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NSTX

Research Plan for Multi-Scale Transport and Turbulence Physics in NSTX

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Stanley M. Kaye

23rd
NSTX PAC Meeting
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NSTX Will Address T&T Issues Critical to ST Physics for Scaling to Next-Step Devices

- What do we need to know in order to move on to the next step?
  - Global studies
    - Scaling of L-H threshold power: I_p, low n_e, high P_{rad}
    - Confinement scaling with aspect ratio, in low recycling regime
  - Study turbulence k-spectrum to determine sources of anomalous transport
  - Scaling of (and coupling among) energy, momentum and particle transport
  - ***Ultimately develop predictive understanding in order to project to next step devices with confidence***

- NSTX is unique in its ability to address critical transport issues!
  - Strong rotational shear that can influence transport
  - Anomalous electron transport can be isolated: ions often close to neoclassical
  - Large range of β_T spanning e-s to e-m turbulence regimes: assess impact of electromagnetic contribution to transport
  - Localized measurements of electron-scale turbulence (ρ_e~0.1 mm)

PAC-21 Items in Transport & Turbulence

1 Pursue high-k measurements, non-linear modeling, high-k_r, k_θ
2 Density peaking and relationship to confinement
3 Develop code validation procedures
35 Role of rational q on electron confinement
39 Magnetic braking as a tool for momentum confinement studies

All issues will be addressed in this talk

Facility and Diagnostic Upgrades Will Aid In Achieving T&T Goals

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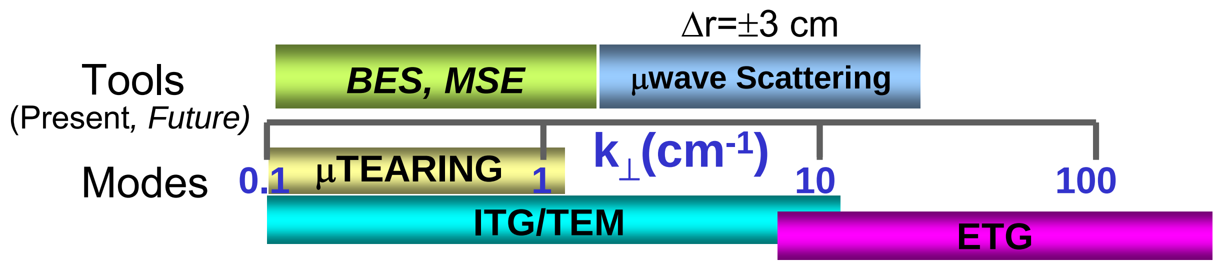
Density control: Lithium plasma facing components (LITER, LLD)
Heating profile measurements for power balance: FIDA, neutron collimator
Rotation measurements: poloidal CHERS
Perturbative energy transport: High resolution edge and core SXR
Fluctuations: internal δB using MSE &/or polarimetry, BES, microwave scattering upgrade to measure high k_θ in addition to high k_r, Doppler reflectometry (edge)
Additional power, current/density profile control: EBW, D pellet injector, 2nd NBI,
Magnetic braking to change ExB shear: Internal non-axisymmetric control coils
Profiles: MSE-LIF, MPTS upgrade, X-point reciprocating probe
Long-pulse discharges: OH/TF sub-cooling, long-pulse divertor

2008-2010
2011+

Full complement of turbulence measurements will cover a wide k-range



Unique set of turbulence diagnostics in terms of spatial resolution across full k-range (2010+)

Strong Coupling of Experiment to Theory Aids in Developing Predictive Understanding

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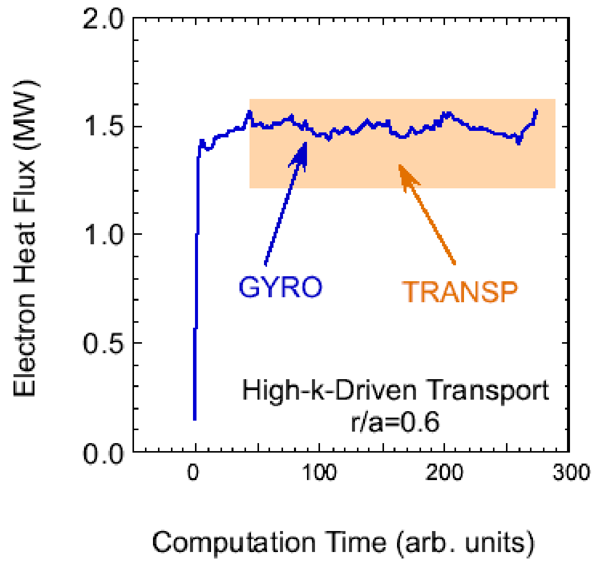
Experiment coupled to gyro-kinetic theory/simulation results

- TRANSP: transport analysis
- GTC-NEO, XGC0: non-local neoclassical
- GS2, GYRO, GTC, GEM, GENE, XGC1: linear and non-linear gyrokinetic codes for turbulence-driven transport

Future

Verification of non-linear ETG simulations underway (GENE, GYRO, GTC)

- pTRANSP (+ TGLF): predictive simulations



NSTX operating regimes will yield results that will test and extend theory

Verification and validation of theory and models at all levels (PAC21-3)

- Synthetic diagnostics in gyro-kinetic codes
- Fluctuation spectra, mode structure
- Transport fluxes, χ's, D's

Ultimate goal: Comprehensive Understanding ⟷ Predictive Tool

Global Studies Have Established Dependences for Confinement and L-H Threshold Power

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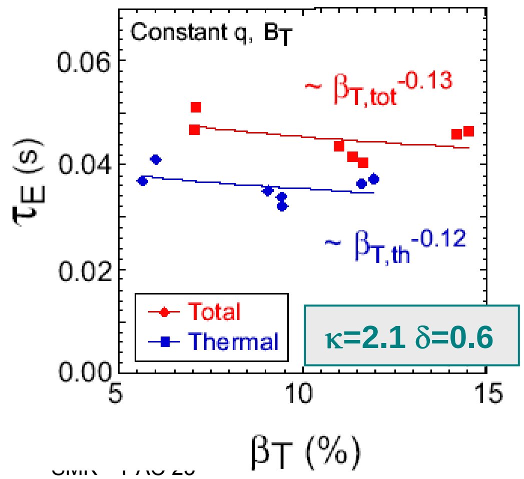
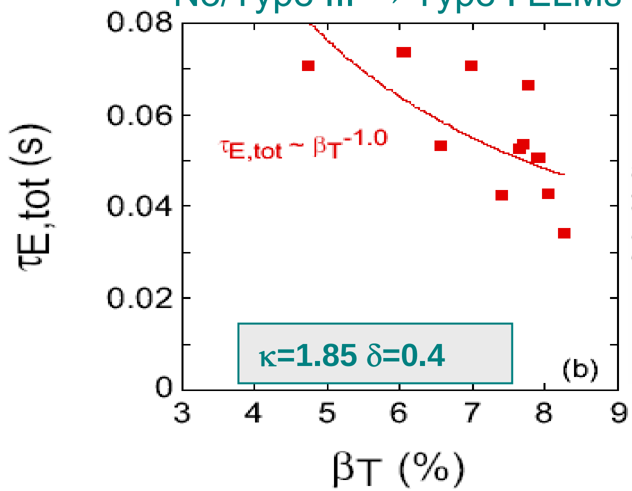
- L-H threshold power
  - Apparent I_p dependence, L-H easier with high-field-side fueling
  - Triangularity, X-point height, configuration important
- Global confinement is good ($H_{98y,2} \leq 1.5$), but dependences differ from those at higher aspect ratio (CDB-6)
  - $\tau_E \sim B_T^{0.9} \leftrightarrow \tau_E^{98y,2} \sim B_T^{0.15}$; $\tau_E \sim I_p^{0.4} \leftrightarrow \tau_E^{98y,2} \sim I_p^{0.9}$ [Kaye, PRL **46** (2006) 848]
- Significant improvement in global confinement with Lithium evaporation

