Results and Challenges from the NSTX Program

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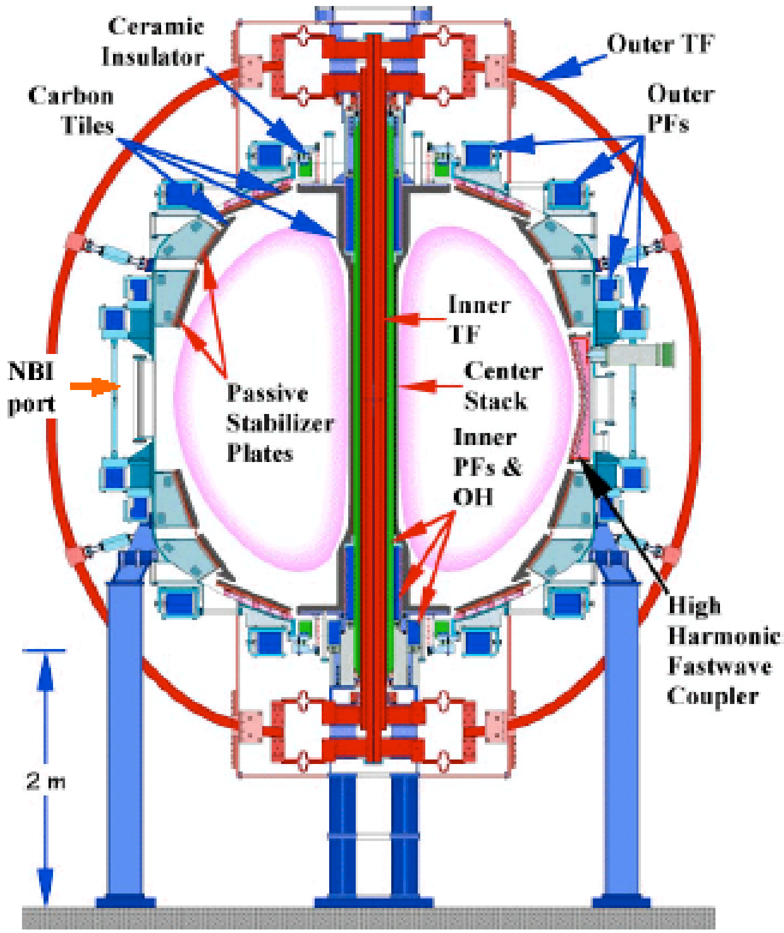
Outline – Focus will be on challenges and opportunities

- NSTX Overview
  - NSTX mission
    - Extend the understanding of toroidal physics to high-β, low-collisionality regimes at low aspect ratio ($R/a \leq 1.4$)
  - Device capabilities
  - Recent highlights (β_t=31%, long duration H-modes, $\beta_n H_{89P}$~11)
  - Attainable physics regimes

- Theory challenges (many based on expt'l results) – emphasized in ST Theory Panel Report
  - **Macroscopic equilibrium and stability**
  - **Microscopic turbulence and transport**
  - Fast particles
  - RF heating and **current drive**
  - Edge/divertor
  - Integration issues

National Spherical Torus Experiment (NSTX)



Parameters	Design	Achieved
Major Radius	0.85m } ⇒ $A \geq 1.27$	
Minor Radius	0.68m	
Elongation	≤2.2	2.5 >
Triangularity	≤0.6	0.8
Plasma Current	1MA	1.5MA
Toroidal Field	0.6T	≤0.45T
Heating and Current Drive		
Induction	0.6Vs	0.6Vs
NBI (90keV)	5MW	5 MW
HHFW (30MHz)	6MW	6 MW
CHI	0.5MA	0.4MA
Pulse Length	≤5s	0.5s

