Kinetic Neoclassical Calculations of Impurity Radiation Profiles*

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NSTX-U Results Review
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PRINCETON PLASMA PHYSICS LABORATORY

Edge Physics Simulation

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Summary

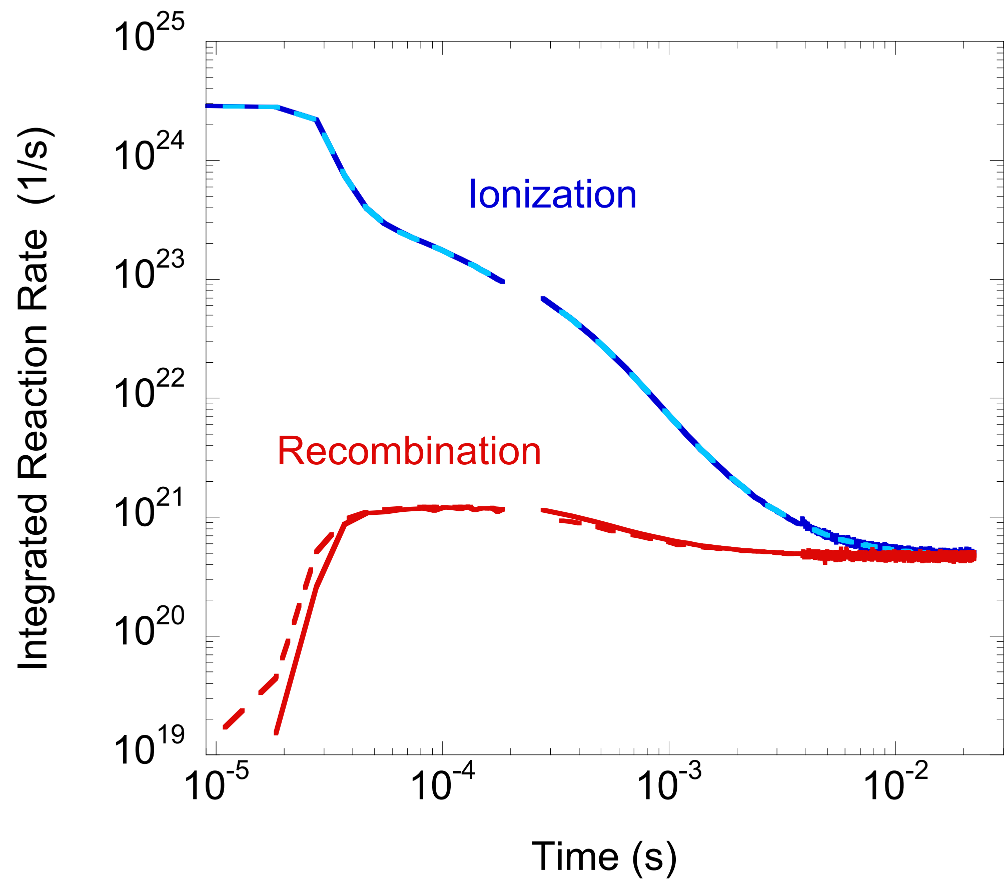
- Modify drift-kinetic code XGC0 to include transport, ionization, and recombination of impurities.
- Use to simulate C and Ne in NSTX H-mode.
- First, demonstrate approach to coronal equilibrium.
- Then, isolate impacts of neoclassical effects on radiated power profile.
- Orbit squeezing & inward pinch result in increased core $P_{\mathrm{rad}}(\psi)$,
  - & changes to ratios of charge state emissions at given T_e.

Objective: Do a Better Job of Simulating Radiated Power Distribution

- Fluid impurity transport models miss kinetic & non-local neoclassical effects.
- $\Rightarrow$ Extend full-f, drift-kinetic XGC0 PIC code to resolve impurity charge states,
  - Particle push integrates guiding center Hamiltonian equations of motion,
  - E_r obtained via Ampere's Law averged over closed flux surfaces.
  - Also: realistic recycling, linear Fokker-Planck operator, ...
  - Had two *fixed* charge impurities,
    - $*$ Add ionization & recombination using ADAS rates.

