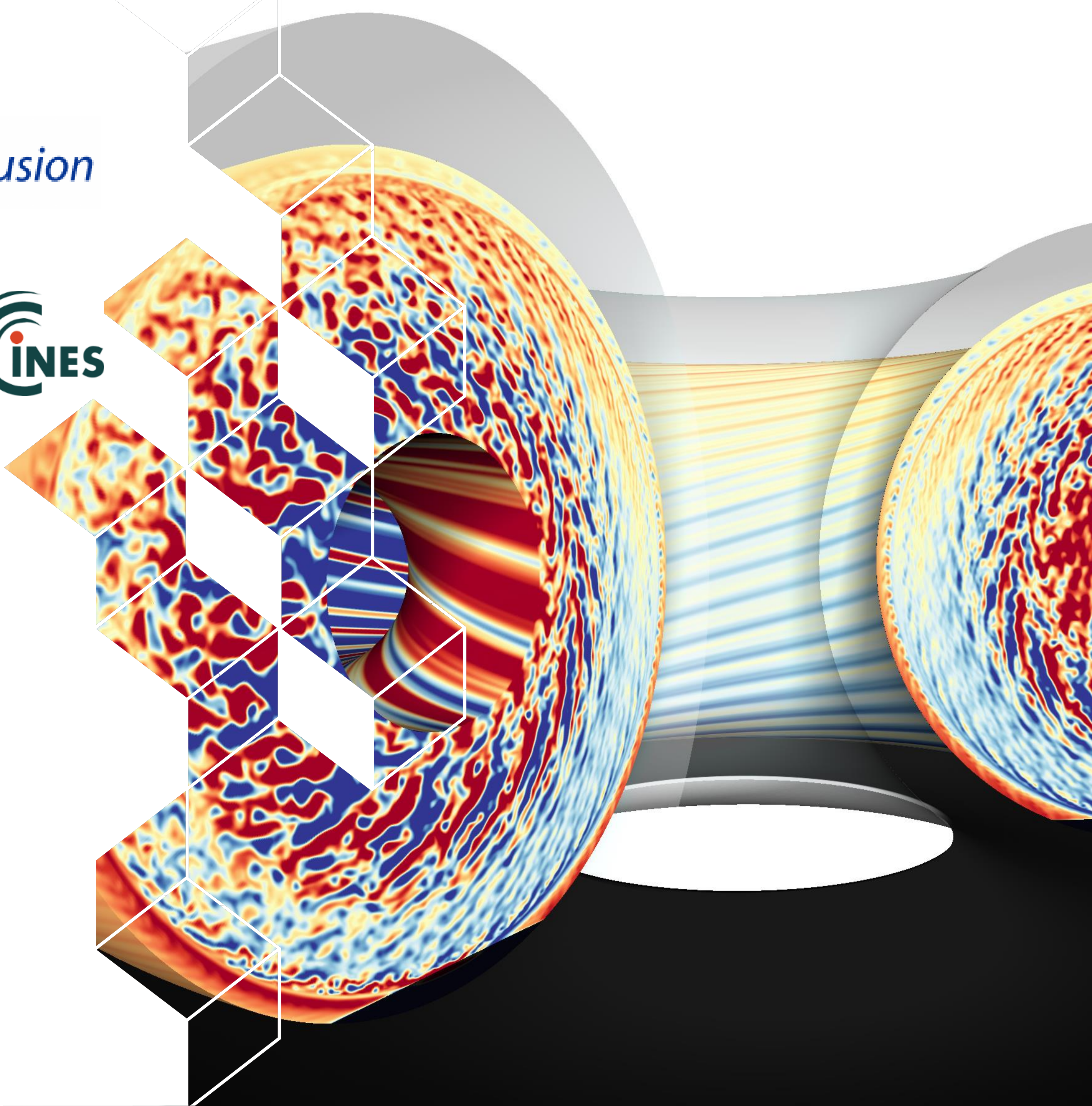
Gysela-axi: a flux-driven full-F gyrokinetic code to simulate axisymmetric tokamak plasmas



