Topic TH-H, Id : #2743

On the selfconsistency between ray-tracing/Fokker-Planck and toroidal MHD equilibrium for the Lower Hybrid current drive prediction

Y. SAVOYE-PEYSSON, R. SAURA, J.-F. ARTAUD, A. EKEDAHL AND J. HILLAIRET

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

Email: yves.savoye-peysson@cea.fr

Context

- *With the highest known current drive efficiency in tokamaks*, the rf wave at the Lower Hybrid (LH) frequency is particularly attractive for current profile shaping or steady-state operation.

- Though the LH wave is not considered in ITER for off-axis current drive in the flat-top phase, it *remains an attractive tool* for existing machines of much smaller size, whose plasma characteristics correspond to the early phase of a burning plasma in a fusion reactor.

- Modeling LH current drive is a challenging task as *power absorption is weak in existing machines*, without a well localized resonance condition.

Context

- Because of the complexity of the physical mechanisms at play and their interplay, *first principle modeling is the appropriate method to have a consistent interpretation of the experimental observations*.

- The *fast electron bremsstrahlung (FEB) in the hard x-ray range of photon energy (20-200 keV)* together with the plasma current are among the most appropriate diagnostics to validate the overall modeling approach for the LH physics, based on *quantitative comparisons*.

- *Considerable progresses* have been made with this methodology during the last past years on the understanding of the LH wave physics, in particular concerning the mechanisms at play for *bridging the spectral gap*.

Context

- While *toroidal refraction in the core plasma* is always present (tokamak geometrical configuration), *density filamentation in the scrape-off layer* between the separatrix and the LH antenna may considerably enhanced the broadening of the launched power spectrum (*tail spectral model, TSM*) and lead to an almost single pass absorption.

- The latter mechanism explains the *robustness of the code predictions* against observations for many machines (Tore Supra, WEST, C-Mod, EAST, HL2-A, …), but also why the LH wave may be fully absorbed in extreme regimes where the spectral gap can never be filled by toroidal refraction in the core plasma, like for large aspect ratio tokamaks (TRIAM-1M, WEST,…).

Context

- However, despite progresses, *modeling consistently the LH-driven current remains a complex challenge* :
  - The *toroidal MHD equilibrium must be consistent with LH current drive predicted by coupled wave propagation (C3PO) and kinetic calculations (LUKE)* (use of different LH models).
  - The *Ohmic electric field which may accelerate LH tail electrons to higher energies must be also consistently evaluated* (critical to assess the possible impact of the LH current drive on runaway electrons).

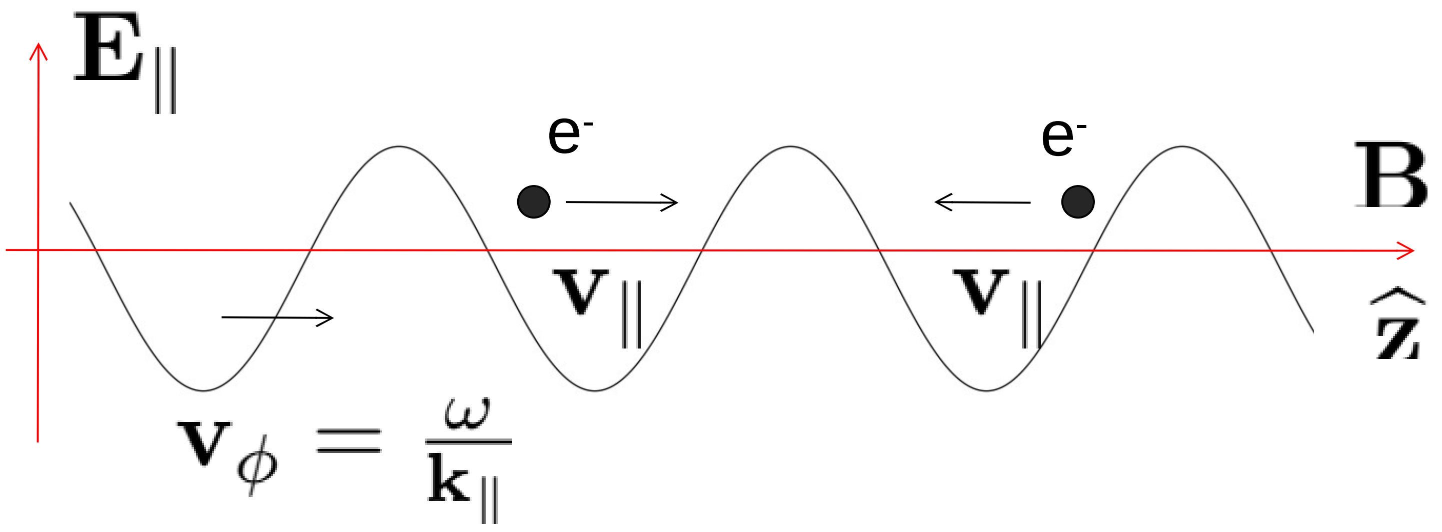
→ ***This problem is addressed by performing self-consistent calculations between METIS tokamak simulator and C3PO/LUKE codes within the SLUKE calculation framework.***

Outline

- **Basics on the LH wave**
- **First principle modeling tools**
- **SLUKE simulation framework**
- **Simulation results**
- **Conclusion and prospect**

Current drive and Landau damping

- Current drive (CD) efficiency **$J/P \sim v_{||}^2$** → using fast electrons for driving a toroidal current in a tokamak reactor will limit the needed fraction of recycled fusion power.
- The **resonant Landau interaction** along the magnetic field lines is a natural mechanism

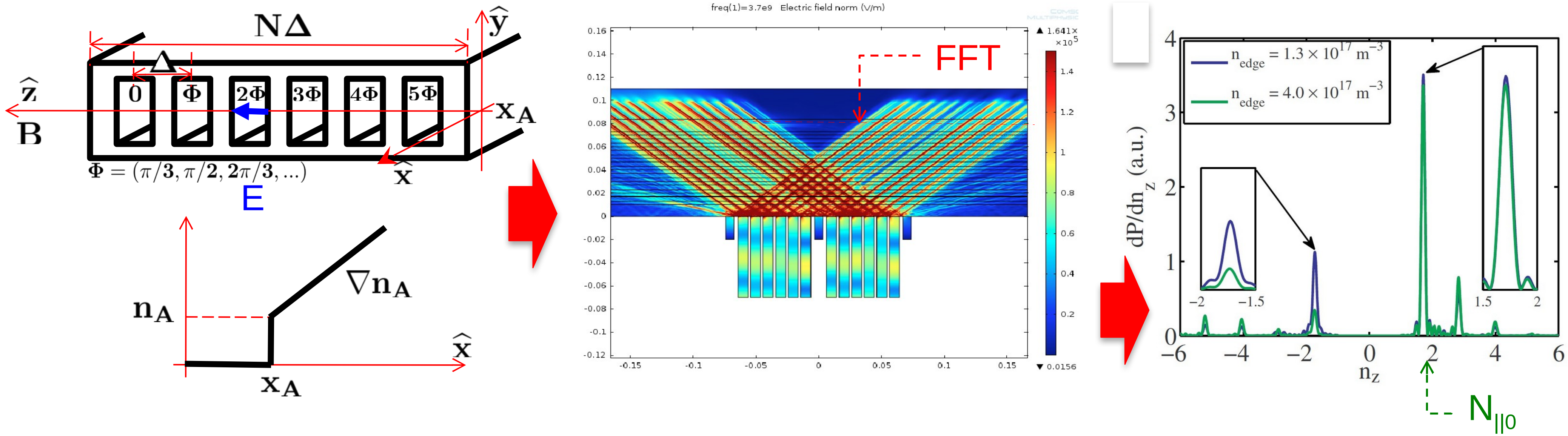


- Electrons gain parallel kinetic energy from the wave and drive a toroidal current ($\partial f/\partial v_{||} < 0$)
- **The <u>slow wave branch</u> at the LH frequency *(1-10 GHz)*** which has a high parallel phase velocity v_ϕ can interact with weakly collisional non-thermal electrons of ***30-130 keV***. From the resonance condition, the parallel refractive index ***$N_{||} = c/v_\phi = 1.4$-3***.

N. Fisch, Rev. Mod. Phys, 59 (1987) 175

Edge plasma coupling

- **LH wave does not propagate in vacuum:** it must be excited by an array of waveguides placed inside the edge cut-off layer where $\omega_{pe} = \omega_{LH}$.



- Wave characteristics at the plasma edge are determined by full-wave calculations (**ALOHA**,…). The power spectrum is deduced from the Fourier transform of the wave electric field structure.
- The power spectrum is made of a main lobe $N_{\|0}$ and multiple satellite lobes. It is used for initial conditions of the ray-tracing calculations.

