CONFERENCE PRE-PRINT

ON THE SELFCONSISTENCY BETWEEN RAY-TRACING/FOKKER-PLANCK AND TOROIDAL MHD EQUILIBRIUM FOR THE LOWER HYBRID CURRENT DRIVE PREDICTION

Y. Savoye-Peysson
CEA, IRFM
Saint-Paul-lez-Durance, France
Email: yves.savoye-peysson@cea.fr

R. Saura, J.-F. Artaud, A. Ekedahl and J. Hillairet
CEA, IRFM
Saint-Paul-lez-Durance, France

Abstract

Calculation of the current driven by the rf wave at the Lower Hybrid (LH) frequency is carried out, with a wave dynamics fully consistent with the toroidal MHD equilibrium. For this purpose, the tokamak solver METIS, the Grad-Shafranov equation solver FEEQS and the LUKE suite of codes, ALOHA/C3PO/LUKE/R5-X2, have been encapsuled in the SLUKE simulation framework, allowing to implement easily such complex calculations and direct quantitative comparisons with experimental observations. It has been applied to the case of the LH wave in the Tore Supra tokamak, whose plasma characteristics are particularly well diagnosed. The general procedure to perform such calculations is presented and two regimes are investigated, in which the Ohmic plasma current is partially or conversely almost fully replaced by the LH-driven one. For the latter, it is shown that despite a strong absorption of the LH wave by considering a broadening of the excited antenna spectrum at the periphery of the plasma, the convergence towards a fully selfconsistent solution remains difficult, leading to a bi-stable regime. A radial transport used as a regularization parameter for the numerical scheme can stabilize this problem. Otherwise, when the Ohmic part of the plasma current predominates, a fast convergence is observed, and the electric field profile is significantly modified after few iterations.

1. INTRODUCTION

The radio-frequency wave at the Lower Hybrid (LH) frequency, ranging between 1 GHz and 10 GHz, has been widely used for nearly forty years in tokamaks in order to reach steady-state operation, while the toroidal current density profile is tailored to achieve enhanced fusion performances [1, 2]. Even if this non-inductive method is so far the best one in term of current drive efficiency, it has not been yet considered for the first phase of operation in ITER [3, 4], because of several technical limitations related in particular to the proximity between the antenna and the plasma in presence of a large neutron flux. Nevertheless, the LH wave remains attractive for many existing tokamaks of smaller sizes to extend the discharge duration, like for WEST [5, 6], EAST [7, 8], HL2-M [9], DIII-D [10, 11] and KSTAR [12, 13], and therefore is still the object of numerous experimental and theoretical investigations [14, 9, 15].

The control of the current density profile by the LH wave has always been a challenge, due to the well known spectral gap problem which is particularly critical in tokamaks of small or medium dimensions[16, 17]. Many physical mechanisms have been considered as potential candidates to bridge it, thus allowing to pull out a tail of energetic electrons resonantly interacting with the LH wave from the thermal bulk. Indeed, to reduce the fast electron collisionality and improve the current drive efficiency, thus limiting the level of the needed recycled rf power for drive non-inductively the plasma current in a reactor, the phase velocity of the LH wave along the magnetic field line must be as large as possible as compared to the thermal one. However, the lack of resonant electrons at the corresponding kinetic energies in a thermal plasma makes it, in principle, transparent to the LH wave. Experimentally, such a regime has never been observed, even for a highly bounded propagation domain which is unbridgeable by toroidal refraction. Indeed, in this case, full current drive is well achieved experimentally, suggesting that one or several physical mechanisms are always at play in tokamaks to bridge it, whatever the geometrical configuration [18, 19, 20, 12, 21, 22, 23] . Among them, the toroidal refraction of the LH wave, as it propagates in the core plasma, has been considered for a long time as the main candidate, though recent LH current drive simulations suggests that the spectral gap is likely already bridged in the Scrape-Off-Layer (SOL), between the antenna and the plasma separatrix.

