# Simulation as a tool to improve wave heating in fusion plasmas, Reality or Dream ?

**S. Heuraux[€], F. da Silva[*], T. Ribeiro[£], B. Després[°], M. Campos- Pinto[°], E. Faudot[€], J. Jacquot[#,£], L. Colas[#], L. Lu[#]**

[€]*Institut Jean Lamour UMR7198 CNRS-U. de Lorraine BP70239 Vandoeuvre F-54506*

[*]*IST_IPFN, Av Rovisco Pais, 1049-001 Lisbon, Portugal*

[£]Max-Planck-Institut fur Plasmaphysik, 85748 Garching, Germany

[°]Laboratory Jacques Louis Lions, UPMC, BP 187, 75252 Paris Cedex 05, France

[#]*CEA_IRFM, Cadarache 13108 Saint Paul Lez Durance, France*

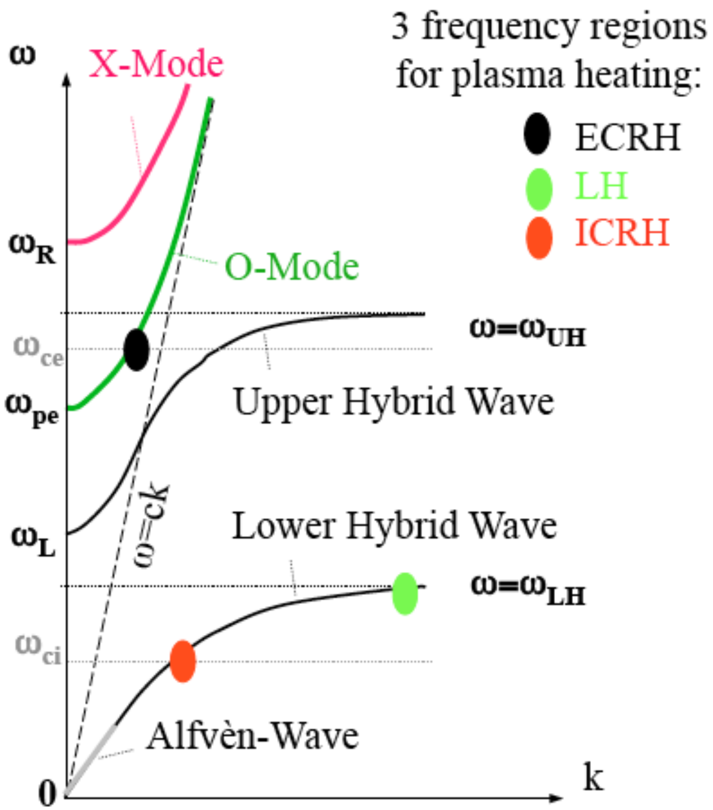
Schedule:

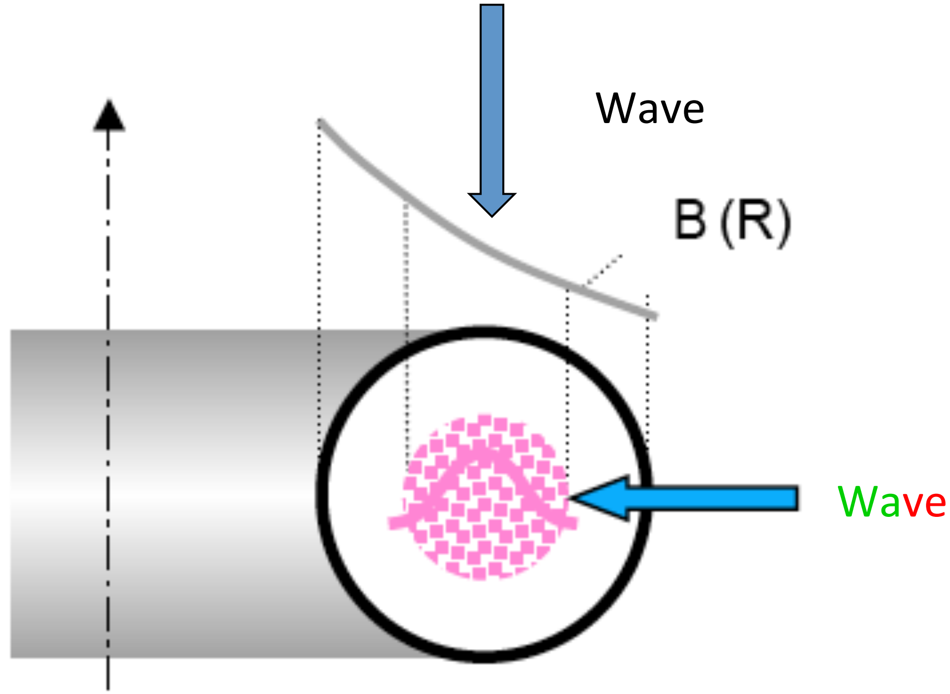
- Wave Heating: an introduction to the ≠ scales, and Physics
- How to build a simulation in wave heating?
- Where we are for the ≠ wave heating systems ?
- What we can expect, till ?
- Conclusion & Open questions

# Wave Heating in Magnetic Plasma

How Wave Heating in fusion plasma ?

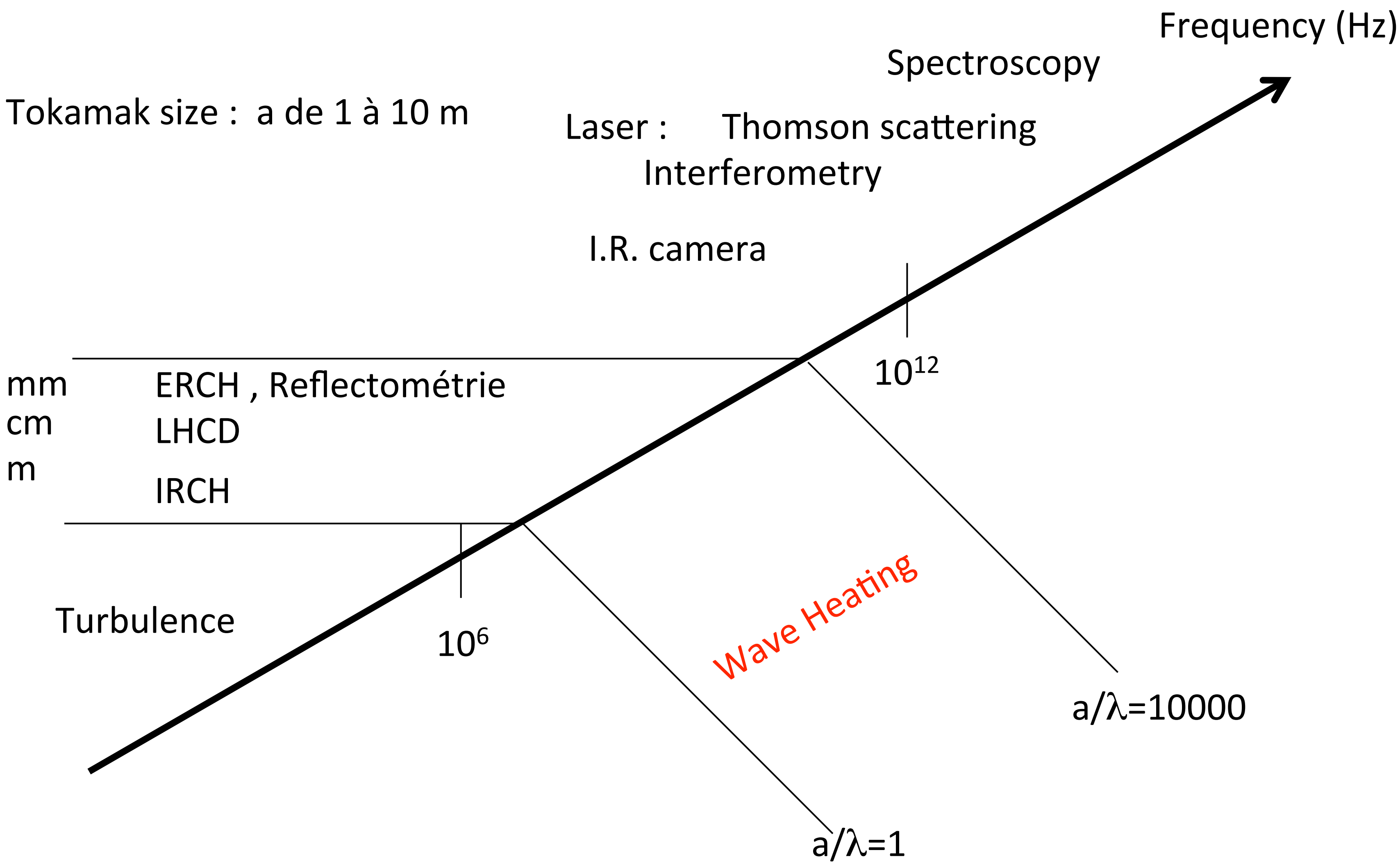
Electron Cyclotron Resonant Heating (ECRH)
Lower Hybrid Resonant Heating (LHRH)
Ion Cyclotron Resonant Heating (ICRH)



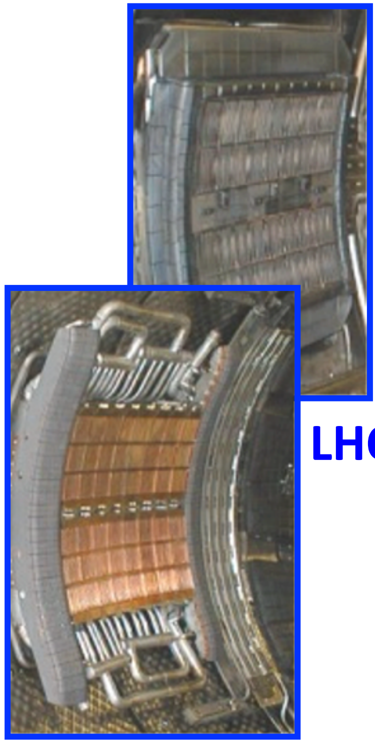

Inhomogeneous and ansitropic medium

# Wave Heating in Magnetized Plasma (scales)

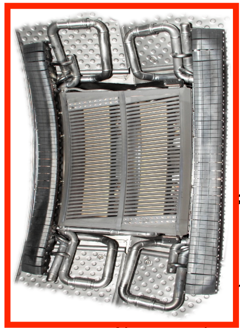


# Wave Heating in Magnetized Plasma

## An example: Tore Supra RF equipment

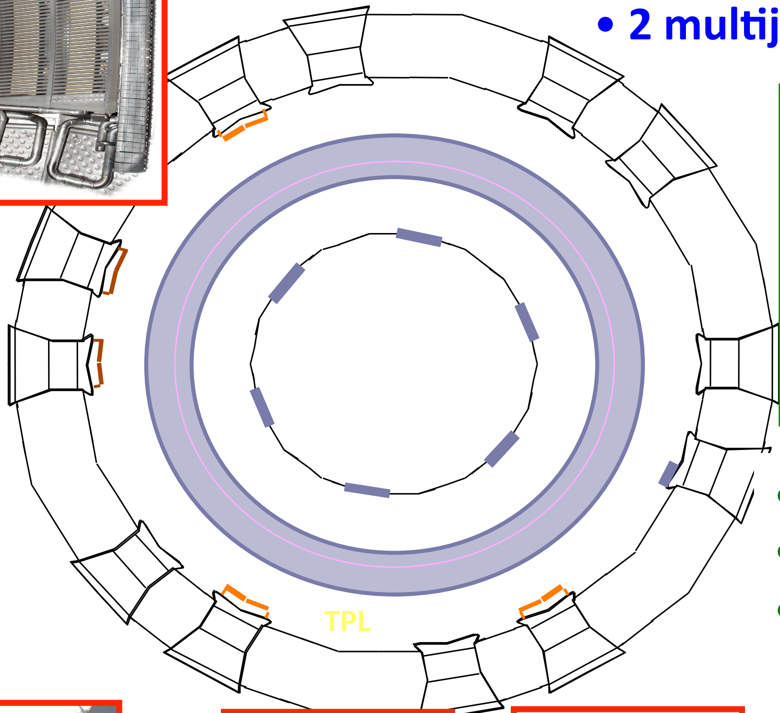


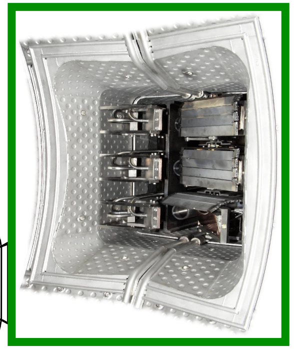
**LHCD**



**ICRH**

- **LHCD 3.7GHz**
- **8MW 16 klystrons 500kW/60s**
- **2 multijunction antennas**

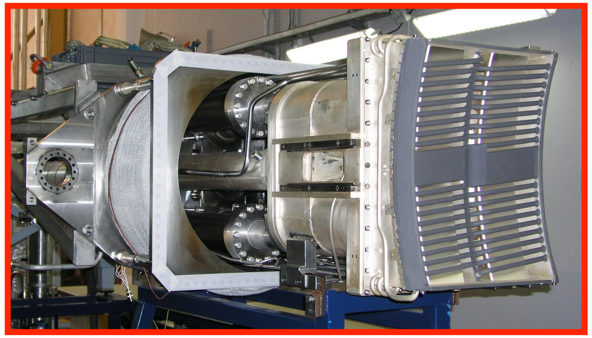


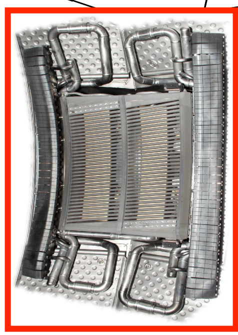
**ECRH**

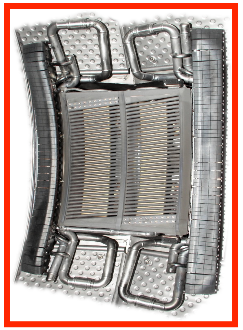
- **ECRH 118GHz**
- **2 gyrotrons ~700kW/10s**
- **1 antenna**

**ITER-like antenna**



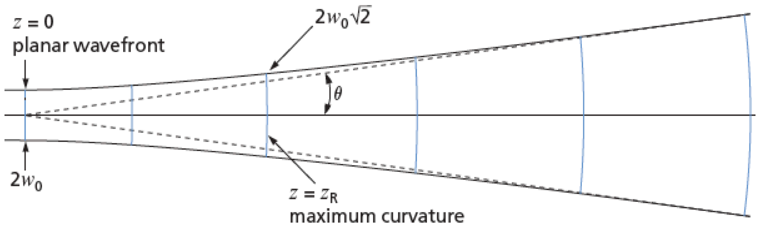
**or**





- **ICRH 40-70 MHz**
- **12MW/30s**
- **3 resonant double loop antennas + ITER-like antenna prototype**

# Electron Cyclotron Resonant Heating




Frequency range:
~100GHz < f < 200GHz

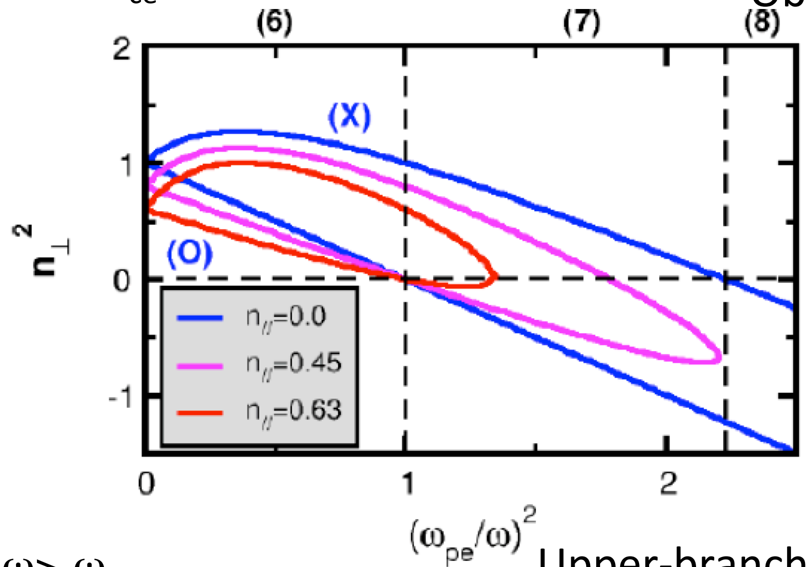
Generators:
Gyrotrons

General principle:
Cyclotron damping of
ordinary (O-mode) extraordinary wave (X-mode) by electrons, either thermal or superthermal.

Main features:
Electron heating (localized)
Non-inductive current drive (localized)
(De-)stabilization of MHD modes (ST, NTM. . . )

# Electron Cyclotron Resonant Heating

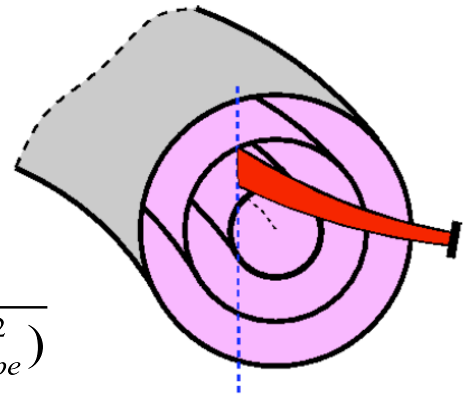
$\omega < \omega_{ce}$ Lower-branch




Oblique propagation

Optical injection controlled by mirrors

Polarisation problem

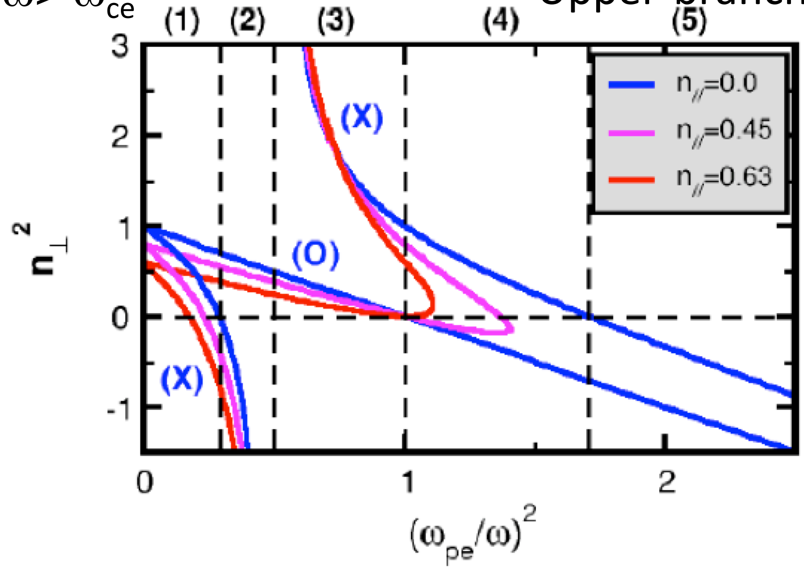


Indexes for propagation

$$N_O^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

$$N_X^2 = 1 - \frac{\omega_{pe}^2(\omega^2 - \omega_{pe}^2)}{\omega^2(\omega^2 - \omega_{ce}^2 - \omega_{pe}^2)}$$

$\omega > \omega_{ce}$ Upper-branch




Electron Cyclotron Resonance conditions giving the absorption position

$$\begin{cases} \omega = n\dfrac{\omega_{ce}}{\gamma} + k_{\|} v_{\|} \\[2ex] \dfrac{\omega_{ce}}{\gamma} = \dfrac{eB_0}{m_{e0}/\sqrt{1 - v^2/c^2}} \end{cases}$$

$\gamma = (1 - v^2/c^2)^{1/2}$ Relativistic corrections

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# Electron Cyclotron Resonant Heating

Force on an electron

$$m\frac{d\vec{v}}{dt} = e\cdot(\vec{E}+\vec{v}\times\vec{B})\cdot\exp(i(\omega t-\vec{k}\vec{x})) \approx e\cdot\vec{E}\cdot\exp(i(\omega t-\vec{k}\vec{x}))$$

Integration along an unperturbed orbit gives for the momentum increase

$$m\Delta\vec{v} = e\vec{E}\int_{-\infty}^{+\infty} dt\exp\left[i\omega t - ik_{\perp}\rho\sin(\omega_c t+\varphi_0) - ik_{\parallel}v_{\parallel 0}t\right]$$

$$= e\vec{E}\sum_{-\infty}^{+\infty}\exp(in\varphi_0)J_n(k_{\perp}\rho)\delta(\omega - n\omega_c - k_{\parallel}v_{\parallel 0})$$

**Motion along <u>B</u>**

**cyclotron**

Energy transfer only if $\omega - n\omega_c = k_{\parallel}v_{\parallel}$ is satisfied

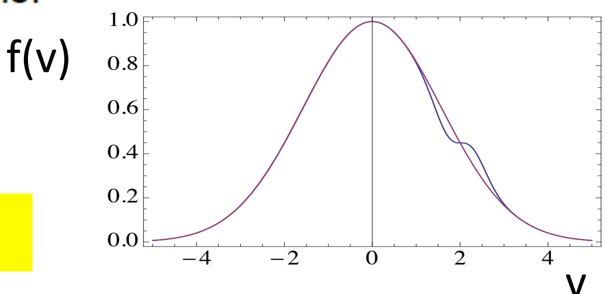
With relativistic effects we have $\omega_c = \omega_{c0}\sqrt{1-v^2/c^2}$

=> Interaction only with resonant particles in velocity space

The same is valid for ions.

