EUROfusion

TSVV4 Progress and Prospects

D. Told, P. Ulbl, TSVV4 Team

EUROfusion Science Meeting on Status of TSVV projects
September 11, 2023

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Outline

- Project structure
- Key achievements
- Selected highlights

TSVV T4 Project Members

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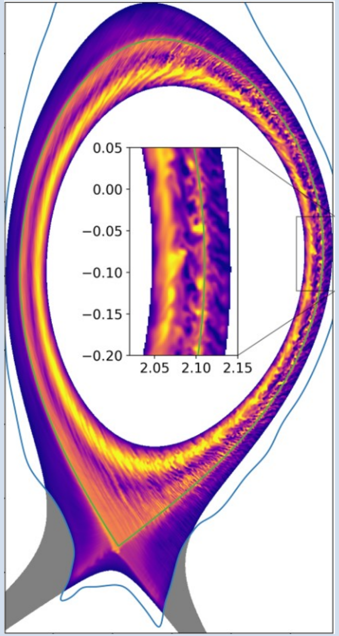
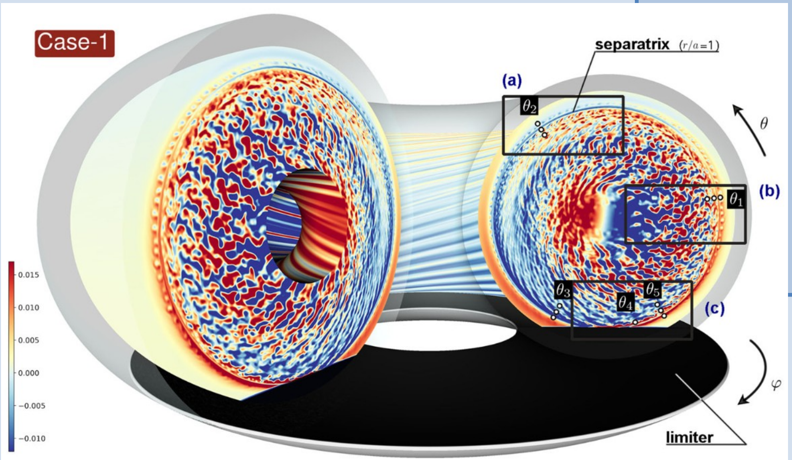
Setup of TSVV Task 4

Key deliverables	Our work
Kinetic codes for the plasma edge ‣ TSVV T1	GENE-X PICLS GyselaX
Deal with open field lines	BIT1 VOICE semi-analytical methods
Limitations of Gyrokinetics	ssV GempicX / BSL6D Moment-based edge GK
Coupling methods	Neutrals Impurities Fluid-kinetic coupling

Aim: GK codes for Edge + SOL

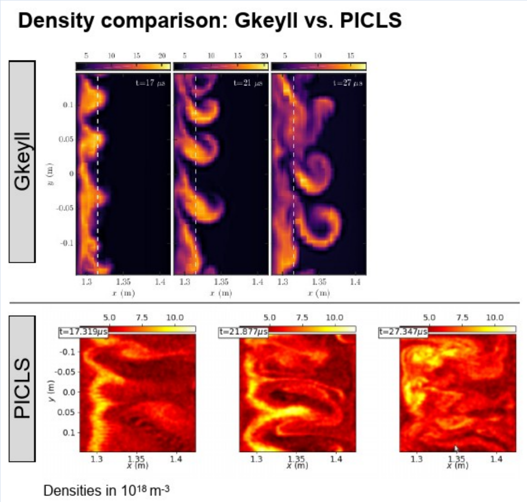


GENE-X /
D. Michels et al.,
Phys. Plasmas 2022



GyselaX /
G. Dif-Pradalier et al.,
Commun. Phys. 2022

PICLS /
A. Bottino
2021



Achieved so far: 1) Main codes

GyselaX

Full-f limiter plasma simulations ‣ **highlight slide**

Immersed boundary condition studies using VOICE (1D1V kinetic)

Recovered major fluid/kinetic properties of sheath (Bohm criterion, space charge)

G. Dif-Pradalier, Comm. Phys. 2022
Y. Munschy, submitted
Y. Munschy, submitted

GENE-X

Arbitrary geometry (open/closed field lines)