Since the LH wave never encounters any cyclotronic resonance along its propagation, its power absorption profile resulting from the electron Landau damping parallel to the magnetic field line is broad and very sensitive to the characteristics of the toroidal magnetohydrodynamic (MHD) equilibrium. As a consequence, there is a potentialy strong interplay between the LH wave propagation, the kinetic absorption and the plasma equilibrium conditions, making the LH wave current drive modeling strongly non-linear. Therefore, this regime requires a fully self-consistent description between the toroidal MHD equilibrium and the LH wave dynamics, the local electric field value being the adjustment variable determined by solving the equation describing the resistive evolution of the plasma current, since this selfconsistency is not temporal [24, 25]. The local level of the electric field itself may modify the tail characteristics driven by the LH wave, accelerating the resonant electrons to further kinetic energies by a synergistic mechanism studied long time ago [26, 25]. Such an approach is therefore not only critical for describing accurately the LH-driven current in a stationnary or steady-state regime, but also to investigate the potential impact of the LH wave on the dynamics of runaway electrons, which are particularly sensitive to the profile of the electric field in the plasma.

In this context, a global study of a self-consistent modeling of the LH current drive with the toroidal MHD equilibrium has been carried out whose first results are reported in this paper. It concerns regimes where the Ohmic plasma current is partially or fully replaced by the LH-driven current. For this purpose, the tokamak solver METIS [27], the solver FEEQS of the Grad-Shafranov equation [28], and the LUKE suite of codes, ALOHA/C3PO/LUKE/R5-X2 [29, 30, 31, 32] which allows direct quantitative comparisons with experimental observations, in particular the Fast Electron Bremsstrahlung (FEB), have been encapsulated in the simulation framework called SLUKE, which has been designed to implement easily such complex chain of calculations. The question of equilibrium selfconsistency is particularly important when the tokamak solver used a LH model that predicts a current and power density profiles significantly different from the one predicted by coupled ray-tracing / kinetic calculations as shown in Fig. 1 for METIS and LUKE. In that case, a selfconsistency procedure must be performed. In Sec. 2, the basics of the LH wave and the first principles modeling are described to highlight the role of each code and their interplay. The SLUKE framework is presented in Sec. 3 before discusing simulations and results in Sec. 4.

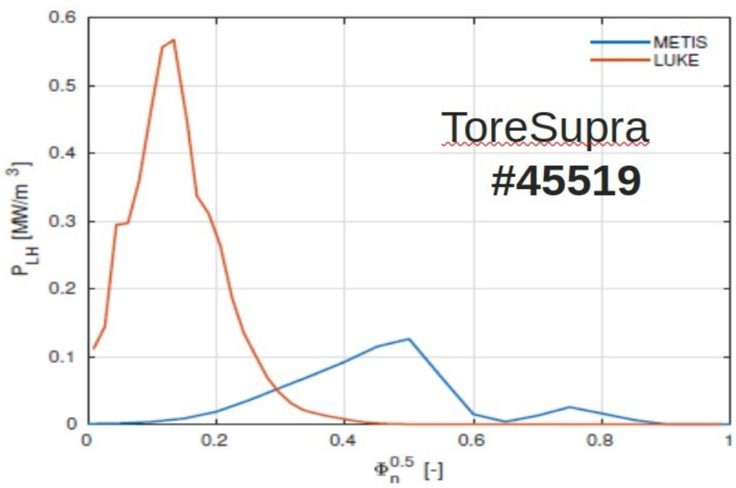

Fig. 1 : Comparison between code predictions for the LH power density radial profiles between METIS (blue) and LUKE (red) codes at the first iteration. The difference arises from a different LH model in METIS. Here Φ_n is the normalized poloidal flux.