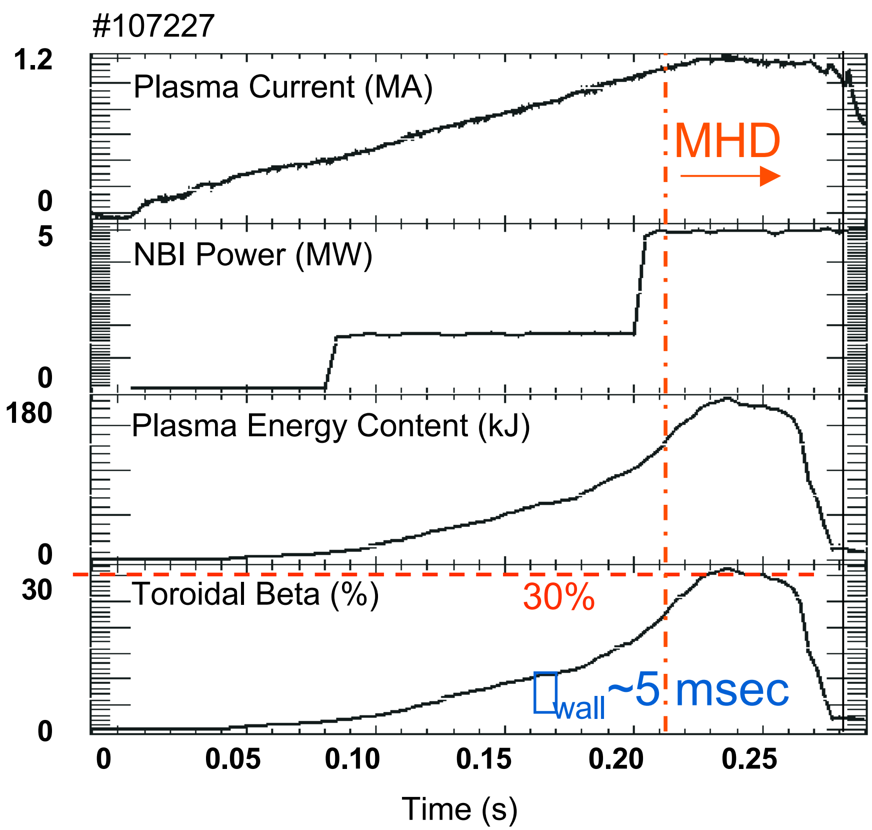
High Performance Plasmas Produced

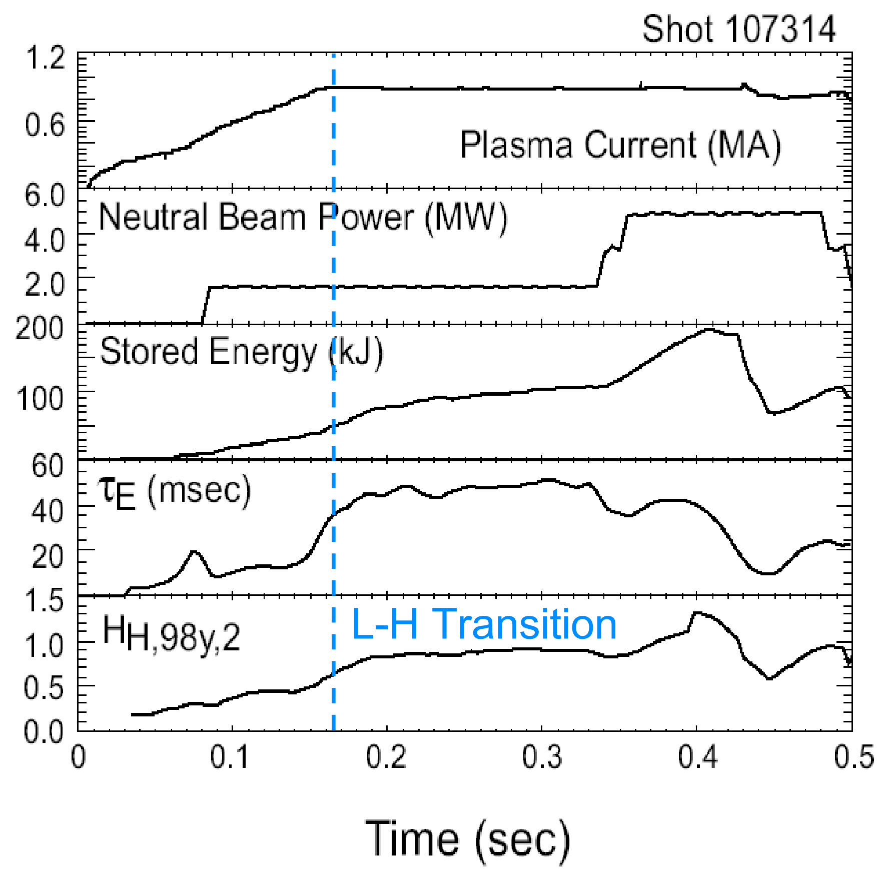
NSTX

Max β_T = 31.5%
β_N = 5 = 7.4ℓ_i > β_N(no-wall)*

<u>Long-Pulse H-mode</u>
B_T = 0.4 T, β_T = 15%, β_N = 4.6

$\beta_T = 2\mu_o\langle p\rangle/B_0^2$

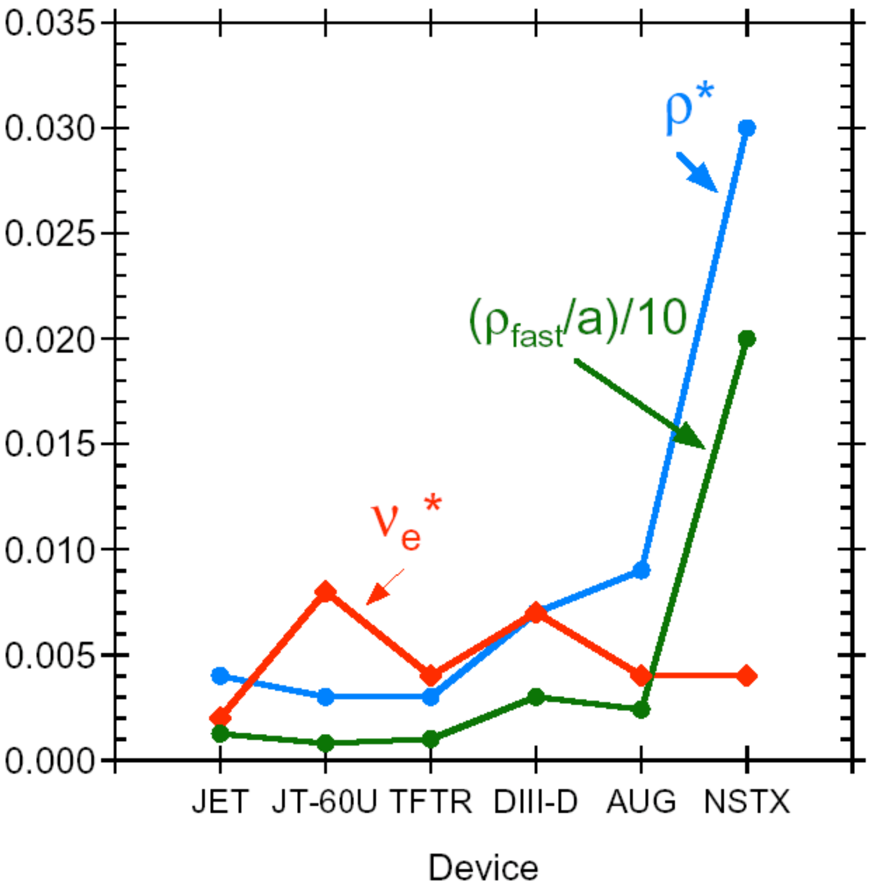


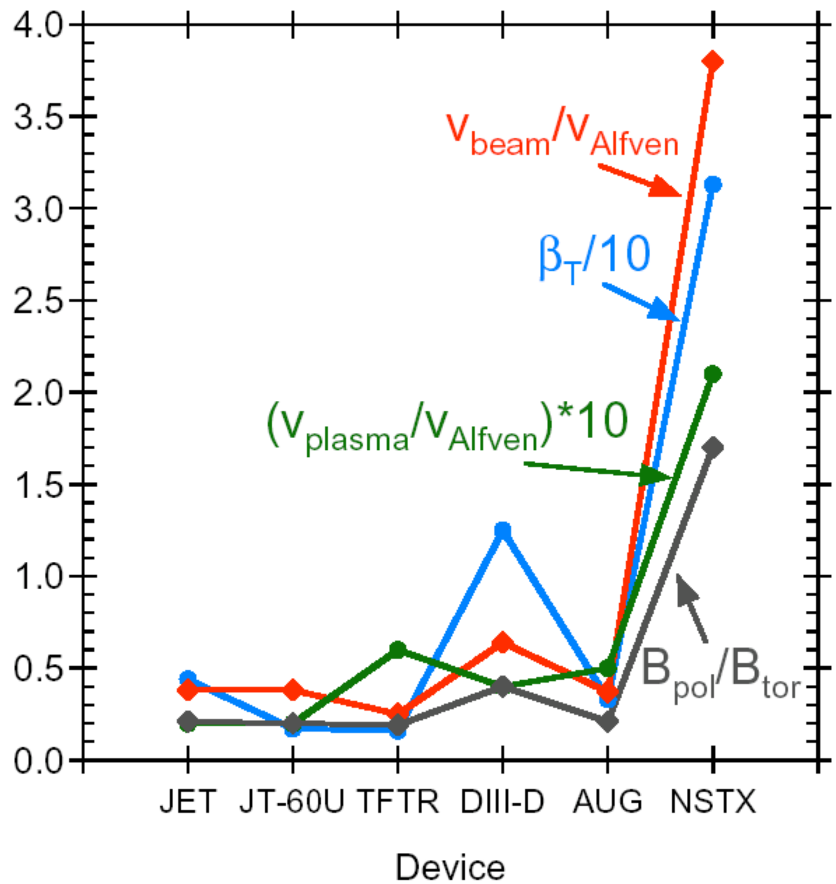


NSTX Accesses Different Parameter Regimes Than Conventional Aspect Ratio Devices

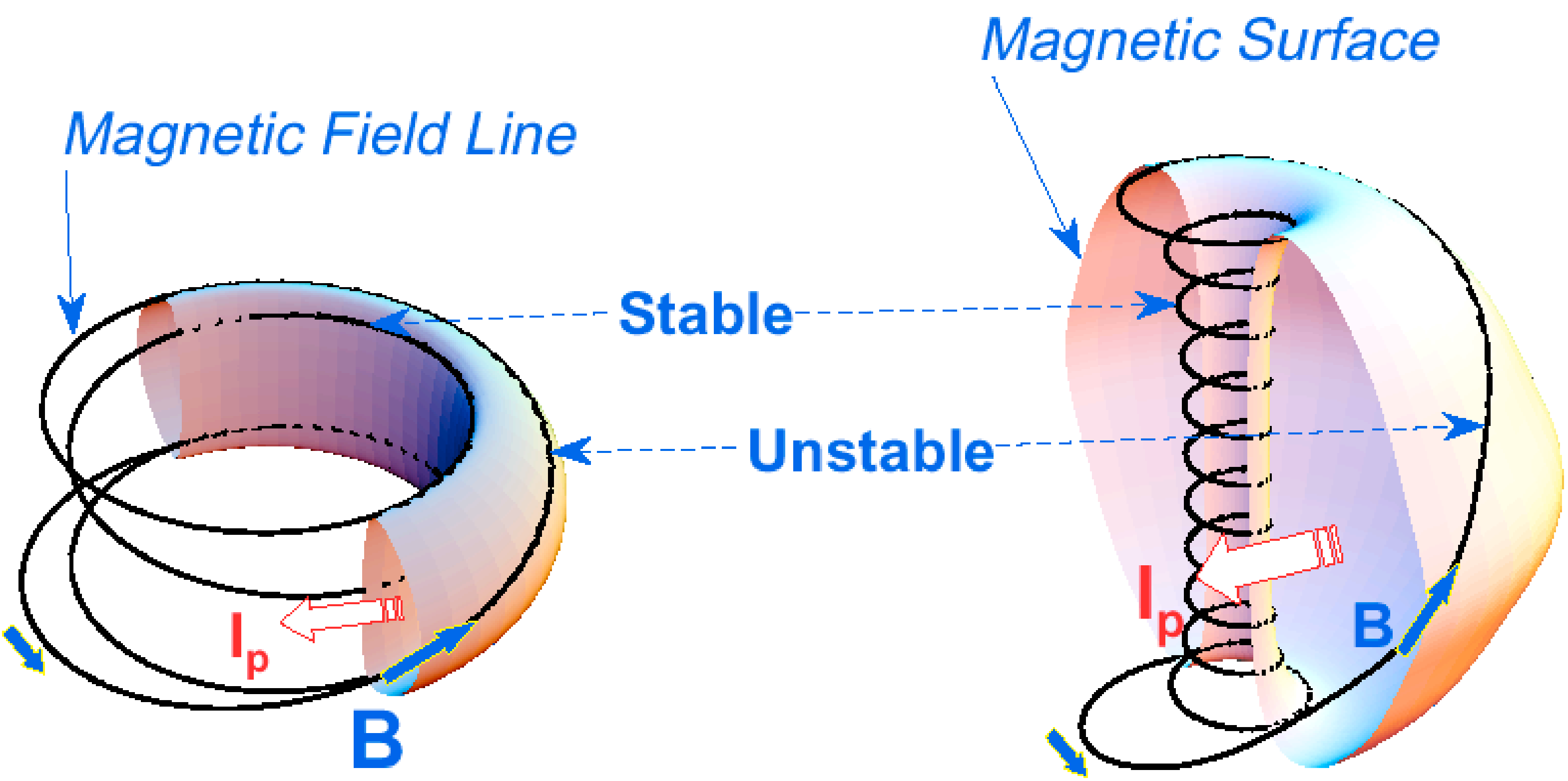
NSTX

Major differences result from lower B_T, higher relative rotation velocity





ST maximizes the field line length in the good curvature (stable) region



R/a~4, □=2, q_a=4

R/a~1.3, □=2, q_a=12

Macroscopic Equilibrium and Stability

ST Features/Theory Issues

- Strong toroidal effects
  - Strong poloidal mode coupling/mode structure global
- High-β_T, large Shafranov shift
  - Magnetic well
  - Enhanced ballooning/interchange stability
- High rotation, rotation shear
  - Modify equilibrium through centrifugal effects
  - Effect on Alfven mode resonance condition, gap structure
  - Mode stabilization due to sheared rotation

