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Research Plan for Transport and Turbulence Physics in NSTX

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and the NSTX Research Team

NSTX PAC-25

LSB B318

February 18 - 20, 2009

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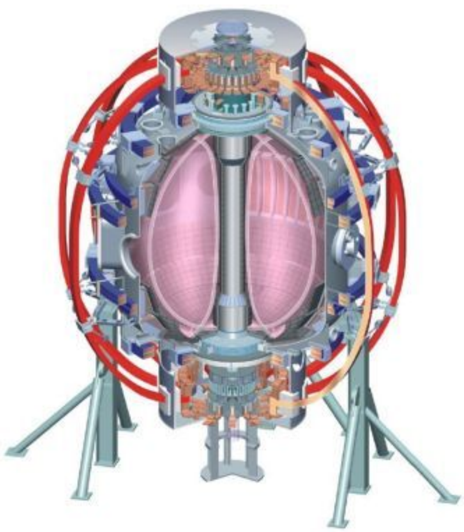

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NSTX Will Address T&T Issues Critical for Predicting Performance in Future Devices

- 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 collisionality 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}

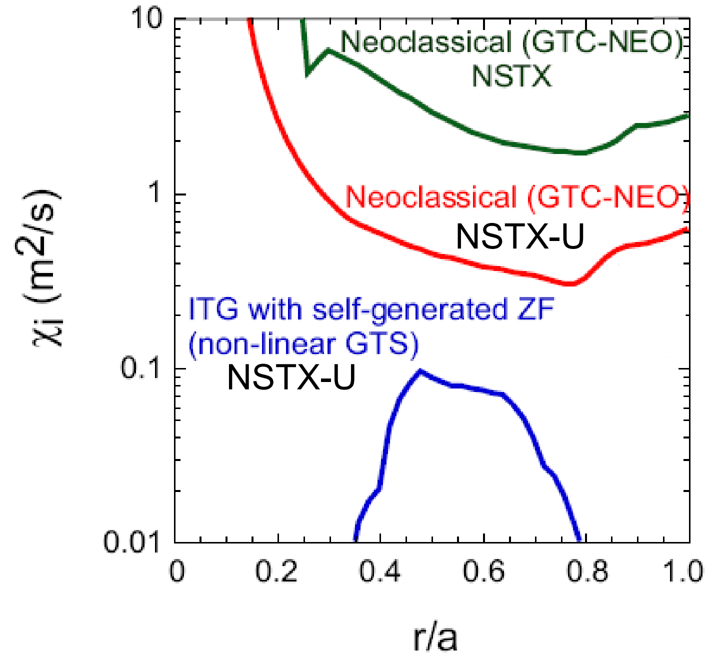
- NSTX is unique in its ability to address critical transport issues!
  - Strong rotational shear that can influence ion and electron transport
  - Anomalous electron transport can be isolated: ions often close to neoclassical
  - Large range of β_T spanning e-s to e-m turbulence regimes: assess impact 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,, P_{NBI}, 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) Validation has begun (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

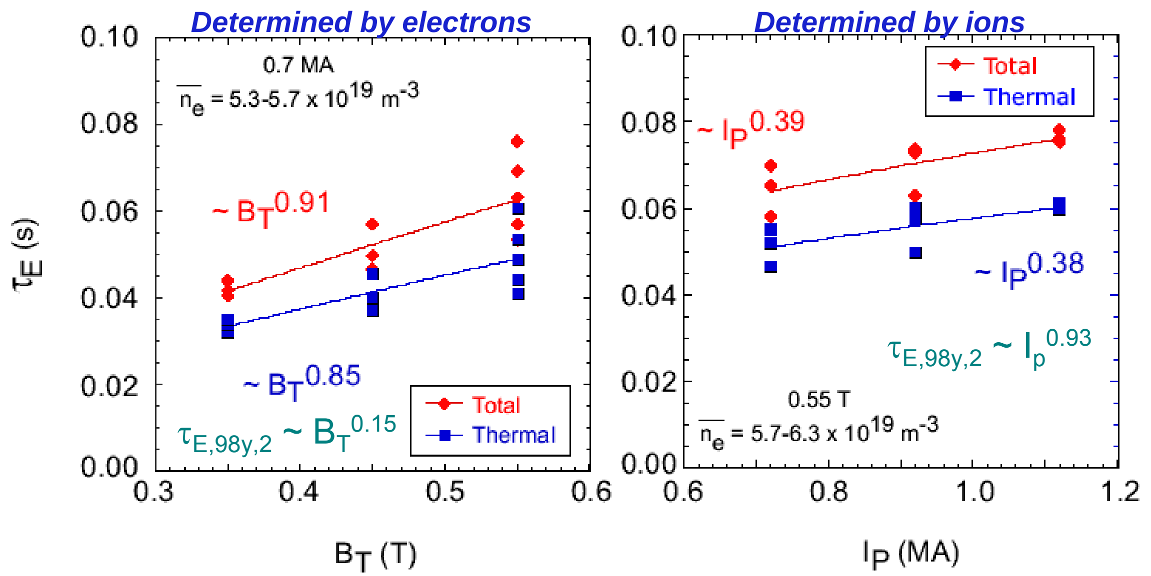
Ultimate goal: Fundamental Understanding ⟷ Predictive Tool

