Preparation of the GYSELA code for L-H transition studies

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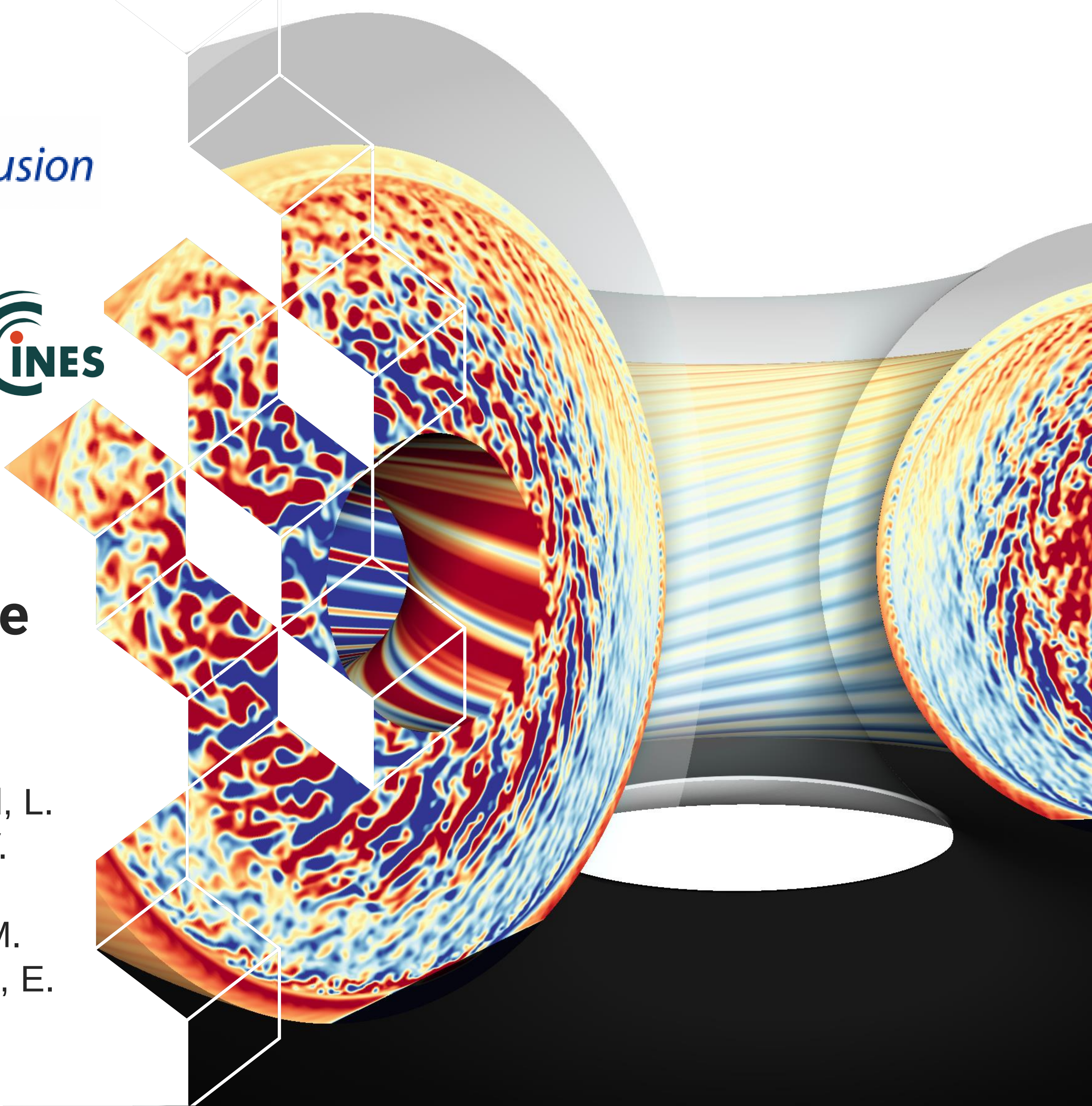

Outline

1. **General context**
2. **Recent upgrades in the GYSELA code (Fortran) to model L-H transition**
   - Poloidally localised boundary conditions
   - Sheath boundary conditions in Vlasov
   - Electromagnetic fluctuations
3. **A new code in development: Gysela-X++**
   - Strategy
   - X-point geometry
   - Neutrals
4. **Conclusion**

Objective: obtain a spontaneous L-H transition in a gyrokinetic code

Status in GYSELA

What physics is a priori needed?

- Poloidally localised boundary conditions (limiter or divertor)  [G. Dif-Pradalier 2022, Donnel 2025]
- Flux driven (power scan & self organisation of profiles) 
- Electromagnetic fluctuations (for saturation of pedestal)  [PhD C. Gillot 2017-2020, PhD R. Bigué 2023-2026]

What physics might be needed?

- Neutrals (in particular particle source)  [PhD M. Protais 2024-2027]
- Sheath boundary condition  [PhD Y. Munschy 2021-2024]
- Electron scale turbulence 
- More finite Larmor effects due to large gradients (kinetic corrections, FLR effects in collisions…) 

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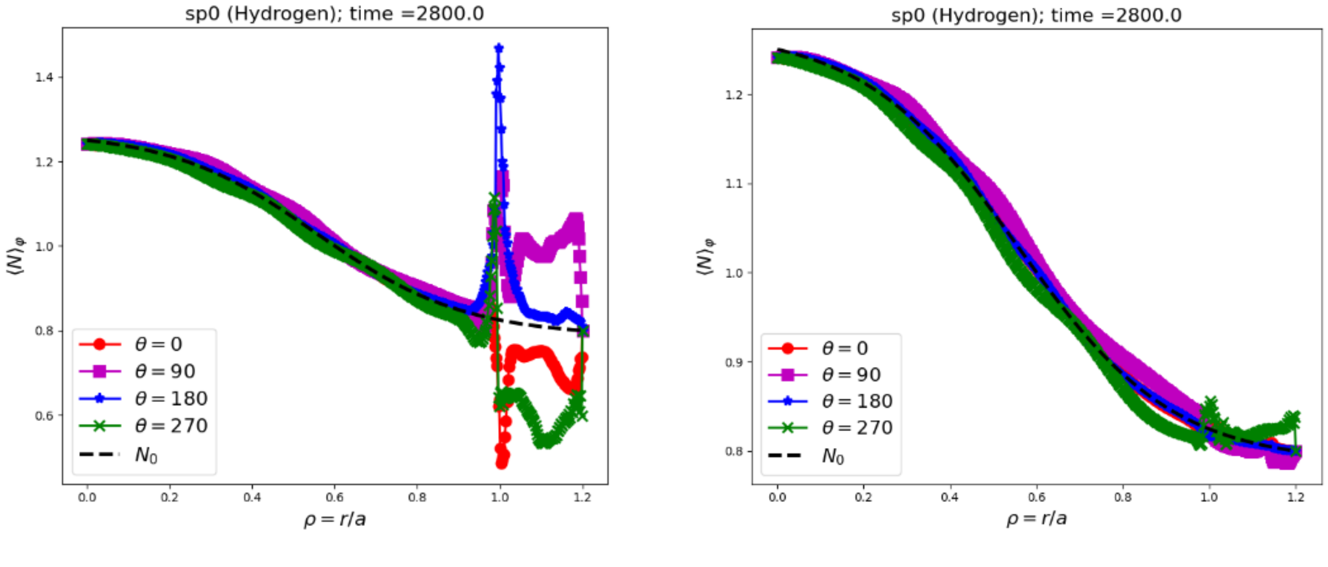
Poloidally localised boundary conditions

