Warm simulations of low-frequency wave propagation in three-dimensional plasmas

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Motivation

- The LEMan (Low-frequency E/M Wave Propagation) code is a fast tool to analyse the propagation of low-frequency waves in 2D and 3D configurations.

- Low-frequency waves are of great interest in plasma physics (destabilisation of global Alfvén modes by fast ions, ICRH, etc…). Several codes are dealing with this domain (AORSA, TORIC, LIGKA, NOVA-K, PENN, etc…).

- Importance to have kinetic effects => A warm model has been implemented (including Landau damping and Kinetic Alfvén Wave (KAW))

- Wide ranges of 3D configurations: stellarators, non-axisymetric components in tokamak (toroidal ripple, localised antenna, etc…)

Main considerations

- Low-frequency waves, long wavelengths => spatial variation of equilibrium quantities over a wavelength non-negligible => need a full-wave formulation

- Geometric effects are important and we want to model 3D configurations => 3D code

- LEMan solves Maxwell's equations:

$$\nabla\times\nabla\times\vec{E}-k_0^2\hat{\varepsilon}\cdot\vec{E}=ik_0\frac{4\pi}{c}\vec{j}_{ext}$$

- The dielectric tensor ε (relating the electric field and the internal current) is determined by the physical model

Wave equation formulation

- Maxwell's equation can be solved in terms of potentials. The advantage of this method is the absence of numerical pollution (resulting from the $\nabla\times\nabla\times$ operator):

$$\begin{cases}\vec{B}=\nabla\times\vec{A}\\ \vec{E}=-\nabla\phi+ik_0\vec{A}\end{cases} \quad and \quad \nabla\cdot\vec{A}=0 \quad \Rightarrow \quad \begin{cases}\nabla^2\vec{A}+k_0^2\hat{\varepsilon}\cdot\vec{A}+ik_0\hat{\varepsilon}\cdot\nabla\phi=-\dfrac{4\pi}{c}\vec{j}_{ext}\\ \nabla\cdot(\hat{\varepsilon}\cdot\nabla\phi)-ik_0\nabla\cdot(\hat{\varepsilon}\cdot\vec{A})=-4\pi\rho_{ext}\end{cases}$$

- 3D plasma equilibrium is computed with the VMEC code.
- The equations are written in the Boozer coordinates (mapped with the TERPSICHORE code):

$$\vec{B}_0=\nabla\varphi\times\nabla\psi+\nabla\phi\times\nabla\theta,$$

where ψ and ϕ are resp. the poloidal and toroidal fluxes. All vectors are projected onto the local magnetic basis:

$$\vec{A}=A_n\frac{\nabla s}{|\nabla s|}+A_b\frac{\vec{B}_0\times\nabla s}{B_0|\nabla s|}+A_{\|}\frac{\vec{B}_0}{B_0}$$

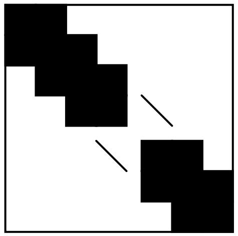
Advantages: simple boundary conditions and dielectric tensor form

Numerical scheme

- The set of equations is solved using the Galerkin weak form method.
- The solution is discretised with finite elements in the radial direction and Fourier harmonics in the poloidal and toroidal directions:

$$f(s,\theta,\varphi) = \sum_{r,m,n} f^{rmn} \psi_r(s) e^{i(m\theta + n\varphi)}$$

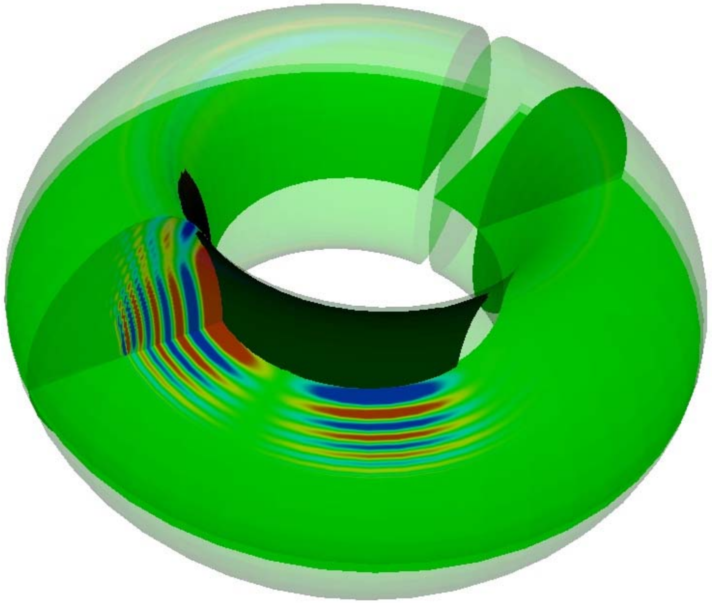
- Results in a block tridiagonal linear system. Several parallelisation schemes are used depending on the physical model or geometry. Computation requires up to 800Gb of memory => shared over all nodes.



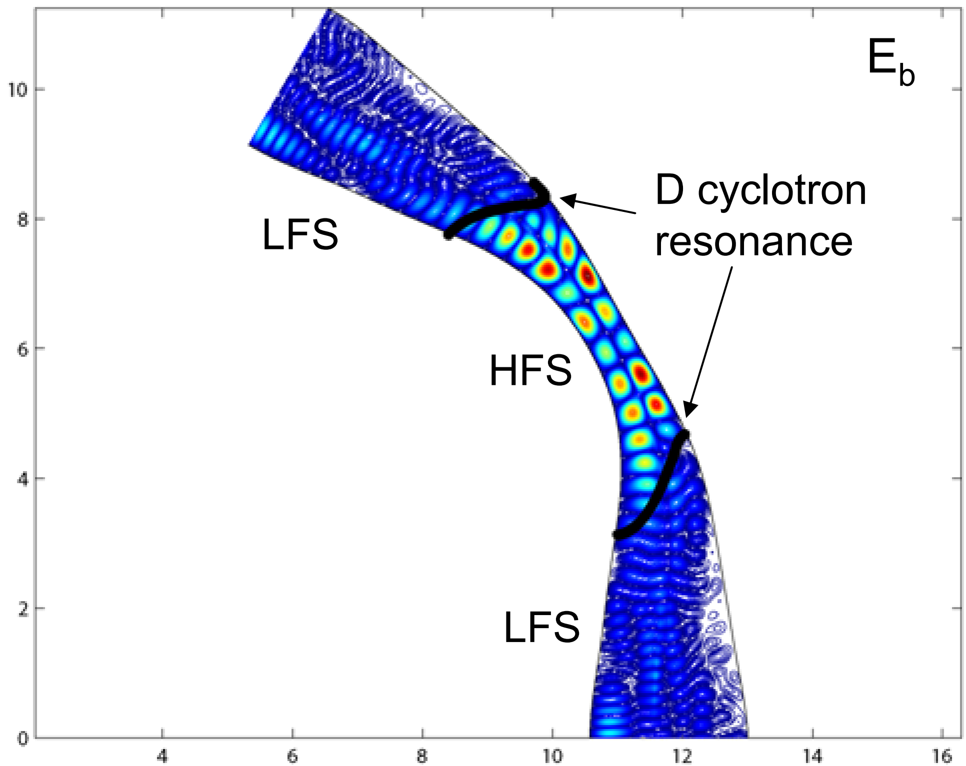
Parallelisation

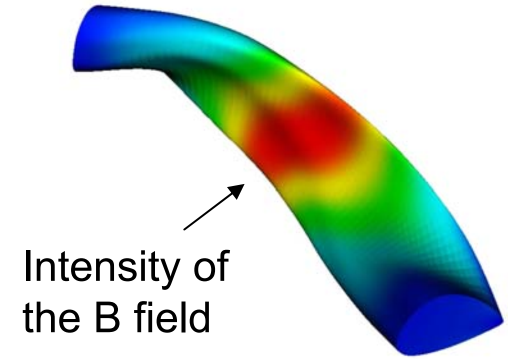
- If the computation of the matrix elements takes more time than the solution of the linear system (this is the case with the warm model presented later) => simple parallelisation on magnetic surfaces gives the best scalability
- If the longest time is spent in the solver (warm model with approximation of k||) => BABE method + OpenMP are applied
- In axisymetric case, with toroidally localised antenna => parallelisation over the toroidal wave number *n*.

