Consistent Recycling in a Coupled Kinetic Plasma - Neutral Transport Code*

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Abstract

The role of neutral fueling in the buildup of the H-mode pedestal is a topic of interest for the FY2011 Joint Research Target on Pedestal Structure. The particular effects of kinetic neutral and plasma phenomena in the pedestal buildup are being examined via the coupled DEGAS 2 Monte Carlo neutral and XGC neoclassical particle transport codes, developed as part of the Center for Plasma Edge Simulation. The coupled codes have recently been used to quantify the particle pinch associated with cold ions resulting from recycling at the plasma edge [1]. The next step in the code development is to use the flux of ions striking material surfaces in XGC as the source of recycled neutral atoms and molecules in DEGAS 2. In this way, the poloidal distribution of the neutral source will evolve consistently with the plasma as the pedestal builds up. XGC will also provide the energy of the ions hitting the surface, allowing the application of detailed plasma material interaction models to determine the relative fractions of atoms and molecules generated by recycling. The atom / molecule ratio in turn impacts the velocity distribution of the neutral species and, thus, their penetration into the core plasma. In this presentation, we will describe the present status of this code development effort and the plans for completing it.

[1] W. Wan, S. E. Parker, Y. Chen, G. Y. Park, C. S. Chang, and D. Stotler, Phys. Plasmas (in press).

Summary

- Previously reported on conservation properties of initial version of coupled kinetic plasma - neutral code XGC0 - DEGAS 2,
  - Physics studies with it have begun.
- Next step is to make treatment of recycling consistent,
  - Use XGC0 distribution of ion fluxes to material surfaces to specify poloidal profile of DEGAS 2 neutral sources.
  - Add time dependence to allow both to evolve consistently.
- Code development progressing steadily; no show-stoppers expected:
  - Time dependence added to DEGAS 2,
  - New common mesh based on boundary used by XGC0 to compile fluxes.
  - Next: add flux distribution to DEGAS 2 argument list.
  - Later: add detailed PMI & molecules.

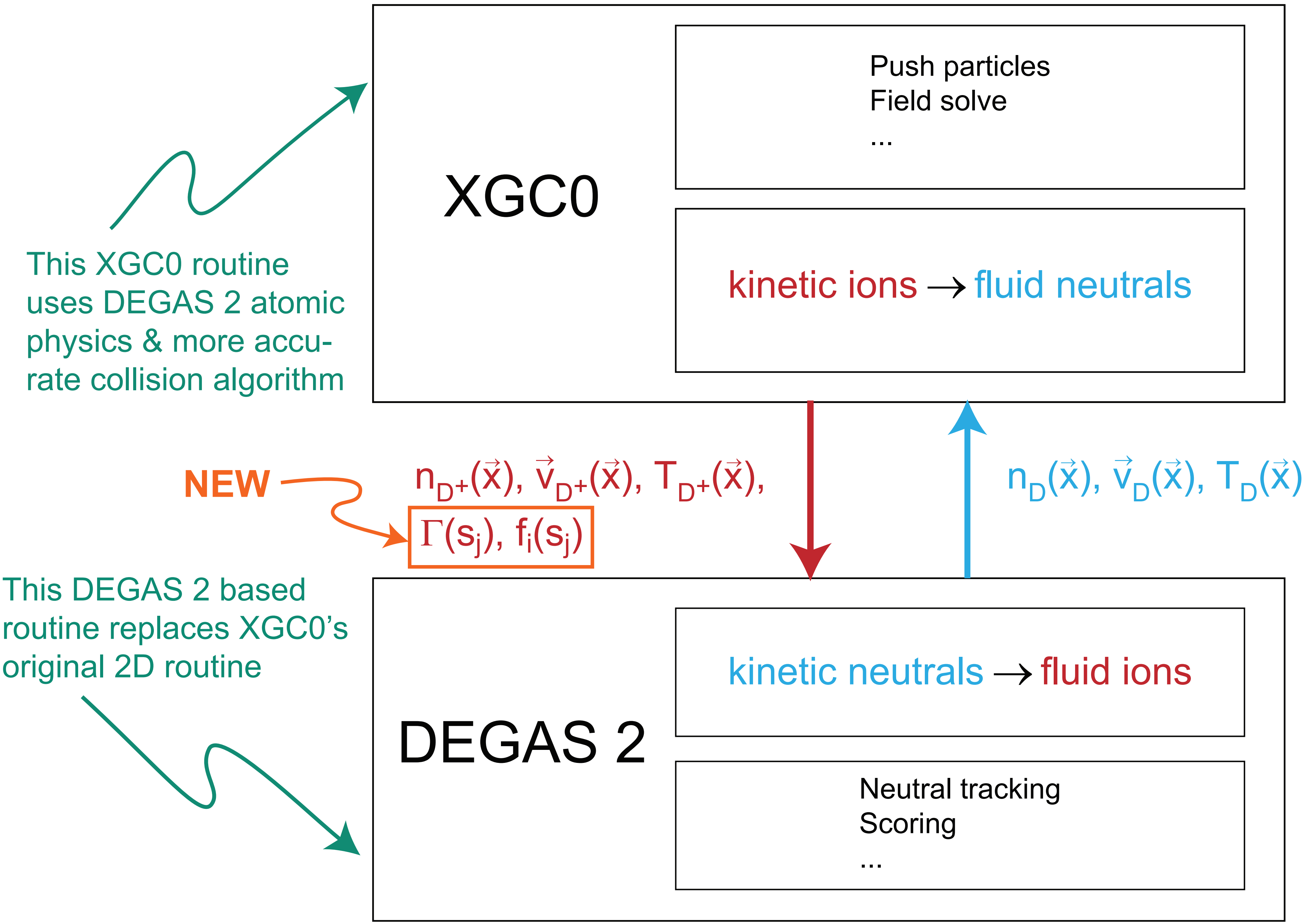
The Center for Plasma Edge Simulation Devoted to Understanding H-Mode Pedestal & ELM Physics