Dirichlet boundaries (Maxwellian BC)

Collision operators: BGK, LBD

Electromagnetics ($A_\parallel$)

Nonlinear quasineutrality equation

Validation on TCV-X21 ‣ **P. Ulbl's part**

D. Michels CPC 2021
D. Michels PoP 2022
P. Ulbl CPP 2022
P. Ulbl PoP 2023

PICLS

Moment-based full-f nonlinear collisions

Second-order particle Lagrangian terms (prep. for nonlinear polarization)

Delta-f model using Maxwellian control variate

Delta-f/full-f transition scheme for noise control in core/edge transition (to be used with limiters in ORB5)

M. Murugappan PoP 2022
A. Stier CPC, submitted

Achieved so far: 2) Sheath studies

Ab-initio sheath simulations – BIT-1

Sheath in ELMing SOL ‣ time-dependent BC

Sheath in blobby SOL

ITER / DEMO collisional sheath,
Dressed Cross-Section Model ‣ **highlight slide**

D. Tskhakaya, EPJ D 2023

Immersed boundary – VOICE

Characterized particle sources / sinks (Krook in the wall, collisions)

Role of mass ratio, T_e on distribution function + sheath potential

Ported to C++, GPU

E. Bourne JCP 2023
Y. Munschy, submitted
Y. Munschy, submitted

Analytical sheath studies

Extended preexisting sheath model for grazing angles:

- added kinetic electrons (ρ_e distortion by sheath electric field)
- multispecies ions

Generalized solver for arbitrary angle

Turbulent gradient effects

A. Geraldini, submitted
A. Geraldini, submitted
S. Zeegers, Master thesis

Very helpful:
Dedicated sheath meetings with everyone involved

Achieved so far: 3) Limits of GK

Hybrid-kinetic simulations using ssV

Enable routine 3d operation of the code

Enabled simulations of fully kinetic ITG

Comparison to GENE successful in both local and global (full-f) mode

F.N. deOliveira-Lopes, submitted

Geometric PIC methods using GempicX

GEMPIC model implemented into AMReX framework

Ported to GPU

BSL6D – semi-Lagrangian hybrid-kinetic code

Fully kinetic ITG + IBW simulations

N. Schild, submitted

Completed so far: 4) Coupling approaches

Gyro-moment approach

Developed flux-tube linear GM code

Benchmarked to GENE

Implemented, compared a range of collision operators

Nonlinear simulations in Z-pinch + Cyclone Base Case

Full-f version applied to linear LAPD device

BJ Frei JPP 2021
BJ Frei JPP 2022
BJ Frei PoP 2022
BJ Frei JPP 2023
BJ Frei, submitted
ACD Hoffmann JPP 2023
ACD Hoffmann, submitted

Coupling to neutrals and impurities

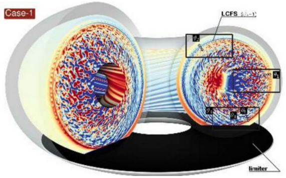
Completed basic neutral model survey:

- Fluid vs. kinetic?
- Code-internal vs. coupling to EIRENE?