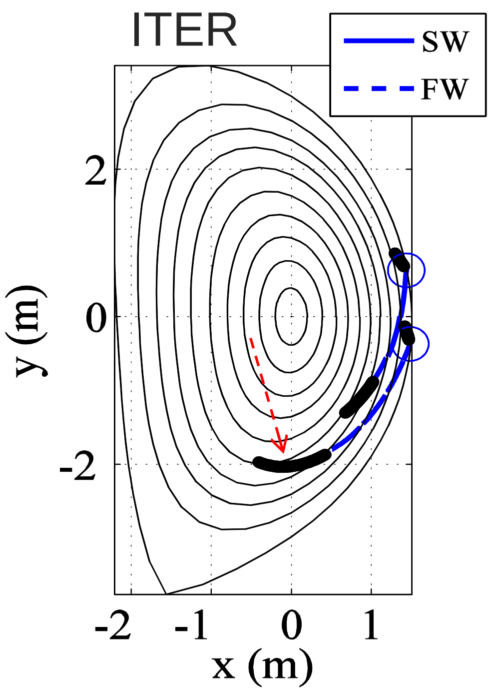
J. Hillairet et al., J., Nuclear Fusion, 50 (2010) 125010

Core plasma propagation boundaries

Full linear absorption

$N_{\parallel} > \mathbf{N_{\parallel L}} \leftrightarrow v_{\phi} < 4\times v_{th}$

$\mathbf{N_{\parallel L} = 6.5/\sqrt{T_e[keV]}}$

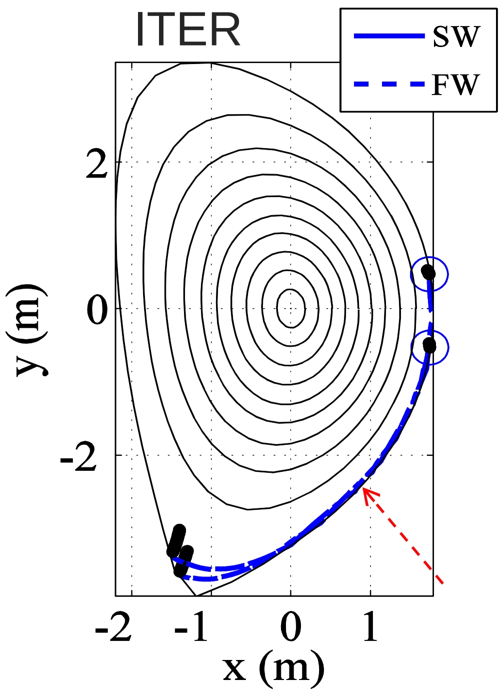


$N_{\parallel 0} = 2.0$

Stix-Golant accessibility

$N_{\parallel} < \mathbf{N_{\parallel a}} \rightarrow$ mode conversion

$\mathbf{N_{\parallel a} \approx \omega_{pe}/\Omega_{ce} \propto \sqrt{n_e}/B}$



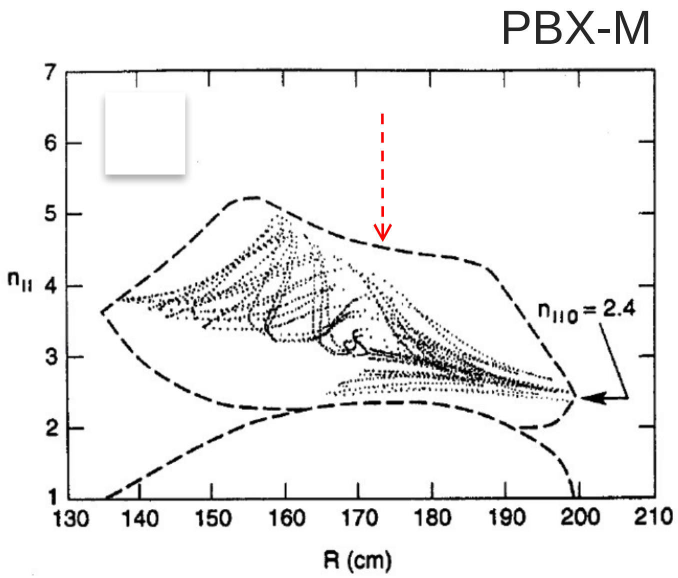
$N_{\parallel 0} = 1.7$

J. Decker et al. Nucl. Fusion, 51 (2011) 073025

KAM surface

$N_{\parallel}$ upshift bounded

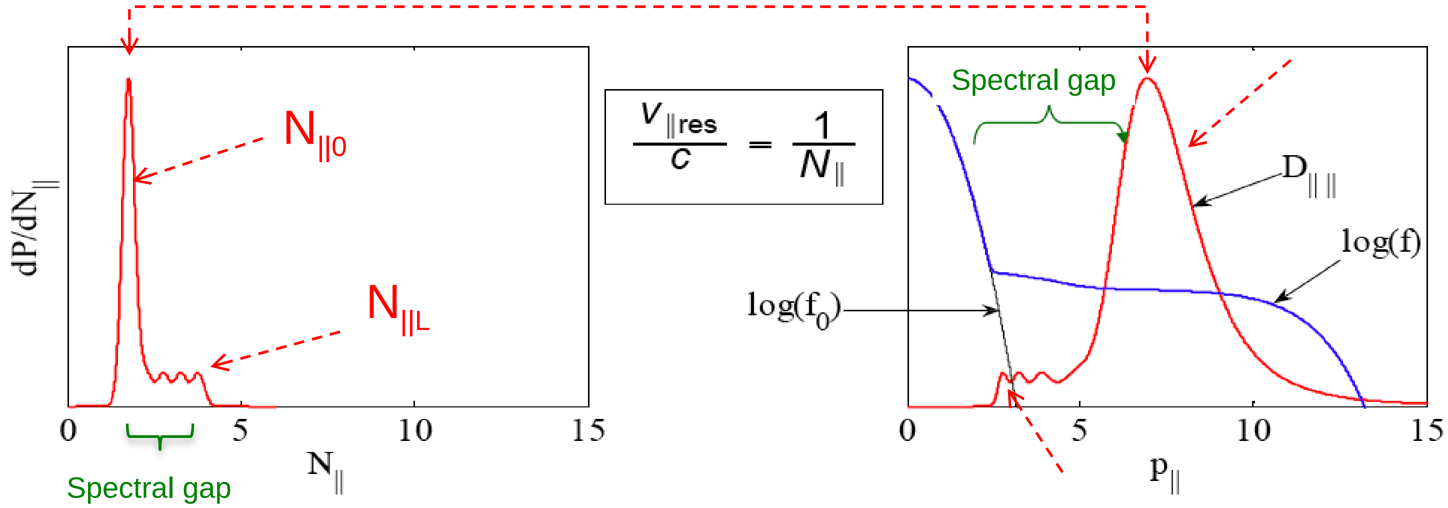
large R/a, $(B_p/B)(\omega_{pe}/\omega) < 1$



F. Paoletti et al. Nucl. Fusion, 34 (1994) 771

Spectral gap and quasilinear selfconsistency

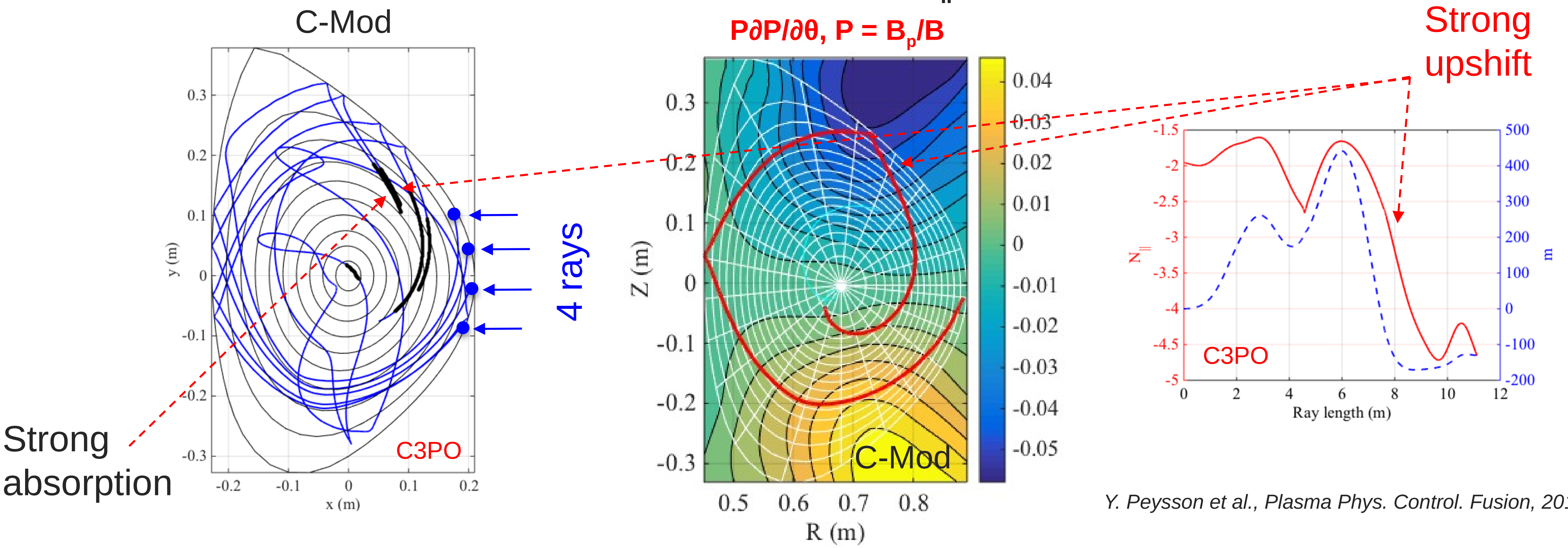
- **$N_{\|a}(0) < N_{\|L}(0) <$ $N_{\|0}$** → the condition of *single pass absorption* is fullfiled.
- **$N_{\|a}(0) <$ $N_{\|0}$ $< N_{\|L}(0)$** → the absorption of the LH wave is weak and the plasma almost transparent (no resonant electrons) → *large spectral gap or multipass absorption regime.* **Spectral properties of the LH wave must change as it propagates from the antenna** to pull out a tail of fast electrons from the thermal bulk such that it can be absorbed. *Magnetic inhomogeneity is the principal mechanism that is considered for bridging the spectral gap.*



- The flattening of the velocity distribution function by Landau damping reduces the wave absorption → the wave diffusion $D_{\|\|}$ and f must be self-consistently determined *(quasilinear)*

