Calculation of rf current drive in tokamaks

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… to Lucas, born yesterday afternoon !

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Theory of Fusion Plasmas, Varenna, Italy, 25-29 August 2008

- current drive is a key tool for real-time control of plasma performances and stability of tokamak plasmas

- keywords for current drive are *localization* and *efficiency.*

- high frequency rf waves are attractive tools for a long time:
  - **Lower Hybrid** (1-10GHz): $D_{QL} \parallel B$
  - **Electron cyclotron** (~100 GHz): $D_{QL} \perp B$

- integrated tokamak modeling put high constraints on the level of accuracy that should be reached by simulations of rf current drive:
    - *interpretation* of the observed phenomenology
    - reliable *prediction* capability

- **physics**: unified multi-wave description (synergism), consistent momentum/configuration space dynamics, neoclassical corrections (high ∇p), locally non-axisymmetric magnetic configuration,…

- **numerics**: high modularity, fast and robust algorithms

Outline

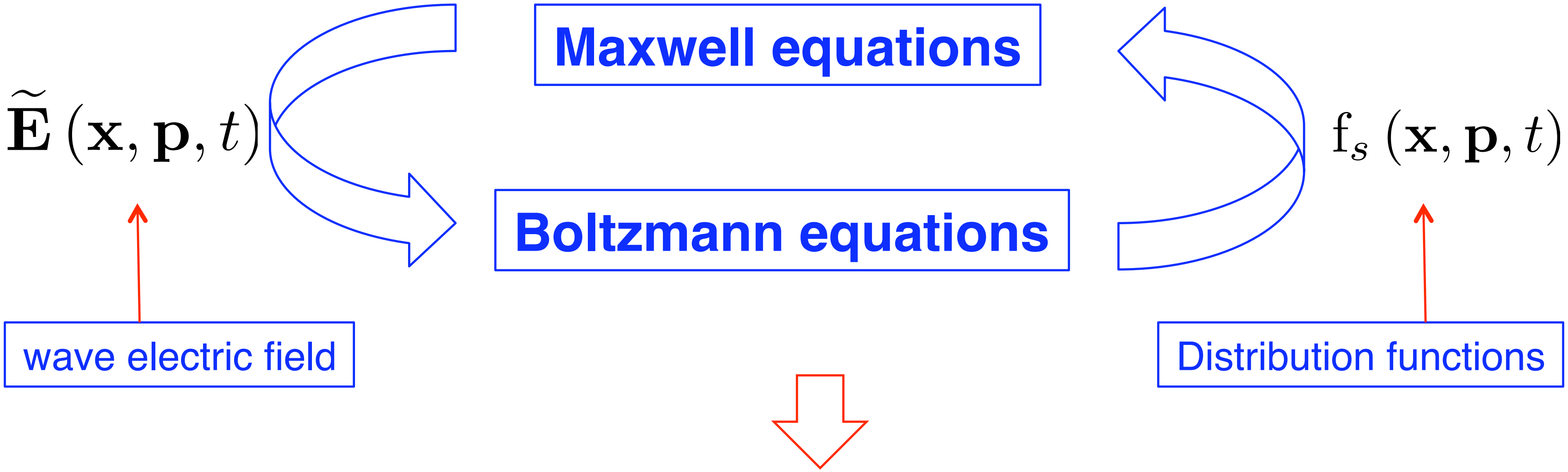
- **background of rf current drive theory**

- **the current drive module**
  - **C3PO** ray-tracing
  - **LUKE** Fokker-Planck

- **rf current drive in tokamaks**
  - **LH** wave: *ITER*, *Tore Supra*
  - **EC** wave: *TCV*

- **conclusion and prospects**

rf current drive theory



$\widetilde{\mathbf{E}}\left(\mathbf{x},\mathbf{p},t\right)$

Maxwell equations

Boltzmann equations

$\mathrm{f}_s\left(\mathbf{x},\mathbf{p},t\right)$

wave electric field

Distribution functions

$$\mathbf{J}\left(\mathbf{x},t\right) = |e|Z_s \iiint d^3\mathbf{p} f_s\left(\mathbf{x},\mathbf{p},t\right)\mathbf{p}/\gamma$$

- Boltzmann equation (ion dynamics ignored (m_e/m_i << 1)

$$\left\{\begin{array}{l} \frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} f + \dot{\mathbf{p}} \cdot \nabla_{\mathbf{p}} f = \boxed{C\left(f, f_s\right)} \\ \dot{\mathbf{p}} = e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \\ \dot{\mathbf{x}} = \mathbf{v} = \mathbf{p}/\gamma \end{array}\right.$$

↓

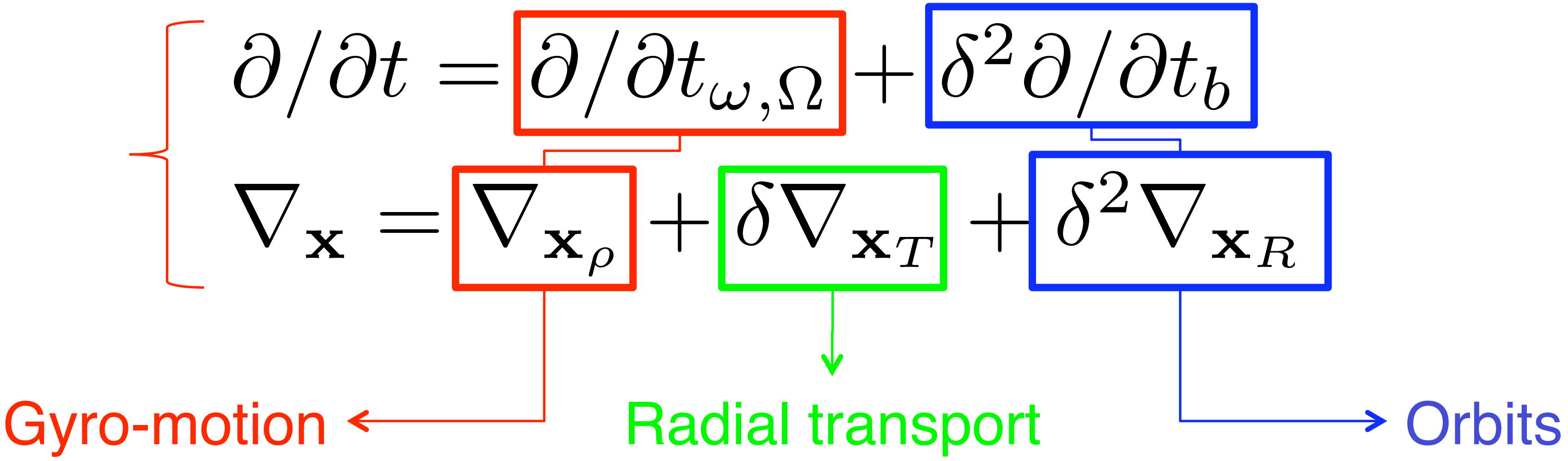
Fokker-Planck
collision operator
$\mathcal{O}\left(1/\log\Lambda\right)$

- Maxwell's equations

$$\left\{\begin{array}{l} \nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t \\ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} - c^{-2} \partial \mathbf{E}/\partial t \end{array}\right.$$

Space- and time-scale ordering

- Small parameter expansion: $\delta^2 \simeq \rho/R \simeq t_b/\Omega$
- In tokamaks, Coulomb collisions $\nu/\Omega \leq \delta^2$



$$\left\{ \begin{array}{l} \partial/\partial t = \boxed{\partial/\partial t_{\omega,\Omega}} + \boxed{\delta^2 \partial/\partial t_b} \\ \nabla_{\mathbf{x}} = \boxed{\nabla_{\mathbf{x}_\rho}} + \boxed{\delta \nabla_{\mathbf{x}_T}} + \boxed{\delta^2 \nabla_{\mathbf{x}_R}} \end{array} \right.$$

Gyro-motion

Radial transport

Orbits

- Expansion in power of δ

$$\left\{\begin{aligned} f &= f_0 + \delta f_1 + \delta^2 f_2 + \ldots \\ \mathbf{B} &= \mathbf{B}_0 + \delta \mathbf{B}_1 + \delta^2 \mathbf{B}_2 + \ldots \\ \mathbf{E} &= \mathbf{E}_0 + \delta \mathbf{E}_1 + \delta^2 \mathbf{E}_2 + \ldots \\ \mathbf{J} &= \mathbf{J}_0 + \delta \mathbf{J}_1 + \delta^2 \mathbf{J}_2 + \ldots \\ C &= \delta^2 C_2 + \ldots \end{aligned}\right.$$

- Magnetic equilibrium: $\mathbf{E}_0 = 0$

- to order δ^0

$$\partial f_0/\cancel{\partial t}_{\omega,\Omega} + \mathbf{v}\cdot\cancel{\nabla}_{\mathbf{x}_\rho} f_0 + \boxed{\Omega\partial f_0/\partial\varphi = 0}$$

gyro-independent

Equilibrium magnetic field and current:

$$\begin{cases} \nabla_{\mathbf{x}_R} \times \mathbf{B}_0 = \mu_0 \mathbf{J}_0 \\ \mathbf{J}_0\left(\mathbf{x},t\right) = e\iiint \mathbf{v}\, f_0\left(\mathbf{x},\mathbf{p},t\right) d^3\mathbf{p} \end{cases}$$

- to order δ^1

$$\partial f_1/\partial t_{\omega,\Omega} + \mathbf{v}\cdot\nabla_{\mathbf{x}_\rho} f_1 + \Omega\partial f_1/\partial\varphi =$$

$$-e\left[\mathbf{E}_1 + \mathbf{v}\times\mathbf{B}_1\right]\cdot\nabla_{\mathbf{p}} f_0 - \mathbf{v}\cdot\nabla_{\mathbf{x}_T} f_0$$

$$\Downarrow$$

$$\mathbf{J}_1\left(\mathbf{x},t\right) = e\iiint \mathbf{v}\, f_1\left(\mathbf{x},\mathbf{p},t\right) d^3\mathbf{p}$$

$$= \boxed{\mathbb{S}}\left(f_0\right)\cdot\mathbf{E}_1 \longleftarrow \text{constitutive relation}$$

conductivity tensor

Maxwell equation linear in **E**$_1$:

$$\nabla_{\mathbf{x}_\rho} \times \nabla_{\mathbf{x}_\rho} \times \mathbf{E}_1 + \mu_0 \mathbb{S}\left(f_0\right) \cdot \partial \mathbf{E}_1 / \partial t_{\Omega,\omega}$$

$$+c^{-2} \partial^2 \mathbf{E}_1 / \partial^2 t_{\Omega,\omega} = 0$$

- to order δ²

$$\partial f_2/\partial t_{\omega,\Omega} + \mathbf{v}\cdot\nabla_{\mathbf{x}_\rho} f_2 + \Omega\partial f_2/\partial\varphi +$$

$$\boxed{\partial f_0/\partial t_b} + \mathbf{v}\cdot\nabla_{\mathbf{x}_R} f_0 + \mathbf{v}\cdot\nabla_{\mathbf{x}_T} f_1 +$$

$$e\left[\mathbf{E}_2 + \mathbf{v}\times\mathbf{B}_2\right]\cdot\nabla_{\mathbf{p}} f_0 +$$

$$e\left[\mathbf{E}_1 + \mathbf{v}\times\mathbf{B}_1\right]\cdot\nabla_{\mathbf{p}} f_1 = C\left(f_0\right)$$

Using linear relation between f_0 and f_1 (order δ^1) + averaging over fast time scales → slow time scale evolution of f_0.

