

Plasma-Facing Components
and Plasma-Materials
Interactions



Fusion Plant Engineering
& System Integration



Drifts and Turbulence in Hermes-3

Ben Dudson, D. Bold, P. Hill, M. Kryjak, B. Shanahan, M.
Tsagaridis, T. Tork, B. Zhu, BOUT++ contributors

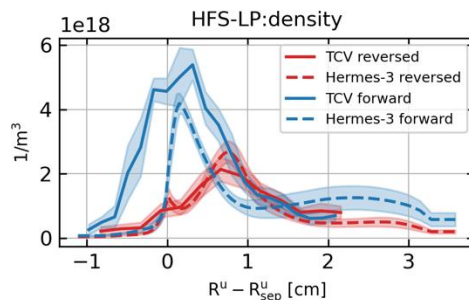
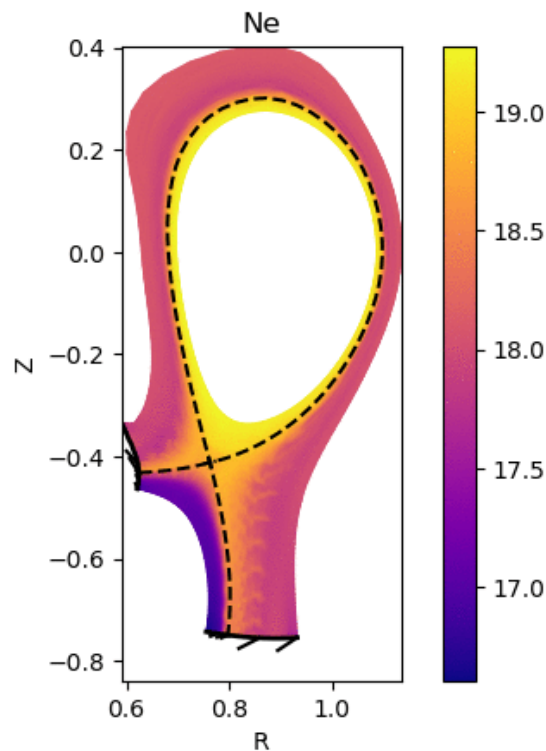
Exhaust Code Workshop, Culham, October 5 - 9, 2026

LLNL Fusion Energy Sciences Program

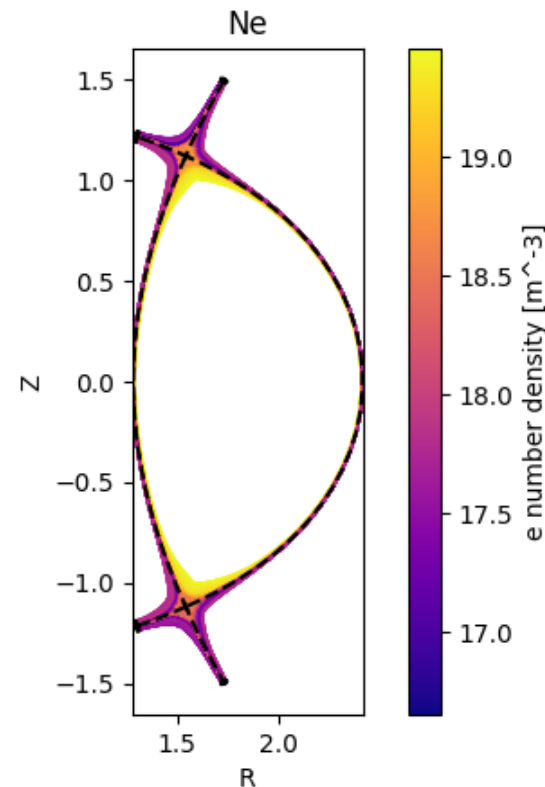
Acknowledgement: DOE Fusion Energy Sciences, SciDAC program

Prepared by LLNL under Contract DE-AC52-07NA27344.

Turbulence validation (TCV-X21) and prediction (SPARC)



Flux-driven simulations predict profiles and fluctuation properties.



Preliminary results

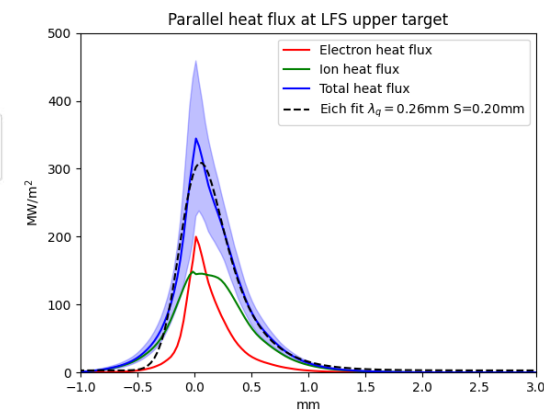
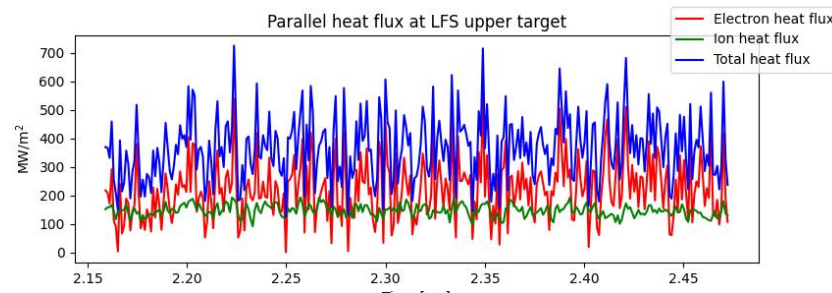
$$\lambda_{int} \approx \lambda_q + 1.64S$$

