Confinement and heating on NSTX: assessing the physics of high beta and low aspect ratio

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for the NSTX Research Team

Presentation to the
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Princeton Plasma Physics Laboratory
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Assessing the attractiveness of the spherical torus requires an aggressive science program

IPPA Goal 2.1: Assess the attractiveness of the ST concept (FY'04)

Unique topical science will form the basis for this assessment

To achieve this, NSTX research is organized along topical lines:

- MHD
- Transport
- Waves-particles (HHFW)
- Coaxial Helicity injection (non-inductive startup)
- Boundary physics

In this talk: a focus on transport and heating research

There have been significant advances in MHD, CHI research

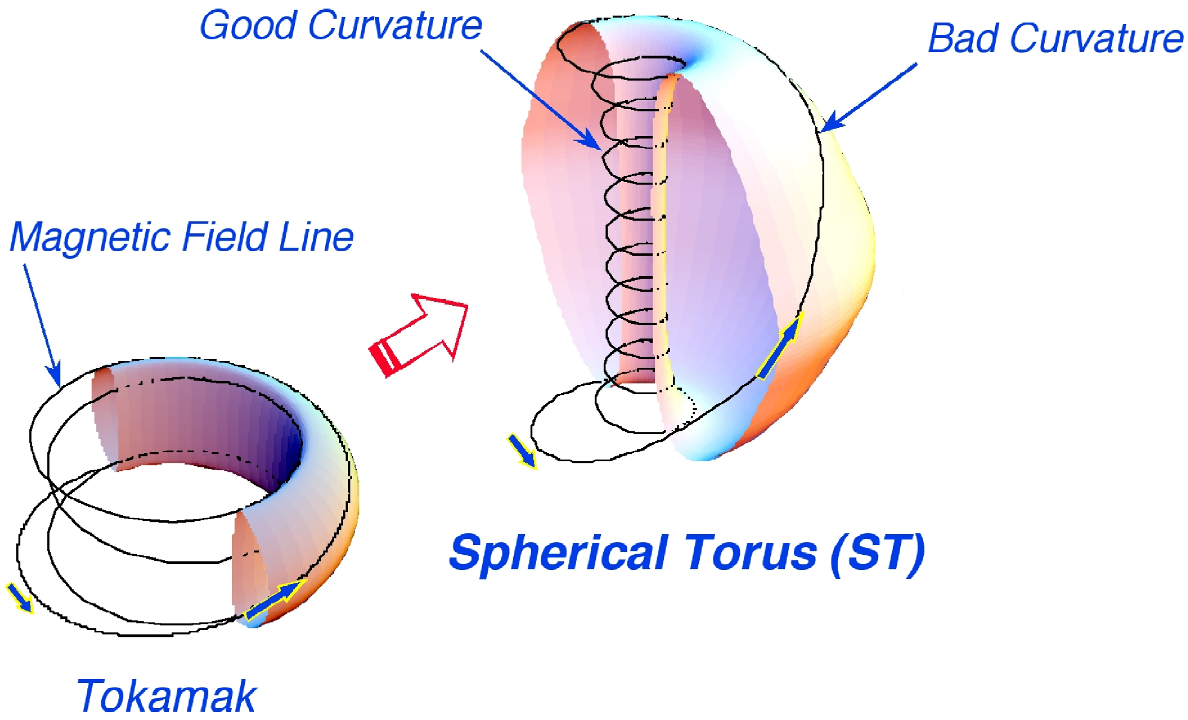
Not discussed in this talk. But topics include:

- MHD: beta limits explored (with Columbia U.)
  - Troyon scaling
  - J(r) variations
  - Wall stabilization & coupling
  - Tearing modes
  - Current driven kinks
- Non-inductive startup (U. Washington)
  - Coaxial Helicity Injection: 350 kA toroidal current
    - Major foci: control, flux closure assessment (measure profiles, magnetics assessment with GA)

NSTX is beginning to access science specific to high beta and low aspect ratio

- Change the aspect ratio: What physics changes?
- Overview of operating scenarios, tools
- Neutral beam heating & transport
- Electron heating & transport
- The edge
- NSTX research and the broader scientific community

Physics differences between low and moderate aspect ratio are born from changes in the B field



High beta, lower aspect ratio (A) ⇒ physics opportunities

Physics	Moderate A, lower β	Lower A $\beta(0) \Rightarrow 1$
Transport	Low k turbulence usually dominant Strong flow shear: possible Electrostatic turbulence	Low k suppressed? *High k dominant*? Strong flow shear: typical? Strong E-M effects?
Waves: externally launched	ICRH available for heating; ECRH available for CD	HHFW, EBW: new absorption/propagation
Wave/particle interactions	$V_{Alfven} > V_{beam} > V_{th}$	$V_{beam} > V_{Alfven} \sim V_{th}$
Edge transport	Smaller Larmor radius Poorer average curvature	Larger Larmor radius Better average curvature ⇒ tests of H mode theories

- Change the aspect ratio: What physics changes?

- Overview of operating scenarios, tools
  - The machine & heating systems
  - Operating scenarios: progress in a year
  - Confinement trends; setting the stage for detailed science