NSTX Will Prioritize Transport Studies to Best Utilize Diagnostic and Facility Upgrade Capabilities

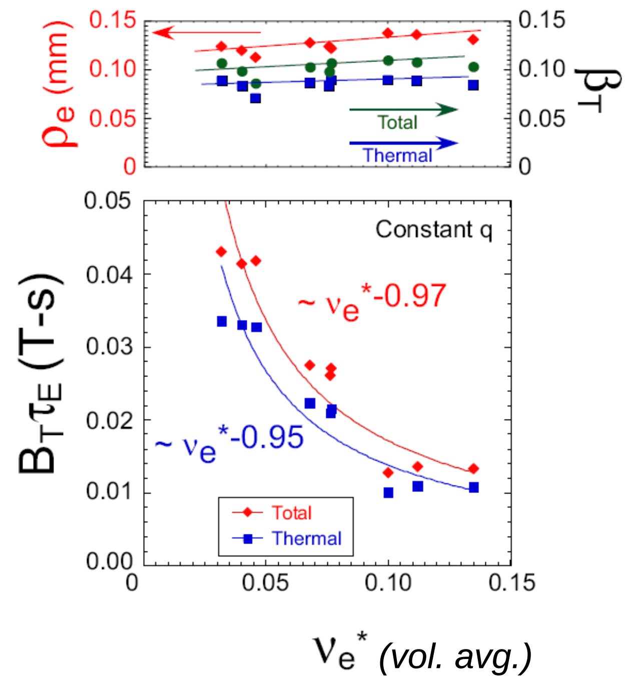
- Global studies (confinement, L-H: FY09-10)
- Electron transport (HHFW: FY09, MSE-LIF: FY11)
- Ion transport (BES: FY10-11)
- Momentum transport (BES: FY10-11)
- Particle transport (edge MPTS: incr.)

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

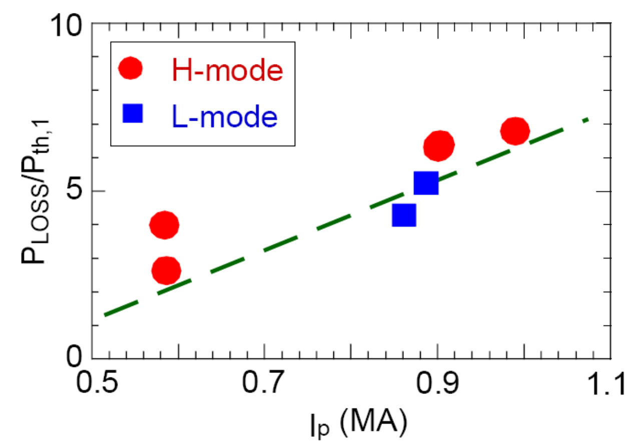
Strong dependence of τ_E on B_T, weaker dependence on I_p



Strong dependence on ν^*



- Experiments have shown importance of edge stability in determining the parametric dependence of τ_E on β (ITPA) (not shown)
- Strong dependence on collisionality motivates CS, NBI, upgrades
- L-H threshold experiments have revealed an apparent I_p dependence



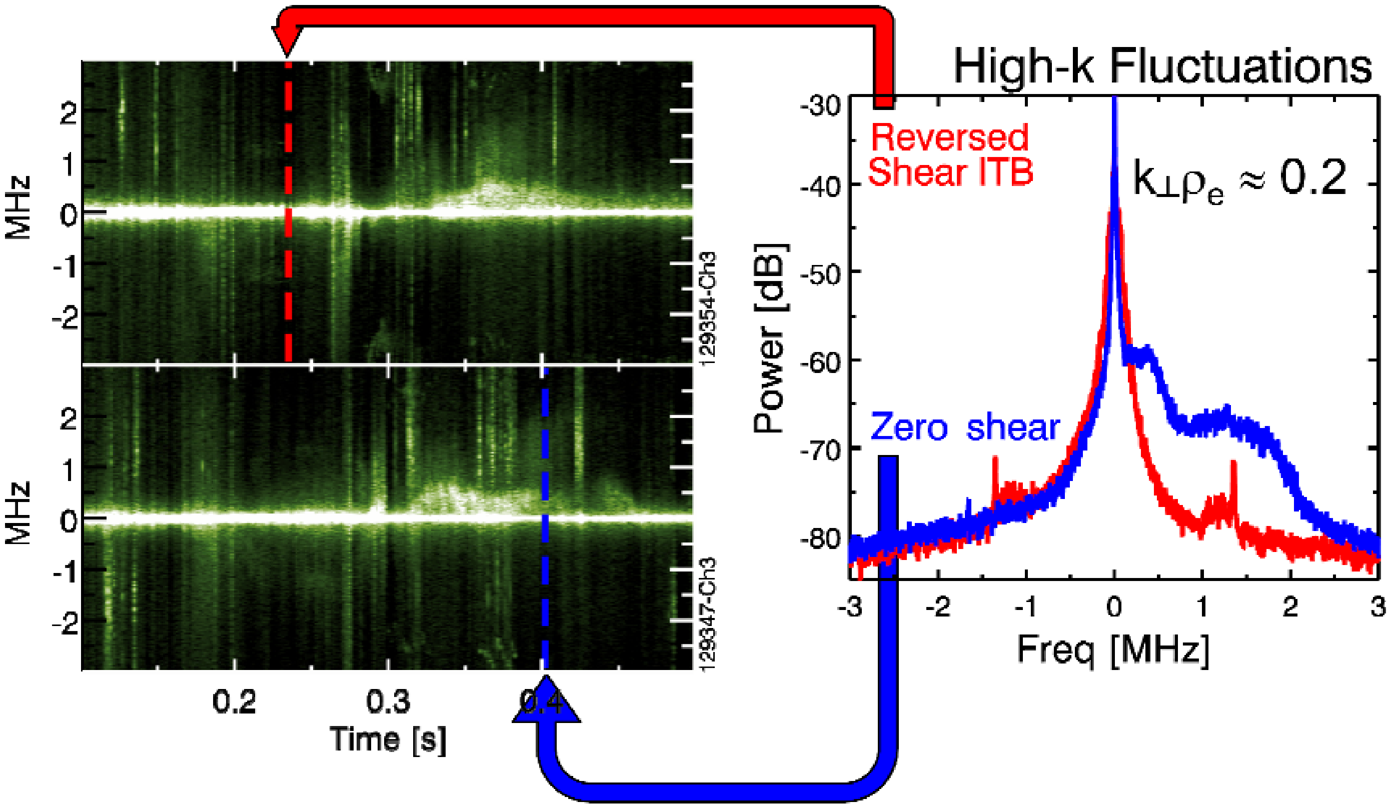
Global Studies Are Important for Being Able to Scale to Future Devices (ST and ITER)

