MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Wendelstein 7-X

ATEP WP 2.3 - Status

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Motivation:

Why do we need a simplified and fast description of wave particle interaction in 3D?

- prediction of unstable modes in W7-X
- predict/find favorable operation regimes with respect to fast particles in W7-X (e.g. relevant for configuration changes of NBI)
- provide guidance and background physics for expensive fully gyro-kinetic global simulations
- assessment of mode damping
- affordably predict fast particle transport due to wave particle interaction

Workpackage 2.3:

- In analogy to the local version two-dimensional gyro-kinetic code LIGKA, a three-dimensional extension will be developed aiming at solving the related eigenvalue problem. The development will rely on realistic stellarator equilibria calculated with VMEC.
- The kinetic part will make use of knowledge from the drift kinetic code CAS3D-K. Due to the many more additional couplings, considerable numerical problems are expected, therefore the passing particle contribution will be focus of the development. The model will be benchmarked against the analytical model of Kolesnichenko et al. and its validity can be tested by comparison with the EUTERPE and the STAE-K code.

Equations at 2D

from P. Lauber et al. Plasma Phys. Control. Fusion 51 (2009) 124009:

$$\omega^2\left(1-\frac{\omega_{*\mathrm{p}}}{\omega}\right)-k_\|^2\omega_A^2R_0^2 = 2\frac{v_{\mathrm{thi}}^2}{R_0^2}\Bigg(-\Big[H(x_{m-1})+H(x_{m+1})\Big] + \tau\left[\frac{N^m(x_{m-1})N^{m-1}(x_{m-1})}{D^{m-1}(x_{m-1})}+\frac{N^m(x_{m+1})N^{m+1}(x_{m+1})}{D^{m+1}(x_{m+1})}\right]\Bigg) \quad (1)$$

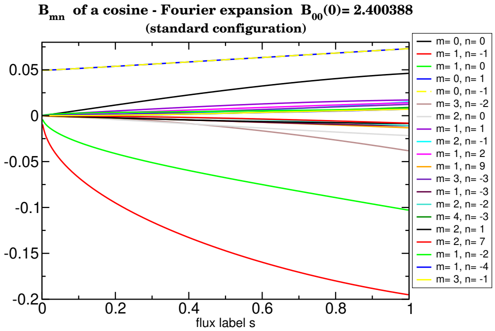
with $x_m = \frac{\omega}{k_{\|,m}v_{\mathrm{th}}}$, $v_{\mathrm{thi}}^2 = 2T_{\mathrm{i}}/m_{\mathrm{i}}$, $\omega_{\mathrm{p}*} = \omega_{*\mathrm{n}}+\omega_{*\mathrm{T}} = T_{\mathrm{i}}/(eB)k_\theta(\nabla n/n)(1+\eta)$ with $\eta = \frac{\nabla T}{T}/\frac{\nabla n}{n}$, $D(x_m) = [1+\tilde{D}(x_{\mathrm{e},m})]+\tau[1+\tilde{D}(x_{\mathrm{i},m})]$, $N^m(x_m) = \tilde{N}^m(x_{\mathrm{i},m})-\tilde{N}^m(x_{\mathrm{e},m})$, $\tilde{D}(x) = (1-\frac{\omega_*}{\omega})xZ(x)-\frac{\omega_*}{\omega}\eta(x^2+xZ(x)(x^2-\frac{1}{2}))$, $2\tilde{N}^m(x) = (1-\frac{\omega_*^m}{\omega})[x^2+xZ(x)(x^2+\frac{1}{2})]-\frac{\omega_*^m}{\omega}\eta[x^4+\frac{x^2}{2})+xZ(x)(\frac{1}{4}+x^4)]$, $H(x_m) = \tilde{H}(x_{m,\mathrm{i}})+\tau\tilde{H}(x_{m,\mathrm{e}})$, $\tilde{H}(x_m) = \frac{1}{2}[(1-\frac{\omega^*}{\omega})\tilde{F}(x_m)-\eta\frac{\omega^*}{\omega}\tilde{G}(x_m)]$, $2\tilde{F}(x) = xZ(x)(\frac{1}{2}+x^2+x^4)+\frac{3x^2}{2}+x^4$, $2\tilde{G}(x) = xZ(x)(\frac{3}{4}+x^2+\frac{x^4}{2}+x^6)+2x^2+x^4+x^6$ and $Z(x)$ the plasma dispersion function. Although obtained in a completely different way, equation (1) is very similar (same coefficients) to the ballooning formulation result. The asymmetry in the

