Advanced RF heating schemes in preparation for ICRF heating and fast ion experiments in the W7-X stellarator

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Motivation

Fast ion confinement is crucial for the demonstrating the viability of the stellarator approach as a nuclear fusion reactor. There are three main ways of generating these fast ions: fusion born fast alphas, NBI, ICRF heating. For the stellarator W7X option two and three are the most feasible short term. The device is currently being upgraded, going from two neutral beams to four. Also ICRF heating should be available in operational phase 2 (OP2.0).
The code package SCENIC is in a unique position to model ICRF heating schemes in 3D geometries, such as W7X, right now. This will be in preparation for OP2.0.
Secondly, a recent extension to the wave model for hot plasma is used to investigate higher harmonic heating in JET. This is important for instance when investigating higher harmonic heating on tritium in the upcoming DT experiments (He-3 minority heating).

3D wave field modelling with SCENIC

Heating in the ICRF typically results in significantly anisotropic distribution functions, where the perpendicular pressure exceeds the parallel pressure by an order of magnitude. This can also affect the magnetic equilibrium, hence ANIMEC (the anisotropic version of VMEC) can also be included in the iterative process. This is however not done for the presented work as there were convergence issues, hence ANIMEC is only ran once. The 3 aforementioned codes combined are referred to as SCENIC [2], see Fig. 1. Lastly, there is also VENUS-NBI that can calculate NBI deposition.

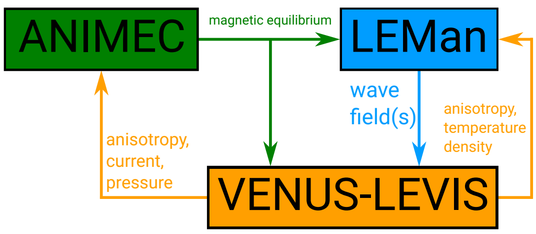
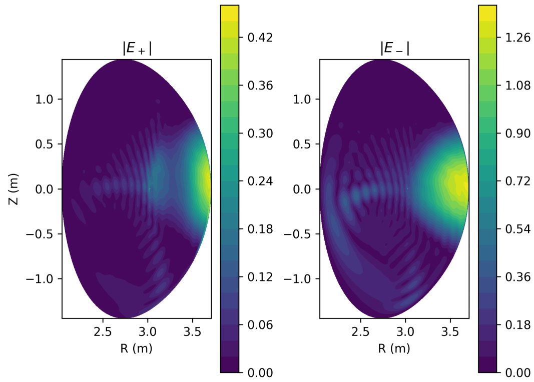


Figure 1: *Cartoon of SCENIC operation.*

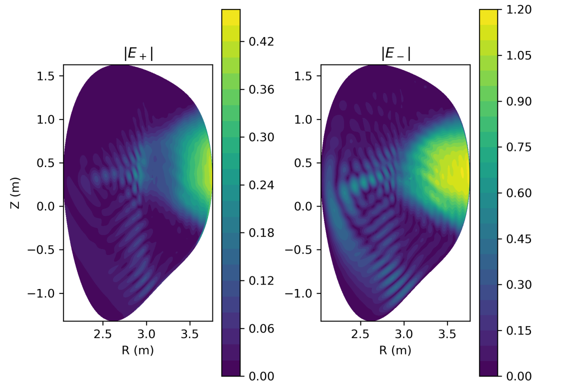
SCENIC can model fully 3D geometries, some examples are shown in Fig. 2, using a fully localised (s, θ, φ) antenna.

Up-down asymmetry in SCENIC

The flux surfaces in ANIMEC are represented as a Fourier series, using the major radius $R(\theta)$ and the vertical position $Z(\theta)$ as a function of the poloidal angle. Often the even and odd behaviour of respectively R, Z in case of up-down symmetric equilibria is exploited to reduce the number of terms in the Fourier series, i.e. by using a Fourier half range series. A recent extension to LEMan removes the restriction of the flux surfaces to be up-down symmetric, an example case is shown in Fig. 3.



