Confinement and heating studies on the National Spherical Torus Experiment (NSTX)

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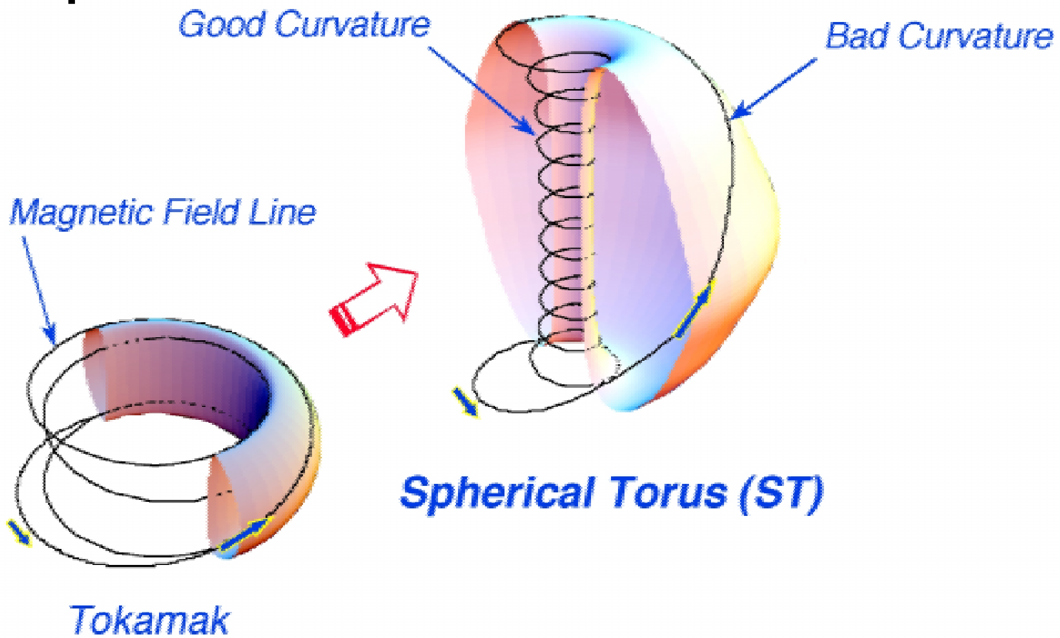
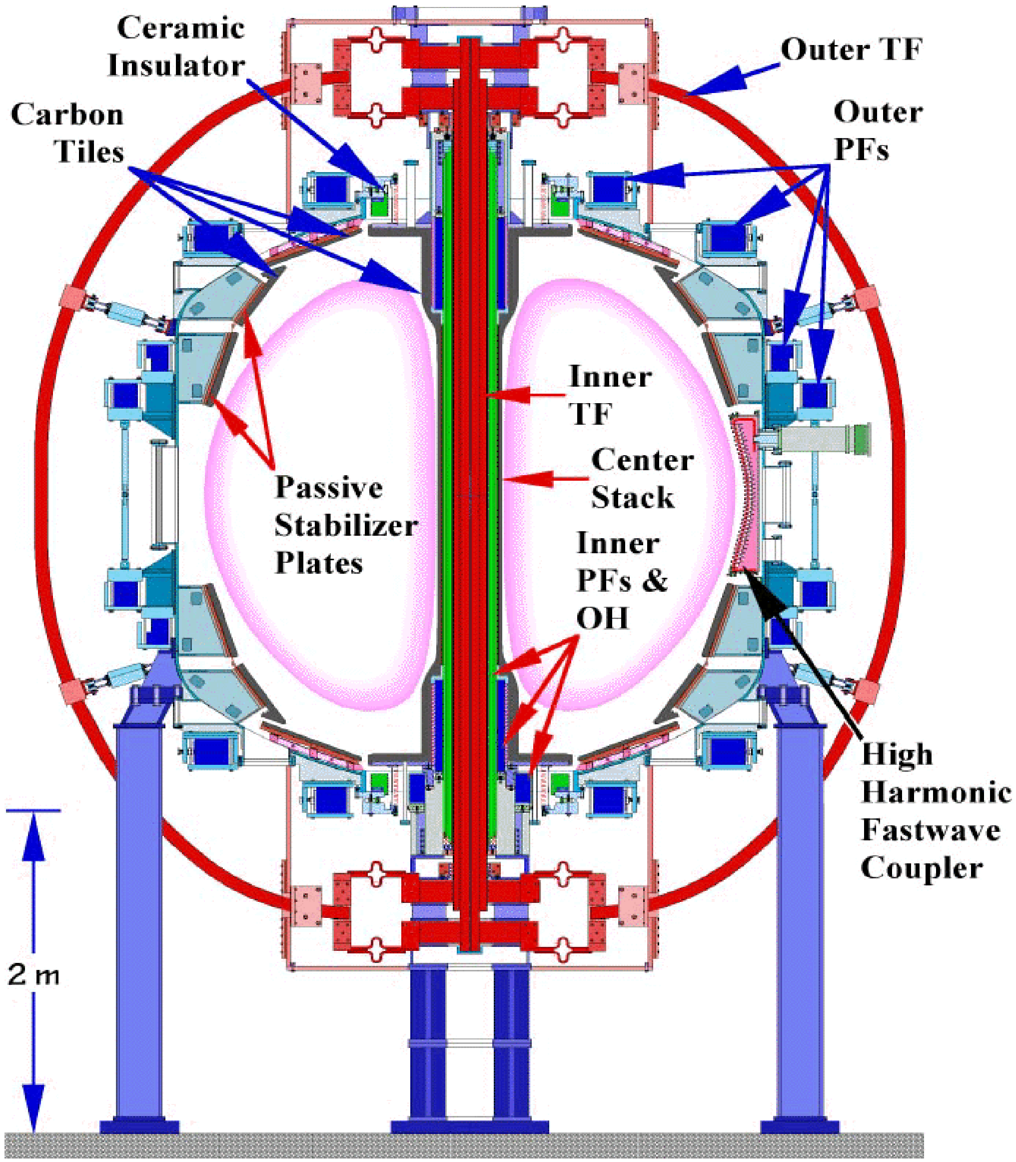
A program goal is to understand the physics specific to high beta and low aspect ratio

- Overview of operating scenarios, tools
- Neutral beam heating & transport
- Electron heating & transport
- The edge

Change the aspect ratio, increase beta: what physics changes?