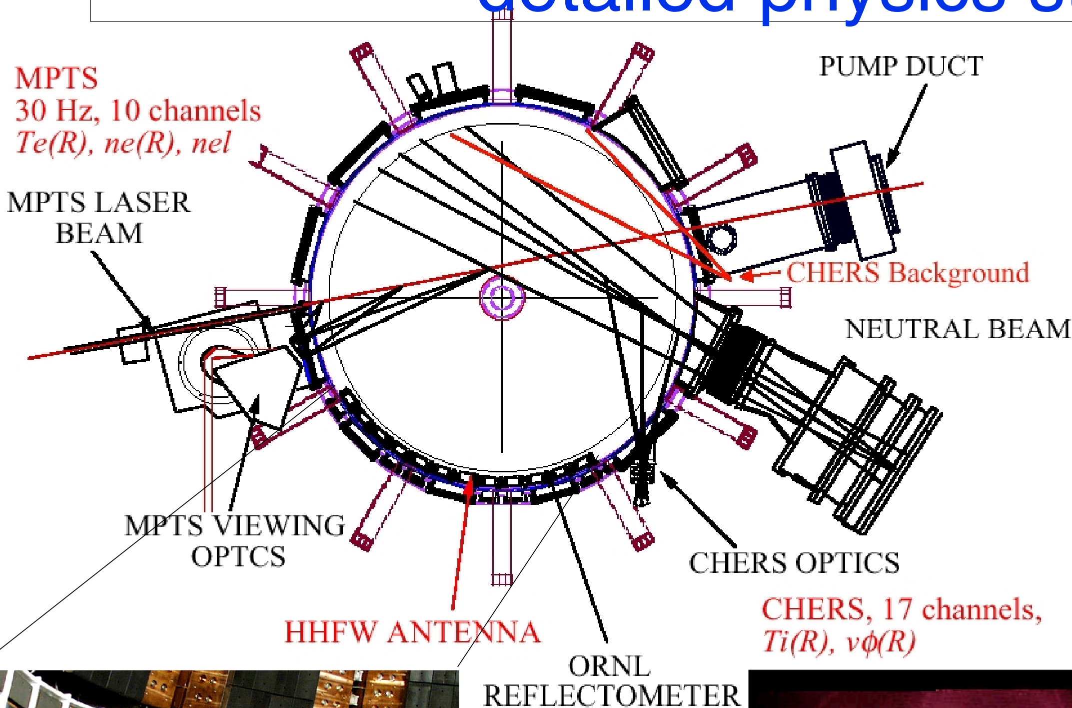
- Neutral beam heating & transport

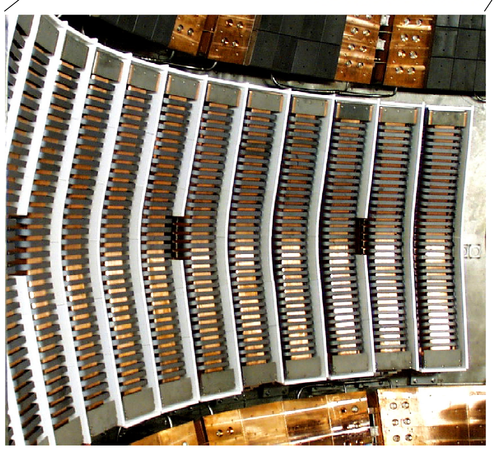
- Electron heating & transport

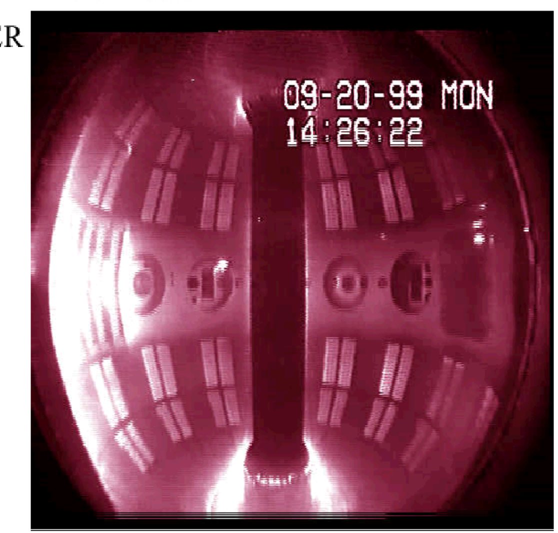
- The edge

- NSTX research and the broader community

Diagnostics, control system are enabling detailed physics studies





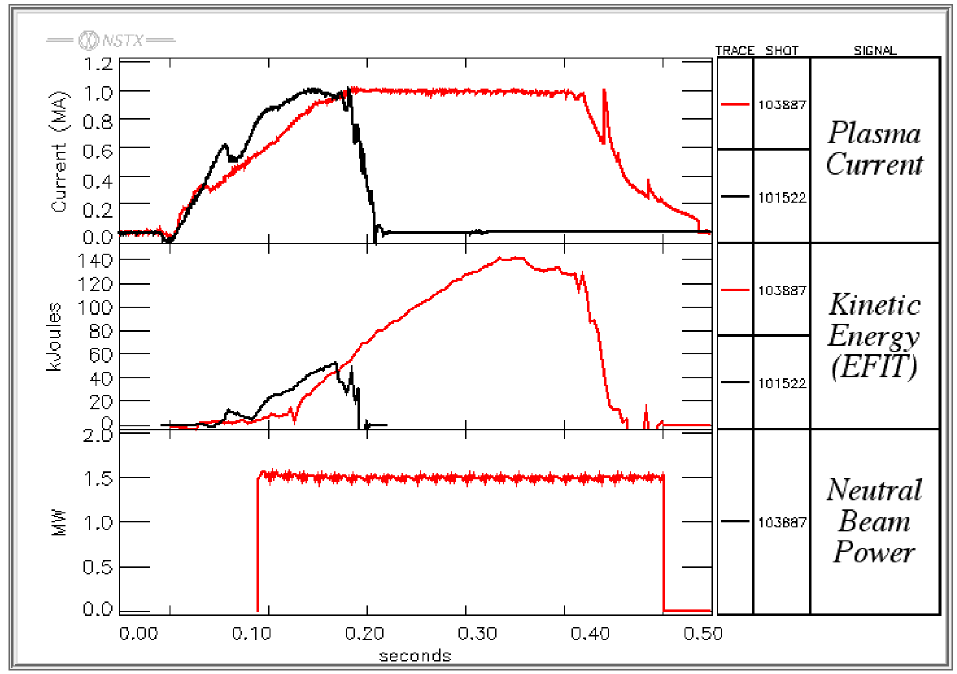


- NSTX, DIII-D poloidal cross sections similar

The NSTX Program has a good baseline scenario, and is developing tools to extend it

- Significant progress in pulse length and reproducibility in a year
  - 1 MA routine; design rating
  - 1.4 MA achieved
- β_T ~ 22% (EFIT); $\beta_T(0)$ ~ 86% (kinetics)
- Tools in place:
  - NBI (5 MW),
  - HHFW heating (**ORNL, GA**; 6 MW)
  - Shape control (**GA**)
  - HeGDC, boronization (MAST)
- Tools being developed:
  - CHI (**UWash**),
  - HHFW CD (**ORNL, GA**)
  - Real-time EFIT (**GA**)
  - Active mode control (**Columbia, GA**)
  - 350˚ C bakeout

Collaborative research a key element



Early transport studies reveal exciting trends

- Confinement times higher than expected from empirical scaling laws

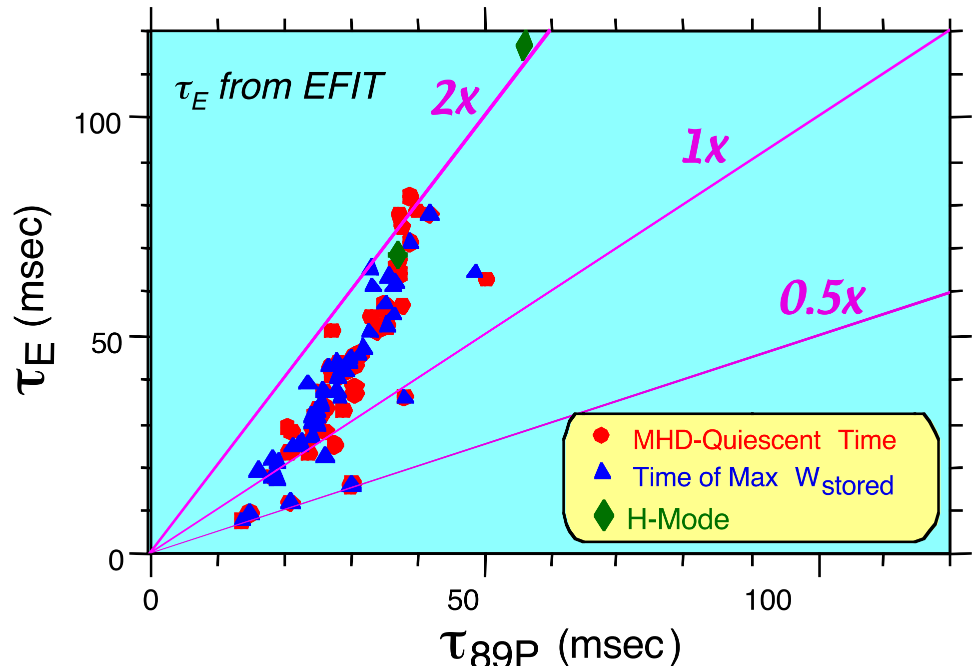
But recall:

IPPA Goal 1.1: Advance transport based on turbulence understanding

⇒ *We must go well beyond the scaling laws*

Directions, this year and next

- local diagnostics, heat flows, edge turbulence studies
- Analysis with/development of microstability codes

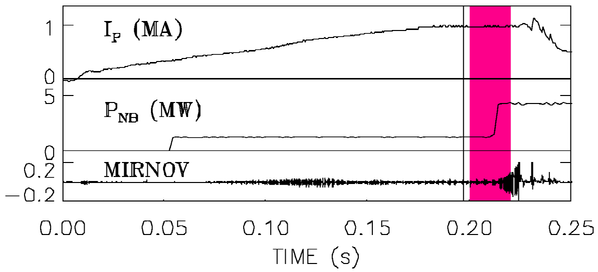


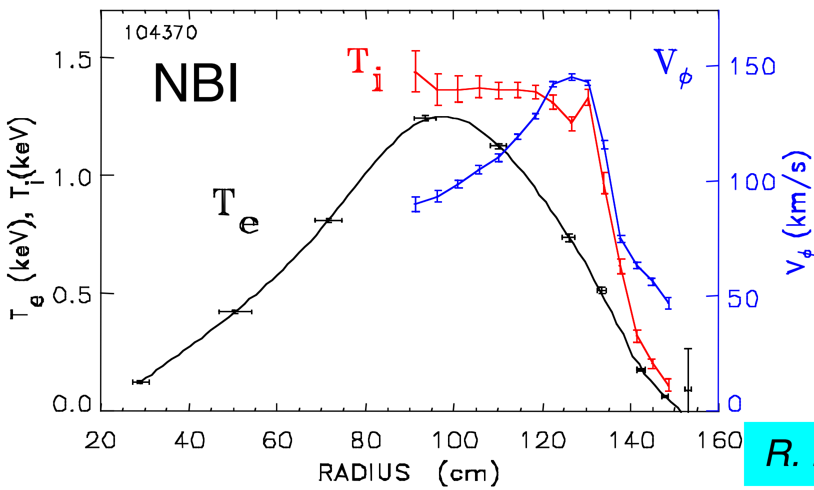
Kaye; Sabbagh (Columbia)

- Change the aspect ratio: What physics changes?
- Overview of operating scenarios, tools
- Neutral beam heating & transport
  - Profile measurements at high beta
  - Power balance: mysteries
  - Seeking a resolution: Experiment/theory interplay
- Electron heating & transport
- The edge
- NSTX research and the broader community

