NSTX

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Research Plan for Transport and Turbulence Physics in NSTX

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S.M. Kaye, PPPL

For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Conference Room LSB-B318
Princeton Plasma Physics Lab
July 28-30, 2008

Culham Sci Ctr
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NSTX Will Address T&T Issues Critical for Predicting Performance in Future Devices

- What do we need to know in order to move on to the next step for STs?
  - Confinement scaling at low aspect ratio
    - In low recycling regime and at higher B_T and I_p
  - Study full turbulence k-spectrum to determine sources of anomalous transport
  - Understand energy, momentum and particle transport and their coupling
  - Develop prediction for L-H threshold power at high B_T, I_p, low n_e, high P_{rad}

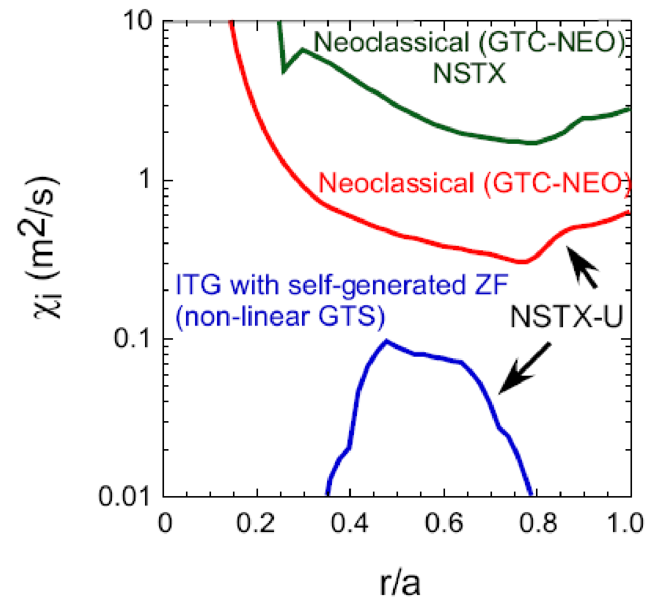
- NSTX is unique in its ability to address critical transport issues!
  - Strong rotational shear that can influence ion and electron transport
  - Anomalous electron transport can be isolated: ions often close to neoclassical
  - Large range of β_T spanning e-s to e-m turbulence regimes: assess impact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

  - ***Ultimately develop predictive understanding in order to project to future devices with confidence***
    - ***Results from a wide range of operating space (higher B_T, I_p, lower ν*) is critical to validating physics models***
  - ***Includes lower ν* ST and non-ST (e.g., ITER)***

Strong Coupling of Experiment to Theory Aids in Developing Predictive Understanding

- Experiment coupled to gyro-kinetic theory/simulation results
  - TRANSP: transport analysis
  - GTC-NEO, XGC0: non-local neoclassical
  - GS2, GYRO, GTS, GEM, GENE, XGC1: linear and non-linear gyrokinetic codes for turbulence-driven transport
  - Verification of non-linear ETG simulations underway (GENE, GYRO, GTS)
  - pTRANSP (+ TGLF): predictive simulations

Future



- ***NSTX operating regimes will yield results that will test and extend theory – higher confidence in predictions also at higher aspect ratio***
  - Validation of theory and models at all levels
  - Synthetic diagnostics in gyro-kinetic codes
  - Fluctuation spectra, mode structure
  - Transport fluxes, χ's, D's

Ultimate goal: Fundamental Understanding ⟷ Predictive Tool

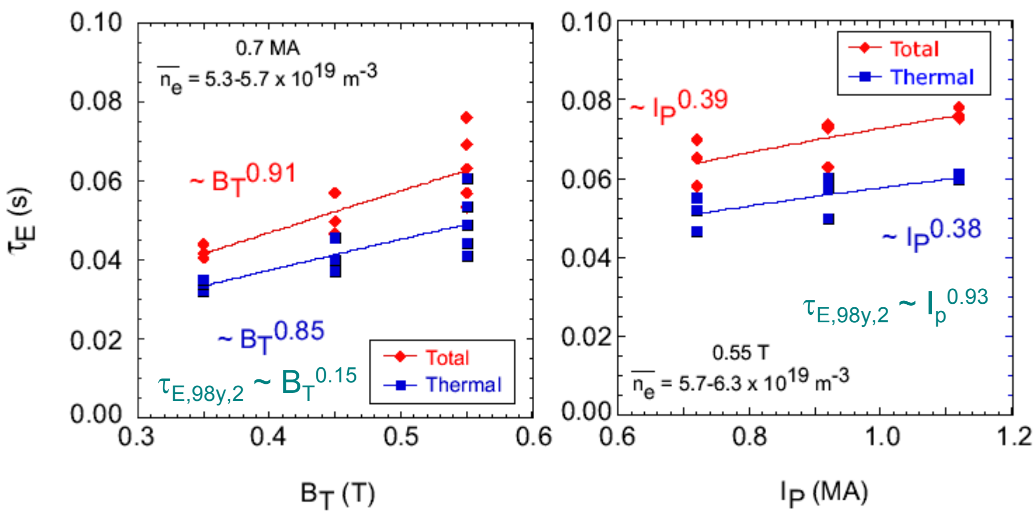
Outline

- Global studies
- Ion transport
- Electron transport
- Momentum transport
- Particle transport
- Summary