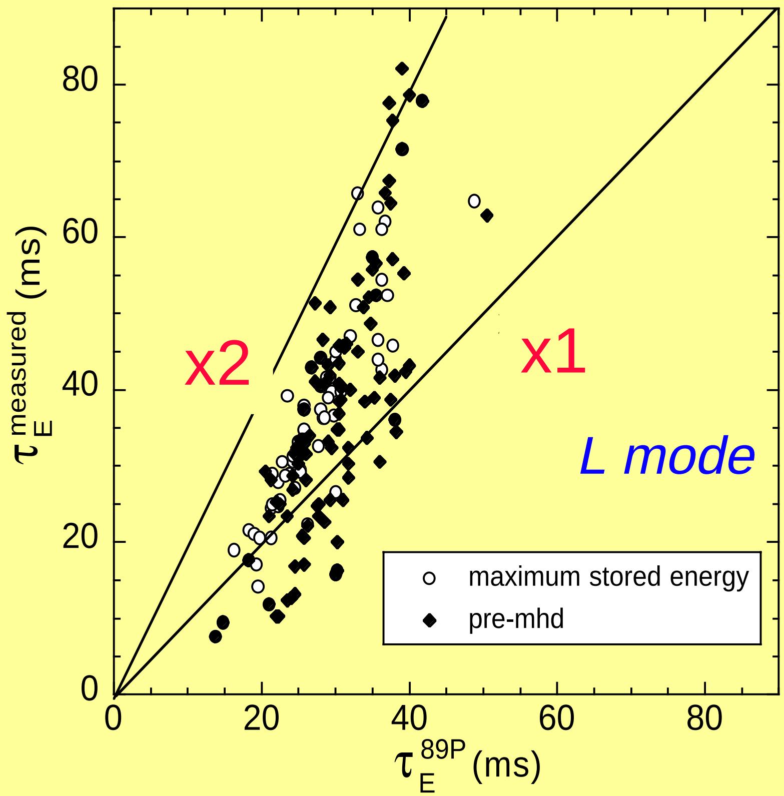


NSTX operational capabilities increasing, and allow confinement studies to begin



Baseline	(Achieved)
Major Radius 0.85 m	
Minor Radius 0.68 m	
Elongation ≤ 2.2	(2.5)
Triangularity ≤ 0.6	(0.7)
Plasma Current 1 MA	(1.4 MA)
Toroidal Field 0.6 T	(≤0.45 T)
Heating and CD	
5 MW NBI	(5 MW)
6 MW HHFW	(6 MW)
0.5 MA CHI	(0.4 MA)
Pulse Length ≤ 5 sec	(0.5 sec)

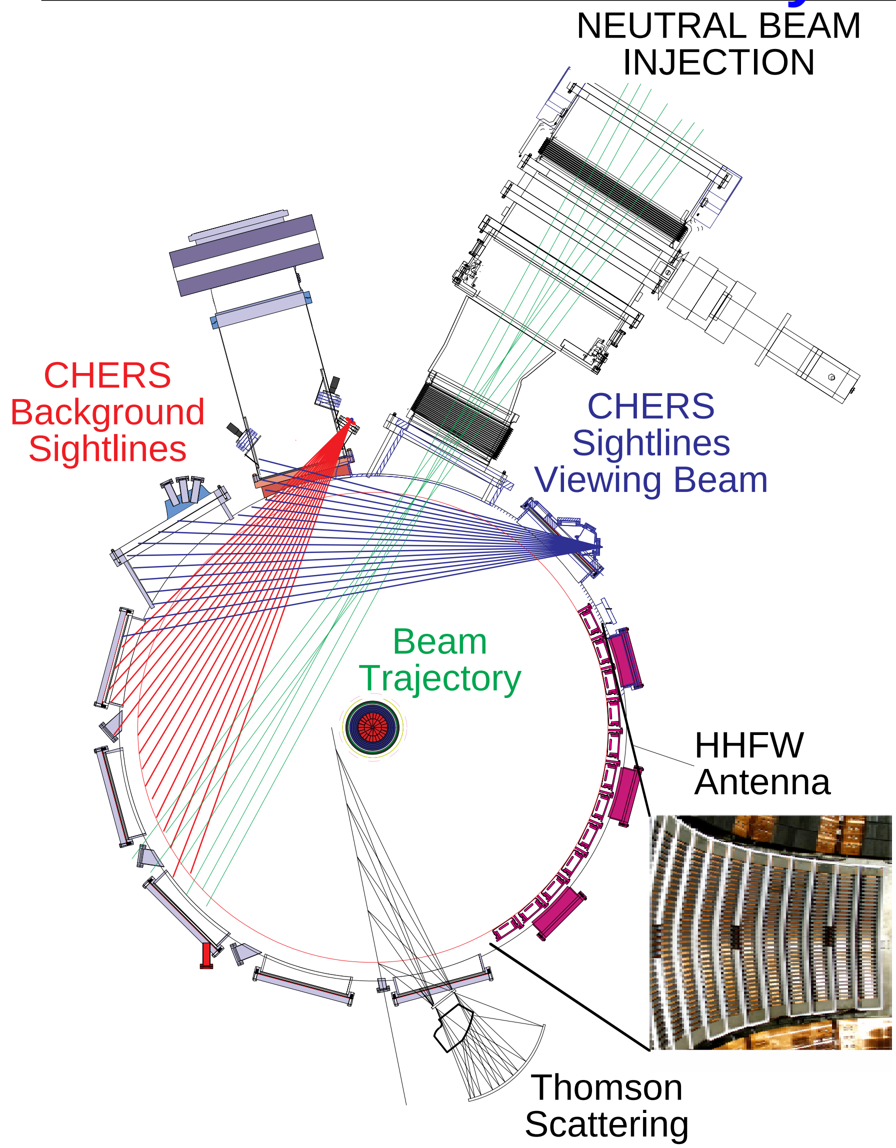
Local transport studies focus on understanding global trends



Kaye; Sabbagh (Columbia)

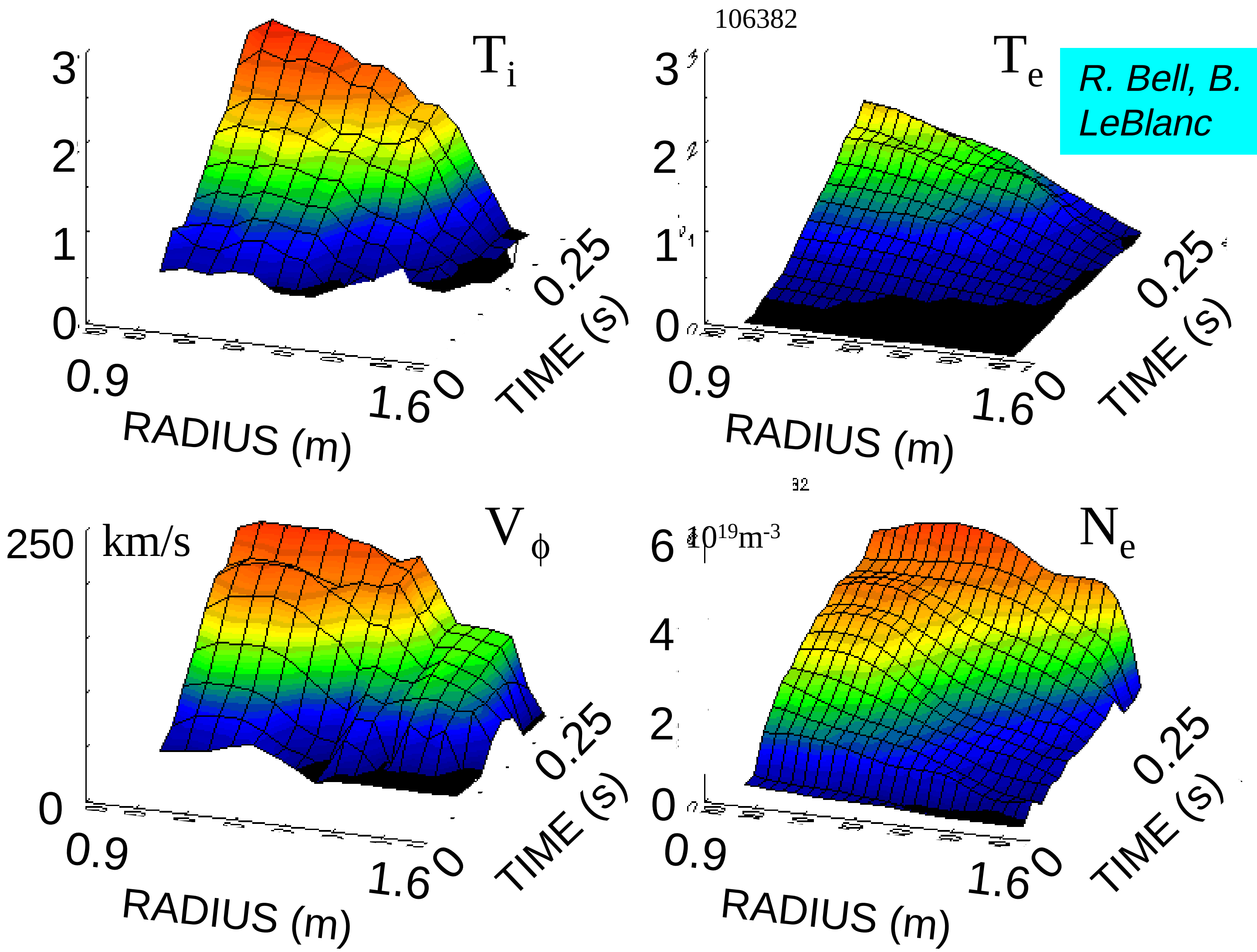
Core transport physics	NSTX
Thermal transport	NBI: Ion thermal energy *higher than expected* with neoclassical ions NBI & HHFW: Electron channel dominates
Heating	Heating puzzle with NBI
Impurity ion particle transport	Close to neoclassical when measured
Theory of instabilities	NBI: $k_\theta \rho_i >> 1$ dominant $k_\theta \rho_i < 1$ stable or suppressed

