Microtearing instabilities and electron transport in NSTX

By

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NSTX Results and Theory Review

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Outline

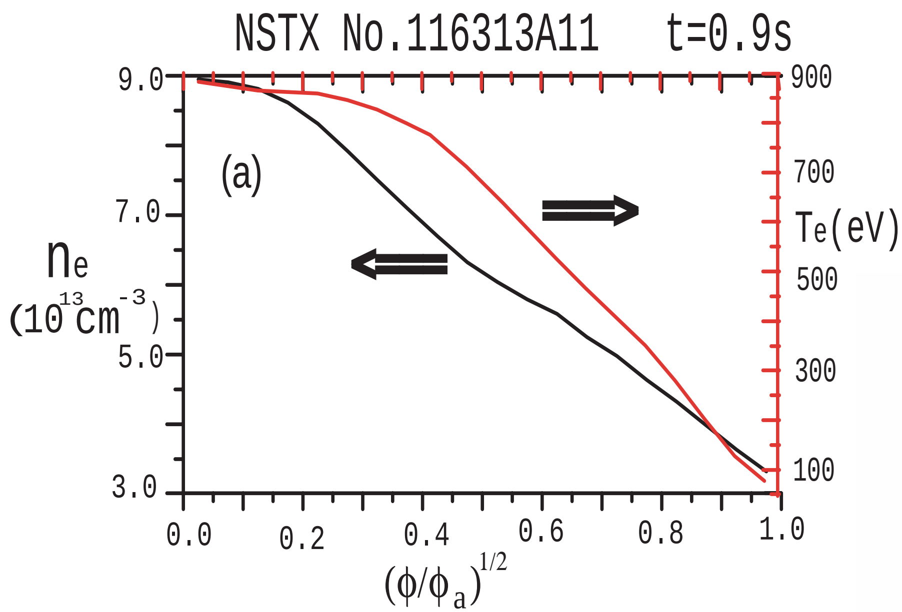
- Introduction
- Calculation of unstable microtearing modes for NSTX experimental data
- Theoretical electron thermal conductivity due to microtearing instabilities in NSTX
- Comparison with TRANSP analysis
- Reversed magnetic shear plasma
- Summary

