



Overview of the GRILLIX code

Andreas Stegmeir¹

¹ Max Planck Institute for Plasma Physics, Boltzmannstraße 2, 85748 Garching bei München

UKAEA exhaust code workshop 2026,
October 6 - 9 2026, Culham Campus, United Kingdom



EUROfusion



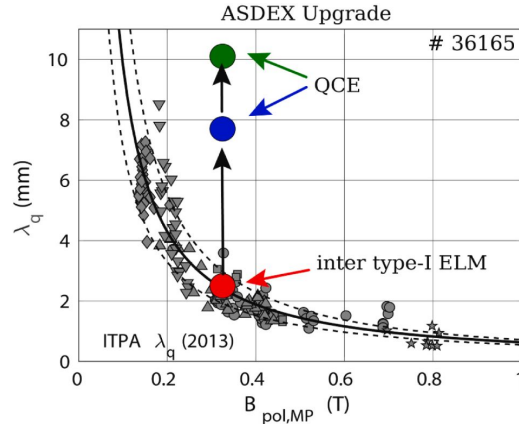
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

GRILLIX in action: Quasi-Continuous Exhaust

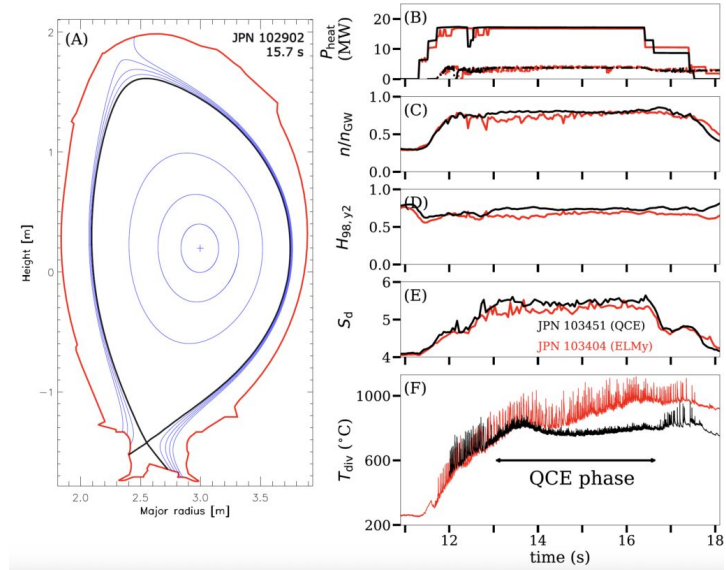
Experimental characteristics of the Quasi-Continuous Exhaust (QCE) regime

- Strong shaping + high fueling
- H-mode like confinement
- No type-I ELMs
- SOL broadening
- Presence of high-frequency, low-amplitude filaments

→ Attractive scenario for reactors

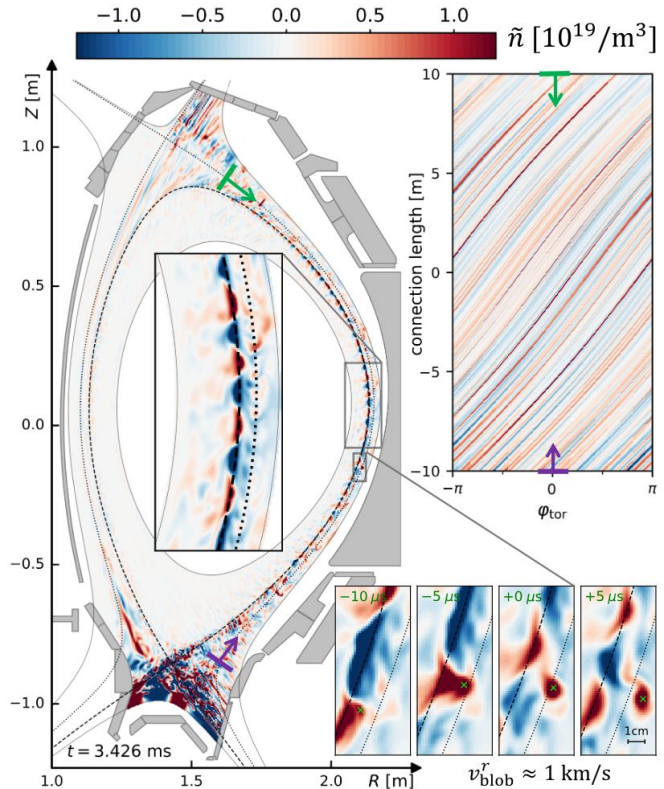


M. Faitsch *et al* 2021 *NME* **26** 100890



M. Faitsch *et al* 2025 *NF* **65** 024003

GRILLIX in action: Quasi-Continuous Exhaust



Validity of GRILLIX model

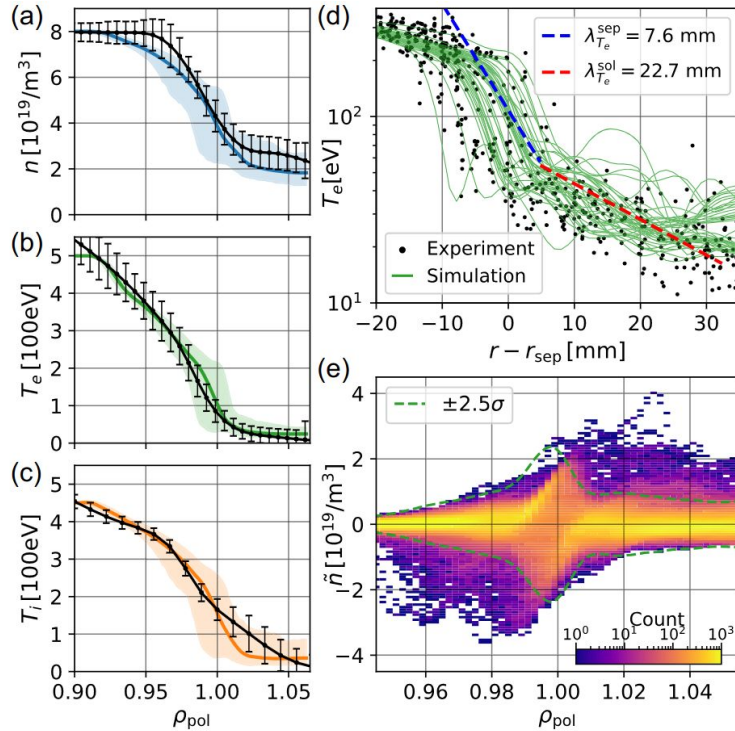
- High collisionality $\rightarrow$ fluid plasma + neutrals model
- Strong shaping ($\sim$ double null) $\rightarrow$ FCI method
- High confinement $\rightarrow$ Electromagnetic effects