2. BASICS OF THE LH WAVE AND FIRST PRINCIPLE MODELING

The resonant Landau interaction along the magnetic field lines of a tokamak is a natural mechanism to accelerate a tail of highly energetic electrons from the thermal bulk up to several hundred keV and therefore drive non-inductively the toroidal plasma current with a high efficiency. The slow branch of the LH wave characterized by a high parallel phase velocity $v_{\|}$ allows this mechanism to be implemented, the corresponding toroidal refractive index ranging between 1.4 and 3, for which resonant fast electron kinetic energies are lying between 30 and 130 keV approximately. LH current drive simulations are based on a perturbative approach from the plasma equilibrium (here given by METIS tokamak solver [27] or with the FEEQS solver [28] of the Grad-Shafranov equation for improved numerical accuracy). As the LH wave does not propagate in vacuum, it must be excited by an array of waveguides placed inside the edge cut-off layer where the electronic plasma frequency ω_{pe} matches the LH wave frequency ω_{LH} in the SOL. Wave characteristics at the antenna are determined by slab fullwave calculations (ALOHA code [29]) and the power spectrum is deduced from the Fourier transform of the wave electric field structure. The excited power spectrum is therefore made of a main lobe at the parallel refractive index $N_{\|0}$ and multiple small satellite ones, all of them being used as initial conditions for propagation calculations.

The domain into which the LH wave can propagate in a non-uniformly magnetized plasma is bounded at low values $N_{\|}$ by the Stix-Golant accessibility condition, and at high $N_{\|}$ values by the kinematic Kolmogorov-Arnold-Moser surface, when the conditions of large R/a and $(B_p/B)(\omega_{pe}/\omega) < 1$ are fulfiled, which is often encountered in tokamaks of small or medium sizes [9]. If the core plasma is too cold, the condition of linear absorption $N_{\|} > N_{\|L}$, where $N_{\|L} = 6.5/\sqrt{T_e}$[keV], can never be achieved, and the plasma is almost transparent to the LH wave, the latter being unable to pull out resonantly a tail of fast electrons from the thermal bulk [9]. In this case, the non-resonant collisional absorption predominates over the resonant Landau damping, a physical process that is always present in the plasma and taken into account in all simulations. In such a regime, if the LH wave propagation is described by rays assuming that the WKB approximation holds locally (C3PO ray-tracing code [30]), a stochastic behaviour is found numerically, extremely sensitive to any small perturbations of the simulations parameters, while conversely, experimental observations are very robust [33]. Even if the spectral upshift due to toroidal refraction is always present, the spectral gap defined by $N_{\|L}$ - $N_{\|0}$ may not be filled before the divergence of neighboring rays (characterized by Liapunov exponents), since resonant absorption is too small. It was suggested that the power spectrum at the separatrix is much broader than the excited one at the antenna, such that the spectral gap is already filled before the wave propagates in the core plasma, because of density fluctuations in the SOL, leading to an enhanced absorption of the LH wave (almost single pass regime) [33]. The Tail Spectral Model (TSM) which described heuristically this mechanism has been largely validated against experimental observations to describe FEB measurements, even in extreme cases where toroidal refraction is almost negligible, ie when R/a >> 1 [9]. Such a mechanism makes code predictions considerably more robust. As the weak damping approximation holds for the LH wave, the propagation may be calculated independently from the absorption. From the characteristics of the rays calculated once by the ray-tracing code C3PO, the power that is transfered from the wave to the electrons along the ray paths is determined by the solver LUKE of the 3-D (2-D momentum space, 1-D configuration space) guiding-center averaged relativistic electron Fokker-Planck equation [31]. The quasilinear self-consistency is therefore performed such that the 2-D electron distribution function in momentum space is consistent with rf diffusion operator [33].

The local value of the eletric field in the plasma as determined by the tokamak solver METIS, which may accelerate electrons to kinetic energies beyond the LH resonant domain is considered in kinetic calculations, as well as the possibility of an anomalous radial transport of the fast electrons which smooth out the LH-driven current. Once calculated, the line-integrated hard x-ray emission is determined by the synthetic diagnostic R5-X2 [32], allowing a direct quantitative comparison with measurements by considering detector's responses. Such a first principle modeling approach allows to characterize accurately all the physical mechanismes at each calculation step, the compatibility between the approximations, and their numerical implementation. It guarantees the overall coherence of the chain of codes, a major constraint for a reliable and accurate description of the physics at play, even if the the solution found by this method is not necessarily unique.