First limiter configuration introduced in GYSELA with adiabatic electrons [G. Dif-Pradalier 2022]

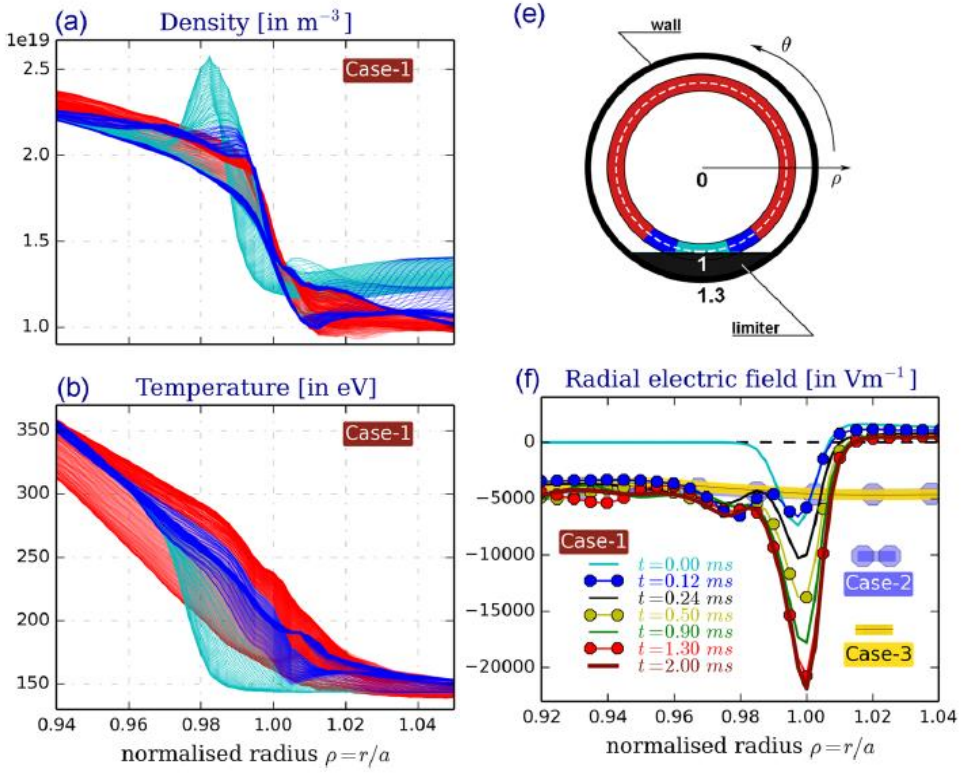
- Penalisation of ion distribution function
- Modification of the quasi-neutrality

➢ First spontaneous formation of pedestal like profiles (no transition)



(a) No update

(b) With update



Generalisation of limiter configuration with kinetic electrons [P. Donnel 2025]

- Penalisation of ion & electron distribution functions: sink of momentum and energy
- Trapped kinetic electrons in the core, Full kinetic electrons in the SOL.

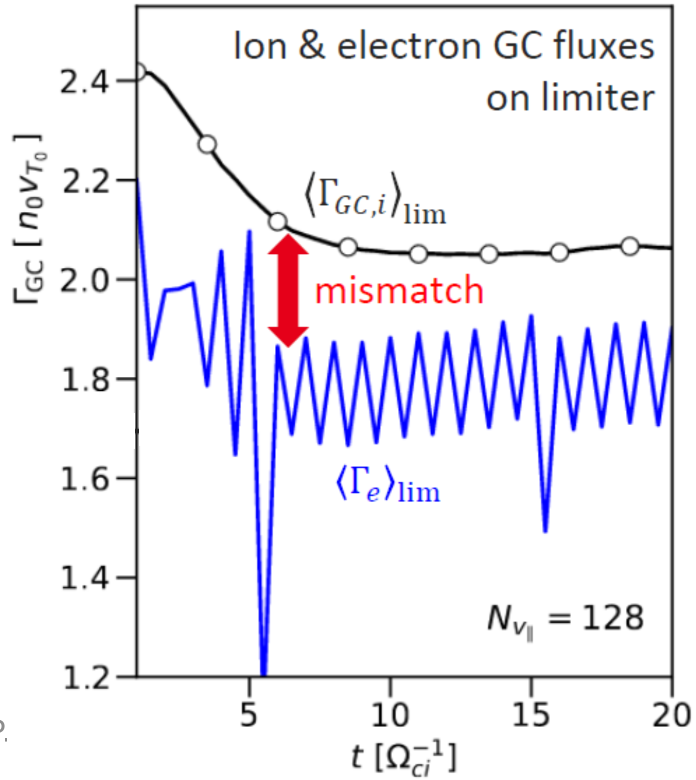
➢ Handling of poloidal asymmetries required

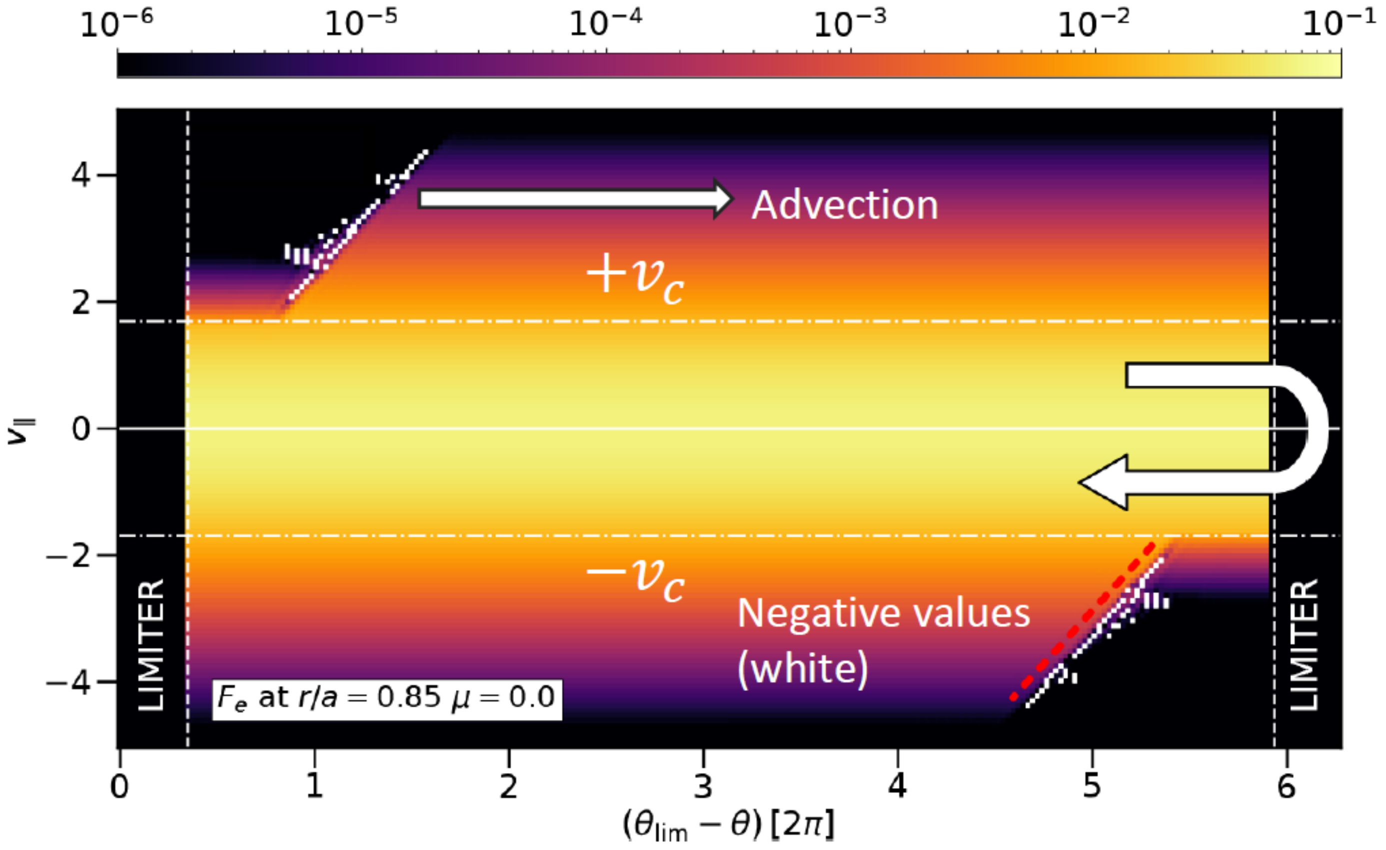
Sheath boundary conditions: axisymmetric limiter

