

Local gyrokinetic simulations of DTT pedestal

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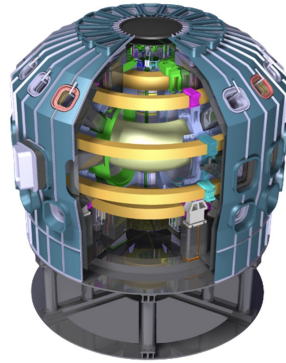
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Outline

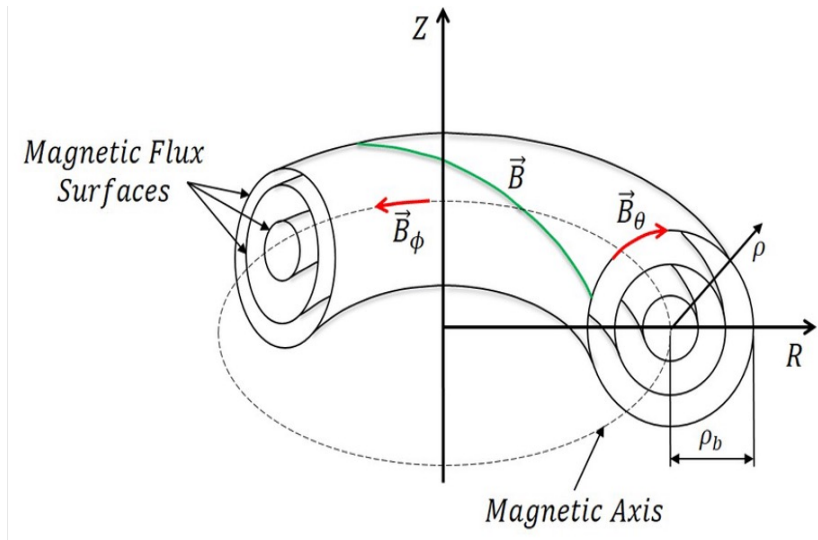
- Introduction and Equilibrium Profiles
- Linear Convergence Scans
- Multiscale Linear Scans
- Nonlinear Simulations

Introduction

Divertor Tokamak Test facility (DTT)



Under construction in Frascati (Italy)



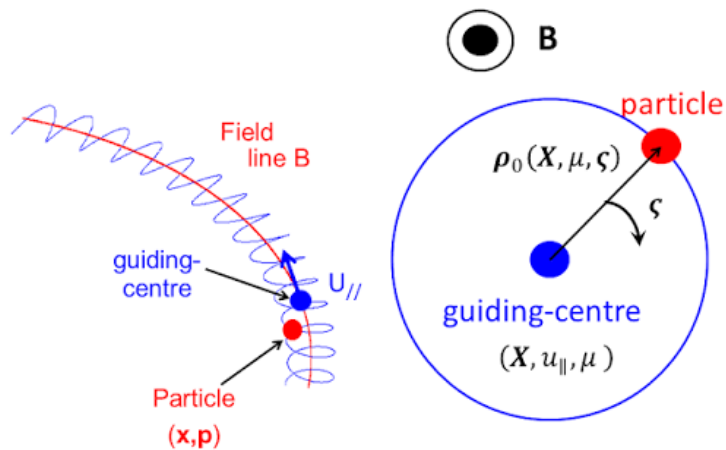
- The Divertor Tokamak Test facility (DTT) is under construction in Frascati, with the purpose of developing alternative designs and materials for the tokamak divertor.
- Heat transport in a tokamak is a central determinant of the energy confinement and, consequently, of the heating power and size required for a fusion reactor.

Introduction

- My work this year: To simulate the edge transport properties of DTT, comparing with reduced models, like EUROPED.
- The plasma performance in Tokamak is heavily dependent on its edge (i.e. the pedestal). However, properties of heat transport at the edge are far less understood than the inner core.
- Heat transport at the edge is dominated by turbulent transport. Classical theories may not be enough. Higher fidelity gyrokinetic edge-plasma simulation therefore has an important role.

Introduction

- Basic theoretical framework : Gyrokinetic theories.
- The trajectories of particles are decomposed into a slow motion of the guiding center along the field line and a fast circular motion.

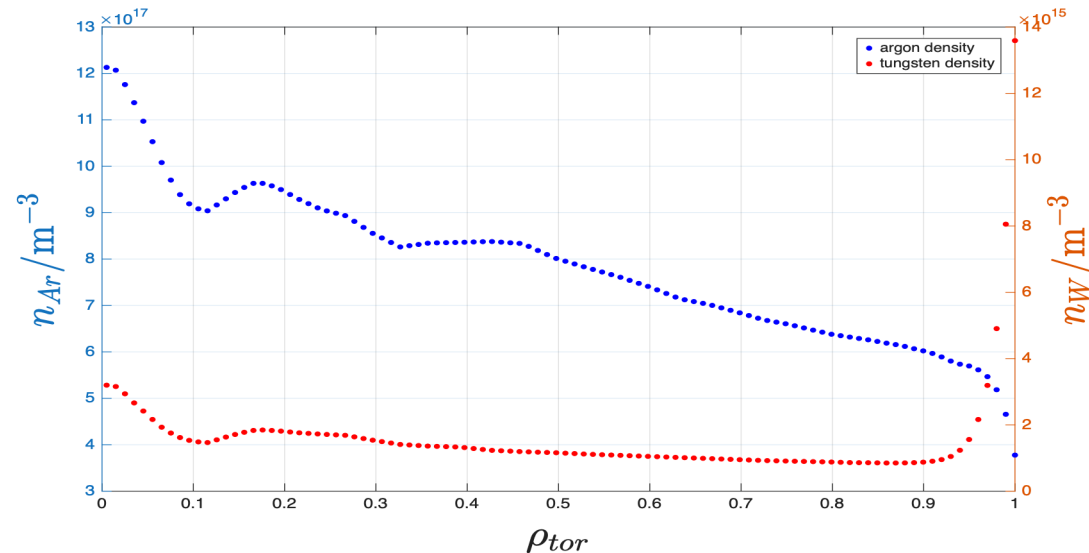
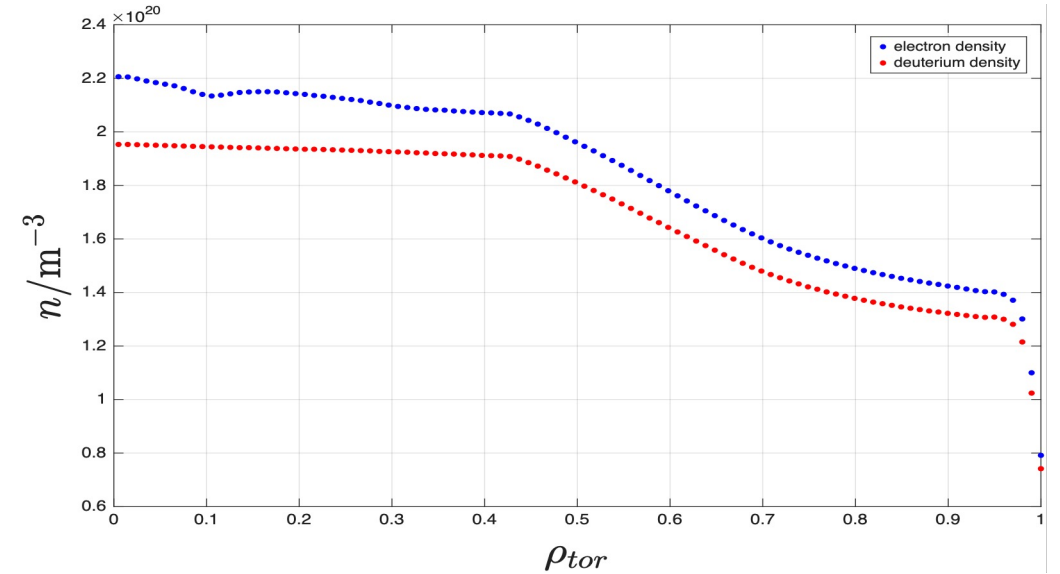
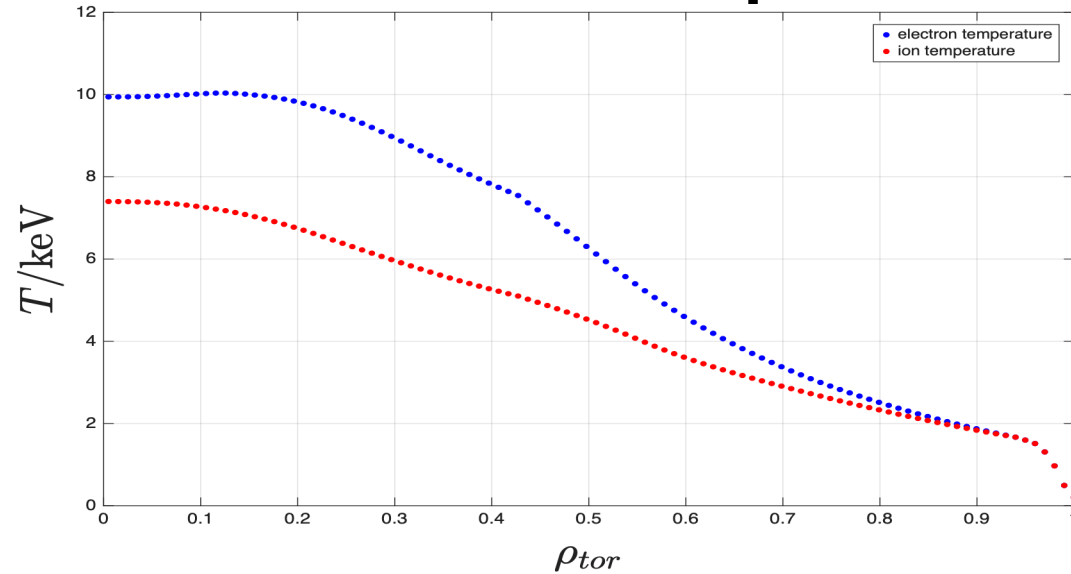


