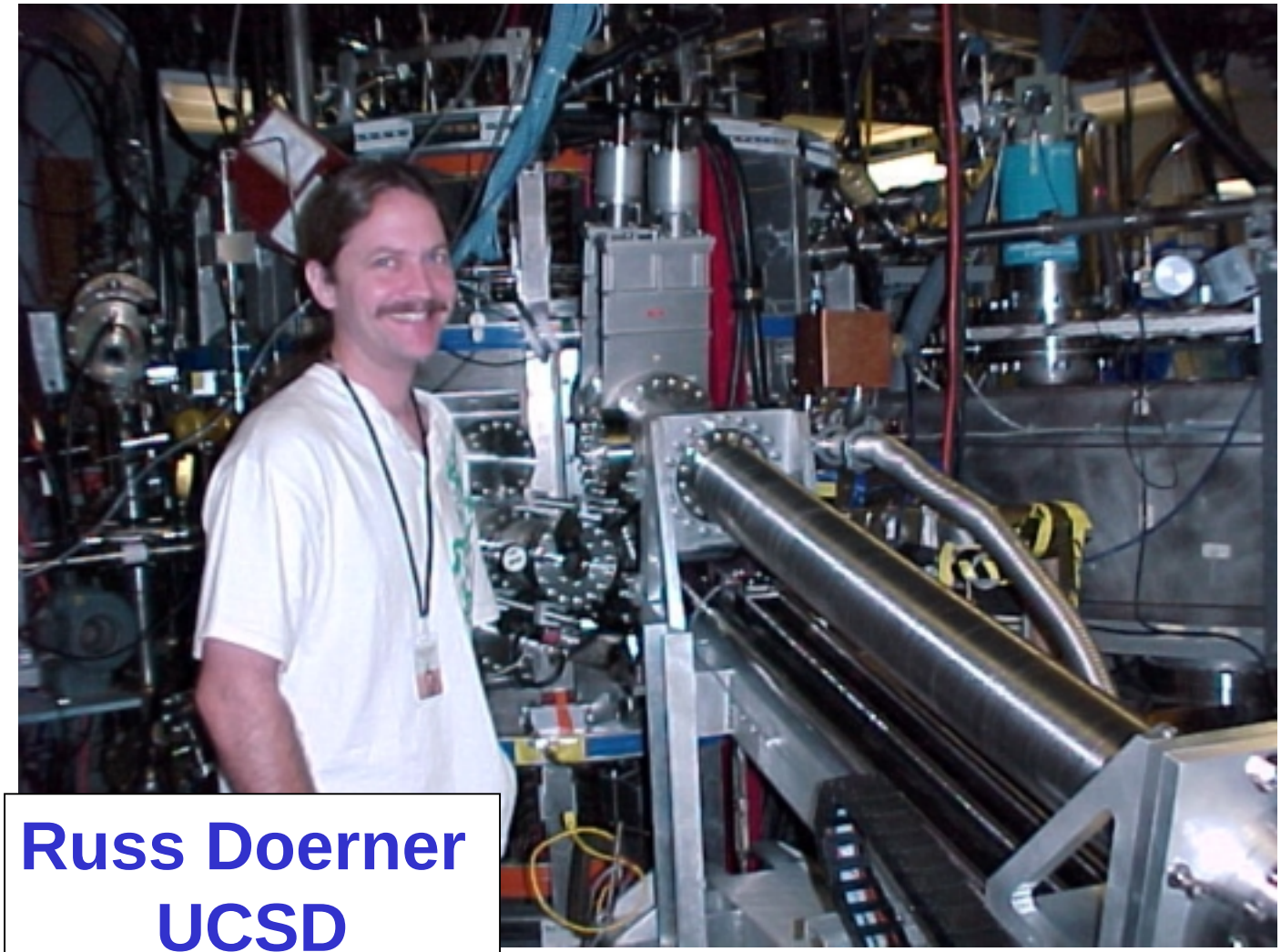
$n_i(0)\cdot T_i(0)\cdot\tau_E$ increased by a factor of 20:

L-mode: 0.48 x10^{20} m^{-3}·keV·sec

Supershot: 9.9 x10^{20} m^{-3}·keV·sec
(with Lithium Wall Conditioning)

Theoretical models of ion heat transport successfully described strong dependence on edge conditions.