> Two ion-species scenario with a localised antenna (the antenna is represented in black)



6-period quasi-isodynamic stellarator





- Stellarator configuration with a dominant mirror component => magnetic beach scenario
- 1676 Fourier harmonics and 100 radial surfaces were required for the computation (~300Gb)
- Cold model

Warm model

- Vlasov equation:

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\frac{\partial f}{\partial \vec{x}} + \frac{q}{m}\left[\vec{E} + \vec{v}\times\vec{B}\right]\cdot\frac{\partial f}{\partial \vec{v}} = 0$$

- Linearization:

$$\frac{\partial \bar{f}}{\partial t} + \vec{v}\cdot\frac{\partial \bar{f}}{\partial \vec{x}} + \frac{q}{m}\vec{B}_0\cdot\frac{\partial \bar{f}}{\partial \vec{v}} + \frac{q}{m}\left[\vec{E}_1 + \vec{v}\times\vec{B}_1\right]\cdot\frac{\partial F}{\partial \vec{v}} = 0$$

- Neglecting terms of order higher than 0 in the Finite Larmor Radius (FLR) expansion:

$$\left[\frac{\partial}{\partial t} + v_{\parallel}\nabla_{\parallel} + \Omega\frac{\partial}{\partial \alpha}\right]\bar{f} = -\frac{q}{m}\vec{E}_1\cdot\frac{\partial F}{\partial \vec{v}} = A(\vec{E},\vec{v})$$

- F is taken as a Maxwellian ($\sim\exp(-v^2/v_{th}^2)$)
- The warm dielectric tensor is obtained after integration of the perturbed distribution function:

$$\vec{j} = q\int f(\vec{v})\vec{v}d^3v$$

Warm model in cylindrical geometry

- Fourier transform in time and Fourier decomposition for the gyro-angle α:

$$\bar{f}(t) = \frac{1}{2\pi}\int f(\varpi)e^{-i\varpi t}d\varpi \qquad f = \sum_{l=-\infty}^{\infty} f_l e^{il\alpha}$$

$$\Rightarrow \quad \left[-i\omega + ik_{\|}v_{\|} + il\Omega\right]f_l = A(\vec{E},\vec{v})$$

- $k_{\|}$ do not vary on a magnetic surface:

$$f_l = \frac{iA(\vec{E},\vec{v})}{\varpi - k_{\|}v_{\|} - l\Omega}$$

- After integration over the velocity, we obtain the dielectric tensor:

$$\varepsilon_{nn} = \varepsilon_{bb} = 1 - \frac{1}{2\varpi}(\tilde{Z}_1 + \tilde{Z}_{-1}) \qquad \varepsilon_{nb} = -\varepsilon_{bn} = -\frac{i}{2\varpi}(\tilde{Z}_1 - \tilde{Z}_{-1}) \qquad \varepsilon_{\|\|} = 1 + \frac{2}{(k_{\|}v_{th})^2}(\varpi_p^2 - \varpi\tilde{Z}_0)$$

$$\varepsilon_{n\|} = \varepsilon_{\|n} = \varepsilon_{b\|} = \varepsilon_{\|b} = 0 \qquad \tilde{Z}_l = \frac{\varpi_p^2}{\varpi - l\Omega}Z^{Sh}(z_l) \quad with \quad z_l = \frac{\varpi - l\Omega}{|k_{\|}|v_{th}}, \quad Z^{Sh}(z) = \frac{z}{\sqrt{\pi}}\int_{-\infty}^{+\infty}\frac{1}{z-x}e^{-x^2}dx$$

Warm model in axisymetric geometry

- Same as used in the PENN code (Brunner, Vaclavik 1993)
- Axisymmetry allows to decompose the perturbed part of the distribution function in a Fourier series along the toroidal direction:

$$f_l(\varphi) = \sum_{n=-\infty}^{+\infty} f_{l,n} e^{in\varphi}$$

- If the *m* (poloidal mode number) of $k_{\|}$ is neglected, the same formulation as for the cylindrical case can be used:

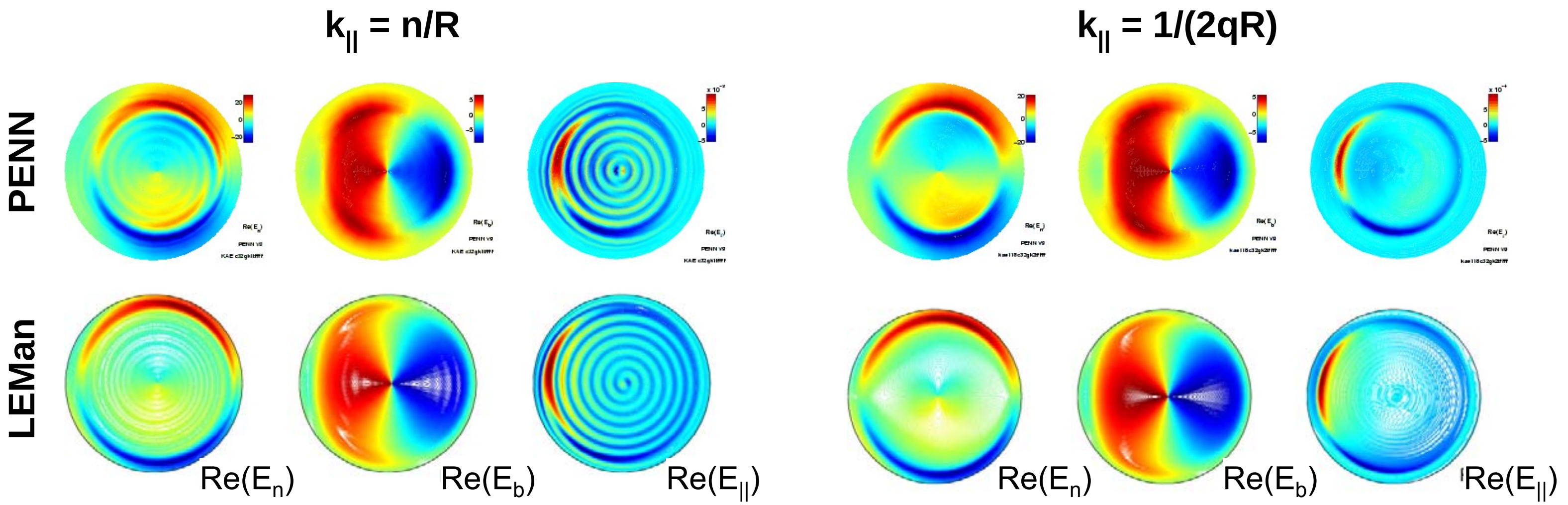
$$f_{l,n} = \frac{iA(\vec{E},\vec{v})}{\varpi - k_{\|}(n,\theta)v_{\|} - l\Omega(\theta)}$$

- Integration leads to the same kind of solution as before.
- For example: $$k_{\|} = \frac{-i}{B_0\sqrt{g}}\left(\phi' \frac{\partial}{\partial\varphi} + \psi' \frac{\partial}{\partial\theta}\right) = \frac{1}{r}\left(n + \frac{m}{q}\right) \approx \frac{n}{r}$$

or $k_{\|} = \dfrac{1}{2qR}$ inside the Δm=1 gap.

Issues with $k_{||}$ approximation

- Hard to make a good approximation in a 3D configuration due to the absence of a simple symmetry as in a tokamak.
- Significant dependence of the wavefield on the approximation used for the parallel wave vector. For example:



KAW in a tokamak with circular cross section.f = 118kHz, n = 1, n_0 = 2.2e19m^{-3}, B_0 = 2.0T, D plasma.

=> A method is needed to keep the exact form of $k_{||}$.

Warm model: general case (1)

- In order to keep the full expression for $k_{||}$, a Fourier decomposition is performed in both the poloidal and toroidal directions:

$$f(\theta,\varphi)=\sum_{m,n=-\infty}^{+\infty} f_{mn}e^{i(m\theta+n\varphi)} \qquad E(\theta,\varphi)=\sum_{m',n'=-\infty}^{+\infty} E_{m'n'}e^{i(m'\theta+n'\varphi)}$$

- After multiplication by a test function g(θ,φ), the linearised Vlasov equation becomes:

$$-i\sum_{\substack{m,n\\m',n'}}\left[\varpi-\frac{v_{\|}}{\sqrt{g}B}\left(\psi' m+\phi' n\right)+l\Omega\right]e^{i[(m-m')\theta+(n-n')\varphi]}g_{m'n'}f_{mn}=-\sum_{m',n'}\frac{q}{m}g_{m'n'}\vec{E}_{m'n'}\cdot\frac{\partial f_0}{\partial\vec{v}}$$

- Integration over θ and φ leads to the linear system $L\vec{f}=\vec{r}$:

$$L_{mm'nn'}(s)=-i\left(4\pi^2\omega-lC^{(1)}_{m-m',n-n'}-(\psi' m+\phi' n)C^{(2)}_{m-m',n-n'}v_{\|}\right)$$

$$with \quad C^{(1)}_{lk}=\int d\theta d\varphi\frac{qB(\theta,\varphi)}{m}e^{i(l\theta+k\varphi)} \qquad C^{(2)}_{lk}=\int d\theta d\varphi\frac{1}{\sqrt{g(\theta,\varphi)}B(\theta,\varphi)}e^{i(l\theta+k\varphi)}$$

$$r_{m'n'}=\int d\theta d\varphi\left(-\frac{q}{mv}\right)\frac{\partial f_0}{\partial v}\left[\frac{v_\perp}{2}\left[E_n(\delta_{l,1}+\delta_{l,-1})+iE_b(\delta_{l,-1}-\delta_{l,1})\right]+v_{\|}E_{\|}\delta_{l,0}\right]e^{-i(m'\theta+n'\varphi)}$$

Warm model: general case (2)

- In matrix form:

$$L=\begin{bmatrix} a_{11}+b_{11}v_{\|} & a_{12}+b_{12}v_{\|} & \cdots & a_{1p}+b_{1p}v_{\|} \\ a_{21}+b_{21}v_{\|} & a_{22}+b_{22}v_{\|} & & \\ \vdots & & \ddots & \\ a_{p1}+b_{p1}v_{\|} & & & a_{pp}+b_{pp}v_{\|} \end{bmatrix}$$

where:

$$a_{(m,n)(m',n')}=-i(4\pi^2\varpi-lC^{(1)}_{m-m',n-n'})$$

$$b_{(m,n)(m',n')}=i[(\psi' m+\varphi' n)C^{(2)}_{m-m',n-n'}]$$

- We have to take into account the dependence of the matrix on $v_{\|}$ in order to perform the integration over velocity space. The solution is written as a rational function of $v_{\|}$:

$$f_{nm}=\frac{\sum_{i=0}^{p-1}c_i v_{\|}^i}{\sum_{j=0}^{p}d_j v_{\|}^j}r_{n'm'}=\sum_{i=1}^{p}\frac{g_i}{h_i-v_{\|}}r_{n'm'}$$

- Partial fraction decomposition into a sum of terms each having the same form as in the cylindrical or approximated axisymmetric cases.

