



Neoclassical calculations in HSX beyond the monoenergetic assumption



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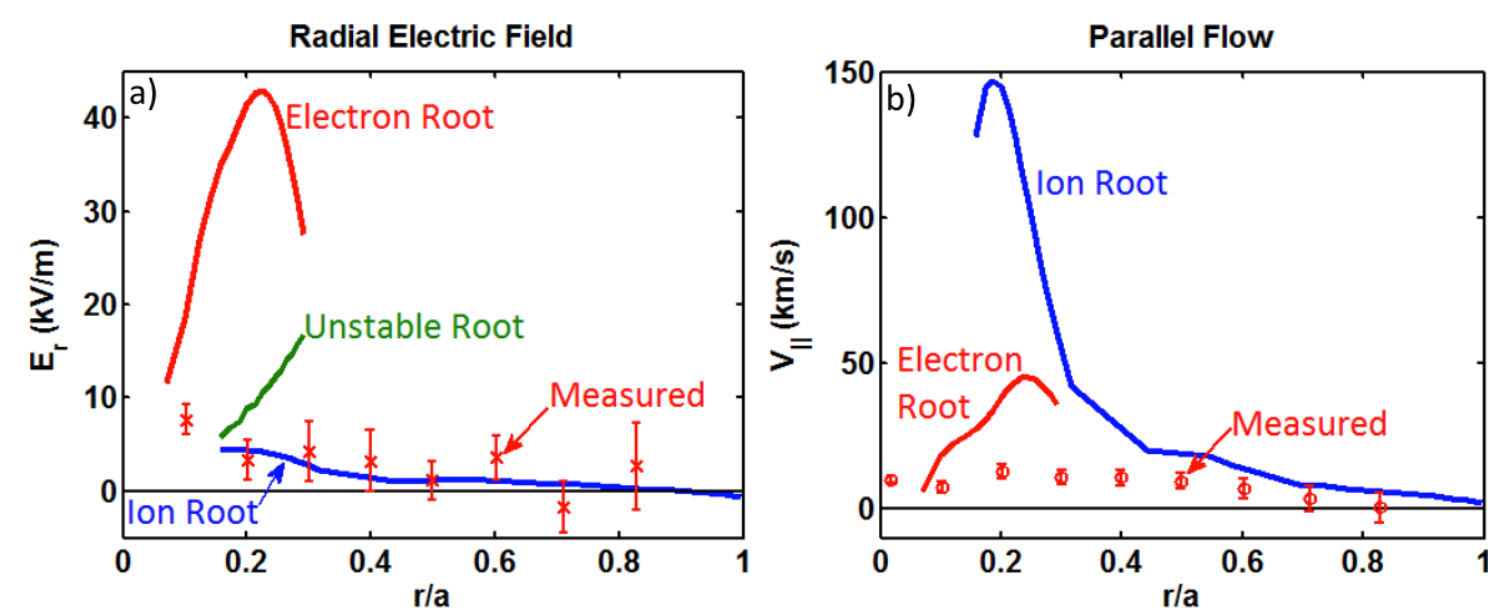
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Overview

- Neoclassical modeling with PENTA / DKES [1] predicts a large electron root in the core of HSX that is not measured experimentally [2].
- DKES, the diffusion coefficient code underlying PENTA, makes a monoenergetic assumption that breaks down at the resonance [3].
- We apply two new codes to HSX that do not make the monoenergetic assumption. The drift-kinetic continuum code SFINCS [4] includes the correct E×B drift, and the global δf Monte-Carlo code FORTEC-3D [5] also includes radial coupling.
- Despite numerical artifacts under continuing investigation, initial results suggest momentum scattering makes little difference at HSX parameters.

PENTA vs. experiment

- Previous work [2] showed that measurements of the radial electric field and flow do not agree with PENTA predictions for the inner half radius.
- In the core, the electron temperature is much greater than the ion temperature. The large temperature difference can drive a large electric field, under which the monoenergetic approximation is invalid.



