NSTX-U

NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

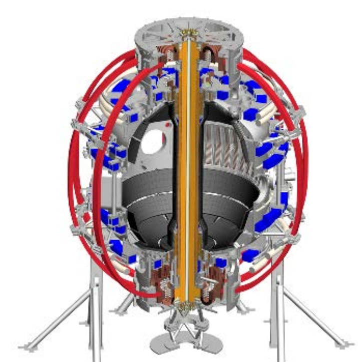
Validating gyrokinetic predictions using NSTX and NSTX-U plasmas

Walter Guttenfelder[1], S.M. Kaye[1], D.M. Kriete[2], Y. Ren[1], R.E. Bell[1], A. Diallo[1], B.P. LeBlanc[1], G.R. McKee[2], M. Podesta[1], S.A. Sabbagh[3], D. Smith[2]

[1]PPPL, [2]UW-Madison, [3]Columbia University

1st Asia-Pacific Conference on Plasma Physics
Chengdu, China
September 18-23, 2017

PPPL



<u>Overview:</u> Understanding confinement scaling at higher field, lower collisionality critical for future spherical tokamaks (ST)

- Numerous *theoretical* transport mechanisms to consider at low aspect ratio $\rightarrow$ requires dedicated effort to validate gyrokinetic simulations

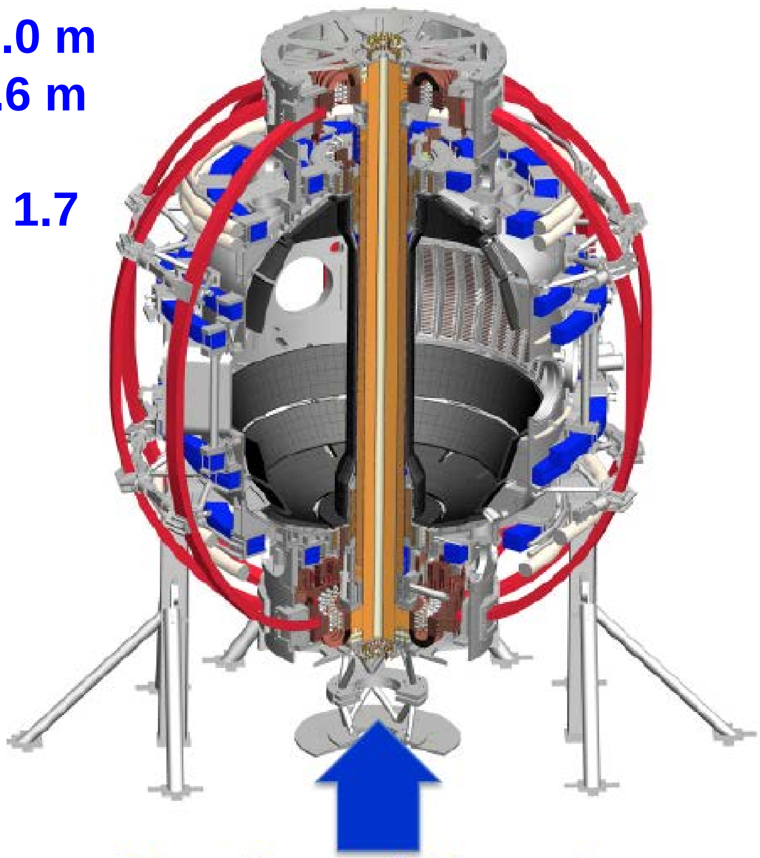
- For high beta NSTX H-modes, electromagnetic microtearing modes (MTM) predicted at high collisionality
- Transition to kinetic ballooning modes (KBM) at low collisionality may set ultimate limit to ST H-mode confinement

- For "low" beta NSTX-U L-modes, more traditional electrostatic drift waves (ITG, ETG) important
- Validation still complicated by residual electromagnetic effects and possibly non-local and/or multi-scale effects

NSTX completed major upgrade in 2015 with goal of $2 \times$ higher B_T, I_p, P_{NBI} and $5 \times$ longer pulse length

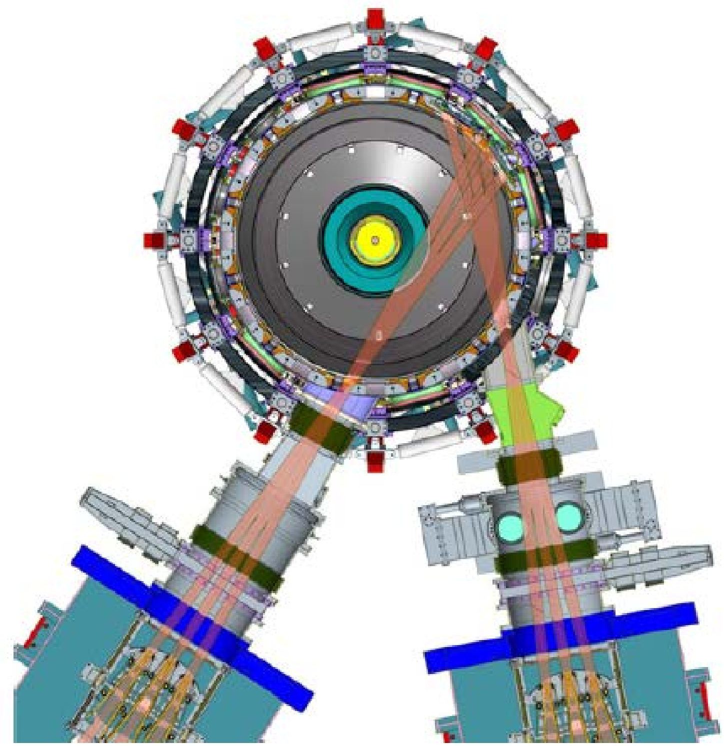
$R = 1.0$ m
$a \leq 0.6$ m

$R/a \approx 1.7$



New Central Magnet

1 Tesla at plasma center, I_p = 2MA, 5s



Original NBI

(R_{TAN} = 50, 60, 70cm)
5MW, 5s, 80keV

New 2nd NBI

(R_{TAN}=110, 120, 130cm)
5MW, 5s, 80keV

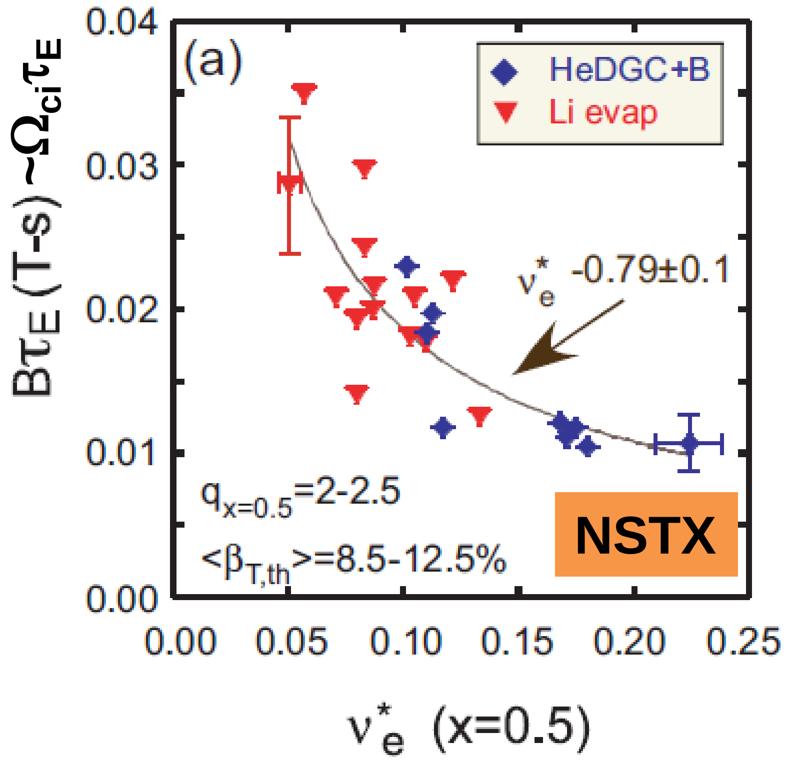
- First run campaign in 2016 [J. Menard, Nucl. Fusion (2017)]
- Presently in outage for PF coil repairs

Normalized energy confinement time scales favorably with collisionality in spherical tokamaks (STs)

- In NSTX and MAST H-modes, dimensionless confinement time scales inversely with collisionality, $\Omega_{ci}\tau_E \sim \nu_*^{-0.8}$ [Kaye, NF (2013); Valovic, NF (2011)]

- Next generation STs (FNSF, CTF, Pilot Plant) will operate at lower ν_*

⇒**What determines transport & confinement scaling?**

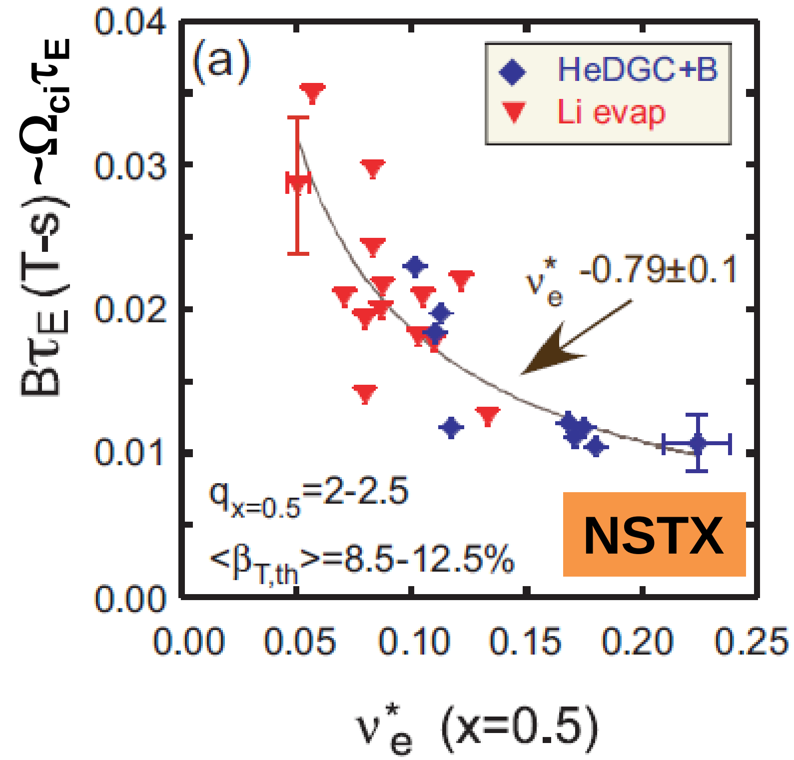


Normalized energy confinement time scales favorably with collisionality in spherical tokamaks (STs)

