Stochastic heating of thermal ions by ETG streamer turbulence

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NSTX 5 Year Plan Ideas Forum

June 24–26, 2002

Princeton Plasma Physics Laboratory

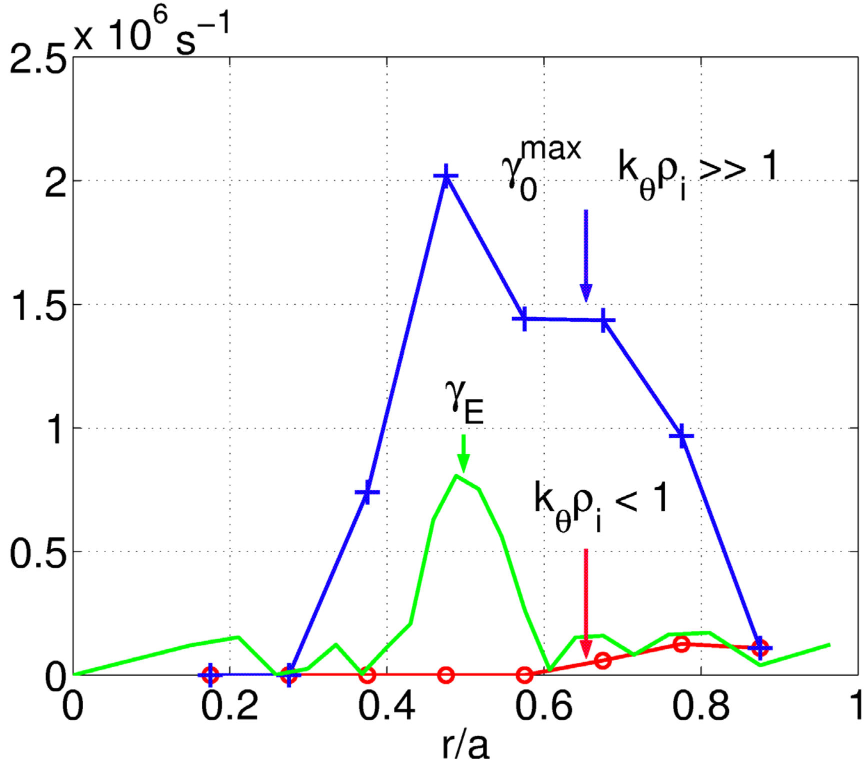
NSTX Motivation 1: Rapid electron transport

- NSTX χ_e typically 5-20m^2/s across profile
  - Simple mixing length estimate for ETG (note $v_{te}^2 \equiv T_e/m_e$) $\Rightarrow$ $\chi_e \sim \rho_e^2 v_{te}/L_{Te} \equiv D_{ETG} = 0.075\ [T_e(\mathrm{keV})]^{3/2} / B^2 L_{Te}$
  - For NSTX near r/a = 0.5:
    - T_e=0.8keV, B=0.3T, L_{Te}=0.4m, D_{ETG} = 1.5 m^2/s
    - For B=0.45T, D_{ETG}=0.7 m^2/s
- ETG χ_e with streamers ~ 10-20 D_{ETG} using s-α equilibria at higher aspect ratio (Dorland et al., PRL, December 2000, 5579)
- Crudely applied to NSTX, **streamer ETG** $\Rightarrow$ χ_e = 10-20m^2/s

Motivation 2: with strong rotation, χ_i can be ≤ 0

- χ_i can be <u>less than</u> neoclassical between $r/a = 0.4$ and 0.8
  - Only possible with ion heating anomaly or diagnostic error
- Linear ETG simulations predict robust instability in same minor radial region
- Can ETG streamers heat ions through dissipation?
- If so, what are the thermodynamic implications?

From GS2 – C. Bourdelle



#104001 at 0.28 s

Estimate of ETG streamer dissipation

- First, estimate normalized fluctuation amplitude $\Phi = e\phi/T_e$
  - Balance KH against streamer growth:

    $$\boldsymbol{\Phi = \rho_e/L_{Te}\, \Gamma^{-1}\, \tau/(1+\tau)\, \gamma/k_\perp^4}$$ *(See Dorland PRL)*

