New modelling capabilities to support the ITER EC H&CD System optimisation and preparation of plasma operation

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Abstract. The ITER Electron Cyclotron Resonance Heating (ECRH) & Current Drive (ECCD) system is planned to be progressively installed and commissioned following the four stage approach of the ITER Research Plan. Starting with an injection of up to 5.8 MW from one Upper Launcher (UL) in the vacuum vessel to assist the plasma breakdown during First Plasma (FP) operation, the system will then be extended to achieve a capability of 20 MW injected power in Pre-Fusion Plasma Operation (PFPO) and Fusion Power Operation (FPO) phases. Development of optical modelling was required to characterize the optical performance of the FP configuration with the so-called First Plasma Protection Components. An optical 3D model using Zemax OpticStudio® has been developed and extended to the UL. Effects of higher order modes, thermal deformations and tolerances on the UL functionality have been characterized and are presented. Finally, in preparation of plasma operation and in the frame of the EC system upgrade layout optimisation, ECRH-ECCD modelling is being undertaken within the ITER Integrated Modelling and Analysis (IMAS) suite.

1 The EC system within the ITER Research Plan

1.1 The four stage approach

The ITER Research Plan defines the strategy to achieve its mission goals through the scientific and technical exploitation of the tokamak and its ancillary systems [1]. It will unfold in four phases, as summarised in Table 1:

- **First Plasma** (FP) for which only one upper launcher of the Electron Cyclotron (EC) system will be operational, associated with 7 gyrotrons injecting 170 GHz waves, leading to a total injected power of up to 5.8 MW into the plasma. The main goal of First Plasma operation is to demonstrate the integrated commissioning of tokamak core components.

- **The 1st Pre-Fusion Power Operation phase** (PFPO-1) for which the full EC system will be operational and inject 170 GHz waves from 24 gyrotrons, providing up to 20 MW inside the plasma (with a possible early 10-20 MW power upgrade under assessment). The 24 beams will be launched from 1 equatorial launcher (EL) and/or 4 upper launchers (UL). The main goal of PFPO-1 is

to commission the main plant systems and to determine the L-H power threshold for ITER.

- **The 2nd Pre-Fusion Power operation phase** (PFPO-2) for which all the H&CD auxiliary systems will be operational: 20 MW of ECRH as described above, 20 MW of ICRH launched via 2 antennas injecting waves of tuneable frequency in the range [40–55] MHz, and 33 MW of 870 keV NBI launched via 2 injection boxes injecting hydrogen beams. The main goal of PFPO-2 is to raise the plasma current and power to the nominal values of 15 MA and 73 MW respectively, and to increase the pulse duration. Qualification of all control systems for MHD instability control is to be proven prior DT operation.

- **The Fusion Power Operation phase** (FPO) in which the NBI system will be the only heating and current drive system modified within the tokamak building. NBI system will inject deuterium beams with an energy of up to 1 MeV and a power of up to 33 MW. The main goal of FPO is to demonstrate Q=10 operation (ITER baseline 15MA/5.3T scenario), long pulse operation (ITER hybrid 12.5MA/5.3T and steady-state 10MA/5.3T scenarios) and to study burning plasma physics.

Accurate EC resonance heating (ECRH) and current drive (ECCD) predictive modelling over the large range of toroidal magnetic fields [1.8T – 5.3T] foreseen in the

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ITER Research Plan is crucial for the preparation of the EC system operation and would allow to optimise the use of the upgraded power.

Table 1. The four stage approach of the ITER Research Plan; for First Plasma the duration includes Integrated Commissioning (11 months), First Plasma operation (1 month) and Engineering Operation (6 months).

Phase	FP	PFPO-1	PFPO-2	FPO
Duration	18 months	18 months	21 months	n x 16 months
Main ion species	H	H, ^{4}He	H, ^{4}He	D, DT
H&CD power (MW)	ECH - 5.8	ECH - 20	ECH – 20 ICRH - 20 NBI – 33	ECH - 20 ICRH - 20 NBI - 33

Hence, an important aspect of the modelling activities described in this paper is to assess the optimal conditions and identify the potential issues for the commissioning and operation of the EC system in the various phases of the ITER Research Plan. It implies an optimisation of the design of the EC system itself but also of the scenarios foreseen in all phases of the ITER Research Plan.