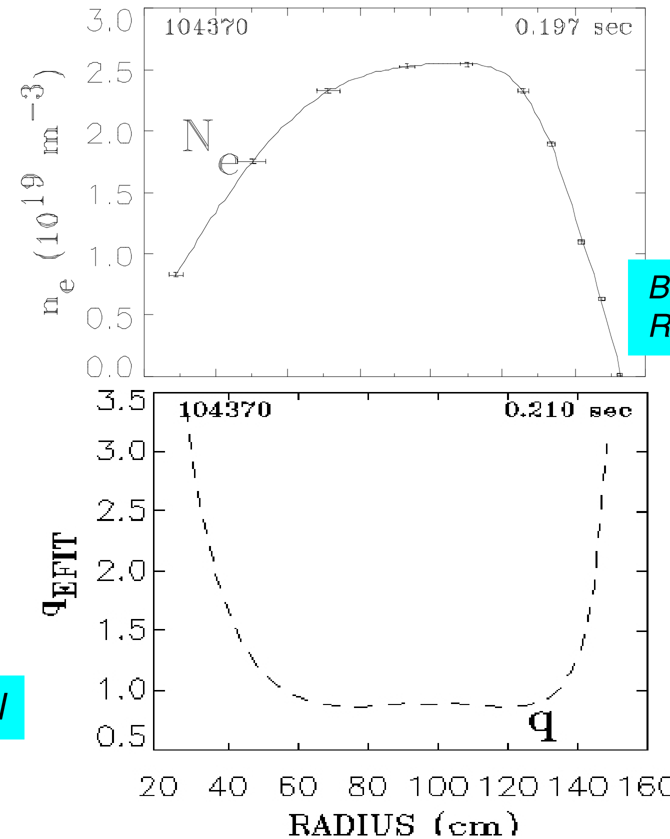
Kinetic profile measurements, magnetics analysis permit studies of local ST physics to begin

$\beta_{T(EFIT)}$ ~ 20%





R. Bell



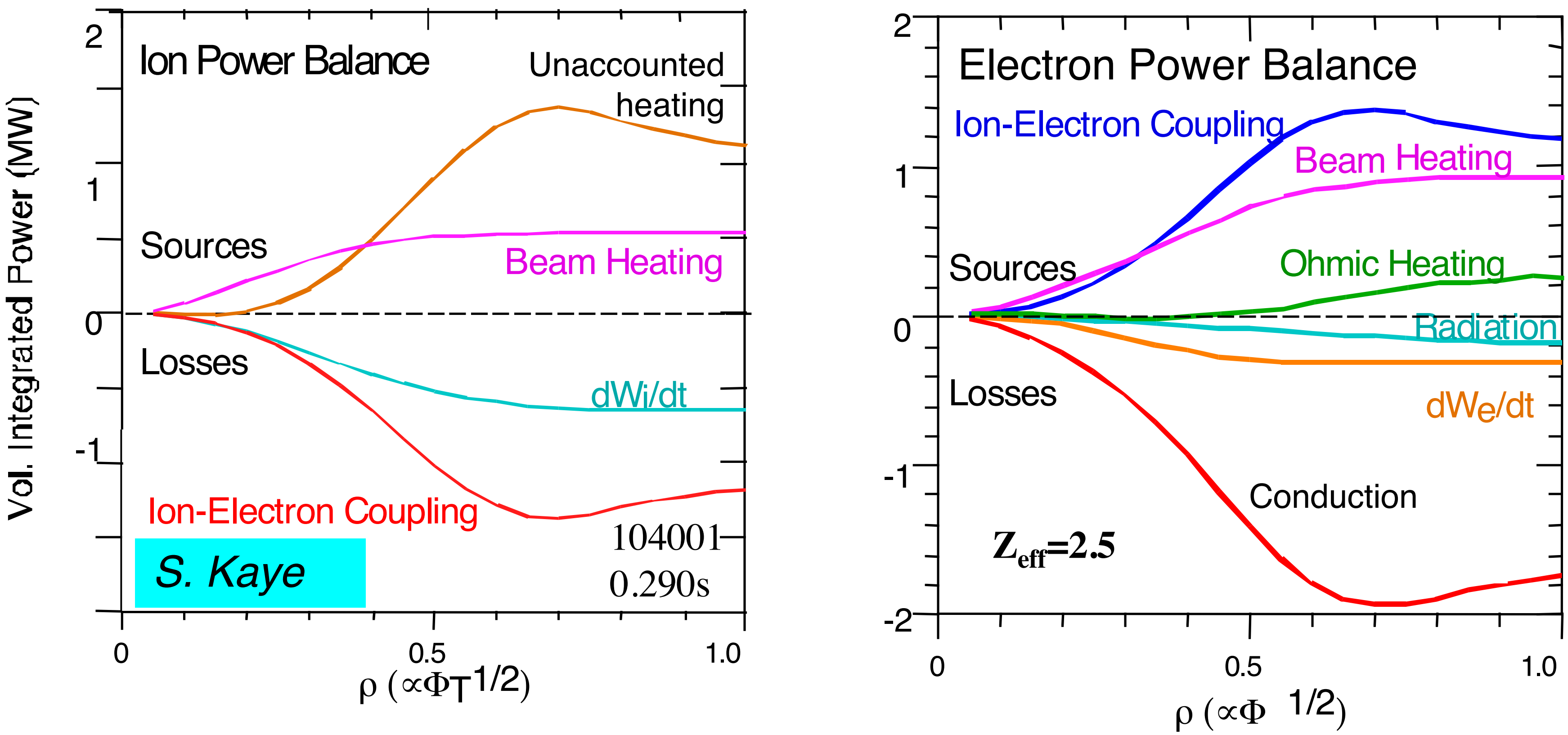
B. LeBlanc, R. Bell

- Broad T_i profile (compared to T_e)
- Large T_i - T_e
- High V_ϕ in core & edge

20% β_T (EFIT)

EFIT: Sabbagh, Paoletti (Columbia)

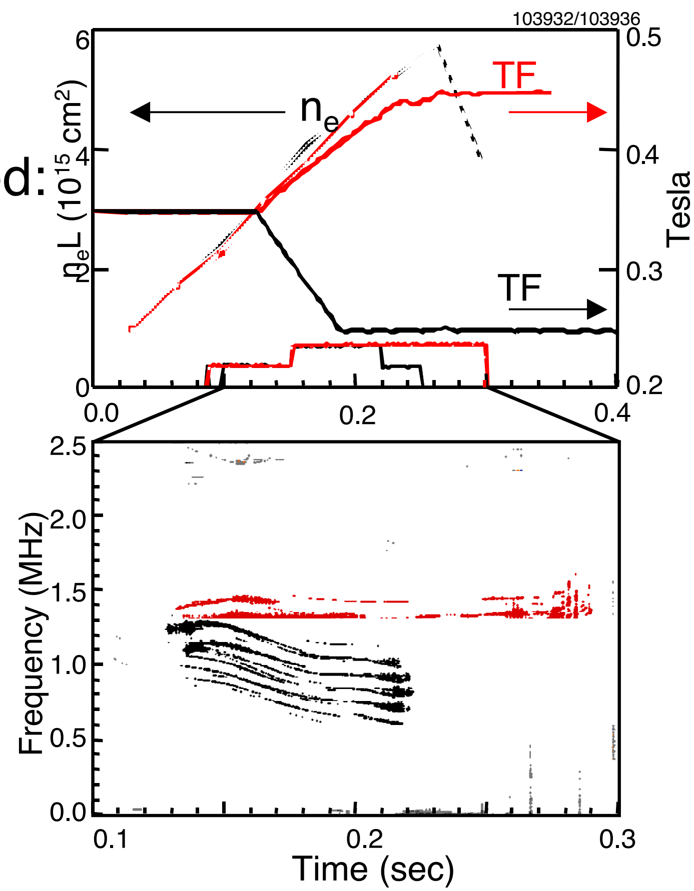
Power balance analysis reveals puzzles



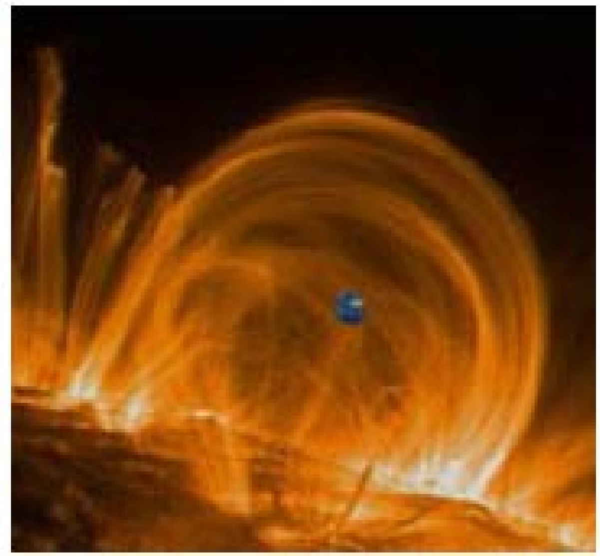
- With NBI: apparent anomalous source of heat to ions, or a heat pinch
  - Diagnostic issue? Heating physics
- If all of the beam heating goes to the ions, and if ion conduction is very small, then the power balance can make sense

