INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

Fluid transport modelling of the plasma core and edge

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Výzkum užitečný pro společnost.

Outline

- Basics of fluid turbulent models.
- Simple 2D model.
  - Equations
  - Implementation
  - Results and limitations
- From kinetic to fluid equations to Braginskii equations.
- 3D GBS modell.
  - Inputs / outputs.
  - Implementation of the GBS code.
  - Results and limitations.
- Fluid codes on GPU using Python and JAX.

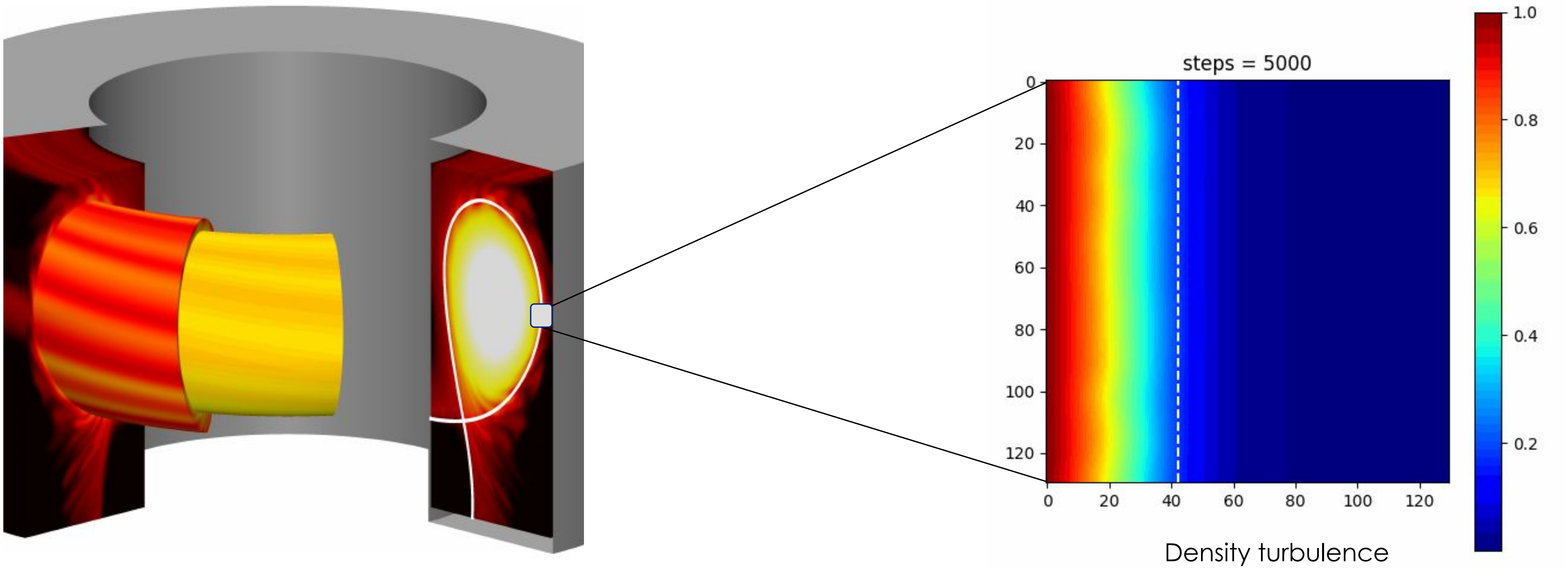
Fluid models basics

- From kinetic equation to fluid equations.
- **Maxwellian distribution is assumed (high collisionality)!**
- Several first moments (up to temperature equations) + closure.
- Much **faster** compared to kinetic simulations, several 3D models exists (**GBS**, TOKAM3X, GRILLIX).
- **Full-size simulations** of medium size machines (COMPASS, TCV, etc).
- Kinetic effects and gyromotions are neglected.
- Describes **edge plasma only** => unable to simulate core plasma (ITGs, ETGs, TEM neglected).

Turbulence v okrajovém plazmatu

Complex 3D model

Simple 2D model



Density turbulence

Towards simple 2D fluid model

Drift reduced approximation

- The momentum equation for each charged particle species reduced to an algebraic expression for the fluid drifts in terms of scalar fields.
- To **separate** the **parallel** and **perpendicular** motion.
- To remove fast temporal scales.
- Can be used because the **turbulence** is much **slower** compared to gyro-frequency and much **larger** compared to the gyro-radius.
- Perpendicular motion given by **ExB** drift, **diamagnetic** drift, and **polarization** drift.

$$\boldsymbol{v}_\perp = \overbrace{\frac{1}{B}\boldsymbol{b}\times\boldsymbol{\nabla}\phi}^{\text{ExB drift}} + \overbrace{\frac{1}{qnB}\boldsymbol{b}\times\boldsymbol{\nabla}p}^{\text{diamagnetic drift}} + \overbrace{\frac{m}{qB}\boldsymbol{b}\times\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla}\right)\boldsymbol{v}}^{\text{polarization drift}},$$

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Simple 2D model - equations

Perpendicular transport:

$$\boldsymbol{v}_\perp = \overbrace{\frac{1}{B}\boldsymbol{b}\times\boldsymbol{\nabla}\phi}^{\text{ExB drift}} + \overbrace{\frac{1}{qnB}\boldsymbol{b}\times\boldsymbol{\nabla}p}^{\text{diamagnetic drift}} + \overbrace{\frac{m}{qB}\boldsymbol{b}\times\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla}\right)\boldsymbol{v}}^{\text{polarization drift}},$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{v}_E = \overbrace{\boldsymbol{\nabla}\left(\frac{1}{B}\right)\cdot\boldsymbol{b}\times\boldsymbol{\nabla}\phi}^{(1)} + \overbrace{\frac{1}{B}\boldsymbol{\nabla}\times\boldsymbol{b}\cdot\boldsymbol{\nabla}\phi}^{(2)} = \mathcal{C}(\phi),$$

Kinetic equation

$$\frac{\partial f}{\partial t} + \nabla\cdot(vf) + \nabla\cdot\left(\frac{F}{m}f\right) = C$$

Density equation

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla}\cdot(n\boldsymbol{v}) = 0,$$

Temperature equation

$$\frac{3}{2}n\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla}\right)T + nT\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{\nabla}\cdot\boldsymbol{q}_\perp = 0,$$

$$\begin{aligned}
\frac{\mathrm{d}n}{\mathrm{d}t} + n\mathcal{C}(\phi) - \mathcal{C}(nT) &= \Lambda(n)\\
\frac{\mathrm{d}T}{\mathrm{d}t} + \frac{2T}{3}\mathcal{C}(\phi) - \frac{7T}{3}\mathcal{C}(T) - \frac{2T^2}{3n}\mathcal{C}(n) &= \Lambda(T)\\
\frac{\mathrm{d}\Omega}{\mathrm{d}t} - \mathcal{C}(nT) &= \Lambda(\Omega)
\end{aligned}$$

$$\Omega = \boldsymbol{\nabla}\times v_E = B^{-2}\boldsymbol{\nabla}\times(\boldsymbol{B}\times\boldsymbol{\nabla}\phi) = \nabla_\perp^2\phi.$$

Simple 2D model - without temperature

2D model without temperature:

- **Turbulence** can be evolved even **without temperature**.
- Considering **constant temperature** - simplification.
- Poisson equation is unchanged.
- Numerical solution:
  - Poisson equation- Poisson solver
  - Operator d/dt
  - Curvature operator C(.)
  - Diffusion operator Λ

$$\frac{dn}{dt} + nC(\phi) - C(n) = \Lambda(n)$$

$$\frac{d\Omega}{dt} - C(n) = \Lambda(\Omega)$$

$$\Delta\phi = \Omega$$

Simple 2D model - implementation

$$\frac{dn}{dt} + nC(\phi) - C(n) = \Lambda(n)$$

Total time derivative -> time change + convection

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x}\frac{\partial \phi}{\partial y} - \frac{\partial f}{\partial y}\frac{\partial \phi}{\partial x}$$

convection

Curvature operator - derivative in y direction

$$C(f) = -\frac{\partial f}{\partial y}$$

Diffusion term -> diffusion in x and y + parallel decay

$$\Lambda(f) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} - \frac{1}{\tau_{||}} f$$

1. derivative in x: $$\frac{\partial f(x,y)}{\partial x} \approx \frac{f(x+\Delta h, y) - f(x-\Delta h, y)}{\Delta h}$$

2. derivative in y: $$\frac{\partial^2 f(x,y)}{\partial x^2} \approx \frac{f(x+\Delta h, y) - 2f(x,y) + f(x-\Delta h, y)}{\Delta h^2}$$

Simple 2D model - Arakawa scheme

- **Convection term** using Arakawa scheme for numerical stability.
- Arakawa conserves:
  - Mean vorticity
  - Mean-square vorticity
  - Kinetic energy

$$\partial\zeta/\partial t = (\partial\zeta/\partial x)(\partial\psi/\partial y) - (\partial\zeta/\partial y)(\partial\psi/\partial x) \equiv J(\zeta, \psi)$$

$$\begin{aligned}
J_{i,j}(\zeta, \psi) = -\frac{1}{12d^2} [&(\psi_{i,j-1} + \psi_{i+1,j-1} - \psi_{i,j+1} - \psi_{i+1,j+1})(\zeta_{i+1,j} - \zeta_{i,j}) \\
&+ (\psi_{i-1,j-1} + \psi_{i,j-1} - \psi_{i-1,j+1} - \psi_{i,j+1})(\zeta_{i,j} - \zeta_{i-1,j}) \\
&+ (\psi_{i+1,j} + \psi_{i+1,j+1} - \psi_{i-1,j} - \psi_{i-1,j+1})(\zeta_{i,j+1} - \zeta_{i,j}) \\
&+ (\psi_{i+1,j-1} + \psi_{i+1,j} - \psi_{i-1,j-1} - \psi_{i-1,j})(\zeta_{i,j} - \zeta_{i,j-1}) \\
&+ (\psi_{i+1,j} - \psi_{i,j+1})(\zeta_{i+1,j+1} - \zeta_{i,j}) \\
&+ (\psi_{i,j-1} - \psi_{i-1,j})(\zeta_{i,j} - \zeta_{i-1,j-1}) \\
&+ (\psi_{i,j+1} - \psi_{i-1,j})(\zeta_{i-1,j+1} - \zeta_{i,j}) \\
&+ (\psi_{i+1,j} - \psi_{i,j-1})(\zeta_{i,j} - \zeta_{i+1,j-1})], \qquad (45)
\end{aligned}$$

Simple 2D model - Poisson Solver

Solve Poisson equation in 2D using **periodical BCs in y**:

- The Poisson equation in 2D:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = \Omega$$

- **Fourier transform** in y direction:

$$\frac{\partial^2 \hat{\phi}}{\partial x^2} - k^2 \hat{\phi} = \hat{\Omega}$$

- Discretization - solving for phi:

$$\frac{\hat{\phi}_{i+1,j} - 2\hat{\phi}_{i,j} + \hat{\phi}_{i-1,j}}{\Delta x^2} - k^2 \hat{\phi}_{i,j} = \hat{\Omega}_{i,j}$$

Simple 2D model - Poisson Solver

Solve Poisson equation in 2D using **general BCs**:

- The Poisson equation in 2D:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = \Omega$$

- Fourier transform cannot be used (no periodic BCs) -> **finite difference** matrix solver [1]:

$$\frac{\phi_{i+1,j} - 2\phi_{i,j} + \phi_{i-1,j}}{\Delta x^2} + \frac{\phi_{i,j+1} - 2\phi_{i,j} + \phi_{i,j-1}}{\Delta y^2} = \Omega_{i,j}$$

Simple 2D model - Boundary conditions

Left:

- Temperature and density set to 1 (normalization).

Right:

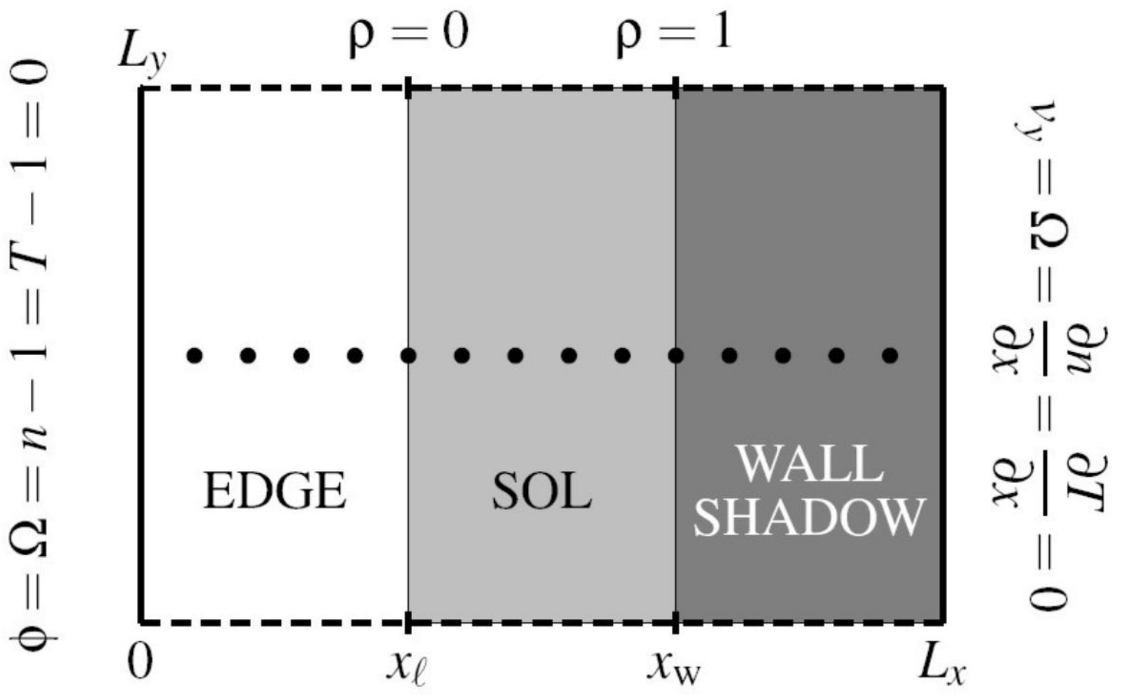
- Neumann for temperature, density and potential.
- Dirichlet for vorticity.