1.2 Description of the ITER EC system

1.2.1 First Plasma

The first plasma breakdown in ITER will be assisted by ECRH. Up to 5.8 MW will be injected via one UL located in the upper port 16 across the magnetic null. The UL optics has been designed for minimizing the power required to stabilise the Neo-classical Tearing Modes (NTMs), which requires a well-focused beam at the resonance in the region of $0.6<\rho T<0.88$ (where ρT is the normalised radius with respect to the toroidal flux). This region is high in the vacuum chamber far from the magnetic null located below the plasma axis. Furthermore, focusing the beams at the resonance results in a large beam expansion upon arrival at the central column. This necessitates a set of mirrors on the inner wall of the vacuum chamber to collect the beams and redirect them across the magnetic null and into a dump in equatorial port 17 (EP-17) (see fig. 1). The FP beam configuration is divided into two sets of beams:

- the lower beams (L-beams) that are launched by the lower steering mirror (LSM) of the UL and then bounce off the LA and LB focusing mirrors

- the upper beams (U-beams) that are launched by the upper steering mirror (USM) of the UL and then bounce of the UA focusing mirror

Estimates of the plasma breakdown performance have been carried out using the Hamiltonian adiabatic formalism [2], helping the definition of EC requirements for ITER First Plasmas.
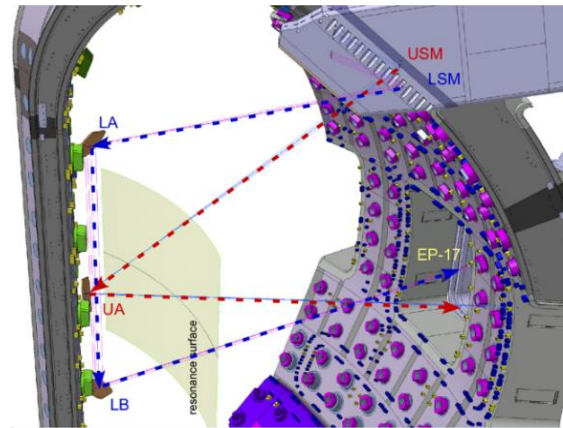

Fig. 1. First Plasma EC beam configuration. In blue are the lower beams launched by the LSM of the UL-16 and redirected to the resonance layer below the plasma null thanks to the LA and LB focusing mirrors. In red are the upper beams launched by the USM and refocused by the UA mirror to cross the resonance layer above the plasma null. The residual non-absorbed power of the beams will be attenuated in the beam dump located in the EP-17.
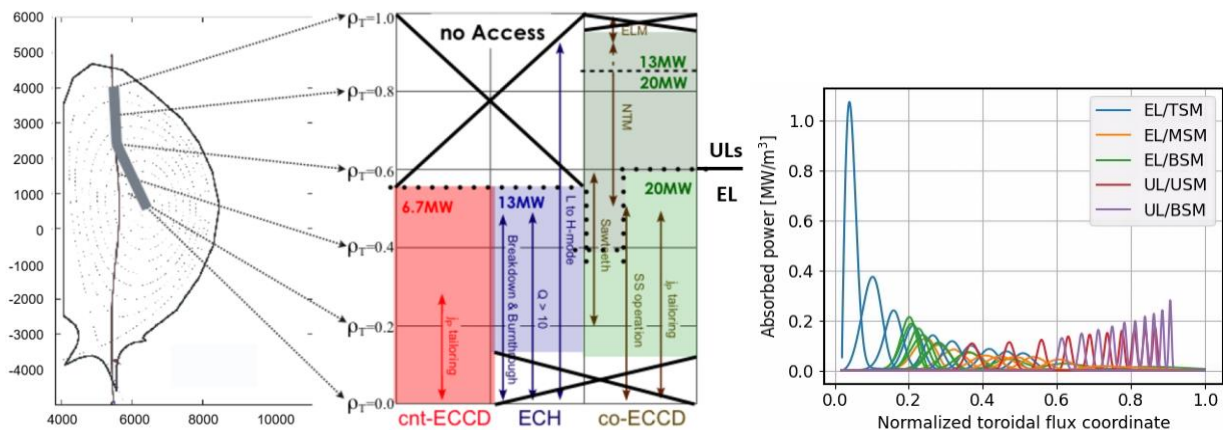

Fig. 2. Left: deposition access of the EL and ULs across the plasma cross section and categorized based on driving counter (cnt) ECCD (shaded red), co-ECCD (shaded green) or pure heating (shaded blue), considering 1MW gyrotrons. Right: radial coverage of EC system when steering the poloidal angle for each mirror of the EL and ULs, as simulated with the TORBEAM wave code [3].