Toroidal refraction upshift and magnetic configuration

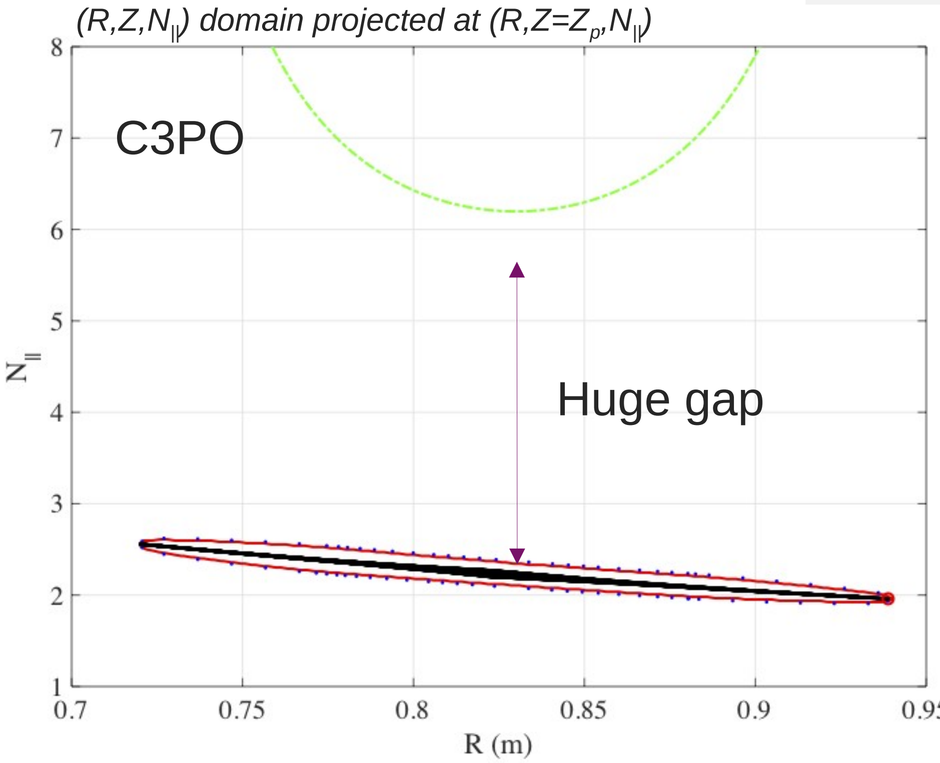
- The LH wave absorption becomes strong when $N_{||}$ is high enough. It occurs when the variation of the poloidal mode number *m* becomes large.
- This effect takes place when the ray trajectory crosses a region of the plasma characterized by a rapidly varying poloidal magnetic field with the poloidal angle θ, followed by an inward propagation after a reflection at the plasma edge.
- **A diverted configuration is favorable to a strong $N_{||}$ upshift (vicinity of the X-point)**

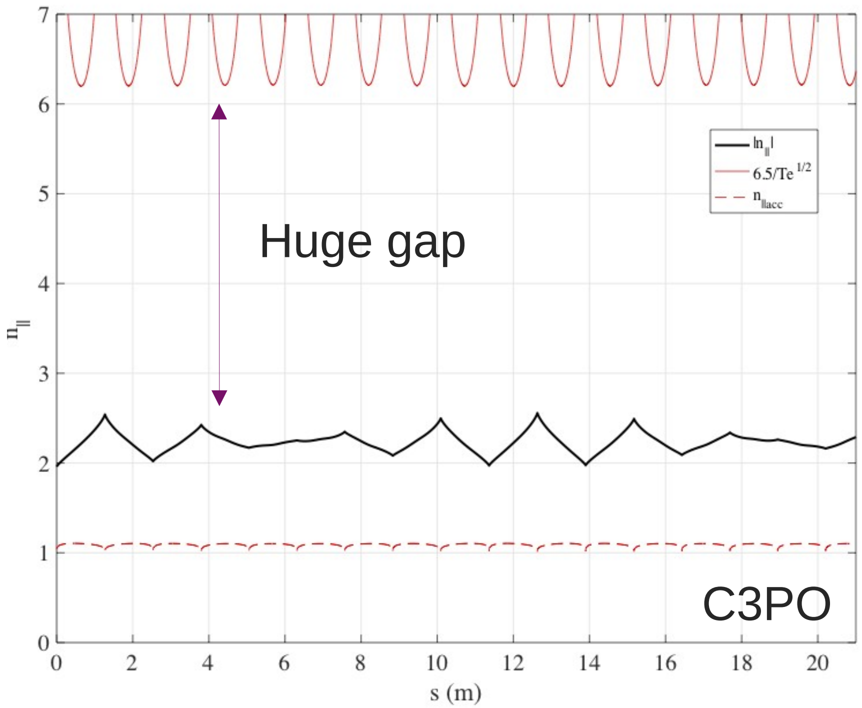


Y. Peysson et al., Plasma Phys. Control. Fusion, 2016, 58, pp. 044008

Kinematics of the LH wave for an extreme spectral gap

TRIAM-1M





V_{loop} = 0V, I_p = 27 kA

$P_{LH} \approx$ 23 kW, f_{LH} = 2.45 GHz

$T_{e0} \approx$ 1.1 keV, B_{T0} = 5.0 T

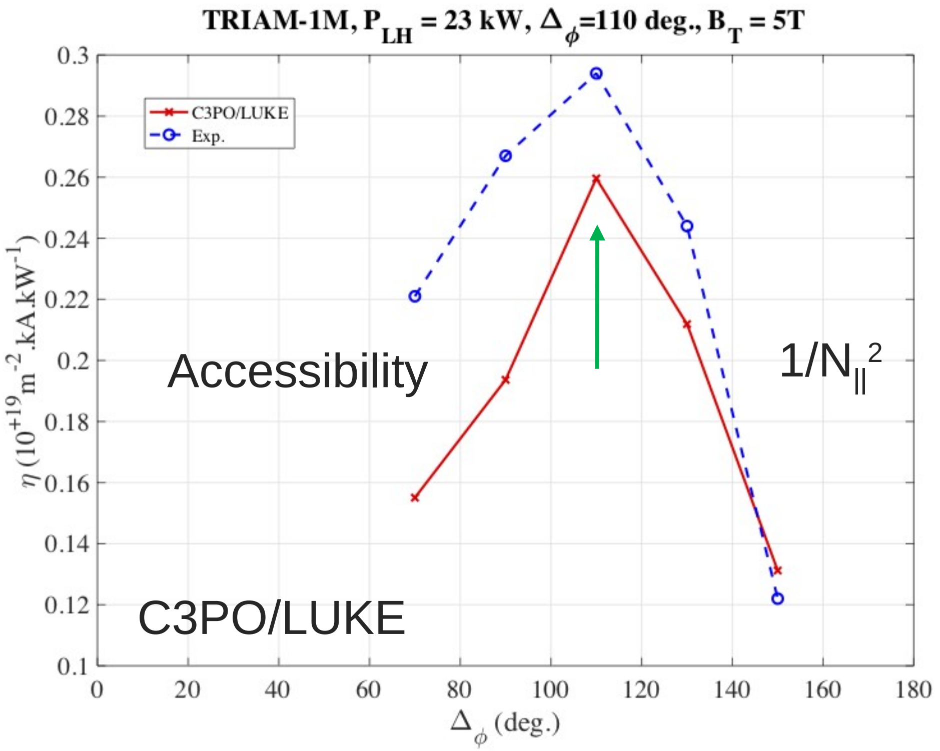
$$\bar{n}_e \simeq 1.7 \times 10^{+18}\, m^{-3}$$

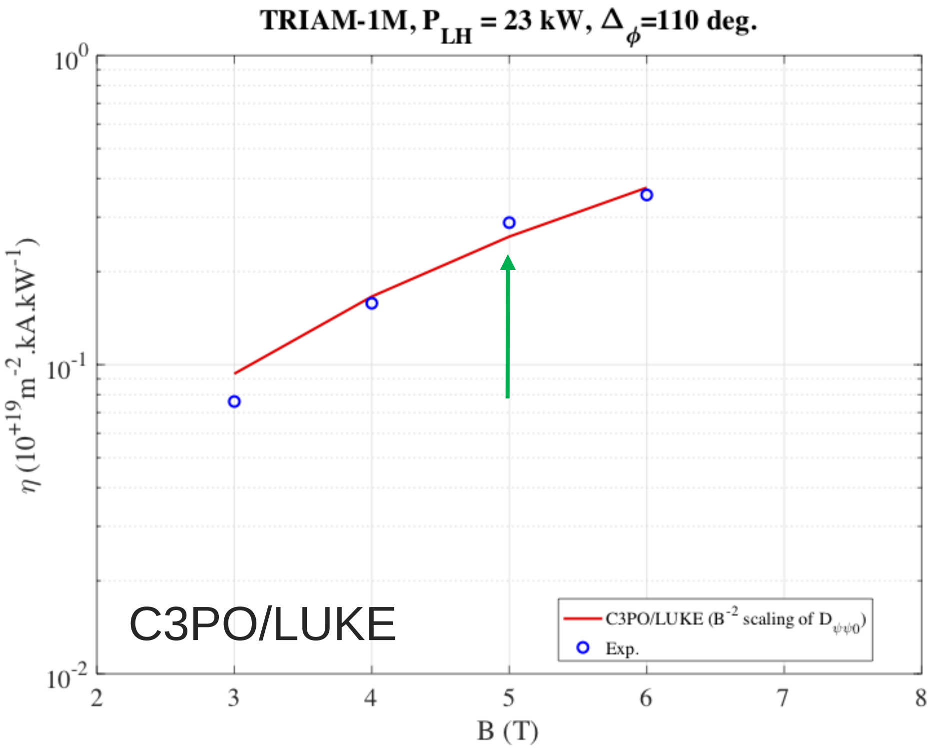
Without TSM : no LH current and HXR signals in contradiction with observations

Y. Peysson et al., J. of Fusion Energy, 39 (2020) 270
H. Zushi, et al., Nucl. Fusion, 43 (2003) 1600
S. Moriyama, et al., Nucl. Fusion, 30 (1990) 47

Current drive calculations with TSM model agree with observations : TRIAM-1M

CD efficiency η





green arrow : reference discharge

Y. Peysson et al., J. of Fusion Energy, 39 (2020) 270

Gyro-Bohm B^{-2} scaling of the anomalous radial transport (L-mode)

Outline

- Basics on the LH wave
- **First principle modeling tools**
- SLUKE simulation framework
- Simulation results
- Conclusion and prospect

First principle modeling tools

- LH current drive simulations are based on a *perturbative approach* from the plasma equilibrium (here given by **METIS** tokamak solver or with the **FEEQS** solver of the Grad-Shafranov equation)

- The excited power spectrum is calculated by the slab full-wave code **ALOHA**. The **TSM model** describes the time averaged spectral broadening by density filamentations in the scrape-off layer and its value at the separatrix.