- In NSTX and MAST H-modes, dimensionless confinement time scales inversely with collisionality, $\mathbf{\Omega_{ci}\tau_E \sim \nu_*^{-0.8}}$ [Kaye, NF (2013); Valovic, NF (2011)]

- Next generation STs (FNSF, CTF, Pilot Plant) will operate at lower ν_*

⇒**What determines transport & confinement scaling?**



- Conventional (R/a=3) tokamak H-modes thought to be governed by electrostatic toroidal drift waves:
  - ($k_\perp\rho_i$~1) Ion temperature gradient (**ITG**, $\gamma \sim \nabla T_i$) & trapped electron mode (**TEM**, $\gamma \sim \nabla T_e, \nabla n_e$)
  - ($k_\perp\rho_e$~1) Electron temperature gradient (**ETG**, $\gamma \sim \nabla T_e$)

Many features of high beta STs are stabilizing to electrostatic, toroidal ITG, TEM & ETG drift waves

Short connection length	⇒	**Smaller average "bad curvature"**
Quasi-isodynamic (~constant B) at high β		**Grad-B drifts stabilizing** [Peng & Strickler, NF 1986]
Large fraction of trapped electrons, BUT precession weaker at low A		**Reduced TEM drive** [Rewoldt, PoP 1996]
Strong coupling to $\delta B_{\perp}$ at high β		**Stabilizing to ES-ITG** [Kim, Horton, Dong, PoFB 1993]
Small inertia (nmR^2) & uni-directional NBI heating gives strong toroidal flow & flow shear		**E×B shear stabilization ($dv_{\perp}/dr$)** [Biglari, Diamond, Terry PoFB 1990]

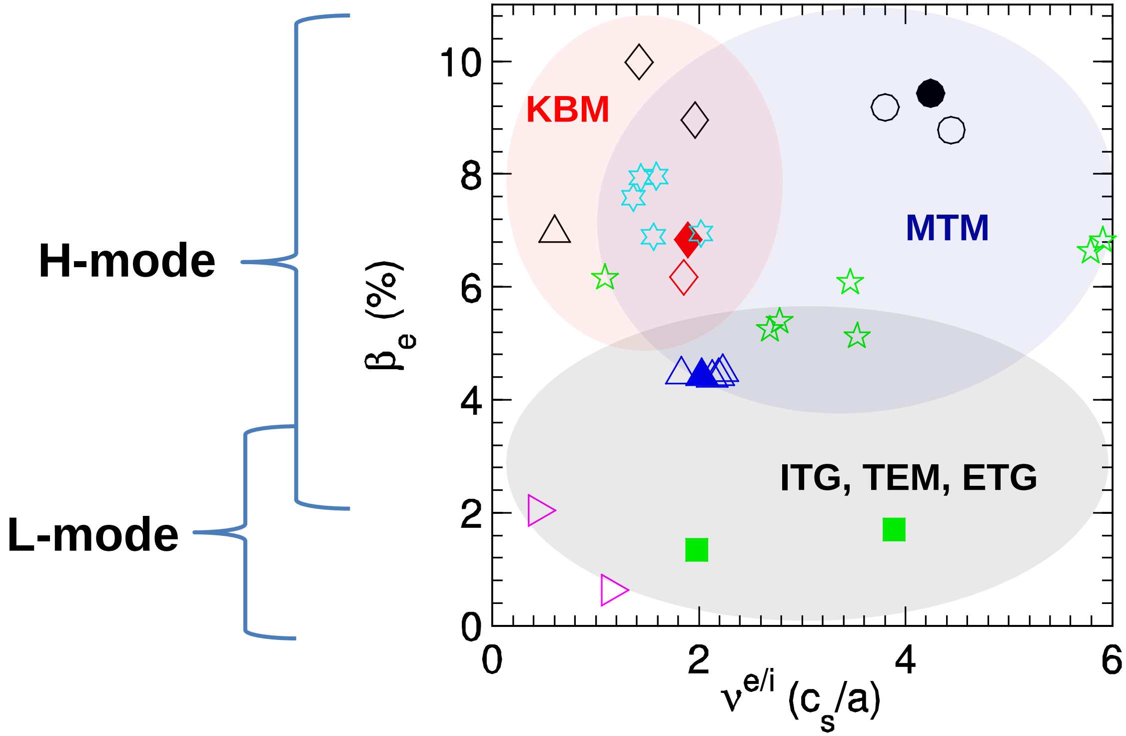
⇒Stabilization of ITG consistent with observed neoclassical ion transport $\chi_i \approx \chi_{i,NC}$

- **BUT** high beta drives electromagnetic instabilities:
  - Microtearing modes (**MTM**) ~ $\beta_e \cdot \nabla T_e$
  - Kinetic ballooning modes (**KBM**) ~ $\alpha_{MHD} \sim q^2 \nabla P / B^2$

- Large shear in parallel velocity can also drive parallel velocity gradient (**PVG**) instability ~$dv_{||}/dr$

At high β, microtearing modes (MTM) and kinetic ballooning modes (KBM) are predicted unstable

- Predicted dominant core-gradient instability correlated with local β and ν
- Multiple instabilities usually predicted for a given experimental discharge



Guttenfelder, NF (2013)

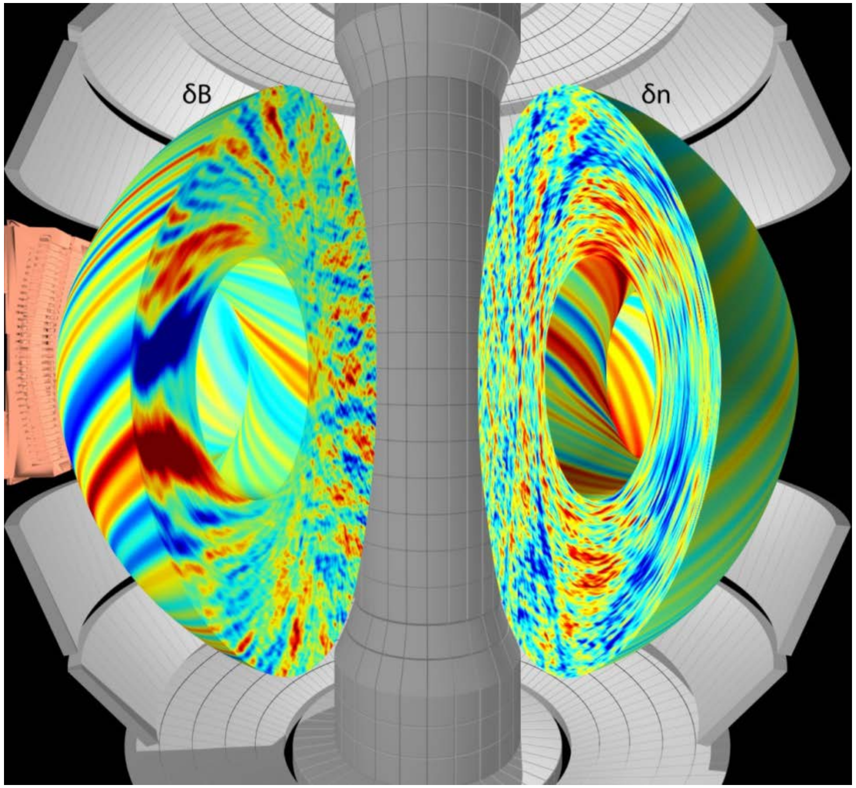
Local **gyrokinetic analyses at r/a~2/3** (GYRO code: fusion.gat.com/theory/Gyro)

NSTX

Nonlinear simulations of core MTM turbulence predict significant transport at high β & ν

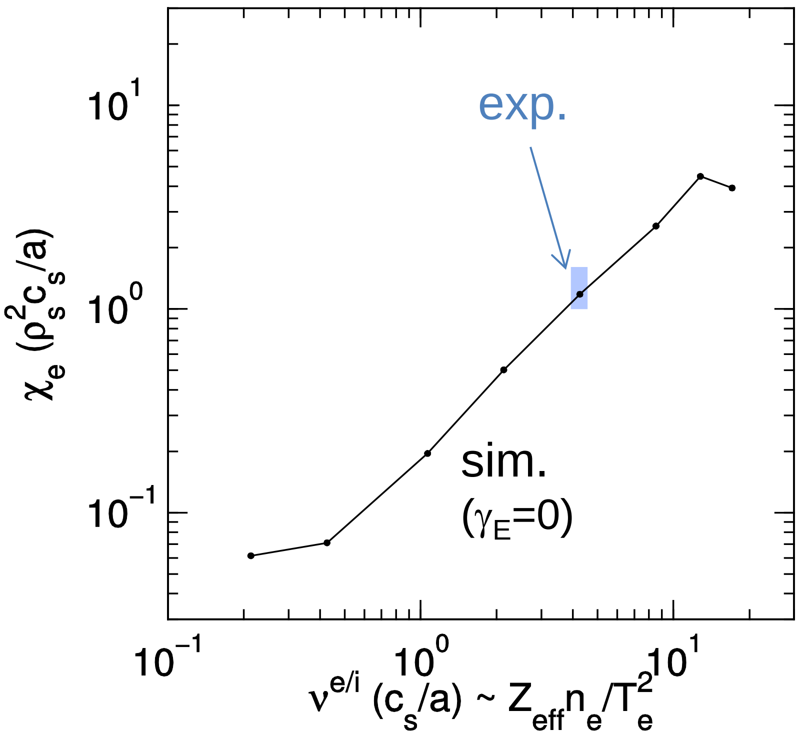
- Large $\delta B/B \sim 10^{-3}$ leads to flutter transport ($\sim v_{||} \cdot \delta B^2$) consistent w/ stochastic transport
  - In the core, driven by ∇T_e with time-dependent thermal force (e.g. Hassam, 1980)
  - *Requires collisionality →* ***not explicitly driven by toroidal "bad-curvature"***
- **Collisionality scaling ($\chi_{e,MTM} \sim \nu_e$) consistent with global confinement ($\tau_E \sim 1/\nu$)**

NSTX MTM simulation



Visualization courtesy F. Scotti (LLNL)