Top and bottom:

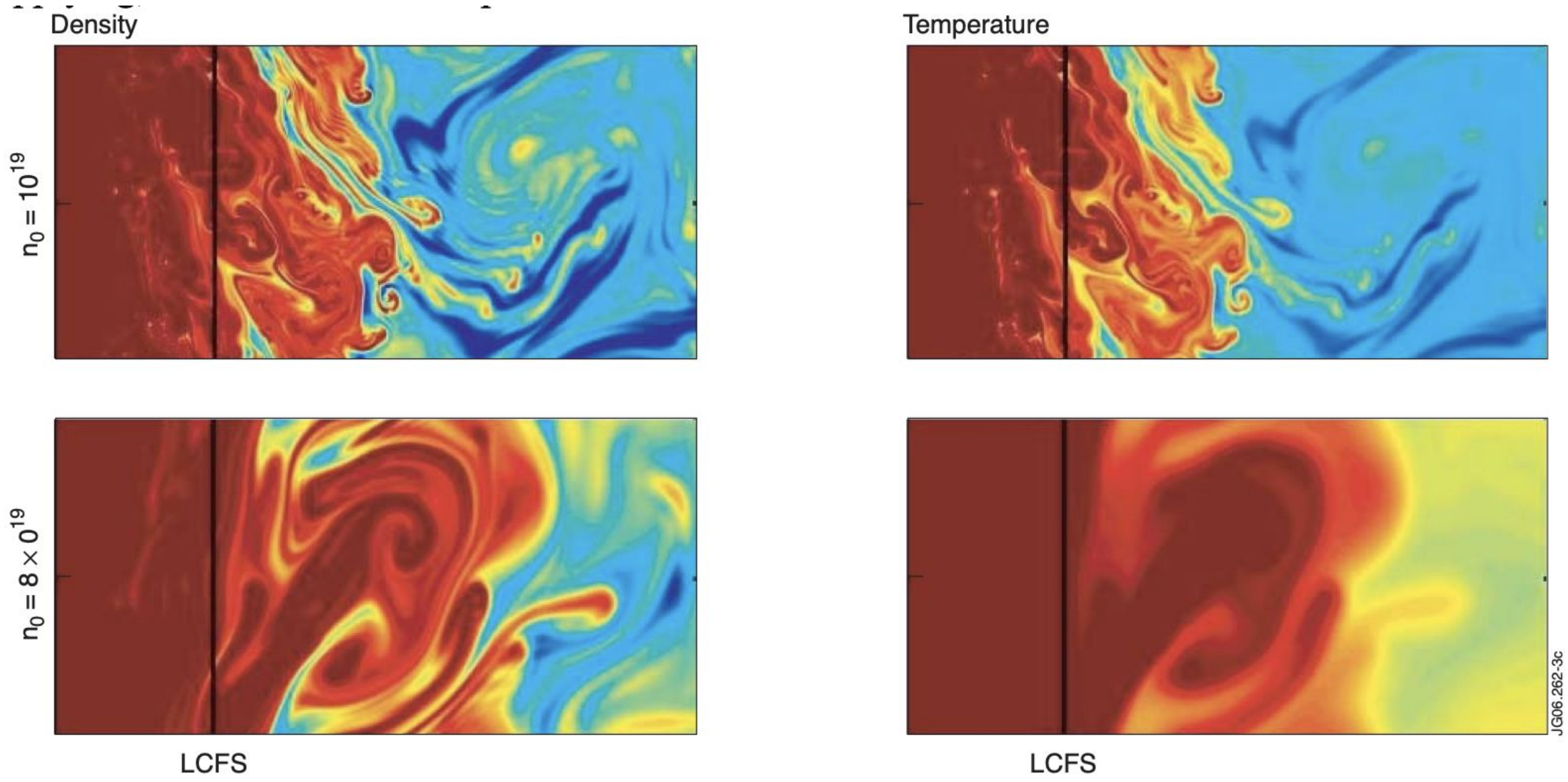
- Periodic boundary conditions for all the fields.

Parallel transport:

- Exponential decay in SOL and WALL SHADOW.
- Represents region of open / closed mg. field lines.



Simple 2D model - results



21st IAEA Fusion Energy Conference

Simple 2D model - limits

Advantages

- Reduced computational resources.
- Faster simulation time
- Easier interpretation of the results.
- Easier implementation (simple equations).
- Some processes can be reasonably approximated by 2D model.
- Validation of more complex 3D codes.

Disadvantages

- Limited accuracy (neglects 3rd dimension).
- Oversimplification (some processes cannot be described in 2D).
- Not possible to perform full-size simulation.
- Cannot describe the complex tokamak geometry.

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Towards complex 3D fluid model

Towards Braginskii equations I

$$\frac{\partial f}{\partial t} + \nabla \cdot (vf) + \nabla \cdot (\frac{F}{m} f) = C$$

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot (n_e \mathbf{v}_e) + n_n \nu_{iz} - n_i \nu_{rec} + S_n$$

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot (n_i \mathbf{v}_i) + n_n \nu_{iz} - n_i \nu_{rec} + S_n$$

$$m_e n_e \frac{d_e \mathbf{v}_e}{dt} = -\nabla p_e - \nabla \cdot \Pi_e - e n_e [\mathbf{E} + \mathbf{v}_e \mathbf{B}] + \mathbf{R}_{ei} + m_e n_n (\nu_{en} + 2\nu_{iz})(\mathbf{v}_n - \mathbf{v}_e)$$

$$m_i n_i \frac{d_i \mathbf{v}_i}{dt} = -\nabla p_i - \nabla \cdot \Pi_i - Z_i e n_i [\mathbf{E} + \mathbf{v}_i \mathbf{B}] - \mathbf{R}_{ei} + m_i n_n (\nu_{iz} + \nu_{cx})(\mathbf{v}_n - \mathbf{v}_i)$$

$$\frac{3}{2} n_e \frac{d_e T_e}{dt} = -p_e \nabla \cdot \mathbf{v}_e - \nabla \cdot \mathbf{q}_e - \Pi_e : \nabla \mathbf{v}_e + Q_e + n_n \nu_{iz} [-E_{iz} - \frac{3}{2} m_e \mathbf{v}_e \cdot (\mathbf{v}_e - \frac{4}{3} \mathbf{v}_n)] - n_n \nu_{en} m_e \mathbf{v}_e \cdot (\mathbf{v}_n - \mathbf{v}_e) + \frac{3}{2} n_e S_{Te}$$

$$\frac{3}{2} n_i \frac{d_i T_i}{dt} = -p_i \nabla \cdot \mathbf{v}_i - \nabla \cdot \mathbf{q}_i - \Pi_i : \nabla \mathbf{v}_i + Q_i + n_n (\nu_{iz} + \nu_{cx}) [\frac{3}{2}(T_n - T_i) + \frac{m_i}{2} (\mathbf{v}_n - \mathbf{v}_i)^2] + \frac{3}{2} n_i S_{Ti}$$

