Towards the Application of the Gyrokinetic Code GENE-X to Tokamak Scrape-Off Layer Turbulence

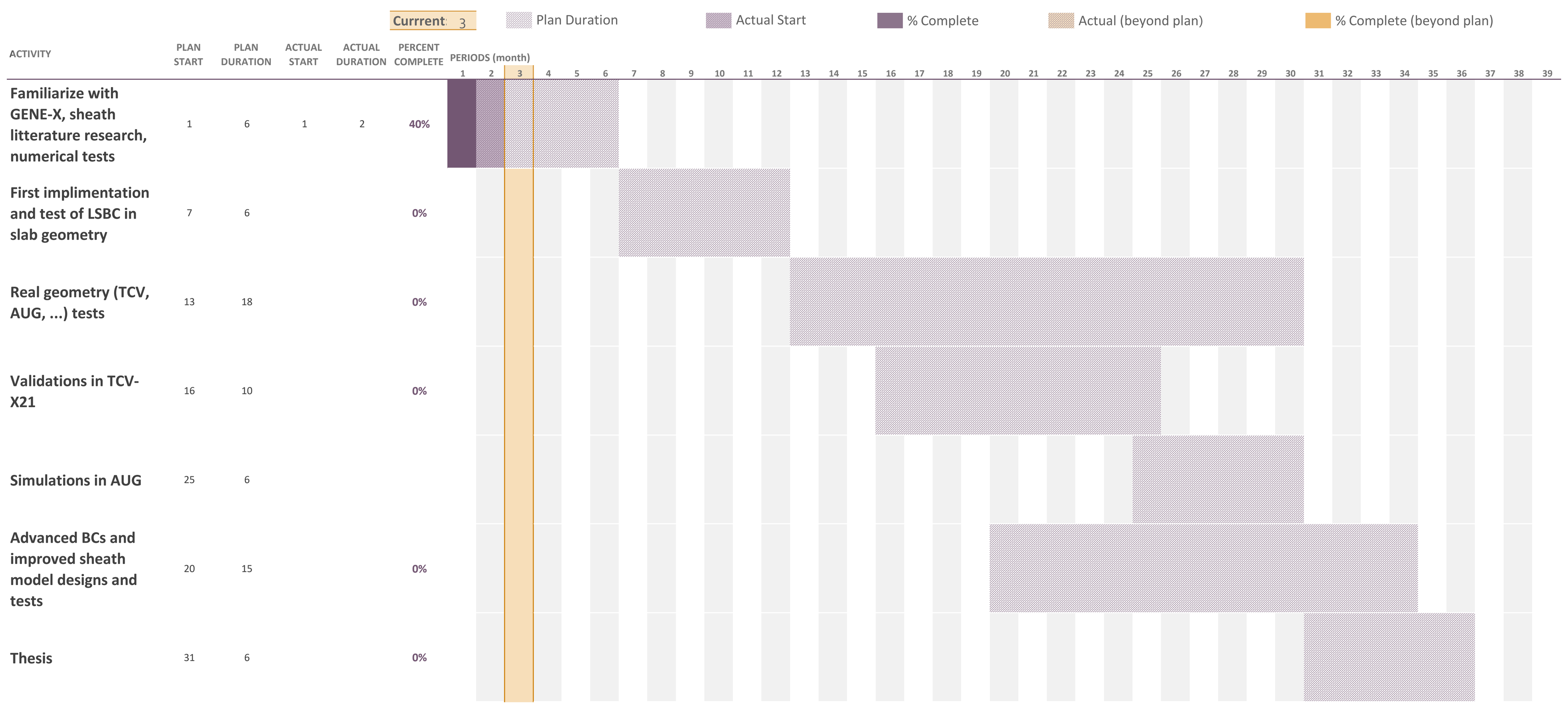
Yantong Tao*[1], Philipp Ulbl[1], Frank Jenko[1, 2]
[1]Max Planck Institute for Plasma Physics, Boltzmannstraße 2, 85748 Garching, Germany, [2]University of Texas at Austin, Austin, TX 78712, USA

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

MOTIVATION FOR MY PHD PROJECT

Understanding and predicting the behavior of turbulence in the scrape-off layer (SOL) of magnetic fusion device is a critical step toward reliable power exhaust control in future reactors. The SOL governs how energy and particles are transported from confined plasma core to the material surfaces, and turbulence plays a dominant role in this transport. One of the most important physical quantities of interest is the heat flux fall-off length, i.e. the distance over which the heat flux decreases exponentially. Accurate prediction of this quantity is especially crucial for future large machines such as ITER, where the narrowness of the heat flux profile leads to extremely high power loads on the divertor targets. Understanding how SOL turbulence is affected by sheath physics is therefore necessary for reliable heat load predictions and for designing effective divertor plates.