(a) Symmetric equilibrium



(b) Asymmetric equilibrium

Figure 3: *Plot of* $|E_+|, |E_-|$ *(A.U.) in a poloidal cross section of JET. 89 Poloidal wave modes used, 1 toroidal mode* $n = -27$*. Species densities (normalised to electron density) are: electrons(1), deuterium(0.955), hydrogen(0.025), Be-9(0.005). An arbitrary number of species can be modelled with LEMan. (On axis, 2.7 T, heating of H).*

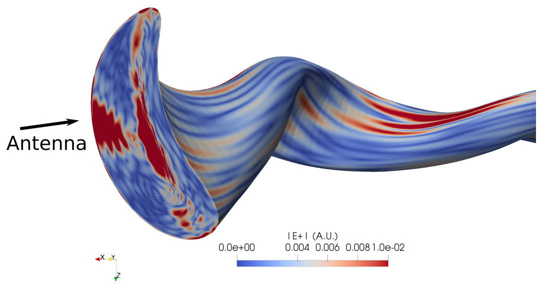


Figure 2: *Plot of* $|E_+|$ *in W7X, cropped at 0.01. Poloidal clipping at the antenna. Here a radial resolution of 250 point, and 30, 29 poloidal, toroidal modes were used resp. Already a hotspot near the antenna can be seen, this becomes even more localised with more toroidal modes, see Ref. [1]. (High mirror equilibrium, minority heating case).*

The main toroidal antenna modes for dipole phasing in JET are $n = \pm 27$, but because of axisymmetry these modes decouple and can be simulated in seperate simulations. Wave fields from both runs are used to determine power deposition on the markers in VENUS-LEVIS.

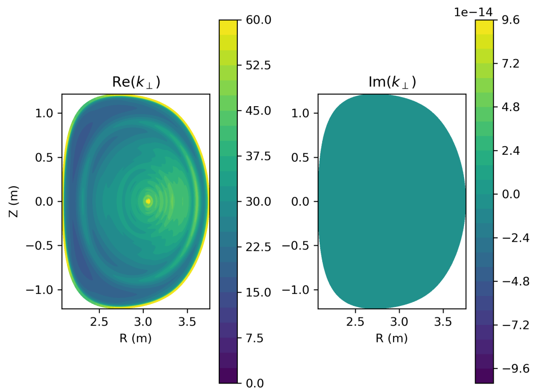
The shape of the equilibrium is found to play a major role regarding the energy of the fast minority ions, see Fig. 4.

Hot plasma dielectric tensor in LEMan

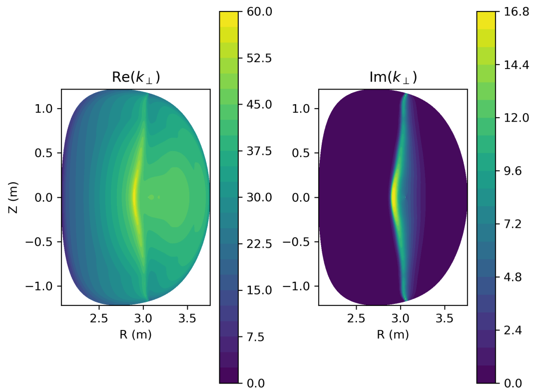
The dielectric tensor for a isotropic distribution function is given by [3]:

$$\mathrm{K} = \begin{pmatrix} K_1 + K_0 \sin^2\psi & K_2 - K_0 \cos\psi \sin\psi & K_4 \cos\psi + K_5 \sin\psi \\ -K_2 - K_0 \cos\psi \sin\psi & K_1 + K_0 \cos^2\psi & K_4 \sin\psi - K_5 \cos\psi \\ K_4 \cos\psi - K_5 \sin\psi & K_4 \sin\psi + K_5 \cos\psi & K_3 \end{pmatrix} \quad (1)$$

The previously shown results were obtained using the warm plasma model, to 0^{th} order in the finite Larmor radius (FLR) parameter. In this simplified model $K_0 = K_4 = K_5 = 0$ and it gets



(a) Warm plasma, for completeness also the imaginary part is shown, but this is exactly 0



(b) Hot plasma

Figure 5: *Similar JET case as in Fig. 3. Showing perpendicular wave number (m^{-1}) (clipped at 60 m^{-1}).*

rid of the modified Bessel functions that are hidden inside the K elements. However this model lacks some effects such as higher harmonic heating and electron transit time magnetic pumping. Higher order expansions of the modified Bessel functions exist, but even those have limited applicability beyond the 2$^{\text{nd}}$ harmonic [4].