Towards Braginskii equations II

- Assumptions on drift reduced limit, electrostatic limit, etc…

$$\frac{\partial n}{\partial t} + \nabla \cdot (\mathbf{V}_{\mathbf{E}\times\mathbf{B}} + \mathbf{V}_{\text{dia,e}} + \mathbf{V}_{\|\text{e}}) = 0$$

$$\frac{nc}{B\omega_\text{i}} \frac{d}{dt}\left(-\nabla_\perp^2 \phi - \frac{1}{en}\nabla_\perp^2 p_\text{i}\right) + \frac{1}{3m_\text{i}\omega_\text{i}}\mathbf{b} \times \kappa \cdot \nabla G_\text{i} + \nabla_\| \frac{j_\|}{e} +$$
$$\nabla \cdot n\left(\mathbf{V}_{\text{dia,i}} - \mathbf{V}_{\text{dia,e}}\right) = 0$$

$$m_\text{e}\frac{dV_{\|\text{e}}}{dt} = -\frac{1}{n}\nabla_\| p_\text{e} - \frac{2}{3}\nabla_\| G_\text{e} + e\nabla_\|\phi - \frac{e}{c}\frac{\psi}{\partial t} + e\frac{j_\|}{\sigma_\|} - 0.71\nabla_\| T_\text{e}$$

$$m_\text{i}\frac{dV_{\|\text{i}}}{dt} = -\frac{1}{n}\nabla(p_\text{i} + p_\text{e}) - p_\text{i}\nabla \times \frac{\mathbf{b}}{\omega_\text{i}} \cdot \nabla V_{\|\text{i}} - \frac{2}{3}\nabla_\| G_\text{i}$$

$$\frac{3}{2}n\frac{dT_\text{i}}{dt} + \frac{3}{2}n\mathbf{V}_{\text{dia,e}} \cdot \nabla T_\text{e} + p_\text{e}\nabla \cdot \left(\mathbf{V}_{\perp\text{e}} + \mathbf{V}_{\|\text{e}}\right) - \frac{5}{2}\frac{c}{e}\nabla \cdot p_\text{e}\left(\frac{\mathbf{b}}{B} \times \nabla T_\text{e}\right) -$$

$$0.71 T_\text{e}\nabla_\| j_\| - \nabla \cdot \left(\chi_{\|\text{e}}\nabla_{\|\text{T}_\text{e}}\right) = 0$$

$$\frac{3}{2}n\frac{dT_\text{i}}{dt} + T_\text{i}\left[m \cdot \left(\mathbf{V}_{\mathbf{EB}} + \mathbf{V}_{\|\text{e}}\right) + \nabla \cdot \left(n\mathbf{V}_{\text{dia,e}}\right)\right] + \frac{5}{2}\frac{c}{e}p_\text{i}\left(\nabla\frac{\mathbf{b}}{B}\right) \cdot \nabla T_\text{i} = 0$$

Towards Braginskii equations III

$$\frac{\partial n}{\partial t} = -\frac{1}{B}[\phi, n] + \frac{2}{eB}\Big[C(p_e) - nC(\phi)\Big] - \nabla_\parallel(n v_{\parallel e}) + D_n \nabla_\perp^2 n + s_n + \nu_{\mathrm{iz}} n_{\mathrm{n}} - \nu_{\mathrm{rec}} n, \quad (1)$$

$$\frac{\partial \Omega}{\partial t} = -\frac{1}{B}\nabla\cdot[\phi, \omega] - \nabla\cdot\left(v_{\parallel i}\nabla_\parallel \omega\right) + \frac{B\Omega_{ci}}{e}\nabla_\parallel j_\parallel + \frac{2\Omega_{ci}}{e} C(p_e + p_i) + \frac{\Omega_{ci}}{3e} C(G_i) + D_\Omega \nabla_\perp^2 \Omega - \frac{n_{\mathrm{n}}}{n}\nu_{\mathrm{cx}}\Omega, \quad (2)$$

$$\frac{\partial U_{\parallel e}}{\partial t} = -\frac{1}{B}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{e}{m_e}\left(\frac{j_\parallel}{\sigma_\parallel} + \nabla_\parallel \phi - \frac{1}{en}\nabla_\parallel p_e - \frac{0.71}{e}\nabla_\parallel T_e - \frac{2}{3en}\nabla_\parallel G_e\right) + D_{v_{\parallel e}} \nabla_\perp^2 v_{\parallel e} + \frac{n_{\mathrm{n}}}{n}(\nu_{\mathrm{en}} + 2\nu_{\mathrm{iz}})(v_{\parallel n} - v_{\parallel e}), \quad (3)$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\frac{1}{B}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{m_i n}\nabla_\parallel(p_e + p_i) - \frac{2}{3 m_i n}\nabla_\parallel G_i + D_{v_{\parallel i}} \nabla_\perp^2 v_{\parallel i} + \frac{n_{\mathrm{n}}}{n}(\nu_{\mathrm{iz}} + \nu_{\mathrm{cx}})(v_{\parallel n} - v_{\parallel i}), \quad (4)$$

$$\frac{\partial T_e}{\partial t} = -\frac{1}{B}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{2}{3}T_e\left[0.71\frac{\nabla_\parallel j_\parallel}{en} - \nabla_\parallel v_{\parallel e}\right] + \frac{4}{3}\frac{T_e}{eB}\left[\frac{7}{2}C(T_e) + \frac{T_e}{n}C(n) - eC(\phi)\right] + \nabla_\parallel(\chi_{\parallel e}\nabla_\parallel T_e) + D_{T_e}\nabla_\perp^2 T_e + s_{T_e} - \frac{n_{\mathrm{n}}}{n}\nu_{\mathrm{en}} m_e \frac{2}{3} v_{\parallel e}(v_{\parallel n} - v_{\parallel e}) - 2\frac{m_e}{m_i}\frac{1}{\tau_e}(T_e - T_i) + \frac{n_{\mathrm{n}}}{n}\nu_{\mathrm{iz}}\left[-\frac{2}{3}E_{\mathrm{iz}} - T_e + m_e v_{\parallel e}\left(v_{\parallel e} - \frac{4}{3}v_{\parallel n}\right)\right], \quad (5)$$

$$\frac{\partial T_i}{\partial t} = -\frac{1}{B}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4}{3}\frac{T_i}{eB}\left[C(T_e) + \frac{T_e}{n}C(n) - eC(\phi)\right] - \frac{10}{3}\frac{T_i}{eB}C(T_i) + \frac{2}{3}T_i\left[(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n} - \nabla_\parallel v_{\parallel e}\right] + \nabla_\parallel(\chi_{\parallel i}\nabla_\parallel T_i) + D_{T_i}\nabla_\perp^2 T_i + s_{T_i} + 2\frac{m_e}{m_i}\frac{1}{\tau_e}(T_e - T_i) + \frac{n_{\mathrm{n}}}{n}(\nu_{\mathrm{iz}} + \nu_{\mathrm{cx}})\left[T_n - T_i + \frac{1}{3}(v_{\parallel n} - v_{\parallel i})^2\right], \quad (6)$$

convection $$[\phi, f] = \mathbf{b}\cdot(\nabla\phi \times \nabla f)$$

curvature $$C(f) = \frac{B}{2}\left(\nabla \times \frac{\mathbf{b}}{B}\right)\cdot\nabla f$$

parallel gadient $$\nabla_\parallel f = \mathbf{b}\cdot\nabla f + \frac{1}{B}[\psi, f]$$

perp. Laplace $$\nabla_\perp^2 f = \nabla\cdot\left[(\mathbf{b}\times\nabla f)\times\mathbf{b}\right]$$