Predicted transport

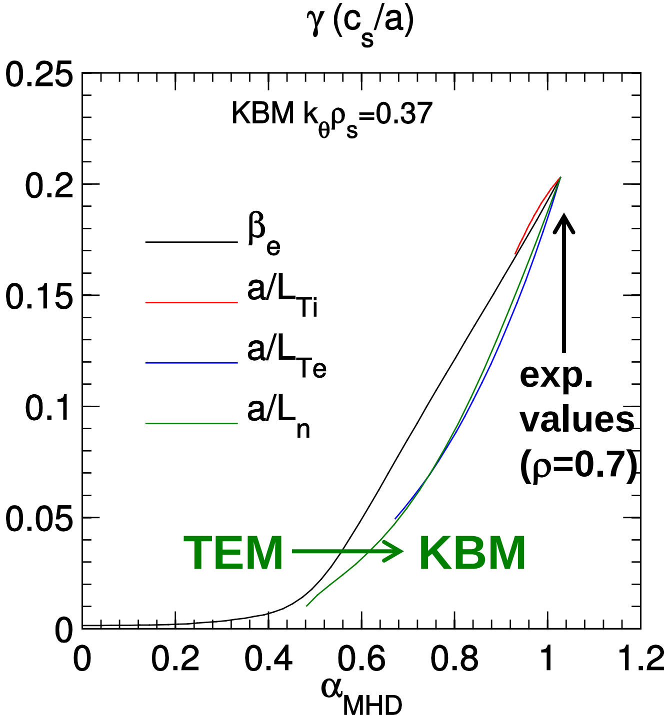


Guttenfelder, PRL (2011), PoP (2012)

At high β & lower ν, KBM modes are predicted *in the core* ⇒ may set limit to NSTX-U confinement scaling

- KBM expected to set maximum ∇P
- Smooth transition from ITG/TEM (no hard onset) – distinct from conventional tokamaks

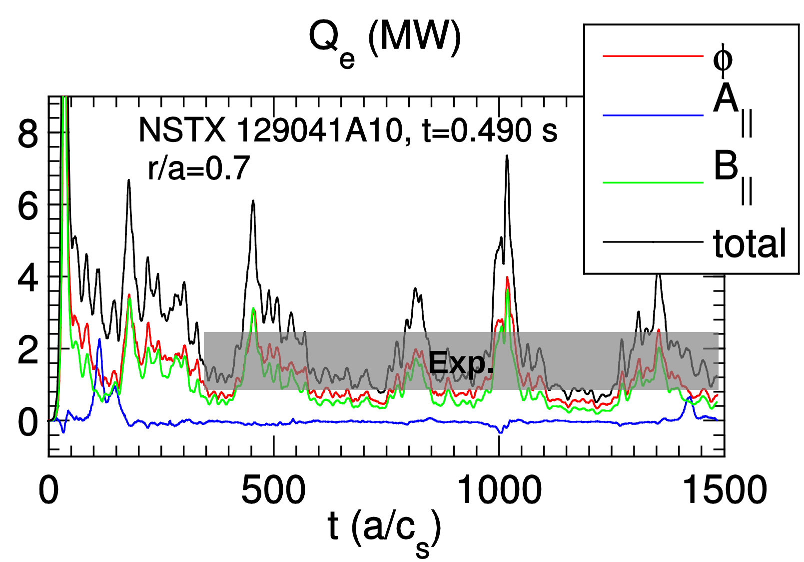
Linear growth rates



$$\alpha_{MHD} = -q^2 R \cdot 2\mu_0 \nabla P / B^2$$

- Nonlinear simulations predict significant transport, strong compressional magnetic component ($\delta B_{||}/B \sim 10^{-3}$)

Nonlinear simulation



NSTX

Guttenfelder, NF (2013)

Electromagnetic simulations at high β are computationally challenging

- Fine radial resolution required for MTM
- Challenging to obtain saturated KBM simulations

Meaningful simulation results are *not* the norm!

- At large $\rho^*=\rho_i/a$, rapid variation of $\gamma_{lin}(r)$, $\gamma_E(r)$ likely requires non-local simulations $\rightarrow$ additional resolution restrictions

$\Rightarrow$**Develop NSTX-U L-modes for code validation and benchmarking at low A=R/a and low β**

- New NSTX-U centerstack allows for long, stationary discharges to provide well diagnosed L-modes for electrostatic code validation at low-A

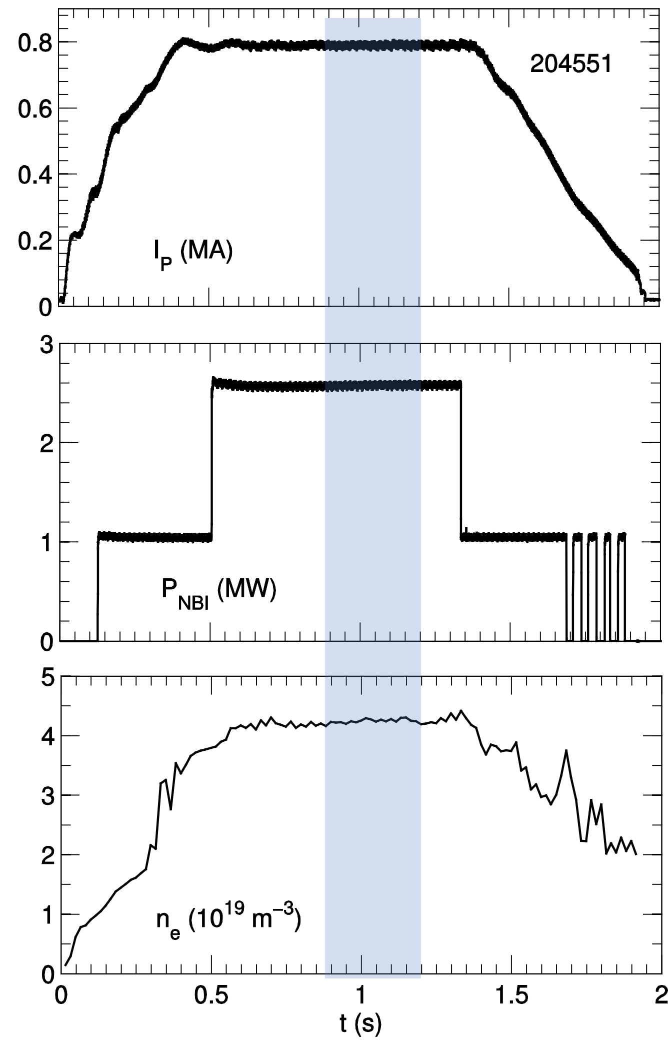
Using stationary, sawtoothing L-modes established during NSTX-U commissioning for validation study

- Wide variety of conditions:
  - $\langle n_e \rangle$=1-4×10^{19} m^{-3}
  - I_p=0.65-1.0 MA (B_T=0.65 T)
  - P_{NBI}=1-3 MW
  - 2^{nd} NBI sources (bigger R_{tan}) had noticeable effect on rotation, tearing stability, locked modes

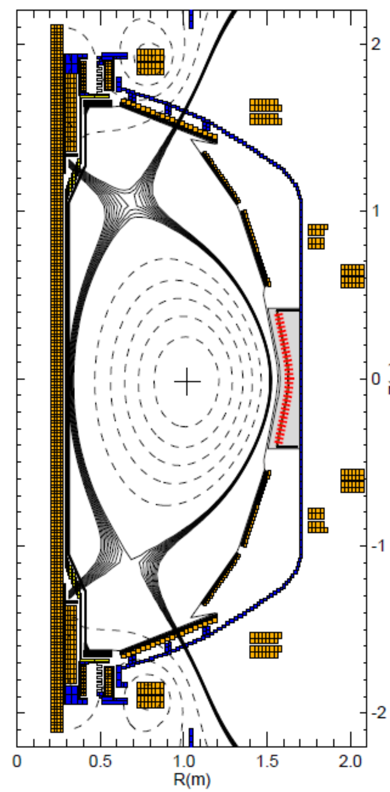
- Flat-top out to 2 sec achieved

- Focus here is on I_P=0.8 MA, 4×10^{19} m^{-3}, P_{NBI}=2.6 MW discharge with good diagnostic coverage