β-scaling high priority ITPA topic (CDB-2): Shape (ELMs) matter ↔ Edge stability

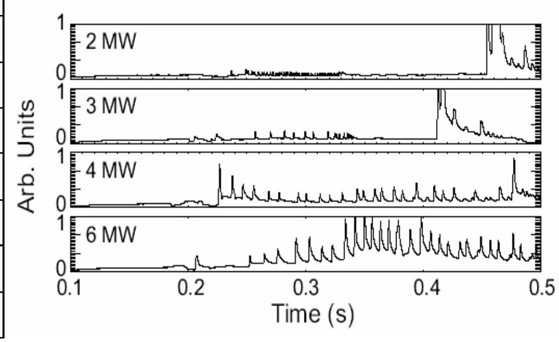
Small Type V ELMs



No/Type III → Type I ELMs



(supported by recent JET and DIII-D results)



Global Scaling Studies are Important for Being Able to Scale to Future Devices

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Most global confinement studies have given way to local transport studies, but important research needs remain

- 2008-2010
  - Determine I_p, B_T, shape dependence of L-H threshold power
  - Effect of rotation on L-H threshold (n=3 braking, HHFW)
  - Dependence of τ_E on R/a for optimizing NHTX, ST-CTF designs
    - Within NSTX and through NSTX/DIII-D similarity experiment (TP-9)
  - Establish effect of Lithium PFC on L-H threshold, global confinement
    - Key component of global **and** local studies
  - Identify source of variation in β-degradation of confinement (CDB-2)
    - ELM suppression in lower κ, δ plasmas using Lithium conditioning

- Global studies could be completed in 2 year time frame (2008-2009), but without understanding the underlying physics issues

- 2011-2013 research will require facility/diagnostic upgrades
  - Evaluate role of X-point in determining P_{L-H}
  - Verify scaling trends at high P_{heat} ($\leq$ 12 MW) to support NHTX, ST-CTF physics designs
  - Scaling in long-pulse discharges ($\leq$ 2.5 s)

Ion Transport Often Found to Be Near Neoclassical In H-modes

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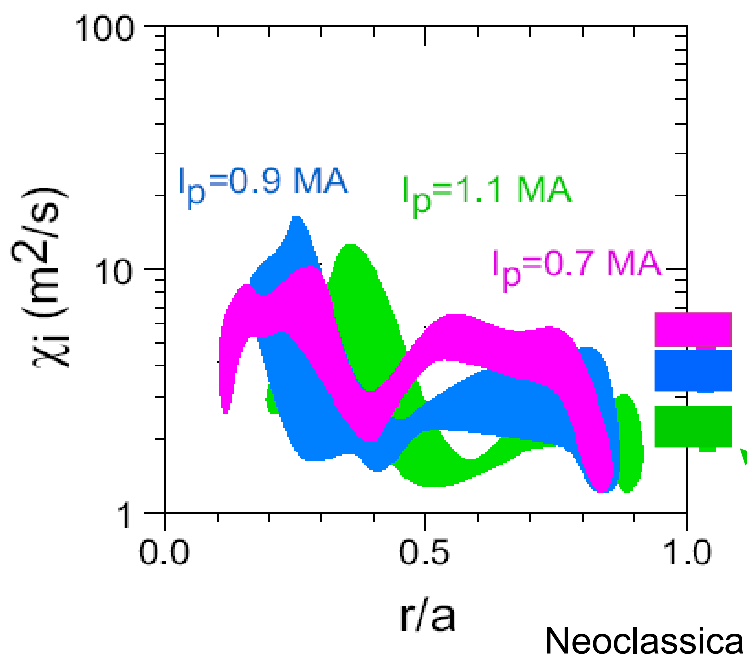
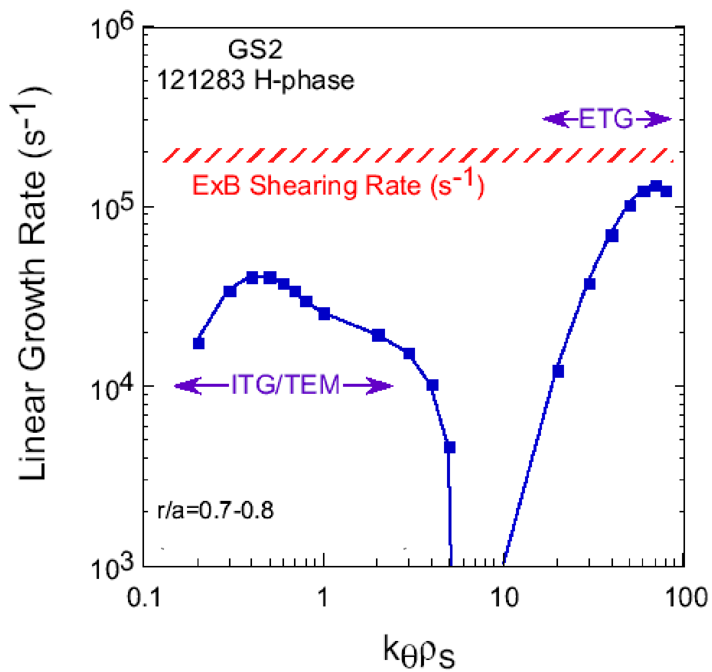
Controls τ_E scaling with I_p



Neoclassical (r/a=0.5-0.8)

Neoclassical levels determined from GTC-Neo: includes finite banana width effects (non-local)

Linear GS2 calculations indicate possible suppression of low-k turbulence by ExB shear during H-phase
- Supported by non-linear GTC results