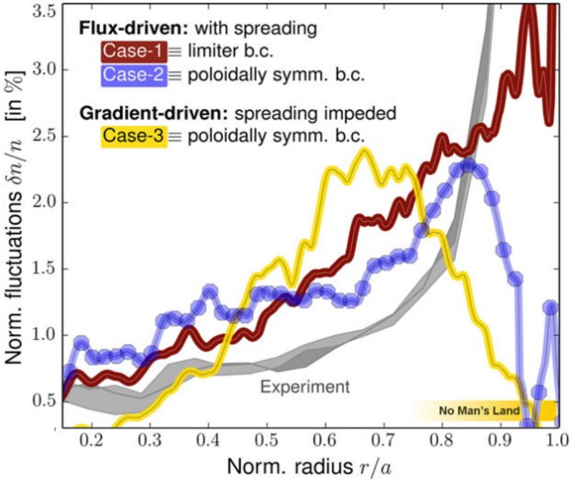
Full-f limiter plasma simulations

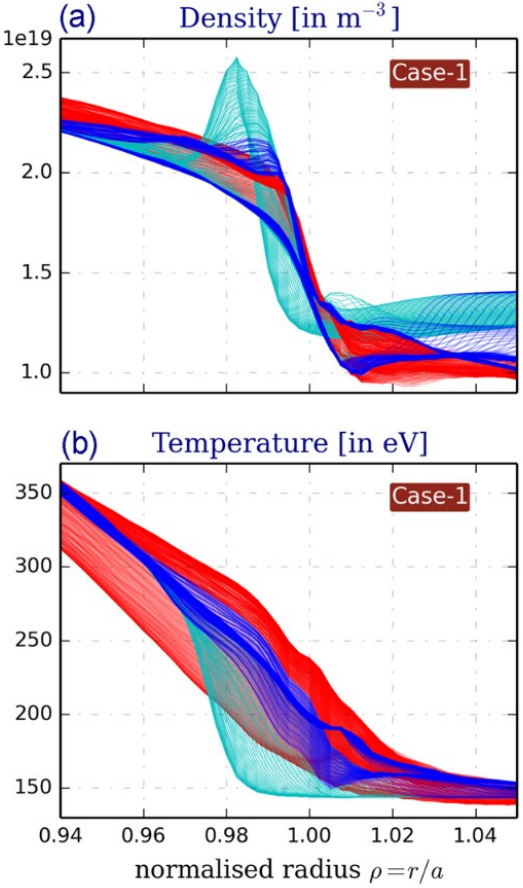
[Dif-Pradalier Comm. Phys. 22]

Studied impact of **poloidally localized limiter** in **GYSELA**



- Limiter acts as sink, steepens profiles nearby
- Acts as turbulence source, raising density fluct. levels compared to poloidally symmetric boundary
- Leads to formation of E_r well





Simulation of ITER inter-ELM SOL

[Courtesy of D. Tskhakaya]

Two new sets of ITER SOL simulations have been performed:

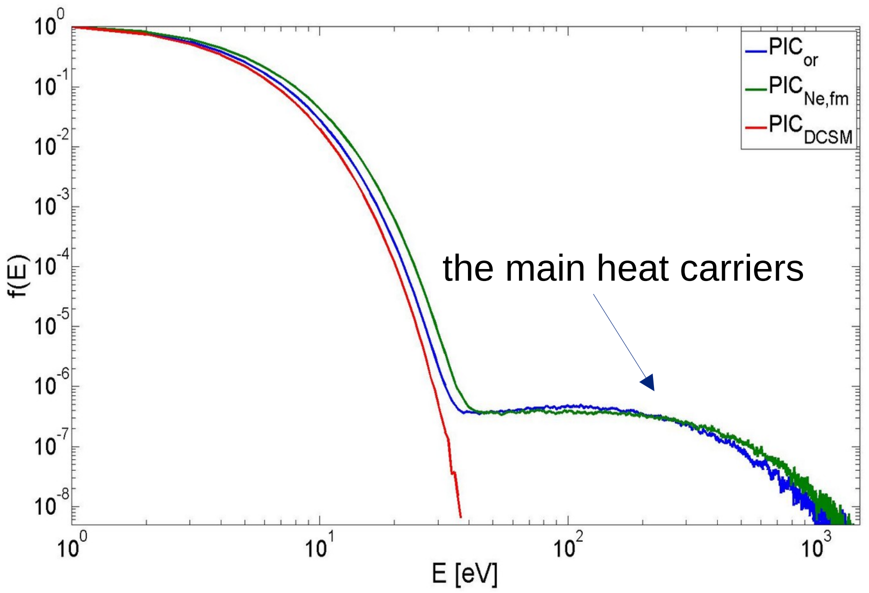
- including higher ionized states of Ne^{+i} (up to i=6)
- including Dressed Cross-Section Model (DCSM). The DCSM [1] does not apply the coronal approximation and takes into the account millions of possible atomic transitions.

No significant influence of the applied model on the plasma profiles has been found, but on the electron power loads to the divertor

q_e [MW/m²]	Original	With $Ne^{+i<7}$	With DCSM
ID / OD	3.7 / 15.7	7,2 / 13.2	0.9 / 0.9

The explanation of these results is the following: the main heat carriers to the divertors are the super-thermal non-Maxwellian collisionless electrons originated from the upstream SOL, which **are absent in the DCSM**.

