# ECRH AND MODE CONVERSION IN OVERDENSE W7-X PLASMAS

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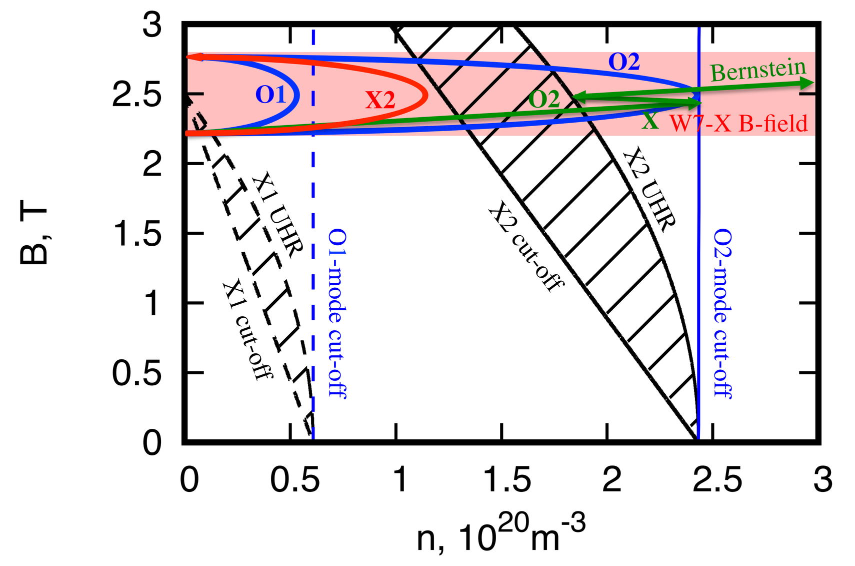
Electron Cyclotron Resonance Heating (ECRH) is the main plasma heating mechanism in the Wendelstein 7-X (W7-X) Stellarator. It is provided by 10 gyrotrons at 140 GHz (corresponding to the second harmonic cyclotron resonance at 2.5 T) with the power of ~1 MW each. X2- and O2-modes were successfully used in a wide range of operation scenarios: X2-mode for low and moderate densities (up to the cutoff at $1.2\times10^{20}$ m$^{-3}$), and O2-mode for higher densities (up to ~$2\times10^{20}$ m$^{-3}$).

Possible operation at yet higher densities would involve double mode-conversion from O- to slow X- and then to a Bernstein-mode [1], i.e. an OXB-scenario (indicated schematically with green arrows). The physics of O-X conversion is outside of applicability of the routinely used geometrical optics approximation (WKB-theory) and should be considered within a full-wave approach [2,3].

For this study, a new, **GPU-capable, 3D cold plasma full-wave code named "CUWA"** has been developed. The code utilizes the Finite Difference Time Domain (FDTD) technique to solve the initial-value problem for Maxwell's equations coupled with the cold plasma response [4,5].




## Finite Difference Time-Domain code CUWA

Maxwell's equations and Plasma response ("cold" electron law of motion),
First order finite difference discretization on staggered grids.

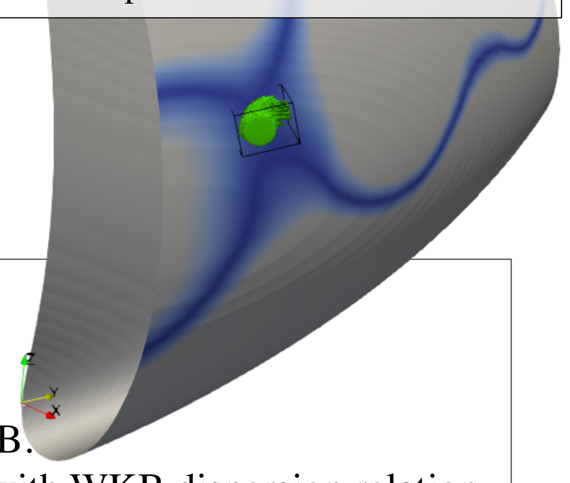
$$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

$$c^2\nabla\times\vec{B}=\frac{1}{\varepsilon_0}\vec{j}+\frac{\partial\vec{E}}{\partial t}$$

$$\frac{\partial\vec{j}}{\partial t}=\varepsilon_0\omega_{pe}^2\vec{E}-\omega_{ce}\left(\vec{j}\times\vec{b}\right)-\nu\vec{j}$$

**Segment of W7-X and "full-wave"**

O-X conversion evanescent layer width, and a contour (green) of electric field strength of an injected wave. Black box – computation domain.

