TSVV-4 Results and Plans for TSVV-C

D. Told, TSVV-4 Team

TSVV1 Progress Workshop 2025

Garching, October 10

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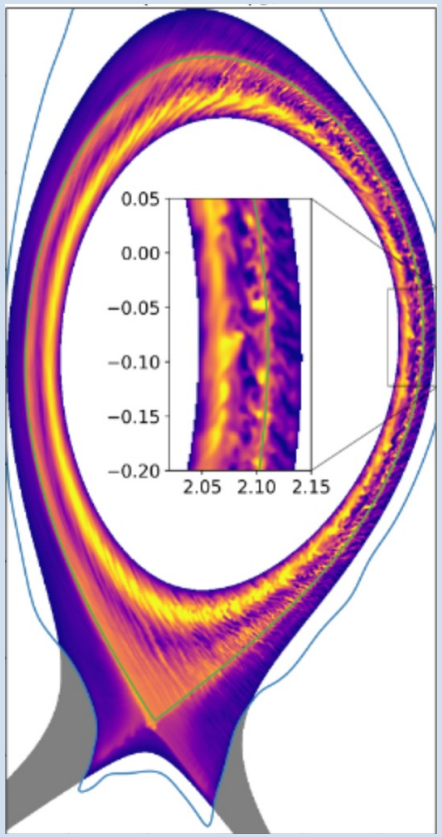
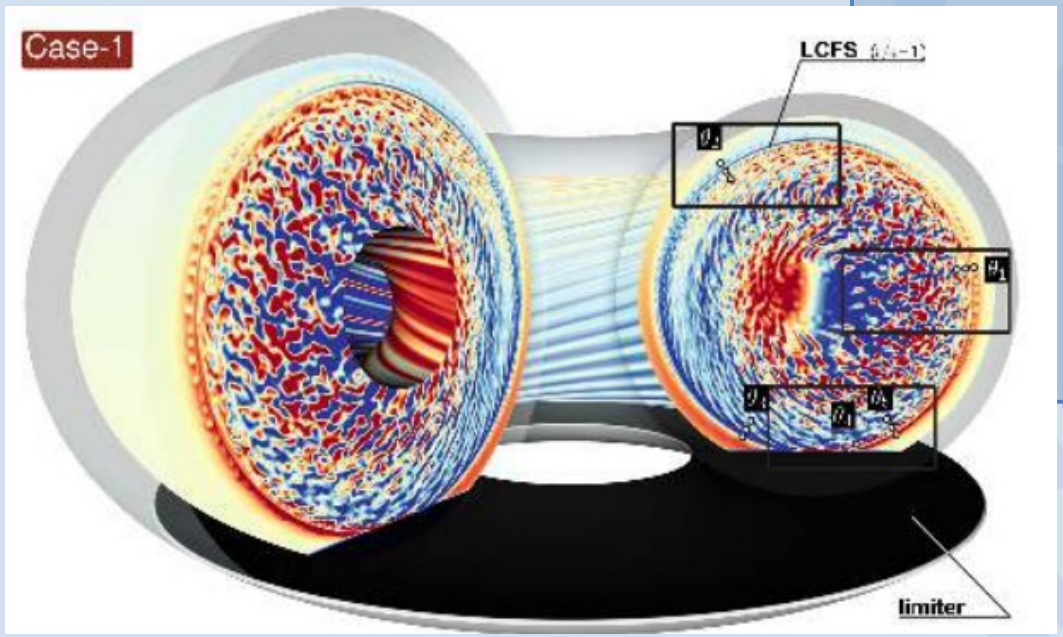
Setup of TSVV Task 4

Key deliverables	Our work
Kinetic codes for the plasma edge ▸ TSVV T1	GENE-X (IPP) PICLS (IPP/SPC) GYSELA (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