- The Drift Kinetic Equation Solver (DKES) [1] solves the drift kinetic equation using a pitch angle scattering collision operator for the monoenergetic transport coefficients D_{11} , D_{13} , D_{33} . This effectively solves for the trajectory model [4] (see SFINCS section, next):

$$\dot{\mathbf{r}} = v_{||} \mathbf{b} + \frac{c}{\langle B^2 \rangle} \frac{d\Phi_0}{d\psi} \mathbf{B} \times \nabla \psi \quad \dot{x} = 0 \quad \dot{\xi} = -\frac{1-\xi^2}{2B\xi} v_{||} \mathbf{b} \cdot \nabla B$$
- PENTA restores momentum conservation through a moment method by including the effect of parallel flow through friction and viscosity relations when solving the drift-kinetic equation, but does not restore energy scattering.

SFINCS shows differences in the HSX core

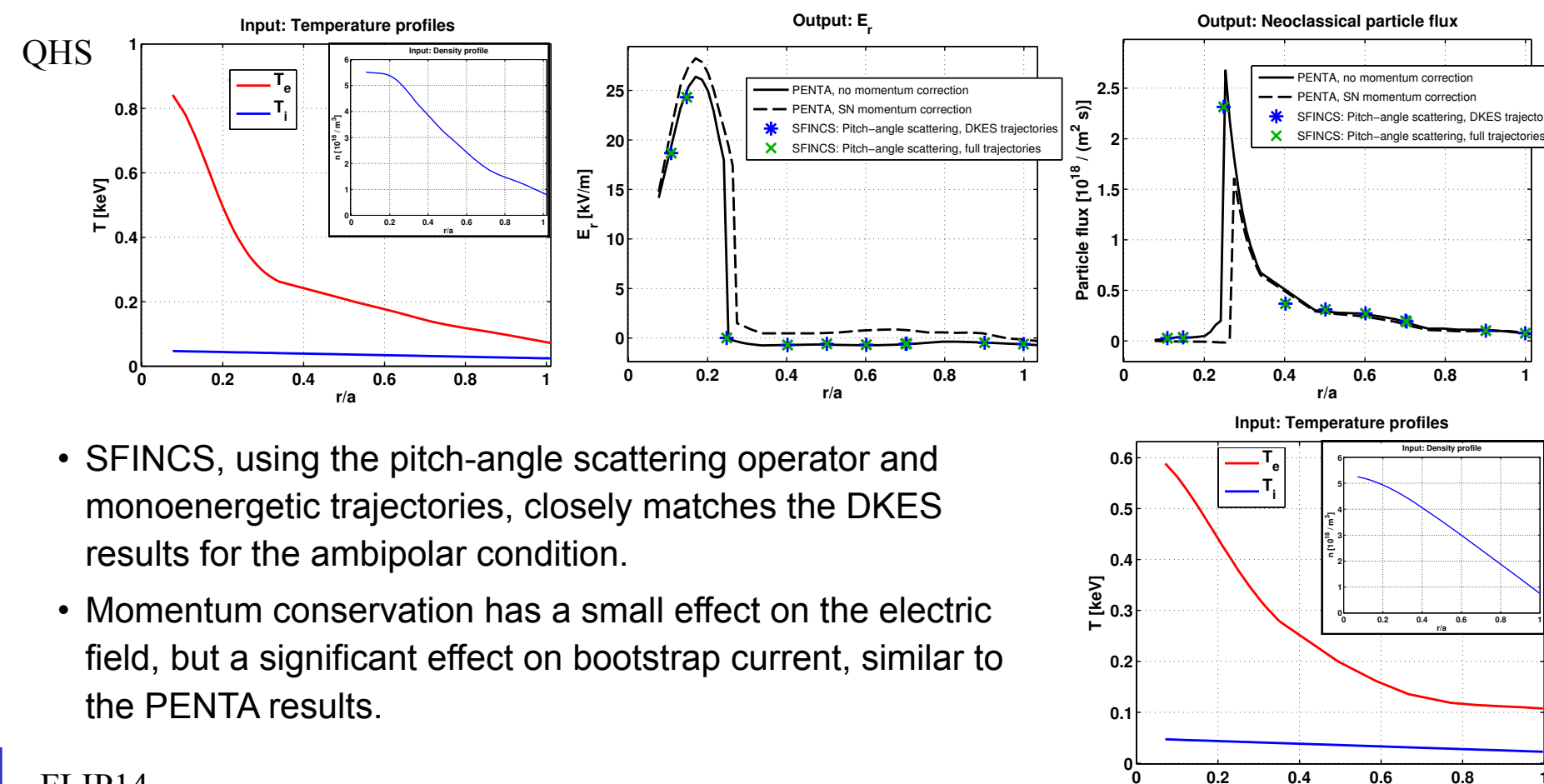
- The Stellarator Fokker-Planck Iterative Neoclassical Conservative Solver (SFINCS) [4] is a drift-kinetic continuum code that can solve the drift-kinetic equation using different collision operators and trajectory models.
- The trajectory model is determined through $\mathbf{r}, x = \frac{v}{v_{Th}}$, and $\xi = \frac{v_{||}}{v}$