Warm model: convolution

- The dielectric tensor is no longer expressed in real space as it was in the cold formulation but is now linking the Fourier components of the electric field and current. Each element now has the following form:

$$\tilde{Z}_l^{nn'mm'} = \sum_i \frac{\varpi_p g_i}{\sqrt{\pi} v_{th}} \int_{-\infty}^{+\infty} \frac{1}{h_i / v_{th} - x} e^{-x^2} dx = -i \frac{\sqrt{\pi}\varpi_p}{v_{th}} \sum_i g_i w(h_i / v_{th})$$

where $w(z) = e^{-x^2} erfc(-iz)$ is the complex error function.

- In order to be able to use mathematical libraries, the integration of the dielectric tensor in the linear system is done with two successive matrix multiplications.

Convergence (radial elements)

- LHD case with B_0 = 0.8T, n_0 = 4.0e19m^{-3}, f = 51.7 kHz, fixed N_m = 139

Coulomb Gauge: $\delta_d = \int_V \left|\nabla \cdot \vec{A}\right| dV \; V^{1/3} / \int_V \left|\vec{A}\right| dV$

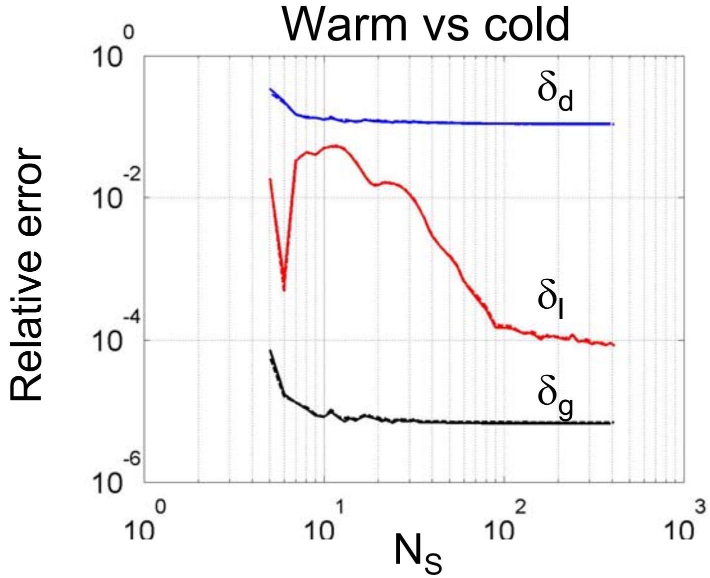
$$\delta_l = \int_0^1 \left| P_{plasma}(s) - P_{ant}(s) - iS_{Poynt}(s) \right| ds / P_{plasma}(1)$$

$$\delta_g = (P_{plasma}(1) - P_{ant}(1)) / P_{plasma}(1)$$

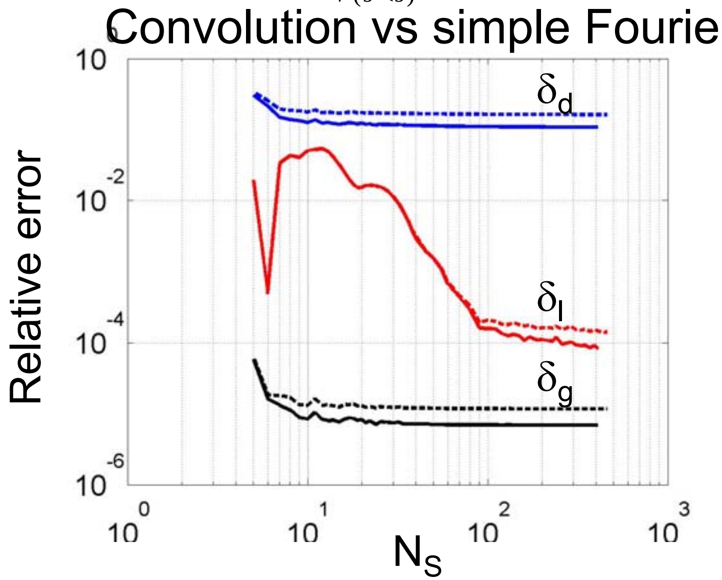
Local and global power balance:

$$P_{plasma}(s) = \frac{\omega}{8\pi} \int_{V(s'<s)} \left(\left|\vec{B}\right|^2 - \vec{E}^* \cdot (\vec{\varepsilon} \cdot \vec{E}) \right) dV'$$

$$P_{ant}(s) = \frac{i}{2} \int_{V(s'<s)} \left(\vec{E}^* \cdot \vec{j} \right) dV'$$



Warm model in solid
Cold convolution in dashed



- Cold convolution in solid
- Simple Fourier decomposition in dashed

Convergence (Fourier harmonics)

- LHD case with B_0 = 0.8T, n_0 = 4.0e19m^{-3}, f = 51.7 kHz, fixed N_S = 100

Coulomb Gauge: $\delta_d = \int_V \left|\nabla \cdot \vec{A}\right| dV \; V^{1/3} / \int_V \left|\vec{A}\right| dV$

$$\delta_l = \int_0^1 \left| P_{plasma}(s) - P_{ant}(s) - iS_{Poynt}(s) \right| ds / P_{plasma}(1)$$

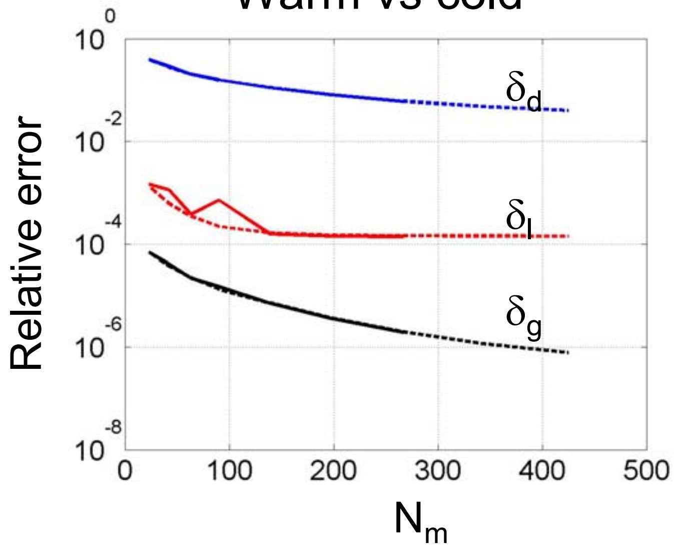
$$\delta_g = (P_{plasma}(1) - P_{ant}(1)) / P_{plasma}(1)$$

Local and global power balance:

$$P_{plasma}(s) = \frac{\omega}{8\pi} \int_{V(s'<s)} \left(\left|\vec{B}\right|^2 - \vec{E}^* \cdot (\vec{\varepsilon} \cdot \vec{E}) \right) dV'$$

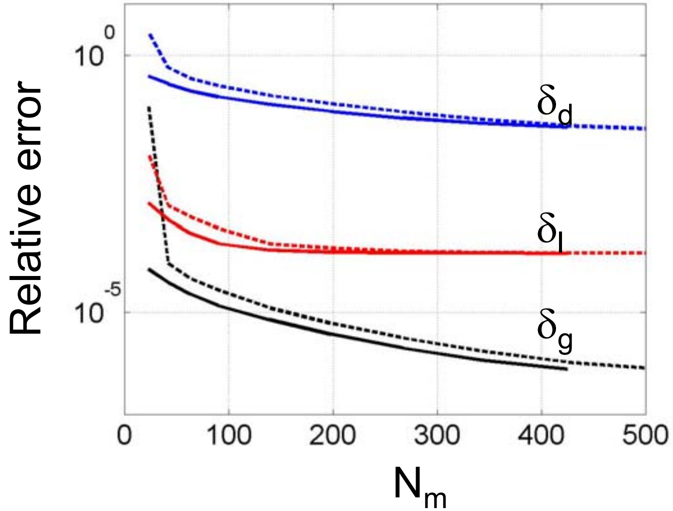
$$P_{ant}(s) = \frac{i}{2} \int_{V(s'<s)} \left(\vec{E}^* \cdot \vec{j} \right) dV'$$