3. SLUKE SIMULATION FRAMEWORK

The implementation of the whole calculation chain represents a considerable numerical challenge. For this purpose, a top layer scriptable framework called SLUKE written in Matlab has been designed in which all codes are incorporated, as well as the access to the experimental databases such that comparisons between modeling results and observations can be automatically performed. Though primarily dedicated to the subject here considered, the SLUKE concept is general and may be applied to any suite of codes, while it can itself be nested. It is based on few text scripts easily customizable. The whole history of the simulations may be kept without saving a huge amount of data (possibility to use version control software), and shared between users to compare simulations or start easily new ones. All input simulation parameters are propagated in a set of dedicated functions allowing to add quickly new physics at low level, but also new models or codes. For this purpose, all existing codes used here have been encapsuled in these dedicated functions, for which data exchange may be done using any suitable numerical standard.

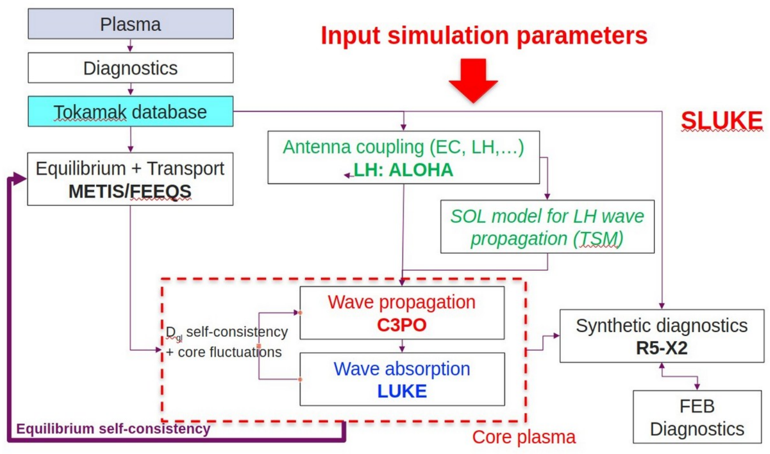

Fig. 2 : SLUKE code set-up. The selfconsistency between METIS and LUKE suite of codes is indicated by the violet line.

In order to avoid complex manipulations of the scripts, a dedicated set of scripts has been developed, which guarantees data consistency. Within this framework, the simulation tools are not becoming black boxes, since all input parameters are gathered in a single text file, while it is convenient to locate at which level they are taken into account.

Enabling distributed and remote computing is also one of the most important step towards automatic simulations. It has been performed by a set of Matlab functions available in a dedicated toolbox called *MatRemote*, where the SSH (Secure Shell) communication protocol has been embedded as well as other useful ones. In order to launch multiple simulations on different machines, processors or cores in a robust way, different workload managers have been considered like SLURM and HTCONDOR, but also other ones. In case of a crash of the local machine from which the simulations are launched, or the remote one on which calculations are performed, the simulations may continue without a general restart from scratch, once the reboot phase is achieved. This is particularly important, especially when simulations at large scale are performed, all of them lasting many hours or even several days. It is interesting to notice that the remote toolbox *MatRemote* may be also used for launching non-Matlab codes (Fortran, C, Python scripts, …). The general diagram that illustrates the simulations here considered with METIS rokamak solver and the LUKE suite of codes is given in Fig.2.

4. SIMULATION RESULTS

The self-consistency between the toroidal MHD equilibrium and kinetic calculations performed with C3PO/LUKE is characterized by a convergence parameter $\delta_{Ip}/I_p = \int |j_{new}-j_{old}| dA_{pol}/I_{pnew}$, which characterizeses the relative change in the plasma current density as iterations are carried out. Here, j_{new} and j_{old} are the new and previous current density profiles respectively for one iteration, I_{pnew} is the new value of the plasma current and dA_{pol} the poloidal element of surface. When the convergence is achieved then δ_{Ip}/I_p is decrasing at each iteration step. It takes into account the change in total current and its shape. Although the numerical convergence of this iterative scheme cannot be formally guaranteed by a defined criterion due to the complexity and coupling between the involved codes, the physics of the problem and the reproducibility of the LHCD regimes, strongly suggest the feasibility of achieving convergence. The iterative sheme is illustrated in Fig. 2, where current and power density profiles are transferred from C3PO/LUKE to METIS solver with appropriate flux surface averaging, while, in return, the toroidal MHD equilibrium is obtained from METIS (or FEEQS) together with the flux surface averaged parallel electric field. Two sets of discharges have been considered to investigate the