Quasilinear kinetic equation

$$\partial f_0/\partial t_b + \mathbf{v}_{cg} \cdot \nabla_{\mathbf{x}_R} f_0$$

$$= C\left(f_0\right) + Q\left(f_0\right) + T\left(f_0\right) + E\left(f_0\right)$$

$$\left\{\begin{array}{l} E\left(f_0\right) = -\nabla_{\mathbf{p}}\left(e\left\langle \mathbf{E}_2\right\rangle_{\Omega,\omega} \cdot f_0\right) \\ Q\left(f_0\right) \equiv \nabla_{\mathbf{p}} \cdot \left(\mathbb{D}_{ql} \cdot \nabla_{\mathbf{p}} f_0\right) \longrightarrow \boxed{\mathbb{D}_{ql} \propto \left|\left|\mathbf{E}_1\right|\right|^2} \\ T\left(f_0\right) \equiv \nabla_{\mathbf{x}_T} \cdot \left(\mathbb{D}_{\mathbf{x}} \cdot \nabla_{\mathbf{x}_T} f_0\right) \end{array}\right.$$

- quasilinear approximation valid for small wave field amplitude
- no electron trapping in the rf wave field (collisions)
- Guiding center approximation

$$\mathbf{v}_{cg} \simeq p_{||}\hat{\mathbf{b}}/\gamma + \boxed{\mathbf{v}_D}$$

(order δ^2)

Expansion to δ^4 for self -consistent rf & boostrap current calculations

$$\mathbf{p} = p_{||}\hat{\mathbf{b}} + \mathbf{p}_{\perp}$$

- pitch-angle cosine: $\xi = p_{||}/p$

$f_0\left(\psi, \theta, \phi, p_{||}, p_{\perp}\right)$ is function of five coordinates

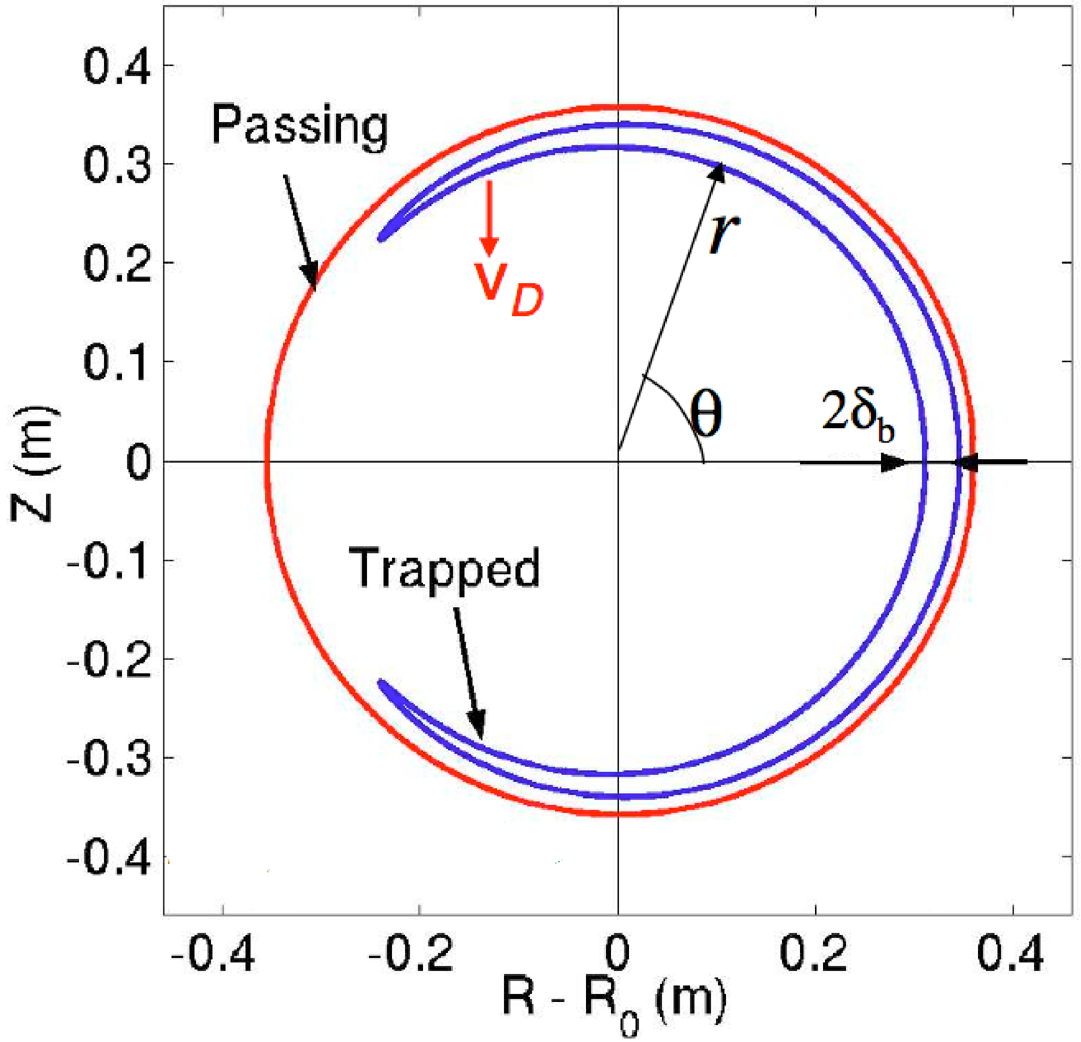
Bounce-averaging

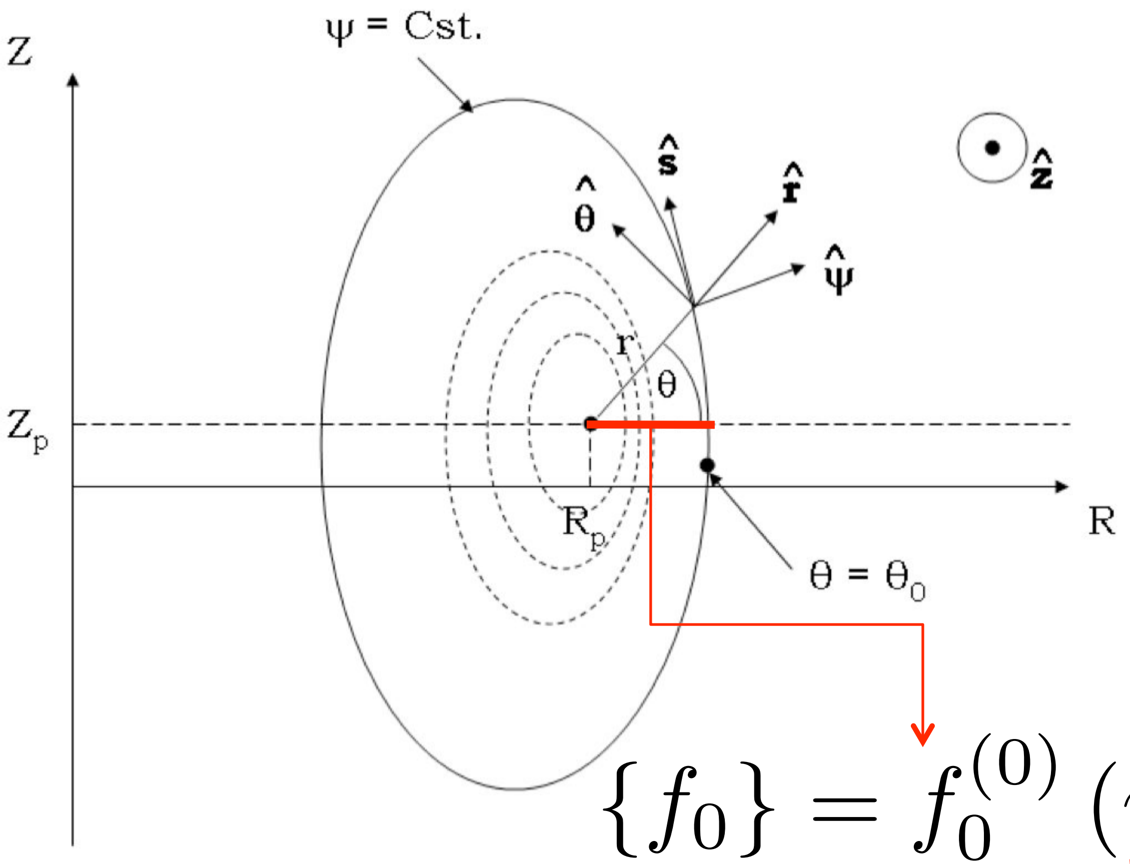
- axisymmetric configuration $\longrightarrow$ averaging over ϕ
- New ordering: low collision or « banana » regime

$$\delta^2 \ll \nu^* \ll 1$$

- Thin banana width approximation $\|\mathbf{v}_D\| / \|\mathbf{v}_{cg}\| \ll 1$

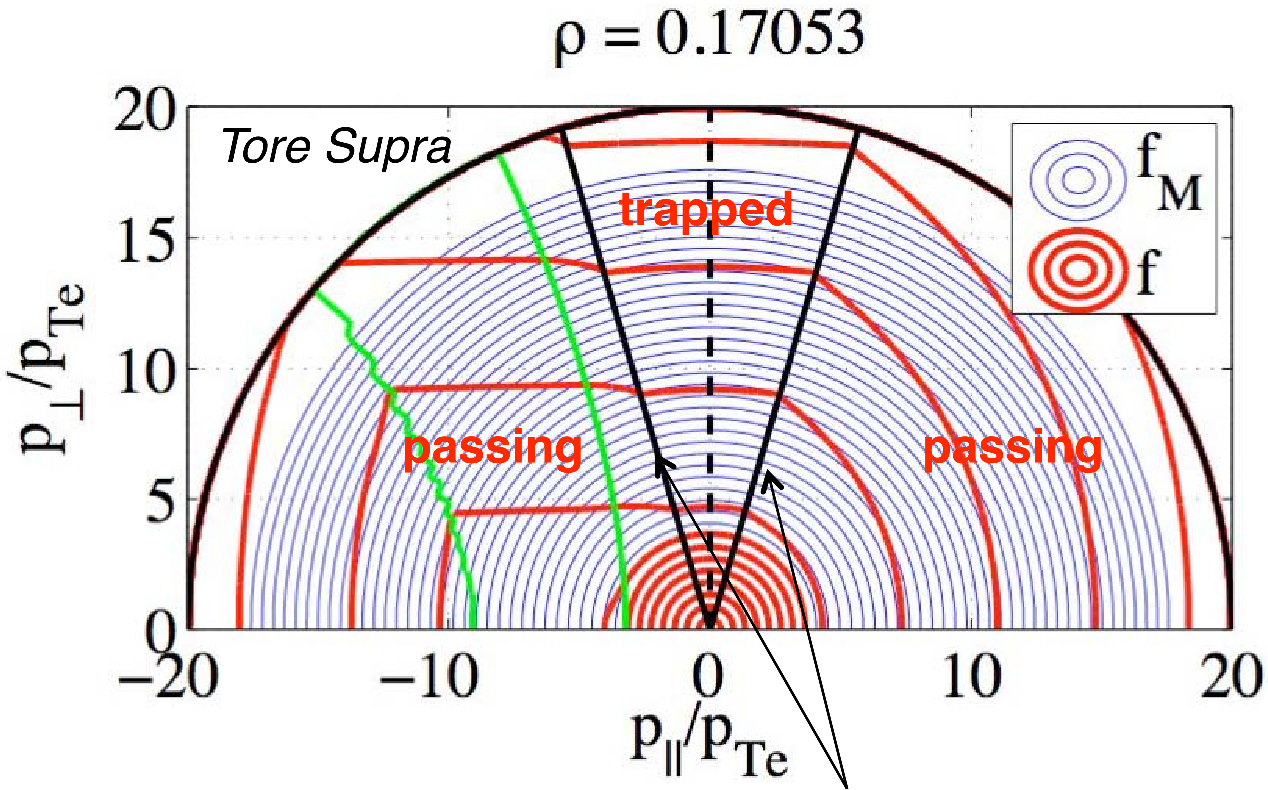
$$\begin{cases} \partial \left\{ f_0 \right\} / \partial t = \left\{ C\left(f_0 \right) \right\} + \left\{ Q\left(f_0 \right) \right\} + \left\{ E\left(f_0 \right) \right\} \\ \left\{ \mathbf{v}_{cg} \cdot \nabla_{\mathbf{x}_R} f_0 \right\} = 0 \\ \left\{ \mathcal{O} \right\} \equiv \frac{1}{\lambda \tilde{q}} \left[\frac{1}{2} \sum_\sigma \right]_T \int_{\theta_{\min}}^{\theta_{\max}} \frac{d\theta}{2\pi} \frac{1}{\left| \hat{\psi} \cdot \hat{\mathbf{r}} \right|} \frac{r}{a_p} \frac{B}{B_P} \frac{\xi_0}{\xi} \mathcal{O} \end{cases}$$


Passing
Trapped
v_D
r
θ
$2\delta_b$
Z (m)
R - R$_0$ (m)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.4
-0.2
0
0.2
0.4



