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A quantitative account of electron energy transport in an NSTX plasma

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In collaboration with

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Introduction

- Anomalous electron transport is an old subject, almost as old as magnetic fusion research itself.
- ITG turbulence apparently explains much of ion transport, electron transport is our new frontier.
- While ETG turbulence is a natural candidate for electron transport in tokamaks, here for NSTX, we estimate stochastic magnetic field transport produced by microtearing instabilities [1,2]

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

Outline

- Properties of microtearing modes
- Growth rate spectra and threshold for an H-mode plasma
- Ubiquitous modes; island chains at many rational-q surfaces
- Nonlinear saturation amplitude of B_r sets island width
- Island chain overlap creates ‘global’ stochastic magnetic field
- Parallel electron motion leads to large effective χ_e
- Comparison between theoretical & experimental χ_e
- Reversed magnetic shear largely stabilizes the modes
- Mitigation of microtearing modes with low collisionality

Why is microtearing important for NSTX?

- “the trapped electron term is too feeble” to overcome stabilizing effects in the core of a conventional tokamak [Connor, PPCF, 1990]
- Microtearing generally important only near the edge of DIII [Ohyabu, PRL(1987)] and Alcator C-Mod [Kesner, Nucl. Fusion 1999].
- Stable in plasma core where T_e is high enough such that $\nu_{ei}<\omega_{*e}$ - but NSTX has low T_e, and high n_e, so ν_{ei} is high

- Can be the most unstable mode in NSTX [Redi, EPS-03]
- High saturation amplitude due to low magnetic field
- Consistent with strong B scaling in NSTX, $\tau_E \sim B^{0.9}$ [Kaye, PRL, 2007] which is due mostly to changes in χ_e alone.

Properties of microtearing modes

- High-m (m~10-20) tearing modes ($k_{||}=0$)
- Driven by only ∇T_e

  Δ' is actually negative at high m (stabilizing)

Different from ITG modes :

	δE_r	δB_r	|| mode structure	k_θ direction
Microtearing	odd	even	extended	electron drift
ITG	even	odd	ballooning	ion drift

δB_r has even parity - creates magnetic islands at q=m/n

- In slab geometry, instability requires: [Wesson, "Tokamaks", 1997]

  (a) $\eta_e = d\ln T_e / d\ln n_e > 0.3$

  (b) collision rate must exceed electron diamagnetic freq., $\nu_{ei} > \omega_{*e}$

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Distinguishing between microtearing and resistive ballooning modes