- Particles move in a 6D phase space. The gyroangle is removed by coordinate transformation. Therefore, we still need to solve a 5D partial differential equation.

Introduction

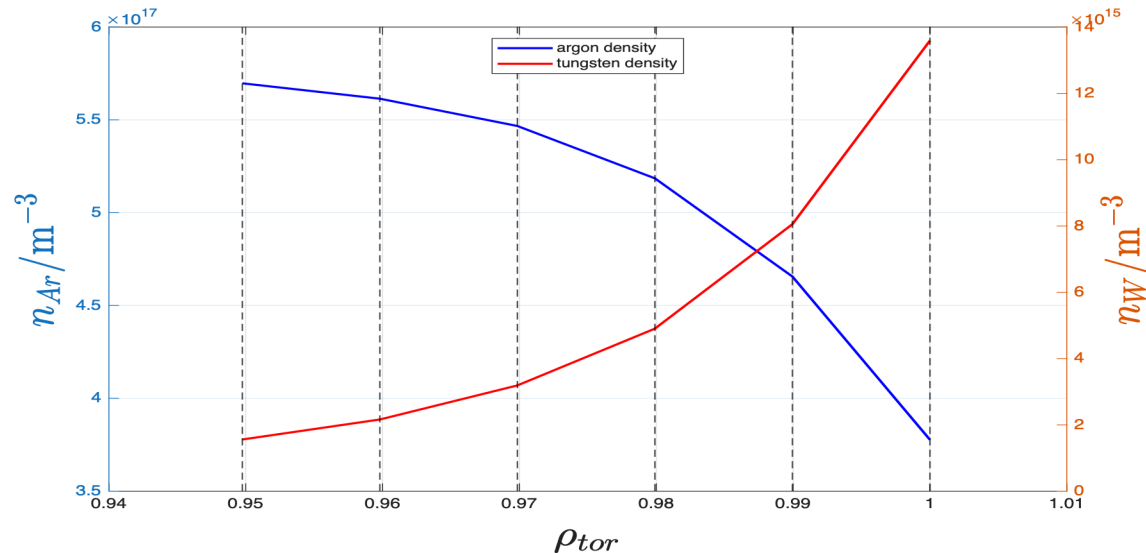
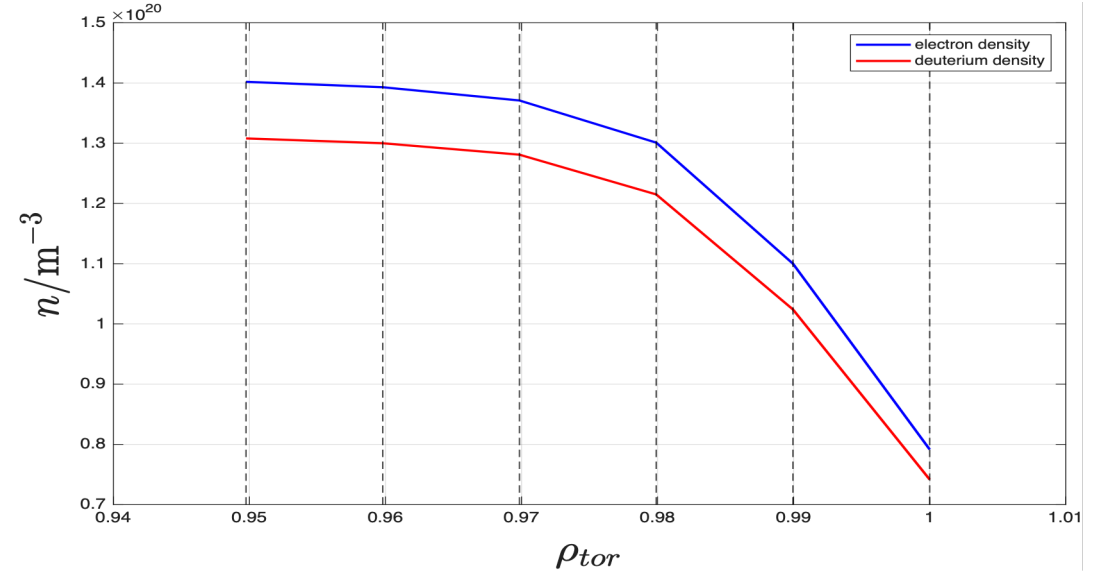
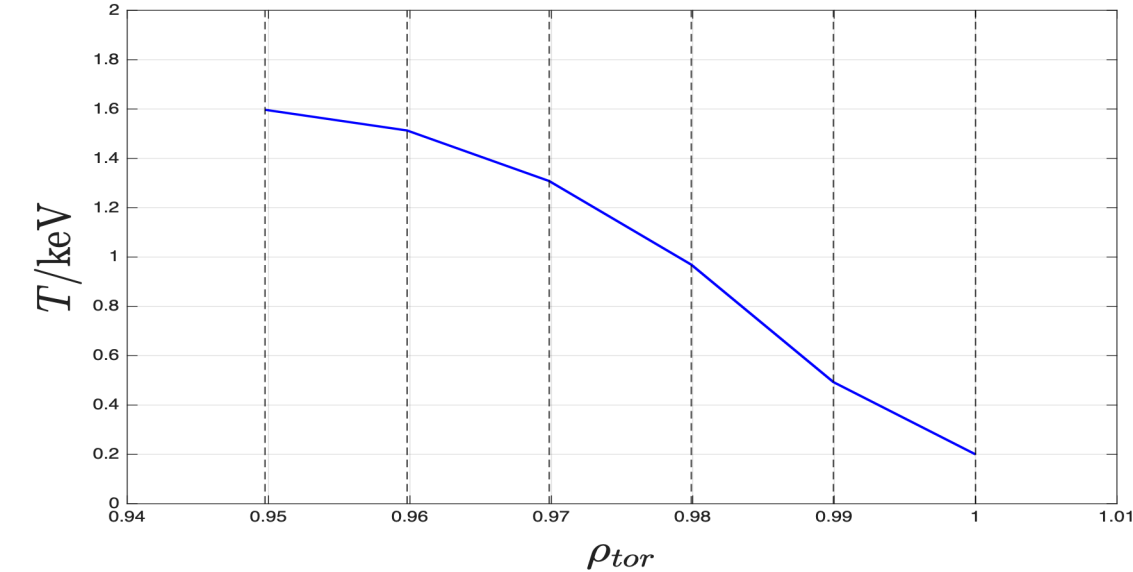
- Here is some basic information about GENE code
- In GENE code, all physical quantities (δf , $\delta\phi$, $\delta A_{\parallel}$ and so on) are solved perturbatively based on equilibrium profiles.
- The fluxes are calculated as the moments of distribution functions.
For example, $\mathbf{\Gamma}_{es} = \int d^3v \delta f \mathbf{v}_E$, $\mathbf{Q}_{es} = \int d^3v \frac{1}{2} m v^2 \delta f \mathbf{v}_E$.
- Linear modes satisfy $\delta f \propto e^{\gamma t + i\omega t}$, where γ is the growth rate and ω is the real frequency.