1.2.2 . PFPO and FPO phases

The system will have a capability of 20 MW injected (from 24 1MW gyrotrons) via a set of 1 Equatorial Launcher (EL) and 4 Upper Launchers for the first phase of the Pre-Fusion Plasma Operation (PFPO-1) [4].

The EL launcher will be used for central heating and current drive accessing the inner half of the plasma volume, as shown in fig. 2. The EL can launch up to 24 beams that are distributed over 3 rows of 8 beams, i.e. 3×6.7MW injected to the plasma (see fig. 3). Each beam set is incident on a single fixed mirror and then a steering mirror which steers the beam in the poloidal plane. The upper set of EL beams is orientated for counter-ECCD injection, whereas the middle and lower sets are oriented for co-ECCD injection. This effectively decouples the current drive from the heating of the EC beams. Indeed, balancing the co and counter contribution provide a net 'zero' driven current (or pure heating).

The four upper launchers are identical and can launch up to 8 beams each, i.e. 6.7 MW, distributed between the lower and upper rows. The ULs will be used in particular for stabilizing MHD activity, which occurs in the outer half of the plasma volume. Each beam is incident on three fixed mirrors, which are used to regroup and focus the beams such that the absorption in the plasma is very localized. As shown in fig. 3. the last mirror is a steering mirror, which directs the beams in a vertical plan with roughly a 20° toroidal injection angle (optimized for peak j_{CD} injecting in the co-current drive direction). The two steering mirrors, upper (USM) and lower (LSM) cover different ranges in the plasma. The resulting heating and current drive access is illustrated in fig. 2. UL access is distinguished from the EL access. As represented in the plot on the right, each steering mirror has its own range of radial coverage.

The ITER EC system has some flexibility in the way the 24 gyrotrons can be operated and how their 24 beams are distributed among the 24 entries of the EL and 4×8 entries of the ULs. As shown in fig. 4, five sets of switches along the transmission lines enables the beam

distribution. The 24 gyrotrons can be distinguished in three different groups. The gyrotrons #1 to #8 can feed either the top row of the EL or the UL 12 and 13. Indeed, each of these two upper launchers is connected to four gyrotrons only. An additional switch redirects the beams either to the top or the bottom row of the UL. The gyrotrons #9 to #16 can feed the middle row of the EL or the UL-15. Finally, the gyrotrons #17 to #24 are connected to the EL or the UL-16 in the same way.

The EC system is designed to accommodate an upgrade up to 20 MW, and the activation of this potential is being considered. This upgrade aims at enhanced physics capabilities combined with an optimized layout to distribute the additional available power among the 56 launcher entries of the five launchers. The potential operational limitations of the system are considered as well as upgraded gyrotrons (>1MW). This requires thermal and structural analysis to define the operational conditions that are acceptable for the system.
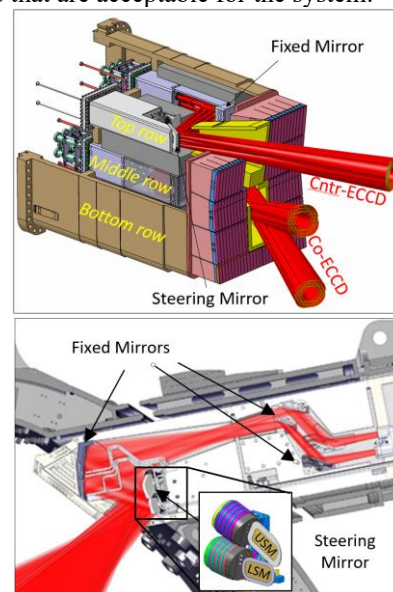