- Frequency

  microtearing: $\omega = \omega_{*e} + c\,\omega_{*T}$, $0 < c < 1$

  resistive ballooning: $\omega \ll \omega_{*e}$

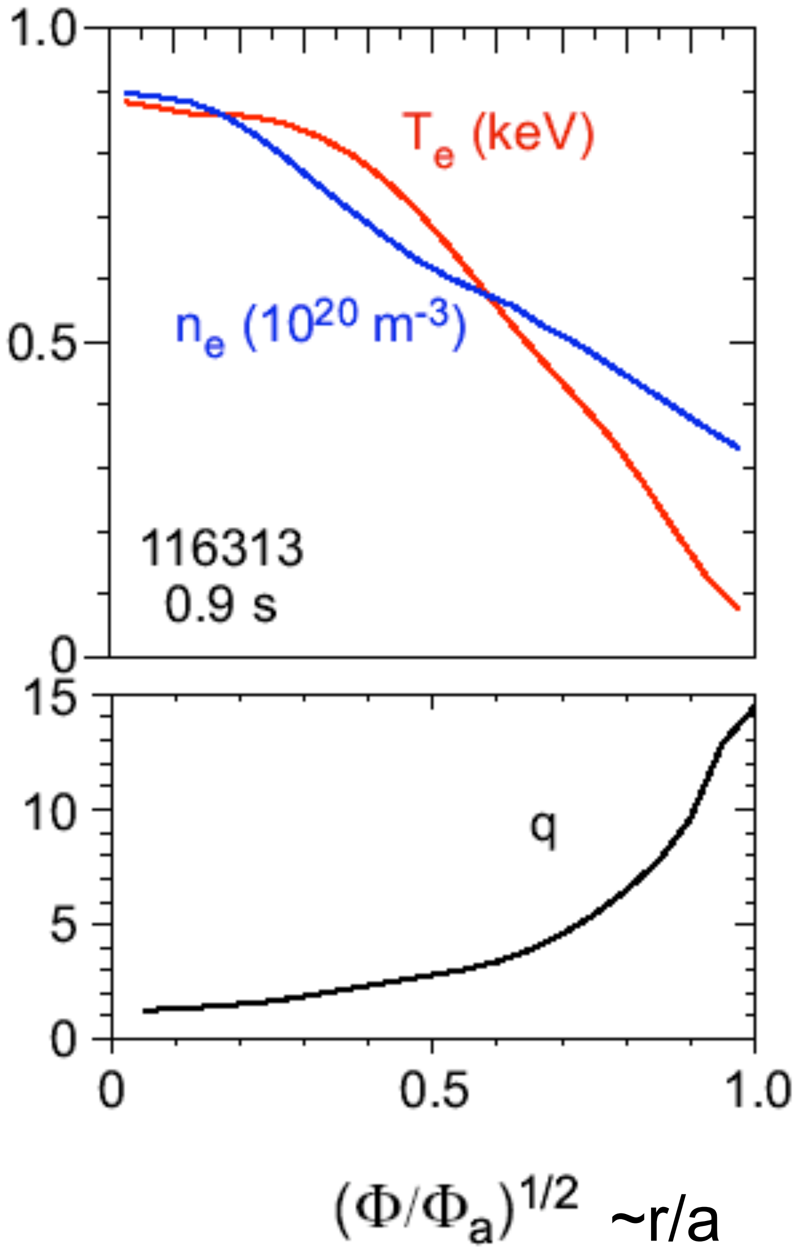
- Mode structure

  microtearing: $k_{||} = 0 \Rightarrow$ mode structure extended along **B**

  resistive ballooning: $k_{||} \neq 0$,

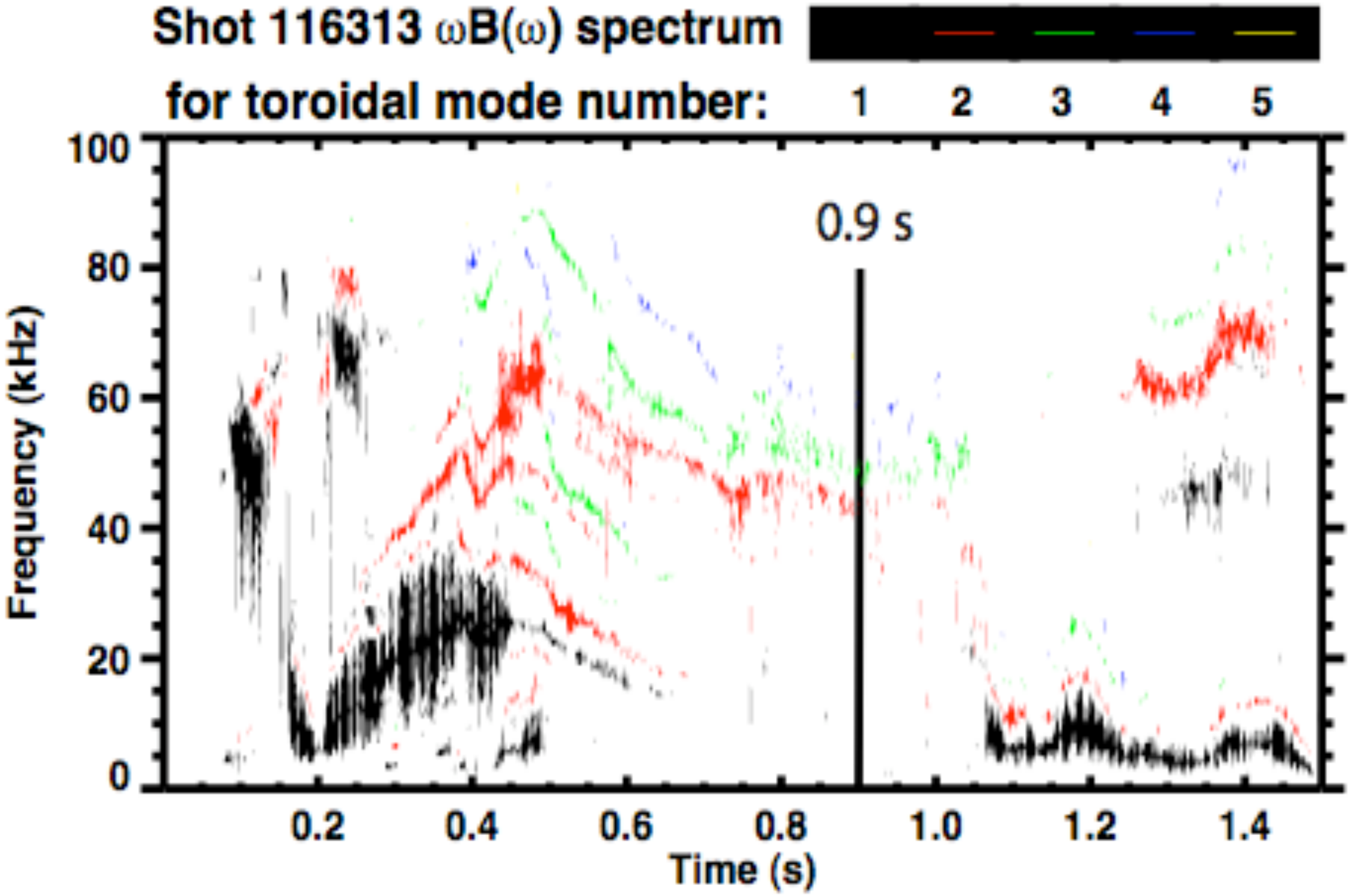
  mode amplitude peaks on low field side, because the bad curvature plays an important role