Equilibrium Profiles



- $T_e > T_i$ in the central region, but they gradually become the same at the edge ($\rho_{tor} \geq 0.95$), due to the higher collisionality.
- The neutrality is always satisfied considering all kinds of particles.
- The electron, deuterium and argon density drops quickly at the edge, while the tungsten density increases abnormally.

Equilibrium Profiles (the Edge)



- In the original equilibrium profile, there are not many data points at the edge, but they are still enough to draw a continuous curve.
- By interpolation, the temperature, density and their derivatives are calculated as equilibrium inputs for further simulations.
- All the following simulations will take place at the pedestal, i.e. $\rho_{tor} = 0.96$, $\rho_{tor} = 0.97$ and $\rho_{tor} = 0.98$.

Linear Convergence Scans

- Before starting simulations, we first need to determine how the computational grids are discretized.
- As stated before, gyrokinetic equations work in a 5D space. Here are the original grids we adopt.

Coordinate	x	z	v	w	y
Physical meanings	Radial coordinate	Field-line coordinate	Parallel velocity	Magnetic moment	Field-line label within a given flux surface
Original grids	$n_x = 48$	$n_z = 64$	$n_v = 48$	$n_w = 8$	$n_{k_y} = 1$

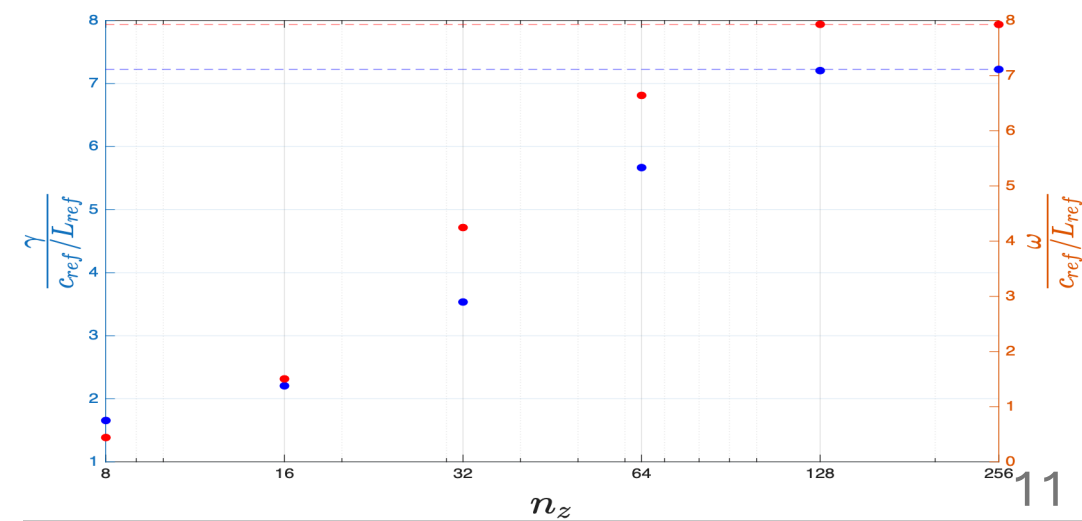
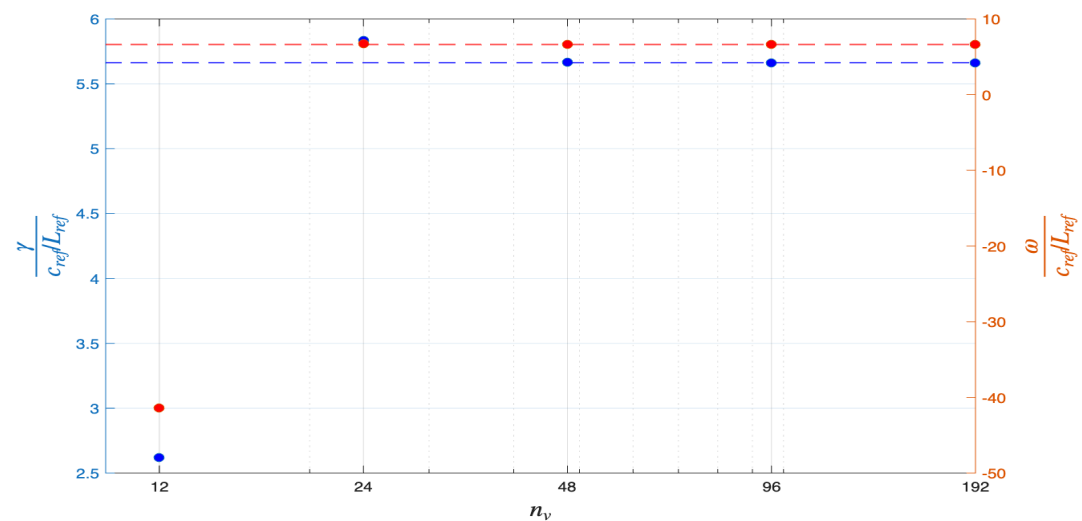
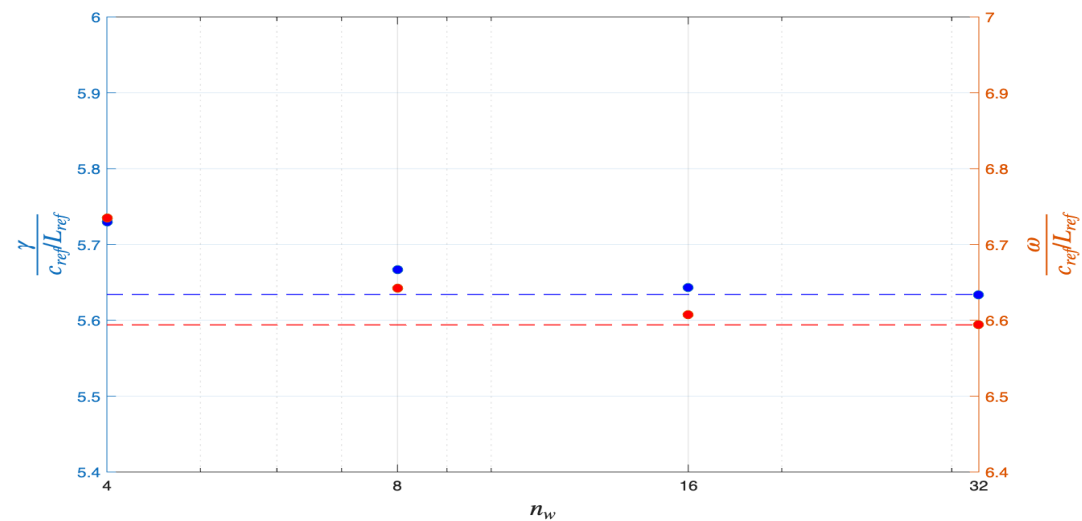
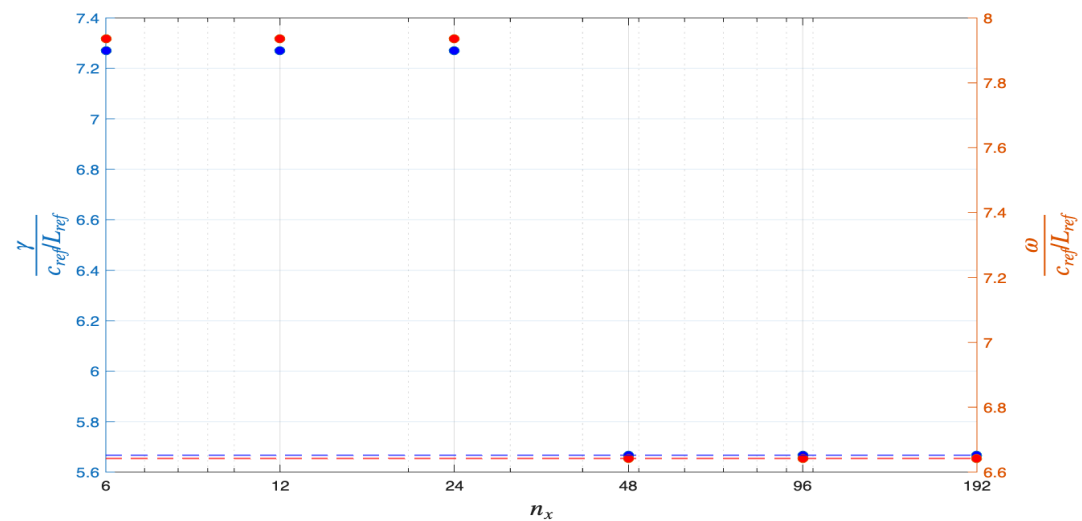
- For local linear simulations, a single k_y is considered each time, since different k_y are nonlinearly coupled.

