



Bachelor Thesis

→ *Bad?*

Size convergence of the $E \times B$ staircase pattern in flux tube simulations of ion temperature gradient driven turbulence

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Correct this
Additional
Not so good

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(*) 29.05.2005 – (+) 12.05.2023

This thesis is dedicated to my cat **Blacky**
~~which is to this date~~ ^{got nearly} 19 years old and followed me

*rework
this?*

since I was 5 years through my life.

You were always a big part of my life and
I will miss you everyday ~~when you are gone~~.

Manuel Lippert
May 9, 2023

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helping

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english

Outside academia, I would like to express my gratitude to my parents, my brother and his wife, my sister and my girlfriend for their encouragement, endurance and support during the time of this thesis. I know sometimes I am an workaholic and I need to be reminded a life outside my academic work.

include daughter about

Abstract

Ion temperature gradient driven turbulence (ITG) close to marginal stability exhibits zonal flow pattern formation on mesoscales, so-called $E \times B$ staircase structures. Such pattern formation has been observed in local gradient-driven flux-tube simulations as well as global gradient-driven and global flux-driven studies.

To reduce the computational effort for the simulations lower input parameter of GKW (Gyro Kinetic Workshop) were tested to find the optimal minimum resolution for the performed simulations.

For convenience a python script (`slurm_monitor.py`) was written which monitors the simulation on the `btrzx1`-cluster and starts/restarts until the completion criteria is fulfilled.

Furthermore, it is shown by multiple box size convergence scans that a mesoscale pattern size of $\sim 57.20 - 76.27 \rho$ is inherent to ITG driven turbulence with Cyclone Base Case parameters in the local limit. This outcome also implies that a typical scale for avalanche-like transport is inherent to ITG driven turbulence.

Zusammenfassung

Ionen-Temperaturgradienten getriebene~~T~~ Turbulenzen (ITG) weisen nahe niedriger Stabilität Zonal FFlow Strukturbildungen, sogenannte $E \times B$ Treppenstrukturen, auf Mesoskalen auf. Solche Strukturbildungen wurden sowohl in lokal gradientengetriebene Flussschlauchsimulationen als auch in global gradientengetriebenen und global flussgetriebenen Untersuchungen entdeckt.

Um den Aufwand der Berechnungen der Simulationen zu reduzieren wurden mehrere kleinere Inputparameter für GKW (Gyro Kinetic Workshop) getestet um die optimal kleinste Auflösung ~~zu finden~~ ausgeführten Simulationen zu finden.
für dich

Zur Einfachheit wurde ein python-Skript (`slurm_monitor.py`) geschrieben, was Simulationen auf den `btrzx1`-Cluster überwacht und gegebenenfalls startet/neustartet bis das Kriterium zur Vollendung erfüllt ist.

Weiterhin wurde doch mehrere radiale konvergierende Boxgrößen-Scans gezeigt, dass eine Mesoskalengröße von $\sim 57_{20}^{27} - 76_{27}^{27} \rho$ inhärent zur ITG getriebenen Turbulenz mit Cyclone Base Parameter in lokalen Limit ist. Dieses Ergebnis impliziert auch, dass eine typische Skala für den lawinenenartig Transport inhärent für die ITG getriebene Turbulenz ist.

Declaration

The author declares that the material presented in this thesis is his own work, unless explicitly stated otherwise. This thesis is based on

LIPPERT, M., RATH, F. & PEETERS, A. G. 2023 Size convergence of the $E \times B$ staircase pattern in flux tube simulations of ion temperature gradient driven turbulence. *Phys. of Plasmas* **7** (3), 969–983

and is a further iteration of this publication (~~brief communication published in the journal “Physics of Plasma”~~). It provides additional plots and paragraphs that were not necessary to be included in the final publication. ~~The format was changed as well because the publication was written in REVTEX 4.1 and this bachelor thesis in scrreprt.~~ The brief communication can be found in Appendix [6.5](#)

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CHAPTER

1

Motivation

Ion temperature gradient driven turbulence close to marginal stability exhibits zonal flow pattern formation on mesoscales, so-called $E \times B$ staircase structures^[16]. Such pattern formation has been observed in local gradient-driven flux-tube simulations^[42, 55, 45] as well as global gradient-driven^[37, 51, 49] and global flux-driven^[16, 17, 54, 28, 29] studies. In global studies, spanning a larger fraction of the minor radius, multiple radial repetitions of staircase structures are usually observed, with a typical pattern size of several ten Larmor radii. By contrast, in the aforementioned local studies the radial size of $E \times B$ staircase structures is always found to converge to the radial box size of the flux tube domain. The above observations lead to the question:

Does the basic pattern size always converges to the box size, or is there a typical mesoscale size inherent to staircase structures also in a local flux-tube description?

The latter case would imply that it is not necessarily global physics, i.e., profile effects, that set

- (i) the radial size of the $E \times B$ staircase pattern
- (ii) the scale of avalanche-like transport events.

These transport events are usually restricted to $E \times B$ staircase structures and considered as a nonlocal transport mechanism^[16]. 

In this bachelor thesis the above question is addressed through a box size convergence scan of the same cases close to the nonlinear threshold for turbulence generation as studied in Ref. [42].

Plasma Physics, Zonal Flows and Gyrokinetic Theory

2

2.1 Charged Particle Motion in Magnetic and Electric Field

In magnetic confinement devices like the tokamak reactor, the charged particles experience magnetic and electric fields which results in distinct motion under ~~tha~~ associated force. Charged particles can be separated in species, e.g. electrons and ions, which will be later on not displayed in the governing equation. Throughout this thesis the charge q or the mass m indicate the quantities of a specific species.

Temperature T

2.1.1 Particle Motion perpendicular to the magnetic field

Due to the Lorentz force particles with a velocity component perpendicular to the homogenous magnetic field v_{\perp} undergo a circular motion in the plane perpendicular to the magnetic field. This type motion has circular frequency which is often referred as *cyclotron frequency* and is defined as,

$$\omega_c = \frac{|q|B}{m} , \quad (2.1)$$

where m and q are the mass and the charge of the particle and B the strength of the magnetic field. The radius, the so called *Larmor radius*, of this motion is given by,

$$\rho_L = \frac{mv_{\perp}}{|q|B} \quad (2.2)$$

referred
which center is often as *gyrocenter*. Note that since the Lorentz force depends on the species of the particle the circulation direction is opposed between electron in ions.

Due to the Coulomb collisions the plasma gets thermalized. Together with the Maxwell-Boltzmann distribution the typical ~~species~~ thermal velocity is

$$v_{\text{th}} = \sqrt{\frac{2T}{m}} , \quad (2.3)$$

where T represents the species temperature. Based on the thermal velocity v_{th} the *thermal Larmor radius* gets introduced as ^[56]

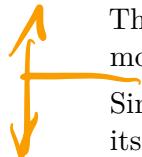
$$\rho = \frac{mv_{\text{th}}}{|q|B} . \quad (2.4)$$

2.1.2 Particle Motion parallel to the magnetic field

In absence of forces in the parallel direction of the magnetic field the particles can stream freely parallel to the homogenous magnetic field. The velocity of this motion is connected to the thermal velocity v_{th} and is dominated by electrons due to their lighter mass compared to ions ($v_{\text{th,e}}/v_{\text{th,i}} = 60$).

When an electric field with a component parallel to the magnetic field E_{\parallel} acts on plasma the charged particles gets accelerated by the electric force

$$F_{\parallel,E} = qE_{\parallel} . \quad (2.5)$$

 The parallel motion follows then from the equation of motion. Here the direction of the motion also depends on the species type.

Since magnetic fields are not always homogenous an inhomogeneous magnetic field with its gradient ∇B contains  a component parallel to the magnetic field which is given by,

$$\nabla_{\parallel}B = \frac{\mathbf{B}}{B} \cdot \nabla B . \quad (2.6)$$

This causes the force

$$F_{\parallel,\nabla_{\parallel}B} = -\frac{mv_{\perp}^2}{2B} \nabla_{\parallel}B = \mu \nabla_{\parallel}B ; \quad \mu = \frac{mv_{\perp}^2}{2B} \quad (2.7)$$

with *magnetic moment* μ which can be an adiabatic invariant (constant of motion) if the variation of the magnetic field over time is smaller than the inverse of the cyclotron frequency ω_c^{-1} and the spatial variation is larger the Larmor radius ρ_L . The caused force has its application in the mirror effect where a charged particle gets reflected due to this force.

2.1.3 Drifts in the Gyrocenter

In the presence of a magnetic field (homogenous, inhomogeneous or perturbed) and electric fields the gyrocenter undergoes slow (compared to the thermal velocity v_{th}) drift motions perpendicular to the magnetic field. There are several examples for this drift motion. According to this thesis topic only the main three drift types will be covered in the following.

1. $E \times B$ Drift:

If an electric field \mathbf{E} with a perpendicular component is present together with the magnetic field \mathbf{B} (both fields are homogenous) the acting Coulomb force and Lorentz force results to a drift of the gyrocenter with

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \quad (2.8)$$

which is called the $E \times B$ drift. Since both acting forces direction depends on the species type the direction of the $E \times B$ drift is for every species the same.

2. ∇B Drift:

Inhomogeneous magnetic field causes a gradient ∇B of the magnetic field. Because of that gradient the gyrocenter undergoes a ∇B drift defined by

$$\mathbf{v}_{\nabla B} = \frac{mv_{\perp}^2}{2q} \frac{\mathbf{B} \times \nabla B}{B^3} . \quad (2.9)$$

The ∇B drift varies thereby on scales which are larger compared to the Larmor radius. The direction of the ∇B drift depends on the species type.

3. Curvature Drift:

Due to centrifugal force acting on the particle in a curved magnetic field the gyrocenter experience a curvature drift given by

$$\mathbf{v}_{\kappa} = \frac{mv_{\parallel}^2}{q} \frac{\mathbf{B} \times \boldsymbol{\kappa}}{B^2} = \frac{mv_{\parallel}^2}{q} \frac{\mathbf{B} \times \nabla B}{B^3} ; \quad \boldsymbol{\kappa} = -(\mathbf{b} \cdot \nabla) \mathbf{b} = \frac{\nabla B}{B} , \quad (2.10)$$

where \mathbf{b} is the unit vector along the magnetic field. To obtain the result for the curvature $\boldsymbol{\kappa}$ in Eq. (2.10) the plasma pressure has to be small in comparison die the magnetic field strength B . In the form of Eq. (2.10) ∇B and curvature drift can be treated similarly.⁵⁶

$$\begin{aligned} \mathbf{b} &= \frac{\mathbf{B}}{B} \\ -(\mathbf{b} \cdot \nabla) \mathbf{b} &= -\left(\frac{\mathbf{B}}{B} \cdot \nabla\right) \frac{\mathbf{B}}{B} = -\frac{1}{B^2} (\mathbf{B} \cdot \nabla) \mathbf{B} = -\frac{1}{B^2} (B_x \partial_x + B_y \partial_y + B_z \partial_z) \mathbf{B} \\ &= -\frac{1}{B^2} \left(\begin{array}{l} B_x \partial_x B_x + B_y \partial_y B_x + B_z \partial_z B_x \\ B_x \partial_x B_y + B_y \partial_y B_y + B_z \partial_z B_y \\ B_x \partial_x B_z + B_y \partial_y B_z + B_z \partial_z B_z \end{array} \right) \end{aligned}$$

$$B^2 = B_x^2 + B_y^2 + B_z^2$$

2.2 Magnetic Confinement in Tokamak

In a tokamak devices strong magnetic fields confine the hot plasma. As mentioned in Chapter 2.1 a magnetic field forces a perpendicular particle motion and a motion containing gyro motion and slow perpendicular gyro center drifts. Because of the much smaller size of the Larmor radius compared to the device size R , the particle and energy losses are caused by the gyro center drift. To avoid this at the end of the field lines the magnetic field in the tokamak devices is shaped like a torus. This type of geometry has nested surfaces with constant magnetic flux, so-called *flux surfaces* and with magnetic field lines which appear on those surfaces. For stability reasons the magnetic field has a toroidal and a poloidal component which also holds equivalence of the plasma pressure.^{50,56} The toroidal component is produced by external coils whereas the poloidal component is provided by the toroidal plasma current. Together the components result in a magnetic field which follows helical trajectories [Fig 2.1]. To characterize the quality of confinement the so-called *plasma beta* is used and is given by

$$\beta = \frac{nT}{\mu_0 B^2 / 2} . \quad (2.11)$$

with n the plasma density, T as temperature, μ_0 the permeability in vacuum and the magnetic field strength B . Respectively, the plasma beta compares the thermal plasma pressure nT to the ambient magnetic field pressure $\mu_0 B^2 / 2$ which indicates when the plasma beta is smaller the confinement is better. In a tokamak reactor the plasma beta has a typical order of few percent.⁵⁶

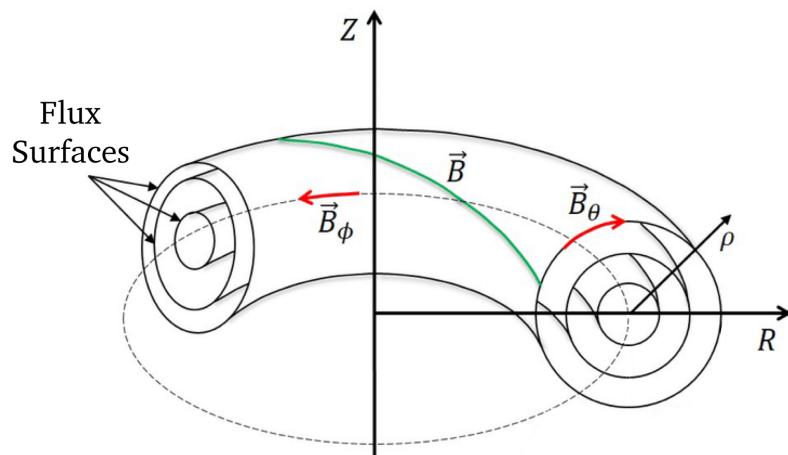


Figure 2.1: Toroidal flux surfaces in tokamak plasma with helical magnetic field (green line) in torus coordinates (ρ (radial), ϕ (toroidal), θ (poloidal)) or cylinder coordinates (Z , R , ϕ).³

Add tokamaks real structure (?)



2.3 Ion Temperature Gradient (ITG) Driven Instability

The described electrostatic forces acting on the tokamak plasma causes a variety of collective phenomena. Microinstabilities is one of this phenomena which are instabilities on the spatial scale of the Larmor radius ρ_L and frequencies much smaller than the cyclotron frequency. ω_c . These instabilities are driven by density and temperature gradients that are present in the tokamak devices. Turbulence caused from microinstabilities are considered as the main reason for the loss of particles energy and momentum from tokamak plasma [6][20][26] which limits the confinement time of tokamak reactors. The most dominant instability in tokamak plasma is the ion temperature gradient (ITG) driven instability [11][12][46].

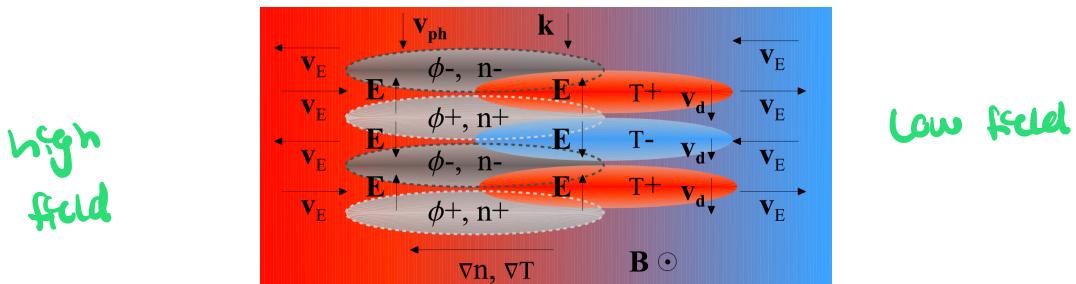


Figure 2.2: Sketch of ion temperature gradient driven instability on the outboard low field side of the tokamak^[10]

The ITG driven is present when a sufficiently large ion temperature gradient occurs and is driven by the so-called bad curvature of the outboard side of the tokamak. The mechanism will be briefly explained with the help of Fig. 2.2^{[4][10][13]}. An ion temperature perturbation ($T^\pm \gtrless 0$ blue and red cells) on the outboard low field side of the tokamak causes the formation of curvature ϕ^\pm and ∇B drift v_d which compresses the plasma ($n_\pm \gtrless 0$, gray cells). This relates to the perturbation of the potential ($\phi^\pm \gtrless 0$) in the adiabatic electron response. As stated in the equation for the electric field ($E = -\nabla\phi$) the perturbation of the potential ϕ causes an electric field E which results in a $E \times B$ drift v_E . The $E \times B$ drifts direction transports hot plasma in the outer hot region of perturbation ($n^+ > 0$, red cell) and cooler plasma into inner cold region perturbation ($n^- < 0$, blue cell) which reinforce the process and instability grows.

The described mechanism causes perturbation on the outboard side of the tokamak this region has a “bad curvature” and instability happens there. On the inboard side the opposing ∇B and ∇T results in a decay of perturbation which is referred to as “good curvature”. Furthermore such turbulent structures are called *eddies* and have a typical radial scale of several Larmor radius. ^[59] Through the explanation above is clear that the initial perturbation is growing when the normalized temperature gradient overcomes a critical value $R/L_{T,c}$. For nonlinear turbulence the critical value is given by $R/L_{T,c} \sim 6$. ^{[18][25]}

2.4 Zonal Flows and Shearing Rate $\omega_{E \times B}$

united

Zonal flows are referred in the tokamak plasma to the $E \times B$ flows [Eq.(2.8)] that is connected to the on flux-surfaces constant electrostatic potential, also called *zonal potential*.^[14] Because of the variation only across flux-surfaces ~~only~~ the zonal flow is tangential to the flux-surfaces and do not contribute to the turbulent transport across flux-surfaces caused by the $E \times B$ motion. Zonal flows are driven nonlinear through turbulent Reynolds stresses.^[15] For more about the mechanism behind zonal flow generation the reader is referred to Ref. 6[19]24[31].

*too much
flux
surfaces*

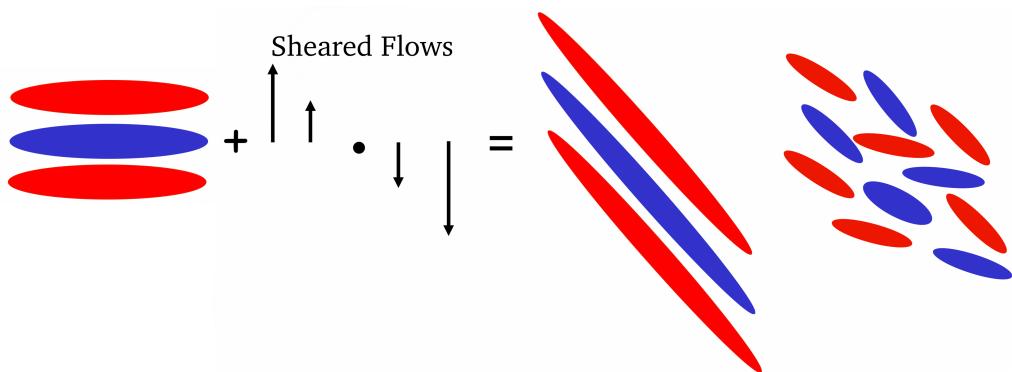


Figure 2.3: Subdued turbulence because if stretched eddies which breaks in smaller structures caused by sheared $E \times B$ drifts^[23]

Furthermore, zonal flows are connected with the radially alternating zonal potential what introduces a velocity shear, i.e., a radial variation of the zonal flow velocity. This causes a shear deformation of turbulent structures which is considered to play a significant role in the suppression of turbulence^{[5][18]} especially the ion temperature gradient driven turbulence^{[40][36][35][57][58]}. The nonlinear generation mechanism causes a shift, also known as Dimits shift^[18], of the critical temperature gradient $R/L_{T,c}$ which leads to a later development of ITG driven turbulence. The shearing process tilted und stretches turbulent eddies, caused be the shear flow, until they break into smaller eddies with reduced radial correlation length [Fig. 2.3] which characterize the shearing as decorrelation process. Turbulence will then be reduced because of this process.^{[5][14][7]}

*Change R_0 into R to correctly parameter
in the latter case.*

When the zonal flows are strong enough to suppress turbulence completely due to the shearing process, pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure. The $E \times B$ staircase pattern has the following properties:

- (1) They occur on a *radial mesoscale* of order of 10ρ which is larger than the Larmor radius but smaller than the machine size R_θ .
- (2) The structure are *quasi stationary* in space and varies on time scales much longer than the typical turbulent time scales.
- (3) They have an *typical amplitude* in terms of the $E \times B$ shearing rate of the order of $10^{-1} v_{th}/R_\theta$.
- (4) Turbulent transport occurs in *avalanches* with propagation strongly linked to the local $E \times B$ shearing rate.^[37]

The $E \times B$ staircase pattern is manifest as radial structure formation in the $E \times B$ shearing rate defined by^{[44][43][42]}

$$\omega_{E \times B} = \frac{1}{2} \frac{\partial^2 \langle \phi \rangle}{\partial x^2}, \quad \text{Major radius } = \text{decreas size?} \quad (2.12)$$

where $\langle \phi \rangle$ is the zonal electrostatic potential normalized by $\rho_* T/e$ ($\rho_* = \rho/R$ is the thermal Larmor radius normalized with the major radius R , T is the temperature, e is the elementary charge). The zonal potential is calculated from the electrostatic potential ϕ on the two-dimensional $x-y$ -plane at the low field side according to^[45]

$$\langle \phi \rangle = \frac{1}{L_y} \int_0^{L_y} dy \phi(x, y, s=0). \quad \text{what's low field side?} \quad (2.13)$$

The $E \times B$ shearing rate $\omega_{E \times B}$ is the radial derivative of the advecting zonal flow velocity^{[21][52]} and quantifies the zonal flow induced shearing of turbulent structures^{[5][21][7]}.

include
picture
of

Shearing rate

As mentioned before the turbulent transport occurs through avalanches which also mediate the turbulence of the ITG driven turbulence in the adiabatic electron approximation. Avalanches are initial when the $E \times B$ sharing rate has a zero crossing with a steep flank and propagates outwards with negative shearing and inwards for positive shearing^{[27][37]}. The fully developed avalanche results in almost completely quenched turbulence. Its development results in a discontinuous step in the dependency of turbulent fluxes on the temperature gradient als known as *finite heat flux threshold*.^{[42][55]}