W. Guttenfelder (submitted)

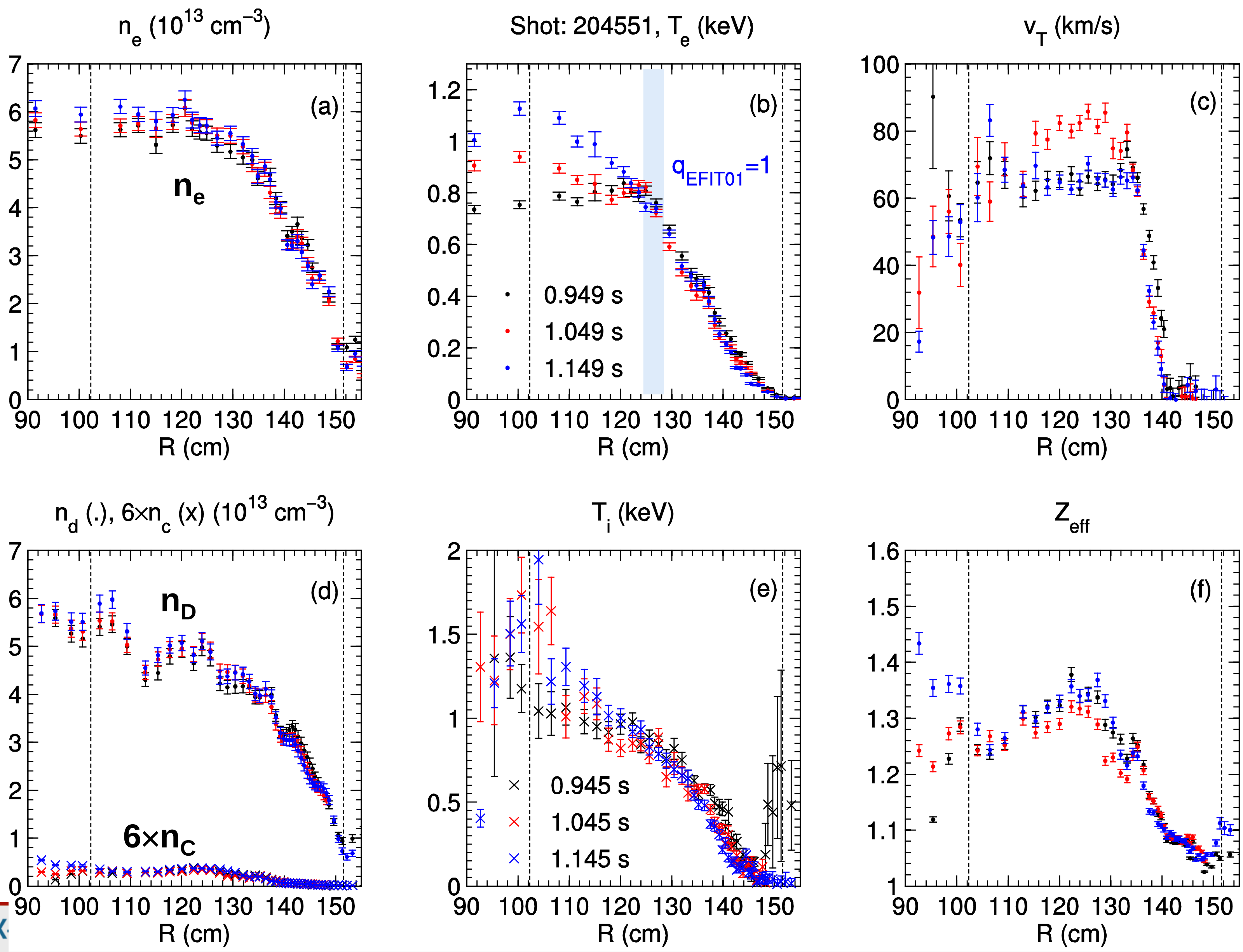


EFIT reconstruction

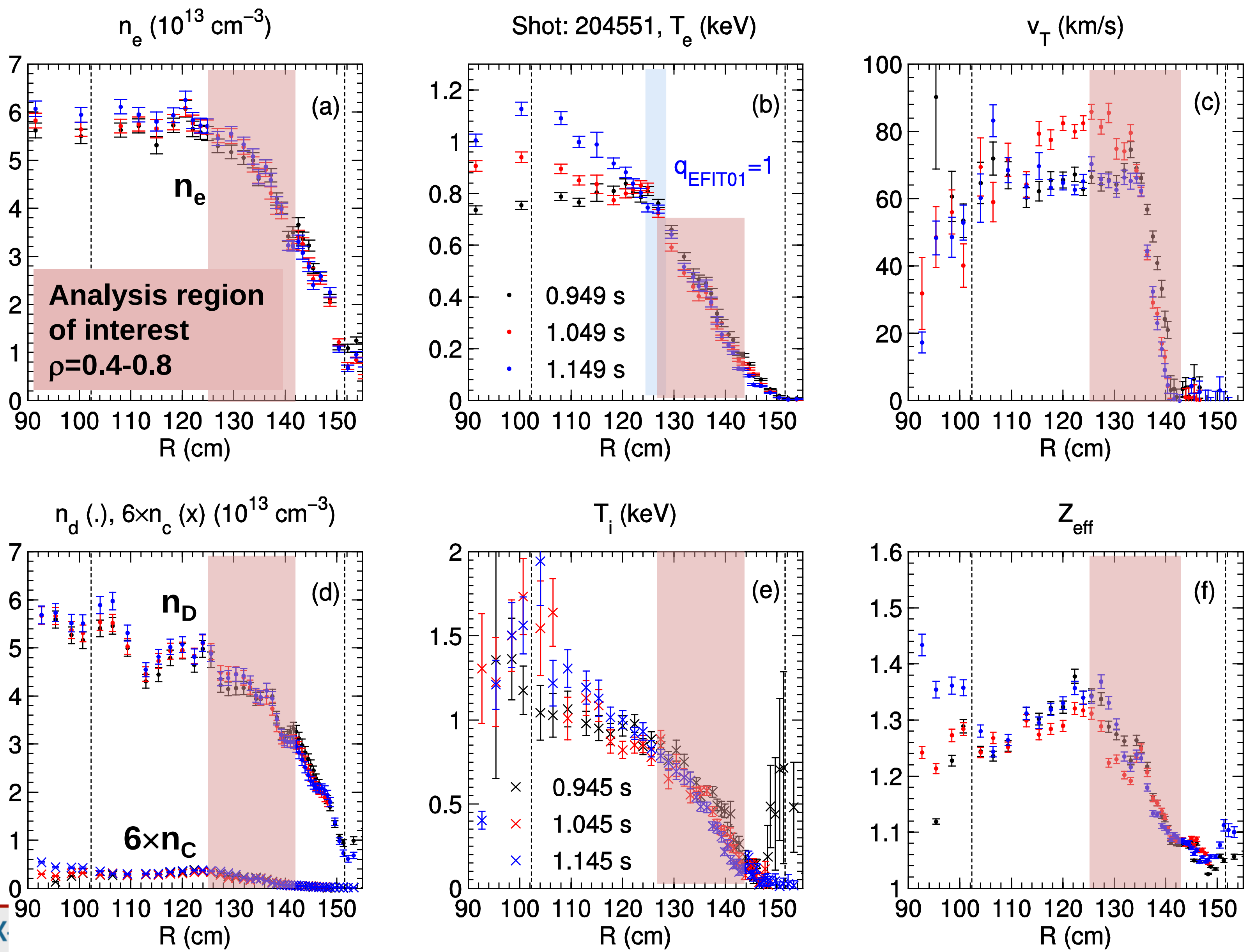


NSTX-U

Kinetic profiles illustrate sawteeth, low carbon impurity, and strong local flow shear in region of interest

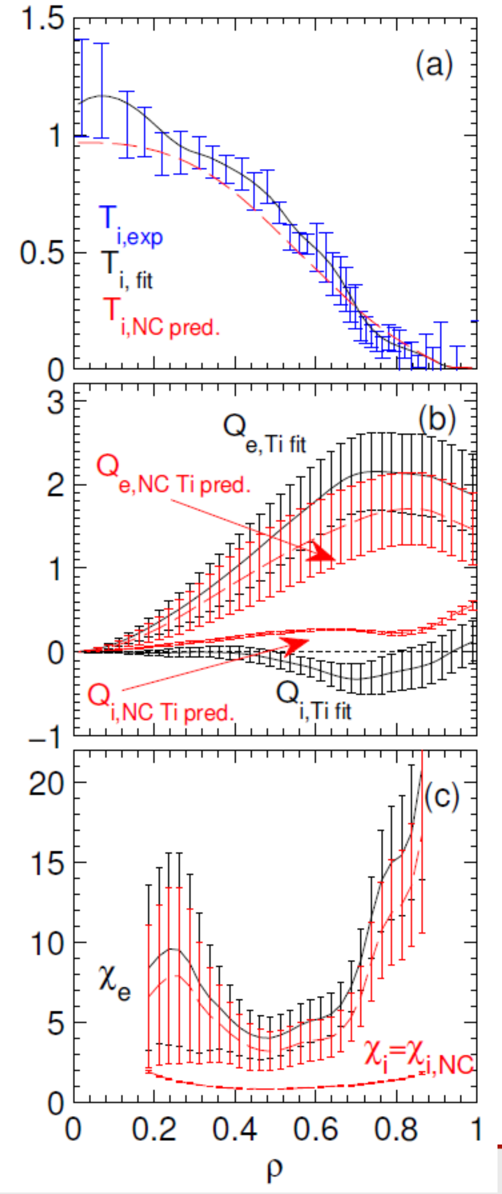


Kinetic profiles illustrate sawteeth, low carbon impurity, and strong local flow shear in region of interest

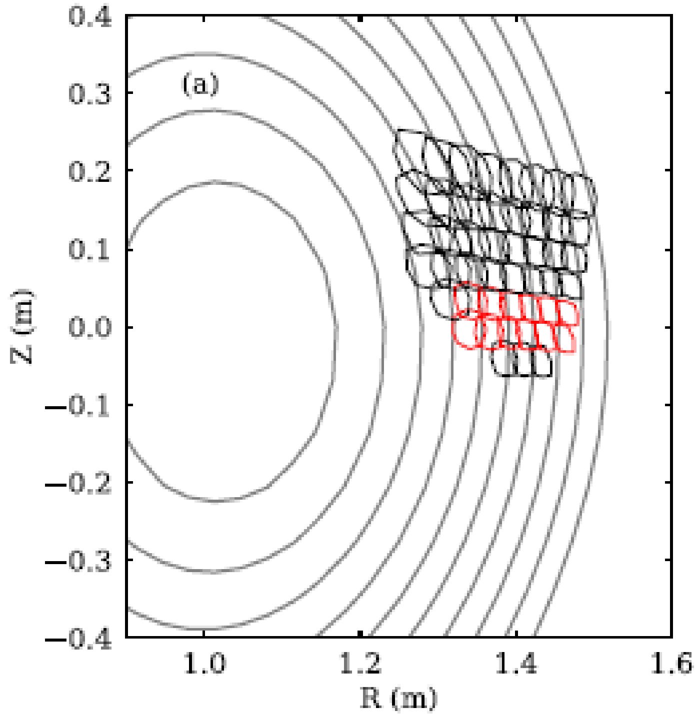


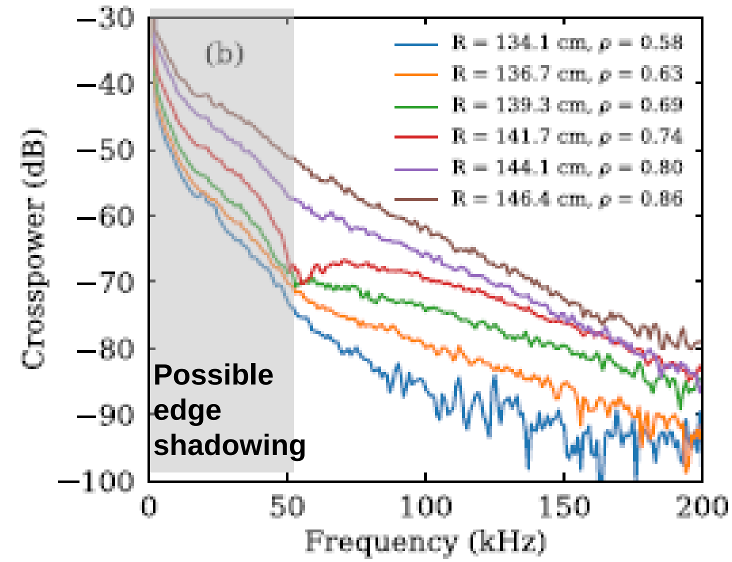
TRANSP analysis shows ion transport near neoclassical even in L-mode

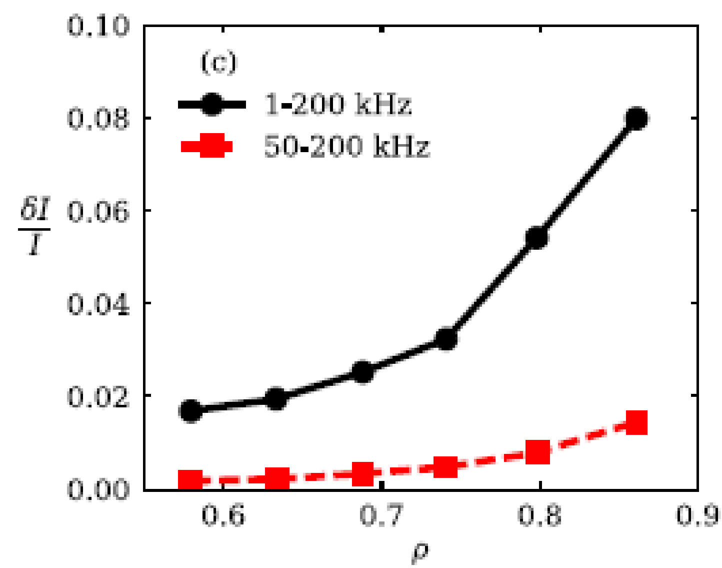
- Electron losses dominant ($\chi_e > \chi_i \approx \chi_{i,NC}$) as also found in H-modes
  - Neoclassical prediction of T_i smaller than experiment by ~10-15%
  - $\Rightarrow$~0.5 MW uncertainty in heat fluxes from collisional coupling