Another recent extension to LEMan is the option to use the hot plasma dielectric tensor. This means no FLR expansion is used. The perpendicular wave number $k_\perp$ is solved from the hot plasma dispersion relation, starting with a guess using the warm dispersion relation, and iterating on this guess with Newton iteration. $k_\perp$ is now a complex quantity, see Fig. 5 and the power deposition is strongly affected.

In the warm JET model nearly 100% is deposited on the hydrogen minorities, but in the hot model this is just 45%, with 41% on deuterium, 15% on electrons (and 0.026% on Be-9). In the core, 2$^{\text{nd}}$ harmonic power absorption by deuterium actually exceeds that of hydrogen, but volume integrated there is still more power deposition on hydrogen. See Fig. 6 for a radial plot of the absorbed power density.

Note that the hot plasma model is limited to a Maxwellian for the fast species for now. Also, note that this section is LEMan only, so no iteration over VENUS-LEVIS.

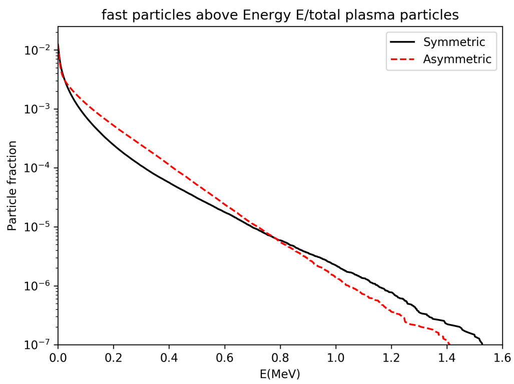


Figure 4: *Cumulative energy plot comparing the symmetric, and asymmetric JET equilibria. Particle fraction is defined as the number of markers in VENUS-LEVIS, above a given energy, normalised by the total number of plasma particles.*

Conclusion & future work

SCENIC can model 3D geometries, including a fully localised antenna. Moreover, arbitrary coordinates can be used for the equilibrium in LEMan. Some difference between the fast ion energies is observed comparing the symmetric and asymmetric equilibria of JET. Another extension of LEMan is the ability to use a hot plasma model, this is found to significantly impact the power deposition.

In the future convergence issues with the hot plasma model for certain parameter ranges ought to be solved. Secondly, statistics of high energy markers should be improved in an efficient way, without violating conservation laws. Then more complicated plasma compositions can be studied in W7X, for instance including impurities and higher harmonic heating. And lastly, the Bi-Maxwellian distribution is yet to be implemented for the hot model.

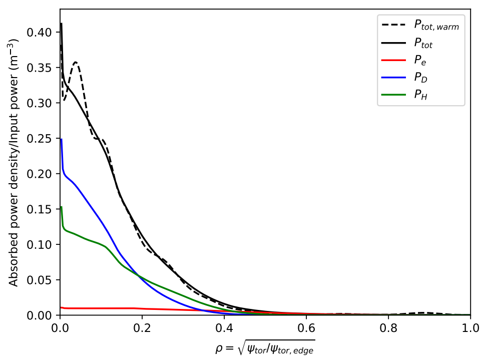


Figure 6: *Absorbed power density for dominant species, toroidally and poloidally averaged, versus radial position and normalised by antenna power. For comparison also the total power from the warm model is shown.*

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was supported in part by the Swiss National Science Foundation. Furthermore, the work would not have been possible without the computer resources of CSCS (project s914) and CINECA.

References

[1] H. Patten, "Development and optimisation of advanced auxiliary ion heating schemes for 3D fusion plasma devices", EPFL, (2018)

[2] M. Jucker, "Self-consistent ICRH distribution functions and equilibria in magnetically confined plasmas", EPFL, (2010)

[3] D.G. Swanson, "Plasma Waves", 2nd Ed., Auburn University, (2003)

[4] M. Brambilla, Plasma Phys. Control. Fusion **44**, 2423 (2002)