Chapter
↑ ITG

2.5 Gyrokinetic Theory

2.5.1 Vlasov Equation

Because of the large number of particle in the fusion plasma a prediction only using Newton-Maxwell dynamics results in an impossible task for computers, but this problem can be solved with a statistical approach. For that the particle density distribution function $f(\mathbf{x}, \mathbf{v}, t)$ in the six dimensional phase space $\{\mathbf{x}, \mathbf{v}\}$ with the particles position \mathbf{x} and velocity \mathbf{v} is needed. Because collisions are happening at much smaller frequencies than the characteristic frequencies connected to turbulence, the collisionless model is often considered^[20] which gives thorough evolution of the particle density distribution function the *Vlasov equation*

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{v}} \cdot \frac{d\mathbf{v}}{dt} = 0. \quad (2.14)$$

To obtain a closed system the Maxwell equations with the particle density n and current density j can be described the distribution function as follows:

$$n = \int d\mathbf{v} f(\mathbf{x}, \mathbf{v}, t) \quad j = q \int d\mathbf{v} v f(\mathbf{x}, \mathbf{v}, t), \quad (2.15)$$

vector \vec{v} (?)

which are substituted into the Maxwell equations

$$\begin{aligned} \nabla \cdot \mathbf{B} &= 0 & \nabla \times \mathbf{B} &= \mu_0 \left(\sum_{\text{species}} j + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \\ \nabla \cdot \mathbf{E} &= \frac{1}{\epsilon_0} \sum_{\text{species}} qn & \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}. \end{aligned} \quad (2.16)$$

The Vlasov equation (2.14) together with the Maxwell equations (2.15) and (2.16) is the basis of the gyrokinetic model.^[30]

2.5.2 Gyrokinetic Ordering

Dynamics in tokamak plasma is described by spatio-temporal scales which is also referred as *gyrokinetic ordering*. This separation is a comparison between the turbulence frequency ω and the cyclotron frequency ω_c ($\omega/\omega_c \sim 10^{-3}$) due to strong external magnetic fields which causes a fast gyro motion. The length scales of the turbulence are associated with the wavevector \mathbf{k} which can be separated into a perpendicular component $k_\perp = |\mathbf{k} \times \mathbf{b}|$ and a parallel component $k_\parallel = |\mathbf{k} \cdot \mathbf{b}|$ where \mathbf{b} is parallel to the poloidal component of the magnetic field. The perpendicular component k_\perp scales with the thermal Larmor radius $k_\perp^{-1} \sim \rho$ which is significantly smaller than the equilibrium density n_0 what can be expressed with the gradient length $L_n = |\nabla \ln n_0|^{-1}$. The gradient length compares with the machine size which leads to the normalized Larmor radius $\rho_* = \rho/R_0 \sim 10^{-3} - 10^{-4}$ with R_0 as major radius of the tokamak. The parallel component k_\parallel on the other hand scales with the machine size. Experiments also show that in the core plasma the fluctuation amplitude of the density perturbation $\delta n/n_0$ and magnetic field fluctuation $\delta B/B_0$, with B_0 as strength of the magnetic field in equilibrium, is of order $\sim 10^{-4}$. Together these separations result in the following result

$$\frac{\omega}{\omega_c} \sim \frac{k_\parallel}{k_\perp} \sim \frac{\rho}{L_n} \sim \frac{\delta n}{n_0} \sim \frac{\delta B}{B_0} \sim \frac{v_d}{v_{th}} \sim \epsilon_g \quad (2.17)$$

with $\epsilon_g \ll 1$ which applies to the typical dynamics of a fusion core plasma.^{[6][20]} The gyrokinetic ordering allows the reduction of parameters in the Vlasov equation (2.14).

2.5.3 Gyrokinetic Equation

For the description for charged particle in the tokamak device the *gyrocenter coordinates* will be used [Fig. 2.4]. In this set of coordinates the gyrocenter follows the magnetic field with the parallel velocity v_{\parallel} . The gyro motion will be described together with the magnetic moment $\mu = \frac{1}{2}mv_{\perp}/\omega_c$, the gyrocenter \mathbf{X} and the gyro phase ζ which gives a parameter set of six quantities $\{\mathbf{X}, v_{\parallel}, \mu, \zeta\}$.

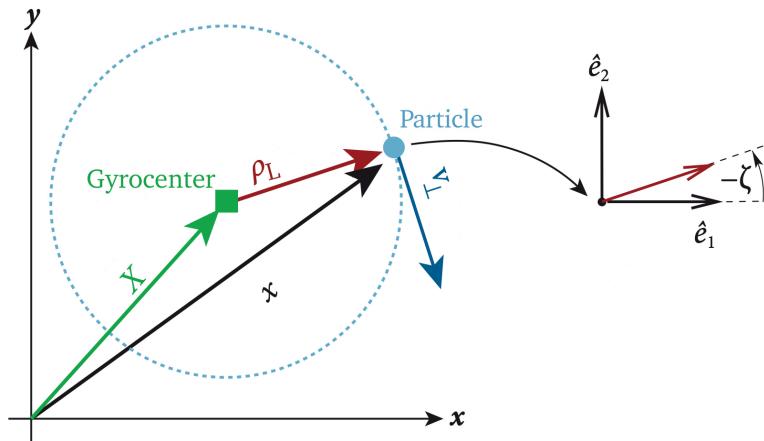


Figure 2.4: Sketch of gyrocenter coordinates where the charged particle performs a circular motion around the gyrocenter.^[31]

In the next step the coordinates of the Vlasov equation (2.14) will be transformed into the gyrocenter coordinates. For that the particle position \mathbf{x} will be described through the gyrocenter position $\mathbf{X} = \mathbf{x} - \boldsymbol{\rho}_L$ with the position Larmor radius vector $\boldsymbol{\rho}_L$. The particle velocity \mathbf{v} gets decomposed into a parallel component $v_{\parallel} = \mathbf{v} \cdot \hat{\mathbf{b}}$ and a perpendicular component $v_{\perp} = |\mathbf{v} \times \hat{\mathbf{b}}|$ which relates to the magnetic moment μ . Through the gyrokinetic ordering a phase space transformation can be performed which is based on the Lie perturbation theory, the Hamiltonian or Lagrangian formalism and an asymptotic expansion in the smallness parameter ϵ_g . In the lowest order is the magnetic moment an exact invariant which makes the gyro phase ζ an ignorable variable.^{[20][8][9]} Taking everything into account the new coordinates of the Vlasov equation are $\{\mathbf{X}, v_{\parallel}, \mu\}$ which transfers the Vlasov equation into the *gyrokinetic equation*

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{X}} \cdot \frac{d\mathbf{X}}{dt} + \frac{\partial f}{\partial v_{\parallel}} \cdot \frac{dv_{\parallel}}{dt} = 0 . \quad (2.18)$$

The time derivative of the magnetic moment μ is zero because the magnetic moment is an exact invariant.

2.5.4 δf Approximation and Local Limit

All simulation in this thesis are performed with GKW (Gyro Kinetic Workshop) uses in the application of the gyrokinetic equation the δf approximation and local limit approximation. For the δf approximation the particle density distribution function f gets separated into perturbation δf and equilibrium f_0 (constant in time) as expressed in the gyrokinetic ordering (2.17). This is given by

$$f = f_0 + \delta f \quad \delta f \sim \rho_* f_0 . \quad (2.19)$$

The distribution function in the equilibrium f_0 is set in GKW to the Maxwell distribution function. The perturbed distribution function δf is considered to vary perpendicular to the poloidal magnetic field in order of the Larmor radius while the perturbation changes with the system size which results in the ordering

$$\nabla_{\perp}(\delta f) = \nabla_{\perp}(f_0) . \quad (2.20)$$

The δf approximation applies for global and local description where the latter case is used in this thesis. The *local limit* on the other hand uses the spatial separation of equilibrium and perturbation and implies that all equilibrium and geometry quantities can be taken constant over the radial extent of the simulation volume. Because of the tokamak symmetry all equilibrium constants are also constant in the toroidal direction where the dependency of the equilibrium magnetic field on the poloidal angle is restrained in general.

In addition to that in GKW the following coordinates get applied with the parameter $\mathbf{X} = \{x, y, s\}$. Here, x is the radial coordinate that labels the flux surfaces normalized by the thermal Larmor radius ρ , y labels the field lines and is an approximate binormal coordinate. Together with the coordinate s which parameterizes the length along the field lines and is referred to as the parallel coordinate these quantities form the Hamada coordinates [22]. This results in the new coordinates $\{x, y, s, v_{\parallel}, \mu\}$. Combining the δf approximation and the Hamada coordinates and the gyrokinetic equation can be formulated as follows

$$\frac{\partial g}{\partial t} + \mathbf{v}_x \cdot \nabla g + (v_{\parallel} \mathbf{b} + \mathbf{v}_D) \cdot \nabla(\delta f) - \frac{\mu B}{m} \frac{\mathbf{B} \cdot \nabla B}{B^2} \frac{\partial(\delta f)}{\partial v_{\parallel}} = S , \quad (2.21)$$

where g is a function which contains the the perturbation δf and the equilibrium f_0 . Furthermore, \mathbf{v}_D and \mathbf{v}_x are drift velocities which are caused by the inhomogeneous magnetic field and inhomogeneous magnetic field (v_D) and through the $E \times B$ drift. The source term S combines from the distribution function in the equilibrium f_0 and a correction term for the collisions as well as the energy injection term. Due to periodic boundary conditions in the radial direction the radially gradients cannot change in time which is also referred as *gradient driven* approach.^[41]

CHAPTER

Methods and Material

3

3.1 Simulation Setup

The gyrokinetic simulations are performed with the non-linear flux tube version of Gyrokinetic Workshop (GKW)^[41] with adiabatic electron approximation. In agreement with Ref. [42], Cyclone Base Case (CBC) like parameters are chosen with an inverse background temperature gradient length $R/L_T = 6.0$ and circular concentric flux surfaces. The numerical resolution is compliant to the "Standard resolution with 6th order (S6)" set-up of the aforementioned reference. A summary of the numerical parameters is given in Tab. [4.1] and for more details about the definition of individual quantities the reader is referred to Refs. [41][42].

| | N_m | N_x | N_s | $N_{\nu_{ }}$ | N_μ | D | ν_d | $D_{\nu_{ }}$ | D_x | D_y | Order | $k_y\rho$ | $k_x\rho$ |
|----|-------|-------|-------|----------------|---------|-----|--------------|----------------|-------|-------|-------|-----------|-----------|
| S6 | 21 | 83 | 16 | 64 | 9 | 1 | $ \nu_{ } $ | 0.2 | 0.1 | 0.1 | 6 | 1.4 | 2.1 |

Table 3.1: Resolution used in this paper: Number of toroidal modes N_m , number of radial modes N_x , number of grid points along the magnetic field N_s , number of parallel velocity grid points $N_{\nu_{||}}$, number of magnetic moment grid points N_μ , dissipation coefficient used in convection along the magnetic field D , the velocity in the dissipation scheme ν_d , dissipation coefficient used in the trapping term $D_{\nu_{||}}$, damping coefficient of radial modes D_x , damping coefficient of toroidal modes D_y , order of the scheme used for the zonal mode, maximum poloidal wave vector $k_y\rho$, and maximum radial wave vector $k_x\rho$

Consistent with Ref. [42] the turbulence level is quantified by the turbulent heat conduction coefficient χ , which is normalized by $\rho^2 v_{\text{th}}/R$ ($v_{\text{th}} = \sqrt{2T/m}$ is the thermal velocity and m is the mass). Furthermore, quantities ρ , R , T , v_{th} and m are referenced quantities from Ref. [42][41].

3.2 Diagnostics

In order to diagnose the temporal evolution of the staircase pattern and to obtain an estimate of its amplitude the radial Fourier transform of the $E \times B$ shearing rate is considered. It is defined by

$$\omega_{E \times B} = \sum_{k_{ZF}} \hat{\omega}_{E \times B}(k_{ZF}, t) \exp(ik_{ZF}x), \quad (3.1)$$


where $\hat{\omega}_{E \times B}$ is the complex Fourier coefficient and $k_{ZF} = 2\pi n_{ZF}/L_x$ defines the zonal flow wave vector with the zonal flow mode number n_{ZF} ranging in $-(N_x - 1)/2 \leq n_{ZF} \leq (N_x - 1)/2$ and the radial box size L_x . Based on the definitions above, the shear carried by the zonal flow mode with wave vector k_{ZF} is defined by $|\hat{\omega}_{E \times B}|_{n_{ZF}} = 2|\hat{\omega}_{E \times B}(k_{ZF}, t)|$. In general, the zonal flow mode that dominates the $E \times B$ staircase pattern, also referred to as the *basic mode* of the pattern in this work, exhibits the maximum amplitude in the spectrum $|\hat{\omega}_{E \times B}|_{n_{ZF}}$.



3.3 btrzx1 Cluster

The simulation itself will be performed on the `btrzx1`-cluster of the University Bayreuth. This cluster has a wall time from 24 hours, an total amount of 345 compute nodes with two AMD Epyc Processors (2nd generation) with 16 cores each and 128 GB of main memory each node and as resource manager Slurm.^[48]

The simulations are performed on the `/scratch` directory because the `/home` folder has an disk space limit of 80 GB which is not enough to perform long runs of GKW.

3.4 Restart Script for Simulation

As stated in Chapter [3.3] the `btrzx1`-cluster has a wall time of 24 hours but since simulations typical run longer than 24 hours one have to restart the simulation after the wall time gets exceeded. Some simulation need even longer so that the simulation itself needs multiple weeks to finish ~~with a result~~ which makes the restart of the simulation a daily task that could be easily forgot ~~often~~. So to eliminate this minor inconveniences the following restart script were written.

As script language `python` was chosen ~~over shell~~ because of its easiness to write code and the variety of tools which can interact with the `bash`~~shell~~. `bash` was also considered

but after some issue occurred regarding the mechanism to check whether a file exist or not, python was selected.

The script was named `slurm_monitor.py` to indicate that this script works with the Slurm resource manager. The source code was pushed to the gkw repository on BitBucket³³ or can be found in Appendix [6.1](#)

3.4.1 How to run Restart Script in Terminal

To run the restart script `python3` has to be installed on the system and should be accessible by the command line. With the following command can be the monitoring started:

```
python3 -u slurm_monitor.py --job-name $JOBNAME
```

Additional parser options can be added to the command above which will be summarized in the upcoming Chapter [3.4.2](#). The script was build to run in the background of the terminal for which there are two approaches:

1. `nohup`: Runs command in the background while terminal can still be used or closed.¹ The command for this method would be:

```
nohup python3 -u slurm_monitor.py --job-name $JOBNAME &> /dev/null &
```

and to cancel the monitoring:

```
python3 -u slurm_monitor.py --job-name $JOBNAME --kill
```

2. `screen`: Opens a virtual terminal session which is detached from the main terminal and can be entered and closed.² Here the command would be:

```
screen -S $SESSION #Create screen session  
python3 -u slurm_monitor.py --job-name $JOBNAME --verbose
```

*the
a window*

and to cancel the monitoring use the keyboard shortcut `Ctrl+C` or kill screen itself with `Ctrl+D`. To leave the screen use `(Ctrl+A) + D` and to enter the screen use:

```
screen -r $SESSION
```

3.4.2 Features of Restart Script

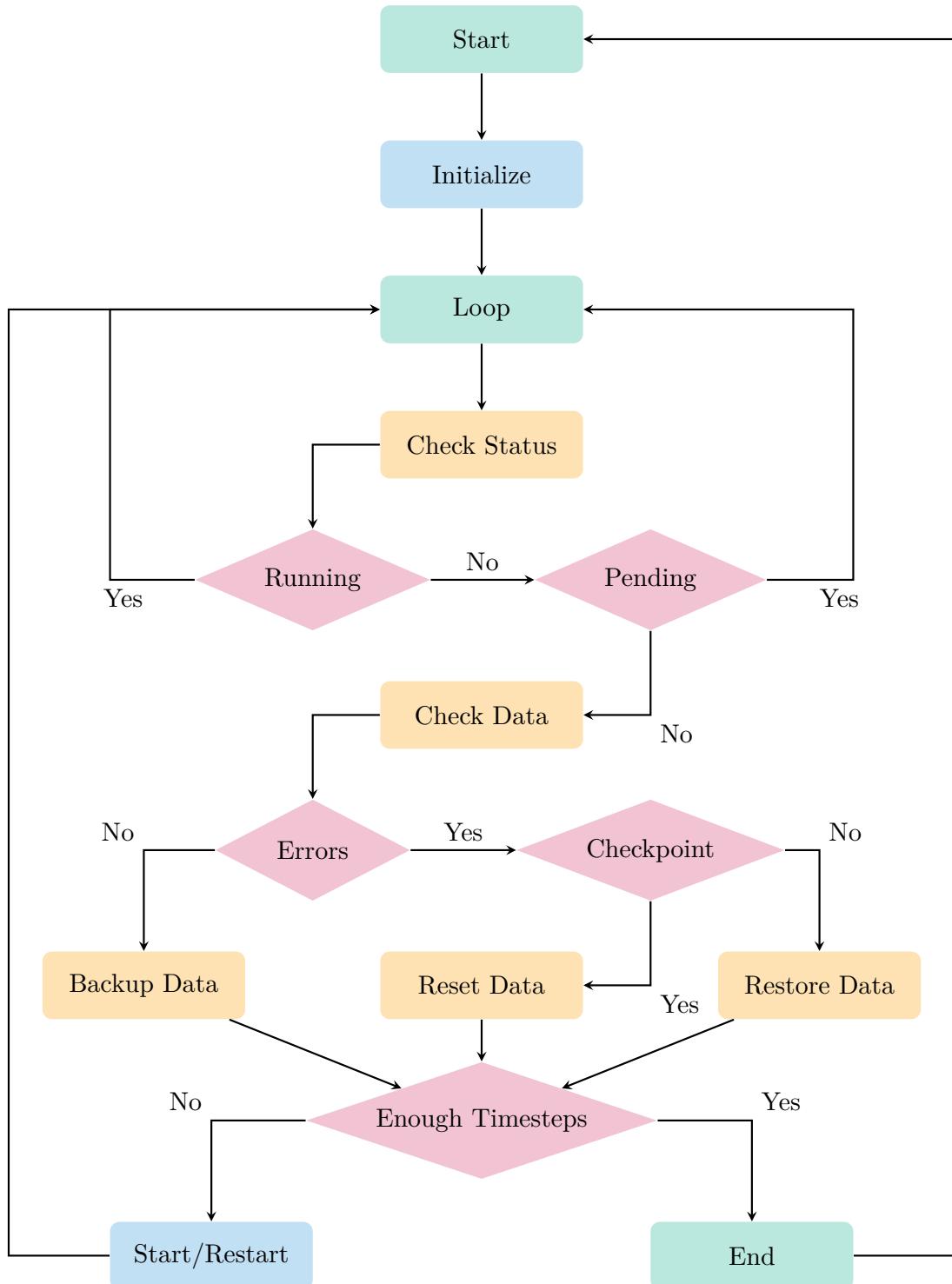
The restart script has several features which can be used via the command line interface as parser options. The following features with the corresponding parser option were implementing:

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Paragraph

- The script has no requirements because it runs on the standard python3 library
- **!Required!** Set job name not longer than 8 characters to identify simulation
`-j [JOBNAME], --job-name [JOBNAME]`
- Creates jobsctipt file with defined content
 (look into variable `jobsctiptContent` to add more option)
 - `--jobsctipt [JOBSCTRIPTFILE]` (default=`jobsctipt-create`)
 - `--nodes [NODES]` (default=3)
 - `--ntask-per-node [TASKS]` (default=32)
 - `--walltime [WALLTIME]` (d-hh:mm:ss) (default=0-24:00:00)
- Start/Restarts simulation until job criteria is suffused
 - `-n [Timesteps]` (default=10000)
 - `--restartfile [RESTARTFILE]` (default=`FDS.dat`)
- Makes backup after each run before Restart and Restore files after failed run
 (uses `rsync` command line utility)
 - Quicklinks: local (simulation folder), home (home folder)
 - `-b [LOCATION], --backup [LOCATION]` (default=None)
- Reset option after run fails and dump files were written
 (rely on `h5py`, `pandas` and `numpy` which get installed by the script itself)
 - `-r, --reset` (default=False)
- Creates status file with current status and progress bars and updates it dynamically
 - `--statusfile [STATUSFILE]` (default=`status.txt`)
- Set form of the output table in status file
 Options: fancy (round box), universial (crossplattform), None (No frame)
 - `--format [FORMATTABLE]` (default=None)
- Sends mail at the beginning, end and restart with status file as attachment
 (`mailx` other equivalent has to be installed, look into `send_mail` function for more info)
 - `--mail [MAILADDRESS]` (mail@server.de) (default=None)
 - `--restart-mail` (default=False)
- Kills monitoring process by using the PID number
 - `--kill` (default=False)
- Set sleep interval after which the status of the current simulation should be checked
 - `--refresh-rate [SLEEPTIME]` (default=300)
- Print output of status file table to console
 - `-v, --verbose` (default=False)

All boolean parameters are switches

3.4.3 General Structure



3.4.4 Status File created from Restart Script

As stated in Chapter 3.4.2 the restart script is writing a status file with the current status and progress bars of the simulation. The output is formatted like a table and can be adjusted in its appearance with the --format parser option [Chapter 3.4.2]. The output types which are written in the status file are listed in Tab. 3.2. To each output prints the restart script the date, time and the duration of the monitoring additionally into the table.

| Type | Information |
|----------|--|
| STARTING | Start of monitoring process or Start/Restart of simulation |
| CONTINUE | If the simulation has performed at least one run |
| CONTROL | Check of the current time steps of the simulation |
| SUCCESS | Stop of monitoring because the time steps condition has been fulfilled |
| IMPORT | Modules h5py, pandas and numpy will be loaded |
| INSTALL | Script installs the modules h5py, pandas and numpy on the user level |
| CHECK | Required modules to use the reset option are already installed |
| WAITING | Simulation is pending in the queue of Slurm |
| RUNNING | Simulation is running on the server |
| BACKUP | The script performs the backup of the data to the predefined location |
| RESTORE | The script reloads the data from the backup folder if errors occur |
| RESET | The simulation gets reset with the use of dump files |
| ERROR | <p>During the monitoring does occur an error</p> <p>Types:</p> <p>No executable (gkw.x), walltime, timeout, no config, hdf5, string error + MPI Abort \Rightarrow Nodes error (?)</p> |

Table 3.2: Output types in status file

To continue, the status file has different style options, e.g., fancy, universal and None which are displayed in Fig. 3.1.

| | | |
|-------|-----------|------|
| fancy | universal | None |
| | | |

Figure 3.1: Styles of output table in status file

In addition to that, it writes down the progress of simulation to the end of the status file in form of a progress bar which gets updated dynamically. The progress bar contains the current time step of the simulation in contrast to the required time steps and the progress of the run itself in seconds in relation to the wall time. It also contains the

current output from `squeue`, if the simulation is running or pending, else the important information of the simulation. An example progress bar ist shown in Fig. 3.2.

```
+-----+
|   JOBID   NAME      USER ST      TIME NODES  NODELIST(REAON)   |
| 970455 3x1.5 bt712347 CG 3:16:01      3  r03n03,r05n[15-16]  |
+-----+
| PROGRESS  [=====>.....]  ( 80%)  20000/25000  |
| RUN 13    [==>.....]  ( 13%)  11462/86400  |
+-----+
```

Figure 3.2: Progress bar example

The progress bar has the advantage that someone can easily access all important information at the glance. To boost productivity the following command could be quite handy:

```
cd $DATA
find . -name $STATUSFILENAME -exec tail -8 {} \;
```

which prints all progress bars of every simulation in the data folder. If one want to see the complete status file change `tail -8` to `cat`. An example status file is displayed in the Appendix 6.2.