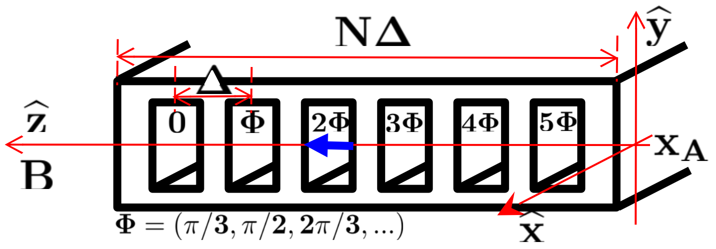
- Weak damping approximation → the propagation may be calculated independently from the absorption : **C3PO** ray-tracing code and **LUKE** a solver of the 3-D guiding-center averaged relativistic electron Fokker-Planck equation.

- The Fast Electron Bremsstrahlung is calculated by the **R5-X2** synthetic diagnostic from the electron distribution function.

The TSM model : from the LH antenna to the separatrix

Full-wave calculation in the SOL

LH antenna

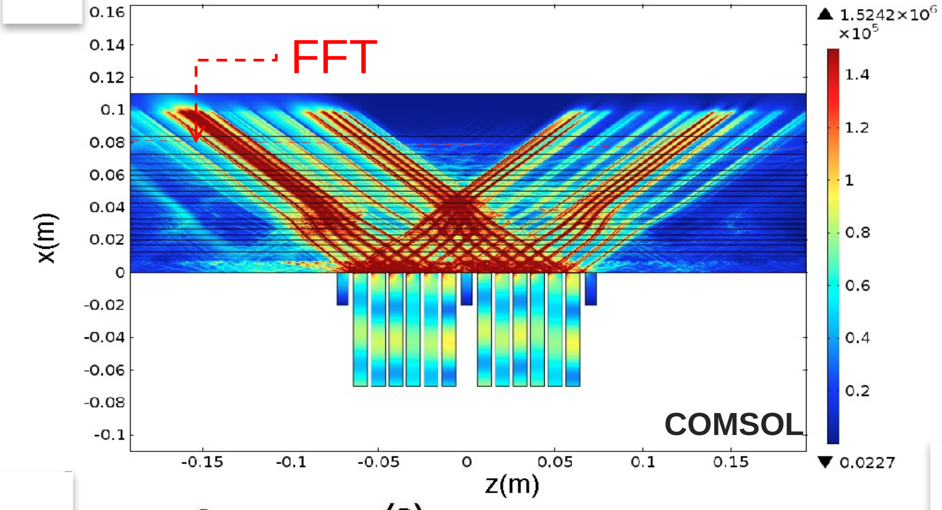


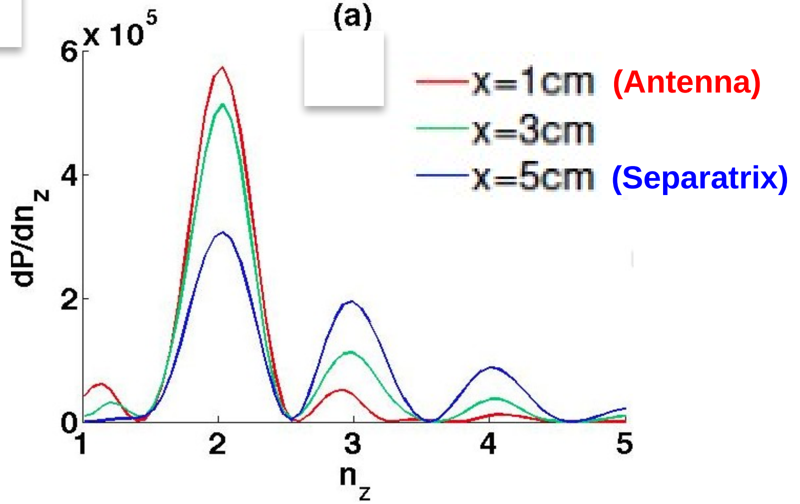
+

Fluctuating SOL (density filamentation)

Lobes may change in amplitude and position randomly (TSM model)

B. Biswas et al. Nucl. Fusion, 2023, 63, pp. 016029





Y. Peysson et al., AIP Conference Proceedings, 2023, 2984, 030012

M. Madi et al. PPCF 57 (2016) 125001

Core plasma propagation by ray tracing (C3PO)

- The LH wave is characterized by a small wavelength (mm $\leq \lambda \leq$ cm).
- In most regions of the plasma, the spatial ordering $\lambda \ll \Phi_{beam} \ll R$ is valid.

$$\mathbf{E}(\mathbf{x},t) = \mathbf{E}_{\mathbf{k},\omega}(\mathbf{x},t)\, e^{iS(\mathbf{x},t)}$$

Quasi plane wave approximation, $\lambda \ll \Phi_{beam}$

Smooth wavefield envelope

WKB approximation, $\lambda \ll R$

S → fast oscillating eikonal phase
Methods for uniform plasmas can be applied locally:

- Fourier space description
- group velocity
- local conductivity tensor

- ***The ray tracing formalism may be used if a wave front exists →*** $\mathbf{k} = \nabla S$, $\omega = -\partial S/\partial t$
- *(no ray stochasticity)*

Peysson, Y. and Decker, J., Theory of Fusion Plasmas (2008), 176

Technical details of the 3-D ray-tracing C3PO

- Curvilinear coordinate system: $(\rho(\psi), \theta, \phi)$
- 2-D axisymmetric configuration (cylinder, dipole, torus) + 3-D perturbation (nested magnetic flux surfaces)
- Vectorization of the magnetic equilibrium: Fourier series + piecewise cubic interpolation using Hermite polynomials: no interpolation performed at each time step
- (4,5) order Runge-Kutta
- rays are calculated inside the separatrix. Specular reflexion enforced - if needed - at ρ=1.
- ray calculation are almost stopped when the rf power is linearly damped
- cold, warm, hot and relativistic dielectric tensors
- written in C (MatLab mex-file)
- *distributed and remote computing capability* (1ray/core, GPU)

Peysson, Y. et al., Plasma Phys. Control. Fusion, 2012, 54, pp. 045003

The 3-D linearized guiding-center averaged relativistic electron Fokker-Planck equation (LUKE)

Magnetic ripple losses
Runaway electron avalanches

- Fully 3-D conservative formulation

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

$$\nabla \cdot \mathbf{S}^{(0)} = \frac{B_0}{\tilde{q}\lambda}\frac{\partial}{\partial \psi}\left(\frac{\tilde{q}\lambda}{B_0}\|\nabla\psi\| S_{\psi}^{(0)}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 S_p^{(0)}\right) - \frac{1}{\lambda p}\frac{\partial}{\partial \xi_0}\left(\lambda\sqrt{1-\xi_0^2}S_{\xi}^{(0)}\right)$$

configuration space

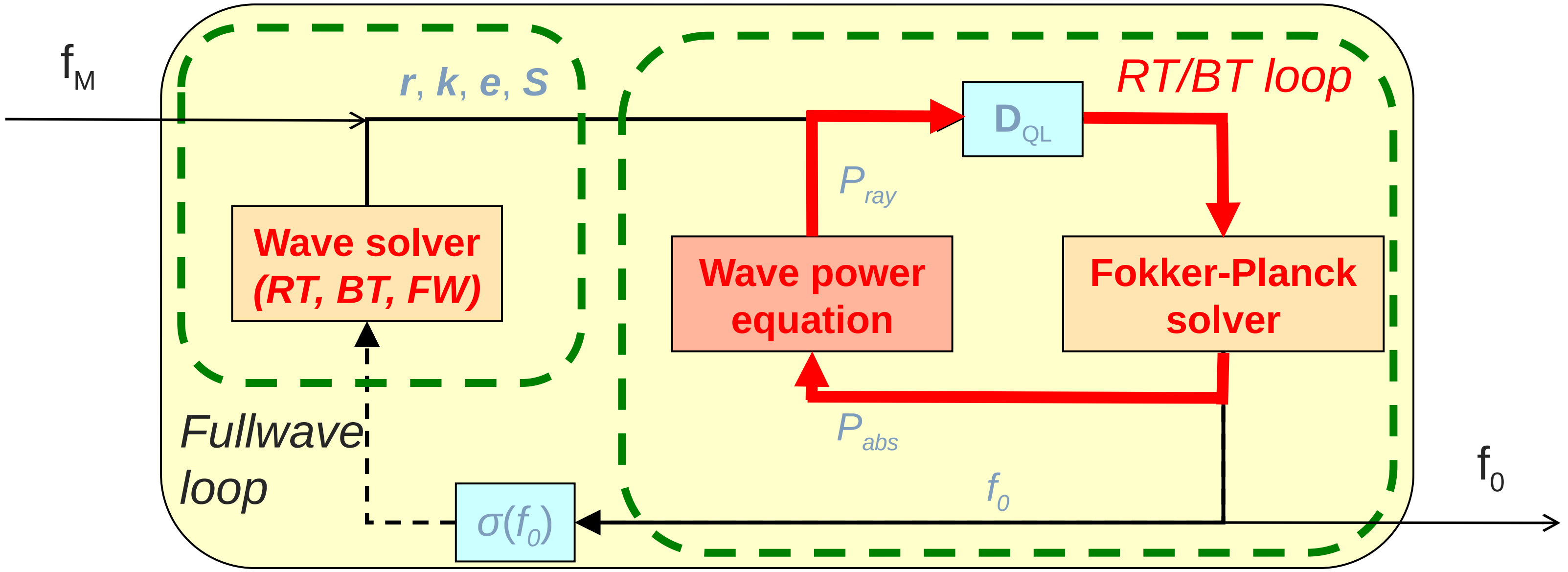
momentum space

Orbit effect

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

Propagation and absorption of the LH wave (C3PO + LUKE)

- In the **weak damping** limit, the propagation (*ray-tracing*) can be split from the absorption (*Fokker-Planck*).
- Propagation, described in the fluid limit ($v_\phi >> v_{th}$), concerns the thermal bulk. Absorption depends of suprathermal electrons and requires a kinetic description. *The quasilinear selfconsistency couples the wave power equation to Fokker-Planck solver.*