Simulation of AUG #36165@6.1s reproduces many key features

- Outboard midplane profiles
- SOL fall off lengths
- Frequency and scale of Quasi-Coherent mode
- Blob characteristics and propagation velocities

K. Zhang *et al* 2026 *PRL* **137** 055102

GRILLIX in action: Quasi-Continuous Exhaust



Validity of GRILLIX model

- High collisionality $\rightarrow$ fluid plasma + neutrals model
- Strong shaping ($\sim$ double null) $\rightarrow$ FCI method
- High confinement $\rightarrow$ Electromagnetic effects

Simulation of AUG #36165@6.1s reproduces many key features

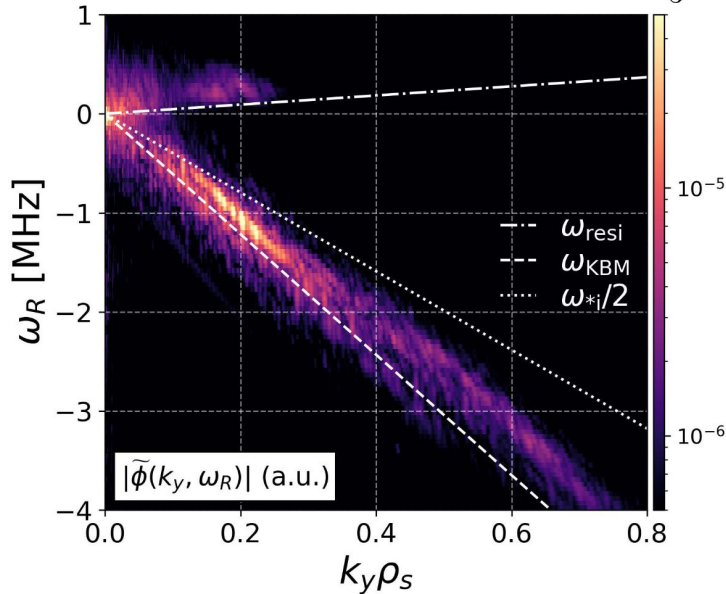
- Outboard midplane profiles
- SOL fall off lengths
- Frequency and scale of Quasi-Coherent mode
- Blob characteristics and propagation velocities

K. Zhang *et al* 2026 *PRL* **137** 055102

GRILLIX in action: Quasi-Continuous Exhaust

Spectrogram reveals two separatrix spanning modes

- Kinetic ballooning mode: $\omega_{\text{kbm}} = \frac{\frac{1}{6} + \eta_i}{1 + \eta_i} \omega_{*i}$
- Resistive X-point mode: $\omega_{\text{resi}} = \frac{\omega_{*e} + 0.71\eta_e\omega_* + \omega_{*i}}{3}$



K. Zhang *et al* 2026 *PRL* **137** 055102

Novel insights:

- Quasi-Coherent mode identified as kinetic ballooning mode
- High α_{MHD} and E_r well broadening necessary
- Instead of resistivity at outboard midplane (α_t) the resistivity at the X-point is relevant

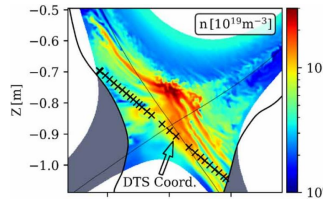
GRILLIX in action: Further applications

Various validations:

- TCV-X21/23: D.S. Oliveira *et al* 2022 *NF* **62** 096001
- Compass: P. Macha 2026 PhD thesis, Czech Technical University in Prague
- AUG: W. Zholobenko *et al* 2021 *NF* **61** 116015

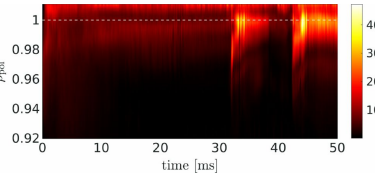
X-point radiator regime:

K. Eder *et al* 2025 *NF* **65** 096029



L-H transition studies

W. Zholobenko *et al* 2026 *PRL* **136** 075101



Stellarator turbulence

A. Stegmeir *et al* 2026 *CPP* e70112

$t = 1.79551 \text{ ms}$



Wendelstein 7-AS

density / [10¹⁹ m⁻³]



Drift reduced Braginskii model:

- Full-f (No Boussinesq + parametric dependencies)

- Electromagnetic + Shafranov filter

K. Zhang *et al* 2024 *NF* **64** 036016

K. Zhang *et al* 2025 *CPC* **314** 109670

- Trans-collisional extensions

C. Pitzal *et al* 2023 *PoP* **30** 122502

W. Zholobenko *et al* 2024 *NF* **64** 106066

plus (not shown explicitly)

- Hyperdissipation
- Coupling to neutrals via sources
- External sources
- Insulating Sheath boundaries

$$\text{Continuity: } \frac{\partial}{\partial t} n + \mathbf{v}_E \cdot \nabla n + \nabla \cdot (n u_{\parallel} \mathbf{b}) = n \mathcal{C}(\phi) - \frac{n}{e} \mathcal{C}(T_e) - \frac{T_e}{e} \mathcal{C}(n) + \frac{1}{e} \nabla \cdot (j_{\parallel} \mathbf{b}),$$

$$\text{Vorticity: } \nabla \cdot \left[\frac{M_i c^2}{B^2} n \frac{d_i}{dt} (\nabla_{\perp} \phi + \frac{\nabla_{\perp} p_i}{en}) \right] = -T_e \mathcal{C}(n) - n \mathcal{C}(T_e) - T_i \mathcal{C}(n) - n \mathcal{C}(T_i) + \nabla \cdot (j_{\parallel} \mathbf{b}) - \frac{1}{6} \mathcal{C}(G),$$

$$\text{Par. momentum: } M_i n \frac{d_i}{dt} u_{\parallel} = -\nabla_{\parallel} (p_e + p_i) + \frac{M_i p_i}{e} \mathcal{C}(u_{\parallel}) - \frac{2}{3} B^{3/2} \nabla_{\parallel} \frac{G}{B^{3/2}},$$

$$\text{Ohm's law: } -\frac{m_e}{e} \frac{d_e}{dt} \frac{j_{\parallel}}{en} = \eta_{\parallel} j_{\parallel} + \frac{1}{c} \frac{\partial}{\partial t} A_{\parallel} + \nabla_{\parallel} \phi - \frac{1}{en} \nabla_{\parallel} p_e - 0.71 \frac{1}{e} \nabla_{\parallel} T_e,$$

$$\text{Ampere's law: } \nabla_{\perp}^2 A_{\parallel} = -\frac{4\pi}{c} j_{\parallel},$$