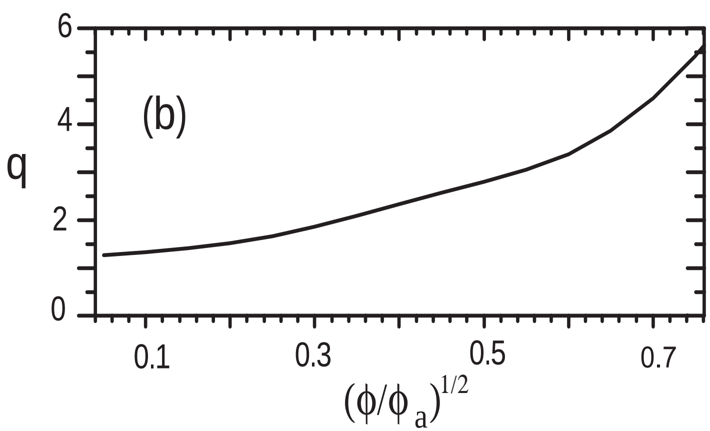
Introduction

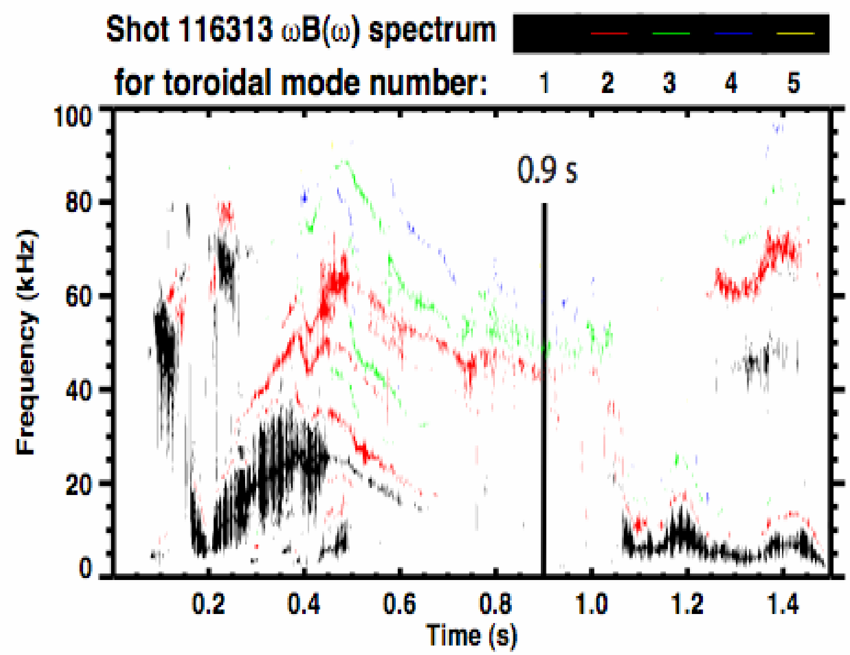
- Anomalous electron transport is an old subject, almost as old as magnetic fusion research itself
- Microtearing modes are unstable only at the edge of conventional tokamaks like D-III and C-MOD
- They are stable in the interior of a tokamak where T_e is high enough such that $\nu_{ei} < \omega_{*e}$
- They can be the most unstable mode in the interior of NSTX[1] and MAST[2], and should saturate at high amplitude due to the low magnetic field[3] and produce magnetic islands

1. M.H. Redi et al., EPS (2003)
2. D.J. Applegate et al.,Plasma Phys.(2004)
3. J.F. Drake et al., Phys. Rev. Lett. 44, 994 (1980)

Plasma Equilibrium







Results from GS2 code

- Two types of instabilities with $k_\theta \rho_s$ in the range of 0.3 - 1.0, ITG & microtearing, with opposite parities for the perturbed fields and opposite poloidal direction of propagation
- Microtearing modes can be the most unstable mode in the region r/a = 0.4 - 0.75 where T_e has steep gradient
- In this region a broad spectrum of microtearing modes are unstable

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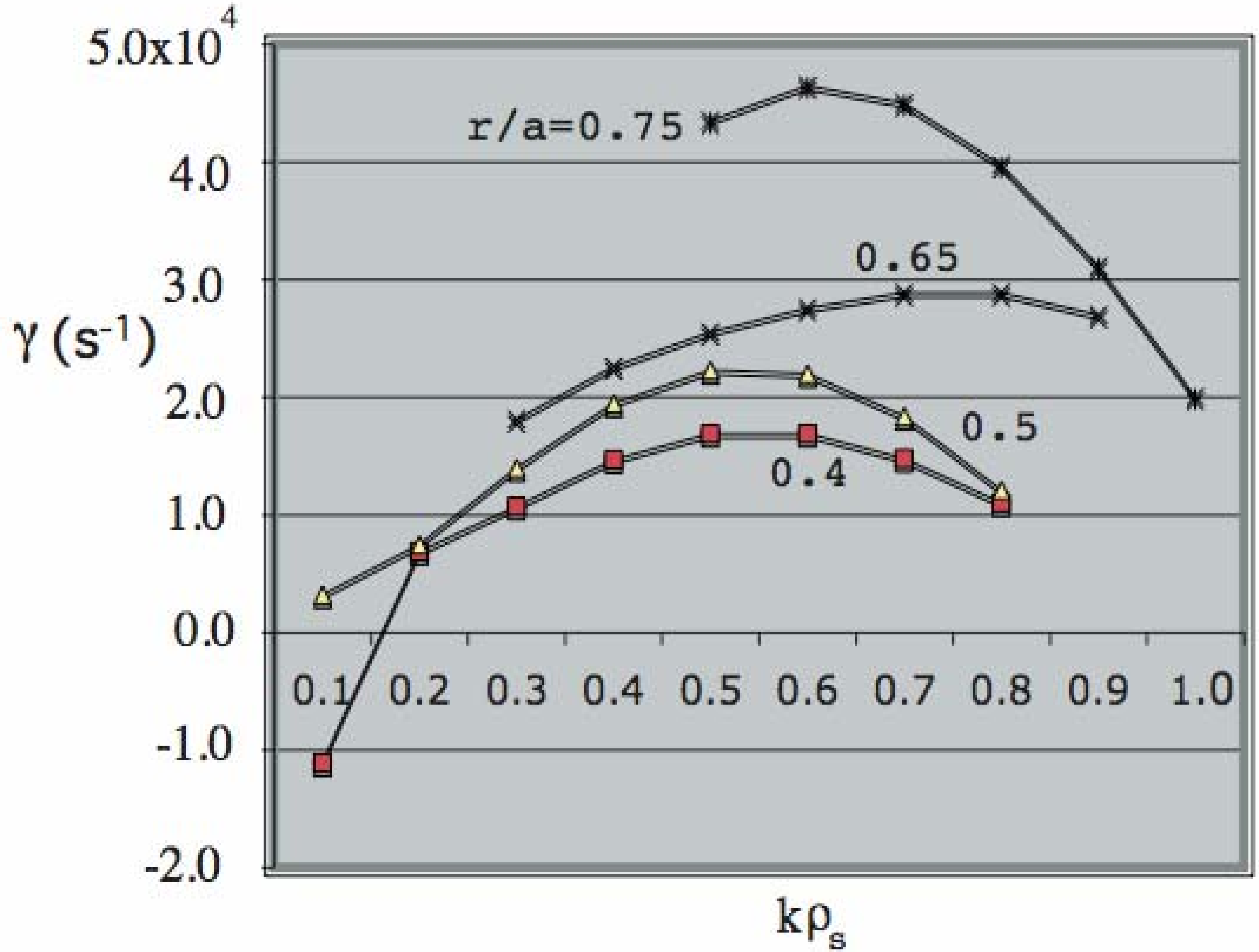

