Non-local Parallel Closures: Implementation and Application to Scrape-Off Layer Modelling

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5th September 2013

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Outline

Model

Physics results

Implementation

How-to

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The Model

Static 1d kinetic equation: $v_{\parallel} \dfrac{\partial f}{\partial \ell} = \dots$

$$\downarrow$$

Moment equations: $\Psi^{A}{}_{B} \dfrac{\partial n^{B}}{\partial \ell} = \dots$

$$\downarrow$$

Decouple: $\zeta_{(A)} \dfrac{\partial n^{A}}{\partial z} = \dots$

$$\downarrow$$

Solve: $q = \sum_{A} \int dz \, (\dots)$

Closures

- Final result[1, 2]:

$$\hat{n}^A(z) = \begin{cases} -\hat{g}^A & \zeta_{(A)} = 0 \\ \hat{n}^A(z_0) \exp\left(\frac{z-z_0}{\zeta_{(A)}}\right) + \int_{z_0}^{z} dz' \exp\left(\frac{z-z'}{\zeta_{(A)}}\right) \frac{\hat{g}^A(z')}{\zeta_{(A)}} & \zeta_{(A)} \neq 0 \end{cases}$$

$$q_{e\parallel} = -\frac{5}{4} v_{Te} T_e n^{(1,1)} = -\frac{5}{4} v_{Te} T_e \sum_B W^{(1,1)}{}_B \hat{n}^B$$

- Also viscosity, friction

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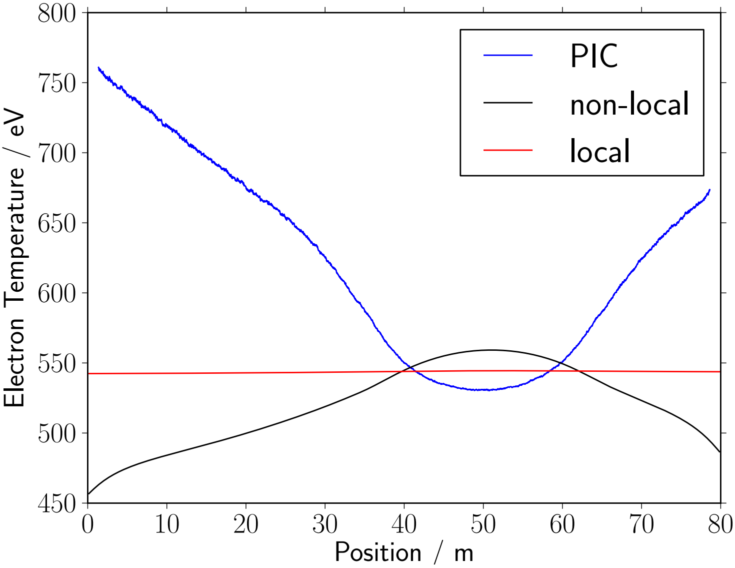
Scrape-Off Layer

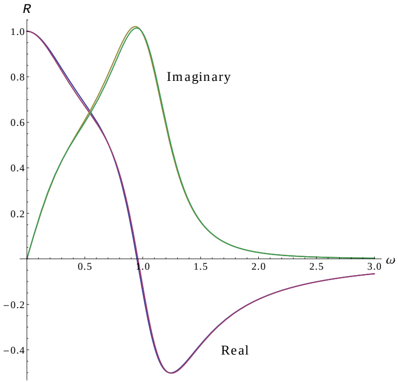


- local heat flux → no gradients (conductivity too high)
- non-local and PIC very different: boundary conditions?

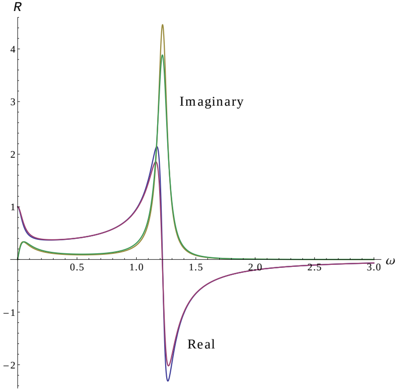
Sheath Boundary Conditions

- $\frac{N}{2}$ conditions on either boundary
- Easy on decoupled basis, e.g. periodic
- But on 'physical' basis (heat-flux, viscosity, etc.) invert $n \times n$ matrix to impose n conditions
  - at present just heat-flux and viscosity imposed
- Recent addition: can handle closed flux surfaces

