Investigation of microtearing mode effects on electron transport in NSTX

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Outline

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

Introduction

- Anomalous electron transport is an old subject, almost as old as magnetic fusion research itself
- While ETG turbulence is a popular candidate for the explanation in tokamaks, here for NSTX, we investigate the stochastic magnetic field effects from microtearing instabilities [1,2]

1. M.H. Redi et al., EPS (2003)
2. D.J. Applegate et al.,Plasma Phys.(2004)

Why is it important for NSTX ?

- Microtearing modes are thought to be important only at the edge of conventional tokamaks like D-III[1] and C-MOD[2]
- 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[3], and should saturate at high amplitude due to the low magnetic field[4]

1. N. Ohyabu et al., Phys. Rev. Lett. 58, 120 (1987)
2. J. Kesner & S. Migliuolo, Nucl. Fusion 39, 163 (1999)
3. M.H. Redi et al., EPS(2003)
4. J.F. Drake et al., Phys. Rev. Lett. 44, 994 (1980)

Properties of microtearing modes

- High-m tearing modes ($k_{||}=0$)
- Driven by T_e gradient
  - Δ' is actually negative at high m (stabilizing)
- Perturbed electric field δE_r has odd parity
  - different from the even parity for ITG modes
- Propagate in the electron drift direction
  - opposite to the ITG mode
- Perturbed magnetic field δB_r has even parity and creates magnetic islands at q=m/n
- In slab geometry, instability requires (a) $\eta_e = d\ln T_e / d\ln n_e > 0.3$
  (b) Electron Coulomb collision rate $\nu_e > \omega_{*e}$
  - energy dependence of ν_e is crucial

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Microtearing modes in toroidal geometry

- In toroidal geometry, trapped particle effects come into play: (1) L. Chen (1977) - collisional detrapping is destabilizing - Krook ν_e (2) Catto (1981) - Lorentz ν_e
- This driving term has to compete with stabilizing effects like: (1) Field line bending effect ($\Delta' \approx -2k_\theta < 0$) (2) Collisional effect of passing electrons (3) Ion orbit effects - stabilizing if $dT_i/dr < dT_e/dr$ - Cowley (1986)
- When all stabilizing terms are retained, the trapped electron term is too feeble to drive microtearing instabilities in the interior of a realistic conventional tokamak - J. W. Connor (1990)

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The GS2 Code

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- Initial-value algorithm
- Flux tube code (ballooning limit)
- Calculate the growth rate and mode structure of the most unstable (fastest growing) eigenmode in a range of wavenumber
- Get input parameters directly from TRANSP output file

Ref: M. Kotschenreuther et al., Comp. Phys. Comm. 88, 128 (1995)
W. Dorland et al., Phys. Rev. Lett. 85, 5579 (2000)