[mm]	λ_q	S	λ_{int}
Upper	0.26	0.2	0.59
Lower	0.35	0.12	0.55

Kuang et al. 2020 [H-mode]

Scaling	OMP heat flux width [mm]
Eich et al. (2013) Regression 14	0.18
Eich et al. (2013) Regression 15	0.3
Eich et al. (2020)	0.43
Goldston (2011)	0.4
Brunner et al. (2018b)	0.35

B.D. Dudson et al 2026 *Nucl. Fusion* **66** 036015
doi:10.1088/1741-4326/ae3627



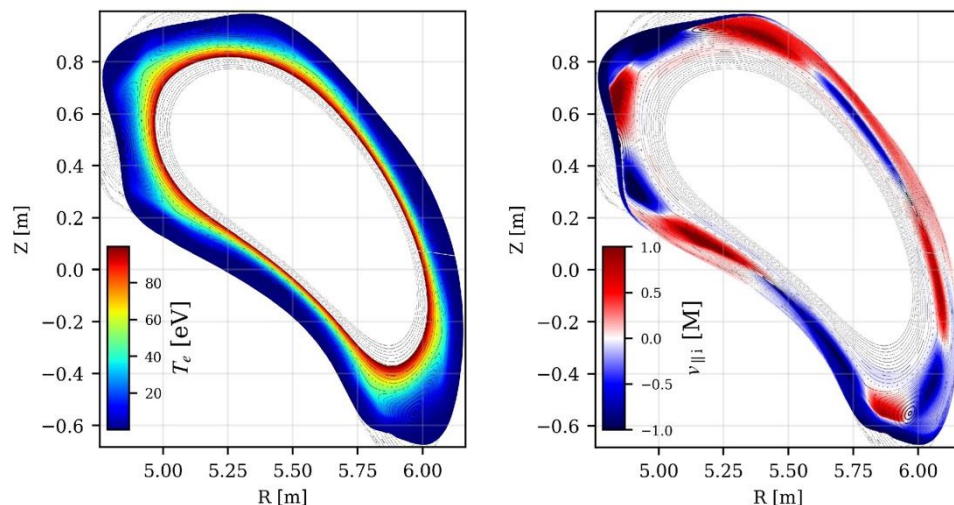
BSTING simulates stellarator transport and turbulence

Fluid modeling of the plasma boundary using the Flux Coordinate Independent (FCI) method

Towards a Mean-Field Braginskii Model for Stellarators

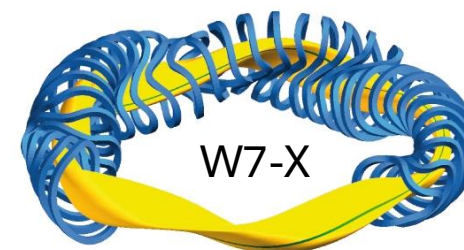
[T. Tork](#) ✉, [F. Reimold](#), [D. Bold](#), [B. Shanahan](#), [B. Dudson](#), [A. Stegmeir](#), [P. Manz](#), [The W7-X Team](#)

First published: 26 July 2026 | <https://doi.org/10.1002/ctpp.70157> | [VIEW METRICS](#)