Fig. 3: Geometry of the EC Upper Launchers with the static and steering mirrors. Top: Equatorial Launcher; Bottom: Upper Launcher. In red are represented the beams that propagate inside the launchers.
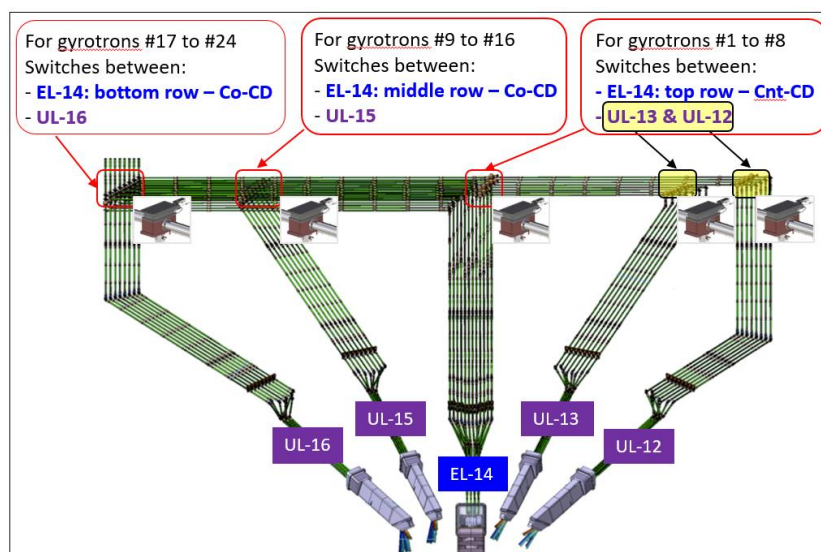

Fig. 4: Gyrotron distribution of 24MW system – 56 beamlines. Five sets of switches along the transmission lines bring flexibility to the EC system operation.

2 Zemax Optic Studio simulations of the EC launching system

2.1 Purpose

In the frame of the design development of the FP configuration of the EC launching system, i.e. UL-16 and LA, LB and UA mirrors described in section 1.2.1, an optical 3D model using Zemax OpticStudio® has been developed. Characterization of the propagation losses was requested to insure a safe level of stray radiation during first plasma operation, as well as a sophisticated model of the beam dump. Presentation of this development and associated results are not yet published and will not be presented in this report. This initial model has been extended to the misalignment assessment in the UL considering several beam deviation contributors: Higher Order Modes (HOM), thermal deformations and mechanical tolerances. Besides the quantification of the beam deviation at the mirrors, the consequences in terms of stray radiation, local hot spots in the launcher and propagation efficiency of the launcher were estimated. Those results associated to the plasma performance analysis performed by GRAY [7] brought to the conclusion in 2021 that a further optimisation of the optical design was necessary before proceeding to the manufacturing. Some modifications of the optical design to mitigate beam misalignment has been tested in Zemax and their impact on the FP launching configuration evaluated.

2.2 System definition

2.2.1 Definition of Gaussian beam source

The Gaussian beams are modelled using the source dll « gaussiansource.dll » available in Zemax. The source behavior have been verified against quasi-optical gaussian beam propagation theory: both beam divergence and ray distribution along beam propagation showed a proper behavior but a minimum of 1.10^6 rays is needed. The Gaussian beams are launched at the tip of the in-vessel waveguides.

2.2.2 Geometry

The optical system (mirrors) and port plug are defined using objects which consist of CAD import (STEP file) from ENOVIA model. A comparison of the interception points of the chief rays on mirrors between Catia and Zemax shows that rays propagate in the same way. The global coordinate system is TGCS (ITER Tokamak Global Coordinate System). Thus, the exact real geometry of both mirrors and surrounding port plug is considered in the ray trace analysis, which is key for complete and realistic beam propagation analysis. Proper absorption coefficient of the different parts has been defined in the model, in particular for the reflective surface of the mirrors.

2.3 Ray trace analysis: evaluation of the beam propagation losses

Ray trace analysis combined with the definition of detectors at different positions in the launchers allows to extract two kind of propagation losses, at the mirrors and in other regions of the UL.

Spillover losses at each mirror for each of the eight beams were calculated using a set of detectors defined just before and just after the mirror reflective surface. Percentage of beam losses and mapping of the losses can be easily extracted from the analysis. Example of the mapping of losses at M4 considering some HOM is illustrated in fig. 5 by plotting the irradiance on the detector placed behind the mirrors. 8 beams of 0.86MW were considered in the model and the pixel size of the detector is 1mm². A peak irradiance of 9MW/m² is obtained, a value 50% much higher than without any HOM considered. This value is extremely high and can damage an impacted surface that is non-actively cooled. Please note that the HOM in the model are simply modelled by a tilt of the beam k-vector and/or an offset at the launching position.

Another type of propagation losses can occur in the launcher if sources of beam deviation are considered in the model. Some critical regions were identified using Zemax. One of them is one L-beam interfering with the steering mechanism between M2 and M3 that leads to local overheating.