PROJECT OUTLOOK GANTT CHART



GENE-X CODE AND ITS BOUNDARY CONDITIONS

GENE-X [1,2] is a full-f gyrokinetic turbulence code that is based on a flux-coordinate independent (FCI) approach. It focuses on the edge and scrape-off layer of magnetic fusion machines.

GENE-X works in gyrocenter coordinates $(\boldsymbol{R}, v_\parallel, \mu)$, where $\boldsymbol{R}$ denotes the gyrocenter position, $v_\parallel$ denotes the parallel velocity, and μ denotes the magnetic moment. The gyrokinetic Vlasov-Maxwell system implemented in GENE-X are the gyrokinetic Vlasov equation

$$\frac{\partial f_\sigma}{\partial t} + \dot{\boldsymbol{R}} \cdot \boldsymbol{\nabla} f_\sigma + \dot{v}_\parallel \frac{\partial f_\sigma}{\partial v_{v_\parallel}} = 0,$$

with

$$\dot{\boldsymbol{R}} = v_\parallel \frac{\boldsymbol{B}^*}{B_\parallel^*} + \frac{c}{q_\sigma B_\parallel^*} \boldsymbol{b} \times (\mu \nabla B + q_\sigma \nabla \phi_1),$$

$$\dot{v}_\parallel = -\frac{\boldsymbol{B}^*}{m_\sigma B_\parallel^*} \cdot (\mu \nabla B + q_\sigma \nabla \phi_1) - \frac{q_\sigma}{m_\sigma c} \frac{\partial A_{1\parallel}}{\partial t};$$

the quasi-neutrality equation

$$-\boldsymbol{\nabla} \cdot \left(\sum_\sigma \frac{m_\sigma c^2}{B^2} n_{0\sigma} \boldsymbol{\nabla}_\perp \phi_1 \right) = \sum_\sigma q_\sigma v_\parallel \mathrm{d}W\,;$$

Ampère's law

$$-\Delta_\perp A_{1\parallel} = 4\pi \sum_\sigma \frac{q_\sigma}{c} \int f_\sigma v_\parallel \mathrm{d}W\,;$$

and the Generalized Ohm's law,

$$-\left(\Delta_\perp + 4\pi \sum_\sigma \frac{q_\sigma^2}{m_\sigma c^2} \int \frac{\partial f_\sigma}{\partial v_\parallel} v_\parallel \mathrm{d}W \right) \frac{\partial A_{1\parallel}}{\partial t}$$
$$= 4\pi \sum_\sigma \frac{q_\sigma}{c} \int \left(\frac{\partial f_\sigma}{\partial t} \right)^* v_\parallel \mathrm{d}W\,.$$

It currently applies Dirichlet boundary conditions on both real space and velocity space domain boundary. For real space domain boundary, the distribution function of each species is set to a Maxwellian with fixed T and n; Potentials are set to zero. For velocity space boundary, the distribution function is set to zero.

SHEATH PHYSICS

In a plasma, when particles hit on the wall, most of them are lost. Rapid electrons (compared to heavier ions) hit on the wall, they are absorbed by the wall with a much larger frequency than solwer ions, which makes the wall have a much lower electric potential than the bulk plasma, and a large electric field towards the wall will be created. In this thin layer (typically several Debye lengths λ_D) with large potential difference, the quasineutrality property does not hold anymore. This layer is called the plasma sheath. It prevents further slow electron escape and keeps the global quasineutrality of the plasma.