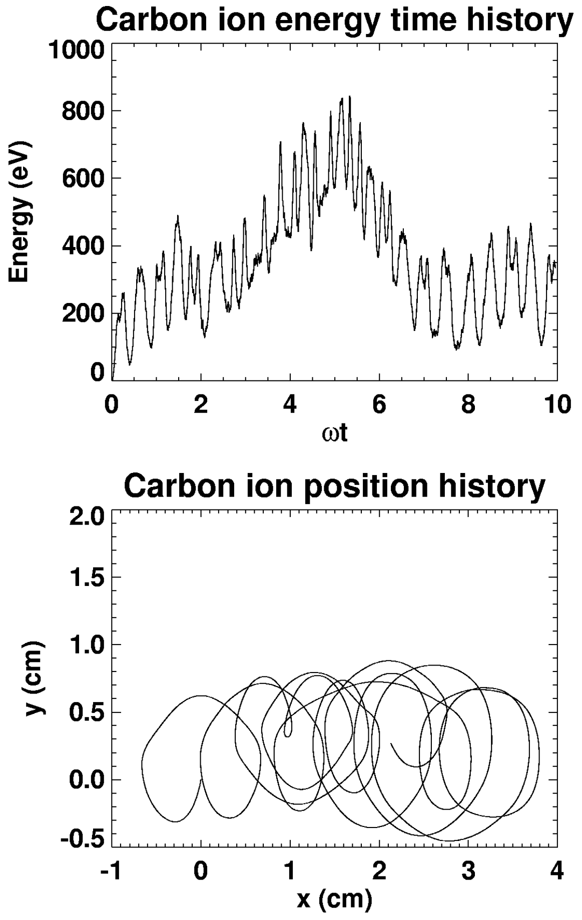
    - Γ = KH growth rate coefficient ≈ 0.2-0.3
    - $\tau = Z_{eff}\, T_e / T_i \approx 1\text{-}2$
    - $\gamma/k_\perp^4 = 10\text{-}30$ for positive shear tokamaks
  - For these coefficients, T_e = 800eV, and NSTX B-fields, $\Phi = 0.5\text{-}5\% \Rightarrow \phi \approx 4\text{-}40\text{V}$ assuming L_{Te}=0.4m
  - Saturated turbulence predicted to have $k_\theta\rho_e \approx 0.2 \Rightarrow$ large fine-scale E-fields ≈ 10-20kV/m

Details of ion heating simulations

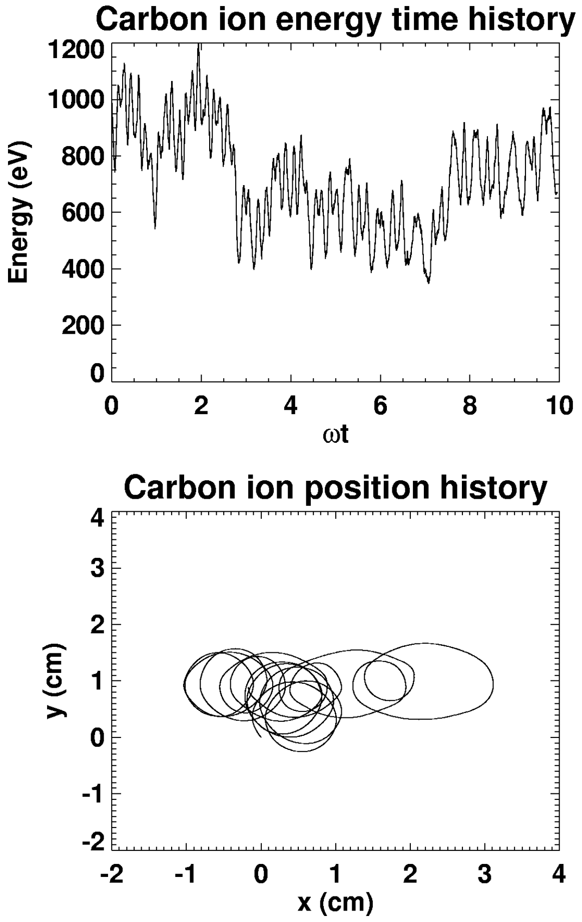
- Solve orbit equation: **$mdv/dt = qv \times B + qE + F_{collision}$** using full test-particle collision operator assuming background Maxwellian ion distribution *with constant T_i*
  - For long integration times, any test-particle heating from wave will be dissipated by the background ions.
  - Equivalently, the test particle temperature is always close to background $T_i \Rightarrow$ many runs needed to determine dT_i/dt vs. T_i
- Simulation parameters:
  - $T_e = T_i = 1\text{keV}$
  - $B=0.3\text{T}$, $\phi = 20\text{V} \Rightarrow$ **$e\phi/T_e = 2\%$**
  - $n_e=4\times10^{19}\text{m}^{-3}$ in deuterium, $Z_{eff}=2$, Carbon impurity ($Z=6$)
  - $k_\theta \rho_e = 0.2 \Rightarrow$ **$\alpha \approx 3$**
  - $\nu=0.11$ ($f\approx250\text{kHz}$)