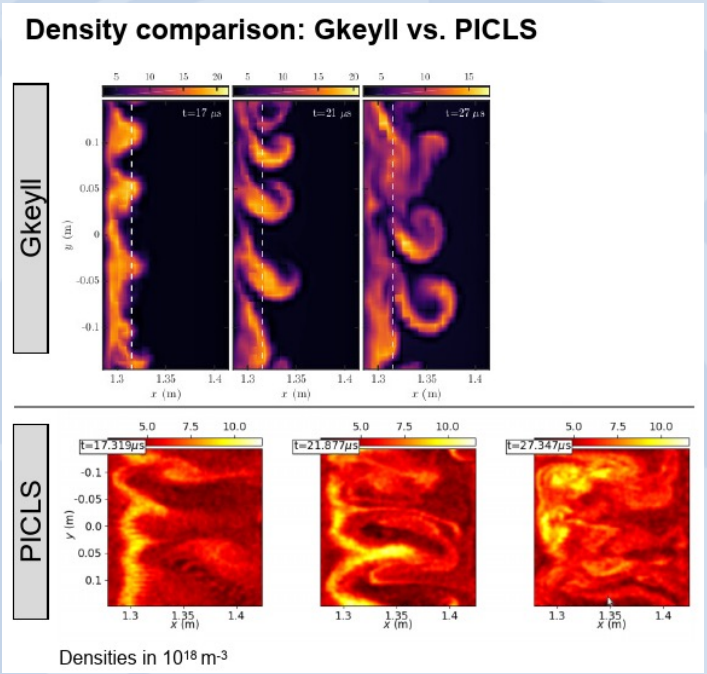


GENE-X /
D. Michels et al.,
Phys. Plasmas 2022



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

PICLS /
A. Bottino
2021



1) Achievements in main gyrokinetic codes

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

GYSELA

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

Arbitrary geometry (open/closed field lines)
Collision operators: BGK, LBD, FPL
Electromagnetics ($A_\parallel$)
Nonlinear quasineutrality equation
Validation on TCV-X21
Gyromoment implemented
Neutrals: pressure-diffusion model
3d geometry

GENE-X

D. Michels CPC 2021, PoP 2022
P. Ulbl CPP 2022, PoP 2023
B. Frei CPC 2025
M. Finkbeiner, submitted
S. Ogier-Collin, submitted

Moment-based **full-f nonlinear collisions**
Second-order particle Lagrangian terms
Both delta-f core and full-f SOL capability
Delta-f/full-f transition scheme
Electromagnetics ($A_\parallel$)

PICLS

EPFL

M. Murugappan PoP 2022 + 2024
A. Stier CPC 2024, PPCF 2025
A. Bottino, PPCF 2025

2) Progress in sheath studies

Ab-initio sheath simulations – BIT1

Sheath in ELMing SOL ▸ time-dependent BC

Sheath in blobby SOL

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

D. Tskhakaya, EPJ D 2023

IPP

IJS

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; $E_r \propto -d_r T_e$**

Sheath heat transmission factors larger (x ~2)

Ported to C++, GPU

Implemented neutrals

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

cea

EPFL

Semi-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, PPCF 2024
A. Geraldini, JPP 2024
A. Geraldini, submitted
S. Zeegers, Master thesis

3) Progress on developing the gyro-moment approach

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 plasma device

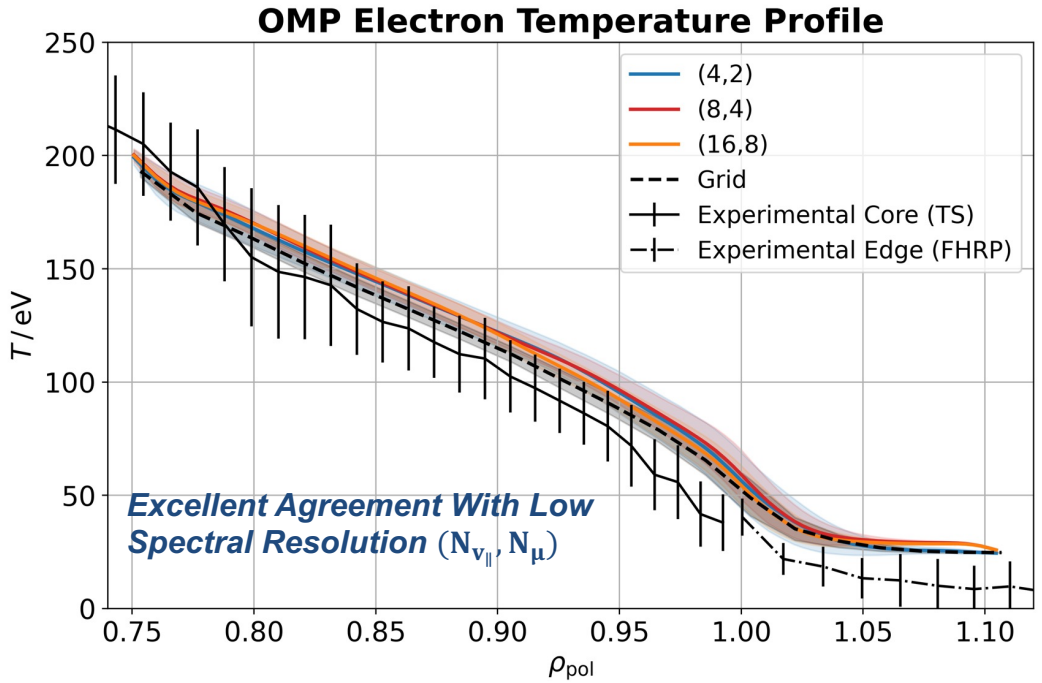
BJ Frei JPP 2021
BJ Frei JPP 2022
BJ Frei PoP 2022
BJ Frei JPP 2023
BJ Frei, PoP 2024
ACD Hoffmann JPP 2023
ACD Hoffmann, JPP 2023
JE Mencke, PPCF 2025