[1] D. Tskhakaya, Europ. J. Phys. D, 2023

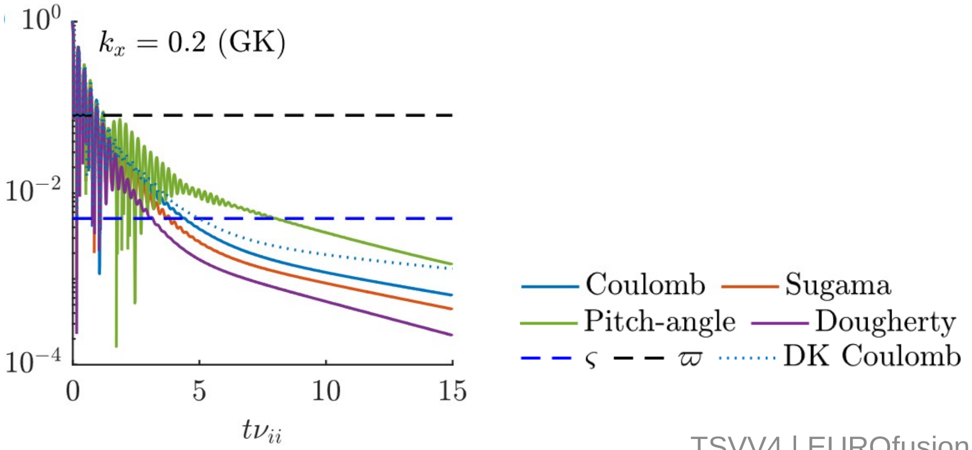


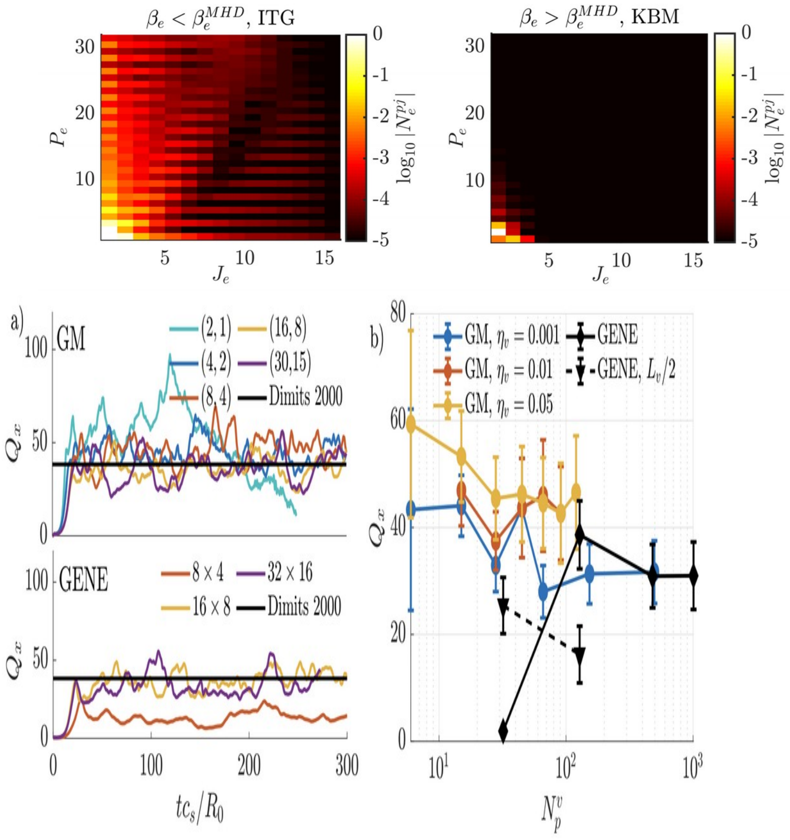
Electron energy distribution function at the ITER outer divertor sheath entrance from different SOL models. "or" denotes the original model including only up to the 5th ionized states of Ne.

Gyro-moment approach

[BJ Frei, JPP 22/23]
[ACD Hoffmann, subm.]