Ion-ion collisions cause significant energy diffusion

Initial E = 1eV



Initial E = 1keV

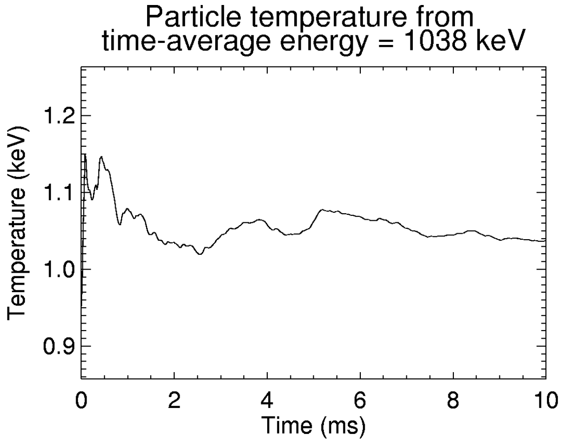


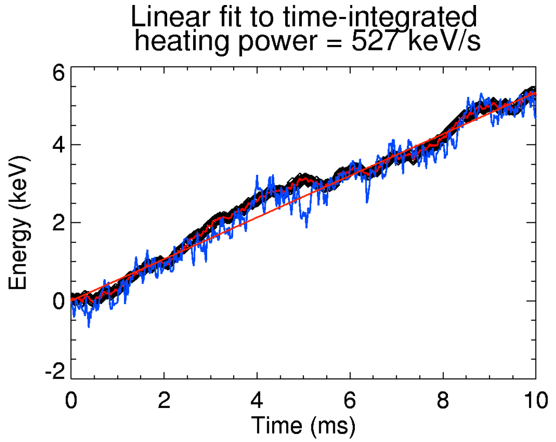
- Collisions can readily move ions in and out of regions of orbit stochasticity

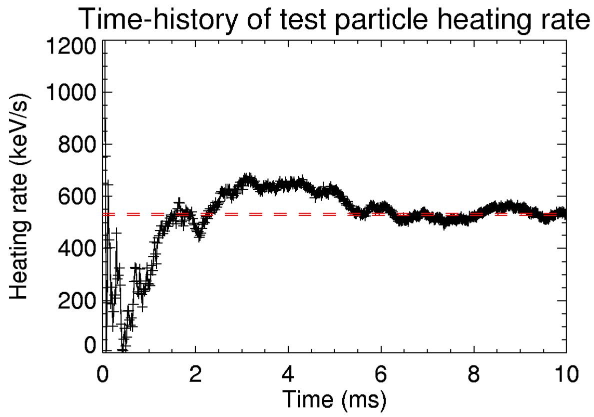
- Collisionality can change mean energy significantly over few wave periods ⇒

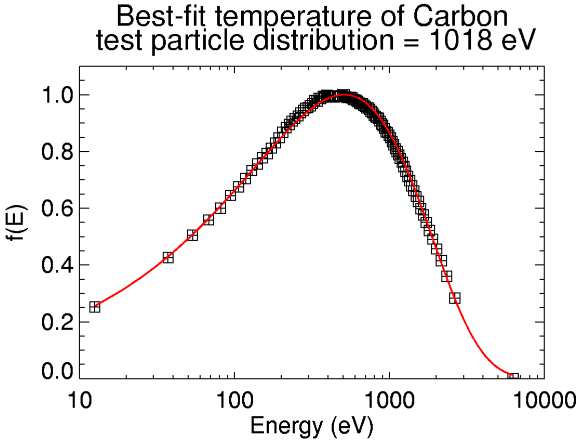
- **Collisions should be strong enough to cause significant decorrelation and heating**

Carbon test-particle energy distribution function becomes Maxwellian with temperature expected from heating