- If ray-tracing fails (Hamitonian chaos, caustics), **full-wave** calculations are necessary (TORLH, LHEAF, …) → *huge computational effort (> 3000 poloidal modes)*

Peysson, Y. and Decker, J., FST, 65 (2014) 22

Decker, J. and Ram A. K., PoP, 13 (2006) 112503

J. C. Wright et al. PoP, 11 (2004) 2473

The solver LUKE of the Fokker-Planck equation

- **Linearized relativistic collision operator (Belaiev-Budker for e-e term)**
- **High-Z atomic physics (Open-ADAS) with partial screening effects for e-i collisions (elastic and inelastic terms)**
- **Kennel-Engelman-Lerche relativistic rf diffusion operator**
- Curvilinear coordinate system (ψ, θ, ϕ)
- 2-D axisymmetric configuration (cylinder, torus, dipole)
- 3-D perturbation (nested magnetic flux surfaces)
- Non-uniform grids (f and fluxes). Usual Chang & Cooper interpolation for p grid *(f_M)*
- Fully implicit time scheme: *stable for large time step Δt*
- Discrete cross-derivatives consistent with boundary conditions *(stable scheme for D_{ql} >> 1)*
- Generalized incomplete LU factorization technique for an arbitrary number of non-zero diagonals *(highly sparse L and U matrices, low memory consumption)*
- written in MatLab
- Iterative inversion method (MatLab build-in or external solvers **MUMPS**, ...)
- *Distributed, parallel and remote computing (GPU for D_{ql} operator)*

R5-X2 synthetic diagnostic for fast electron bremsstrahlung

- *Quantum relativistic cross-sections* for e-i and e-e bremsstrahlung.
- *Account for the multi-species in the plasma*, including high-Z impurities consistently with LUKE Fokker-Planck calculations.
- *Partial screening effect for e-i bremsstrahlung (Born approximation)*
- Full integration along diagnostic chords and convolution with detector response → *direct quantitative comparison between modeling and experimental observation.*

Peysson, Y. and Decker, Phys. Plasmas, 2008, 15, 9, pp. 092509

Outline

- Basics on the LH wave
- First principle modeling tools
- **SLUKE simulation framework**
- Simulation results
- Conclusion and prospect

SLUKE concept

SLUKE is a **top layer scriptable framework** for existing LUKE codes (ALOHA, METIS, FEEQS, C3PO, LUKE, R5X2,...)

- The *concept is general* and may be applied to any existing suite of codes. It may be nested.
- Based on few **text scripts (no GUI)** → easily customizable, *keep whole history of simulations, single call,…*
- Existing codes are encapsulated in general SLUKE functions → new codes may be introduced (METIS → RAPTOR, …)
- **All input simulation parameters are propagated** in SLUKE functions → *add new physics at low level, new models, new codes*,…
- Data exchange may be done with any standard (IMAS,…)
- **Dedicated *object-language* for accurate manipulation of input parameters**

Remote and distributed computation capability

- *Enabling distributed and remote computing is one of the most important step towards automatic simulations* → done for MatLab functions

- *Embedded* ***SSH*** (SCP) communication protocol + *workload manager* (PBS, SLURM, TORQUE, HTCONDOR,…) : very robust and widely used.

- *A dedicated general toolbox* **MatRemote** has been designed for this purpose allowing a very simple syntax for distributed computing :

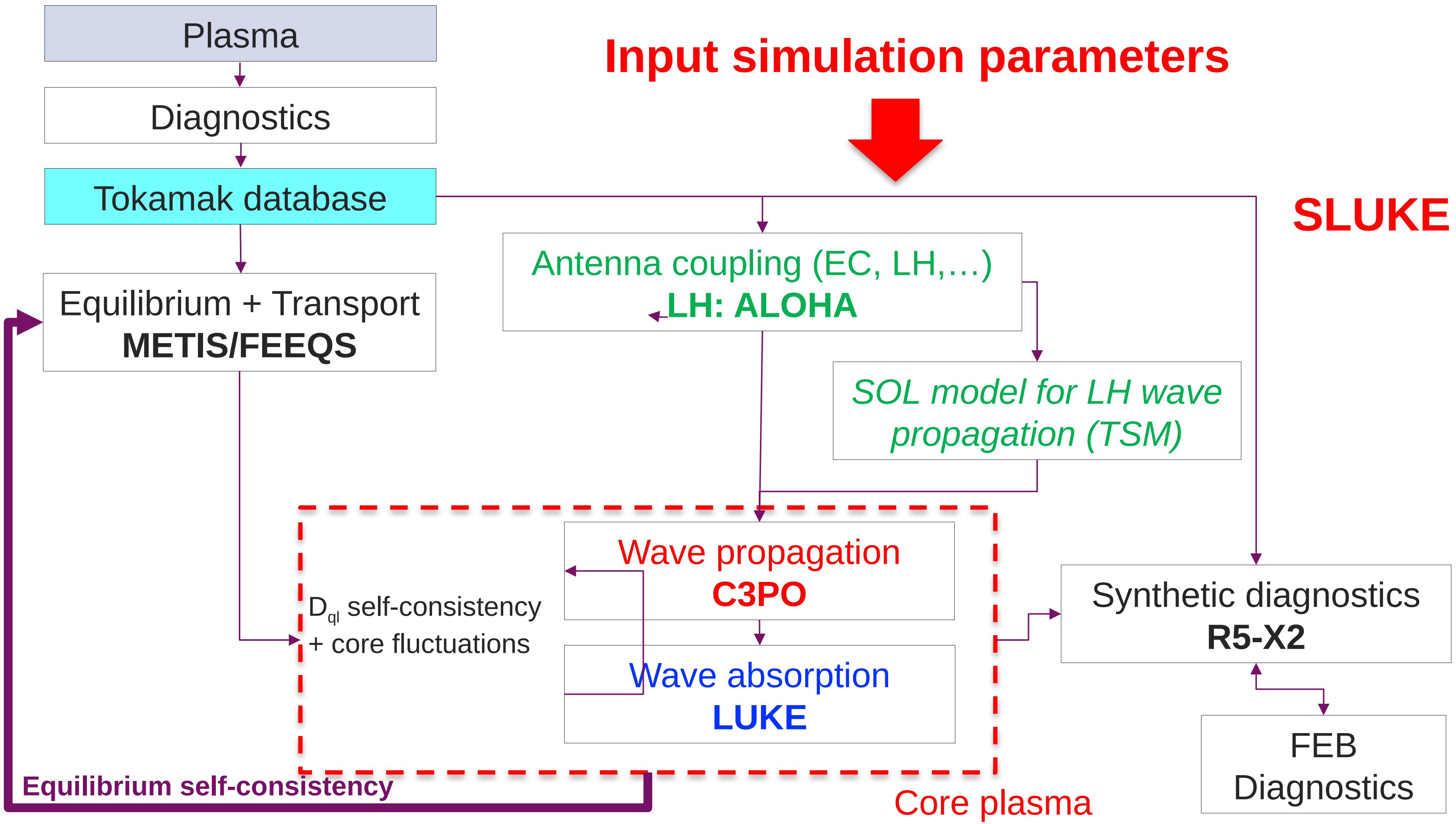
$[b_1,b_2,\ldots] = \textbf{any\_Matlab\_function}(a_1,a_2,a_3\ldots)$

↓

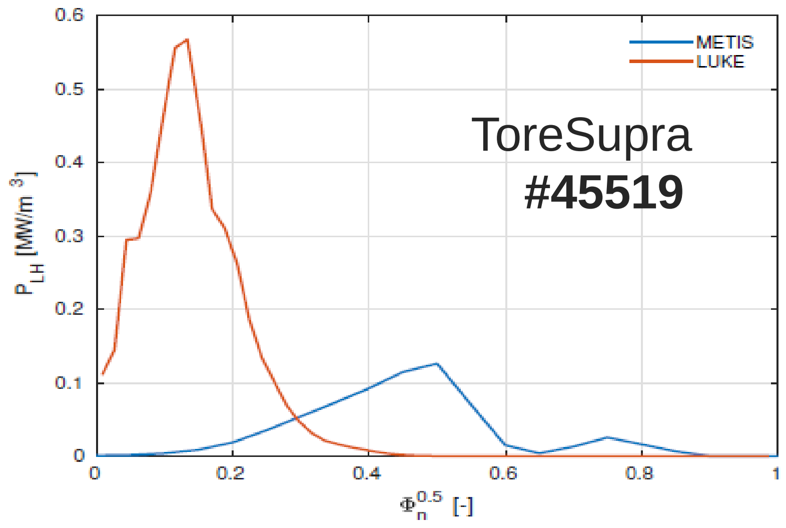
$\{[b_1,b_2,\ldots]\} = \text{remotecomputing}(@\textbf{any\_Matlab\_function},\{a_1,a_2,a_3\ldots\},2,\{a_{2\_range}\},\text{computer\_id})$

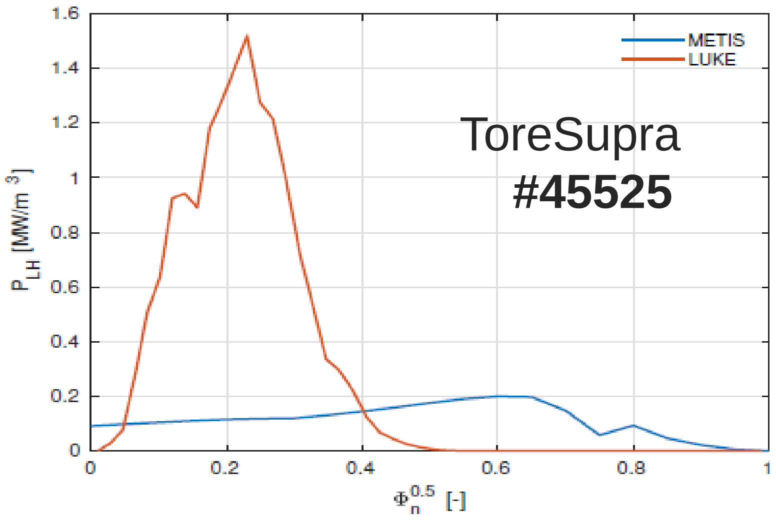
The toolbox may be also used for launching non-Matlab codes (Fortran, C, Python scripts, …)

METIS-SLUKE methodology



LH power deposition profiles METIS vs LUKE





- METIS, the tokamak solver, uses a simple model for the LH-driven current to reconstruct the electric field and the plasma equilibrium.
- However, the LH deposition predicted by LUKE, the kinetic solver, does not match the data used to generate the input equilibrium (different assumptions).
- It is necessary to provide LUKE's results as input to METIS.