Sheath boundary conditions have been introduced in GYSELA [PhD Y. Munschy 2021-2024]

- Absorption of fast electrons & all ions
- Reflection of slow electrons ($v_{||} < v_c$)
- New model to compute v_c: Flux-averaged sheath $\langle\Gamma^i\rangle_{lim} = \langle\Gamma^e\rangle_{lim}$

➢ Without QN & collisions: behaviour as expected





But problem of flux matching when included in the splitting scheme of GYSELA

➢ when QN is introduced, leads to numerical instability

Simplifying the problem: toroidally thin limiter

Axisymmetric limiter

Possible causes for mismatch

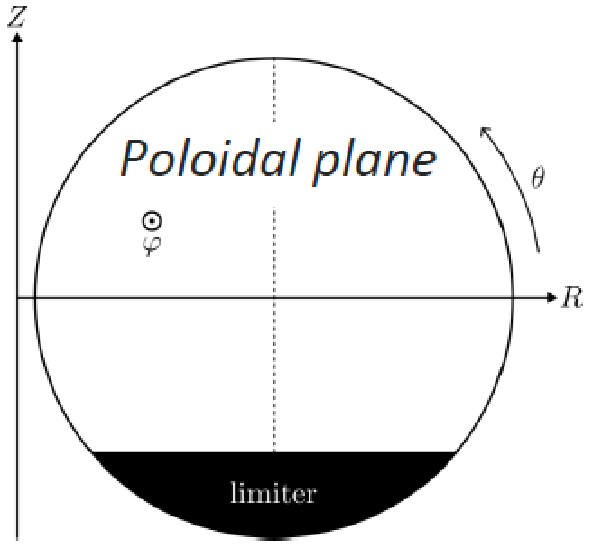
Limiter immersed in quasineutrality domain

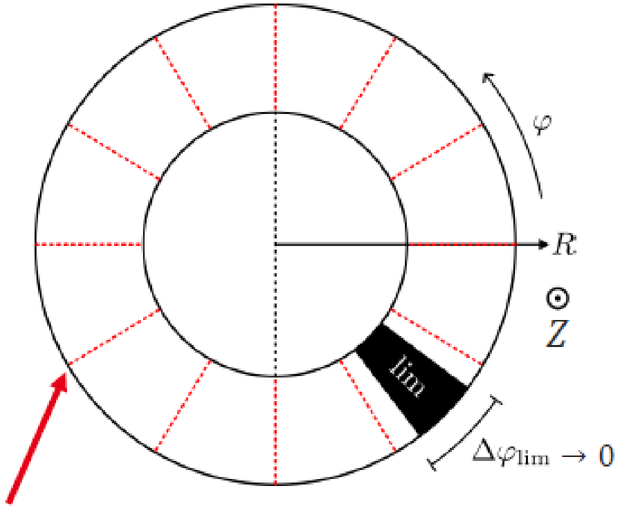
flux-averaged v_c

Infinitely thin limiter

Infinitely thin limiter located **between two toroidal grid points**

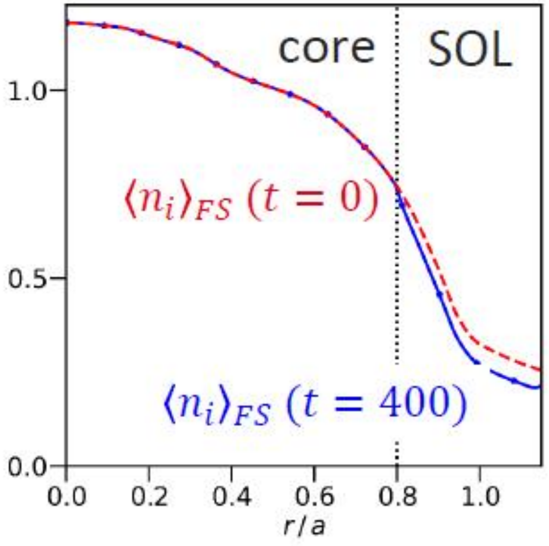
Cutoff velocity computed with **conducting sheath** $v_c = \sqrt{2e\phi/m_e}$



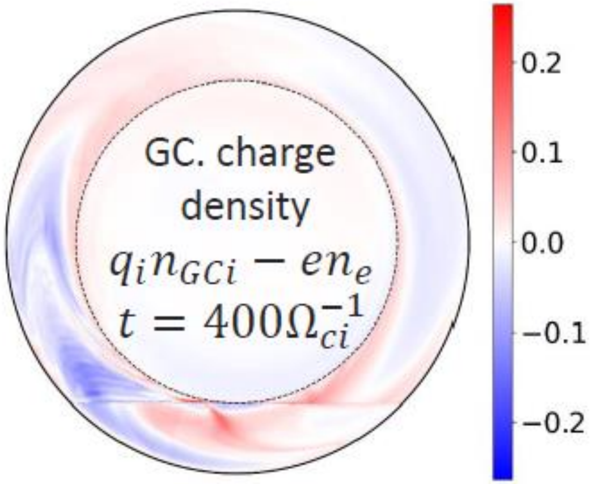


Resolved toroidal angles

Thin toroidal limiter physics at early simulation times



- Thin lim. allows for reaching longer simulation times ☺
  - ➢ One order of magnitude longer than for axisymmetric limiter
- Boundary condition $\phi(r_{\max}) = 0 \rightarrow v_c(r_{\max}) = 0$