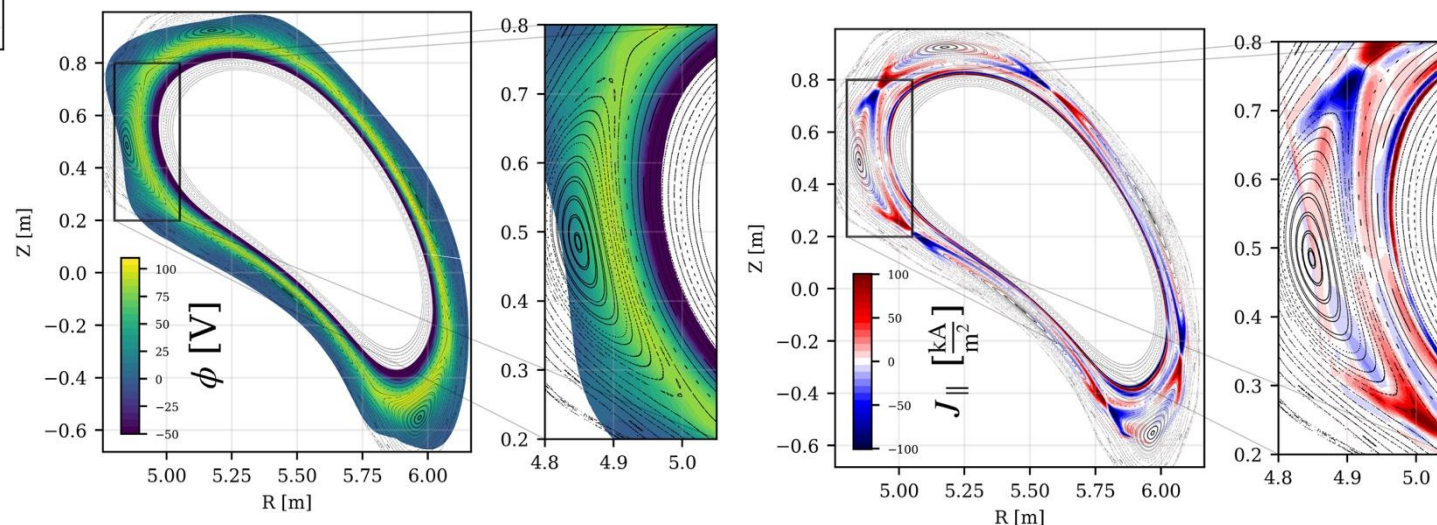


(a) Electron temperature

(b) Parallel ion velocity



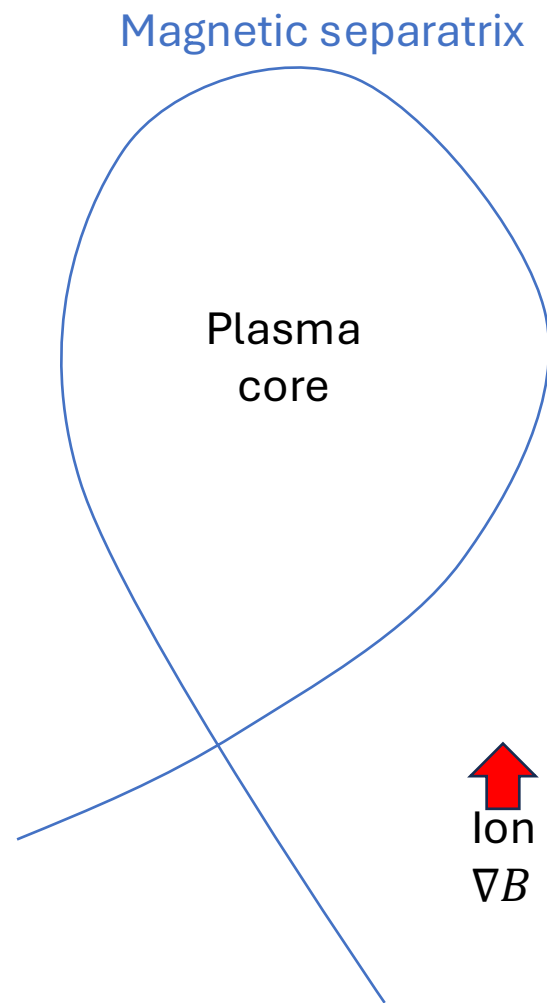
Relaxation method finds steady-state potential and currents.



Tobias Tork's talk on Tuesday

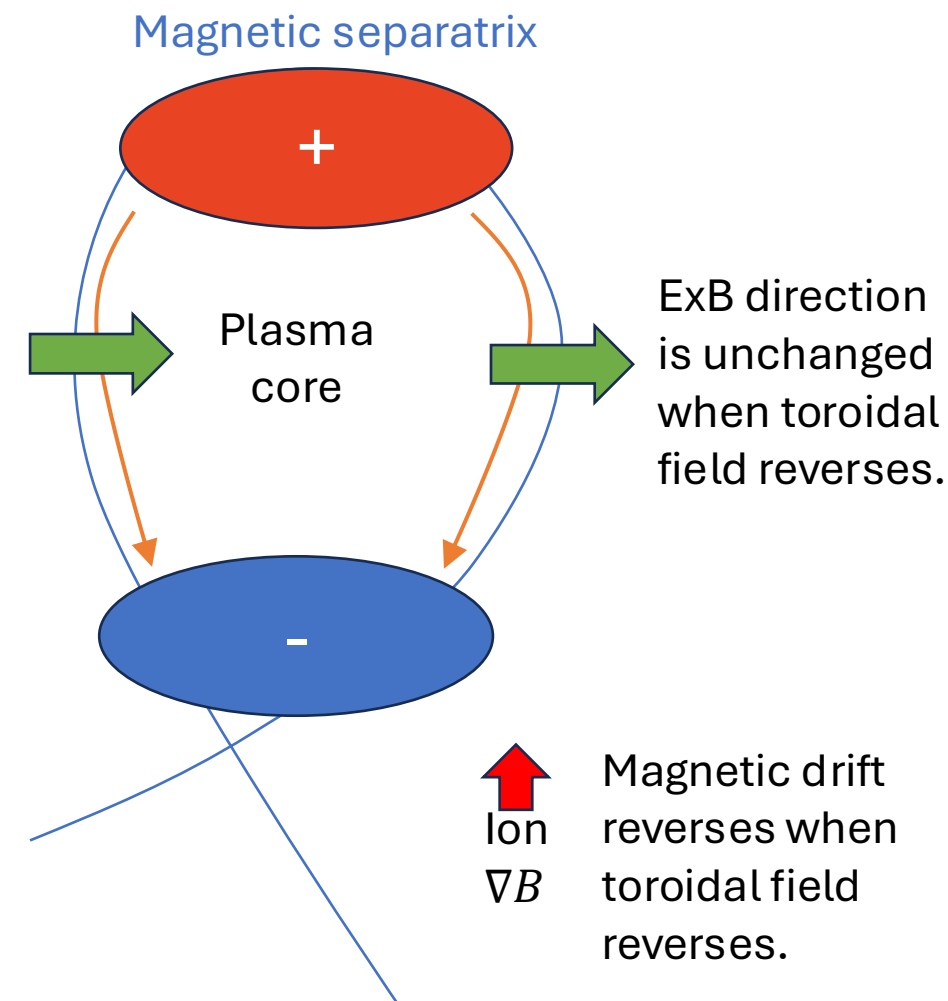
Drifts and Turbulence simulations have the same ingredients