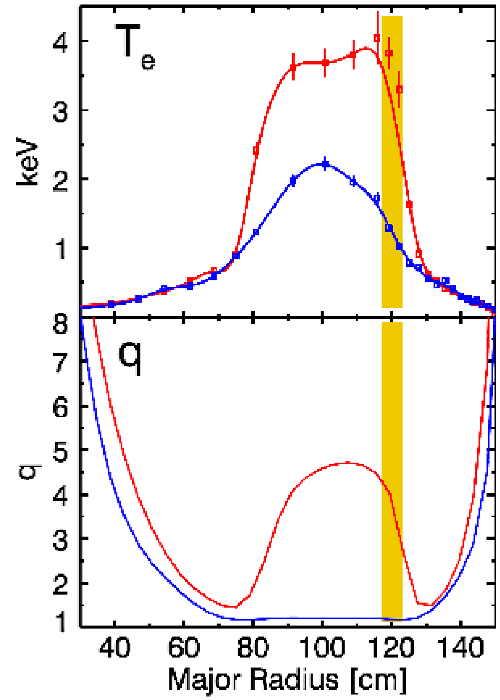
Are differences in parametric scalings due to low R/a or operation in present β (B_T, I_p) ν^* range?

- **2009-2011**
  - Identify source of variation in β-degradation of confinement (FY09, TC-1)
    - ELM suppression in lower κ, δ plasmas using Lithium conditioning
  - Characterize L-H threshold (I_p, B_T, species, shape, X-point) (FY09, TC-4)
    - Effect of rotation (n=3 braking, HHFW)
  - Establish effect of lower collisionality on confinement (LLD, HHFW) (FY10)
    - Key component of global **and** local studies
  - Dependence of τ_E on R/a for optimizing future ST designs (FY10, TC-12)
    - Within NSTX and through NSTX/DIII-D similarity experiment

- *Center stack upgrade will yield factor of two increase in each of B_T, I_p, up to factor of 10 (typ. ~4-5) reduction in ν^**
  - Assess B_T, I_p and ν^* dependences in expanded operating space
  - Characterize L-H threshold (H-mode access, confinement quality)
  - Verify scaling trends at high P_{heat} (≤ 12 MW)

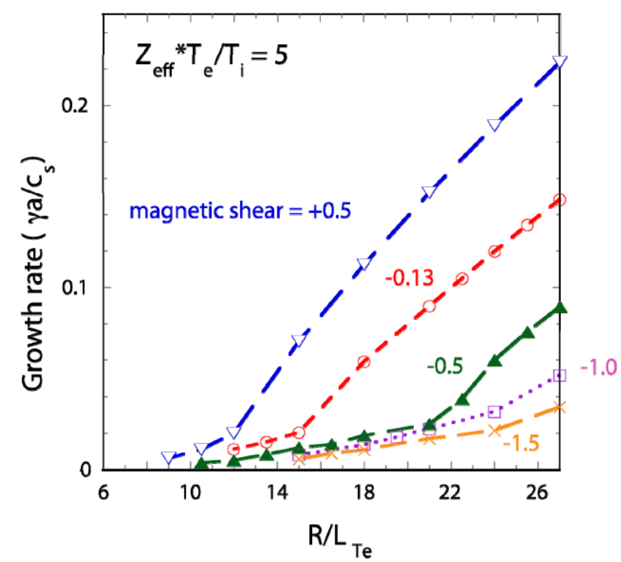
Reversed Magnetic Shear Predicted and Shown to Suppress High-k Fluctuations at Low ExB Shear