Linear Convergence Scans

- Every time we change the grid discretization of one coordinate and keep the other four fixed.
- Representative points are chosen as $k_y = 0.3\rho_{ref}^{-1}$ for ion scale and the peak point of growth rate for electron scale.
- As default, the growth rate γ and the real frequency ω are required to be calculated to three decimal places, i.e. $\omega_{prec} = 0.001$.
- If the simulation takes too long or even don't converge, we lower the requirement and set $\omega_{prec} = 0.01$.

Take $\rho_{tor} = 0.98$ ion
scale for example

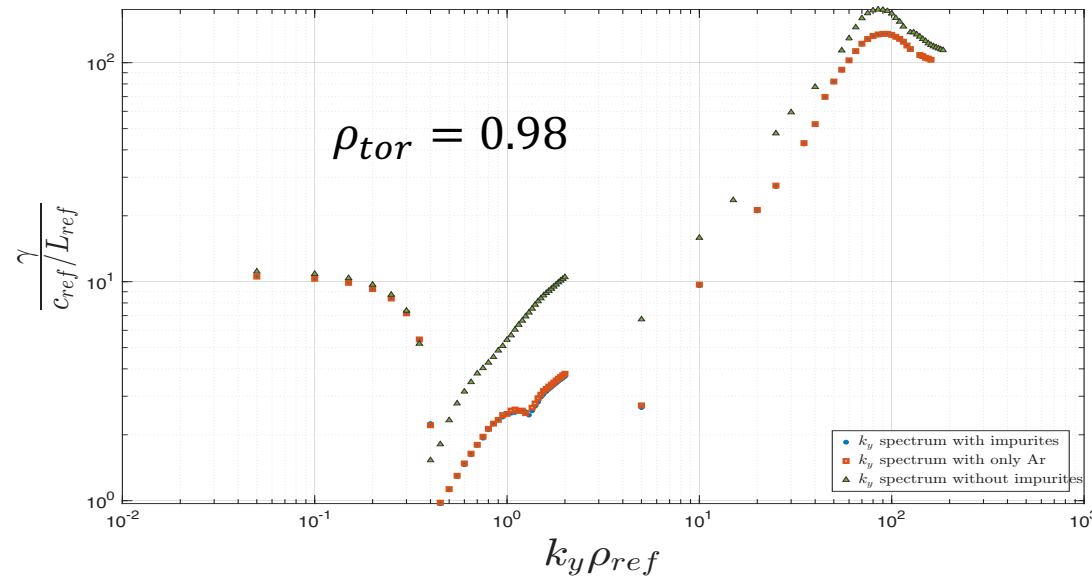
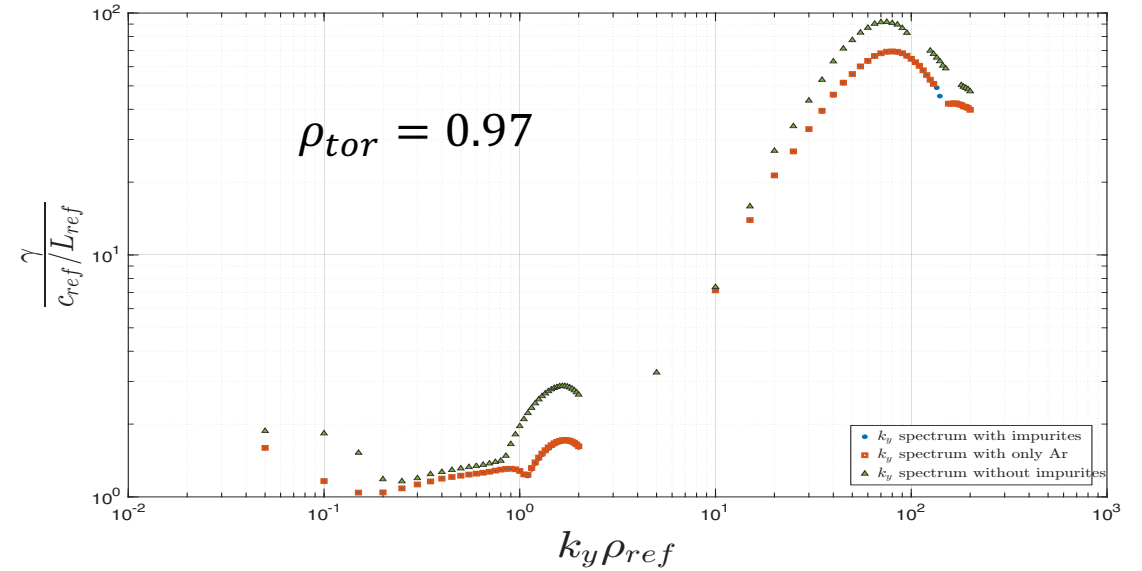
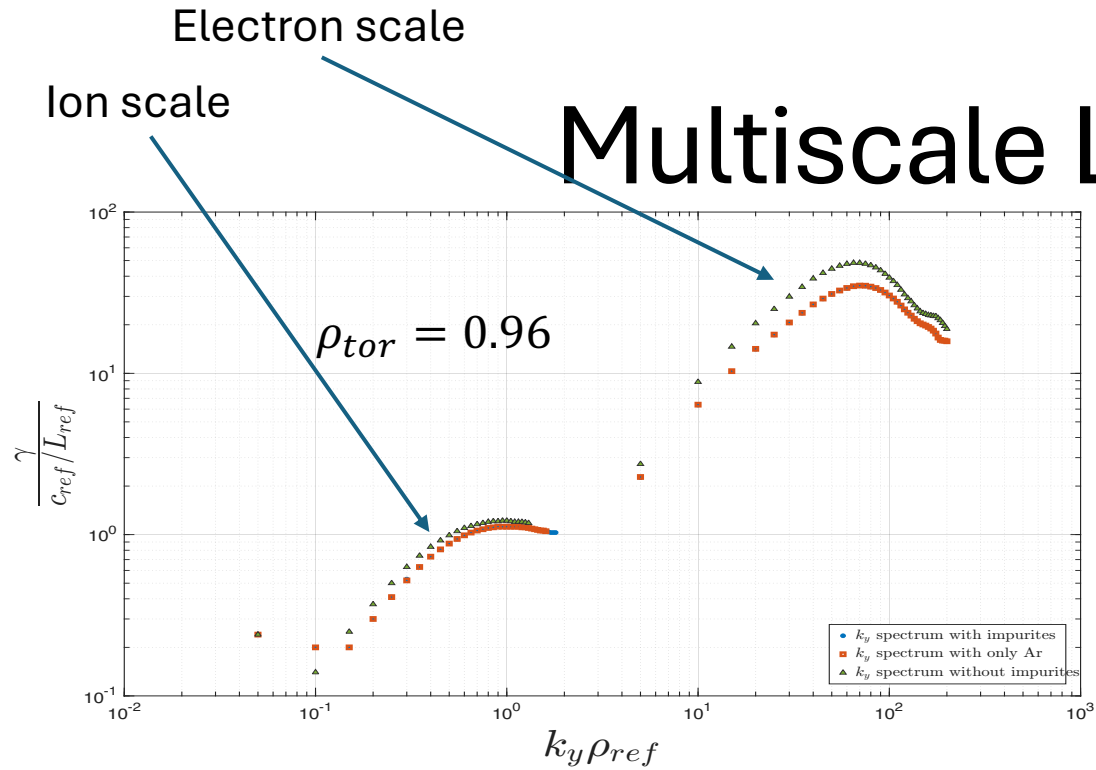
Linear Convergence Scans