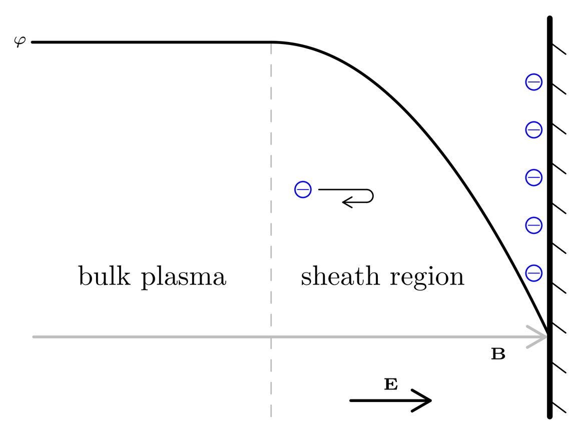


Figure 1: Plasma sheath diagram

NUMERICAL CONSIDERATIONS IN 1X SPACE

From a numerical perspective, the boundary conditions plays a determinant role in the property of the solutions of PDEs. Different boundary numerical schemes and boundary conditions can make the evolution of a function have very different behavior.

As a test case, we can solve the constant advection equation with different finite difference schemes and different boundary conditions.

The equation can be written as

$$\partial_t u + V_0 \partial_x u = 0,$$

where t is the time and $x \in [0,1]$ is 1D space coordinate, $\mathrm{V}_0 = 1/3$ is the advection speed.

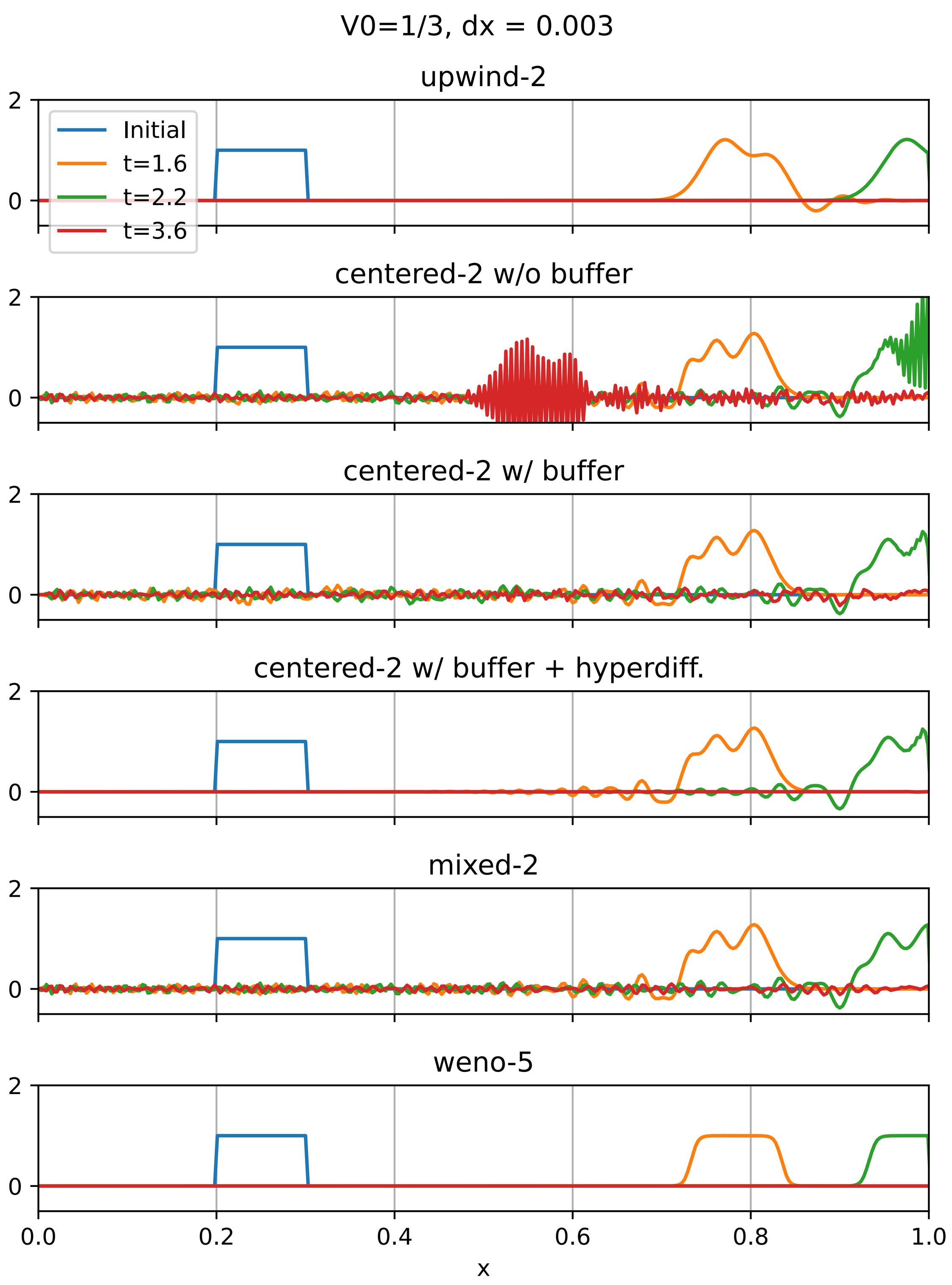


Figure 2: Solutions of constant advection equation in 1D.