Results → Future directions → Upgrades

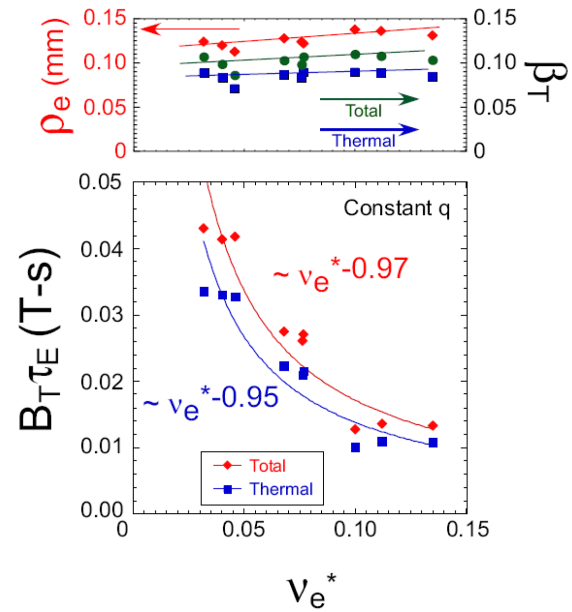
Global Studies Reveal Parametric Dependences That Differ From Those at Higher Aspect Ratio

Strong dependence of τ_E on B_T, weaker dependence on I_p

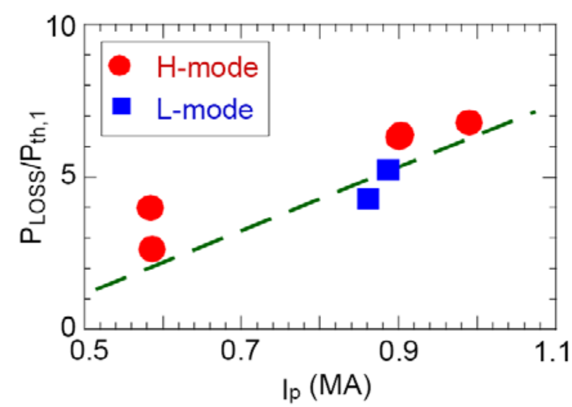


Recent MAST results have supported these conclusions

Strong dependence on ν^*

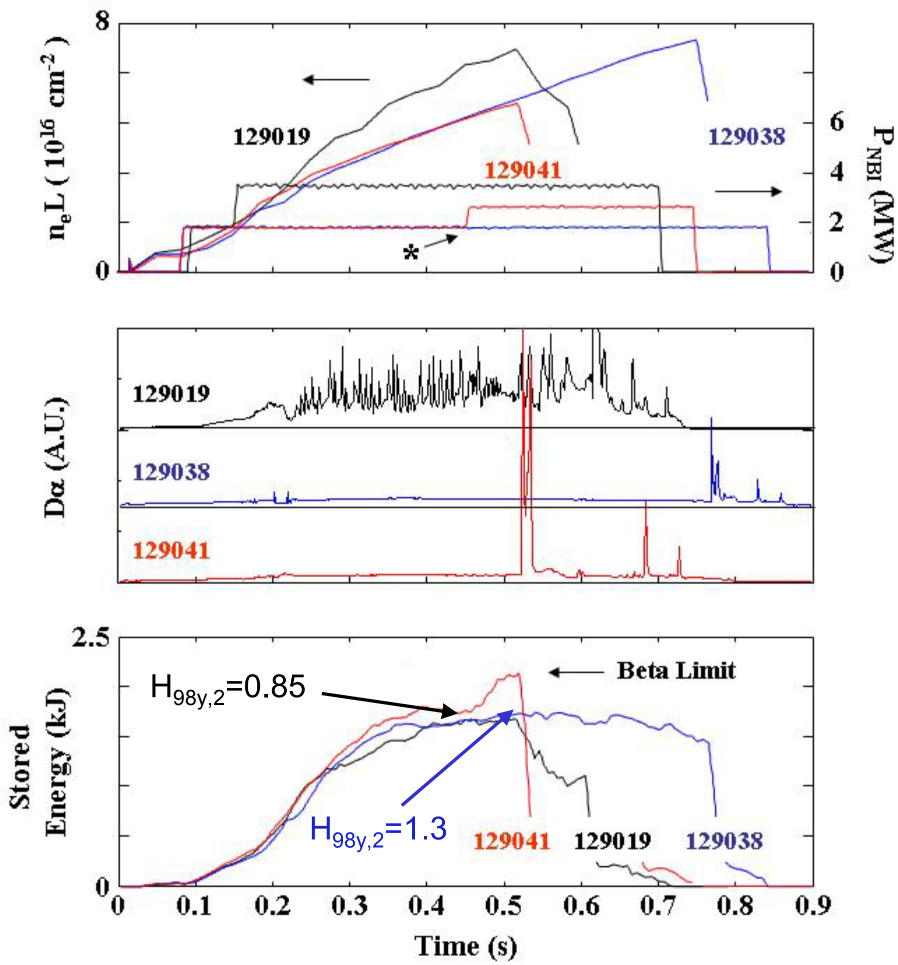


- Experiments have shown importance of edge stability in determining the parametric dependence of τ_E on β (ITPA)
- L-H threshold experiments have revealed an apparent I_p dependence



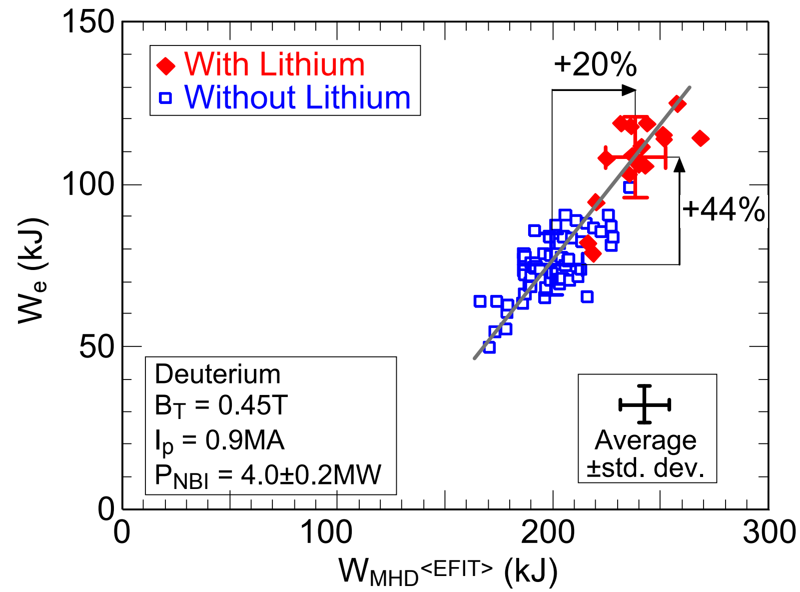
Upgraded center stack will give an additional factor of 2 range in B_T, I_p, factor of up to 10 reduction in ν^*