P. Donnel and the Gysela team

Outline

1. Context: development of Gysela-X++

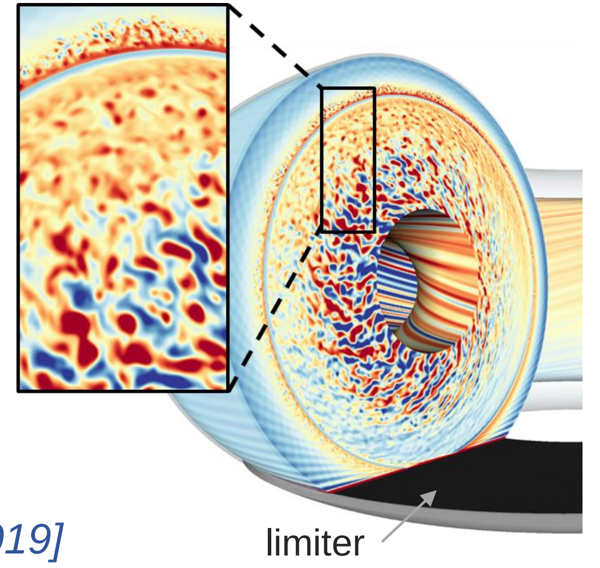
2. Gysela-axi a major milestone

3. Current status of the code and next steps

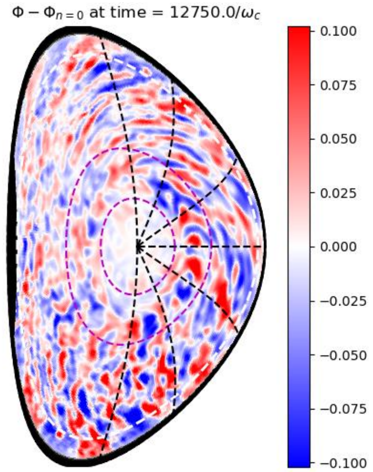
4. Conclusion

GYSELA: GYrokinetic SEmi-LAgrangian code [Grandgirard et al., CPC 2016]

- GYSELA (GYrokinetic SEmi-LAgrangian): first gyrokinetic code based on a **semi-Lagrangian scheme**
- From beginning, **accurate strategy but more HPC demanding**:
  - **Global**: simulate entire tokamak → boundary conditions (SOL-like, limiter)
  - **Full-f**: multi-scale physics
  - **Flux-Driven** (heat, momentum, … sources) → steady state on τ_E
  - **Collision operator** → synergy between neoclassical & turbulent transports



- Permanent improvements of the physics model
  - **Electrons:** From adiabatic response to **kinetic** *[C. Ehrlacher 2018, V. Grandgirard 2019]*
  - **Multi-ion species** → impurity transport *[D. Estève 2018, G. Lo-Cascio 2022, K. Lim 2023]*
  - Geometry: from circular to **shaped plasmas** + ripple *[E. Bourne 2023, R. Varennes 2023, PhD L. De Gianni 2023-2026]*
  - Boundary conditions: from simple buffer to more **realistic immersed boundaries** *[E. Caschera 2018, Dif-Pradalier 2022, PhD Y. Munschy 2021-2024]*
  - From electrostatic (constant magnetic field) to **electromagnetic** *[PhD C. Gillot 2017-2020, PhD R. Bigué 2023-2026, Z. Qu 2026]*
  - ECRH sources *[P. Donnel 2022]* & Kinetic plasma neutrals inelastic collisions *[PhD M. Protais 2024-2027]*

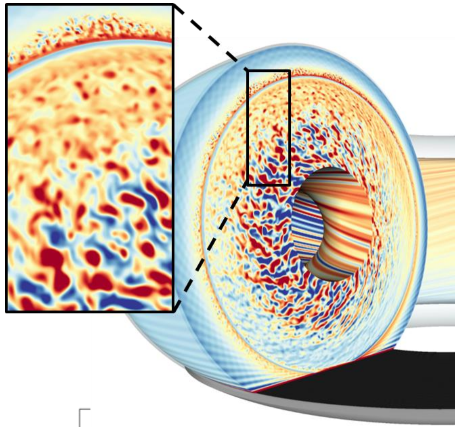


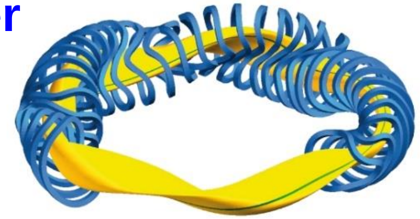
Roadmap for Gysela-X++ towards exascale

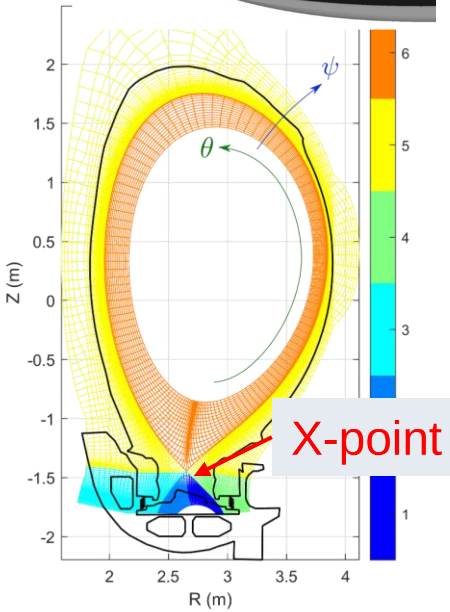
→ Why do we choose to rewrite GYSELA ?