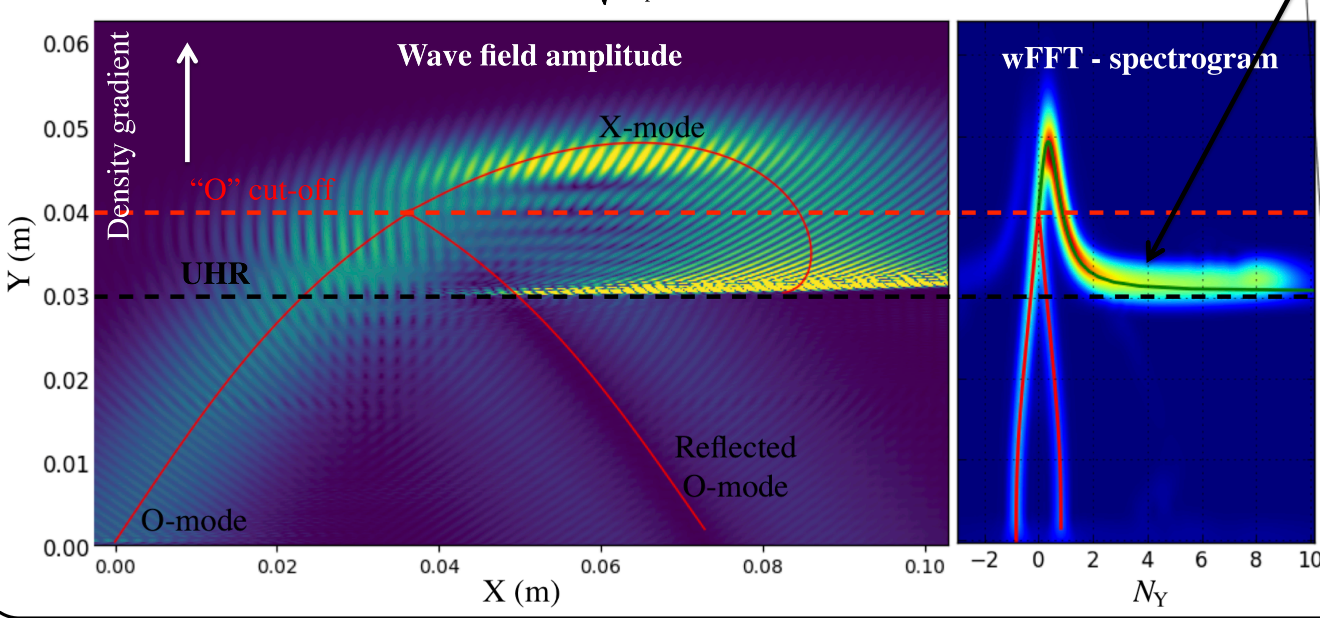


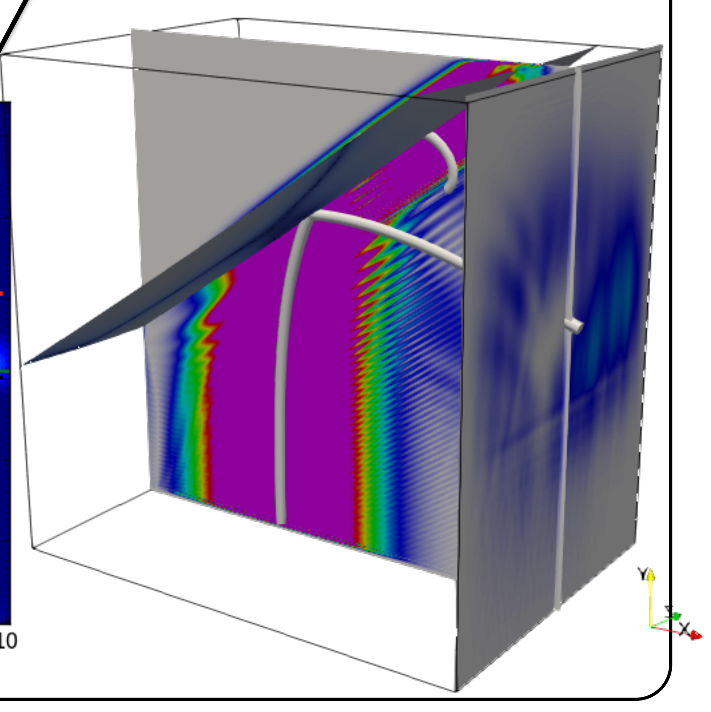
- **GPU-based FDTD** (very fast)
- **CPML** [6,7] boundary conditions.
- Equilibriums: VMEC 3D equilibriums / EQDSK.
- Ray-Tracing. Computation domain built "around" the WKB.
- GPU-based Windowed Fourier transform. Benchmarking with WKB dispersion relation.