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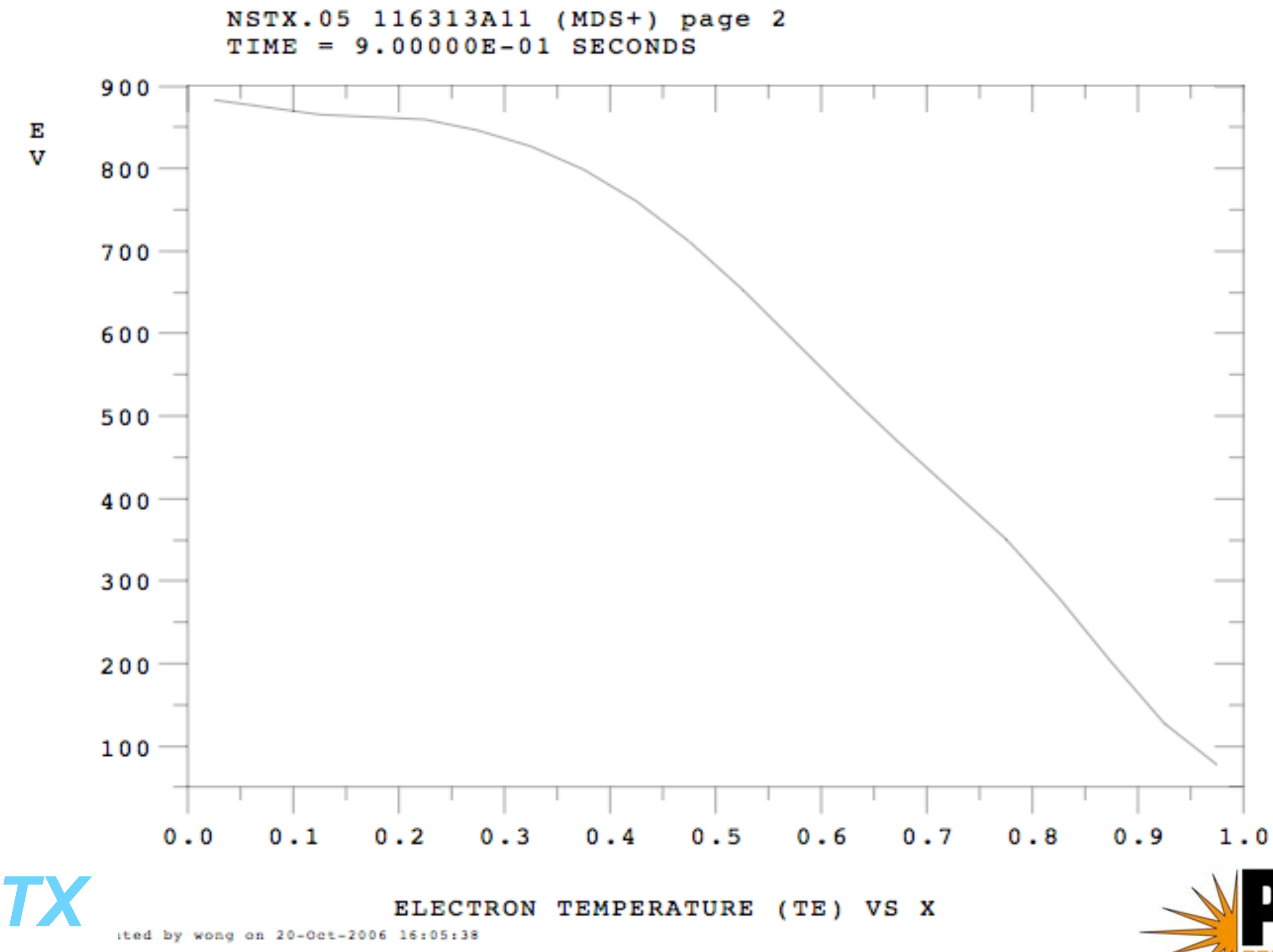