Astrophysics and observed MHD may hold one clue to the power balance puzzle

- Being investigated: Compressional Alfven Eigenmodes
- Modes excited by fast ions; waves transfer energy to thermal ions



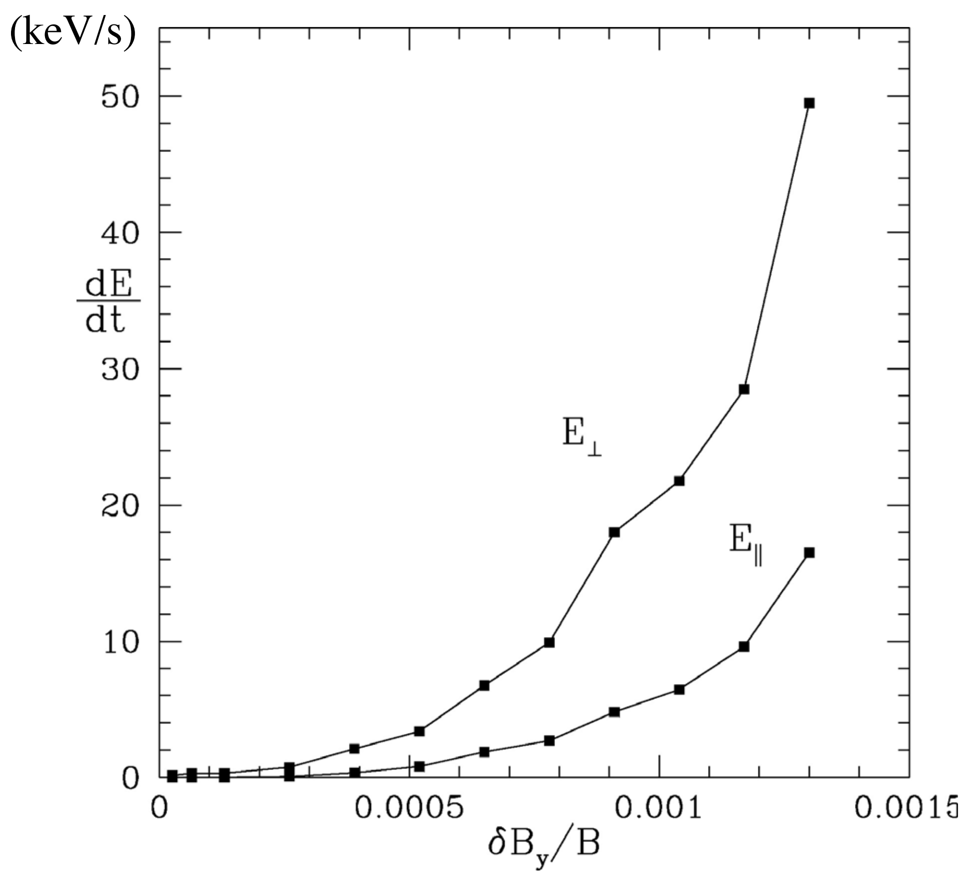
Fredrickson



- Theory of stochastic wave heating of corona developed (White)
- Application of theory to ST has begun
- $V_{beam} > V_{Alfven}$ key

Gates, Gorelenkov, White

Beam-driven Compressional Alfven Waves may heat ions on NSTX

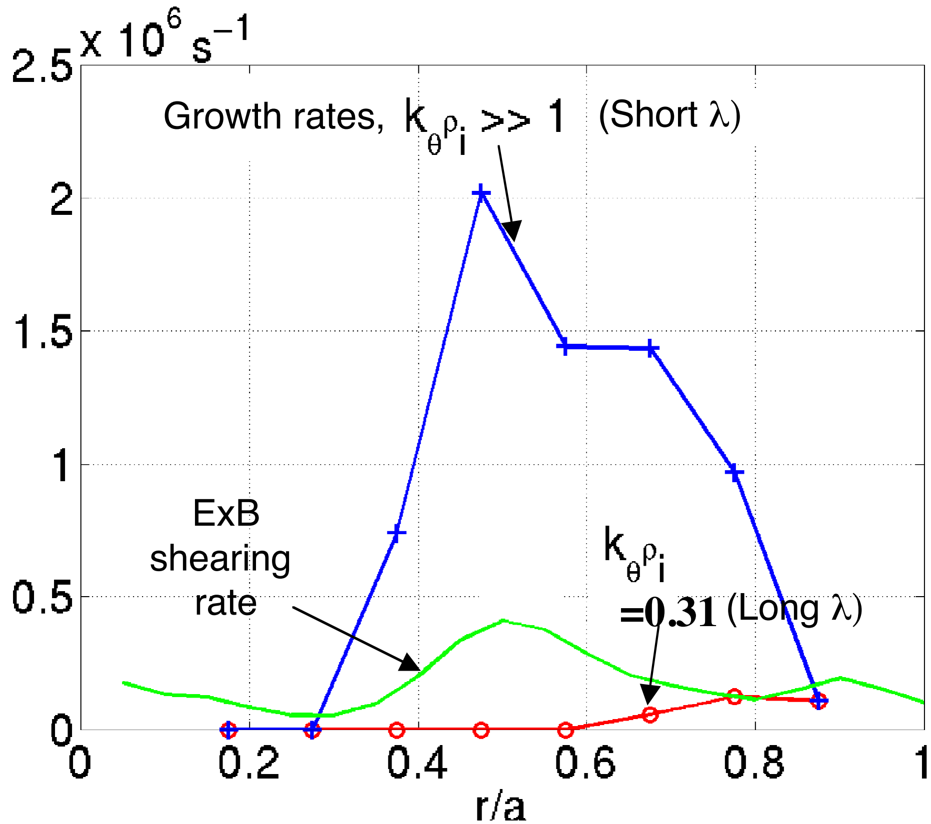


- Simulations of compressional Alfven modes give stochastic ion heating.
- e.g.-- $\delta B/B = 0.001$ with 20 modes centered at half Alfven frequency
- Possible relevance to interpretation of ion-heating on NSTX

D. Gates, N. Gorelenkov, R. White

Theory: short wavelength modes may dominate transport; long wavelength modes may be suppressed

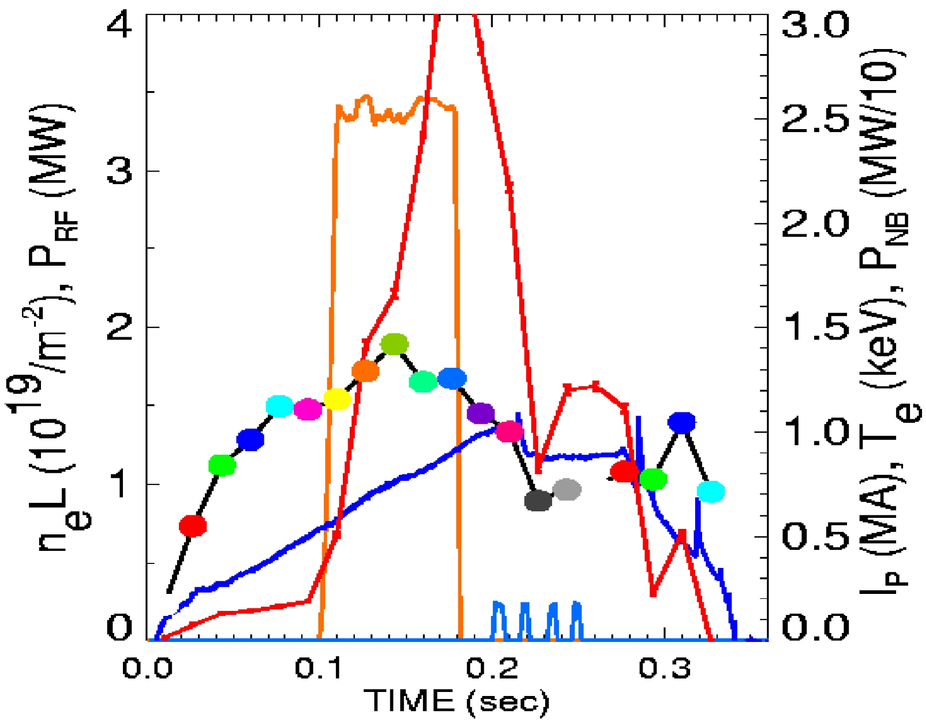
- Long wavelengths: growth rate lower than **ExB** shear rate
  - Large λ associated with ion thermal transport
- Short wavelengths: growth rates large
  - Responsible for electron thermal transport?
  - Non-linear simulations begun