$$\begin{aligned} \text{Electron temp.: } \frac{d_e}{dt} T_e = & -\frac{2}{3} \left[\frac{7}{2} \frac{T_e}{e} \mathcal{C}(T_e) + \frac{T_e^2}{en} \mathcal{C}(n) - T_e \mathcal{C}(\phi) \right] - \frac{2}{3} T_e \nabla \cdot (v_{\parallel} \mathbf{b}) + \frac{2}{3} 0.71 \frac{T_e}{en} \nabla \cdot (j_{\parallel} \mathbf{b}) + \frac{2}{3} \frac{\eta_{\parallel} j_{\parallel}^2}{n} \\ & - \frac{2}{3} \frac{1}{n} \nabla \cdot (q_{\parallel, i} \mathbf{b}) - \frac{2m_e}{M_i \tau_e} (T_e - T_i), \end{aligned}$$

$$\begin{aligned} \text{Ion temp.: } \frac{d_i}{dt} T_i = & -\frac{2}{3} \left[\frac{T_i}{e} \mathcal{C}(T_e) + \frac{T_e T_i}{en} \mathcal{C}(n) - T_i \mathcal{C}(\phi) - \frac{5}{2} \frac{T_i}{e} \mathcal{C}(T_i) \right] - \frac{2}{3} T_i \nabla \cdot (v_{\parallel} \mathbf{b}) + \frac{2}{3} T_i \frac{j_{\parallel}}{en^2} \nabla_{\parallel} n \\ & - \frac{2}{3} \frac{1}{n} \nabla \cdot (q_{\parallel, i} \mathbf{b}) + \frac{2}{9n\eta_i} G^2 + \frac{2m_e}{M_i \tau_e} (T_e - T_i), \end{aligned}$$

$$\text{Shafranov filter: } \frac{\partial}{\partial t} A_s = \frac{A_s - A_{\parallel}}{\lambda}, \quad \nabla_{\parallel} = (\mathbf{b}_0 + \mathbf{b}_s) \cdot \nabla$$

GRILLIX plasma model



Drift reduction model extensions

Parallel heat flux extensions:

A) Flux limiter

$$q_{\parallel,j} = -\chi_{\parallel,j}^{SH} \left(1 + \frac{\chi_{\parallel,j}^{SH}}{\alpha_j n v_{T,j} R_0 q} \right)^{-1} \nabla_{\parallel} T_j$$

→ Introduces free parameters α_j

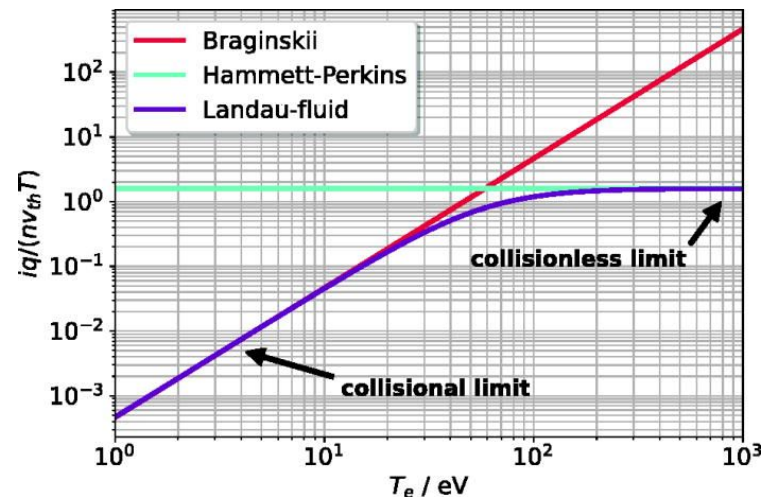
B) Landau-Fluid closure

$$q_{\parallel,j,k} = -A \frac{ik_{\parallel}}{|k_{\parallel}| + \delta_j / \lambda_{mfp,j}} T_{j,k}$$

→ Self consistent

→ Formulation in wavenumber space $k_{\parallel}$ cumbersome

C. Pitzal *et al* 2023 *PoP* **30** 122502



3 moment fluid neutrals model:

N. Horsten et al 2017 *NF* **57** 116043

W. v. Uytven et al 2020 *CPP* **60** 7

Charge exchange: $D^+ + D^0 \leftrightarrow D^0 + D^+$,

- **Describes:** Ionisation: $e^- + D^0 \rightarrow 2e^- + D^+$,
Recombination: $2e^- + D^+ \rightarrow e^- + D^0$,
 $e^- + D^+ \rightarrow D^0 + \text{photon}$
- **Dominated by pressure diffusion**
- **Sources in neutrals = sinks in plasma model ($S_n = -S_N$)**
- **Recycling boundary conditions (particles)**

$$\text{Continuity: } \frac{\partial N}{\partial t} = \nabla \cdot \left[\frac{1}{mnk_{cx}} \nabla_{\perp} (NT_N) - \Gamma_{N\parallel} \mathbf{b} \right] + S_N,$$

$$\text{Par. momentum: } \frac{\partial \Gamma_{N\parallel}}{\partial t} = \nabla \cdot \left[\frac{1}{mnk_{cx}} \nabla_{\perp} (\Gamma_{N\parallel} T_N) - \frac{\Gamma_{N\parallel}^2}{N} \mathbf{b} \right] - \frac{\nabla_{\parallel} p_N}{m} + S_{\Gamma},$$

$$\text{Pressure: } \frac{\partial p_N}{\partial t} = \nabla \cdot \left[\frac{5}{3} \frac{1}{mnk_{cx}} \nabla_{\perp} (p_N T_N) - \frac{5}{3} p_N v_{N\parallel} \mathbf{b} \right] + \frac{2}{3} v_{N\parallel} \nabla_{\parallel} p_N + \frac{2}{3} \frac{p_N}{nk_{cx}} (\nabla_{\perp} v_{N\parallel})^2 + S_p,$$

$$S_N = -k_{iz} n N + k_{rec} n^2,$$

$$S_{\Gamma} = -k_{iz} n N v_{N\parallel} + k_{rec} n^2 u_{\parallel} + k_{cx} n N (u_{\parallel} - v_{N\parallel}),$$

$$S_p = -k_{iz} n N T_N + k_{rec} n^2 T_i + k_{cx} n N (T_i - T_N) + \frac{mn}{3} (nk_{rec} + Nk_{cx}) (u_{\parallel} - v_{N\parallel})^2$$

K. Eder et al 2025 *PPCF* **67** 065034

Energy theorem:

- Energy densities (plasma model):

$$E_{\perp} := \frac{nM_i(\mathbf{v}_E + \mathbf{v}_*^i)^2}{2}, \quad E_{\parallel} := \frac{nM_i u_{\parallel}^2}{2}, \quad E_{\parallel e} := \frac{nm_e}{2} \left(\frac{j_{\parallel}}{en} \right)^2,$$

$$E_{the} := \frac{3}{2} nT_e, \quad E_{thi} := \frac{3}{2} nT_i, \quad E_{em} := \frac{\mathbf{B}_{\perp}^2}{8\pi} = \frac{1}{8\pi} |\nabla_{\perp} A_{\parallel}|^2$$

