Full-orbit Toroidal Accelerated PArticle Simulator (TAPAS) to Study the Transport and Losses of Energetic Particles in Fusion Devices: Coupling with Far3D code

H. BETAR[1], D. Zarzoso[1], J. Varela[2], D. Del-Castillo-Negrete[3]

[1] *Aix-Marseille Université, CNRS, Centrale Marseille, M2P2 UMR 7340, Marseille, France*

[2] *Universidad Carlos III de Madrid, 28911 Leganes, Madrid, Spain*

[3] *Oak Ridge National Laboratory, Oak Ridge, TN 37831-8071, United States of America*

Abstract

In this paper, we briefly present the Toroidal Accelerated PArticle Simulator (TAPAS) and its recent developments, enabling the integration of charged particle trajectories in both the 6D phase space and its reduced 5D version resulting from gyro-kinetic ordering. Furthermore, we provide preliminary results of coupling TAPAS with the gyro-fluid Far3D code to investigate the transport of energetic particles (EPs) in the presence of Alfvén eigenmodes (AEs) in DIII-D tokamak.

TAPAS Code

In current and future fusion devices, energetic particles (EPs) play a crucial role, making their study a matter of utmost importance. The Toroidal Accelerated PArticle Simulator (TAPAS) is a GPU particle code that enables the integration of equations of motion for a large number of particles. These equations can be represented in either 6D phase space, allowing for the resolution of dynamics occurring on time and spatial scales of the order of the cyclotron time and Larmor radius of the charged particles, or in a 5D phase space resulting from gyro-kinetic ordering. The main steps in TAPAS begin by initializing the magnetic equilibrium and equilibrium metric and establishing the toroidal coordinate system (CS). Next, the code finds the new positions of the particles, and performs field interpolation at them. Then, the new velocities of the particles are calculated, taking into account the interactions with the interpolated electromagnetic fields and collisions with different species. In its initial version, as detailed in Ref [1], TAPAS primarily focused on integrating particle trajectories in circular geometry, where the flux surfaces were concentric circles. The equations of motion were solved in 5D phase space. This version of the code was utilized to investigate the influence of tearing modes on EPs dynamics, with electromagnetic perturbations being computed using analytical formulas. However, as previously mentioned, the new version of TAPAS incorporates the Boris algorithm to integrate the equations in 6D phase space. Additionally, it no longer necessitates analytical formulas for fields. Instead,

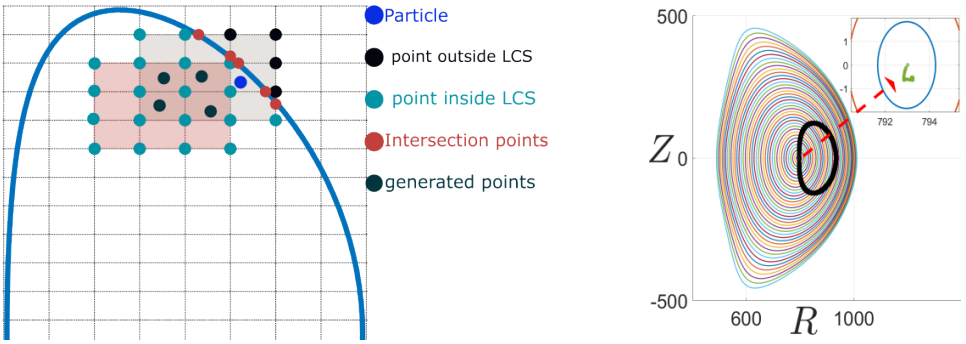

Figure 1: Left frame: interpolation strategy at the particle position. Right frame: the green and black curves are the trajectories of the same particle using different approximation methods in DIII-D equilibrium (The green trajectory (as observed in the inset) is not correctly calculated, whereas the black one is) -see the main text.