Linear Convergence Scans

- When the relative errors of γ (growth rate) and ω (real frequency) decrease to less than 3%, we adopt it in the following simulations.
- In this case, it is $n_x = 48$, $n_z = 128$, $n_v = 48$, $n_w = 16$.
- The same procedures are repeated at $\rho_{tor} = 0.96$ and $\rho_{tor} = 0.97$, for ion scale and electron scale, respectively.
- Linear convergence scans can not only tell us the most suitable grid discretization for the following local linear simulations, but also apply to future nonlinear simulations.

Multiscale Linear Scans

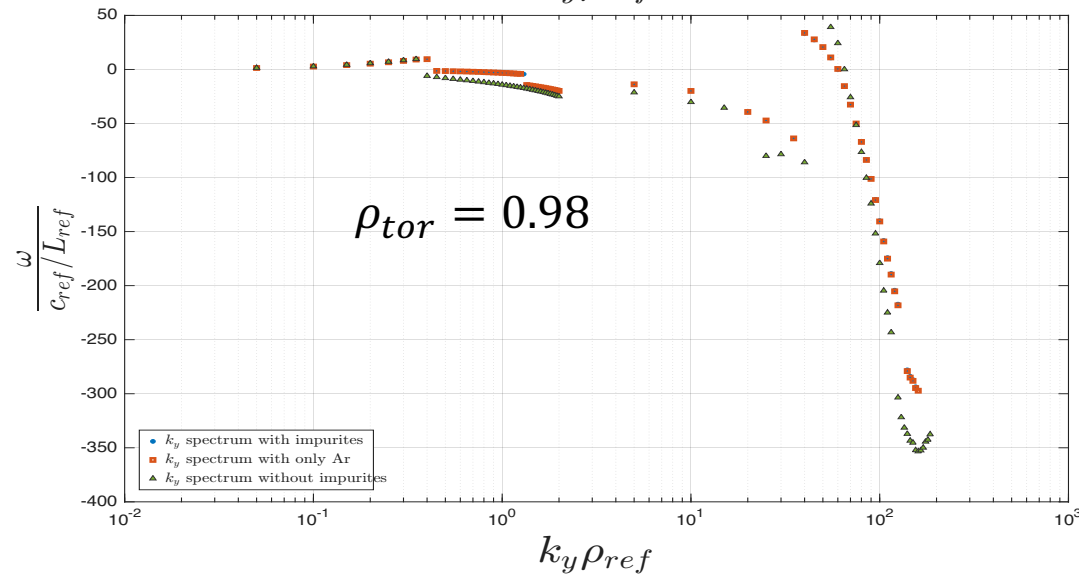
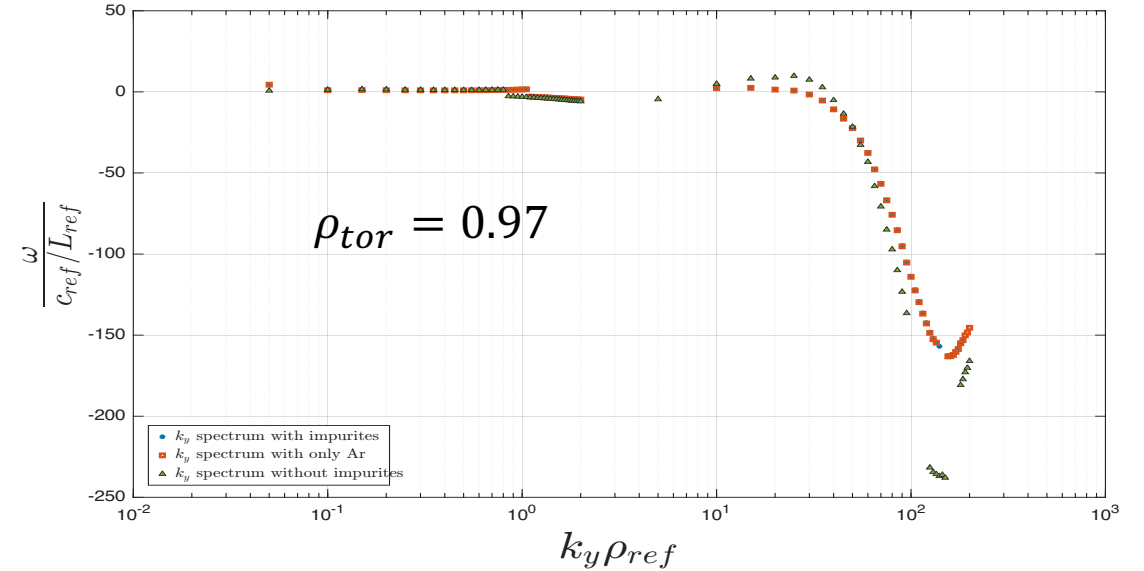
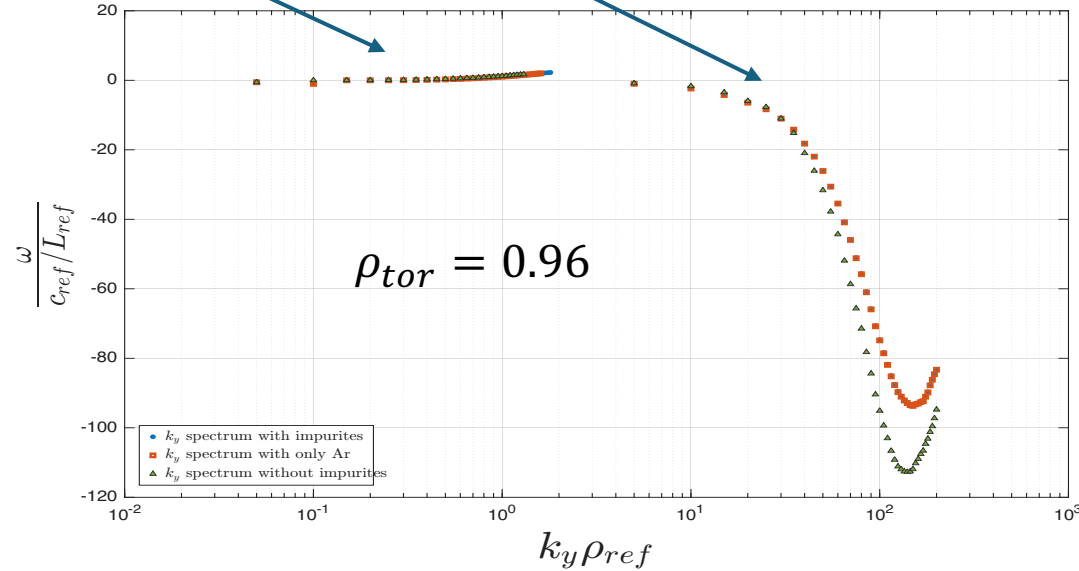


- We show the k_y dependence of growth rate in normalized units.
- The impurity Ar markedly stabilizes the plasma, while W has nearly no influence.
- The plasma becomes more unstable at the outer region.
- We need the real frequency to characterize these micro-instabilities.