$k_{//} > 0$
n =1

$k_{//}$= 0 no damping

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No more Maxwellian =>

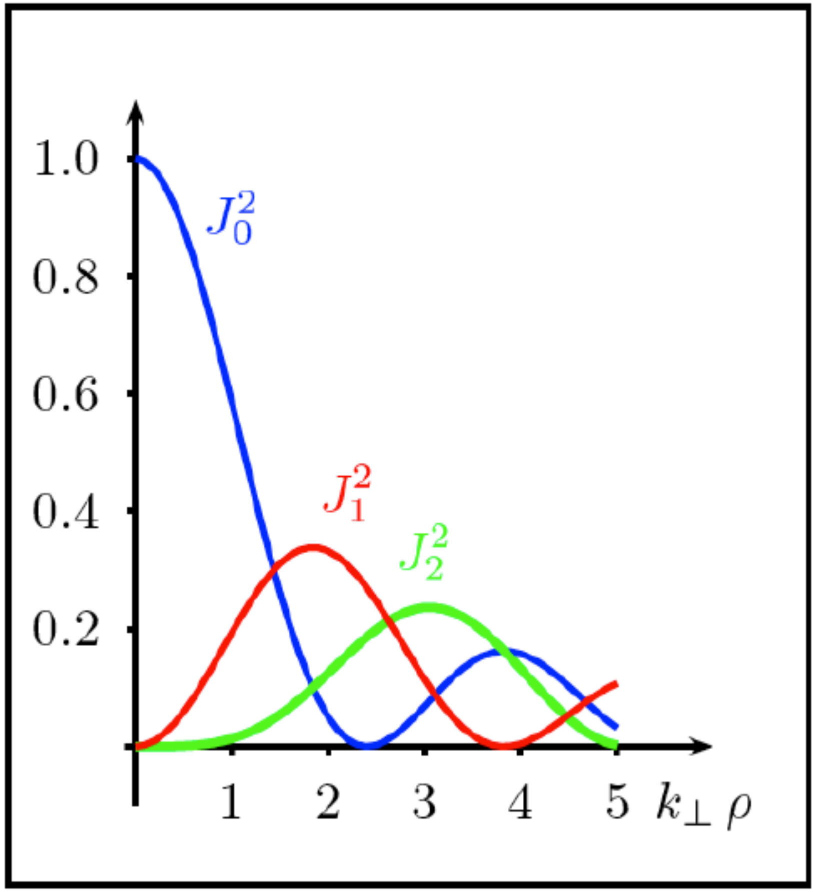
needs an eq. to describe f(v) evolution during heating

# Electron Cyclotron Resonant Heating

$$m\Delta\vec{v} = e\vec{E}\int_{-\infty}^{+\infty} dt \exp\left[i\omega t - ik_\perp \rho \sin(\omega_c t + \varphi_0) - ik_\parallel v_{\parallel 0} t\right]$$

$$= e\vec{E}\sum_{-\infty}^{+\infty} \exp(in\varphi_0) J_n(k_\perp \rho)\delta(\omega - n\omega_c - k_\parallel v_{\parallel 0})$$

Role of the harmonics

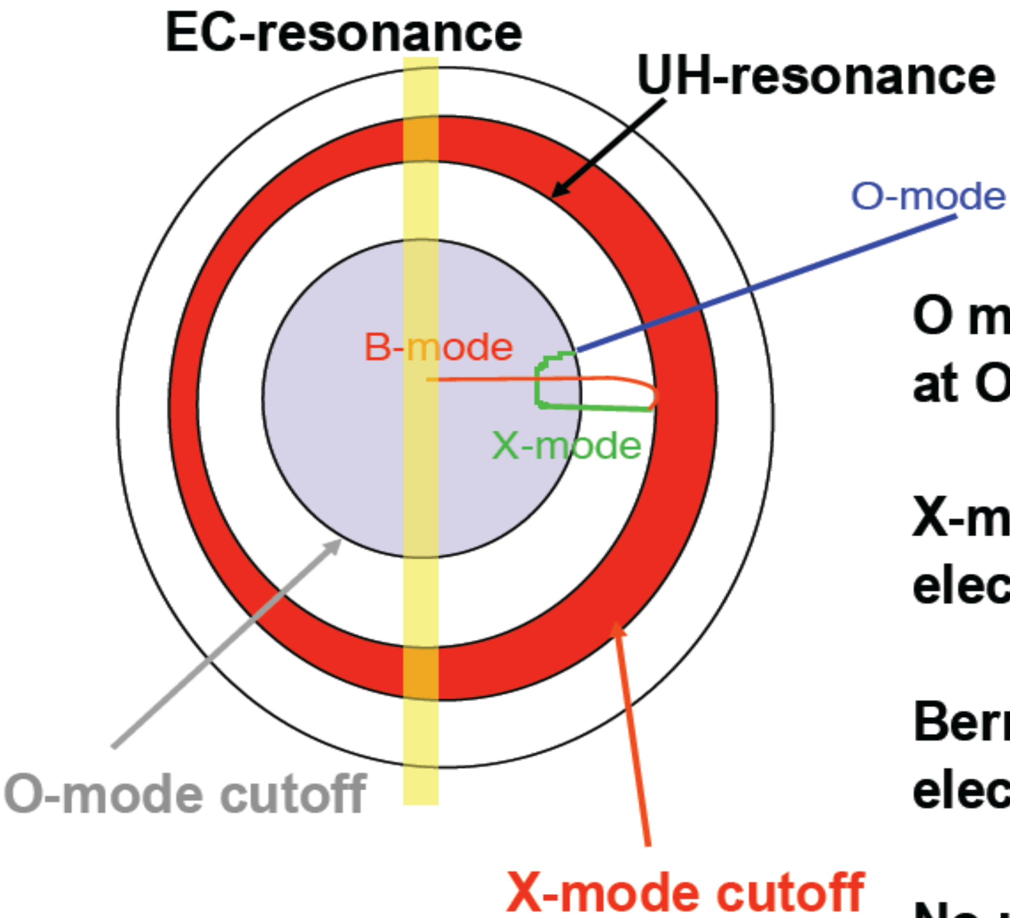


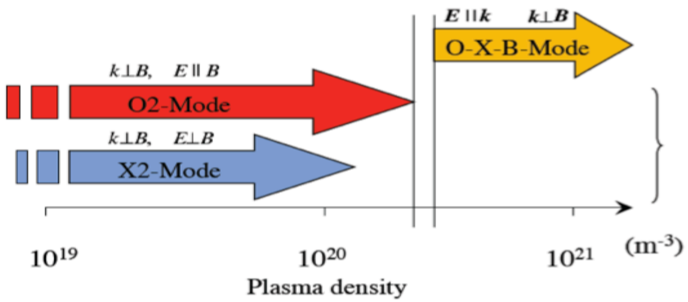

- At the **fundamental** resonance ($n = 1$), the dominant term for **thermal** particles is $\mathbf{J_0(k_\perp \rho)E_+}$. For **fast** particles, the dominant term becomes $\mathbf{J_2(k_\perp \rho)E_-}$ (*FLR effect*)
- At the $\mathbf{1^{st}}$ **harmonic** resonance ($n = 2$), the dominant term is $\mathbf{J_1(k_\perp \rho)E_+}$ (*FLR effect*).

(FLR) Finite Larmor Radius

Should all the order take into account ? Full Larmor effects against FLR effect?

# Mode Conversion OXB-Heating




**Mode conversion process under certain launch angles and for minimum density.**

**O mode converts into X mode at O-mode cutoff.**

**X-mode converts into electrostatic electron (Bernstein) wave.**

**Bernstein wave absorbed by electron cyclotron damping.**

**No upper density limit.**

What is the role of fluctuations of the conversion process ?

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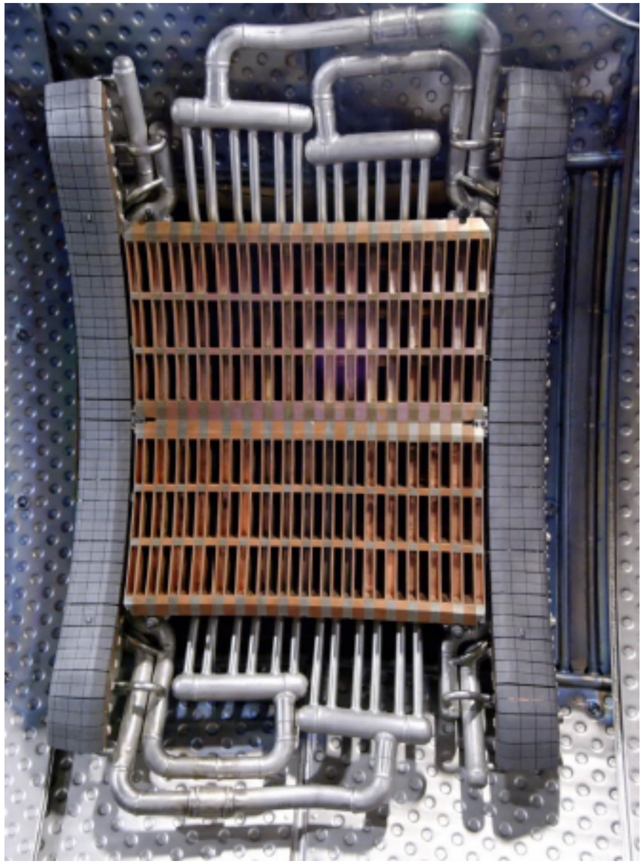
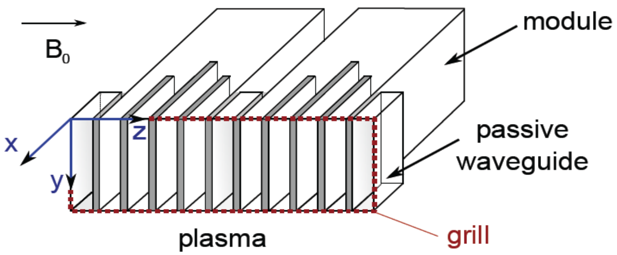
# Lower Hybrid Resonant Heating and Current Drive (LHCD)






Frequency range:

3 GHz < f < 15 GHz

Generators:

Klystrons, Gyrotrons

General principle:

Landau damping of toroidally asymmetric slow wave by superthermal electrons.

Main features:

Non-inductive current drive (bulk)
Peripheral current drive (reactor)
Induced rotation

# Lower Hybrid Heating and Current Drive

## *Using the range of the pulsation of the LH wave*

$$\begin{cases} \epsilon_{xx} = 1 - \sum_j \frac{\omega_{pj}}{\omega^2 - \Omega_{cj}^2} \\ \epsilon_{xy} = -\epsilon_{yx} = i \sum_j \frac{\omega_{pj}}{\omega} \frac{\Omega_{cj}}{\omega^2 - \Omega_{cj}^2} \\ \epsilon_{zz} = 1 - \sum_j \frac{\omega_{pj}}{\omega^2} \end{cases}$$

$$\begin{cases} \epsilon_{xx} = S \cong 1 \underset{+}{-} \frac{\omega_{pe}^2}{\Omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2} \\ \epsilon_{xy} = iD \cong i \frac{\omega_{pe}^2}{\omega \Omega_{ce}} \\ \epsilon_{zz} = P \cong 1 - \frac{\omega_{pe}^2}{\omega^2} \end{cases}$$

$$N_\perp^2 = \frac{K_\perp \widetilde{K}_\perp - K_\times^2 + K_\parallel \widetilde{K}_\perp}{2K_\perp} \pm \left[ \left( \frac{K_\perp \widetilde{K}_\perp - K_\times^2 + K_\parallel \widetilde{K}_\perp}{2K_\perp} \right)^2 + \frac{K_\parallel}{K_\perp} (K_\times^2 - \widetilde{K}_\perp^2) \right]^{1/2}$$

$N_\perp = k_\perp c/\omega$

$$\widetilde{K}_\perp = K_\perp - N_\parallel^2$$

$$N_{\perp s}^2 = \frac{1}{2S}\left(B + \sqrt{B^2 - 4SC}\right)$$ Slow wave

C/S

$$N_{\perp f}^2 = \frac{1}{2S}\left(B - \sqrt{B^2 - 4SC}\right)$$ Fast wave

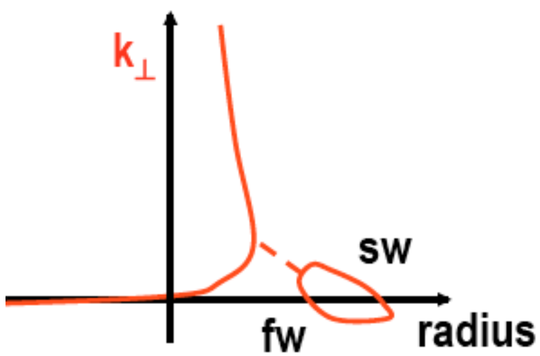
The condition of resonance is S = 0 → $\omega_{LH}^2 = \frac{\omega_{pi}^2}{1 + \omega_{pe}^2/\Omega_{ce}^2}$

The cut-off of the slow wave corresponds to $N_\perp = 0$
the value of $n_c$ is around $10^{17} m^{-3}$

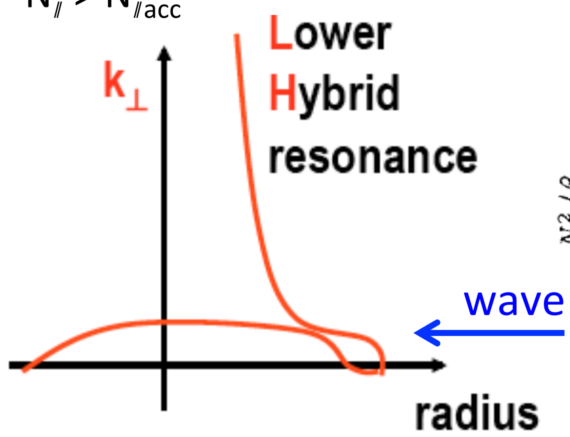
# Lower Hybrid Heating and Current Drive (LHCD)

$$N_{\parallel acces.} = \frac{\omega_{pe}}{\Omega_{ce}} + \left(1 + \frac{\omega_{pe}^2}{\Omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2}\right)^{1/2} \quad \text{if } n_e^2 \gg n_c^2$$

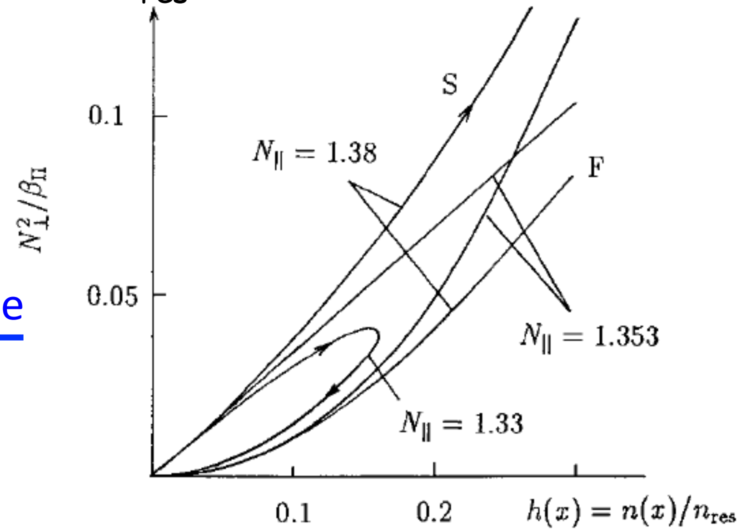
$N_{/\!/} < N_{/\!/acc}$




$N_{/\!/} > N_{/\!/acc}$




B= 3T, ν=1 GHz, p=0.353, $n_{res}$= 3.1 $10^{19}$ $m^{-3}$

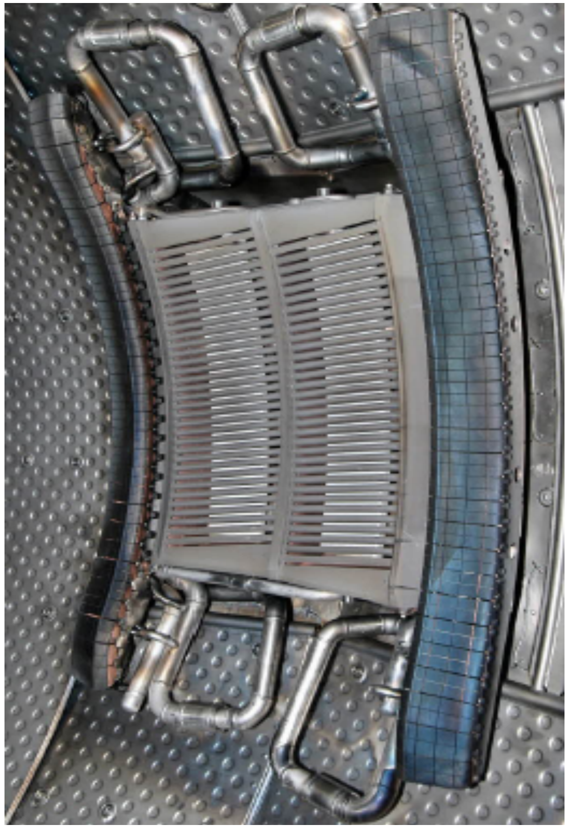


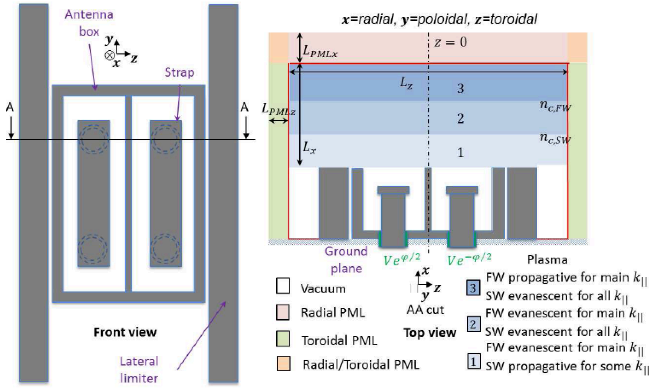

$v_{Te} > (1/3)c/N_\parallel$ wave absorption

$c/N_\perp \sim v_{Ti}$ ion Landau damping

$v_i > c/N_\perp$ stochasting heating

# Ion Cyclotron Resonant Heating (ICRH)






Frequency range:

30MHz < f < 100MHz

Generators:

Tetrodes, diacrodes

General principle:

Cyclotron damping of fast wave by ions, either thermal or superthermal (fast).