NSTX Systems, Diagnostics, Analysis Tools Enable Study of Local Transport



- NBI: 80 kV, deuterium
- HHFW: 30 MHz, 12 strap antenna
- MPTS: $T_e(R,t)$, $N_e(R,t)$ 10 ch., 60 Hz
- CHERS: $T_i(R,t)$, $V_\phi(R,t)$ 16 ch., 20 ms
- EFIT: Equilibrium
- TRANSP: Transport Analysis
- GS2: Gyrokinetic Analysis

Neutral beam heating yields high ion temperatures in high current plasmas



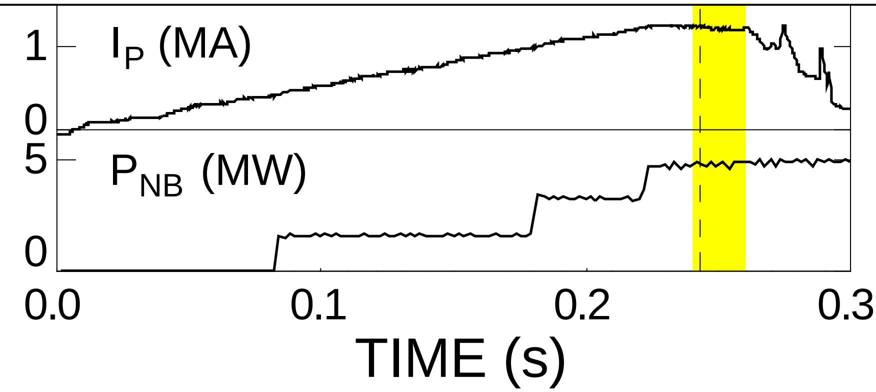
R. Bell, B. LeBlanc

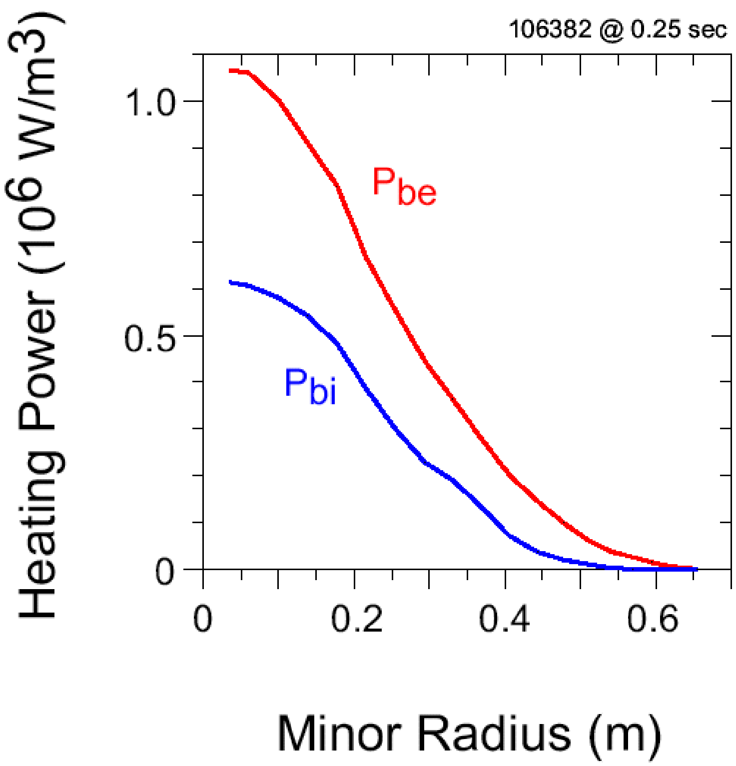
- $T_i > T_e$
- T_i broad
- Edge V_ϕ pedestal
- Large V_ϕ: co-directed NBI

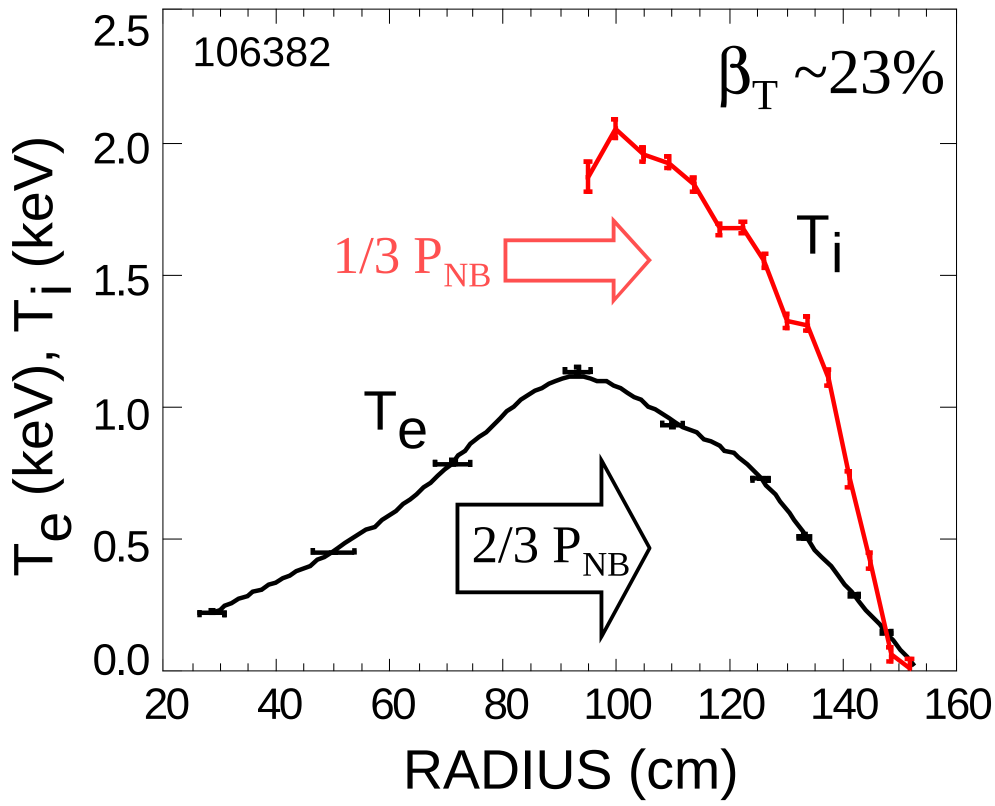
L mode
1.2 MA, 0.33 T
4.8 MW NBI

Ion Thermal Confinement Better Than Electrons

- $T_i > T_e$
- Classical P_{NB} 2:1 electrons:ions
- Peaked NB deposition







Power Balance Points To Puzzles

Power Source/Sink	ELECTRONS (MW)	IONS (MW)	NET (MW)
OHMIC Heating	1.2	0	1.2
BEAM Heating	2.77	1.42	4.19
i-e Coupling	2.73	-2.73	0
dW/dt	0.11	-0.54	-0.43
Other*	-0.66	0.26	-0.4
NET POWER IN	6.15 MW	-1.59 MW	4.56 MW
“Misplaced Heating”	< -1.59 MW	>1.59 MW	0.0 MW
NET POWER OUT	< 4.56 MW	> 0.0 MW	4.56 MW

TRANSP 106382A01 @ 0.25 s

*Beam Thermalization, Rotation, Radiation, Convection

More Power Out of Ions Than In!