χ_i routinely anomalous in high density L-modes

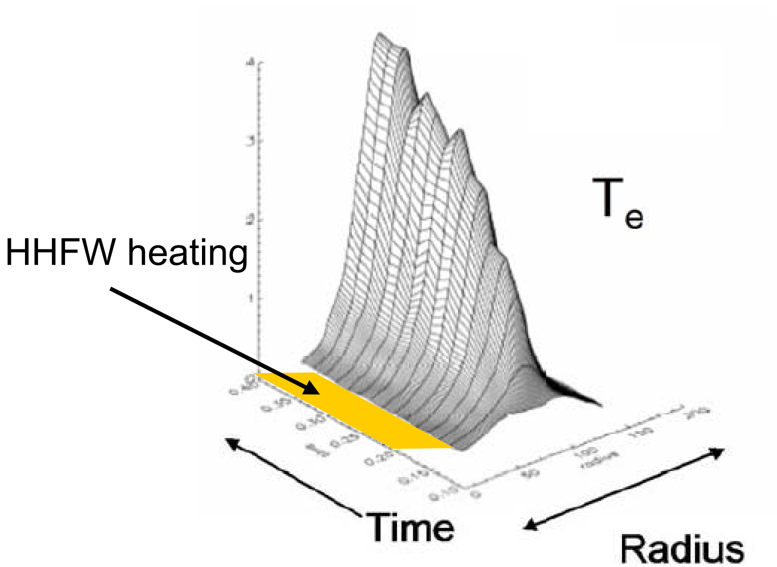
Should Neoclassical Ion Transport Be Expected in Next-Step Devices?

- 2008-2010
  - Actively change ITG/TEM driving/damping terms (T_e/T_i, ExB shear, collisionality) using NBI, HHFW and magnetic braking
  - Relation of first low-k turbulence (prototype BES) measurements to transport
    - Preliminary validation of neoclassical and low-k turbulent transport theories
  - Ion internal transport barrier studies: relation to current profile, integer q, ExB shear
  - Validation of orbit shrinking/squeezing theory (L_{Ti}~ρ_i near edge in some cases)

- Reduction to 2 year program (2008-2009) would compromise our ability to relate ion transport to low-k turbulence (prototype BES only)

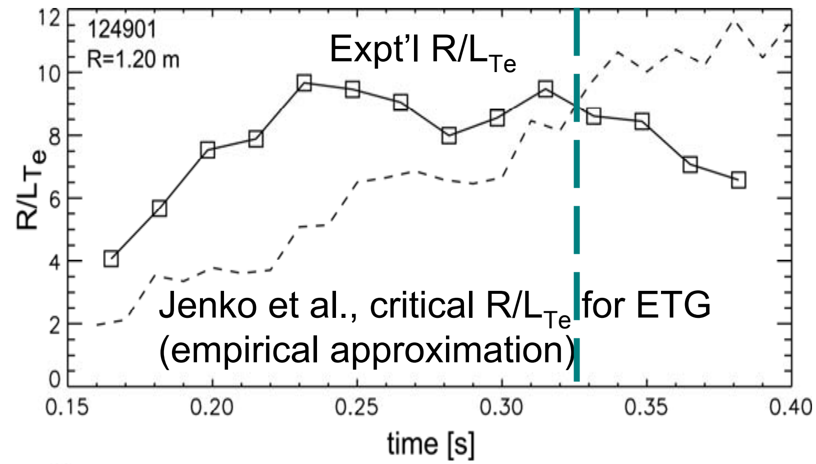
- 2011-2013: Additional run and analysis time, coupled with theory development, would allow for comprehensive studies to be completed
  - Detailed comparison of inferred χ_i and measured low-k fluctuation spectra to gyro-kinetic predictions:
    - Assessment of non-local transport due to large ρ^*
    - Zonal Flow dynamics in edge and core (test theoretical q-dependence)
    - *Comprehensive validation of neoclassical and low-k turbulent transport theories*
  - Neoclassical theory development with full FLR
  - Assessment of ion transport and turbulence levels at high P_{heat} and for various input torques, q-profiles
  - ***Establish a predictive understanding of the transition between neoclassical and turbulent ion transport***

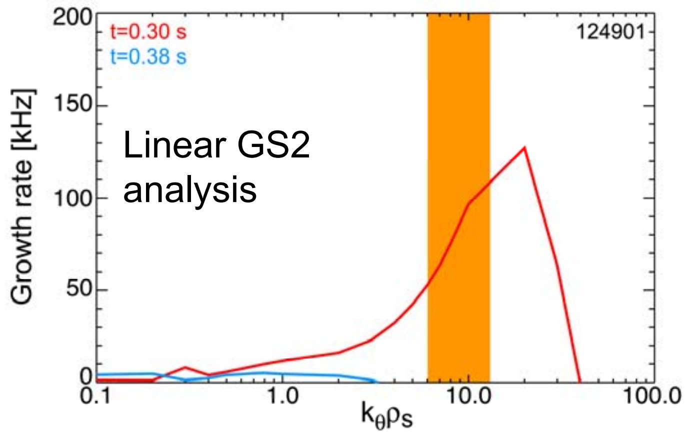
NSTX Is In an Excellent Position to Study and Understand the Key Areas of Electron Turbulence and Critical Gradient Physics (PAC21-1)

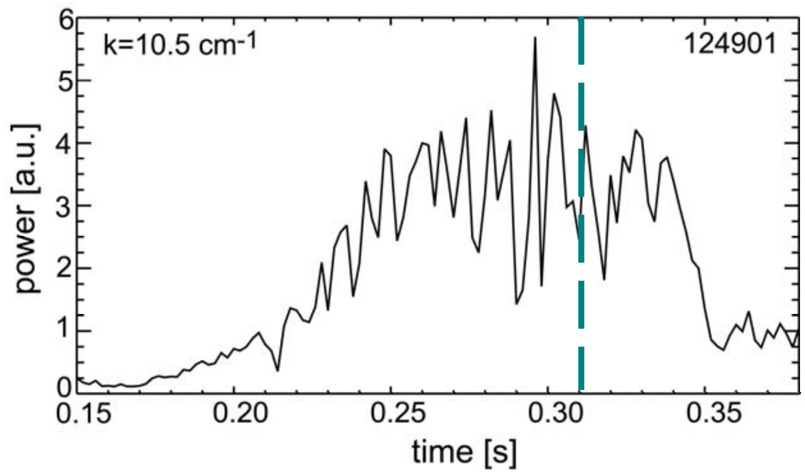


High-k scattering diagnostic ($\Delta r=\pm 3$ cm)

k-range of fluctuations in ETG/high-k TEM range







High fluctuation level when R/L_{Te} is greater than critical value for ETG

Electron Transport Is Consistent with ETG Drive in Many Cases (PAC21-1)