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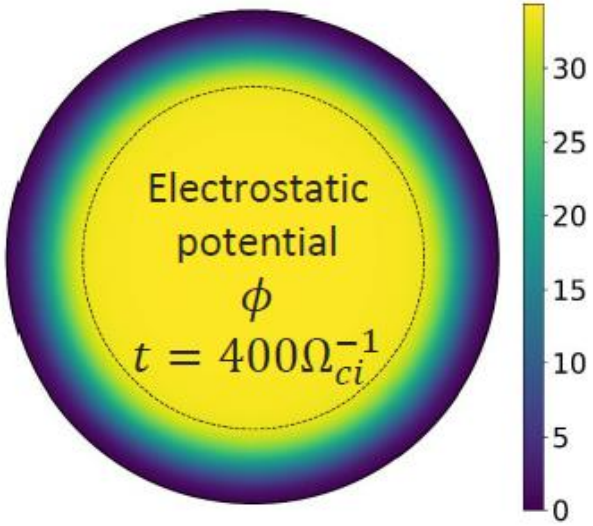
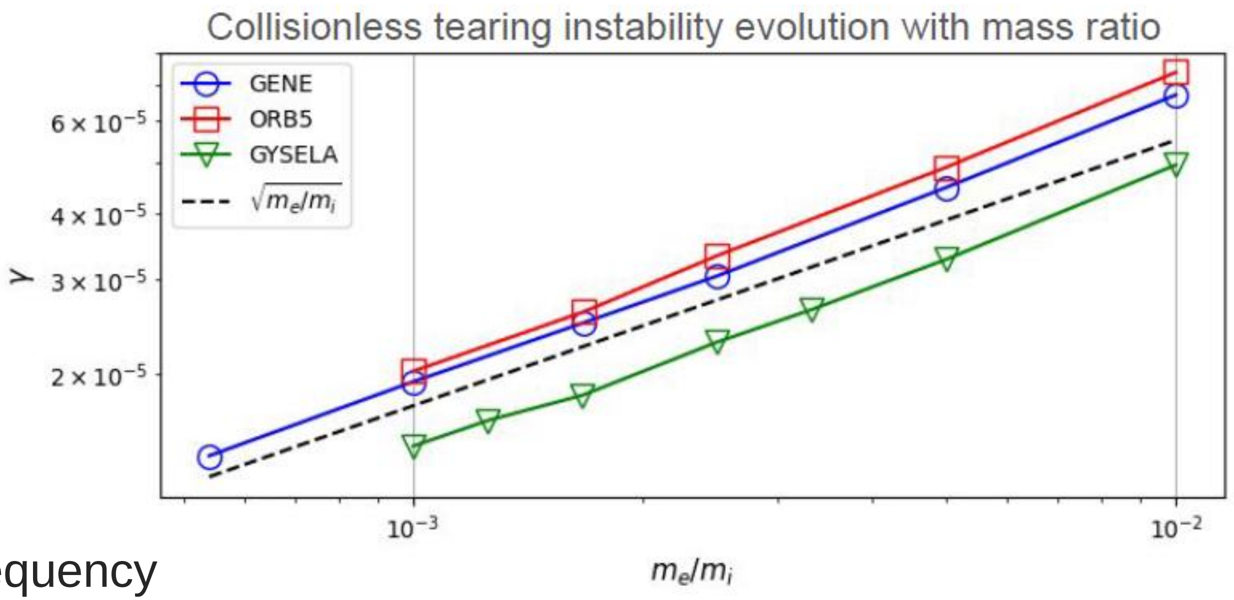
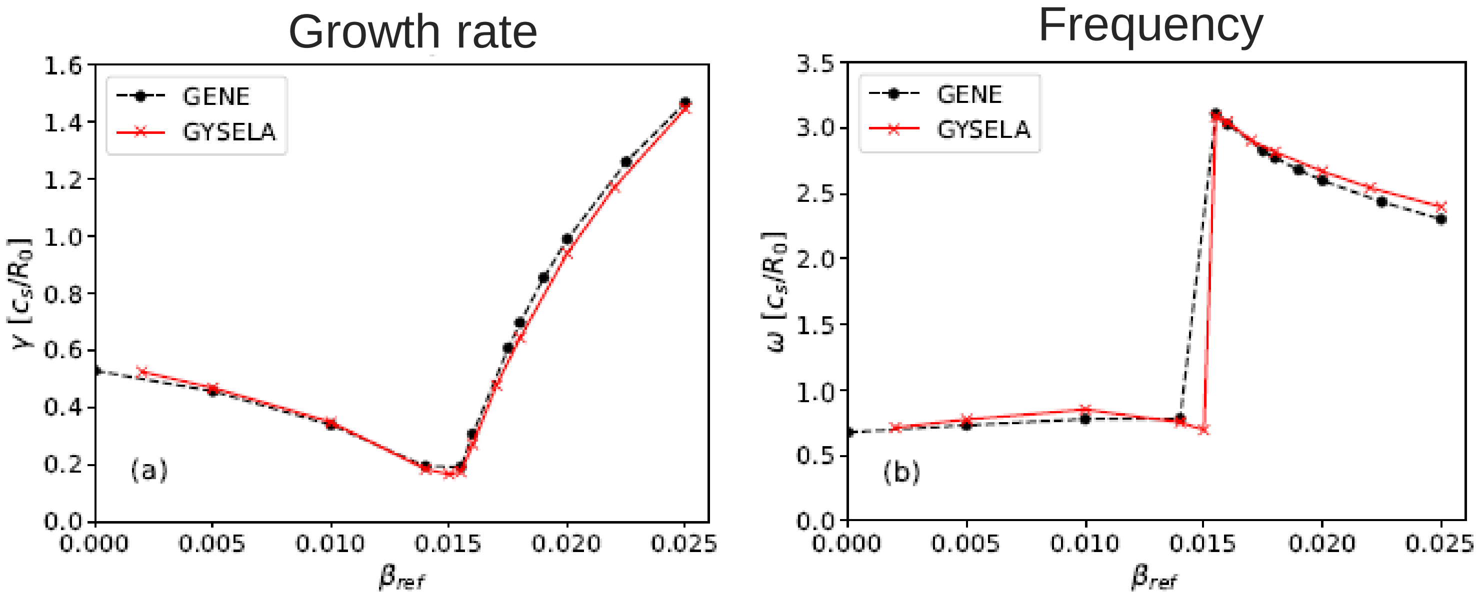


This work will continue in TSVV-C

All linear electromagnetic instabilities retrieved in GYSELA

Tearing (both collisionless and collisional)
[PhD R. Bigué 2023-2026]





ITG / KBM transition
in linear simulations
[courtesy of Z. Qu]

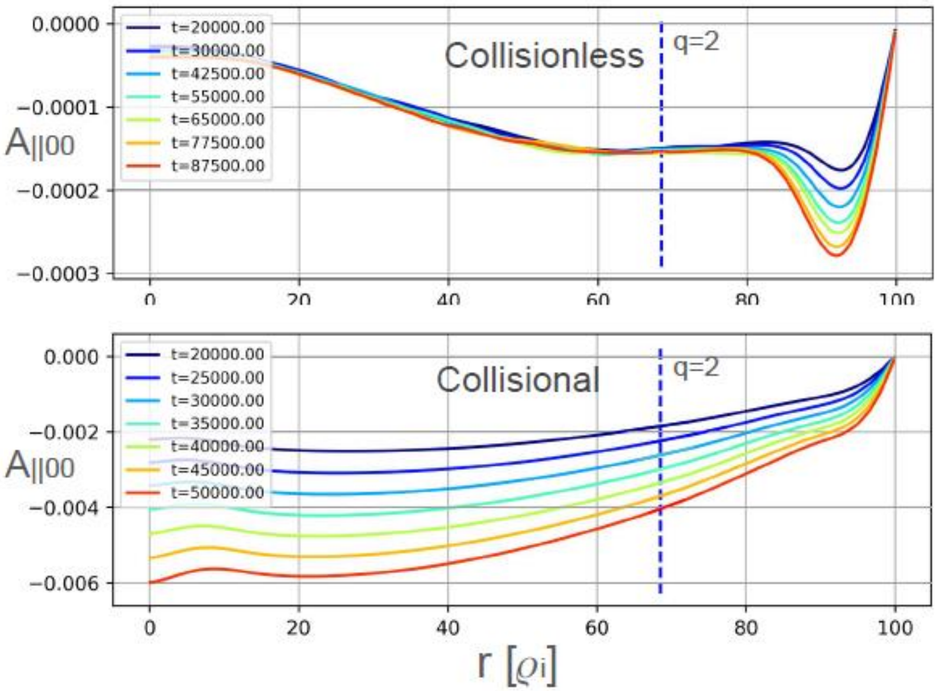
But NL saturation with all modes allowed still problematic