- **Gysela-X++** = GYSELA in modern C++ with **X-point** for **exascale** ITER core-edge turbulence simulations
  (+ **Stellarator** via BPI / Renaissance Fusion)

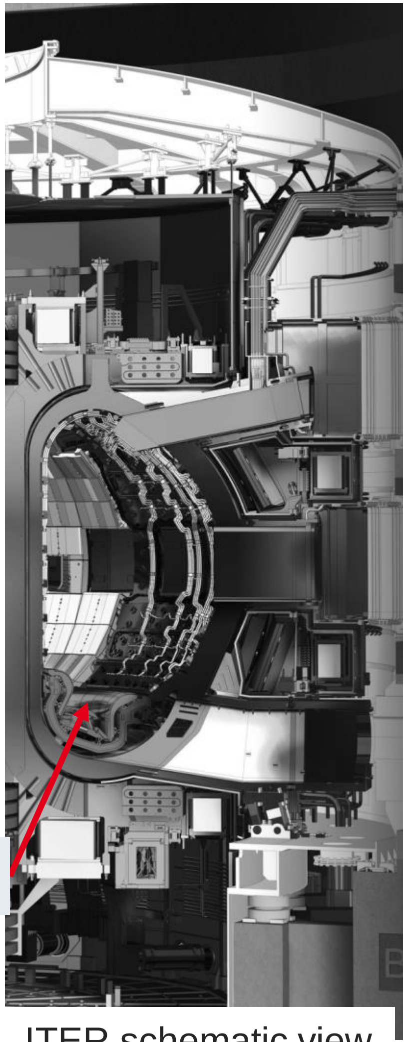
  - **Rewriting of the code in modern C++ with MPI + Kokkos**
    - Portable code on new exascale architectures
  - **Non-uniform meshes**
    - relevant density & temperature gradients at edge-SOL
  - Semi-Lagrangian scheme for **multi-patches**
    - **X-point** geometry
  - Implementation of a **3D scalable Poisson solver**
    - X-point & stellarator configuration
  - **Scalable I/O and in-situ diagnostics**