48 channel BES system shows broadband (f<200 kHz) ion-scale density fluctuations



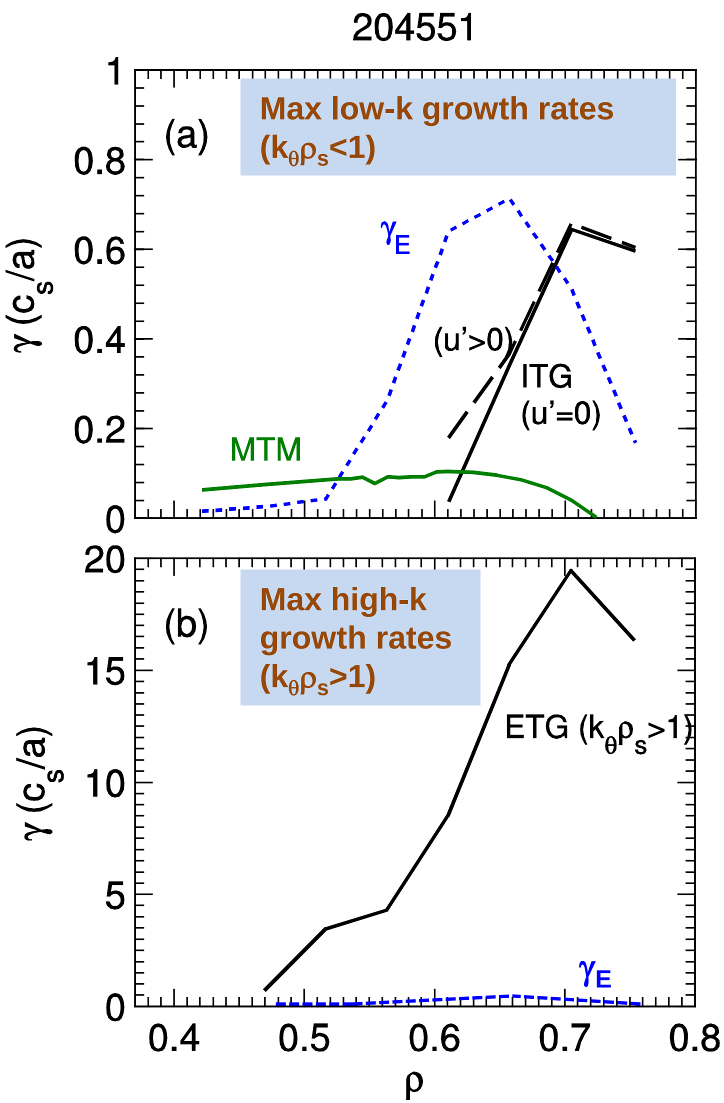




- Ion-directed mode (f>50 kHZ) identified from poloidal cross-phase
  - Low frequency (f<50 kHz) modes are electron-directed, BUT ~100% radial correlation and zero phase shift → likely shadowing from edge fluctuations
- 0.1-1.5% fluctuation amplitude (50-200 kHz)

Linear GYRO simulations predict spectra of ITG & microtearing modes (MTM) at low $k_\theta \rho_s$ and ETG at high-$k_\theta \rho_s$

- ITG modes propagates in ion direction, consistent with BES measurement
- Surprised to find MTM unstable ⇒ sufficient beta (4.1%) and large collisionality enhances MTM
- Strong *local* E×B shearing rates ($\gamma_E > \gamma_{ITG}, \gamma_{MTM}$ at ρ=0.55-0.7)
- Electron scale ($k_\perp \rho_s$>>1) ETG also linearly unstable ($\gamma_{ETG} >> \gamma_E$) in region of strong E×B shear

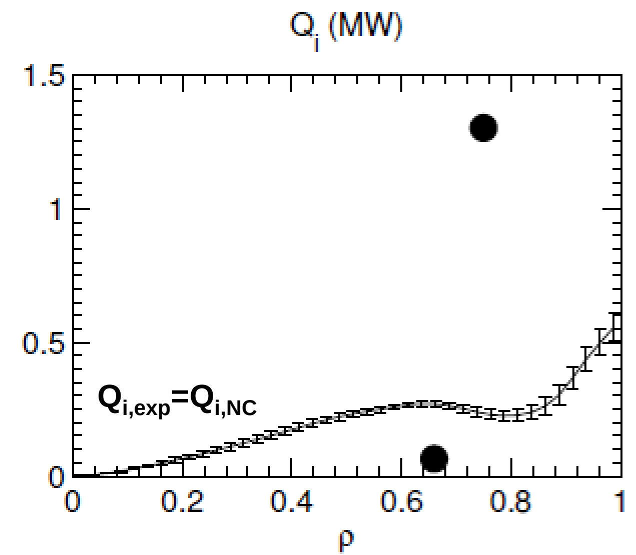


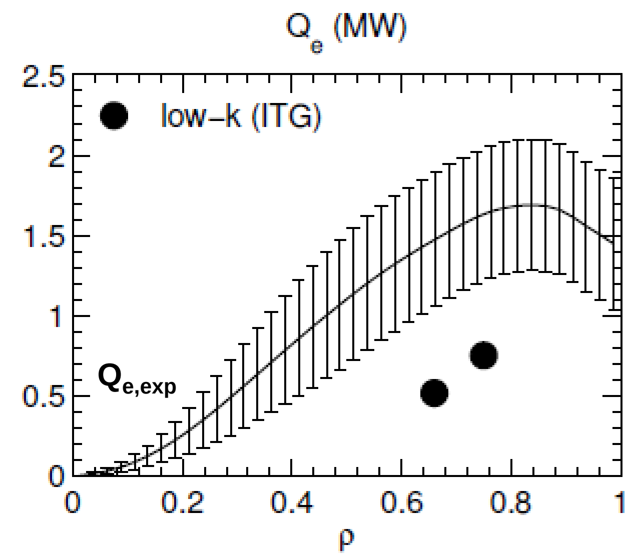
Local, nonlinear ion-scale simulations give significant transport outside strong E×B shear region

Ion scale simulation domain
$[L_r, L_\theta] = [120,120]\ \rho_i$
max $[k_r\rho_i, k_\theta\rho_i] = [1.9, 1.3]$

ρ=0.65-0.75

- ITG provides $Q_{e,ITG} \leq 0.5 \times Q_{e,exp}$
- Large $Q_{i,ITG}$ at ρ=0.75 inconsistent with $Q_{i,exp}=Q_{i,NC}$
- $(\delta n/n)_{ITG}$~ 1-4% similar to BES measurements – *need synthetic diagnostic for proper comparison*





Local, nonlinear ion-scale simulations give significant transport outside strong E×B shear region

Ion scale simulation domain
$[L_r, L_\theta] = [120,120]\ \rho_i$
$\max\ [k_r\rho_i, k_\theta\rho_i] = [1.9, 1.3]$

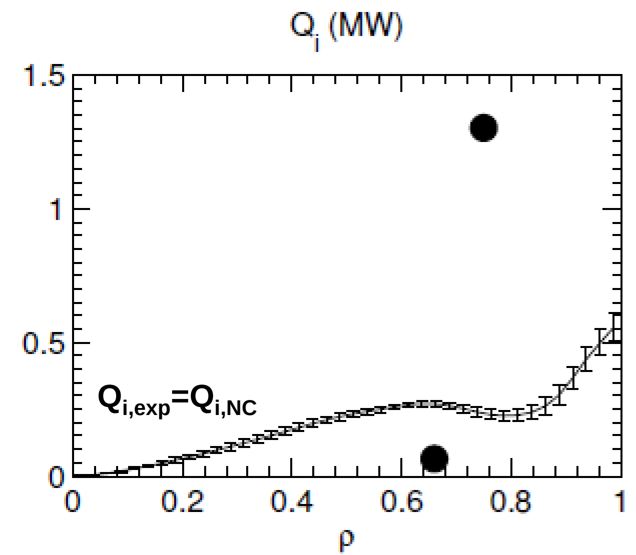
ρ=0.65-0.75

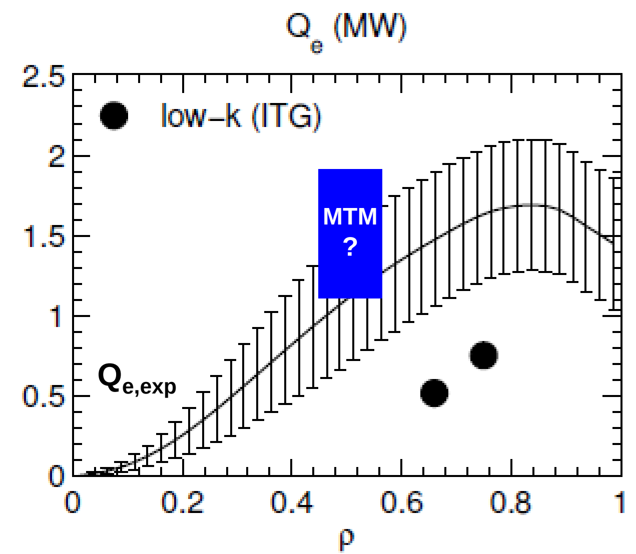
- ITG provides $Q_{e,ITG} \leq 0.5 \times Q_{e,exp}$
- Large $Q_{i,ITG}$ at ρ=0.75 inconsistent with $Q_{i,exp}=Q_{i,NC}$
- $(\delta n/n)_{ITG}$~ 1-4% similar to BES measurements – *need synthetic diagnostic for proper comparison*

ρ=0.45-0.55

- Initial MTM simulations provide $Q_{e,MTM}$ >1 MW
- $Q_{i,MTM}$=0 consistent with experiment

⇒*Needs resolution refinement*





Local, nonlinear ion-scale simulations give significant transport outside strong E×B shear region

Ion scale simulation domain
$[L_r, L_\theta] = [120,120]\ \rho_i$
max $[k_r\rho_i, k_\theta\rho_i] = [1.9, 1.3]$