A Significant Improvement in Global Confinement Is Observed With Lithium Evaporation



- Suppression of ELMs
- Similar stored energy at lower power than for non-Lithium shots

- Increase in total stored energy mostly due to electrons



Developing an understanding of underlying physics (energy transport, edge stability, impurity evolution)

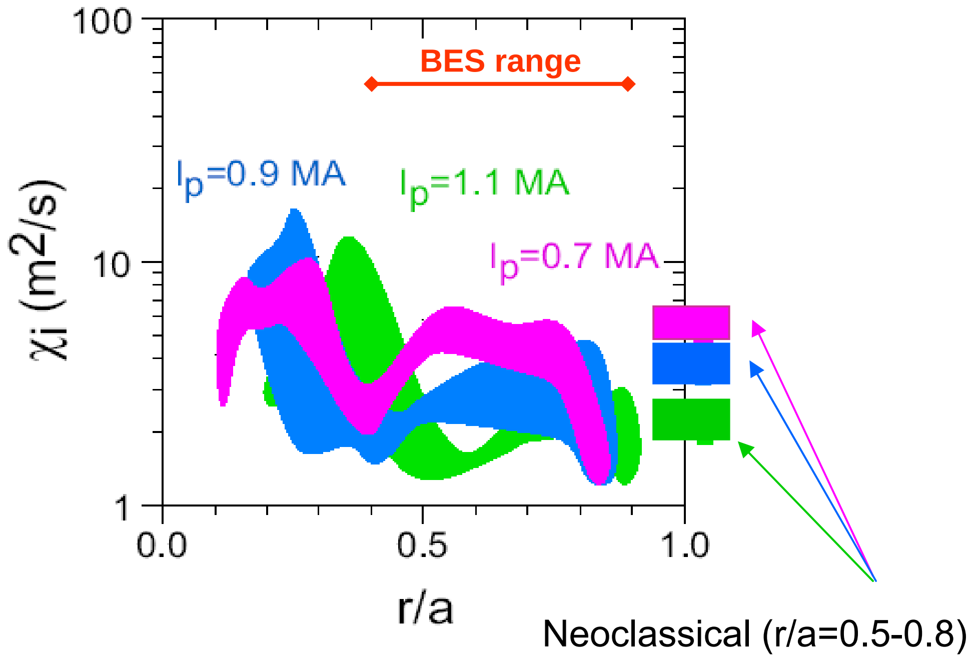
Global Studies Are Important for Being Able to Scale to Future Devices (ST and ITER)

Are differences in parametric scalings due to low R/a or operation in present B_T, I_p, ν^* range?

- **2009-2011**
  - Establish effect of lower collisionality (LLD) on global confinement
    - Key component of global **and** local studies
  - Dependence of τ_E on R/a for optimizing future ST designs
    - Within NSTX and through NSTX/DIII-D similarity experiment (TP-9)
  - Identify source of variation in β-degradation of confinement (CDB-2)
    - ELM suppression in lower κ, δ plasmas using Lithium conditioning
  - Characterize L-H threshold (I_p, B_T, species, shape)
    - Effect of rotation (n=3 braking, HHFW)
- **2012-2013:** *Center stack upgrade will yield factor of two increase in each of B_T, I_p, factor of 10 reduction in ν^**
  - Assess B_T, I_p and ν^* dependences in expanded operating space
  - Characterize L-H threshold (H-mode access, confinement quality)
  - Evaluate role of X-point in determining $P_{L\text{-}H}$
  - Verify scaling trends at high P_{heat} (≤ 12 MW) - incremental

Ion Transport Typically Found to be Near Neoclassical in H-mode Plasmas

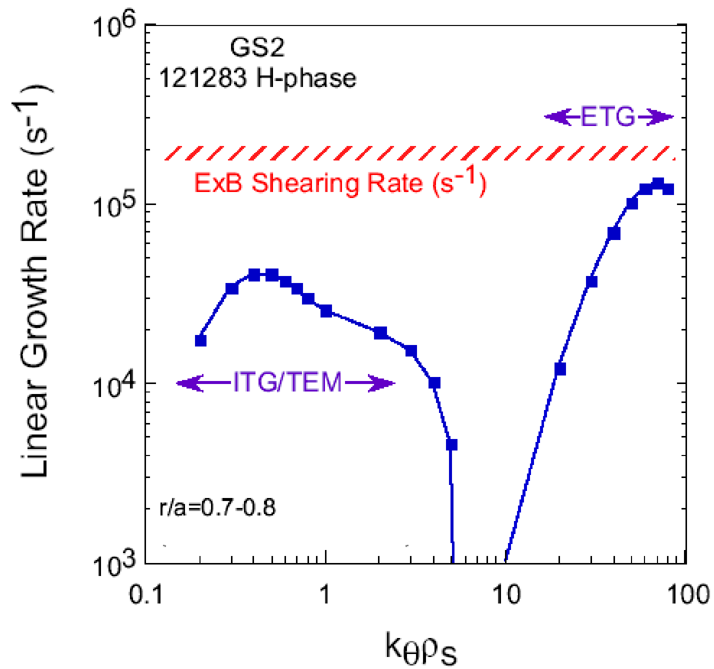
Controls τ_E scaling with I_p



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

Need BES to confirm conclusions

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 ($\gamma_{lin, ITB} > \gamma_{ExB}$)

Should Neoclassical Ion Transport Be Expected in Future STs?