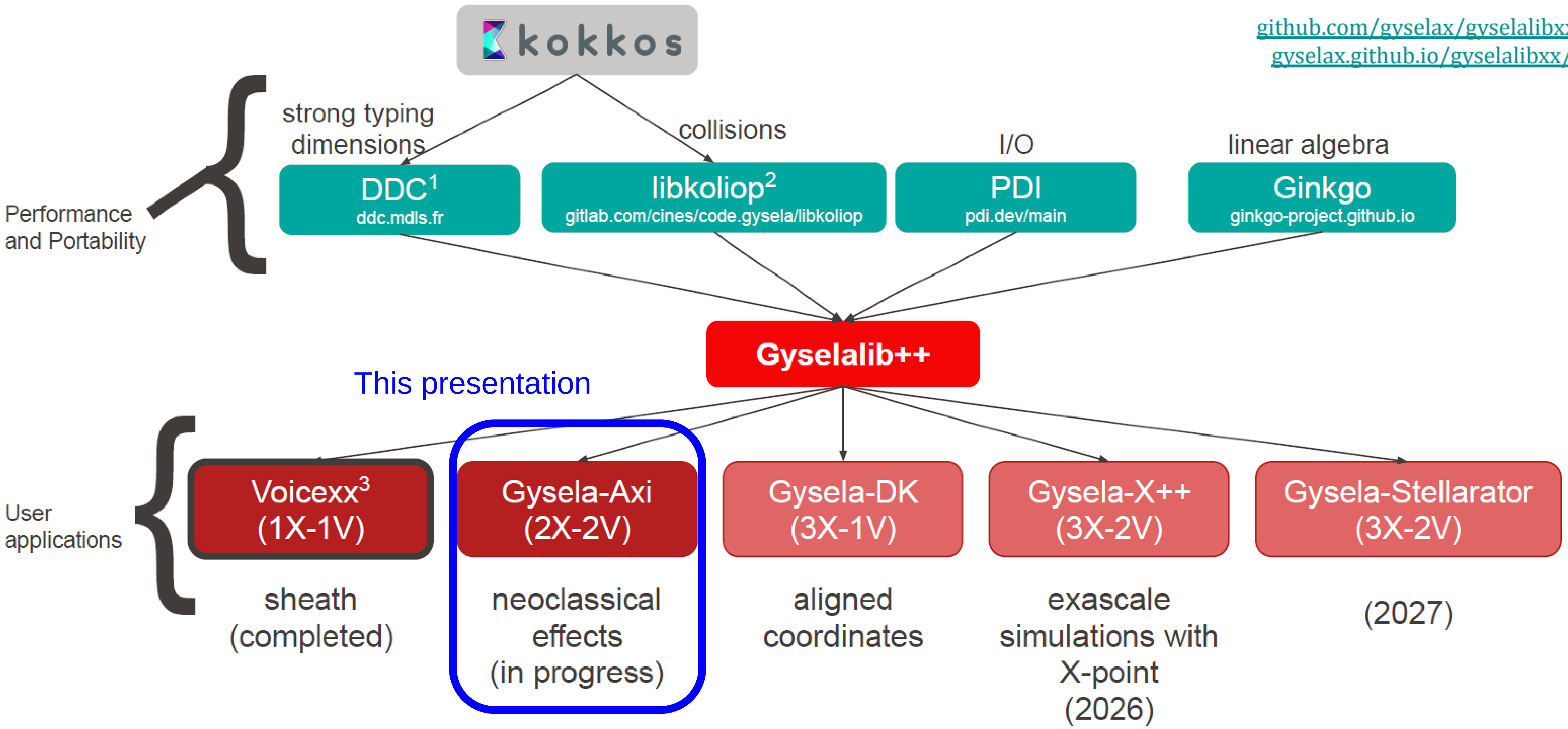


SOLEDGE-3X
X-point geometry


ITER schematic view

Gyselalib++: a new modular library in C++

github.com/gyselax/gyselalibxx/
gyselax.github.io/gyselalibxx/



1 T. Padioleau et al. DDC: The Discrete Domain Computation library, JOSS, submitted
2 P. Donnel et al. A multi-species collisional operator for full-F global gyrokinetics codes: Numerical aspects and verification with the GYSELA code, CPC 2019
3 E. Bourne et al. Non-uniform splines for semi-Lagrangian kinetic simulations of the plasma sheath, JCP 2023

Outline

Advection equations = same as Gysela Fortran but assuming axi-symmetry (for now electrostatic)

- Spatial Advection

$$\frac{dx^i}{dt} = v_\parallel \boldsymbol{b}_s^\star \cdot \boldsymbol{\nabla} x^i + \boldsymbol{v}_{Ds} \cdot \boldsymbol{\nabla} x^i + \boldsymbol{v}_E \cdot \boldsymbol{\nabla} x^i$$

Drifts

$$\boldsymbol{v}_{Ds} \cdot \boldsymbol{\nabla} x^i = \left(\frac{m_s v_\parallel^2 + \mu B}{q_s B_{\parallel s}^\star B} \right) [B, x^i]$$

$$\boldsymbol{v}_E \cdot \boldsymbol{\nabla} x^i = \frac{1}{B_{\parallel s}^\star} [\phi, x^i]$$

Usage of general coordinates = ease the change of geometry (tokamak / stellarator)

$$[F, G] = \boldsymbol{b} \cdot (\boldsymbol{\nabla} F \times \boldsymbol{\nabla} G) = \frac{\epsilon^{ijk}}{J_x} \partial_i F \partial_j G b_k$$

- Advection in parallel direction

$$m_s \frac{dv_\parallel}{dt} = -\mu \boldsymbol{b}_s^\star \cdot \boldsymbol{\nabla} B - q_s \boldsymbol{b}_s^\star \cdot \boldsymbol{\nabla} \phi + \frac{m_s v_\parallel}{B} \boldsymbol{v}_E \cdot \boldsymbol{\nabla} B$$

Time-splitting for Boltzmann equation (= with given electric field)

- A time-splitting of Strang is applied to the 4D non-linear Boltzmann equation:

$$B^*_{\|s}\frac{\partial \bar{F}_s}{\partial t} + \nabla\cdot\left(\frac{d\mathbf{x_G}}{dt}B^*_{\|s}\bar{F}_s\right) + \frac{\partial}{\partial v_{G\|}}\left(\frac{dv_{G\|}}{dt}B^*_{\|s}\bar{F}_s\right) = \mathcal{C}(\bar{F}_s) + S$$