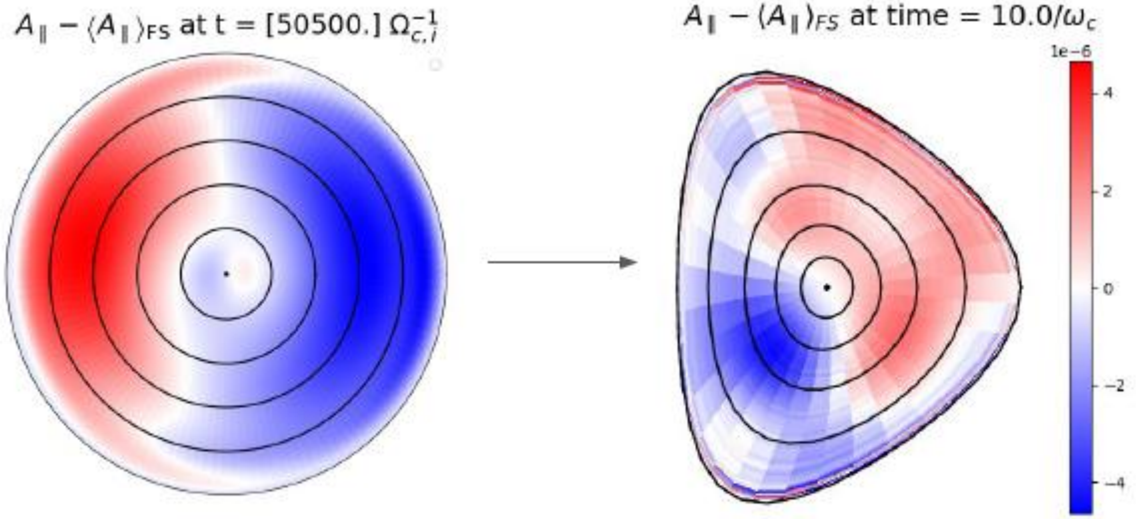
Axisymmetric evolution of $A_{||}$ needed in GYSELA

- GYSELA being flux-driven, the axisymmetric component of $A_{||}$ needs to be taken into account

- Necessity of self-consistency between initial distribution functions and magnetic equilibrium

  $\Rightarrow$ start from Grad-Shafranov solution





OLD solver

NEW solver= Grad-Shafranov solution

- Magnetic relaxation well captured

- Resistive diffusion of magnetic equilibrium

- Paving the way for NL profile evolution

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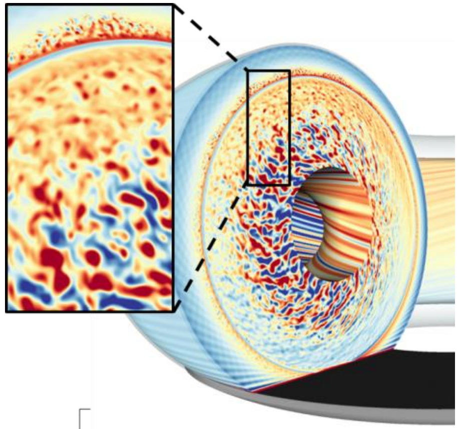
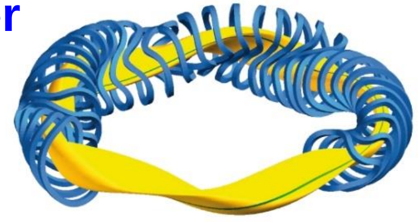
Roadmap for Gysela-X++ towards exascale

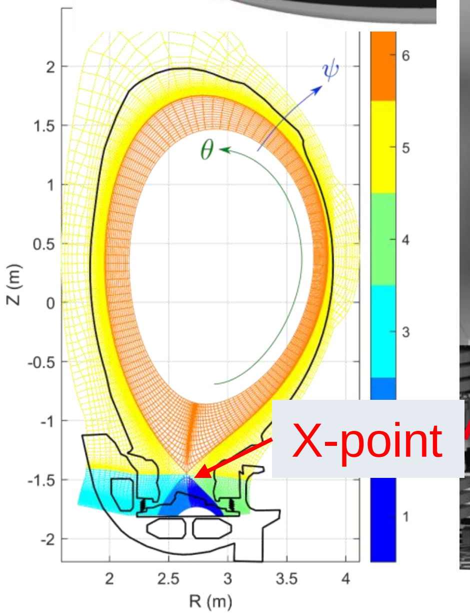
→ Why do we choose to rewrite GYSELA ?

- **Gysela-X++** = GYSELA in modern C++ with X-point for exascale ITER core-edge turbulence simulations
  (+ 3D 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**