Need Extra Ion Heating to Balance Power

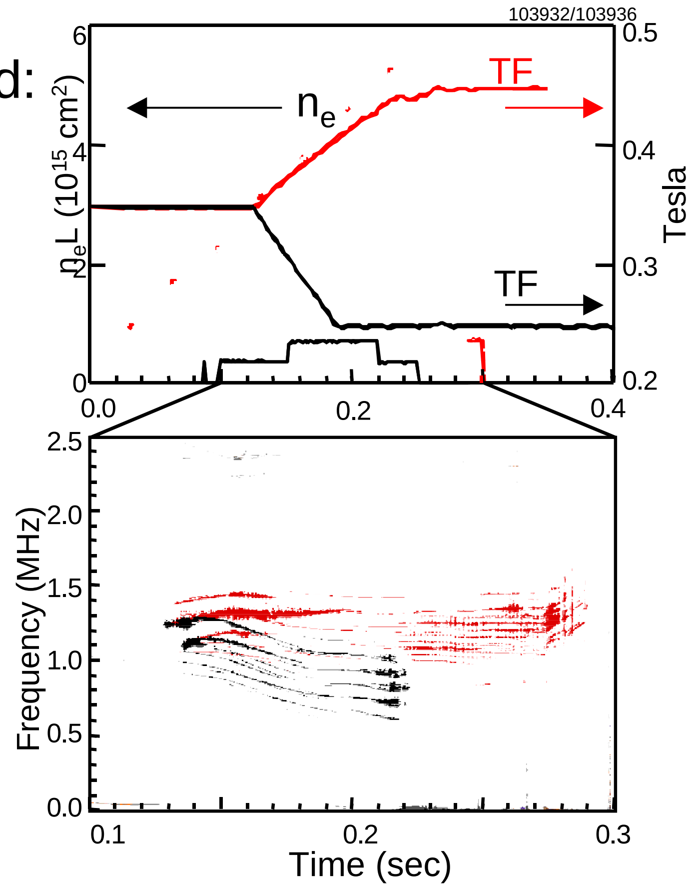
Summary of power balance with NBI

- T_i consistently larger than T_e , despite expected large fraction of electron heating by beams
  - $\Rightarrow$ electron conduction is the dominant loss channel
- Power balance makes sense if
  - χ_i is exceptionally low
  - Ions get more heat from fast ions than expected classically
- Diagnostic validation ongoing
- Non-classical effects in heating and Q_{ie} being explored

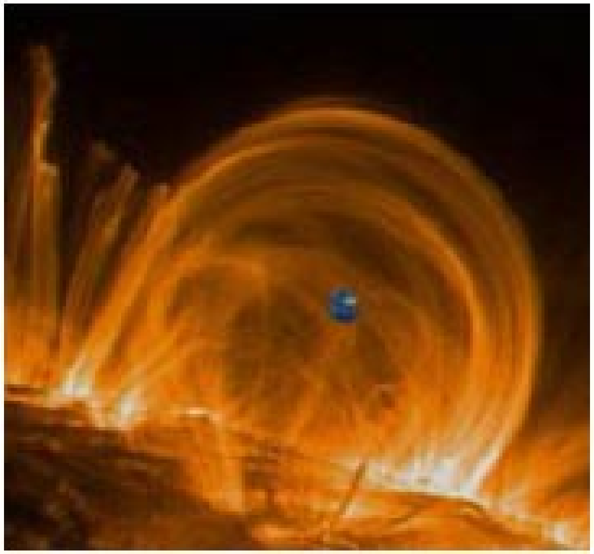
Astrophysics and observed MHD may hold one clue to the power balance puzzle

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

Fredrickson



However, initial study suggests:
low $E_{beam} \Rightarrow$ no CAE modes observed,
but ion stored energy is still too high



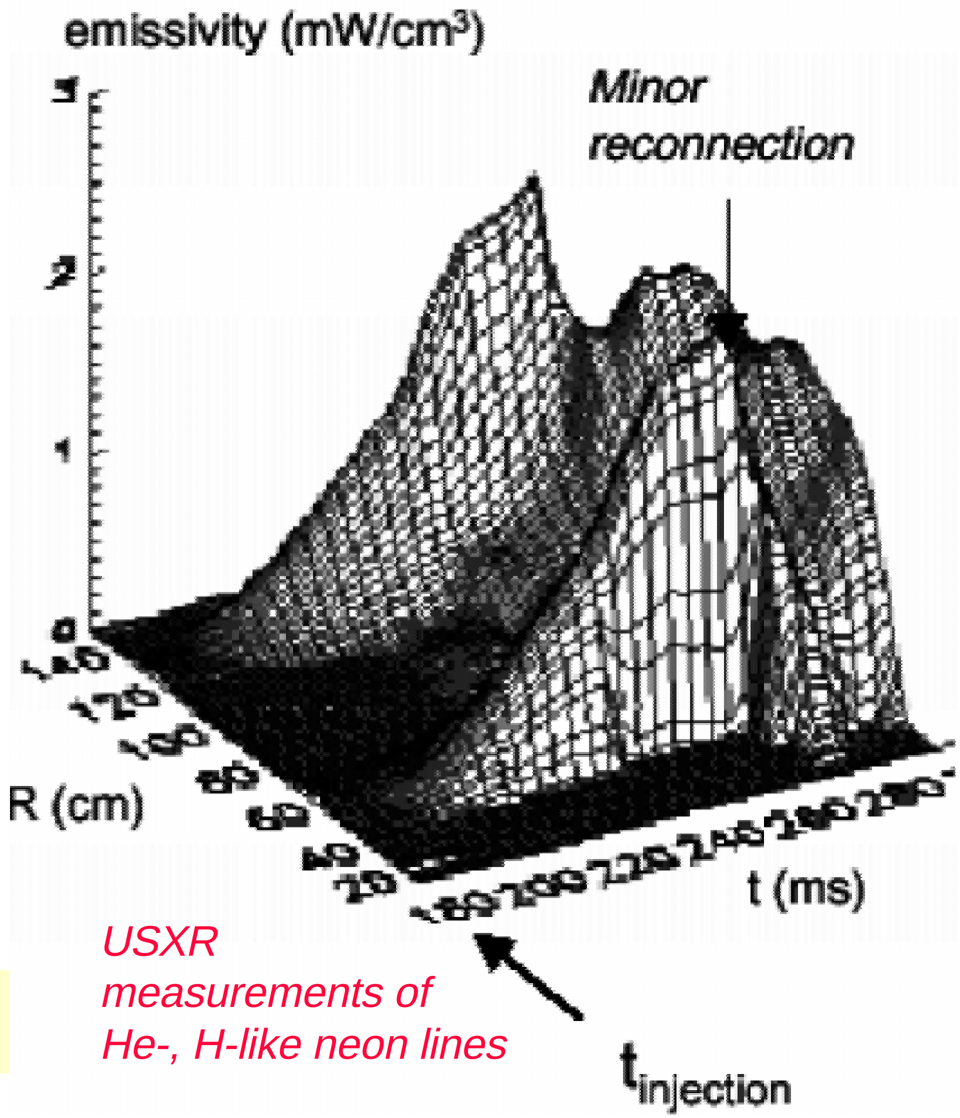
- Theory of stochastic wave heating of corona developed (White)
- Application of theory to ST has begun
- $V_{beam} > V_{Alfven}$ key