Multiscale Linear Scans

Electron scale

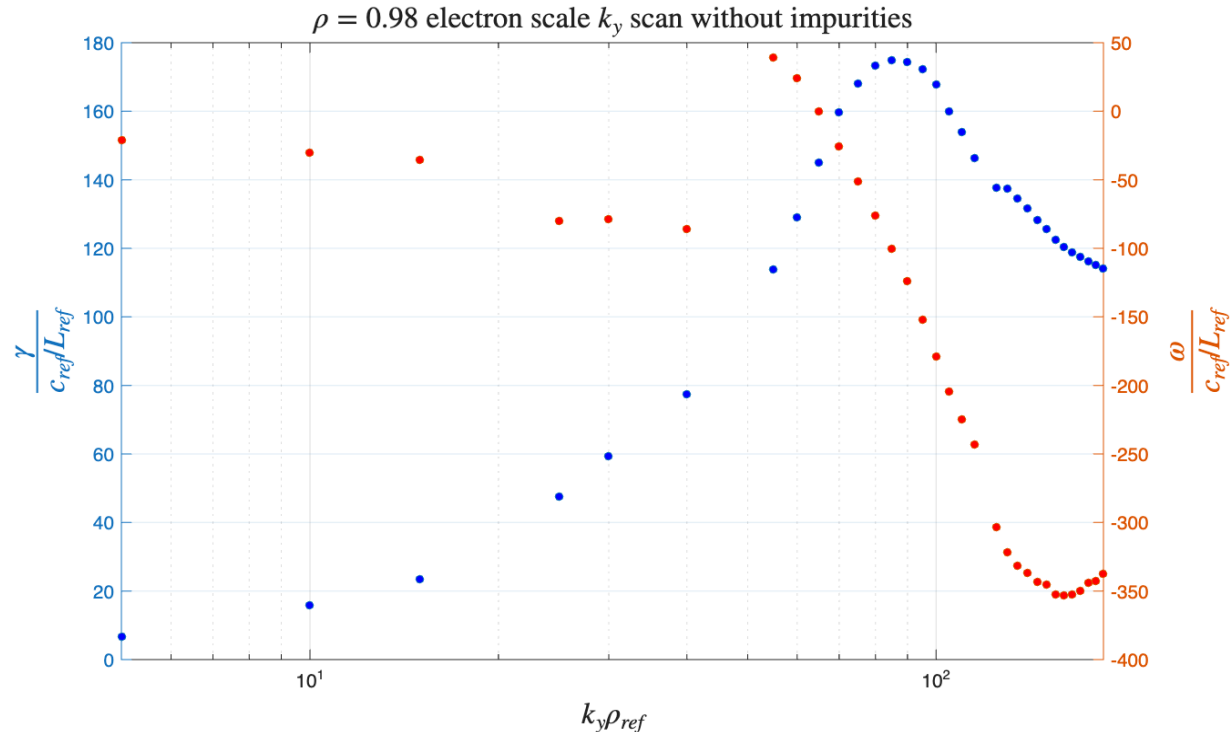
Ion scale



- We show the k_y dependence of real frequency.
- At ion scale, we firstly observe some KBMs for very small k_y .
- As k_y increases, at $\rho_{tor} = 0.96$, only ITG is observed, while at $\rho_{tor} = 0.97$ and $\rho_{tor} = 0.98$, both ITGs (at small k_y) and TEMs (at intermediate k_y) are observed.
- The spectra contributions at electron scale correspond to electron temperature gradient modes (ETGs).

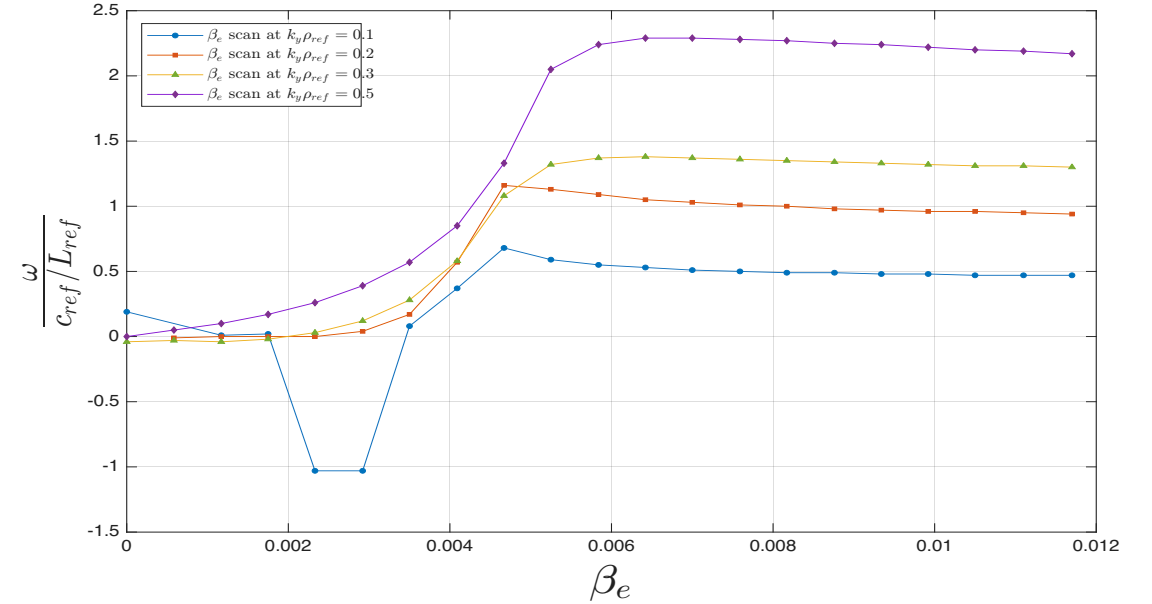
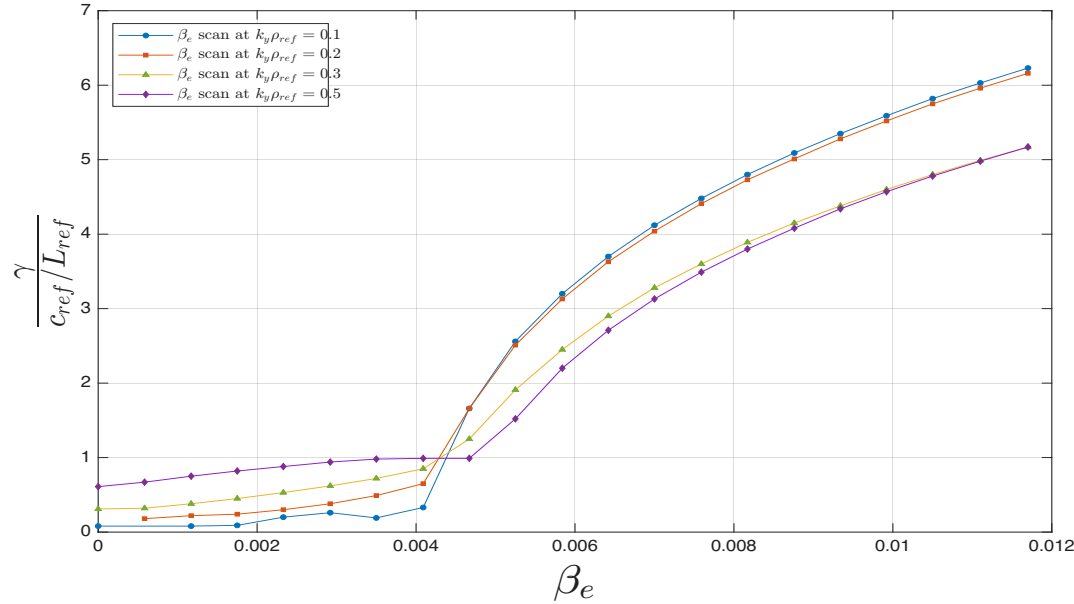
Multiscale Linear Scans

- Simulations without impurities for electron scale at $\rho_{tor} = 0.98$. One branch of ETGs have uncommon positive real frequency.