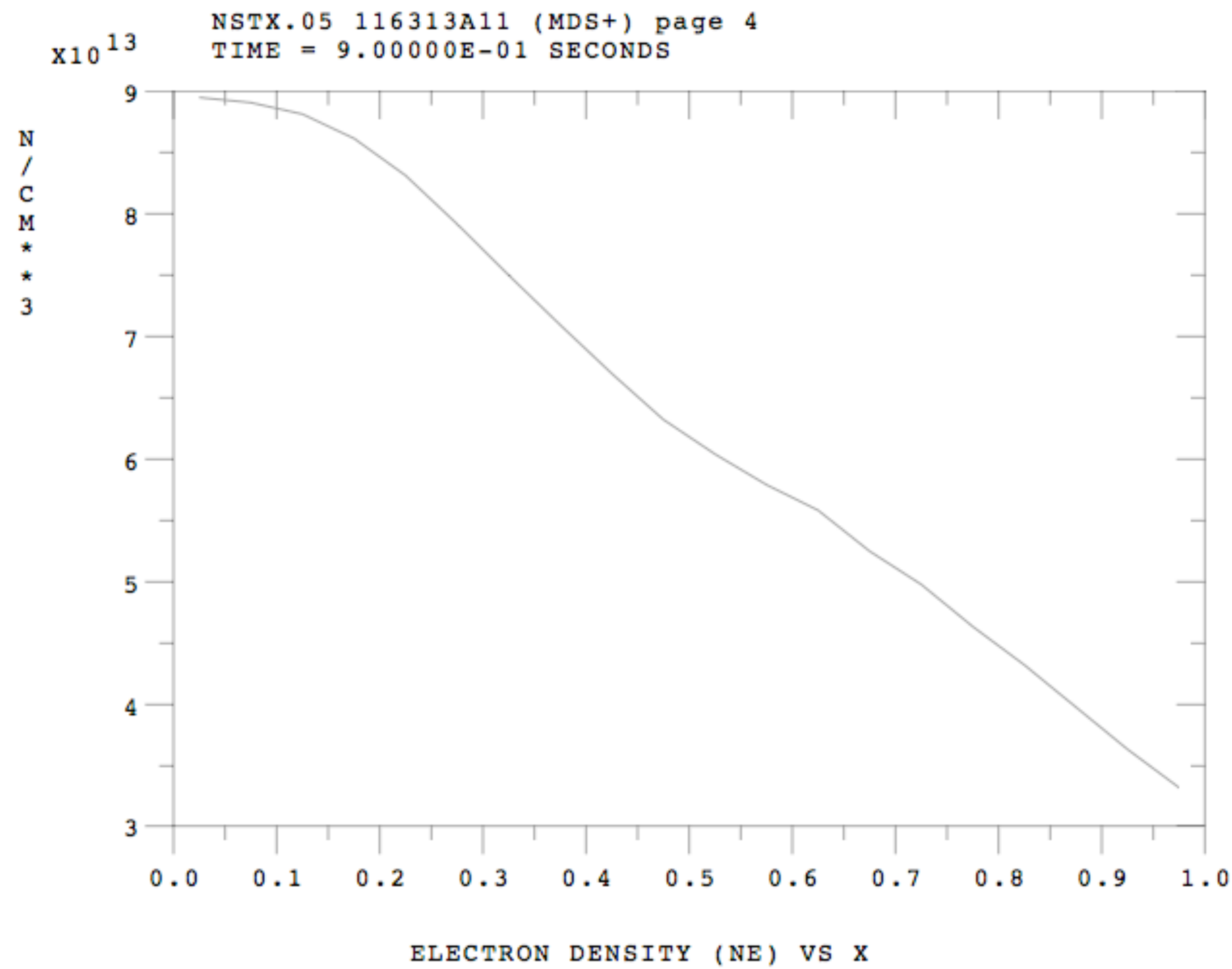