Gyroviscous terms
$$G_i = -\eta_{0i}\left[2\nabla_\parallel v_{\parallel i} + \frac{1}{B}C(\phi) + \frac{1}{enB}C(p_i)\right]$$
$$G_e = -\eta_{0e}\left[2\nabla_\parallel v_{\parallel e} + \frac{1}{B}C(\phi) - \frac{1}{enB}C(p_e)\right]$$

Operators used in fluid codes

Poisson bracket

$$[\phi, f] = \frac{B_\varphi}{B}(\partial_Z\phi\,\partial_R f - \partial_R\phi\,\partial_Z f)$$

Curvature operator

$$C(f) = \frac{B_\varphi}{B_0}\partial_Z f$$

Perpendicular laplacian

$$\nabla_\perp^2 f = \partial_{RR}^2 f + \partial_{ZZ}^2 f$$

Parallel laplacian

$$\nabla_{||} f = \partial_Z\Psi\,\partial_R f - \partial_R\Psi\,\partial_Z f + \frac{B_\varphi}{B_0}\partial_\varphi f$$

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Derivatives in 3D model

$$(\partial_Z f)_{i,j,k} = \frac{1}{\Delta Z}\left(\frac{1}{12} f_{i,j,k-2} - \frac{2}{3} f_{i,j,k-1} + \frac{2}{3} f_{i,j,k+1} - \frac{1}{12} f_{i,j,k+2}\right)$$

$$(\partial_{ZZ} f)_{i,j,k} = \frac{1}{\Delta Z^2}\left(-\frac{1}{12} f_{i,j,k-2} + \frac{4}{3} f_{i,j,k-1} - \frac{5}{2} f_{i,j,k} + \frac{4}{3} f_{i,j,k+1} - \frac{1}{12} f_{i,j,k+2}\right)$$

- Poisson equation:

$$\nabla \cdot (n \nabla_\perp \phi) = \Omega - \frac{\nabla_\perp^2 p_i}{e}$$

- Ampere equation:

$$\left(\nabla_\perp^2 - \frac{e^2 \mu_0}{m_e} n\right) v_{\parallel e} = \nabla_\perp^2 U_{\parallel e} - \frac{e^2 \mu_0}{m_e} n v_{\parallel i} + \frac{e^2 \mu_0}{m_e} \bar{j}_\parallel$$

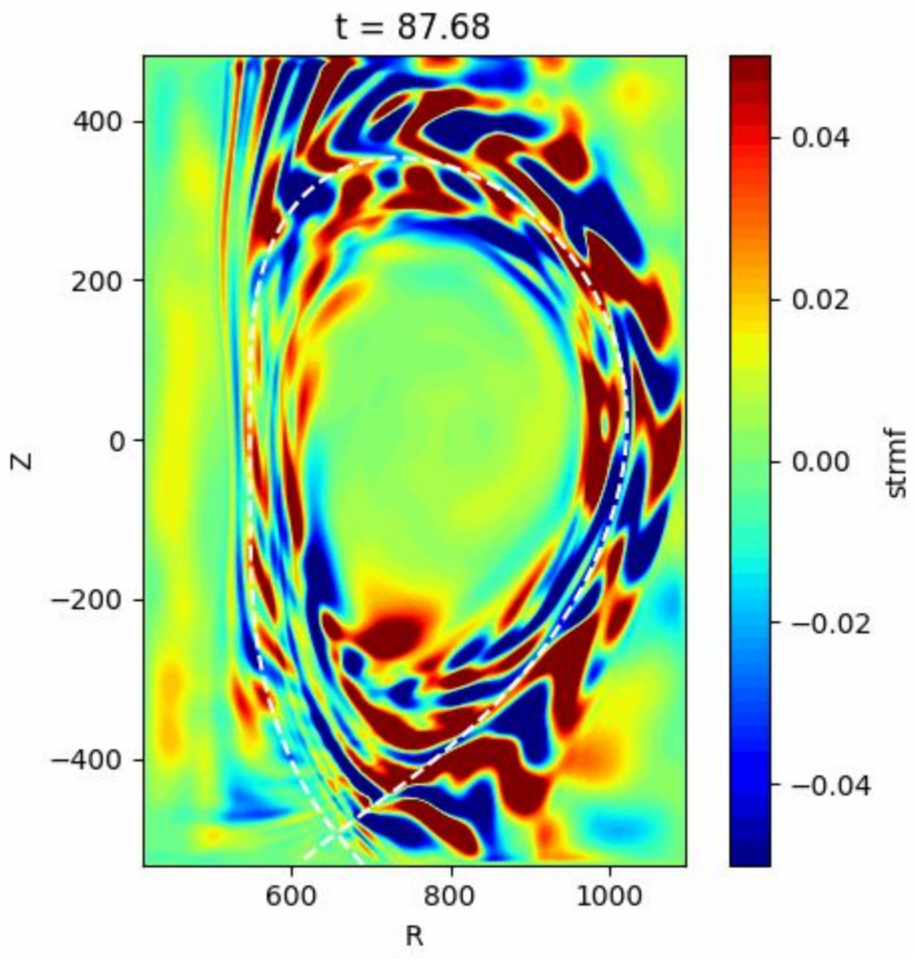
Complex 3D codes

3D, flux-driven turbulence codes, based on drift-reduced Braginskii model:

- **GBS**
  - Non-aligned grid, includes plasma core, kinetic neutrals, electromagnetic effects, ion dynamics.
- GRILLIX
  - Cylindrical grid, includes plasma core, electron-ion heat exchange, drift corrections at the magnetic presheath.
  - Evolves parallel component of the electromagnetic vector potential $A_{\parallel}$.
- TOKAM3X
  - Electron-ion heat exchange, drift corrections at the magnetic presheath.
- BOUT++
  - Framework for writing plasma simulations.
  - Any set of equations can be inserted and solved.
  - Can perform fluid or kinetic simulations.

GBS - FLUID TURBULENCE SIMULATION

- **G**lobal **B**raginskii **S**olver - first principle, 3D, flux-driven, global, **turbulence code** for plasma edge simulations based on Braginskii equations.
- Full plasma volume, Divertor geometry, electromagnetic effects, kinetic neutrals, ion temperature dynamics, **self-consistent turbulence evolution**.
- High computational requirements (~2000 cores, ~5-10 M CPU hours / simulation), however still lower compared to full kinetic models.