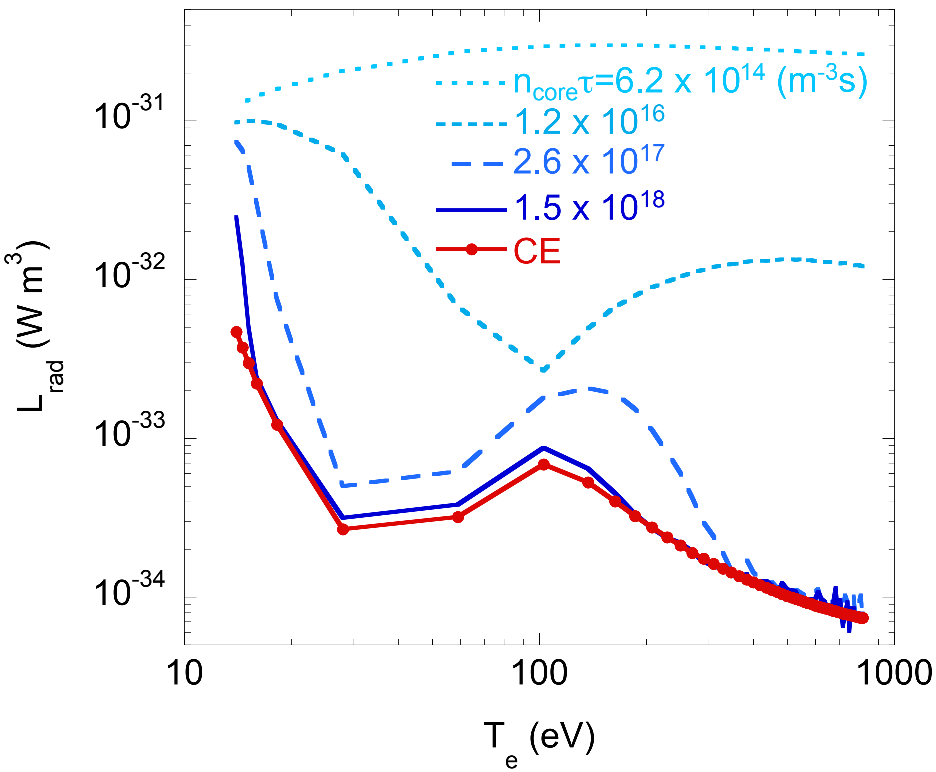
Approach to Coronal Equilibrium

- Comparing with CE $\Rightarrow n_e$ & T_e fixed for all runs.
- This run: disable *all* physical processes except ionization & recombination.
- Profiles from NSTX H-mode 139047.
- All C^+ initially.



- Dashed $\Rightarrow$ rate computed from local n_e, T_e.
- Solid $\Rightarrow$ actual rate after Monte Carlo collisions.