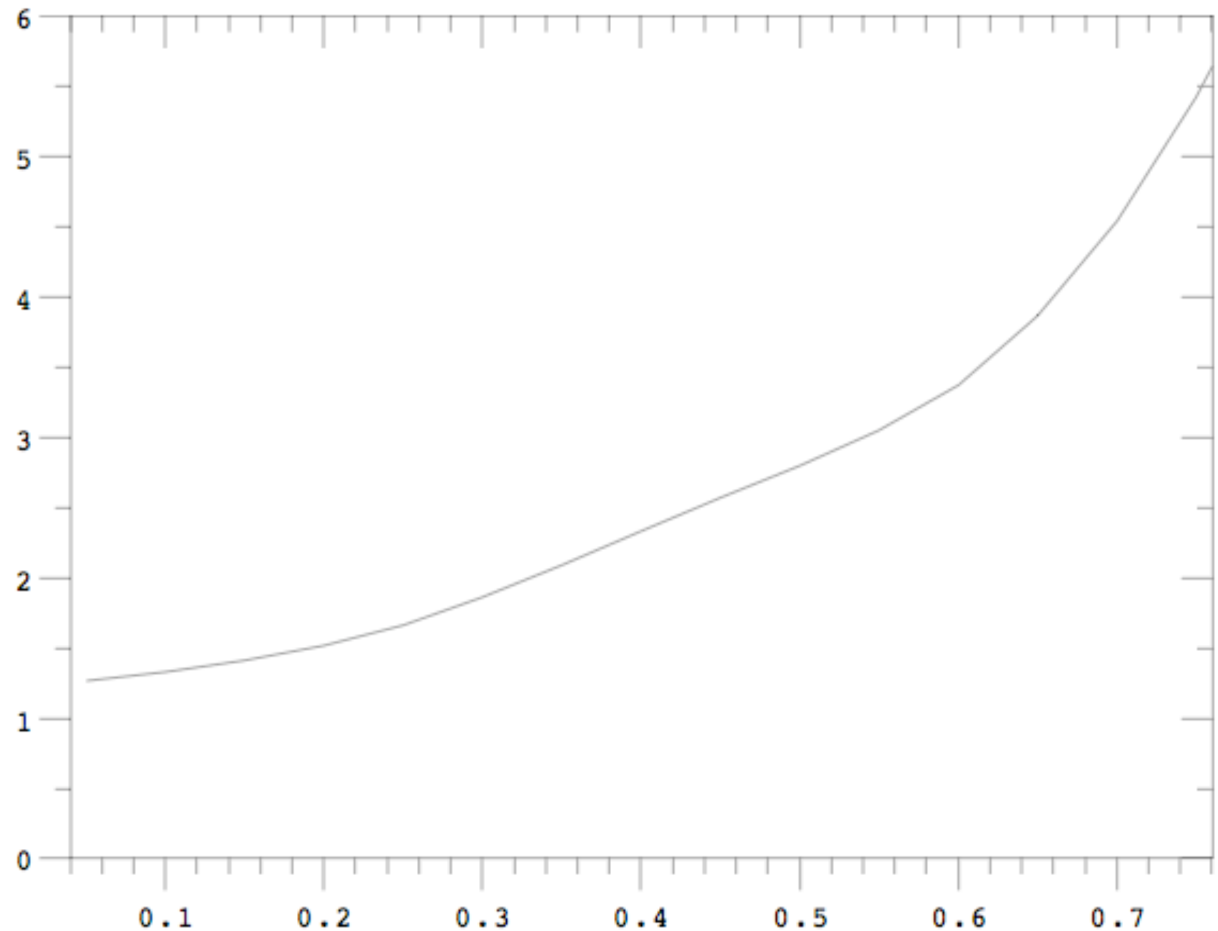
Plasma equilibrium for NSTX #116313 at 0.9 s