- **Magnetic drifts $\Leftrightarrow$ Diamagnetic current**
 - Balanced by parallel currents driven by a poloidal electric field
- **Sheath potential**
and parallel electron force balance
 - Depends on electron temperature
 $\Rightarrow$ Radial electric field in SOL
- **ExB drift**
 - Poloidal electric field causes radial drift (Pfirsch-Schluter transport)
 - Radial electric field causes poloidal drift



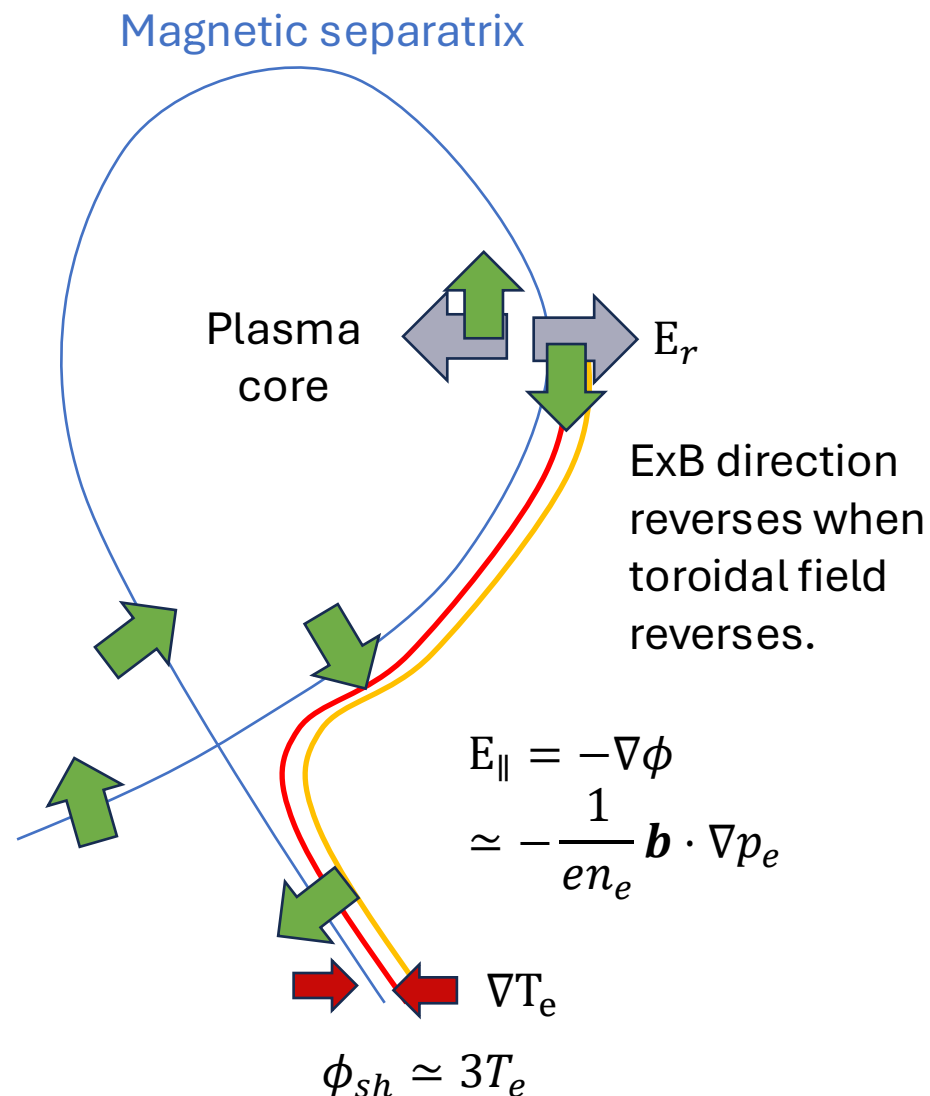
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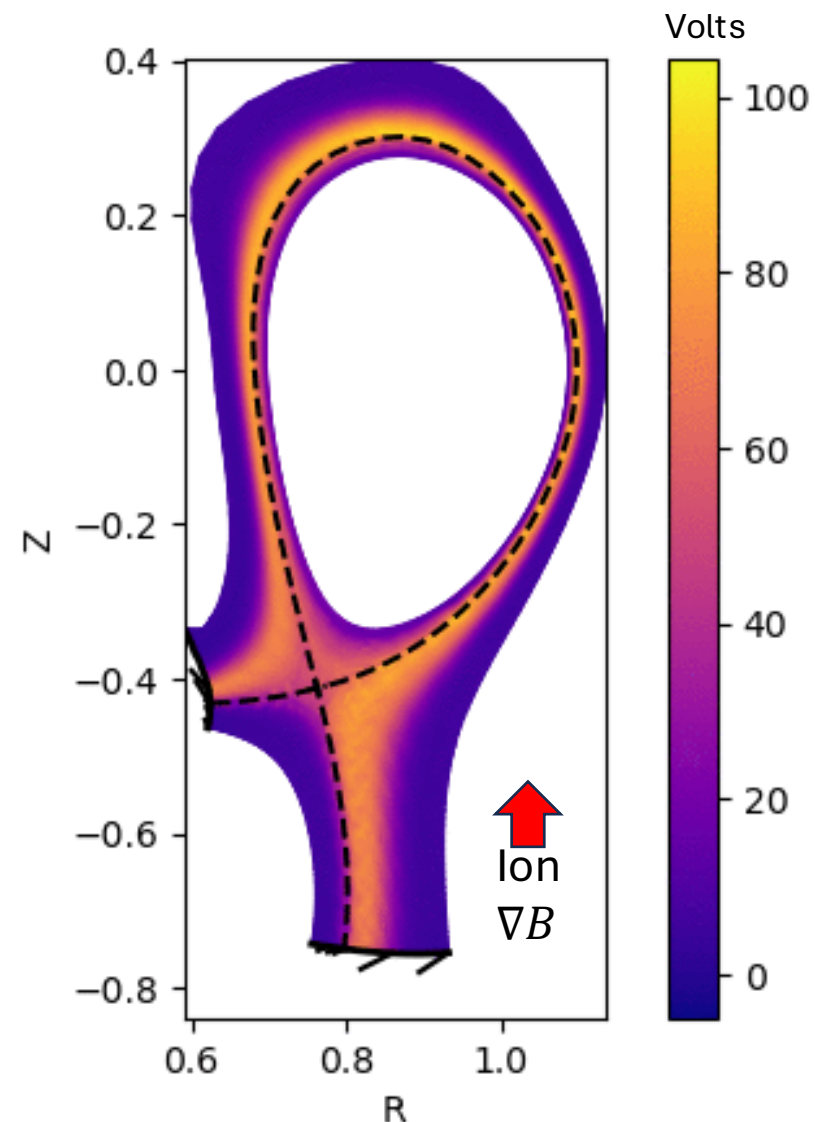
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Both 2D transport 'with drifts' and 3D turbulence simulations have fast processes: Electron dynamics, Alfvén waves, Geodesic Acoustic Modes (GAMs).