- Let us define three advection operators (with $\mathcal{X}_G = (r,\theta)$)

$$B^*_{\|s}\frac{\partial \bar{F}_s}{\partial t} + \boldsymbol{\nabla}\cdot\left(B^*_{\|s}\frac{d\mathcal{X}_G}{dt}\bar{F}_s\right) = 0 \qquad : (\tilde{\mathcal{X}}_G)$$

$$B^*_{\|s}\frac{\partial \bar{F}_s}{\partial t} + \frac{\partial}{\partial\varphi}\left(B^*_{\|s}\frac{d\varphi}{dt}\bar{F}_s\right) = 0 \qquad : (\tilde{\varphi})$$

Axi-symmetry

$$B^*_{\|s}\frac{\partial \bar{F}_s}{\partial t} + \frac{\partial}{\partial v_{G\|}}\left(B^*_{\|s}\frac{dv_{G\|}}{dt}\bar{F}_s\right) = 0 \qquad : (\tilde{v_{G\|}})$$

➠ Semi-Lagrangian scheme

When going to 5D, just need to add a 1D advection in the toroidal direction

- And the collision operator ($\tilde{\mathcal{C}}$) on a Δt : $\partial_t\bar{F}_s = \mathcal{C}(\bar{F}_s)$ ➠ Crank-Nicolson
- And the source operator ($\tilde{\mathcal{S}}$) on a Δt : $\partial_t\bar{F}_s = \mathcal{S}$ ➠ Crank-Nicolson
- Then, a Boltzmann solving sequence ($\tilde{\mathcal{B}}$) is performed:

$$(\tilde{\mathcal{B}}) \equiv (\tilde{\mathcal{S}},\, \tilde{\mathcal{C}})\left(\frac{\tilde{v_{G\|}}}{2},\, \frac{\tilde{\varphi}}{2},\, \tilde{\mathcal{X}}_G,\, \frac{\tilde{\varphi}}{2},\, \frac{\tilde{v_{G\|}}}{2}\right)$$

Coupling with quasi-neutrality :predictor-corrector scheme

- Prediction:
  - Computes $\mathrm{F}(t_n + 0.5\Delta\mathrm{t})$ solving the Boltzmann equation with $\Phi(t_n)$
  - Solves the quasi-neutrality equation to compute $\Phi(t_n + 0.5\Delta\mathrm{t})$
- Correction
  - Computes $\mathrm{F}(t_n + \Delta\mathrm{t})$ solving the Boltzmann equation with $\Phi(t_n + 0.5\Delta\mathrm{t})$
  - Solves the quasi-neutrality equation to compute $\Phi(t_n + \Delta\mathrm{t})$ for next time step

Quasi-neutrality equation (for now full kinetic electrons only)

$$-\boldsymbol{\nabla}_\perp \cdot \left(\alpha \boldsymbol{\nabla}_\perp \phi^{FKE}\right) = \sum_i e_i \delta \bar{n}_i - e \delta \bar{n}_e \qquad \alpha_s = \frac{m_s \langle \bar{n}_s \rangle_\varphi}{\langle B \rangle_\varphi^2}$$

Gysela-axi: a testbed for new developments

New features can be tested with a reduced cost/complexity:

- X-point geometry
- More realistic boundary conditions
- Neutrals (M. Protais's presentation)
- Sources (e.g. ECRH)

Theoretical predictions for GAM dynamics and neoclassical are done with axisymmetry: good framework for verification

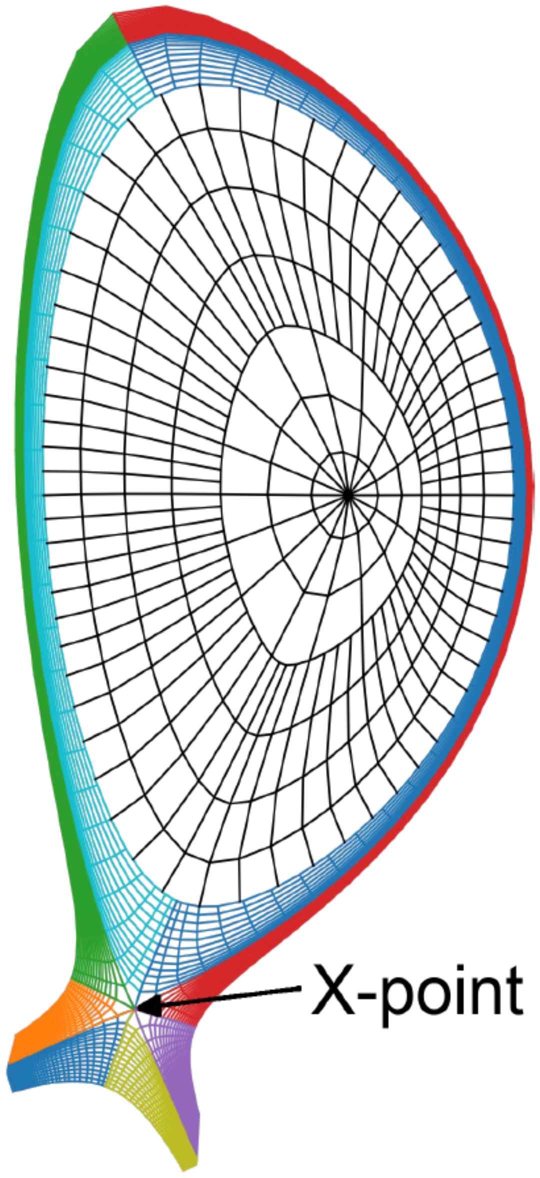
Also a good testbed for new algorithms / new solvers / improve numerical efficiency

