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Piecewise Field-Aligned Finite Element Method for Multi-Mode Nonlinear Particle Simulations

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Nonlinear kinetic effects play a crucial role in determining plasma confinement and require efficient and accurate multi-mode nonlinear gyrokinetic simulations. The piecewise field-aligned finite element method (PFA-FEM) is introduced as an advancement in particle simulation employing FEMs, characterized by its utilization of traditional grids and field-aligned basis functions built upon locally defined field-aligned coordinates. This method offers several advantages, including the avoidance of grid deformation, reduction in grid numbers along one direction [1], and enhanced accuracy in field solving while maintaining rigorous particle assignment and field interpolation. Moreover, its compatibility with triangular meshes facilitates seamless integration into the TRIMEG code for further enhancements [2].

For the core plasmas in nested magnetic flux surfaces, the Clebsch coordinates are constructed in each toroidal sub-domain. The grid is defined in (r,ϕ,θ) coordinates as shown in Fig. 1, where r,ϕ,θ are radial-like, toroidal and poloidal coordinates. The basis functions are aligned along the magnetic field in (r,ϕ,η), where $\eta=\theta-\int_{\phi_i}^{\phi}\frac{d\phi'}{q(\theta')}$, with i denoting the index of the toroidal domain, q representing the local safety factor, and the integration performed along the magnetic field. In addition to the benefit of avoiding grid deformation and reducing the grid number in one direction, the scheme can be extended to higher-order finite element methods. Furthermore, the (r,ϕ,θ) grid is defined without a shift, allowing easy applications using triangular meshes.

For the whole volume plasma with open field lines, the grid is defined in (R,Z,ϕ) cylindrical coordinates. The field-following coordinates (R_0,Z_0,ϕ) are constructed by following the magnetic field from a point (R,Z,ϕ) to the reference toroidal position ϕ_i of a toroidal subdomain. The backward field line tracing is adopted to construct the field-following coordinates as shown in Fig. 2, $R_0=R-\int_{\phi}^{\phi_i}\frac{\boldsymbol{B}\cdot\nabla R\prime}{\boldsymbol{B}\cdot\nabla\phi\prime}d\phi'$, $Z_0=Z-\int_{\phi}^{\phi_i}\frac{\boldsymbol{B}\cdot\nabla Z\prime}{\boldsymbol{B}\cdot\nabla\phi\prime}d\phi'$. The finite element basis functions are defined in (R_0,Z_0,ϕ) where equations can be expressed. In addition to the backward field line tracing, the forward field line tracing is used for the interpolation of the perturbed field at the particle location according to $R=R_0+\int_{\phi_i}^{\phi}\frac{\boldsymbol{B}\cdot\nabla R\prime}{\boldsymbol{B}\cdot\nabla\phi\prime}d\phi'$, $Z=Z_0+\int_{\phi_i}^{\phi}\frac{\boldsymbol{B}\cdot\nabla Z\prime}{\boldsymbol{B}\cdot\nabla\phi\prime}d\phi'$.

The validation through the linear benchmarking using the Cyclone-like parameters demonstrates excellent agreement with prior research. Furthermore, its effectiveness in nonlinear simulations is demonstrated, particularly in the presence of phase space zonal structures [3], for the studies of energetic particle transport in constant of motion space [4]. Additionally, its versatility extends to electromagnetic simulations [5,6,7] and whole volume simulations employing unstructured meshes [2]. Notably, its relevance to ongoing gyrokinetic studies and application in stellarator configurations is emphasized [8,9].

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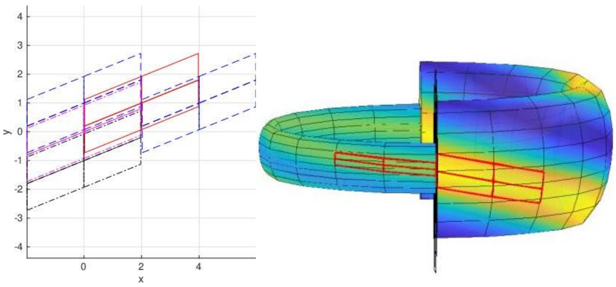

Figure 1. PFA-FEM for the core plasma

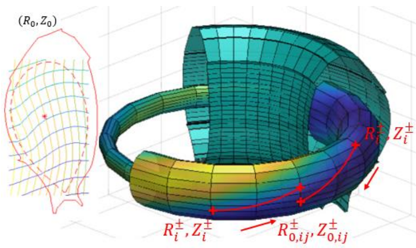

Figure 2. PFA-FEM for the whole volume plasma