- Conservation on analytical level (also combined with neutrals model)

B. Scott *et al* 2001 *IPP report* 5/92

K. Eder *et al* 2025 *PPCF* **67** 065034

$$\frac{\partial}{\partial t} (E_{\perp} + E_{\parallel} + E_{the} + E_{thi} + E_{em} + E_{\parallel e} + E_{neutrals}) + \nabla \cdot (\underbrace{\dots\dots\dots}_{\text{Transport terms}}) = \text{external sources/sinks}$$

- Transfer and transport terms can be identified and diagnosed
- In the code: Some subtle approximations must be made for practical/technical reasons mostly due to FLR effects, e.g.
 - Neglect of polarisation velocity in advective derivative B. de Lucca *et al* 2026 *JPP* **92** E6
 - Gyroviscous stress tensor is messy A. Zeiler *et al* 1999 *IPP report* 5/88

Are these approximations ok? More consistency via development of gyrofluid models?



Back of envelope consideration: Why field alignment?

Let's have a look at space and time scales of interest:

$$k_{\perp} \sim \rho_s^{-1}, \quad k_{\parallel} \sim (qR_0)^{-1}, \quad \omega \sim \begin{cases} \omega_* \sim \frac{c_s}{a}, & \text{from micro-instabilities} \\ v_{SAW} k_{\parallel} \sim \frac{c_s}{\sqrt{\beta} q R_0}, & \text{from parallel response (non-adiabaticity)} \end{cases}$$

Shear Alfvén wave propagates non-adiabaticity along magnetic field lines

$$\frac{\partial^2}{\partial t^2} \left(\tilde{n} - \frac{e\tilde{\phi}}{T_e} \right) = v_{SAW}^2 \nabla_{\parallel}^2 \left(\tilde{n} - \frac{e\tilde{\phi}}{T_e} \right), \quad v_{SAW}^2 = c_s^2 \frac{1 + k_{\perp}^2 \rho_s^2}{\beta + \mu k_{\perp}^2 \rho_s^2}$$

an explicit time integration scheme demands for stability (CFL): $\Delta t \lesssim \frac{\Delta x_{\parallel}}{v_{SAW}}$

→ Aligned scheme: $\Delta x_{\parallel} \sim R_0$

→ Non-aligned scheme: $\Delta x_{\parallel} \sim q\rho_s$

→ Cost (Number of operations) of non-aligned vs aligned scheme scales like:

A. Stegmeir *et al* 2023 *CPC* **290** 108801

$$\underbrace{\frac{R_0}{q\rho_s}}_{\text{More spatial points}} \cdot \underbrace{\frac{R_0}{q\rho_s}}_{\text{Stricter time-step}}$$

Notes:

- Scaling becomes even worse when considering parallel heat conduction
- In implicit treatments one pays the price with algorithmic complexity and/or solver iterations
- Electrostatic models are very demanding (only resistivity/electron inertia slows down parallel response)

B. D. Dudson *et al* 2021 *PPCF* **63** 125008

Flux-Coordinate Independent approach

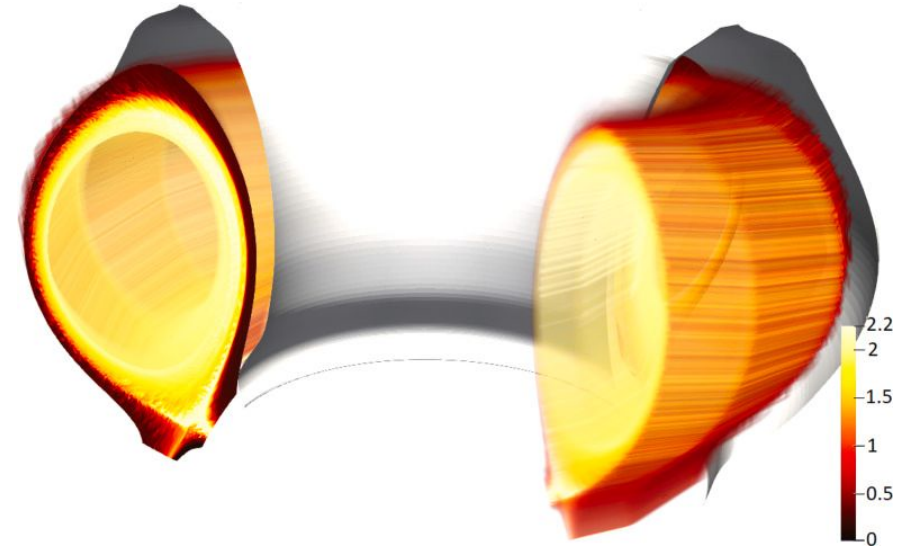
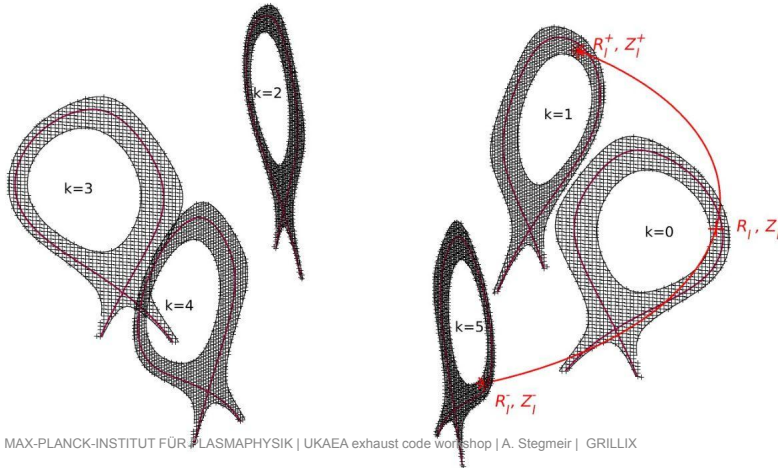
Overview

F. Hariri and M. Ottaviani 2013 *CPC* **184** 2419

A. Stegmeir *et al* 2016 *CPC* **198** 139

- Set of few poloidal locally Cartesian planes
- Field line tracing + interpolation
- Mimetic finite differences (toroidally staggered meshes) suppresses spurious numerical diffusion
- No coordinate singularities
- Compatible with stellarator geometries