Plasma profiles for an NSTX H-mode plasma



~r/a

No low frequency MHD at time of interest

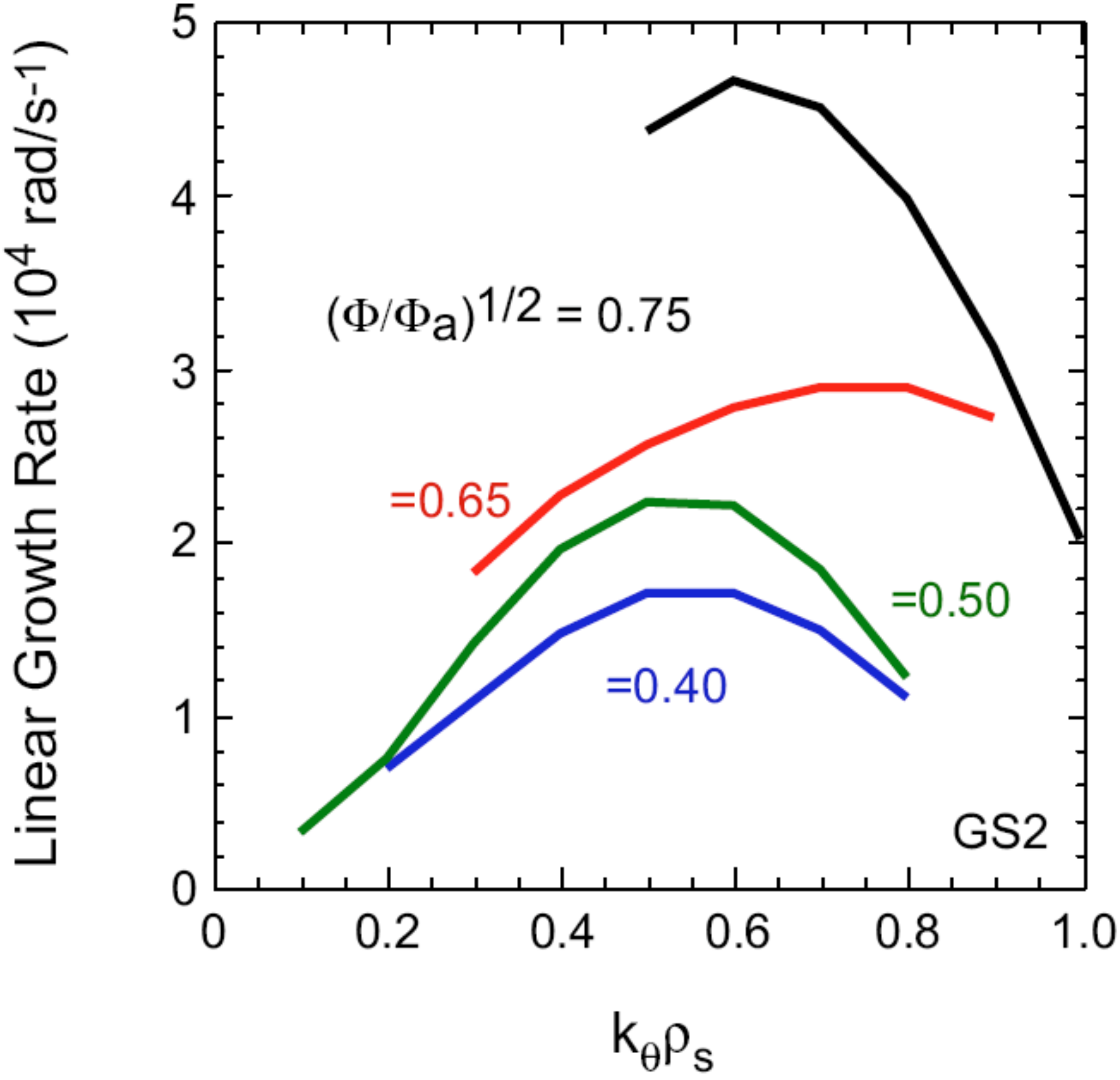


The GS2 gyrokinetic stability code

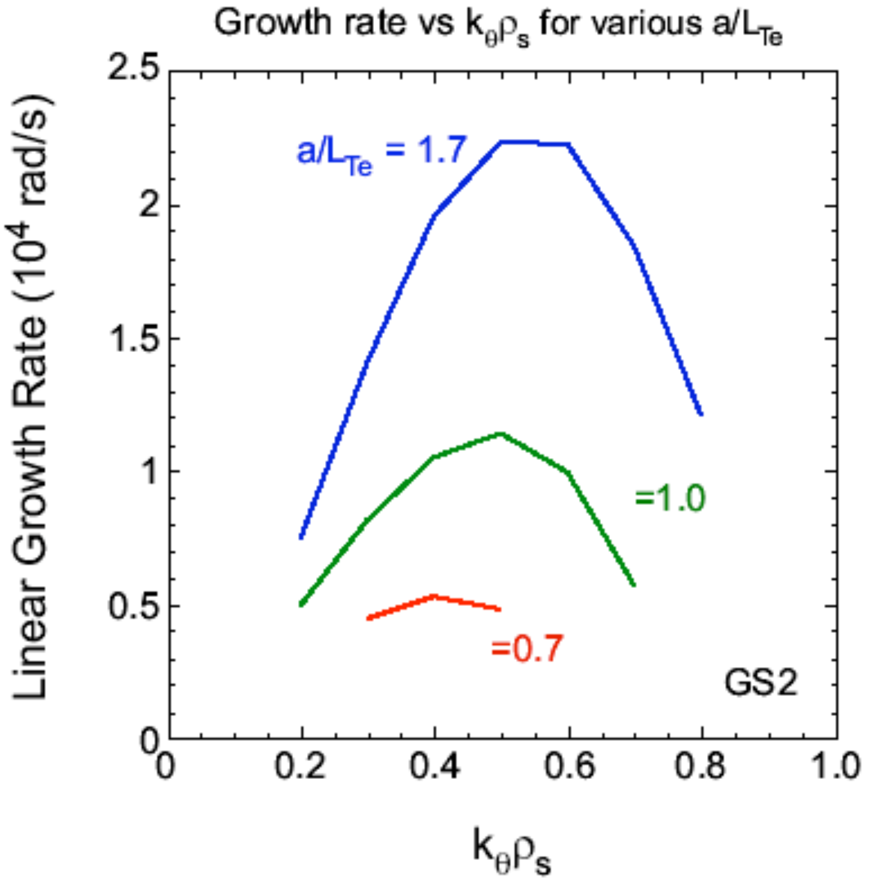
- flux tube geometry; ballooning coordinates
- the initial-value algorithm finds the
- growth rate and parallel mode structure of the most unstable eigenmode with a given k_θ
- get experimental profile input from TRANSP