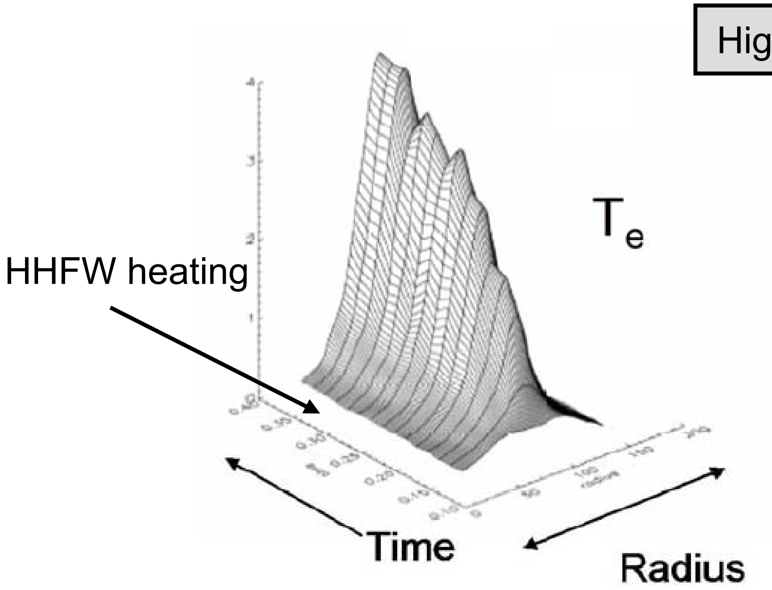
- **2009-2011**
  - Actively change ITG/TEM driving/damping terms (T_e/T_i, ExB shear, collisionality) using NBI, HHFW and magnetic braking
  - Relation of low-k turbulence (BES) measurements to transport
    - Preliminary validation of neoclassical and low-k turbulent transport theories
  - Ion internal transport barrier studies: relation to current profile, integer q, ExB shear
  - Validation of orbit shrinking/squeezing theory ($L_{Ti} \sim \rho_i$ near edge in some cases)

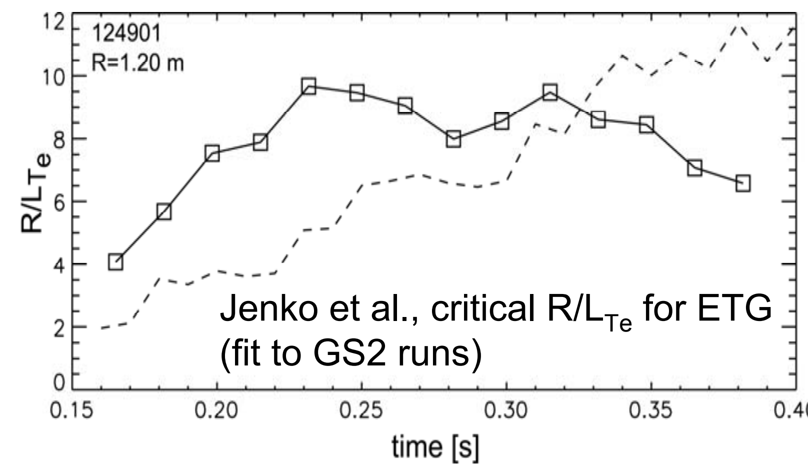
- **2012-2013**: $\chi_{i,neo}$ in NSTX-U estimated to be factor of 10 lower than in NSTX – ***with low $\chi_{i,neo}$, will turbulent transport be dominant?***
  - Assessment of ion transport and turbulence levels at high B_T, I_p, P_{heat}, lower ν^*, and for various input torques, q-profiles
  - Detailed 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)
    - *Assess applicability of neoclassical vs low-k turbulent transport*
  - Comparison to neoclassical theory with multi-ion species and full Larmor radius effects

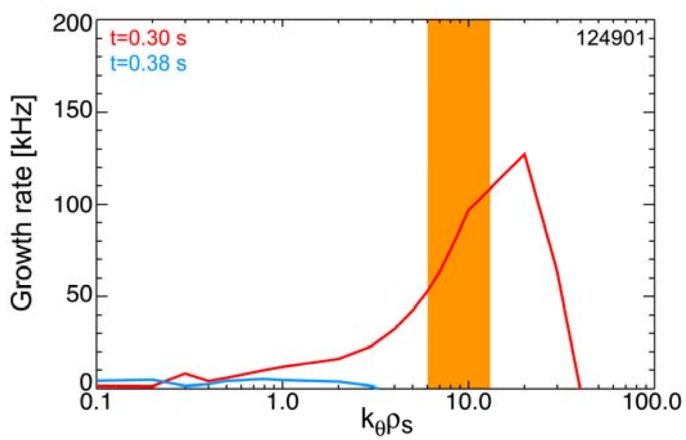
Develop a predictive understanding of the transition between neoclassical and turbulent ion transport

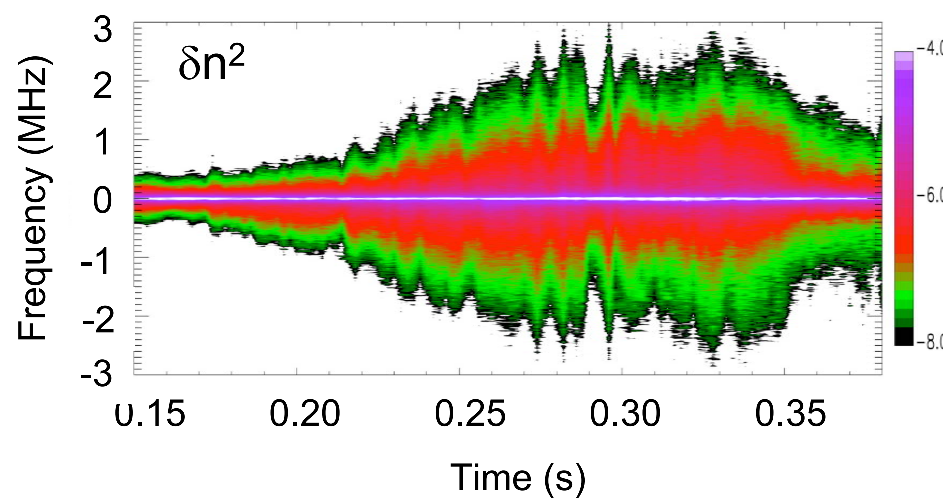
NSTX Has Unique Plasma Conditions to Study Electron Turbulence and Critical Gradient Physics