Full-*f* spectral approach speeds up GENE-X by ~50x

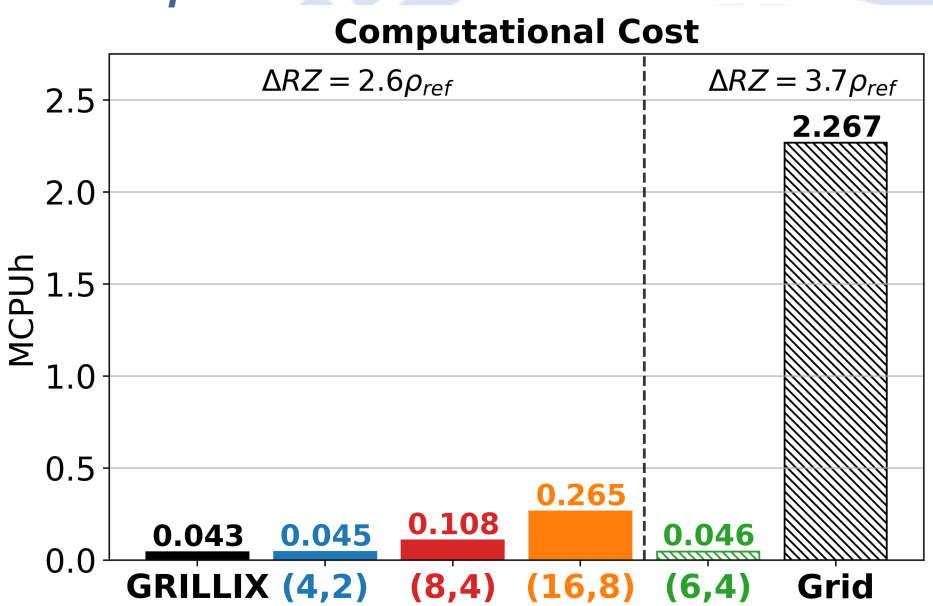
Spectral Velocity-Space Expansion (Hermite-Laguerre poly.) of the full-f distribution function

$$f_\alpha \simeq \sum_{p=0}^{N_{v_\parallel}} \sum_{j=0}^{N_\mu} \mathcal{N}_\alpha^{pj} H_p(v_\parallel) L_j(\mu) F_{\mathcal{M}\alpha}$$

TCV-X21 L-mode dominated by **TEM turbulence**



Computational cost of 0.5 ms of TCV-X21



BJ Frei, CPC, 109817 (2025)

Key Takeaways:

- Numerical implementation **verified using MMS**
- **Excellent agreement** (profiles, turbulence, and transport) between **spectral** and **grid-based** simulations
- Large **reduction** of **computational cost ⇒ gain in efficiency**