A. Stegmeir *et al* 2026 *CPC* **318** 109874





Flux-Coordinate Independent approach

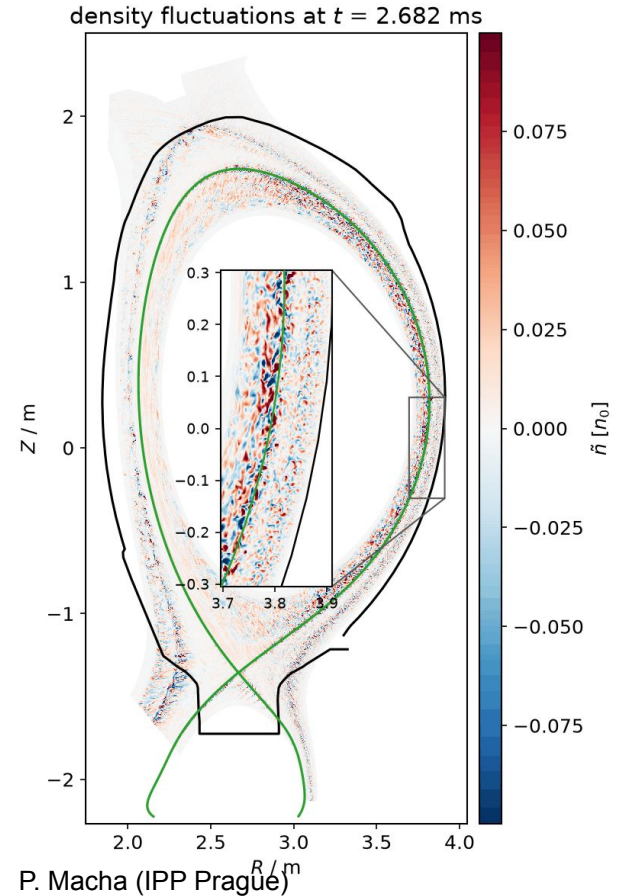
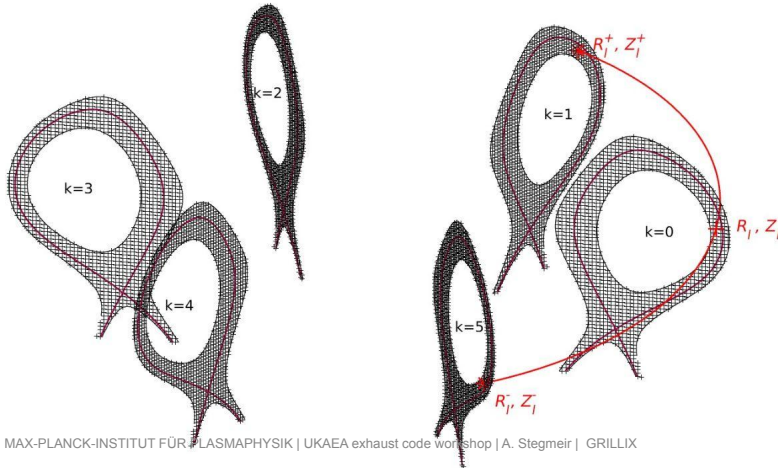
Overview

F. Hariri and M. Ottaviani 2013 *CPC* **184** 2419

A. Stegmeir *et al* 2016 *CPC* **198** 139

- Set of few poloidal locally Cartesian planes
- Field line tracing + interpolation
- Mimetic finite differences (toroidally staggered meshes) suppresses spurious numerical diffusion
- No coordinate singularities
- Compatible with stellarator geometries

A. Stegmeir *et al* 2026 *CPC* **318** 109874



Flux-Coordinate Independent approach

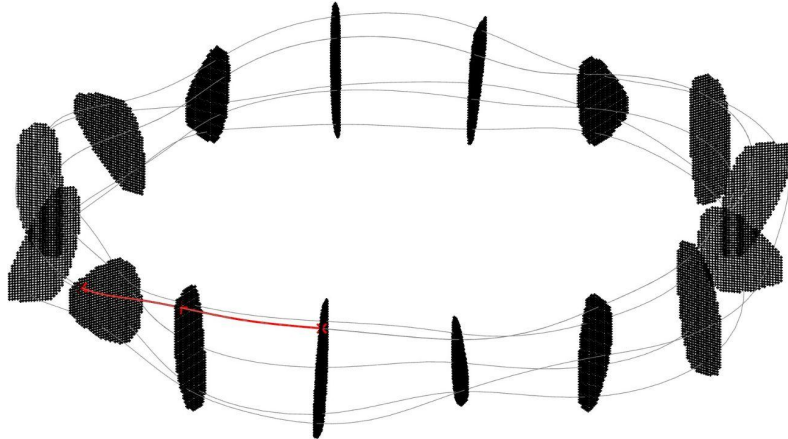
Overview

F. Hariri and M. Ottaviani 2013 *CPC* **184** 2419

A. Stegmeir *et al* 2016 *CPC* **198** 139

- Set of few poloidal locally Cartesian planes
- Field line tracing + interpolation
- Mimetic finite differences (toroidally staggered meshes) suppresses spurious numerical diffusion
- No coordinate singularities
- Compatible with stellarator geometries

A. Stegmeir *et al* 2026 *CPC* **318** 109874



$t = 1.79551 \text{ ms}$





Elliptic solvers

3D solver

- Parallel heat fluxes and parallel momentum damping are stiff
- Generalised elliptic problem along field lines (3D)

$$\lambda \phi - \nabla \cdot (\mathbf{b} \chi \nabla_{\parallel} \phi) = f$$

- Krylow methods (iterative, matrix free, MPI)
→ Usage Parallel Iterative Methods (PIM) library
R.D. da Cunha and T. Hopkins 1995 *ANM* **19** 19

2D solver

- For electromagnetic and electrostatic potentials and for stiff CX diffusion terms
- Set of generalised elliptic problems within 2D planes

$$\lambda \phi - \nabla \cdot (\chi \nabla_{\perp} \phi) = f$$

- In-house developed geometric multigrid solver
A. Stegmeir *et al* 2026 *PASC '26* article no. 6

Plasma model:

$$\text{Continuity: } \frac{\partial}{\partial t} n + \mathbf{v}_E \cdot \nabla n + \nabla \cdot (n u_{\parallel} \mathbf{b}) = n \mathcal{C}(\phi) - \frac{n}{e} \mathcal{C}(T_e) - \frac{T_e}{e} \mathcal{C}(n) + \frac{1}{e} \nabla \cdot (j_{\parallel} \mathbf{b}),$$

$$\text{Vorticity: } \nabla \cdot \left[\frac{M_i c^2}{B^2} n \frac{d_i}{dt} (\nabla_{\perp} \phi + \frac{\nabla_{\perp} p_i}{en}) \right] = -T_e \mathcal{C}(n) - n \mathcal{C}(T_e) - T_i \mathcal{C}(n) - n \mathcal{C}(T_i) + \nabla \cdot (j_{\parallel} \mathbf{b}) - \frac{1}{6} \mathcal{C}(G),$$

$$\text{Par. momentum: } M_i n \frac{d_i}{dt} u_{\parallel} = -\nabla_{\parallel} (p_e + p_i) + \frac{M_i p_i}{e} \mathcal{C}(u_{\parallel}) - \frac{2}{3} B^{3/2} \nabla_{\parallel} \frac{G}{B^{3/2}},$$