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



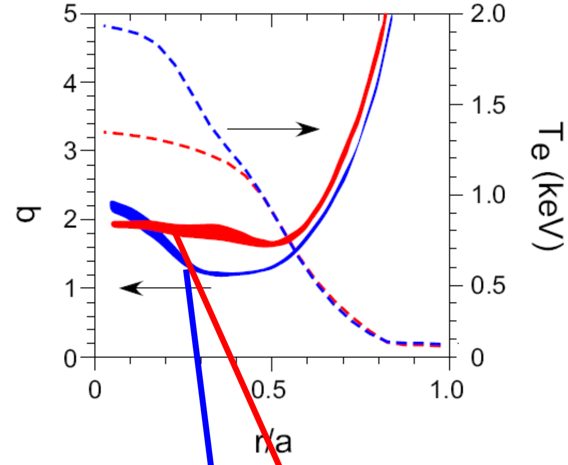


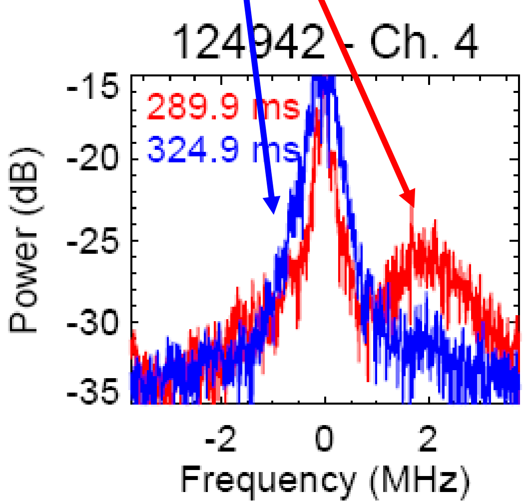




Electron Transport Correlates with High-k Turbulence (ETG-range) in Many Plasma Regimes

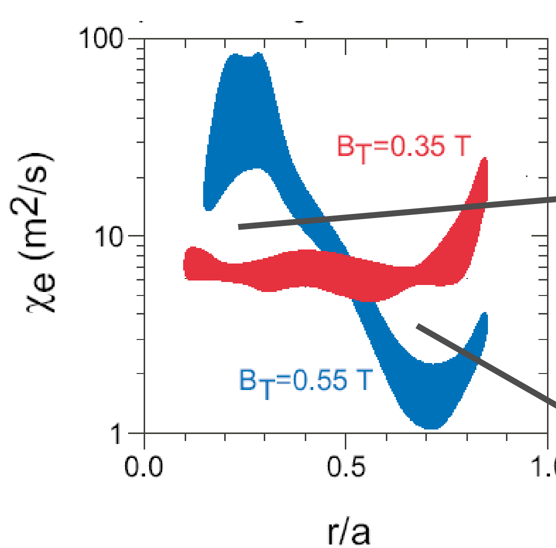
Reduction in electron transport with reversed magnetic shear (i.e., χ_e drops as T_e peaks)

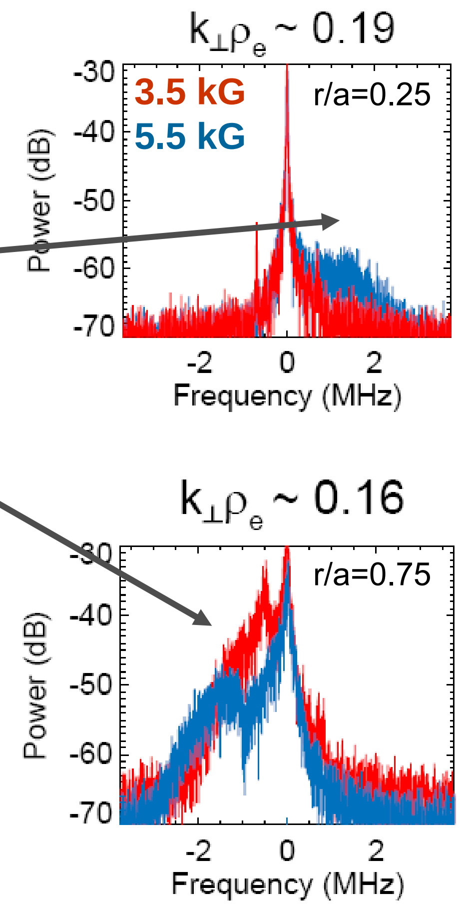




Electron transport anomalous: controls B_T scaling

Consistent with variation of high-k fluctuations

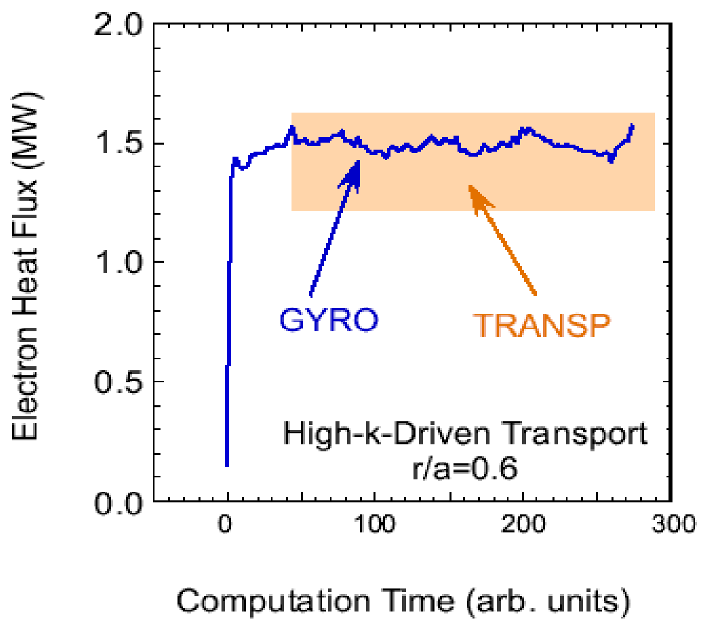




Fluctuations in ETG k-range increase with decreased shear reversal ($k_\theta\rho_e$=0.23)