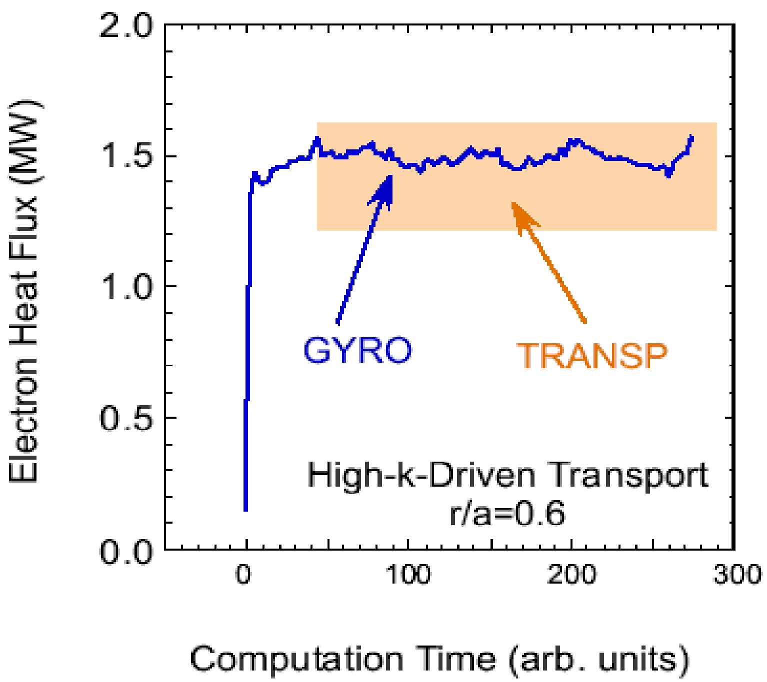
ExB shearing rate low from cold ions, slow toroidal rotation (RF heated L-mode plasmas)

GYRO simulations confirm low growth rates at strongly reversed magnetic shear



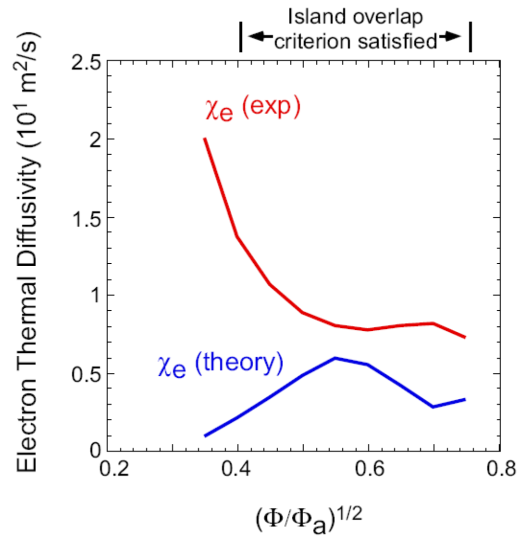
Electron Transport May be Controlled by Multiple Mechanisms (Including E-M)

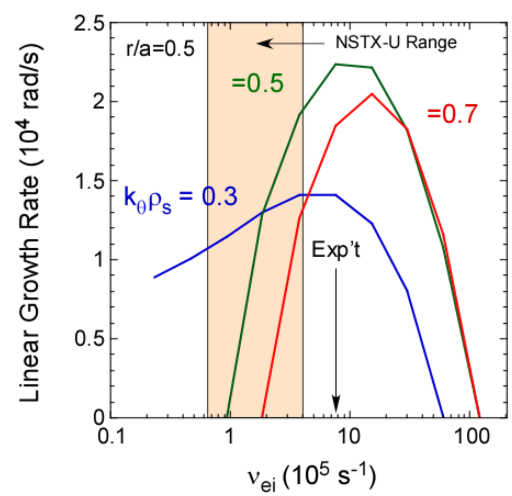
Heat flux due to high-k electron modes (ETG) consistent with levels inferred from TRANSP in H-modes for r/a>0.5