ρ=0.65-0.75

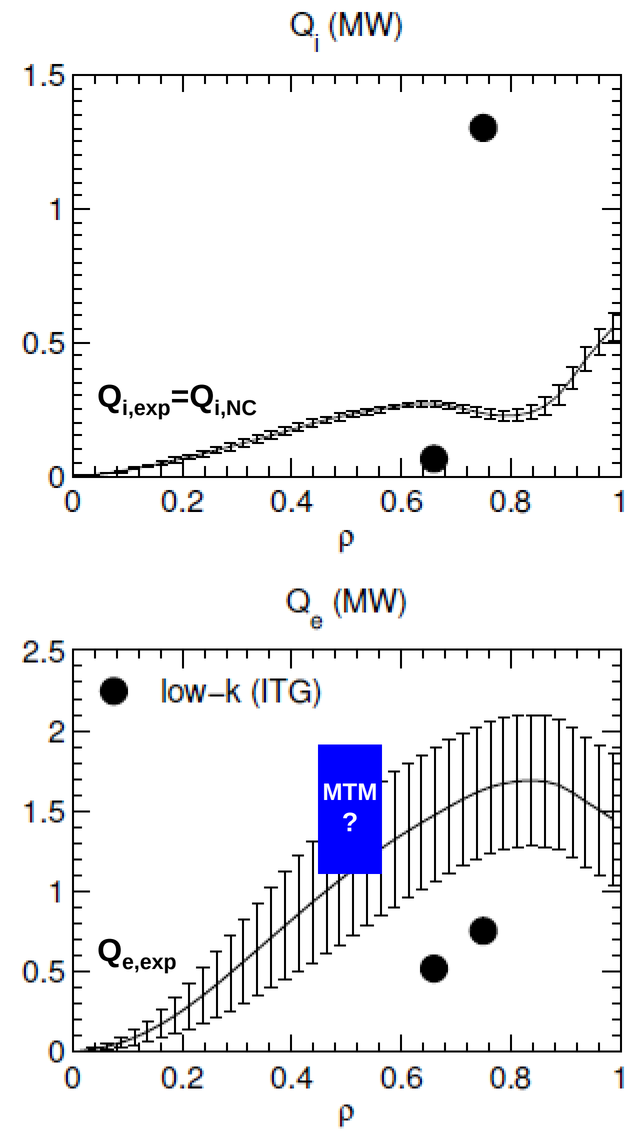
- ITG provides $Q_{e,ITG} \leq 0.5 \times Q_{e,exp}$
- Large $Q_{i,ITG}$ at ρ=0.75 inconsistent with $Q_{i,exp}=Q_{i,NC}$
- $(\delta n/n)_{ITG}$~ 1-4% similar to BES measurements – *need synthetic diagnostic for proper comparison*

ρ=0.45-0.55

- Initial MTM simulations provide $Q_{e,MTM}$ >1 MW
- $Q_{i,MTM}$=0 consistent with experiment

⇒*Needs resolution refinement*

- Local ion-scale simulations alone insufficient
  - Need to vary inputs within exp. uncertainties



Local, nonlinear ion-scale simulations give significant transport outside strong E×B shear region

Ion scale simulation domain
$[L_r, L_\theta]$ = [120,120] ρ_i
max $[k_r\rho_i, k_\theta\rho_i]$ = [1.9, 1.3]

ρ=0.65-0.75

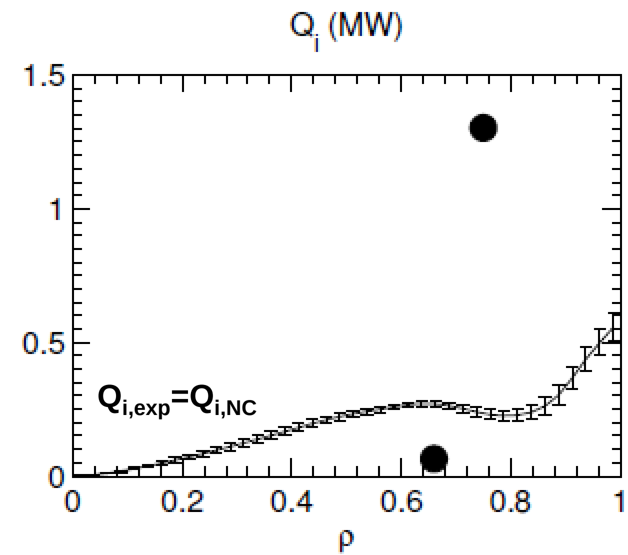
- ITG provides $Q_{e,ITG} \leq 0.5 \times Q_{e,exp}$
- Large $Q_{i,ITG}$ at ρ=0.75 inconsistent with $Q_{i,exp}=Q_{i,NC}$
- $(\delta n/n)_{ITG}$~ 1-4% similar to BES measurements – *need synthetic diagnostic for proper comparison*

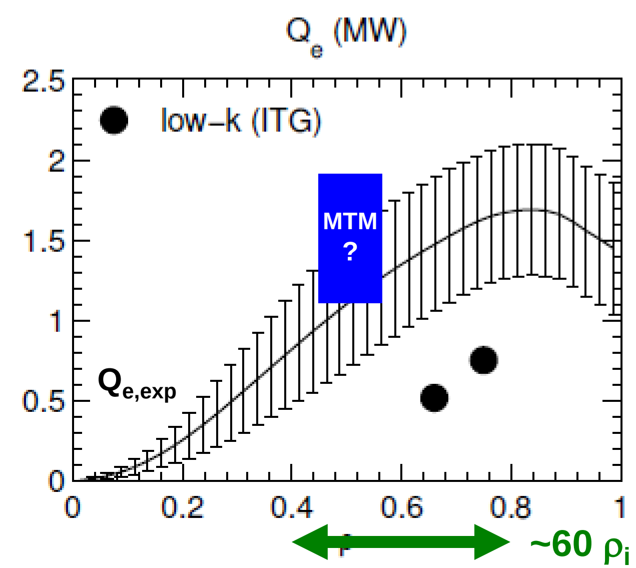
ρ=0.45-0.55

- Initial MTM simulations provide $Q_{e,MTM}$ >1 MW
- $Q_{i,MTM}$=0 consistent with experiment

$\Rightarrow$*Needs resolution refinement*

- Local ion-scale simulations alone insufficient
  - Need to vary inputs within exp. uncertainties
- Strong variation in turbulence, stability and E×B shear at relatively large $\rho_*=\rho_i/a \Rightarrow$ ***motivates global simulations [see Y. Ren talk]***





Local, nonlinear electron-scale simulations give significant electron transport inside strong E×B shear region

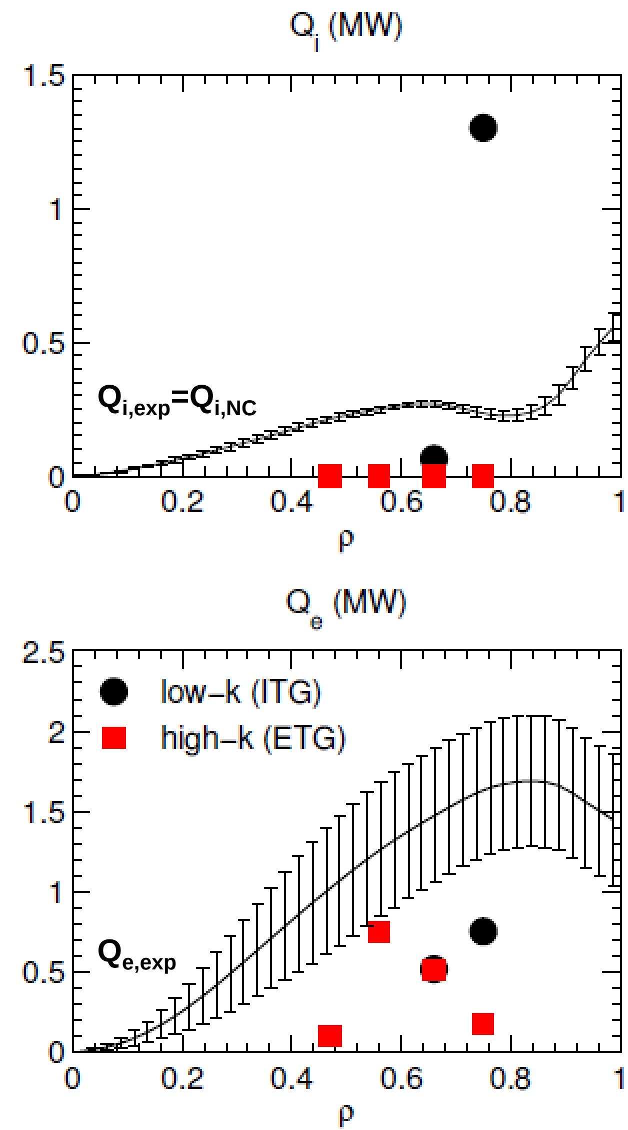
Electron scale simulation domain

$[L_r, L_\theta] = [6,4]\ \rho_i$

$\max [k_r\rho_i, k_\theta\rho_i] = [50,73]$

ρ=0.55-0.65

- ETG provides $Q_{e,ITG} \leq 0.7 \times Q_{e,exp}$
  - Need to vary inputs within exp. uncertainties
- $Q_{i,ETG}$=0 consistent with experiment



Local, nonlinear electron-scale simulations give significant electron transport inside strong E×B shear region

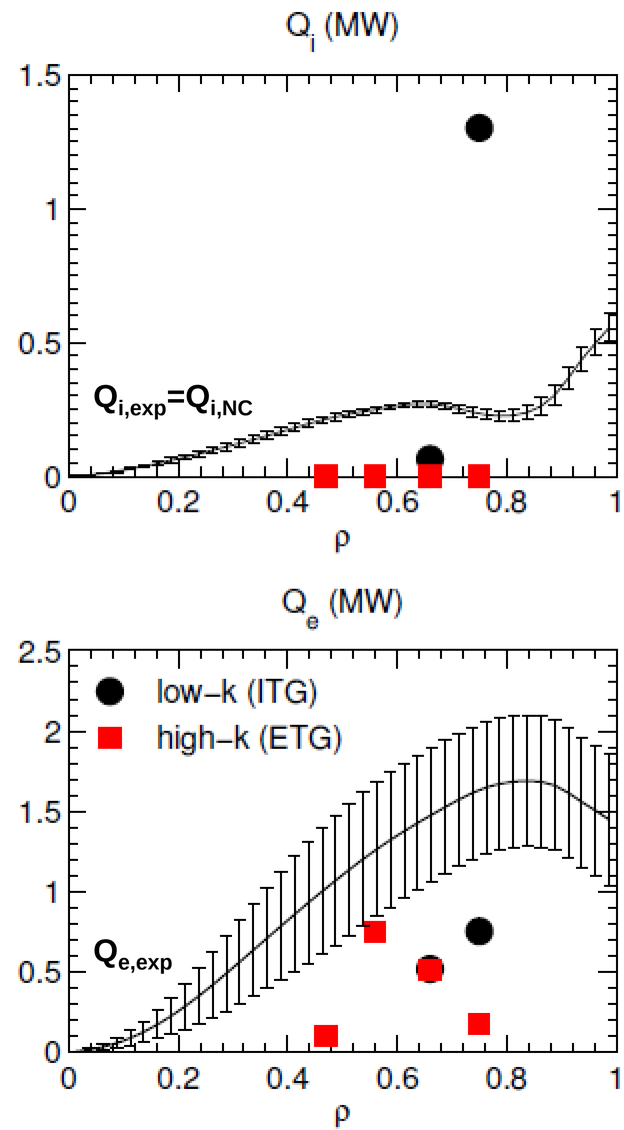
Electron scale simulation domain
$[L_r, L_\theta]$ = [6,4] ρ_i
max $[k_r\rho_i, k_\theta\rho_i]$ = [50,73]