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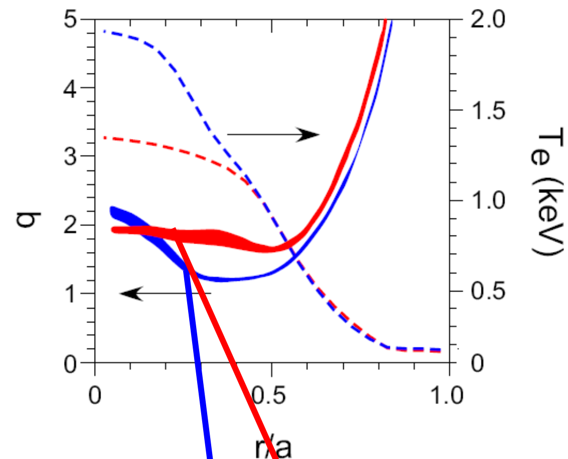
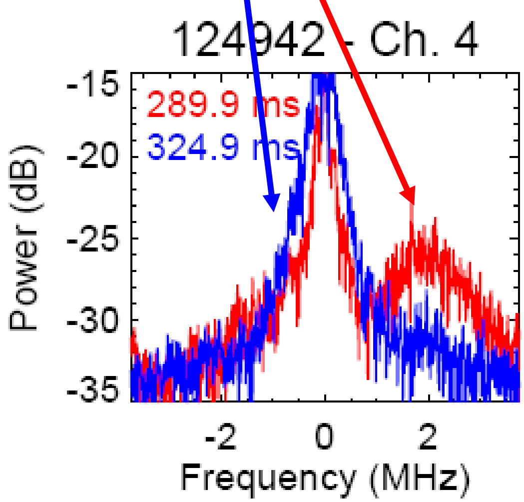
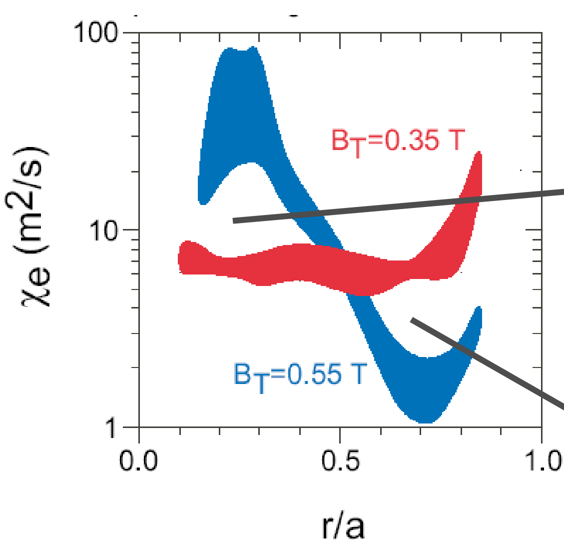
Reduction in electron transport with reversed magnetic shear (i.e., χ_e drops as T_e peaks)

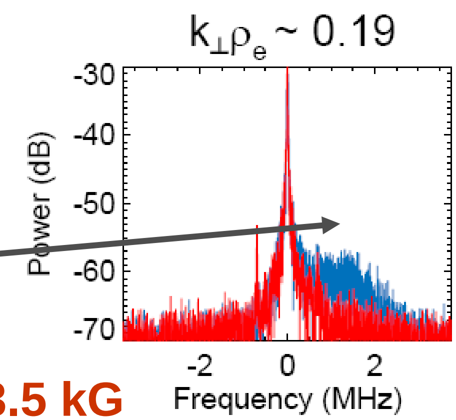




Electron transport anomalous: controls B_T scaling

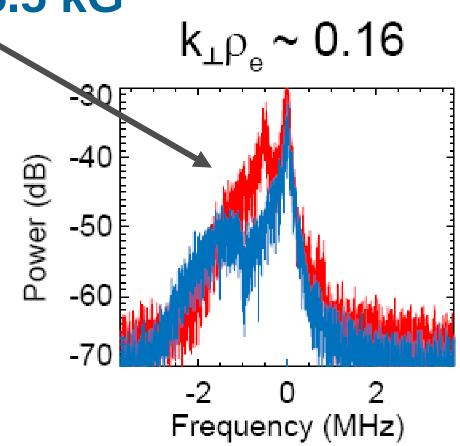
Consistent with variation of high-k fluctuations





3.5 kG

5.5 kG

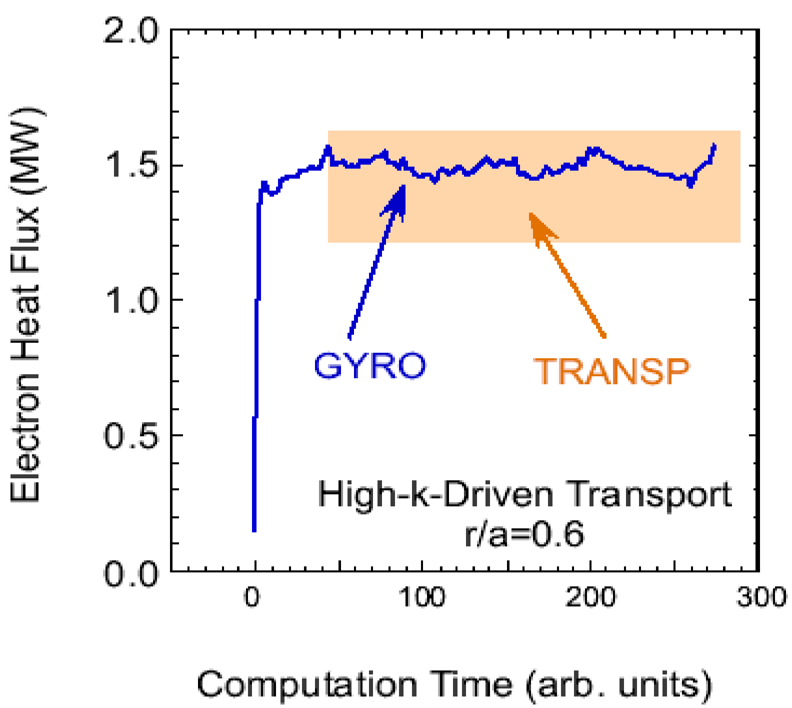


Fluctuations in ETG k-range increase with decreased shear reversal ($k_\theta \rho_e$=0.23)

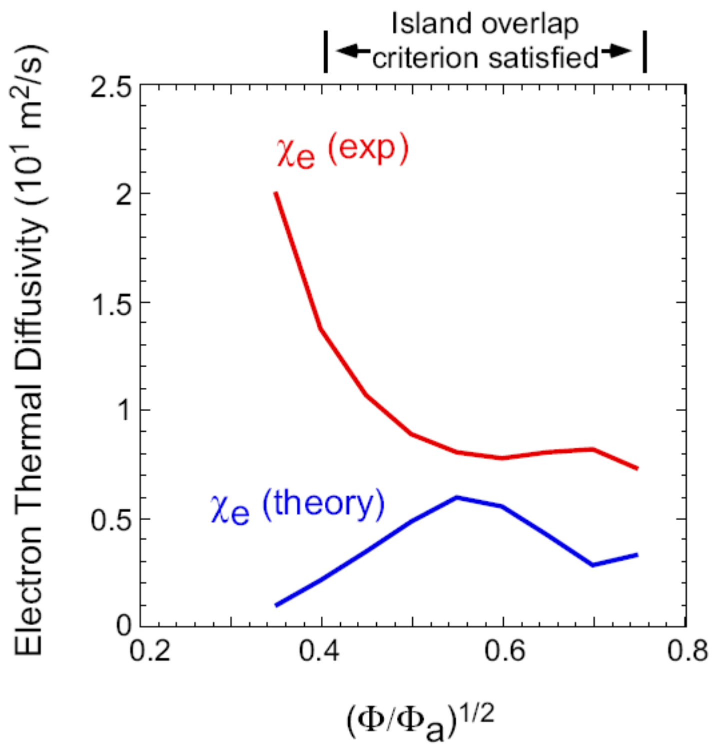
Electron Transport May be Controlled by Multiple Mechanisms (PAC21-1)