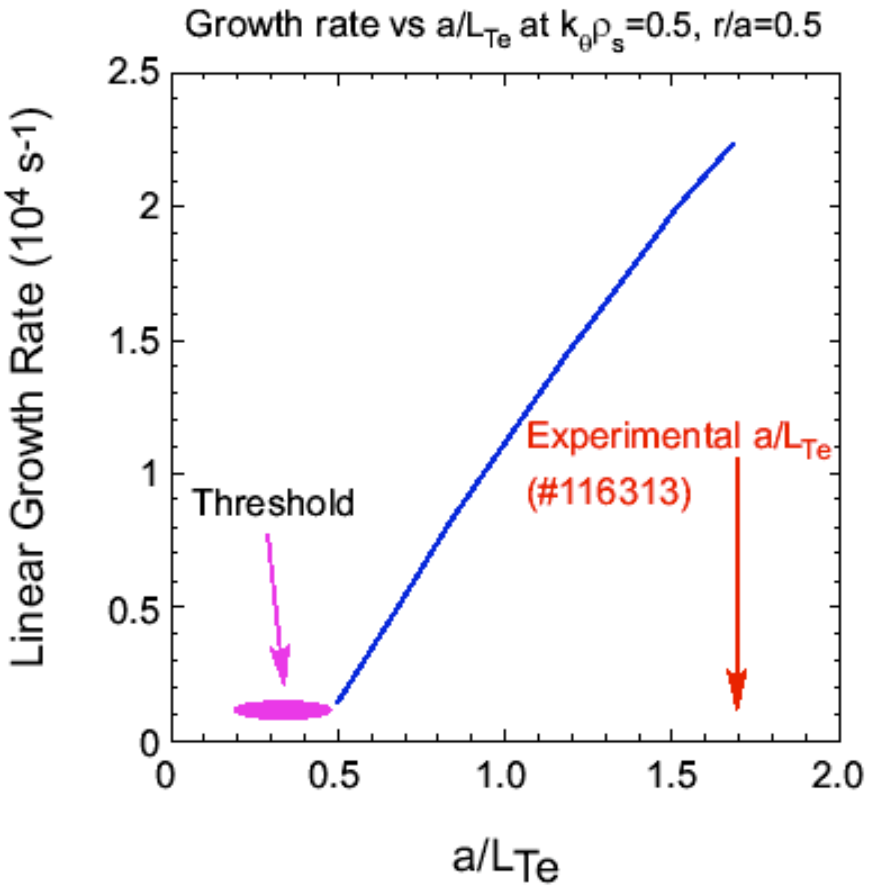
Ref: M. Kotschenreuther et al., Comp. Phys. Comm. 88, 128 (1995)
W. Dorland et al., Phys. Rev. Lett. 85, 5579 (2000)

Microtearing modes are broadly unstable



Experimental ∇Te is well above threshold


Growth rate vs $k_\theta \rho_s$ for various a/L_{Te}


Growth rate vs a/L_{Te} at $k_\theta \rho_s$=0.5, r/a=0.5

Compare GS2 with analytic theory

Choose $r/a = 0.5$ where:

n_e=6.5E+13 cm^{-3}, T_e=650 ev, L_{Te}=42 cm, L_{ne}=78 cm,

B=5 kG, T_i=800 ev, and

(1) $k_{||} = 1/(4\pi Rqn_{period}) \sim 2.3 \times 10^{-4}\ cm^{-1} \sim 0$ [Nyquist k]

require $n_{period} \sim 9$ for GS2 convergence.

(2) $k_\theta = 0.9\ cm^{-1}$, $\omega_{*e} = 1.7 \times 10^5$ rad/s, $\omega_{*T} = 3.1 \times 10^5$ rad/s,

GS2: $\omega = 2.8 \times 10^5$ rad/s, so $\omega = \omega_{*e} + 0.35\ \omega_{*T}$

(3) instability threshold is $\eta_e \sim 0.5 > 0.3$, the slab threshold

(4) $\nu_{ei} > \omega_{*e}$ is satisfied where GS2 finds that microtearing modes are unstable.

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Nonlinear saturation sets island width

The only available nonlinear theory [Drake, PRL, 1980] finds that unstable short wavelength modes are nonlinearly coupled to long wavelength modes which are stable.

Saturation of the modes occurs when

Growth and damping rates balance with $\delta B/B \approx \rho_e/L_T$,

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

Typically, ρ_e~0.01 cm, L_T~30 cm , and $\delta B/B \sim 3\times10^{-4}$

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

Caveats: 1. Assumes negligible magnetic shear

2. Theory developed for conventional tokamak, not ST's

3. Has not been checked with gyrokinetic simulations

Development of a stochastic magnetic field

- Magnetic islands in toroidal plasmas (Kerst-1962)

  Field line eq. : $d\mathbf{x}/d\tau = \mathbf{B}(\mathbf{x}) \Rightarrow$ Hamilton's eq.

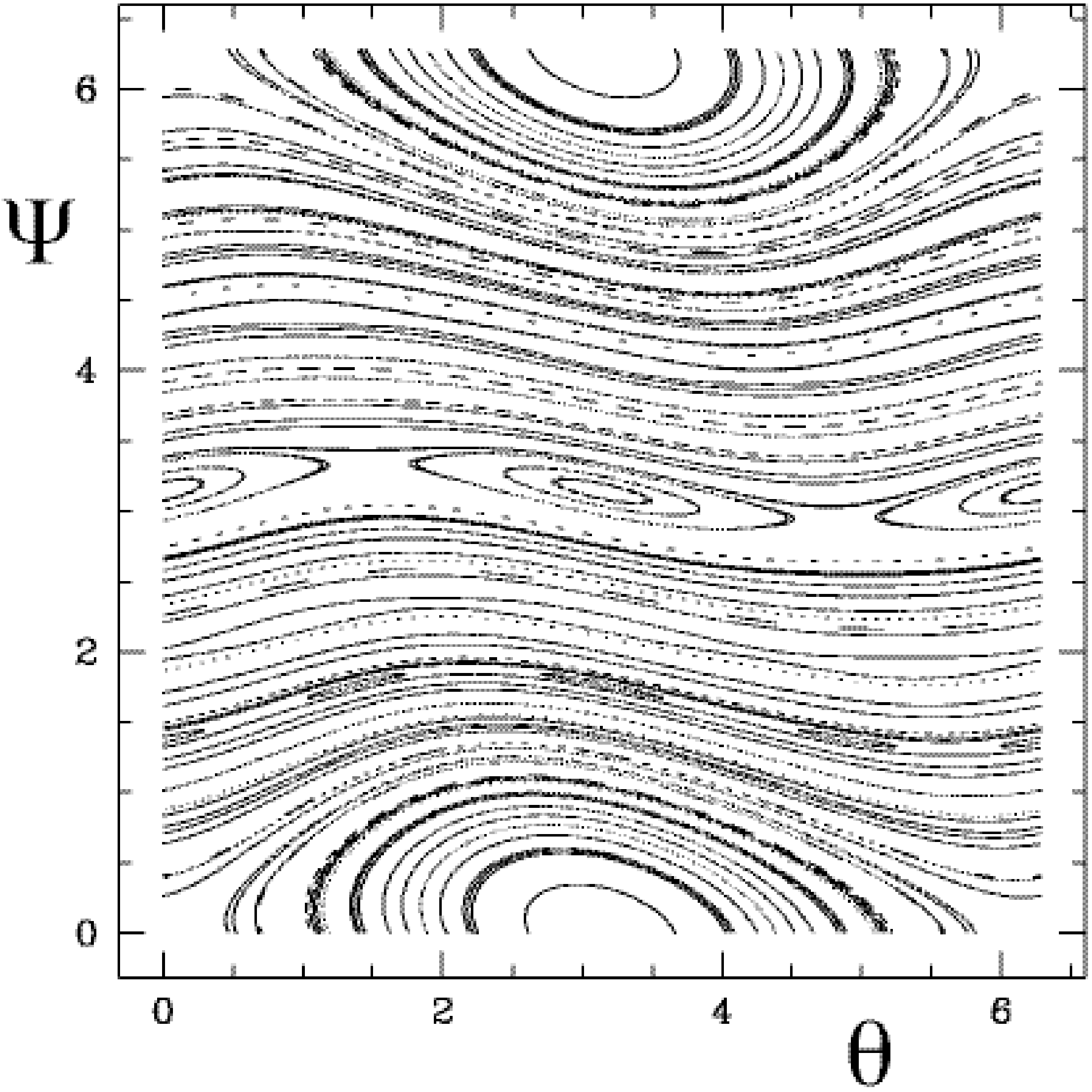
  In flux coordinates: (ψ_t,θ,ϕ) - canonical coordinates of the field lines, the eq become the Hamilton's eq, with ψ_p as the Hamiltonian
- Magnetic braiding - Stix (1973)
- Magnetic flutter - Callen (1977)
- Studies of chaotic fields use a standard map:

$$\theta_n = \theta_{n-1} + \Psi_{n-1},$$
$$\Psi_n = \Psi_{n-1} + K \sin \theta_{n-1}$$

- Vary K to find transition from local to global stochasticity

Narrow stochastic regions surround small island chains

Stochastic field lines are very localized near the separatrices (K=0.4)



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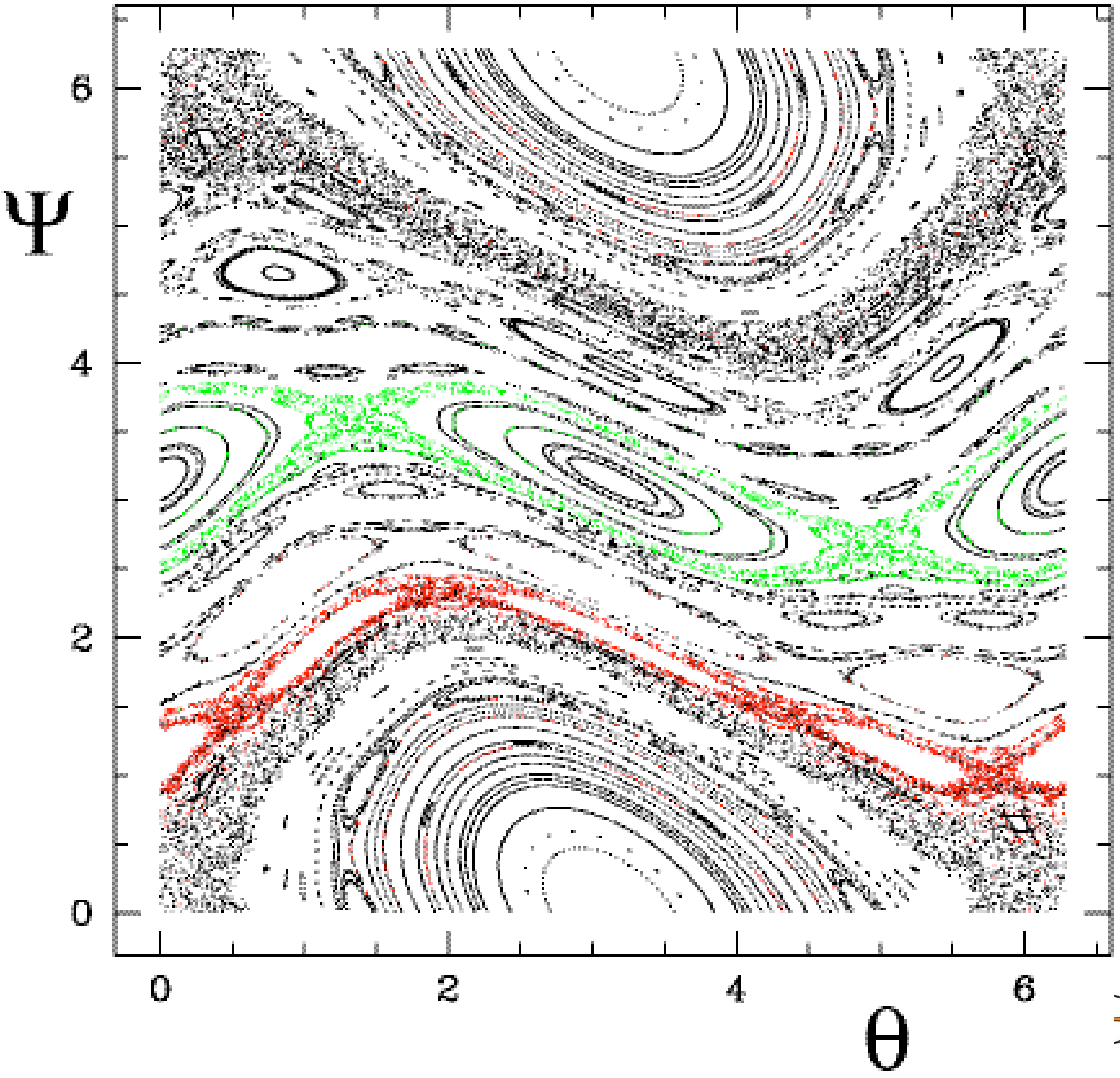
Island chain overlap with large islands produces global stochasticity

A single stochastic field line wanders through each of the red and green regions



K = 0.95 < 0.9716
global stoch. thres
Greene[1979]

