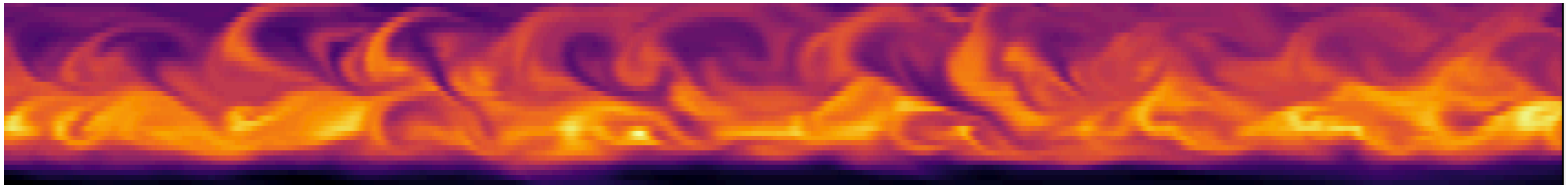

Kinetic simulations of plasma turbulence using the discontinuous Galerkin finite element method

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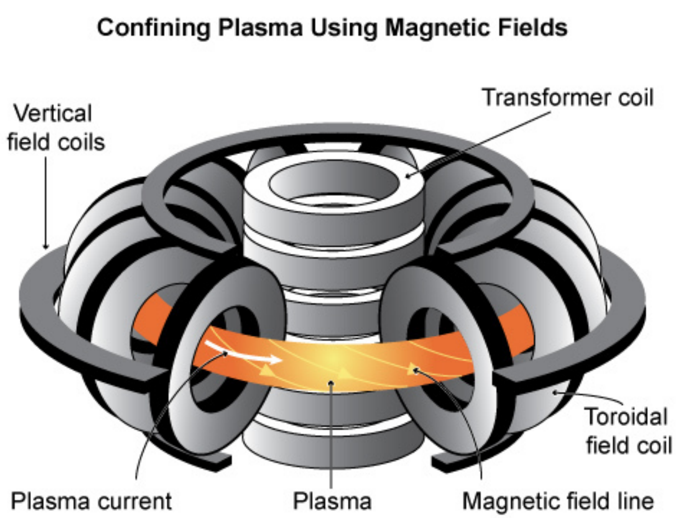
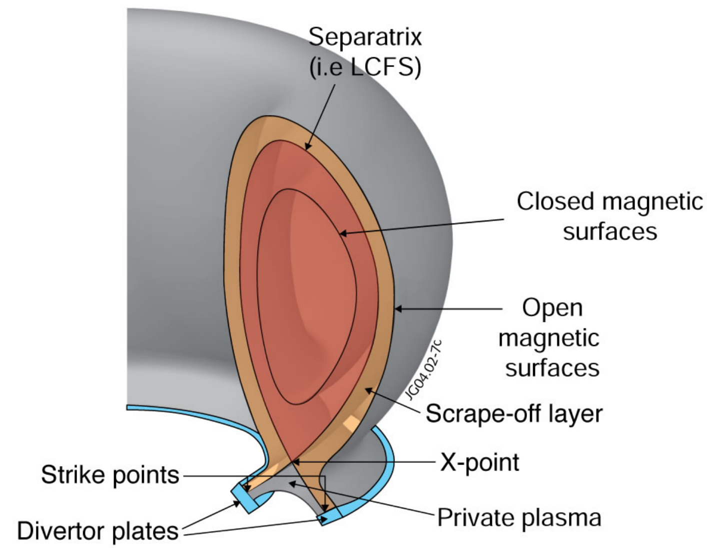
HPC is vital to plasma fusion research

- Necessary to understand turbulence in magnetically confined fusion devices like **tokamaks** in the effort to achieve a "break-even" energy point in fusion experiments like ITER.
- Outside the separatrix, in the **scrape-off layer** (SOL), magnetic field lines connect to the wall. Much of the thermal power flows along field lines to divertor plates at the bottom. Suppressing SOL turbulence can improve core plasma confinement.
- Until recently, most SOL modeling has been with fluid codes, which may miss important kinetic effects on transport along field lines.