ρ=0.55-0.65

- ETG provides $Q_{e,ITG} \leq 0.7 \times Q_{e,exp}$
  - Need to vary inputs within exp. uncertainties
- $Q_{i,ETG}$=0 consistent with experiment

- Electron scale simulations sufficient for experimental validation *only if* ion scale turbulence locally suppressed

- **Can not rule out multiscale interactions where $Q_{e,high-k}$ ~ $Q_{e,low-k}$** [Howard, PoP (2016)]; may be more important from a global perspective



Summary: Understanding confinement scaling ($\tau_E \sim 1/\nu$) at low collisionality critical for future spherical tokamaks (ST)

- Numerous *theoretical* transport mechanisms to consider at low aspect ratio $\rightarrow$ requires dedicated effort to validate gyrokinetic simulations

- For high beta NSTX H-modes, electromagnetic microtearing modes (MTM) predicted at high collisionality ($\chi_{e,MTM} \sim \nu_e$)
- Transition to kinetic ballooning modes (KBM) at low collisionality may set ultimate limit to ST H-mode confinement $\rightarrow$ focus of future NSTX-U exps.

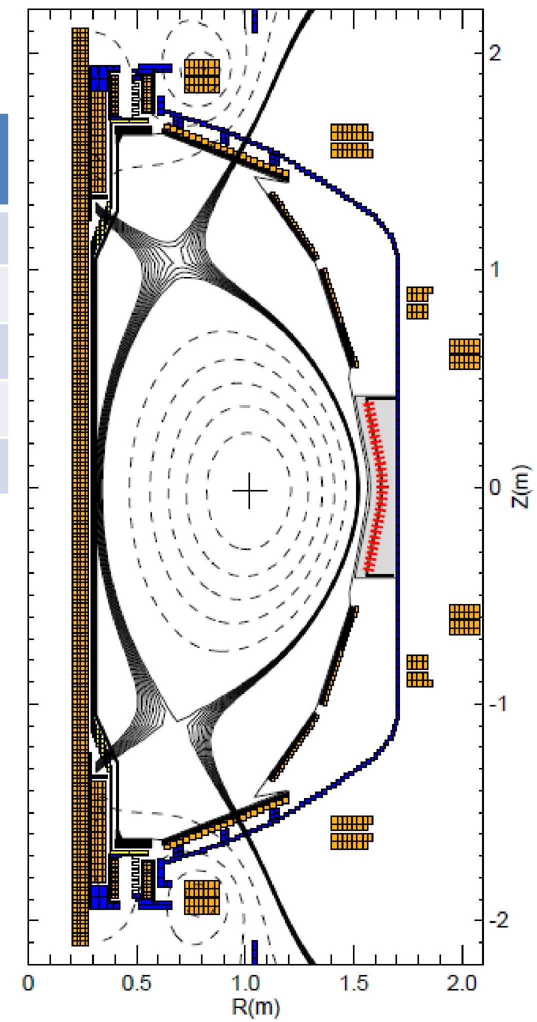
- For "low" beta NSTX-U L-modes, multiple ion scale (ITG, MTM) and electron scale (ETG) simulations can contribute to electron heat loss
- **Local, single-scale simulations fail to capture L-mode transport**
- Future work to quantify uncertainties and possible non-local and multi-scale effects

- *Acknowledgements: This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.*

Characteristic equilibrium parameters of NSTX-U diverted L-modes

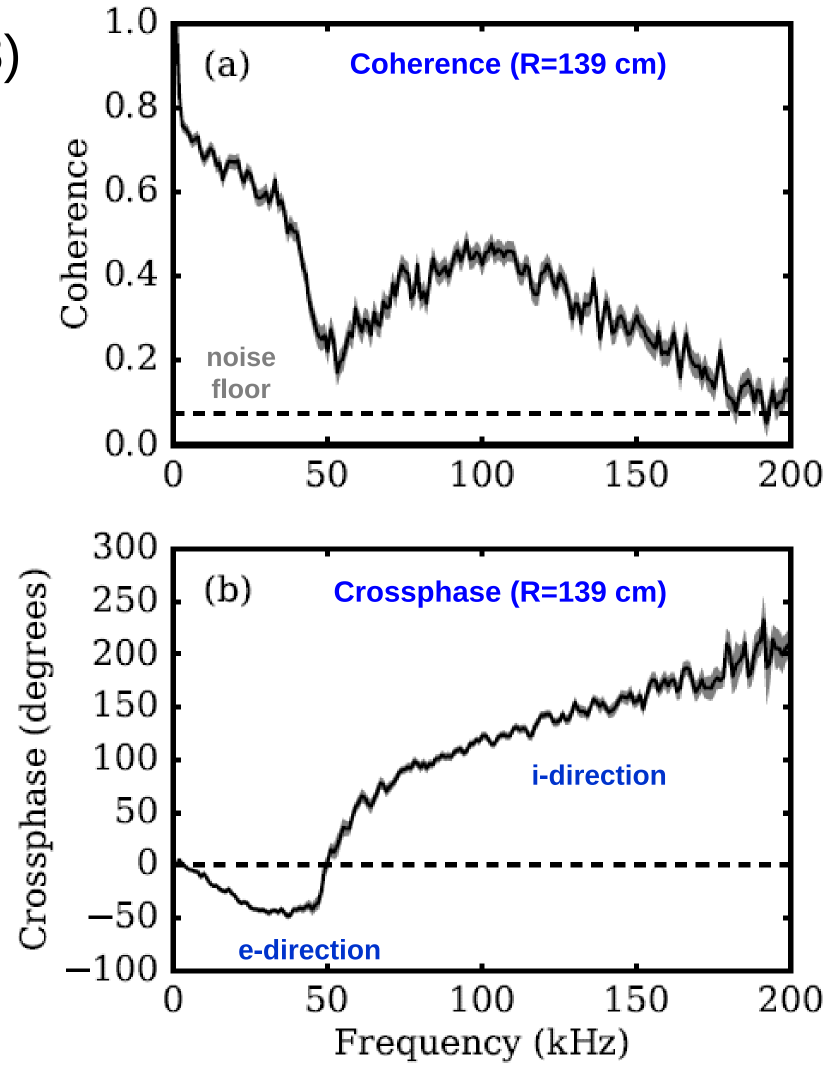
Shot	B_T (T)	I_p (MA)	P_{NBI} (MW)	R_{tan} (cm)	n_e (10^{19} m^{-3})	W_{MHD} (kJ)	q_{95}	β_N	β_T (%)	ν_{*e} (ρ=0.65)	$1/\rho_{*s}$ (ρ=0.65)
204179	0.63	0.64	1.1	60	1.7	50	4.8	1.4	2.4	0.043	117
204508	0.63	0.79	1.1	60	3.4	62	4.6	1.3	2.7	0.15	143
204551	0.63	0.79	2.6	70,60	4.3	95	4.8	2.0	4.1	0.27	145
204651	0.63	0.64	1.0	50	3.1	42	5.1	1.1	1.9	0.40	172
204963	0.63	0.64	0.94	60	3.1	62	5.5	1.7	2.8	0.36	167

- Spanning a range of β_N=1.1-2
- Focusing first analysis on higher density, higher β_N discharge 204551 as it has low uncertainty in T_i, v_{Tor}



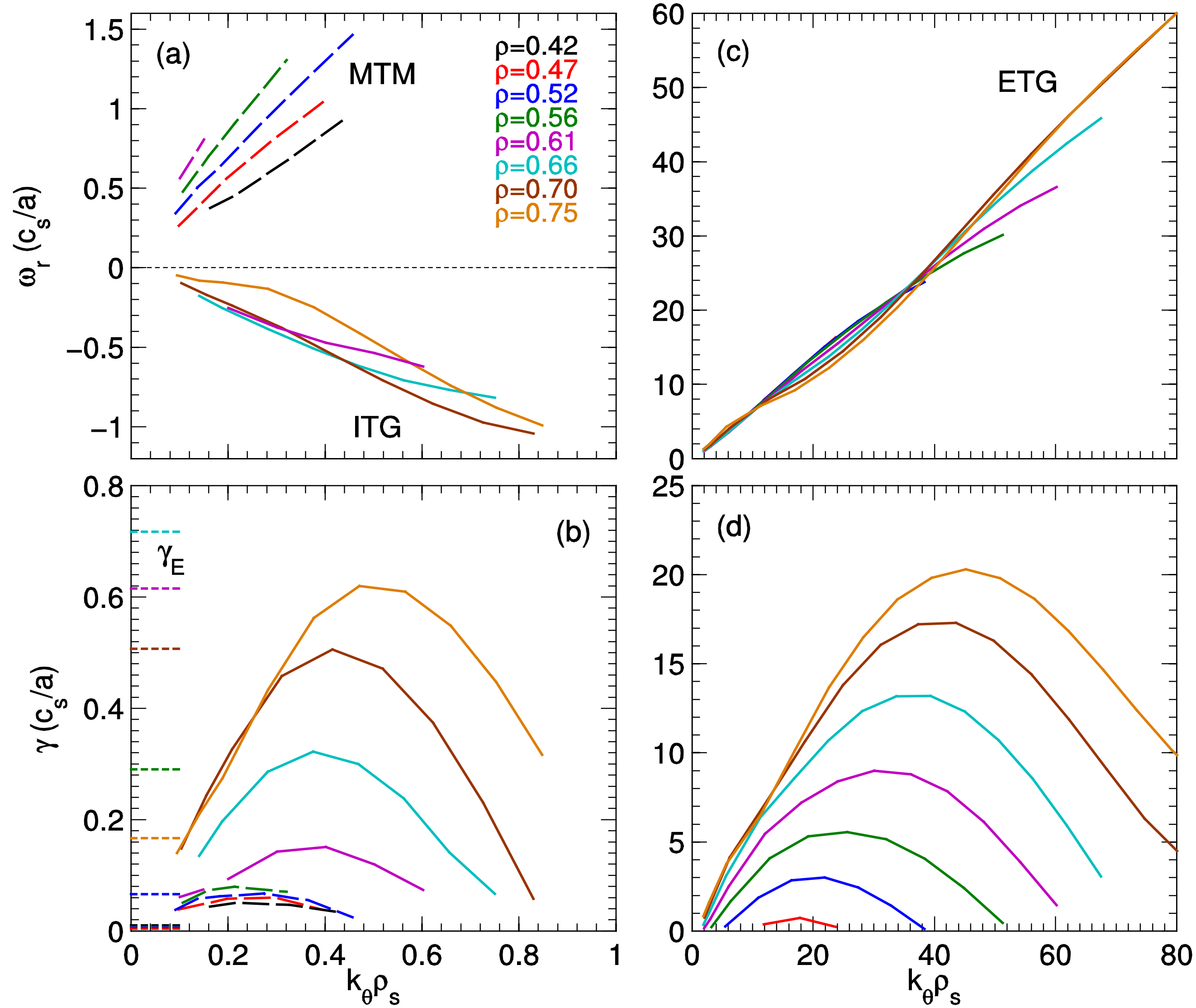
BES poloidal cross-phase shows dual-mode propagation