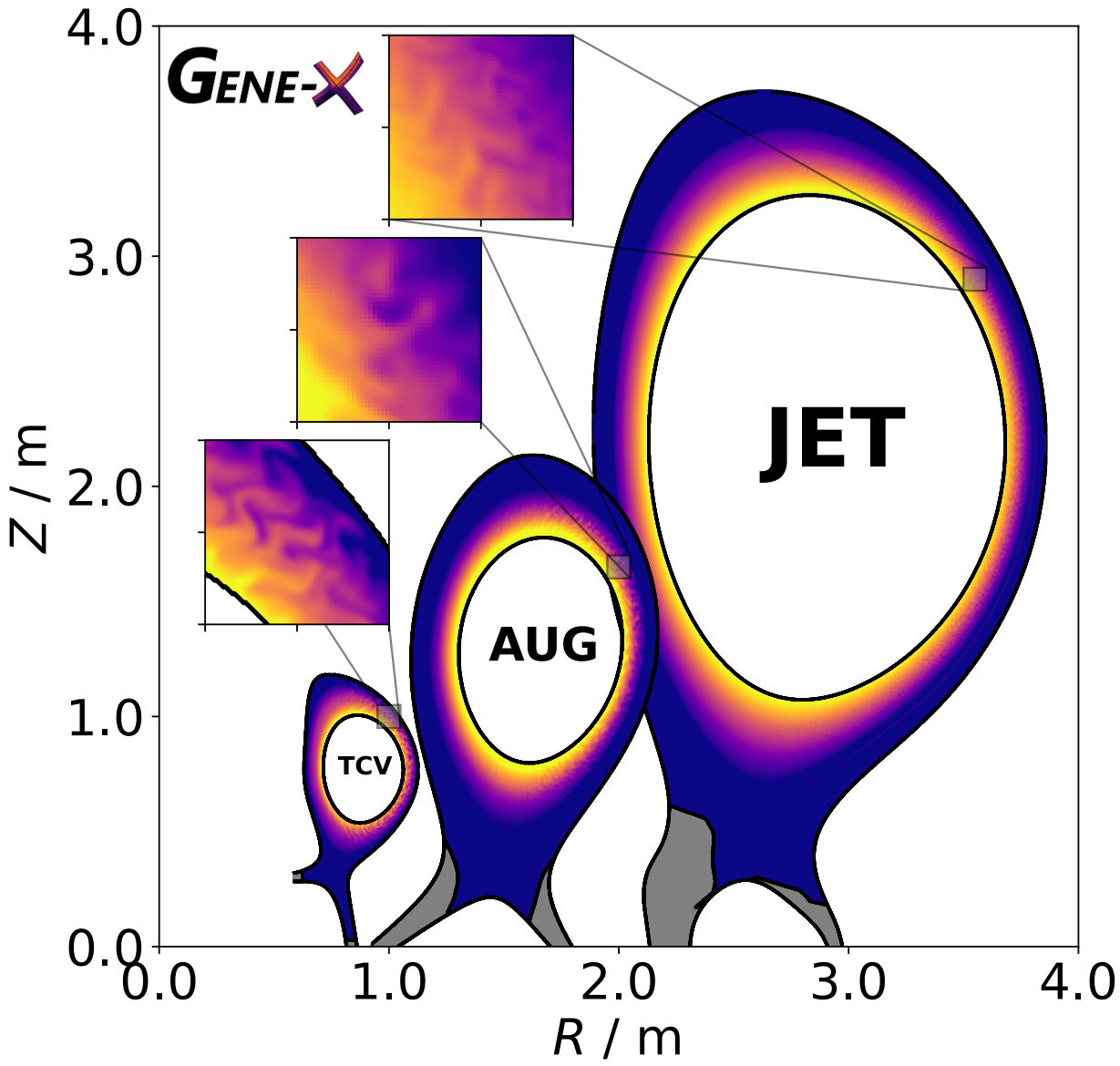
Further validation of GENE-X underway

Many new validation exercises with GENE-X:

- TCV with NT/PT (Ulbl NF 2025)
- DIII-D with NT

Both gyro-moment approach and GPU porting enable simulations of larger machines.

Appetizer:
JET L-mode validation ⇒



GENE-X added 1-mom fluid neutrals model

Status of GENE-X neutrals (S. Ogier-Collin):

- In general, follows GRILLIX path thanks to shared infrastructure
- Add neutrals as simple in-code model before coupling to any external code

- Choice: pressure-diffusion model (1-moment) from Horsten (NF 2017), as already added in GRILLIX

(limiter)

$$\frac{\partial N}{\partial t} = \nabla \cdot \frac{\tilde{D}_\mathrm{N}}{T_\mathrm{i}} \nabla N T_\mathrm{i} - k_\mathrm{iz} n N + k_\mathrm{rec} n^2 \qquad D_\mathrm{N} = \frac{c_{\mathrm{s,N}}^2}{\nu_\mathrm{cx}} = \frac{T_\mathrm{i}/m_\mathrm{i}}{k_\mathrm{cx} n}$$

Eqs. from Zholobenko NF 2021

What additional developments are needed beyond those done for GRILLIX?