$$\dot{\mathbf{r}} \cdot (\nabla f_1)_{x,\xi} + \dot{x} \left(\frac{\delta f_1}{\delta x} \right)_{r,\xi} + \dot{\xi} \left(\frac{\delta f_1}{\delta \xi} \right)_{r,x} - C = - (v_m \cdot \nabla \psi) \left(\frac{\delta F}{\delta \psi} \right)_{w_0} + \frac{Ze}{T} v_{||} \frac{B \langle E_{||} B \rangle}{\langle B^2 \rangle} F$$
- Can use either pitch-angle scattering, or the linearized Fokker-Planck collision operator.
- Momentum is conserved through the Fokker-Planck collision operator and the full trajectory model [4]:

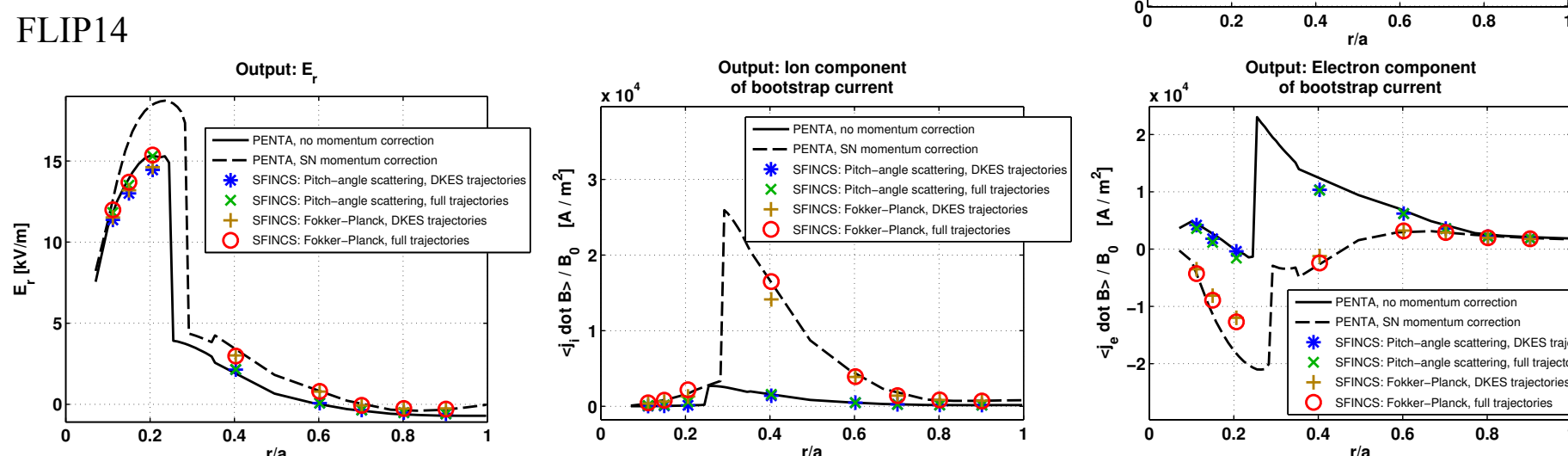
$$\dot{x} = - (v_m \cdot \nabla \psi) \frac{Ze}{2Tx} \frac{d\Phi_0}{d\psi} \quad \dot{\mathbf{r}} = v_{||} \mathbf{b} + \frac{c}{B^2} \frac{d\Phi_0}{d\psi} \mathbf{B} \times \nabla \psi$$

$$\dot{\xi} = -\frac{1-\xi^2}{2B\xi} v_{||} \mathbf{b} \cdot \nabla B + \xi(1-\xi^2) \frac{c}{2B^3} \frac{d\Phi_0}{d\psi} \mathbf{B} \times \nabla \psi \cdot \nabla B$$