Drifts and Turbulence: What is the difference?

Both require parallel currents => Electron and ion flows

$$\frac{\partial}{\partial t}(m_e n v_{\parallel e}) = -\nabla \cdot [m_e n v_{\parallel e} (\mathbf{v}_{E \times B} + \mathbf{b} v_{\parallel e} + \mathbf{v}_{de})] - \mathbf{b} \cdot \nabla p_e - e n E_{\parallel} + F_{ei}$$

$$\frac{\partial}{\partial t}(m_i n v_{\parallel i}) = -\nabla \cdot [m_i n v_{\parallel i} (\mathbf{v}_{E \times B} + \mathbf{b} v_{\parallel i} + \mathbf{v}_{di})] - \mathbf{b} \cdot \nabla p_i + Z_i e n E_{\parallel} - F_{ei}$$

Both require quasineutrality <=> Current continuity

Polarisation current

$$\frac{\partial \omega}{\partial t} = -\nabla \cdot \left[\frac{m_i}{2B^2} \nabla_{\perp} (\mathbf{v}_{E \times B} \cdot \nabla p_i) + \frac{\omega}{2} \mathbf{v}_{E \times B} + \frac{m_i n_0}{2B^2} \nabla_{\perp}^2 \phi \left(\mathbf{v}_{E \times B} + \frac{\mathbf{b}}{n_0 B} \times \nabla p_i \right) \right]$$

$$+ \underbrace{\nabla \cdot \mathbf{j}_{\parallel}}_{\text{Parallel current}} + \underbrace{\nabla \cdot \left[(p_e + p_i) \nabla \times \frac{\mathbf{b}}{B} \right]}_{\text{Diamagnetic current}}$$

$$\omega = \nabla \cdot \left[\frac{m_i n_0}{B^2} \nabla_{\perp} \left(\phi + \frac{p_i}{n_0} \right) \right]$$

Most instabilities are stable if only n=0 (axisymmetric) mode is allowed.

- Exception: X-point interchange ‘churning mode’.

[D.Power’s talk later today](#)

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Parallel current

Diamagnetic current

Anomalous viscosity

$$\frac{1}{\lambda} \frac{\partial \phi}{\partial t} + \omega = \nabla \cdot \left[\frac{m_i n_0}{B^2} \nabla_{\perp} \left(\phi + \frac{p_i}{n_0} \right) \right]$$

Artificial time-derivative

Most instabilities are stable if only n=0 (axisymmetric) mode is allowed.

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D.Power’s talk later today

Steady-state solvers can make approximations to damp transients

- Assumes that the $t \rightarrow \infty$ solution is independent of the path taken.
- Calculate ω from ϕ so can include full density (non-Boussinesq)

N.M.Li et al. “Calculation of two-dimension radial electric field in boundary plasmas by using BOUT++” CPC 228 (2018) 69–82
<https://doi.org/10.1016/j.cpc.2018.03.003>

Drifts and Turbulence: What is the difference?