5.0x10^4
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
γ (s^-1)
r/a=0.75
0.65
0.5
0.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
kρs

Nonlinear saturation

While the GEM code is still in development stage, we rely on exiting nonlinear theory.

The nonlinear term causes an energy flow from short (unstable) to long wavelength modes which are stable. Growth and damping rates balance at $\delta B/B \approx \rho_e/L_T$,

and low magnetic field implies large ρ_e and high $\delta B/B$.

Ref: J. F. Drake et al., Phys. Rev. Lett. 44, 994 (1980)

Overlapping resistive layers

Resistive layers overlap when $m > m_o = q(2q'\rho_s)^{-1/2}$ or $k>k_o$

For shot 116313A11 at 0.9 s :

$\rho_s=(2T_e/m_i)^{1/2}/\omega_{ci}$, B=5kG, a=65cm, $\rho=r/a$

ρ	q	T_i	T_e	ρ_s	$q'=dq/dr$	m_o	$k_o=m_o/r$
0.4	2.3	900ev	780ev	1.1cm	$0.06cm^{-1}$	6.3	$0.24cm^{-1}$
0.5	2.8	800	680	1.1	0.068	7.2	0.22
0.6	3.2	630	560	1.0	0.13	6.3	0.16
0.7	4.5	470	440	0.8	0.29	6.5	0.14

* D.A. D'Ippolito et al., Phys. Fluids 23, 771 (1980)

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Global stochastic magnetic field

- When adjacent island chains are separated by KAM surfaces(as electron transport barriers), stochastic field lines are localized near the separatrix
- When adjacent island chains overlap, global stochastic magnetic field is expected
- One can estimate the island width from $(\delta B_r)_{mn}$ and find that adjacent islands overlap (usually the KAM surfaces are destroyed before islands overlap - the 2/3 rule)
- Substantial electron transport should ensue when either adjacent resistive layers or island chains overlap

  - see D'Ippolito et al.,Phys.Fluids(1980)

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Electron thermal conductivity in stochastic magnetic field