Warm vs cold



Warm model in solid
Cold convolution in dashed

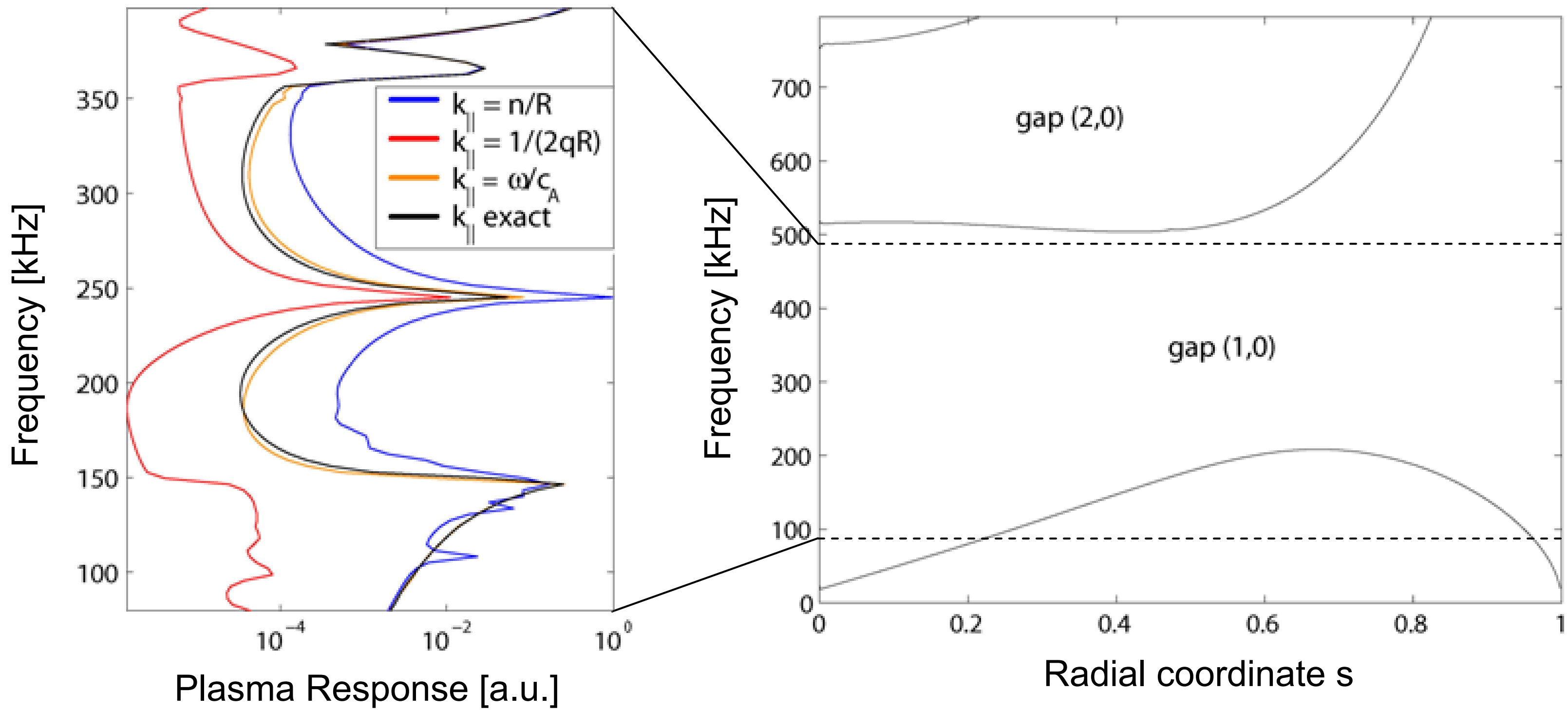
Convolution vs simple Fourier



- Cold convolution in solid
- Simple Fourier decomposition in dashed

Comparison of different models

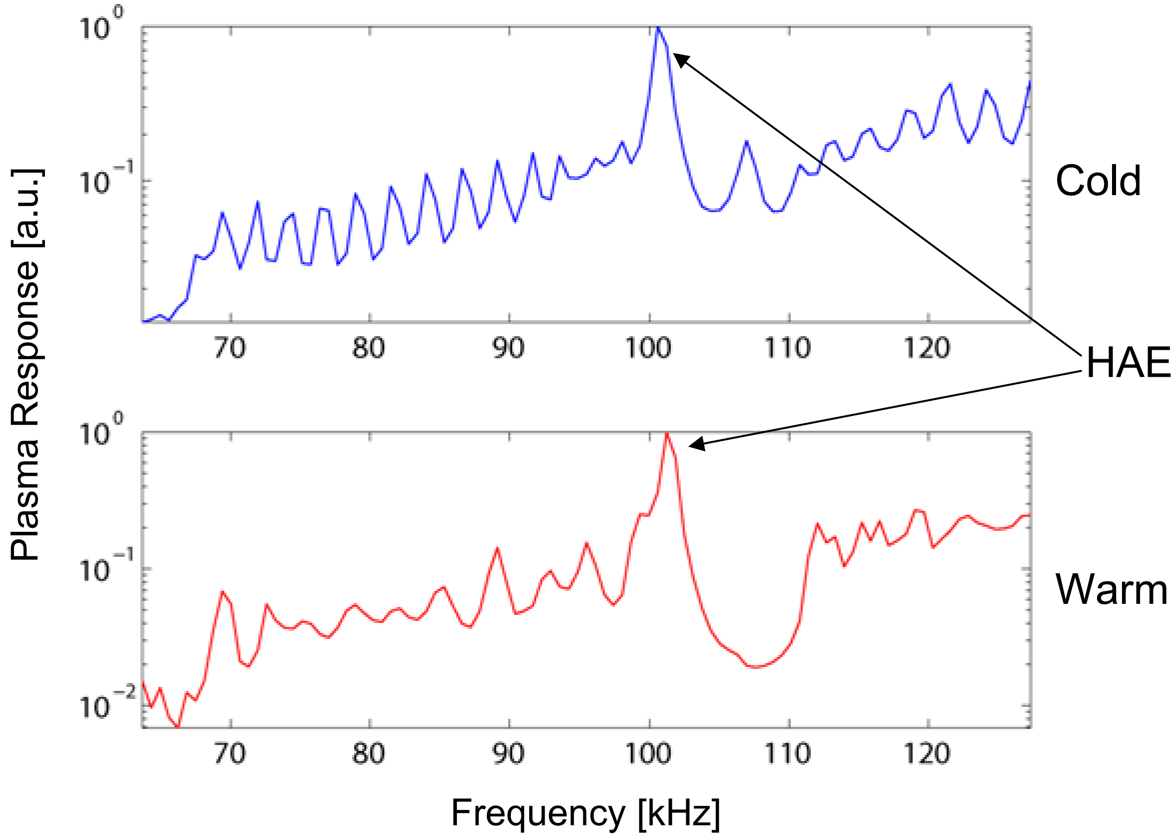
- JET-like equilibrium (n_0=3.2e19m^{-3}, B_0=3.4T, Antenna: (m,n) = (-1,1))



- All the models give almost the same value for the TAE frequency but the damping of this global mode is different.

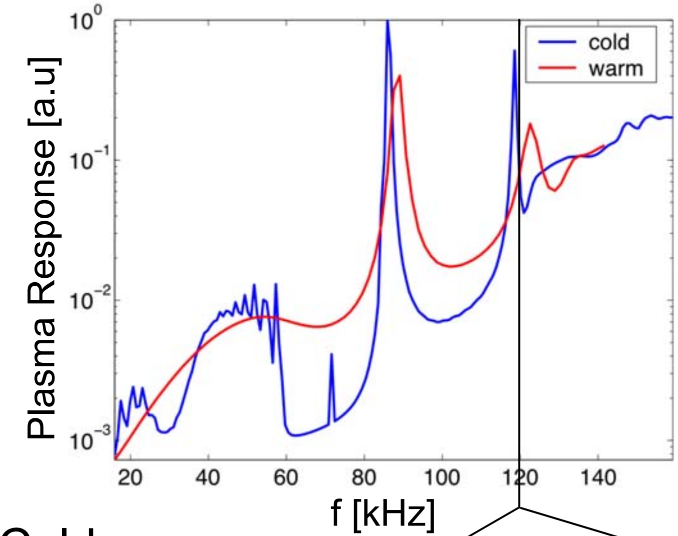
Toroidal helix: cold and warm models

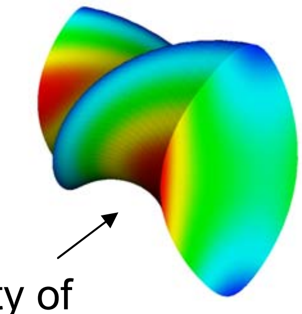
- Comparison between cold and warm scan of a helical configuration with aspect ratio 7. n_0 = 4.0e19 m^{-3}, T_0 = 500 eV, B_0 = 0.8 T.



Large Helical Device (LHD)

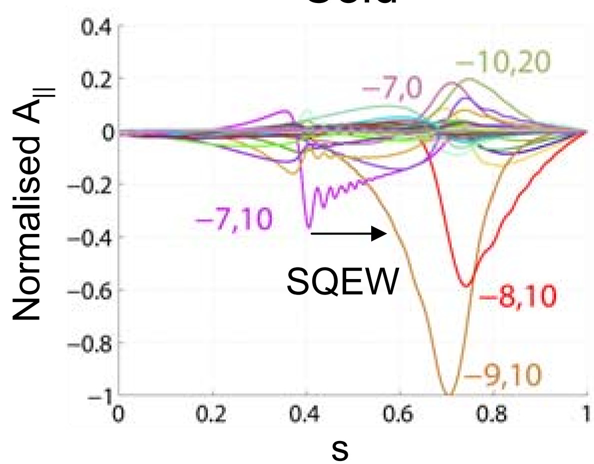
Parameters:
- n_0 = 4.0e19 m^{-3}
- T_0 = 500 eV
- B_0 = 0.8 T
- H plasma