Low-k microtearing important at mid-radius in NSTX H-modes

Driven by ∇T, damped by strongly reversed magnetic shear

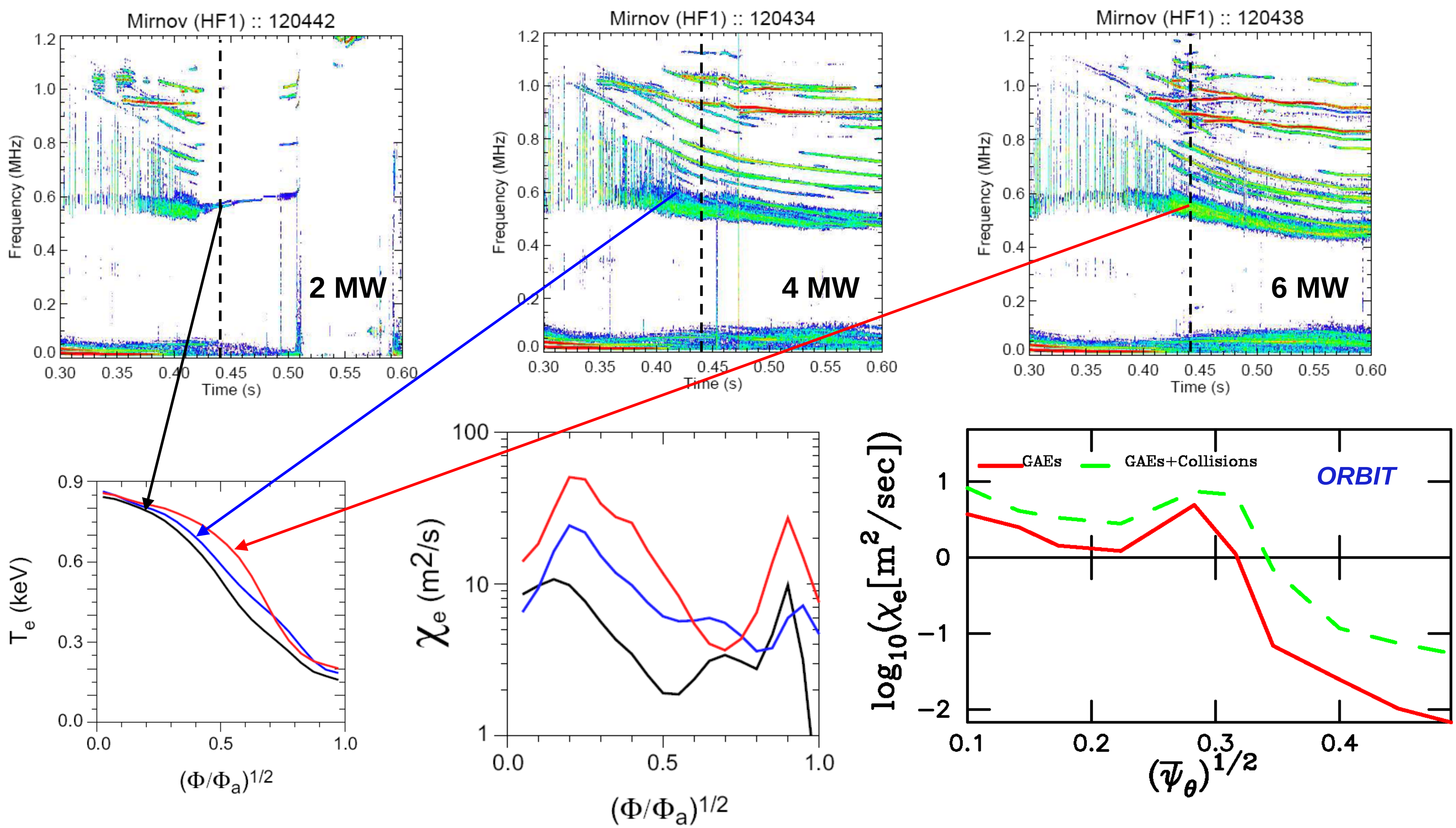




Strong confinement dependence on collisionality may indicate importance of microtearing

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



- ORBIT: χ_e ~$10 m^2/sec$ → $\delta Br/B$ ~10^{-2}, consistent with $\delta n_e/n$ ~4×10^{-4} measurements (high-k)

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

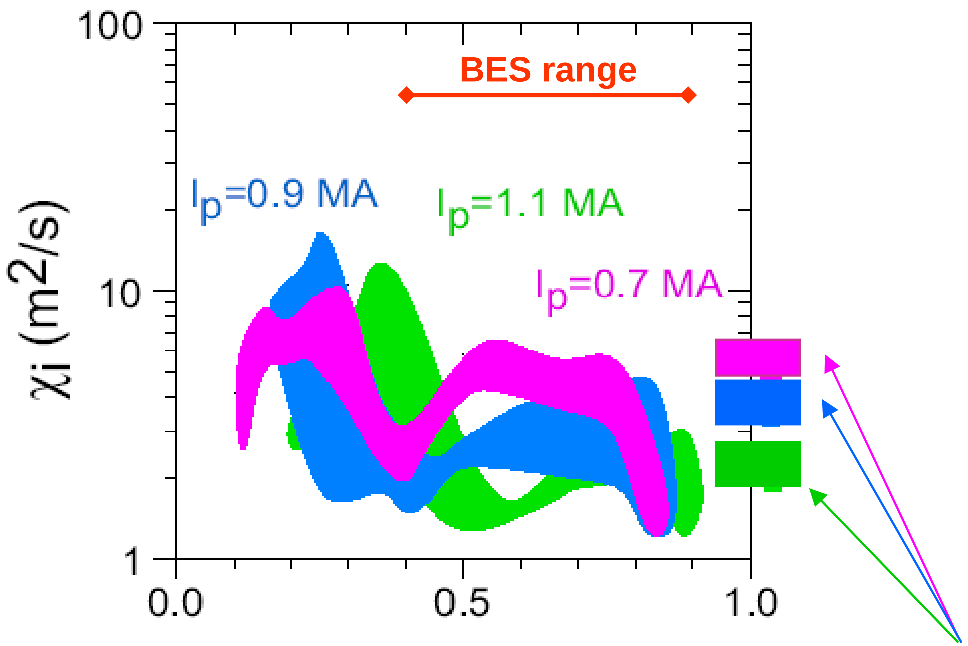
- **2009-2011**
  - Microtearing mode studies (SXR PHA, internal δB?, FY09-10)
  - Investigate *AE effects on electron transport (BES, FY09-11)
  - Investigate TEM/ETG using present high-k_r system (FY09-10)
  - Role of reversed magnetic shear, low order rational q for eITB formation (MSE-LIF, FY11)
  - Perturbative electron transport using ELMs and impurity pellets
  - Validate physics models using gyrokinetic calculations
    - Coupled to GPS-SciDAC project, synthetic diagnostics