$$\text{Ohm's law: } -\frac{m_e}{e} \frac{d_e}{dt} \frac{j_{\parallel}}{en} = \eta_{\parallel} j_{\parallel} + \frac{1}{c} \frac{\partial}{\partial t} A_{\parallel} + \nabla_{\parallel} \phi - \frac{1}{en} \nabla_{\parallel} p_e - 0.71 \frac{1}{e} \nabla_{\parallel} T_e,$$

$$\text{Ampere's law: } \nabla_{\perp}^2 A_{\parallel} = -\frac{4\pi}{c} j_{\parallel},$$

$$\text{Electron temp.: } \frac{d_e}{dt} T_e = -\frac{2}{3} \left[\frac{7}{2} \frac{T_e}{e} \mathcal{C}(T_e) + \frac{T_e^2}{en} \mathcal{C}(n) - T_e \mathcal{C}(\phi) \right] - \frac{2}{3} T_e \nabla \cdot (v_{\parallel} \mathbf{b}) + \frac{2}{3} 0.71 \frac{T_e}{en} \nabla \cdot (j_{\parallel} \mathbf{b}) + \frac{2}{3} \frac{\eta_{\parallel} j_{\parallel}^2}{n} - \frac{2}{3} \frac{1}{n} \nabla \cdot (q_{\parallel, i} \mathbf{b}) - \frac{2m_e}{M_i \tau_e} (T_e - T_i),$$

$$\text{Ion temp.: } \frac{d_i}{dt} T_i = -\frac{2}{3} \left[\frac{T_i}{e} \mathcal{C}(T_e) + \frac{T_e T_i}{en} \mathcal{C}(n) - T_i \mathcal{C}(\phi) - \frac{5}{2} \frac{T_i}{e} \mathcal{C}(T_i) \right] - \frac{2}{3} T_i \nabla \cdot (v_{\parallel} \mathbf{b}) + \frac{2}{3} T_i \frac{j_{\parallel}}{en^2} \nabla_{\parallel} n - \frac{2}{3} \frac{1}{n} \nabla \cdot (q_{\parallel, i} \mathbf{b}) + \frac{2}{9n\eta_i} G^2 + \frac{2m_e}{M_i \tau_e} (T_e - T_i),$$

$$\text{Shafranov filter: } \frac{\partial}{\partial t} A_s = \frac{A_s - A_{\parallel}}{\lambda}, \quad \nabla_{\parallel} = (\mathbf{b}_0 + \mathbf{b}_s) \cdot \nabla$$

Neutrals model:

$$\text{Continuity: } \frac{\partial N}{\partial t} = \nabla \cdot \left[\frac{1}{mnk_{cx}} \nabla_{\perp} (NT_N) - \Gamma_{N\parallel} \mathbf{b} \right] + S_N,$$

$$\text{Par. momentum: } \frac{\partial \Gamma_{N\parallel}}{\partial t} = \nabla \cdot \left[\frac{1}{mnk_{cx}} \nabla_{\perp} (\Gamma_{N\parallel} T_N) - \frac{\Gamma_{N\parallel}^2}{N} \mathbf{b} \right] - \frac{\nabla_{\parallel} p_N}{m} + S_{\Gamma},$$

$$\text{Pressure: } \frac{\partial p_N}{\partial t} = \nabla \cdot \left[\frac{5}{3} \frac{1}{mnk_{cx}} \nabla_{\perp} (p_N T_N) - \frac{5}{3} p_N v_{N\parallel} \mathbf{b} \right] + \frac{2}{3} v_{N\parallel} \nabla_{\parallel} p_N + \frac{2}{3} \frac{p_N}{nk_{cx}} (\nabla_{\perp} v_{N\parallel})^2 + S_p,$$

GPU porting of 2D elliptic solver



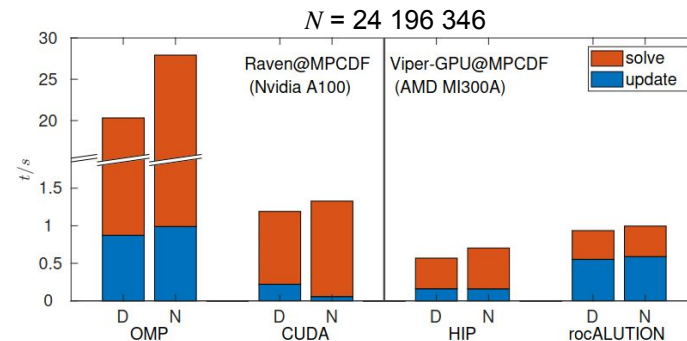
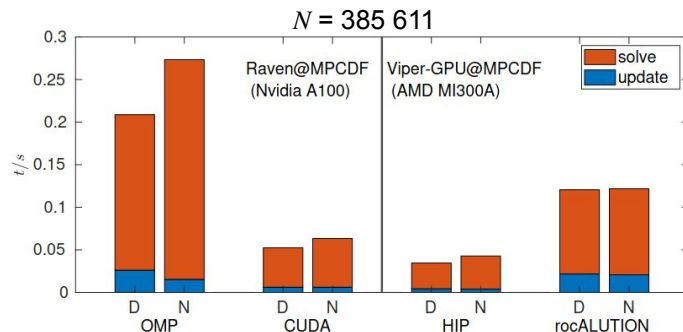
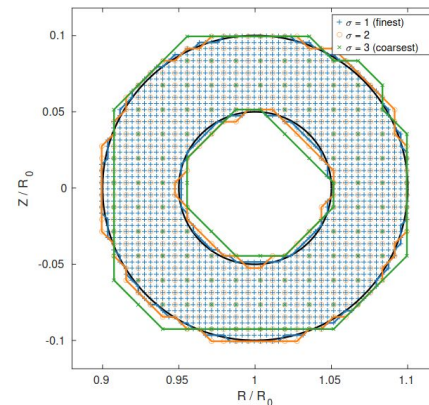
2D multigrid solver

- Set of generalised elliptic problems within 2D planes $\lambda\phi - \nabla \cdot (\chi \nabla_{\perp} \phi) = f$
- Formulation of discrete problem on multiple coarseness levels (σ)
- Operations (Prolongation/Restriction/smoothers) originally parallelised via OpenMP

GPU port

A. Stegmeir *et al* 2026 PASC '26 article no. 6

- GPU attempts within Fortran failed due to poor compilers
- Rewritten as separate library in C++, callable from Fortran
- CUDA and HIP backends available
- `Speed-ups` of factor 4-20 depending on problem size