Landau damping of fast wave electrons

Main features:

Electron / ion heating

Non-inductive current-drive (central)

Induced rotation

# Ion Cyclotron Resonant Heating (ICRH)

Frequency range: 10MHz < f < 100MHz

$$\left|\varepsilon_{\parallel}\right| >> \left|n_{\parallel}^{2}\right|, \left|\varepsilon_{\perp}\right|, \left|\varepsilon_{\times}\right|$$

$\varepsilon_{\perp} \neq n_{\parallel}^{2}$ out of the coupling region

Stix's dielectrc tensor

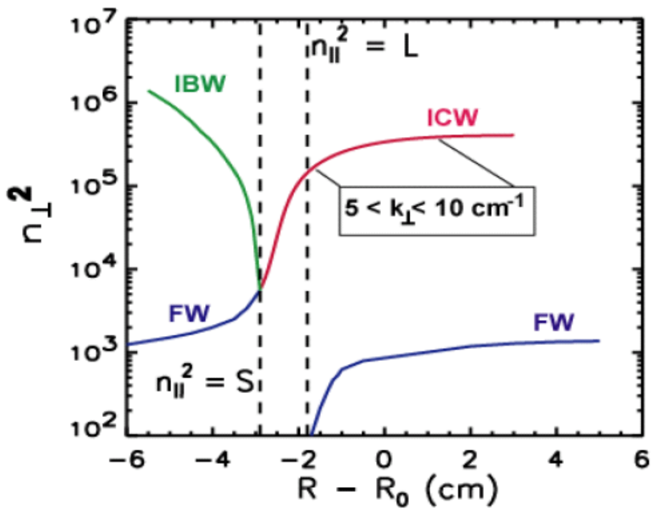
$$\bar{\bar{\varepsilon}} = \varepsilon_0 \begin{bmatrix} \varepsilon_\perp & -i\varepsilon_\times & 0 \\ i\varepsilon_\times & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{bmatrix}$$

Fast wave

$$n_{\perp FW}^{2} = \frac{\left(\varepsilon_{\perp} - n_{\parallel}^{2}\right)^{2} - \varepsilon_{\times}^{2}}{\left(\varepsilon_{\perp} - n_{\parallel}^{2}\right)} \quad \text{with } \left|\varepsilon_{\parallel}\right| >> \left|n_{\perp FW}^{2}\right|,$$

Slow wave

$$n_{\perp SW}^{2} = \varepsilon_{\parallel}\left(1 - \frac{n_{\parallel}^{2}}{\varepsilon_{\perp}}\right) \quad \text{with } \left|\varepsilon_{\parallel}\right| \approx \left|n_{\perp FW}^{2}\right|.$$




F.W. Perkins, Nucl. Fusion 17, 1197 (1977)

Mode conversion possible

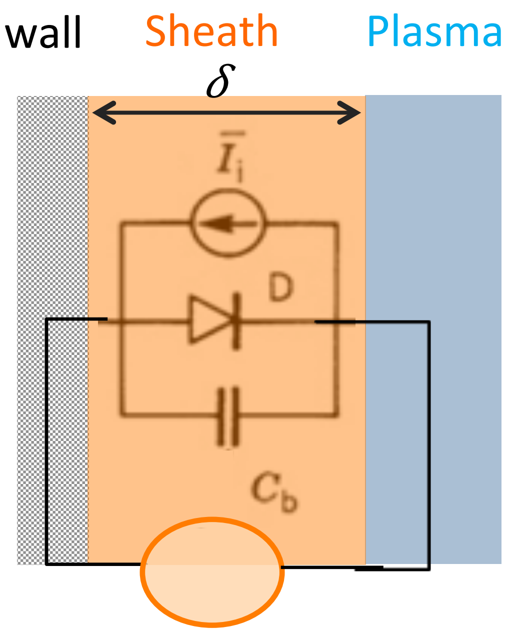
IBW ion Bernstein Wave (Hot plasma)
ICW ion Cyclotron Wave

# Ion Cyclotron Resonant Heating (ICRH)

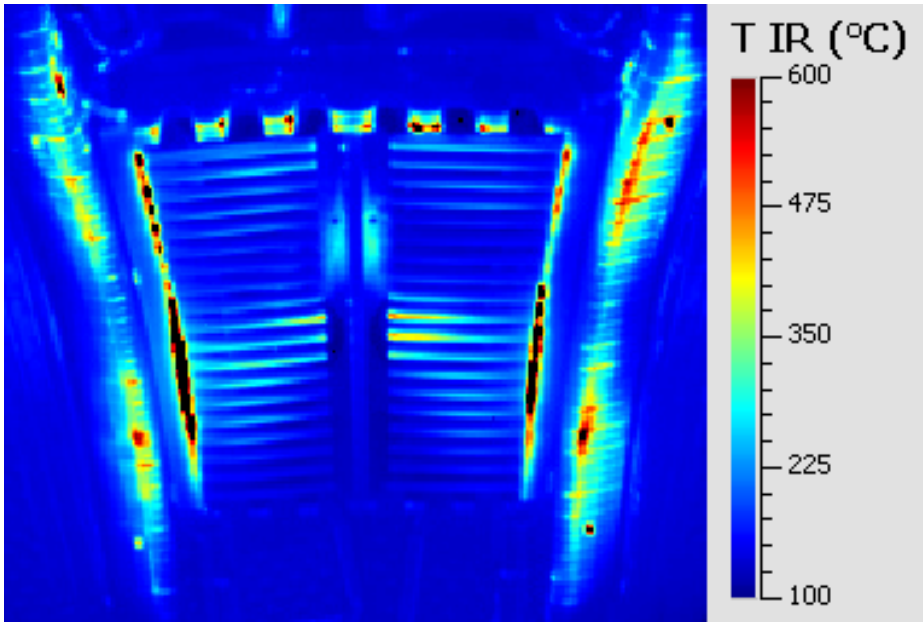
Underlying physics

- Rectification of sheaths voltages by the slow wave
- Interactions related to electrical design of the antenna

Need of self-consistent modeling of RF sheaths closer to first principles




•Observations: enhanced heat loads, sputtering, density modification on ICRH antennas and connected objects (Tore Supra, AUG, C-Mod, JET,…)




IR image
front face Tore Supra antenna
New faraday screen

# Wave absorption computation

Formal expression from Maxwell's equation

$$H\,.\ \nabla \times \boldsymbol{E} = -\frac{\partial B}{\partial t} \qquad E\,.\ \nabla \times \boldsymbol{H} = \boldsymbol{j} + \epsilon_0 \frac{\partial E}{\partial t} = \frac{\partial D}{\partial t}$$

$$\nabla \cdot (\mathbf{A} \times \mathbf{B}) = \mathbf{B} \cdot \nabla \times \ \mathbf{A} - \mathbf{A} \cdot \nabla \times \mathbf{B}$$

$$\nabla \cdot (\boldsymbol{E} \times \boldsymbol{H}) + \boldsymbol{E} \cdot \frac{\partial D}{\partial t} + \boldsymbol{H} \cdot \frac{\partial B}{\partial t} = 0$$

$$\nabla \cdot \boldsymbol{P} + \frac{\partial W}{\partial t} = 0$$

Energy conservqtion

where

$$\boldsymbol{P} = \frac{1}{2\mu_0} \mathrm{Re}(\boldsymbol{E}_0 \times \boldsymbol{B}_0^*)$$

Poynting' vector

$$\frac{\partial W}{\partial t} = \frac{1}{2} \mathrm{Re}\left( \left( \frac{\boldsymbol{B}^*}{\mu_0} \cdot \frac{\partial \boldsymbol{B}}{\partial t} \right) + \epsilon_0 \boldsymbol{E}^* \cdot \frac{\partial}{\partial t} (\boldsymbol{K} \cdot \boldsymbol{E}) \right)$$

W wave energy

for monochromatic wave becomes $\boldsymbol{D}_\omega(\boldsymbol{k}, \omega) = \epsilon_0 \boldsymbol{K}(\boldsymbol{k}, \omega) \cdot \boldsymbol{E}_\omega(\boldsymbol{k}, \omega)$

$$\boldsymbol{B} = \mu_0 \boldsymbol{H} \longrightarrow \frac{1}{2} \omega_{\mathrm{i}} \frac{\boldsymbol{B} \cdot \boldsymbol{B}^*}{\mu_0} + \frac{\epsilon_0}{2} (\omega_{\mathrm{i}} \mathrm{Re}(\boldsymbol{E}^* \cdot \boldsymbol{K} \cdot \boldsymbol{E}) + \omega_{\mathrm{r}} \mathrm{Im}(\boldsymbol{E}^* \cdot \boldsymbol{K} \cdot \boldsymbol{E}))$$

# Wave absorption computation

$$\boldsymbol{K}(\boldsymbol{k},\omega) = \boldsymbol{K}_{\mathrm{H}}(\boldsymbol{k},\omega) + i\boldsymbol{K}_{\mathrm{I}}(\boldsymbol{k},\omega) \qquad (\omega = \omega_{\mathrm{r}} + i\omega_{\mathrm{i}},\ |\omega_{\mathrm{i}}| \ll |\omega_{\mathrm{r}}|)$$

$$\boldsymbol{K}(\boldsymbol{k},\omega_{\mathrm{r}} + i\omega_{\mathrm{i}}) \approx \boldsymbol{K}_{\mathrm{H}}(\boldsymbol{k},\omega_{\mathrm{r}}) + i\omega_{\mathrm{i}}\frac{\partial}{\partial\omega_{\mathrm{r}}}\boldsymbol{K}_{\mathrm{H}}(\boldsymbol{k},\omega_{\mathrm{r}}) + i\boldsymbol{K}_{\mathrm{I}}(\boldsymbol{k},\omega_{\mathrm{r}})$$

wave energy

$$W_0 = \frac{1}{2}\mathrm{Re}\left(\frac{\boldsymbol{B}_0^*\cdot\boldsymbol{B}_0}{2\mu_0} + \frac{\epsilon_0}{2}\boldsymbol{E}_0^*\cdot\boldsymbol{K}_{\mathrm{H}}\cdot\boldsymbol{E}_0 + \frac{\epsilon_0}{2}\boldsymbol{E}_0^*\cdot\left(\omega_{\mathrm{r}}\frac{\partial}{\partial\omega_{\mathrm{r}}}\boldsymbol{K}_{\mathrm{H}}\right)\cdot\boldsymbol{E}_0\right)$$

$$= \frac{1}{2}\mathrm{Re}\left(\frac{\boldsymbol{B}_0^*\cdot\boldsymbol{B}_0}{2\mu_0} + \frac{\epsilon_0}{2}\boldsymbol{E}_0^*\cdot\left(\frac{\partial}{\partial\omega}(\omega\boldsymbol{K}_{\mathrm{H}})\right)\cdot\boldsymbol{E}_0\right)$$

Wave Energy transfert

$$\frac{\partial W_0}{\partial t} = -\omega_{\mathrm{r}}\frac{1}{2}\epsilon_0\boldsymbol{E}_0^*\cdot\boldsymbol{K}_{\mathrm{I}}\cdot\boldsymbol{E}_0 - \nabla\cdot\boldsymbol{P}$$

absorbed power

$$F(\boldsymbol{r},t) = \int_{-\infty}^{\infty} f(\boldsymbol{k})\exp i(\boldsymbol{k}\cdot\boldsymbol{r} - \omega(\boldsymbol{k})t)\mathrm{d}\boldsymbol{k} \qquad \frac{\partial}{\partial k_i}(\boldsymbol{k}\cdot\boldsymbol{r} - \omega(\boldsymbol{k})t) = 0$$

$$i = x, y, z$$

$$\frac{x}{t} = \frac{\partial\omega(\boldsymbol{k})}{\partial k_x} \qquad \boldsymbol{v}_{\mathrm{g}} = \left(\frac{\partial\omega}{\partial k_x}, \frac{\partial\omega}{\partial k_y}, \frac{\partial\omega}{\partial k_z}\right)$$

Group Velocity

17

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# Wave absorption computation

absorbed power $P^{\rm ab} = \omega_{\rm r}\left(\frac{\epsilon_0}{2}\right)\boldsymbol{E}^*\cdot\boldsymbol{K}_{\rm I}\cdot\boldsymbol{E}$ or $P^{\rm ab} = \frac{1}{2}{\rm Re}(\boldsymbol{E}^*\cdot\boldsymbol{j})_{\omega=\omega_{\rm r}}$

as

$$P^{\rm ab} = \omega_{\rm r}\left(\frac{\epsilon_0}{2}\right){\rm Re}\left(\boldsymbol{E}^*\cdot(-i)\boldsymbol{K}\cdot\boldsymbol{E}\right)_{\omega=\omega_{\rm r}} \qquad \boldsymbol{j} = -i\omega\boldsymbol{P} = -i\epsilon_0\omega(\boldsymbol{K}-\boldsymbol{I})\cdot\boldsymbol{E}$$

Expliciting the components

$$P^{\rm ab} = \omega\frac{\epsilon_0}{2}\left(|E_x|^2{\rm Im}K_{xx} + |E_y|^2{\rm Im}K_{yy} + |E_z|^2{\rm Im}K_{zz}\right.$$
$$\left. + 2{\rm Im}(E_x^*E_y){\rm Re}K_{xy} + 2{\rm Im}(E_y^*E_z){\rm Re}K_{yz} + 2{\rm Im}(E_x^*E_z){\rm Re}K_{xz}\right)$$

For ICRH at n$^{\rm th}$ harmonic in hot Maxwellian plasma

$$P^{\rm ab}_{\pm{\rm n}} = \omega\left(\frac{\omega_{\rm pj}}{\omega}\right)^2 G_{\rm n}\left(\frac{\epsilon_0}{2}\right)\alpha_{\rm n}|E_x \pm iE_y|^2$$

Need to have the good polarization

with $\zeta_{\rm n} = (\omega - {\rm n}|\Omega_{\rm i}|)/(2^{1/2}k_z v_{\rm Ti})$

$$G_{\pm{\rm n}} \equiv {\rm Im}\zeta_0 Z_{\pm{\rm n}} = \frac{k_z}{|k_z|}\pi^{1/2}\zeta_0\exp(-\zeta^2_{\pm{\rm n}})$$



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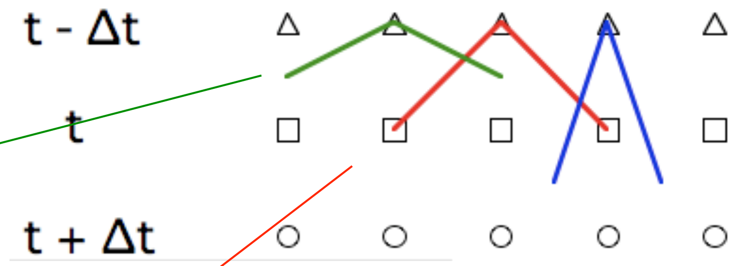
How to build a simulation in wave heating?
After
Knowing something about numerical computation

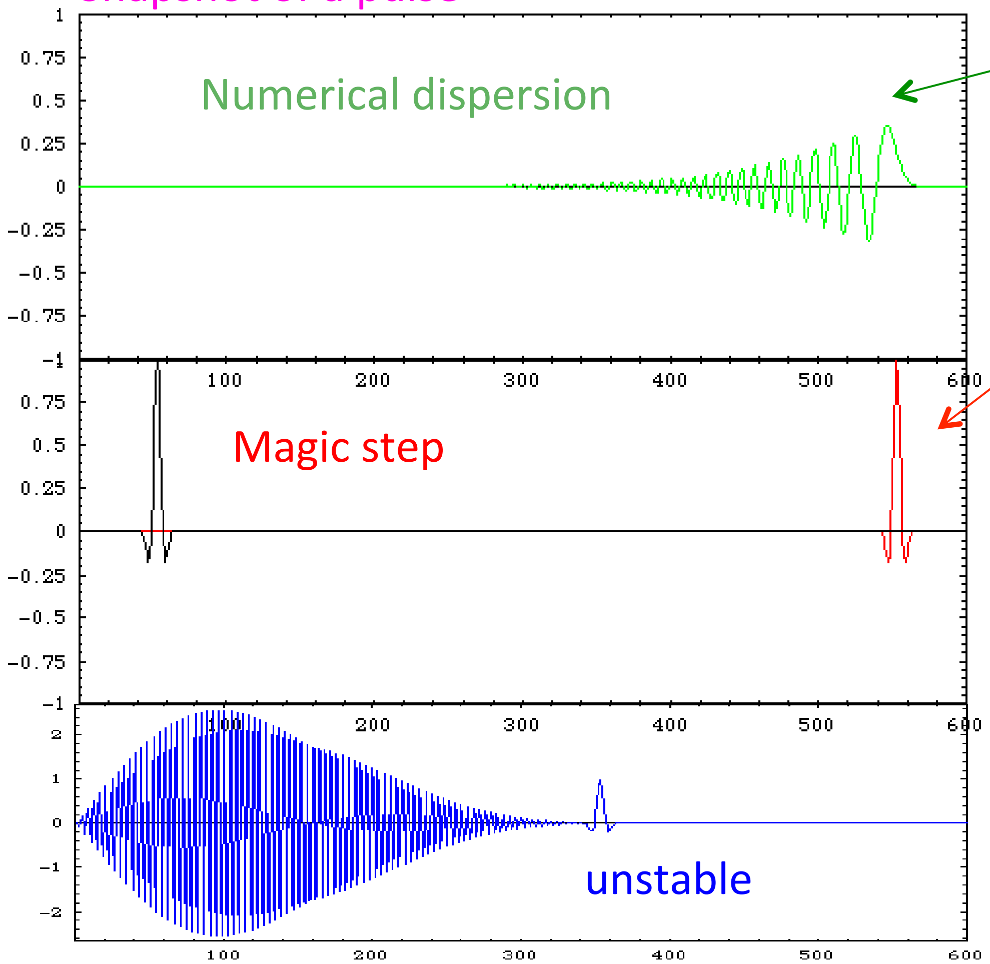
# An example from FDTD - Stability and accuracy

Stability 1D : $c^2 \frac{\Delta t^2}{\Delta x^2} \leq 1$ CFL

3D: $3c^2 \Delta t^2 < \Delta x^2$




Snapshot of a pulse




FDTD plasma

J.L. Young *Radio Science* **29** 1513 (1994)

Introduction of collisions
-> Yee's algorithm instable

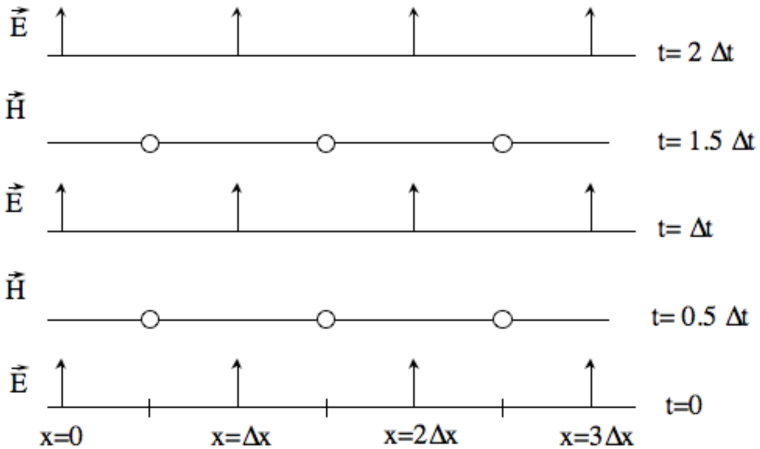
scheme to improve

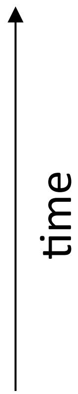
S. Cummer IEEE Ant.prop **45** 392 (1997)

Huang Computer Physics Communications 166 42 (2005)

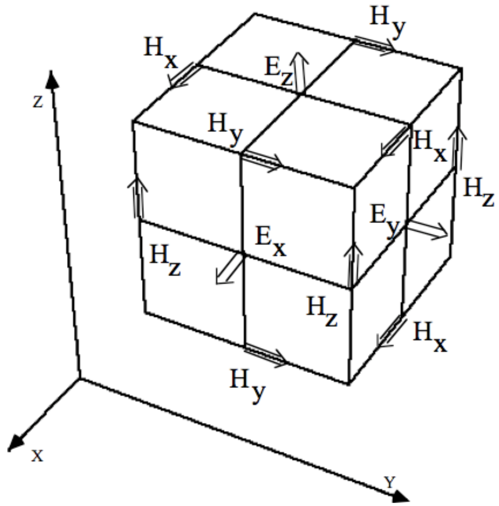
# FDTD 2D or 3D

TE ($E_z$,$H_x$,$H_y$) and TM($E_x$,$E_y$,$H_z$) decoupled nodes : Yee's algorithm



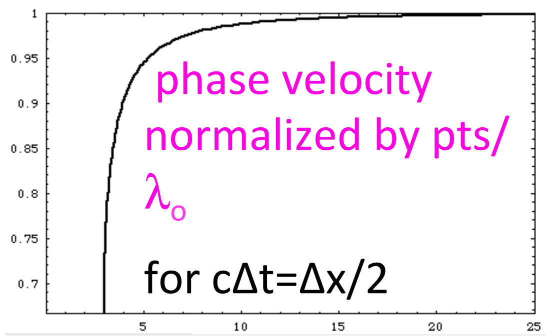




S. Hacquin IRW2011 website ERCC




Explicity Scheme + boundary conditions (PML or ABC or PEC) + source EM

But the dispersion relation Yee's scheme ≠ from physical dispersion relation

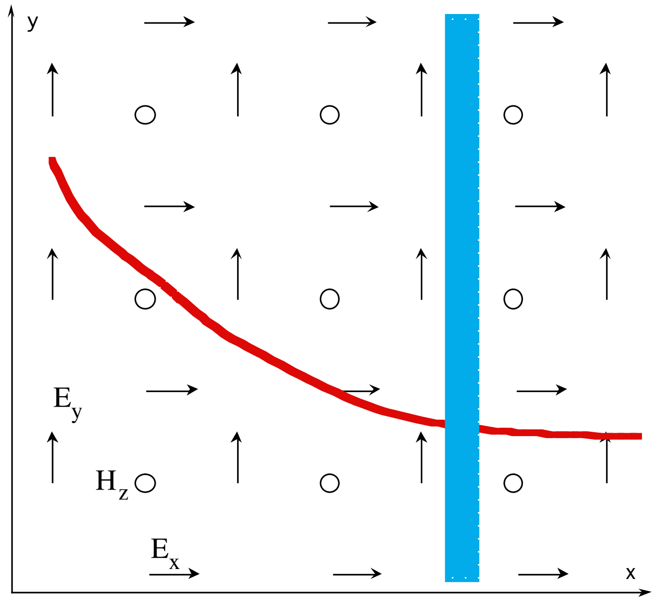



Numerical Dispersion ~1.27 % with 10 pts/$\lambda_o$

~47° spurious phase shift after 1000 pts

# FDTD 2D or 3D

Scheme mesh point repartition




Problems ofcontours definition

-thin objects

- complex objects

Solutions : Sub-domains

Adapted coordinates

possible unstructured mesh see Taflove's book

Introduction of relativistic corrections for moving objects, if stable

Analytic Description of the plasma or via simulation (parex.code PIC semi implicit)
Smithe *et al* Phys. of plasmas 14, 056104 (2007)

How to make the good choice ?