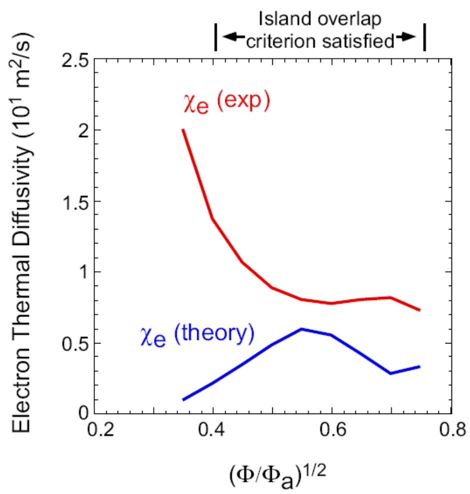
Electron Transport May be Controlled by Multiple Mechanisms (Including E-M)

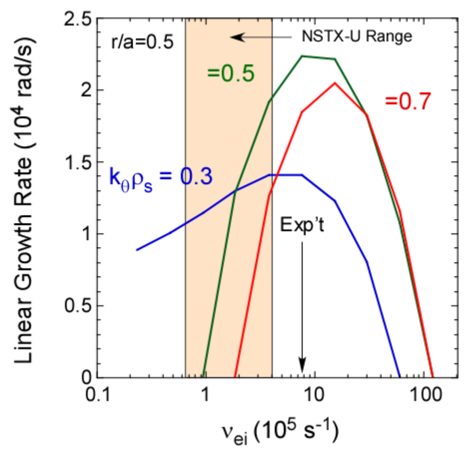
Heat flux due to high-k electron modes (ETG) consistent with levels inferred from TRANSP in H-modes for r/a>0.5



Low-k microtearing important in low shear/"Hybrid" discharges

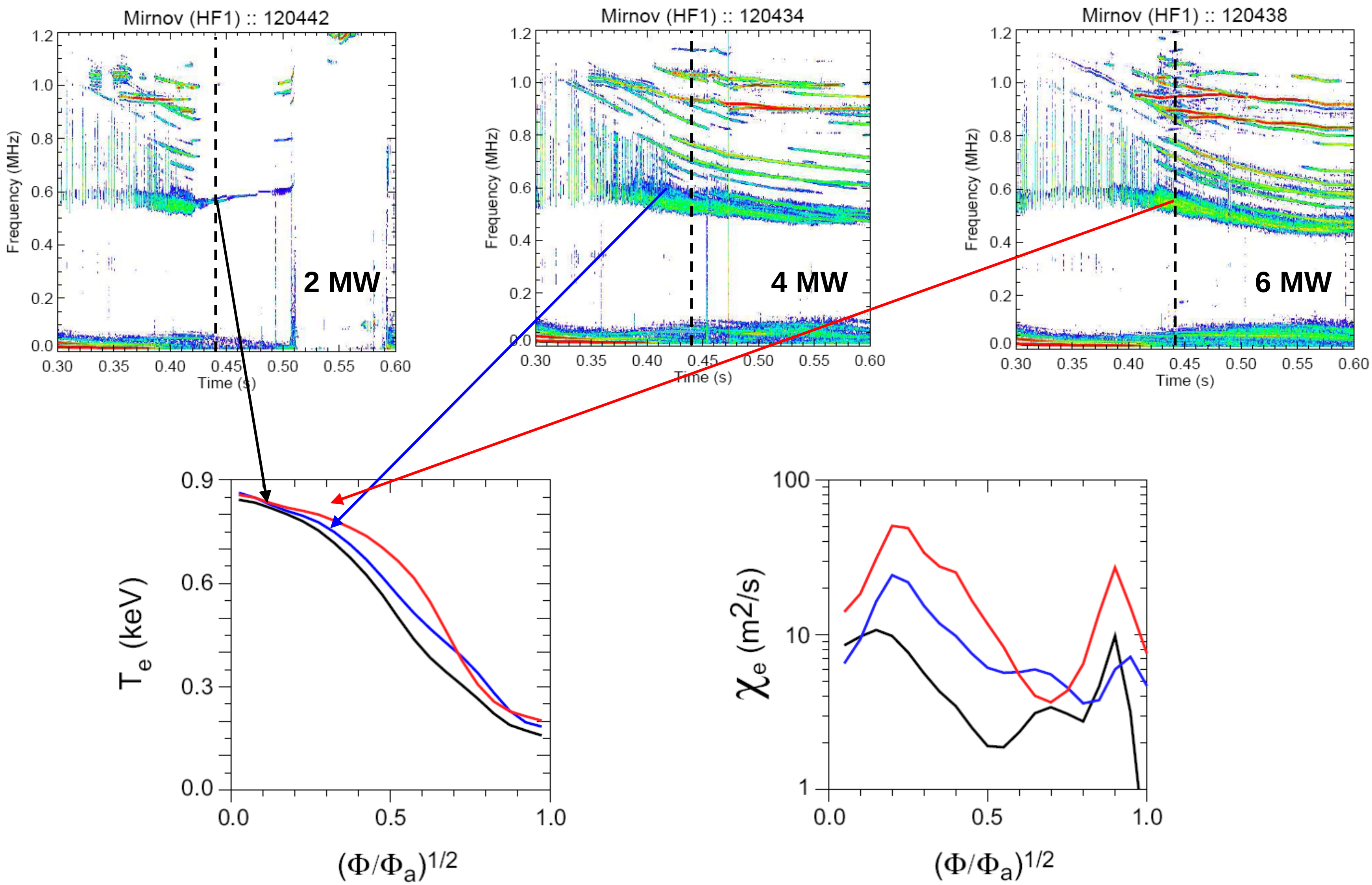
Driven by ∇T, damped by strongly reversed magnetic shear