Particle temperature from time-average energy = 1038 keV


Linear fit to time-integrated heating power = 527 keV/s

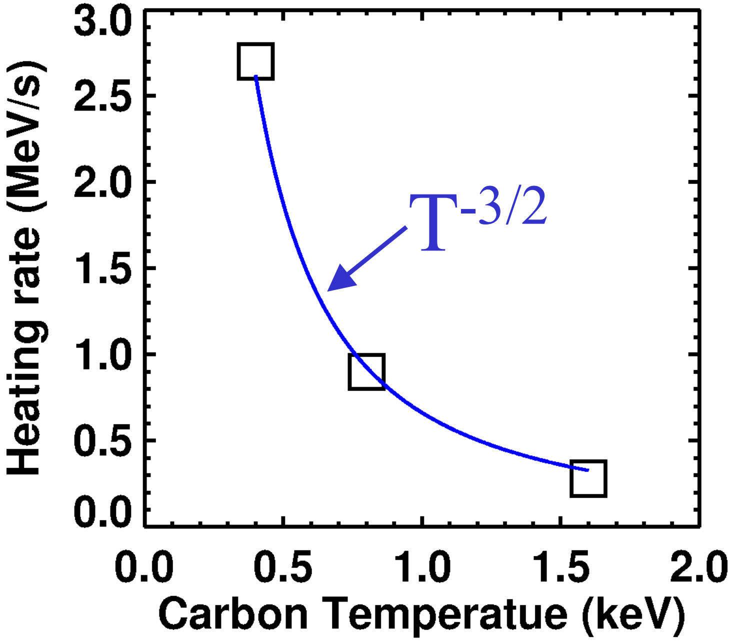

Time-history of test particle heating rate


Best-fit temperature of Carbon test particle distribution = 1018 eV

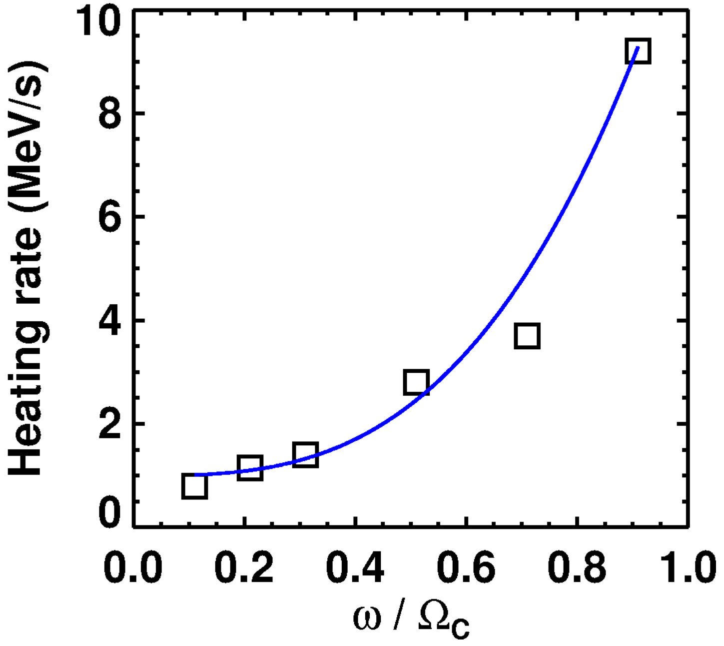
- Fully converged Carbon heating rate is $\approx$ 600keV/s $\Rightarrow$ 130kW/m^3

Parametric scaling of heating rates

- Heating proportional to $\nu_{collision}$
- Heating susceptible to other de-correlation processes



- Heating rate increases with ω
  - Does stochastic energy increase?
- Cyclotron resonance evident



- Presently working on determining role of non-zero k_{radial}
  - Initial indications are that higher k_r results in **weaker** dissipation

Experimental Considerations:

- Density/potential fluctuation characteristics:
  - Wavelength: $k_\theta \rho_e \approx 0.2, \quad k_r \rho_e << 1$
  - Amplitude: 0.5-2%, maximum near ½ radius, ~ 1/B
  - Frequency: broadband f ~ 100-400kHz

- Possible techniques for understanding physics:
  - Strong reverse shear should suppress ETG
  - Z_{eff} would influence ETG heating power density
  - Higher B-field might reduce heating anomaly
  - Heat electrons in regimes w/ NC ions, but w/o beams
    - Can ∇p driven E_r shear in NSTX stabilize ITG ?
    - If so, NBI followed by HHFW might eliminate CAE in hot ion regime