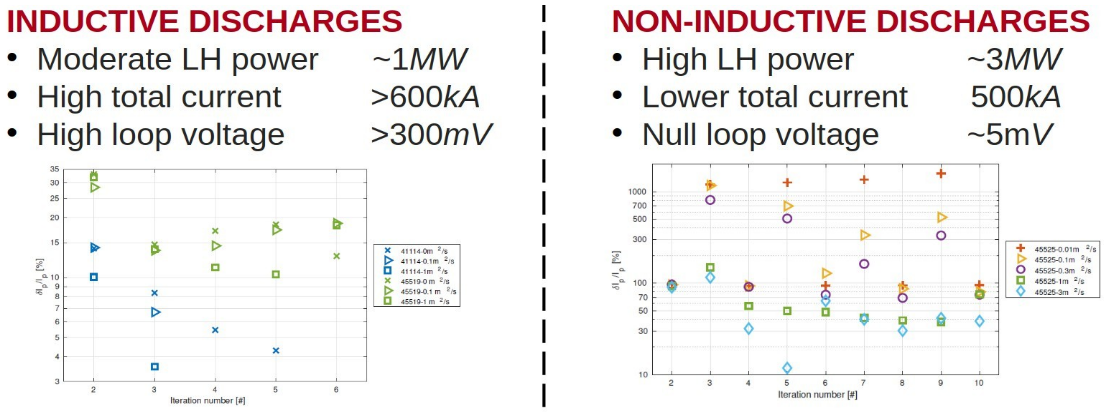

Fig. 3 : Relative variations of the plasma current Ip with iterations for the “inductive” (left) group of discharges and “non-inductive” (right) ones. On the left side, the blue signs correspond to the discharge #41114, and the green one to #45519. The cross, triangle and squares correspond to an increase D_{rr} value 0, 0.1 and 1 m2/s. On the right side, the convergence is for the discharge #45525, with D_{rr} ranging from 0 to 3 m^2/s.

consequences of the toroidal MHD consistency on current density profiles prediction, Tore Supra shots #41114 and #45519 for the group of “inductive” discharges for which the Ohmic current predominate the LH one, and conversely the “non-inductive” set of discharges #32299 and #45525 where the LH-driven current is dominant. For the “inductive” one, the LH input power is moderate, about 1 MW and the plasma current is large, above 600 kA. Consequently the loop voltage is rather high, larger than 300 mV. As shown in Fig. 3, the convergence is fast and $\delta I_p/I_p$ is decreasing down to 5% approximately in three iterations for discharge #41114 while a plateau is reached #45519 at about 15-20%.

The introduction of an anomalous radial diffusion D_{rr} as a numerical regularization parameter does not lead to qualitative changes in this case on the converged solution (FEB profiles, current level,…). As displayed in Fig. 4, the current density profile evolves marginally, while the parallel electric field changes significantly. For the discharge #41114, the parallel electric field changes for r/a > 0.6, while for the discharge #45519, it changes at all radii. The evolution of the parallel electric field is consistent and particularly relevant at the plasma edge. For the group of "non-inductive" discharges characterized by a higher input LH power of 3 MW, a lower plasma current of 500 kA approximately and an almost null loop voltage less than 5 mV, the convergence is much more difficult to be achieved as shown in Fig. 3 since $\delta I_p/I_p$ cannot decrease with iterations and bi-stable regime is observed with large jump of the plasma current that are not observed experimentally. A trend to obtain a convergence is only observed if D_{rr} is large, above 1m^2/s. The bi-stability is clearly visible in Fig.5 where two families of 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. The stabilizing effect of D_{rr} can be well observed on the current density profile during the series of iterations in Fig. 5, since the shape of the current density profile remains almost similar.