## Choice : Links between assumptions and wave propagation equation

(Hyps: inhomogeneous plasma)

Plane-Gaussian + dispersion relation -> Ordinary Differential Eqs set

Monochromatic wave ("full-wave", stationary plasma, no Doppler)
+ Monomode -> Helmholtz
+ Multi-modes + coupling terms-> set of coupled Helmholtz Eqs

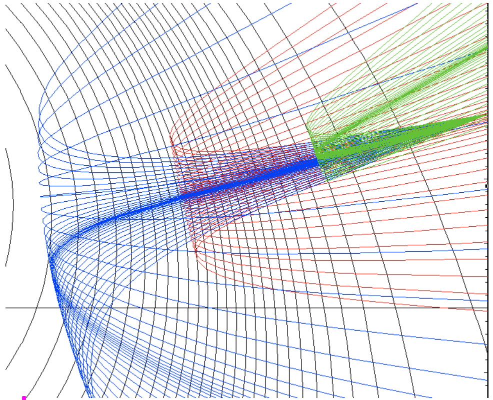
Multi-frequencies monomode (pulse)
+ "*stationnary*"case -> Wave equation
+ n(t) -> Wave equation + eqs of motion
or eqs Maxwell + eqs of motion

Multi-frequencies multi-modes
+ couplaging -> set of wave equations
+ polarisation -> eqs Maxwell + 'J-solver' (linear case)
-> eqs Maxwell + PIC code or Vlasov (non-linear)

# From ray tracing to wave equation (1)

## Quasi-optic description without scattering

ITER case with $\nabla_y n$



Ray tracing

D. G. Swanson "**Plasma Waves", 2nd Ed IoP 2003,ch6.5,** ISBN 0 7503 0927 X

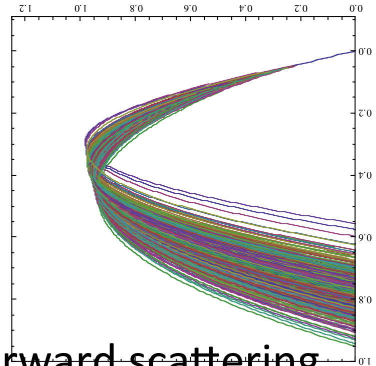
$$\text{Hyp. WKB :} \quad \left|\frac{dk}{dx}\right| \ll k^2, \quad \left|\frac{d^2k}{dx^2}\right| \ll \left|\frac{dk}{dx}\,k\right|$$

Single mode description D(w,**k**,**r**,t)=0

Set of coupled Odes to solve

RungeKutta 4th order

$$\begin{cases} \dfrac{\partial \vec{r}}{\partial \tau} = -\dfrac{\partial D(\omega,\vec{k},\vec{r},t)}{\partial \vec{k}} \\ \dfrac{\partial \vec{k}}{\partial \tau} = \dfrac{\partial D(\omega,\vec{k},\vec{r},t)}{\partial \vec{r}} \end{cases} \qquad \begin{cases} \dfrac{\partial t}{\partial \tau} = \dfrac{\partial D(\omega,\vec{k},\vec{r},t)}{\partial \omega} \\ \dfrac{\partial \omega}{\partial \tau} = -\dfrac{\partial D(\omega,\vec{k},\vec{r},t)}{\partial t} \end{cases}$$



Forward scattering

Can be extended to Gaussian beam propagation by one ODE associated to amplitude or using stationnary phase method

G. V. Pereverzev Phys. Plasmas **5**, 3529 (1998) **R.A. Cairns**, **V. Fuchs** Nucl. Fusion **50** (2010) 095001

Or eikonal method with wavepacket for the amplitude description (as quantum phy.)

A. Richardson, P. Bonoli, J. Wright, PoP **17** (2010) 052107

# From ray tracing to wave equation (2)

## Monochromatic and single polarisation probing system

Helmholtz's equation (full-wave)

Hyp: monochromatic wave, steady state plasma ($\Delta t$ or $l_{corr} >> 4r_c/c$)

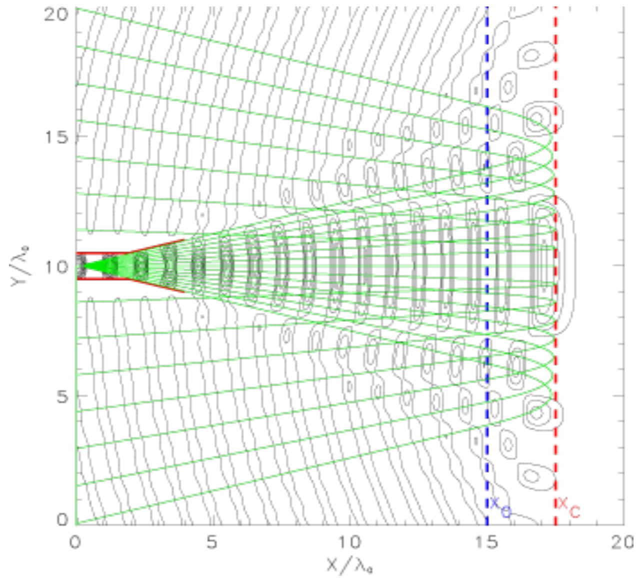
Single mode description: Computation of the index *N(r)*

$$\Delta\vec{E} + N^2(\vec{r})\vec{E} = 0$$

Finite Difference
4th order (Numerov)

Be careful in multi dimensional case, possible cross derivatives more complicated to solve especially for X-mode

No Doppler
O-mode other method




C. Fanack, PhD Thesis or *et al* PPCF **38**, 1915 (1996)
S. Heuraux, F. da Silva DCDS_S 5, 307 (2012)
H.G. James JGR-SP 116, A07306 (2011)

# Finite Element Method

## Monochromatic multi-polarisation probing system

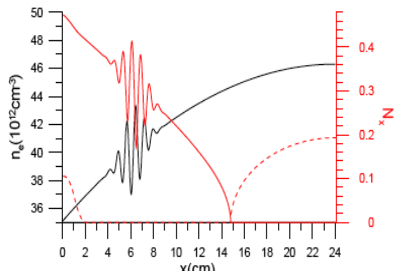
Actually only few developments on FEM with dispersive media:

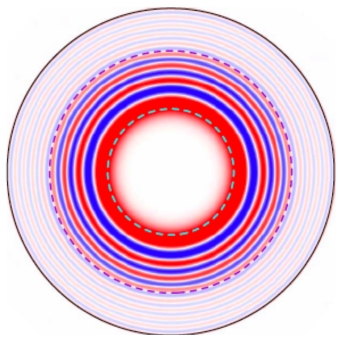
In plasma only using equivalent dielectric (Ph Lamalle for ICRH or F. Braun & L. Colas) for ICRH (HFSS or COMSOL multi-Physics) including boundary sheath conditions L. Colas, **J. N. Mat 390-391** (2009) 959-962,
For LHCD O. Meneghini PoP, **16** (2009) 090701

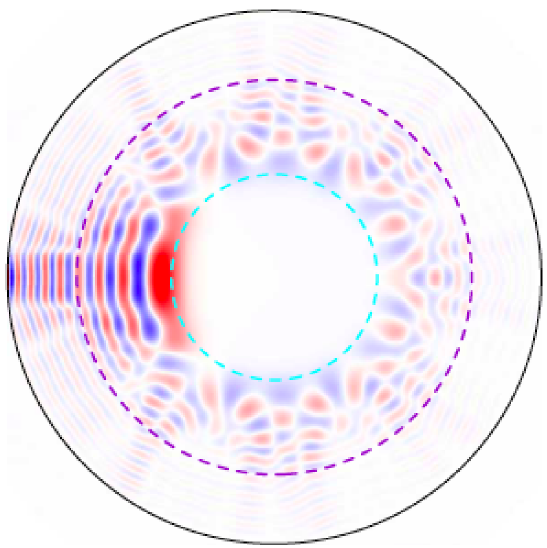
Accurate method in vacuum and in complex geometry (commercial software)

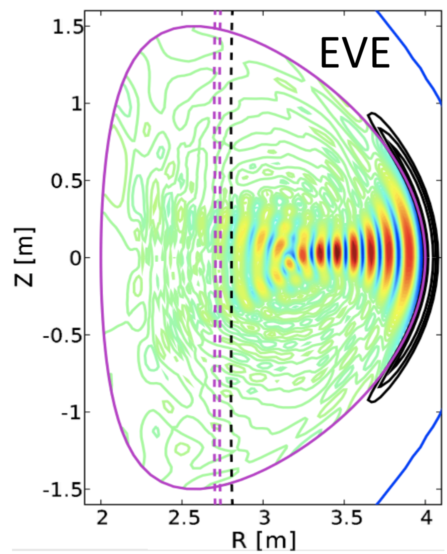
ALCYON was ICRH code based on functionals, replaced by EVE code developed by R. Dumont (CEA_cadarache) and needs a lot of memory (~10-20 Gbytes)
R. Dumont Nuc Fus 49 075033 (2009)

In the case of high frequency possible ? Yes
M. Irzak, et al Nuc Fus **35** 1341 (1995)



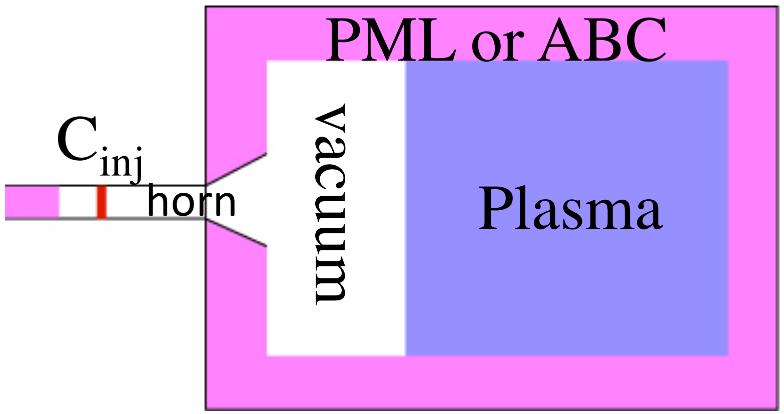





Resonances generated by Bragg resonant perturbation with ≠ sources

# Numerical Method to solve Helmholtz Equation

$$\Delta\vec{E} + N^2(\vec{r})\vec{E} = 0$$




Cautions: description of the border
(anisotropic case,
Object descriptions)

Boundary Conditions (PML or ABC)
J.P. Bérenger JCP 114, 195 (1994) Prix URSI 2013.
FL Teixeira *et al* I. J. Num. Mod-ENDF, 13 441 (2000).

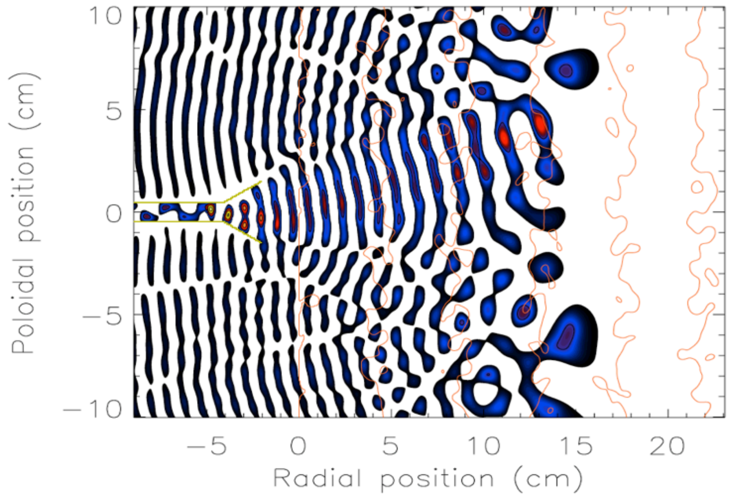
1D:
Runge-Kutta RK 45 (needs accurate I.C.)
or
2D Finite Difference scheme ( $4^{th}$ order)
or
Transmission Line Method (paraxial approx.)
Or
FEM (generalized or not)
W. Facco *et al* µwave Opt Tech Lett 54, 2709 (2012).

No condition stability,
Collisions (use of complex number)
All plasma (hot, relativistic…)

limitations:
- -no intrinsic Doppler (no Doppler no scattered wave)
- -calculus of total fields $E_{tot}$ (asymptotic state description)
- -approximations on copmlex objects

# Wave Equations

$E_z > 0$ contours in turbulent plasma




Wave equation (quasi-steady state)

Hyp: ($t_f$, $\Delta t$ or $\tau_{corr}$ >> $4r_c/c$)

$$\partial_t^2 \vec{E} - c^2 \Delta \vec{E} + \omega_{pe}^2(\vec{r})\vec{E} = 0$$

Hacquin et al, J. of Computational Physics **174**, 1 (2001),

O-mode or plasma isotrope (E // B)

$$\begin{cases} \dfrac{\partial^2 E_x}{\partial t^2} + c^2 \dfrac{\partial^2 E_x}{\partial x \partial y} - c^2 \dfrac{\partial^2 E_x}{\partial y^2} + \omega_p^2 E_x = \omega_p^2 v_y \\ \dfrac{\partial^2 E_y}{\partial t^2} + c^2 \dfrac{\partial^2 E_y}{\partial x \partial y} - c^2 \dfrac{\partial^2 E_y}{\partial x^2} + \omega_p^2 E_y = \omega_p^2 v_x \\ \dfrac{\partial}{\partial t} v_x = -\omega_c v_y - \omega_c E_x \\ \dfrac{\partial}{\partial t} v_y = \omega_c v_x - \omega_c E_y \end{cases}$$

Set of PDEs described X-mode (E⊥B)

Cohen et al, Plas. Phys. Cont Fusion **40**, 75 (1998),

# Method to solve Wave Equations

Hyperbolic PDE

- Finite Difference in time and space ($4^{th}$ order space, $2^{nd}$ or $4^{th}$ in time)
  + Eqs dynamics of particles $4^{th}$ ordre G.C. Cohen ed Springer (2002).

-Transmission Line Matrix: Maxwell Eqs <=> circuit potential–current Eqs
C.N. Klimov, Progress in Electromagnetics Research Symposium,July 18–22, Osaka, 2001.

-New methods at higher order appear
C. Agut Commun. Comput. Phys., 11, 691 (2012)
Stable under condition (condition CFL: Courant, Friedrichs et Lewy)

+ PML ou ABC + Source (transparent or/and unidirectional)
D. Rabinovich IJNM-BE 26,1351 (2010) F. da Silva JCP **203**, 467 (2005)

Possibility to reduce the computation time
- use of sub-domains
- near fields –far fields transform

A. Taflove ed Artechouse (2000)

Accurate Scheme: relative error $10^{-3}$ after propagation of 100m in plasma

Possibility to have size description
Limitations : Collisions -> stable if low

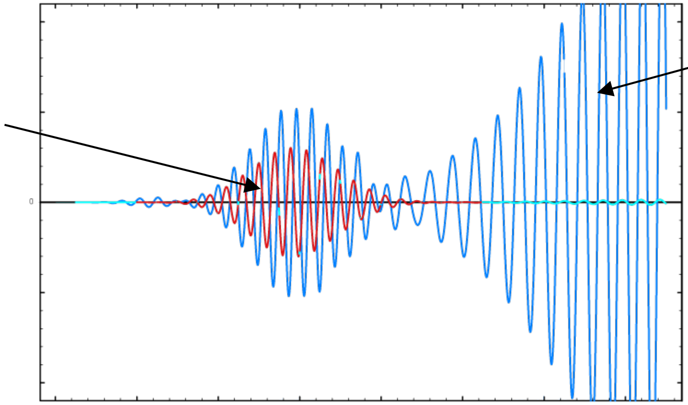
# Cross polarisation simulations

1D Case: O-mode -> X-mode

$$
\begin{cases}
\partial_t^2 E_z - c^2 \partial_x^2 E_z + \omega_{pe}^2(x,t) E_z = C_{OX}\left(E_x, E_y\right) \\
\partial_t^2 E_x + \omega_{pe}^2(x,t) E_x = -\omega_{pe}^2(x,t) v_y + C_{XOx}\left(E_z\right) \\
\partial_t^2 E_y - c^2 \partial_x^2 E_y + \omega_{pe}^2(x,t) Ey = \omega_{pe}^2(x,t) v_x + C_{XOy}\left(E_z\right) \\
\partial_t \vec{v} = -\frac{e}{m_e} \vec{E} - \frac{e}{m_e} \vec{v} \times \vec{B}
\end{cases}
$$

Depolarisation O->X on magnetic fluctuations

Finite Difference explicit scheme




N. Katsuragawa, H. Hojo, A. Mase J. Phys. Soc. Jpn. **67** (1998) 2574-2577

Possibility to describe Heating by double mode conversion O-X-B

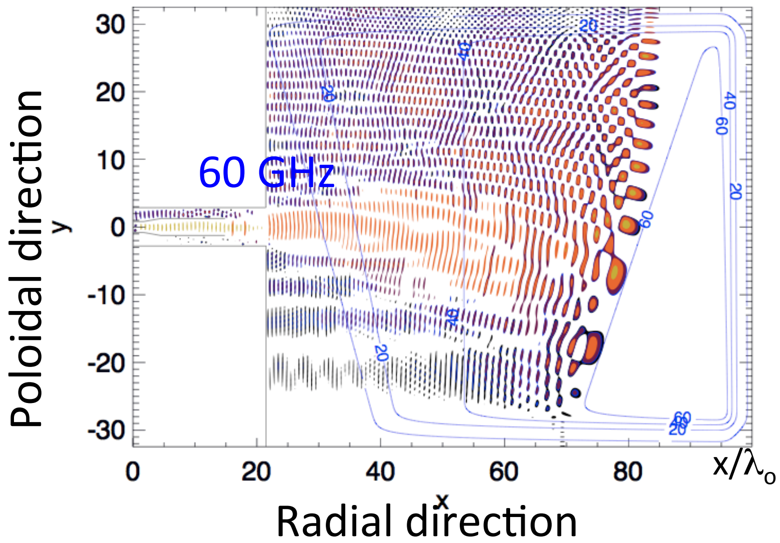
# Full description: Maxwell's equations

## Velocity field mapping, Shear layer detection

Hyp: linear response of the plasma

ρ total density of charges
*j* current density

Associated model fluid or kinetic




F. da Silva et al , J Plasma Phys. **72** 1205 (2006), et Rev. Sci Instr. 79, 10F104 (2008)
C. Lechte, IEEE TPS 37 (2009) 1099.

$$\begin{cases} \nabla . \vec{B} = 0 \\ \nabla . \vec{E} = \dfrac{\rho}{\varepsilon_o} \\ \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} = \mu_o \vec{j} + \dfrac{1}{c^2}\dfrac{\partial \vec{E}}{\partial t} \end{cases}$$

TE and TM modes are usually treated separately

Yee's algorithm
+
J solver

Eqs Maxwell Eqs + Vlasov or PIC,
Required too much computation time for reflectometry simulations

M. Drouin et al JCP 229 4781 (2010)
T. Jenkins et al Phys. Plasmas 20 012116 (2013)
A. Stock et al IEEE Trans. on Plas Sci 40 1860 (2012)

# Commercial software some remarks

UNIVERSITÉ DE LORRAINE

# Finite Elements Method

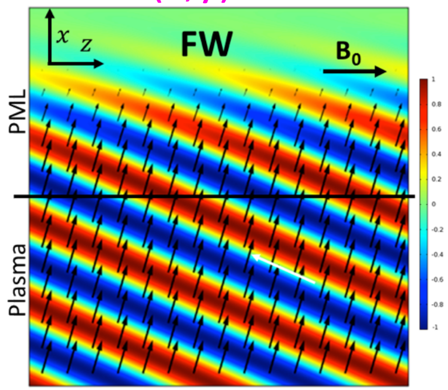
## multi-polarisations possible, single-frequency

Pbs with commercial software: PML in anisotropic with $\varepsilon < 0$

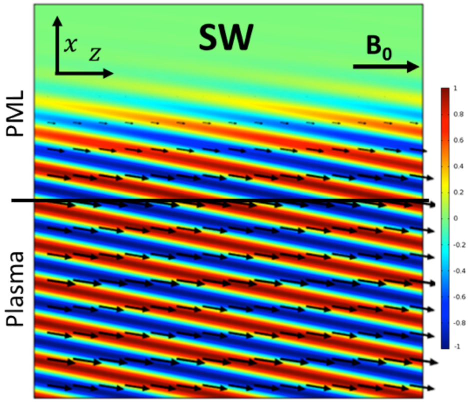
high anisotropy $\varepsilon_{per} << \varepsilon_{para}$

Asymptotic preserving scheme : a possible solution

Contours E(x,y) Fast Wave




Contours E(x,y) Slow Wave




No way to have a physical solution with PML in anisotropic medium with FW and SW ($\nu \sim \nu_{ci}$)

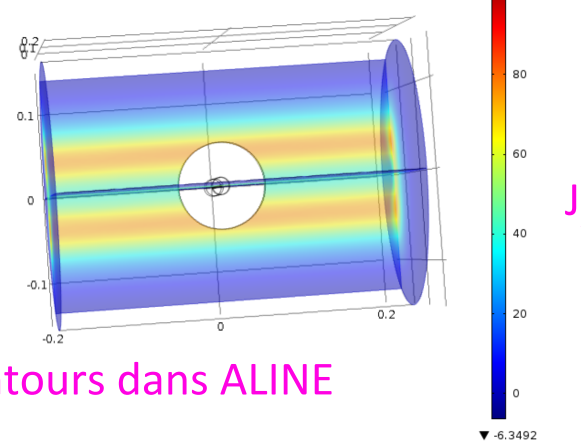
Worth Direction for the Poynting vector for the slow wave

J. Jacquot Plas. Ph. C. Fusion **55,** 115004 (2013).

DC potential seems good

Follows the magnetic field lines

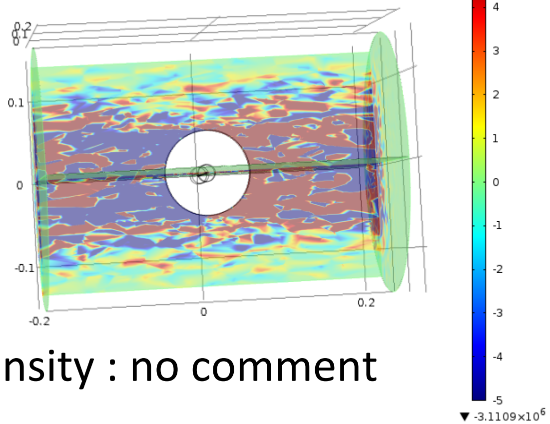
Hyp: flute OK




$V_{DC}$ (x,y) contours dans ALINE

High anisotropy $\varepsilon_{//}/\varepsilon_{\perp}=10^5$

$J_x$ contours




Current density : no comment

Heuraux

# Finite Element Method used in Wave Heating

Accurate method in vacuum in the case of complex geometry (commercial software)

Developments FEM integrating dispersion effects

Plasma ⬄ equivalent dielectric + new boundary conditions " Sheath Boundary conditions" (COMSOL) O. Meneghini, S. Shiraiwa, R. Parker PoP, **16** (2009) 090701, H. Kohno et al Phys of Plasmas 19 (2012) 012508, L. Colas Phys. of Plasmas **19**, 092505 (2012) .