NSTX

Heat flux due to high-k electron modes (ETG) consistent with levels inferred from TRANSP in L- & H-modes for r/a>0.5



Low-k microtearing important in low shear/“Hybrid” discharges

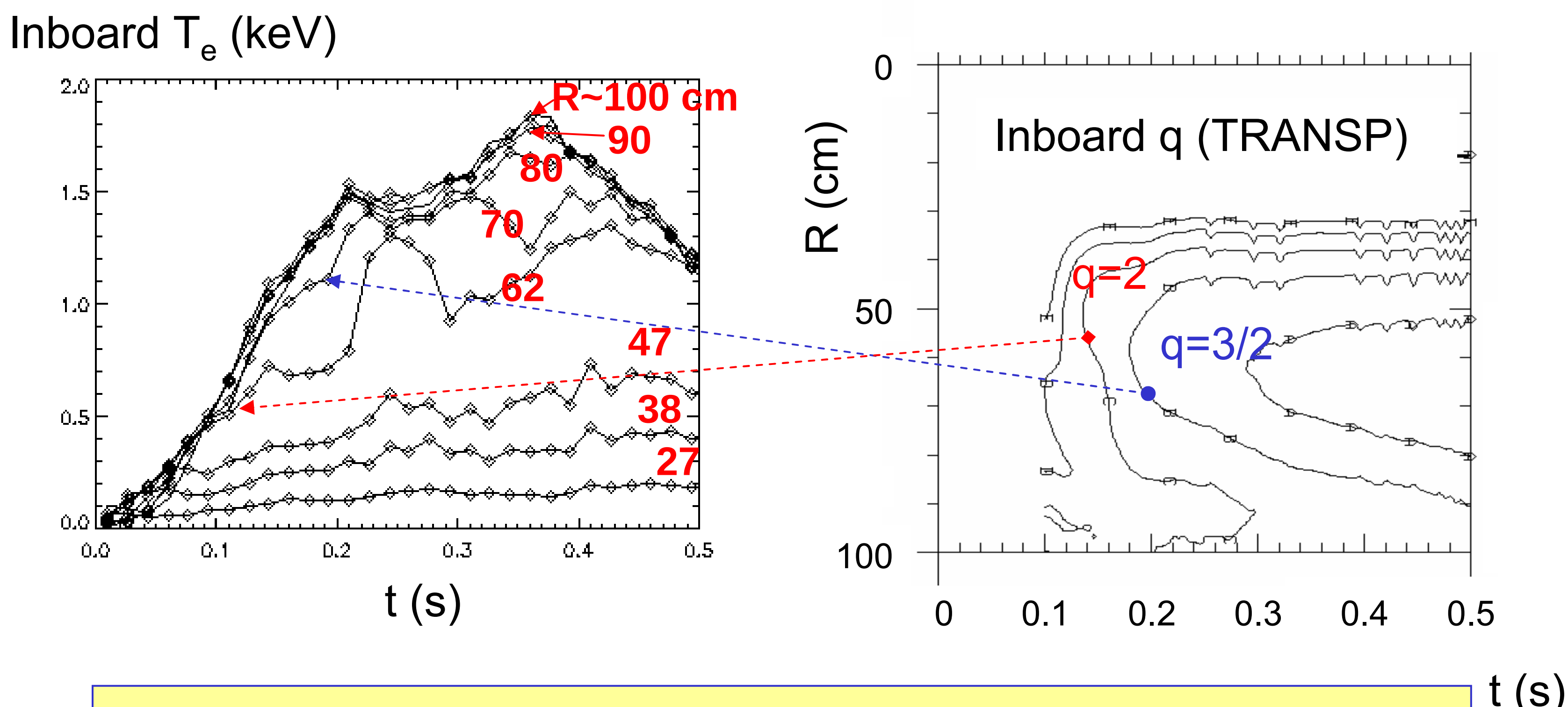


Driven by ∇T, damped by strongly reversed magnetic shear

Role of Rational-q Evident in Negative Shear L-mode (PAC21-35)

NSTX

2 MW, low n_e L-mode



- Spontaneous T_e increases when q approaches rational values
- Zonal flow/magnetic geometry effect (M. Austin *et al* PoP 2006)
- NSTX good test bed for zonal flow physics (~$\rho*$)

What are the Root Causes of Anomalous Electron Transport and Under What Conditions?

NSTX

- 2008-2010
  - Investigate TEM/ETG using present high-k_r system
    - Test collisionality dependence of TEM/ETG transport (HHFW, Lithium conditioning)
    - Establish critical gradient using HHFW to change R/L_{Te}: compare with results of linear gyrokinetic calculations to ID responsible mode
    - Turbulence spreading
  - Measure full range of medium-to-high k_r, k_θ turbulence
    - Unique with respect to spatial resolution
    - Mode structure, full frequency spectra, dispersion characteristics
    - Radial streamer identification
  - Perturbative electron transport using ELMs and pellets
    - Relation to high-k turbulence and critical gradients
  - Role of reversed magnetic shear, low order rational q for eITB formation (MSE-LIF)
  - Microtearing mode investigation using internal δB measurements with MSE, polarimetry
    - Scope out sensitivity requirements during 2008
    - Change driving/damping terms: β, ν^*, ∇T, q', ExB shear

Compare measurements to results of gyrokinetic calculations with built in synthetic diagnostics for Verification and Validation of physics models – coupled to GTC-SCIDAC project

- ***Proposed FY10 Transport Milestone: Study turbulence regimes responsible for ion and electron energy transport***

Extending Operation and Upgrades Beyond 2010 Would Allows for a Deeper Understanding of Electron Transport

NSTX

- 2011 – 2013:
  - Local modification of electron transport and turbulence
    - Assess turbulence spreading with full low and high-k fluctuation measurements
  - Microtearing mode investigations with internal δB, full low-k for mode structure in NBI and non-NBI plasmas
  - Modulated EBW to probe local critical gradient physics
  - Verify transport trends at high P_{heat}, varying input torque (2nd NBI)
  - *High-k turbulence/control a collaborative opportunity for NSTX/C-MOD/DIII-D*

  - ***Additional opportunities for data analysis and more comprehensive V&V for confident extrapolation to next-step devices***