- Need source terms for gyrokinetic distribution functions (ready for 3-moment model)
- Derive, add + test those terms (EF Pinboard: S. Ogier-Collin, #40191)

GYSELA: 1-mom fluid neutrals added to VOICE testbed

Neutrals in VOICE (Y. Munschy, M. Protais):

- VOICE = 1d1v fully kinetic, with same numerics as GYSELA (semi-Lagrangian)
- Within TSVV-4, focused on immersed boundary condition treatment of sheath physics
- Recently added pressure-diffusion model
- Use different grids for plasma + neutrals

Studied neutrals in combination with sheath physics:

- Observe ionization + CX, recycling
- How do those interact with ions accelerating towards the sheath?

Next:

- Physics studies, e.g. heat transmission factor

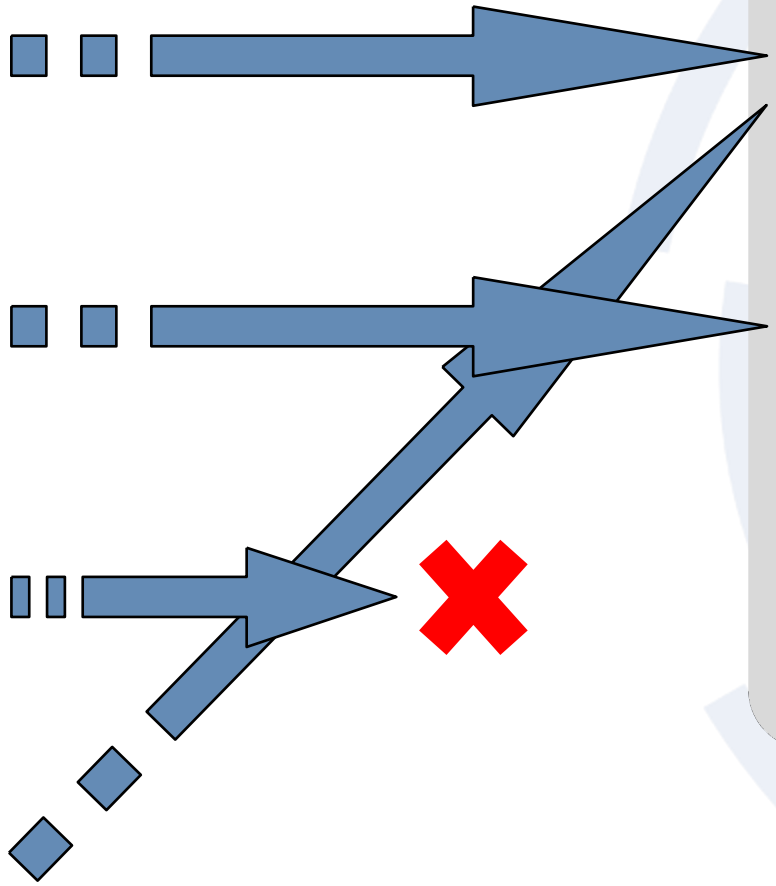
More GYSELA achievements: see Peter Donnel's talk from October 08!

E. Bourne (JCP '23), Y. Munschy (NF '24 x2)

Moving into TSVV-C: Scope changes

TSVV-4

- **Kinetic codes for the plasma edge ▸ TSVV T1**
- **Deal with open field lines**
- **Limitations of Gyrokinetics**
- **Coupling methods**



TSVV-C

- **Build capability** to predict exhaust w. GK, neutrals + impurities
- Develop realistic **boundary conditions** using full kinetics
- **Apply tools** to key tokamak and stellarator questions
- Develop **reduced models** for integrated modelling

HPC

TSVV-C proposal: How we address the call

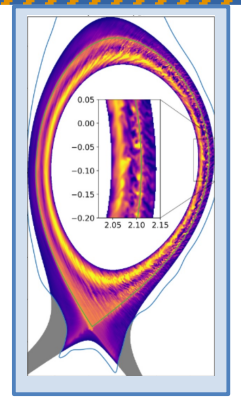
Build capability to predict exhaust w. GK, neutrals + impurities