rplot generated by wong on 20-Oct-2006 16:05:38

NSTX.05 116313A11 (MDS+) page 7
TIME = 9.00000E-01 SECONDS



Q PROFILE (Q) VS XB

rplot generated by wong on 20-Oct-2006 16:05:38

Results from GS2 code

- Microtearing modes can be the most unstable mode in the region r/a = 0.35 - 0.75
- In the region where T_e has steep gradient (r/a=0.4-0.75), a broad spectrum of microtearing modes are unstable
- $k_\theta \rho_i$ is in the range of 0.3 - 1.0, comparable to ITG modes

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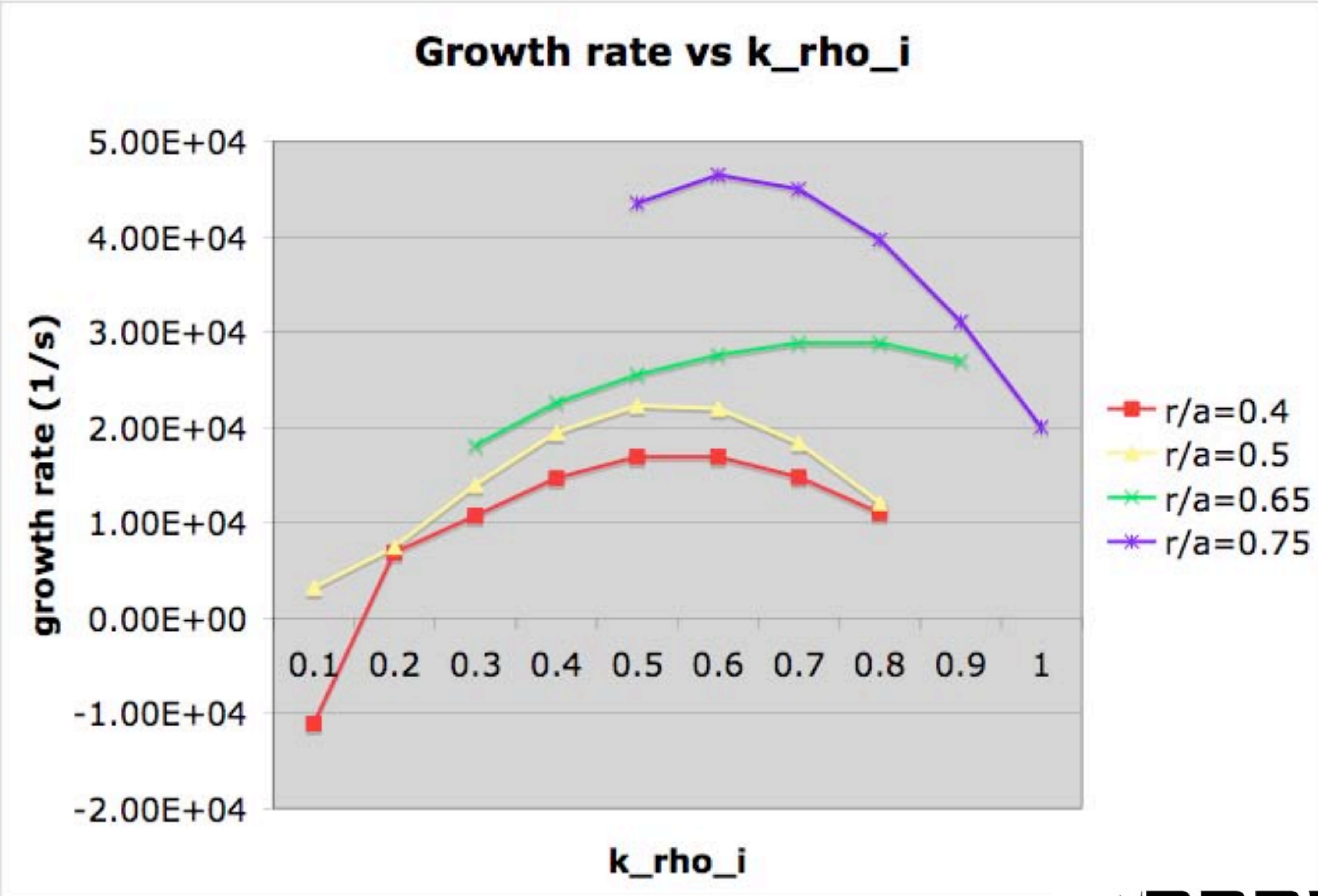
Growth rate vs k_rho_i
growth rate (1/s)
5.00E+04
4.00E+04
3.00E+04
2.00E+04
1.00E+04
0.00E+00
-1.00E+04
-2.00E+04
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
k_rho_i
r/a=0.4
r/a=0.5
r/a=0.65
r/a=0.75

Cautionary Remark

- The GS2 code only finds the most unstable mode
- Microtearing modes may still be unstable at other values of $k\rho_i$, but they do not appear in the GS2 output because some other modes (usually the ITG) are more unstable
- ITG and microtearing modes have opposite k_θ, which is reflected in the opposite signs of their real frequency

Bench-mark with analytic theory

Plasma parameters taken from TRANSP#116313A11, 0.9 s

$\eta_e > 0.3$ in the region $0.35 < \rho < 0.75$

Choose $\rho = 0.5$ where:

n_e=6.5e13 cm^{-3}, T_e=650 ev, L_{Te}=42 cm, L_{ne}=78 cm, B=5 kG, T_i=800 ev,

$\nu_e > \omega_{*e}$ is satisfied when microtearing modes are unstable according to the GS2 code