- Ion mode found R=134-144 cm (ρ=0.6-0.8)
- Low frequency (f<50 kHz) electron mode found at all radii
  - Outer most radii has strong electron mode only
- Concern that electron mode could be due to shadowing from large amplitude edge fluctuations (strong radial correlation, zero phase shift)



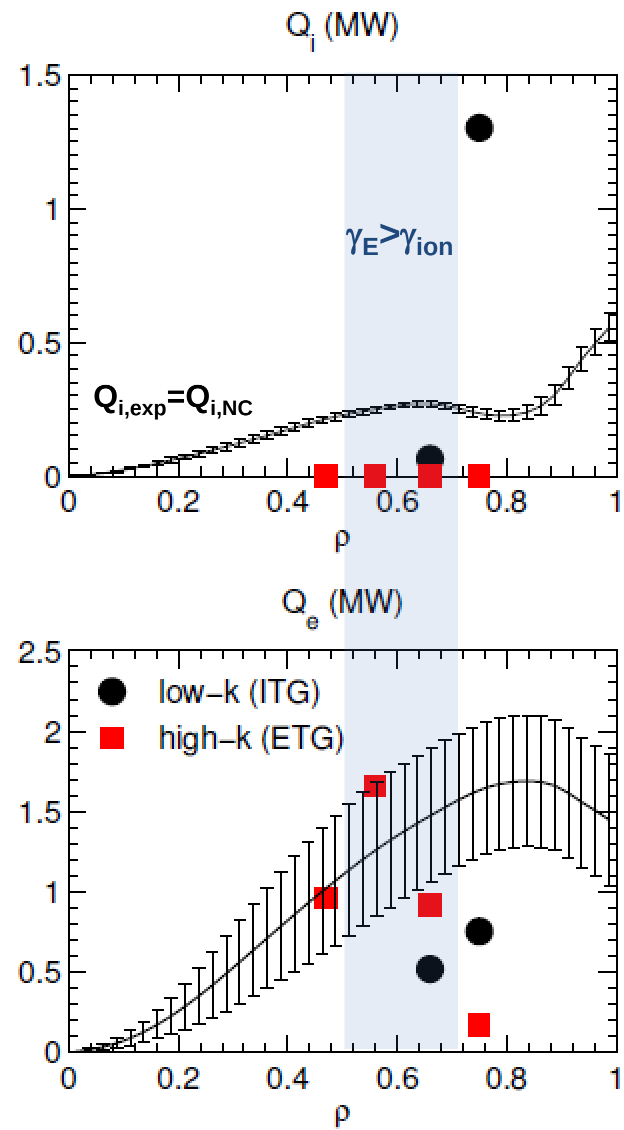
Linear GYRO* simulations predict spectra of ITG & microtearing modes (MTM) at low $k_\theta\rho_s$ and ETG at high-$k_\theta\rho_s$

- ITG modes propagates in ion direction
  - Propagation direction consistent with BES ion mode (strong Doppler shift also in ion direction)
- MTM propagates in electron direction
  - Surprised to find MTM unstable ⇒ sufficient beta (4.1%) and large collisionality enhances MTM

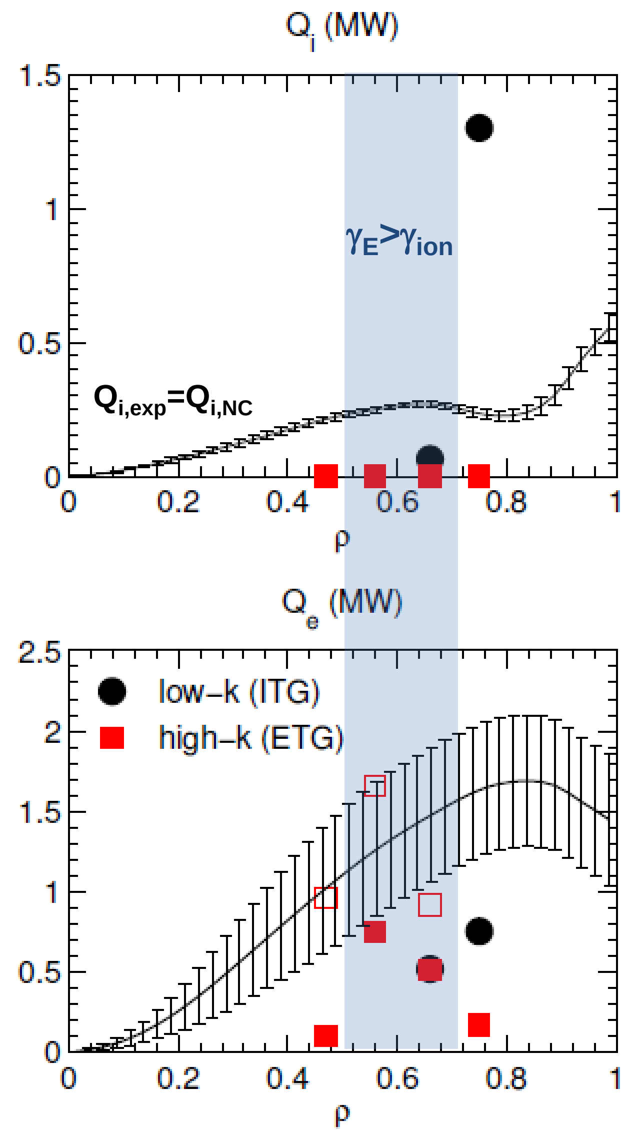


*GYRO (Candy, Waltz, 2003)

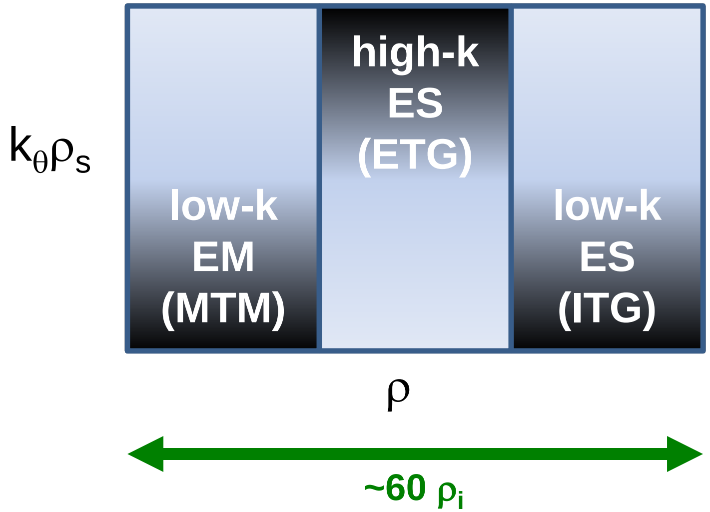
Uncertainty in Z_{eff} – using lower Z_{eff} gives significant increase in ETG transport



Uncertainty in Z_{eff} – using lower Z_{eff} gives significant increase in ETG transport



•

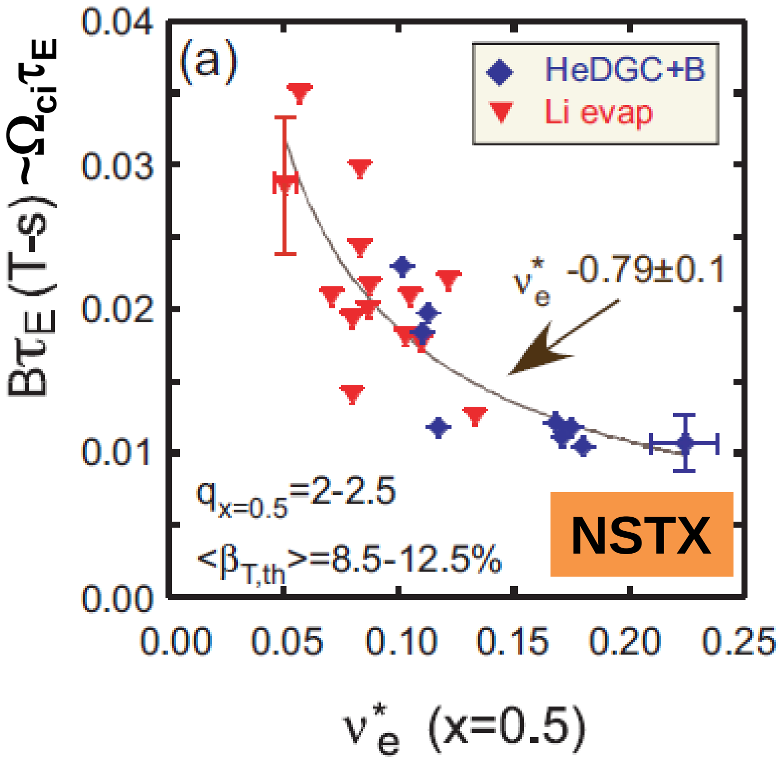


$k_\theta \rho_s$
low-k
EM
(MTM)
high-k
ES
(ETG)
low-k
ES
(ITG)
ρ
~60 ρ_i

Normalized energy confinement time scales favorably with collisionality in spherical tokamaks (STs)

- In NSTX and MAST H-modes, dimensionless confinement time scales inversely with collisionality, $\Omega_{ci}\tau_E \sim \nu_*^{-0.8}$ [Kaye, NF (2013); Valovic, NF (2011)]
- Next generation STs (FNSF, CTF, Pilot Plant) will operate at lower ν_*

⇒**What determines transport & confinement scaling?**



- Conventional (R/a=3) tokamak H-modes thought to be governed by electrostatic toroidal drift waves:
  - ($k_\perp\rho_i$~1) Ion temperature gradient (**ITG**, $\gamma\sim\nabla T_i$) & trapped electron mode (**TEM**, $\gamma\sim\nabla T_e,\nabla n_e$)
  - ($k_\perp\rho_e$~1) Electron temperature gradient (**ETG**, $\gamma\sim\nabla T_e$)
- **Many features of high-β, low A=R/a equilibria are stabilizing to ITG,TEM, ETG**