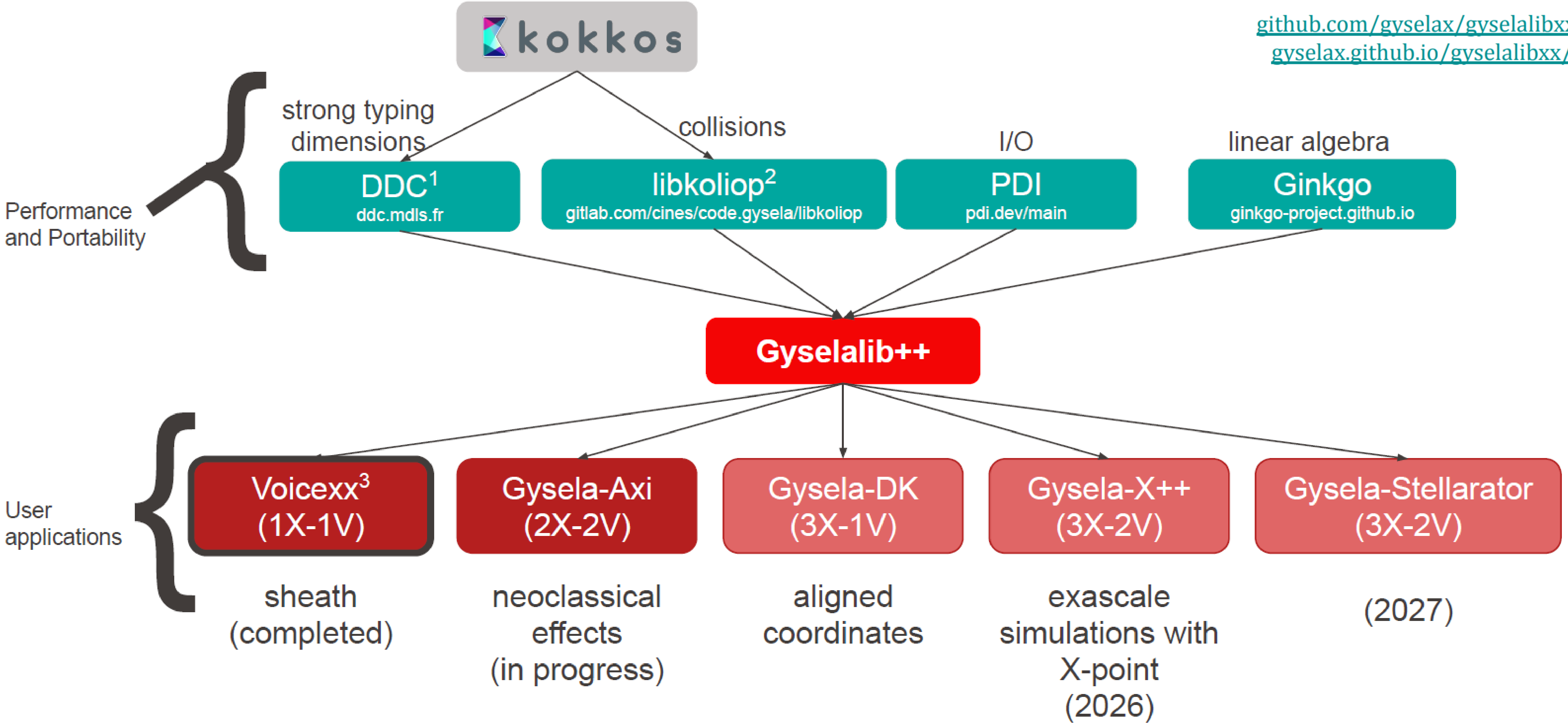


SOLEDGE-3X
X-point geometry


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

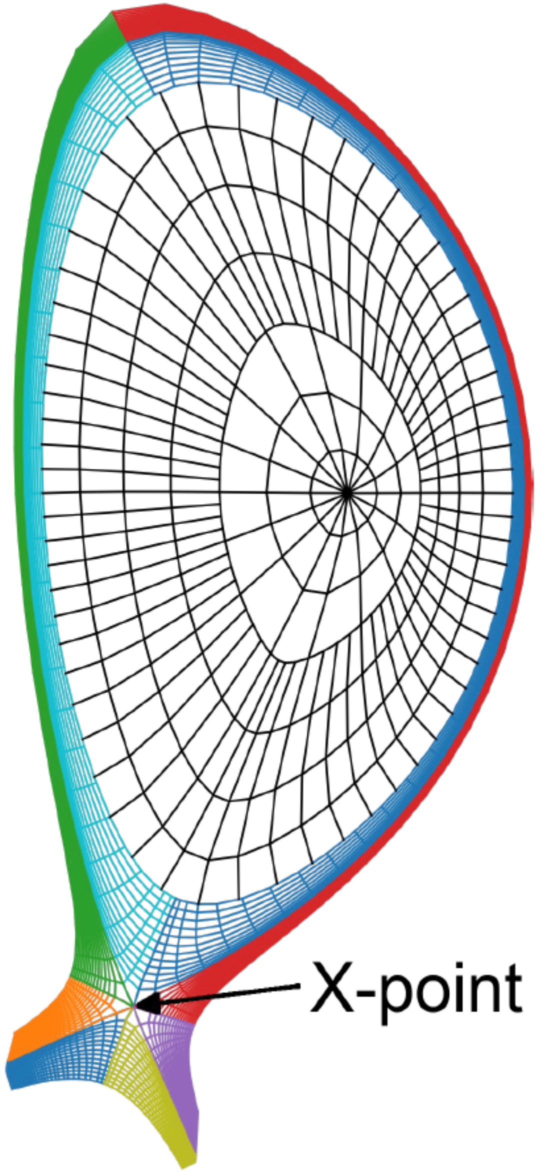
Handling an X-point

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

There are 2 main axes of research to handle this:

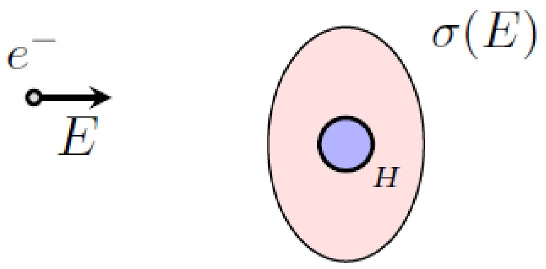
- Semi-Lagrangian Advection
  - P. Vidal (IPP) PhD 2022-2025
- Poisson solver
  - A. Hoffmann (IPP) PhD 2023-2026
    - Multi-patch (CONGA) FEEC solver
  - HyTeg A. Dasari (CERFACS) PhD 2024-2028
  - Without patches as a starting point:
    - GMGPolar coupling (CERFACS)
    - Porting of Zoni's polar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

NB: Same grid generation as SOLEDGE

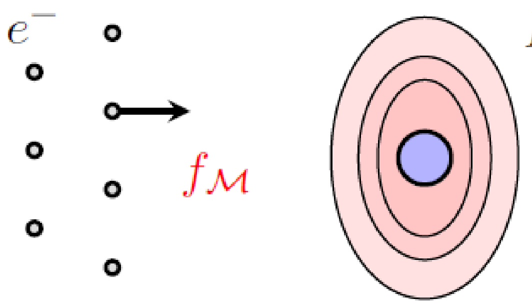


Kinetic plasma-neutrals interaction

Cross section σ



Reaction rate coefficient $\langle \sigma v \rangle$



[PhD M. Protais 2024-2027]

New analytical derivation: work in progress

$$\left(\frac{\partial f_i}{\partial t}\right)_{\text{ion}} (\mathbf{v}) = \int |\mathbf{v} - \mathbf{v}'| \sigma_i(|\mathbf{v} - \mathbf{v}'|) f_N(\mathbf{v}) f_e(\mathbf{v}') \, d^3\mathbf{v}'$$

(Example: impact of ionization on the ion species)

No transport: neutrals frozen in time, only kinetic interactions with the plasma
Study of charge-exchange and ionization
$\rightarrow$ compare impact on turbulence and plasma transport of fluid vs kinetic source
Part of the TSVV-C (2026-2027) call

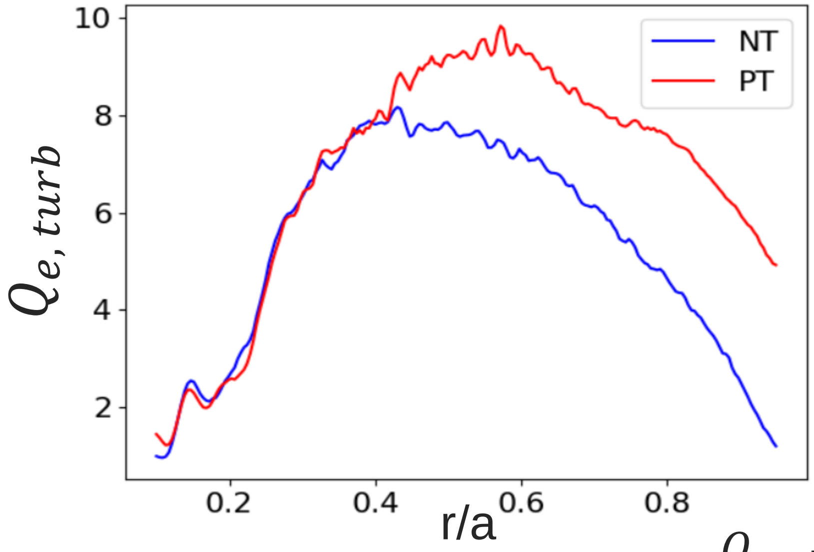
Conclusions

- The **GYSELA code (Fortran)** now includes a good part of the physics mandatory to address L-H transition
  - Way forward: perform simulations with everything activated at the same time (limiter + sheath boundary condition + electromagnetism)
  - Intrinsic limitations: fixed homogeneous grid, no X-point, exascale difficult