When islands overlap, magnetic field lines become stochastic with diffusion coeff D_M, the electron thermal conductivity in the collisional regime ($\lambda_{mfp} << L_c$) can be estimated by :

$$\chi_e = D_M v_e(\lambda_{mfp}/L_c) \text{ where } D_M \approx R|\delta B|^2/B^2$$

Ref: A.B. Rechester & Rosenbluth, Phys. Rev. Lett. 40, 38 (1978)
T.H. Stix, Nucl. Fusion 18, 353 (1978)
B.B. Kadomtsev & O.P. Pogutse (IAEA,Innsbruck-1978)

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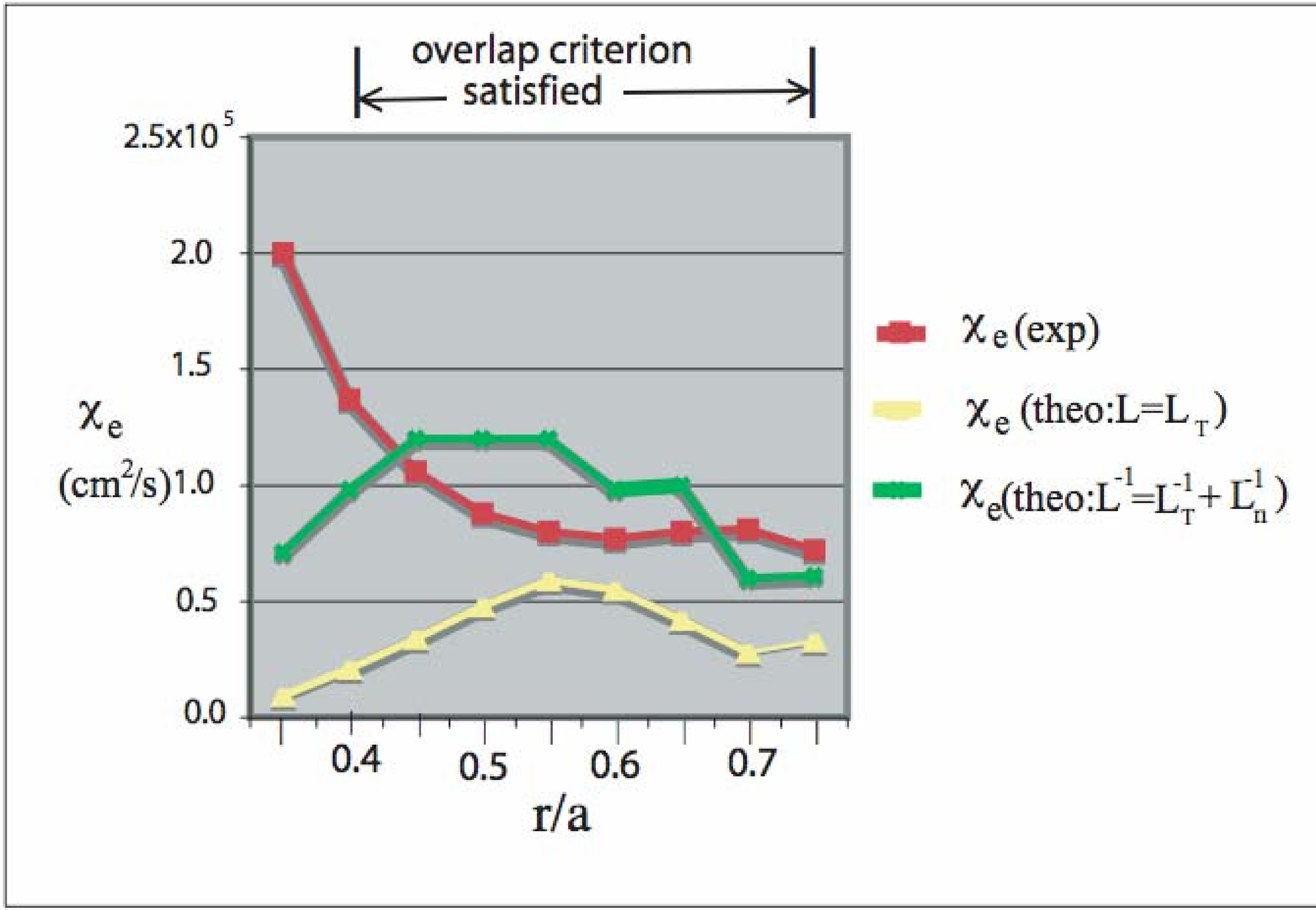
Field line correlation length