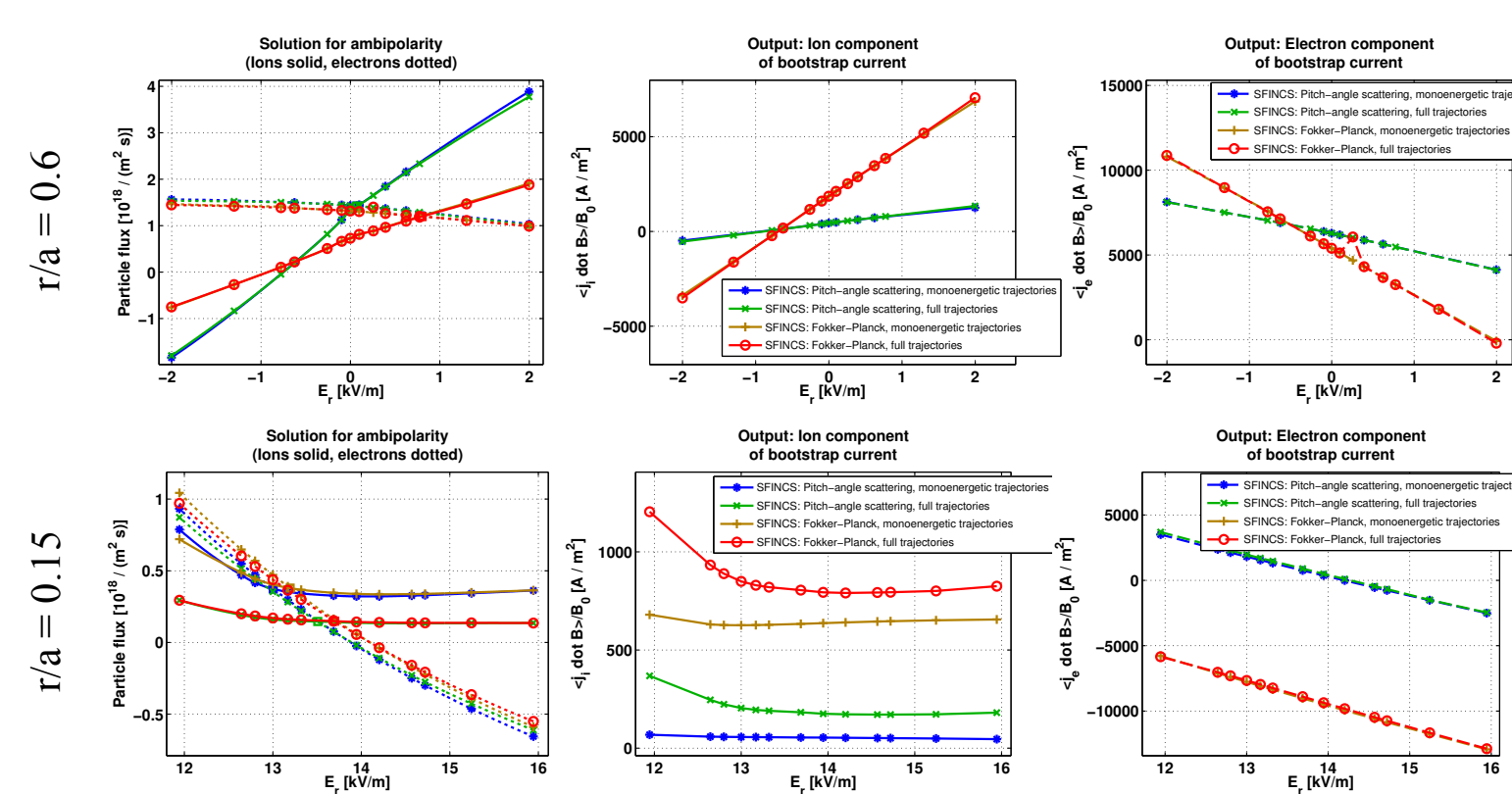
- SFINCS is used to solve a quasi-helically symmetric configuration (QHS), and a configuration using auxiliary field coils to break the symmetry (FLIP14). The electron root is chosen where it exists.