C. Bourdelle (PPPL), W. Dorland (U. MD)

- Change the aspect ratio: What physics changes?
- Overview of operating scenarios, tools
- Neutral beam heating & transport
  - State of research: promise, surprises, theory
- Electron heating & transport
  - HHFW: recent progress
  - The electron transport problem
  - Experiment/theory exchange
    - Assessing the heating source
    - Predicted vs. observed trends
- The edge
- NSTX research and the broader community

High harmonic fast wave is an efficient heater of electrons

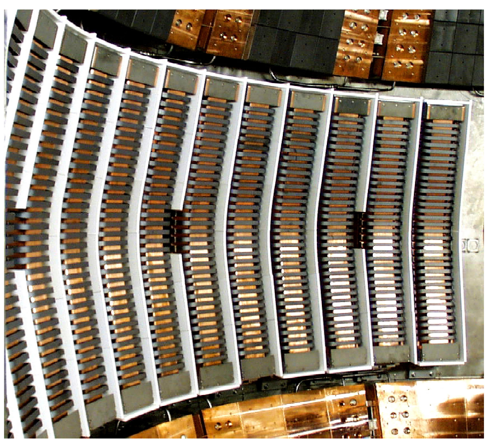


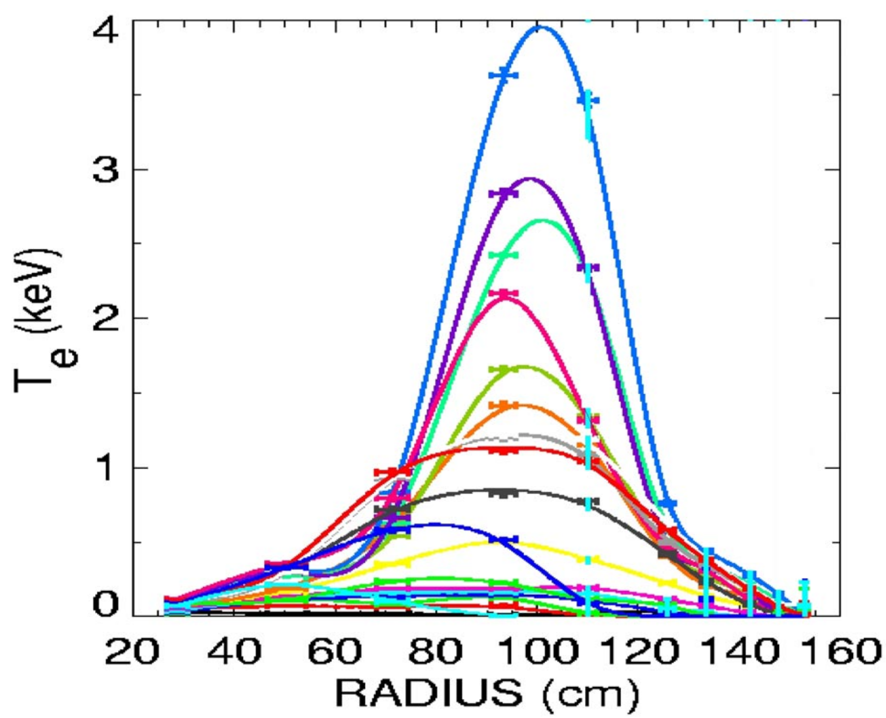
M. Ono (1995): Fast wave decay (absorption) rate:

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

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

With ORNL





Electron thermal transport is one of the outstanding physics problems of high temperature plasmas

- One of the two major transport problems identified in Snowmass and within the Transport Task Force
- Major question: what is the cause?
  - Short wavelength turbulence?
  - Electromagnetic effects?
- NSTX is an ideal laboratory for this
  - HHFW a powerful control knob on T_e
  - Already evidence that electron channel may be dominant
  - ST ideal for high k fluctuation measurements
    - Strong shear, low A $\Rightarrow$ spatial localization possible with scattering
    - Modes likely scale with ρ_e $\Rightarrow$ larger scale size at high beta, low B

Benchmarking with advanced theory and data key to understanding HHFW

Approach: *benchmark and test* faster models against most sophisticated theory and measurements

Benchmark with complete wave theory
AORSA-2D (Batchelor, Jaeger, ORNL) (SciDAC)

Faster model: Ray tracing
CURRAY (Mau, UCSD); HPRT (Rosenberg, P.U., Menard)

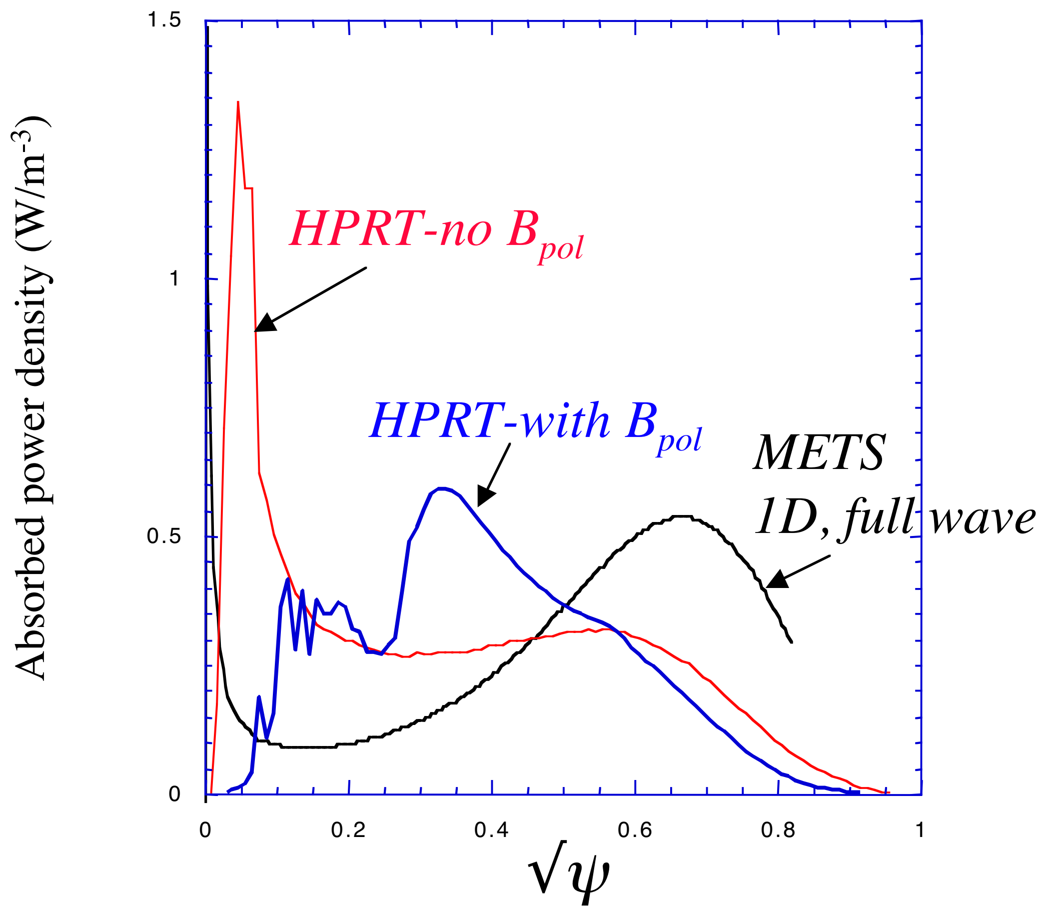
Analysis of transport, current drive
TRANSP

Faster model: Full wave
TORIC (Bonoli, MIT); METS (Phillips; SciDAC)

Benchmarking with NSTX Data
Wave-particle interactions
Source measurements

Heating source calculations being performed for recent NSTX plasmas

- Measured NSTX kinetic profiles serve as input
- Inclusion of 2-D effects important to source profile
- HPRT results serve as input to preliminary transport analysis
- Initial benchmark strategy: compare to ΔT_e before, shortly after start of HHFW