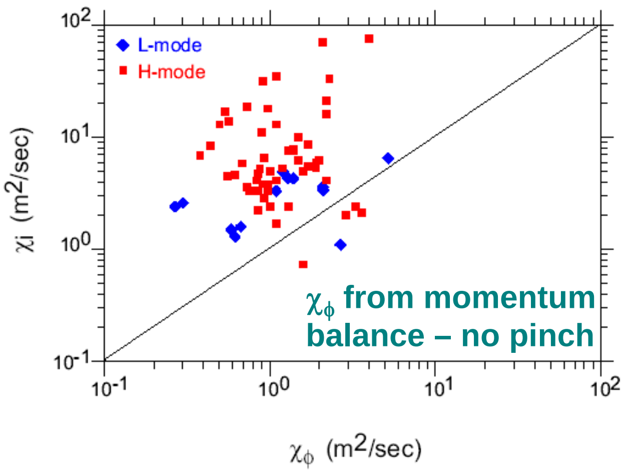
- Reduction to a 2 Year Program (2008-2009) would severely impact ability to achieve goals
  - Limits to discharge/tool development
  - Less opportunity to analyze data and propose follow-on experiments
  - Unavailability of high-k_θ diagnostic

Momentum Transport Studies Will Focus on High-Rotation Plasmas, Relation to Energy Transport and Scaling to Next-Step Devices

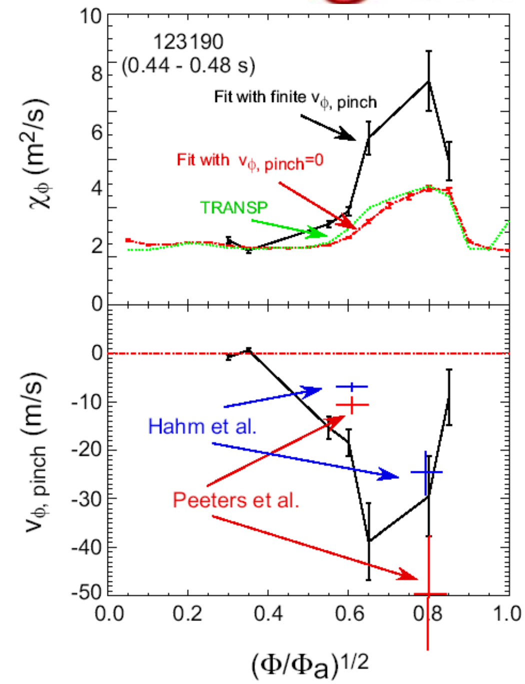
NSTX

TP-6.3

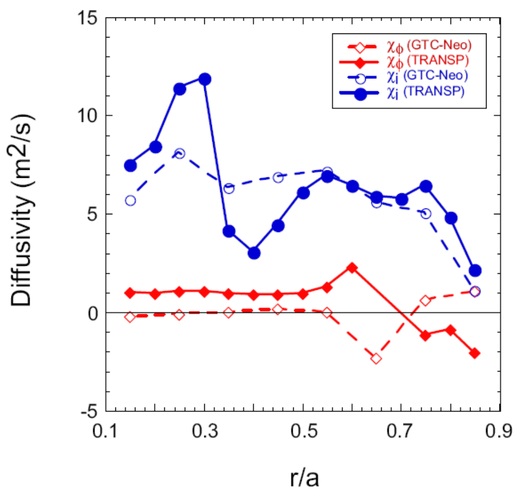
$\chi_\phi << \chi_i$, is common in NSTX, unlike in present higher R/a devices



Perturbative momentum transport studies using magnetic braking indicate significant inward pinch **(PAC21-39)**

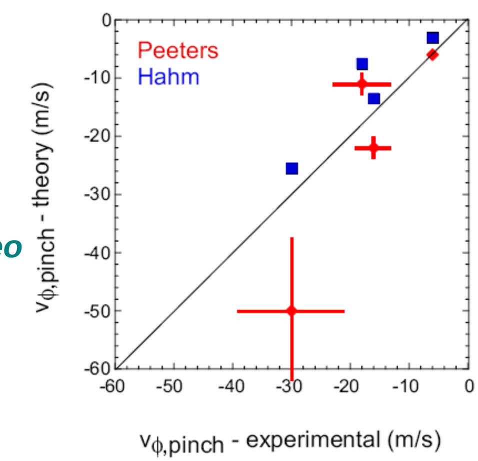


$\chi_\phi > \chi_{\phi,neo}$, even though $\chi_i \sim \chi_{i,neo}$



Theory gives v_{pinch}/c_f based on low-k turbulence

Good agreement with expt



$\Gamma_{i,turb} < \Gamma_{i,neo}$ while $\Gamma_{\phi,turb} > \Gamma_{\phi,neo}$

Momentum transport may be the best probe of low-k turbulence

What is the Source of Momentum Transport, and How Does it Couple to Energy Transport?

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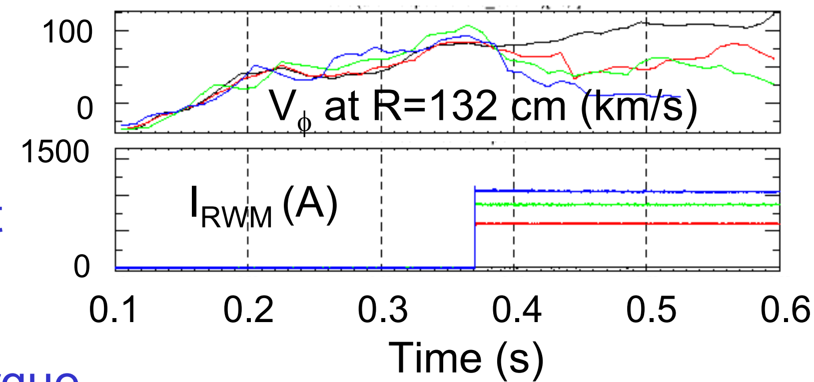
NSTX can explore momentum transport by varying input torque using magnetic braking and NBI

TP-6.3



- 2008 – 2010
  - Validation of neoclassical theory using v_θ measurements
  - Effect of rotation on plasma confinement (FY08 Joule milestone)
    - Relation of Γ_ϕ to $\Gamma_{i,e}$
  - Determine v_{pinch}, χ_ϕ with varying input torque
    - Tests of inward pinch, NTV theories
  - First comparisons with full low-k turbulence measurements
  - Supports development of confident extrapolation to next-step device

- Shortening run would compromise ability to assess momentum transport with respect to low-k turbulence (prototype BES only)

- 2011-2013: Extended program duration
  - Zonal flows/GAMs and relation to other microinstabilities
  - Further v_{pinch}, χ_ϕ assessment with off-midplane control coils, 2^{nd} NBI

NSTX & MAST Have Collaborated to Study Density Profile Peaking (PAC21-2, CDB-9)