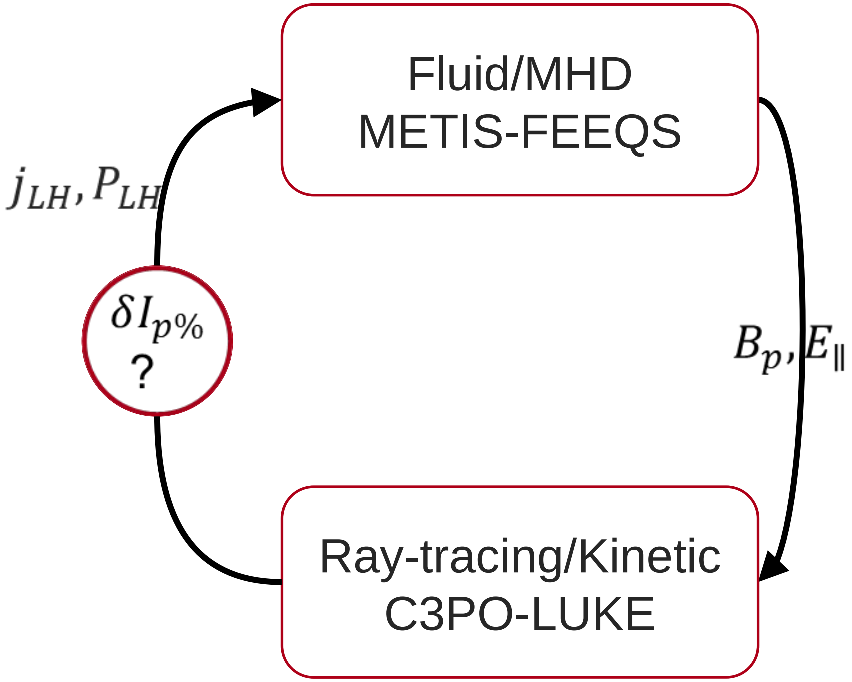
J-.F. Artaud, et al., J. Fusion Energy, 2020, 39, 270-291

The convergence logic

Convergence parameter:

$$\delta I_{p\%} = \frac{1}{I_p^{new}} \int |j_{new} - j_{old}| \, dA_{pol}$$

Takes into account the change in **total current** and in **current shape**



Although numerical convergence of this iterative scheme cannot be formally guaranteed by numerical tool due to the complexity and coupling between the involved codes, the physics of the problem and the reproducibility of LHCD regimes, strongly suggest the feasibility of achieving convergence in practice

Outline

- Basics on the LH wave
- First principle modeling tools
- SLUKE simulation framework
- **Simulation results**
- Conclusion and prospect

Simulation details

- Calculations have been restricted to Tore Supra discharges which are well diagnosed and characterized by accurate **Te** measurements (data validation). The automatic procedure is achieved with *autoTSmetis script* allowing to run METIS code with input of external current and power density profiles from LUKE kinetic calculations.

- Two set of discharges have been considered, one with Ohmic current dominant over the LH one, and another where LH current drive is predominate (even full non-inductive regime)

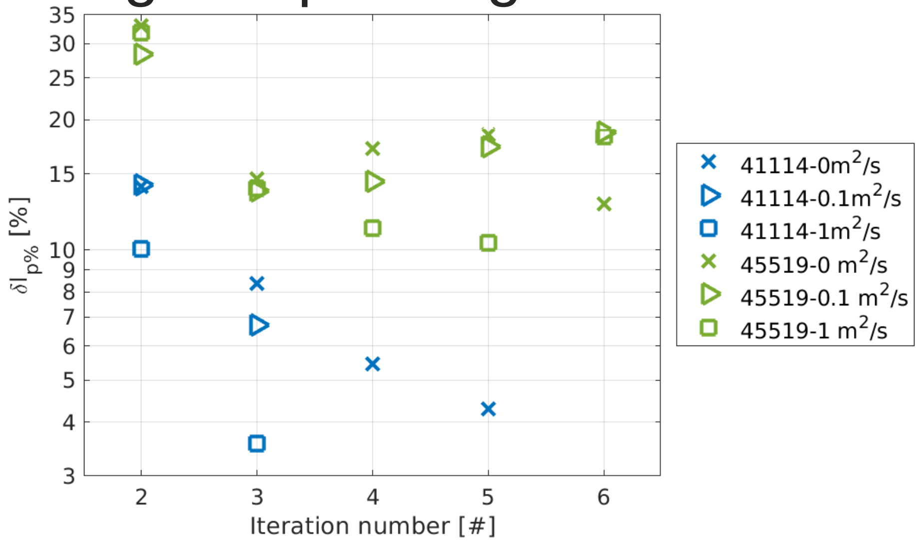
- Tore Supra discharges are :

inductive	non-inductive
#41114	#32299
#45519	#45525

Simulation details

INDUCTIVE DISCHARGES

- Moderate LH power ~1*MW*
- High total current >600*kA*
- High loop voltage >300*mV*



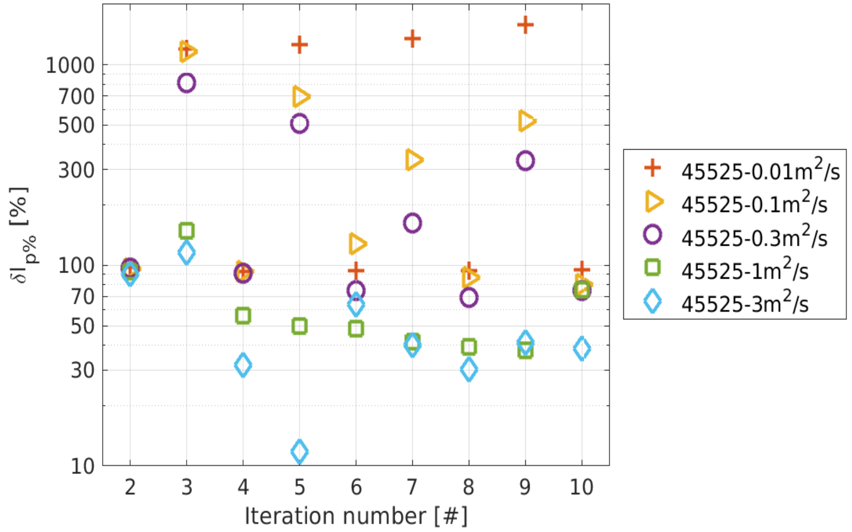
Low $\delta I_{p\%}$ → Low LH current

Quick convergence

D_{rr}: no qualitative changes

NON-INDUCTIVE DISCHARGES

- High LH power ~3*MW*
- Lower total current 500*kA*
- Null loop voltage ~5m*V*



High $\delta I_{p\%}$ → no consistent conv.