Time Evolution of L_{rad}

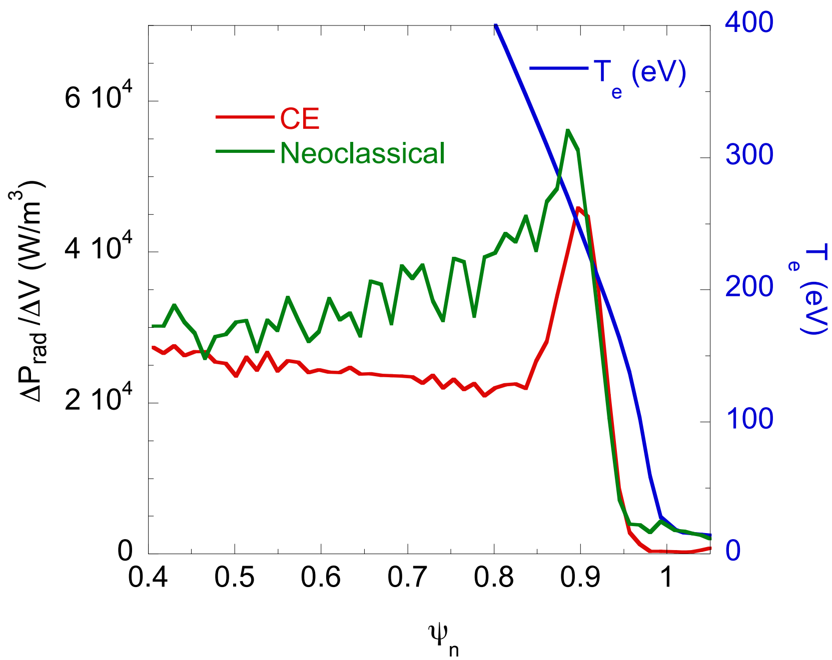


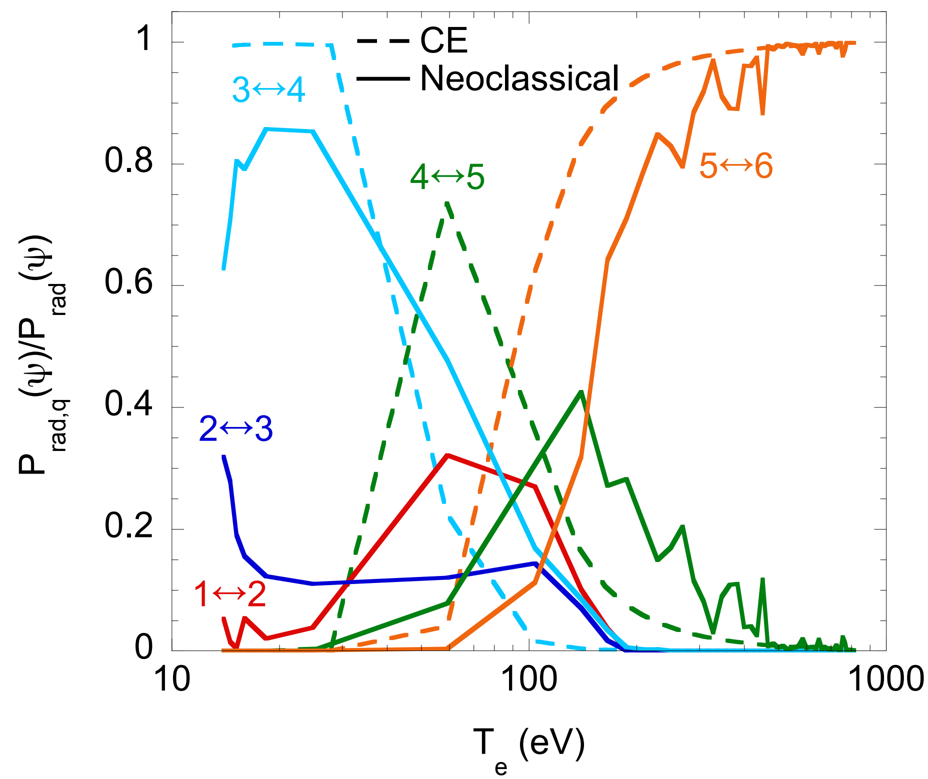
- Emulate Carolan (1983), Post (1995).
  - n_e & time enter only as $n_e\tau$.
- T_e, n_e variation is actually radial variation along profile.
  - $n_{\mathrm{core}} = 6.8 \times 10^{19}$,
  - $n_{\mathrm{SOL}} = 3.1 \times 10^{18}\ \mathrm{m}^{-3}$.

$$L_{\mathrm{rad}}(T_e, n_e) = (\sum_q P_{\mathrm{rad},q})/(n_e \sum_q n_q);$$

$$P_{\mathrm{rad},q} = n_q n_e P_{\mathrm{ion},q}(T_e, n_e) + n_{q+1} n_e P_{\mathrm{rec},q+1}(T_e, n_e)$$

Add NC Effects ⇒ Modest Increase in $P_{\text{rad}}(\psi)$ & Large Changes in $P_{\text{rad}}^{q+1}(\psi)/P_{\text{rad}}^{q}(\psi)$





- In CE: $P_{\text{rad,tot}} = 0.18$ MW,
- With neoclassical effects: $P_{\text{rad,tot}} = 0.24$ MW.
- Ne: similar, with 65% increase.