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Nonlinear saturation

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)

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Overlapping islands

Islands 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, ρ=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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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 (mfp << L_c) can be estimated by :

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

Ref: A.B. Rechester & Rosenbluth, Phys. Rev. Lett. 40, 38 (1978)
T.H. Stix, Nucl. Fusion 18, 353 (1978)

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Field line correlation length

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

1. J.A. Krommes et al., J. Plasma Phys. 30, 11 (1983)
2. J.A. Krommes, private communication

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χ_e due to saturated microtearing modes

Put $\delta B/B=\rho_e/L_T$, get $\chi_e = (\rho_e/L_T)^2 R v_e(mfp/L_c) = (\rho_e/L_T)^2 v_e^2/(\nu_{ei} q)$

Use parameters from #116313A11 at 0.9s, $L_c = qR$

ρ	Z_{eff}	T_e	n_e	ρ_e(cm)	v_e	L_T(cm)	$\nu_{ei}(s^{-1})$	q	χ_e^{exp}	$\chi_e^{theo}(cm^2/s)$
0.35	2.31	820ev	7.2e13	1.36e-2	1.2e9	133	8.1e5	2.0	2.0e5	0.093e5
0.40	2.16	780	6.8	1.33	1.17	80	7.8	2.3	1.37	0.21
0.45	2.03	735	6.5	1.29	1.14	57	7.6	2.6	1.06	0.34
0.50	1.92	680	6.2	1.24	1.09	42	7.7	2.8	0.88	0.48
0.55	1.82	620	5.8	1.19	1.04	33	7.9	3.0	0.80	0.59
0.60	1.75	560	5.65	1.13	0.99	28	8.6	3.4	0.77	0.55
0.65	1.74	500	5.4	1.06	0.94	25	9.7	3.9	0.80	0.42
0.70	1.77	430	5.1	0.99	0.87	22	11.7	4.6	0.81	0.28
0.75	1.84	380	4.8	0.93	0.82	15	13.8	5.6	0.74	0.33

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 3)
- In the region $\rho \leq 0.4$, $L_n < L_T \geq$80cm, the driving term from dT_e/dr is too weak, and χ_e may be determined by some other mechanism
- Get much better agreement (within 40%) in the entire range (ρ=0.40-0.75) if we replace L_T by L where $L^{-1} = L_T^{-1} + L_n^{-1}$