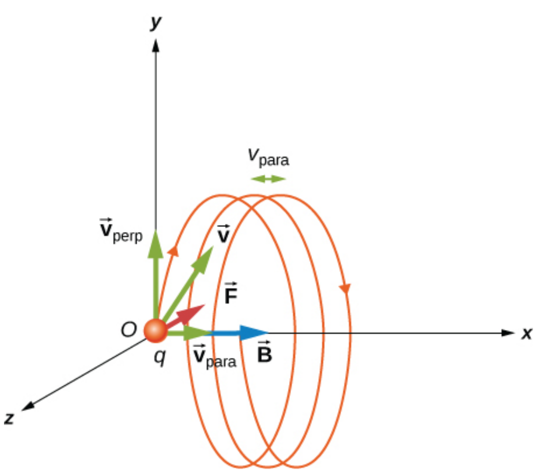




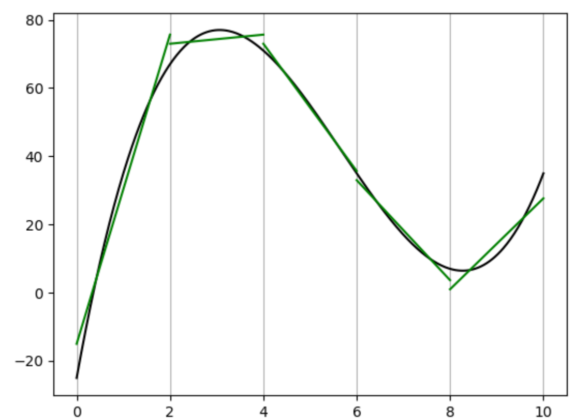
Gyrokinetics and Gkeyll

- **Gyrokinetics**: “model rings not particles”
- In plasmas, charged particles gyrate quickly around magnetic field lines
- If times scales of interest >> gyro-period and if disturbances along field lines >> gyro-radii, one can average over gyro-motion to reduce dimensionality of the probability distribution function

$$f(x,y,z,v_x,v_y,v_z,t) \rightarrow f(x,y,z,v_{||},v_{\perp})$$

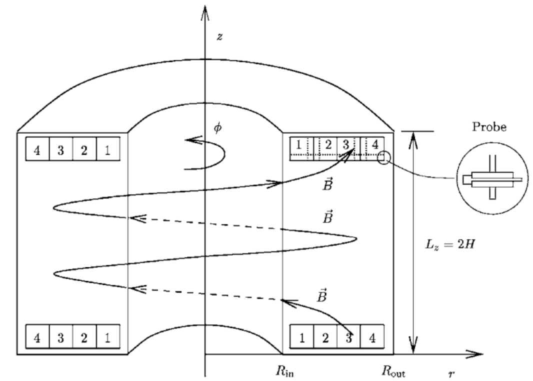


- **Gkeyll** is a computational framework for kinetic and fluid plasma simulations (http://gkyl.rtfd.io)
- Uses the modal **discontinuous Galerkin (DG)** computational method
  - Benefits: local and parallelizable, easily extends to higher orders, handles shocks well, maintains conservation properties



DG projection of the function $(x - 5)^3 - 2x^2 + x + 100$

Gyrokinetic modeling of Texas Helimak



- Helimak experiment has helical, open field lines and allows investigation on of SOL-like turbulence in simple geometry (*R*, *z*, *φ*)
- Extensive diagnostics facilitate comparison with computational models
- Helimak simulations using **Gkeyll** solve a gyrokinetic equation in the long-wavelength limit using the gyro-center distribution function, $f(\mathbf{R}, v_\parallel, \mu, t)$

$$\frac{\partial \mathcal{J} f}{\partial t} + \nabla \cdot (\mathcal{J}\{\mathbf{R}, H\} f) + \frac{\partial}{\partial v_\parallel}(\mathcal{J}\{v_\parallel, H\} f) = \mathcal{J} C[f] + \mathcal{J} S$$

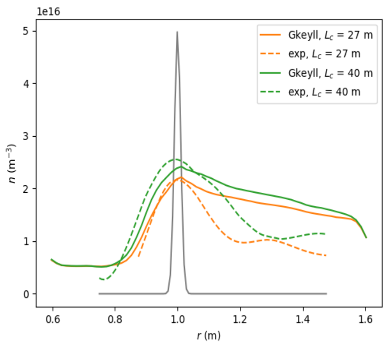
- Electric potential solved from gyrokinetic Poisson equation:

$$-\nabla_\perp \cdot \left(\frac{n_{i0} m_i}{q_i B^2} \nabla_\perp \phi \right) = \sigma_g(\mathbf{R}, t) = e[n_i(\mathbf{R}, t) - n_e(\mathbf{R}, t)]$$