Handling an X-point

Patches are required to handle the X-point geometry along field lines.

There are 2 main axes of research to handle this:

- Semi-Lagrangian Advection
  - P. Vidal (IPP) PhD 2022-2025
- Poisson solver
  - A. Hoffmann (IPP) PhD 2023-2026
    - Multi-patch (CONGA) FEEC solver
  - HyTeg A. Dasari (CERFACS) PhD 2024-2028
  - Without patches as a starting point:
    - GMGPolar coupling (CERFACS)
    - Porting of Zoni's polar spline solver E. Malaboeuf (CINES) PhD 2025-2028



NB: Same grid generation as SOLEDGE

Gysela-axi as initial condition for Gysela-X++

One difficulty for global flux-driven gyrokinetic codes is to set the initial condition. If the choice is bad (= F0 far from steady state in the δf formalism), large transient can make the code crash. Even without a crash, the numerical cost to solve this transients in 5D is probably useless.

For electrostatic core simulation, we know a steady state solution: canonical Maxwellian

In presence of X-point / neutrals: no analytical expressions even without turbulence

→An axisymmetric code is probably good enough to solve the transients with a limited numerical cost

Outline

Status and next steps for Gysela-axi

A first electrostatic version with full kinetic electrons has been implemented (with B* = B). Collisions are already included [E. Malaboeuf 2025]

This version is currently being verified:

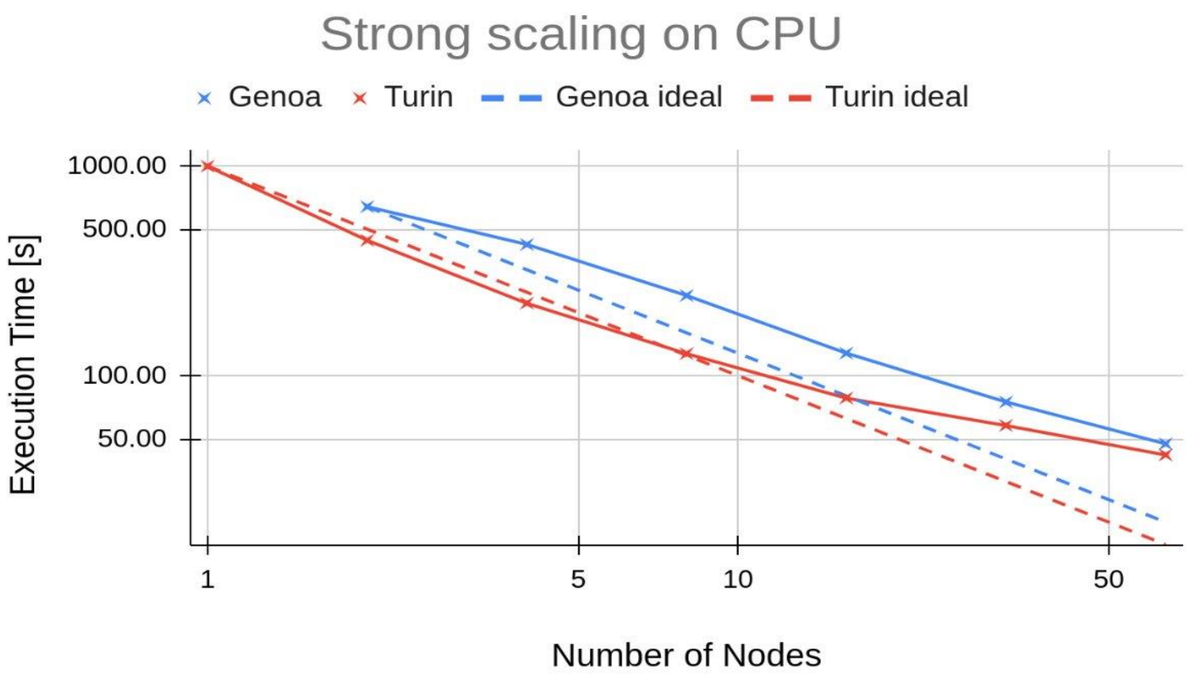
- GAM damping & residual (collisionless) → problem in the advection near the magnetic axis detected, under resolution
- Neoclassical physics