- Allows smooth transition from GK system down to Braginskii
- Benchmarked against EM flux-tube GENE
- Applied to different collision operators (e.g. Sugama, GK Coulomb)
- First runs with nonlinear collisions
- Nonlinear Cyclone Base Case benchmark

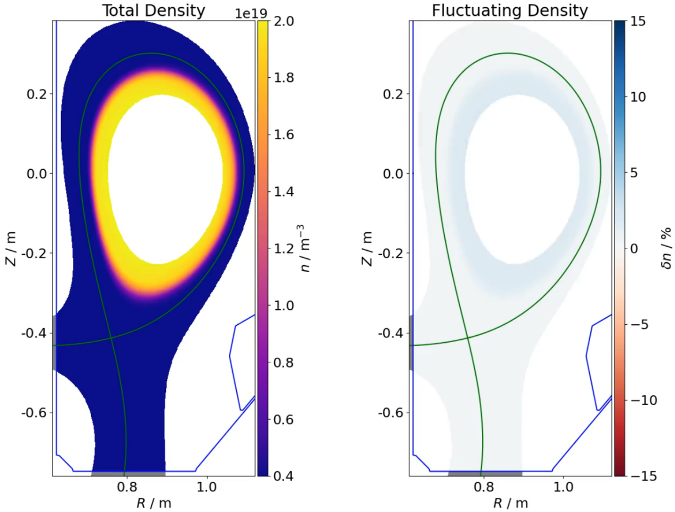




The GENE-X code within TSVV4

P. Ulbl

What is GENE-X?



GENE-X

P. Ulbl et al., PoP (2023)

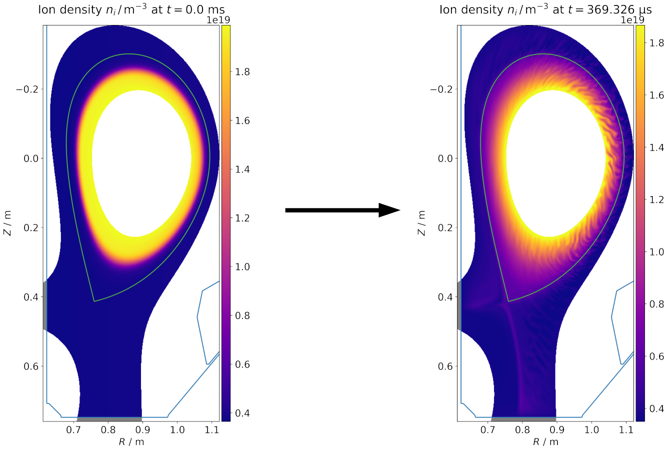
Simulation time
$t = 0.00\ \mu s$

GENE-X is a gyrokinetic turbulence code for X-point geometries

Features:

- Eulerian code
- global
- non-linear
- full-f
- electromagnetic
- collisional

GENE-X can simulate from the core to the wall.



Why do we need GENE-X?

8 Challenges for the realisation of fusion energy

1. Regimes of operation (incl. confinement)
2. Heat exhaust
3. ...

[EUROfusion. (2022, Sep 15). European Research Roadmap to the Realisation of Fusion Energy. www.euro-fusion.org/eurofusion/roadmap]

Specific examples:

- Physics of the LH transition
- Alternative improved confinement regimes (I-mode, QH-mode, etc.)
- Effects of plasma shaping on confinement (e.g. negative triangularity)
- Heat flux fall-off length λ_q for ITER
- ...

GENE-X goals are in line with project plan

X-Point capabilities (M111+M113) *2020/21*

Collisions (M112) *2021/22*

Extension to 3D geom. (M116) *2023/24*

Electromagnetic effects (M115) *2021*

Nonlinear QN (M114) *2022*

Neutrals / Impurities (M117) *2025*

(ACH) 5D loop optimization
MPCDF (R. Lago) *2021*

(ACH) Grid reordering
BSC (A. Soba) *2023*

Relation to other TSVVs:

- Strong synergies with GRILLIX code (TSVV3)
  → shared code basis for geometry, equilibrium, etc.