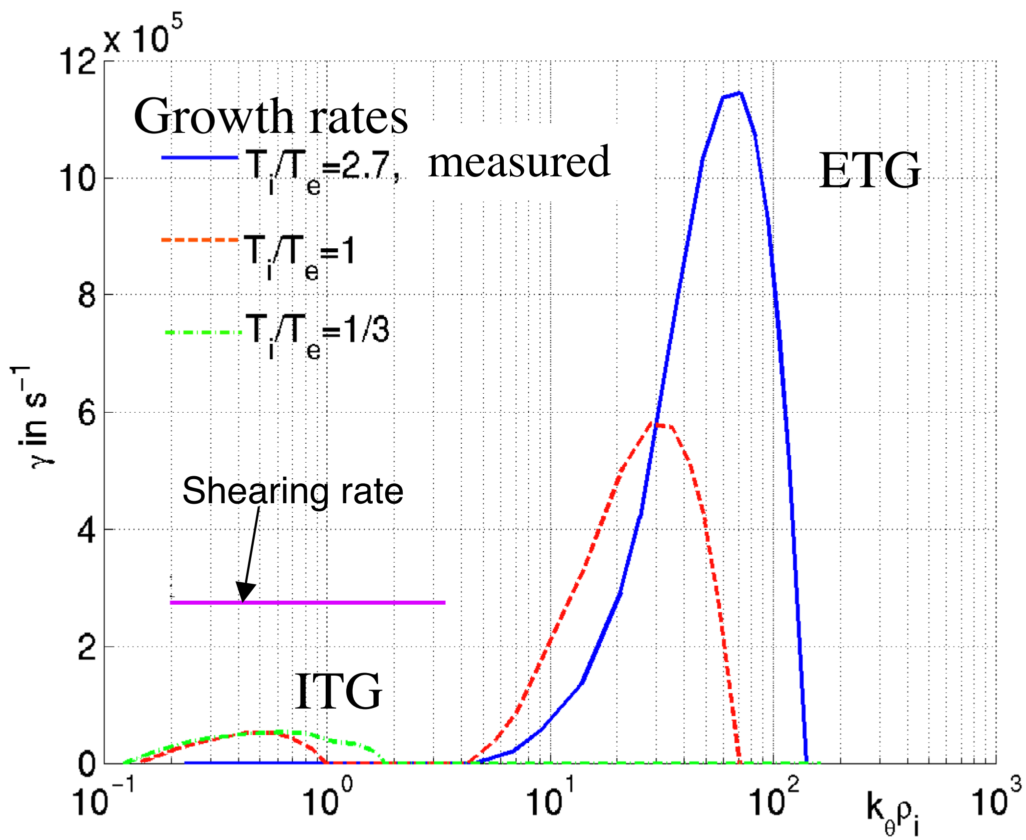
Rosenberg, P.U.; Menard, Phillips

Turbulence theory suggests testable trend for transport experiments

Conduct a theory experiment: vary T_i/T_e, keeping other profiles constant

- Theory indicates:
  - high T_i/T_e stabilizes ion modes
  - high T_e/T_i *stabilizes electron modes*

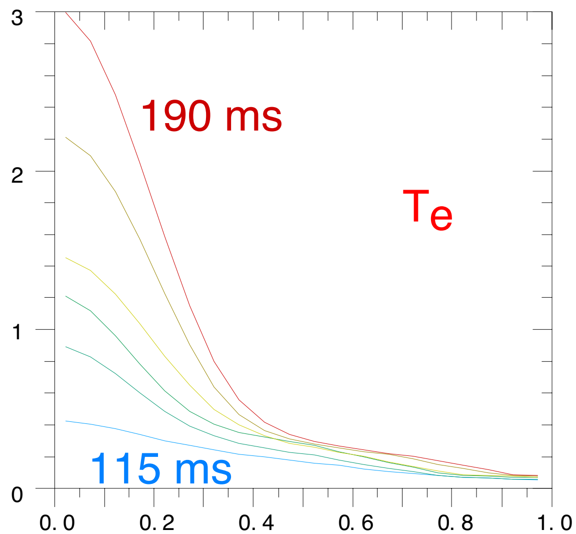
- *Do we see signatures of this in measured confinement trends?*

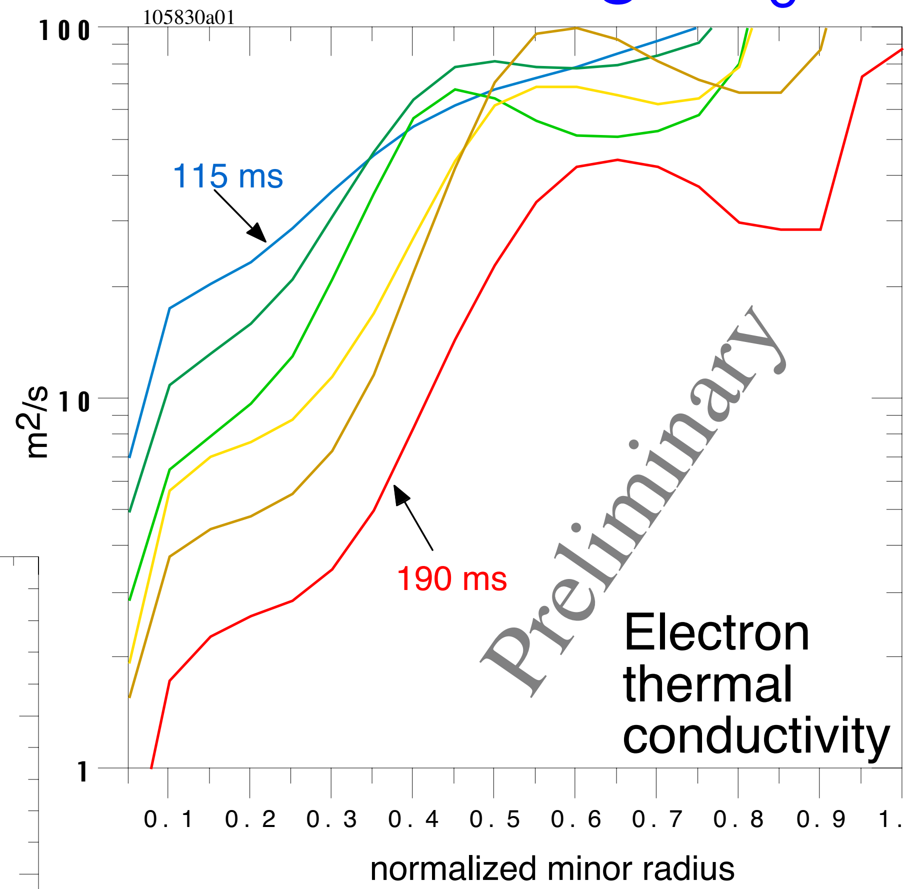


C. Bourdelle

Power balance analysis reveals that reduced electron transport correlated with high T_e

- Core χ_e drops as high T_e develops
  - Steep gradients due to transport changes, not source
- Heating source from HPRT ray tracing (Rosenberg)