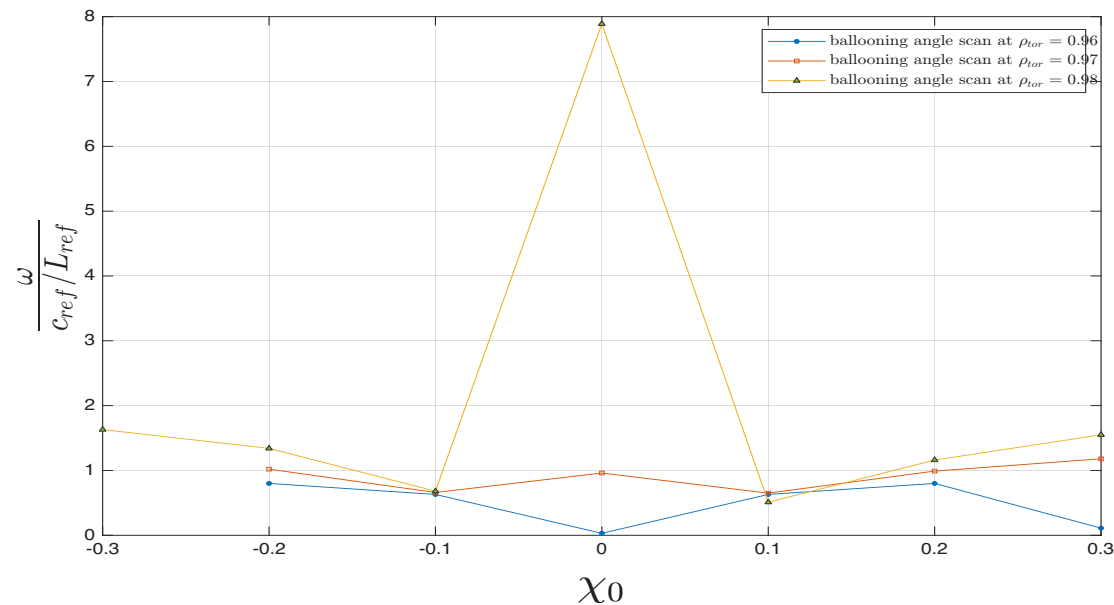
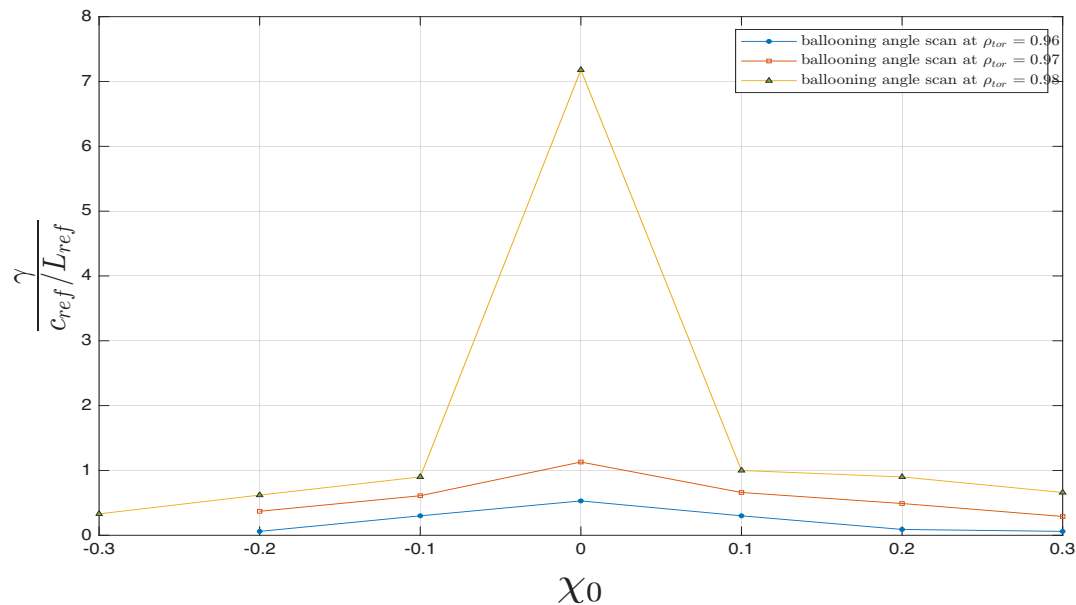
- The curve shapes with and without impurities look very similar. Therefore, the conclusion is robust.
- In agreement with a recent published paper, see *Facundo Sheffield, Tobias Görler, Frank Jenko; On ion-frequency electron temperature gradient modes. Phys. Plasmas 1 December 2025; 32 (12): 122301*
- May bring new challenges to nonlinear simulations in the future.

β_e Scans



- $\beta_e = \frac{p_e}{p_B} = \frac{8\pi n_{e0} T_{e0}}{B_0^2}$. In SI units, $\beta_e \uparrow \Rightarrow \mu_0 \uparrow \Rightarrow$ magnetic fluctuations $\uparrow$
- We show the β_e dependence of growth rate and real frequency at $\rho_{tor} = 0.96$ for ion scale.
- β_e obviously increases linear instabilities.
- A transition from ITG to KBM is observed as β_e increases.

χ_0 Scans



- Mathematical definition of ballooning angle χ_0 : The angle at which the fast phase does not vary radially through safety factor $q(x)$

$$\mathcal{A}(x, \chi, \varphi) = \hat{\mathcal{A}}(x, \chi, \varphi) e^{-in\{\varphi - q(x)[\chi - \chi_0]\}}$$

- We show the ballooning angle scans at $k_y \rho_{ref} = 0.3$, at different radial positions.
- Although usually set as zero for linear simulations, χ_0 is crucial to accurately predict the transport level in nonlinear runs. Thus we need the benchmarks.
- The growth rates have their peak values at $\chi_0 = 0$, especially for KBMs.

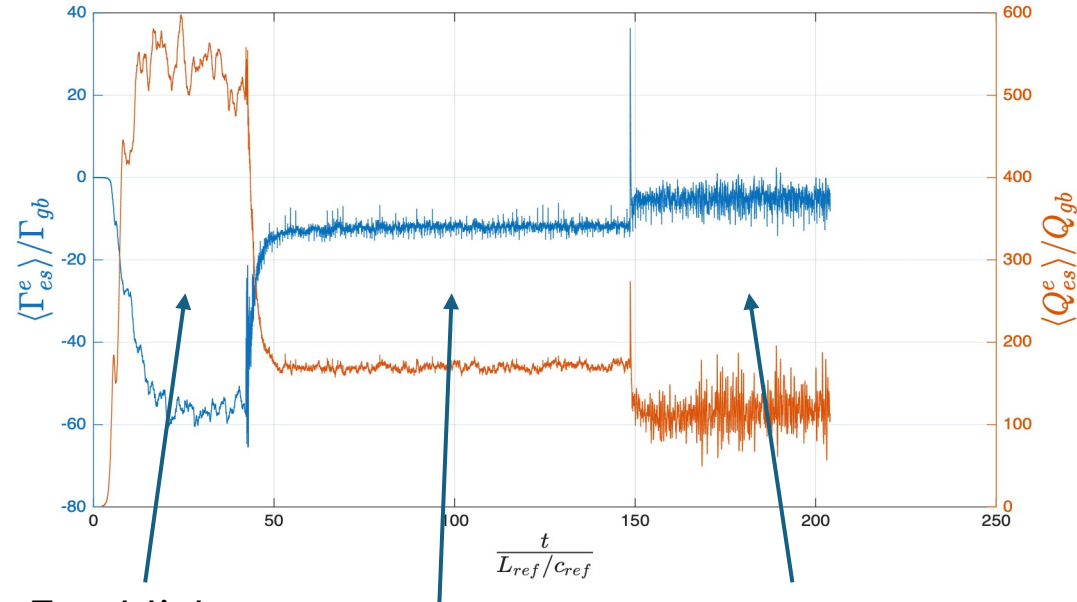
Nonlinear Simulations

- I also tried to run some preliminary local nonlinear simulations without impurities.
- Need much more time computational resources.
- **Three stages of running**
 - 1、 The system firstly went through a drastic evolution to establish a steady state.
 - 2、 We turned on $E \times B$ shearing, which stabilizes the system.
 - 3、 We added a finite β_e (turned on electromagnetic fluctuations) to observe corresponding variation of heat and particle transport.