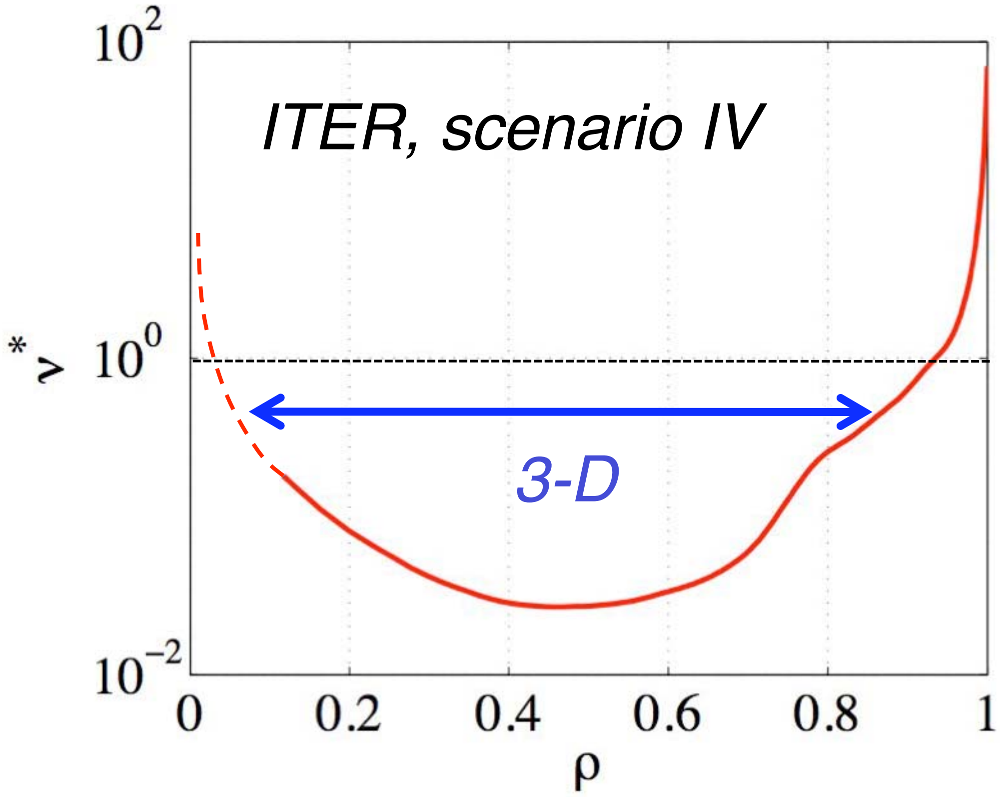
$$\{f_0\} = f_0^{(0)}\left(\underbrace{\psi, p, \xi_0}_{\textit{3-D}}\right)$$

All the electron dynamics is projected at $B=B_{min}$



$$\xi_{0T} = \sqrt{1 - \frac{B_{\min}(\psi)}{B_{\max}(\psi)}}$$

Momentum space dynamics on the magnetic flux surface ψ



Domain of validity of the bounce-averaging procedure

rf wave dynamics

$$(\boxed{\lambda}, \boxed{\phi_B}, \boxed{R})$$

wave length   beam width   gradients length

$$\begin{cases} \lambda \ll \phi_B \\ \lambda \ll R \end{cases}$$

$\lambda \ll \phi_B$ ⇨ quasi-plane wave approximation

$\lambda \ll R$ ⇨ WKB approximation

$$\mathbf{E}_1\left(\mathbf{x},t\right)=\boxed{\mathbf{E}_{\mathbf{k},\omega}\left(\mathbf{x},t\right)}e^{i\overbrace{\left[\boxed{\mathbf{k}_1\left(\mathbf{x},t\right)}\cdot\mathbf{x}-\boxed{\omega\left(\mathbf{x},t\right)}t\right]}^{\text{Eikonal } S(k,\,\omega,x,t)}}$$

Quasi-plane wave approximation

WKB approximation

Smooth wavefield envelope

$$\begin{cases}\lim_{t\to-\infty}\left\|\mathbf{E}_{\mathbf{k},\omega}\right\|^2=0\\ \lim_{\|\mathbf{x}\|\to\infty}\left\|\mathbf{E}_{\mathbf{k},\omega}\right\|^2=0\end{cases}$$

Methods for uniform plasmas can be applied locally:

- *Fourier space description*
- *group velocity*
- *local conductivity tensor*

rf wave dynamics

complexity ↓

$\lambda \ll \phi_B \ll R$ ⇒ ray-tracing

$\lambda \sim \phi_B \ll R$ ⇒ beam-tracing

$\lambda \ll \phi_B \sim R$ ⇒ WKB full-wave

$\lambda \sim \phi_B \sim R$ ⇒ full-wave

Model validity ↓

$$\boxed{\lambda \ll \phi_B \ll R}$$

- Narrow spectral width transverse to the beam (v_G)

$$\|\Delta \mathbf{k}_1 \times \mathbf{v}_G\| \,/\, \|\mathbf{k}_1 \times \mathbf{v}_G\| \sim \lambda/\phi_B$$

- weak damping approximation along the beam

$$|\nabla_{\mathbf{x}} \mathbf{E}_{\mathbf{k},\omega} \cdot \mathbf{v}_G| \,/\, |\mathbf{E}_{\mathbf{k},\omega} \cdot \mathbf{v}_G| \ll \|\mathbf{k}_1\|$$

$$|\partial \mathbf{E}_{\mathbf{k},\omega}/\partial t \cdot \mathbf{v}_G| \,/\, |\mathbf{E}_{\mathbf{k},\omega} \cdot \mathbf{v}_G| \ll \omega$$

$$\Downarrow$$

Wave equation:

$$\mathbb{D}_{\mathbf{k},\omega} \cdot \mathbf{E}_{\mathbf{k},\omega} = i \nabla_{\mathbf{k}} \mathbb{D}_{\mathbf{k},\omega} : \nabla_{\mathbf{x}} \mathbf{E}_{\mathbf{k},\omega}$$

- dispersion tensor

$$\mathbb{D}_{\mathbf{k},\omega} = \mathbf{nn} - n^2\mathbb{I} + \mathbb{K}_{\mathbf{k},\omega}\left(f_0\right)$$

- Permitivity and susceptibility tensors

$$\mathbb{K}_{\mathbf{k},\omega}\left(f_0\right) = \mathbb{I} + \mathbb{X}_{\mathbf{k},\omega}\left(f_0\right)$$

$$\mathbb{X}_{\mathbf{k},\omega}\left(f_0\right) = i\mathbb{S}_{\mathbf{k},\omega}\left(f_0\right) / \left(\varepsilon_0\omega\right)$$

- wave refractive index

$$\mathbf{n} = \frac{c}{\omega}\mathbf{k}_1 n_{\|}\hat{\mathbf{b}} + \mathbf{n}_{\perp}$$

- wave polarization vector

$$\mathbf{e}_{\mathbf{k},\omega} = \mathbf{E}_{\mathbf{k},\omega} / \left\|\mathbf{E}_{\mathbf{k},\omega}\right\|$$

Weak damping ordering

- Assuming ω and $n_{||}$ are real (rf wave propagates)
- weak damping approximation:

$$\delta \sim \left| \mathbb{D}^{A}_{\mathbf{k},\omega}(i,j) \right| / \left| \mathbb{D}^{H}_{\mathbf{k},\omega}(i,j) \right| \ll 1$$

where $\mathbb{D}_{\mathbf{k},\omega} = \mathbb{D}^{H}_{\mathbf{k},\omega} + i\mathbb{D}^{A}_{\mathbf{k},\omega}$

$$\Downarrow$$

Expansion in powers of δ → $\left\{ \begin{array}{l} n_{\perp} = n_{\perp r} + i n_{\perp i} \\ \mathbf{e}_{\mathbf{k},\omega} \\ \mathbb{D}_{\mathbf{k},\omega} \end{array} \right.$

- to order δ^0

$$\mathbb{D}^{H}_{\mathbf{k},\omega}\left(n_{\perp 0}\right)\cdot\mathbf{e}_{\mathbf{k},\omega,0}=0$$

$$\Downarrow$$

dispersion relation satisfied by propagative eigenmodes

$$\det\left(\mathbb{D}^{H}_{\mathbf{k},\omega}\right)=\mathcal{D}(n_{\perp 0},n_{\|},\omega)=0$$

$$\rightarrow n_{\perp 0}=n_{\perp 0}\left(n_{\|},\omega\right)$$

$$n_{\perp i0}=0$$

- to order δ^1

Equation of energy transfer between wave and electrons

$$\mathbf{v}_G \cdot \nabla_{\mathbf{x}} \left\|\mathbf{E}_1\right\| + \frac{\mathbf{e}^*_{\mathbf{k},\omega,0} \cdot \mathbb{D}^A_{\mathbf{k},\omega} \cdot \mathbf{e}_{\mathbf{k},\omega,0}}{\partial\left(\mathbf{e}^*_{\mathbf{k},\omega,0} \cdot \mathbb{D}^H_{\mathbf{k},\omega} \cdot \mathbf{e}_{\mathbf{k},\omega,0}\right)/\partial\omega} \left\|\mathbf{E}_1\right\| = 0$$

Weak damping approximation

⇩

Separation propagation/absorption

Resonance condition

- non-resonant contribution

$$\mathbb{D}^{H}_{\mathbf{k},\omega} \longrightarrow$$ principal value of $\mathbb{S}_{\mathbf{k},\omega}$

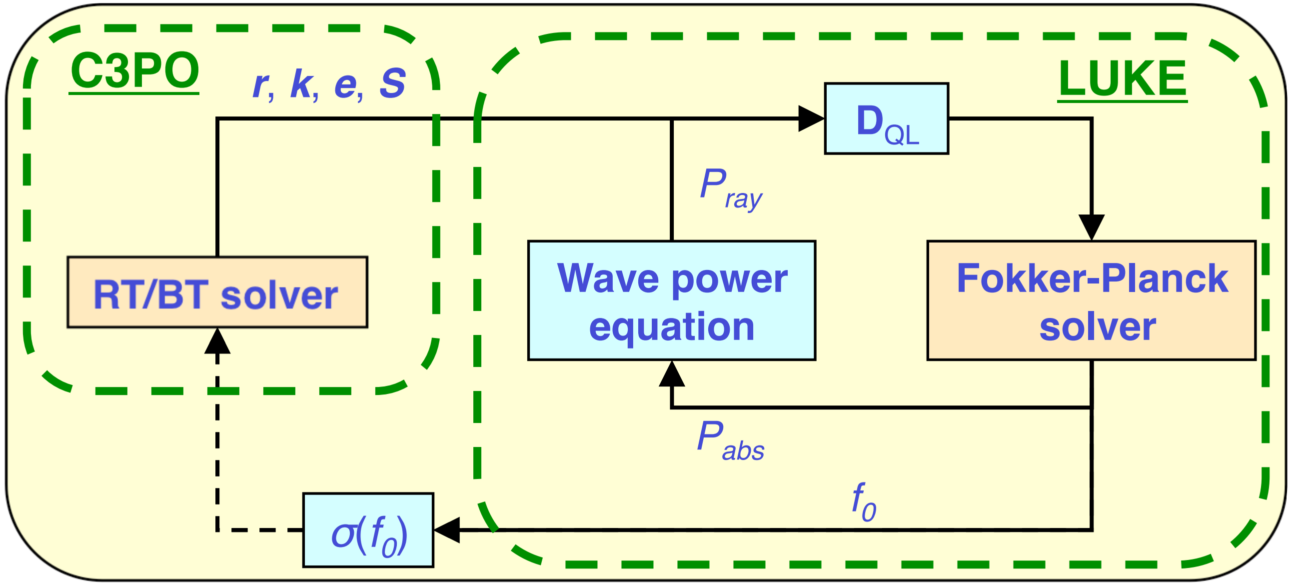
$$\boxed{\mathbb{D}^{H}_{\mathbf{k},\omega}\left(f_0\right) \simeq \mathbb{D}^{H}_{\mathbf{k},\omega}\left(f_M\right)}$$

- resonant contribution $\gamma - n_{\|}p_{\|} - n\Omega/\omega = 0$

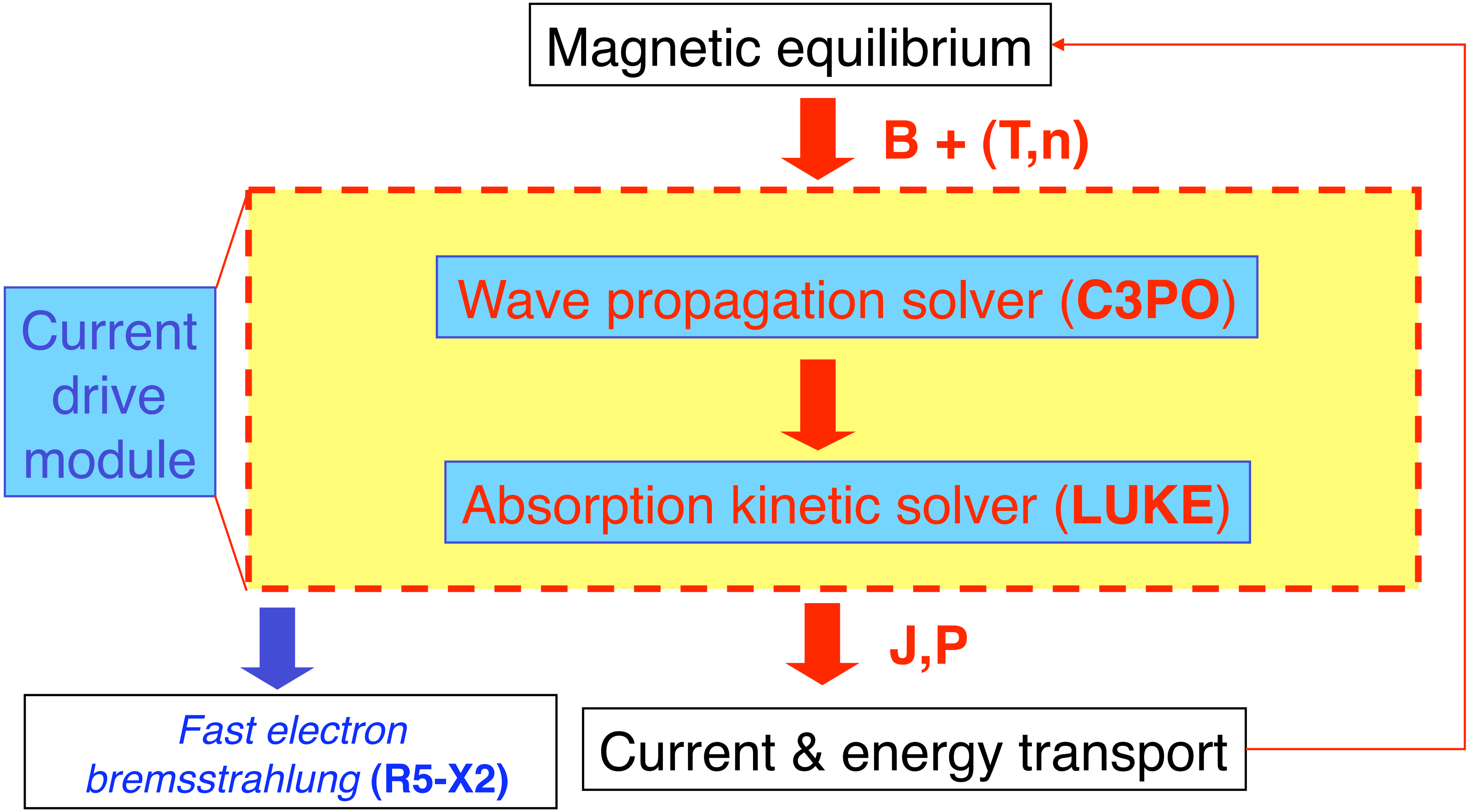
$$\mathbb{D}^{A}_{\mathbf{k},\omega} \longrightarrow$$ resonant part of $\mathbb{S}_{\mathbf{k},\omega}$