- Recycling source keeps $C^{+} \leftrightarrow C^{2+}$ & $C^{2+} \leftrightarrow C^{3+}$ nontrivial.
- $C^{\geq 3+}$ shifted inward.

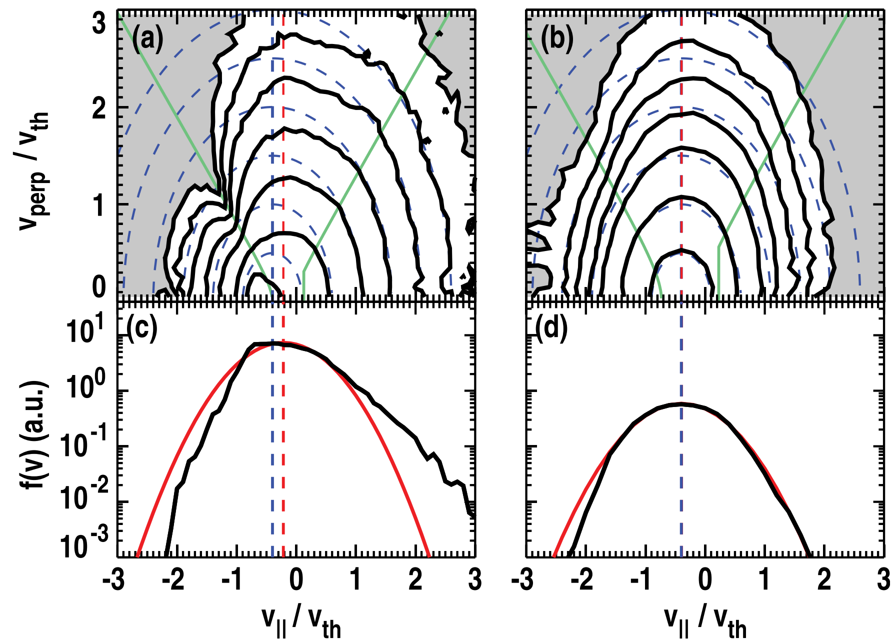
Future Work

- Include kinetic electrons & effects of $P_{\rm rad}$ on energy balance.
- Include diffusive anomalous transport & core particle, momentum, energy sources $\Rightarrow$ simulate individual discharges.
- Replace simple neutral model with DEGAS 2,
- Accurate treatment of SOL via XGCa.

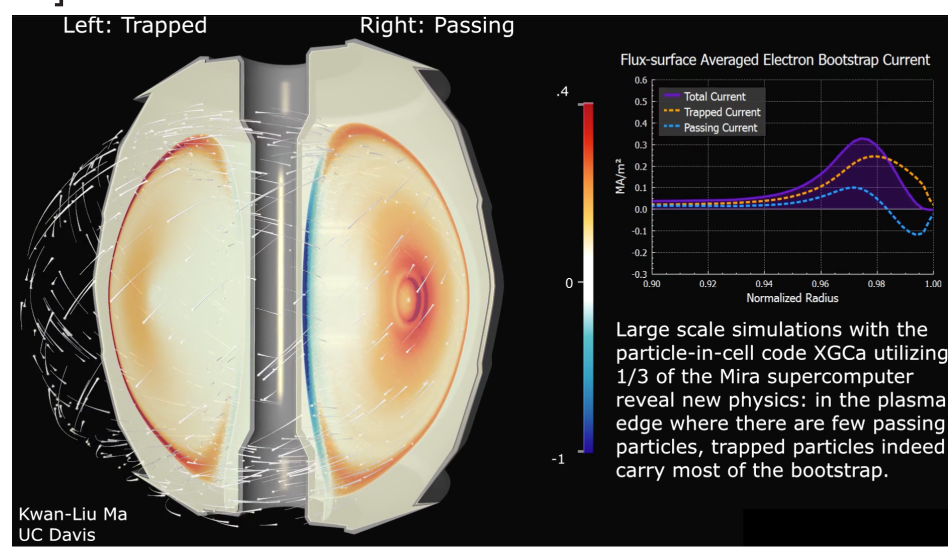
BACKUP SLIDES

XGC Code Family Continues to Mature within EPSi

- XGC0: Full-f, drift-kinetic, multi-species PIC transport code.
- XGCa: Axisymmetric variant of XGC1 (Churchill P.2.23),
- XGC1: 5-D edge gyrokinetic PIC code.



