TSVV-04 — Gyrokinetic / Kinetic Codes for the Edge and SOL

D. Told[1] and the TSVV-04 Team

[1] *Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*

TSVV-04 Project Members

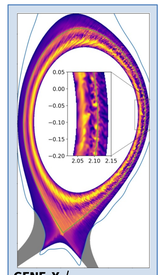
D. Told[1], A. Bottino[1], S. Brunner[2], L. Chôné[3], S. Costea[4], G. Dif-Pradalier[5], S. Ernst[2], B. Frei[2], A. Geraldini[2], V. Grandgirard[5], A. Hoffmann[2], F. Jenko[1], J. Kovacic[4], K. Kormann[1,6], D. Liu[1], J.E. Mencke[2], D. Michels[1], Y. Munschy[5], M. Murugappan[2], A. Mustonen[1,6], S. Ogier-Collin[1], P. Ricci[2], E. Poulsen[1], Y. Sarazin[5], M. Smedberg[1], E. Sonnendrücker[1], A. Stier[1], D. Tskhakaya[7], P. Ulbl[1], N. Vadot[2], L. Villard[2], S. Zeegers[2]

1) Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
2) Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, CH-1015, Lausanne, CH
3) Helsinki ACH, University of Helsinki, 00014 University of Helsinki, FI
4) LECAD Laboratory, Faculty Of Mechanical Engineering, University of Ljubljana, 1000 Ljubljana, SLO
5) CEA, IRFM, F-13108 Saint Paul Lez Durance, France
6) Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, DE
7) Institute of Plasma Physics of the Czech Academy of Sciences, U Slovanky 2525/1a, 182 00, Prague 8, CZ

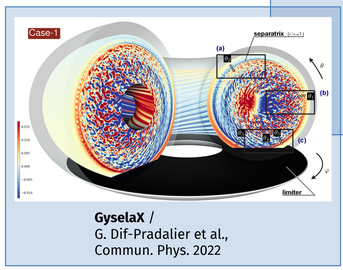
Our Mission: Develop kinetic codes for modeling exhaust

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

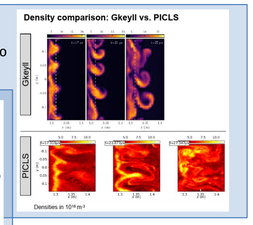
Aim: GK codes for Edge + SOL



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



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



PICLS /
A. Bottino
2021

Work up to 2024: Main gyrokinetic codes

GyselaX

Full-f limiter plasma simulations with prescribed sources
Core-edge-SOL physics with adiab. electrons (with kin. electrons: under development)
Nonlinear quasineutrality equation
2D field solver for **arbitrary geometry** (shaped magn. equil.)
Electromagnetics ($A_\parallel$)
Neoclassical physics, multi-species **collision operators**

G. Dif-Pradalier, Comm. Phys. 2022
Y. Munschy, NF 2024
Y. Munschy, NF 2024

GENE-X

Arbitrary geometry (open/closed field lines)
Dirichlet boundaries (Maxwellian BC)
Collision operators: BGK, LBD, FPL
Electromagnetics ($A_\parallel$)
Nonlinear quasineutrality equation
Validation on TCV-X21

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
M. Murugappan, submitted
A. Stier CPC 2024

Work up to 2024: 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

D. Tskhakaya, EPJ D 2023

Immersed boundary – VOICE (1D1V kinetic)

Physics of Debye sheath recovered
Self-organization of plasma: source-collisions-sheath Agreement and differences w.r.t. fluid predictions:
Mass ratio dependence; **shape of f_e and f_i**; $E_r \propto -d_r T_e$
Heat sheath transmission factors larger (x ~2) than fluid. predictions
Ported to C++, GPU

E. Bourne JCP 2023
Y. Munschy, NF 2024
Y. Munschy, NF 2024

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

Work up to 2024: 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

TSVV-04 Publication List

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, CPC 2024

Work up to 2024: 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, PoP 2024
ACD Hoffmann JPP 2023
ACD Hoffmann, JPP 2023

TSVV-04 Highlights

Coupling to neutrals and impurities

Completed basic **neutral model survey**:
- Fluid vs. kinetic?
- Code-internal vs. coupling to EIRENE?

Implementation into **GENE-X** and **VOICE** of **pressure-diffusive model**

Work plan for 2025

- **GENE-X**: Inclusion of **neutral and impurity physics**
- **GyselaX**: Inclusion of **neutral physics**, testing of **immersed boundary implementation** with kinetic ions and electrons
- **PICLS**: **Coupling with core codes** for limiter simulations, **finalizing the EM implementation**
- **BIT-1**: Continuation of **DEMO divertor** and **ITER SOL simulations**.
- **Semi-analytical sheath model**: Development of **coupling schemes** for with gyrokinetic code(s)
- **Hybrid code ssV**: Continued characterization of **fully kinetic ITG physics**
- **GEMPICX**: Implementation of **cylindrical coordinates**
- **Gyro-moment approach**: Further development of **full-f moment approach**

Plans for 2026/27

- Further work on **neutral models** for all GK codes:
  - Moving to higher moments
  - Eventually explore coupling to EIRENE
- **Further develop sheath** boundary conditions for all codes
- Develop **benchmark cases** tractable by all our GK codes (e.g. LAPD + sheath + neutrals)
- **Implement $B_\parallel$** magnetic fluctuations for all codes
- Develop methods to **deal with large temperature disparities** core ⇔ edge
- Explore efficient ways to treat **impurities + radiation**
- **Further develop fully kinetic/hybrid codes** ssV/GEMPICX
- **Further development of gyro-moment approach**

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.