- A rigorous theory[1] on plasma transport in stochastic magnetic fields is extremely complex. The precise formula for the field line correlation length L_c is unknown
- We use $L_c=qR$ = field line connection length[2,3] instead of the Kolmogorov-Lyapunov length
- For NSTX plasmas, the electrons are weakly collisional: $1 < L_c/ \lambda_{mfp} < 10$

1. J.A. Krommes et al., J. Plasma Phys. 30, 11 (1983)
2. J.A. Krommes, private communication
3. B.B. Kadomtsev et al., IAEA (1978)

Comparison between χ_e^{exp} and χ_e^{theo}

- Drake's theory assumes $L_n >> L_T$ which is not strictly valid in the experiment
- In the region where $L_n > L_T$ (ρ=0.45-0.75), the agreement between χ_e^{exp} and χ_e^{theo} is not bad (within a factor 2.5)
- Get better agreement (within 40%) in the entire range (ρ=0.40-0.75) if we replace L_T by L where $L^{-1} = L_T^{-1} + L_n^{-1}$. However, microtearing is mainly driven by ∇T_e; so the true value is probably somewhere in between.
- In the region $\rho \lesssim 0.4$, $L_n < L_T \gtrsim 80$cm, the driving term from dT_e/dr is too weak, microtearing stable at $\rho \lesssim 0.3$, and χ_e there is determined by some other mechanism

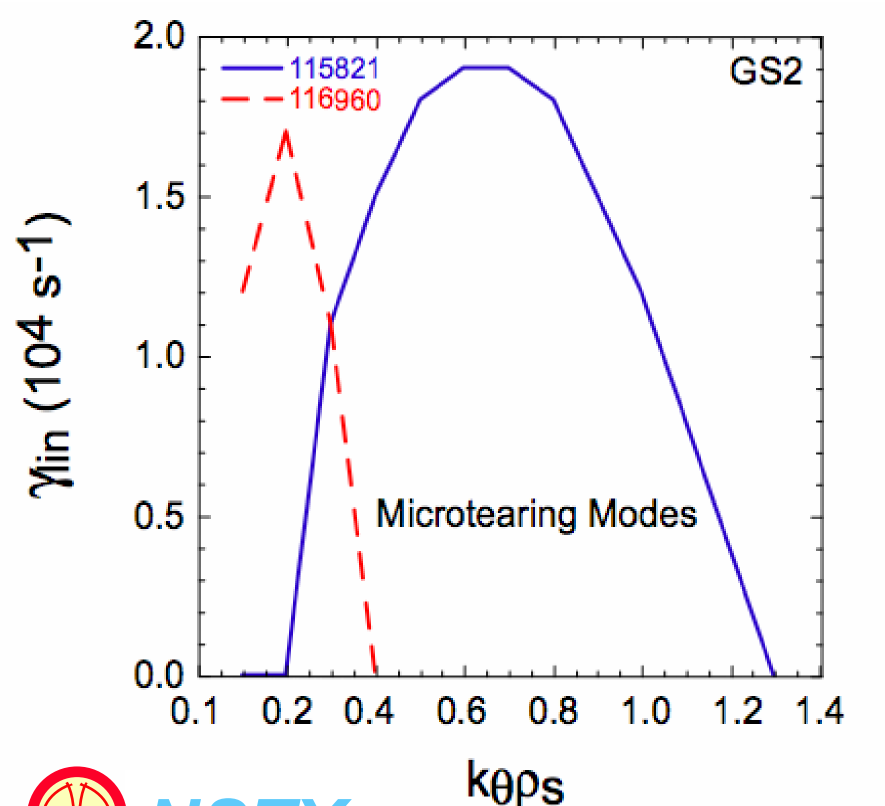

overlap criterion
satisfied
2.5x10^5
2.0
1.5
1.0
0.5
0.0
χe
(cm²/s)
0.4
0.5
0.6
0.7
r/a
χe (exp)
χe (theo:L=L_T)
χe(theo:L⁻¹=L_T⁻¹+ L_n⁻¹)