XGC0 D^+ and C^{6+} velocity distributions [Battaglia 2014].



XGCa bootstrap current calculations [R. Hager, K. Ma]

Implementation of Impurity Ionization & Recombination

- Add q/Z to list of phase space parameters.
  - For low-Z, include all charge states,
  - Will require "bundled" representations for high-Z.
- Evolve q via Monte Carlo ionization & recombination,
  - Generalized collisional radiative rates from ADAS,
    - All are "96" files; C files dated Nov. 4, 1999, Ne are June 11, 2014.
  - Loaded into DEGAS 2 & accessed by new interface.
  - Electrons created, removed, cooled, etc., *but* T_e, n_e fixed here.
- Evaluate rates, etc. on 2-D mesh:
  - 50 surfaces $0.4 \leq \psi_n \equiv \psi/\psi_{\text{sep}} \leq 1$; 4 poloidal divisions each.
  - 5 SOL cells each above & below X-point, $1 \leq \psi_n \leq 1.05$,
  - 1 PFR cell.
  - $\Rightarrow$ relatively simple model of open field lines.
  - XGCa will provide more detailed treatment.

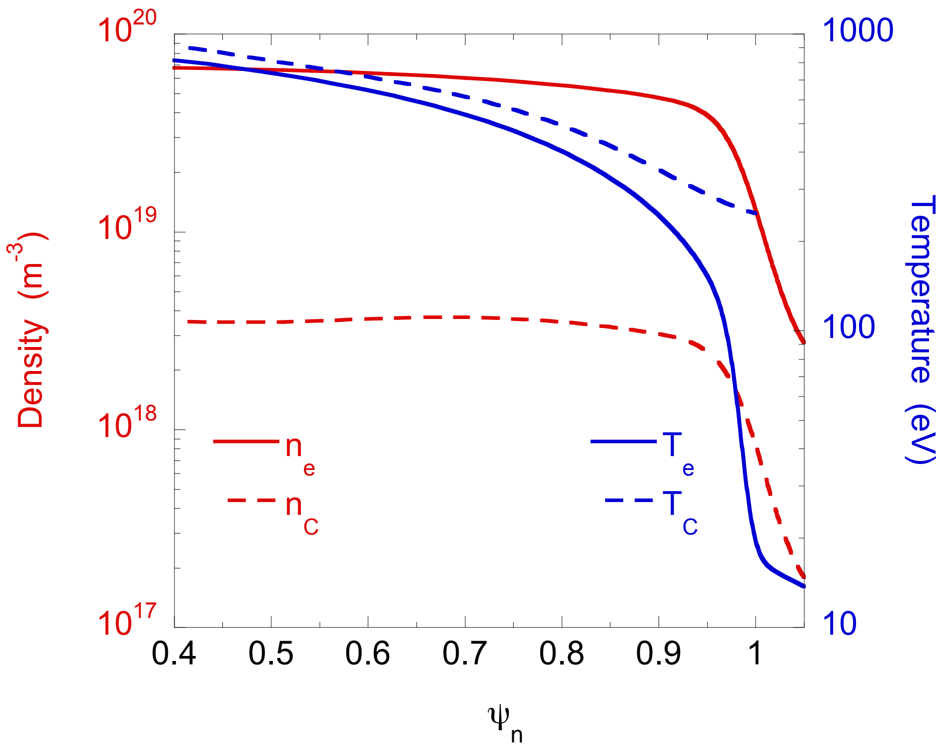
$q = 1$ Source from Neutral Ionization // Coulomb Collisions

- Monte Carlo ionization of 2-D neutral density profile:
  - $n_0(\psi, \theta)$ from Monte Carlo calculation using fluid plasma background.
  - Source of neutrals: recycling with user specified rate,
    - Spatial profile = poloidal distribution of D^+ lost to walls.
    - 99% recycling rate for impurities here.
    - 3 eV thermal energy distribution.
  - Impurity neutrals only undergo ionization,

- Linear Fokker-Planck collision operator:
  1. "Background" species loop $\rightarrow$ loop over species & charge states,
     - For each, do Monte Carlo Coulomb collisions with all other "test" species $\rightarrow$ species & charge states.
  2. Apply "restoring" force on background particles.
  3. Enforce particle, momentum, and energy conservation.