Landau Damping



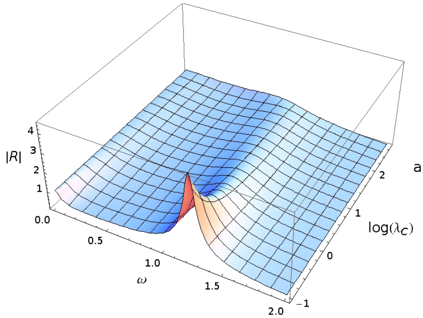
Collisionless, vs. Hammett-Perkins

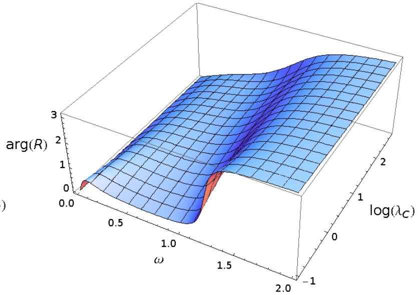


Collisional, vs. Braginskii

- Reproduces asymptotic limits

Landau Damping





- Span full range of collisionality with 900 moments

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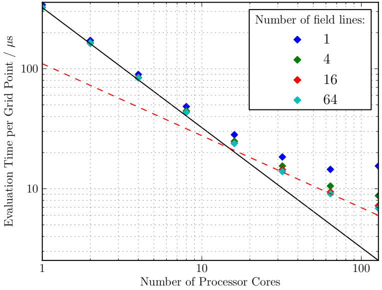
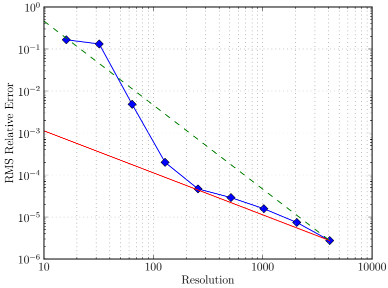
- Basically brute force
- Loop over field lines once for each moment
- Then set initial value (non-locally)

Performance and Scaling



Scaling with splitting in y



Spatial Convergence

- 400 moment model, $256 \times 256 \times 256$ grid, 4096 procs: $\sim 2 - 3\,\mathrm{s}$ per evaluation

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Input File

```
[non_local_parallel]
moments_number = 10
gradT_drive = false
gradV_drive = false
VeminusVi_drive = false
calculate_heatflux = false
calculate_viscosity = false
calculate_friction = false
y_periodic = false
bc_heatflux = false
bc_viscosity = false
```

Note: refactored version coming soon

Initialize

```
#include <non-local_parallel.hxx>
NonLocalParallel* nonlocalparallel;

physics_init(bool restarting) {
nonlocalparallel = new NonLocalParallel(e, m_e,
is_y_staggered);
...
```

Calculate

```
physics_run(BoutReal t) {
nonlocalparallel->set_n_electron(n);
nonlocalparallel->set_T_electron(Te);
nonlocalparallel->set_V_electron(Ve);
nonlocalparallel->set_j_parallel(jpar);
nonlocalparallel->set_heat_flux_boundary_condition(q_bc);
nonlocalparallel->set_viscosity_boundary_condition(pi_bc);
nonlocalparallel->calculate_closures();
if (flat_guard_cells)
  nonlocalparallel->set_neumann_boundary_conditions();
else
  nonlocalparallel->set_boundary_gradients();

ddt(Te) = -2./3./n
          * Grad_par(nonlocalparallel->electron_heat_flux);
// Also nonlocalparallel->electron_viscosity and
nonlocalparallel->electron_friction
...
```

References

[1] J.T. Omotani and B.D. Dudson.
Non-local approach to kinetic effects on parallel transport in fluid models of the scrape-off layer.
Plasma Physics and Controlled Fusion, 55(5):055009, 2013.

[2] J.Y. Ji, E.D. Held, and C.R. Sovinec.
Moment approach to deriving parallel heat flow for general collisionality.
Physics of Plasmas, 16(2):022312, 2009.

Conclusions/Status

- Calculate kinetic closures for parallel electron dynamics
- Wide collisionality range
- No assumption of small fluctuations
- Accurate (if converged)
- Full tokamak geometry coming soon

But:

- May be slow
- More development of sheath boundary conditions needed