Gates, Gorelenkov, White

Low ion particle transport consistent with low ion thermal transport

- After neon puff, almost no neon penetrates the core until MHD event near 260 ms
- Modelling suggests core diffusivity < 1 m^2/s, near neoclassical theory

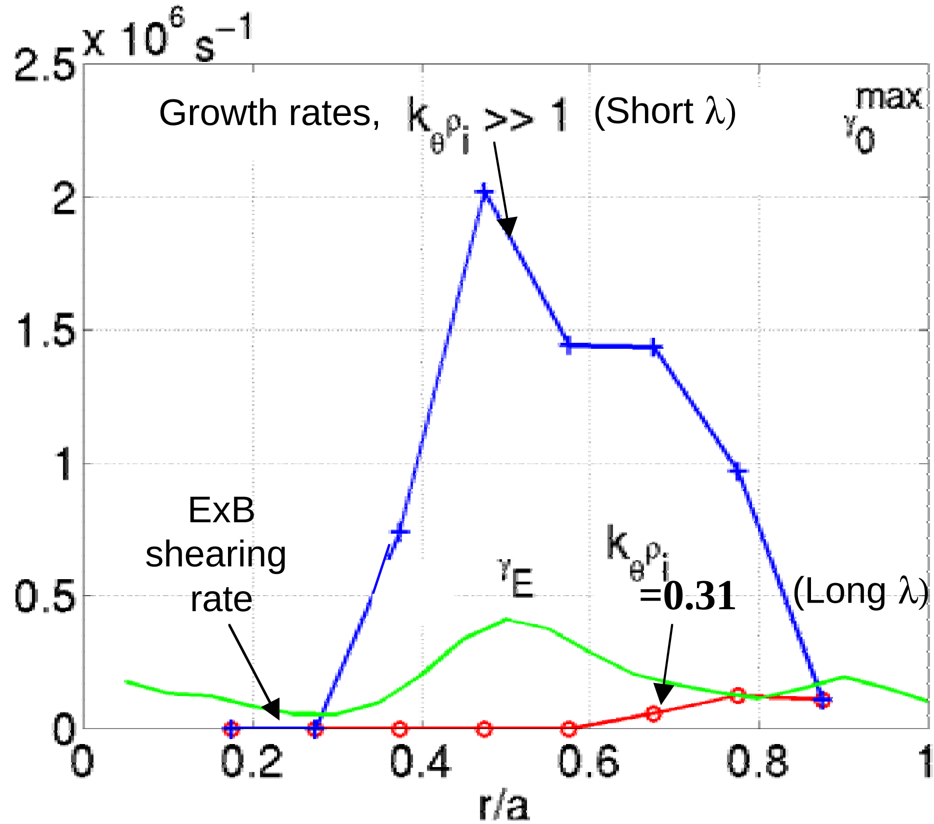
Signals from difference of similar plasmas wtih and without neon puff



D. Stutman
JOHNS HOPKINS UNIVERSITY

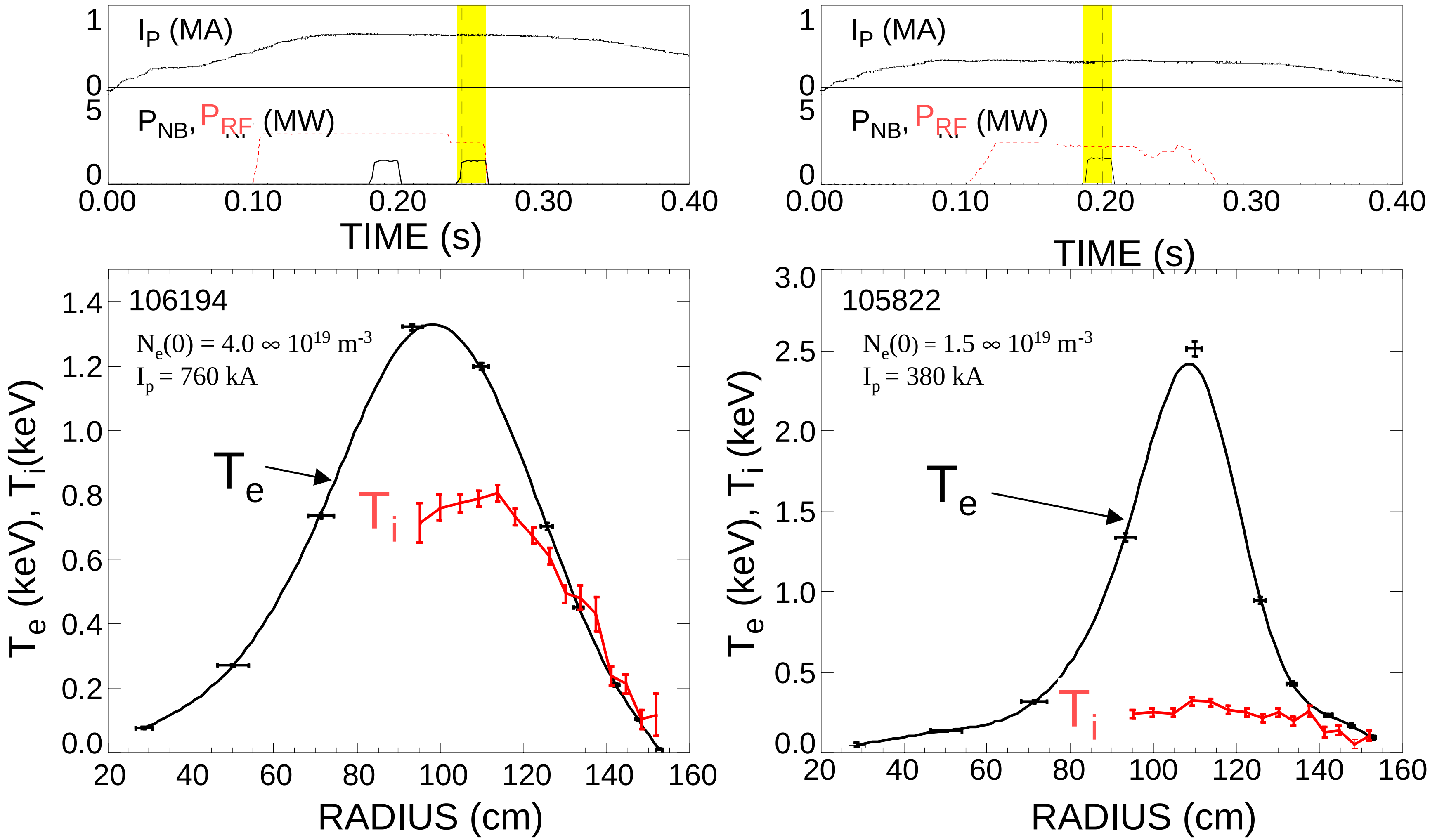
Theory: short wavelength modes may dominate transport, long wavelength modes may be suppressed