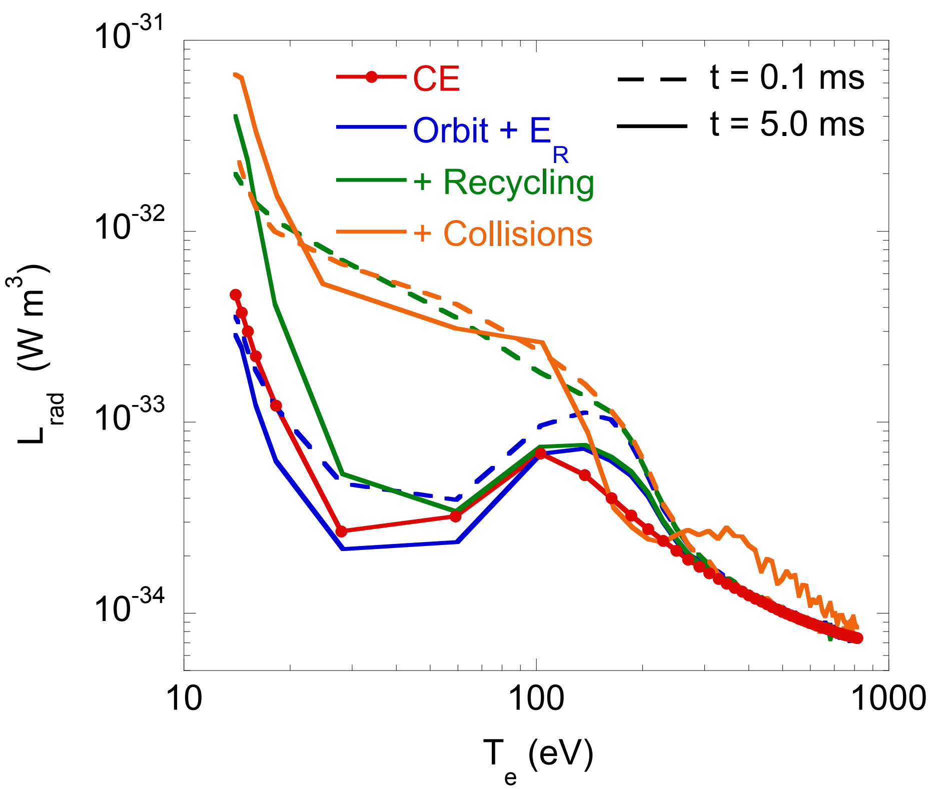
Apply to NSTX H-Mode Plasma

- Electron & carbon profiles input to XGC0,
  - Similar to NSTX H-mode discharge 139047 at 580 ms.
  - No initial toroidal rotation.
  - Initial D^+ density computed from quasi-neutrality.
- For comparison with coronal equilibrium, fix T_e, n_e in all simulations.