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$$\frac{\partial}{\partial t}(m_i n v_{\parallel i}) = -\nabla \cdot [m_i n v_{\parallel i}(\mathbf{v}_{E \times B} + \mathbf{b} v_{\parallel i} + \mathbf{v}_{di})] - \mathbf{b} \cdot \nabla p_i + Z_i e n E_{\parallel} - F_{ei}$$

Both require quasineutrality <=> Current continuity

$$\underbrace{\frac{1}{\lambda} \frac{\partial \phi}{\partial t}}_{\text{Evolve potential not vorticity}} = -\nabla \cdot \left[\underbrace{\frac{m_i}{2B^2} \nabla_{\perp}(\mathbf{v}_{E \times B} \cdot \nabla p_i)}_{\text{Polarisation current}} + \frac{\omega}{2} \mathbf{v}_{E \times B} + \frac{m_i n_0}{2B^2} \nabla_{\perp}^2 \phi \left(\mathbf{v}_{E \times B} + \frac{\mathbf{b}}{n_0 B} \times \nabla p_i \right) \right] + \underbrace{\nabla \cdot \mathbf{j}_{\parallel}}_{\text{Parallel current}} + \underbrace{\nabla \cdot \left[(p_e + p_i) \nabla \times \frac{\mathbf{b}}{B} \right]}_{\text{Diamagnetic current}} + \underbrace{\nabla \cdot (\mathbf{v} n_0 \nabla_{\perp} \phi)}_{\text{Anomalous viscosity}}$$

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Method used in UEDGE
[See A.Holm talk next!](#)

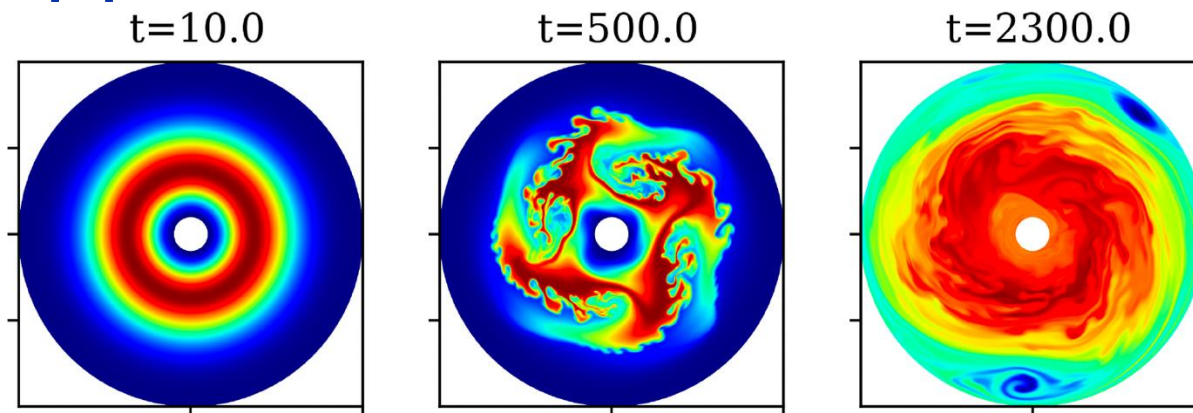
Removing the Boussinesq approximation

Drift-reduced fluid modeling of rapidly rotating plasmas

Edward A. Tocco^{1†}, B. D. Dudson², I. Abel¹ and B. Zhu²

¹University of Maryland, USA

²Lawrence Livermore National Laboratory, USA



The Simakov-Catto vorticity equation can be rewritten as:

$$\frac{\partial \omega}{\partial t} = -\nabla \cdot (\omega \mathbf{v}_E)$$

$$-\nabla \cdot \left[\frac{m_i}{2B^2} \nabla_{\perp} (\mathbf{v}_E \cdot \nabla p_i) + \frac{n}{2B^2} (\nabla_{\perp}^2 \varphi) \mathbf{v}_{di} - \nabla \cdot \left(\frac{m_i}{2B^2} \nabla_{\perp} p_i \right) \mathbf{v}_E \right]$$

$$+ \nabla \cdot \left[\frac{m_i (\mathbf{v}_E \cdot \mathbf{v}_E)}{2} \frac{\mathbf{b} \times \nabla n}{B} \right] \quad \begin{array}{l} \text{Centrifugal force} \\ \Rightarrow \text{Rotation Driven Interchange} \end{array}$$

$$+ \nabla \cdot (\mathbf{J}_d + \mathbf{J}_{ci}),$$

Ion diamagnetic terms

$$\mathbf{v}_{di} = \frac{\mathbf{b} \times \nabla p_i}{nB},$$

$$\omega = \nabla \cdot \left[\frac{m_i}{B^2} (n \nabla_{\perp} \varphi + \nabla_{\perp} p_i) \right]$$

<https://doi.org/10.48550/arXiv.2603.15347>

Accepted in J. Plasma Phys. (2026)

Electromagnetic induction and flutter

Induction modifies the parallel electric field

$$\frac{\partial}{\partial t}(m_i n v_{\parallel i}) = -\nabla \cdot [m_i n v_{\parallel i}(\mathbf{v}_{E \times B} + \mathbf{b} v_{\parallel i} + \mathbf{v}_{di})] - \mathbf{b} \cdot \nabla p_i + Z_i e n E_{\parallel} - F_{ei}$$

$$E_{\parallel} = -\nabla_{\parallel} \phi - \frac{\partial A_{\parallel}}{\partial t}$$

Each charged species has a momentum*

$$p_s = m_s n_s v_{\parallel s} + Z_s e n_s A_{\parallel}$$

$$\frac{\partial p_s}{\partial t} = \dots + Z_s e A_{\parallel} \frac{\partial n_s}{\partial t}$$

Solve at each step:

$$-\frac{1}{\beta_{em}} \nabla_{\perp}^2 A_{\parallel} + \sum_s \frac{Z_s^2 n_s}{A} A_{\parallel} = \sum_s \frac{Z_s}{A} p_s$$