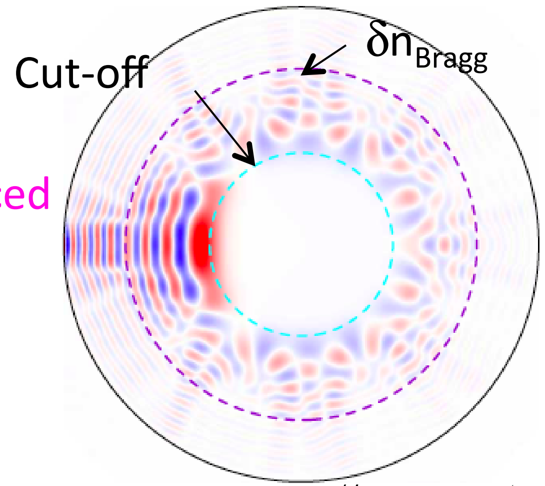
## Necessity to have homemade codes

code EVE, based on variational method R. Dumont (~10-20Gbytes)
Distribution function non-Maxwellian R. Dumont Nuc Fus 49 075033 (2009)

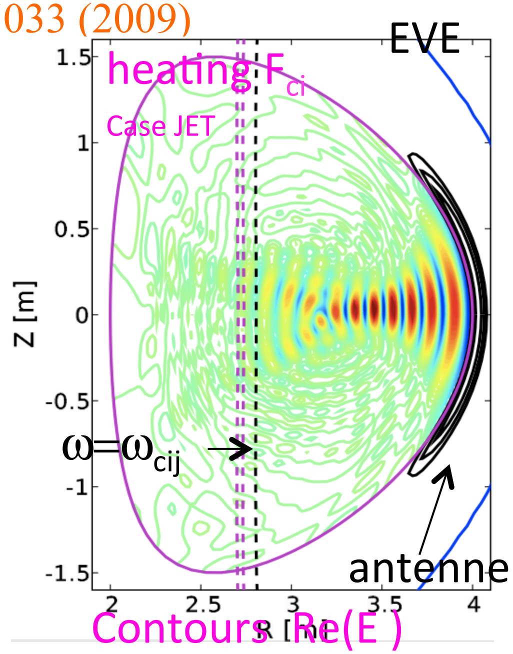
Model for high frequency possible
+ mode conversion
M. Irzak, et al Plas Phys Cont. Fus. 50 025003 (2008).

Enhanced electric field induced by Bragg resonant perturbations

S. Heuraux et al IEEE Trans. Plasma Sci **38**, 2150 (2010)




S. Heuraux et al



Works and computational events

- ICRH (role of RF sheath)
- ECRH (role of density fluctuations)

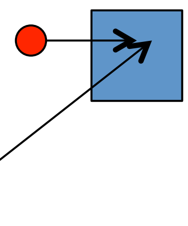
# ICRH Heating modelling review

Wave equation at fixed frequency to reduce to

$$\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2}\left(\mathbf{E} + \frac{i}{\omega \epsilon_0}\mathbf{j}\right) = i\omega\mu_0 \mathbf{j}_{ant}$$

where $$\mathbf{j}(\mathbf{r}) = \sum_s \int d^3\mathbf{r}' \underbrace{\bar{\bar{\sigma}}_s(\mathbf{r},\mathbf{r}')}_{\text{Conductivity kernel}} \cdot \mathbf{E}(\mathbf{r}')$$ Non-local

t'= t



| Code | General geom? | MC? | FLR | Numerical methods |
|---|---|---|---|---|
| AORSA | Yes | Yes | all orders | Fourier collocation in $k_x, k_y, k_\phi$ |
| EVE | Yes | Yes | 2nd order | Variation method; tor and pol modes; radial finite elements |
| CYRANO | No | No | 2nd order | Variation method; tor and pol modes; radial finite elements |
| PSTELION | Approx | Yes | 2nd order | Finite differences in radial coordinate |
| TORIC | Yes | Yes | 2nd order | Variation method; tor and pol modes; radial finite elements |
| TASK/WM | No | No | 2nd order | Tor and pol modes; radial finite element |

FLR Finite Larmor Radius expansion

$$\mathbf{j}(\mathbf{r}) = \bar{\bar{\sigma}}_s^{(0)} \cdot \mathbf{E}(\mathbf{r}) + \bar{\bar{\sigma}}_s^{(1)} \cdot (\mathbf{r}_c \cdot \nabla)\mathbf{E}(\mathbf{r}) + \frac{1}{2}\bar{\bar{\sigma}}_s^{(2)} \cdot (\mathbf{r}_c \cdot \nabla)^2 \mathbf{E}(\mathbf{r}) + \ldots$$

With 1 >> $|\mathbf{r}_c \cdot \nabla| \sim k_\perp \rho_i$

All orders (spectral treatement)

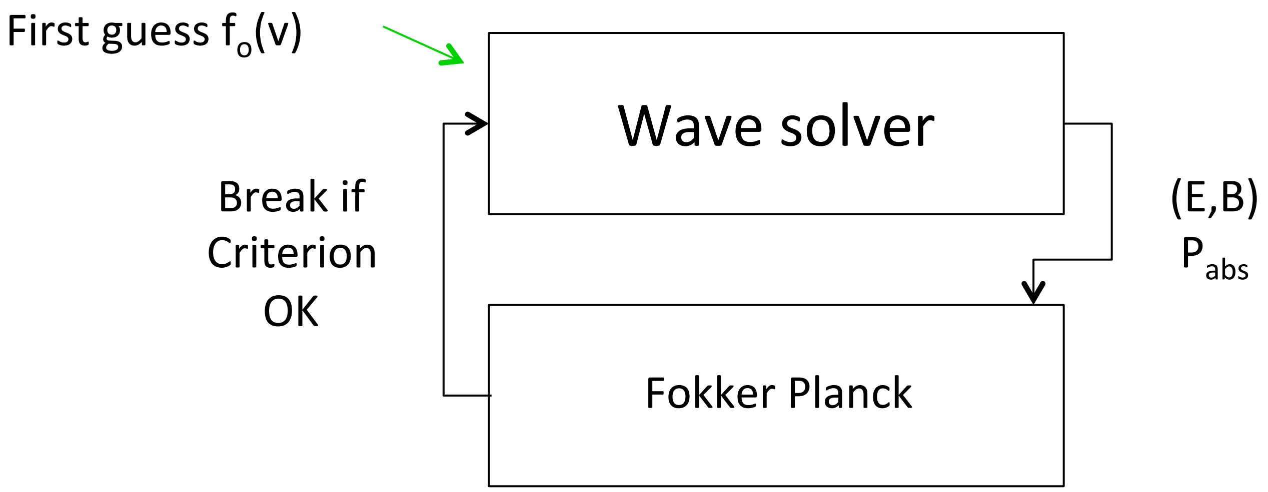
$\mathbf{E} \propto \exp(i\mathbf{k}_\perp \cdot \mathbf{r})$ $k_\perp \rho_i$ any value

$$\mathbf{j}(\mathbf{r}) = \mathbf{j}(\mathbf{r}_{gc}) \sum_{p=-\infty}^{\infty} J_p(k_\perp \rho_i) e^{ip\phi_c}$$

Budny Nuc. Fus. 2012

# ICRH Heating modelling

To determine the (E,B) fields, f(v) needed and changes during heating so iteratively wave equation and Fokker-Planck are solved




Or in Electromagnetic PIC code (VORPAL) Smithe AIP Conf 1580 2014

Or in GTC code but le wave is electrostatic (Kuley PoP 2013)

In fact $J_{ant}$ should also change (antenna-coupling code needed) done in TOMCAT 1D

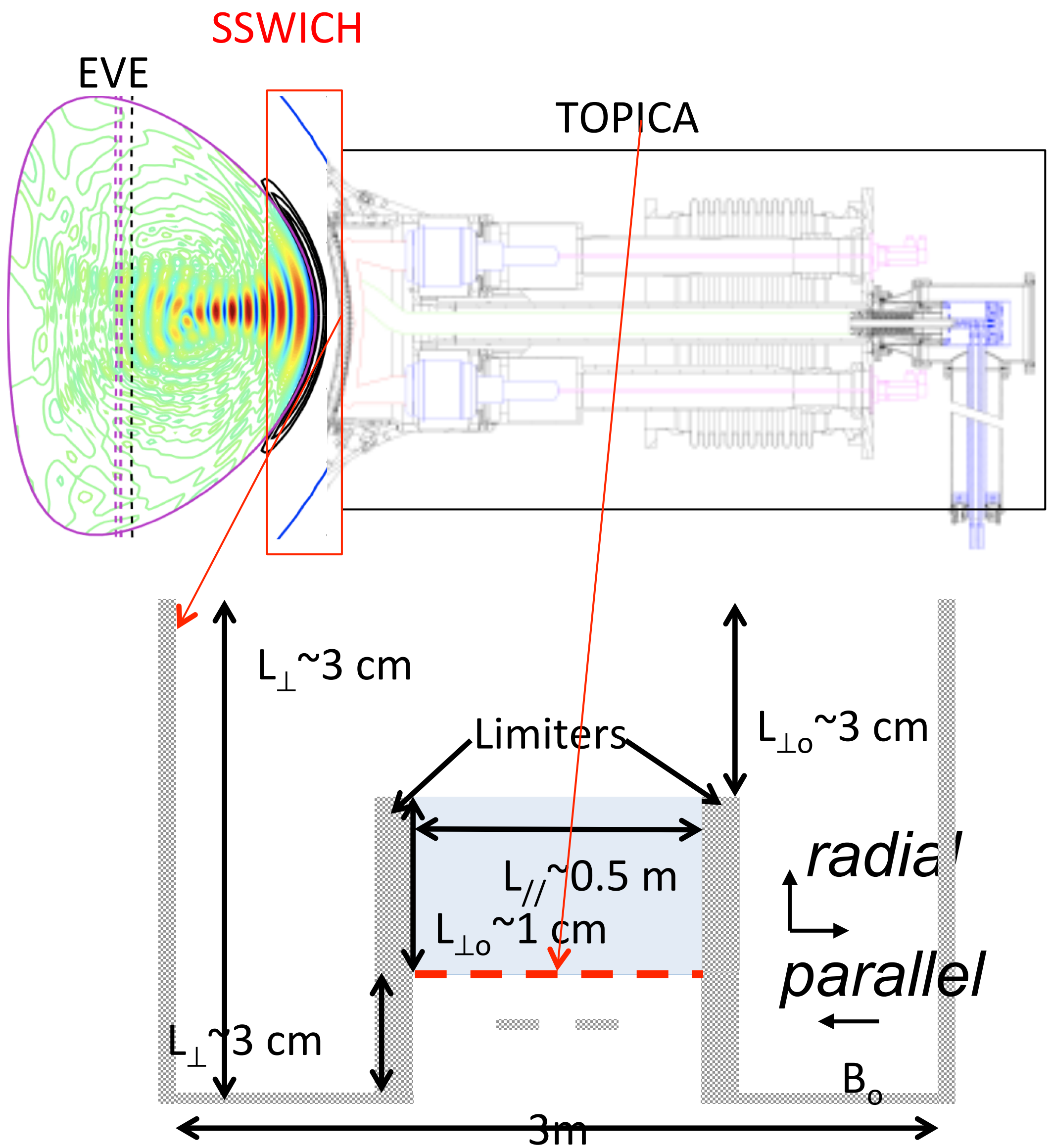
# ICRH Heating modelling

Goal : Predict self-consistently the behaviour of an antenna design

Optimization of the antenna-plasma coupling reducing hot spot, impurity generations

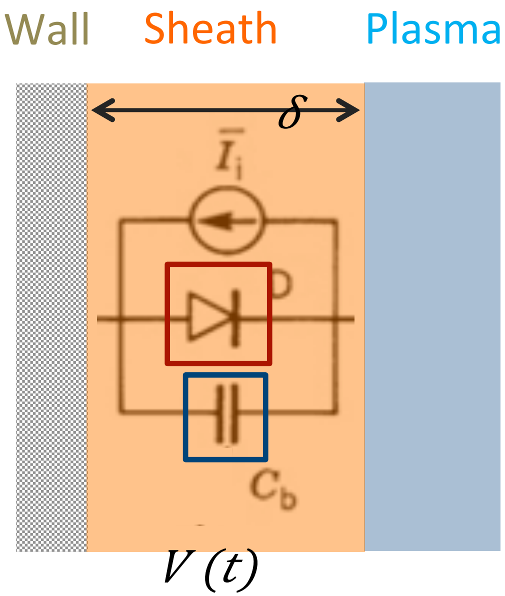
Including in a long term
- ponderomotive effects
- convective cells

Role of the turbulence




$. Heuraux et al

# RF sheath Physics: Sheath Boundary Conditions




Waves => RF oscillations
Of sheath voltage
$V(t) = V_{DC} + V_{RF}\cos(\omega t)$
$V_{RF} \propto E_{//RF}$

Capacitance -> Wave prop.
Net oscillation charge
$C_{sh} = \varepsilon_{sh}/\delta$
Thin sheaths => sheath boundary conditions instead metallic (D'Ippolito2006

RF voltage => rectification of DC I-V characteristic
$I = i_{sat}[1-\exp((V_f+V_b-V_{DC})/Te)]$
$V_b = T_e \ln[I_o(V_{RF}/Te)]$ ⬄ DC biasing at the wall
Radial DC current transport modelled with effective $\sigma_{DC}$

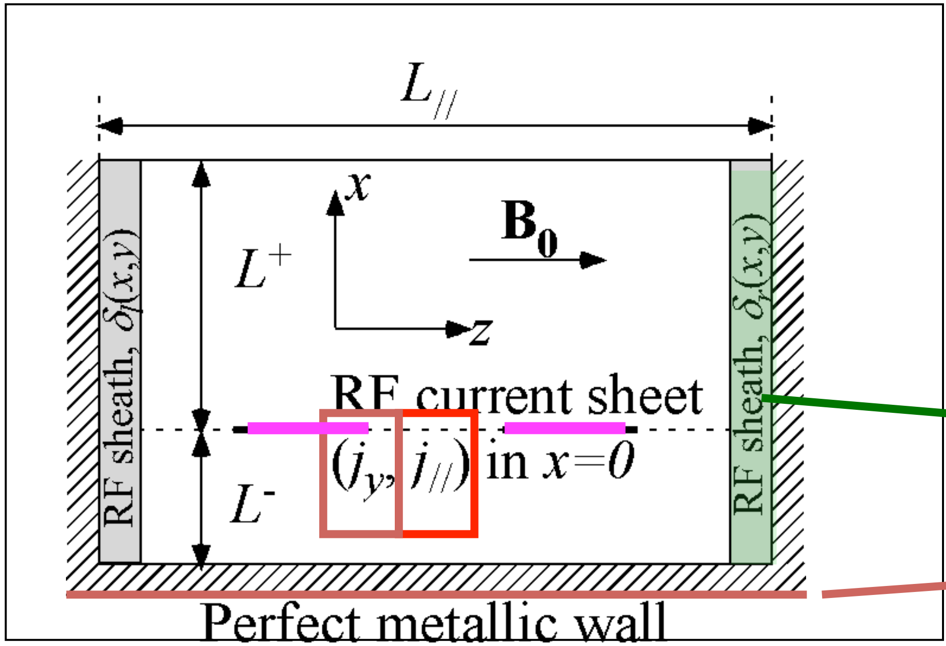
# Slow Wave (SW) part in SSWICH

$$\varepsilon_{//}\Delta_{//}E_{//} + \varepsilon_{\perp}\Delta_{\perp}E_{//} + \varepsilon_{//}\varepsilon_{\perp}k_0^2E_{//} = \ldots$$

$$\ldots - i\omega_0\mu_0\varepsilon_{\perp} j_{//ant}(x,y,z) + \frac{\partial_{//}\rho_{ant}(x,y,z)}{\varepsilon_0}$$

$$-i\omega_0\rho_{ant} + \mathrm{div}\,\mathbf{j}_{\mathbf{ant}} = 0$$

SW equation with source terms $j_{//}$, $j_y$ homogeneous plasma + current sheet ➔ semi-analytic results




- RF-sheath BCs

$$\varepsilon_{\perp}\Delta_{\perp}\left(\varepsilon_{//}\delta E_{//} / \varepsilon_{sh}\right) = \ldots$$

$$\ldots = \pm\varepsilon_{//}\partial_{//}E_{//}$$

PEC at outer wall

- Analogy with lateral $E_{//ap}$=0

# Self-consistent non-linear ICRH wave propagation and RF sheath rectification

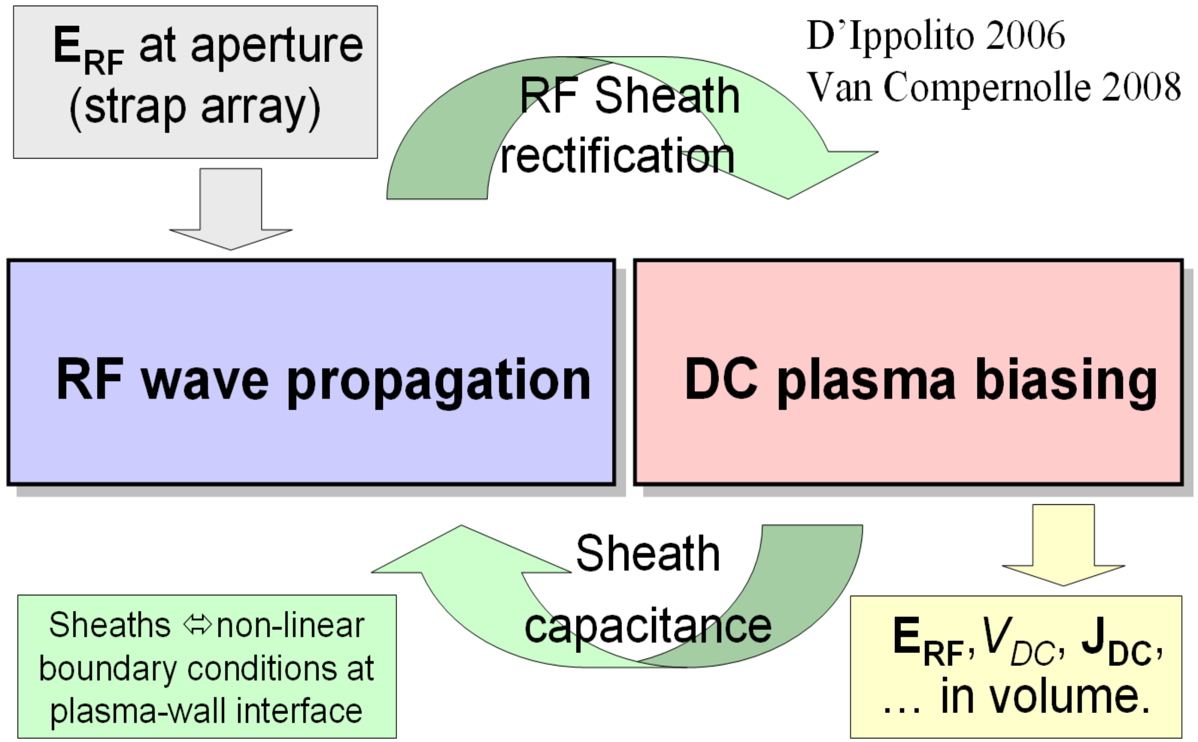
- RF sheath rectification treated as Slow Wave propagation self-consistently coupled with DC edge plasma biasing. Non-linear coupling is ensured *via* RF and DC sheath boundary conditions.