NSTX Has Achieved $\beta_{t,n}$ Up to Maximum No-Wall Limit

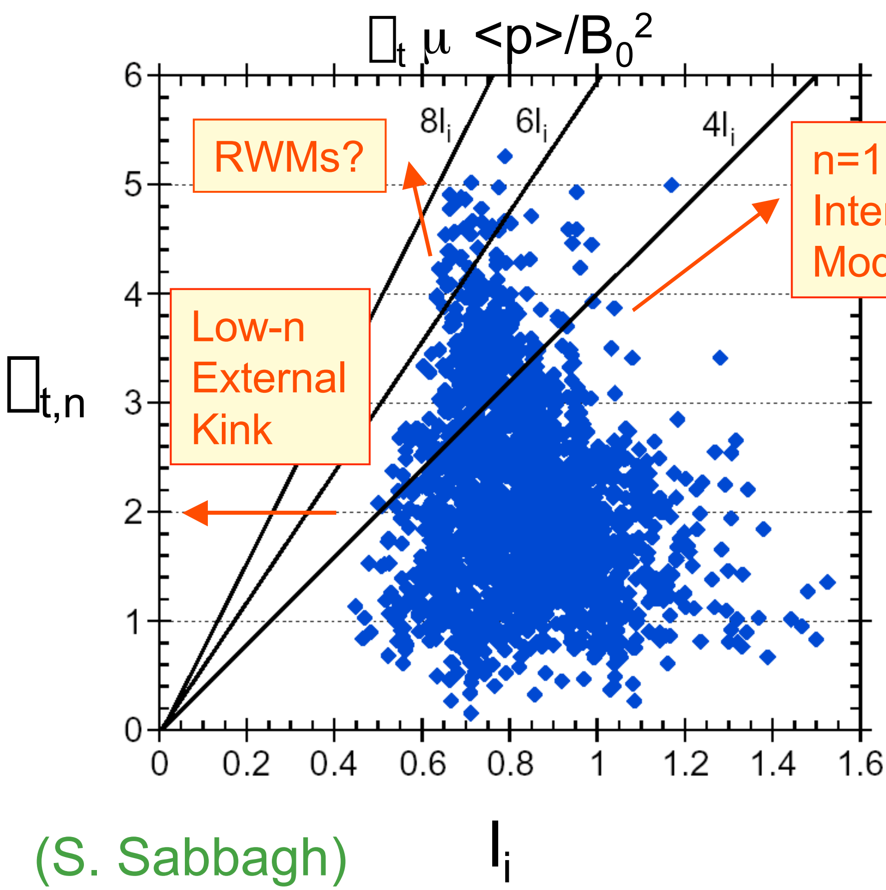
NSTX

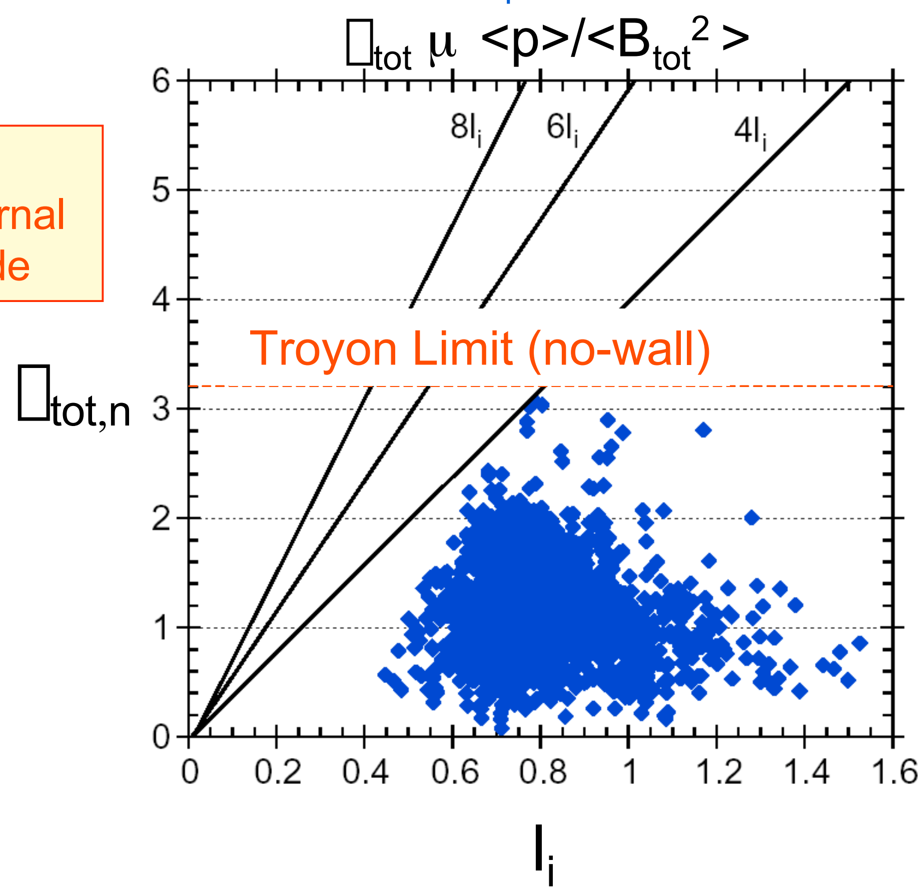
Limit for individual discharges is profile dependent

Non-wall stabilized plasmas in excess of $7l_i$ (limit is $4l_i$ in higher R/a)

$\beta_{tot,n} = 4l_i$ more of an invariant for all R/a

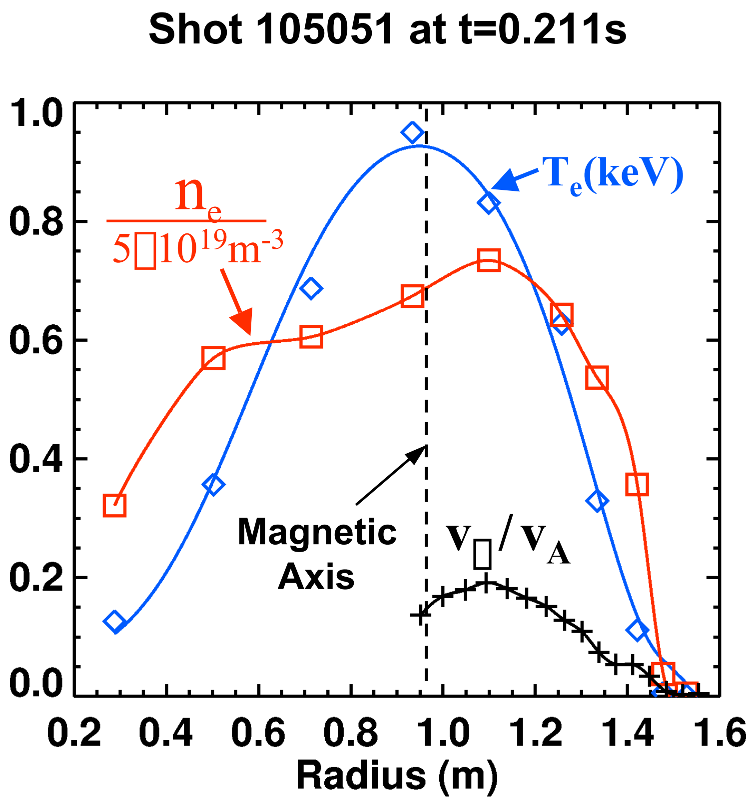
- Is there a theoretical basis for the $4l_i$ limit?





(S. Sabbagh)

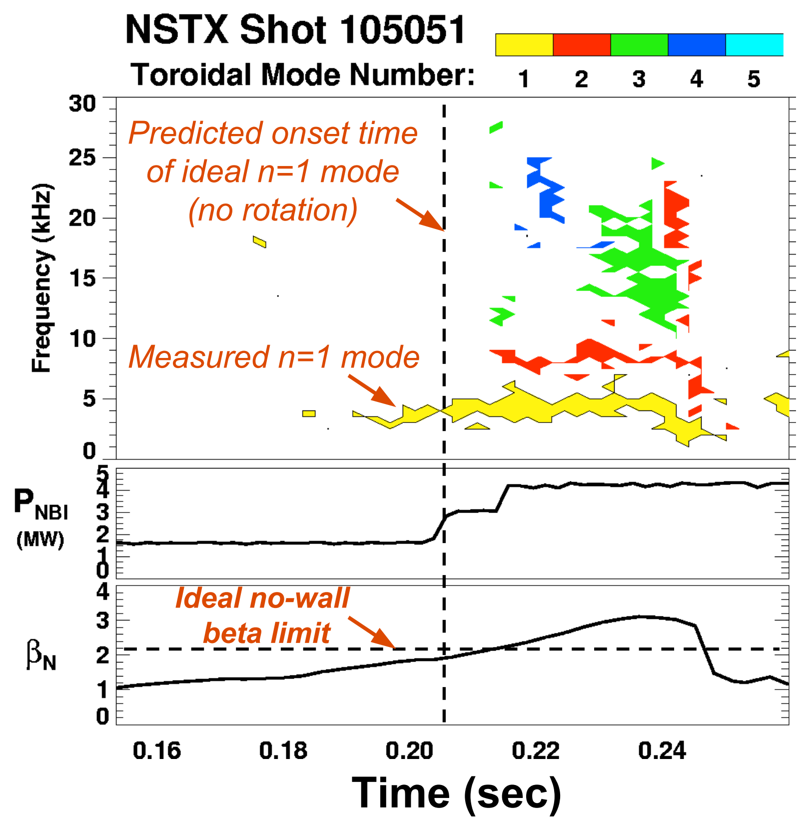
High Rotation Rates Have Large Impact on Equilibrium and Stability



M3D Predictions (W. Park, J. Menard - this meeting)

- Density no longer a flux surface function

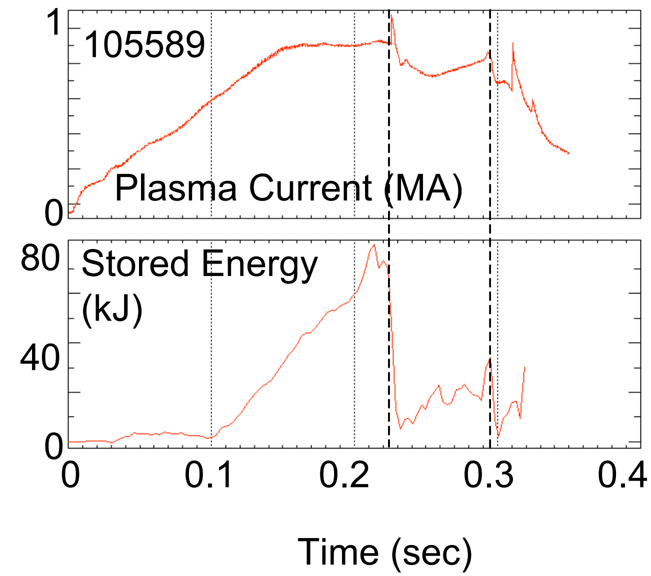
- β_n exceeds no wall limit



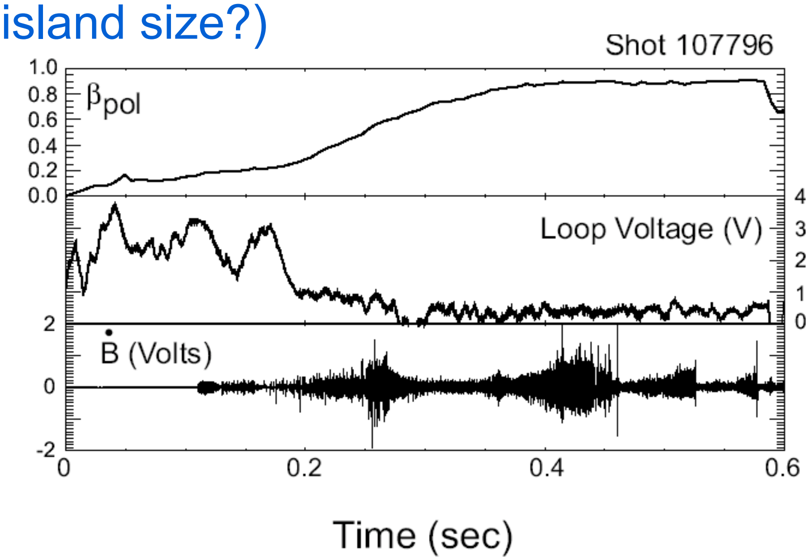
- Rotation shear suppression of n=1 internal kink mode growth (by factor of 5)

Other Challenges

- Reconnection Events
  - Ubiquitous; result in plasma energy loss
  - 3D modeling required



- Neoclassical Tearing Modes
  - Candidate modes seen, but $\square_p$~1 achieved
  - Effect of toroidicity on □'
  - FLR effects ($\square_i$ ~ 1-3 cm ~ threshold island size?)