## Full-wave O-X conversion

- O-mode is launched from vacuum
- O-mode propagates and reflects from the cut-off ($\omega_p=\omega_0$)
- At the cut-off the X-mode is generated
- X-mode propagates toward UHR ($\sqrt{\omega_p^2+\omega_c^2}=\omega_0$)

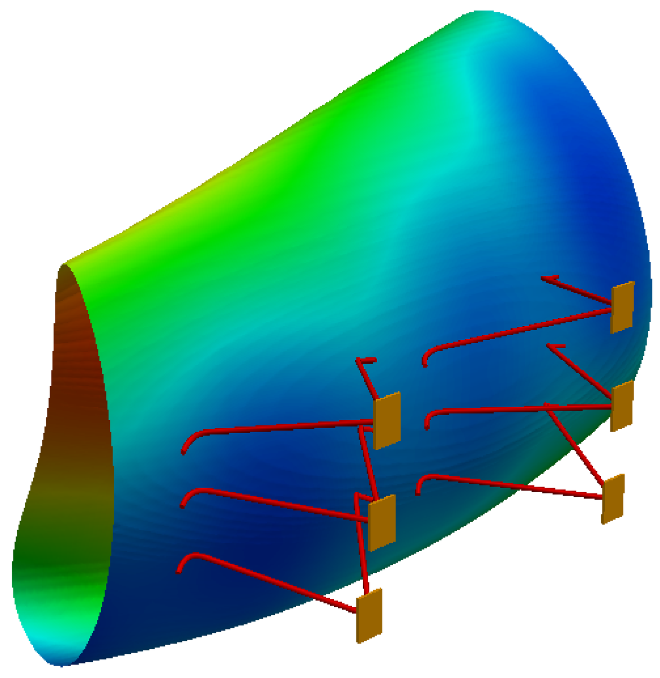
Excellent agreement of the evolution of the wave refractive index between full-wave and ray-tracing.