The GENE-X project is progressing well

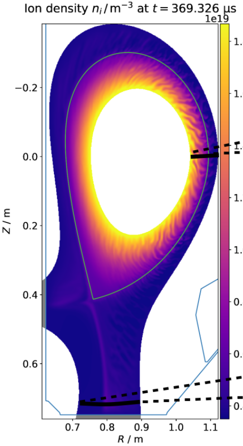
Key features / developments:

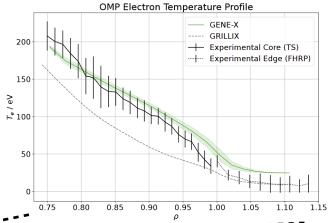
- Modern software engineering (object-oriented Fortran, unit tests, coding standards, in-code documentation, etc.)
- Massively parallelized on CPUs; tested with 2 compilers on 4 different machines (at MPCDF, CINECA, BSC)
- GPU porting in progress - targeting multi vendor support
- Code optimizations are performed at various levels in parallel to new developments
- Verification and Validation conducted and published

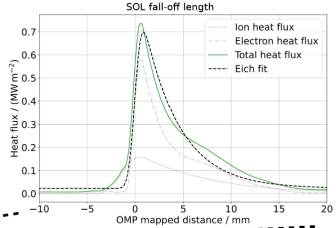
Publications:

- Numerics + Verification: D. Michels, A. Stegmeir, P. Ulbl et. al, Comput. Phys. Commun. 264, 107986 (2021)
- Collisions: P. Ulbl, D. Michels and F. Jenko, Contrib. Plasma Phys. e202100180 (2021)
- X-point + EM: D. Michels, P. Ulbl, W. Zholobenko et. al, Phys. Plasmas 29, 032307 (2022)
- Validation + Effects of Collisions: P. Ulbl, T. Body, W. Zholobenko et. al, Phys. Plasmas 30, 052507 (2023)

Highlight: Simulations enable accurate reproduction of key experimental observables in TCV







- Simulations reproduce key aspects of the experiment
- Divertor heat flux fall-off follows Eich-fit function

SOL fall-off length λ_q: Exp. **5.5 mm***

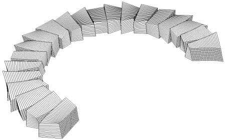
Fluid Models*		**GENE-X (Gyrokinetic)**	
GRILLIX	1.1 mm	No Coll	1.34 mm
GBS	11.6 mm	Coll BGK	**4.68 mm**
TOKAM3X	0.1 mm	Coll LBD	**3.75 mm**

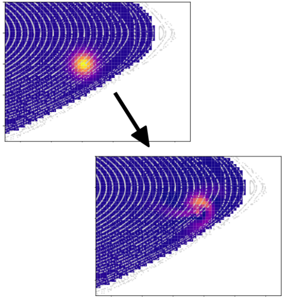
*[D. S. Olivera, T. Body et. al, Nucl. Fusion 62, 096001 (2022)]

- Results published open access
  P. Ulbl, et. al, Phys. Plasmas 30, 052507 (2023)
- Data published open access
  `DOI: 10.5281/zenodo.7894731`

Outlook on 2023+

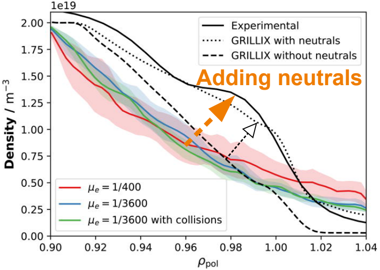
3D Extension:



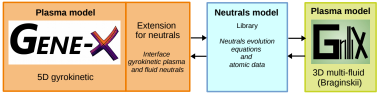


[M. Smedberg]

Neutral Physics:



Adapted from [D. Michels, P. Ulbl et. al, Phys. Plasmas 29, 032307 (2022)]



[S. Ogier-Collin]

Code Developments:

- GPU + Optimizations (short term)
- Open Access (mid term)
- Interfaces, Docs (long term)

Applications:

- H-mode simulations →Collaborations with TSVV1

Contact:
philipp.ulbl@ipp.mpg.de

“To do”: Main codes

GyselaX

2D field solver for arbitrary geometry + nonlinear Poisson equation

Translate VOICE boundary to Gysela

Neutrals / Impurities

GENE-X

Generalize to 3D geometry

Neutrals

Impurities

Improved sheath boundary conditions

Improved gyrokinetics

$B_\parallel$ electromagnetics

PICLS

Electromagnetics, improved edge GK

Coupling to neutrals + impurities

Coupling with core codes for limiter simulations, crossing separatrix

Improved sheath boundary conditions

Geometry improvements

[highlighted] = as defined by milestones

Conclusions + Outlook

- Parallel development of three gyrokinetic SOL codes:
- **PICLS — GyselaX — GENE-X**
- Additional focus areas:
- **Sheath physics — Limitations of gyrokinetics — Coupling methods**
- Have made good progress in each of these, but still work to do.