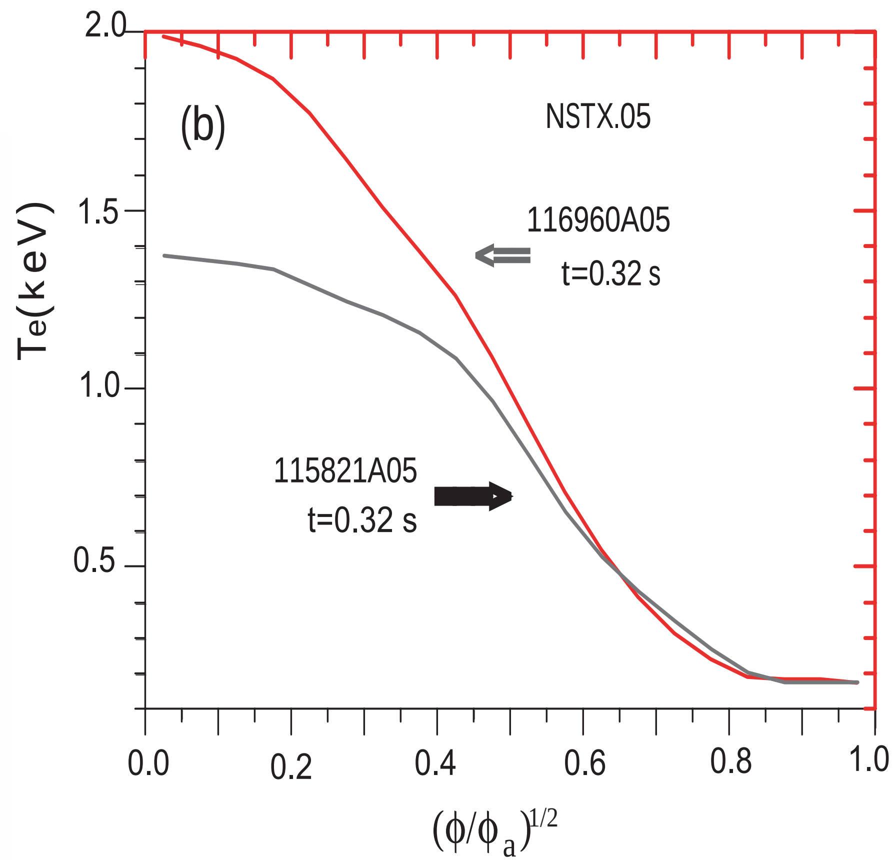
Higher $T_e(0)$ when microtearing modes are stabilized by reversed magnetic shear