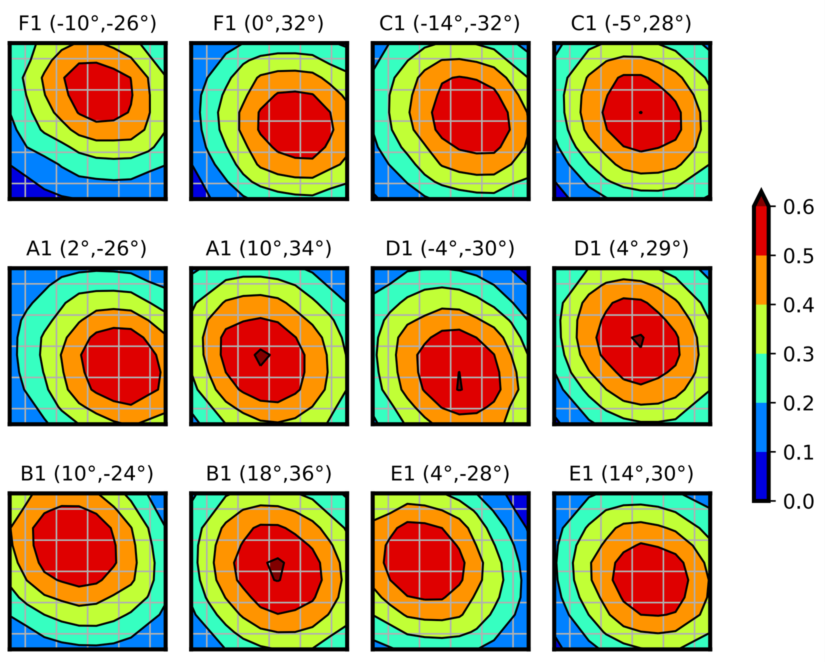


## Conversion efficiency in W7-X

The ECRH antennas setup in W7-X is shown schematically in the left figure. For the six steerable antennas (orange), a ray-tracing study gives 12 "WKB-optimal" rays.
O-X conversion efficiency calculated with 3D full-wave for each of the 12 rays varying the aiming angles ([-2.5º; +2.5º]) around those predicted by the ray-tracing (indicated above each of the contour plots). The density length scale $L\equiv n_e/\nabla n_e=1/15m$.






**Expected conversion efficiency ~ 50%**

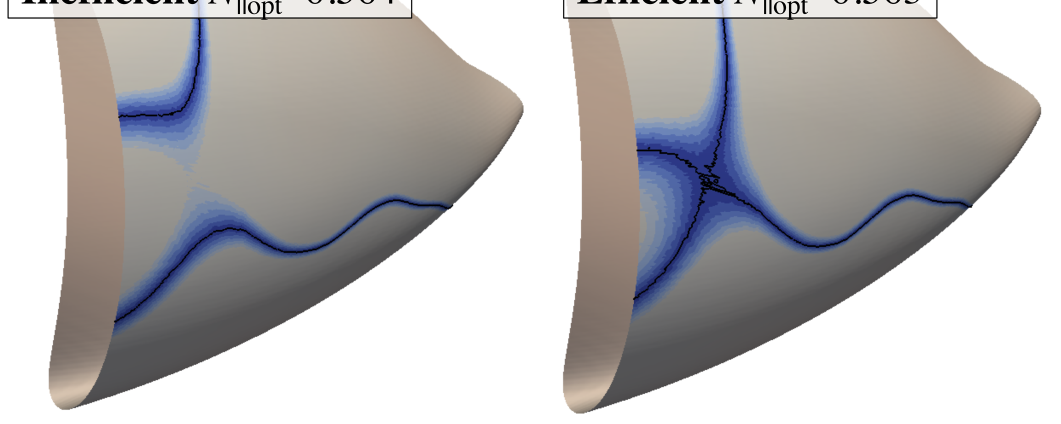
## Optimized conversion scenario

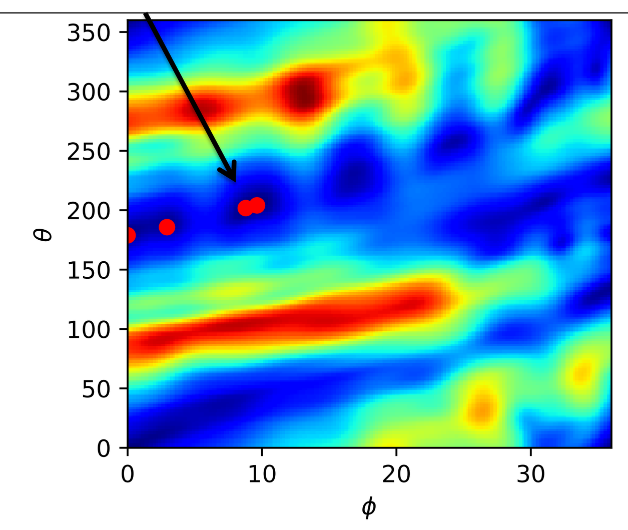
Conversion happens when the "turning" points for both modes are "close". The evanescent layer thickness varies within the beam due to equilibrium variation and beam k-spectrum. WKB provides an estimate for the thickness of the evanescent layer [8]. The crossing of the two surfaces is parameterized by ($N_{\parallel}$).
Conditions for efficient conversion:

$$\begin{cases}\omega_p=\omega\\ N_{\parallel opt}^2=1-\dfrac{\omega_p^2}{\omega\left(\omega+\omega_c\right)}\end{cases}$$

Efficient conversion locations can be identified: The function representing the Gaussian-weighted gradient of the thickness of the evanescent layer on the cutoff surface is shown. A few minima of this function are marked with red dots.