**DC current generation:**

- the differential biasing of adjacent flux tubes connected electrically *via* DC transverse plasma conductivity
- asymmetric RF solicitation at both ends of the field line

***SSWICH problem***

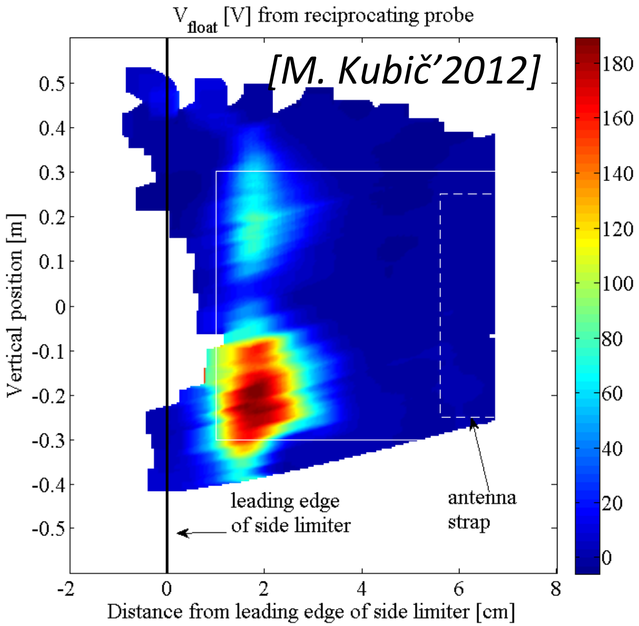
***Self-consistent Sheaths & Waves for IC Heating***

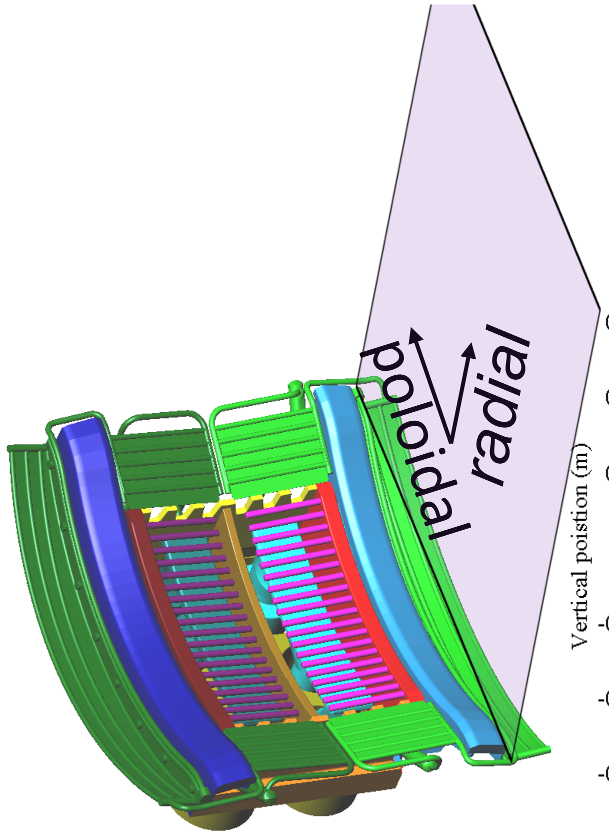



Colas EPS 2010, Jacquot RF conf 2013

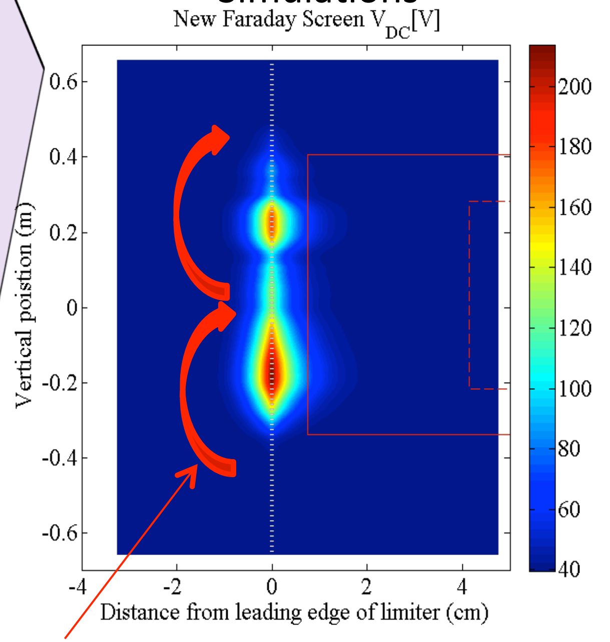
# Comparison with experiments

Probe measurements on Tore Supra




Simulations




Convective cells

Guess also by Wukitch 2013

○ ***In agreement with experiments***:

- Relative comparison Faraday screens
- DC potential in free SOL
- 2-hump poloidal structures
- Up-down asymmetry

○ ***In disagreement***:

- Maximum located radially on leading edge [Cziegler'2012, Colas'2013]

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# Conclusions on ICRH modelling

The description of the wave propagation-absorption takes into account 3D geometry and the evolution of the distribution function for any phasing of the active antennas (monopole, dipole, ….).

In most of the simulations, the current density on the antenna is fixed which is not the case in the experiments. In fact the antenna-plasma coupling is sensitive to the distance cut-off strap, that is to say to the edge plasma properties. So the comparison with experiment has to follow edge plasma evolution (assumed to be slow).

In fact due the rectification process induced by RF-sheath, an inhomogeneous DC potential map is generated in front of the antenna structure that creates convection cells which redistribute the density in the vicinity of the antenna thus the coupling. This is the reason why the role of the RF-sheath and its consequences have to be known including its perturbations on the Slow Wave.

To have a relevant simulation Slow and Fast have to be describe together take into account the modifications of the density in front of the antenna to integrate the changes of the coupling. This imposes also to use a Sheath boundary condition valid for any oblique incidence angle of the magnetic field line to the wall, which is not the case for grazing angles.

Open questions: What is the role of the turbulence on the RF sheath, especially the grazing angle ? What is the influence of the density fluctuations on the mode conversion?

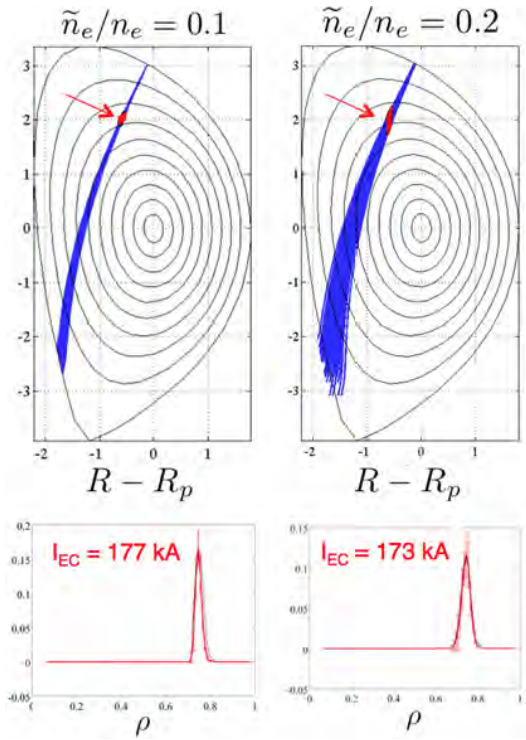
Role of the density fluctuations on the wave Heating

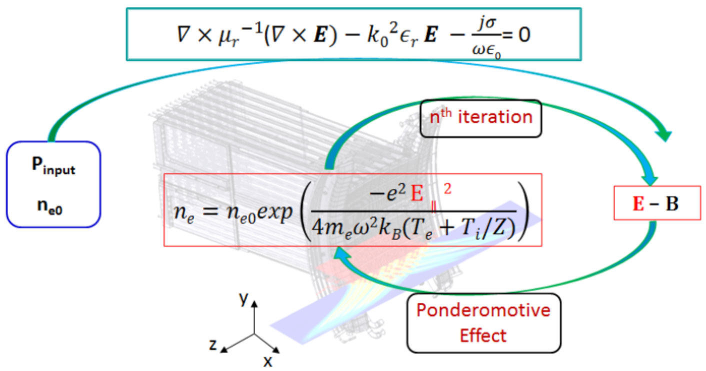
# Role of the density fluctuations on wave heating

In 90's this question was addressed, recently it becomes again a hot topic

-for ECRH, to evaluate if the beam properties stays good enough for magnetic island control using ray tracing (linked to the control of NTM) Peysson FST 2014

-for LHCD, to evaluate the impact of density depletion induced by ponderomotive effects on the coupling (COMSOL, PICCOLO-2D)
Preynas Nuc. Fus. 2013
and on the wavenumber spectrum emitted by the grill (set of waveguides) Peysson PPCF 2011




The wavenumber spectrum of the turbulence permits to fulfil the Bragg scattering conditions => Ray tracing not relevant => Full-wave code + fluctuations
Following a flavour on what happens during wave propagation in fluctuating plasmas

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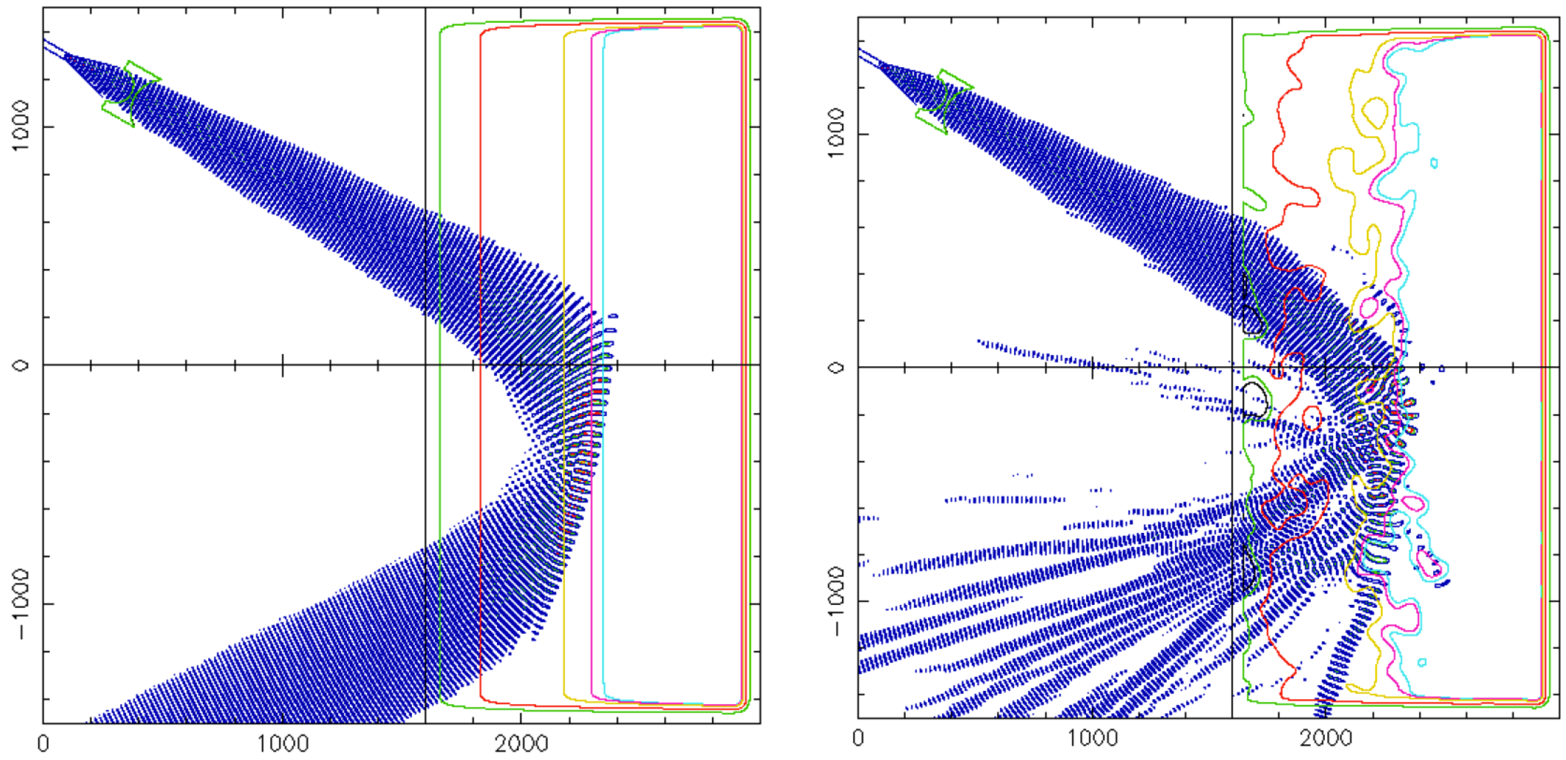
# Role of the density fluctuations on wave heating

Density fluctuations with Gaussian wavenumber spectrum with $k_f < 2\ k_{Airy}$
No bragg backscattering
$\delta n = \mathrm{sum}(a_n \sin(2\pi n/L_{box}\ x + \varphi_{rand}),\ n=1..n_{max})\ a_n = \exp(-(k_f/2k_{Airy})^2)$ compute via FFT

Contours E_field>0 ($\nu$= 40 GHz, $\delta$n= 10% RMS)




On a single run the beam is divided in sub-beams

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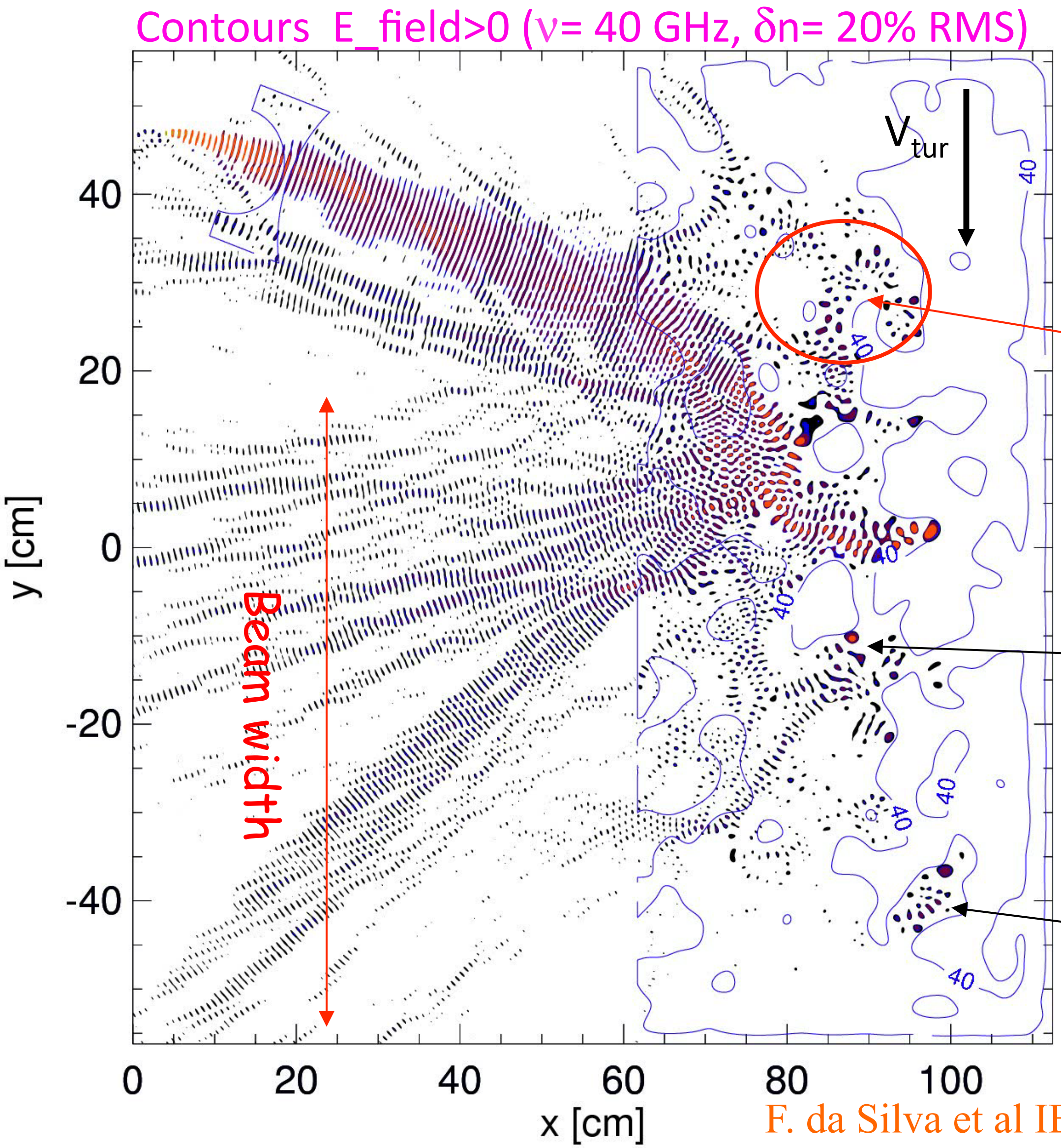
# 2D wave propagation in a moving turbulent plasma (O-mode)




Moving Turbulence

-> Doppler shift $V_{tur}$

Beam broadening

multi-diffusion

Local resonance

Wave trapping

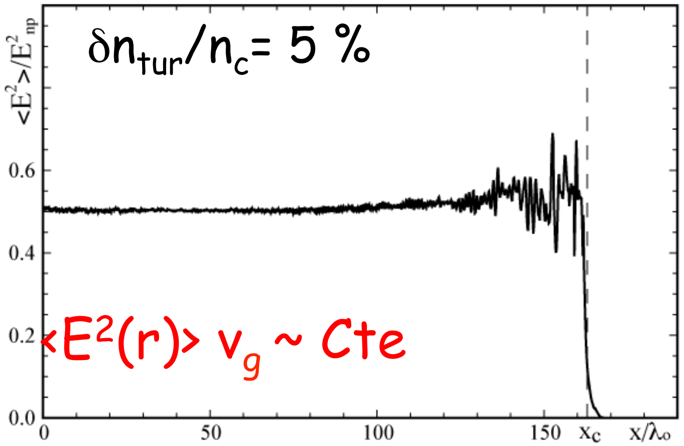
F. da Silva et al IEEE Trans. Plasma Sci **38**, 2144 (2010)

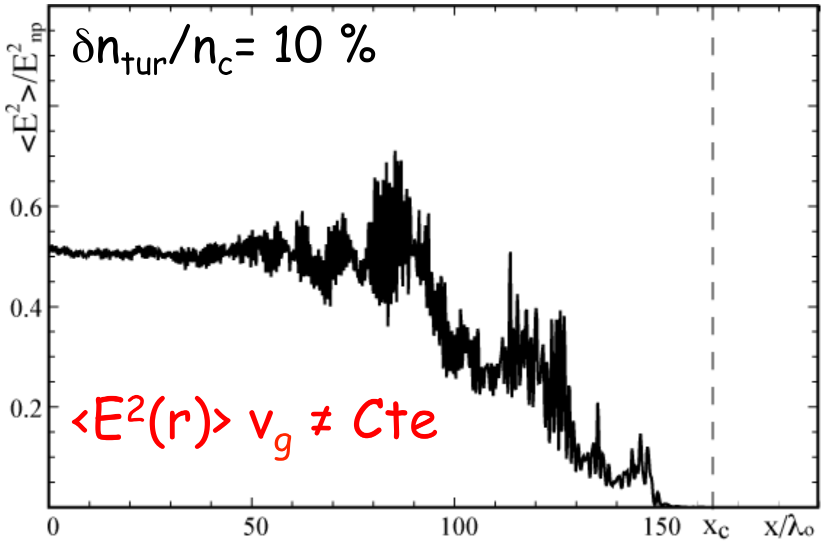
In such case, is a time-average able to provide something ?

# Time average or averaged over N samples (1D)

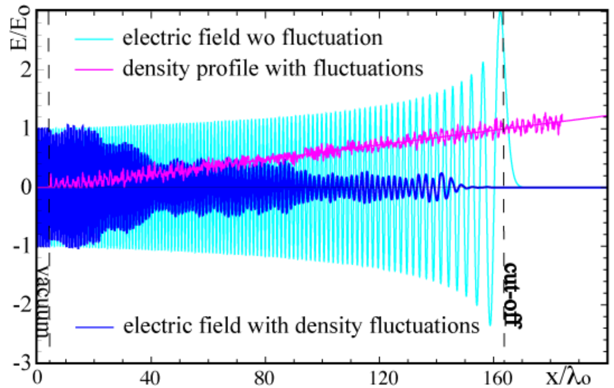
Density gradient length L= 160 $\lambda_o$, homogneneous turbulence $\delta n_{tur}$ with cut-off

Average value (over $10^4$ samples) of electromagnetic flux of probing wave




Resonances win and permit to the probing wave to reach the cut-off




The theory is based on a photon diffusion equation only valid at moderate fluctuation level

*Gusakov et al. plasma phys EPS conf dublin* **2010**
*Heuraux et al Cont Plasma Phys 2011*