Experiments with Liquid Lithium PFC's are Underway on CDX-U



Russ Doerner
UCSD

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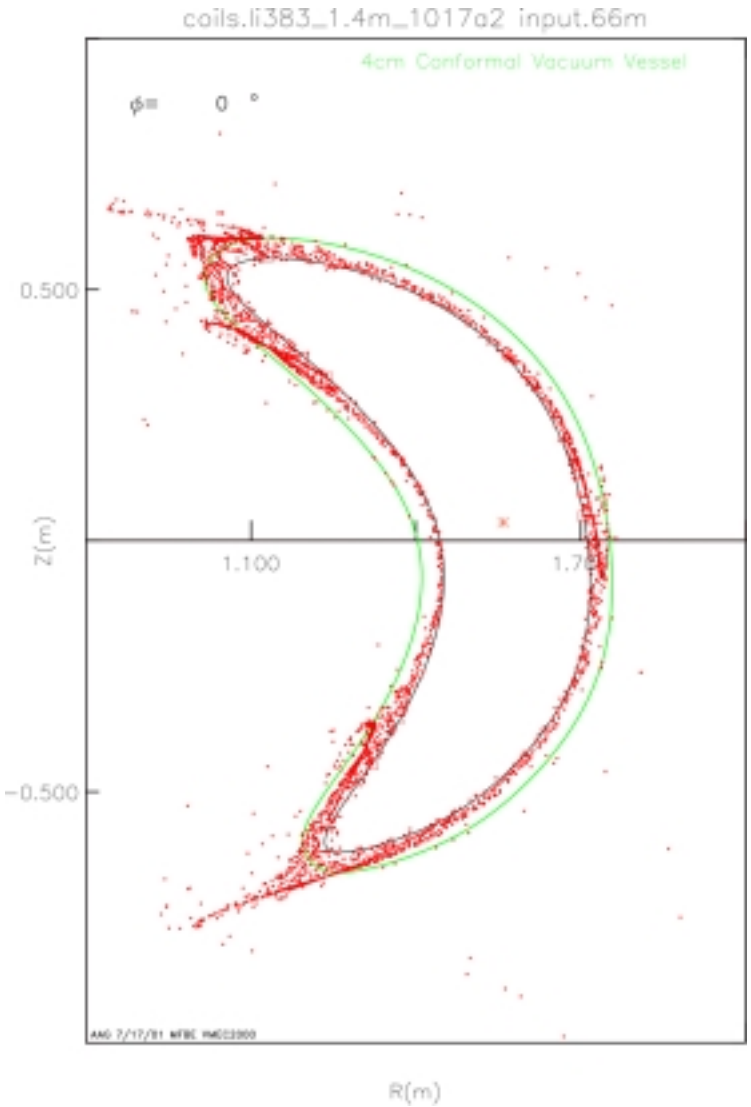
NCSX Will Test Effects of Stochasticity on Plasma-Material Interactions



- Magnetic field lines leave edge of plasma in stochastic pattern.
- Allows cooler and hotter field lines to be in close contact.
- May allow recombination in more compact volume.