**Inefficient** $N_{\parallel opt}$=0.564 | **Efficient** $N_{\parallel opt}$=0.563



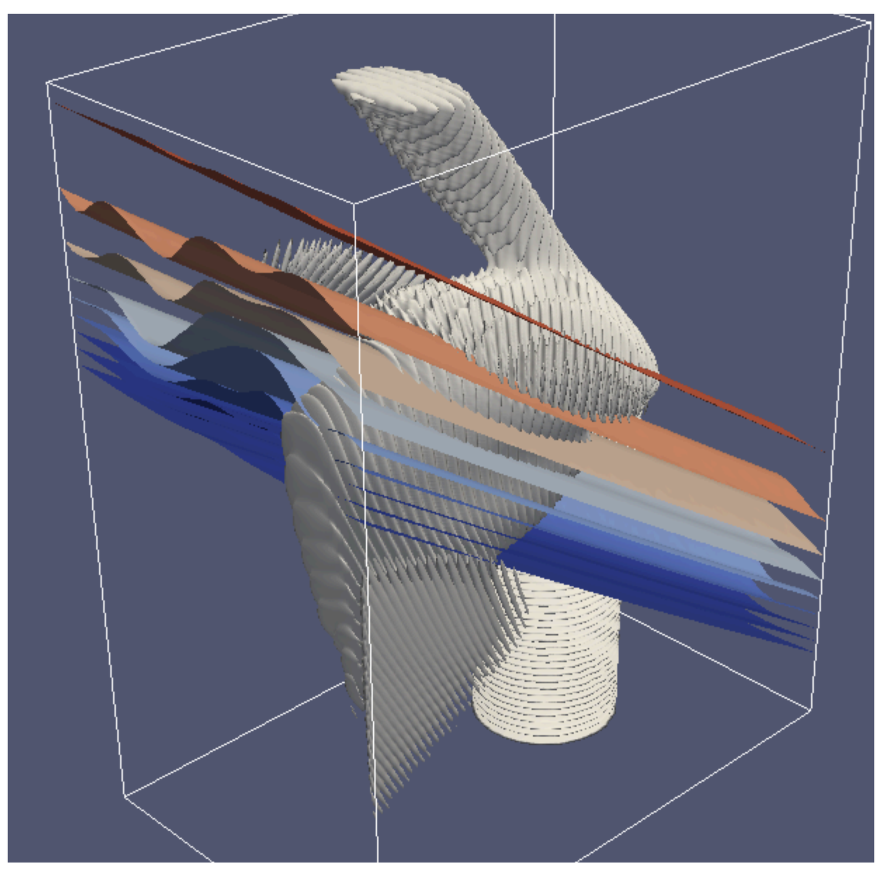



**Expected conversion efficiency ~ 85%**

## Effect of turbulence on conversion efficiency

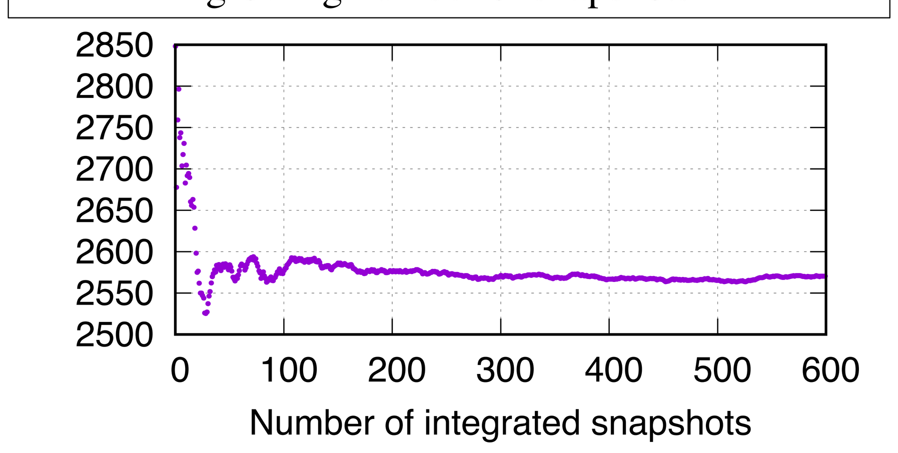
The effect of plasma turbulence on the conversion efficiency was noticed in the pioneering OXB experiments on W7-AS [9]. Their detrimental role was conjectured in that work. However, theoretical considerations presented in Ref. [10] suggest that plasma fluctuations most likely cannot be responsible for the low efficiency of OXB heating. We address this problem by direct numerical calculation of the O-X conversion in perturbed plasma.