- Other FLR Effects
  - $\square_f$, $\square_i$ on ideal MHD

Transport/Fast Ion Behavior

ST Features/Theory Issues

- Local □$_t$ □ 1 (51% achieved experimentally in core)
  - Electromagnetic effects
- Trapped particle fraction □ 1
  - Validity of fluid treatment of electrons
- □$_i$/L~0.2 (near outboard edge); □$_i$~1 to 3 cm
  - Validity of spatial scale length ordering
- High ExB flow (>200 km/sec), flow shear (10^5 to 10^6/sec)
  - Effect on □instability thresholds, turbulence characteristics
  - Dominant (?) role of electron transport
- V_{fast}/v_{Alfven} ~3 to 4
  - Fast ion driven instabilities (Alfvenic modes)
- □$_{fast}$/a~1/5-1/3
  - Fast ion confinement, non-adiabatic behavior

Validity of present gyrokinetic treatment?

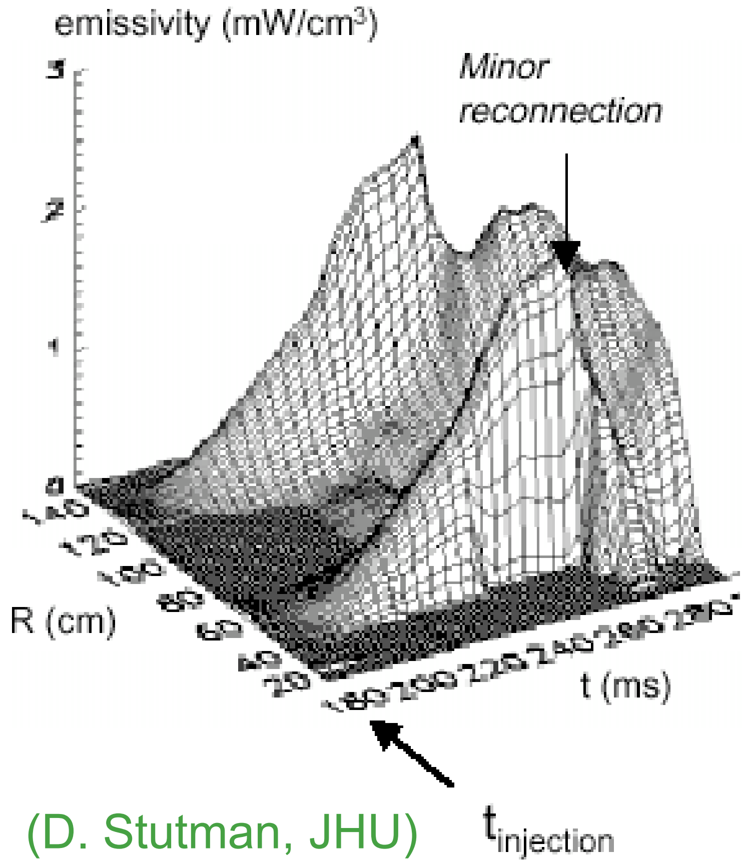
Low Ion Transport Observed in Experiment and Supported by Theory

NSTX

Neon puff exp'ts indicate almost no neon penetration to core

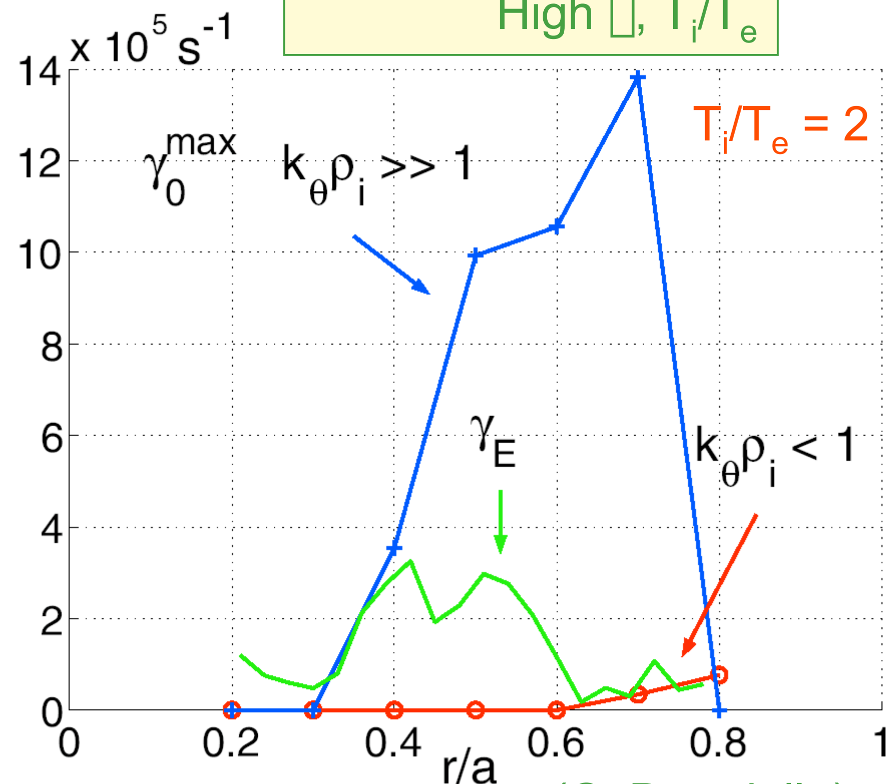
GS2 calcs indicated short wavelength modes may dominate transport

D ~ 1 m²/sec



(D. Stutman, JHU)

Long □ (ITG): □<□$_{ExB}$
Short □ (ETG): □>□$_{ExB}$
High □, T_i/T_e

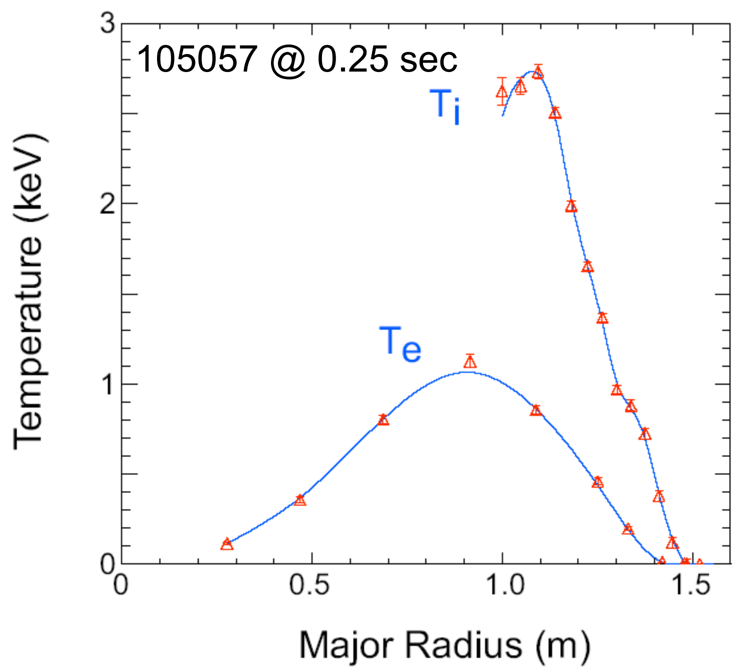


(C. Bourdelle)

NSTX Results Point to New Paths for Describing Transport Properties of Plasmas

High T_i/T_e cannot be supported purely within classical collisional framework

Something more than classical collisional heating and energy exchange may need to be considered in order to properly infer heat diffusivities



Some Possibilities

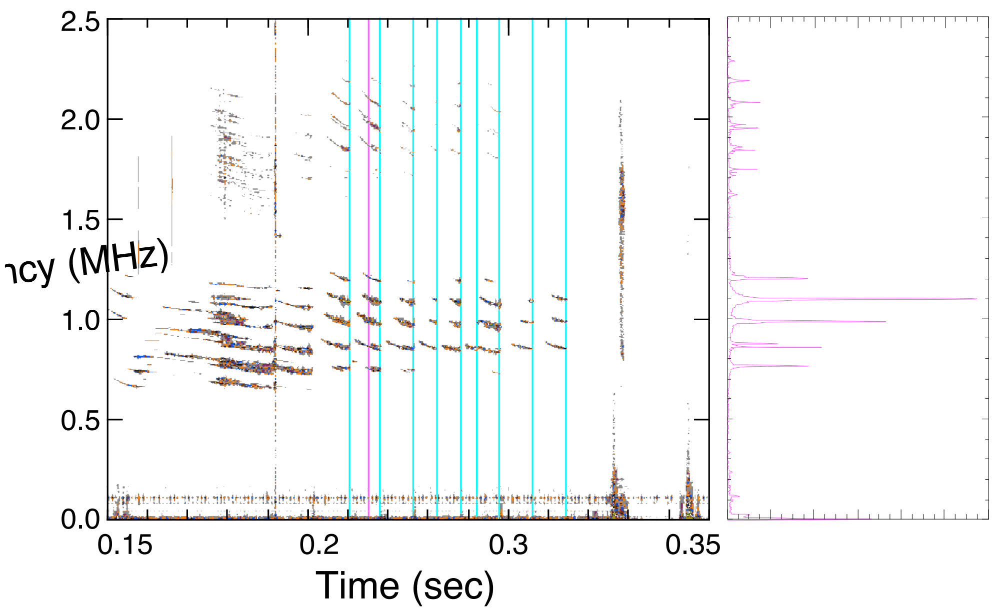
- Anomalous thermal ion heating
- Heat pinch
- Heating deposition modification