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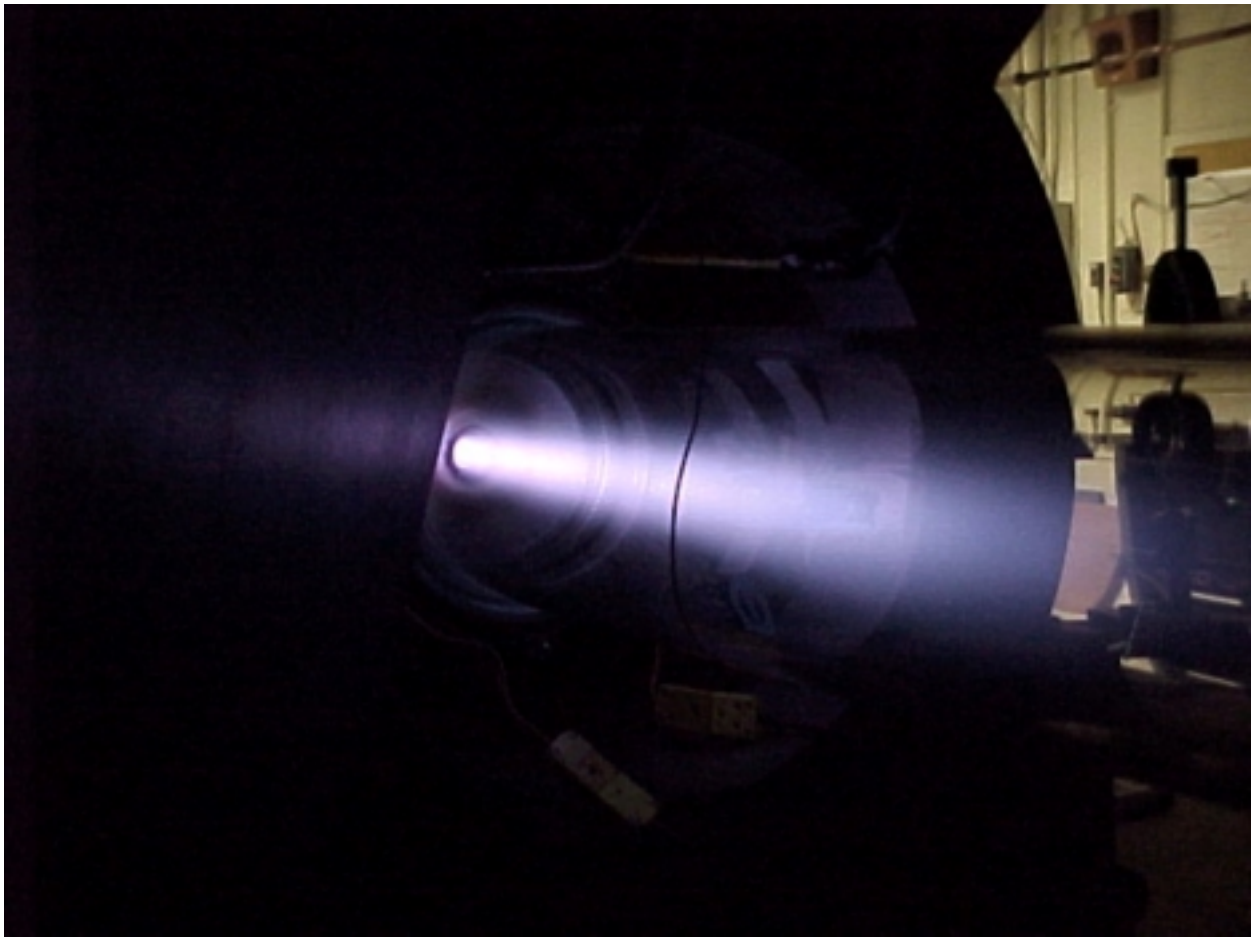
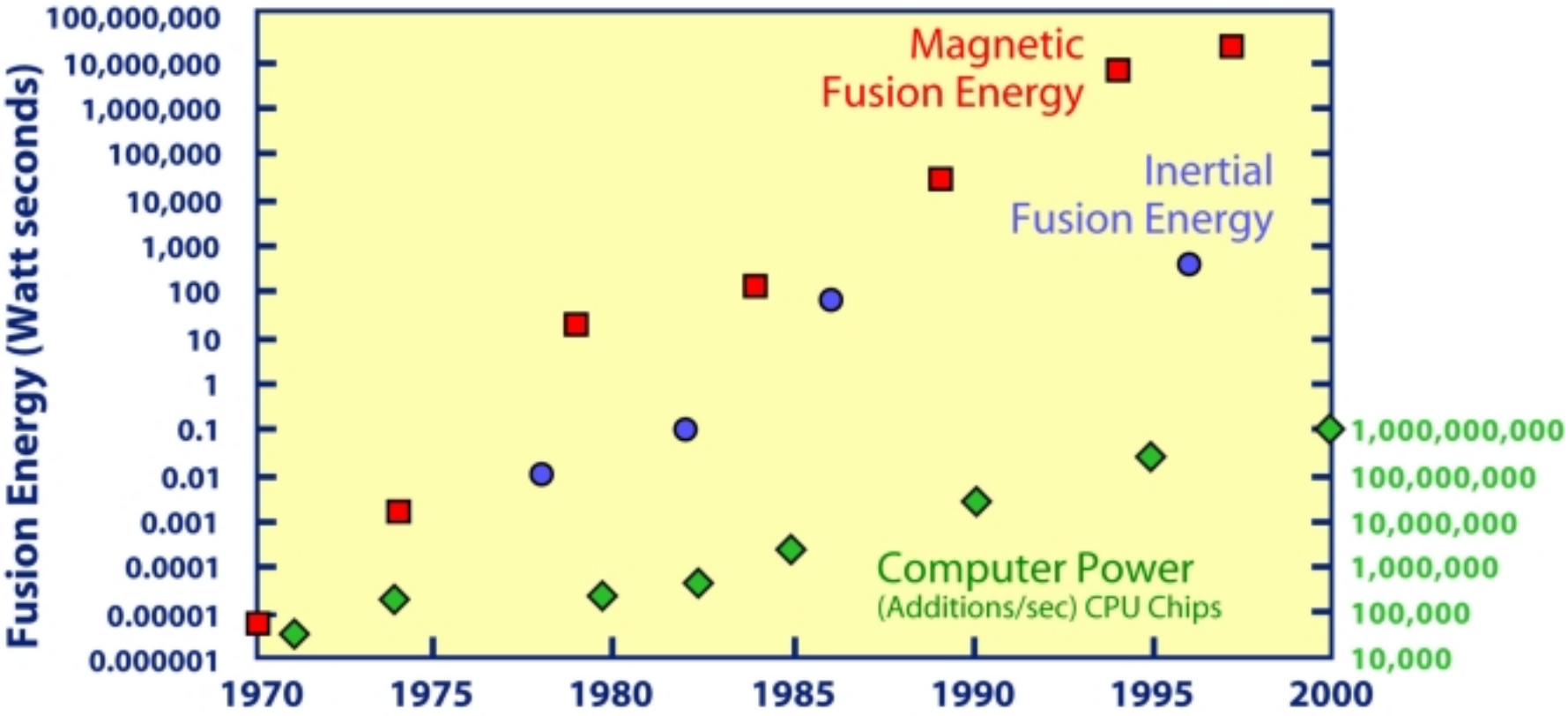
Magnetic Nozzle Experiment



Can expansion cooling of a plasma cause recombination?
Applications in plasma processing and space thrusters.

Progress in Fusion Energy has Outpaced Computer Speed



Recent Scientific Excitement Driven by Strong Coupling Between Theory and Experiment

- PPPL is addressing the fundamental topics of high-temperature plasma science.
- Addressing key scientific issues for the development of fusion energy.
- Strong impact on other fields of science.

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