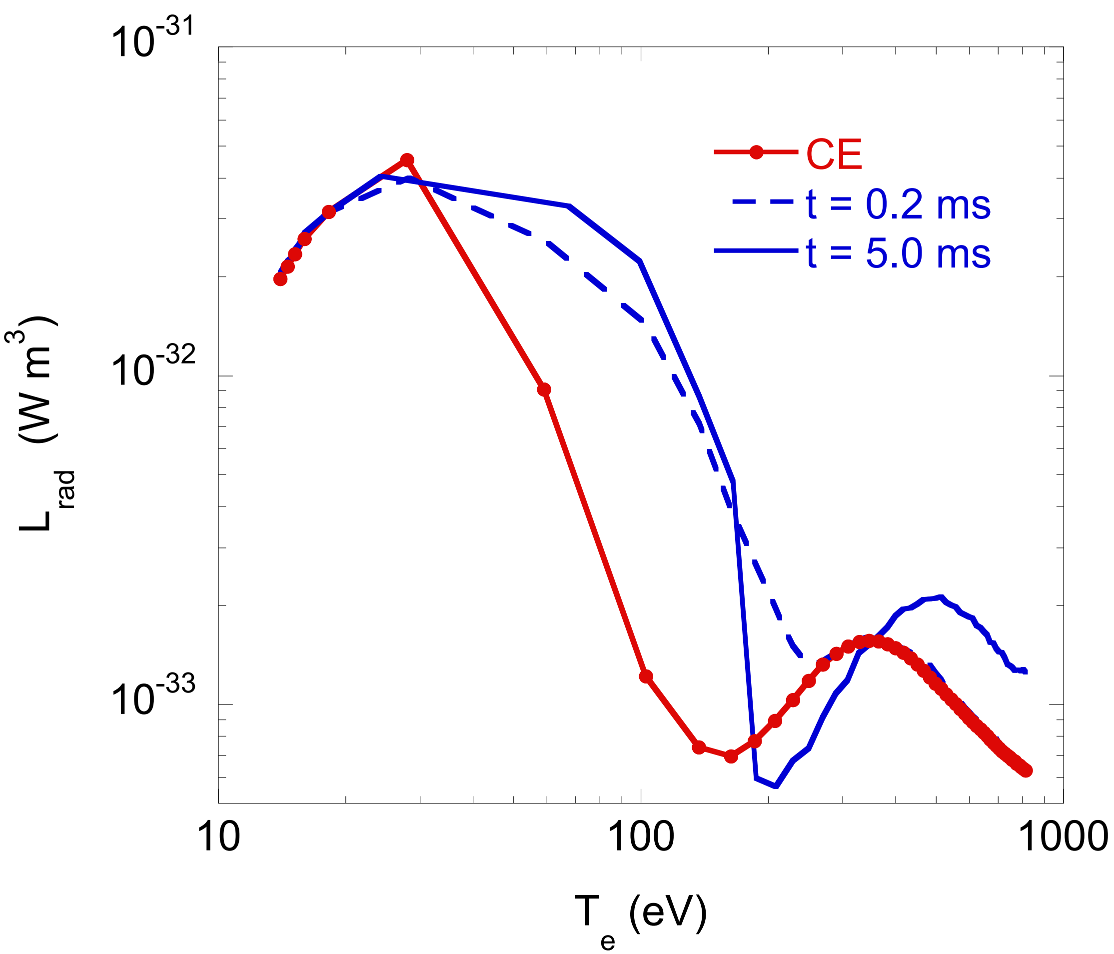
Neoclassical Effects on L_{rad}

- Initialize each run with CE charge state distribution.
- Add effects in stages:



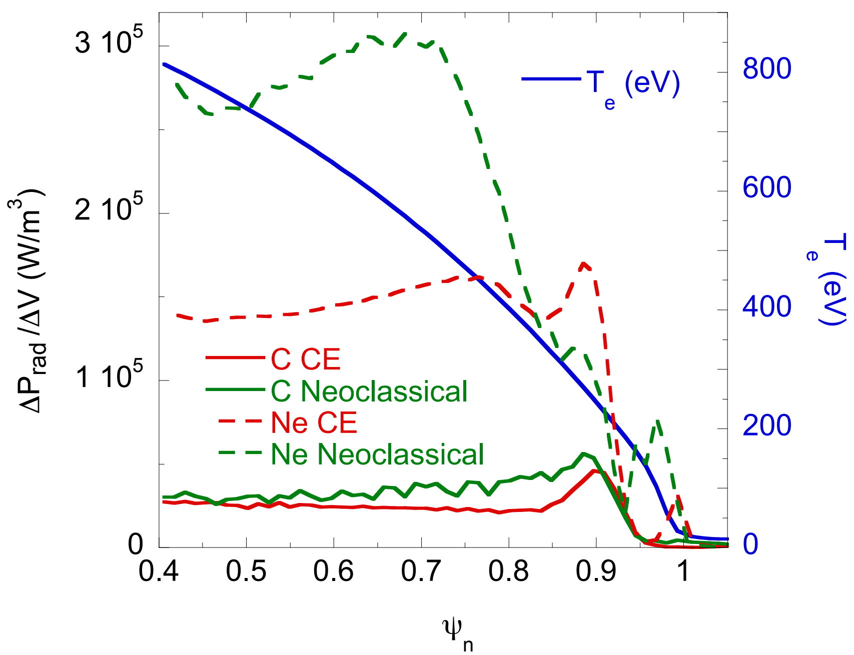
1. Particle push & E_r
   $\Rightarrow$ orbit width & squeezing.
2. Impurity source via recycling,
   - Replace orbit- & X-loss,
   - Transient except for SOL.
3. Collisions,
   - Pitch angle scattering moves ions from confined to loss orbits,
   - $\Rightarrow$ steady source of C^{+}.
   - Anomalous transport would have same effect.
   - Inward pinch increases C^{4+}, C^{5+} in core,
   - $\Rightarrow$ more realistic E_r profile.