- Multi-institutional prototype Fusion Simulation Project funded in 2005.
- Goal is to understand:
  - Pedestal build-up (e.g., for FY2011 JRT on Pedestal Structure),
  - L-H mode transition,
  - ELM crash & cycle.
- Involves multiple codes covering different physics, time & length scales:
  - Neoclassical & turbulent plasma transport,
  - Open & closed flux surfaces,
  - Large scale instabilities (ELM's),
  - Neutral transport,
  - Plasma-wall interactions.

Kinetic Character of Both Plasma & Neutrals Essential in Edge

- For plasma:
  - Low collisionality,
  - Steep gradients,
  - Large particle orbits,
  - Non-Maxwellian distributions.
- For neutrals:
  - Atoms & molecules recycled from wall,
  - Uncollided dissociation products,
  - CX with non-Maxwellian ions.
- $\Rightarrow$ CPES pursuing fully kinetic plasma-neutral simulation.
  - XGC0 guiding center neoclassical particle transport code,
  - And Monte Carlo neutral transport,
    - XGC0's built-in rudimentary 2-D treatment,
    - Or more general, flexible, 3-D model based on DEGAS 2.

Computational Effort Required for Good Statistics Minimized by Colliding Kinetic Species with Fluid Background



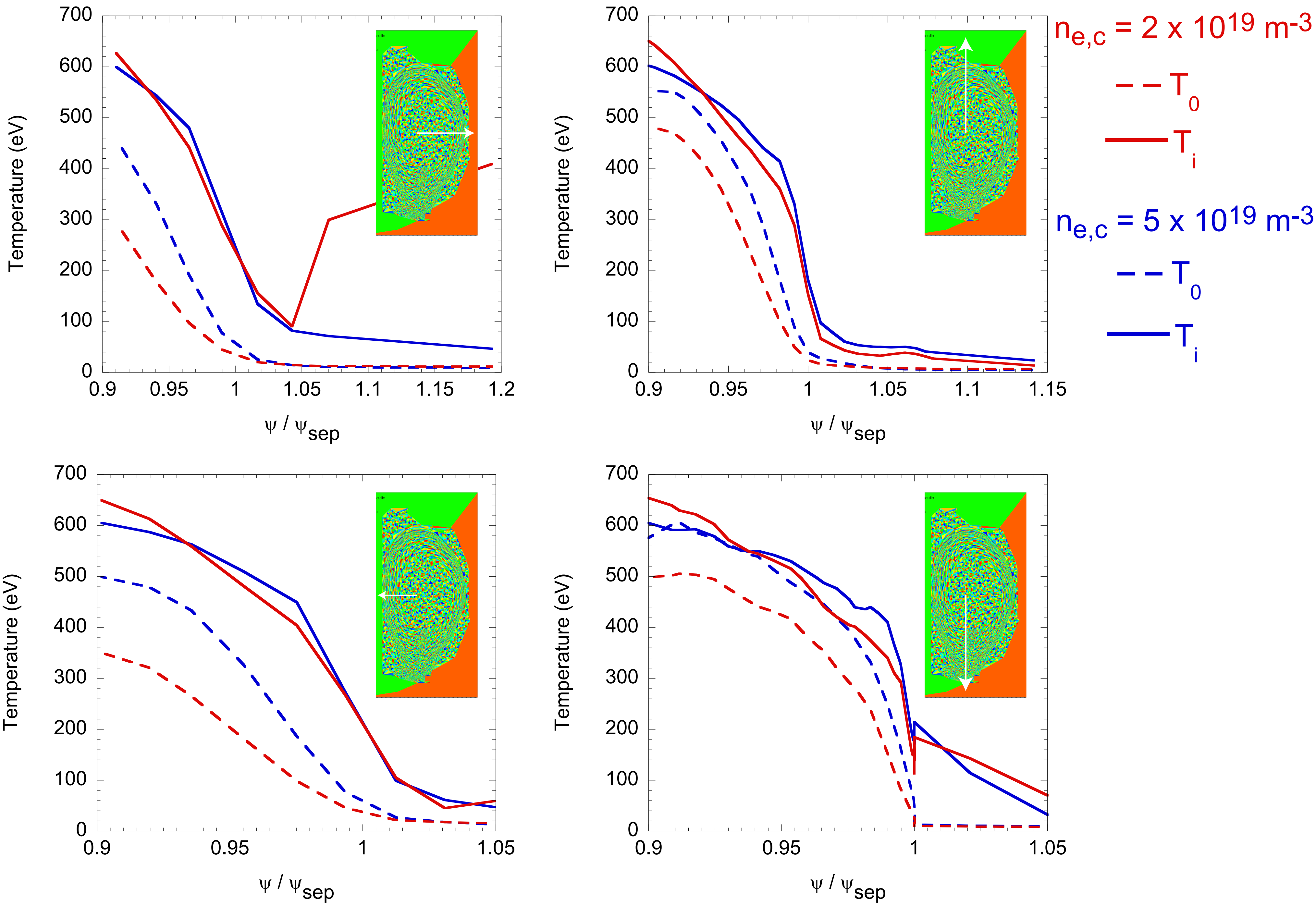
Previously Investigated Conservation Properties of XGC0 - DEGAS 2

- Steady-state neutral transport calculation,
- Fixed, poloidally uniform neutral source profile.
- Statistical mass conservation guaranteed by design of coupling algorithm.
- But, energy non-conservation significant compared to total exchange rate,
  - Due to velocity dependence of CX cross section & non-Maxwellian ion & neutral distributions.
  - Momentum exchange rates appear to exhibit similar behavior.
- Associated error in global energy conservation $< 1\%$
  $\Rightarrow$ code OK for physics studies.