Observations of High-f MHD Activity May Be a Source of Anomalous Ion Heating

NSTX

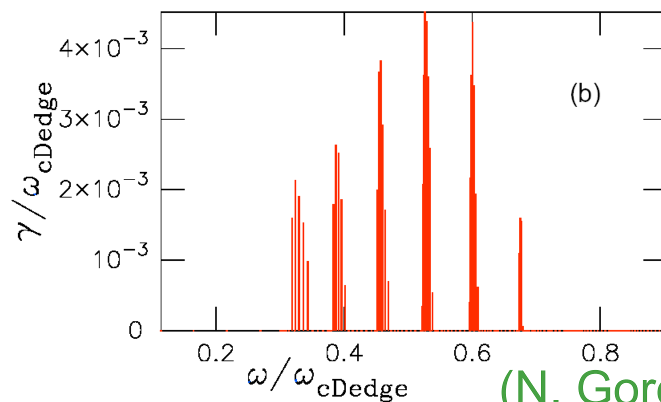
CAE activity ubiquitous in NBI discharges

v_{fast}/v_{Alfven} ~ 3 to 4

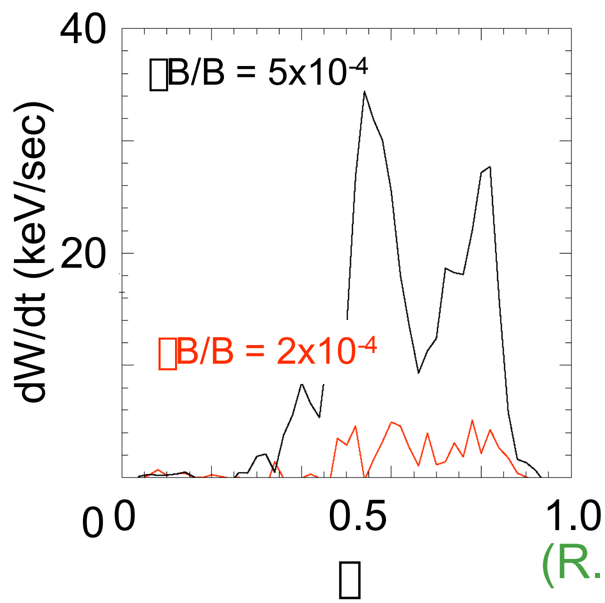


(E. Fredrickson)

Linear CAE Growth Rates



(N. Gorelenkov)



(R. White)

Stochastic heating of thermal ions may be large

Non-linear, self-consistent calcs required

Gates, Gorelenkov and White, PRL 87 (2001) 205003-1

Other Possible Transport Mechanisms

- Stochastic heating due to ETGs (J. Menard)
  - Balance ETG/streamer and Kelvin-Helmholtz growth
  - Saturated E-fields large enough for making thermal ion orbits stochastic and providing significant heating ($\delta n/n \sim 2\%$)

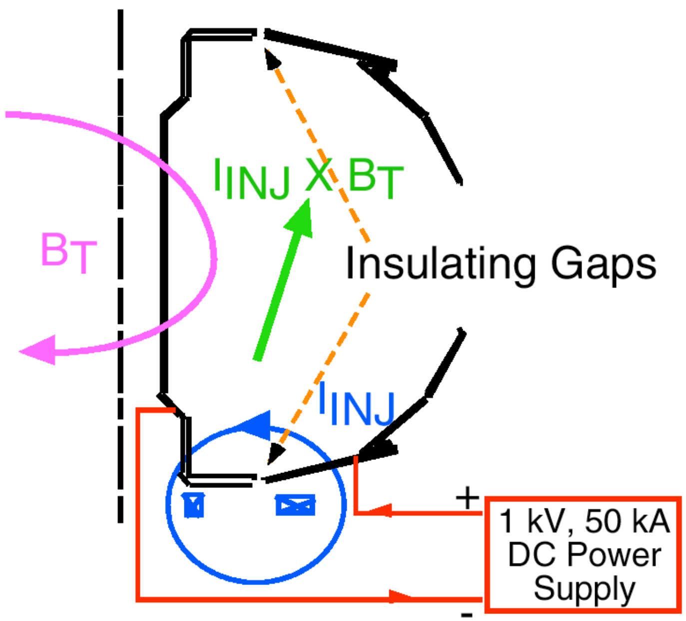
  - *Theory challenge: streamer formation critical to this hypothesis*

- Pinch due to thermal-fast ion friction (W. Houlberg)
  - Parallel torque provides additional particle/heat pinch
    - Inward for co-injection, outward for counter-injection

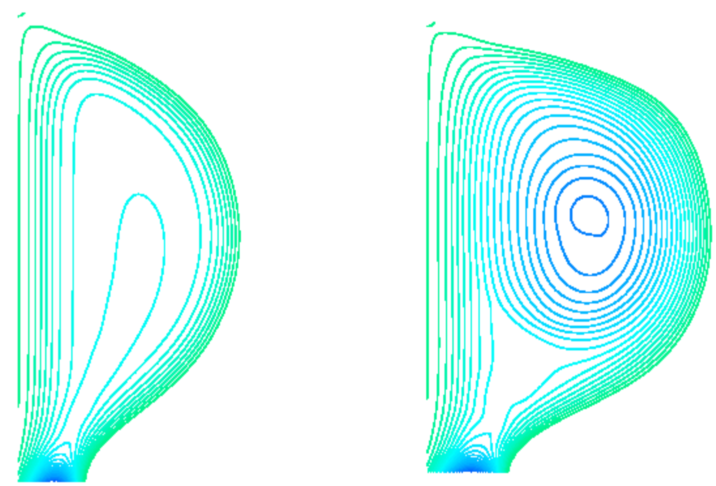
  - *Theory challenge: Determine magnitude of parallel force*

Non-Inductive Current Drive Crucial to Furthering the ST

Co-Axial Helicity Injection (CHI) Generates Toroidal Current Non-Inductively



- Inject poloidal current on open field lines in lower divertor
- Plasma moves up into main chamber
  - Injected current restricted to edge
- Toroidal current develops to maintain force-free configuration
- Magnetic reconnection may redistribute edge current to interior, forming closed flux surfaces

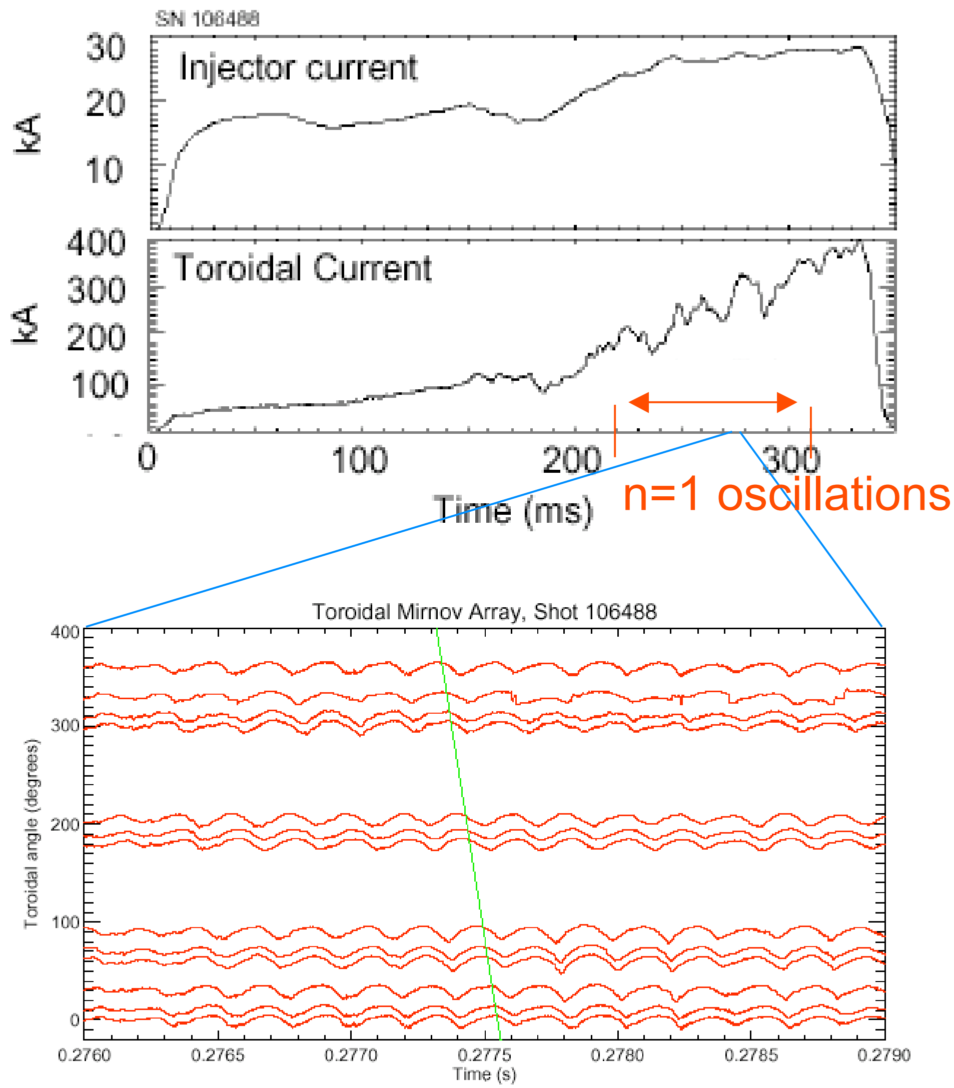


(X. Tang, LANL)

High currents, strong MHD observed During CHI start-up studies

- Up to 390 kA of toroidal current was produced; discharges sustained for 330 msec
- Strong *n* = 1 oscillations observed
  - Robust for I_{tor}>300 kA
- Fluctuations in I_p not observed in other CHI experiments
- *May reflect non-axisymmetric MHD leading to reconnection*

(R. Raman, U. Wash.)