PAC23-4

- CS/NBI upgrades important for electron transport studies
  - Reduce microtearing drive by operating at higher B_T, I_p → lower ν^*
  - Modify GAE modes by reduced fast ion drive (higher B_T)
  - HHFW in H-modes provide additional e^- heating source (EBW incr.)

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

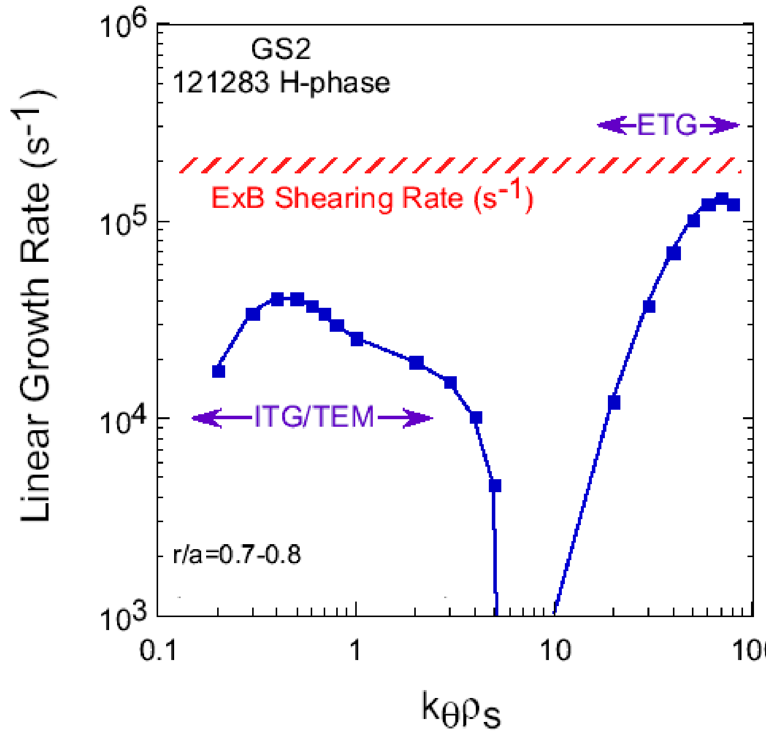
Controls τ_E scaling with I_p



Neoclassical (r/a=0.5-0.8)

Linear GS2 calculations indicate possible suppression of low-k turbulence by ExB shear during H-phase

- Supported by non-linear GTS results



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

Need BES to confirm conclusions

- compare active change of ITG drive/suppression with low-k measurements

χ_i routinely anomalous in high density L-modes ($\gamma_{lin,\ ITG} > \gamma_{ExB}$)

PAC23-4

Should Neoclassical Ion Transport Be Expected in Future STs?

- **2009-2011**
  - Ion internal transport barrier studies: relation to current profile, integer q, ExB shear (FY09)
  - Actively change ITG/TEM driving/damping terms (T_e/T_i, ExB shear, collisionality) using NBI, HHFW and magnetic braking (FY10-11)
  - Relation of low-k turbulence (BES) measurements to transport (FY10-11)
    - Preliminary validation of neoclassical and low-k turbulent transport theories
  - Validation of orbit shrinking/squeezing theory ($L_{Ti} \sim \rho_i$ near edge in some cases) (FY11)

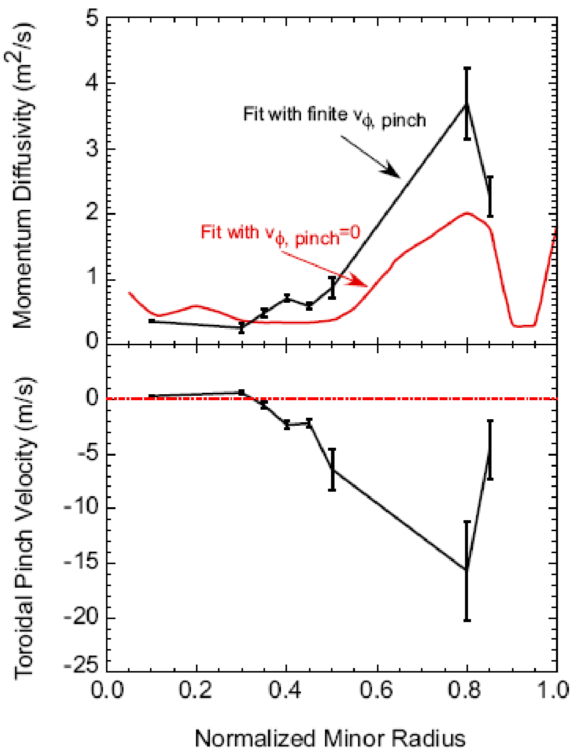
- **CS/NBI Upgrades**: $\chi_{i,neo}$ in NSTX-U estimated to be up to ~x10 lower than in NSTX – ***with low $\chi_{i,neo}$, will turbulent transport be dominant?***
  - Assessment of ion transport and turbulence levels at high B_T, I_p, P_{heat}, lower ν^*, and for various input torques, q-profiles
  - Detailed comparison of inferred χ_i and measured low-k fluctuation spectra to gyro-kinetic predictions:
  - 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