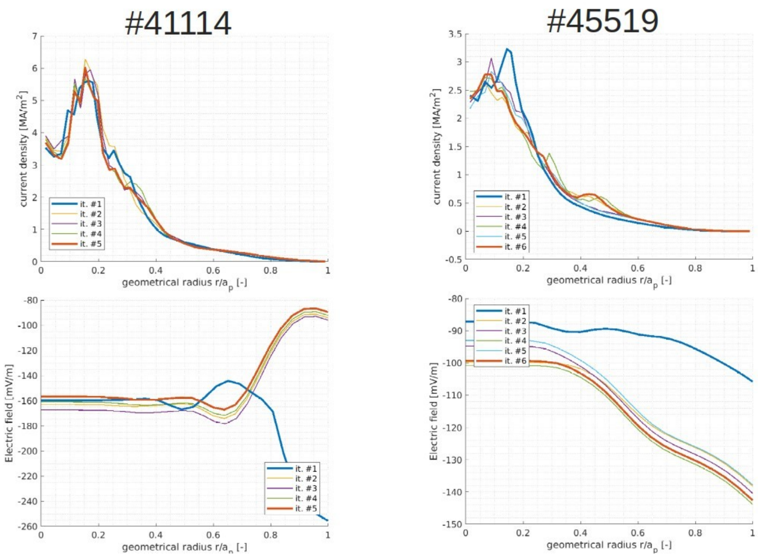

Fig. 4 : Current density and parallel electric field profiles as functions of the number of iterations for discharges #41114 and #45519 belonging to the "inductive" group of discharges.

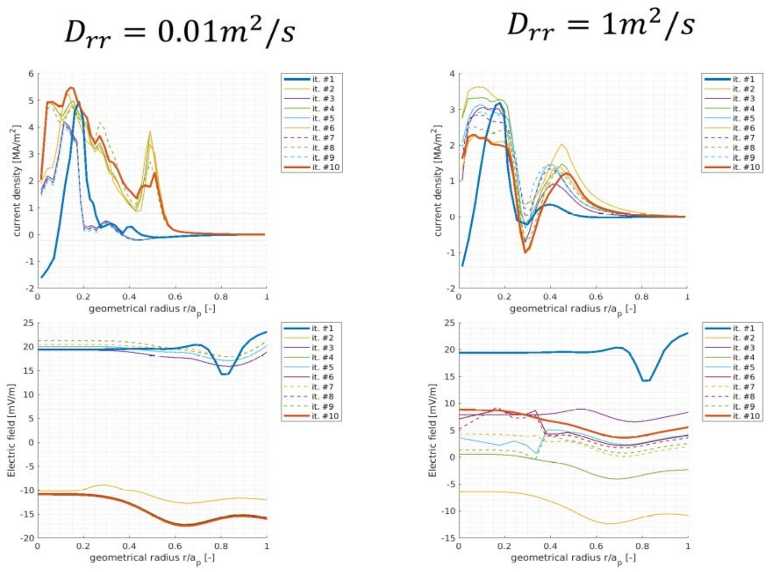

Fig. 5: Current density and parallel electric field profiles as functions of the number of iterations for discharges #45525 and belonging to the "non-inductive" group of discharges. On the left side, simulations are performed with a very low D_{rr} value. The bistable regime is clearly visible on the parallel electriuc field profiles. Conversely, on the right side, when D_{rr} = 1 m^2/s, a convergence is observed on both the current density and parallel electric field profiles.

Comparison between experimental HXR signals in the photon energy range 60-80 keV and synthetic diagnostic predictions by the R5-X2 code from the first and the last simulations are shown in Fig. 7 using the best-matching diffusion coefficient D_{rr} for the two groups. It is found that for all cases, there is better agreement for the solution corresponding to the last iteration, better than for the initial one. Even if this positive results is encouraging, it must be considered with caution, regarding the difficulty to converge for the "non-indictive" group.

5. CONCLUSION AND PROSPECT

Simulations of the LH wave curent drive in which the toroidal MHD equilibrium is self-consistent with kinetic calculations have been successfully performed using METIS tokamak solver and the LUKE suite of codes. They have been carried out using the newly developed framework SLUKE, which allows to manage remotely a large number of simulations on a distributed set of computers, in a simple numerical environment. Calculations have been performed for Tore Supra discharges which are well diagnosed and characterized by accurate electas it is possible to run METIS code with inputs of external current and power density profiles from LUKE kinetic calculations.