- **Gysela-X++**: Rewriting in **modern C++**, more modular & scalable on different accelerated architectures
  - Realistic temperature gradients at the edge: Patches
  - Realistic geometry: X-point & stellarators
  - Additional physics: neutrals, ECRH/ECCD source…
  - Based on DDC library + Kokkos
  - Axisymmetric version under testing

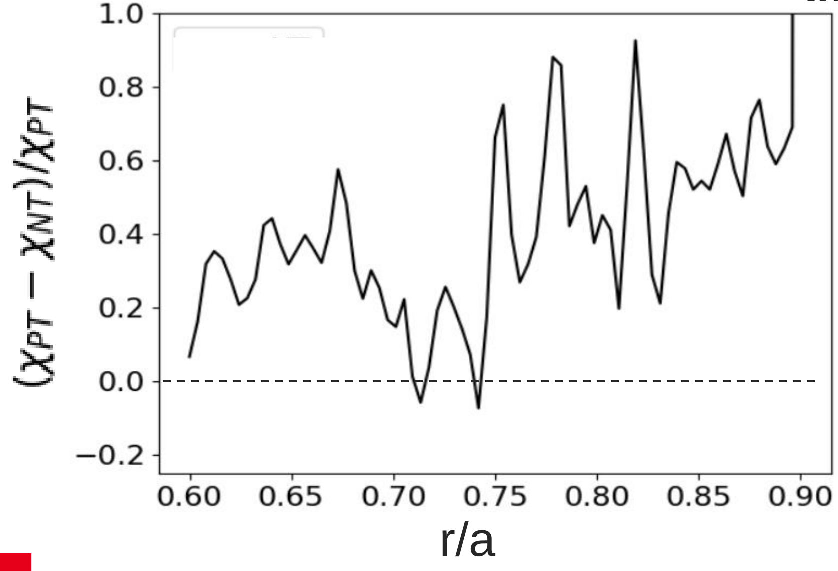
Backup slides

HEAT TRANSPORT AT THE EDGE LOWER FOR NT

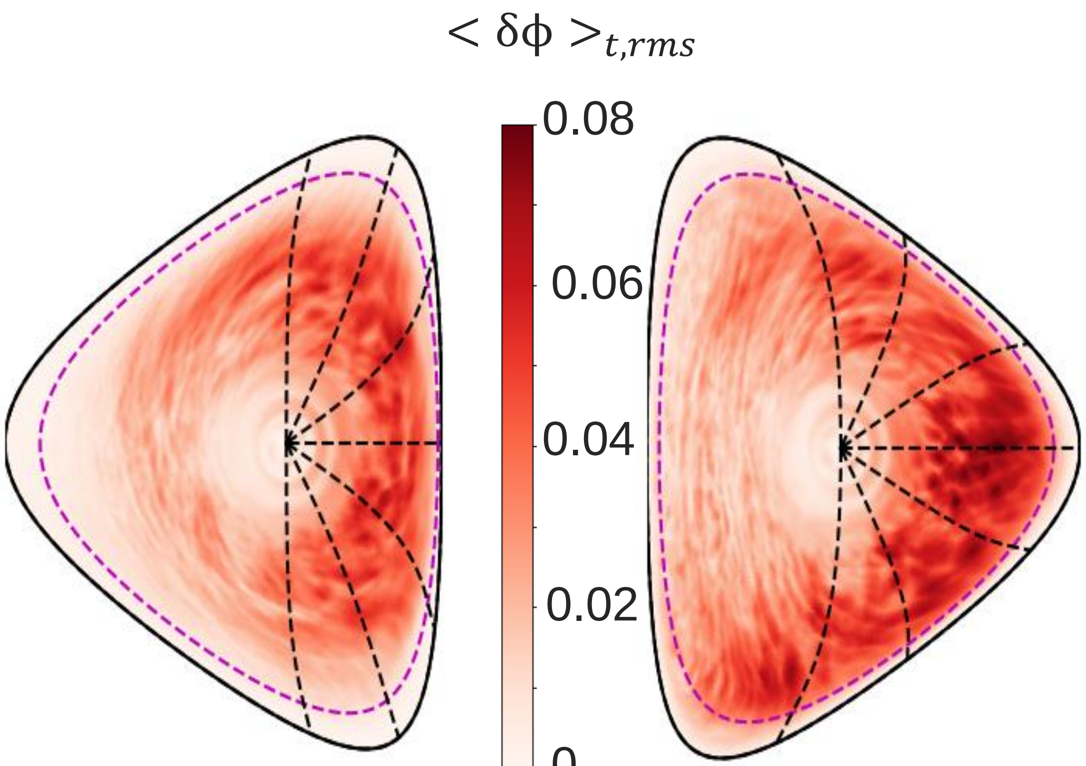


Evolution of profiles

$$\chi_{\mathrm{eff}} = -\frac{Q_{turb}}{n\frac{dT_e}{dr}}$$



[PhD L. De Gianni 2023-2026]