Collisionality predicted to be low enough in NSTX-U for suppression of microtearing

Recent Observations Indicate High-Frequency Core E-M Fluctuations May Also Cause Electron Transport



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

- **2009-2011**
  - 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
    - Effect of ExB suppression on high-k modes
    - Turbulence spreading
  - Perturbative electron transport using ELMs and impurity 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 2009 (sensitivity to a few Gauss is necessary)
    - Change driving/damping terms: β, ν^*, ∇T, q', ExB shear
  - 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
  - Validate physics models using gyrokinetic calculations
    - Coupled to GTS-SciDAC project

NSTX Upgrades in 2012-2013 Enable Key Physics Tests

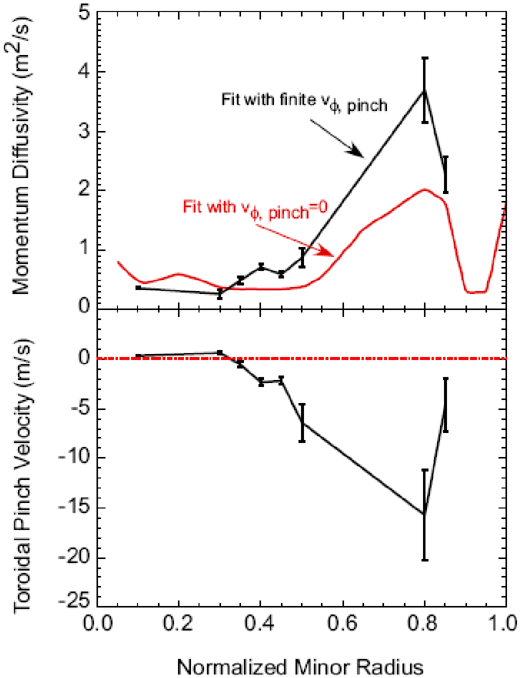
- Can make tests of TEM/ETG modes by eliminating:
  - Microtearing by operating at higher B_T, I_p, lower ν^*
  - GAE modes by reduced fast ion drive (operation at higher B_T)

- **2012 – 2013**
  - New center stack provides higher B_T, I_p, lower ν^*
  - Microtearing mode investigations with internal δB, full low-k for mode structure in NBI and non-NBI plasmas
  - EBW for local modification of electron transport and turbulence
    - Assess turbulence spreading with full low and high-k fluctuation measurements
  - Modulated EBW to probe local critical gradient physics (incremental)
  - Verify transport trends at high P_{heat}, varying input torque with 2^{nd} NBI (incremental)

Would look forward to an NSTX/C-Mod/DIII-D collaboration on high-k turbulence and its relation to electron transport

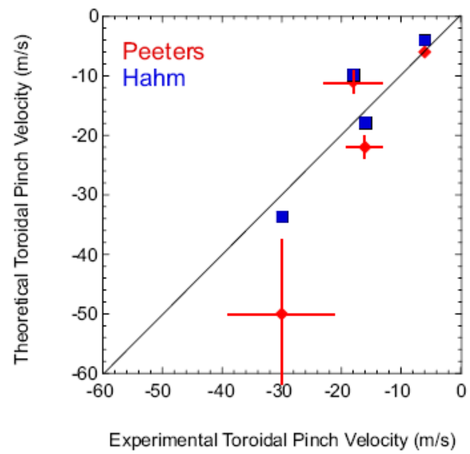
What is the Source of Momentum Transport, and How Does it Couple to Energy Transport?

- In NSTX, $\chi_\phi^{ss} > \chi_i, >> \chi_e$ (TP-6.3)
- Perturbative momentum transport studies using magnetic braking indicate significant inward pinch



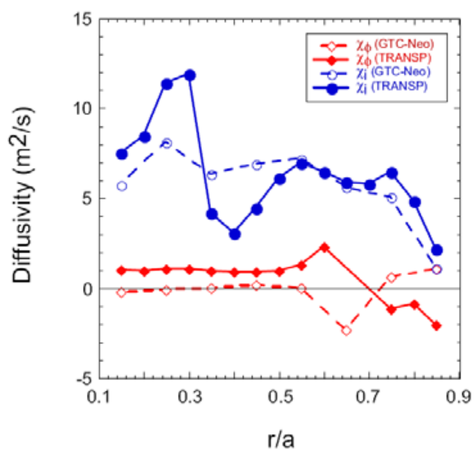
- Theory gives v_{pinch}/χ_ϕ based on low-k turbulence

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



Will Rotation/Rotation Shear be High Enough in Future Devices to Suppress Turbulence?

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

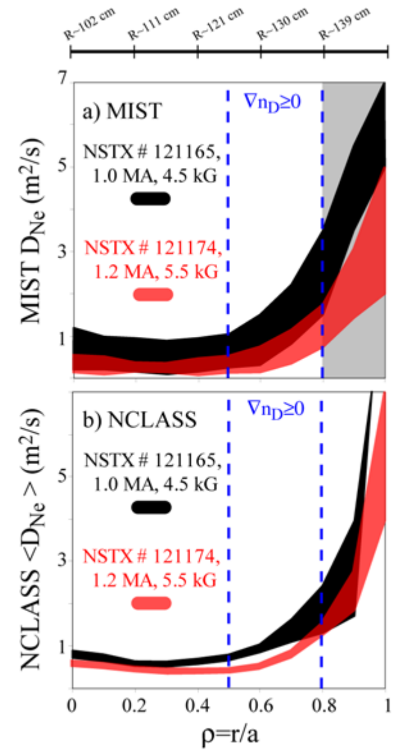
TP-6.3

- **2009 – 2011**
  - Test neoclassical theory using v_θ measurements
  - Effect of rotation on plasma confinement (continuation of FY08 Joule milestone work)
    - Relation of Γ_ϕ to $\Gamma_{i,e}$
  - Determine v_{pinch}, χ_ϕ with varying input torque
    - Tests of inward pinch, NTV theories
  - Comparisons with low-k turbulence measurements