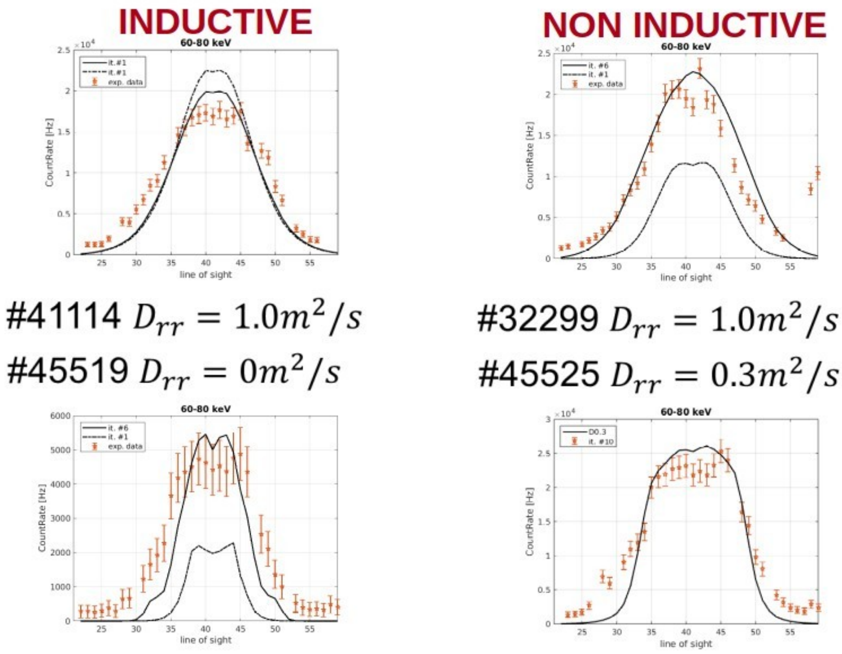

Fig. 6: Comparison between HXR measurements (points with error bars) and code predictions using R5-X2 synthetic diagnostic with toroidal MHD equilibrium selfconsistency, for the first iteration (dashed line) and after the achieved convergence (full line). Though an anomalous radial transport is used mostly to regularize the convergence, improved agreement is observed.

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 field has notably evolved. For discharges whose plasma current is dominated by the LH-driven component, the convergence is more difficult to be reached as the current density profile changes significantly at each iteration step (bi-stable effect), a consequence of large non-linear effects in this case. Nevertheless, a favorable tendency is observed when the radial diffusion coefficient is introduced as a regularisation parameter in the iterative procedure with a high enough level.

These first results highlight how sensitive to the toroidal MHD equilibrium are full LH current drive simulations, even if ray stochasticity is very weak when the spectral broadening in the SOL is considered (TSM model). A statistical analysis 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. New numerical schemes to improve convergence will be also considered.

REFERENCES

[1] N.J. Fisch, Theory of current drive in plasmas, Rev. Mod. Phys., **59, 1 (**1987) 175.

[2] P. T. Bonoli, Review of recent experimental and modeling progress in the lower hybrid range of frequencies at ITER relevant parameters, Phys. Plasmas, **21** (2014) 061508.

[3] Y. Peysson et al., Current Challenges in the First Principle Quantitative Modelling of the Lower Hybrid Current Drive in Tokamaks, EPJ Web of Conferences, **157** (2017) 02007.

[4] X. Litaudon et al., Modelling of hybrid scenario: from present-day experiments towards ITER, Nucl. Fusion, **53** (2013) 073024.

[5] M. Goniche et al., First lower hybrid current drive experiments on the WEST tokamak, AIP Conf. Proc., (2020).

[6] L. Delpech et al., Evolution of the Tore Supra Lower Hybrid Current Drive System for WEST, Fusion Engineering and Design, **96-97** (2015) 452-.

[7] M. Wang et al., Improvement of lower hybrid current drive systems for high-power and long-pulse operation on EAST, Nuclear Engineering and Technology, **54** (2022) 4102.

[8] F.K. Liu et al., Development of 4.6 GHz lower hybrid current drive system for steadystate and high performance plasma in EAST, Fusion Engineering and Design, **113** (2016) 131.

[9] Y. Peysson et al., Lower Hybrid Current Drive in High Aspect Ratio Tokamaks, Journal of Fusion Energy, **39** (2020) 270.