GPU porting of 2D elliptic solver

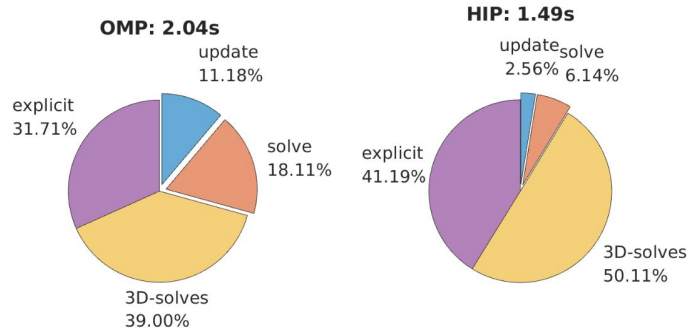
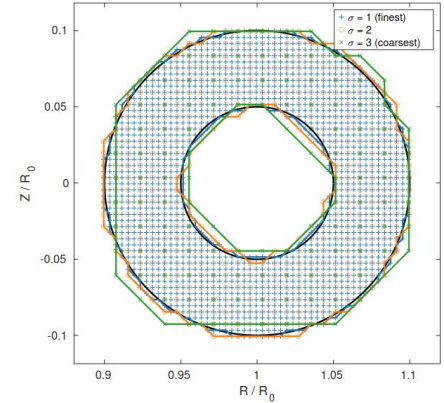
2D multigrid solver

- Set of generalised elliptic problems within 2D planes $\lambda\phi - \nabla \cdot (\chi \nabla_{\perp} \phi) = f$
- Formulation of discrete problem on multiple coarseness levels (σ)
- Operations (Prolongation/Restriction/smoothers) originally parallelised via OpenMP

GPU port

A. Stegmeir *et al* 2026 PASC '26 article no. 6

- GPU attempts within Fortran failed due to poor compilers
- Rewritten as separate library in C++, callable from Fortran
- CUDA and HIP backends available
- Speed-up of factor 4-20 depending on problem size



GPU port of other parts ongoing

→ Rewrite whole code in C++ with supported by AI agents



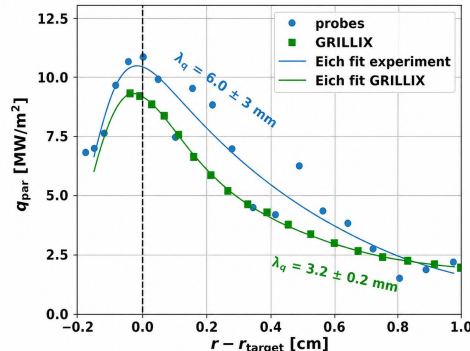
Boundaries (@targets)

Immersed boundary approach

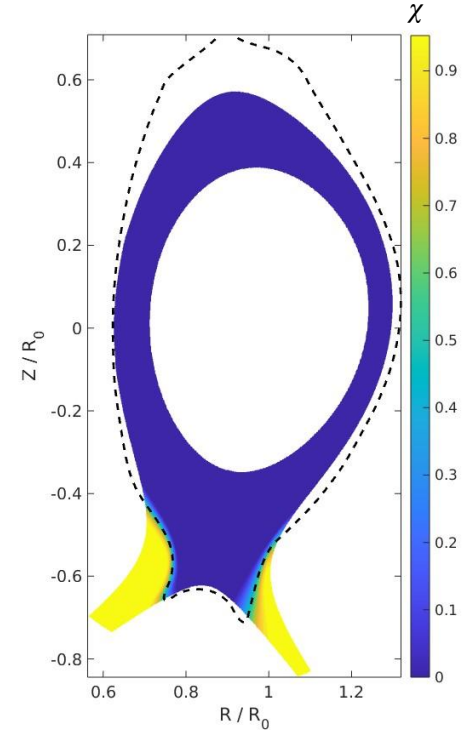
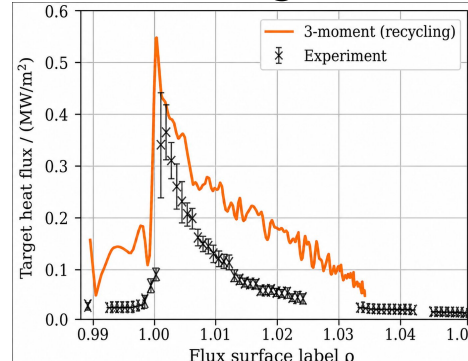
- Boundaries are problematic in FCI as generally not conformal with magnetic field
- Enforce boundary conditions at targets via source

$$\partial_t f = F(t, \mathbf{x}, f) \rightarrow \partial_t f = (1 - \chi)F(t, \mathbf{x}, f) + \frac{\chi}{\epsilon} (f_{bnd} - f)$$
- Introduction of free parameters/function ϵ, χ
- Introduction of unphysical boundary layer
- Applied robustly in most FCI codes
 - GDB: B. Zhu *et al* 2018 *CPC* **232** 46
 - GRILLIX: A. Stegmeir *et al* 2023 *CPC* **290** 108801
 - FELTOR: M. Wiesenberger and M. Held 2024 *PPCF* **66** 065003
- Simulated target profiles still in reasonable agreement with experiment

COMPASS #13824



AUG #38839@1.3s





Boundaries (@targets), Can we do better?

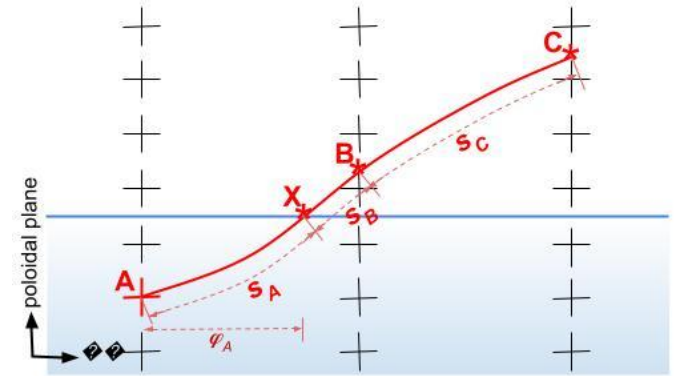
Taylor based method

touched upon in A. Stegmeir *et al* 2018 *PPCF* **60** 035005

- Obtain value on guard point according to Taylor expansion along magnetic fields around intersection point

$$u_A = \frac{1}{2D} [(s_A - s_B)(s_A - s_C)(s_C - s_B)u_X - s_A s_C u_B + s_A s_B u_C],$$
$$D = \frac{1}{2} s_B s_C (s_C - s_B)$$

- More exact and consistent with spirit of finite difference method
- Subtle technical issues in FCI
 - Underlying system can become degenerate ($s_B s_C \sim 0$)
 - Complexified by toroidal staggering
 - Overloading necessary for non-axisymmetric geometries
- Tests so far indicate that it is robust for simpler systems (transport models)
- To be further tested in turbulent environment
- See also Leg Value Fill method P. Hill *et al* 2017 *CPC* **213** 9



Boundaries (@targets), Can we do better?