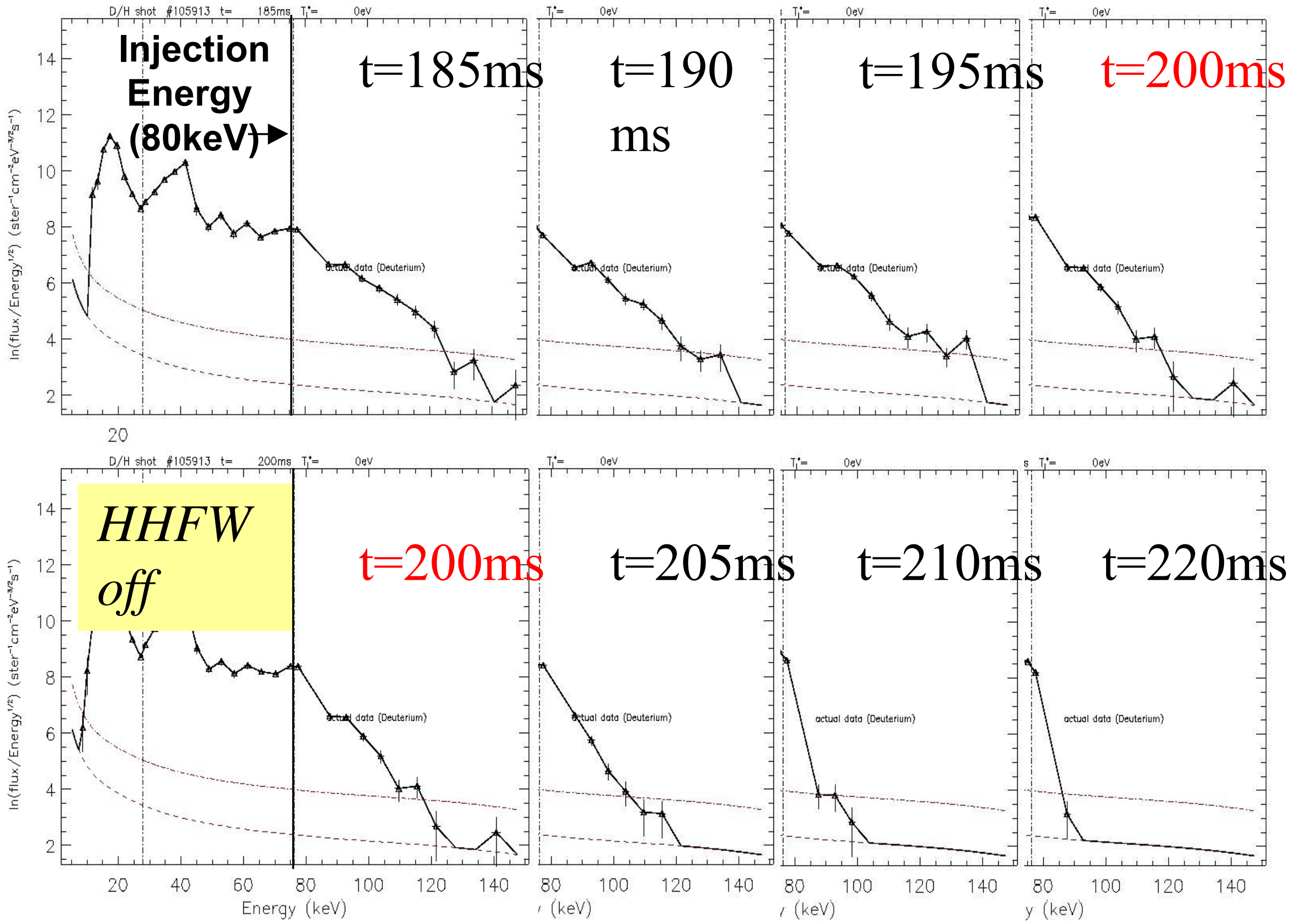
LeBlanc

Recent data is the foundation of important tests of wave-particle interactions theory

- HHFW turns off at t=200ms
- NBI Source A on throughout

- D^+ tail extends to 140keV
- Tail saturates in time during HHFW

SciDAC goal: Self-consistent wave-particle treatment



Rosenberg, Medley, Menard

- Change the aspect ratio: What physics changes?
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- Neutral beam heating & transport
  - State of research: promise, surprises, theory
- Electron heating & transport
  - State of research: promise, surprises, theory
- **The edge**
  - Differences between low and moderate aspect ratio, higher and lower beta
  - H modes
  - Edge turbulence data and theory
- NSTX research and the broader community

At the edge, differences between ST and tokamak are large

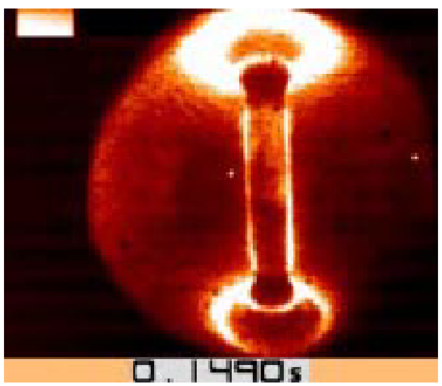
- Large mirror ratio, small B field
- Higher beta
- Larger Larmor radius
  - Stabilization of curvature modes? Pedestal changes?
- Larger ExB velocity
- Large good average curvature
- Larger magnetic shear

Goal: assess impact of these differences on edge turbulence dynamics, H mode access requirements, heat exhaust

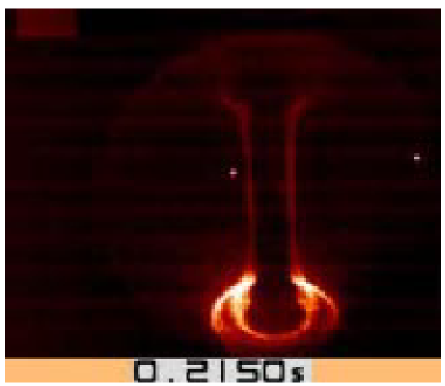
Bifurcations to enhanced plasma confinement state observed with both NBI and HHFW

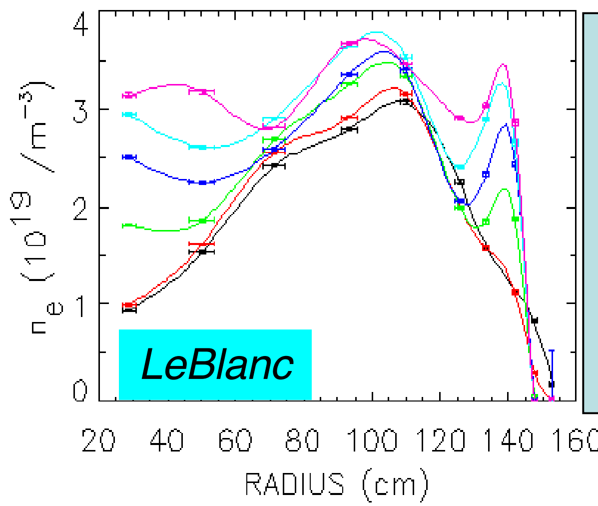
Visible light, false color

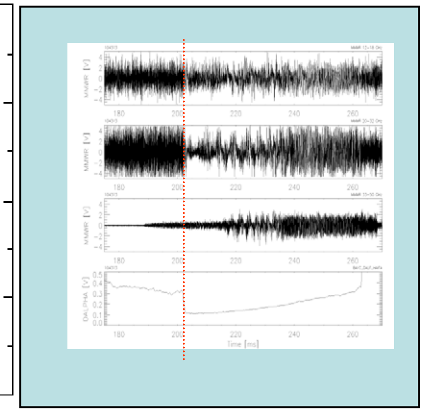
Before transition



After transition







- NBI: Power required ~ 10x that predicted from empirical scaling laws:
  - Strong magnetic shear?
  - Poloidal damping? Wall neutrals?

- Change in edge transport evident in density profile

- Fluctuations reduced at H mode transition

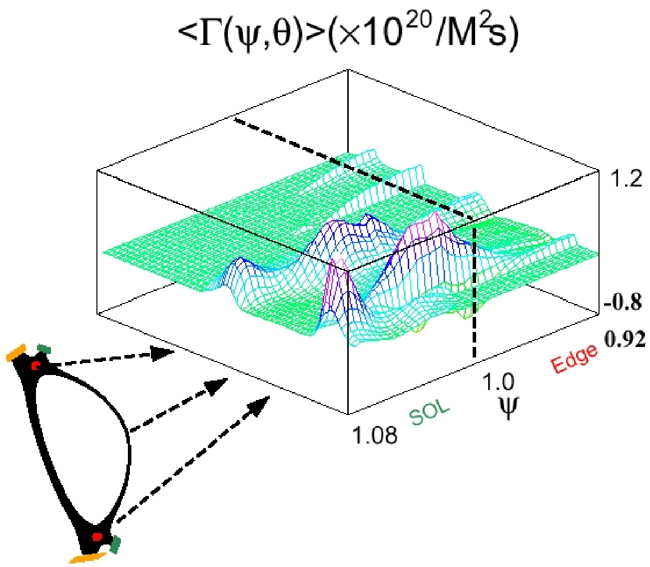
Edge reflectometry: *Peebles, Kubota (UCLA)*

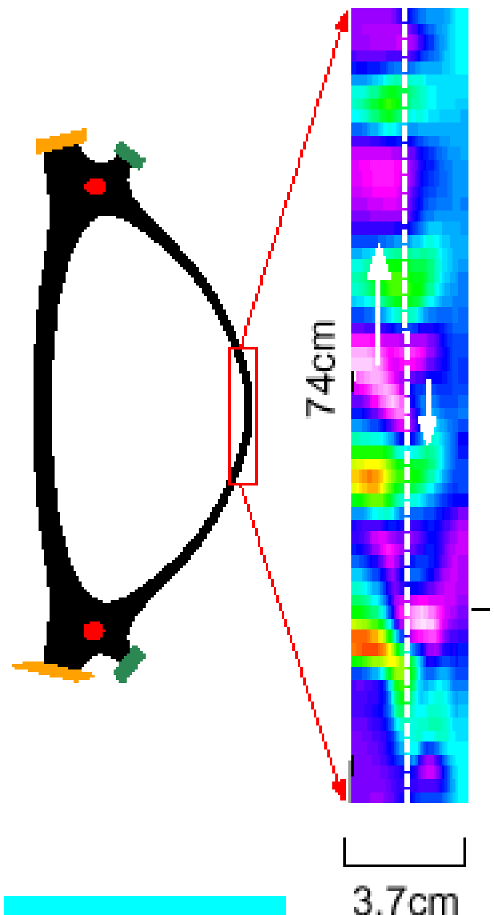
Fast camera: Maqueda (LANL)