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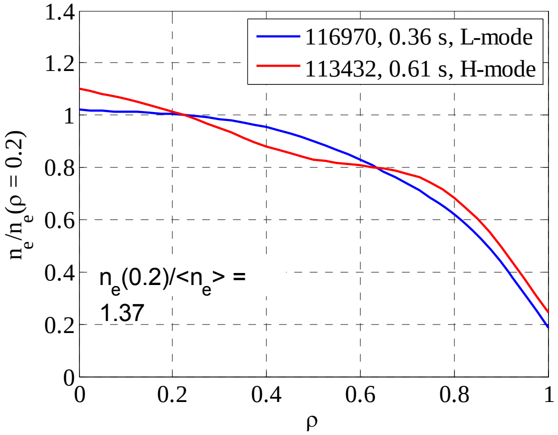
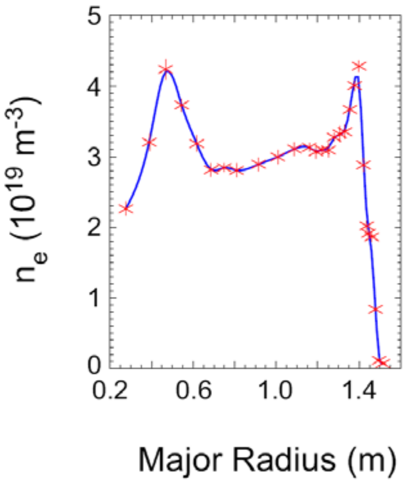
Joint database submitted to ITPA

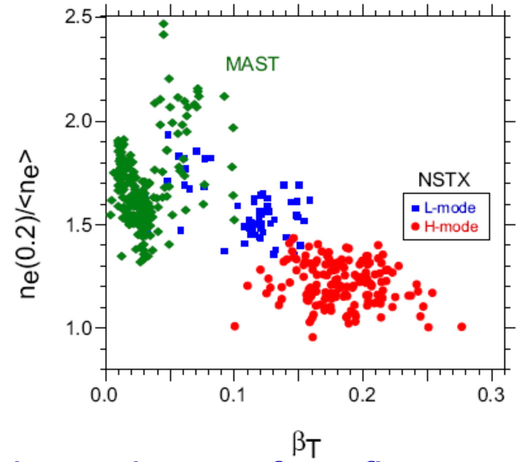
- L- & H-modes in NSTX can have similar peaking



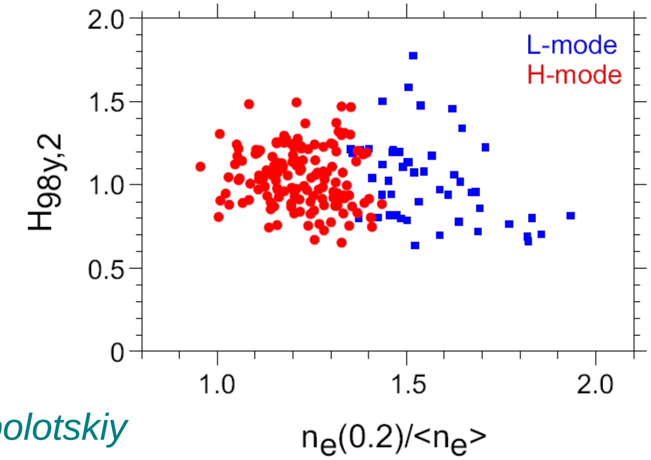
- H-modes exhibit large ears during early part of H-phase



NSTX shows some 0-D trends similar to those at higher R/a (peaking varies inversely with ν_{eff}, n_e/n_{GW}), *but lower peaking at higher* β_T



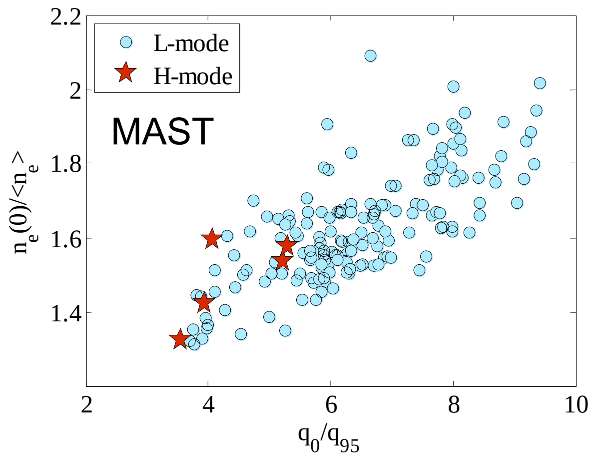
Little dependence of confinement on density peaking