- Long λ, low k (ITG, TEM):
  *growth rate < **E**x**B** shear rate*
  - Large λ associated with ion thermal transport
  - Low aspect ratio: Analysis suggests ∇β strongly stabilizing
- Low λ, high k (ETG):
  growth rates large
  - Responsible for electron thermal transport?
  - Non-linear simulations begun to estimate possible fluxes



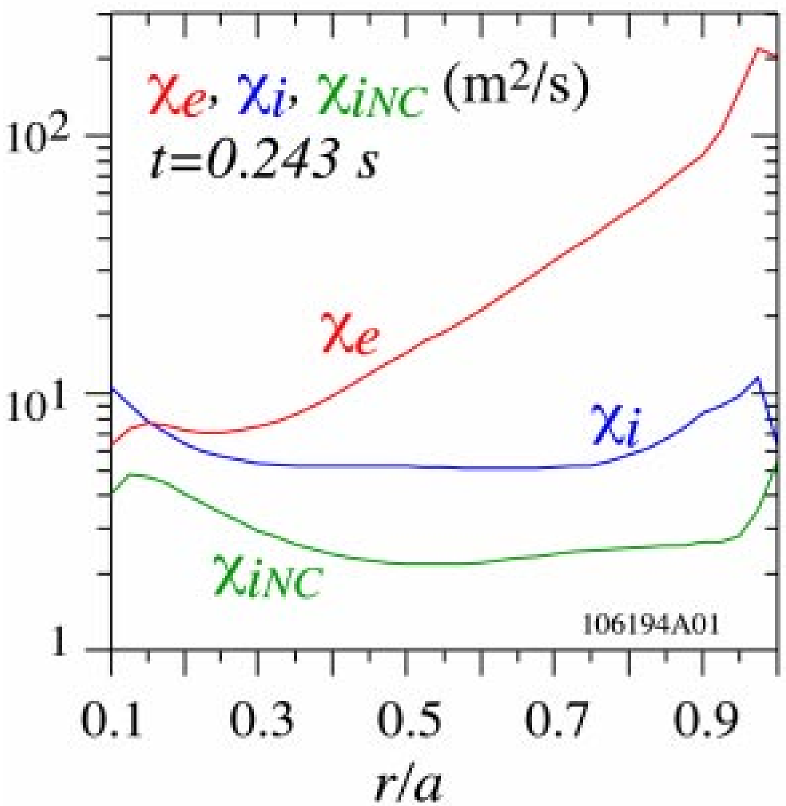
C. Bourdelle (PPPL), W. Dorland (U. MD)

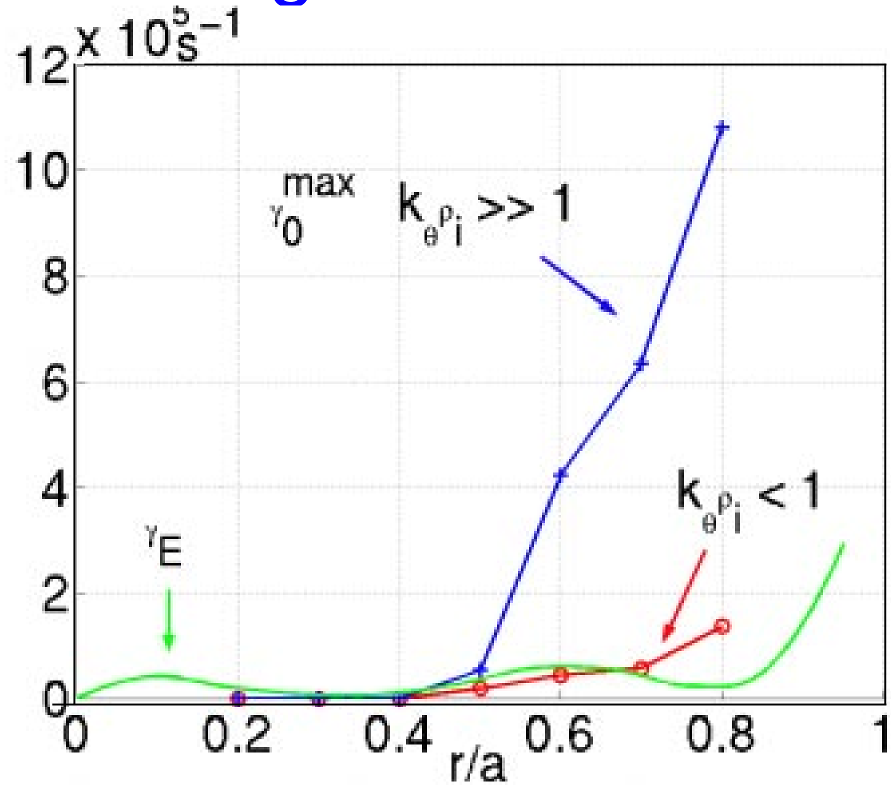
High Harmonic Fast Wave (HHFW) Heats Electrons