REFERENCES

[1] D. Michels et al. In: *Comp. Phys. Commun.* 264 (2021), p. 107986. DOI: 10.1016/j.cpc.2021.107986.

[2] D. Michels et al. In: *Phys. Plasmas.* 1 March 2022; 29 (3): 032307. DOI: 10.1063/5.0082413.

[3] P. Ulbl, et al. In: *Phys. Plasmas* 1 May 2023; 30 (5): 052507. DOI: 10.1063/5.0144688.

BOHM CRITERION

For a quasi-neutral plasma to maintain a stable sheath structure, the ion speed v_i (or parallel speed $v_{i,\parallel}$ if $\boldsymbol{B}$ is not perpendicular to the wall) at the sheath entrance must be equal to or larger than the sound speed

$$c_s = \sqrt{\frac{e(T_e + T_i)}{m_i}},$$

this is called the Bohm sheath criterion. In order for all the ions entering the sheath to satisfy the Bohm criterion, there must be a potential drops before the sheath entrance to accelerate ions. This is where the presheath comes in.

The presheath is a wider, quasi-neutral transiton region that connects the bulk plasma to the sheath. In this region, a weak electric field exists that gragualllly accelerates ions towards the sheath, allowing them to meet the Bohm condition by the time they reach the sheath edge.

LOGICAL SHEATH BOUNDARY CONDITIONS (LSBC)

The sheath structure can not be fully resolved in gyrokinetic simulations. We should start from some reduced models. Logical sheath boundary conditions offer a physically motivated, simplified alternative that captures the essential effect of the sheath on particle fluxes while omitting the sheath complexity at the same time.

The key idea is to ensure that the net current into the wall is zero, while allowing the sheath to reflect low-enerfy electrons. In this approach, the sheath is not explicitly resolved, but its effect is modeled through a velocity space cutoff at the sheath entrance. The cutoff velocity v_c is determined dynamically at each step to maintain zero net current.

The zero net current equation used in LSBC can be written as

$$\int_{-\infty}^{0} f_i(0, v) v \mathrm{d}v = \int_{-\infty}^{0} f_e(0, v) v \mathrm{d}v + \int_{0}^{v_{esc}} f_e(0, v) v \mathrm{d}v.$$

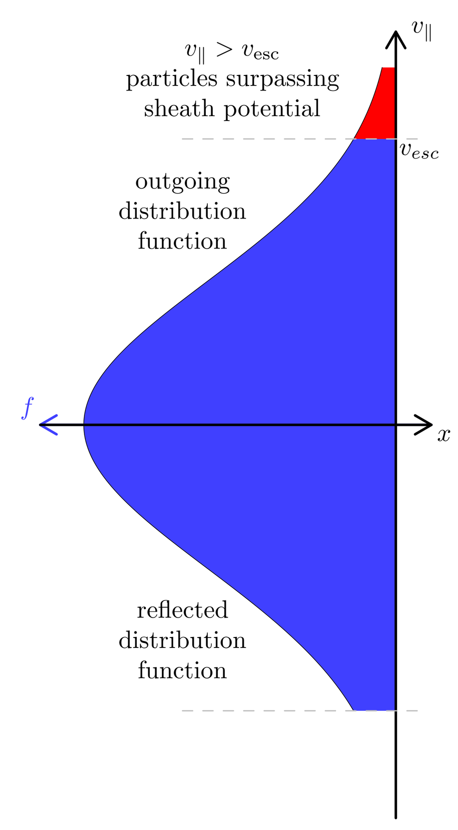


Figure 3: Applicatioon of LSBC to an incident electron distribution function

TOK Retreat 2025, Beilngries, Germany, May 7-9, 2025

*Corresponding author: yantong.tao@ipp.mpg.de

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.

EUROfusion