Three main open issues (affecting each code to different degree):

- More physical boundary conditions
- SOL Geometry
- SOL physics (neutrals, impurities)

Conclusions + Outlook

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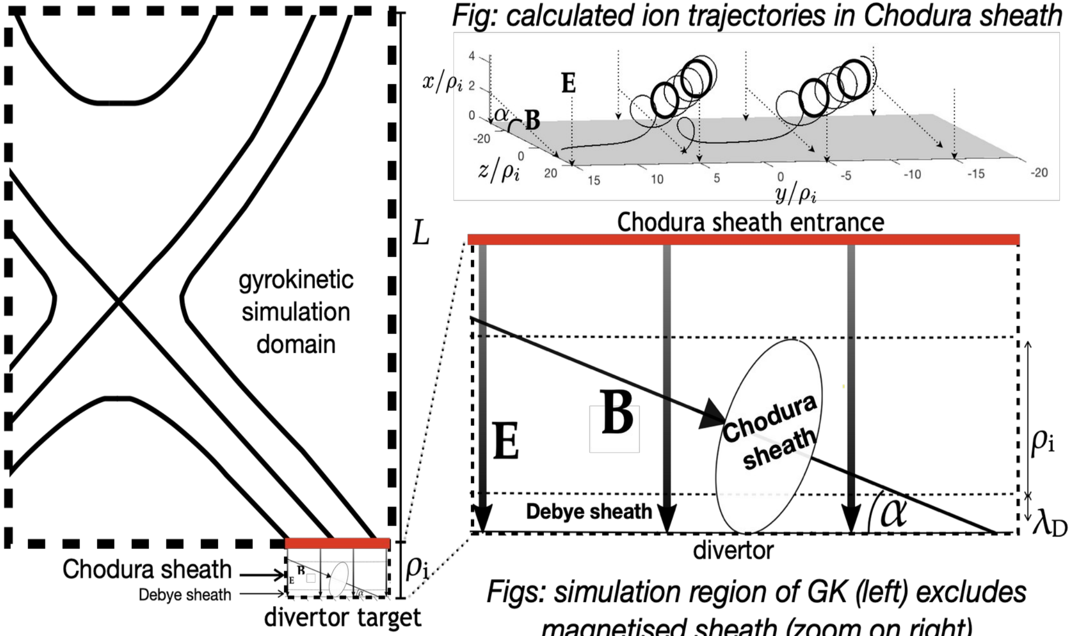
Thank you for your attention!

Backup Slides

Analytical studies of magnetized sheath

- Exploit small parameters (e.g. magnetic field angle) for analytical progress
- Solve sheath using cheap numerical methods by iterating for direct steady state
- Interfacing with gyrokinetics can provide first principles boundary conditions

Fig: calculated ion trajectories in Chodura sheath

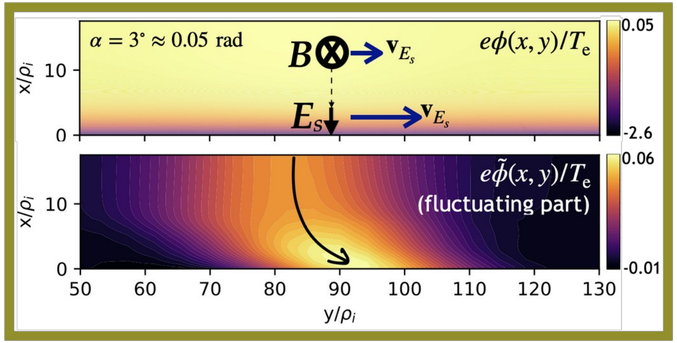


Figs: simulation region of GK (left) excludes magnetised sheath (zoom on right)