3.4.5 Support for other Resource Managers

The general idea behind the restart script could be adapted for other resource managers. For example in the early stage of the development the script was changed to support the PBS/Torque resource manager which mainly runs on the `btrzx2`-cluster of the University of Bayreuth⁴⁷ and supports the research of Dominik Müller for his Bachelor Thesis³⁹ with the RHMD-code³⁸. The script was named `torque_monitor.py` and can be found in the GitHub Repository of this thesis³² or in the Appendix 6.3. But note that due to the early adaptation the code does lack many features of `slurm_monitor.py` and was not maintained actively.

CHAPTER

4

Results and Discussion



The performed simulation for this chapter are documented Appendix [6.4]

4.1 Variation of Computational Resolution

At the beginning of this work the goal is to estimate the minimal resolution needed to run the simulation without fearing numerical dissipation. Numerical dissipatation can therefore result to no formation of zonal flow stuctures, which cause an permanent turbulent state of the simulation. The goal behind this testing is to reduce **calculation time** and **costs** of the simulation.

Because of that, the criteria for the best resolution should be:

- (1) Subdued turbulence after **short** time periods
- (2) Stability for **long** time periods

and the following procedure will be applied for verification:

1. Reduce only one number of grid points and look if criterias (1), (2) are satisfied
2. Reduce to known **minimum** number of grid points to verify result in general.

4.1.1 Benchmark

Starting from the “Standard resolution with 6th order (S6)” [Tab. 3.1] the first step is to reproduce the result of Ref. [42] in Section IV. Note that, because of selected circular cencentric geometry the used inverse background temperature gradient length is $R/L_T = 6.0$ instead of $R/L_T = 7.0$ which was used in Section IV of Ref. [42] for $s\text{-}\alpha$ geometry. In Fig. 4.1 the obtained data is simular to the results from Ref. [42] with subdued turbulence after $\sim 3000R/v_{\text{th}}$.

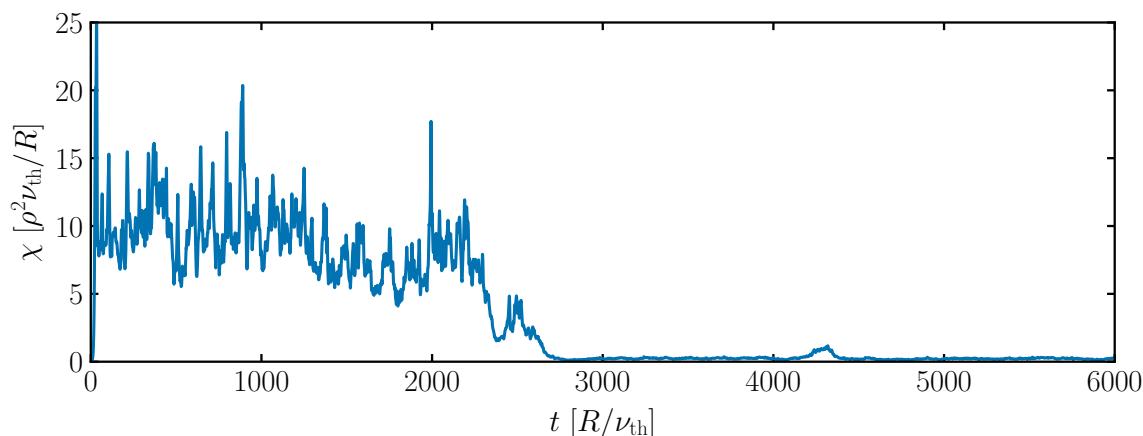


Figure 4.1: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for benchmark

As next step an approach to the finite heat flux threshold were made to verify the selection of the gradient length R/L_T . As in Ref. [42] in Section V conclude is the finite heat flux threshold approximately located at a gradient length of $R/L_T = 6.3$ for circular geometry [FIG. 4 of Ref. [42]]. Therefore following parameters were used:

$$R/L_T \in [6.0, 6.3].$$

As seen in Fig. 4.2 for $R/L_T = 6.3$ no suppression of turbulence occur in the whole time domain, which is in agreement with Ref. [42].

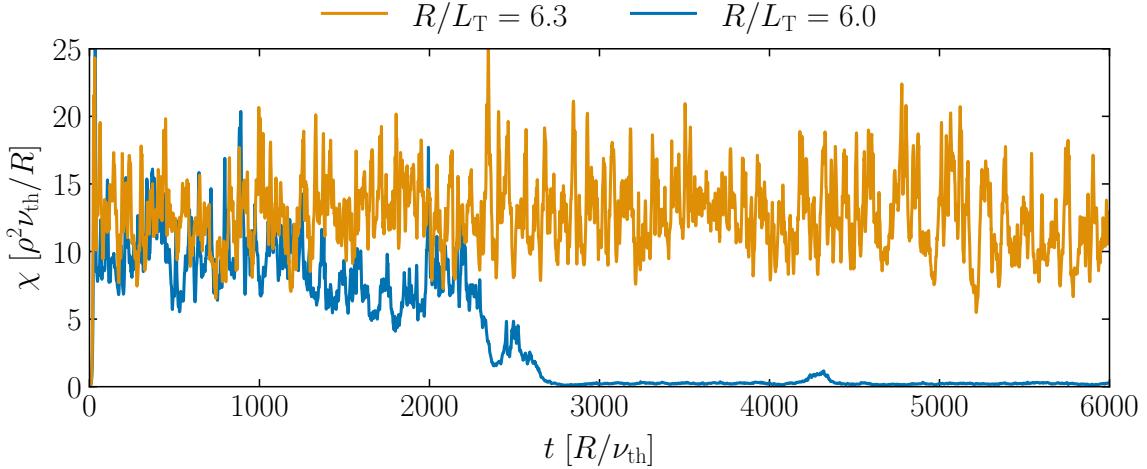


Figure 4.2: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ and $R/L_T = 6.3$ for benchmark

4.1.2 Reduction of parallel Velocity Grid Points $N_{\nu_{\parallel}}$

In the following the number of grid points for the parallel velocity $N_{\nu_{\parallel}}$ is reduced to:

$$N_{\nu_{\parallel}} \in [16, 32, 48, 64].$$

In Fig. 4.3 is clearly visible that the resolution with $N_{\nu_{\parallel}} = 16$ is not suitable for criteria (1) because here the turbulence is not subdued after a long time period. But resolution $N_{\nu_{\parallel}} = 32$ is as well not acceptable according to criteria (2) since the suppressed turbulence state gain instability after $\sim 3000R/v_{\text{th}}$.

So to conclude only grid points with $N_{\nu_{\parallel}} = 48, 64$ are satisfying the set criteria. Due to criteria (1) the selected resolution will be

$$N_{\nu_{\parallel}} = 48.$$

With this number of grid points the time till turbulence subdued is halved compared to the benchmark case, i.e., turbulence suppression occur after $\sim 1500R/v_{\text{th}}$.

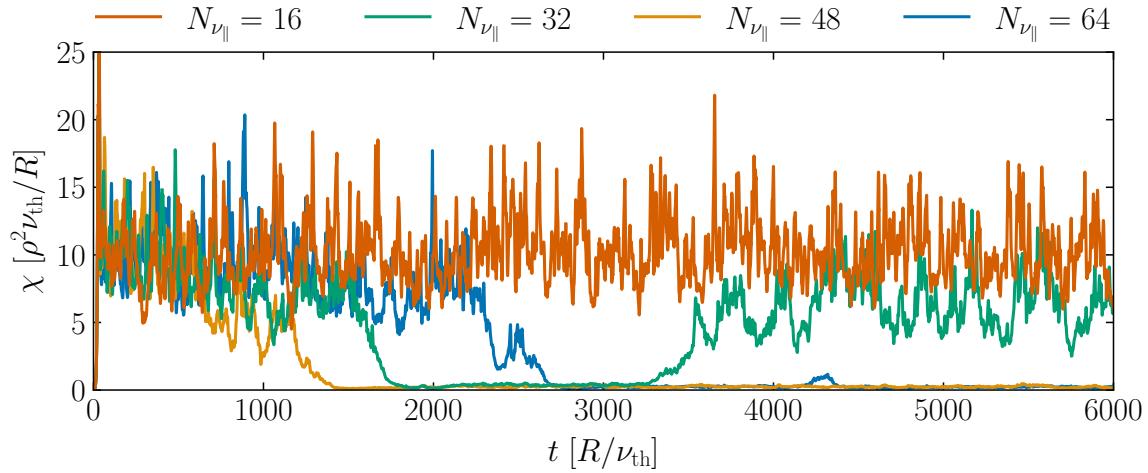


Figure 4.3: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for reduced parallel velocity grid points $N_{\nu_{\parallel}}$

4.1.3 Reduction of Magnetic Moment Grid Points N_{μ}

As next step the number of grid points for the magnetic moment N_{μ} were reduced with

$$N_{\mu} \in [6, 9].$$

As in Fig. 4.4 shown, the reduction of grid points for the magnetic moment does not significantly impact the suppression of turbulence. The turbulence enters the stationary state in both cases after $\sim 3000R/v_{\text{th}}$.

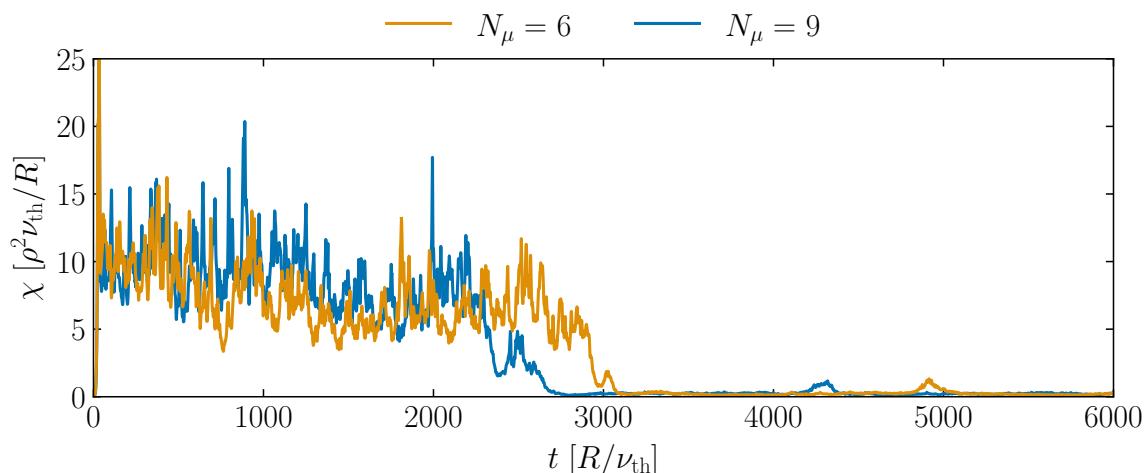


Figure 4.4: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for reduced magnetic moment grid points N_μ

To conclude a curial result the number of grids point for the parallel velocity got reduced to $N_{\nu_{||}} = 48$ according to Chapter 4.1.2. In this case the turbulence does not subdue for the resolution $N_\mu = 6$ which leads, with the both criteria in mind, to the following resolution |

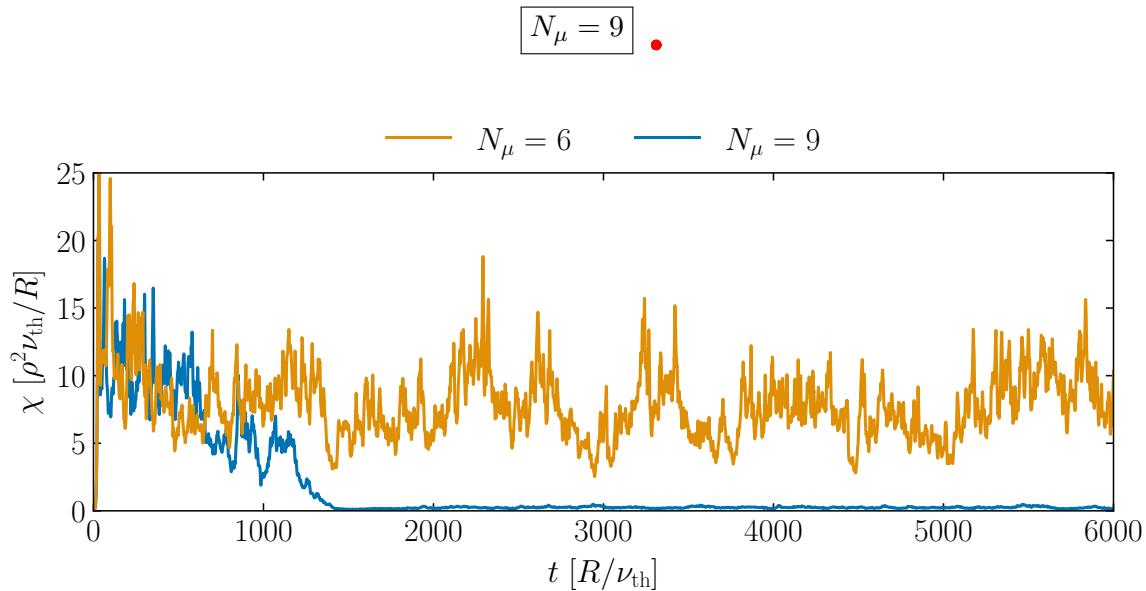


Figure 4.5: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ and $N_{\nu_{||}} = 48$ for reduced magnetic moment grid points N_μ

4.1.4 Reduction of Magnetic Field Grid Points N_s

In the final step the number of grid points for the magnetic field N_s get reduced with the following parameters |

$$N_s \in [12, 16] .$$

can be seen

In Fig. 4.6 is clearly visible that the reduction to $N_s = 12$ does not satisfy the criteria (2) because the the stationary state of the turbulence gets instabil after $\sim 2500R/v_{th}$. This concludes to the following resolution |

$N_s = 16$

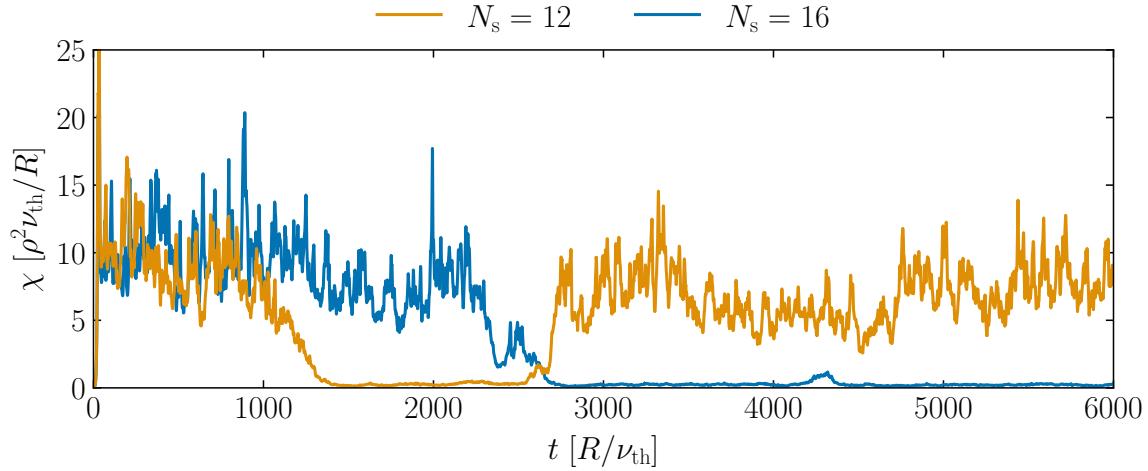


Figure 4.6: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for reduced magnetic field grid points N_s

4.1.5 Final Resolution for Simulation

Together with the results of Chapter 4.1.2, 4.1.3 and 4.1.4 the final resolution used in the upcoming simulations are displayed in Tab. 4.1 with reduced number of grid points for the parallel velocity $N_{\nu_{||}}$.

| | N_m | N_x | N_s | $N_{\nu_{ }}$ | N_μ | D | ν_d | $D_{\nu_{ }}$ | D_x | D_y | Order | $k_y\rho$ | $k_x\rho$ |
|----|-------|-------|-------|----------------|---------|-----|--------------|----------------|-------|-------|-------|-----------|-----------|
| S6 | 21 | 83 | 16 | 48 | 9 | 1 | $ \nu_{ } $ | 0.2 | 0.1 | 0.1 | 6 | 1.4 | 2.1 |

Table 4.1: Resolution used in this paper: Number of toroidal modes N_m , number of radial modes N_x , number of grid points along the magnetic field N_s , number of parallel velocity grid points $N_{\nu_{||}}$, number of magnetic moment grid points N_μ , dissipation coefficient used in convection along the magnetic field D , the velocity in the dissipation scheme ν_d , dissipation coefficient used in the trapping term $D_{\nu_{||}}$, damping coefficient of radial modes D_x , damping coefficient of toroidal modes D_y , order of the scheme used for the zonal mode, maximum poloidal wave vector $k_y\rho$, and maximum radial wave vector $k_x\rho$

needed?

4.2 Size Convergence of $E \times B$ Staircase Pattern

In the following the box size is increased relative to the standard box size ($L_x, L_y = (76.27, 89.76) \rho$) in the radial and binormal direction. The increased box sizes are indicated by the real parameter N_R for radial and N_B for the binormal direction with the nomenclature $N_R \times N_B$ throughout this work. Note that, the number of modes in the respective direction, i.e., N_x and N_m , respectively, is always adapted accordingly to retain a spatial resolution compliant to the standard resolution [Tab. 4.1] and standard box size.

4.2.1 Radial increased Box Size

In the first test the radial box size is increased while the binormal box size is kept fixed to the standard size. The scan covers the realizations⁴¹

$$N_R \times N_B \in [1 \times 1, 2 \times 1, 3 \times 1, 4 \times 1].$$

Each realization exhibits an initial quasi-stationary turbulent phase and a second final⁴² phase with almost suppressed turbulence [Fig. 4.7(a)]. The latter state is indicative for the presence of a fully developed staircase pattern as depicted in Fig. 4.10. This type of structure is characterized by intervals of almost constant shear with alternating sign satisfying the Waltz criterion $|\omega_{E \times B}| \approx \gamma^{53,52}$ (γ is the growth rate of the most unstable linear ITG driven Eigenmode), connected by steep flanks where $\omega_{E \times B}$ crosses zero. Fig. 4.10(a) shows a striking repetition of the staircase structure, with the number of repetitions equal to N_R . Hence, the basic size of the pattern not only converges with increasing radial box size, the converged radial size turns out to at least roughly agree with the standard radial box size of Ref. [42].

Due to the lack of a substantial turbulent drive in the final suppressed state no further zonal flow evolution is observed [Fig. 4.7(b)] and one might critically ask whether the structures shown in Fig. 4.10 represent the real converged pattern in a statistical sense. Note that in the 3×1 case the initial quasi-stationary turbulent state extends up to a few $\sim 10^4 R/v_{th}$. During this period the zonal flow mode with $n_{ZF} = 3$, i.e., the mode that dominates the staircase pattern in final suppressed phase, undergoes a long-term evolution with a typical time scale of several $\sim 10^3 R/v_{th}$.

Hence, several of such cycles are covered by the initial turbulent phase, which is evident from the occurrence of phases with reduced amplitude around $t \approx 8000 R/v_{th}$ and $t \approx 18000 R/v_{th}$. It is the $n_{ZF} = 4$ zonal flow mode, i.e., the next shorter radial scale mode, that dominates the shear spectrum $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ in the latter two phases (not shown). This demonstrates a competition between the $n_{ZF} = 3$ and $n_{ZF} = 4$ modes. Most

importantly, no secular growth of the $n_{\text{ZF}} = 1$ (box scale) zonal flow mode is observed during the entire quasi-stationary turbulent phase [Fig. 4.7(b) dotted line]. The above discussion indicates that although the $n_{\text{ZF}} = 3, 4$ zonal modes compete, the pattern scale does not converge to the radial box scale but rather to a mesoscale of $\sim 57.20 - 76.27 \rho$ (i.e., $n_{\text{ZF}} = 4, 3$ in the 3×1 case).