[10] S.J. Wukitch et al., High Field Side Lower Hybrid Current Drive Simulations for Off- axis Current Drive in DIII-D, EPJ Web of Conferences, **157** (2017) 02012.

[11] A.H. Seltzman et al., A high field side multijunction launcher with aperture impedance matching for lower hybrid current drive in DIII-D advanced tokamak plasmas, Nuclear Fusion, **59, 9** (2019) 096003.

[12] Y.S Bae et al., Design of 5.0-GHz KSTAR lower-hybrid coupler, Fusion Engineering and Design, **65, 4** (2003) 569.

[13] S. Park et al., Progress of KSTAR 5-GHz Lower Hybrid Current Drive System, Fusion Science and Technology, **63, 1** (2013) 49.

[14] B. Biswas et al.e, Spectral broadening from turbulence in multiscale lower hybrid current drive simulations, Nucl. Fusion, (2023), 63, pp. 016029.

[15] M.H. Li et al., First experimental results of the PAM LHCD launcher at 2.45 GHz on EAST, Nucl. Fusion, **63** (2023) 096014.

[16] H. Takahashi, The generalized accessibility and spectral gap of lower hybrid waves in tokamaks, Phys. Plasmas, **1, 7** (1994) 2254.

[17] S. Ide et al., Enhancement of Absorption of Lower Hybrid Wave by Filling the Spectral Gap, Phys. Rev. Letters, **73, 17** (1994) 2312.

[18] Cesario, R et al., Modeling of a lower-hybrid current drive by including spectral broadening induced by parametric instability in tokamak plasmas, Phys. Rev. Lett., **92** (2004) 175002.

[19] Bertelli, N. et al., The effects of the scattering by edge plasma density fluctuations on lower hybrid wave propagation, Plasma Phys. Control. Fusion, **55** (2013) 074003.

[20] R. Cesario et al., Spectral broadening of lower hybrid waves produced by parametric instability in current drive experiments of tokamak plasmas, Nucl. Fusion, **46** (2006) 462.

[21] M. Preynas et al., Experimental characterization and modelling of non-linear coupling of the lower hybrid current drive power on Tore Supra, Nuclear Fusion, **53, 1** (2013) 013012.

[22] G.M. Wallace et al., Advances in lower hybrid current drive technology on Alcator C-Mod, Nucl. Fusion, **53** (2013) 073012.

[23] P.T. Bonoli and E. Ott, Accessibility and Energy Depositon of Lower-Hybrid Waves in a Tokamak with Density Fluctuations, Phys. Rev. Lett., **46** (1981) 424.

[24] F.L. Hinton and R.D. Hazeltine, Theory of plasma transport in toroidal confinement systems, Rev. Mod. Phys., **48, 2** (1976) 239.

[25] V. Basiuk et al., Simulations of steady-state scenarios for Tore Supra using the CRONOS codes, Nucl. Fusion, **43** (2003) 822.

[26] C. F. F. Karney et al., Comparison of the theory and the practice of lower-hybrid current drive, Phys. Rev. A, **32 4** (1985) 2554.

[27] J.F. Artaud et al., Metis: a fast integrated tokamak modelling tool for scenario design, Nuc. Fusion, **58** (2018) 105001.

[28] Jacques Blum et al., Automating the design of tokamak experiment scenarios, Journal of Computational Physics, **394** (2019) 594.

[29] J. Hillairet et al., ALOHA: an Advanced Lower Hybrid Antenna coupling code, Nuclear Fusion, **50, 12** (2010) 125010.

[30] Y. Peysson et al., A versatile ray-tracing code for studying rf wave propagation in toroidal magnetized plasmas, Plasma Phys. Control. Fusion, **54** (2012) 045003.

[31] Y. Peysson and J. Decker, Numerical simulations of the radio-frequency driven toroidal current in tokamaks , Fusion Science and Technology, **65** (2014) 22.

[32] Peysson Y. and Decker J., Fast electron bremsstrahlung in axisymmetric magnetic configuration, Phys. Plasmas, **15, 9** (2008) 092509.

[33] J. Decker et al. , Damping of lower hybrid waves in large spectral gap configurations, Phys. Plasmas, **21** (2014) 092504