Theory Challenges

- Identify process necessary to transport current to interior and form closed flux surfaces

- Hypothesis
  - Peaked edge current drives low-n kink
  - Flux closure possible with sufficient drive/resistivity

- Combine 3D equilibrium, stability and non-linear dynamics to study CHI physics
  - Model (X. Tang) shows □B/B~10% needed for flux closure (preliminary)
  - Need to better calibrate calculations to experimental values (□, □, □)

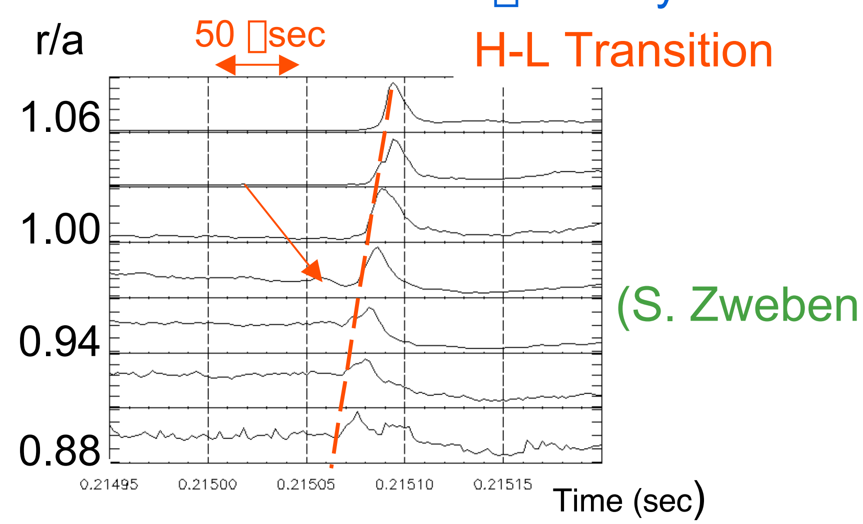
- *Advances in understanding reconnection physics important*

Some Additional Challenges

- Understand transport and stability physics that define plasma profiles
  - Are profiles consistent with bootstrap current required for steady-state?

- RF Physics (HHFW, EBW)
  - $□_i$, $□_b$, $□_□$, $□R_{fi}$ comparable
    - Implications for validity of present day models/codes
  - Determination of current drive
    - Applicability of Ehst-Karney, self-adjoint approaches for HHFW
    - EBW issues of harmonic overlap
  - Self consistent treatment of f_e, f_i, and effect on macro and □stability

- Edge Physics
  - Kinetic modeling of SOL
  - L/H dynamics
    - Time scales
    - I_p scaling of P_{th}



Summary

- NSTX operates in parameter regimes different than those of conventional aspect ratio devices
- Experimental results have exhibited “expected” good confinement and stability properties
  - Need to understand details of why
- Exciting new physics to study
  - Means to establish theoretical underpinnings for advancement of ST concept
- We can help establish links with appropriate experimentalists
  - J. Manickam: ST Theory Coordinator
  - S. Kaye: Head, NSTX Physics Analysis

U.S. National NSTX Research Team Collaboration and International Research Cooperation

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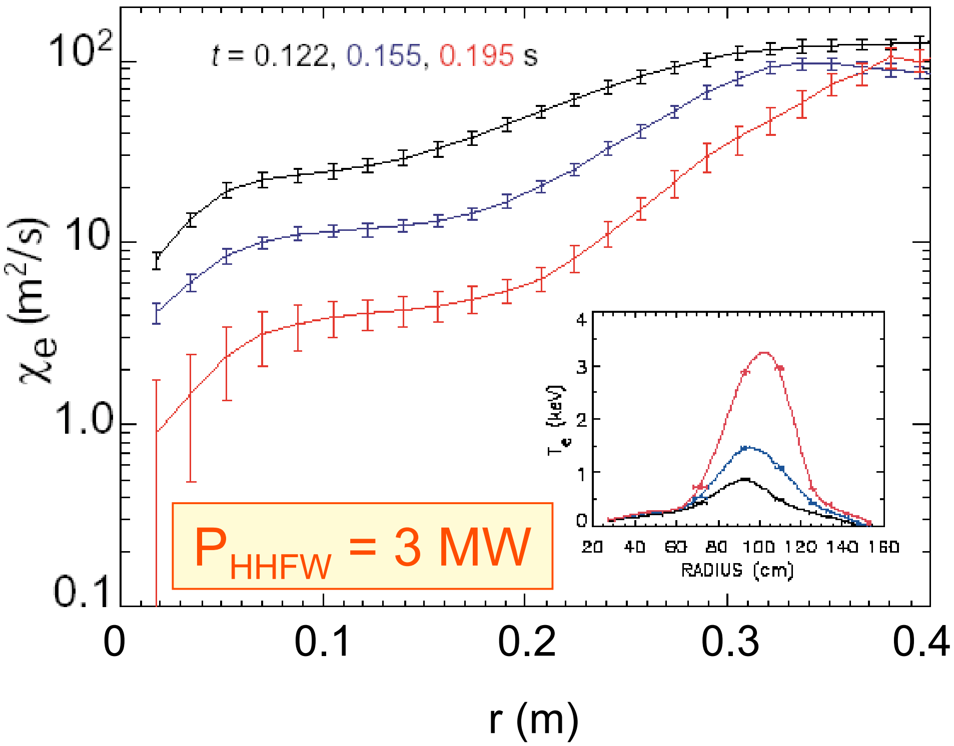
*In cooperation with DOE OFES Theory, OFES Technology, Astrophysics, or SBIR programs

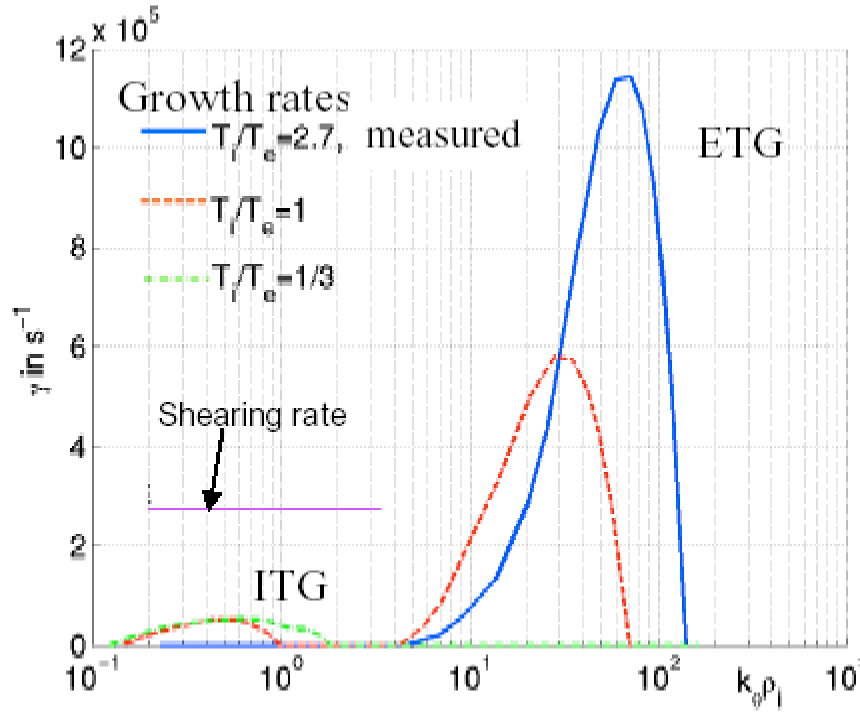
RF Heating Leads To Improved Electron Transport

Electron ITB Formation Possible

Observations Consistent with decrease In ETG with increasing T_e/T_i (GS2)

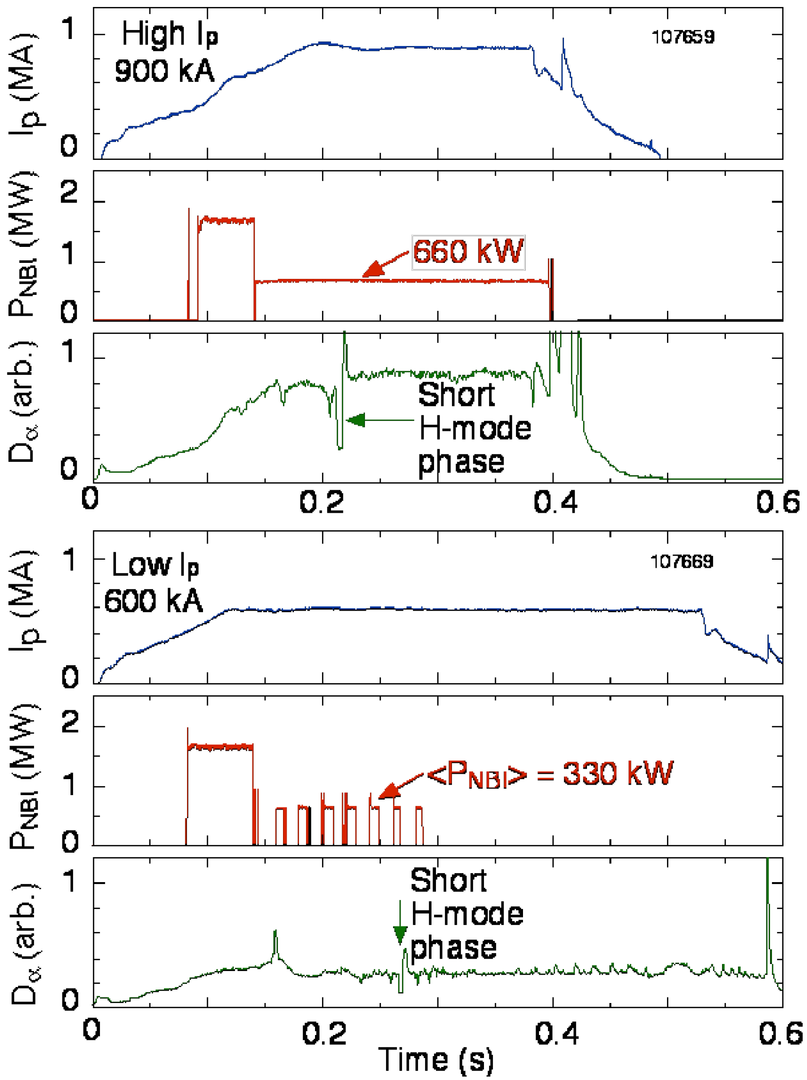


(B. LeBlanc)