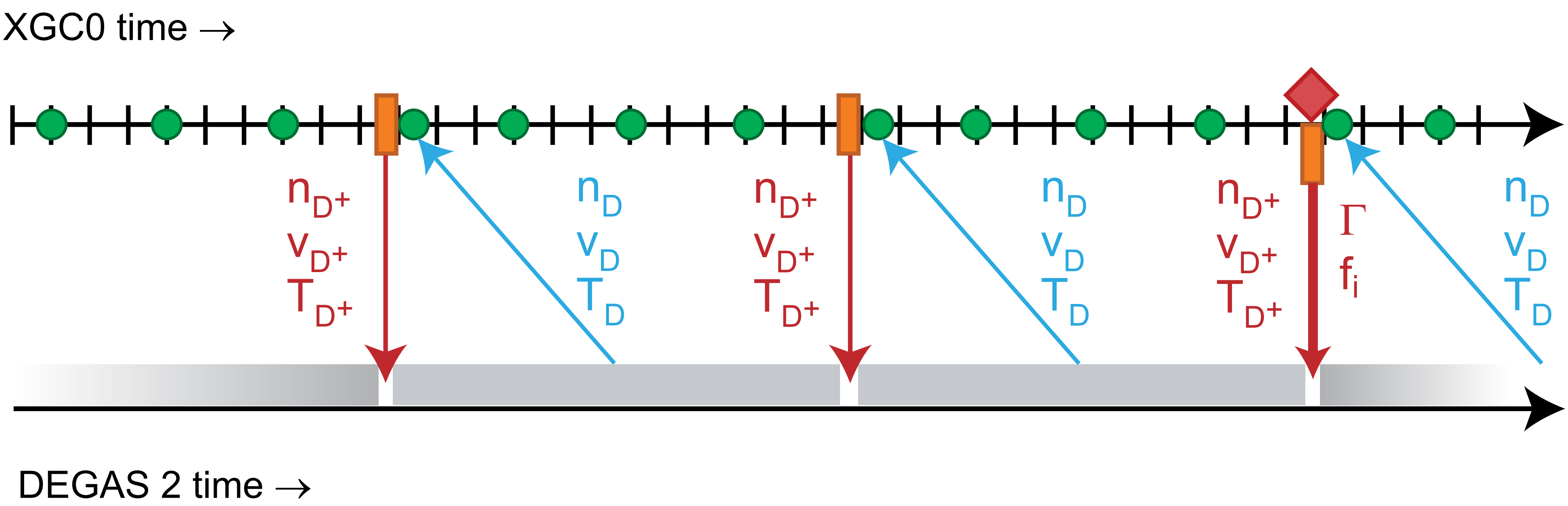
Use XGC0 - DEGAS 2 to Estimate Temperature of Ions Resulting from Recycling

- “Natural fueling” [W. Wan et al., Phys. Plasmas **17**, 040701 (2010)]:
  - Outward heat flux carried by hot ions,
  - To maintain quasi-neutrality, cold ions pinch in.
- Ionization of atoms from recycling $\Rightarrow$ source of cold ions in edge pedestal.
  - See: W. Wan et al. Phys. Plasmas (2011) (in press).
  - Possible contribution to rapid pedestal density buildup after ELM.
- Wan uses GEM gyrokinetic turbulence simulations to estimate pinch velocity associated with cold ion component.
- XGC0 - DEGAS 2 simulations show that ions from recycling (assuming $T_{i,c} = T_0$) are colder than background.
  - Local neutral $f(\vec{v})$ not likely sensitive to DEGAS 2 source profile.
  - But, neutral density probably is $\Rightarrow$ realistic simulation of pedestal ionization requires profile based on ion losses to material surfaces.