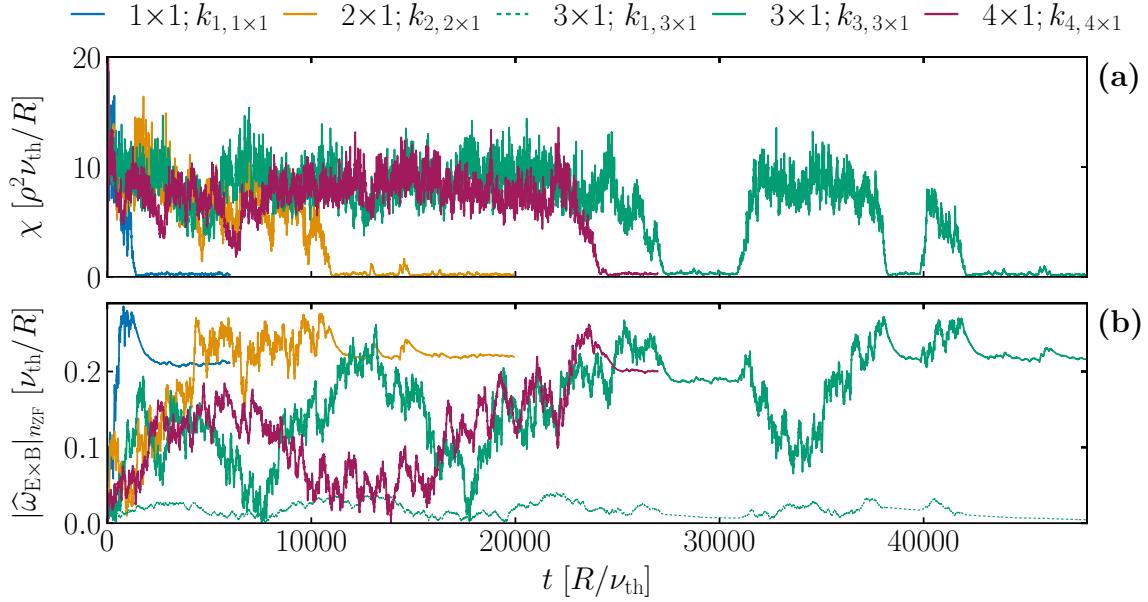


Figure 4.7: (a) Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for radial increased box sizes
 (b) Time traces of $|\hat{\omega}_{E \times B}|_{n_{\text{ZF}}}$ for radial increased box sizes

4.2.2 Isotropic increased Box Size

Since the radially elongated simulation domain might inhibit the development of isotropic turbulent structures, in the second test the radial and binormal box size is increased simultaneously. This scan covers the realizations

$$N_R \times N_B \in [1 \times 1, 2 \times 2, 3 \times 3].$$

Interestingly, suppression of the turbulence by the emergence of a fully developed staircase pattern always occurs after $\sim 1000 R/\nu_{\text{th}}$ [Fig. 4.8(a)], i.e., significantly faster compared to the 3×1 and 4×1 realizations. As shown in Fig. 4.10(b) also this test confirms the convergence of the staircase pattern size to a typical mesoscale that is distinct from the radial box size in the $N_R > 1$ realizations.

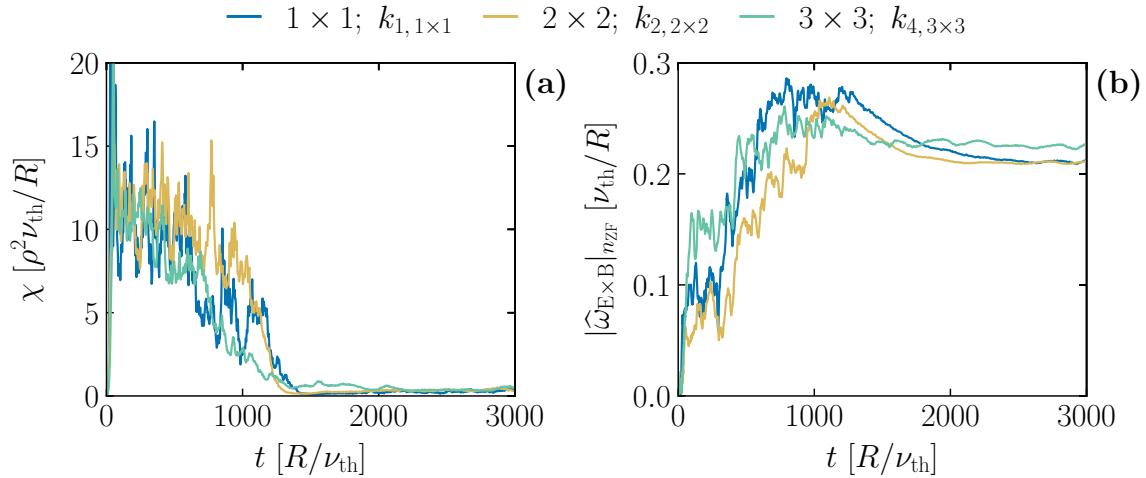


Figure 4.8: (a) Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for isotropic increased box sizes
 (b) Time traces of $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ for isotropic increased box sizes

By contrast to the radial box size scan the 3×3 realization shows a stationary pattern with four repetitions of the fully developed staircase structure, i.e., a somewhat smaller pattern size [Fig. 4.8(b), Fig. 4.10(b)]. Whether this is related to a possible pattern size dependence on the binormal box size or to the competition between patterns with the two sizes $\lambda \in [57.20, 76.27] \rho$ as observed in the first test is addressed in the next paragraph.

4.2.3 Binormal increased Box Size

In a third test the binormal box size is varied with the radial box size fixed to $N_R = 3$. This test covers the realizations

$$N_R \times N_B \in [3 \times 1.5, 3 \times 2.5, 3 \times 3, 3 \times 5].$$

As in the isotropic scan the turbulence subdued and a fully developed staircase pattern forms after $\sim 2000 R/v_{th}$ [Fig. 4.9(a)]. The convergence of staircase pattern can be seen in Fig. 4.10(c) and confirms again a size of a typical mesoscale. Fig. 4.10(c) also confirms that indeed a competition between patterns with two sizes $\lambda \in [57.20, 76.27] \rho$ causing the different results for 3×1 and 3×3 . The zonal flow mode number varies between $n_{ZF} = 3, 4$ which can be seen in Fig. 4.10(c) in the 3×2.5 realization. The staircase structure has a pattern between 3 and 4 repetitions which get represented in the second repetition with no significant plateau at positive shear. Instead the pattern returns immediately after reaching the maximum shear ($+\gamma$) to the minimum shear ($-\gamma$) of the third repetition in a steep flank. The Fourier analysis of this case yields no definitely basic mode rather two dominating modes with $n_{ZF} = 3, 4$ with a fraction of the maximum amplitude $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ each [Fig. 4.9(b)].

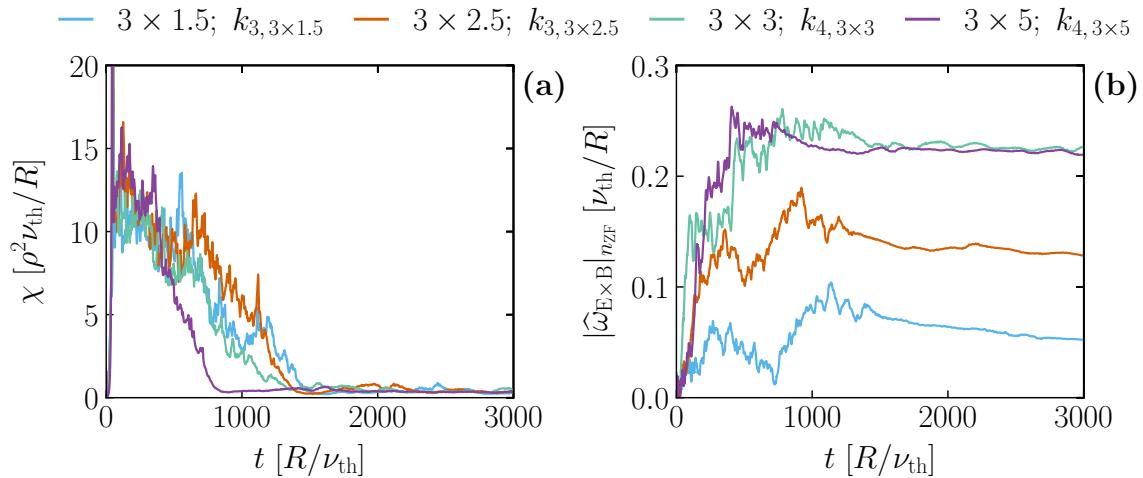


Figure 4.9: (a) Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for binormal increased box sizes
 (b) Time traces of $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ for binormal increased box sizes

4.2.4 Staircase Structures in Comparison

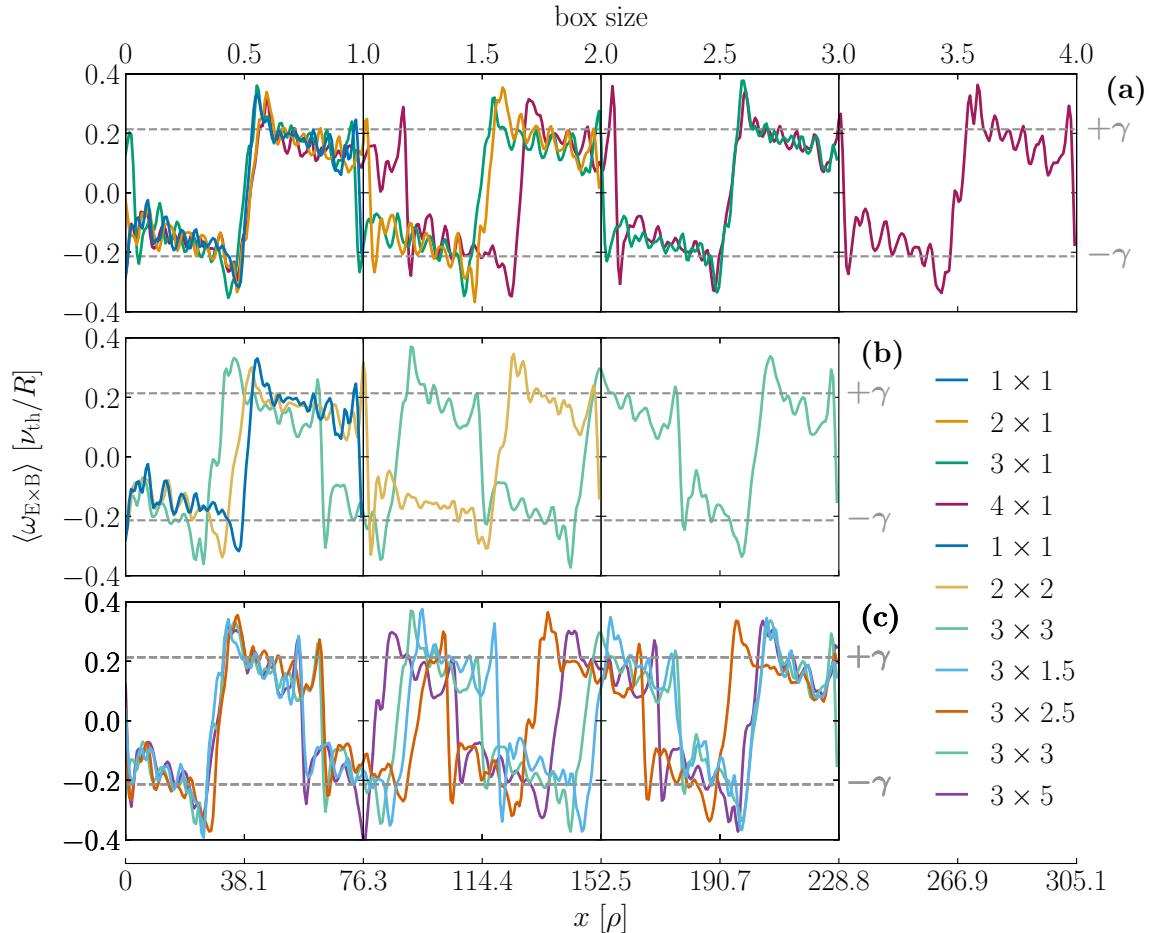


Figure 4.10: Comparison of shearing rate $\langle \omega_{E \times B} \rangle$ for each box sizes scan averaged over given time interval and the growth rate $\pm \gamma$ of the most unstable linear ITG driven Eigenmode. The staircase structures are radially shifted with respect to each other till alignment for better visibility.

- (a) **radial:** $t_{1 \times 1} \in [2000, 5000]$, $t_{2 \times 1} \in [15000, 18000]$,
 $t_{3 \times 1} \in [43000, 45000]$, $t_{4 \times 1} \in [26000, 28000]$
- (b) **isotropic:** $t_{1 \times 1} \in [2000, 5000]$, $t_{2 \times 2} \in [2000, 3000]$,
 $t_{3 \times 3} \in [2000, 3000]$
- (c) **binormal:** $t_{3 \times 1.5} \in [2000, 3000]$, $t_{3 \times 2.5} \in [2000, 3000]$,
 $t_{3 \times 3} \in [2000, 3000]$, $t_{3 \times 5} \in [1000, 3000]$

4.3 The finite Heat Flux Threshold

In the final test the inverse background temperature gradient length R/L_T is varied at fixed 3×3 box size. Since suppression of turbulence usually occurs at later times when approaching the finite heat flux threshold from below^[42], the analysis aims to lengthen the phase during which the zonal flow varies in time due to turbulent Reynolds stresses. This scan covers realizations with^[41]

$$R/L_T \in [6.0, 6.2, 6.4] .$$

In the case of $R/L_T = 6.2$ turbulence suppression is observed for $t > 11000 R/v_{\text{th}}$, while stationary turbulence during the entire simulation time trace of $12000 R/v_{\text{th}}$ is found for $R/L_T = 6.4$ [Fig. 4.11]. The finite heat flux threshold, hence, is^[41]

$$R/L_T|_{\text{finite}} = 6.3 \pm 0.1$$

in accordance to Ref. [42]. Although the initial quasi-stationary turbulence in the former case is significantly longer compared to the $R/L_T = 6.2$ realization discussed in the second test, a stationary pattern with basic zonal flow mode $n_{\text{ZF}} = 3$ establishes. Again, the $n_{\text{ZF}} = 1$ (box scale) zonal flow mode does not grow secularly during the entire turbulent phase. Also, this test confirms the statistical soundness of the converged pattern size of $\sim 57.20 - 76.27 \rho$.

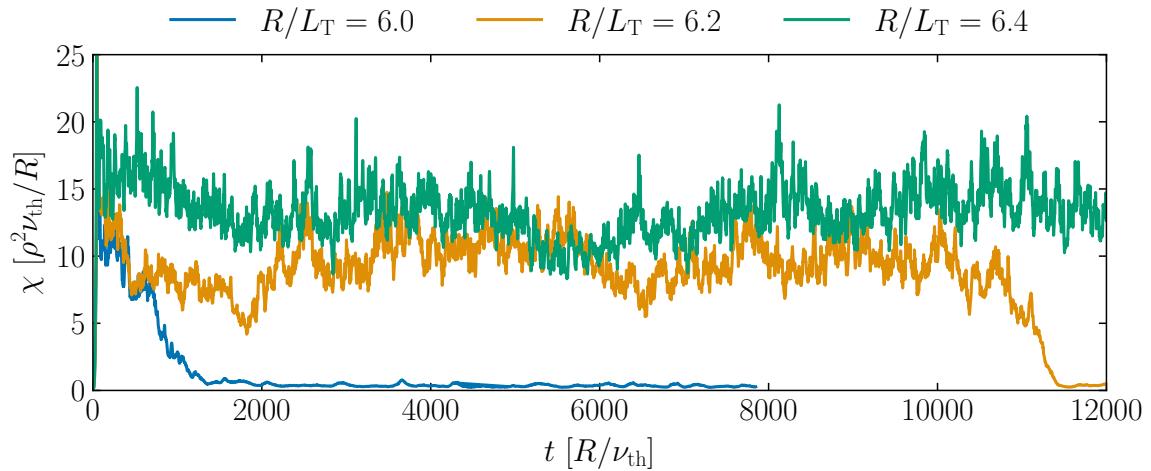


Figure 4.11: Time traces of the heat conduction coefficient χ for different gradient lengths R/L_T

CHAPTER

5

Closure

In this thesis the minimal resolution for simulations with GKW in the Cyclone Base parameter were observed in which the number of grid points for the parallel velocity $N_{v\parallel}$ could be reduced from 64 to 48. → which halves the time of suppression.

Additional the active development of an restart script in python leads to further convenience during the performance of a simulation on the btrzx1 cluster.

task performing

Through careful tests this bachelor thesis confirms the radial size convergence of the $E \times B$ staircase pattern in local gyrokinetic flux tube simulations of ion temperature gradient (ITG) driven turbulence. A mesoscale pattern size of $\sim 57.20 - 76.27 \rho$ is found to be intrinsic to ITG driven turbulence for Cyclone Base Case parameters. This length scale is somewhat larger compared to results from global studies with finite ρ_* , which report of a few 10ρ ^[16], and has to be considered the proper mesoscale in the local limit $\rho_* \rightarrow 0$. The occurrence of this mesoscale implies that non-locality, in terms of Ref. [16] is inherent to ITG driven turbulence, since avalanches are spatially organized by the $E \times B$ staircase pattern^{[37][16][44][42]}.

CHAPTER

Appendix 6

6.1 slurm_monitor.py

```
#!/usr/bin/env python3

# AUTHOR =====
#   ↪ =====
# Manuel Lippert (GitHub: ManeLippert (https://github.com/ManeLippert))
# =====
#   ↪ =====

# MODULES =====
#   ↪ =====

import datetime, time, os, sys, subprocess, math, argparse, pkg_resources

# PARSER =====
#   ↪ =====

description_text = """

===== DESCRIPTION =====
→ =====

FEATURES:
o NO REQUIREMENTS: Default script runs with standard python3 library
o Creates jobscript file with defined content
  (look into variable "jobscriptContent" to add more option)
o Start/Restarts job until criteria is suffused (default=10000)
o Makes backup after each run before Restart and Restore files after failed
  ↪ run
  (uses rsync command line utility)
o Reset option after run fails and dump files were written
  (rely on "h5py" & "pandas" & "numpy" which get installed by the script)
o Creates status file with current status and progress bars and updates it
  ↪ dynamically
  Progress: Total progress of simulation
  Run X : Progress of current run
o Sends mail at the beginning, end and restart (default=False) with status
  ↪ file
  as attachment
  (mailx has to be installed, look into "send_mail" function for more info)

START SCRIPT IN BACKGROUND:

o WITH NOHUP:
  Command:
    >>> nohup python3 -u slurm_monitor.py --job-name $JOBNAME &> /dev/null &

  Kill Process:
    >>> python3 -u slurm_monitor.py --job-name $JOBNAME --kill
```

```

o WITH SCREEN (has to be installed):
Create Screen:
>>> screen -S $SESSION

Command:
>>> python3 -u slurm_monitor.py --job-name $JOBNAME --verbose

Leave Screen:
>>> ((Strg + a) + d)

Enter Screen:
>>> screen -r
or
>>> screen -r $SESSION

Kill Process:
>>> ^C (Strg + c)
or
>>> (Strg + d) (kill Screen itself)

OUTPUT STATUS:
Just run the file will create an dynamic output (recommended with using
    ↪ screen) or
>>> cd $DATA && find . -name $STATUSFILENAME -exec tail -8 {} \;

=====
    ↪ =====
"""

parser = argparse.ArgumentParser(description=description_text,
    ↪ formatter_class=argparse.RawTextHelpFormatter)
#parser._action_groups.pop()

required = parser.add_argument_group("required arguments")

required.add_argument("-j", "--job-name", dest="jobname", nargs="?",
    ↪ type=str, required= True,
        help="job name not longer than 8 character")

additional = parser.add_argument_group("additional arguments")

additional.add_argument("-n", dest="timesteps", nargs="?", type=int,
    ↪ default=10000,
        help="required timesteps
    ↪ (default=10000)")

additional.add_argument("-r", "--reset", dest="reset", action="store_true",
    ↪ help="Uses Dumpfiles to reset Simulation
    ↪ (default=False)")

additional.add_argument("-v", "--verbose", dest="verbose",
    ↪ action="store_true",
        help="activate output of script"

```

```

    ↵ (default=False))

additional.add_argument("-b", "--backup", dest="backup", nargs="?", type=str,
                      help="backup location for files
    ↵ (default=None)\n"+
                           "- local (creates backup in simulation
    ↵ folder)\n"+
                           "- home (creates backup in home folder)")

additional.add_argument("--jobscrip", dest="jobscripFile", nargs="?",
                      type=str, default="jobscrip-create",
                      help="jobscrip to run SLURM job
    ↵ (default=jobscrip-create)")

additional.add_argument("--ntask-per-node", dest="tasks", nargs="?",
                      type=str, default="32",
                      help="MPI task per node
    ↵ (default=32)")

additional.add_argument("--nodes", dest="nodes", nargs="?", type=str,
                      default="3",
                      help="number of nodes
    ↵ (default=3)")

additional.add_argument("--walltime", dest="wallTime", nargs="?", type=str,
                      default="0-24:00:00",
                      help="walltime of server (d-hh:mm:ss)
    ↵ (default=0-24:00:00)")

additional.add_argument("--mail", dest="mail", nargs="?", type=str,
                      help="mail address (mail@server.de)
    ↵ (default=None)")

additional.add_argument("--restart-mail", dest="restartmail",
                      action="store_true",
                      help="mail after every restart
    ↵ (default=False)")

additional.add_argument("--statusfile", dest="statusFile", nargs="?",
                      type=str, default="status.txt",
                      help="file with output from nohup command
    ↵ (default=status.txt)")

additional.add_argument("--restartfile", dest="restartFile", nargs="?",
                      type=str, default="FDS.dat",
                      help="restart file with data
    ↵ (default=FDS.dat)")

additional.add_argument("--format", dest="formattable", nargs="?", type=str,
                      help="format of output table
    ↵ (default=None)\n"+
                           "- fancy (round box)\n"+
                           "- universal (crossplatform)\n"+

```

```
        "- None (No frame)")

additional.add_argument("--refresh-rate", dest="sleepTime", nargs=?,
    ↪ type=int, default=300,
        help="time interval to check status in sec
    ↪ (default=300)")

additional.add_argument("--kill", dest="kill", action="store_true",
        help="kills monitor process
    ↪ (default=False)")

args = parser.parse_args()

# VARIABLES =====
    ↪ =====

outputCriteria = ["0", "Run successfully completed"]

slurmFiles = [f for f in os.listdir() if "slurm-" in f]
runCounter = len(slurmFiles)

nTimestepsCurrent = 0

currentTime = "00:00:00"

dataFilename = "gkwdata.h5"

check1Filename, check2Filename = "DM1.dat", "DM2.dat"
check1Bin, check2Bin = check1Filename.replace(".dat", ""),
    ↪ check2Filename.replace(".dat", "")

# PARSER VARIABLES =====
    ↪ =====

emailAddress = args.mail
RESTARTMAIL = args.restartmail

backupLocation = args.backup

jobName = args.jobname
tasks = args.tasks
nodes = args.nodes
wallTime = args.wallTime

nTimestepsRequired = args.timesteps

jobscriptFilename = args.jobscriptFile
restartFilename = args.restartFile
restartBin = restartFilename.replace(".dat", "")

statusFilename = args.statusFile
#statusFile = open(statusFilename, "r+")