- $T_e > T_i$ with auxiliary power to electrons

Electron Loss Channel Also Dominant with HHFW Heating



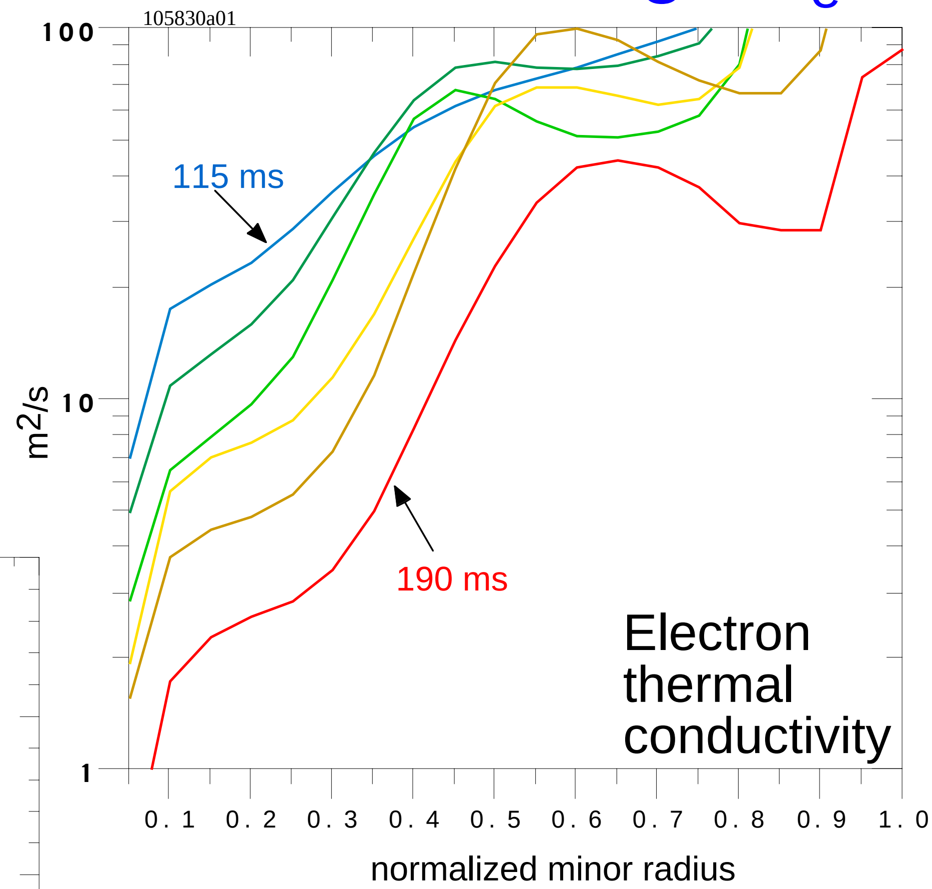


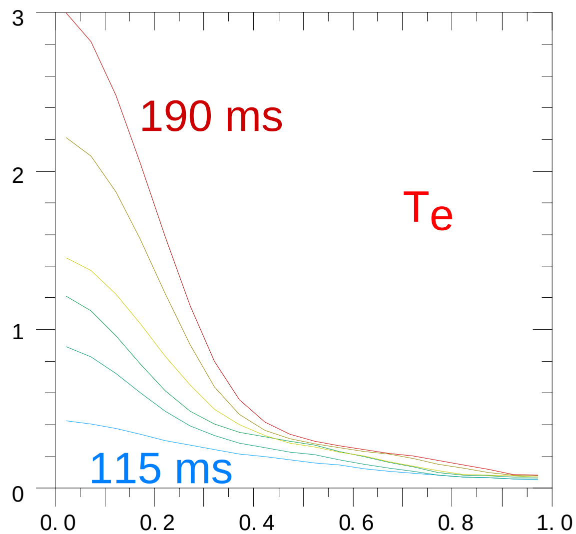
- Power deposition: HPRT ray tracing code
- χ_i ~ 2-2.5 χ_i^{NC} , $\chi_e >> \chi_i$

- ETG unstable
- Low k_θ modes ITG +TEM

Power balance analysis reveals that reduced electron transport is 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)



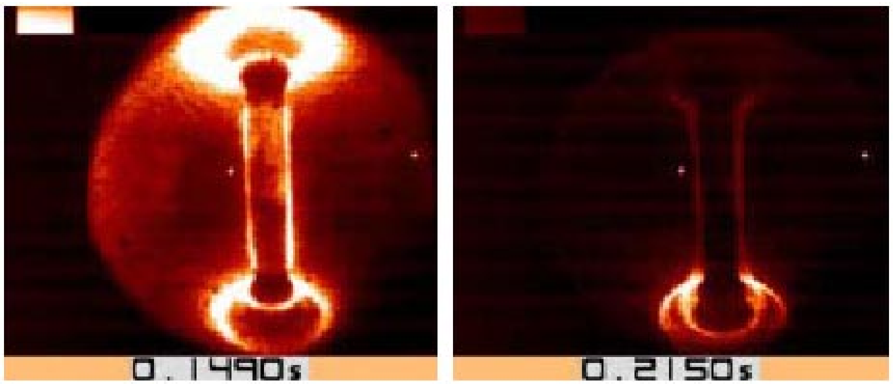


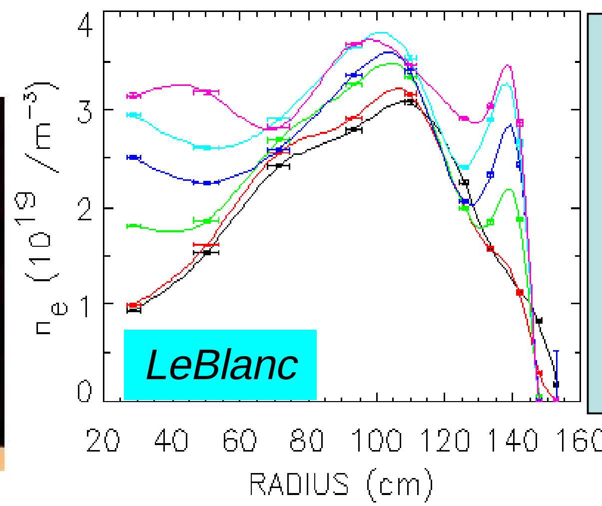
LeBlanc

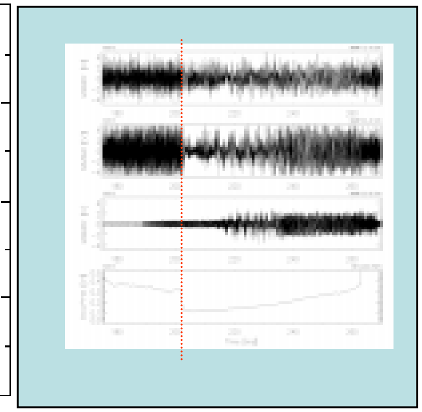
Bifurcations to enhanced plasma confinement state observed with both NBI and HHFW

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

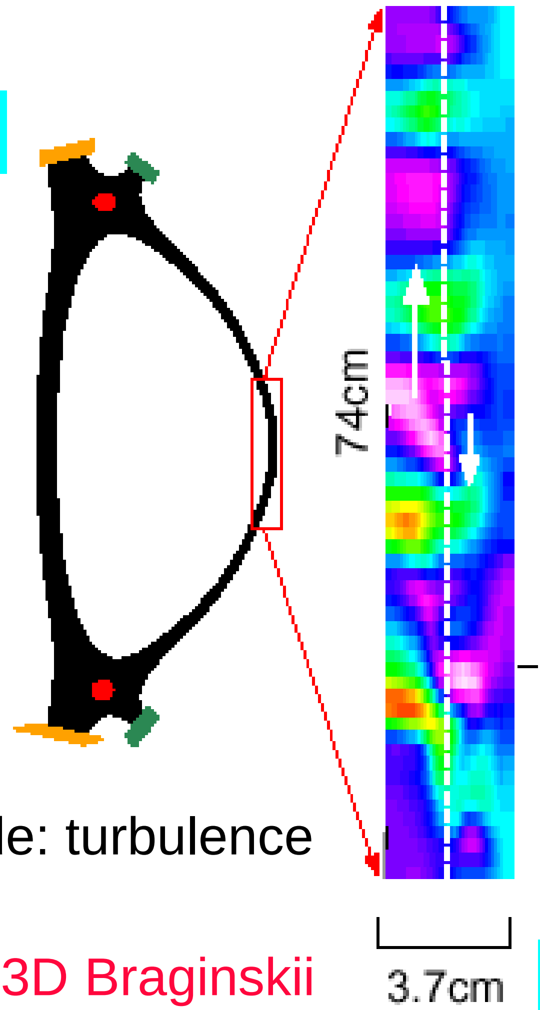
Edge reflectometry: *Peebles, Kubota (UCLA)*