$$\boxed{\mathbb{D}^{A}_{\mathbf{k},\omega}\left(f_0\right) \neq \mathbb{D}^{A}_{\mathbf{k},\omega}\left(f_M\right)}$$

- the ray-tracing $\delta \mathcal{D}(n_{\perp 0}, n_{\parallel}, \omega) = 0$ is function of f_M.
- the wave amplitude, i.e. the quasilinear diffusion coefficient D_{ql} must be calculated self-consistently with the distribution f_0.
- Global consistency: *power lost by the wave = power gained by electrons from quasilinear operator*



The current drive module



Magnetic equilibrium

B + (T,n)

Current drive module

Wave propagation solver (**C3PO**)

Absorption kinetic solver (**LUKE**)

J,P

Fast electron bremsstrahlung **(R5-X2)**

Current & energy transport

The ray-tracing C3PO

- Separation between plasma dispersion models and the metric associated to the magnetic equilibrium

$$\frac{\partial \mathbb{X}^s_{ij}}{\partial \mathbf{Y}} = \frac{\partial \mathbb{X}^s_{ij}}{\partial n_\perp}\frac{\partial n_\perp}{\partial \mathbf{Y}} + \frac{\partial \mathbb{X}^s_{ij}}{\partial n_\parallel}\frac{\partial n_\parallel}{\partial \mathbf{Y}}$$

$$+ \frac{\partial \mathbb{X}^s_{ij}}{\partial \beta_{Ts}}\frac{\partial \beta_{Ts}}{\partial \mathbf{Y}} + \frac{\partial \mathbb{X}^s_{ij}}{\partial \overline{\omega}_{ps}}\frac{\partial \overline{\omega}_{ps}}{\partial \mathbf{Y}} + \frac{\partial \mathbb{X}^s_{ij}}{\partial \overline{\Omega}_s}\frac{\partial \overline{\Omega}_s}{\partial \mathbf{Y}}$$

$$\mathbf{Y} = (\mathbf{X}, \mathbf{k}, t, \omega)$$

$$\beta_s = \sqrt{kT_s/m_s c^2}$$

$$\overline{\omega}_{ps} = \omega_{ps}/\omega \qquad \overline{\Omega}_s = \Omega_s/\omega$$

- Curvilinear coordinate system: $(\rho(\psi), \theta, \phi)$
- Vectorization of the magnetic equilibrium: Fourier series + piecewise cubic interpolation using Hermite polynomials: no interpolation performed at each time step
- 6th order Runge-Kutta
- rays are calculated inside the separatrix. Specular reflexion enforced (if needed) at $\rho=1$.
- ray calculation stopped when the rf power is linearly damped
- cold, warm, hot and relativistic dielectric tensors
- written in C (MatLab mex-file)
- distributed computing capability (1ray/processor)

The Fokker-Planck solver LUKE

- Fully 3-D conservative formulation

$$\partial f^{(0)}/\partial t + \nabla \cdot \mathbf{S}^{(0)} = s_{+}^{(0)} - s_{-}^{(0)}$$

momentum space

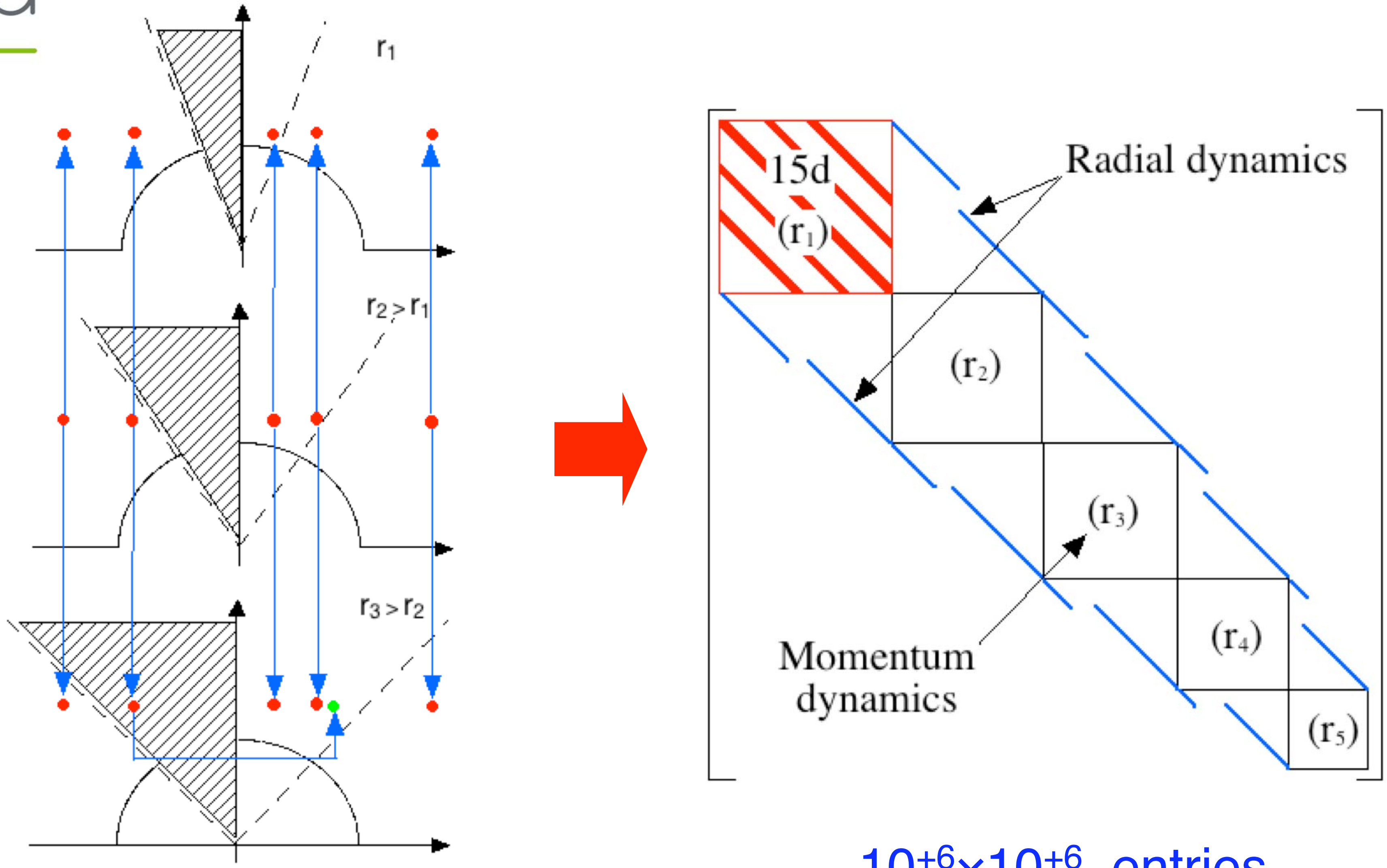
$$\nabla \cdot \mathbf{S}^{(0)} = \boxed{\frac{B_0}{\tilde{q}\lambda}\frac{\partial}{\partial \psi}\left(\frac{\tilde{q}\lambda}{B_0}\left\|\nabla\psi\right\| S_{\psi}^{(0)}\right)}$$

$$\boxed{+\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 S_p^{(0)}\right) - \frac{1}{\lambda p}\frac{\partial}{\partial \xi_0}\left(\lambda\sqrt{1-\xi_0^2}S_{\xi}^{(0)}\right)}$$

configuration space

$$\mathbf{S}^{(0)} = -\mathbb{D}^{(0)} \cdot \nabla f^{(0)} + \mathbf{F}^{(0)} f^{(0)}$$

- Non-uniform grids (f and fluxes)
- Fully implicit time scheme: *large time step* $\Delta t \nu_c \sim 10^{+4}$
- Usual Chang & Cooper interpolation for p grid
- Linear interpolation for radial and pitch-angle grids
- Discrete cross-derivatives consistent with boundary conditions → *high rf power densities*
- Generalized incomplete LU factorization technique for an arbitrary number of non-zero diagonals (highly sparse L and U matrices)
- written in MatLab
- Iterative inversion method (MatLab built-in or external linear solvers **MUMPS**, PETSc, SUPERLU)
- Distributed and parallel computing
- *Coupled with ray-/beam tracing and full-wave codes*



$10^{+6} \times 10^{+6}$ entries

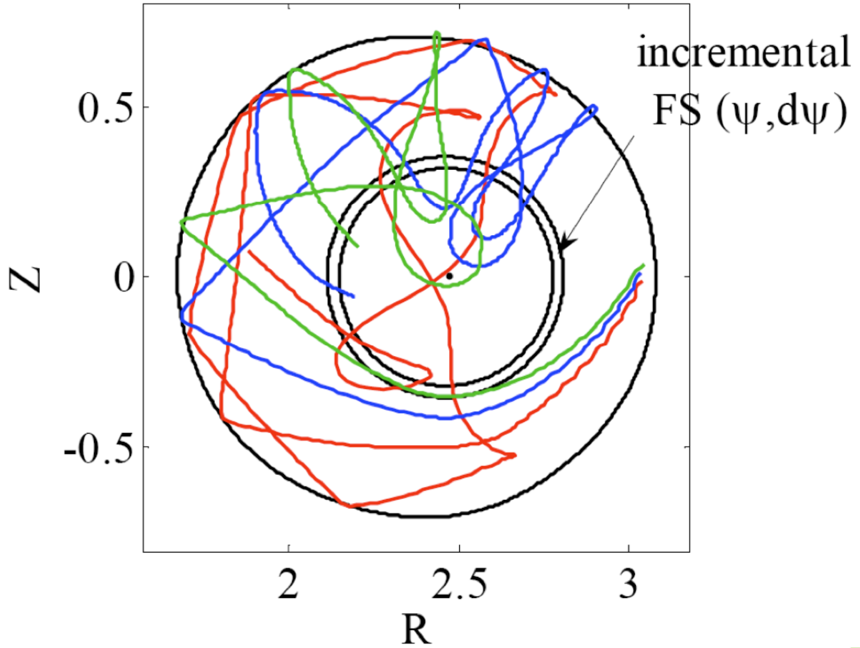
rf current drive simulations

- The RF wave is described by a set of rays
- The plasma is divided into incremental flux surfaces
- D_{ql} is calculated on each flux surface:
    - contribution of all rays
    - contribution of all passes of the same ray