PAC23-4

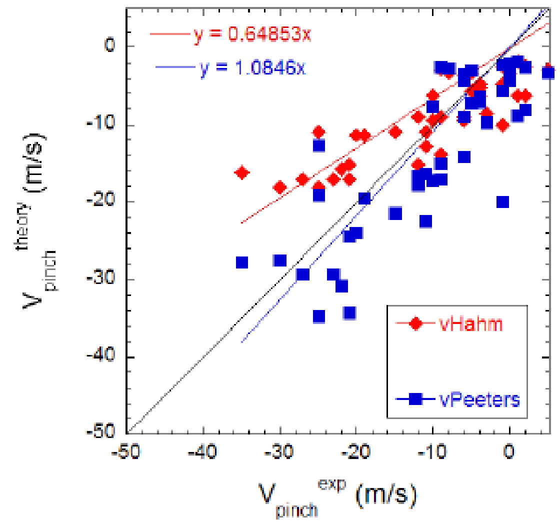
Momentum Transport may be the Best Probe of Low-k Turbulence

- In NSTX, $\chi_\phi^{ss} < \chi_i, << \chi_e$ (TC-15)
- Perturbative momentum transport studies using magnetic braking indicate significant inward pinch



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

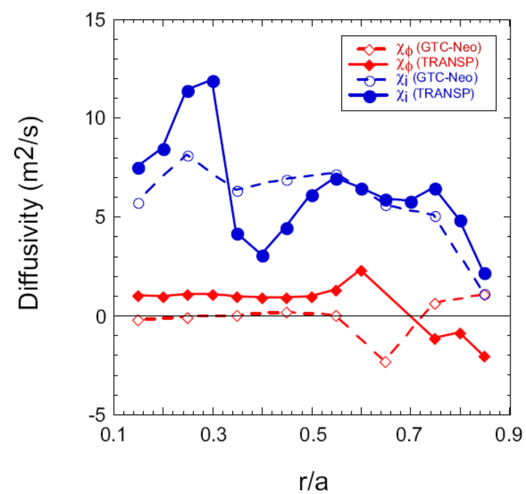
Good agreement with expt



PAC23-5

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

Residual low-k fluctuations predicted to drive anomalous momentum transport – validate with n.l. gyro. codes (FY11)



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

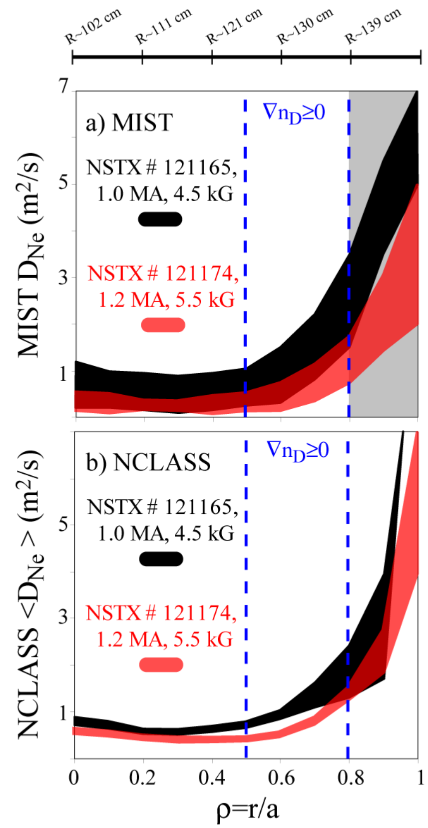
TC-15

- **2009 – 2011**
  - Test neoclassical theory using v_θ measurements (joint NSTX/DIII-D, FY09)
  - Effect of rotation on plasma confinement (energy, particle) (FY09) (continuation of FY08 Joule milestone work) ***PAC23-5***
    - Relation of Γ_ϕ to $\Gamma_{i,e}$
  - Determine v_{pinch}, χ_ϕ with varying input torque (FY10)
    - Tests of inward pinch, NTV theories
  - Zonal flows/GAMs and relation to other microinstabilities (BES, FY10)
  - Comparisons with low-k turbulence measurements (BES, FY10-11)

- **CS/NBI Upgrades:** 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)
  - Further v_{pinch}, χ_ϕ assessment with off-midplane control coils, 2nd NBI