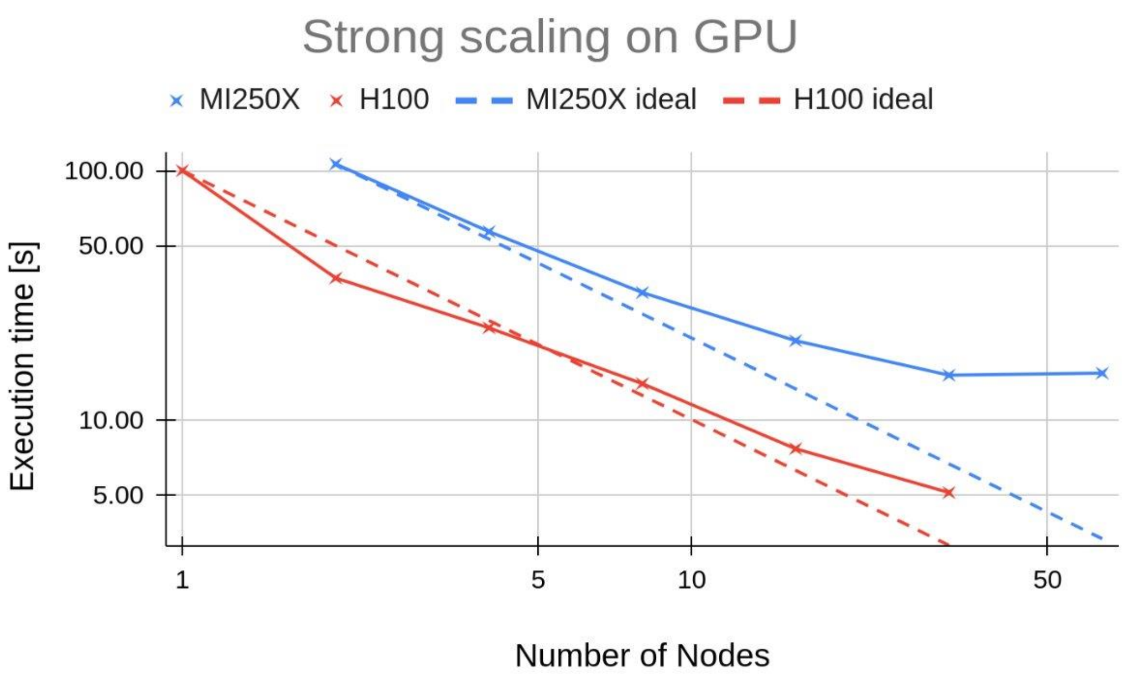
Next steps of implementation (should be quite fast as identical to the Fortran version):

- B* corrections
- Alternative models of electrons: adiabatic & hybrid [P. Donnel 2025]
- Simplified limiter version (immersed boundary conditions)
- Electromagnetic version (A// only) [Z. Qu 2026]

Gyselalib++ : Kokkos backend = **efficient portability on both CPU and GPU** architectures

- Kokkos strategie ensures efficient portability on both CPU and (AMD, NVIDIA) GPU architectures
- Promising results for Landau4D case (256 x 256 x 256 x 256) up to 64 nodes (512 GPU)
  - Adastra (CINES/France) : AMD CPU Genoa + AMD GPU MI250X
  - Pitagora (CINECA/Italy) : AMD CPU Turin + NVIDIA GPU H100





[E. Bourne, 2026]

Conclusions

- **Gysela-X++** = GYSELA in modern C++ with **X-point** for **exascale** ITER core-edge turbulence simulations
  - Require to harvest exascale supercomputers: usage of state of the art HPC libraries (Kokkos, DDC, PDI…)
  - Development of new capacities, hard to implement in the current Fortran version (X-point, neutrals, patches)