Taylor based method

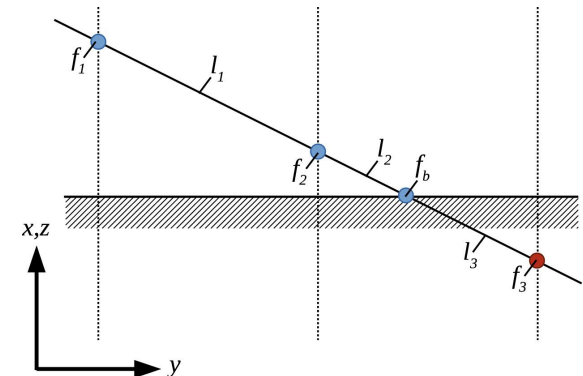
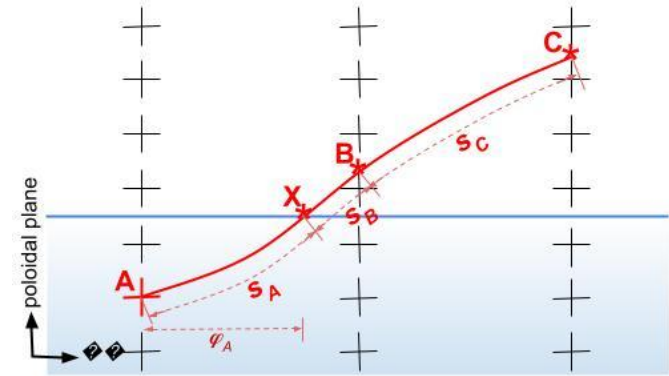
touched upon in A. Stegmeir *et al* 2018 *PPCF* **60** 035005

- Obtain value on guard point according to Taylor expansion along magnetic fields around intersection point

$$u_A = \frac{1}{2D} [(s_A - s_B)(s_A - s_C)(s_C - s_B)u_X - s_A s_C u_B + s_A s_B u_C],$$

$$D = \frac{1}{2} s_B s_C (s_C - s_B)$$

- More exact and consistent with spirit of finite difference method
- Subtle technical issues in FCI
 - Underlying system can become degenerate ($s_B, s_C \sim 0$)
 - Complexified by toroidal staggering
 - Overloading necessary for non-axisymmetric geometries
- Tests so far indicate that it is robust for simpler systems (transport models)
- To be further tested in turbulent environment
- See also Leg Value Fill method P. Hill *et al* 2017 *CPC* **213** 9



A field line leaving the boundary. f_2 is located on a grid point, while f_1, f_3 are located on intersection points with the adjacent perpendicular planes, and f_b is located on the intersection with the boundary. l_1, l_2, l_3 are distances along the field lines between the four points above.



Deficiencies

- **Boundaries**

- Free parameters in immersed approach and unphysical boundary layer
- Well posed boundary conditions itself ?
- → Taylor based methods, see backup slide and Leg Value Fill method P. Hill *et al* 2017 *CPC* **213** 9]

- **Consistency with polarisation velocity** B. de Lucca *et al* 2026 *JPP* **92** E6

- Advective derivative
- Gyroviscous stress tensor
- Complexifies extension to multispecies model A. Poulsen *et al* 2020 *PoP* **27** 032305
- → Gyrofluid models with separate parallel and perpendicular temperatures

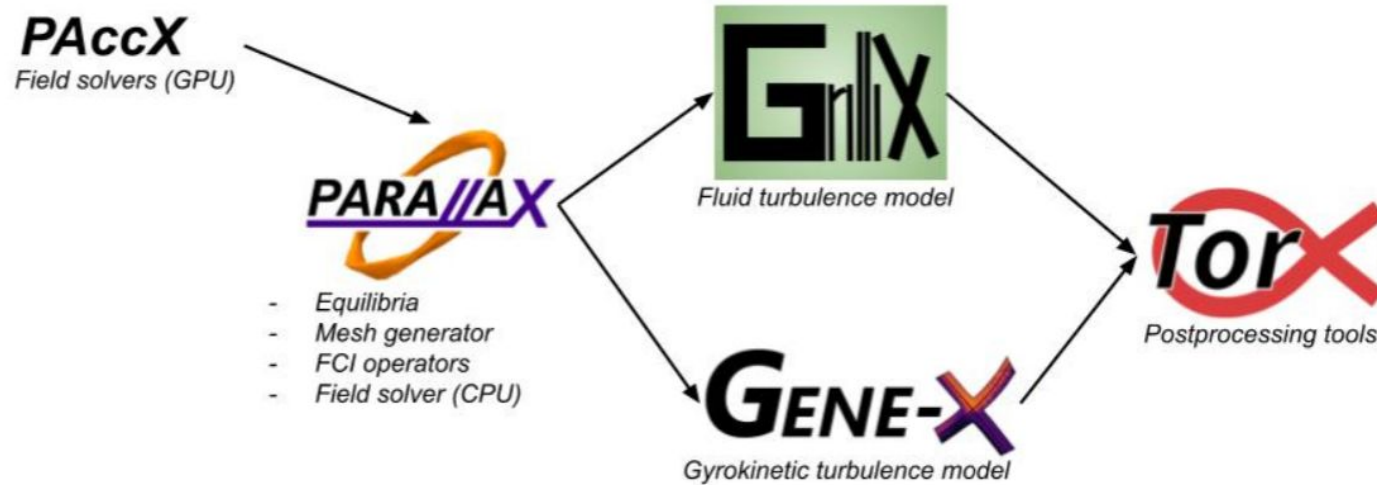
- **Kinetic Neutrals**

- Fluid assumptions often not valid
- → Coupling to Eirene via Styx, Kindness, Hybrid models

- **GPU porting**

- Poor compiler support for Fortran
- Only parts have been ported so far
- → porting to C++ with GPU backends ongoing with support from AI agents

Phoenix framework



GENE-X D. Michels *et al* 2022 *PoP* **29** 032307

- Gyrokinetic model sharing same code basis
- Grid version and moment version available B. Frei *et al* 2025 *CPC* **316** 109817
- Many resources currently being invested in further development



Lessons learned (personal view)

- **Consistency first, higher fidelity second**
 - Don't add terms randomly, add effects
 - Sometimes adding an effect helps (e.g. electromagnetic and neutrals made life easier)
 - Sometimes we have to be pragmatic, but be aware of it
- **Verify and test whatever you can**
 - Understand your system
 - Takes more than 90% of time in development
 - Verify also if the system breaks when expected
 - Run production cases not at the very limit of computational capabilities
- **Coding lessons**
 - Keep a single code base
 - Be open to new developments but don't follow every trend
 - Fortran is a dead end for GPUs
 - Don't use super advanced features, not everything needs to have an abstract layer
 - AI agents are very helpful, but apply them on isolated parts/modules