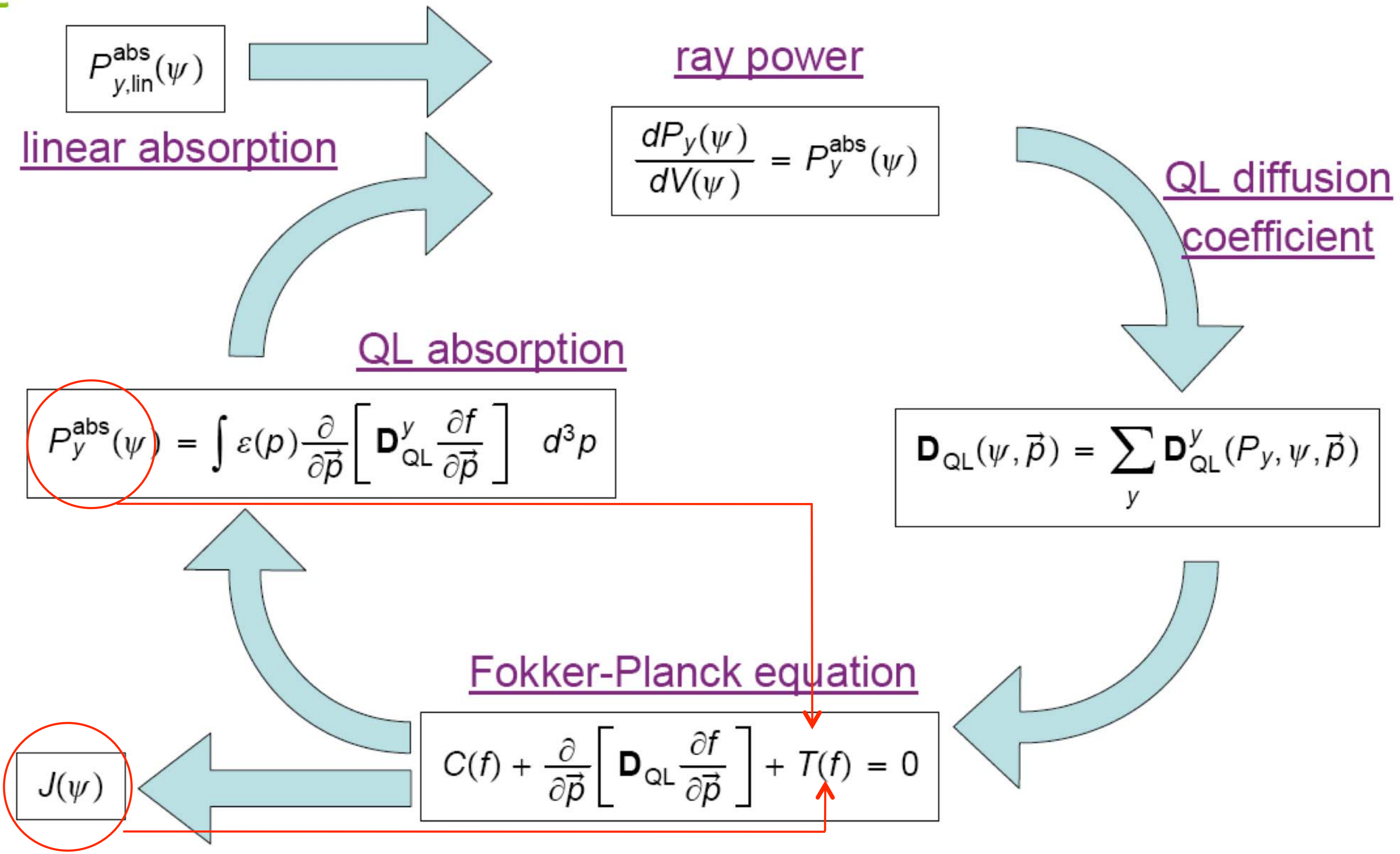
$$\mathbf{D}_{\mathrm{QL}}(\psi,\vec{p}) = \sum_{y} \mathbf{D}_{\mathrm{QL}}^{y}(P_y,\psi,\vec{p})$$

Ray power flow equation

$$\frac{dP_y(\psi)}{dV(\psi)} = \boxed{P_y^{abs}(\psi)} \xrightarrow{} \boxed{\text{Unknown}}$$



Self-consistent calculations



$P^{abs}_{y,lin}(\psi)$

linear absorption

ray power

$$\frac{dP_y(\psi)}{dV(\psi)} = P_y^{abs}(\psi)$$

QL diffusion coefficient

$$\mathbf{D}_{QL}(\psi,\vec{p}) = \sum_y \mathbf{D}^y_{QL}(P_y,\psi,\vec{p})$$

Fokker-Planck equation

$$C(f) + \frac{\partial}{\partial \vec{p}}\left[\mathbf{D}_{QL}\frac{\partial f}{\partial \vec{p}}\right] + T(f) = 0$$

QL absorption

$$P_y^{abs}(\psi) = \int \varepsilon(p)\frac{\partial}{\partial \vec{p}}\left[\mathbf{D}^y_{QL}\frac{\partial f}{\partial \vec{p}}\right] d^3p$$

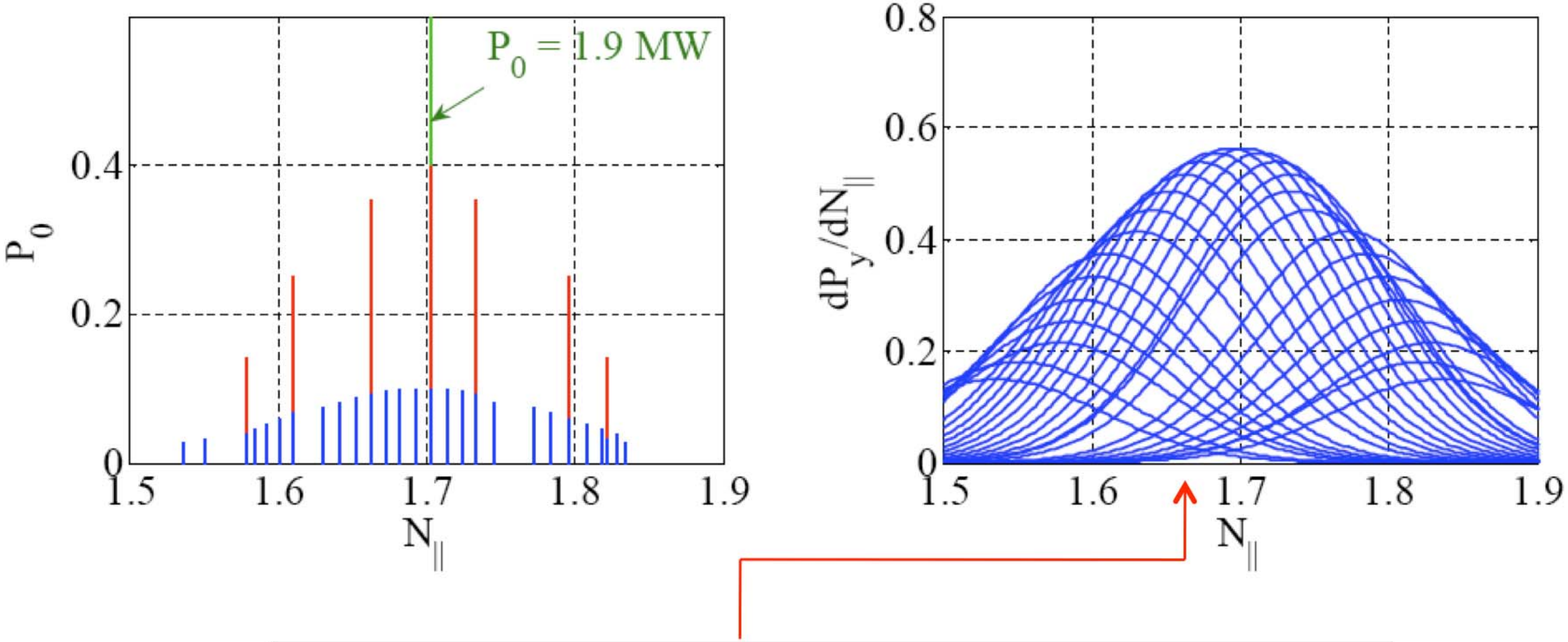
$J(\psi)$

Few ray simulations

- **The quasilinear convergence is carried out using the power flow along each ray**, and not on the global power absorption profile.

- **This technique requires to use a reduced number of rays** (one per poloidal antenna row, one for the positive and negative lobes for the LH wave), *otherwise very weak or no convergence.*

- The small number of rays allows to reduce considerably the computational effort, and to interpret **$\Delta n_{||}$ as a real spectral width** (*consistency with Fourier theory).*

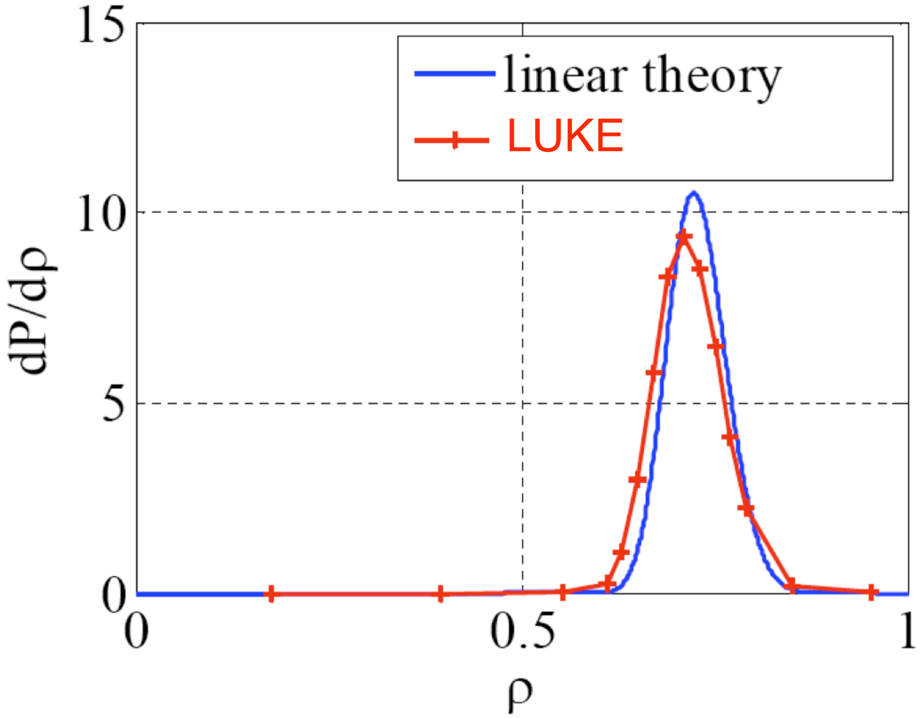


case	28 rays	7 rays	1 ray
$\Delta N_\parallel$ (each ray)	0.1	0.2	0.4

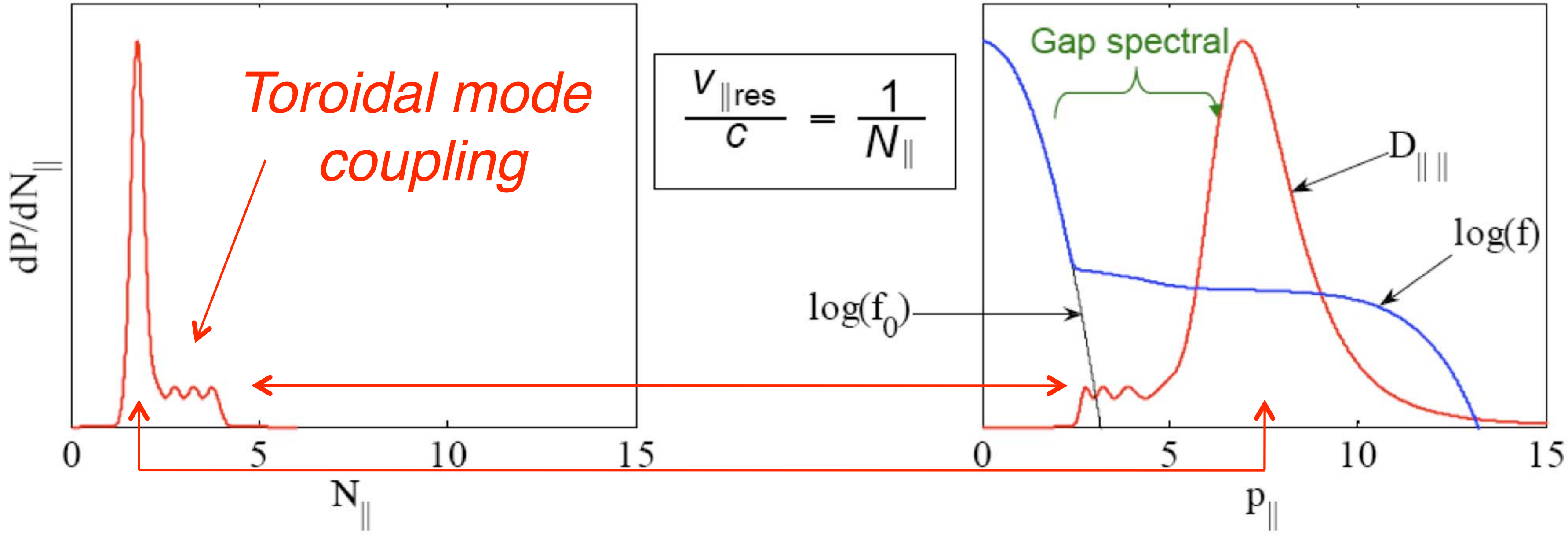
J. Decker, and Y. Peysson, in *33rd EPS Conference on Plasma Phys. and Contr. Fusion*, 2006.