Threshold for ‘global’ stochasticity

- When adjacent island chains are separated by good surfaces, stochastic zones are very localized.
- When many adjacent island chains overlap, a ‘global’ network of stochastic magnetic field is created.
- Resistive boundary layer of $2\rho_s$ sets a minimum width [Porcelli (PRL-1991)].
- Overlap of either the adjacent resistive layers or the island chains is sufficient [D’Ippolito et al.,Phys.Fluids(1980)]

Resistive layers are overlapping

Resistive layers ($d \sim 2\rho_s$) overlap when

$m > m_c = q(2q'\rho_s)^{-1/2}$, or $k_\theta > k_c$ ($k_c = m_c/r$)

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

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_c	$k_c = m_c/r$
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

Resistive layers overlap for $k\rho_s > 0.1\text{-}0.2$

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Island chains are overlapping

- Is stochasticity parameter $S = w/\delta r > 1$?
- Separation between adjacent island chains: $\delta r = 1/(n^2 q')$
- Island width = $w = 4\,[\,b_{mn}\,R\,q^2/(mq')\,]^{1/2}$ - J. Krommes
- $b = \delta B/B = \rho_e/L_T$, ($b \sim 3\times10^{-4}$)
- $b^2 = \sum b^2_{mn} = \Delta n\,\delta m\,b^2_{mn}$
- Spectral width: $\Delta n = \Delta m/q >> 1$, ($\Delta m \sim 20$)
- $\delta m = \Delta k_{||}/(Rq) \geq 1$ measures spread in $k_{||}$
- $S = 4m\,[\,(m/\Delta m)^{1/2}(m/\delta m q)^{1/2}\,R\,q'/q\,b\,]^{1/2}$, ($q \sim 2.8$)
- For #116313, get: $w \geq \rho_s$, and $S \geq 1$

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Stochastic magnetic field produces a large electron thermal conductivity

When islands overlap, magnetic field lines become stochastic, over a characteristic length, D_M

Parallel electron motion produces a ‘radial’ thermal conductivity (for the collisional regime, $\lambda_{mfp} << L_c$):

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

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)

Field line correlation length sets heat flux

- A rigorous theory[1] of plasma transport in stochastic magnetic fields is extremely complex; a precise formula for the field line correlation length L_c is unknown.
- R & R worked with a cylinder with $\langle B_\theta \rangle = 0$, and use

  L_c = Kolmogorov length ($\rightarrow \mu^{3/4}/\nu^{1/4}$ in fluid mechanics)

  = e-folding length of flux tube circumference
- We use $L_c = qR$ = field line connection length[2,3] instead. For NSTX plasmas, the electrons are collisional:

  $1 < L_c/\lambda_{mfp} < 10$

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

χ_e due to saturated microtearing modes

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

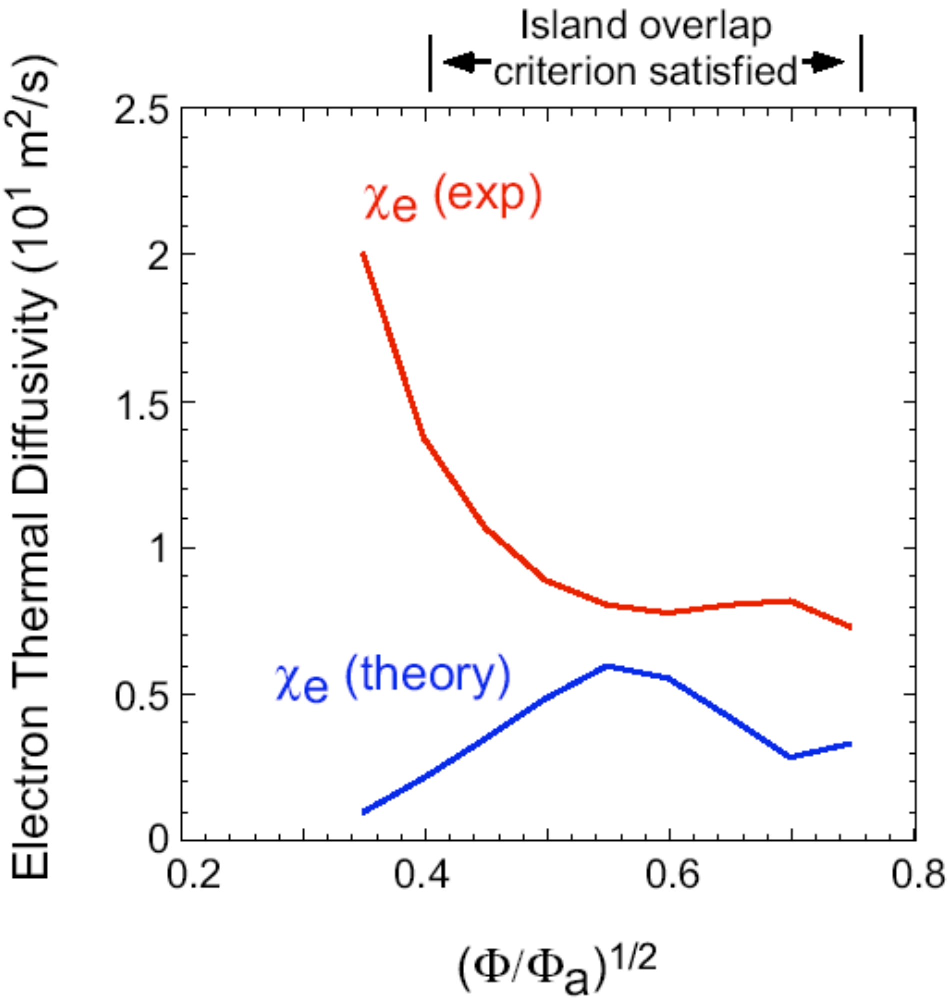
Use parameters from #116313A11 at 0.9s, $L_c = qR$