```

```
formatTable = args.formattable
VERBOSE = args.verbose
RESET = args.reset

# Kill process of monitoring
kill = args.kill

# Changing this value can cause problems in writing status file
sleepTime = args.sleepTime

def outputFilename(info):
    return "./slurm-" + info + ".out"

## JOBSCRIPT CONTENT =====
#> =====

jobscriptContent = """#!/bin/bash -l

# jobname
#SBATCH --job-name=""" + jobName + """

# MPI tasks
#SBATCH --ntasks-per-node=""" + tasks + """

# number of nodes
#SBATCH --nodes=""" + nodes + """

# walltime
#           d-hh:mm:ss
#SBATCH --time=""" + wallTime + """

# execute the job
time mpirun -np $SLURM_NTASKS ./gkw.x > output.dat

# end
exit 0
"""

jobName = jobName[0:8]

## FLAGS =====
#> =====

startOutputFlag = "Submitted batch job "
restartFlag = "FILE_COUNT"

## SWITCHES =====
#> =====

if emailAddress==None:
    EMAIL = False
else:
    EMAIL = True
```

```

if backupLocation==None:
    BACKUP = False
else:
    BACKUP = True

## PATHS =====
#> =====

user = os.getlogin()
folder = os.getcwd()
path = folder.split(user + "/") [1]

# Set backup location
if BACKUP:
    # If local has been specified as backupLocation, then the backup is
    #> copied to the same directory as the simulation folder
    # (simFolder) is located in. The backup is copied to a directory with
    #> name simFolder + "-backup".
    if backupLocation == "local":
        simFolder = path.split("/") [-1]
        backupPath = folder + "/.." + simFolder + "-backup"

    # Create backup in home folder
    elif backupLocation == "home":
        simFolder = path.split("/") [-1]
        backupPath = "~/" + simFolder + "-backup"

    # Otherwise, use the backupLocation parsed as argument.
    else:
        if backupLocation[-1] != "/":
            backupLocation += "/"
        backupPath = backupLocation + path

    if not os.path.exists(backupPath):
        os.makedirs(backupPath)

## COMMANDS =====
#> =====

commandJobRunning = "squeue --states=running --name " + jobName
commandJobPending = "squeue --states=pending --name " + jobName

commandMonitorKill = "ps ax | grep " + jobName + " | awk '{print $1}'"

commandJobStarting = "sbatch"

commandBackup = ["rsync", "-a", "", backupPath]
commandRestore = ["rsync", "-a", "-I", "--exclude=" + statusFilename,
    #> backupPath + "/", ""]

## FUNCTIONS =====
#> =====

```

```

## PROGRESSBAR =====
→ =====

def progressbar(required_value, current_value, barsize=42,
                prefix="",
                progress_fill="=", progress_fill_top="",
→ progress_fill_bot="",
                progress_unfill=".",
                progress_bracket=["[", "]"]):

    x = int(barsize*current_value/required_value)
    percent = int(100*current_value/required_value)

    try:
        percent_format = " (" + (int(math.log10(100)) -
→ int(math.log10(percent))) * " " + "{}%)"
    except ValueError:
        percent_format = " (" + int(math.log10(100)) * " " + "{}%)"

    try:
        ratio_format = " " + (int(math.log10(required_value)) -
→ int(math.log10(current_value))) * " " + "{}/{}"
    except ValueError:
        ratio_format = " " + int(math.log10(required_value)) * " " + "{}/{}"

    bar_format = "{} " + progress_bracket[0] + progress_fill_bot + "{}" +
→ progress_fill_top + "{}" + progress_bracket[1] + percent_format +
→ ratio_format
    bar = bar_format.format(prefix, progress_fill*x,
→ progress_unfill*(barsize-x), percent, current_value, required_value)

    return bar

## OUTPUT TABLE =====
→ =====

def message(string, add):
    string = string + add + "\n"
    return string

def print_table_row(content,
                    delete_line_index = -10, table_width = 80,
                    output_type = None,
                    TIMEINFO = True, WRITEFILE=True):

    current_value, required_value = nTimestepsCurrent, nTimestepsRequired,
    run_conter = runCounter
    current_time, required_time = currentTime, wallTime

    msg=""
    table_inner_width = table_width - 4

```

```

table_content_width = table_inner_width - 47

if formatTable == "fancy":
    table_outline = ["└", "┐", "└", "┘", "├", "┤", "|", " ", "─"]

if formatTable == "universal":
    table_outline = ["+─", "++", "+─", "─+", "+─", "++", "|", " ", "─"]

if formatTable == None:
    table_outline = ["─", "─", "─", "─", "─", "─", "─", " ", " ", "─"]

sep_top = table_outline[0] + table_inner_width*table_outline[8] +
    ↪ table_outline[1]
sep_mid = table_outline[4] + table_inner_width*table_outline[8] +
    ↪ table_outline[5]
sep_end = table_outline[2] + table_inner_width*table_outline[8] +
    ↪ table_outline[3]

row_cols    = [2, 10, table_content_width, 13, 11, 13, 2]
row_format = "".join(["{:<" + str(col) + "}" for col in row_cols])

progress_cols    = [2, table_inner_width, 2]
progress_format = "".join(["{:<" + str(col) + "}" for col in
    ↪ progress_cols])

progressbar_content = [progressbar(required_value, current_value,
    ↪ progress_fill_top=">",
                           prefix="PROGRESS")]
progressbar_content.insert(0, table_outline[6])
progressbar_content.insert(len(progressbar_content), table_outline[7])

required_time = get_time_in_seconds(required_time)
current_time  = get_time_in_seconds(current_time)

jobStatus = subprocess.getoutput("squeue --name " +
    ↪ jobName).strip().split("\n")

try:
    jobStatusHeader = [" " + jobStatus[0]]
    jobStatusInfo   = [jobStatus[1][11:11+table_inner_width]]
except IndexError:
    jobStatus_cols    = [12, 12, 10, table_inner_width- 71, 13, 11, 13]
    jobStatus_format = "".join(["{:<" + str(col) + "}" for col in
        ↪ jobStatus_cols])

    jobStatusHeader = ["OUTPUT", "NAME", "USER", "", "DATE", "TIME",
    ↪ "W:DD:HH:MM:SS"]
    jobStatusInfo   = [content[0], jobName, user, "", time_date(),
    ↪ time_time(), time_duration(startTime, pastTime)]

    jobStatusHeader    = [jobStatus_format.format(*jobStatusHeader)]
    jobStatusInfo     = [jobStatus_format.format(*jobStatusInfo)]

```

```

jobStatusHeader.insert(0, table_outline[6])
jobStatusHeader.insert(len(jobStatusHeader), table_outline[7])
jobStatusInfo.insert(0, table_outline[6])
jobStatusInfo.insert(len(jobStatusInfo), table_outline[7])

try:
    progressbartime_content = [progressbar(required_time, current_time,
    ↪ progress_fill_top=">",
    ↪ prefix="RUN " +
    ↪ str(run_conter) + (2 - int(math.log10(run_conter)))*" " + "")]
except ValueError:
    progressbartime_content = [progressbar(required_time, current_time,
    ↪ progress_fill_top=">",
    ↪ prefix="RUN " +
    ↪ str(run_conter) + 2*" " + "")]
progressbartime_content.insert(0, table_outline[6])
progressbartime_content.insert(len(progressbartime_content),
    ↪ table_outline[7])

content[1] = content[1][-table_content_width-1:]
content.insert(0, table_outline[6])
if TIMEINFO:
    if output_type == "header":
        content.append("DATE")
        content.append("TIME")
        content.append("W:DD:HH:MM:SS")
    else:
        content.append(time_date())
        content.append(time_time())
        content.append(time_duration(startTime, pastTime))

content.insert(len(content), table_outline[7])

if output_type == "header":
    delete_line_index = -1

    msg += sep_top + "\n"
    msg += row_format.format(*content) + "\n"
    msg += sep_end + "\n"

elif output_type == "middle":
    if VERBOSE:
        sys.stdout.write("\x1b[1A"*(-delete_line_index + 1))

    msg += sep_mid + "\n"
    msg += row_format.format(*content) + "\n"
    msg += sep_end + "\n"

elif output_type == "update":
    if VERBOSE:
        sys.stdout.write("\x1b[1A"*(-delete_line_index + 1))

    msg += sep_end + "\n"

```

```
else:
    if VERBOSE:
        sys.stdout.write("\x1b[1A"*(-delete_line_index + 1))

    msg += row_format.format(*content) + "\n"
    msg += sep_end + "\n"

msg += " "*table_width + "\n" + " "*table_width + "\n"

msg += sep_top + "\n"
msg += progress_format.format(*jobStatusHeader) + "\n"
msg += progress_format.format(*jobStatusInfo) + "\n"
msg += sep_mid + "\n"
msg += progress_format.format(*progressbar_content) + "\n"
msg += progress_format.format(*progressbartime_content) + "\n"
msg += sep_end + "\n"

if VERBOSE:
    print(msg, flush=True)
if WRITEFILE:
    delete_write_line_to_file(statusFilename, msg, end=delete_line_index)

## PIP INSTALL =====
→ =====

def pip_install(modules):
    required = modules
    installed = {pkg.key for pkg in pkg_resources.working_set}
    missing = required - installed

    if missing:
        subprocess.check_call([sys.executable, "-m", "pip", "install",
        → "--user", *missing],
        stdout=subprocess.DEVNULL,
        → stderr=subprocess.DEVNULL)

        print_table_row(["INSTALL", "Required Modules installed"])
    else:
        print_table_row(["CHECK", "Modules already installed"])

## FILE =====
→ =====

def get_value_of_variable_from_file(filename, file_index, relative_index,
→ string):
    try:
        content = [i.strip().split() for i in open(filename).readlines()]
        index = [idx for idx, s in enumerate(content) if string in
        → s][file_index]
        value = content[index][relative_index]
        return value
    except IndexError:
```

```

print_table_row(["ERROR", "String not found in file"])
quit()

def find_string_in_file(filename, string):

    with open(filename) as f:
        if string in f.read():
            return True
        else:
            return False

def delete_write_line_to_file(filename, add = "", start=None, end=None):

    with open(filename, "r") as file:

        try:
            lines = file.readlines()[start:end]
            content = "".join(lines)

        except IndexError:
            pass

        content += add

        write_file(filename, content)

def write_file(filename, content):

    with open(filename, "w") as file:
        file.write(content)
        file.flush()

# Reset gkwdata.h5 with the use of dump files DM1, DM2
# AUTHOR: Florian Rath
# IMPORT: gkw_reset_checkpoint.py
#         (https://bitbucket.org/gkw/gkw/src/develop/python/gkw_reset_checkpoint.py)
def reset_simulation(SIM_DIR, NTIME=None, use_ntime=False):

    # Function that deletes all data in interval [nt_reset:nt_broke].
    # ncol considers, if data series is ordered by a multiple interger of
    # ntime.
    def reset_time_trace(indata, dim, ncol, nt_reset):

        # Shift dimension dim to 0.
        data_shifted = np.moveaxis(indata, dim, 0)

        # Reset data.
        data_shifted_trimmed = data_shifted[0:int(nt_reset*ncol),]

        # Shift dimension back.
        out = np.moveaxis(data_shifted_trimmed, 0, dim)

        # free memory

```

```

    del data_shifted
    del data_shifted_trimmed

    return out

# Checks if file has binary format.
def is_binary(filename):
    try:
        with open(filename, 'tr') as check_file:
            check_file.read()
        return False
    except:
        return True


# Check for specific files that are no ordinary data files.
def is_file_exception(filename):

    # substrings that have to be checked
    check_list = ['geom.dat', 'DM1.dat', 'DM2.dat', 'FDS.dat', '.o',
    ↪ 'FDS',
    ↪ 'input.dat', 'perform_first.dat', 'perform.dat',
    ↪ 'output.dat',
    ↪ 'gkwdata.meta', 'gkw_hdf5_errors.txt',
    ↪ 'kx_connect.dat',
    ↪ 'jobscript', 'Poincare1.mat', 'perfloop_first.dat',
    ↪ 'par.dat',
    ↪ 'input_init.dat', 'sgrid', 'gkw', '.out', 'status.txt']
    for key in check_list:
        if key in filename:
            return True

    return False


# Check if given file is a PBS or SLURM jobscript.
def is_jobscript(filename):
    with open(filename, 'r') as file:
        for line in file:
            if '#PBS -l' in line:
                return True
            if '#SBATCH' in line:
                return True

    return False


def get_timestep(FILE):
    if(os.path.isfile(SIM_DIR+'/'+FILE+'.dat')):
        EXISTS = True
        with open(SIM_DIR+'/'+FILE+'.dat', 'r') as file:
            for line in file:
                if 'NT_REMAIN' in line:

```

```

        expr = line.replace(' ', '')
        expr = expr.replace(',', '')
        expr = expr.replace('\n', '')
        REMAIN = int(expr.split('=')[1])
    if 'NT_COMPLETE' in line:
        expr = line.replace(' ', '')
        expr = expr.replace(',', '')
        expr = expr.replace('\n', '')
        COMPLETE = int(expr.split('=')[1])
    else:
        REMAIN, COMPLETE, EXISTS = None, None, False

    return REMAIN, COMPLETE, EXISTS

HDF5_FILENAME = "gkwdata.h5"
RESTARTFILE, DUMPFIELD1, DUMPFIELD2, = "FDS", "DM1", "DM2"

# Change to simulation directory.
if(not os.path.isdir(SIM_DIR)):
    return
else:
    os.chdir(SIM_DIR)

# Check if hdf5-file exists.
if(not os.path.isfile(HDF5_FILENAME)):
    return

# First, read hdf5 file and determine the number of big time steps NTIME,
# requested in the input.dat file.
f = h5py.File(HDF5_FILENAME, "r+")

# Get requested big time steps from the /control group in the hdf5-file.
if(NTIME==None):
    NTIME = int(f['input/control/ntime'][:])

# Get number of big time steps after which simulation broke.
# If time.dat exists read this file to obtain number of time steps after
# which simulation broke.
if(os.path.isfile('time.dat')):
    tim = pd.read_csv(SIM_DIR+'time.dat', header=None, sep='\s+').values
    NT_BROKE = tim.shape[0]
# Else, get time from hdf5-file.
else:
    NT_BROKE = f['diagnostic/diagnos_growth_freq/time'].shape[1]

# Set NT_BROKE for output files holding temporal derivates and therefore
# one timestep less.
NT_BROKE_DERIV = NT_BROKE-1

# Close the hdf5-file again.

```

```

f.close()

# Get the number of remaining big time steps NT_REMAIN from checkpoint
# files FDS.dat. This is used lateron to determine the most recent
# checkpoint file.
NT_REMAIN, NT_COMPLETE, FDS_EXISTS = get_timestep(RESTARTFILE)

# Get the number of remaining big time steps NT_REMAIN[1/2] from
# checkpoint
# files DM[1/2]. This is used lateron to determine the most recent
# checkpoint file.
NT_REMAIN1, NT_COMPLETE1, DM1_EXISTS = get_timestep(DUMPF1LE1)
NT_REMAIN2, NT_COMPLETE2, DM2_EXISTS = get_timestep(DUMPF1LE1)

# Check if FDS is the most recent checkpoint file. In this case
# resetting the simulation makes no sense.
if(FDS_EXISTS):
    DM1_OLD, DM2_OLD = False, False
    if(DM1_EXISTS):
        if(NT_COMPLETE1 < NT_COMPLETE):
            DM1_OLD = True
    if(DM2_EXISTS):
        if(NT_COMPLETE2 < NT_COMPLETE):
            DM2_OLD = True
    if(DM1_OLD and DM2_OLD):
        return

# Now determine which checkpoint file is the recent one.
if(DM1_EXISTS and DM2_EXISTS):
    if(NT_REMAIN1 > NT_REMAIN2):
        NT_REMAIN, NT_COMPLETE, DUMPF1LE = NT_REMAIN2, NT_COMPLETE2,
    ↪ DUMPF1LE2
    else:
        NT_REMAIN, NT_COMPLETE, DUMPF1LE = NT_REMAIN1, NT_COMPLETE1,
    ↪ DUMPF1LE1

elif(DM1_EXISTS and not DM2_EXISTS):
    NT_REMAIN, NT_COMPLETE, DUMPF1LE = NT_REMAIN1, NT_COMPLETE1,
    ↪ DUMPF1LE1

elif(DM2_EXISTS and not DM1_EXISTS):
    NT_REMAIN, NT_COMPLETE, DUMPF1LE = NT_REMAIN2, NT_COMPLETE2,
    ↪ DUMPF1LE2

else:
    return

if(not use_ntime):
    # Find the total number ob big time steps the simulation time trace
    ↪ should have,

```

```

# when considering the big time steps already completed as well as
→ the big time
    # steps that remain. Can be different from NTIME, since the
→ simulation could
    # have been restarted several times such that NTIME > NT_COMPLETE.
NTOT = NT_COMPLETE + NT_REMAIN
N_REQUEST = NTOT

    # Determine the time steps to which the time trace files have to be
→ reset.
    # Use NTOT here, since NTIME could have been changed at some point,
→ or NT_COMPLETE
    # could be larger than NTIME.
    NT_RESET = NTOT-NT_REMAIN
else:
    # Determine the time steps to which the time trace files have to be
→ reset.
    NT_RESET = NTIME-NT_REMAIN
    N_REQUEST = NTIME

# Same for files holding time derivatives.
NT_RESET_DERIV = NT_RESET-1

# -----
# Cycle over all nodes of hdf5-file and reset time trace datasets.

# Check if hdf5-file exists.
if(os.path.isfile(HDF5_FILENAME)):

    # Find all possible keys items, i.e. both groups and datasets
    f = h5py.File(HDF5_FILENAME, "a")
    h5_keys = []
    f.visit(h5_keys.append)

    # Cycle over all keys items and check, if any dimension has size
→ NT_BROKE,
        # i.e., it is a time trace file.
        for item in enumerate(h5_keys):

            data = f.get(item)

            # Consider datasets only.
            if(isinstance(data, h5py.Dataset)):

                #Check if any dimension is an integer multiple of NT_BROKE,
→ by checking
                    # the residual of the division.
                    res = [None]*len(data.shape)
                    for i in range(len(data.shape)):
                        res[i] =
→ data.shape[i]/NT_BROKE-np.floor(data.shape[i]/NT_BROKE)

                    if 0.0 in res:

```

```

# Check which dimension is integer multiple of NT_BROKE
# and save dimension as well as integer.
new_shape = data.shape
for i in range(len(data.shape)):
    ncol = data.shape[i]/NT_BROKE
    res = ncol - np.floor(ncol)
    if(res == 0):
        dim = i
        ncol = int(ncol)
        # adjust new shape to ncol*NT_RESET
        y = list(new_shape)
        y[dim] = int(ncol*NT_RESET)
        new_shape = tuple(y)
        break

# Reset dataset (.resize discards data with indices
→ larger than
# ncol*NT_RESET along dimension dim).
dset = f[item]
dset.resize(int(ncol*NT_RESET),dim)

# After having repaired all datasets, close the hdf5-file again.
f.close()

# -----
# Cycle over all csv-files and reset time trace.
for filename in os.listdir(SIM_DIR):

    # First perform some checks on files; cycle if file is binary, an
→ exception
    # or a jobscript.
    if(is_binary(filename)):
        continue
    if(is_file_exception(filename)):
        continue
    if(is_jobscript(filename)):
        continue

    # no file
    if(not os.path.isfile(filename)):
        continue

    # Load csv file.
    data = pd.read_csv(SIM_DIR+'/'+filename, header=None,
→ sep='\s+').values

    #Check if any dimension is an integer multiple of NT_BROKE, by
→ checking
    #the residual of the division.
    res = [None]*len(data.shape)

```

```

# residul for output that holds time derivatives and therefore nt-1
→ datapoints
    res_deriv = [None]*len(data.shape)
    for i in range(len(data.shape)):
        res[i] = data.shape[i]/NT_BROKE-np.floor(data.shape[i]/NT_BROKE)
        res[i] =
    ↪ data.shape[i]/(NT_BROKE_DERIV)-np.floor(data.shape[i]/(NT_BROKE_DERIV))

    # ordinary files
    if 0.0 in res:

        #Check which dimension is integer multiple of NT_BROKE
        #and save dimension as well as integer.
        for i in range(len(data.shape)):
            ncol = data.shape[i]/NT_BROKE
            res = ncol - np.floor(ncol)
            if(res == 0):
                dim = i
                ncol = int(ncol)
                break

        # Load original dataset.
        original_data = data
        # print('\t Original shape: \t'+str(original_data.shape))

        # Reset time trace.
        reset_data = reset_time_trace(original_data,dim,ncol,NT_RESET)
        # print('\t Reset shape: \t' +str(reset_data.shape))

        # Save resetted data.
        pd.DataFrame(reset_data).to_csv(filename, sep='\t', header=None,
    ↪ index=None)

        # files holding time derivatives
        if 0.0 in res_deriv:

            # Check which dimension is integer multiple of NT_BROKE
            # and save dimension as integer.
            for i in range(len(data.shape)):
                ncol = data.shape[i]/NT_BROKE_DERIV
                res = ncol - np.floor(ncol)
                if(res == 0):
                    dim = i
                    ncol = int(ncol)
                    break

            # Load original dataset.
            original_data = data

            # Reset time trace.
            reset_data =
    ↪ reset_time_trace(original_data,dim,ncol,NT_RESET_DERIV)

```

```

# Save resetted data.
pd.DataFrame(reset_data).to_csv(filename, sep='\t', header=None,
→ index=None)

# -----
# Finally, copy most recent dump file to FDS[/.dat].
# Copy the most recent dump file to FDS[/.dat].
copyfile(SIM_DIR+'/' +DUMPFFILE, SIM_DIR+'/' +'FDS')
copyfile(SIM_DIR+'/' +DUMPFFILE+'.dat', SIM_DIR+'/' +'FDS.dat')

# First line of the so produced FDS.dat has to be modified.
old_text = '!Dump filename: '+DUMPFFILE
new_text = '!Dump filename: +'+'FDS'

# Replace first line in FDS.dat to set the correct file name.
with fileinput.input(SIM_DIR+'/' +'FDS.dat', inplace=True) as f:
    for line in f:
        line.replace(old_text, new_text)

def check_and_delete_file(filenames):

    for filename in filenames:
        if(os.path.isfile(filename)):
            os.remove(filename)

def check_checkpoint_files():
    DM1, DM2 = False, False

    if(os.path.isfile(check1filename) and os.path.isfile(check1Bin)):
        DM1 = True
    if(os.path.isfile(check2filename) and os.path.isfile(check2Bin)):
        DM2 = True

    return DM1, DM2

def get_timestep_from_restartfile(filename, flag):
    return int(get_value_of_variable_from_file("./" + filename, 0, 2,
→ flag).replace(", ", ""))
    → flag).replace(", ", "")

def get_ntimestepCurrent(filenames):

    ntimestep = 0

    for f in filenames:
        if(os.path.isfile(f)):
            ntimestepFile = get_timestep_from_restartfile(f, restartFlag)

            if ntimestepFile > ntimestep:
                ntimestep = ntimestepFile