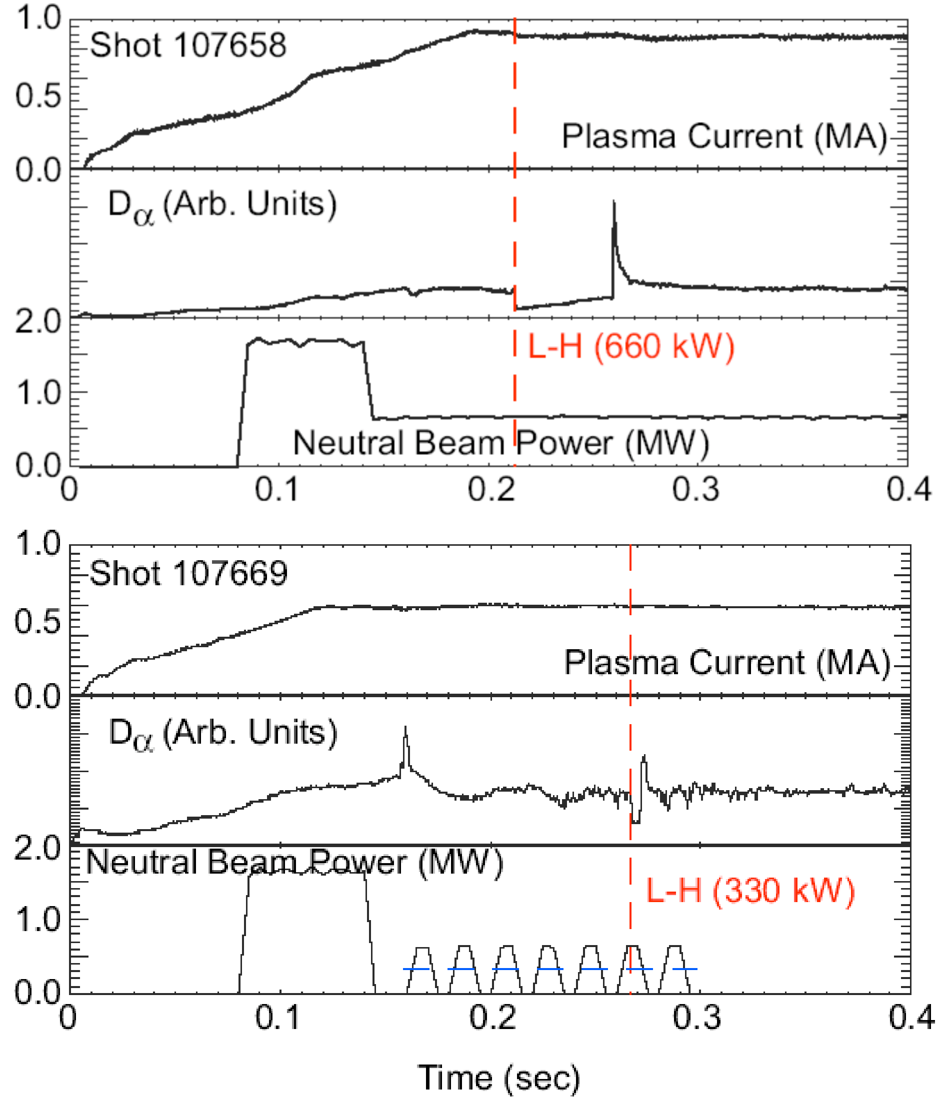


(C. Bourdelle)

“Dithering” or very short H-mode phase when power is near P_{th}



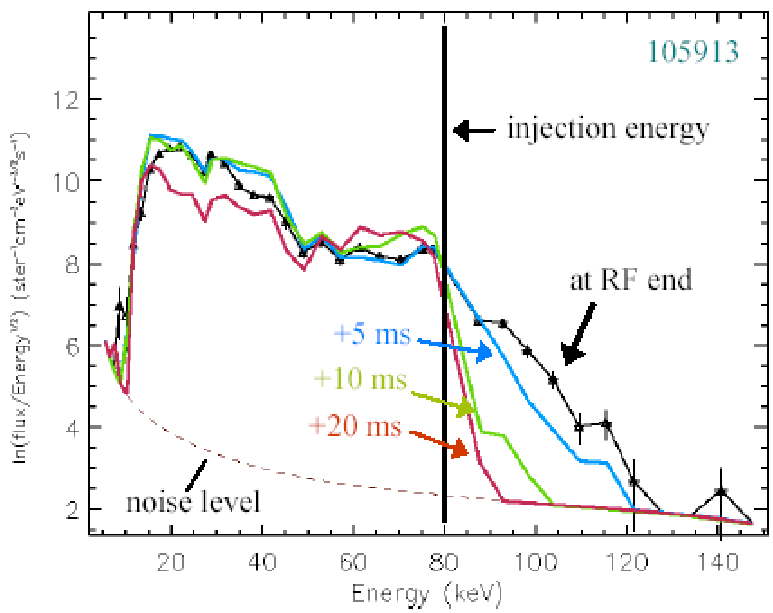
L-H Threshold Experiments Reveals I_p Dependence

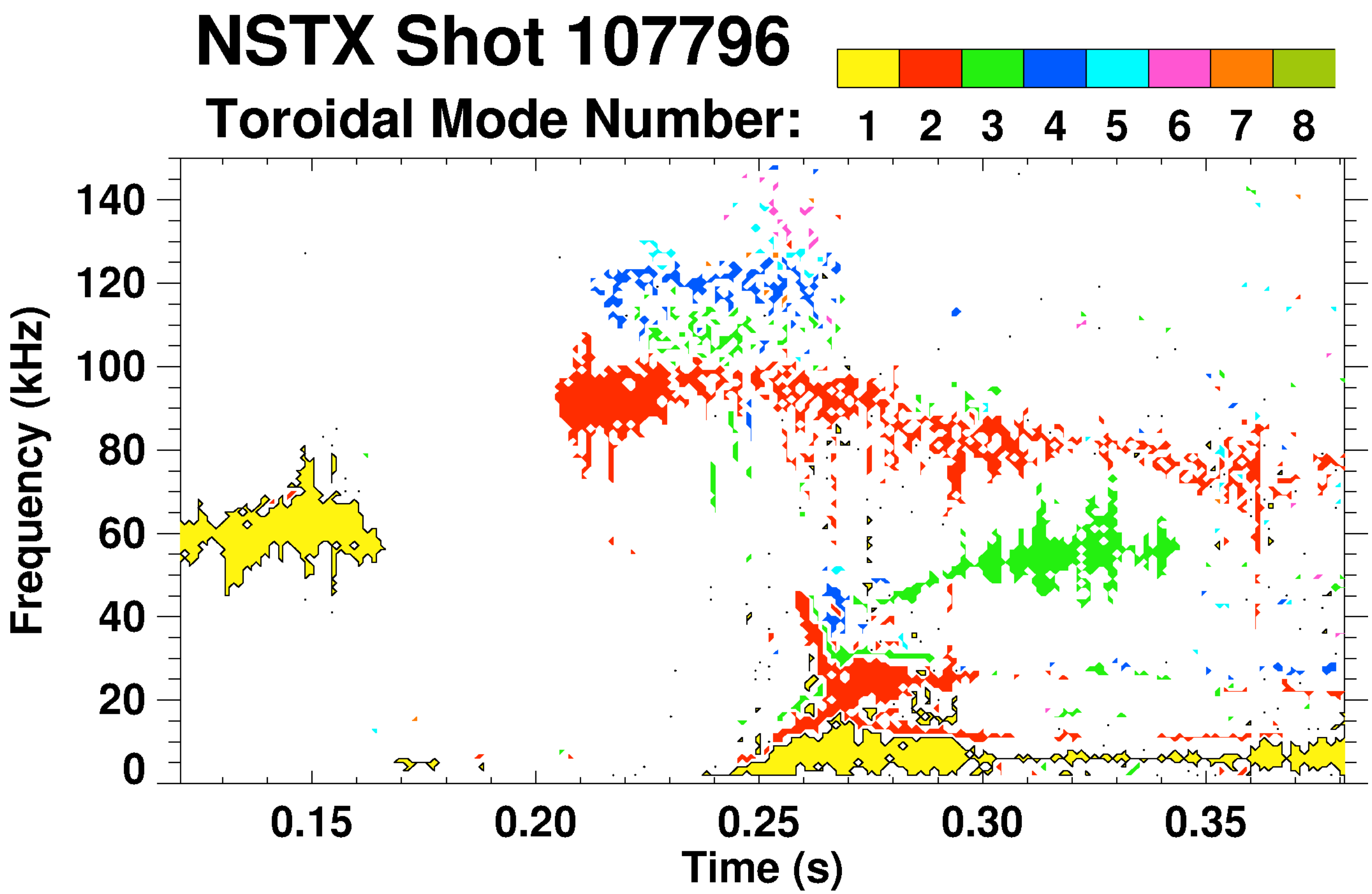


Fast Ion Issues

- Large □$_{fast}$ (~ □$_b$)
  - May lead to non-adiabatic behavior, enhanced radial diffusion and modification of heating deposition profile (V. Yavorskij)

- HHFW accelerates NBI ions to energies well above the injection energy
  - Is this well understood within the framework of HHFW absorption?
    - *Need to incorporate full fast ion distribution function*