H mode: Maingi, Bush (ORNL); LeBlanc

Theory indicates complex turbulent structures may exist in NSTX edge

- BOUT code: turbulence modeling
  - 2-fluid,3D Braginskii equation code

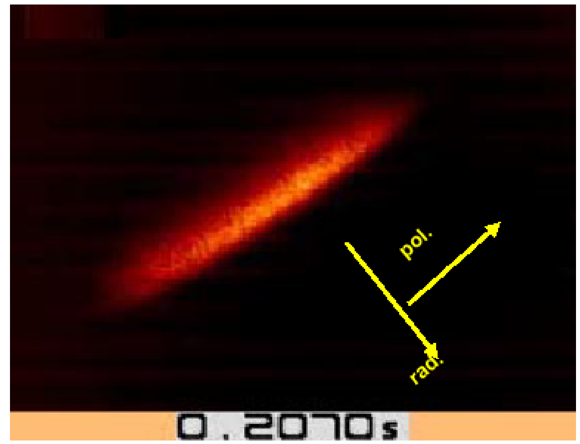




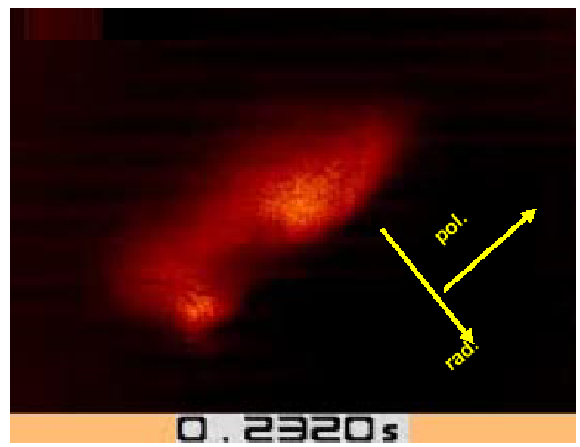
Xu (LLNL)

Imaging of edge reveals qualitative differences in H- and L-mode turbulence

- Helium puffed; emission viewed along a field line
- He^0 emission observed with a fast-framing, digital, visible camera
  - 1000 frames/sec, 10 μs exposure each frame



During H mode



After H-L transition

Maqueda, LANL; Zweben

Los Alamos
NATIONAL LABORATORY

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- The edge
- NSTX research and the broader community
  - High beta turbulence; astrophysics opportunities
  - Intermachine research

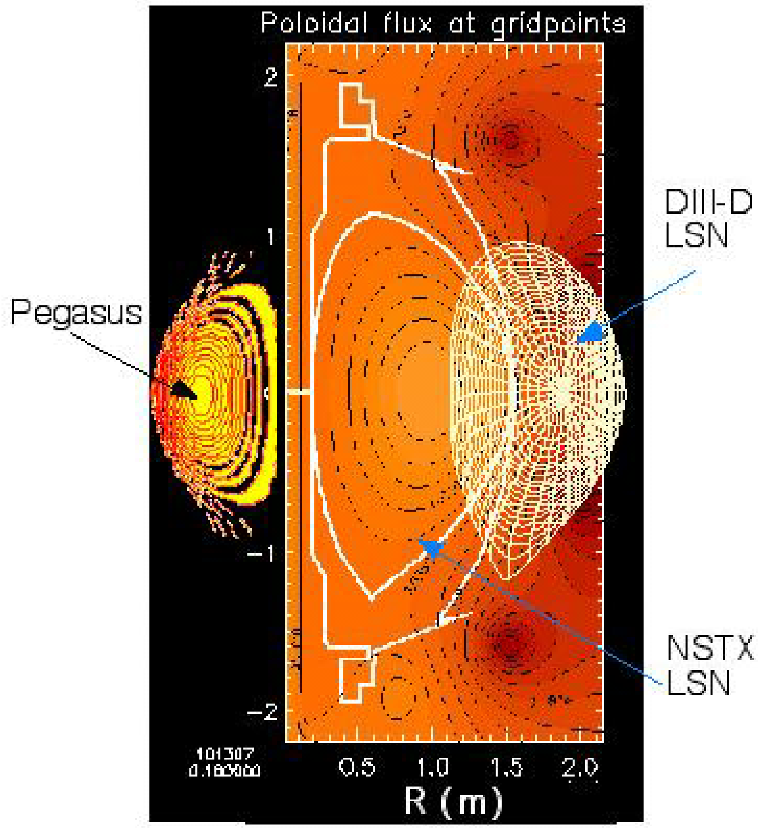
Inter-machine research will help reveal the physics of beta & aspect ratio

- Amplifies scientific strength of national and international programs

- DIII-D: similar cross section shape, size
  - RWM assessment work (Columbia, GA)
  - Beam-induced MHD proposal (UC Irvine)
  - Transport proposals (GA)

- Pegasus: aspect ratio can match at 1.25
  - Logical connection for studying physics of A
  - EBW startup research

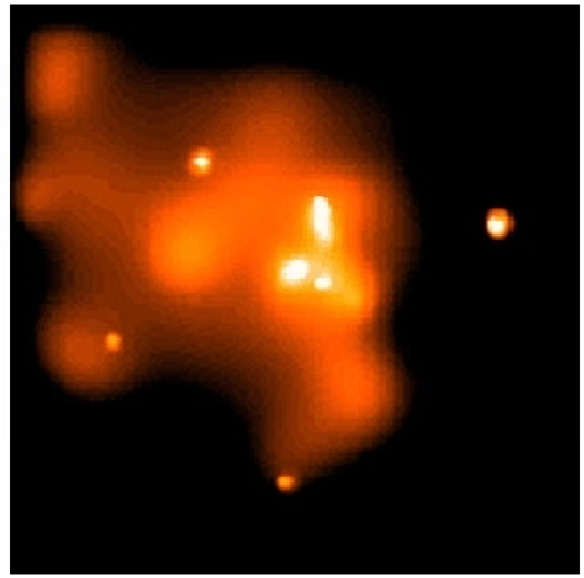
- MAST: similar size and A; wall is far
  - Wall/no wall influence on neutral density and H mode thresholds



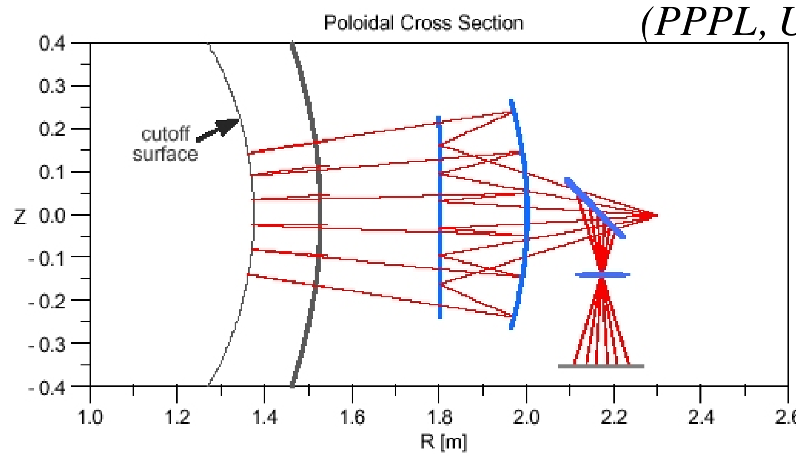
Paoletti, Sabbagh (Columbia)

Opportunity: physics link with other fields via high beta turbulence

- Build on FESAC transport & turbulence goal
- Astrophysics: Turbulence in accretion disks, active galactic nuclei
  - Opportunity to benchmark turbulence codes at high beta
- Requires qualitative advance in the way we do business
  - diagnostics: spatial, low k, high k resolution



From Chandra; our galaxy's core, 0.5 - 10 keV x rays



Imaging Reflectometry (PPPL, UC Davis)

NSTX is addressing physics unique to high beta and low A

- FESAC attractiveness goal ⇒ strong science essential
- High beta, low aspect ratio ⇒ new physics
- Diagnostics allow detailed physics studies to begin
- Theory contributions already central to analysis, motivating experiments
- Opportunities for linkages with other fields