- **Gysela-axi** = a major milestone in this project
  - Test the implementation / strategy of development
  - Perfect testbed for the developments of new features with a limited numerical cost
  - Foreseen to be routinely used in pair with the 5D version to lower the overall numerical cost

- **Gysela-stellarator** = another code aiming at simulating core stellarator plasmas will also be developed in parallel to Gysela-X++

Acknowledgments

https://gyselax.github.io/

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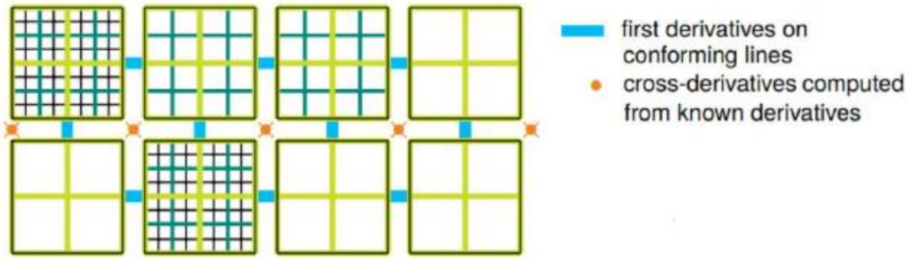
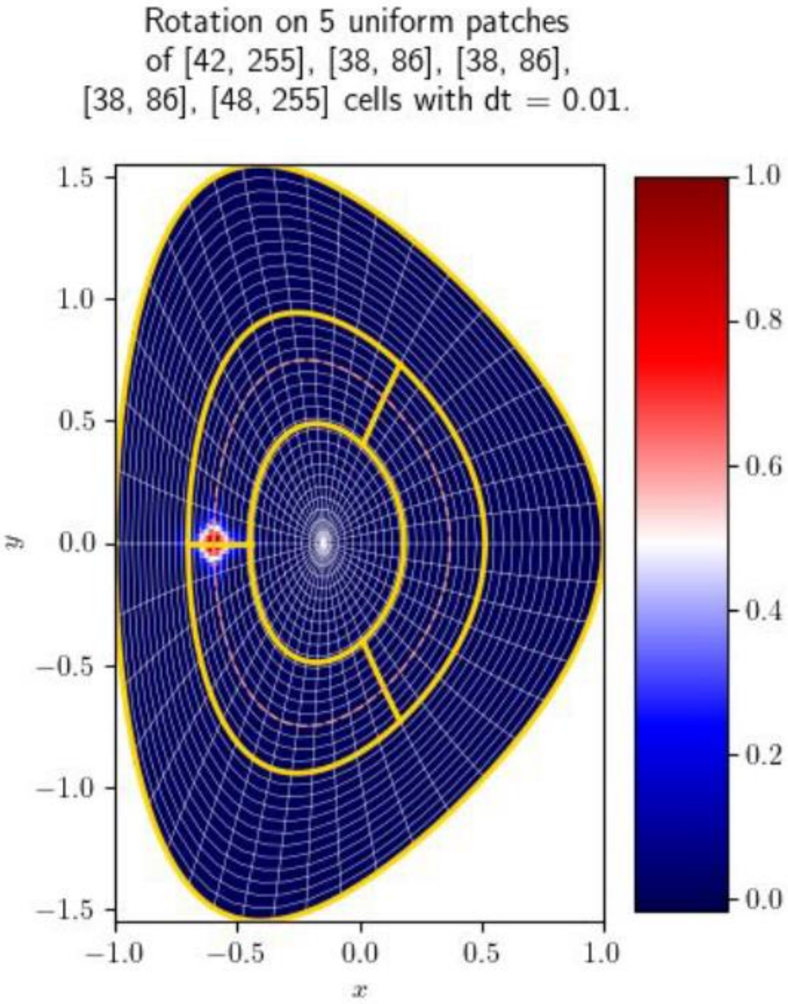
Backup slides

Semi-Lagrangian multi-patch advection

- Strang splitting is used to break the problem into 1D or 2D advections
- Patch-wise spline interpolation with treatment of interfaces
  P. Vidal et al. (2025) *Local cubic spline interpolation for Vlasov-type equations on a multi-patch geometry.* arXiv preprint arXiv:2505.22078



- Local spline interpolation is carried out by DDC
  - Batched LAPACK solvers upstreamed to Kokkos Kernels
    Asahi, Y. et al. (2024) *Development of performance portable spline solver for exa-scale plasma turbulence simulation.* SC24-W: Workshops of the International Conference for High Performance Computing, Networking, Storage and Analysis. IEEE.
  - Ginkgo iterative solvers



[P. Vidal 2022-2025]