the current version of the code implements multi-dimensional B-spline interpolation to approximate fields at particle positions. When utilizing an experimental or numerical equilibrium, it is important to address two subtle issues that are generally relevant to this type of particle simulators. These issues pertain to evolving particle dynamics near the last closed surface (LCS) and in proximity to the magnetic axis. The code solves the equations of motion in a Cartesian CS, while the equilibrium fields obtained from external simulations are estimated in a generalized toroidal geometry, such as the Boozer CS for example. Consequently, after calculating the new position of a particle, it is necessary to transform its Cartesian coordinates to toroidal coordinates in order to interpolate the equilibrium fields at the particle's updated location. This process involves determining the toroidal coordinates (ρ, θ, ϕ) based on the known cylindrical coordinates of the particle (R, Z, ϕ). In solving this problem, as illustrated in the left frame of Fig.1, the particle may be located in a region where some interpolation nodes lie outside the physical domain. Consequently, the fields at these nodes are undefined. To address this issue, we have developed a correcting algorithm that assigns physical values to these missing nodes. This is achieved by solving the inverse problem of Lagrange interpolation, which entails finding the field values at these nodes such that they accurately reproduce pre-chosen values within the physical domain. Also, in many plasma simulations conducted in toroidal geometry, it is common to avoid points located exactly at the magnetic axis ($\rho = 0$) due to divergence issues associated with some quantities. Therefore, special treatment is required when a particle enters this region defined by the first closed surface provided by the experimental equilibrium. One popular approach is to approximate the magnetic equilibrium using circular geometry. However, we have observed that this treatment can lead to unphysical particle trapping, as illustrated in the zoomed-in part of the right frame of Fig.1, where an unphysically trapped particle's trajectory is represented by the green curve inside the first closed surface. To overcome this issue, we employ a multi-dimensional Taylor expansion to approximate the particle trajectory inside

the first closed surface, resulting in a well-resolved trajectory represented by the black curve in the right frame of Fig.1. It is important to note that another problem can arise due to the numerical accuracy of equilibrium codes used to calculate the flux surfaces. In fact, the accuracy of some of these codes can be questionable near the magnetic axis, indicating that the choice of the point around which Taylor expansion is performed to predict the particle's trajectory inside the first closed surface must be made carefully. In the new version of TAPAS, an important addition is the inclusion of collisions through a collision operator. This operator can act on either particle velocity (full-orbit version) or guiding-center velocity (guiding-center version). By using this collision operator, TAPAS can now accurately simulate the impacts of collisions between EPs and various background electrons and ions.

Investigating the Dynamics of Energetic Particles in the Presence of Alfvén Eigenmodes in DIII-D tokamak: Coupling TAPAS with Far3D

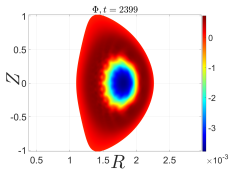

Figure 2: Top frames: Φ, $\frac{\partial \Phi}{\partial r}$, $<\frac{\partial \Phi}{\partial r}>_\theta$, and ψ as obtained with Far3D. Bottom frames: radial and poloidal distributions of the number of confined particles using TAPAS where the first and the second frames correspond to $0 \leq r_{NBI} \leq 0.14a$ and $015a \leq r_{NBI} \leq 0.30a$, respectively.

In this section, our focus is on utilizing TAPAS to investigate the transport of energetic particles in the presence of Alfvén eigenmodes (AEs). The electromagnetic perturbations, including the magnetic stream function ψ and the electrostatic potential Φ, are obtained from the gyro-fluid Far3D code (see Ref[2] and references therein). We performed several non-linear simulations to investigate the influence of the neutral beam injector (NBI) operation regime on the saturation phase of AEs in DIII-D plasma [5]. In this present study, we specifically focus on the non-linear simulation with a chosen value of $\beta_{EP} = p_{EP}/B^2 = 0.03$. The EPs are characterized by a temperature of 21.4 KeV, whereas the thermal plasma has a temperature of 2.1 KeV at the magnetic axis. The initial profiles for densities and temperatures of different species were derived using the kick model and the TRANSP-NUBEAM code[3]. Linear analysis with Far3D demonstrates the destabilization of various families of AEs, with the modes associated with the poloidal number $m = 3$ exhibiting the fastest growth. This is consistent with the findings of the