GBS - SIMULATION DOMAIN

Set of **Mag**netic boundary conditions
(Bohm Chodura boundary conditions)

$$v_{\|i} = \pm c_s \sqrt{1 + \frac{T_i}{T_e}},$$

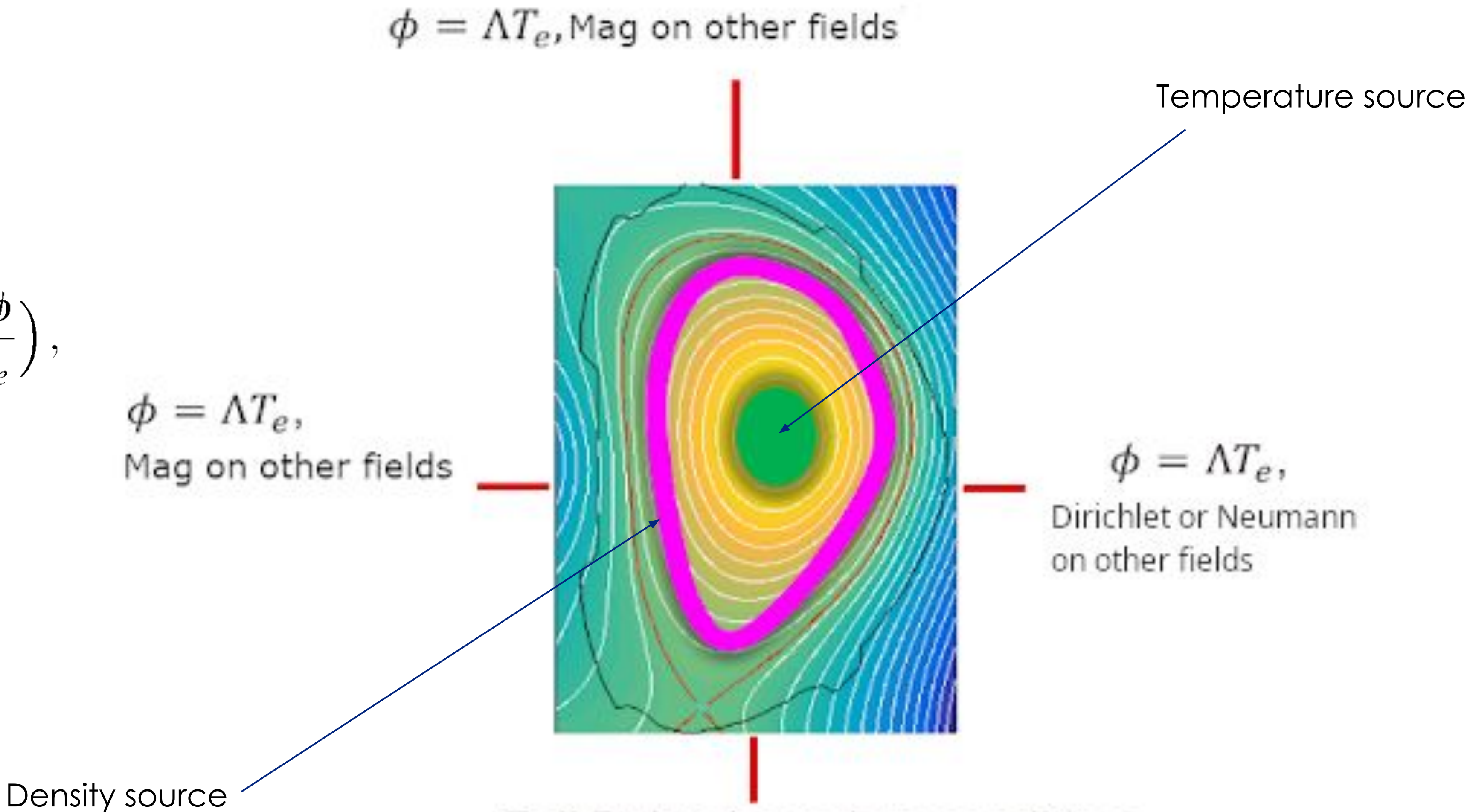
$$v_{\|e} = \pm c_s \sqrt{1 + \frac{T_i}{T_e}} \exp\left(\Lambda - \frac{e\phi}{T_e}\right),$$

$$\partial_s n = \mp \frac{n}{c_s \sqrt{1 + \frac{T_i}{T_e}}} \partial_s v_{\|i},$$

$$\partial_s T_e = \partial_s T_i = 0,$$

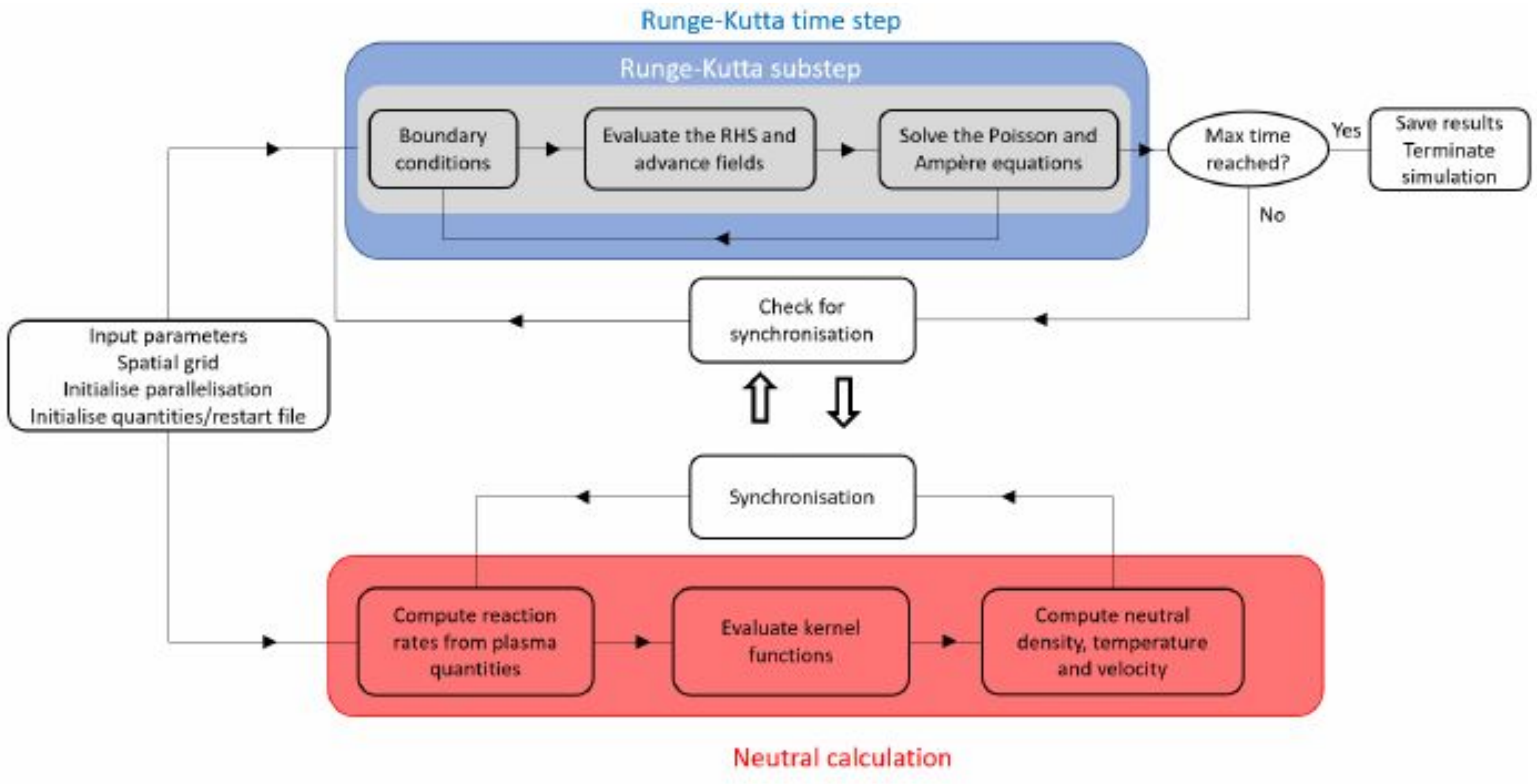
$$\Omega = \mp \frac{m_i n}{e} c_s \sqrt{1 + \frac{T_i}{T_e}} \partial^2_{ss} v_{\|i},$$

$$\partial_s \phi = \mp \frac{m_i c_s}{e \sqrt{1 + \frac{T_i}{T_e}}} \partial_s v_{\|i},$$