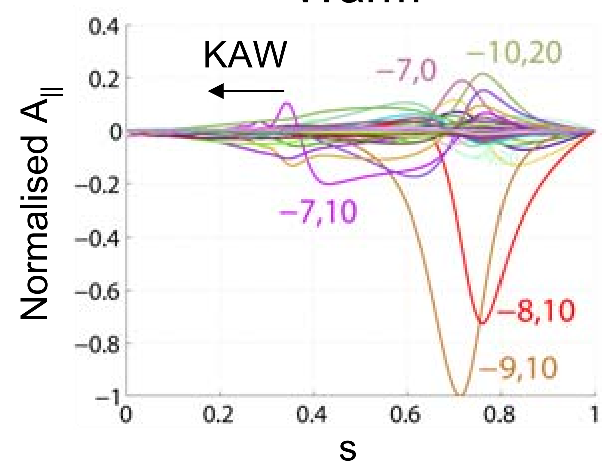


Intensity of the B field

Cold

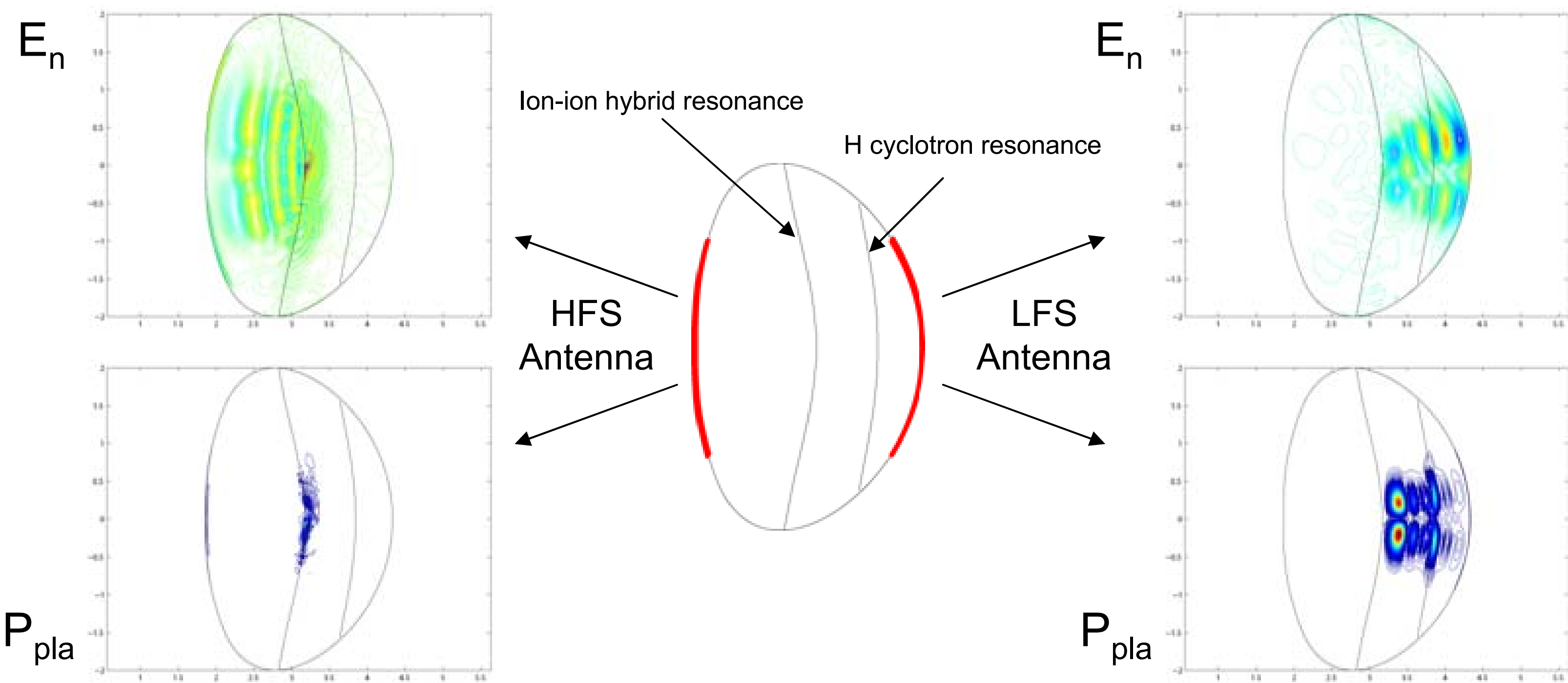


Warm



JET ICRH case

- Ion-ion hybrid resonance scenario (70% D, 30% H, n_0=3.2e19m^{-3}, B_0=3.4T), $k_{||}$=n/R



- The same phenomena as in the previous cold model computations are recovered. Absorbtion at the resonance (HFS), reflection at the cut-off (LFS).
- The only difference is the absoption at the H species cyclotron resonance

Why another method for ICRH?

- Convolution method inappropriate when the resonance is crossing the magnetic surfaces (gives oscillations)
- Hard exercise to invert a polynomial matrix where diagonal elements are smaller than off-diagonal ones
- Poor scaling between number of Fourier harmonics and time of computation (good for a few modes but really problematic when it increases)

=> Solution: determine a sufficiently accurate value of the parallel wave vector that depends only on spatial parameters.

The iterative method

- Take an initial guess for $k_{||}$.
- After a run, the wavefield is the obtained.
- In the Alfvén domain, the kinetic effects on propagation are essentially determined by $\varepsilon_{|| \, ||}$, we concentrate on $E_{||}$.
- $E_{||}$ is inserted inside the equation already presented for the convolution model:

$$\begin{bmatrix} a_{11}+b_{11}v_{||} & a_{12}+b_{12}v_{||} & \cdots & a_{1p}+b_{1p}v_{||} \\ a_{21}+b_{21}v_{||} & a_{22}+b_{22}v_{||} & & \\ \vdots & & \ddots & \\ a_{p1}+b_{p1}v_{||} & & & a_{pp}+b_{pp}v_{||} \end{bmatrix} \begin{bmatrix} f_{0,1} \\ f_{0,2} \\ \vdots \\ f_{0,p} \end{bmatrix} = -\frac{q}{m}\frac{\partial F}{\partial v_{||}} \cdot \begin{bmatrix} E_{||1} \\ E_{||2} \\ \vdots \\ E_{||p} \end{bmatrix}$$

- f_0 is obtained => $k_{||}(v_{||})$
- To obtain a $k_{||}$ that does not depend on $v_{||}$, we take it relative to $j_{||}$:

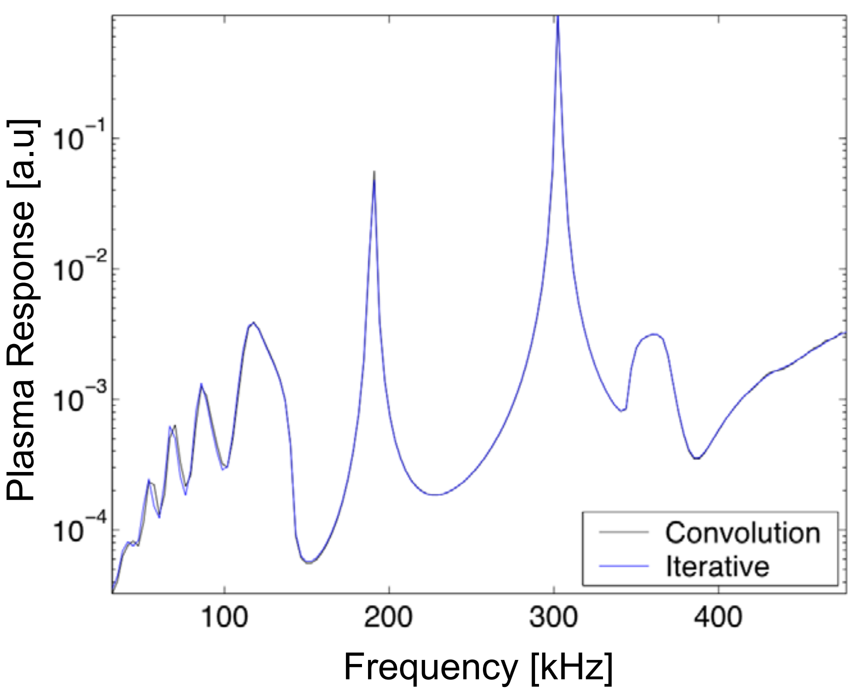
$$k_{eff}\, j_{||} = k_{eff} \int f_0(v_{||}) v_{||} d^3v = \int k_{eff}\, f_0(v_{||}) v_{||} d^3v \cong \int k_{||}(v_{||})\, f_0(v_{||}) v_{||} d^3v \quad \Rightarrow \quad k_{eff} = \frac{\int k_{||}(v_{||})\, f_0(v_{||}) v_{||} d^3v}{\int f_0(v_{||}) v_{||} d^3v}$$

Iterative vs convolution

- Good agreement between the two methods in the Alfvén domain

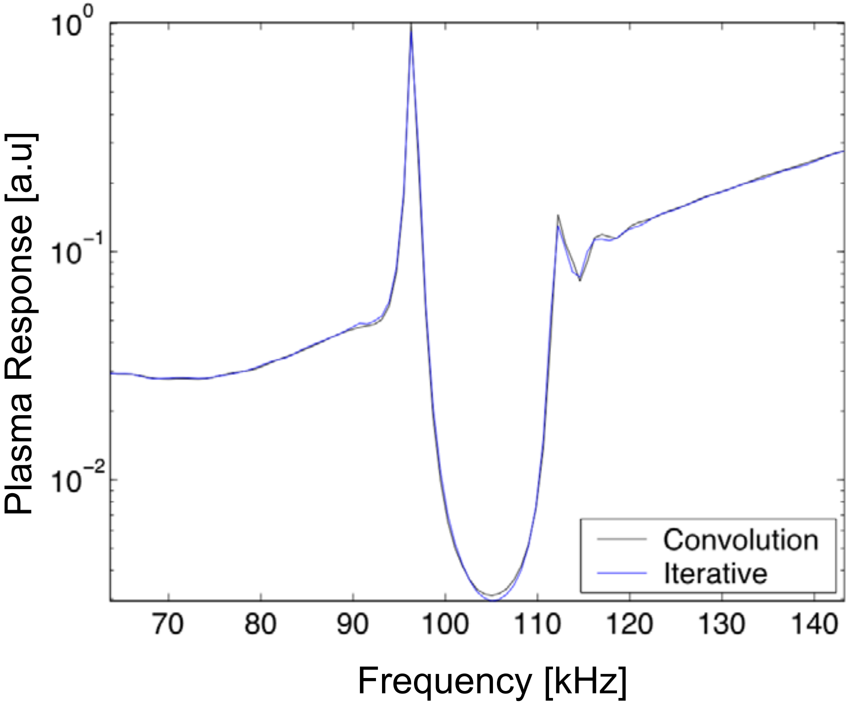
JET-like equilibirium

n_0 = 3.2x10^{19} m^{-3}, B_0 = 3.4 T,
$T_e = T_i$ = 1.0 keV * (1-s)