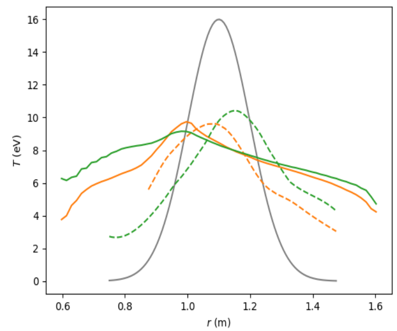
- Moments of *f* give the fluid moments, including density, momentum and temperature
- Other features:
  - Non-orthogonal field-line following coordinate system
  - Conducting sheath BCs in parallel direction (along *B* field)
  - Dirichlet BCs in radial direction (*x*)
  - Periodic BCs in poloidal or bi-normal direction (*y*)

Simulation results

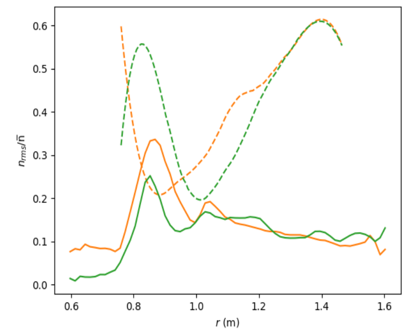
- Simulations completed on ~24,000 CPU-hours on TACC 's Stampede 1 cluster with output files in HDF5.
- Post-processing completed using Postgkyl, a Python post-processing tool for Gkeyll.



Density

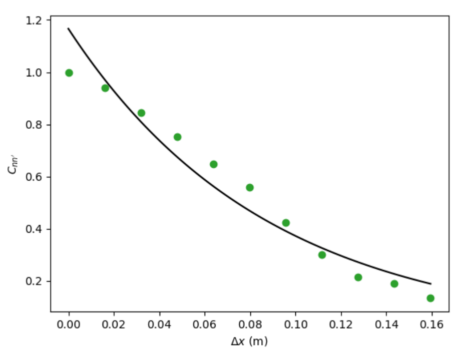


Electron temperature



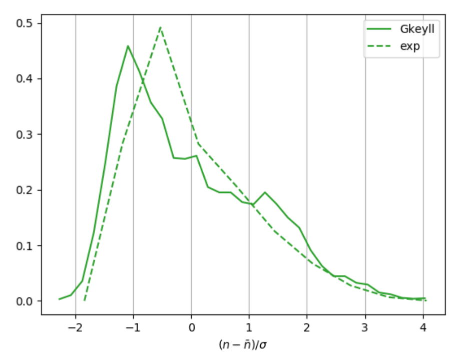
Turbulence levels

- Orange and green lines represent different magnetic field line connection lengths, L_c
- Experimental data is represented by dashed lines.
- Source profiles (in gray) are narrow, but steady state profiles are wider due to turbulence.



Radial cross-correlation

This plot gives a decay length of 8.75 cm, close to experimental value of 8.67 cm.



PDF at *R* = 1.3 m

The PDF is skewed to events below the mean density and consistent with fluid simulations and experiment.

Current work

- We are upgrading Gkeyll to a new version that is mostly written in LuaJIT, with time-critical components in C++
- It has been optimized for Knight's Landing (KNL) chips on Stampede 2 at TACC with MPI-3's shared memory methods
- Using **modal DG** results in a sparse mass matrix: core kernels are pre-generated using Maxima computer algebra system (CAS)
- Discretization of energy-conserving gyrokinetic Lenard-Bernstein collision operator to reproduce SOL simulations with Gkeyll v2.0

$$\frac{\partial f_\alpha}{\partial t} = C_{\alpha\beta}[f_\alpha]$$

$$C_{\alpha\beta}[f_\alpha] = \nu_{\alpha\beta}\frac{\partial}{\partial v_\parallel}\left[(v_\parallel - u_{\parallel,\alpha})f_\alpha + v_{t,\alpha\beta}^2\frac{\partial f_\alpha}{\partial v_\parallel}\right] + \nu_{\alpha\beta}\frac{\partial}{\partial \mu}\left[2\mu f_\alpha + 2\frac{m_\alpha v_{t,\alpha\beta}^2}{B}\mu\frac{\partial f_\alpha}{\partial \mu}\right]$$

References:

[1] http://gkyl.readthedocs.io

[2] Shi, E. L., et al. (2017). J. Plasma Phys., http://doi.org/10.1017/S002237781700037X

[3] Shi, E.L., Princeton Ph.D. (2017) **arXiv:1708.07283v1**

[4] J. Juno, A. Hakim, et al., J. Comp. Phys. (2018)., https://doi.org/10.1016/j.jcp.2017.10.009