$\delta I_{p\%}$ → Bi-stable behaviour

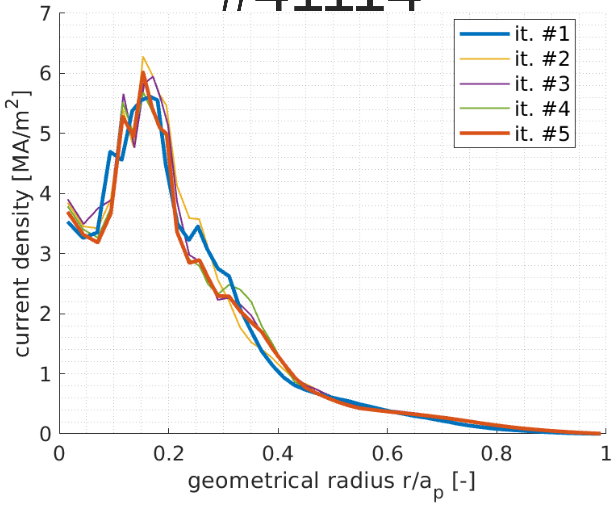
D_{rr}: convergence is stabilised

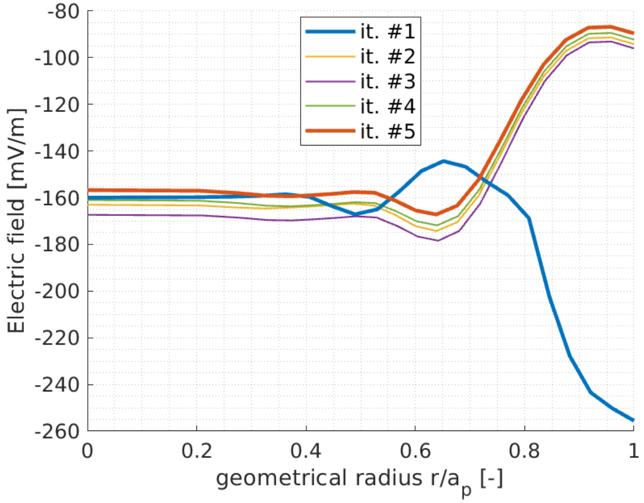
Simulation details

#41114

INDUCTIVE DISCHARGES

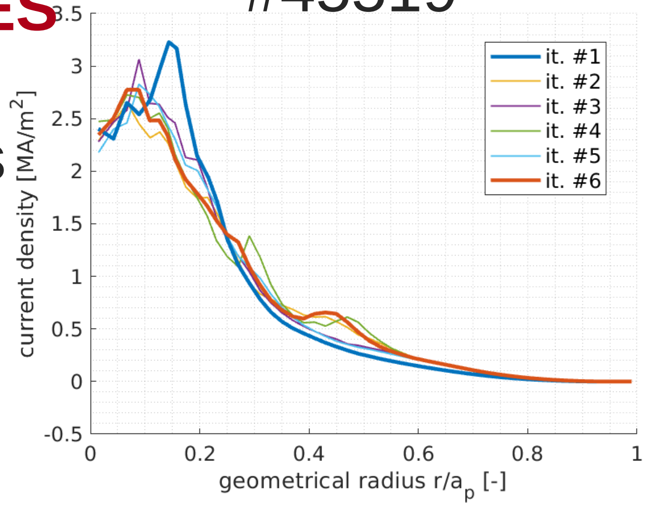
#45519

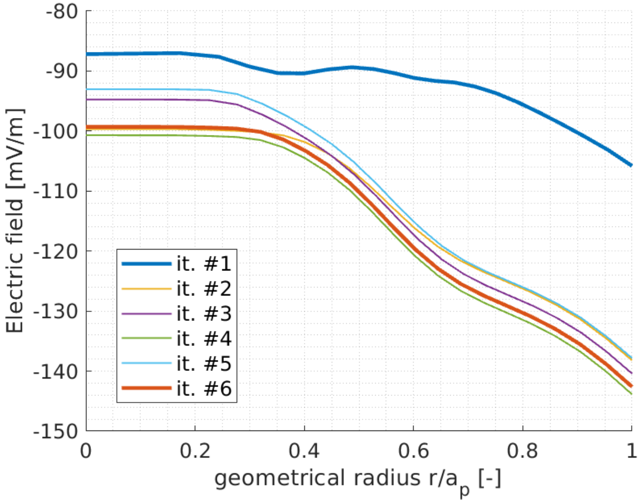




$$D_{rr} = 0m^2/s$$

Despite minor variations in the localization of LH-driven current, significant changes are observed in the parallel electric field profile. The evolution of the electric field is consistent and particularly relevant at the plasma edge

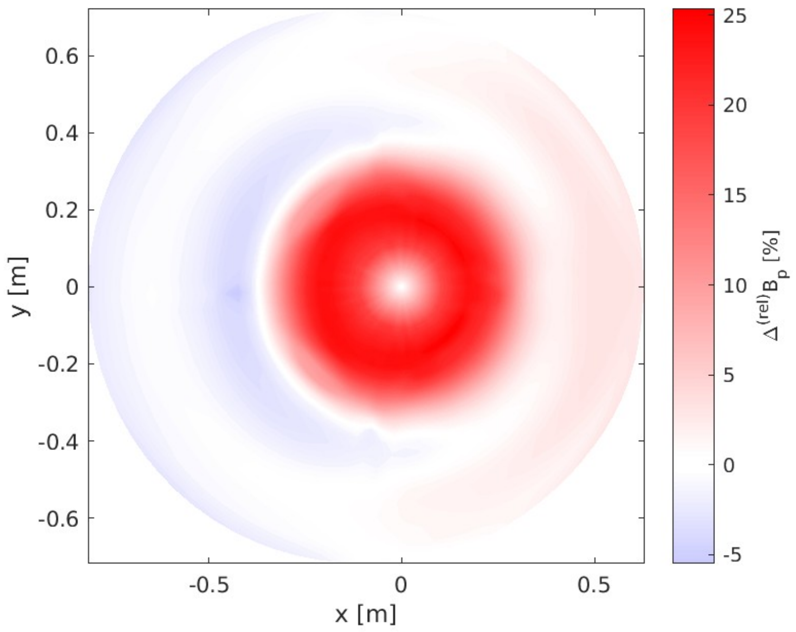




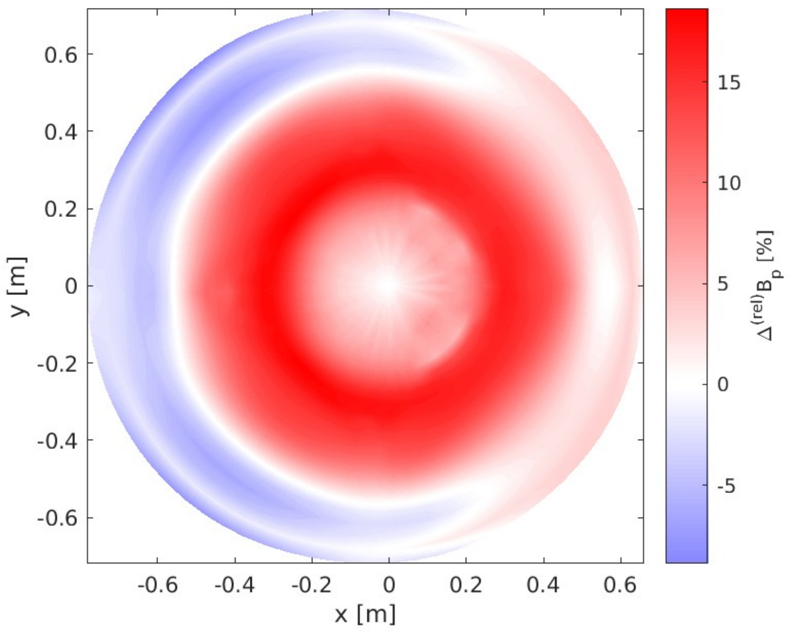
$$D_{rr} = 0m^2/s$$

Simulation details

#41114



#45519

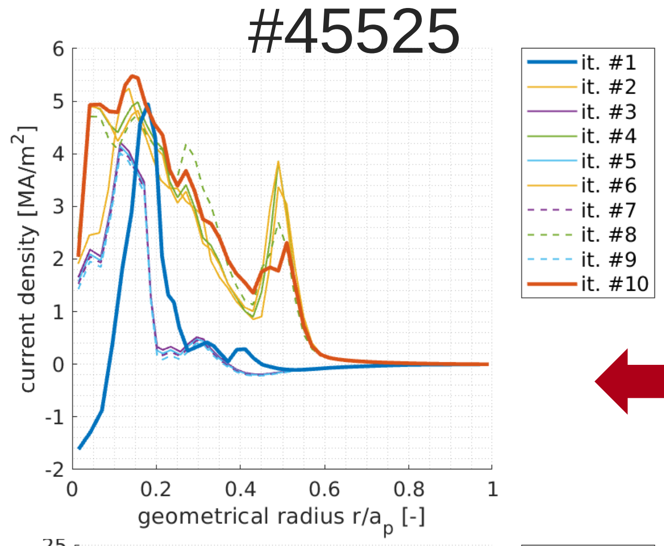


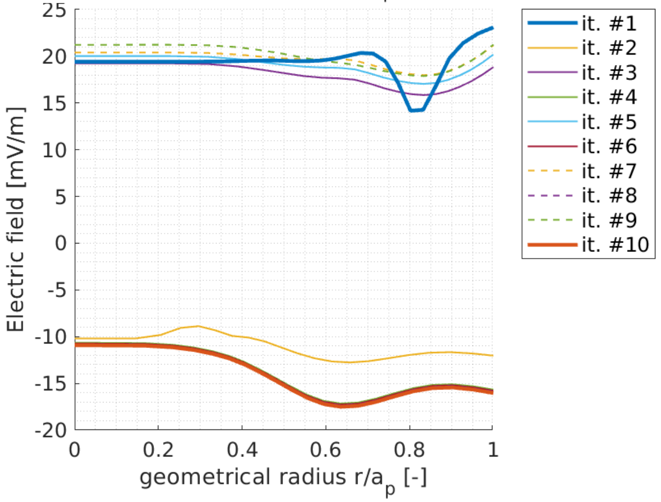
$$k_{\parallel} \simeq \frac{1}{B}\left(B_P \frac{m}{r} + B_T \frac{n}{R}\right)$$

The increase of the magnetic field in the core enhances the upshift and accounts for the improved absorption of the LH wave

Peysson, Y. et al., J. Fusion Energy, 2020, 39, 270-291

Simulation details





$D_{rr} = 0.01 m^2/s$

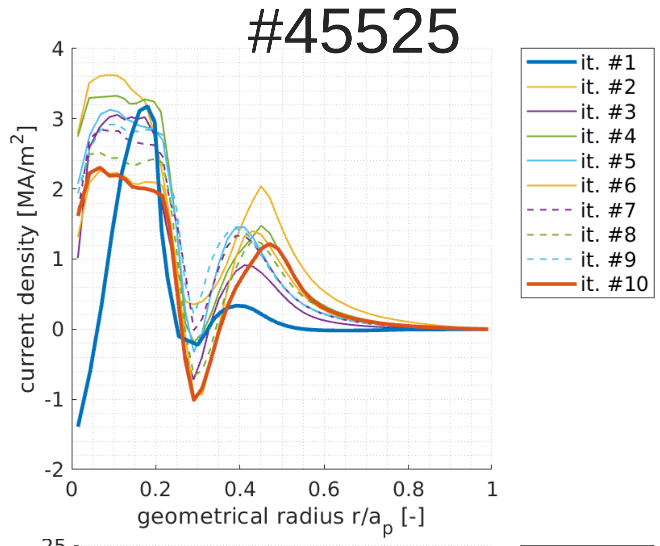
NON-INDUCTIVE DIS.

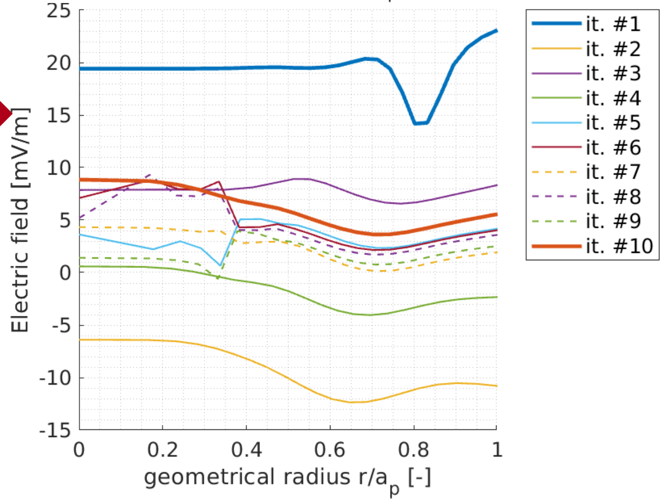
Convergence depends on D_{rr}

Bi-stable behavior: alternates profiles. no convergence to a single state.