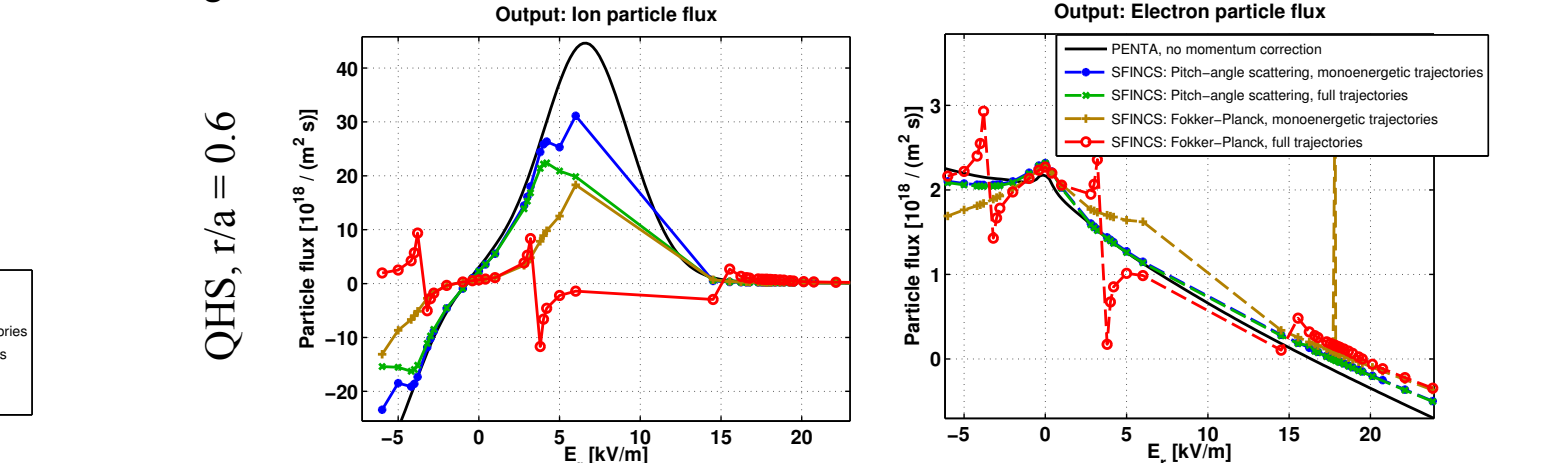
- SFINCS, using the pitch-angle scattering operator and monoenergetic trajectories, closely matches the DKES results for the ambipolar condition.
- Momentum conservation has a small effect on the electric field, but a significant effect on bootstrap current, similar to the PENTA results.