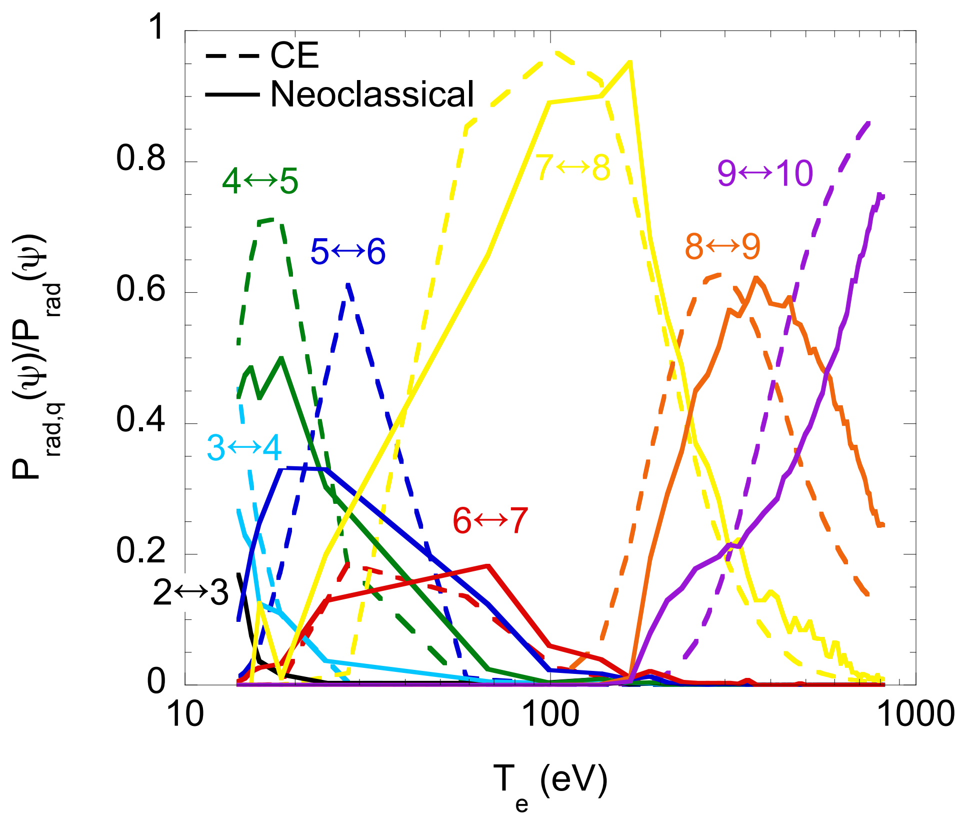
Neon Simulation Similar



- Initial $n_{\mathrm{Ne}} = n_{\mathrm{C}}/2$.
- Note $\sim 2\times$ increase for $T_e > 300$ eV.

Ne Radiation Density $\sim 2\times$ CE in Core





- In CE: $P_{\mathrm{rad,tot}} = 0.95$ MW,
- With neoclassical effects: $P_{\mathrm{rad,tot}} = 1.57$ MW.

- Ne^{+} & Ne^{2+} trivial in CE,
- Ne^{+} in neoclassical case also.