Despite high $\delta I_{p\%}$, current profile shape become stable.

D_{rr}: stabilizing effect. It blend the exact LH deposition location



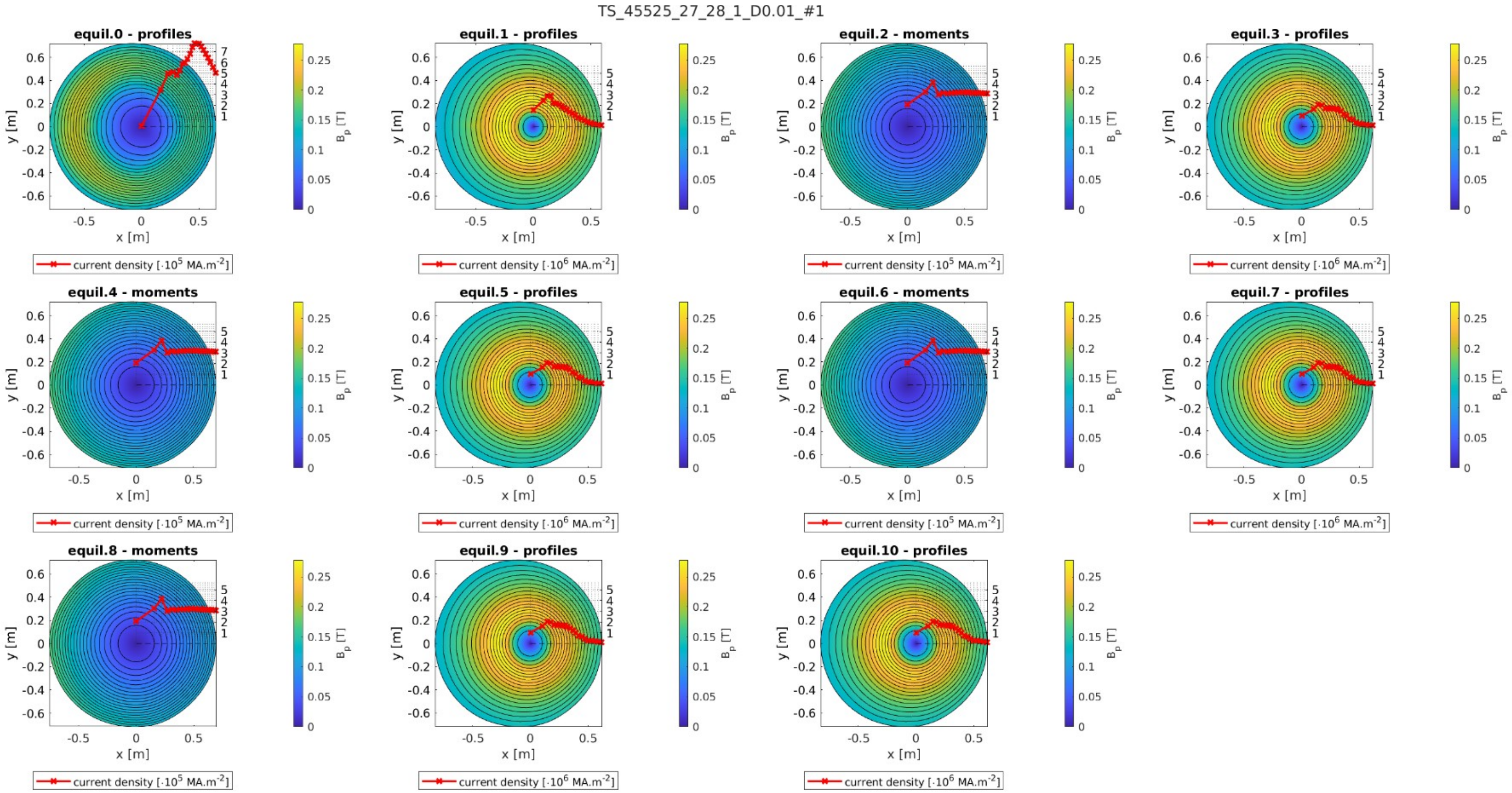


$D_{rr} = 1 m^2/s$

Simulation details

#45525

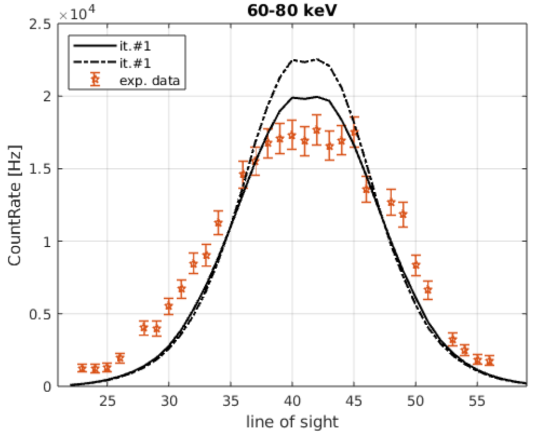
$$D_{rr} = 0.01 m^2/s$$



When bi-stability occurs, two families of equilibria and deposition profiles alternate. Current difference reduction schemes does not change the behavior, suggesting the cause is the interaction among the solvers (METIS and LUKE) rather than the magnetic reconstruction

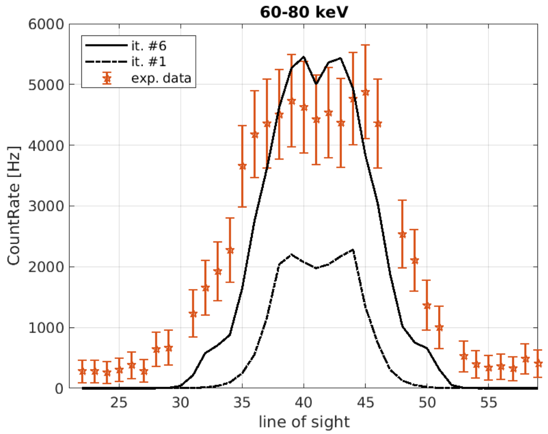
Simulation details

INDUCTIVE DIS.



#41114 $D_{rr} = 1.0m^2/s$

#45519 $D_{rr} = 0m^2/s$

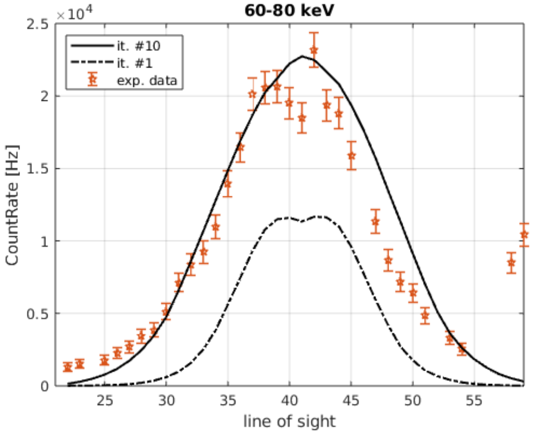


Comparison between experimental HXR signal (orange) and synthetic diagnostics (R5-X2) from the first (dashed) and the last simulation (solid) for the best-matching diffusion coefficient.

In all cases, there is good agreement with the R5-X2 signal from last iteration, better than the one from the first one.

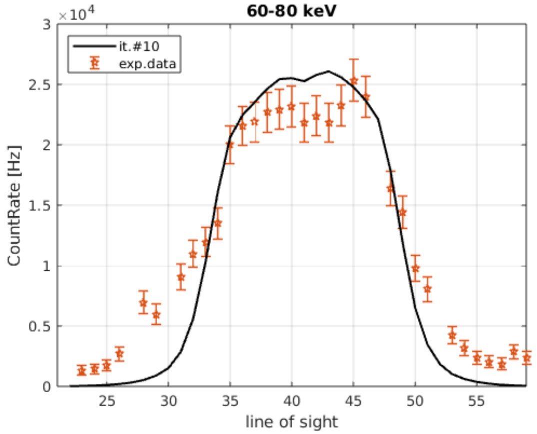
More reliable HXR profiles!

NON INDUCTIVE DIS.



#32299 $D_{rr} = 1.0m^2/s$

#45525 $D_{rr} = 0.3m^2/s$



Outline

- Basics on the LH wave
- First principle modeling tools
- SLUKE simulation framework
- Simulation results
- **Conclusion and prospect**

Conclusion and prospect

- The SLUKE scripts have been successfully set-up within the SLUKE framework to perform self-consistent calculations between METIS (coupled or not to FEEQS) and C3PO/LUKE.

- *Calculations have been restricted to Tore Supra discharges* which are well diagnosed and characterized by accurate **Te** measurements (data validation). The automatic procedure is achieved with *autoTSmetis script* available to run METIS code with input of external current and power density profiles from LUKE kinetic calculations.

- Calculations require a considerable numerical effort, and may last several days to be achieved. They are fully automatized within SLUKE.

Conclusion and prospect

- A clear convergence is observed for discharges where the Ohmic component of the plasma current predominates over the LH one.
- The converged solution is consistent with FEB measurements while the profile of the Ohmic electric has notably evolved.
- For discharge whose plasma current is dominated by the LH-driven component, the convergence is more difficult to be reached as the current location change stays important (bi-stable effect), as a result of non-linear effects. Nevertheless, a favorabletendency is observed when a radial diffusion coefficient is introduced and high enough.

Conclusion and prospect

- First results highlight the sensitivity of the full LH current drive simulation to the toroidal MHD equilibrium, even if ray stochasticity is almost negligible by considering spectral broadening in the SOL (TSM model).

- A statistical analysis based on a larger number of discharges is foreseen to validate at large scale the role played by the toroidal MHD consistency with kinetic calculations on the robustness of the numerical predictions against experimental observations.

- The work performed for Tore Supra will be extended to WEST tokamak using METIS tokamak code. (plasma poloidal shape became important aspect of the discharge)