Nonlinear Simulations

Heat and Particle Flux of Electron

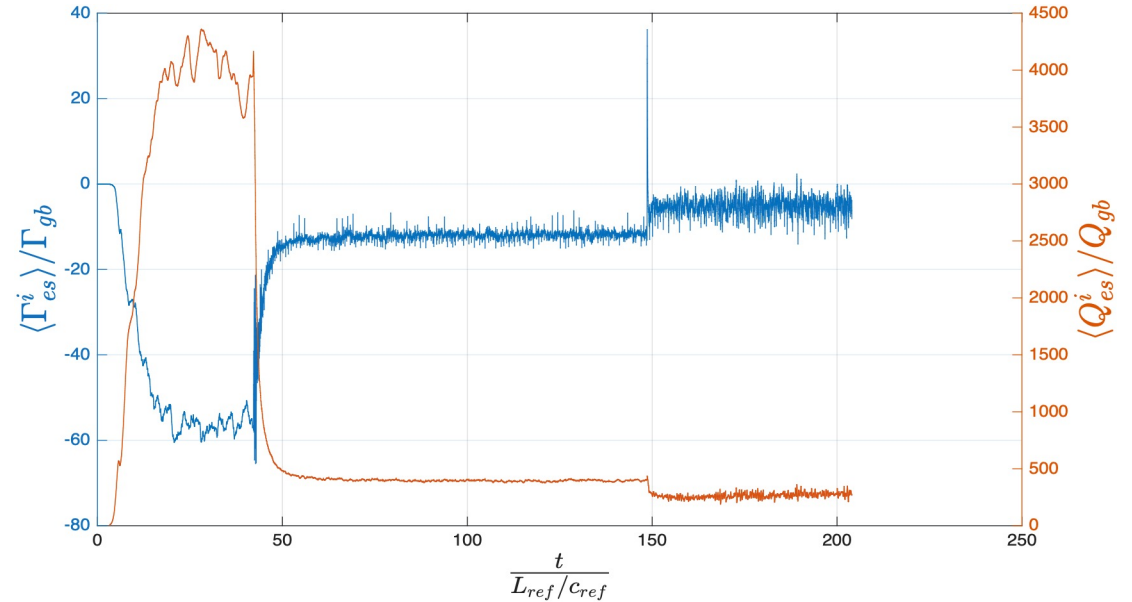
Heat and Particle Flux of Ion



Establish a steady state

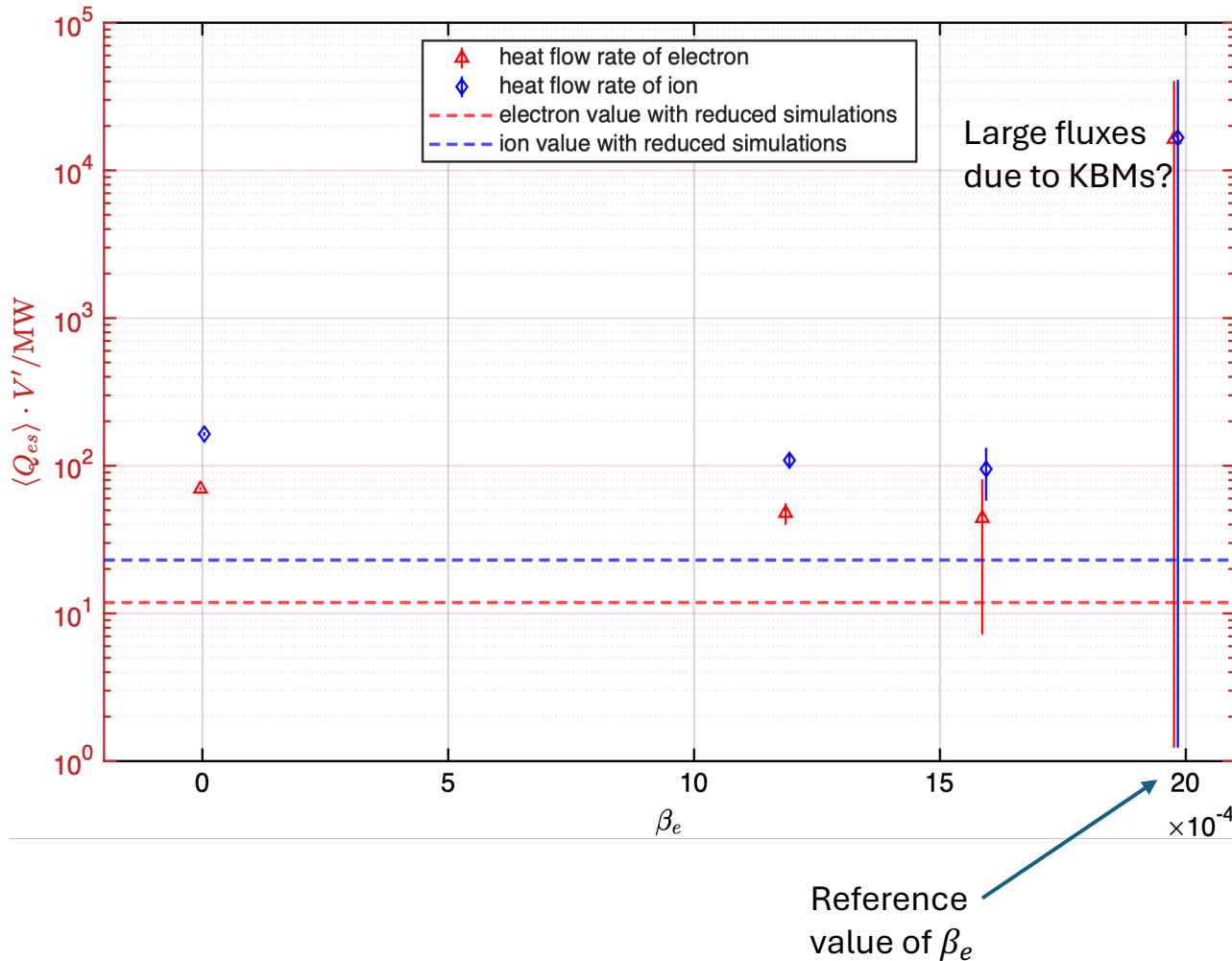
$E \times B$ shearing is turned on

A small β ($\sim 10^{-3}$) is turn on



- This nonlinear simulation at $\rho_{tor} = 0.97$ clearly exhibits the three stages described before.
- The particle fluxes are same for electron and ion due to neutrality.
- The heat fluxes decrease about 30% after turning on β_e , which means a nonlinear electromagnetic stabilization of the fluxes.

Nonlinear Simulations



- We show the dependence of ion and electron heat flow rates on β_e . The dashed lines are the results from reduced model computed with JINTRAC.
- When β_e approaches to reference value ($\sim 2 \times 10^{-3}$), the system can't converge to a steady state, which implies that we may overestimate the electron pressure $n_e T_e$.
- The integral of the sources is only about one-quarter of heat fluxes from gyrokinetic simulations. This suggests me to consider impurity effects in the future.

Conclusions

- I performed linear convergence scans to decide the proper grid discretization. The relative errors of γ and ω induced by finite grids are less than 3%.
- I performed multiscale linear scans to observe the most unstable modes under different parameters. All modes appeared in spectra are characterized.
- I ran nonlinear simulations at $\rho_{tor} = 0.97$ and analyzed the heat and particle fluxes with respect to parameter β_e . The results were compared with reduced models.

Future Works

- I will further explore the difference between the heat sources and the turbulent fluxes obtained with gyrokinetic theory. The first test will be to try to add impurities.
- Afterwards, I will focus on global ion scale simulations and flux-tube electron scale runs.
- The KBM may not show up in the global runs. If this is the case, maybe the DTT pedestal performance could be even better.

Thank You for Listening!