Linear limit

In the limit of low RF power level (D≈0), the result from the relativistic linear theory is well recovered (1A/1W)



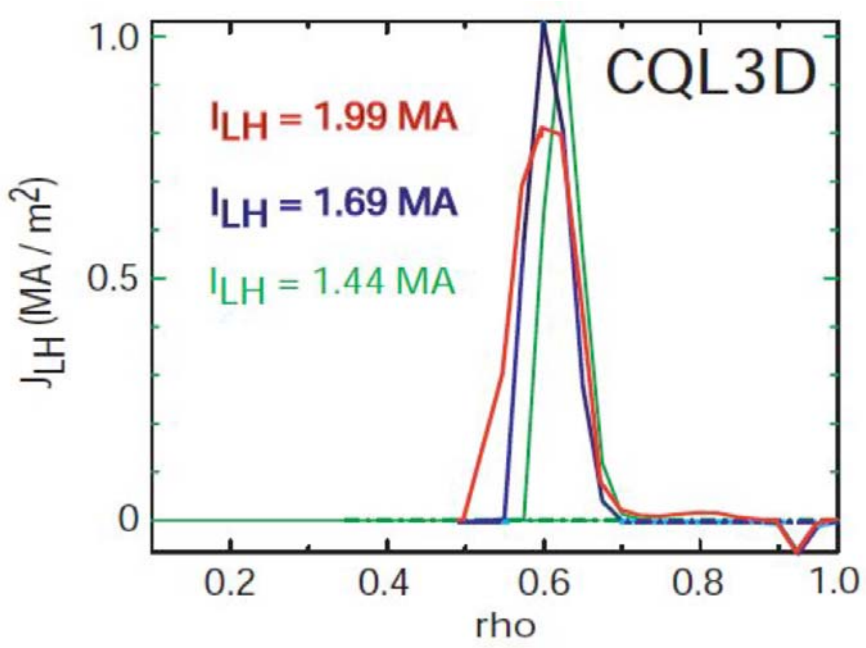
LH current drive simulations

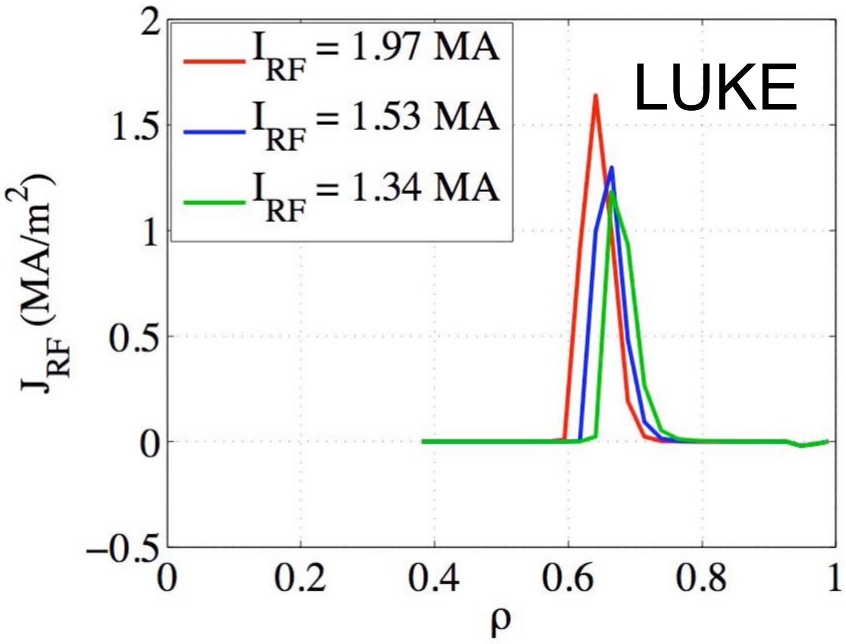


$$\frac{V_{\parallel res}}{c} = \frac{1}{N_\parallel}$$

The spectral gap is bridged by a small fraction of the LH power at high $n_{||}$ which pulls out a tail of fast electrons from the bulk which itself contributes to absorb the remaining part of the power at low $n_{||}$.

LHCD in ITER (Scenario IV)





GENRAY - CQL3D: 80 rays

C3PO - LUKE: 3 rays

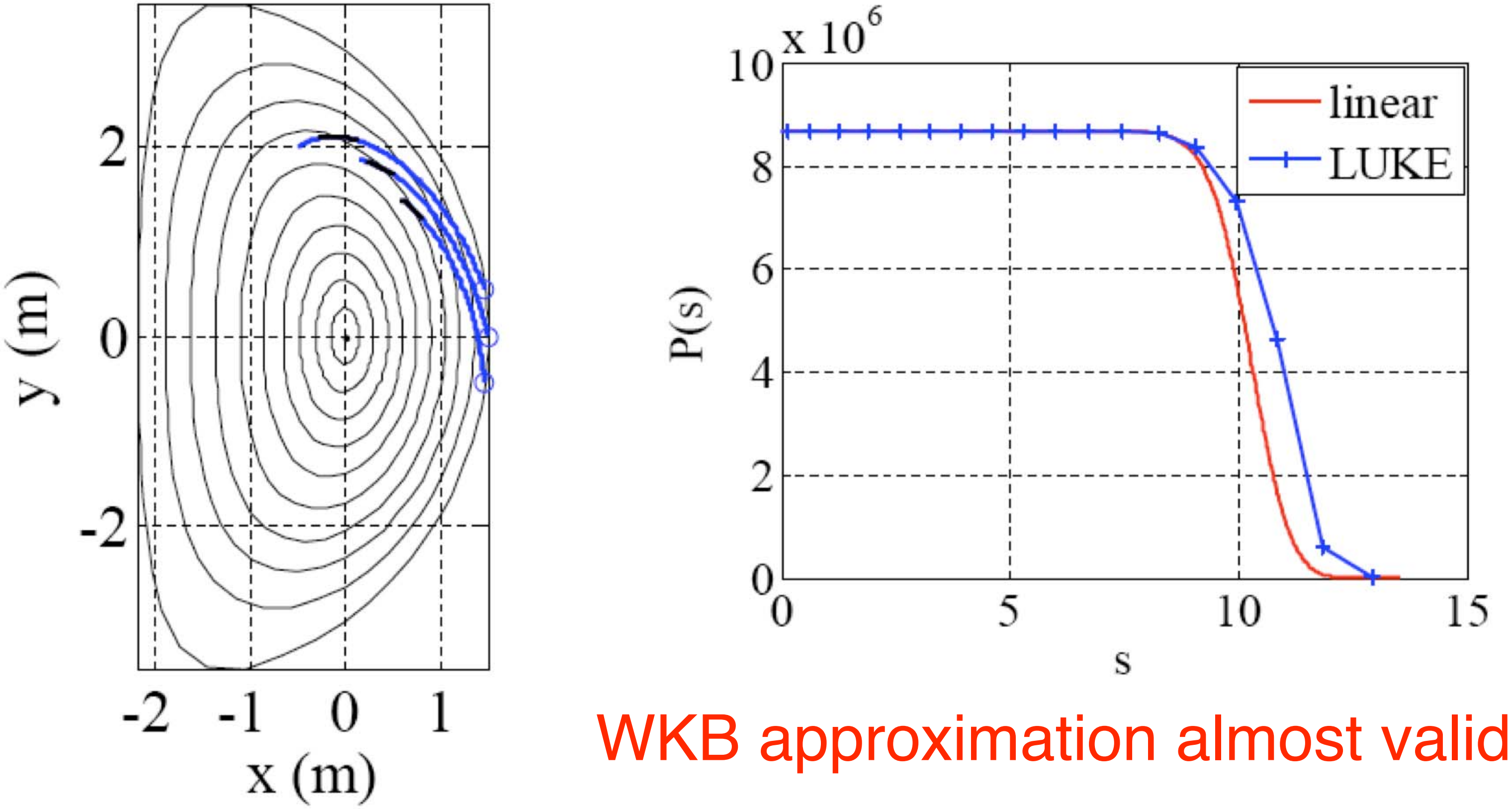
- $n_{||} = 1.9$
- $n_{||} = 2.0$
- $n_{||} = 2.1$

↔

$v_{||}/c \propto 1/n_{||}$

P. T. Bonoli, et al., in *Proceedings of the 21st IAEA Conference*

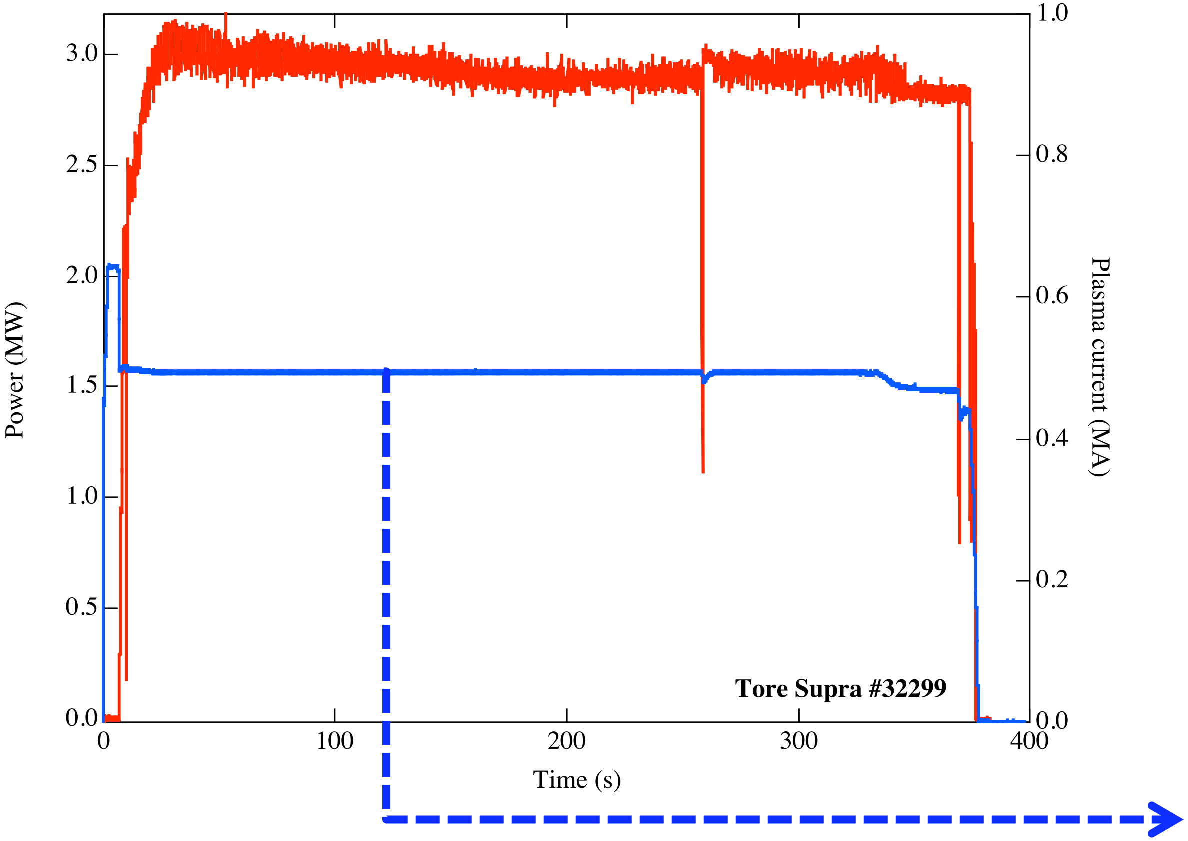
LHCD in ITER (Scenario IV)



WKB approximation almost valid

Almost linear single pass absorption: results are independent of the number of rays !