```

```

    return ntimestep

def get_time_from_statusfile(filename, line_index):
    with open(filename, "r") as file:
        line = file.readlines()[line_index]

        content = line.split(" ")
        time = content[-2]
        time_sec = get_time_in_seconds(time)

    return time_sec

## TIME =====
#→ =====

def format_num(time):
    if time < 10:
        return "0" + str(time)
    else:
        return str(time)

def get_time_as_string(sec):

    mins, sec = sec // 60, sec % 60
    hours, mins = mins // 60, mins % 60
    days, hours = hours // 24, hours % 24
    weeks, days = days // 7, days % 7

    timeConvertedString = (str(int(weeks)) + ":" +
                           format_num(int(days)) + ":" + format_num(int(hours)) +
#→ ":" +
                           format_num(int(mins)) + ":" + format_num(int(sec)))

    return timeConvertedString

def get_time_in_seconds(time):

    # Format D-HH:MM:SS or HH:MM:SS or MM:SS

    time = time.replace("-", ":")
    time_split = time.split(":")

    seconds = [7*24*60*60, 24*60*60, 60*60, 60, 1]
    seconds = seconds[-len(time_split):]

    time_sec = sum([a*b for a,b in zip(seconds, map(int,time_split))])

    return time_sec

def time_date():
    e = datetime.datetime.now()
    return "%s-%s-%s" % (format_num(e.year), format_num(e.month),

```

```
    ↵ format_num(e.day))

def time_time():
    e = datetime.datetime.now()
    return "%s:%s:%s" % (format_num(e.hour), format_num(e.minute),
    ↵ format_num(e.second))

def time_duration(startTime, pastTime):
    stop = time.time()
    return get_time_as_string(stop - startTime + pastTime)

## STATUS =====
    ↵ =====

def get_job_status():

    jobStatusRunning =
    ↵ subprocess.getoutput(commandJobRunning).strip().split()
    jobStatusPending =
    ↵ subprocess.getoutput(commandJobPending).strip().split()

    return jobStatusRunning, jobStatusPending

def set_output_type():
    jobStatusRunning, jobStatusPending = get_job_status()

    if jobName in jobStatusRunning:
        outputType = "running"
    elif jobName in jobStatusPending:
        outputType = "pending"
    else:
        outputType = "no Output"

    return outputType

def get_error_type(filename):

    slurm_errors = {"executable": ["error on file ./gkw.x (No such file or
    ↵ directory)", "No executable found"],
                    "walltime": ["process killed (SIGTERM)", "Exceeded wall
    ↵ time"],
                    "timeout": ["DUE TO TIME LIMIT", "Exceeded time limit"],
                    "config": ["couldn't open config directory", "Config not
    ↵ loading"],
                    "hdf5": ["HDF5-DIAG", "Writing h5 file failed"]}

    for key in slurm_errors:
        if find_string_in_file(filename, slurm_errors[key][0]):
            return slurm_errors[key][1]

    return "Unknown error occurred"

## MAIL =====
```

```

↔ =====
def send_mail(recipient, subject, body = None):

    recipient = recipient.encode("utf_8")

    subject = subject.replace(" ", "_")
    subject = subject.encode("utf_8")

    if body == None:
        body = "For futher information open attachment"

    body = body.encode("utf_8")

    attachmentPath = folder + "/" + statusFilename
    attachment = attachmentPath.encode("utf_8")

    process = subprocess.Popen(["ssh", "master", "/usr/bin/mailx", "-s",
        ↪ subject, "-a", attachment, recipient],
        stdin=subprocess.PIPE)
    process.communicate(body)

## KILL JOB =====
↔ =====

PID = subprocess.getoutput(commandMonitorKill).split("\n")[0]
if kill:
    subprocess.run(["kill", PID])
    quit()

# START/RESTART JOB =====
↔ =====

startTime = time.time()
outputType = set_output_type()
jobStatusRunning, jobStatusPending = get_job_status()

# Set current Time for progress bar
if outputType == "running":
    jobStatusRunningNameIndex = [idx for idx, s in
        ↪ enumerate(jobStatusRunning) if jobName in s][0]
    currentTime = jobStatusRunning[jobStatusRunningNameIndex + 3]
elif outputType == "pending":
    jobStatusPendingNameIndex = [idx for idx, s in
        ↪ enumerate(jobStatusPending) if jobName in s][0]
    currentTime = jobStatusPending[jobStatusPendingNameIndex + 3]
else:
    currentTime = "00:00:00"

# Set pastTime and create status file if necessary. When status file exist
    ↪ append next lines
WRITEHEADER = True
if not os.path.isfile(statusFilename):

```

```

pastTime = 0
write_file(statusFilename, "")
else:
    try:
        pastTime = get_time_from_statusfile(statusFilename, -11)
        WRITEHEADER = False
    except IndexError:
        pastTime = 0

print_table_row(["OUTPUT", "INFO"], output_type="header",
    ↪ WRITEFILE=WRITEHEADER)

## BEGIN =====
    ↪ =====

# Check if timesteps criterion is satisfied, send mail and end monitoring
# else continue monitoring and set output type accordingly
nTimestepsCurrent = get_ntimestepCurrent([restartFilename, check1Filename,
    ↪ check2Filename])

if nTimestepsCurrent >= nTimestepsRequired:
    print_table_row(["CONTROL", "Current Timesteps " +
    ↪ str(nTimestepsCurrent)], output_type="middle")
    print_table_row(["SUCCESS", "Stop monitoring " + jobName])

    if EMAIL:
        send_mail(emailAddress, "Ended Job " + jobName)

    quit()

# Continue monitoring and send mail
else:

    if outputType != "no Output":
        print_table_row(["CONTINUE", "Continue monitoring " + jobName],
    ↪ output_type="middle")
        print_table_row(["CONTROL", "Current Timesteps " +
    ↪ str(nTimestepsCurrent)])

        if EMAIL:
            send_mail(emailAddress, "Continued Job " + jobName)

    elif os.path.isfile(restartFilename):
        print_table_row(["CONTINUE", "Continue monitoring " + jobName],
    ↪ output_type="middle")

        if EMAIL:
            send_mail(emailAddress, "Continued Job " + jobName)

    else:
        print_table_row(["STARTING", "Start monitoring " + jobName],
    ↪ output_type="middle")

```

```

if BACKUP:
    print_table_row(["BACKUP", backupPath])
    subprocess.run(commandBackup)

if EMAIL:
    send_mail(emailAddress, "Started Job " + jobName)

if RESET:
    pip_install({"h5py", "pandas", "numpy"})

    import h5py, fileinput
    import pandas as pd
    import numpy as np
    from shutil import copyfile

    print_table_row(["IMPORT", "Load numpy, pandas, h5py"])

#else:
#    pip_install({"h5py"})
#    import h5py
#    print_table_row(["IMPORT", "Load module h5py"])

## MONITOR ROUTINE =====
#→ =====

while True:

    # Check job status to monitor current state
    jobStatusRunning, jobStatusPending = get_job_status()

    # Job running
    if jobName in jobStatusRunning:

        jobStatusRunningNameIndex = [idx for idx, s in
        ↪ enumerate(jobStatusRunning) if jobName in s][0]
        jobID = jobStatusRunning[jobStatusRunningNameIndex - 2]

        currentTime = jobStatusRunning[jobStatusRunningNameIndex + 3]
        nTimestepsCurrent = get_ntimestepCurrent([restartFilename,
        ↪ check1Filename, check2Filename])

        if outputType == "running":
            print_table_row(["RUNNING", "Job is executed"])
            outputType = "no Output"
        else:
            print_table_row(["RUNNING", "Job is executed"],
            ↪ output_type="update")

        time.sleep(sleepTime)

    # Job pending
    elif jobName in jobStatusPending:

```

```

jobStatusPendingNameIndex = [idx for idx, s in
↪ enumerate(jobStatusPending) if jobName in s][0]
jobID = jobStatusPending[jobStatusPendingNameIndex - 2]

currentTime = jobStatusPending[jobStatusPendingNameIndex + 3]
nTimestepsCurrent = get_ntimestepCurrent([restartFilename,
↪ check1Filename, check2Filename])

if outputType == "pending":
    print_table_row(["WAITING", "Job is pending"])
    outputType = "running"
else:
    print_table_row(["WAITING", "Job is pending"],
↪ output_type="update")

time.sleep(sleepTime)

# Job start/restart
else:

    # Check errors and making Backup
    while True:
        try:
            outputContent =
↪ open(outputFilename(jobID)).readlines()[-5].replace("\n", "")

            # Create Backup if run is successful
            # If scan of output.dat is needed: Scans for string "Run
↪ Successful in output.dat and returns bool value"
            #runSuccess = find_string_in_file("output.dat",
↪ outputCriteria[1])
            #if outputCriteria[0] in outputContent and runSuccess:

            if outputCriteria[0] in outputContent:

                # Check if h5 file is closed before start/restart
↪ simulation
                    # than check if FDS/FDS.dat is updated
                    try:
                        f = open(dataFilename)
                        #f = h5py.File(dataFilename)
                        f.close()

                        # Check if FDS/FDS.dat is updated after run and has
↪ equally time stamp as gkwdata.h5
                        timestamp_data =
↪ int(os.path.getmtime(dataFilename))
                        timestamp_restart =
↪ int(os.path.getmtime(restartFilename))

                        wallTime_sec = get_time_in_seconds(wallTime)
                        timestamp_remain = timestamp_data - timestamp_restart

```

```

# FDS/FDS.dat does not get written at the same time
↪ as gkwdata.h5
    # For that a time interval have to be considered
    # To be certain the half wall time is set aus time
↪ interval
    if timestamp_remain > wallTime_sec/2:

        print_table_row(["ERROR", "FDS/FDS.dat not
↪ updated"])

        # Reset simulation and save as backup
        if RESET:

            DM1, DM2 = check_checkpoint_files()

            if (DM1 or DM2):
                print_table_row(["RESET", "Reset to last
↪ checkpoint."])
                reset_simulation(folder)

                # Update backup
                if BACKUP:
                    print_table_row(["BACKUP",
↪ backupPath])
                    subprocess.run(commandBackup)

                # Restore backup to rerun simulation
                elif BACKUP:
                    print_table_row(["RESTORE", backupPath])
                    subprocess.run(commandRestore)

                elif BACKUP:
                    print_table_row(["BACKUP", backupPath])
                    subprocess.run(commandBackup)

                break
            except OSError:
                time.sleep(sleepTime)

        else:
            print_table_row(["ERROR",
↪ get_error_type(outputFilename(jobID))])

            # Reset simulation and save as backup
            if RESET:

                DM1, DM2 = check_checkpoint_files()

                if (DM1 or DM2):
                    print_table_row(["RESET", "Reset to last
↪ checkpoint."])
                    reset_simulation(folder)

```

```

        # Update backup
        if BACKUP:
            print_table_row(["BACKUP", backupPath])
            subprocess.run(commandBackup)

        # Restore backup to rerun simulation
        elif BACKUP:
            print_table_row(["RESTORE", backupPath])
            subprocess.run(commandRestore)

        break

    # Wait sleepTime and check output file again
    except (IndexError, FileNotFoundError):
        time.sleep(sleepTime)

    # If jobID undefined break cycle
    except NameError:
        break

    # Check if timesteps criterion is satisfied, send mail and end
    ↪ monitoring
        nTimestepsCurrent = get_ntimestepCurrent([restartFilename,
    ↪ check1Filename, check2Filename])
        print_table_row(["CONTROL", "Current Timesteps " +
    ↪ str(nTimestepsCurrent)])

        if nTimestepsCurrent >= nTimestepsRequired:
            print_table_row(["SUCCESS", "Stop monitoring " + jobName])

        if EMAIL:
            send_mail(emailAddress, "Ended Job " + jobName)
            break

    # Delete checkpoint files
    check_and_delete_file([check1Bin, check1Filename, check2Bin,
    ↪ check2Filename])

    # Create jobsript
    if jobsriptFilename == "jobsript-create":
        jobsriptFilename = "jobsript"
        write_file(jobsriptFilename, jobsriptContent)

    # Start Job and send restart mail (if activated)
    startOutput = subprocess.check_output([commandJobStarting,
    ↪ jobsriptFilename]).decode("utf-8").replace("\n", "")
    jobID = startOutput.split(startOutputFlag)[1]

    runCounter += 1

    print_table_row(["STARTING", startOutput], output_type="middle")

    try:

```

```
if RESTARTMAIL and EMAIL:
    send_mail(emailAddress, "Restart Job " + jobName)
except NameError:
    continue

time.sleep(30)

# Set output type to running or pending
outputType = set_output_type()

## RESTART =====
→ =====
```

6.2 Status File

| OUTPUT | INFO | DATE | TIME | W:DD:HH:MM:SS |
|----------|----------------------------|------------|----------|---------------|
| STARTING | Start monitoring 3x1.5 | 2023-01-23 | 09:58:18 | 0:00:00:00:00 |
| BACKUP | /scratch/bt712347/backup/ | 2023-01-23 | 09:58:18 | 0:00:00:00:00 |
| | | | | |
| STARTING | Submitted batch job 903536 | 2023-01-23 | 09:58:20 | 0:00:00:00:01 |
| RUNNING | Job is executed | 2023-01-23 | 09:58:50 | 0:00:00:00:31 |
| BACKUP | /scratch/bt712347/backup/ | 2023-01-24 | 09:38:08 | 0:00:23:39:49 |
| CONTROL | Current Timesteps 2086 | 2023-01-24 | 09:38:49 | 0:00:23:40:30 |
| | | | | |
| STARTING | Submitted batch job 905108 | 2023-01-24 | 09:38:49 | 0:00:23:40:30 |
| RUNNING | Job is executed | 2023-01-24 | 09:39:19 | 0:00:23:41:01 |
| BACKUP | /scratch/bt712347/backup/ | 2023-01-25 | 09:18:41 | 0:01:23:20:22 |
| CONTROL | Current Timesteps 4179 | 2023-01-25 | 09:19:35 | 0:01:23:21:16 |
| | | | | |
| STARTING | Submitted batch job 906542 | 2023-01-25 | 09:19:35 | 0:01:23:21:16 |
| RUNNING | Job is executed | 2023-01-25 | 09:20:05 | 0:01:23:21:46 |
| BACKUP | /scratch/bt712347/backup/ | 2023-01-26 | 08:59:21 | 0:02:23:01:03 |
| CONTROL | Current Timesteps 6289 | 2023-01-26 | 09:00:38 | 0:02:23:02:19 |
| | | | | |
| STARTING | Submitted batch job 907237 | 2023-01-26 | 09:00:38 | 0:02:23:02:19 |
| RUNNING | Job is executed | 2023-01-26 | 09:01:08 | 0:02:23:02:49 |
| BACKUP | /scratch/bt712347/backup/ | 2023-01-27 | 08:40:56 | 0:03:22:42:37 |
| CONTROL | Current Timesteps 8411 | 2023-01-27 | 08:42:23 | 0:03:22:44:04 |
| | | | | |
| STARTING | Submitted batch job 910236 | 2023-01-27 | 08:42:23 | 0:03:22:44:04 |
| RUNNING | Job is executed | 2023-01-27 | 08:42:53 | 0:03:22:44:34 |
| BACKUP | /scratch/bt712347/backup/ | 2023-01-28 | 02:41:23 | 0:04:16:43:05 |
| CONTROL | Current Timesteps 10000 | 2023-01-28 | 02:42:50 | 0:04:16:44:31 |
| SUCCESS | Stop monitoring 3x1.5 | 2023-01-28 | 02:42:50 | 0:04:16:44:31 |
| | | | | |
| CONTINUE | Continue monitoring 3x1.5 | 2023-02-09 | 18:22:46 | 0:04:16:44:31 |
| BACKUP | /scratch/bt712347/backup/ | 2023-02-09 | 18:22:46 | 0:04:16:44:31 |
| CONTROL | Current Timesteps 10000 | 2023-02-09 | 18:22:47 | 0:04:16:44:31 |
| | | | | |
| STARTING | Submitted batch job 936758 | 2023-02-09 | 18:22:47 | 0:04:16:44:31 |
| WAITING | Job is pending | 2023-02-09 | 18:23:17 | 0:04:16:45:01 |
| | | | | |
| CONTINUE | Continue monitoring 3x1.5 | 2023-02-11 | 00:12:32 | 0:04:16:45:01 |
| BACKUP | /scratch/bt712347/backup/ | 2023-02-11 | 00:12:32 | 0:04:16:45:01 |
| CONTROL | Current Timesteps 10000 | 2023-02-11 | 00:12:34 | 0:04:16:45:02 |
| | | | | |
| STARTING | Submitted batch job 937665 | 2023-02-11 | 00:12:34 | 0:04:16:45:02 |
| WAITING | Job is pending | 2023-02-11 | 00:13:04 | 0:04:16:45:32 |
| RUNNING | Job is executed | 2023-02-11 | 01:58:08 | 0:04:18:30:36 |
| BACKUP | /scratch/bt712347/backup/ | 2023-02-12 | 01:38:54 | 0:05:18:11:22 |
| CONTROL | Current Timesteps 14497 | 2023-02-12 | 01:41:22 | 0:05:18:13:50 |
| | | | | |

6 Appendix

```

| STARTING Submitted batch job 937946 2023-02-12 01:41:22 0:05:18:13:50 |
| RUNNING Job is executed 2023-02-12 01:41:52 0:05:18:14:20 |
| BACKUP /scratch/bt712347/backup/ 2023-02-13 01:22:37 0:06:17:55:06 |
| CONTROL Current Timesteps 18985 2023-02-13 01:25:40 0:06:17:58:08 |
+-----+
| STARTING Submitted batch job 938797 2023-02-13 01:25:40 0:06:17:58:08 |
| RUNNING Job is executed 2023-02-13 01:26:10 0:06:17:58:38 |
| BACKUP /scratch/bt712347/backup/ 2023-02-13 06:51:20 0:06:23:23:48 |
| CONTROL Current Timesteps 20000 2023-02-13 06:54:11 0:06:23:26:40 |
| SUCCESS Stop monitoring 3x1.5 2023-02-13 06:54:11 0:06:23:26:40 |
+-----+
| CONTINUE Continue monitoring 3x1.5 2023-02-13 15:34:37 0:06:23:26:40 |
| BACKUP /scratch/bt712347/backup/ 2023-02-13 15:34:37 0:06:23:26:40 |
| CONTROL Current Timesteps 20000 2023-02-13 15:34:38 0:06:23:26:40 |
+-----+
| STARTING Submitted batch job 939062 2023-02-13 15:34:38 0:06:23:26:41 |
| RUNNING Job is executed 2023-02-13 15:35:08 0:06:23:27:11 |
| BACKUP /scratch/bt712347/backup/ 2023-02-14 11:31:13 1:00:19:23:15 |
| CONTROL Current Timesteps 20000 2023-02-14 11:38:17 1:00:19:30:19 |
+-----+
| STARTING Submitted batch job 952358 2023-02-14 11:38:17 1:00:19:30:19 |
| RUNNING Job is executed 2023-02-14 11:38:47 1:00:19:30:49 |
| ERROR SLURM Job failed to execute 2023-02-14 15:38:58 1:00:23:31:01 |
| RESTORE /scratch/bt712347/backup/ 2023-02-14 15:38:58 1:00:23:31:01 |
| CONTROL Current Timesteps 20000 2023-02-14 15:44:44 1:00:23:36:46 |
+-----+
| STARTING Submitted batch job 956235 2023-02-14 15:44:44 1:00:23:36:46 |
| RUNNING Job is executed 2023-02-14 15:45:14 1:00:23:37:17 |
| ERROR SLURM Job failed to execute 2023-02-15 11:01:35 1:01:18:53:38 |
| RESTORE /scratch/bt712347/backup/ 2023-02-15 11:01:44 1:01:18:53:46 |
| CONTROL Current Timesteps 20000 2023-02-15 11:06:52 1:01:18:58:54 |
+-----+
| STARTING Submitted batch job 969292 2023-02-15 11:06:52 1:01:18:58:54 |
| RUNNING Job is executed 2023-02-15 11:07:22 1:01:18:59:24 |
| ERROR SLURM Job failed to execute 2023-02-16 10:48:07 1:02:18:40:09 |
| RESTORE /scratch/bt712347/backup/ 2023-02-16 10:48:07 1:02:18:40:09 |
| CONTROL Current Timesteps 20000 2023-02-16 10:51:17 1:02:18:43:20 |
+-----+
| STARTING Submitted batch job 970455 2023-02-16 10:51:17 1:02:18:43:20 |
| WAITING Job is pending 2023-02-16 10:51:47 1:02:18:43:50 |
| RUNNING Job is executed 2023-02-16 12:56:50 1:02:20:48:53 |
| BACKUP /scratch/bt712347/backup/ 2023-02-16 16:11:56 1:03:00:03:59 |
+-----+
+-----+
| JOBID PARTITION NAME USER ST TIME NODES NODELIST (REASON) |
| 970455 normal 3x1.5 bt712347 CG 3:16:01 3 r03n03,r05n[15-16] |
+-----+
| PROGRESS [=====>.....] ( 80%) 20000/25000 |
| RUN 13 [===>.....] ( 13%) 11462/86400 |
+-----+

```

6.3 torque_monitor.py

```
#!/usr/bin/env python3

# AUTHOR: Manuel Lippert (GitHub: ManeLippert
#         ↪ (https://github.com/ManeLippert))
#
# DESCRIPTION:
# Script that starts a given job (shell script) with Sun Grid Engine until
# ↪ the previous defined timestep are completed.
# It also sends an mail alert when the job gets started and ended.

# IMPORTANT:
# Take a look in the Variable Section but overall everthing should work
# ↪ automatically

# START SCRIPT:
# To start the script in the background following command is needed:
#
# >>> nohup python3 -u monitor_job.py &> status.txt &
#
# Output:
#
# >>> [1] 10537
#
# This will write every output in the file jobstatus.txt that will be send
# ↪ as attachment to the defined mail address.

# LIST PRGRESS:
# To see which progress is in background running following command is needed:
#
# >>> ps ax | grep monitor_job.py
#
# Output:
#
# >>> 10537 pts/1      S          0:00 python3 -u monitor_job.py
# >>> 23426 pts/1      S+         0:00 grep --color=auto monitor_job.py
#
# This will give you the ID to kill monitoring script with the command:
#
# >>> kill 10537
#
# This will kill the monitor script.

# OUTPUT STATUS:
# To see all status.txt files with one command follwing command is needed:
#
# >>> cd $DATA && find . -name status.txt -exec tail --lines=+10 {} \;

'''
```

```
#####
#          Modules
#
#####
'''
```

```
import datetime
import time
from time import sleep
import os
import subprocess
```

```
'''
```

```
#####
#          VARIABLES
#
#####
'''
```

```
#####
# ADDITIONAL #####
#emailAddress = 'Dominik.Mueller@uni-bayreuth.de'
#backupLocation = '/scratch/bt712347/backup'
```

```
#####
# FILENAMES #####
# Finds File that ends with .sh
for file in os.listdir():
    if file.endswith('.sh'):
        jobscriptFilename = file

# Rename jobscript
dirName = os.getcwd().split('/')[-1]
os.rename(jobscriptFilename, dirName + '.sh')
jobscriptFilename = dirName + '.sh'

monitorFilename = 'status.txt'

# Finds File that ends with .json
for file in os.listdir():
    if file.endswith('.json'):
        inputFilename = file

restartFilename = inputFilename

# Declared as function for dynamic changes
def outputFilename(info):
    return jobscriptFilename + '.o' + info
```

```
#####
# FLAGS #####

```

```

walltimeFlag = 'time='

startOutputFlag = '.mgmt'

outputCriteria = 'WARNING'

inputFlag = '"Number'

restartFlag = 'ETA:'
restartString = '          "Restart from step": '

##### SLEEP TIME #####
sleepTime = 5*60

##### COMMANDS #####
commandJobStatus = 'qstat -u'
commandJobStarting = 'qsub'

''''
#####
#                         FUNCTIONS
######
''''

##### INFORMATIONS #####
def read_file_to_string(file):
    content = ''.join(open(file).readlines())

    return content

def get_value_of_variable_from_input_file(file, string, idx):
    try:
        content = [i.strip().split() for i in open(file).readlines()]
        index = [idx for idx, s in enumerate(content) if string in s][idx]
        value = int(content[index][4].split(',')[0])
        return value
    except IndexError:
        print('! String not in input file !')
        quit()

def get_value_of_variable_from_output_file(file, string, idx):
    try:
        content = [i.strip().split() for i in open(file).readlines()]
        index = [idx for idx, s in enumerate(content) if string in s][idx]
        value = int(content[index - 1][0])
        return value
    except IndexError:
        print('! String not in input file !')