Neutral Temperature Less Than Ion Temperature At All Poloidal Angles

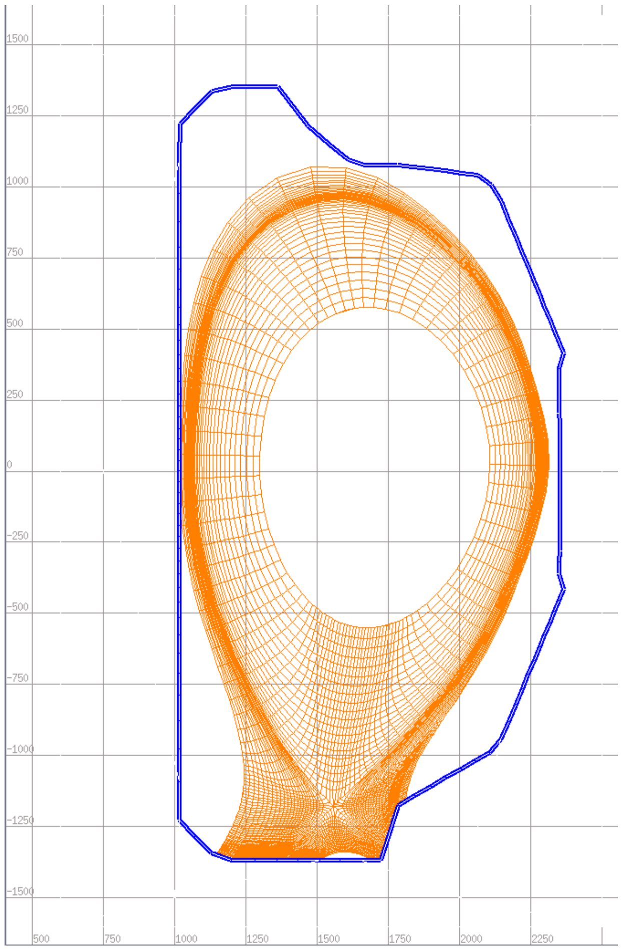


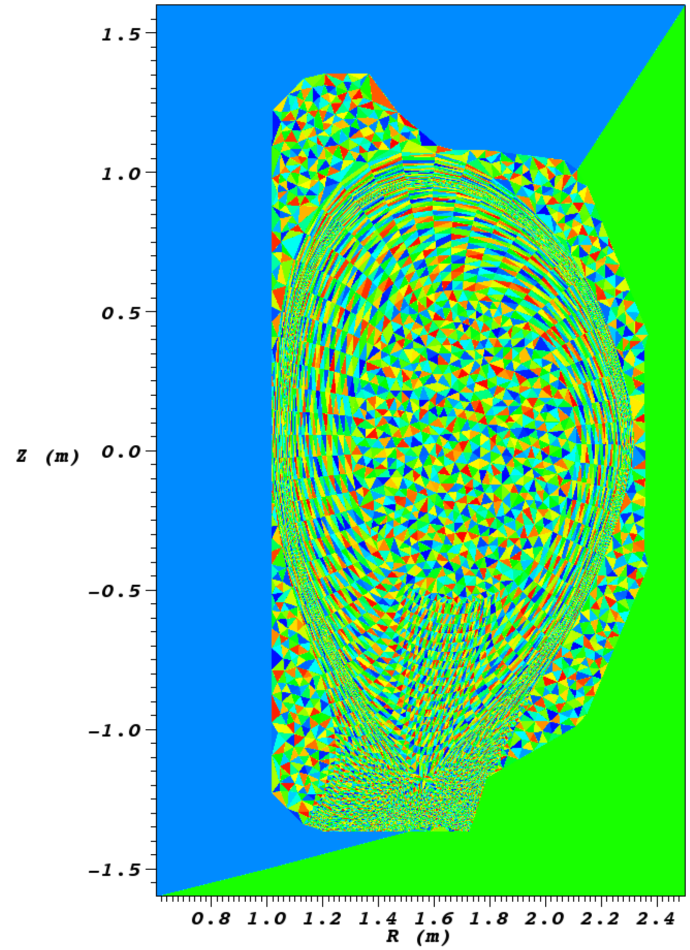
Consistent Treatment of Recycling Requires Time Dependence & Transfer of Plasma Fluxes to Material Surfaces



- Kinetic ion → fluid neutral collisions
  - Rescale neutral density using specified recycling coefficient.
- Compute plasma moments
- Compile boundary fluxes
- Kinetic neutral → fluid ion collisions now time dependent
  - Neutral moments averaged over interval,
  - Neutrals still in plasma saved for next interval.
  - Accuracy & stability of algorithm to be analyzed.

New Vessel Filling Triangular Mesh Using Uniform Poloidal Angle Boundary





- Uniform poloidal angle discretization of boundary used by XGC0 to compile particle & heat fluxes.
- Boundary segments become source locations in DEGAS 2.

- Generate flux surface following mesh & tile remaining regions with triangles.
- Also: made XGC0 test for crossing boundary precise ⇒ no “lost” ions.

XGC0 - DEGAS 2 Code Development

- Complete implementation of the above & begin testing,
  - Add ion flux distribution to DEGAS 2 argument list,
  - Revise DEGAS 2 source specification with each call.
- Add detailed plasma-material interactions to DEGAS 2 calculation,
  - Facilitated by energy distribution of ions striking surfaces compiled by XGC0.
  - Relative backscattering / desorption fractions & associated energy distributions determine atom $f(\vec{v})$ &, thus, penetration depth.
- Incorporate molecules into XGC0 kinetic plasma $\longrightarrow$ fluid neutral interactions,
  - Challenge: preserve conservation properties of existing system.
  - Enough for DEGAS 2 to also return D_2 & D_2^+ densities?

Incident Ion Energy Distribution from XGC0 Allows Use of Detailed PMI Model