FLIP14 - an ion root (top) and electron root (bottom) solution



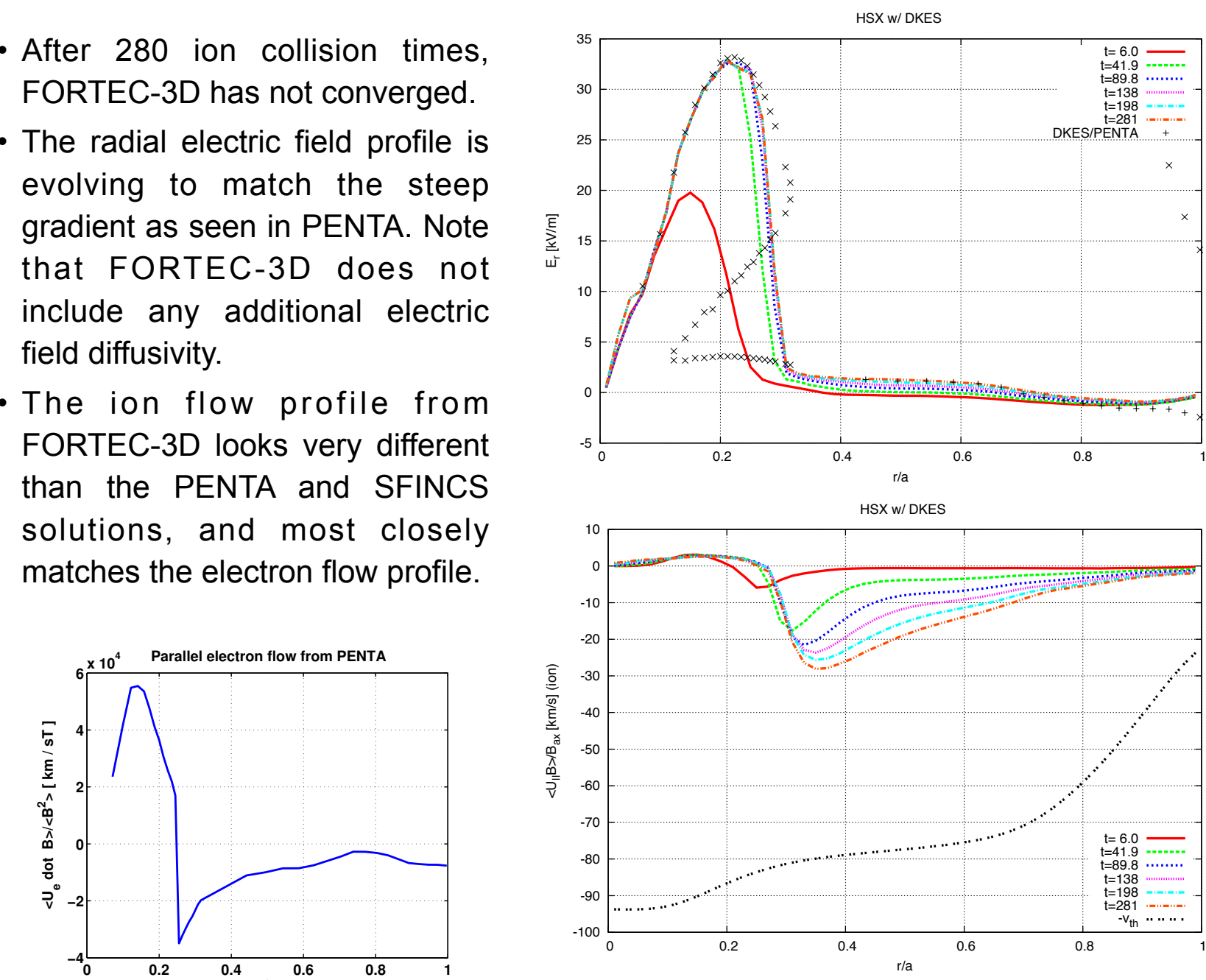
- Ion root solutions exist outside $r/a \sim 0.2$
 - The trajectory model has almost no effect at HSX parameters.
- Electron root solutions exist in the core.
 - Ion flux changes significantly with trajectory model, but shows only small changes with collision model.
 - Ion bootstrap current shows large variation with both model and trajectory.
 - Electrons behave as at the ion root.
- Discontinuities are seen in solutions, primarily in the full trajectory model.
 - These seem to depend on the location of the electric field resonance
 - These alter solutions away from $E_r = 0$, and do not affect the ion root.
- Large spikes in the ion flux peak appear for all trajectory models and collision operators.
- These discontinuities and spikes are under investigation.



FORTEC-3D

- FORTEC-3D [5] is a global δf Monte Carlo code designed to investigate the effect of finite orbit widths in 3-d configurations.
- It is used to solve the time evolution of the electric field and neoclassical fluxes self-consistently with the linearized Fokker-Planck collision operator.
- FORTEC-3D is currently a single-species code, and is only used to solve for the ions, while the electron behavior is previously determined by PENTA.

- After 280 ion collision times, FORTEC-3D has not converged.
- The radial electric field profile is evolving to match the steep gradient as seen in PENTA. Note that FORTEC-3D does not include any additional electric field diffusivity.
- The ion flow profile from FORTEC-3D looks very different than the PENTA and SFINCS solutions, and most closely matches the electron flow profile.



References

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