```

```

quit()

def get_job_information_from_jobscript_flag(content, flag):
    index = [idx for idx, s in enumerate(content) if flag in s][0]
    info = content[index].split(flag, 1)[1]

    return info

##### FILE #####
def write_add_string_into_file(file, substring, add, comment = None):
    # open file
    with open(file, 'r') as f:
        # read a list of lines into data
        data = f.readlines()

    try:
        index = [idx for idx, s in enumerate(data) if substring in s][0]
        data[index] = substring + add + '\n'

    except IndexError:
        index = [idx for idx, s in enumerate(data) if '\n' in s][1]
        data.insert(index, '\n')
        data.insert(index + 1, comment)
        data.insert(index + 2, substring + add + '\n')

    # replace line
    with open(file, 'w') as f:
        f.writelines(data)

##### TIME #####
def get_time_in_seconds(time):
    # Check time format of time
    if len(time) < 5:
        ## d:hh:mm:ss
        if len(time) == 4:
            timeSeconds = int(time[0])*24*60*60 + int(time[1])*60*60 +
    ↳ int(time[2])*60 + int(time[3])
        ## hh:mm:ss
        elif len(time) == 3:
            timeSeconds = int(time[0])*60*60 + int(time[1])*60 + int(time[2])
        ## mm:ss
        elif len(time) == 2:
            timeSeconds = int(time[0])*60 + int(time[1])
        ## ss
        elif len(time) == 1:
            timeSeconds = int(time[0])
    else:
        print('! Time format is not supported !')
        quit()

    return timeSeconds

```

```

def format_num(time):
    if time < 10:
        return '0' + str(time)
    else:
        return str(time)

def get_time_converted(sec):
    mins, sec = sec // 60, sec % 60
    hours, mins = mins // 60, mins % 60
    days, hours = hours // 24, hours % 24
    weeks, days = days // 7, days % 7

    timeConverted = (str(int(weeks)) + ':' +
                      format_num(int(days)) + ':' + format_num(int(hours)) + ':' +
                      format_num(int(mins)) + ':' + format_num(int(sec)))

    return timeConverted

def time_date():
    e = datetime.datetime.now()
    return '%s-%s-%s' % (format_num(e.year), format_num(e.month),
                         format_num(e.day))

def time_time():
    e = datetime.datetime.now()
    return '%s:%s:%s' % (format_num(e.hour), format_num(e.minute),
                         format_num(e.second))

def time_duration(startTime):
    stop = time.time()
    return get_time_converted(stop - startTime)

##### TABLE #####
def table_row_format(content):
    if len(content) == 7:
        cols = [2, 10, 29, 13, 11, 13, 2]
    elif len(content) == 6:
        cols = [2, 10, 29, 13, 24, 2]
    elif len(content) == 5:
        cols = [2, 10, 25, 41, 2]
    elif len(content) == 4:
        cols = [2, 10, 66, 2]
    else:
        cols = [2, 76, 2]

    i, sep = 0, []

    while i < len(cols):
        if i == 0:
            sep.append('o' + (cols[i]-1)*'-')
        elif i == (len(cols)-1):

```

```

        sep.append((cols[i]-1)*'-' + 'o')
    else:
        sep.append(cols[i]*'-')

    i += 1

    row_format = "".join(["{:<" + str(col) + "}" for col in cols])

    return row_format, sep

def print_table_row(content, output_type = None, time_info = True):

    if isinstance(content[0], list):

        i = 0
        while i < len(content):
            content[i].insert(0, '| ')
            if time_info:
                if output_type == 'header':
                    content[i].append('DATE')
                    content[i].append('TIME')
                    content[i].append('W:DD:HH:MM:SS')
                else:
                    content[i].append(time_date())
                    content[i].append(time_time())
                    content[i].append(time_duration(startTime))
            content[i].insert(len(content[i]), '| ')
            i += 1

        row_format, sep = table_row_format(content[0])

        if output_type == 'header':
            print('\n')
            print(row_format.format(*sep))
            for row in content:
                print(row_format.format(*row))
            print(row_format.format(*sep))

        elif output_type == 'end':
            for row in content:
                print(row_format.format(*row))
            print(row_format.format(*sep))

        else:
            for row in content:
                print(row_format.format(*row))
    else:
        content.insert(0, '| ')
        if time_info:
            if output_type == 'header':
                content.append('DATE')
                content.append('TIME')

```

```

        content.append('W:DD:HH:MM:SS')
    else:
        content.append(time_date())
        content.append(time_time())
        content.append(time_duration(startTime))
    content.insert(len(content), ' | ')

    row_format, sep = table_row_format(content)

    if output_type == 'header':
        print('\n')
        print(row_format.format(*sep))
        print(row_format.format(*content))
        print(row_format.format(*sep))

    elif output_type == 'end':
        print(row_format.format(*content))
        print(row_format.format(*sep))

    else:
        print(row_format.format(*content))

#####
# STATUS #####
def get_job_status(user):
    jobStatus = subprocess.getoutput(commandJobStatus + user).strip().split()

    return jobStatus

def set_output_type(user):
    jobStatus = get_job_status(user)

    if jobName in jobStatus:
        outputType = 'running'
    else:
        outputType = 'no Output'

    return outputType

#####
# MAIL #####
def send_mail(recipient, subject, body = None):

    recipient = recipient.encode('utf_8')

    subject = " " + subject + " "
    subject = subject.encode('utf_8')

    if body == None:
        body = 'For futher information open attachment'

    body = body.encode('utf_8')

```

```

attachmentPath = folder + '/' + monitorFilename
attachment = attachmentPath.encode('utf_8')

process = subprocess.Popen(['ssh', 'master', '/usr/bin/mailx', '-s',
                           ↳ subject, '-a', attachment, recipient],
                           stdin=subprocess.PIPE)
process.communicate(body)

'''

#####
#          JOB INFORMATIONS
#
#####
'''


#####
#          OUTPUT STRING #####
jobInformations = []

#####
#          START WATCH #####
startTime = time.time()

#####
#          OUTPUT INIT #####
print_table_row(['OUTPUT', 'JOB INITIALIZE'], output_type='header')

#####
#          USER #####
user = os.getlogin()

#####
#          JOB NAME #####
jobName = jobsfilename

if len(jobName) > 16:
    jobName = jobName[0:16]

jobInformations.append(['INFO', 'Name', jobName])

#####
#          FILE PATH #####
folder = os.path.dirname(os.path.abspath(__file__))
path = os.path.dirname(os.path.abspath(__file__)).split(user + '/') [1]

#####
#          MAIL ADDRESS #####
try:
    emailNotification = True
    jobInformations.append(['INFO', 'E-Mail', emailAddress])
except NameError:
    emailNotification = False

```

```

#####
# JOB SCRIPT #####
#####

try:
    jobsCript = [filename for filename in os.listdir('.') if
    ↪ filename.startswith(jobsCriptFilename)][0]
    print_table_row(['SUCCESS', 'Found ' + 'jobsCript file'])

except IndexError:
    print_table_row(['ERROR', 'No jobsCript found'])
    # Send error mail
    if emailNotification:
        send_mail(emailAddress, 'Failed Job ' + jobName)
    quit()

jobsCriptContent = open(jobsCript, 'r').read().splitlines()

#####
# Timesteps #####
#####

# Number of required timesteps
try:
    nTimestepsRequired = 0

    for i in range(10):
        nTimestepsRequired += get_value_of_variable_from_input_file('./' +
    ↪ inputfilename, inputFlag, i)

    print_table_row(['SUCCESS', 'Found ' + 'input file'], output_type='end',
    ↪ time_info=True)
except FileNotFoundError:
    print_table_row(['ERROR', 'No input file found'], output_type='end')
    # Send error mail
    if emailNotification:
        send_mail(emailAddress, 'Failed Job ' + jobName)
    quit()

jobInformations.append(['INFO', 'Required Timesteps', nTimestepsRequired])

#####
# Walltime #####
#####

walltime = get_job_information_from_jobsCript_flag(jobsCriptContent,
    ↪ walltimeFlag).replace('-', ':').split(':')
walltimeSeconds = get_time_in_seconds(walltime)

jobInformations.append(['INFO', 'Walltime/s', walltimeSeconds])

#####
# Backup Path #####
#####

try:
    # Backup location
    if backupLocation[-1] != '/':
        backupLocation += '/'

```

```

backupPath = backupLocation + path

# Create backup directory if do not exist
if not os.path.exists(backupPath):
    os.makedirs(backupPath)

# BackUp switch
backup = True

jobInformations.append(['INFO', 'Backup Path', backupLocation])

except NameError:
    # BackUp switch
    backup = False

#####
##### OUTPUT INFO #####
#####

print_table_row(['OUTPUT', 'JOB INFORMATIONS', 'VALUE'],
    ↪ output_type='header', time_info=False)
print_table_row(jobInformations, output_type='end', time_info=False)

'''

#####
##### START/RESTART JOB #####
#####

#####
##### OUTPUT MONITOR #####
#####

print_table_row(['OUTPUT', 'JOB MONITORING'], output_type='header')

#####
##### BEGIN #####
#####

outputType = set_output_type(user)

# read restart file
## If gkw has run requiered timesteps stop already here
while True:
    try:

        identity = ['']
        # find last output file
        for file in os.listdir():
            if '.sh.o' in file:
                identity.append(file.split('.sh.o')[1])

        nTimestepsCurrent = get_value_of_variable_from_output_file('./' +
    ↪ outputFilename(max(identity)), restartFlag, -1)
        nTimestepsCurrent = int((nTimestepsCurrent // 1e4) * 1e4)

```

```

# Output current timesteps
if outputType == 'running':
    print_table_row(['CONTROL', 'Current Timesteps ' +
→ str(nTimestepsCurrent)])

    # Check if gkw has run requiered timesteps
    if nTimestepsCurrent >= nTimestepsRequired:
        print_table_row(['SUCCESS', 'Stop monitoring'],
→ output_type='end')

        # Send end email
        if emailNotification:
            send_mail(emailAddress, 'Ended Job ' + jobName)

        quit()

    # Continue
    else:
        print_table_row(['CONTINUE', 'Continue monitoring'])

        # Send continue mail
        if emailNotification:
            send_mail(emailAddress, 'Continued Job ' + jobName)
        break

# Start
except (FileNotFoundException, NameError):
    print_table_row(['STARTING', 'Start monitoring'])

    # Making backup
    if backup:
        print_table_row(['BACKUP', backupLocation], output_type='end')
        subprocess.run(['rsync', '-a', '', backupPath])

    # Send start mail
    if emailNotification:
        send_mail(emailAddress, 'Started Job ' + jobName)
    break

#####
##### MONITOR ROUTINE #####
#####

while True:

    jobStatus = get_job_status(user)

    # Job running
    if jobName in jobStatus:
        # Job ID Running
        jobStatusNameIndex = [idx for idx, s in enumerate(jobStatus) if
→ jobName in s][0]
        jobID = jobStatus[jobStatusNameIndex -3].split(startOutputFlag)[0]

        # Set output type

```

```

if outputType == 'running':
    print_table_row(['RUNNING', 'Job is executed'])
    outputType = 'no Output'

sleep(sleepTime)

# Job start/restart
else:

    # Check error and making Backup
    while True:
        try:
            outputContent = read_file_to_string('./' +
→ outputfilename(jobID))

            if outputCriteria in outputContent:

                print_table_row(['ERROR', 'NaN Value in surf_dens'])

                quit()

            else:

                # Making backup
                if backup:
                    print_table_row(['BACKUP', backupLocation],
→ output_type='end')
                    subprocess.run(['rsync', '-a', '', backupPath])

                outputType = 'restart'

                break

        # If jobID is not defined or file is not generated
        except (IndexError, FileNotFoundError):
            sleep(30)
        except NameError:
            break

    # Check Timesteps
    try:
        nTimestepsCurrent = get_value_of_variable_from_output_file('./'
→ + outputfilename(jobID), restartFlag, -1)
        nTimestepsCurrent = int((nTimestepsCurrent // 1e4) * 1e4)

        print_table_row(['CONTROL', 'Current Timesteps ' +
→ str(nTimestepsCurrent)])

        # Check if gkw has run requiered timesteps
        if nTimestepsCurrent >= nTimestepsRequired:
            print_table_row(['SUCCESS', 'Stop monitoring'],
→ output_type='end')

```

```
# Send end email
if emailNotification:
    send_mail(emailAddress, 'Ended Job ' + jobName)
break

# write restart timestep in input file
else:
    write_add_string_into_file(restartFilename, restartString,
→ str(nTimestepsCurrent))

except (FileNotFoundException, NameError):
    pass

# Start Job
startOutput = subprocess.check_output([commandJobStarting,
→ jobscriptFilename]).decode('utf-8').replace('\n', '')
jobID = startOutput.split(startOutputFlag)[0]

print_table_row(['STARTING', startOutput])

# Set output type
if outputType == 'restart':
    # Send end email
    if emailNotification:
        send_mail(emailAddress, 'Restart Job ' + jobName)

    sleep(30)

    outputType = set_output_type(user)

##### RESTART #####
##### RESTART #####
```

6.4 Simulation parameter

| | R/L_T | box size | N_s | $N_{\nu_{ }}$ | N_μ | d_{tim} | $k\rho^{\max}$ | N_{mod} | N_x |
|----|---------|----------|-------|----------------|---------|------------------|----------------|------------------|-------|
| 1 | 6.0 | 1x1 | 12 | 16 | 6 | 0.02 | 1.4 | 21 | 83 |
| 2 | 6.0 | 1x1 | 12 | 32 | 6 | 0.02 | 1.4 | 21 | 83 |
| 3 | 6.0 | 1x1 | 12 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 4 | 6.0 | 1x1 | 12 | 64 | 9 | 0.02 | 1.4 | 21 | 83 |
| 5 | 6.0 | 1x1 | 16 | 16 | 9 | 0.02 | 1.4 | 21 | 83 |
| 6 | 6.0 | 1x1 | 16 | 32 | 9 | 0.02 | 1.4 | 21 | 83 |
| 7 | 6.0 | 1x1 | 16 | 48 | 6 | 0.02 | 1.4 | 21 | 83 |
| 8 | 6.0 | 1x1 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 9 | 6.0 | 1x1 | 16 | 48 | 9 | 0.025 | 1.4 | 21 | 83 |
| 10 | 6.0 | 1x1 | 16 | 48 | 9 | 0.02 | 0.7 | 11 | 83 |
| 11 | 6.0 | 1x1 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 43 |
| 12 | 6.0 | 1x1 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 63 |
| 13 | 6.0 | 1x1 | 16 | 64 | 6 | 0.02 | 1.4 | 21 | 83 |
| 14 | 6.0 | 1x1 | 16 | 64 | 9 | 0.02 | 1.4 | 21 | 83 |
| 15 | 6.0 | 2x1 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 16 | 6.0 | 2x2 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 17 | 6.0 | 3x1 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 18 | 6.0 | 3x1.5 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 19 | 6.0 | 3x1.5 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 20 | 6.0 | 3x2.5 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 21 | 6.0 | 3x3 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 22 | 6.0 | 3x5 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 23 | 6.0 | 4x1 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 24 | 6.2 | 2x2 | 16 | 64 | 9 | 0.02 | 1.4 | 21 | 83 |
| 25 | 6.2 | 3x3 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |
| 26 | 6.3 | 1x1 | 16 | 64 | 9 | 0.02 | 1.4 | 21 | 83 |
| 27 | 6.4 | 3x3 | 16 | 48 | 9 | 0.02 | 1.4 | 21 | 83 |

Table 6.1: Parameters of simulations performed for this thesis

| | R/L_T | box size | time | timestep | error_index | stable | n_{ZF} | backup |
|----|---------|----------|---------|----------|-------------|--------|----------|--------|
| 1 | 6.0 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 2 | 6.0 | 1x1 | 12000.0 | 20000 | | False | 0 | True |
| 3 | 6.0 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 4 | 6.0 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 5 | 6.0 | 1x1 | 12000.0 | 20000 | | False | 0 | True |
| 6 | 6.0 | 1x1 | 12000.0 | 20000 | | False | 0 | True |
| 7 | 6.0 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 8 | 6.0 | 1x1 | 6000.0 | 10000 | | True | 1 | True |
| 9 | 6.0 | 1x1 | 7125.0 | 10000 | | True | 1 | True |
| 10 | 6.0 | 1x1 | 6000.0 | 10000 | | True | 1 | True |
| 11 | 6.0 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 12 | 6.0 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 13 | 6.0 | 1x1 | 12000.0 | 20000 | | True | 1 | True |
| 14 | 6.0 | 1x1 | 12000.0 | 20000 | | True | 1 | True |
| 15 | 6.0 | 2x1 | 18000.0 | 30000 | | True | 2 | True |
| 16 | 6.0 | 2x2 | 18000.0 | 30000 | | True | 2 | True |
| 17 | 6.0 | 3x1 | 48000.0 | 80000 | | True | 3 | True |
| 18 | 6.0 | 3x1.5 | 16840.3 | 28068 | | True | 4 | True |
| 19 | 6.0 | 3x1.5 | 14170.0 | 23618 | 23618 | True | 3 | True |
| 20 | 6.0 | 3x2.5 | 6000.0 | 10000 | | True | 3, 4 | True |
| 21 | 6.0 | 3x3 | 7847.0 | 13083 | | True | 4 | True |
| 22 | 6.0 | 3x5 | 4769.0 | 7958 | | True | 4 | True |
| 23 | 6.0 | 4x1 | 30000.0 | 50000 | 47084 | True | 4 | True |
| 24 | 6.2 | 2x2 | 6000.0 | 10000 | | True | 2 | True |
| 25 | 6.2 | 3x3 | 14682.7 | 24475 | 14473-16132 | True | 3 | True |
| 26 | 6.3 | 1x1 | 6000.0 | 10000 | | False | 0 | True |
| 27 | 6.4 | 3x3 | 12000.0 | 20000 | | False | 0 | True |

Table 6.2: Time steps with index which should be exclude in data analysis. Additional the stable column which indicates if turbulence subdued in simulation with the corresponding zonal flow mode number n_{ZF} (0 stands for turbulence not stable) and if the data is saved on the NAS of TPV (backup column)

| | path |
|----|--|
| 1 | ./data/S6_rlt6.0/boxsize1x1/Ns12/Nvpar16/Nmu6 |
| 2 | ./data/S6_rlt6.0/boxsize1x1/Ns12/Nvpar32/Nmu6 |
| 3 | ./data/S6_rlt6.0/boxsize1x1/Ns12/Nvpar48/Nmu9 |
| 4 | ./data/S6_rlt6.0/boxsize1x1/Ns12/Nvpar64/Nmu9 |
| 5 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar16/Nmu9 |
| 6 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar32/Nmu9 |
| 7 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar48/Nmu6 |
| 8 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar48/Nmu9 |
| 9 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar48/Nmu9/dtim0.025 |
| 10 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar48/Nmu9/krhomax0.70/Nmod11 |
| 11 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar48/Nmu9/Nx43 |
| 12 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar48/Nmu9/Nx63 |
| 13 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar64/Nmu6 |
| 14 | ./data/S6_rlt6.0/boxsize1x1/Ns16/Nvpar64/Nmu9 |
| 15 | ./data/S6_rlt6.0/boxsize2x1/Ns16/Nvpar48/Nmu9 |
| 16 | ./data/S6_rlt6.0/boxsize2x2/Ns16/Nvpar48/Nmu9 |
| 17 | ./data/S6_rlt6.0/boxsize3x1/Ns16/Nvpar48/Nmu9 |
| 18 | ./data/S6_rlt6.0/boxsize3x1.5/Ns16/Nvpar48/Nmu9 |
| 19 | ./data/S6_rlt6.0/boxsize3x1.5/Ns16/Nvpar48/Nmu9/Broken |
| 20 | ./data/S6_rlt6.0/boxsize3x2.5/Ns16/Nvpar48/Nmu9 |
| 21 | ./data/S6_rlt6.0/boxsize3x3/Ns16/Nvpar48/Nmu9 |
| 22 | ./data/S6_rlt6.0/boxsize3x5/Ns16/Nvpar48/Nmu9 |
| 23 | ./data/S6_rlt6.0/boxsize4x1/Ns16/Nvpar48/Nmu9 |
| 24 | ./data/S6_rlt6.2/boxsize2x2/Ns16/Nvpar64/Nmu9 |
| 25 | ./data/S6_rlt6.2/boxsize3x3/Ns16/Nvpar48/Nmu9 |
| 26 | ./data/S6_rlt6.3/boxsize1x1/Ns16/Nvpar64/Nmu9 |
| 27 | ./data/S6_rlt6.4/boxsize3x3/Ns16/Nvpar48/Nmu9 |

Table 6.3: Data location for each simulation

Size convergence of the $E \times B$ staircase pattern in flux tube simulations of ion temperature gradient driven turbulence

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(Dated: 9 May 2023)

The radial size convergence of the $E \times B$ staircase pattern is addressed in local gradient-driven flux tube simulations of ion temperature gradient (ITG) driven turbulence. It is shown that a mesoscale pattern size of $\sim 57.20 - 76.27 \rho$ is inherent to ITG driven turbulence with Cyclone Base Case parameters in the local limit.