LHCD in Tore Supra



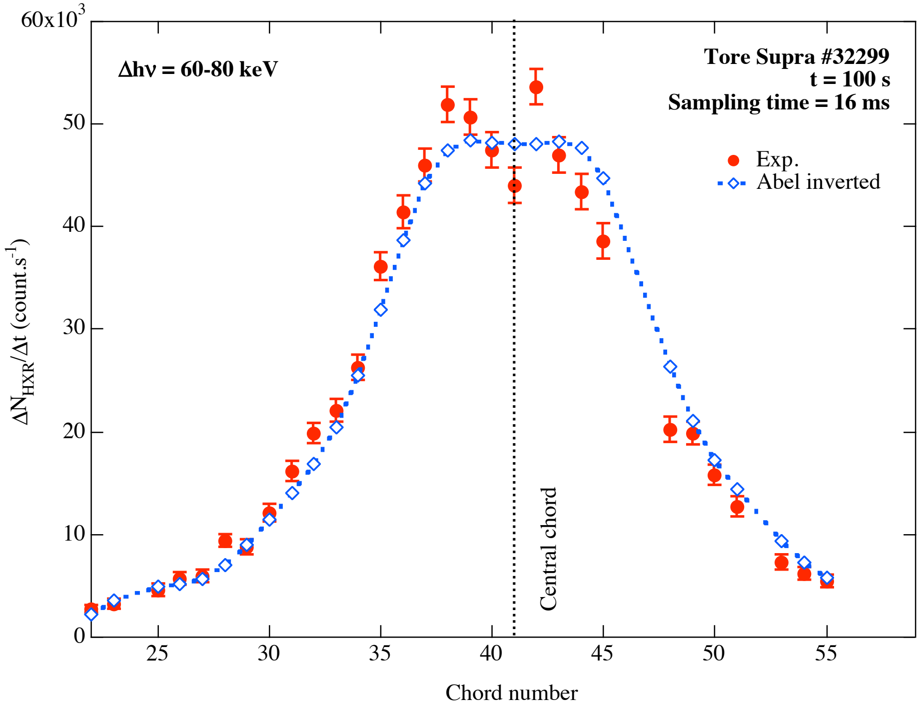
- Full LHCD (6 min.)
- 2 antennas
- $n_{\|0}$ =1.7 ± 0.2
- P_{lh} = 3 MW
- directivity: 0.6 & 0.7

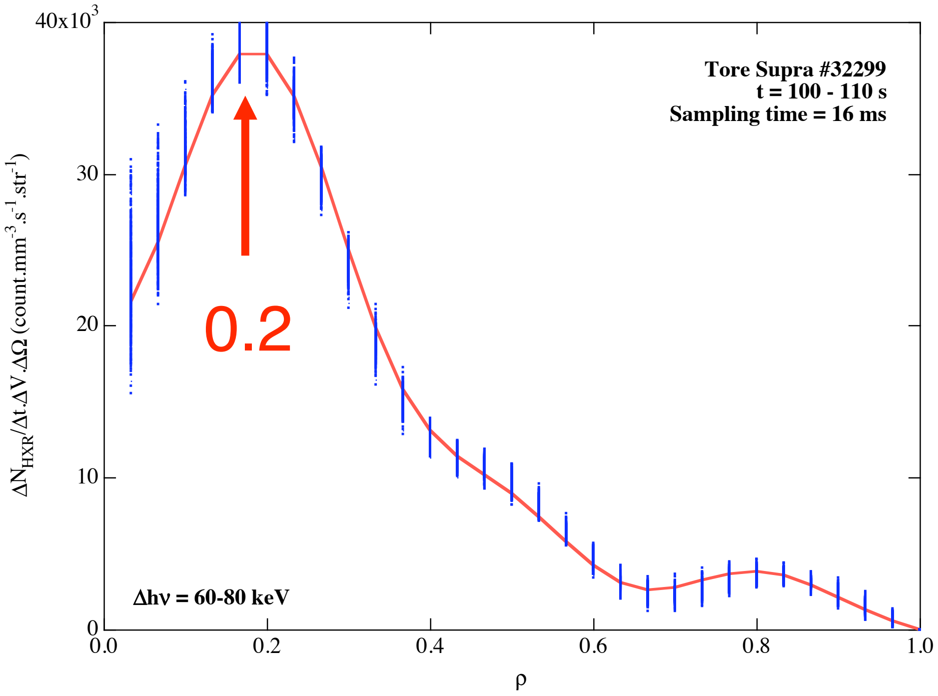
$I_p \approx 500$ kA

D. van Houtte, et al., *Fusion Eng. and Design* **74**, 651–658 (2005).

Fast electron bremsstrahlung (HXR)

Δk = 60-80 keV

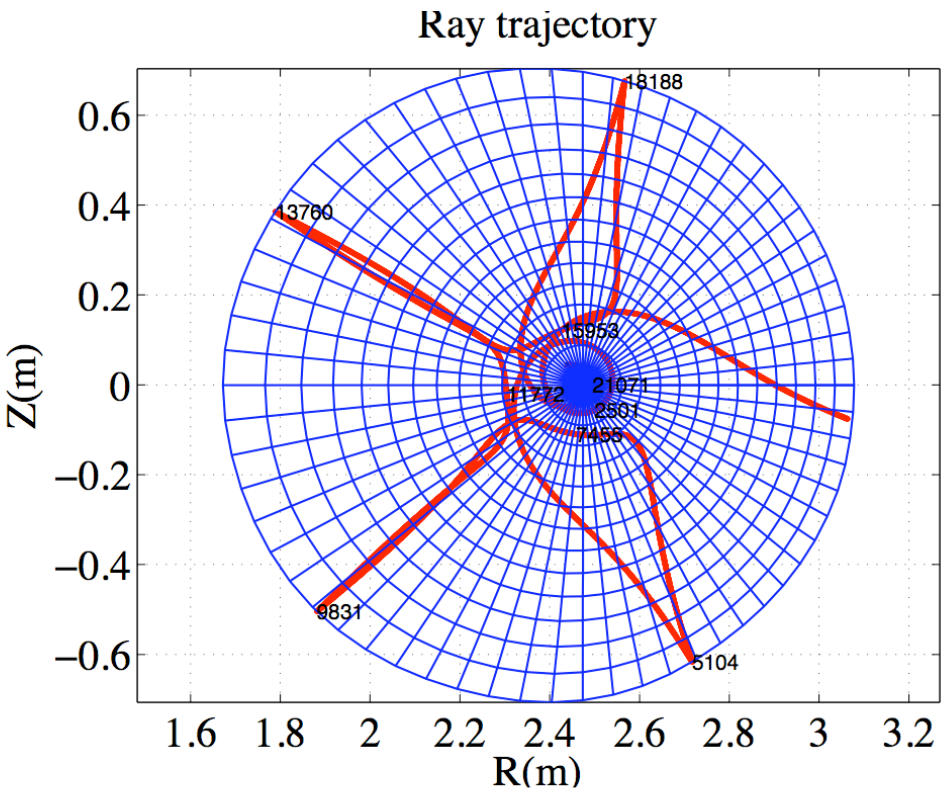


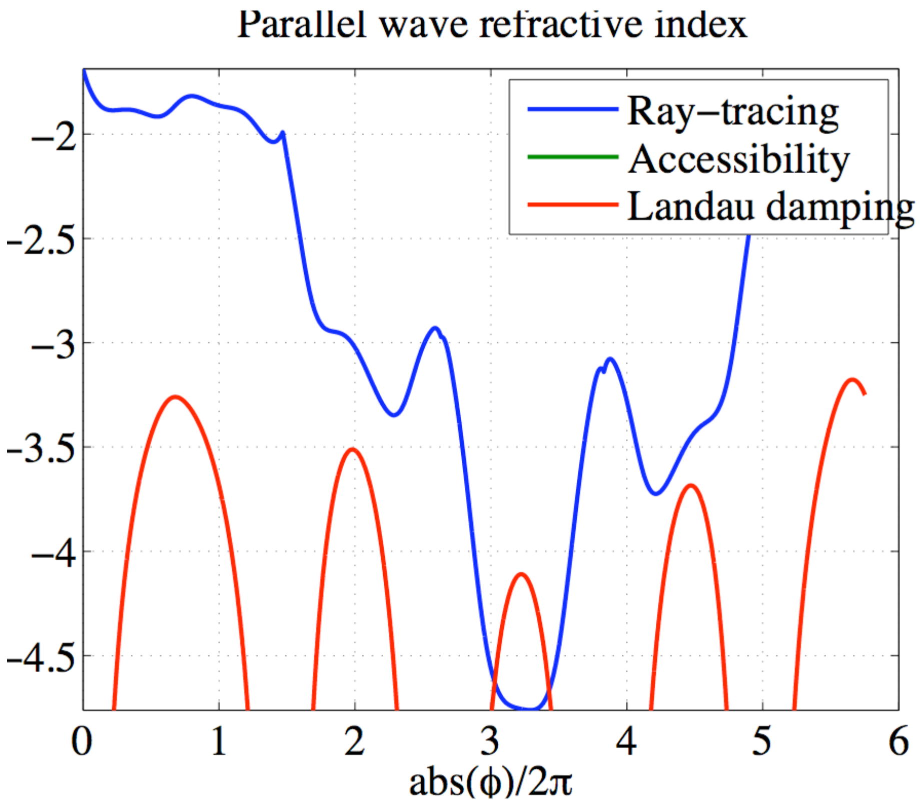


Line-integrated profile ⇨ Abel inverted profile

Y. Peysson, et al., in vol. 4 of *Advances in Plasma Physics Research*, Nova Science Publisher, Inc. New York, 2003.

Ray-tracing (C3PO)

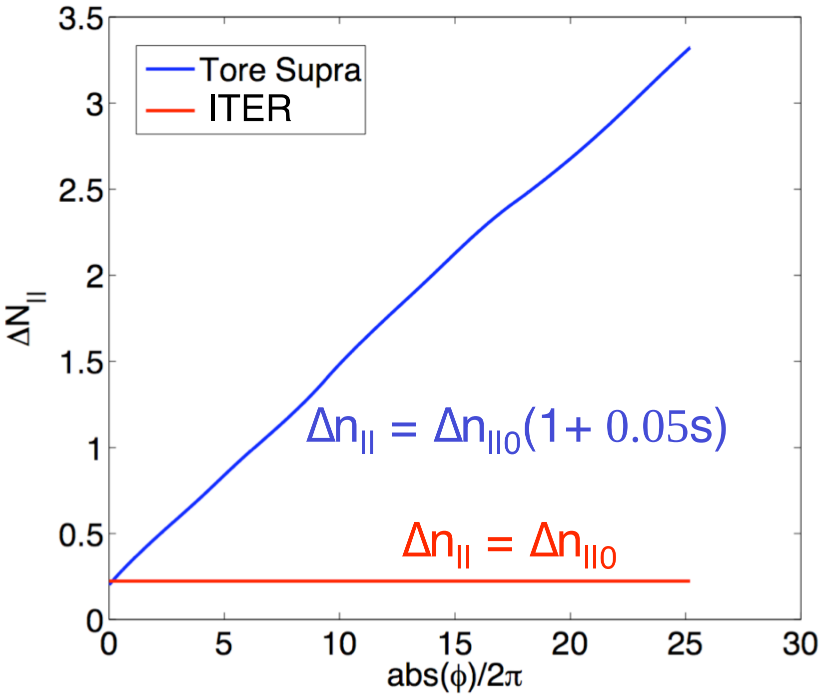


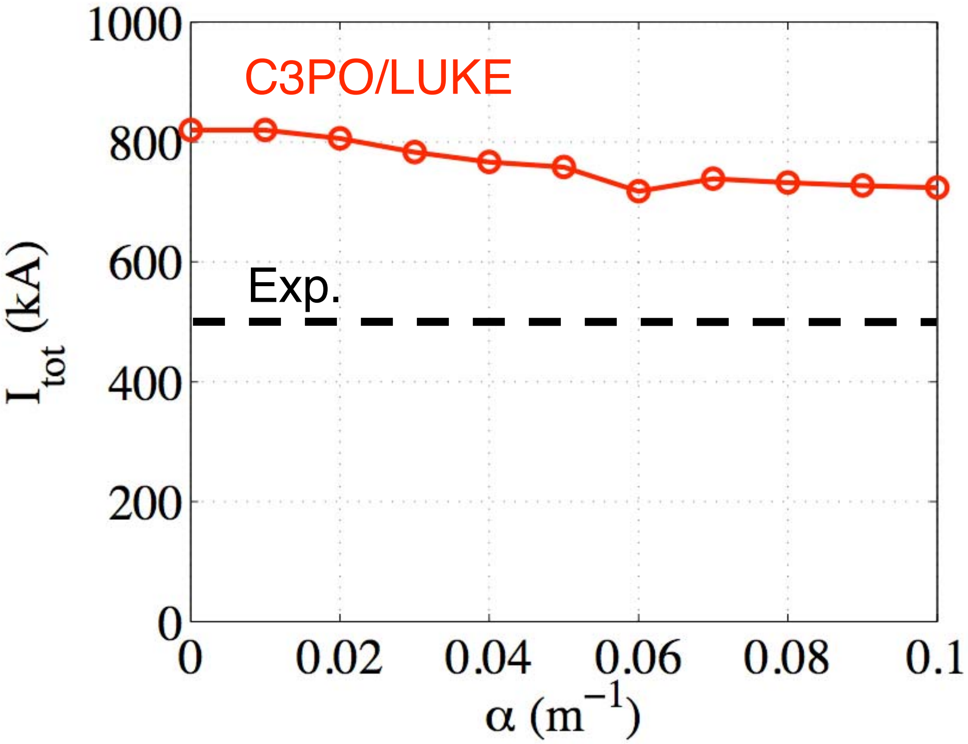


WKB approximation not valid !