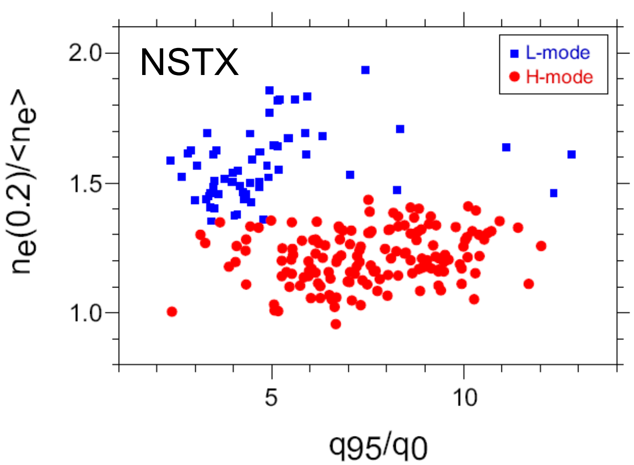


Includes RS L-modes

Differences Between NSTX and MAST Exist

MAST exhibits a dependence on current profile, while NSTX does not

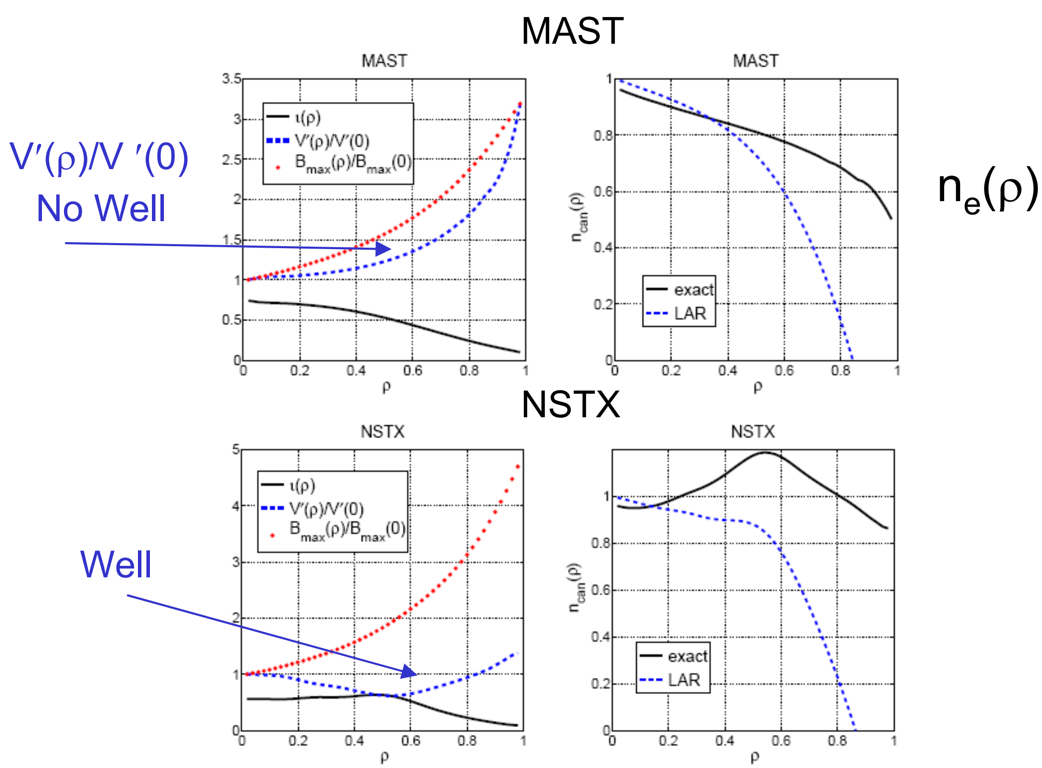




NSTX generally less peaked than MAST

Theory indicates 0D framework insufficient for understanding particle pinch (Mischenko, PoP, 2007)

- Plasma diamagnetism/well depth affects pinch
  - Strong well → weak inward pinch
- NSTX operates at higher β (deeper well)



Low Recycling Edge Could Have Significant Impact for Next-Step Devices

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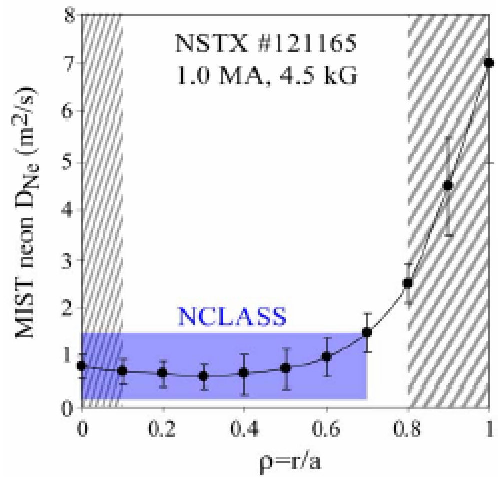
- 2008 - 2010
- D & particle transport in NBI-fueling dominated core
  - In conjunction with energy & momentum transport
- Impurity transport using gas puffing, TESPEL
  - Previous experiments/modeling indicate neoclassical transport level for injected Neon in H-mode
- Effect of low ν, recycling due to Lithium on $n_e(r)$, particle transport



- Shortening run would compromise ability to schedule experiments and assess particle transport with respect to low-k turbulence (prototype BES only)

- 2011 – 2013
  - D & particle transport in outer region: requires extended modeling for determining S(r)
  - Helium transport studies using He puffing or He discharges (FY2009 Joule milestone)
  - Determine role of low-k turbulence in controlling particle transport: validation of particle transport models
  - Perturbative particle transport studies continue with second beamline

A 3 Yr NSTX Program Would Enhance Our Predictive Capability for Transport While Providing New Understanding of Plasma Transport for all Confinement Concepts

- A 3 Yr NSTX program will address the most critical physics issues required for extrapolating to a next-step device with confidence
  - Global studies of confinement and L-H threshold power
  - Relation of ion and electron transport to turbulence
  - Momentum transport as a probe of low-k turbulence
- A successful conclusion to the 3 Yr program will require an acceleration of diagnostic implementation, operation and physics analysis
  - Low-k, high-k_θ implemented by 2010
  - Additional run time to take advantage of upgraded capability
  - Additional personpower resources for physics analysis, code running, V&V (post-docs?)
- A two year program only (2008-2009) would severely compromise our ability to address the key physics issues adequately
  - Less run time, fewer opportunities for experiments, development
  - Availability of diagnostics and personpower
- Run time beyond 2010 would enable significant advances in understanding the critical physics areas for scaling to the next step with confidence
  - More comprehensive understanding of energy and momentum transport
  - Particle transport studies
  - Facility and diagnostic upgrades: 2^{nd} beam, off-midplane CC, EBW, long-pulse
  - Further theory development
  - ***Comprehensive predictive capability***

Transport and Turbulence Plans (2008-2010)

NSTX

FY07 | 08 | 09 | 10 | 11 | 12 | 13

Program

Global Confinement
- L-H threshold, τ_e on R/a, b-scaling, effect of Li

Ion Transport
- ITG/TEM driving/damping terms, ion ITB
- role of RS, q on iITB, low-k

Electron Transport
- ETG/TEM/microtearing, perturbative e^- transport
- High-k_q, role of RS, q on eITB

Momentum Transport
- Validate neo theory, v_ϕ on τ_E, v_{pinch}/χ_ϕ
- Probe of low-k

Particle Transport
- Core transport, impurity transport, effect of Li

Tools
- pCHERS, FIDA, high-resolution edge SXR, internal dB with MSE
- Prototype BES, MSE-LIF, LLD
- High-k_θ, full BES, MPTS higher spatial resolution, EBW
- Integrated high and low-k non-linear gyrokinetics (GTC-NEO, GYRO, GEM, GTC, GS2); pTRANSP – Verification and Validation

Base Plan
+10% increment

Transport and Turbulence Plans (2008-2010, 2011-2013)

NSTX

FY07 | 08 | 09 | 10 | 11 | 12 | 13

Program

Global Confinement
- L-H threshold, τ_e on R/a, b-scaling, effect of Li
- X-point on L-H, scaling at high power
- Scaling in long pulse

Ion Transport
- ITG/TEM driving/damping terms, ion ITB
- role of RS, q on iITB, low-k
- Detailed low-k/model validation, neo theory, ion trends a high power

Electron Transport
- ETG/TEM/microtearing, perturbative e^- transport
- High-k_q, role of RS, q on eITB
- Microtearing in non-NBI, local modification of e^- T&T, e^- transport at high power

Momentum Transport
- Validate neo theory, v_ϕ on τ_E, v_{pinch}/χ_ϕ
- Probe of low-k
- ZF/GAMs, v_{pinch}/χ_ϕ with off m-p CC, higher torque

Particle Transport
- Core transport, impurity transport, effect of Li
- Outer transport, He transport, perturbative transport, relation to low-k

Tools

- pCHERS, FIDA, high-resolution edge SXR, internal dB with MSE
- Prototype BES, MSE-LIF, LLD
- High-k_θ, full BES, MPTS higher spatial resolution, EBW
- Neutron collimator, off-midplane control coils, magnetic turbulence diagnostic, 2nd NBI, higher power EBW
- TF/OH sub-cooling, Long pulse divertor
- 2nd NBI, Long-pulse divertor
- Integrated high and low-k non-linear gyrokinetics (GTC-NEO, GYRO, GEM, GTC, GS2); pTRANSP – Verification and Validation

Base Plan
+10% increment