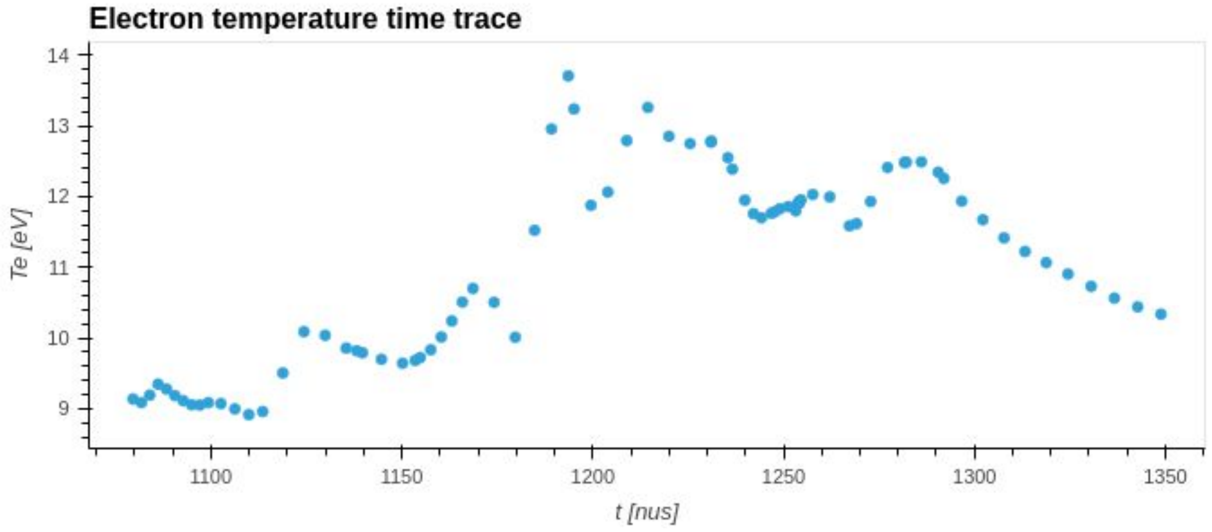


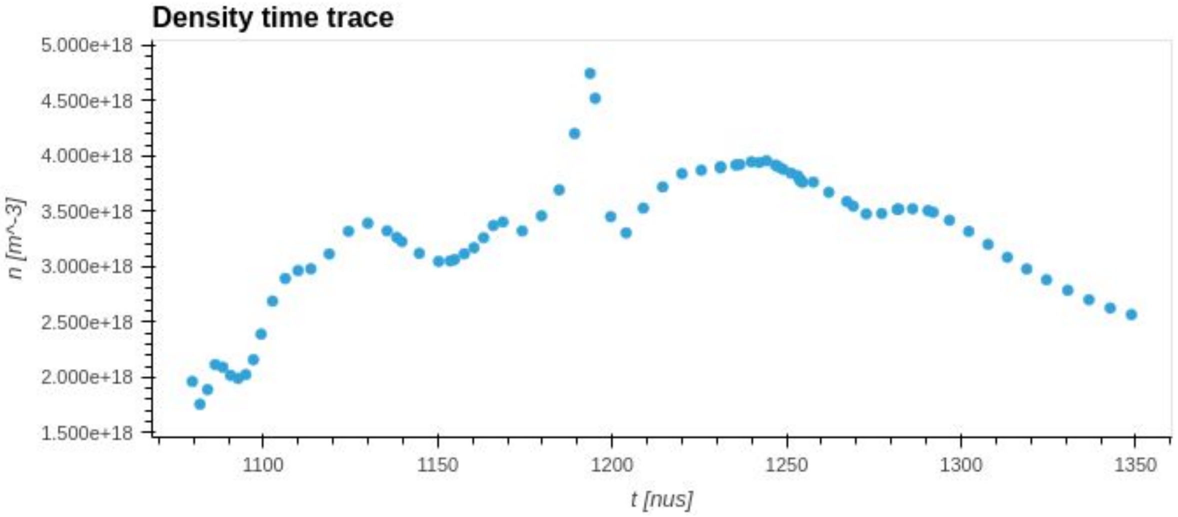
Full Bohm boundary conditions
(J. Loizu PoP 2012)