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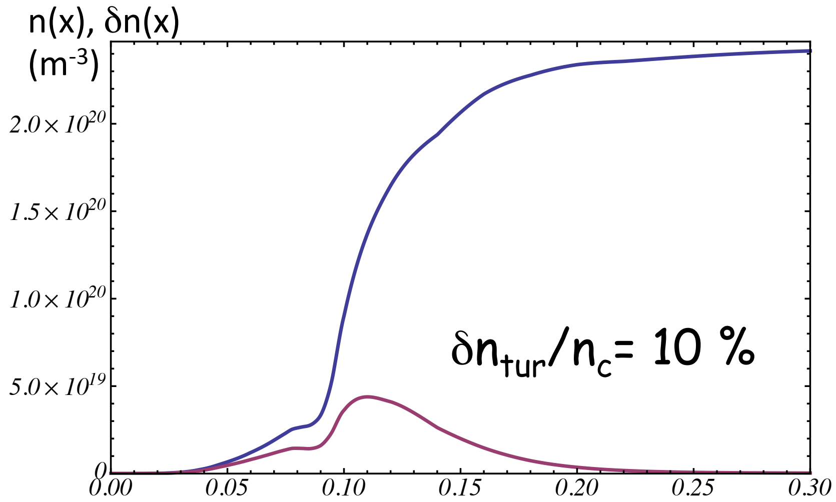
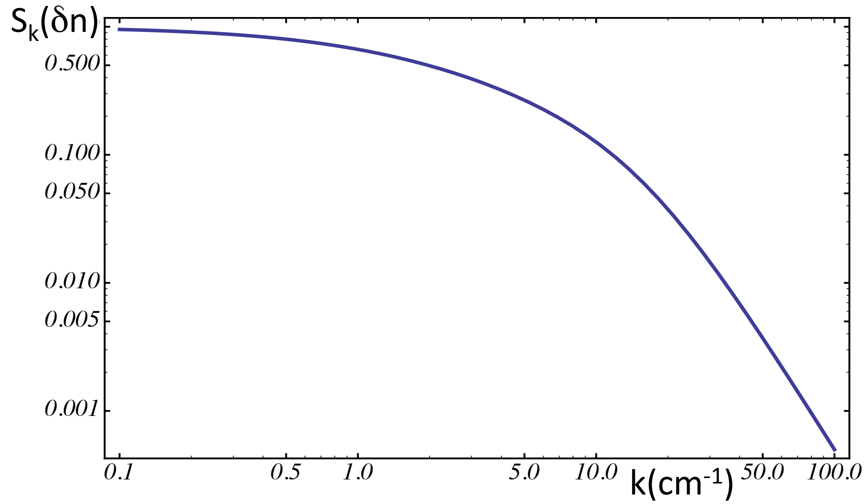
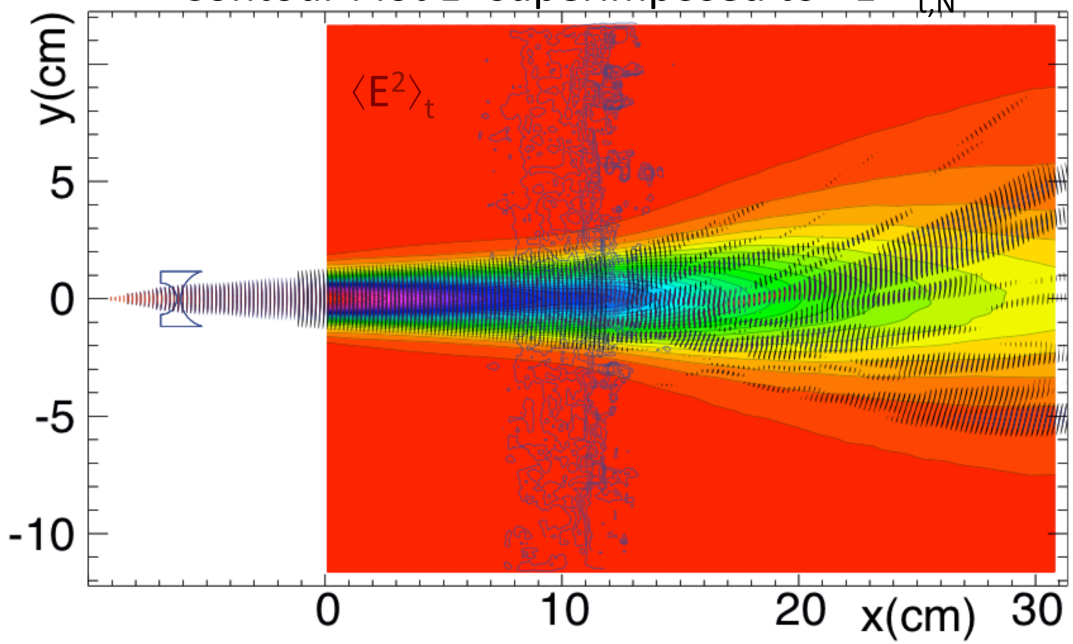
# Beam broadening in the ITER case of ERCH

Launched frequency 170 GHz , Gaussian beam (O-mode)



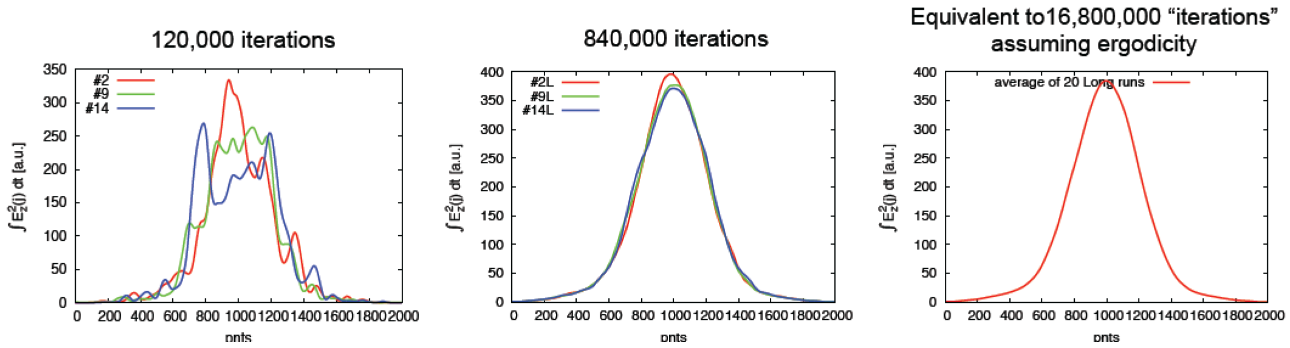




Contour Plot $E^2$ superimposed to $<E^2>_{t,N}$



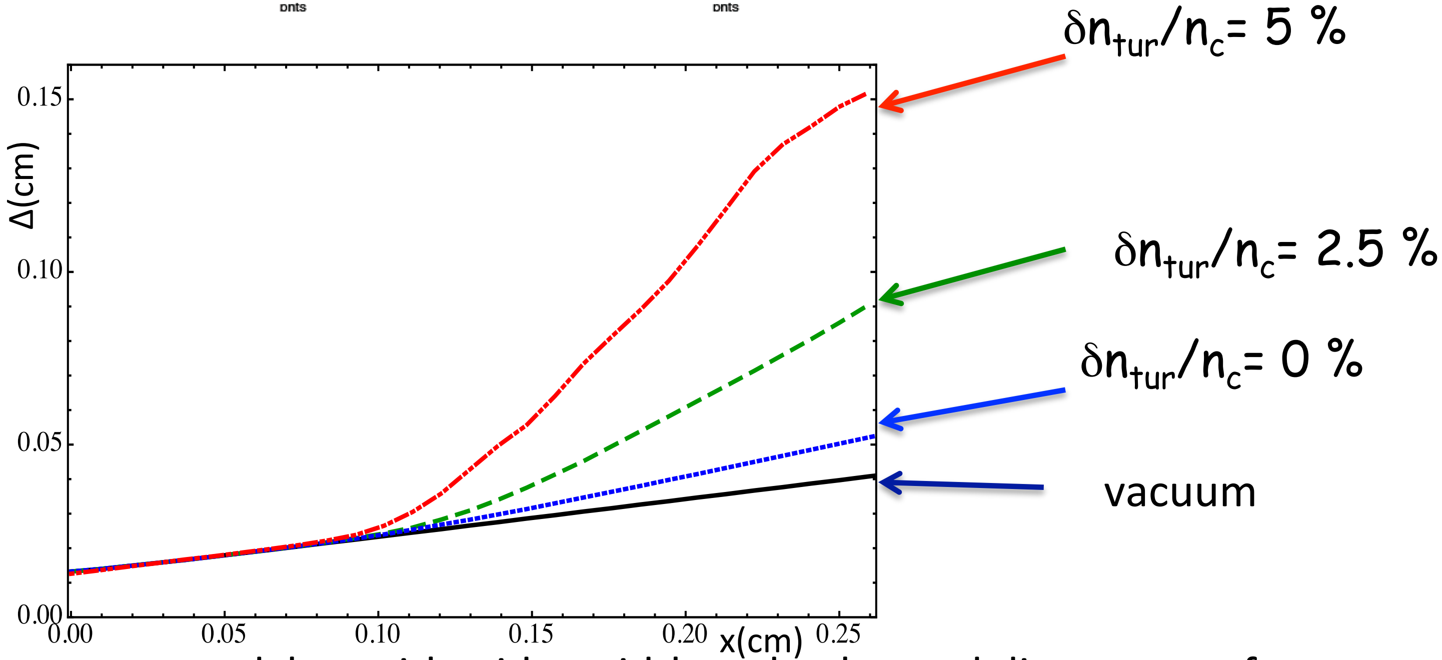

A Gaussian beam is recovered after 20 times $N^t=10^6$ steps

# Beam broadening in the ITER case of ERCH (2)




Averaging details

Beam width




*Gaussian shape recovered but with wider width and enhanced divergence after turbulence zone crossing (small increase of divergence big effect long path).

*Beam broadening sensitive to the wavenumber spectrum

Sysoeva Nuc Fus submit.

Is it the same for X-mode ?

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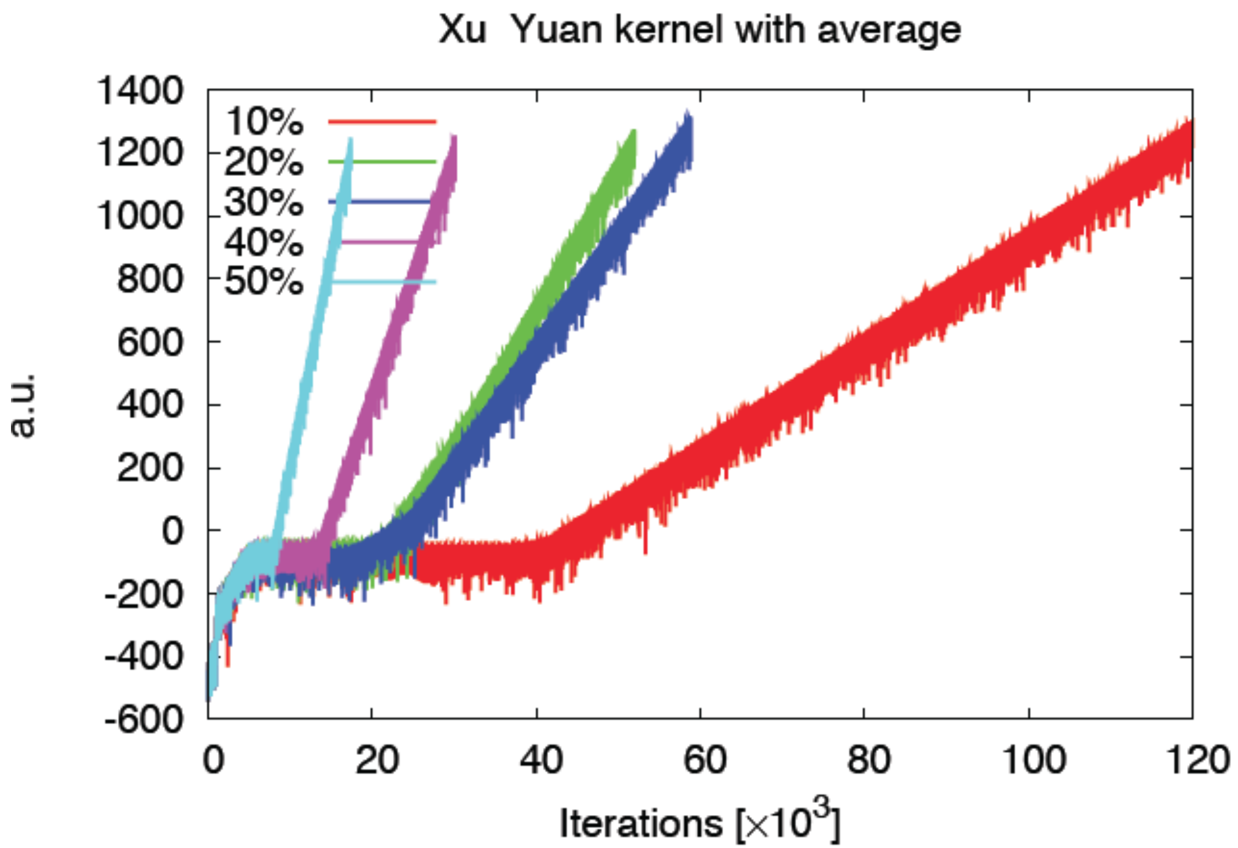
# X-mode FDTD J-solver (REFMULX)



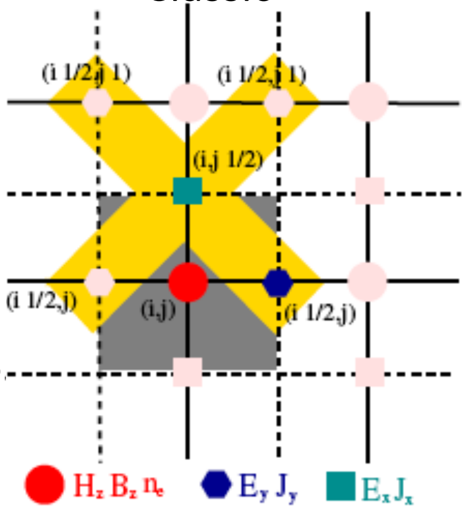

Need to reconsider the numerical scheme (unstable)

# X-mode FDTD J-solver Improvement

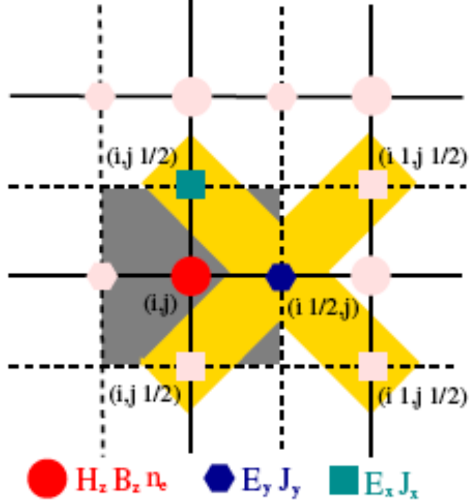
Previous schemes (unstable)

$$\varepsilon_0 \frac{\mathrm{E}^{n+1}-\mathrm{E}^n}{\Delta t} - \nabla \times \mathrm{H}^{n+1/2} = -\mathrm{J}^{n+1}$$
$$\mu_0 \frac{\mathrm{H}^{n+1/2}-\mathrm{H}^{n-1/2}}{\Delta t} + \nabla \times \mathrm{E}^n = 0$$
$$\frac{\mathrm{J}^{n+1/2}-\mathrm{J}^{n-1/2}}{\Delta t} = \varepsilon_0 \omega_p^2 \mathrm{E}^n + \omega_c \mathrm{b} \times \frac{\mathrm{J}^{n+1/2}+\mathrm{J}^{n-1/2}}{2}$$

Classic

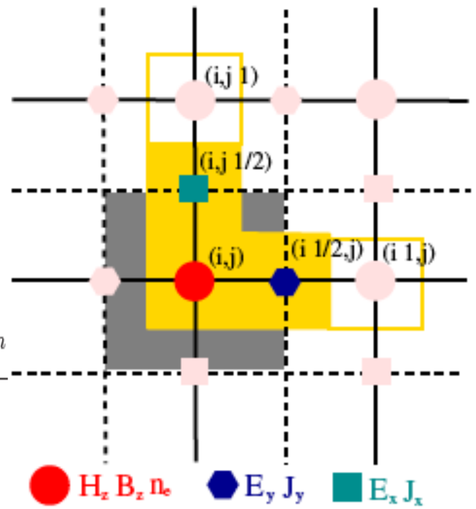


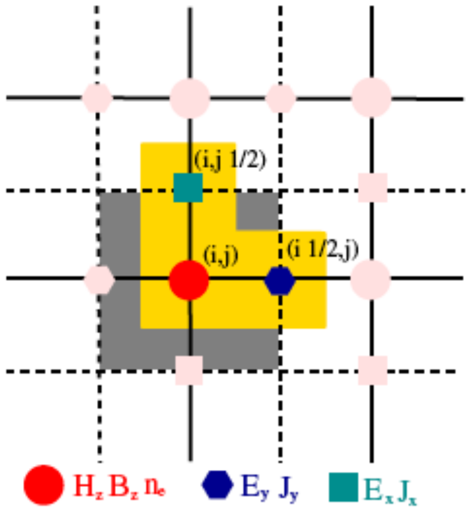

Xu Yuan




New schemes proposes by
Després – Campos Pinto

$$\varepsilon_0 \frac{\mathrm{E}^{n+1}-\mathrm{E}^n}{\Delta t} - \mathrm{R}\mathrm{H}^{n+1/2} = -\frac{\mathrm{J}^{n+1}+\mathrm{J}^n}{2}$$
$$\mu_0 \frac{\mathrm{H}^{n+1/2}-\mathrm{H}^{n-1/2}}{\Delta t} = -\mathrm{R}^T \mathrm{E}^n$$
$$\frac{\mathrm{J}^{n+1}-\mathrm{J}^n}{\Delta t} = \varepsilon_0 S^n(\omega_p^2) \frac{\mathrm{E}^n+\mathrm{E}^{n+1}}{2} + S^n(\omega_c) \mathrm{b} \wedge_h^n \frac{\mathrm{J}^{n+1}+\mathrm{J}^n}{2}$$




Preserve the pseudo energy

da Silva JCP submit.

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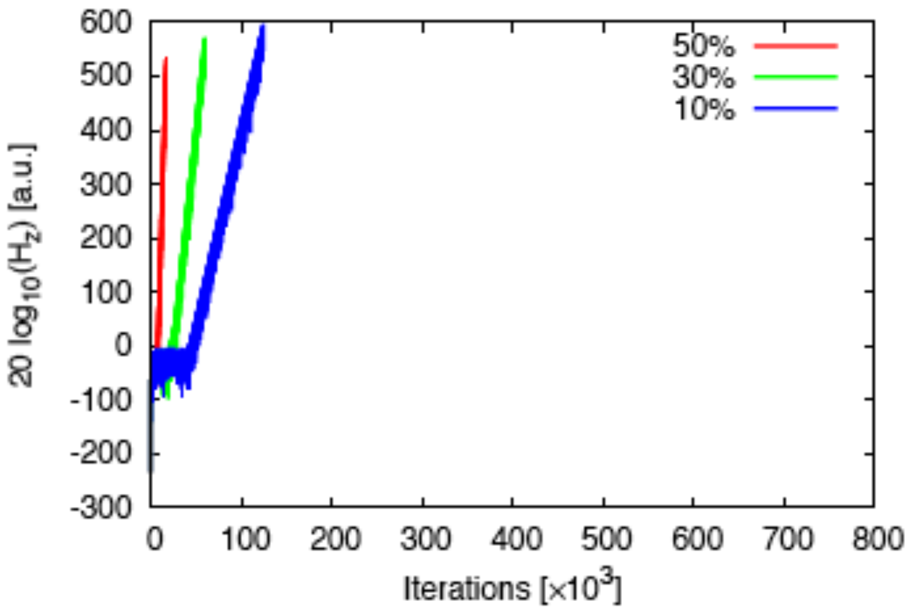
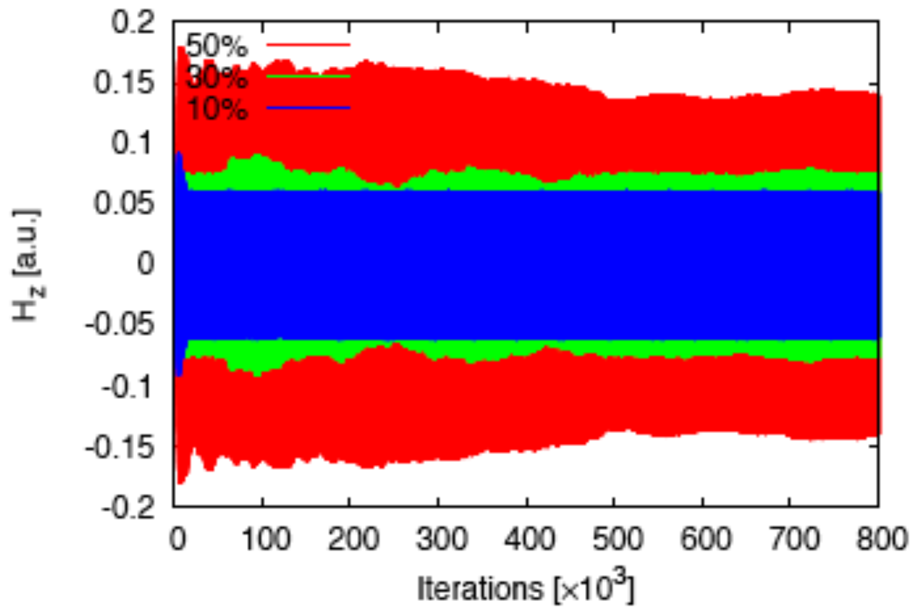
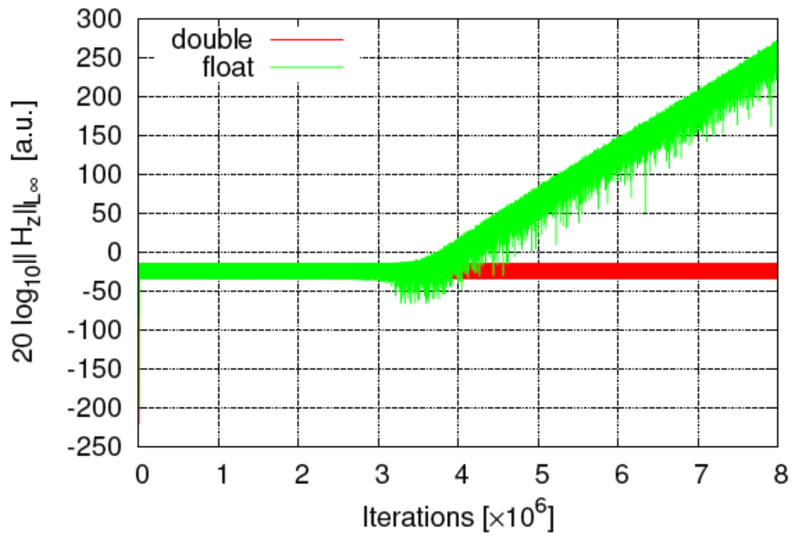
# X-mode FDTD J-solver Improvement (2)




But adding motion => again becomes unstable => need to integrate $\partial_t n$




the numerical instability disappears

Real –>Double

Single -> Parallel computing

Use hybrid parallel scheme MPI + OpenMP

euraux et al

# Conclusions

What one can do to optimize or Define a simulation ?