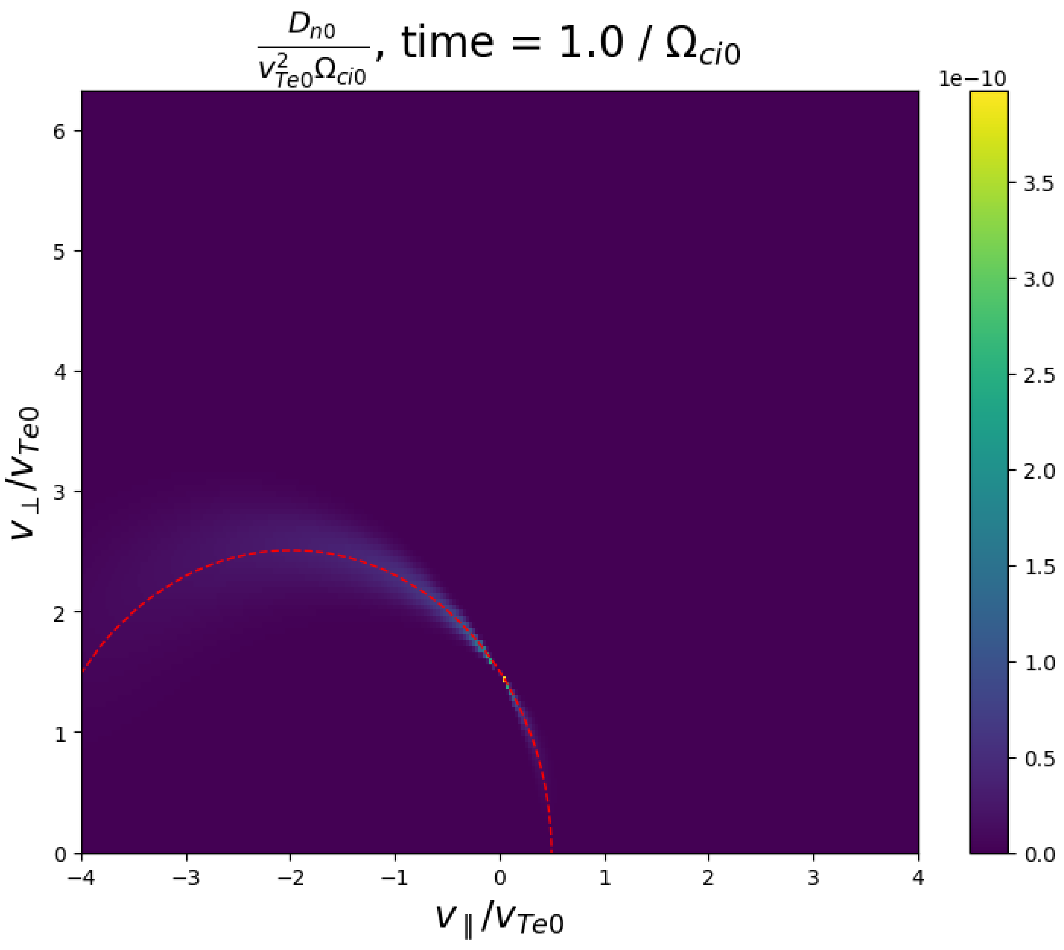
Lower fluctuations in NT

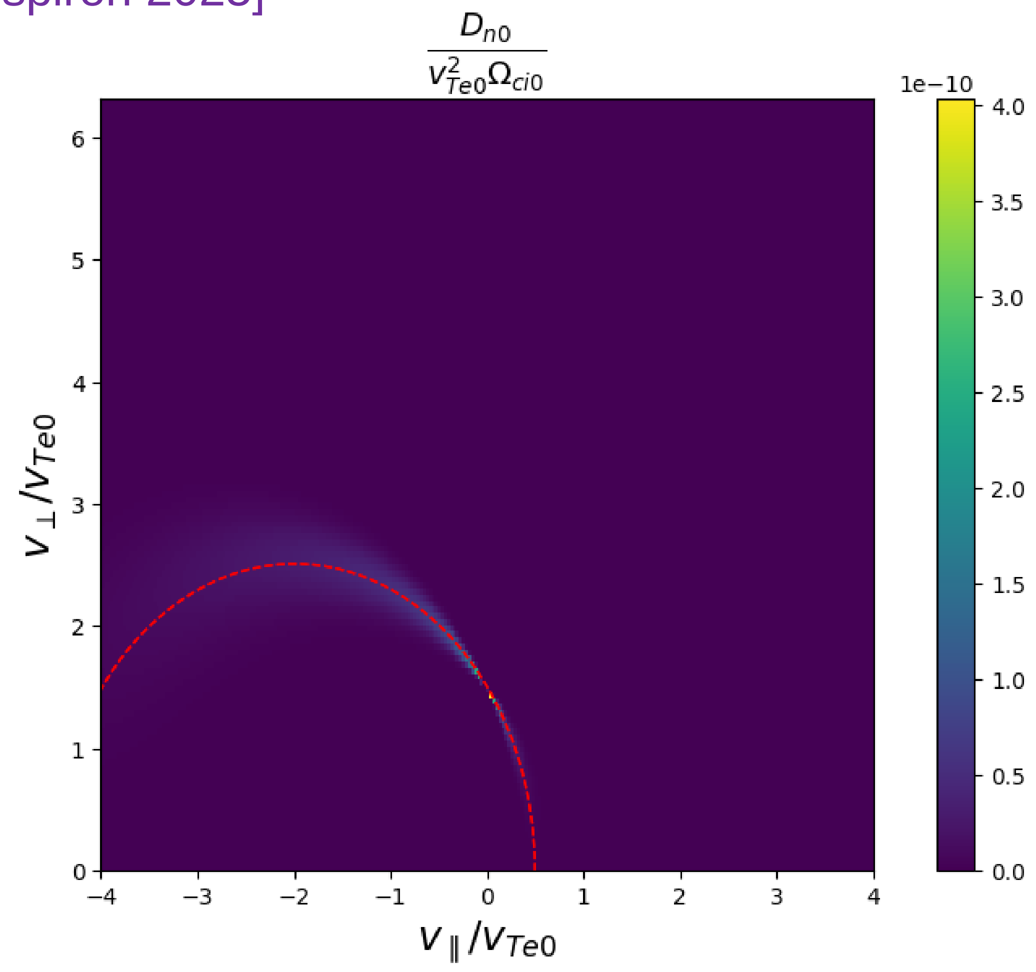
EC source : GYSELA and semi-analytical script in agreement

GYSELA

Python script

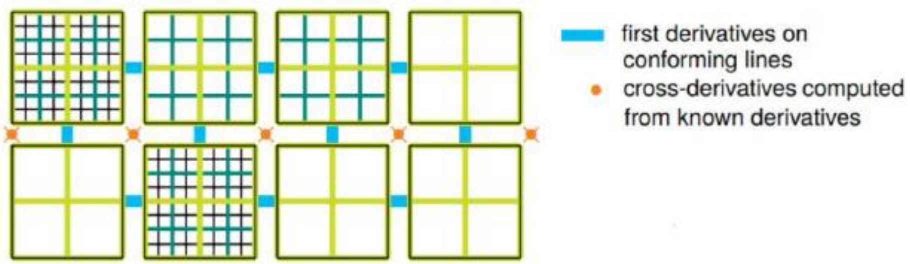
[M2 internship L. Grospiron 2025]



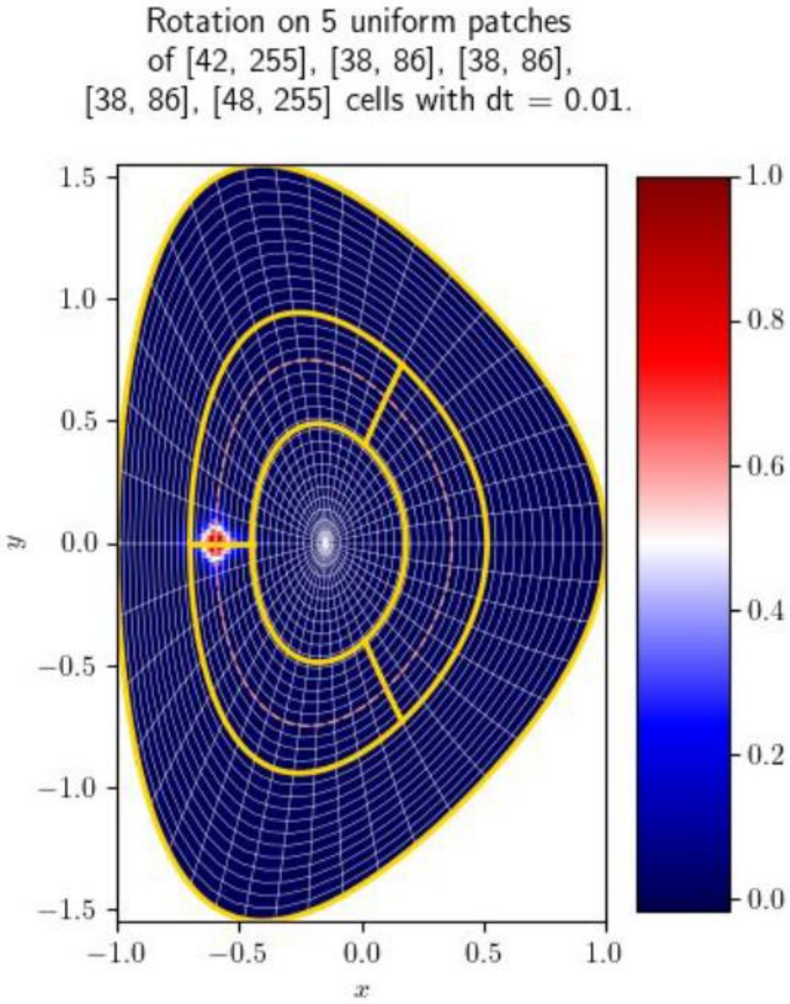


Semi-Lagrangian multi-patch advection

- 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]