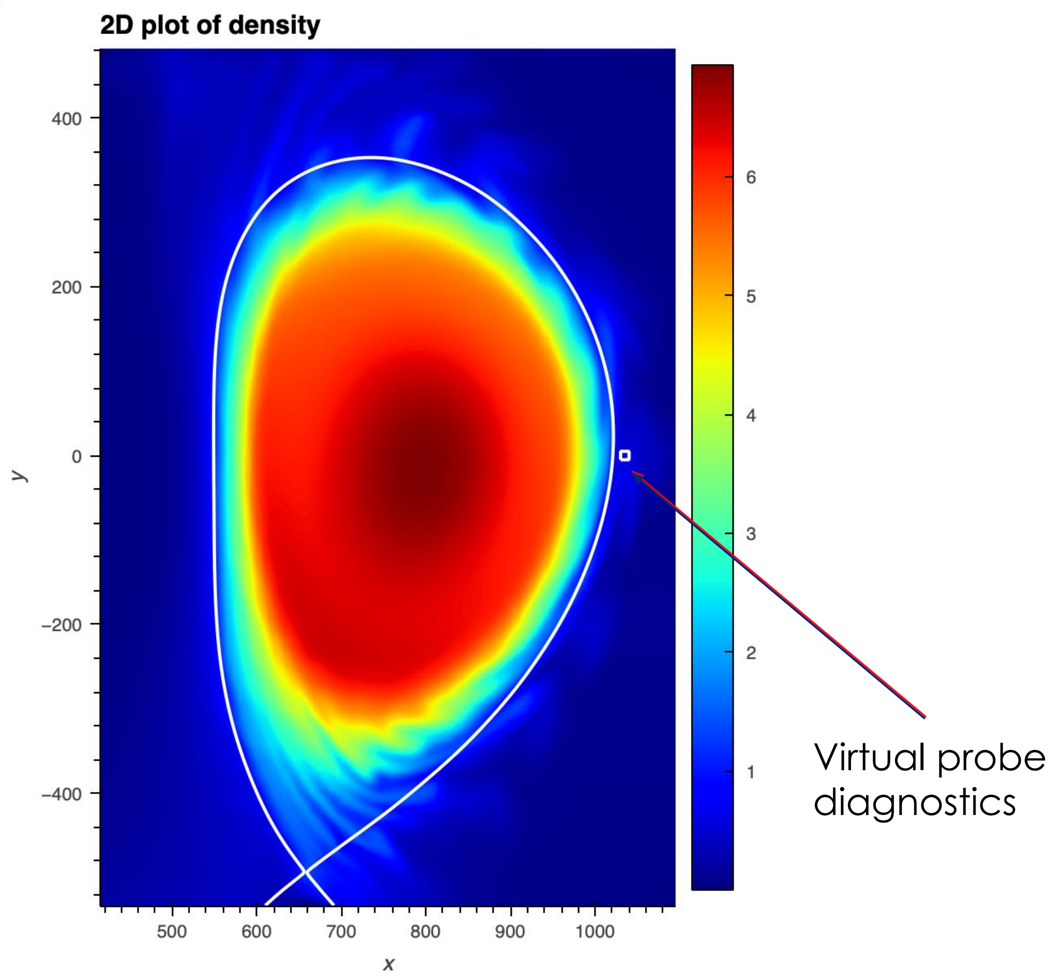
GBS - SIMULATION DOMAIN



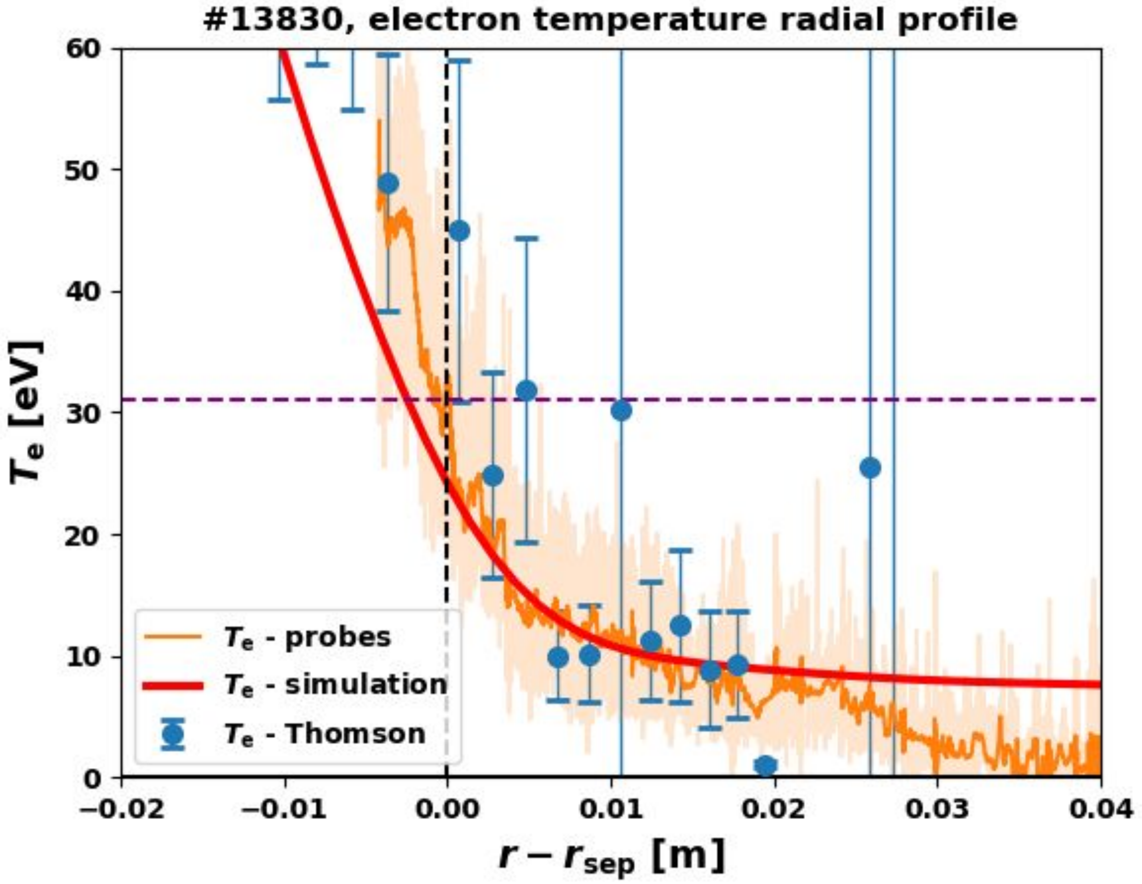
SIMULATION RESULTS EXAMPLES





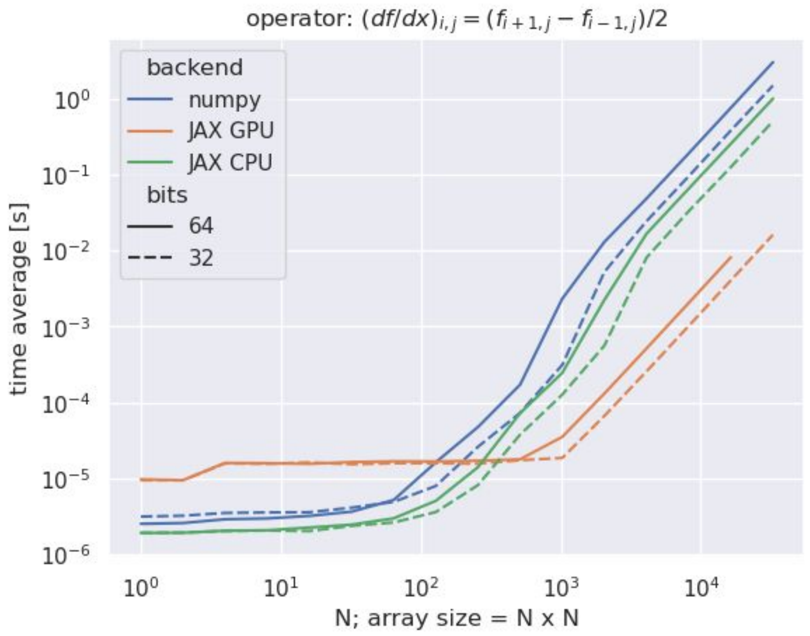


SIMULATION RESULTS EXAMPLES



Boosting simulation using GPU

- Python allows simple transformations of the code to GPU.
- All the fluid terms can be transformed.
- Central difference: $\frac{\partial f(t,x,y)}{\partial x} \approx \frac{f(t,x+\Delta h,y) - f(t,x-\Delta h,y)}{2\Delta h}$
- Compare of speeds using **numpy** vs **NUMBA** vs **JAX CPU** vs **JAX GPU**.
- Huge boost on GPU.
- Problem - limited memory on GPUs.



GPUs using Python

- **JAX** - module for calculations on GPU.
- Very easy to use and to convert code into JAX.
- Numpy-like syntax - **very easy to be used.**
- The code is parallelized along GPU automatically.
- JAX insluces **JIT** (just-in-time) compiler boosting the code.
- Uses machine learning for boosting the code even more.

many simple cores
parallel operations
fast computing
fast memory access

several fast cores
universal
sequential operations
a lot of memory

Conclusions

- Turbulence plays a key role in particle and heat transport.
- Understanding and controlling turbulence in plasma edge can lead to better confinement.
- Simulations can provide **interpretation** or prediction on turbulent transport.
- Fluid models offer **higher speeds** while still **encompassing important physics.**
  - Much faster compared to kinetic / gyrokinetic codes.
  - Does not include kinetic effects (Maxwellian distribution is assumed).
- Simple 2D model can be written very easily, providing still good results.
- Complex 3D models are more complicated, but almost the only way to perform full-size simulations.
- Consider using GPUs in your future works.

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