PAPER

Edge Turbulent Transport in Electromagnetic Simulations using Hermes-3

T Ashton-Key^{1,2,*}, Y Andrew¹, B D Dudson³, R Kingham¹, E Kim^{4,5}

Tom Ashton-Key's poster on Wednesday
Sidney Williams' talk on Tuesday

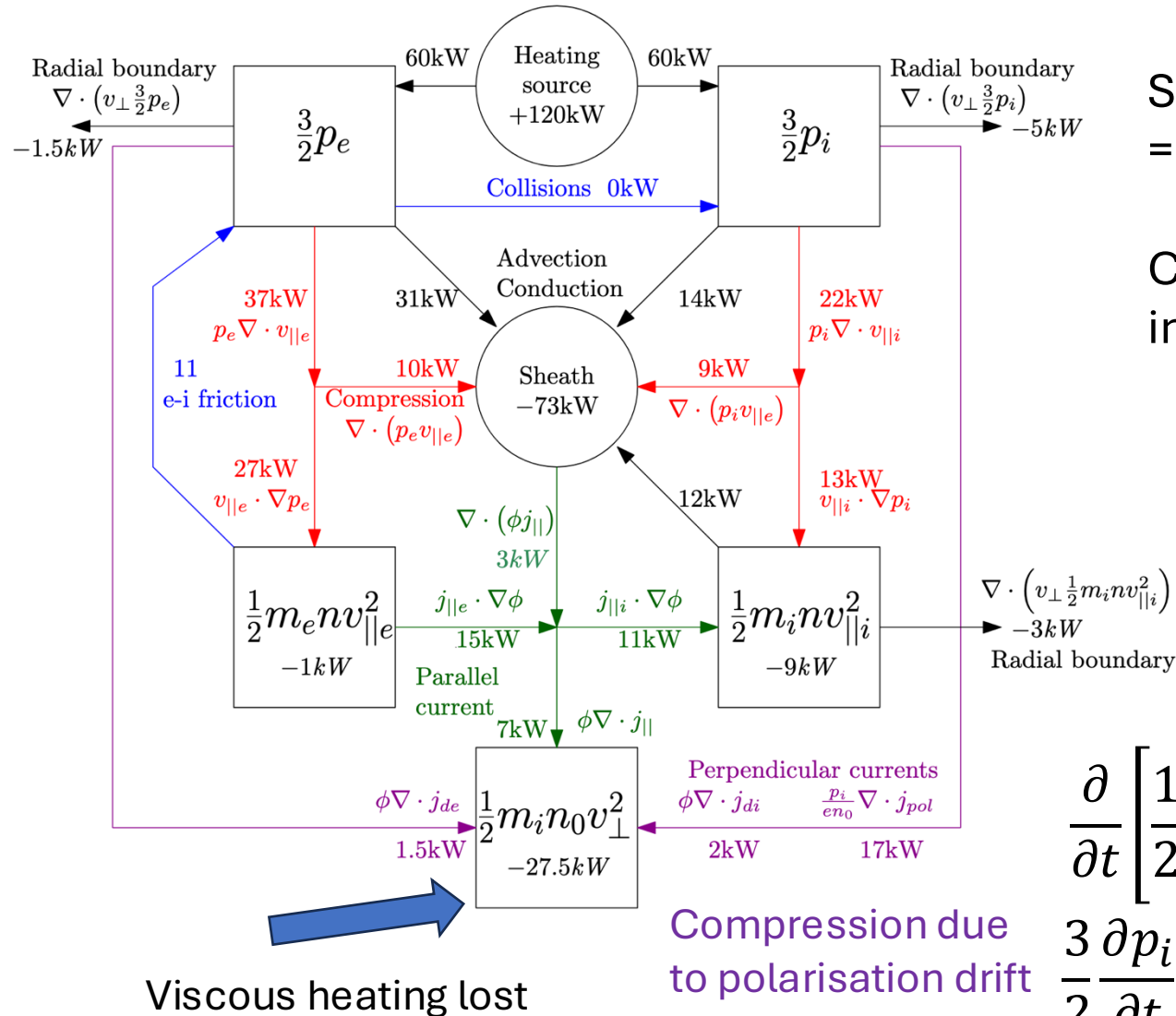
Flutter modifies the parallel derivatives e.g:

$$\begin{aligned} \mathbf{b} \cdot \nabla f &= \mathbf{b}_0 \cdot \nabla f + \delta \mathbf{b} \cdot \nabla f \\ &= \mathbf{b}_0 \cdot \nabla f + \frac{1}{B} \nabla \times (\mathbf{b} A_{\parallel}) \cdot \nabla f \end{aligned}$$

Limitations:

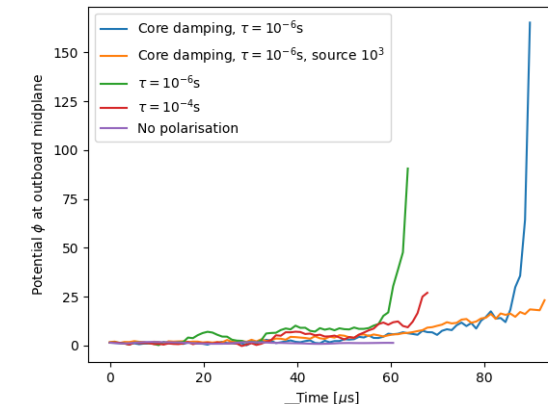
- Toroidal average is removed
=> No Shafranov shift or q profile evolution
- Bootstrap current implementation not yet finished.