X

Analytical studies of magnetized sheath (2)

- Solve for reflected electron velocity distribution and sheath current-potential relation including electron gyroradius sheath physics [1]
- First 2D kinetic sheath profiles incl. weak turbulence (figure below)
- Analytical derivation of magnetised sheath constraints [2]
- Developed novel numerical scheme to solve steady state sheath with general magnetic field incidence (previously only small) [3]



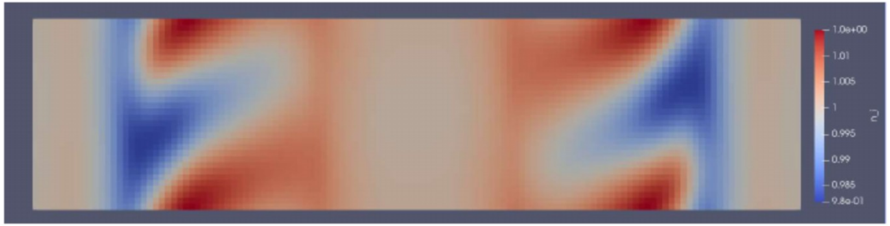
[1] A. Geraldini, S. Brunner, F. Parra, *Sheath constraints on turbulent magnetised plasmas*, to be submitted to PPCF, EUROfusion pinboard ID 35707

[2] A. Geraldini, F. Parra, R. Ewart, S. Brunner, *Enhanced critical magnetic field angle for a monotonic sheath with electron gyro-orbits*, to be submitted to JPP, EUROfusion pinboard ID 35708

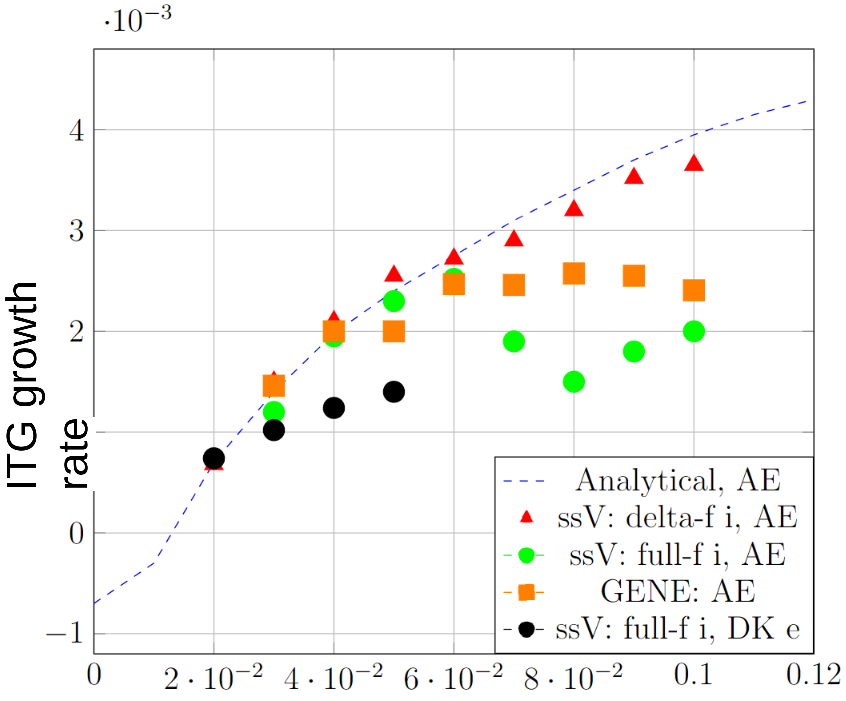
[3] S. Zeegers, Masters thesis: *Studying the Region of Magnetised Plasmas Near a Solid Surface*

Full-f hybrid-kinetic ITG runs using ssV

- Challenge in simulating low-frequency physics with full kinetics: **Numerical dissipation**
- Settled on 5th order flux-conserving scheme with SLMPP limiter to allow ITG modes to develop
- Successfully **reproduced ITG physics in full-f** setting and found agreement with GENE (global slab)
- New challenge: are differences at higher gradients physical (=non-GK?) or numerical?



Ion density fluctuations in ⊥ plane



Ion temperature gradient