- **2012-2013:** Does relation between χ_i/χ_ϕ, χ_e/χ_ϕ change at higher B_T, I_p, lower ν^*?
  - Study momentum confinement in expanded operating space
    - $\chi_{i,neo}$ (NSTX-U) ~ 0.1 $\chi_{i,neo}$ (NSTX)
  - Zonal flows/GAMs and relation to other microinstabilities
  - Further v_{pinch}, χ_ϕ assessment with off-midplane control coils, 2nd NBI (incremental)

Low Recycling Edge Could Have Significant Impact in Future Devices

- **2009 - 2011**
  - 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 n, recycling due to Lithium on ne(r), particle transport



- **2012 – 2013**
  - Study core particle transport at lower ν^*
  - D & particle transport in outer region: requires extended modeling for determining S(r)
  - Helium transport studies using He puffing or He discharges
  - Determine role of low-k turbulence in controlling particle transport
  - Perturbative particle transport studies with 2nd NBI (incremental)

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

2009-2011
2012-2013
Incremental

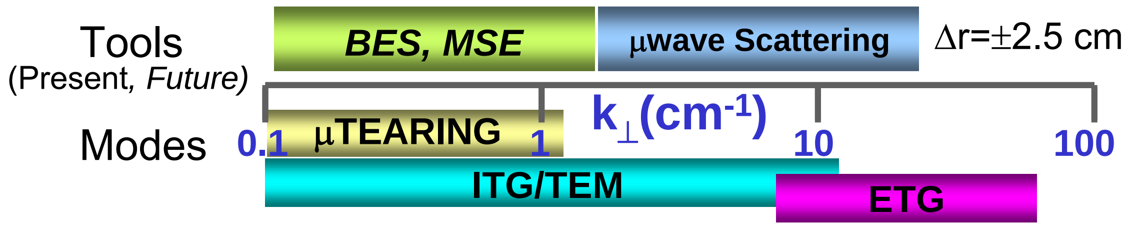
Facility

- Higher B_T, I_p: New center stack
- Higher power/Current profile control: 2nd Neutral Beam, EBW

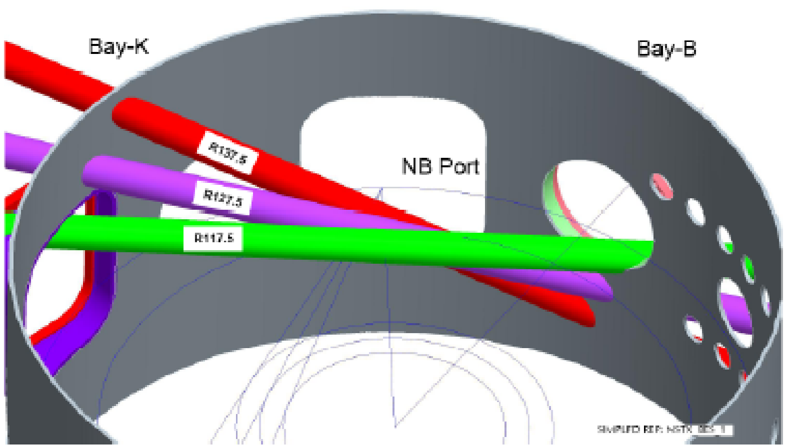
Diagnostics

- Collisionality 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)
- Profiles: MSE-LIF, X-point reciprocating probe, MPTS upgrade
- Magnetic braking to change ExB shear: Internal non-axisymmetric control coils

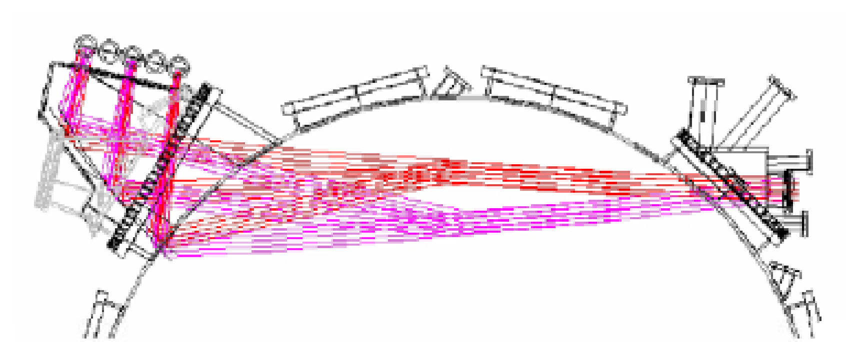
Full Complement of Turbulence Measurements Will Cover a Wide k-Range



BES - planned sightline views (r/a=0.4 to 0.9)



μwave Scattering (3 MHz) – scannable from r/a~0.25 to 0.9



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

The NSTX Five year Program Will Provide Physics Basis for Higher-Confidence Performance Predications for Future Devices (ST and non-ST)

- The NSTX program will address the most critical physics issues for future devices
  - 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
  - Particle transport studies
- The Five Year Program will benefit from facility and diagnostic upgrades, additional operation and more mature physics analysis
  - BES implemented by 2009-2010, high-k_θ implemented by 2010
  - High B_T, I_p, lower ν^* capability in 2012
  - Off-midplane control coils, 2nd NBI, EBW (incremental)
- Further theory/modeling development, including gyrokinetic codes with implementation of synthetic diagnostics, neoclassical theory with multi-species and full Larmor radius effects, predictive transport codes (pTRANSP) and models (e.g., TGLF)

Significant progress towards comprehensive predictive capability

Transport and Turbulence Plans 2009-2013