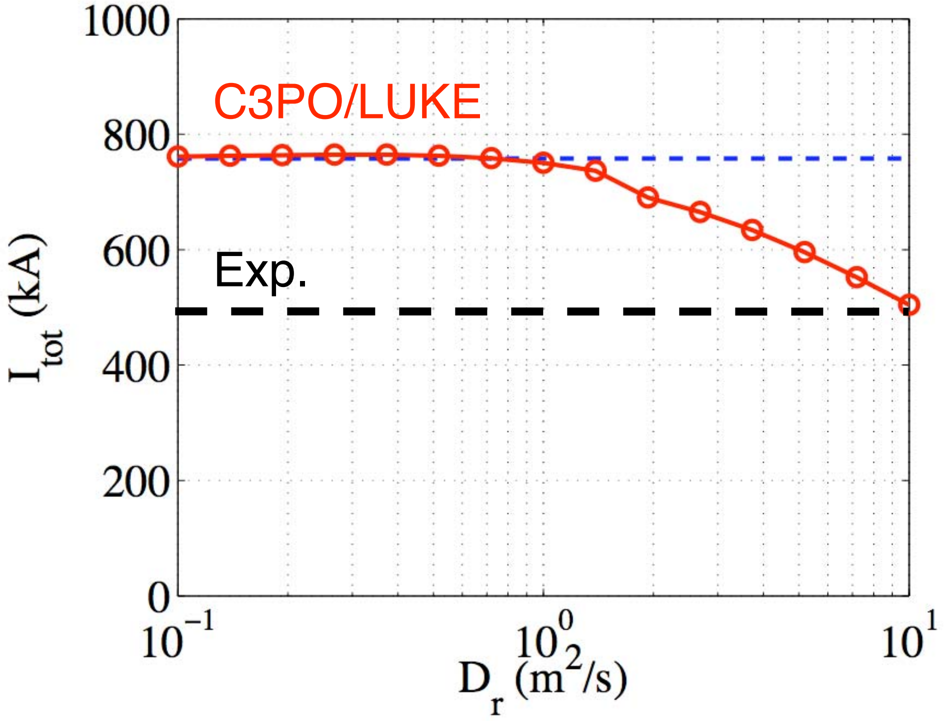
$n_{||0} = -1.7$

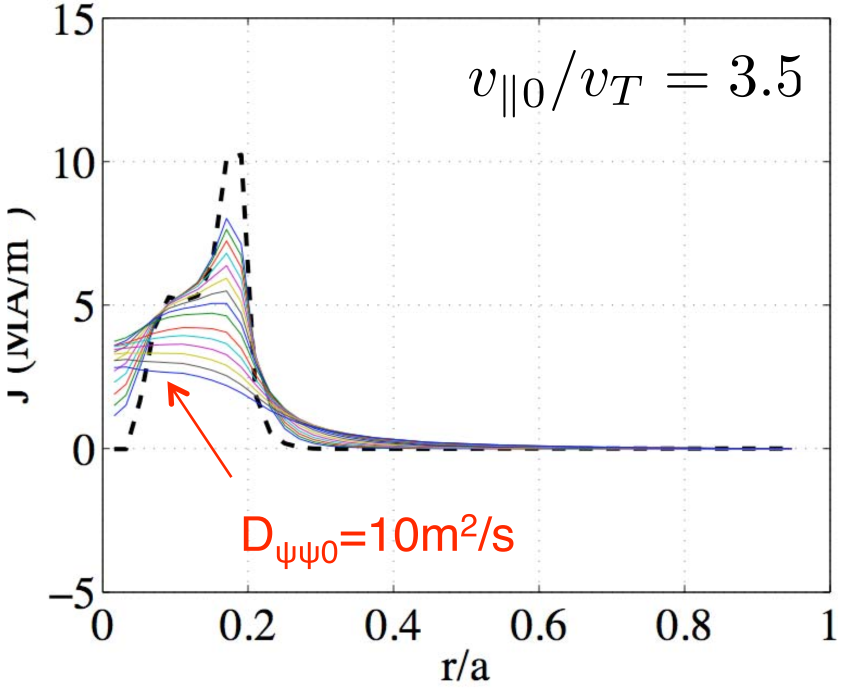
Spectral width model





Fast electron transport model

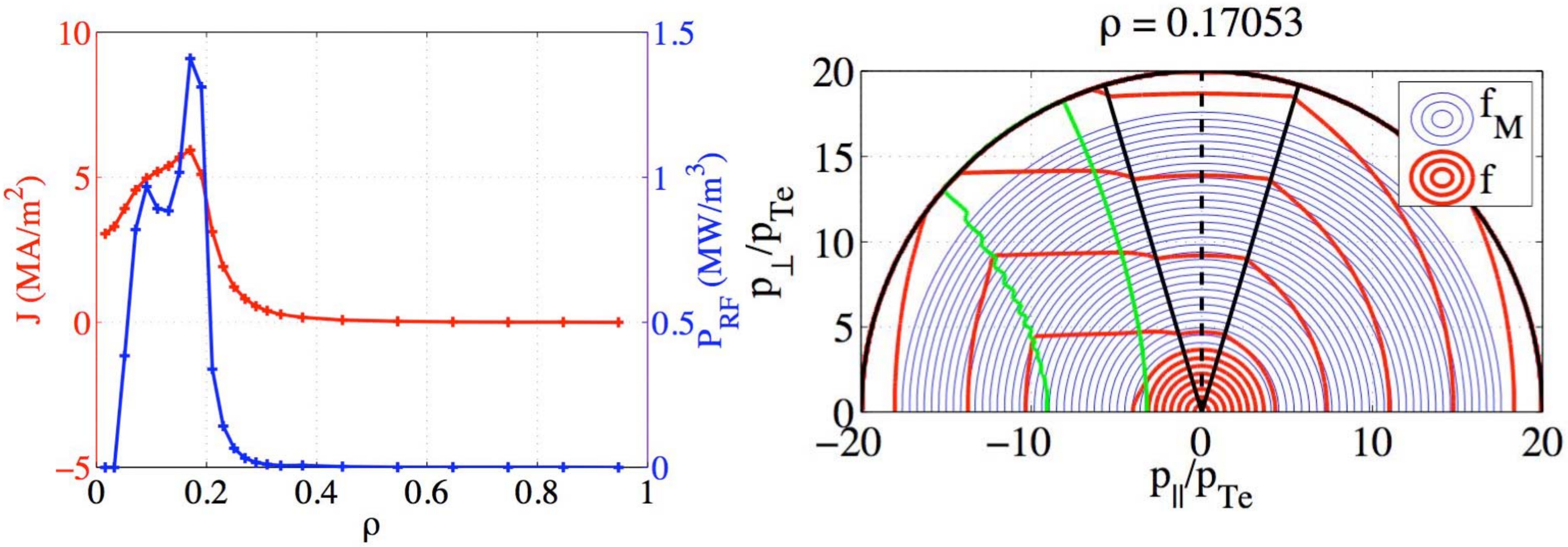




$D_{\psi\psi 0}$=10m^2/s

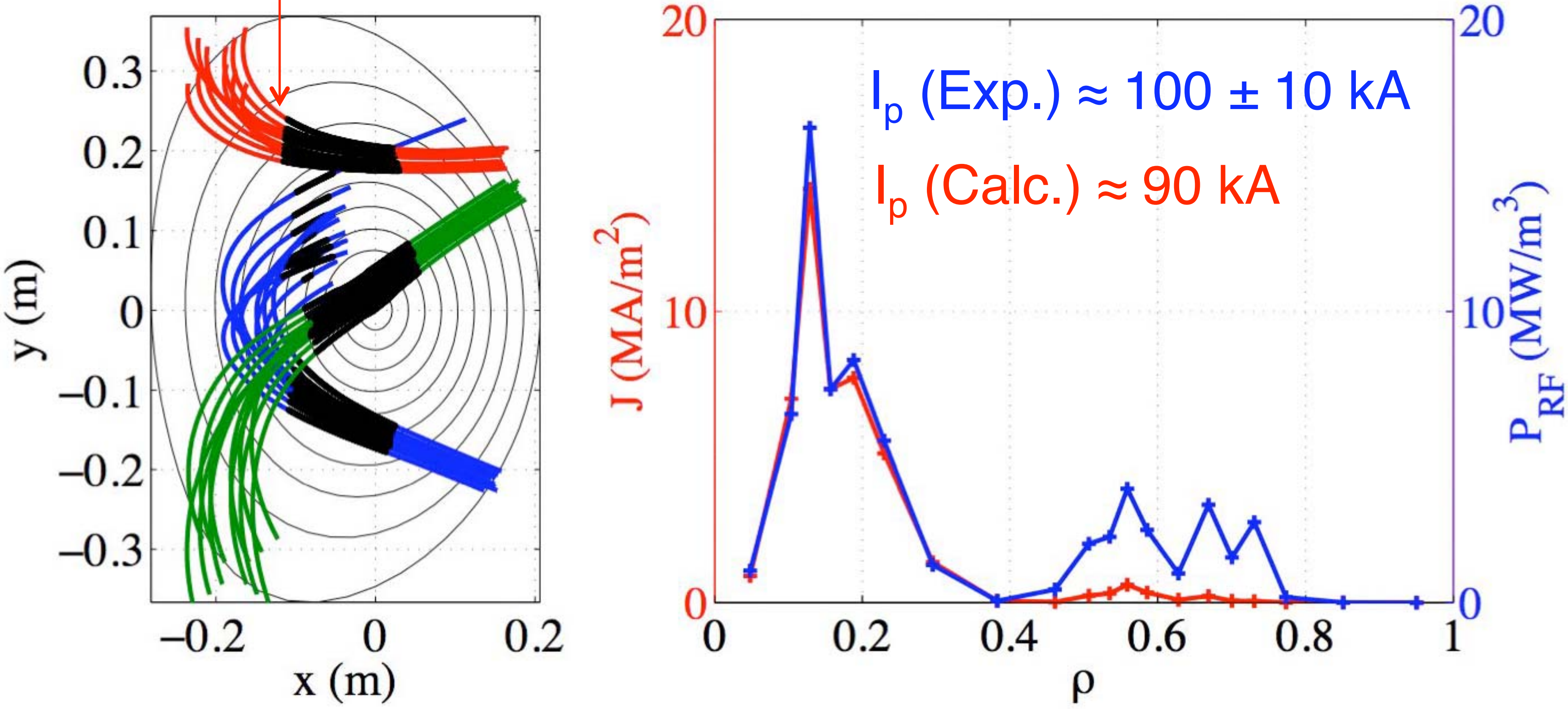
$$D_{\psi\psi} = D_{\psi\psi 0} \left(|v_{\|}| - v_{\|0}\right) H \left(|v_{\|}| - v_{\|0}\right)$$

LHCD in Tore Supra



- predicted LH current too large by 40%
- large fast electron radial transport *inconsistent* with exp.
- weak effect of spectral broadening

ECCD in TCV



12 beamlets/ray

I_p (Exp.) ≈ 100 ± 10 kA

I_p (Calc.) ≈ 90 kA

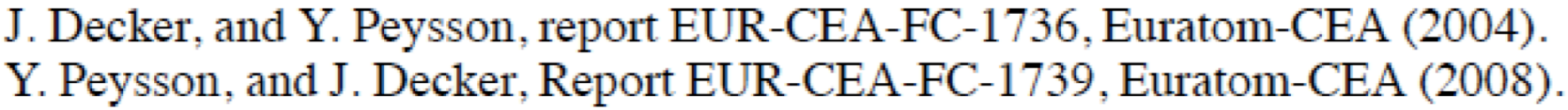
O. Sauter, et al., *Phys. Rev. Lett.* **84**, 3322–3325 (2000).

Conclusions & prospects

- A new current drive module for integrated tokamak modeling has been developed.
- Based on a strict implementation of the rf wave theory: *few ray approach*
- Fast electron radial dynamics consistent with quasilinear self -consistency: both P_{rf} *and* J_{rf} *depend on the radial transport.*
- Advanced algorithms for fast and robust calculations
- **LHCD**: linear theory holds for ITER and WKB approximation almost valid. Partial agreement with experiment on Tore Supra with toroidal spectral upshift and anomalous fast electron radial transport.
- **ECCD**: good agreement for full current drive in TCV without anomalous fast electron radial transport.

- **LHCD**: More physics must be incorporated in simulations within the WKB approximation for filling the spectral gap: *fluctuations*
- **LHCD**: C3PO ray-tracing → WKB full-wave for LH (ELECTRE-T)
- **LUKE**: bounce → orbit averaging + toroidal quasilinear operator (wave-induced radial transport, consistent description of the rf and bootstrap currents, ion physics)
- **LUKE**: electron back current calculations from non-Maxwellian ion distribution
- advanced tools: LUKE 3-D (ψ,p, ξ) → (θ,p, ξ), LUKE 4-D for edge current drive physics
- …

References



J. Decker, and Y. Peysson, report EUR-CEA-FC-1736, Euratom-CEA (2004).
Y. Peysson, and J. Decker, Report EUR-CEA-FC-1739, Euratom-CEA (2008).

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LUKE: 2 articles submitted to Comp. Phys. Comm.