Low Recycling Edge Could Have Significant Impact in Future Devices

- **2009 - 2011**
  - Investigate RMP modification of particle transport (FY09, PAC23-5)
  - Effect of low n, recycling due to Lithium on $n_e(r)$, particle transport (LLD, FY10)
  - Determine role of low-k turbulence in controlling particle transport (BES, FY10-11)
  - Impurity, He transport using gas puffing, TESPEL?
    - Isotopic dependence important for Li transport
  - D & particle transport in outer region: extended modeling for determining S(r), edge diag., imp. transp. codes



- **CS/NBI Upgrades**
  - Study core particle transport at lower ν^*
  - Perturbative particle transport studies with 2nd NBI

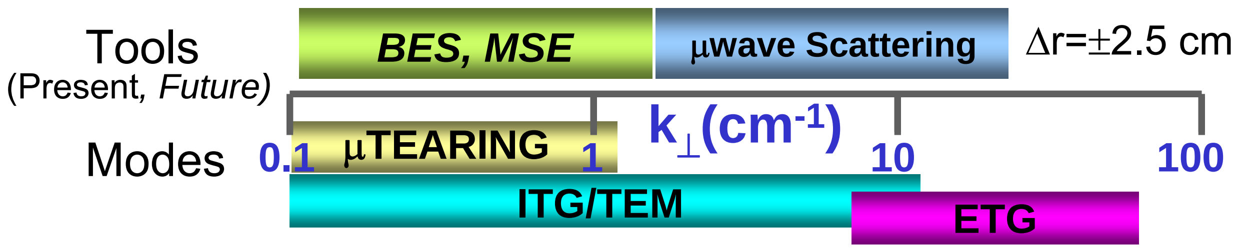
The NSTX Program Will Provide Physics Basis for Higher-Confidence Performance Predications for Future Devices (ST and non-ST)

- Address critical physics issues for future devices
  - Global studies of confinement and L-H threshold power (LLD, HHFW)
  - Relation of ion and electron transport to turbulence (BES, HHFW)
  - Momentum transport as a probe of low-k turbulence (BES, MSE-LIF)
  - Particle transport studies (LLD)
- Upgrades will advance progress in understanding T&T
  - LLD, BES implemented by 2010, MSE-LIF implemented by 2011
  - High B_T, I_p, P_{NBI}, lower ν^* capabilities expand operating range
  - Longer term: Off-midplane control coils, EBW (both 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

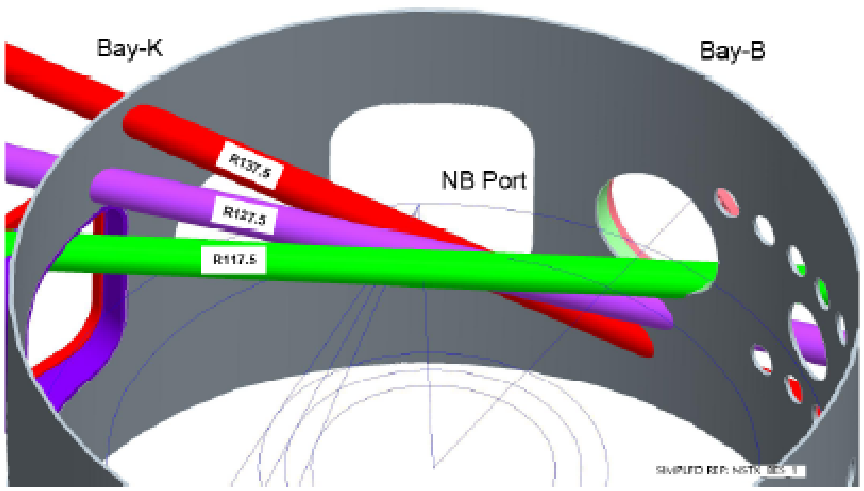
Backup Slides

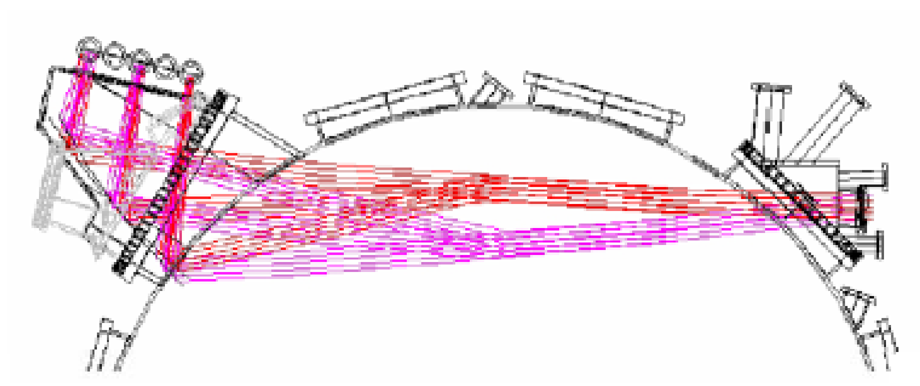
Full Complement of Turbulence Measurements Will Cover a Wide k-Range



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+)