ρ	Z_{eff}	T_e	n_e	ρ_e(cm)	v_e	L_T(cm)	$\nu_{ei}(s^{-1})$	q	χ_e^{exp}	$\chi_e^{theo}(m^2/s)$
0.35	2.31	820eV	7.2e13	1.36e-2	1.2e9	133	8.1e5	2.0	2.0e5	0.93
0.40	2.16	780	6.8	1.33	1.17	80	7.8	2.3	1.37	2.1
0.45	2.03	735	6.5	1.29	1.14	57	7.6	2.6	1.06	3.4
0.50	1.92	680	6.2	1.24	1.09	42	7.7	2.8	0.88	3.8
0.55	1.82	620	5.8	1.19	1.04	33	7.9	3.0	0.80	5.9
0.60	1.75	560	5.65	1.13	0.99	28	8.6	3.4	0.77	5.5
0.65	1.74	500	5.4	1.06	0.94	25	9.7	3.9	0.80	4.2
0.70	1.77	430	5.1	0.99	0.87	22	11.7	4.6	0.81	2.8
0.75	1.84	380	4.8	0.93	0.82	15	13.8	5.6	0.74	3.3

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

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

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

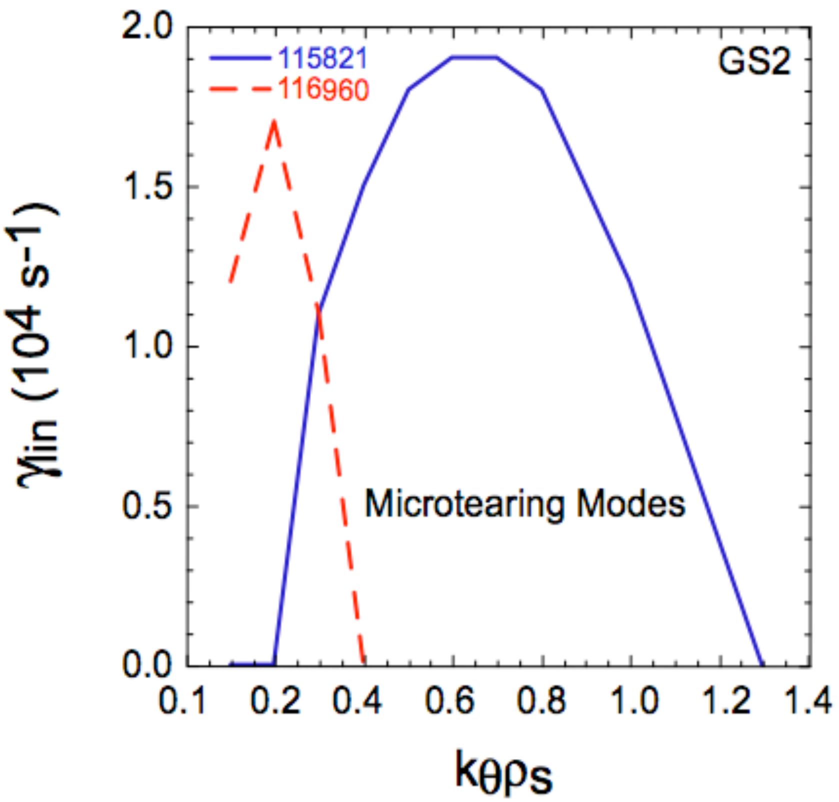


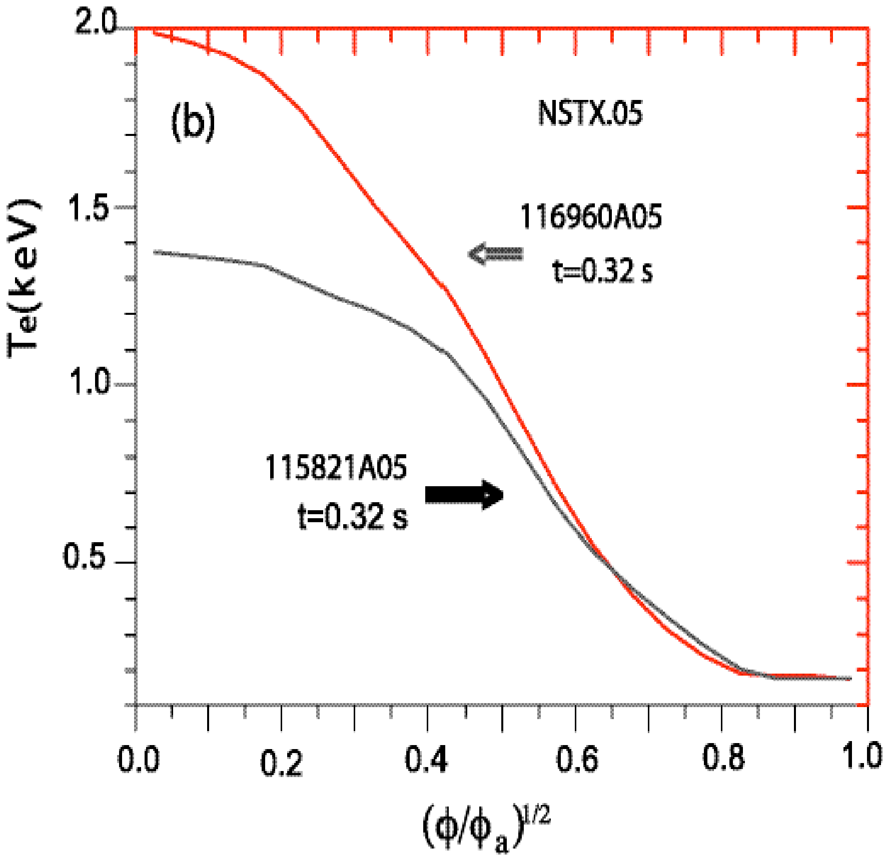
Higher $T_e(0)$ seen when microtearing modes are stabilized by reversed magnetic shear