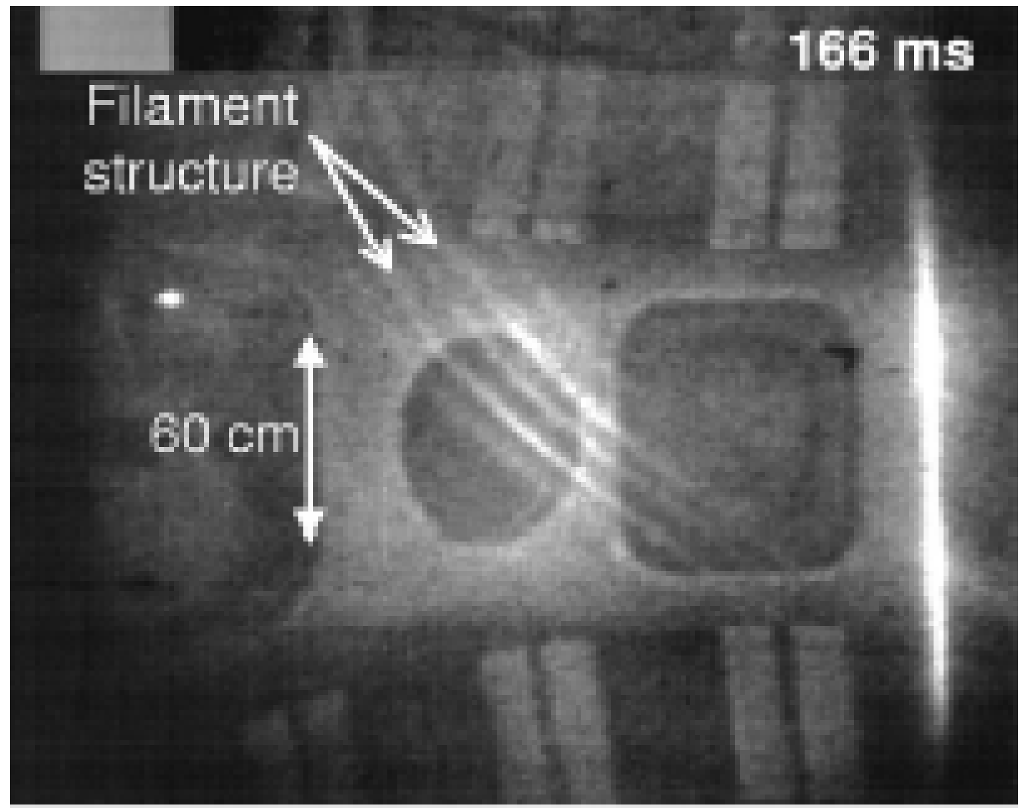
Fast camera: Maqueda (LANL)

H mode: Maingi, Bush (ORNL); LeBlanc

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

Xu, LLNL





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

Maqueda, LANL; Zweben

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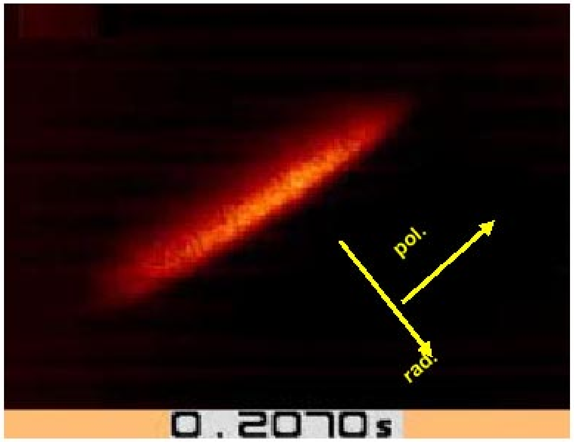
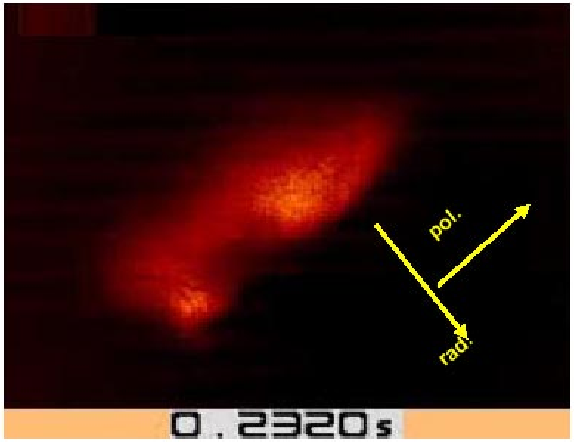
Imaging of edge reveals qualitative differences in H- and L-mode turbulence

- 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

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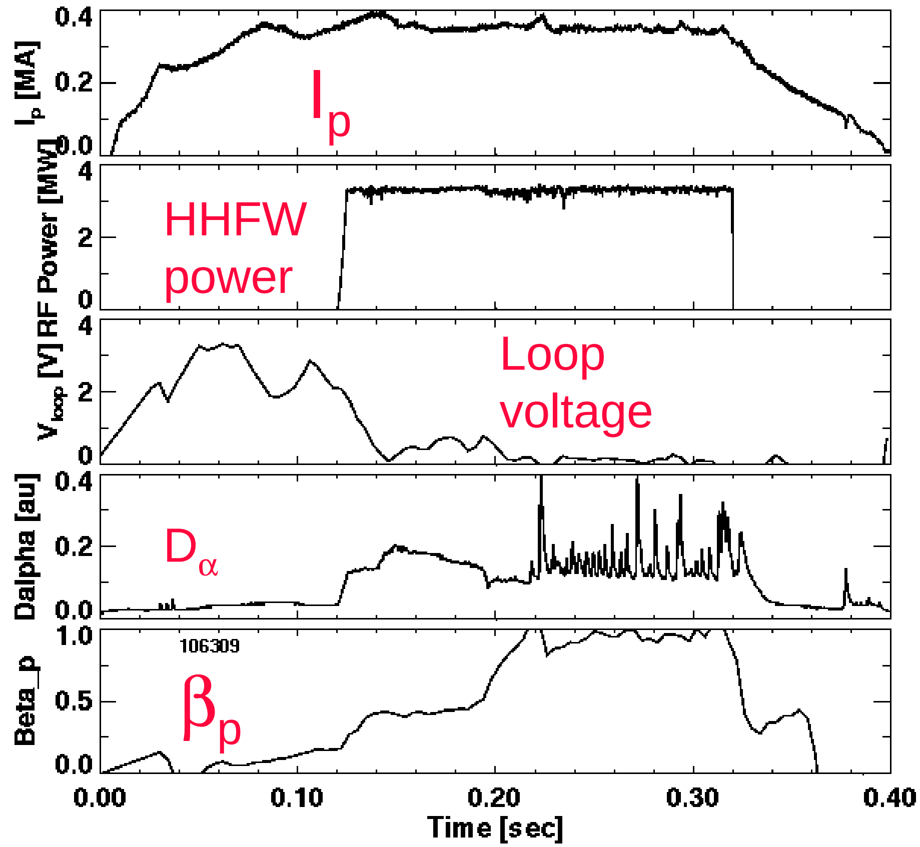
HHFW-driven H modes found

- LSN
- Lower current (350 - 500 kA)
- He and D
- ELMy, ELM-free
- β_p = 1 observed
  - Large bootstrap?
  - Large dip in surface voltage



Starting scenario for future CD work?

Studies of underlying physics of ST transport has begun

- Kinetic profiles are enabling initial local transport analysis

- *NBI*: $T_i > T_e$, despite prediction that 2/3 P_{NBI} goes to electrons
  - Electrons are the dominant loss channel
  - Ion heating not understood
  - Low particle transport correlated with low ion thermal confinement
  - **E**x**B** shear suppression of low k modes seen in analysis at high beta
  - Exploring role of ETG

- *HHFW*: $T_e > T_i$
  - Electrons are the dominant loss channel
  - Reductions in χ_e with strong central T_e peaking
  - Possible role of T_e/T_i in determining χ_e to be investigated

Summary (2)

- L-H transitions observed with NBI and HHFW
  - Turbulent structures observed in L mode state; modelling underway
  - P_{th} ~ 850 kW for NBI; ≈ similar-sized tokamaks, >> scaling
    - Role of strong poloidal damping at low aspect ratio?

- Near-term transport goals and plans
  - Understand ion heating
  - Turbulence measurements to be extended into core
  - Scans of beta: is beta or $\nabla\beta$ favorable for transport?

- Long-term goals
  - Establish a physics-based understanding of the underlying causes of ST transport trends
    - Comparison with moderate-aspect-ratio trends will reveal new physics relevant to all