Growth rate at ρ=0.3, t=0.32s

#115821 - normal shear

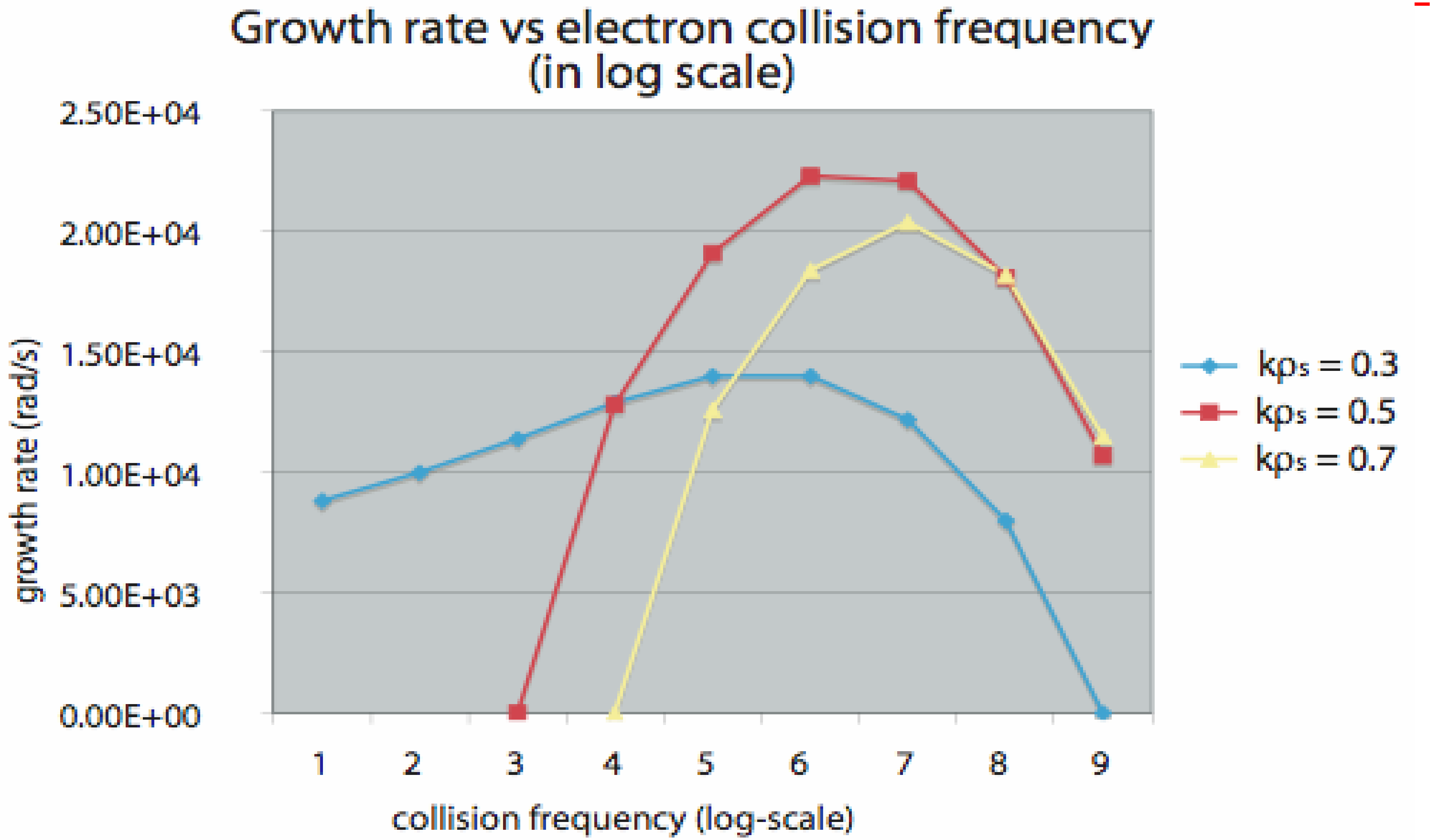
#116960 - reversed shear





Instability depends on ν_{ei}

(#116313A11, t=0.9s, r/a=0.5)



(Note: γ set to 0 for stable modes)

Final Remark

NSTX has the flexibility to operate in many regimes. What I show here is just one type of discharge that allows us to study the effect of microtearing modes. There are several ways to improve electron confinement in ST:

1. Raise B_T
   - HHFW heating efficiency improves
2. Raise T_e so that $\nu_e < \omega_{*e}$
   - can get $T_e(0)$ ~ 4 keV by HHFW heating
3. Reversed magnetic shear
   - High m modes stabilized and $T_e(0)$ becomes significantly higher with same NBI power

Summary

- Quantitative analysis of anomalous electron transport in NSTX is carried out without adjustable parameter
- In the region of strong T_e gradient, χ_e observed in the experiment is in reasonable agreement with nonlinear microtearing mode theory (within 2.5). This is not surprising because of the low toroidal magnetic field. The high mode amplitude causes global stochastic magnetic field, and Rechester-Rosenbluth theory applies.
- Microtearing modes are stable in reversed shear plasmas where $T_e(0)$ is substantially higher.
- Existing nonlinear theory can be improved by electromagnetic gyrokinetic simulation (GEM code).