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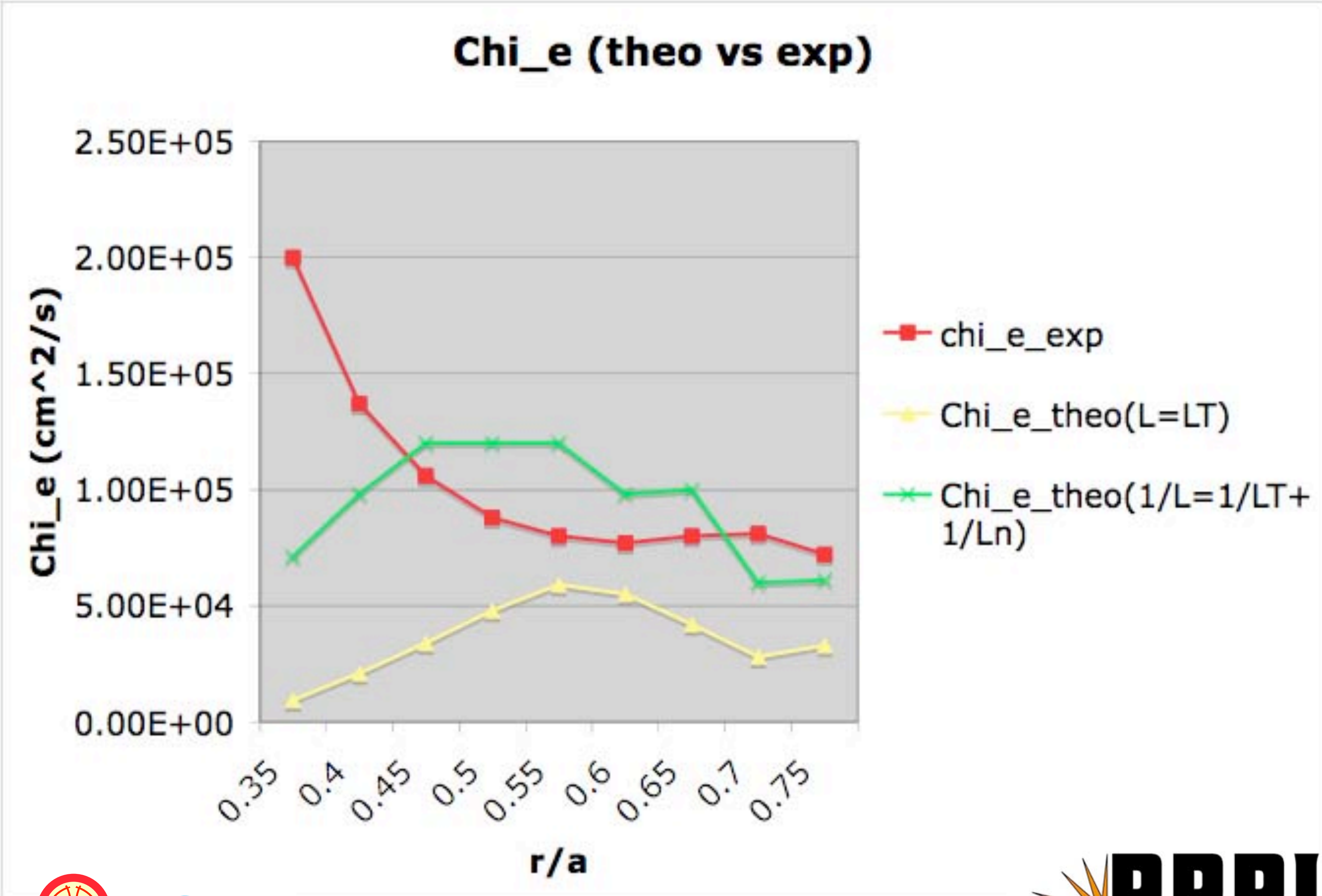
χ_e due to saturated microtearing modes

Put $\delta B/B=\rho_e/L_T$, get $\chi_e = (\rho_e/L_T)^2 R v_e(mfp/L_c)= (\rho_e/L)^2 v_e^2/(\nu_{ei} q)$

Use parameters from #116313A11 at 0.9s, $L_c= qR$

ρ	Z_{eff}	T_e	n_e	ρ_e(cm)	L_n	L_T(cm)	$\nu_{ei}(s^{-1})$	q	χ_e^{exp}	χ_e^{theo}(cm^2/s)
0.35	2.31	820ev	7.2e13	1.36e-2	75	133	8.1e5	2.0	2.0e5	0.71e5
0.40	2.16	780	6.8	1.33	69	80	7.8	2.3	1.37	0.98
0.45	2.03	735	6.5	1.29	65	57	7.6	2.6	1.06	1.2
0.50	1.92	680	6.2	1.24	78	42	7.7	2.8	0.88	1.2
0.55	1.82	620	5.8	1.19	78	33	7.9	3.0	0.80	1.2
0.60	1.75	560	5.65	1.13	83	28	8.6	3.4	0.77	0.98
0.65	1.74	500	5.4	1.06	48	25	9.7	3.9	0.80	1.0
0.70	1.77	430	5.1	0.99	52	22	11.7	4.6	0.81	0.60
0.75	1.84	380	4.8	0.93	35	15	13.8	5.6	0.74	0.61



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Summary

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- Quantitative analysis of anomalous electron transport in NSTX is carried out
- In the region of strong T_e gradient, χ_e observed in experiment is in reasonable agreement with nonlinear microtearing mode theory (within 3X)
- This is not surprising because of the low toroidal magnetic field
- More analysis is needed on more data before a definitive conclusion can be made

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