Straight helix

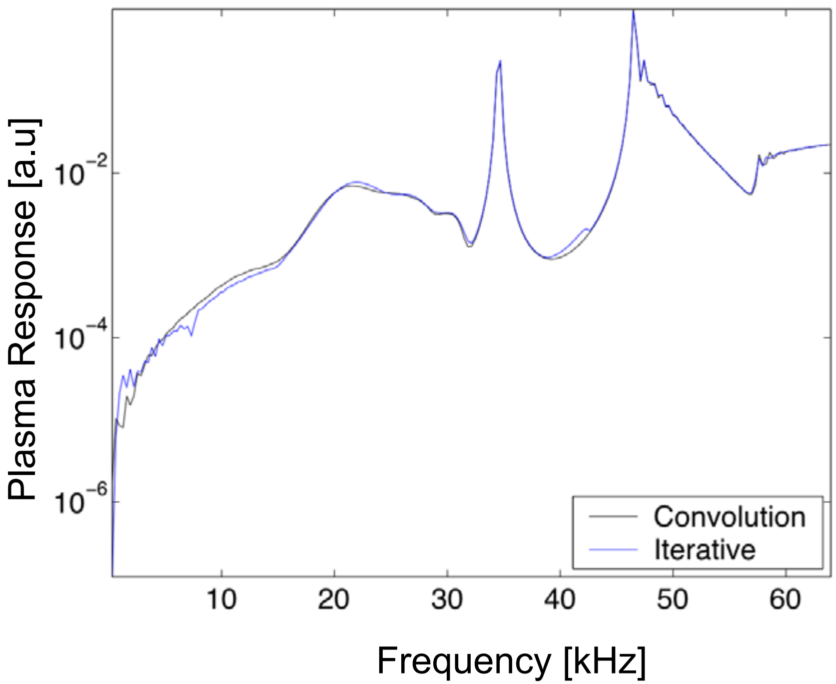
n_0 = 4.0x10^{19} m^{-3}, B_0 = 0.8 T,
$T_e = T_i$ = 1.0 keV



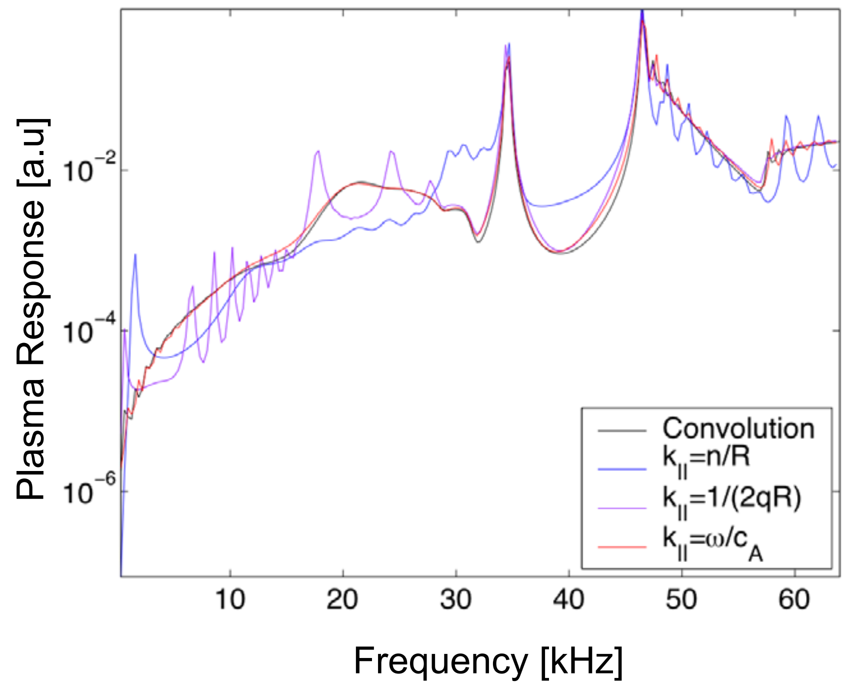
Iterative method vs approximations

- Results for a circular cross section torus with convolution model vs…

… iterative method



… several approximations



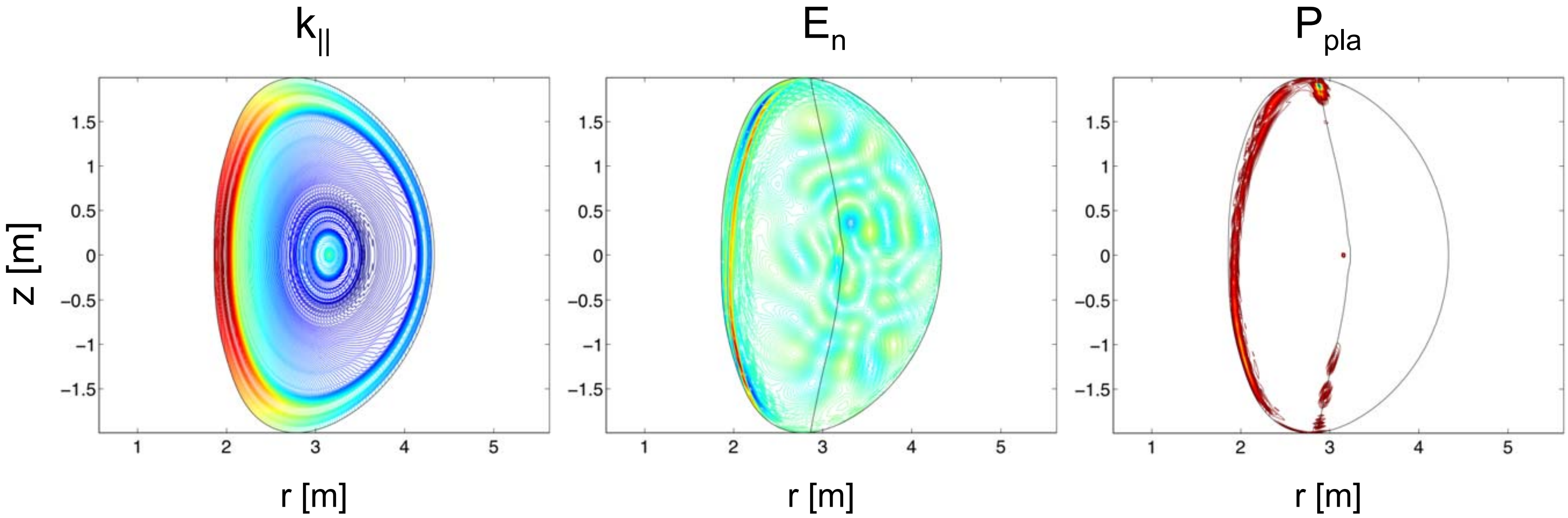
Parameters: $n_0 = 4.0\times10^{19}\ m^{-3}$, $B_0 = 0.8$ T, $T_e = T_i = 1.0$ keV

ICRH with the iterative method

- The parallel wave vector is computed here relatively to the fundamental component of the distribution function f_1 (with ω-Ω):

$$Lf_1 = -\frac{q}{m}\frac{\partial F}{\partial v_\perp}(E_n + iE_b) \qquad j_{n,1} = \int \frac{v_\perp}{2} f_1(v_\parallel) d^3v \quad \Rightarrow \quad k_{eff} = \frac{\int k_\parallel(v_\parallel) f_1(v_\parallel) v_\perp d^3v}{\int f_1(v_\parallel) v_\perp d^3v}$$

- Simulation in a JET-like configuration (after 10 iterations):

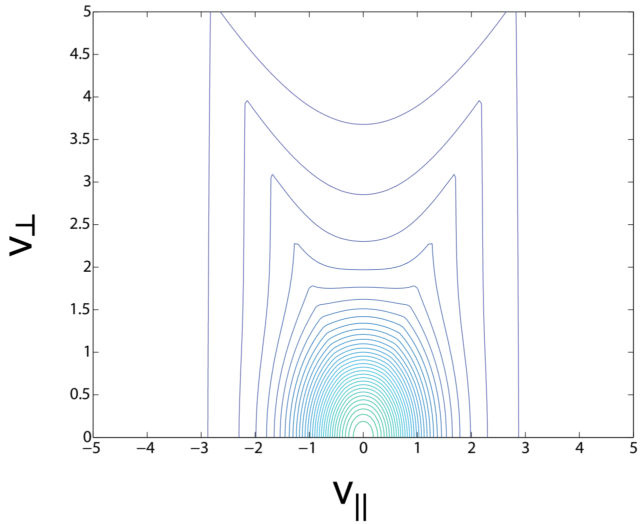


Bi-Mawellian distribution function

- In order to model fast ions population => a dielectric tensor based on a non-Maxwellian distribution function has to be included in the code
- A bi-Mawellian can play such a role:

$$F_h(s,\varepsilon,\mu) = N(s)\left(\frac{m_h}{2\pi T_\perp(s)}\right)^{3/2} \exp\left[-m_h\left(\frac{\mu B_C}{T_\perp(s)} + \frac{|\varepsilon - \mu B_C|}{T_\parallel(s)}\right)\right]$$

$B_C/B = 1.3$
$T_\perp/T_\parallel = 4.2$
$T_\perp/T_t = 20$
$\alpha = 0.1$



Dielectric tensor based on a bi-Maxwellian (1)

- After integration and taking account of the absolute value, we obtain:

B<B$_C$:

$$\varepsilon_{xx}=\varepsilon_{yy}=1-\frac{1}{2\varpi}\sum_s\frac{\sqrt{T_\parallel/T_\perp}}{C_+}\left(\overline{Z}_1^\parallel+\overline{Z}_{-1}^\parallel\right)$$

$$\varepsilon_{xy}=-\varepsilon_{yx}=-\frac{i}{2\varpi}\sum_s\frac{\sqrt{T_\parallel/T_\perp}}{C_+}\left(\overline{Z}_1^\parallel-\overline{Z}_{-1}^\parallel\right)$$

$$\varepsilon_{zz}=1+\sum_s\frac{2}{(k_\parallel v_\parallel^{th})^2}\frac{\sqrt{T_\parallel/T_\perp}}{C_+}\left(\overline{\varpi}_p^2-\varpi\overline{Z}_0^\parallel\right)$$

$$\overline{Z}_l^\parallel=\frac{\overline{\varpi}_p^2}{\varpi-l\Omega}Z^{Sh}\left(\frac{\varpi-l\Omega}{k_\parallel v_\parallel^{th}}\right)$$

$$\overline{Z}_l^\perp=\sqrt{\frac{B_C-B}{B_C}}\frac{\overline{\varpi}_p^2}{\varpi-l\Omega}Z^{Sh}\left(\sqrt{\frac{B_C}{B_C-B}}\frac{\varpi-l\Omega}{k_\parallel v_\perp^{th}}\right)$$

$$C_\pm=\frac{B_C}{B}\pm\frac{T_\perp}{T_\parallel}\left(1-\frac{B_C}{B}\right)$$

$$\overline{\varpi}_p^2=\frac{q^2N(s)}{\varepsilon_0 m}$$

B>B$_C$:

$$\varepsilon_{xx}=\varepsilon_{yy}=1-\frac{1}{2\varpi}\sum_s\left[\frac{\sqrt{T_\parallel/T_\perp}}{C_+}\left(\overline{Z}_1^\parallel+\overline{Z}_{-1}^\parallel\right)+\frac{C_+-C_-}{C_+C_-}\left(\overline{Z}_1^\perp+\overline{Z}_{-1}^\perp\right)\right]$$

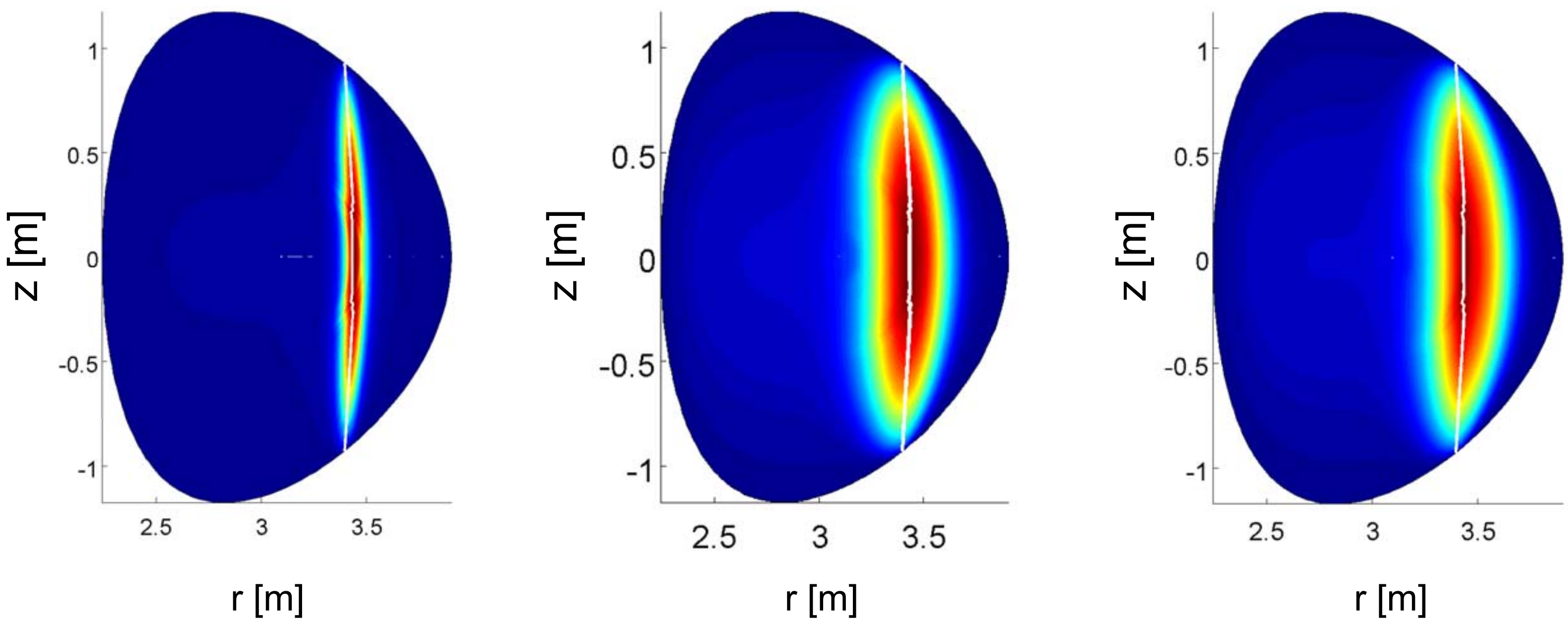
$$\varepsilon_{xy}=-\varepsilon_{yx}=-\frac{i}{2\varpi}\sum_s\left[\frac{\sqrt{T_\parallel/T_\perp}}{C_+}\left(\overline{Z}_1^\parallel-\overline{Z}_{-1}^\parallel\right)+\frac{C_+-C_-}{C_+C_-}\left(\overline{Z}_1^\perp-\overline{Z}_{-1}^\perp\right)\right]$$

$$\varepsilon_{zz}=1+\sum_s\frac{2}{(k_\parallel v_\parallel^{th})^2}\left[\frac{\sqrt{T_\parallel/T_\perp}}{C_+}\left(\overline{\varpi}_p^2-\varpi\overline{Z}_0^\parallel\right)-\frac{C_++C_-}{C_+C_-}\frac{B_C}{B}\left(\sqrt{\frac{B_C-B}{B_C}}\overline{\varpi}_p^2-\varpi\overline{Z}_0^\perp\right)\right]$$

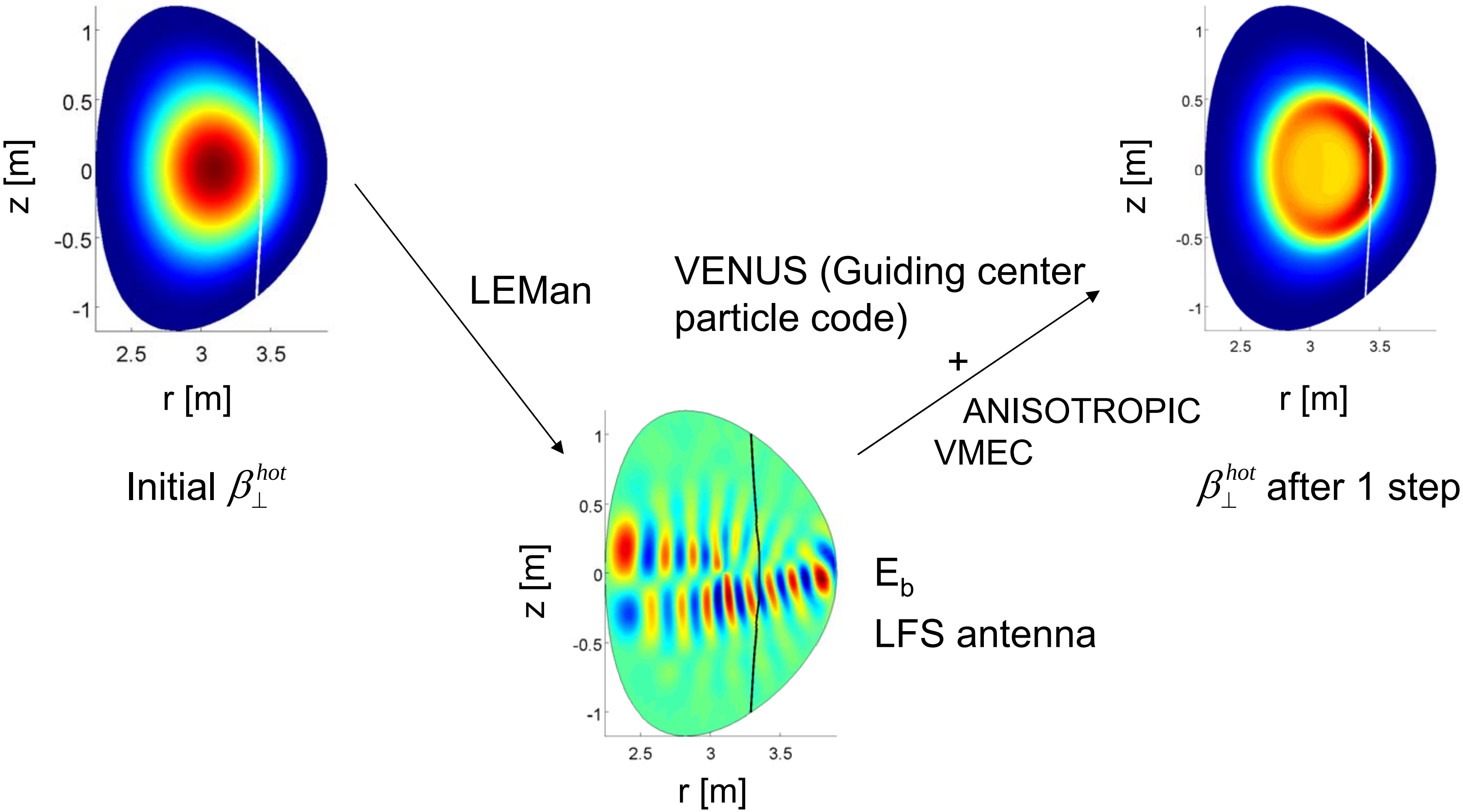
Dielectric tensor based on a bi-Maxwellian (2)