-determination of the main physical effects and dependencies
-> type of equation to solve
-analysis of geometry and problem reduction
-> coordinate and dimension (xD)
-Wanted Accuracy, data size and nature of input -output option (parallel programming or not)
->Numercial scheme and Boundary conditions / initial conditions
-analysis of wanted quantities
-> internal or post-processing
-To be integrated in a suite of code (ITM or ….)
-> fulfil the format and procedure of data exchanges

Choice: better to use high order scheme
+ better accuracy or speed-up,
+ less numerical dispersion,
However
- need more memory
- less stable (if CFL) ( optimal order?)

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# Conclusions

Commercial software are
+ Versatile,
+ Many diagnostics and tools.
However there are limitations
- PML strongly anisotropic (integration of APS)
- Multimode PML (open problem)
- Condition of edge-type "sheath" in magnetized plasmas
- Non-linear or other non-trade effects

Most of the simulation to ensure that:
+ Access to often non-measurable quantities (E2)
+ Include many effects (code evaluating the response of plasma)
+ Improve interpretive tools
+ To develop new diagnostics.

Open questions on wave heating:
+ role of the density fluctuations (ECCD, LHCD, on Sheath Boundary Conditions)
+ role material properties on SBC (secondary emission, ionization, …..)
+ true self-consistent description wave propagation-coupling-near field (IRCH ),
+ ponderomotive effects important?
+ depolarization processes

Code validation how to do it ?

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Stix's book
Swanson's book

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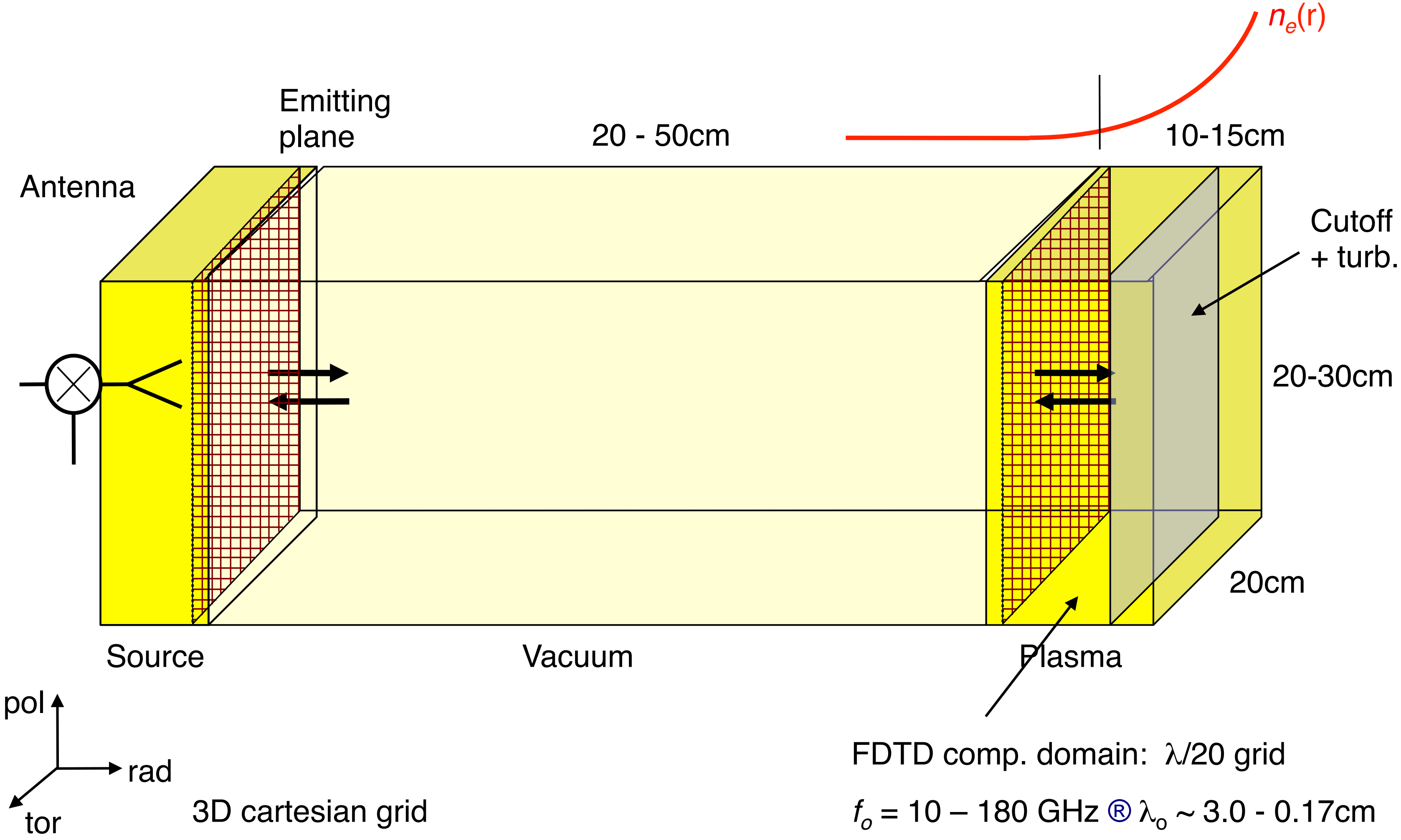
+ references in the lecture note

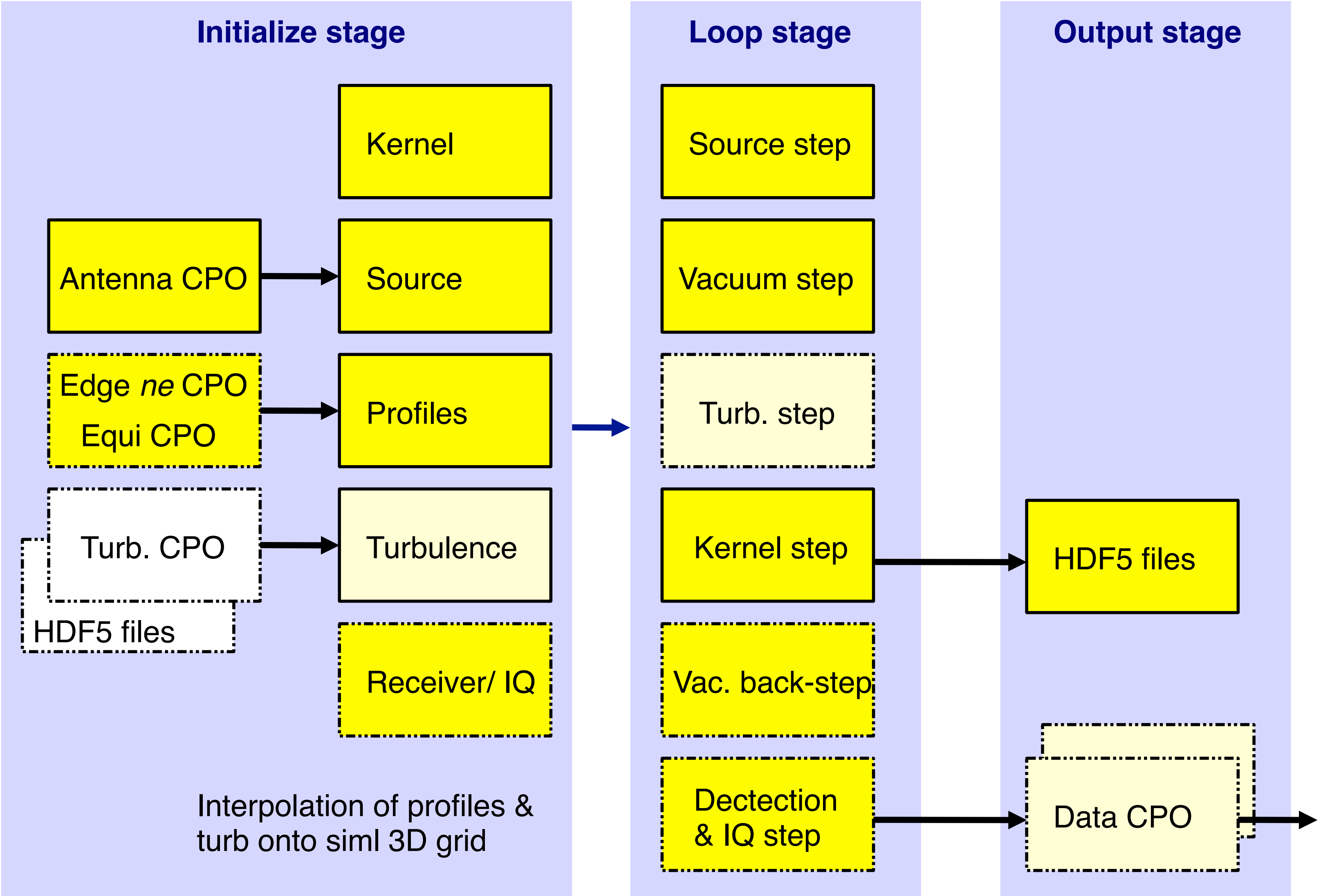
# 3D FDTD Maxwell's equations solver

## *ERCC #European Reflectometry Code Consortium# : 3D full-wave code status*

Large physical domain forces use of mixed scheme = source + vac + FDTD



# ERCC: erc3d code module status

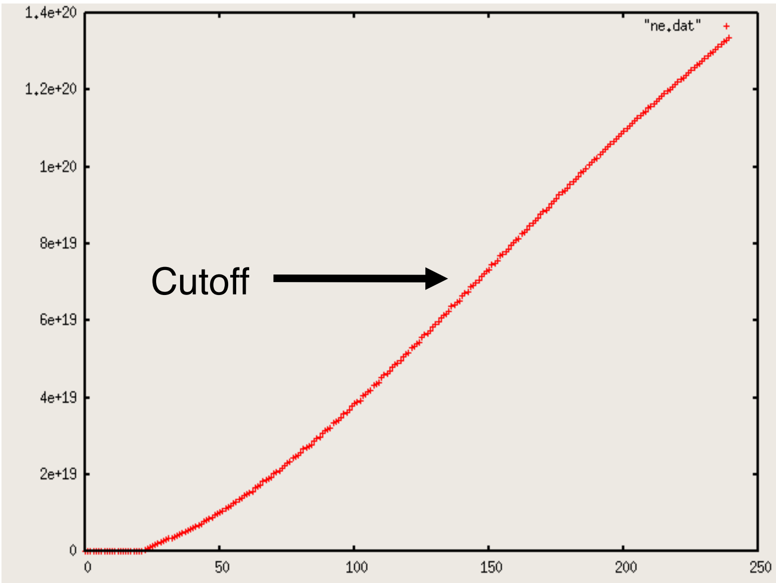



$. Heuraux et al

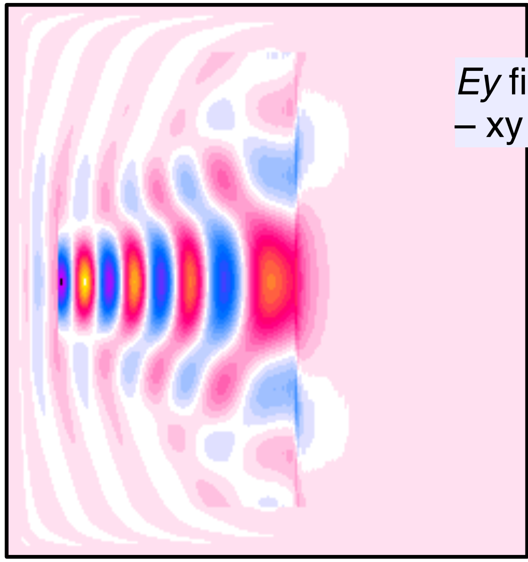
## ERCC: erc3d code – example results

- Launch $f_o$ = 70.245 GHz
- Δx = l/20 = 0.2134 mm
- Gaussian beam: $w_o$ ~ 4 mm
- Grid size: 240 x 240 ξ 240 points

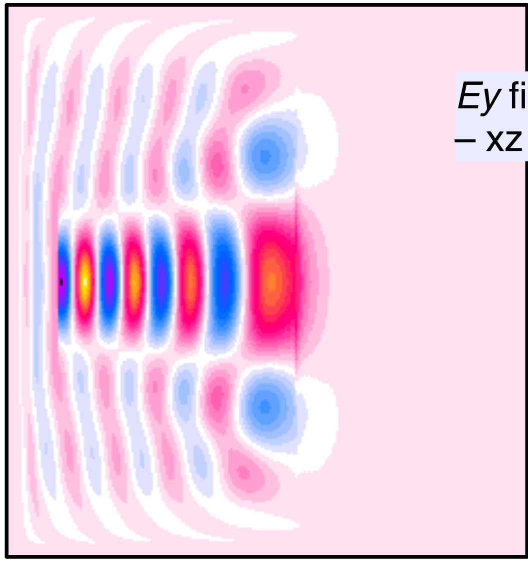
Input density profile from “coreprof” CPO




x (radial) in grid points



*Ey* field
– xy plane



*Ey* field
– xz plane

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*ERCC: erc3d code – numerical requirements and near future*

**Critical issues**

- Large domain: e.g. 32GB RAM ® 6 x$10^8$ grid points ® 13 field components SP= 17cm cube grid! Need lots of memory!
- Time: 1 CPU = 6000 hrs for 2048 snap shots (extrapolated from 2D code) ® Need lots of CPUs!
- Parallelization: "snap-shot" (easy) but... "domain" (hard but necessary) Need expertise/manpower

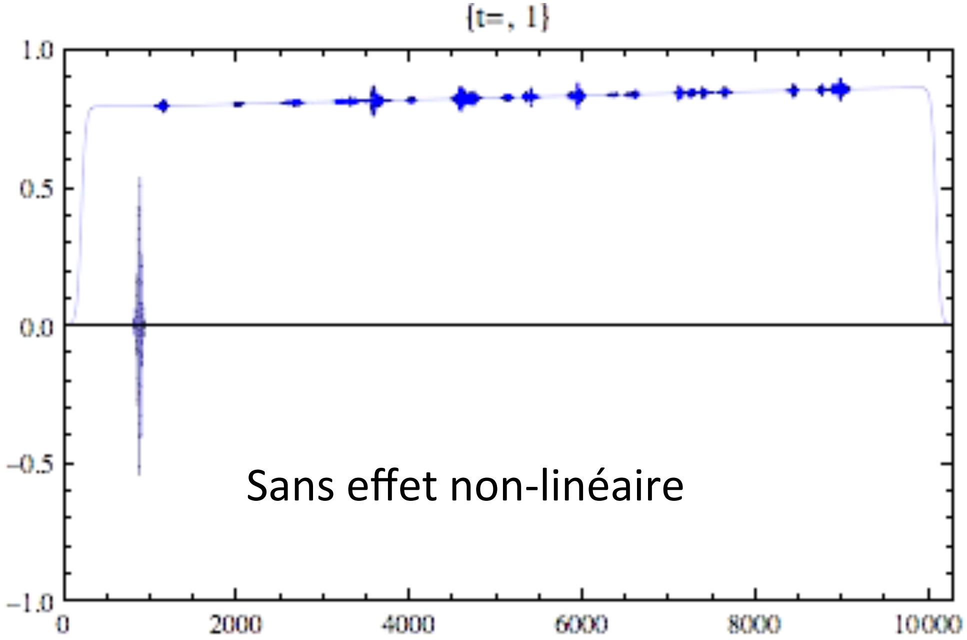
**Next step**

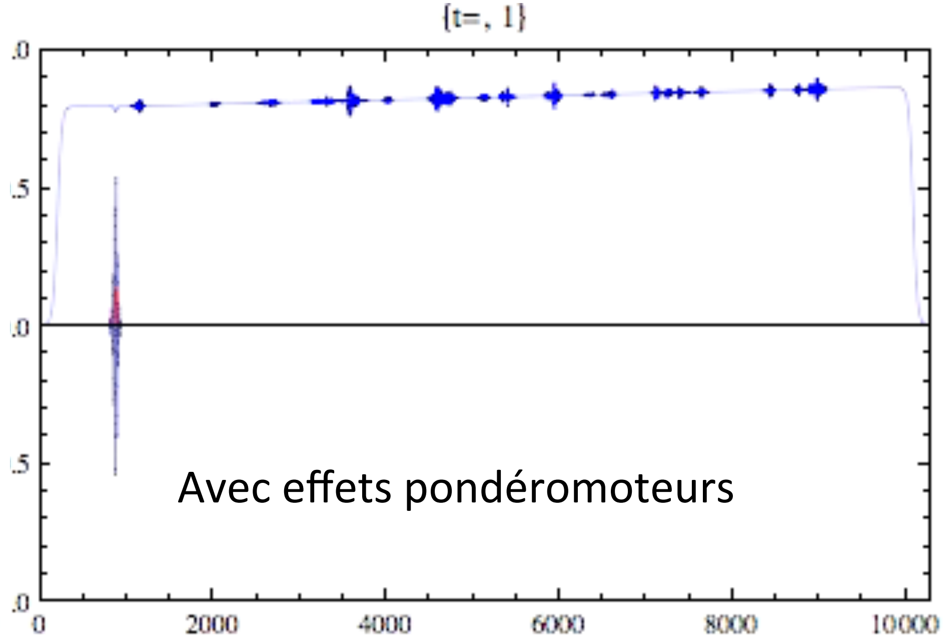
- Validation and verification against both 2D code & experimental data
- Synthetic turbulence – soon.
- Numerical turbulence coming from turbulence code need effort for data exchange
- Any help are welcomed, thank you.

# Utilisation des ondes solitaires (solitons) comme sonde

pulse non dispersif: conserve sa localisation
spectre connu si paramètres plasma connus
profils de densité et de température

Evolution temporelle de l'onde dans un plasma inhomogène turbulent



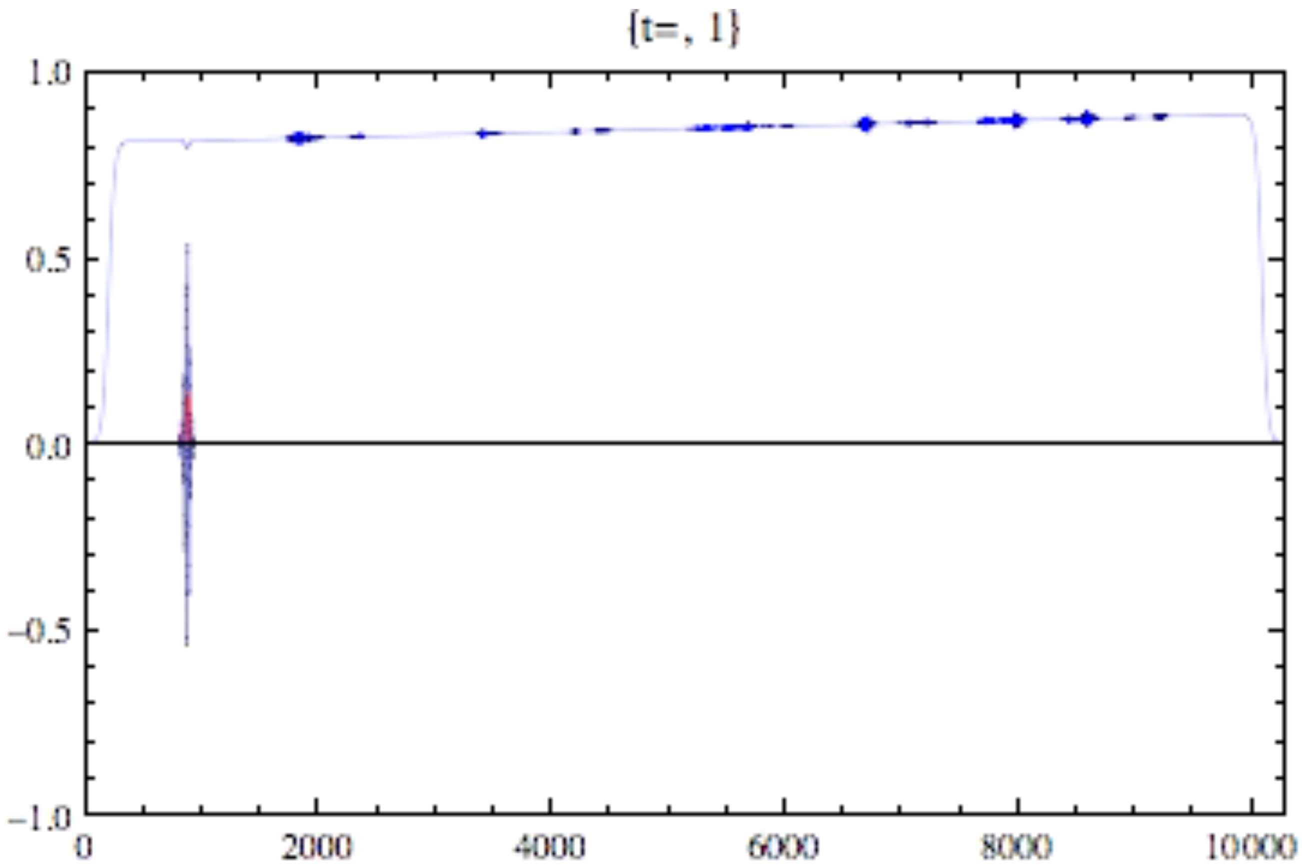




Champ diffusé α $E^2$ mais spectre large (efficacité réduite)

Heuraux CR Physique 2014

# Sondage par solitons : avec effets de température en plus

$E_{soliton}(x,t)$ dans un plasma inhomogène turbulent avec profil de température




Élargissement du soliton dû à une réduction des effets non-linéaires