Snapshot of the wave field (white contours) in the OX conversion scenario with a perturbed density profile. The surfaces of constant density are shown in colour. The wave field is significantly scattered by the density fluctuations.

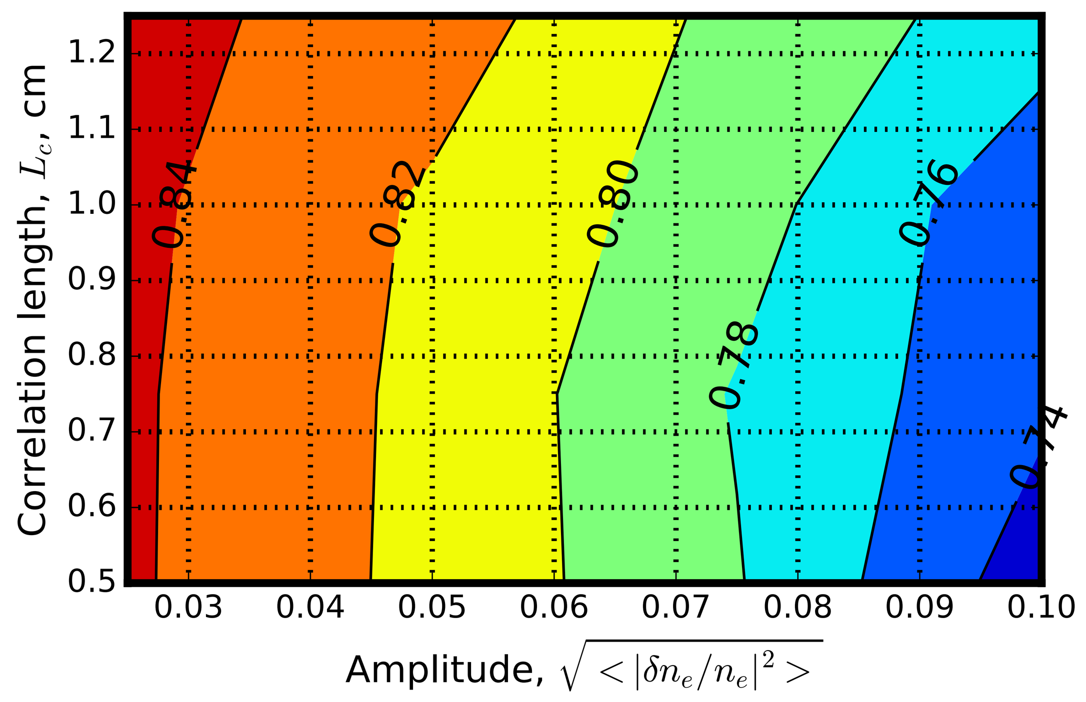


Averaging over a large number of individual calculations (with statistically independent fluctuations) is necessary to evaluate the conversion efficiency.

Reflected O-mode intensity averaged over the growing number of snapshots




Dependence of the conversion efficiency on the relative amplitude and the correlation length of the imposed fluctuations




**Density fluctuations expected in W7-X should not have a significant effect (< 10%) on the O-X conversion efficiency.**

## Conclusion

The O-X conversion process defines efficiency of the entire OXB heating scheme, which is suitable for heating of overdense plasmas. In this work, we conducted a comprehensive study of the O-X conversion efficiency in realistic W7-X parameters.

**For realistic W7-X equilibrium and ECRH parameters, the efficiency of the scheme is low and is not expected to exceed 50-60%.**

However, we also demonstrated that a **significant improvement of the conversion (~ 85%)** could be achieved if the equilibrium is tailored in such a way that the conversion occurs at the location where the evanescent layer width weighted over the beam profile is minimized.

**It was also shown that the density fluctuations expected in W7-X should not have a significant effect (< 10%) on the O-X conversion efficiency.**

## References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