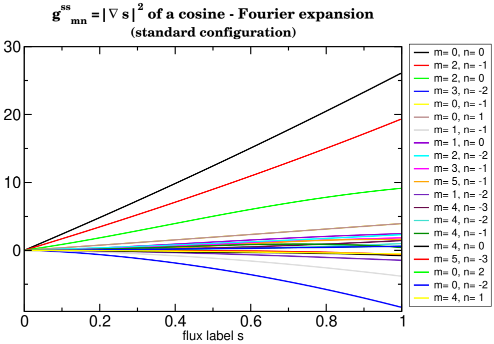
Milestones Workpackage 2.3:

WP2.3-M1 Derive equations for local LIGKA version in 3D
Mid 2022
on going activity (slightly delayed)
expected at end of October 2022

WP2.3-M2 Local eigenvalue code in 3D (LIGKA) including passing particles
End 2023
(activities still in time)

Stellarator specific modifications





$$B(r,\vartheta,\varphi) = B_0\left(\epsilon_{00}(r) + \epsilon_t(r)\cos\vartheta + \epsilon_h(r)\cos(m_h\vartheta + n_h\varphi) + \epsilon_m(r) cos\varphi\right)$$

$$g^{ss}(r,\vartheta,\varphi) = \sum_{i=1}^{n_g} \epsilon_i^g(r)\cos(m_i\vartheta + n_i\varphi)$$

Stellarator specific modifications

- ☑ large aspect ratio in Boozer coordinates to keep the integrals analytically tractable
- ☑ decomposition of the particle motion
- ☑ quasi-neutrality, Ampère's law
- ☑ kinetic equation
- ☐ compose terms (tedious, but straight-forward)
- ☐ decide upon approximation on the left hand side of Eq. (1) (MHD coupling in W7-X is strong $\Rightarrow n_g$ must have a certain size otherwise the quantitative agreement in the MHD limit is not sufficient)

Finite $E_{\parallel}$ extension for EUTERPE/ CKA-EUTERPE

- in CKA-EUTERPE: use modified Ohm's law

$$\frac{\partial}{\partial t}A_{\parallel} = -\mathbf{b}\cdot\nabla\phi - \frac{1}{q_{\mathrm{e}}n_{\mathrm{e0}}}\mathbf{b}\cdot\nabla p_{\mathrm{e}}$$

  - leads to increased damping of Alfvén eigenmodes
  - compare with fully kinetic result and with HAGIS (cf. Mirjam Schneller's dissertation)
- revive A. Zocco's electron fluid model installed earlier in EUTERPE

$$\frac{\partial}{\partial t}\left(A_{\parallel} - d_{\mathrm{e}}^2\nabla^2 A_{\parallel}\right) = -\mathbf{b}\cdot\nabla\phi + \frac{\eta}{\mu_0}\nabla_{\perp}^2 A_{\parallel} - \left[\frac{k_{\mathrm{B}}T_{\mathrm{e0}}}{q_{\mathrm{e}}n_{\mathrm{e0}}}\mathbf{b}\cdot\nabla n_{\mathrm{e}} + \frac{k_{\mathrm{B}}T_{\mathrm{e0}}}{q_{\mathrm{e}}B}\frac{\mathbf{b}\times\nabla p_{\mathrm{e0}}}{p_{\mathrm{e0}}}\cdot\nabla A_{\parallel}\right]$$

Collisionless skin depth $d_{\mathrm{e}}^2 = \frac{m_{\mathrm{e}}}{\mu_0 n_{\mathrm{e0}} e^2}$, $p_{\mathrm{e0}} = n_{\mathrm{e0}}T_{\mathrm{e0}}$ $\eta = \nu\frac{m_{\mathrm{e}}}{e^2 n_{\mathrm{i0}}}$

- will be reported mainly in TSVV