Energy conservation, Viscosity, Polarisation drift



Significant energy losses from perpendicular flow.
=> How to account for viscous (numerical) heating?

Compression of polarisation drift can cause instabilities in which potential rises rapidly in PFR.



$$\frac{\partial}{\partial t} \left[\frac{1}{2} n_0 m_i \left| \frac{\nabla_{\perp} \phi}{B} + \frac{\nabla_{\perp} p_i}{n_0 B} \right|^2 \right] = -\frac{p_i}{en_0} \nabla \cdot (J_{||} + J_d) + \dots$$

$$\frac{3}{2} \frac{\partial p_i}{\partial t} = -p_i \nabla \cdot (\mathbf{v}_{E \times B} + \mathbf{b} v_{||i}) + \frac{p_i}{en_0} \nabla \cdot (J_{||} + J_d) + \dots$$

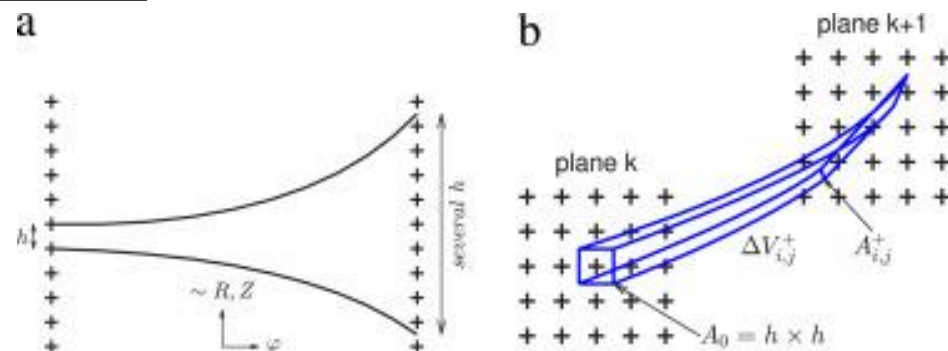
Support Operator Method for FCI simulations

- Conservation to machine precision with arbitrary cell connectivity.
- PETSc handles MPI communication.
- Matrix coefficients are calculated in mesh generator, stored in CSC format.
- Handles partial boundary intersection.
- **Limitation:** Operators are linear. Spitzer conduction, slope limiters require multiple operations.

Advances in the flux-coordinate independent approach

CPC 213, 111 (2017)

Andreas Stegmeir^a, Omar Maj^a, David Coster^a, Karl Lackner^a, Markus Held^b, Matthias Wiesenberger^b

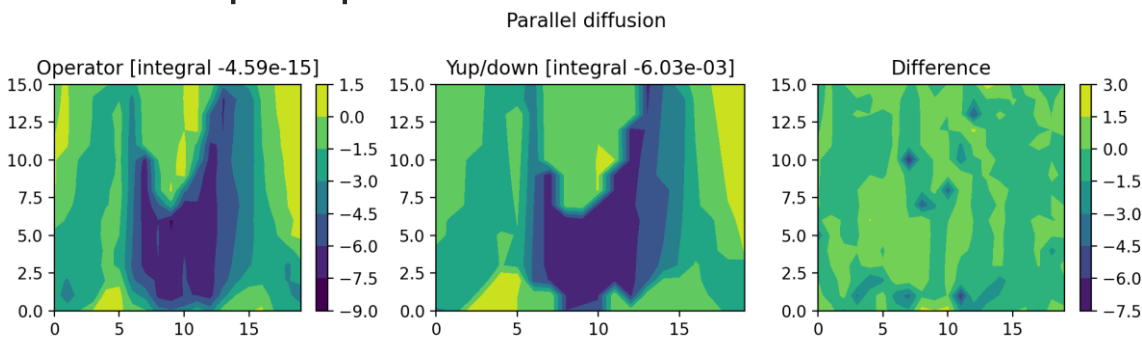


```
// Support-operator divergence from half-step gradients
auto Div_minus = Neg_inv_dV * Grad_plus.transpose() * DV_leg_plus; // C <- L+
auto Div_plus = Neg_inv_dV * Grad_minus.transpose() * DV_leg_minus; // C <- L-

// Cell-centered divergence paired with the cell-centered gradient
auto Div_par = Neg_inv_dV * Grad_par.transpose() * DV; // C <- C

// Diffusion operator assembled from the half-step pieces
auto Div_par_Grad_par =
    ((Div_minus * Grad_plus) + (Div_plus * Grad_minus)) * 0.5; // C <- C
```

BOUT++ PETSc operators code



Discussion: Applications and limitations of (gyro-)fluid models for edge & divertor modeling

- **SOL/divertor transport in future devices?**

- Gyrokinetic models show trapped electron mode (TEM) can dominate in the edge
=> Is this an electron drift/interchange mode in drift-reduced models?
- What is the role of fluid vs gyrokinetic models?
- Do fluid need to describe trapped particles? e.g. $p_{\parallel} / p_{\perp}$ or other closures?
=> Revival of full-f gyro/Landau-fluid models?

- **H-mode and other confinement regimes**

- L-H transition, access conditions and effects of geometry, fueling etc.
- Nonlinear (reduced) MHD long used to study e.g ELMs
- Access to other regimes? Negative Triangularity?