NSTX Shot 107796
Toroidal Mode Number:
1
2
3
4
5
6
7
8
Frequency (kHz)
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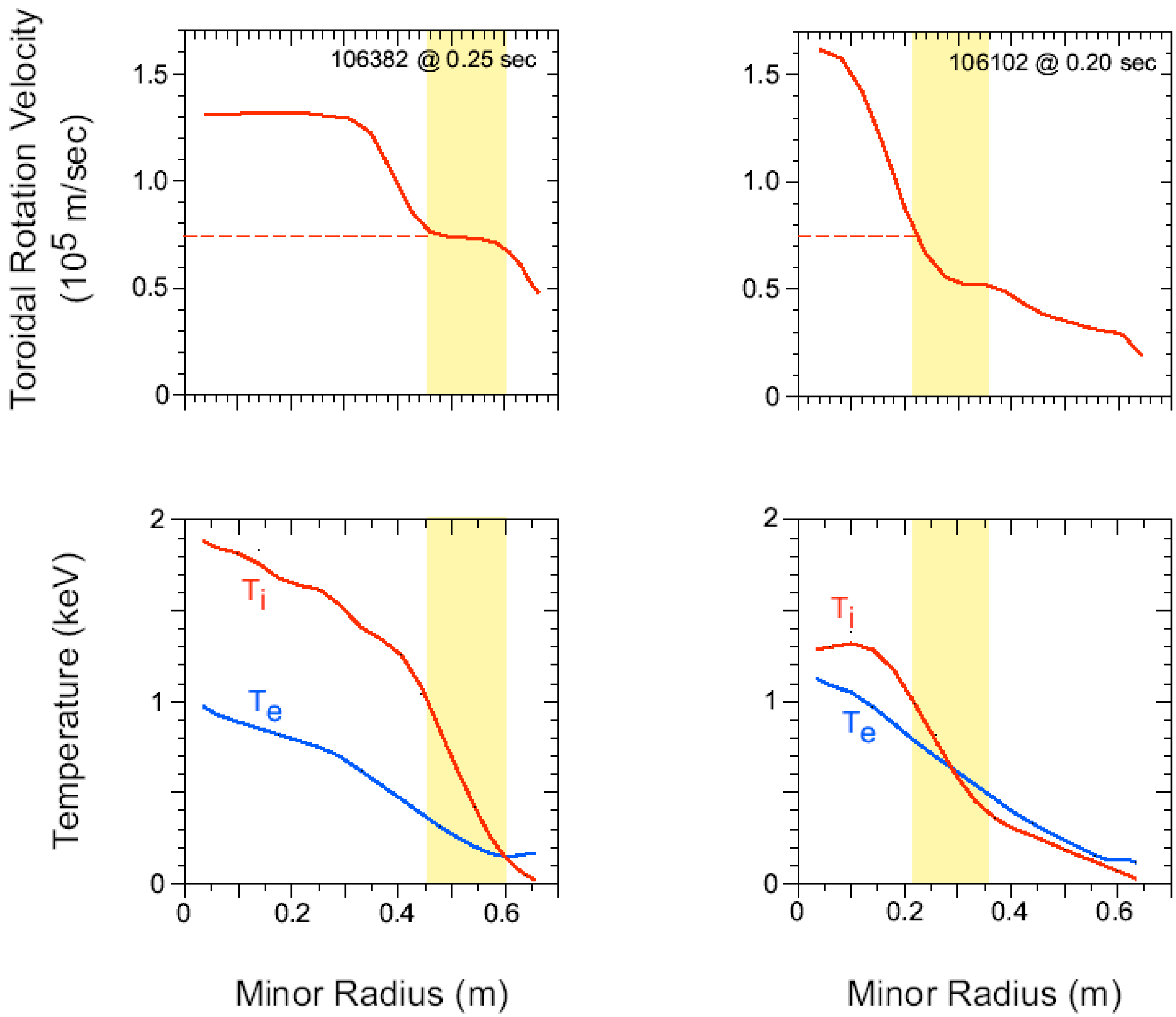
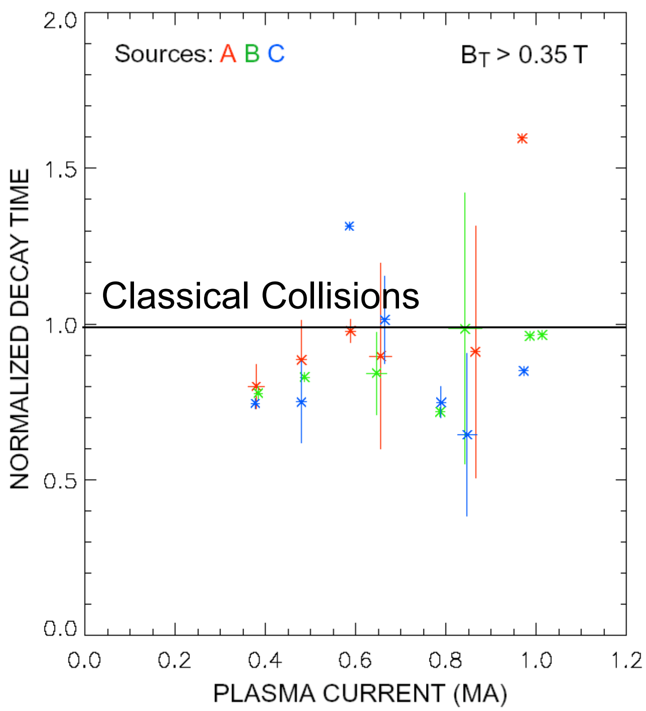
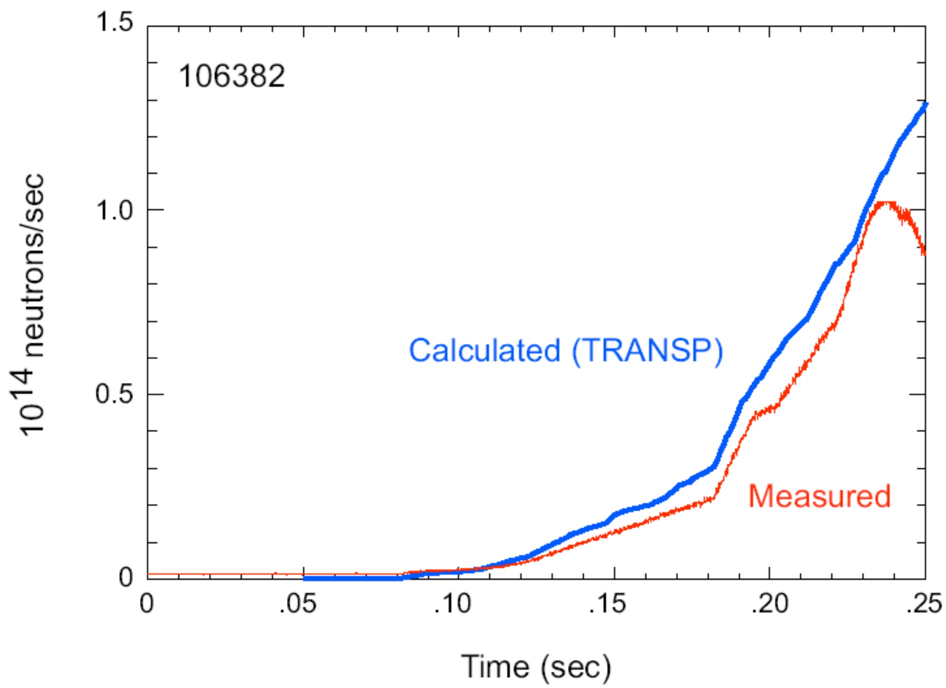
120
100
80
60
40
20
0
0.15
0.20
0.25
0.30
0.35
Time (s)



Toroidal Rotation Velocity
(10^5 m/sec)
106382 @ 0.25 sec
106102 @ 0.20 sec
1.5
1.0
0.5
0
Temperature (keV)
2
1
0
T_i
T_e
0
0.2
0.4
0.6
Minor Radius (m)
Minor Radius (m)

Fast Ion Confinement Appears to Be Classical





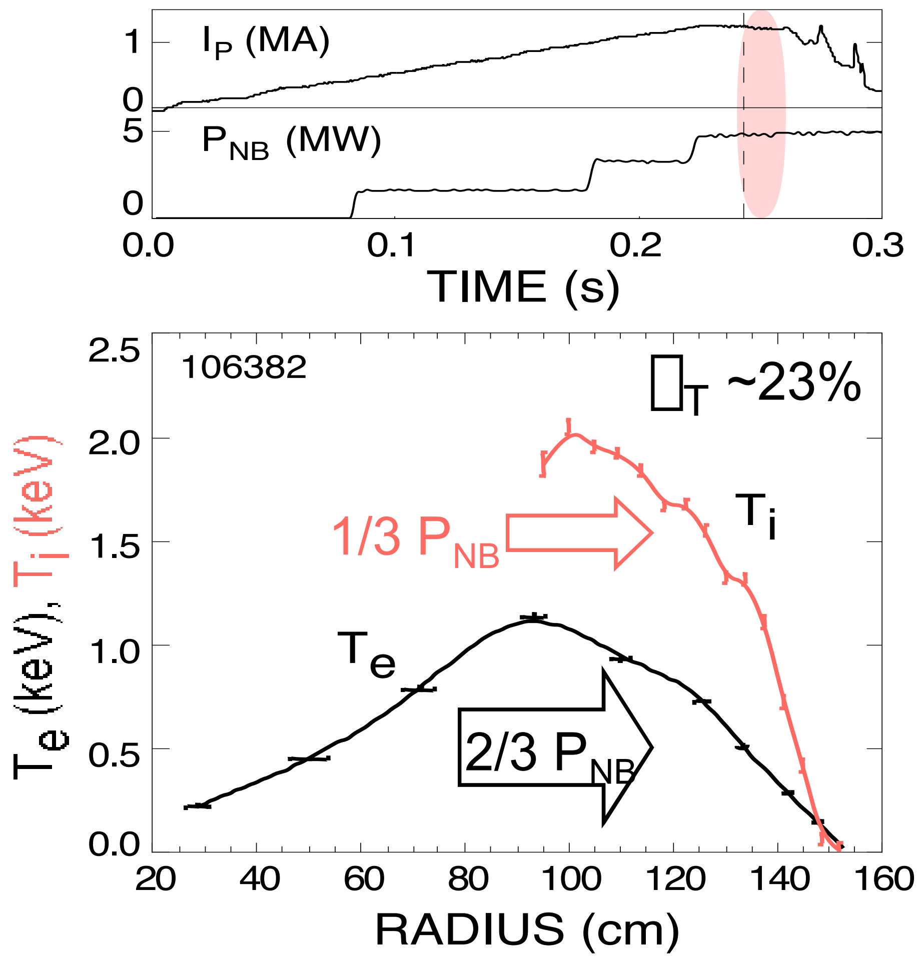
Beam Blip XP (Heidbrink)

Measured neutron rates in rough agreement with that expected from classical behavior

Ion Thermal Confinement Appears Better Than That of Electrons

Experimental Result

- $T_i > T_e$, especially in outer region



Theory Challenge

- Classical $P_{nb,e} \sim 2\ P_{nb,I}$
- Peaked NB deposition