Apply tools to key tokamak and stellarator questions

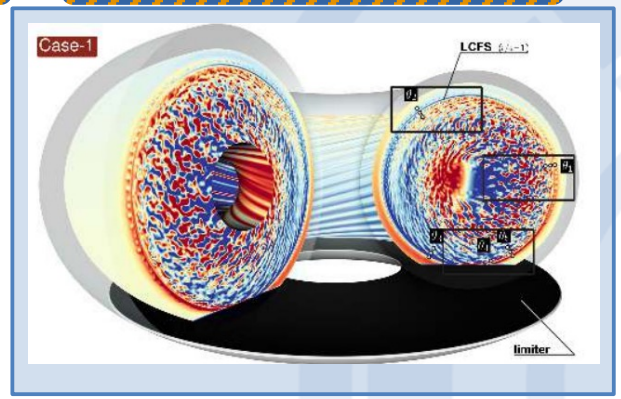
Develop realistic **boundary conditions** using full kinetics

Develop **reduced models** for integrated modelling

GENE-X (IPP/SPC)



GYSELA (CEA)



Gyro-Moment (SPC)

JOREK-GK (CEA)

BIT1 (IPP-CR, JSI)

Steady-state approach (SPC)

Separatrix BC database (with TSVV-B)

SOL transport modelling (DIFFER)

TSVV-C proposal: Building predictive capability

Build capability to predict exhaust w. GK, neutrals + impurities

Apply tools to key tokamak and stellarator questions

Develop realistic **boundary conditions** using full kinetics

Develop **reduced models** for integrated modelling

GENE-X (IPP/SPC)

- Advanced collision operators
- Finite-β stellarator equilibria
- 3-moment fluid neutrals
- Sheath boundary conditions
- PIROCK time stepping

JOREK-GK (CEA)

- Couple kinetic neutrals to GK
- Couple kinetic impurities to GK

GYSELA (CEA)

- Kinetic neutrals source
- Surrogate sheath model

Gyro-Moment (SPC)

- GM with extended ordering in toroidal geometry
- Nonlinear collisions
- Electromagnetics
- Boundary conditions

TSVV-C proposal: Addressing key questions

Build capability to predict exhaust w. GK, neutrals + impurities

Apply tools to key tokamak and stellarator questions

Develop realistic **boundary conditions** using full kinetics

Develop **reduced models** for integrated modelling

GENE-X (IPP/SPC)

- Isotope effect + impurity studies
- Validation with improved neutrals + sheath
- W7-X validation

GYSELA (CEA)

- Impact of kinetic neutrals on turbulence + transport
- Limiter simulations with surrogate sheath model

TSVV-C proposal: Sheath physics

Build capability to predict exhaust w. GK, neutrals + impurities

Apply tools to key tokamak and stellarator questions

Develop realistic **boundary conditions** using full kinetics

Develop **reduced models** for integrated modelling

BIT1 (IPP-CR, JSI)

- Effect on impurities on sheath
- Effect of blobs/ELMs on sheath

Steady-state approach (SPC)

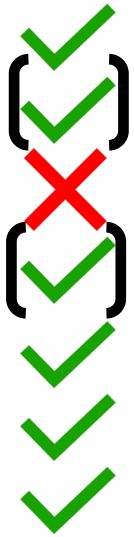
- Add kinetic electrons + neutral collisions
- Extend to 2D3V
- Effect of tangential fluctuations on sheath

Comparing TSVV-C to our 2024 survey

Top wish list items from last year's TSVV-1 workshop:

Which ones will TSVV-C tackle?

- "Beyond GK": **edge-ordered GK**?
- **$B_{\parallel}$ fluctuations**
- "**Peeling drive**"
- Large **temperature differences** core—edge
- **Impurities**
- Accurate **sheath** boundaries
- **Kinetic neutrals** (+ additional complexity)



We have ~85% overlap.

Summary

TSVV-4 codes have made impressive progress, moving towards reactor-relevant capabilities.

- All GK codes are now **electromagnetic**
- GENE-X has been **extended to 3d** and includes neutrals
- VOICE studied **immersed sheath boundary**, **includes neutrals**, **transfer to GYSELA** ongoing
- BIT1 studied sheath in **transient events** and **reactor conditions**

TSVV-C will build on this foundation and focus increasingly on applications.

Two main gyrokinetic codes in TSVV-C: GYSELA, GENE-X.