- Component ε_{nn} of the dielectric tensor of a plasma composed of deuterium and 1% of…

…thermal hydrogen …fast H with $T_{\perp}/T_{||}=1$ …fast H with $T_{\perp}/T_{||}=10$



Test of integrated modeling



Conclusions

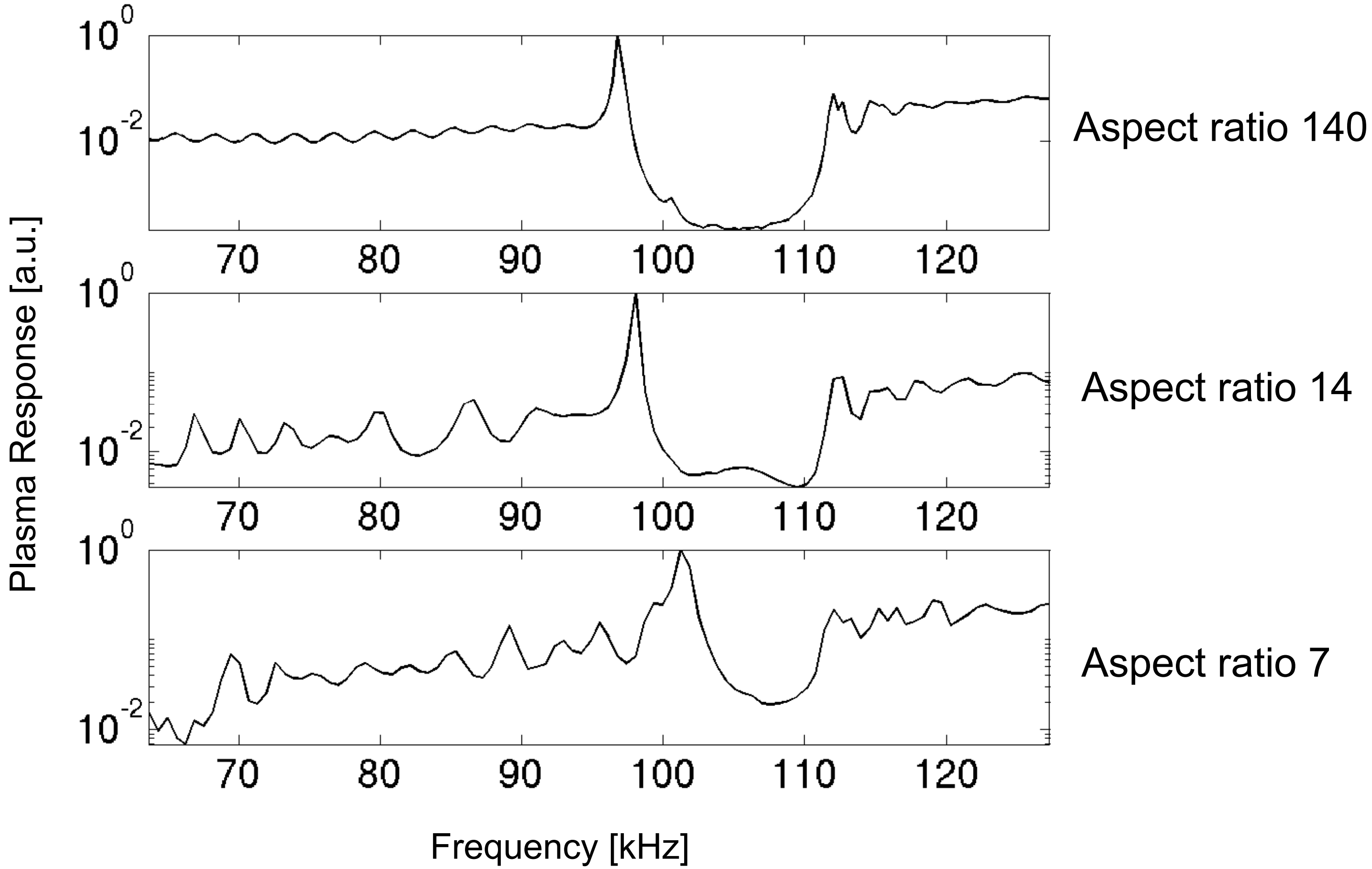
- The convolution formulation for a consistent $k_{||}$ gives good results for both 2D and 3D configurations in the Alfvén domain. Nevertheless computation is problematic in ICRF range.

- A new iterative method has thus been implemented in order to be able to avoid the problem caused by the inversion of a polynomial matrix. Comparisons have been performed against the previous method, giving a good agreement. A first case has been computed in the ICRF domain.

- A first result from integrated modelling of wave absorption and heating has been obtained. It couples an anisotropic version of the VMEC 3D equilibrium code with the LEMan code to determine the location and magnitude of heat deposition and then with VENUS guiding centre particle code to calculate the hot particle response that is fitted with the pressure moments of the Bi-Maxwellian distribution function. The aim is to iteratively obtain an equilibrium state that is fully self-consistent with the applied heating.

Toroidal helix: different aspect ratios

- Comparison between helix cases with aspect ratios 140, 14 and 7.



Convergence

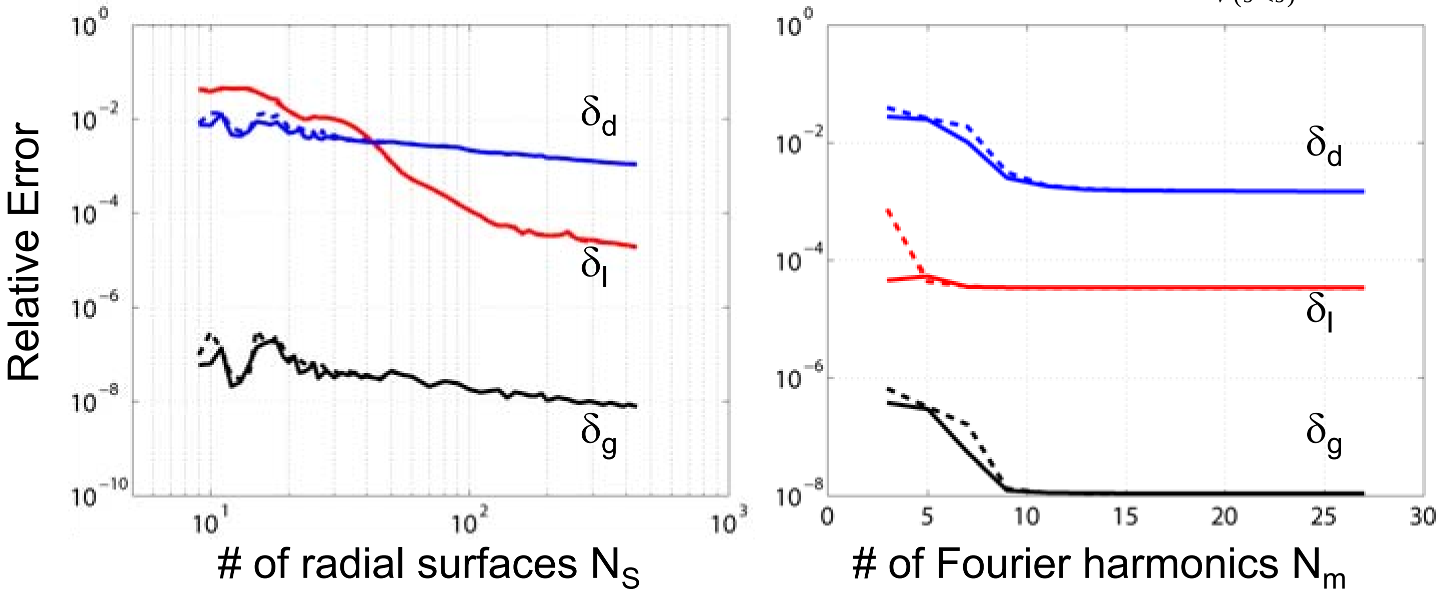
- Circular cross section torus with aspect ratio 5

Coulomb Gauge: $\delta_d = \int_V \left|\nabla \cdot \vec{A}\right| dV \; V^{1/3} \Big/ \int_V \left|\vec{A}\right| dV$

Local and global power balance:

$$\delta_l = \int_0^1 \left| P_{plasma}(s) - P_{ant}(s) - iS_{Poynt}(s) \right| ds \,/\, P_{plasma}(1) \qquad P_{plasma}(s) = \frac{\omega}{8\pi} \int_{V(s'<s)} \left(\left|\vec{B}\right|^2 - \vec{E}^* \cdot (\vec{\varepsilon} \cdot \vec{E}) \right) dV'$$

$$\delta_g = (P_{plasma}(1) - P_{ant}(1)) \,/\, P_{plasma}(1) \qquad P_{ant}(s) = \frac{i}{2} \int_{V(s'<s)} \left(\vec{E}^* \cdot \vec{j} \right) dV'$$



Warm in solid
Cold in dashed

Future work

- A bimaxwellian distribution function will be added in the order to include the effect of fast ions on the computed wavefield. A coupling with a particle simulation δf code (VENUS) will permit to study behaviour of the particles in the case of global modes or ICRH.

- The method has to be improved to allow computation of ICRH cases with the full model.

- Other benchmarks have also to be performed in order to verify the veracity of the results obtained with LEMan.