Growth rate at ρ=0.3, t=0.32s

#115821 - normal shear

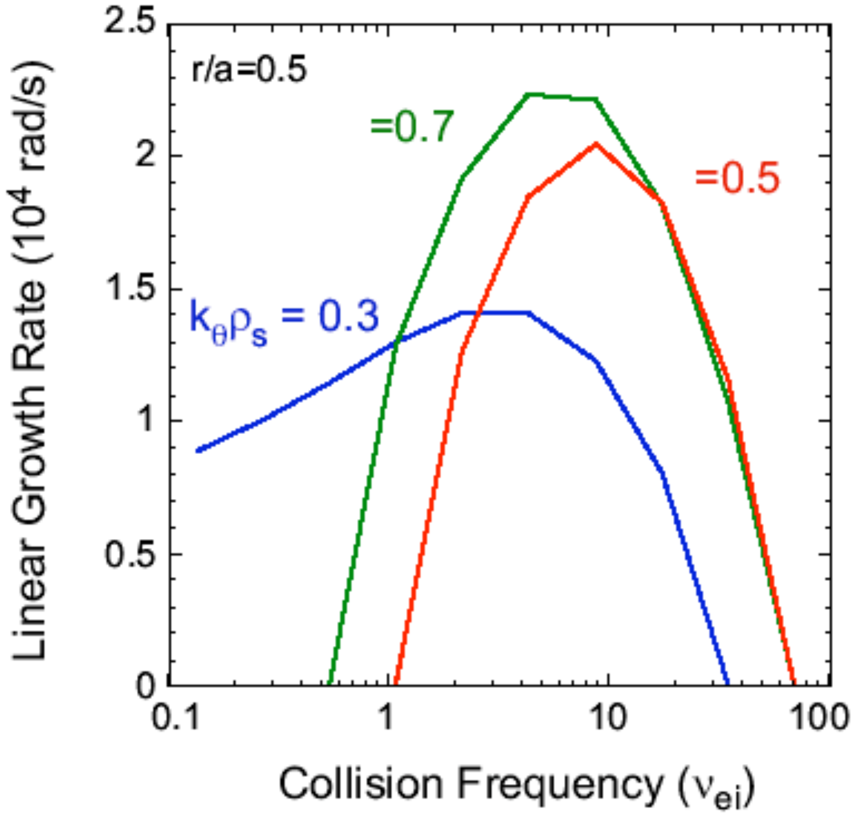
#116960 - reversed shear

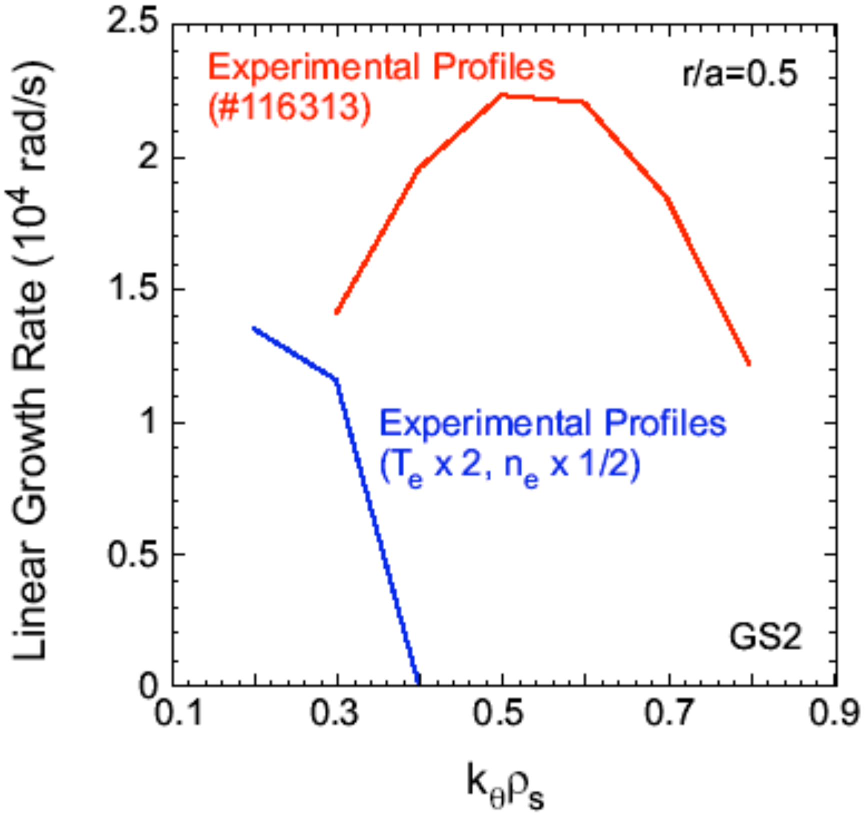




Microtearing modes are stable at low ν_{ei}

Reduce transport by lowering n_e and raising T_e





Means of improving electron confinement

NSTX has the flexibility to operate in many regimes, several of which alleviate the effect of microtearing modes:

1. Reversed magnetic shear
   - High m modes stabilized and $T_e(0)$ becomes significantly higher with same NBI power
2. Raise B_T to reduce saturation level
   - $\tau_E \sim B_T^{0.9}$
   - HHFW heating efficiency also improves, enabling
3. Higher T_e so that $\nu_e < \omega_{*e}$
   - can get $T_e(0) \sim 4$ keV by HHFW heating

Summary

- Quantitative analysis carried out - no adjustable parameter
  - theoretical χ_e is in reasonable agreement with experiment.
- This is not surprising because of the low toroidal magnetic field, which leads to high mode amplitude, causing global stochastic magnetic field, and Rechester & Rosenbluth's theory applies.
- Microtearing modes are more stable in reversed shear plasmas
  - and T_e in the core is substantially higher.
- The microtearing instability is not an intrinsic problem in STs
  - should become stable at higher T_e (lower collisionality).
- This result does not rule out ETG or other anomalous loss mechanism.
- More detailed calculations with GEM, a global electromagnetic gyrokinetic simulation code, will begin soon; will include magnetic flutter.

NSTX sessions

Oral session CO3 Monday morning

Poster session TP8 Thursday afternoon

NSTX Research Forum
November 27-29, 2007
http://nstx-forum-2008.pppl.gov/index.html