Ion temperature gradient driven turbulence close to marginal stability exhibits zonal flow pattern formation on mesoscales, so-called $E \times B$ staircase structures¹. Such pattern formation has been observed in local gradient-driven flux-tube simulations^{2–4} as well as global gradient-driven^{5–7} and global flux-driven^{1,8–11} studies. In global studies, spanning a larger fraction of the minor radius, multiple radial repetitions of staircase structures are usually observed, with a typical pattern size of several ten Larmor radii. By contrast, in the aforementioned local studies the radial size of $E \times B$ staircase structures is always found to converge to the radial box size of the flux tube domain. The above observations lead to the question: *Does the basic pattern size always converges to the box size, or is there a typical mesoscale size inherent to staircase structures also in a local flux-tube description?* The latter case would imply that it is not necessarily global physics, i.e., profile effects, that set (i) the radial size of the $E \times B$ staircase pattern and (ii) the scale of avalanche-like transport events. These transport events are usually restricted to $E \times B$ staircase structures and considered as a nonlocal transport mechanism¹. In this brief communication the above question is addressed through a box size convergence scan of the same cases close to the nonlinear threshold for turbulence generation as studied in Ref. 2.

The gyrokinetic simulations are performed with the non-linear flux tube version of Gyrokinetic Workshop (GKW)¹² with adiabatic electron approximation. In agreement with Ref. 2, Cyclone Base Case (CBC) like parameters are chosen with an inverse background temperature gradient length $R/L_T = 6.0$ and circular concentric flux surfaces. The numerical resolution is compliant to the "Standard resolution with 6th order (S6)" set-up of the aforementioned reference, with a somewhat lowered number of parallel velocity grid points. It has been carefully verified that this modification preserves the same physical outcome as the original study. A summary of the numerical parameters is given in Tab. I and for more details about the definition of individual quantities the reader is referred to Ref. 2 and 12.

| | N_m | N_x | N_s | N_{V_\parallel} | N_μ | D | v_d | D_{V_\parallel} | D_x | D_y | Order | $k_y \rho$ | $k_x \rho$ |
|----|-------|-------|-------|-------------------|---------|-----|-----------------|-------------------|-------|-------|-------|------------|------------|
| S6 | 21 | 83 | 16 | 48 | 9 | 1 | $ v_\parallel $ | 0.2 | 0.1 | 0.1 | 6 | 1.4 | 2.1 |

TABLE I: Resolution used in this paper for further information the author links to Ref. 2.

In the following the box size is increased relative to the standard box size $(L_x, L_y) = (76.27, 89.76) \rho$ in the radial and binormal direction. Here, x is the radial coordinate that labels the flux surfaces normalized by the thermal Larmor radius ρ , y labels the field lines and is an approximate binormal coordinate. Together with the coordinate s which parameterizes the length along the field lines and is referred to as the parallel coordinate these quantities form the Hamada coordinates¹³. The increased box sizes are indicated by the real parameter N_R for radial and N_B for the binormal direction with the nomenclature $N_R \times N_B$ throughout this work. Note that, the number of modes in the respective direction, i.e., N_x and N_m , respectively, is always adapted accordingly to retain a spatial resolution compliant to the standard resolution [Tab. I] and standard box size.

The $E \times B$ staircase pattern is manifest as radial structure formation in the $E \times B$ shearing rate defined by^{2,14,15}

$$\omega_{E \times B} = \frac{1}{2} \frac{\partial^2 \langle \phi \rangle}{\partial x^2}, \quad (1)$$

where $\langle \phi \rangle$ is the zonal electrostatic potential normalized by $\rho_* T/e$ ($\rho_* = \rho/R$ is the thermal Larmor radius normalized with the major radius R , T is the temperature, e is the elementary charge). The zonal potential is calculated from the electrostatic potential ϕ on the two-dimensional x - y -plane at the low field side according to⁴

$$\langle \phi \rangle = \frac{1}{L_y} \int_0^{L_y} dy \phi(x, y, s=0). \quad (2)$$

The $E \times B$ shearing rate $\omega_{E \times B}$ is the radial derivative of the advecting zonal flow velocity^{16,17} and quantifies the zonal flow induced shearing of turbulent structures^{16,18,19}.

Consistent with Ref. 2 the turbulence level is quantified by the turbulent heat conduction coefficient χ , which is normalized by $\rho^2 v_{th}/R$ ($v_{th} = \sqrt{2T/m}$ is the thermal velocity and m is the mass). Furthermore, quantities ρ , R , T , v_{th} and m are referenced quantities from Ref. 2 and 12.

^{a)}Repository of this work:

<https://github.com/ManeLippert/Bachelorthesis-Shearingrate-Convergence>

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In order to diagnose the temporal evolution of the staircase pattern and to obtain an estimate of its amplitude the radial Fourier transform of the $E \times B$ shearing rate is considered. It is defined by

$$\omega_{E \times B} = \sum_{k_{ZF}} \hat{\omega}_{E \times B}(k_{ZF}, t) \exp(ik_{ZF}x), \quad (3)$$

where $\hat{\omega}_{E \times B}$ is the complex Fourier coefficient and $k_{ZF} = 2\pi n_{ZF}/L_x$ defines the zonal flow wave vector with the zonal flow mode number n_{ZF} ranging in $-(N_x - 1)/2 \leq n_{ZF} \leq (N_x - 1)/2$. Based on the definitions above, the shear carried by the zonal flow mode with wave vector k_{ZF} is defined by $|\hat{\omega}_{E \times B}|_{n_{ZF}} = 2|\hat{\omega}_{E \times B}(k_{ZF}, t)|$. In general, the zonal flow mode that dominates the $E \times B$ staircase pattern, also referred to as the *basic mode* of the pattern in this work, exhibits the maximum amplitude in the spectrum $|\hat{\omega}_{E \times B}|_{n_{ZF}}$.

In the first test the radial box size is increased while the binormal box size is kept fixed to the standard size. The scan covers the realizations $N_R \times N_B \in [1 \times 1, 2 \times 1, 3 \times 1, 4 \times 1]$. Each realization exhibits an initial quasi-stationary turbulent phase and a second final² phase with almost suppressed turbulence [Fig. 1(a)]. The latter state is indicative for the presence of a fully developed staircase pattern as depicted in Fig. 2. This type of structure is characterized by intervals of almost constant shear with alternating sign satisfying the Waltz criterion $|\omega_{E \times B}| \approx \gamma^{17,20}$ (γ is the growth rate of the most unstable linear ITG driven Eigenmode), connected by steep flanks where $\omega_{E \times B}$ crosses zero. Fig. 2(a) shows a striking repetition of the staircase structure, with the number of repetitions equal to N_R . Hence, the basic size of the pattern not only converges with increasing radial box size, the converged radial size turns out to at least roughly agree with the standard radial box size of Ref. 2.

Due to the lack of a substantial turbulent drive in the final suppressed state no further zonal flow evolution is observed [Fig. 1(b)] and one might critically ask whether the structures shown in Fig. 2 represent the real converged pattern in a statistical sense. Note that in the 3×1 case the initial quasi-stationary turbulent state extends up to a few $\sim 10^4 R/v_{th}$. During this period the zonal flow mode with $n_{ZF} = 3$, i.e., the mode that dominates the staircase pattern in final suppressed phase, undergoes a long-term evolution with a typical time scale of several $\sim 10^3 R/v_{th}$. Hence, several of such cycles are covered by the initial turbulent phase, which is evident from the occurrence of phases with reduced amplitude around $t \approx 8000 R/v_{th}$ and $t \approx 18000 R/v_{th}$. It is the $n_{ZF} = 4$ zonal flow mode, i.e., the next shorter radial scale mode, that dominates the shear spectrum $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ in the latter two phases (not shown). This demonstrates a competition between the $n_{ZF} = 3$ and $n_{ZF} = 4$ modes. Most importantly, no secular growth of the $n_{ZF} = 1$ (box scale) zonal flow mode is observed during the entire quasi-stationary turbulent phase [Fig. 1(b) dotted line]. The above discussion indicates that although the $n_{ZF} = 3, 4$ zonal modes compete, the pattern scale does not converge to the radial box scale but rather to a mesoscale of $\sim 57.20 - 76.27 \rho$ (i.e., $n_{ZF} = 4, 3$ in the 3×1 case).

Since the radially elongated simulation domain might inhibit the development of isotropic turbulent structures, in the second test the radial and binormal box size is increased simultaneously. This scan covers the realizations $N_R \times N_B \in [1 \times 1, 2 \times 2, 3 \times 3]$. Interestingly, suppression of the turbulence by the emergence of a fully developed staircase pattern always occurs after $\sim 1000 R/v_{th}$ [Fig. 3], i.e., significantly faster compared to the 3×1 and 4×1 realizations. As shown in Fig. 2(b) also this test confirms the convergence of the staircase pattern size to a typical mesoscale that is distinct from the radial box size in the $N_R > 1$ realizations.

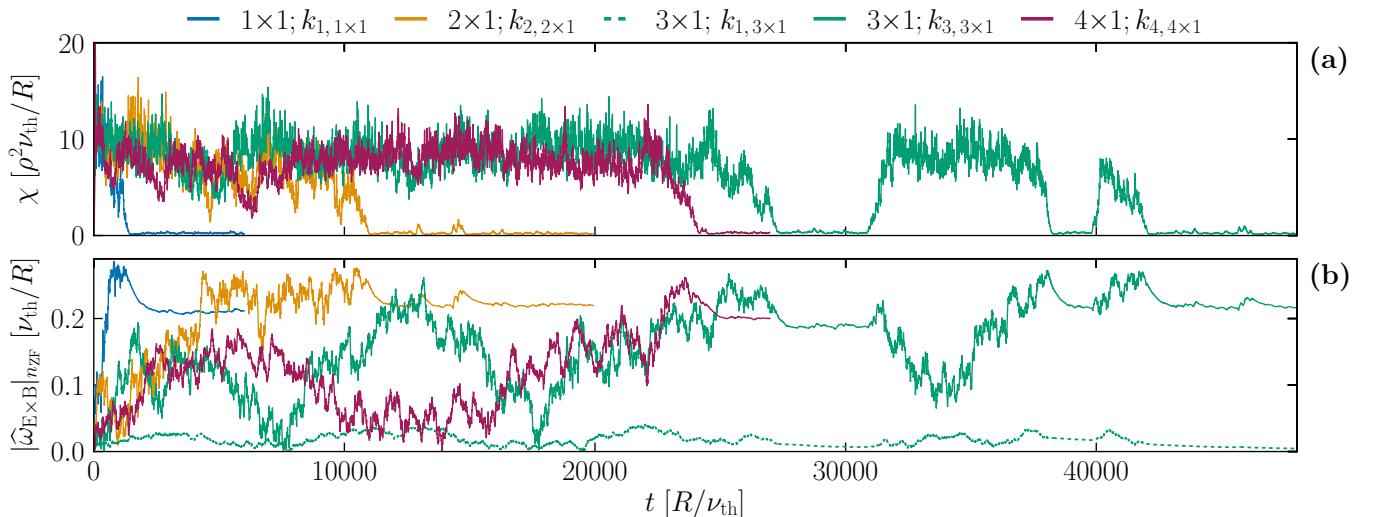


FIG. 1: (a) Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for radial increased box sizes
(b) Time traces of $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ for radial increased box sizes

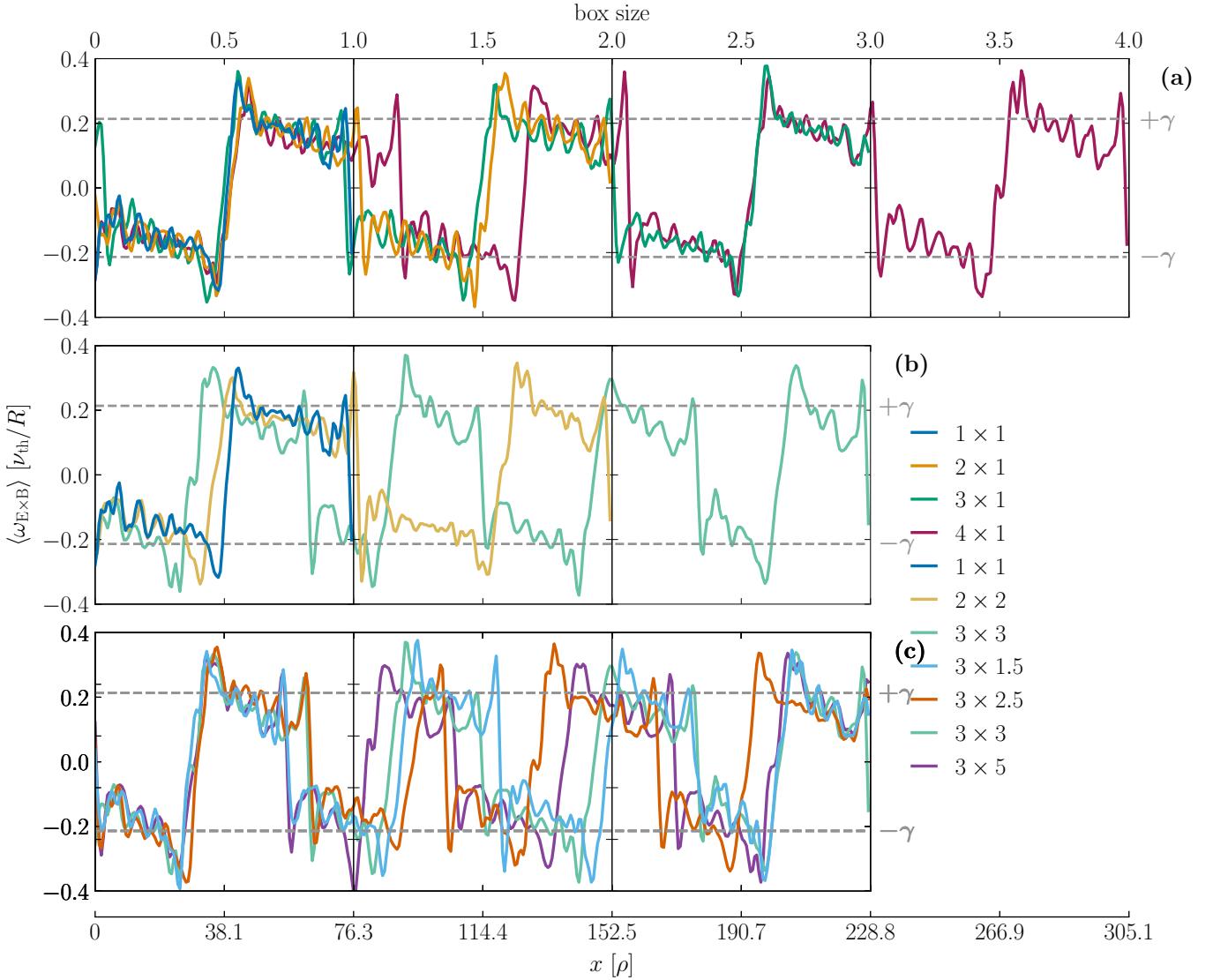


FIG. 2: Comparison of shearing rate $\omega_{E \times B}$ for each box sizes scan averaged over given time interval and the growth rate $\pm\gamma$ of the most unstable linear ITG driven Eigenmode. The staircase structures are radially shifted with respect to each other till alignment for better visibility.

- (a) **radial:** $t_{1 \times 1} \in [2000, 5000]$, $t_{2 \times 1} \in [15000, 18000]$, $t_{3 \times 1} \in [43000, 45000]$, $t_{4 \times 1} \in [26000, 28000]$
- (b) **isotropic:** $t_{1 \times 1} \in [2000, 5000]$, $t_{2 \times 2} \in [2000, 3000]$, $t_{3 \times 3} \in [2000, 3000]$
- (c) **binormal:** $t_{3 \times 1.5} \in [2000, 3000]$, $t_{3 \times 2.5} \in [2000, 3000]$, $t_{3 \times 3} \in [2000, 3000]$, $t_{3 \times 5} \in [1000, 3000]$

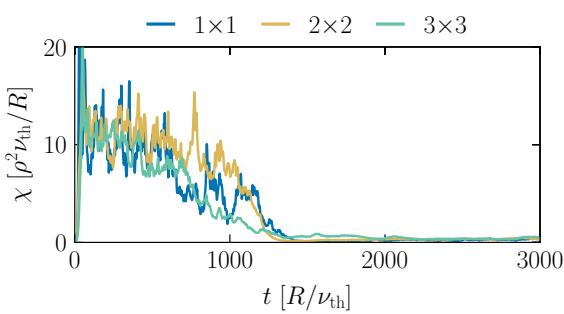


FIG. 3: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for isotropic increased box sizes

By contrast to the radial box size scan the 3×3 realization shows a stationary pattern with four repetitions of the fully developed staircase structure, i.e., a somewhat smaller pattern size. Whether this is related to a possible pattern size dependence on the binormal box size or to the competition between patterns with the two sizes $\lambda \in [57.20, 76.27] \rho$ as observed in the first test is addressed in the next paragraph.

In a third test the binormal box size is varied with the radial box size fixed to $N_R = 3$. This test covers the realizations $N_R \times N_B \in [3 \times 1.5, 3 \times 2.5, 3 \times 3, 3 \times 5]$. As in the isotropic scan the turbulence subdued and a fully developed staircase pattern forms after $\sim 2000R/\nu_{th}$ [Fig. 4]. The convergence of staircase pattern can be seen in Fig. 2(c) and confirms again a size of a typical mesoscale. Fig. 2(c) also confirms that indeed a competition between patterns with two sizes $\lambda \in [57.20, 76.27]\rho$ causing the different results for 3×1 and 3×3 . The zonal flow mode number varies between $n_{ZF} = 3, 4$ which can be seen in Fig. 2(c) in the 3×2.5 realization. The staircase structure has a pattern between 3 and 4 repetitions which get represented in the second repetition with no significant plateau at positive shear. Instead the pattern returns immediately after reaching the maximum shear ($+\gamma$) to the minimum shear ($-\gamma$) of the third repetition in a steep flank. The Fourier analysis of this case yields no definitely basic mode rather two dominating modes with $n_{ZF} = 3, 4$ with a fraction of the maximum amplitude $|\hat{\omega}_{E \times B}|_{n_{ZF}}$ each (not shown).

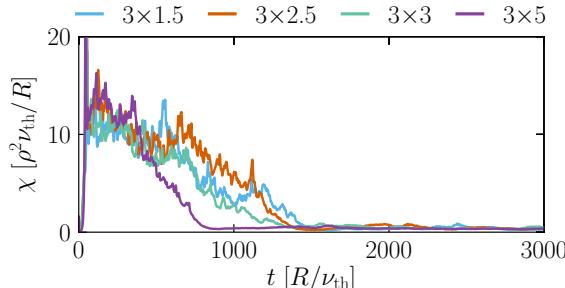


FIG. 4: Time traces of the heat conduction coefficient χ for $R/L_T = 6.0$ for binormal increased box sizes

In the final test the inverse background temperature gradient length R/L_T is varied at fixed 3×3 box size. Since suppression of turbulence usually occurs at later times when approaching the finite heat flux threshold from below², the analysis aims to lengthen the phase during which the zonal flow varies in time due to turbulent Reynolds stresses. This scan covers realizations with $R/L_T \in [6.0, 6.2, 6.4]$. In the case of $R/L_T = 6.2$ turbulence suppression is observed for $t > 11000R/\nu_{th}$, while stationary turbulence during the entire simulation time trace of $12000R/\nu_{th}$ is found for $R/L_T = 6.4$. The finite heat flux threshold, hence, is $R/L_T|_{\text{finite}} = 6.3 \pm 0.1$ in accordance to Ref. 2. Although the initial quasi-stationary turbulence in the former case is significantly longer compared to the $R/L_T = 6.2$ realization discussed in the second test, a stationary pattern with basic zonal flow mode $n_{ZF} = 3$ establishes. Again, the $n_{ZF} = 1$ (box scale) zonal flow mode does not grow secularly during the entire turbulent phase. Also, this test confirms the statistical soundness of the converged pattern size of $\sim 57.20 - 76.27\rho$.

Through careful tests this brief communication confirms the radial size convergence of the $E \times B$ staircase pattern in 94

local gyrokinetic flux tube simulations of ion temperature gradient (ITG) driven turbulence. A mesoscale pattern size of $\sim 57.20 - 76.27\rho$ is found to be intrinsic to ITG driven turbulence for Cyclone Base Case parameters. This length scale is somewhat larger compared to results from global studies with finite ρ_* , which report of a few $10\rho^1$, and has to be considered the proper mesoscale in the local limit $\rho_* \rightarrow 0$. The occurrence of this mesoscale implies that non-locality, in terms of Ref. 1, is inherent to ITG driven turbulence, since avalanches are spatially organized by the $E \times B$ staircase pattern^{1,2,5,14}.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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CHAPTER

Eidesstattliche Erklärung

Hiermit erkläre ich, Manuel Lippert, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder nicht veröffentlichten Schriften entnommen wurden, sind als solche kenntlich gemacht. Die Arbeit hat in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen.

Bayreuth, den May 9, 2023

Manuel Lippert