Propagation losses generate stray radiation everywhere in the launcher, a load that needs to be quantified carefully and to be taken properly into account in the structural analysis of the port plug and sub-components. A particular attention to sensitive components such as the springs and the bellows of the M4 steering mechanism is requested since their cooling is intrinsically limited by their geometry. It has to be stressed that the degradation of the global efficiency of the launcher due to a certain category of beam deviation was characterised. For instance, losses go from 0.3% for the nominal configuration up to 1.3% when thermally deformed mirror surfaces are considered, with an increase from 0.27% to 1.2% for the losses at M4 mirror. This Zemax model has many other capabilities like the detection and characterisation of ghost (that is a portion of a beam badly reflected by a surrounding sub-mirror).
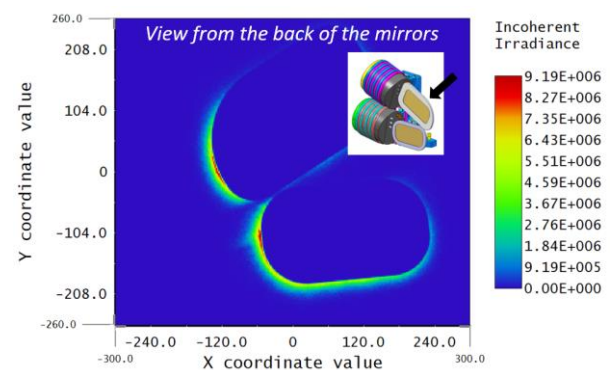

Fig. 5: Irradiance in W/m² of the detector placed right after the M4 mirrors to characterise the spillover considering beam deviation from HOM.

For example, part of L-beams are reflected by the upper M3 mirror instead of the lower mirror. This has been quantified and needs to be mitigated in the up-coming optimization of the optical design. All the analysis performed with Zemax were complemented by some parallel analysis performed by the European Fusion Laboratory ISTP-CNR using GRASP and by the University of Stuttgart using PROFUSION [5].

3 EC simulations within the ITER Integrated Modelling & Analysis Suite

3.1 The Integrated Modelling & Analysis Suite

The ITER Integrated Modelling and Analysis Suite IMAS is the collection of physics software that will be used to support ITER operation and research as defined in the ITER Integrated Modeling Programme [6].

It uses standard Interface Data Structures (IDS) to represent experimental and simulated data. IDSs are used to get/put data from/to storage, they are applicable to any fusion device, and they are passed between IMAS physics models to build up integrated modelling workflows. The global set of IDSs represent the IMAS Data Dictionary. IMAS will be capable of high physics fidelity predictive simulations of ITER plasmas and will be used for ITER data processing and analysis. IMAS is only used for off-line analysis so it will not be used as part of the Plasma Control System.

The use of a standard data model such as IMAS offers a great level of modularity and flexibility, ensuring the use of identical input data when changing model, making it ideal also for code benchmarking: for example, excellent agreement was recently found in between TORBEAM [3] and GRAY [7] in IMAS [6].

3.2 EC modelling in IMAS

Modelling in IMAS relies on the execution of models that exclusively exchange IDSs. IMAS EC modelling can be undertaken in various contexts like standalone EC simulations, or in physics workflows within a suite of codes for transport modelling.

3.2.1 Input and output data for EC modelling

In IMAS, EC wave codes always receive a minimal set of input IDS data, which are:
- *equilibrium* to describe the magnetic configuration of a given scenario
- *core_profiles* which provides the kinetic profiles (densities, temperature, etc.) for a given scenario
- *ec_launchers* which provides the geometry of the EC system together with the configured waveforms, i.e. the scheduled time evolution of the applied power, polarization and steering angles.

The results of EC codes in IMAS involve specific output IDSs. The evaluation of ECRH and ECCD is often performed using a wave code only. However, for more accurate results, wave codes can be associated to a

Fokker-Planck calculation to simulate the evolution of the distribution of EC-accelerated electrons inside the plasma. These two types of code provide their results using the following IDSs:
- *waves* from EC wave propagation codes
- *distributions* from EC Fokker-Planck codes

As an illustration of EC wave modelling, Fig. 6 shows the ray tracing generated by the TORBEAM code [3] when taking its input from an ITER DT baseline 15MA / 5.3T scenario of the IMAS database (130012/3/public/ITER) and the EC launcher geometry from the Machine Description database (120000/2/public/ITER_MD), applying power on all mirrors of the EL and all mirrors of one of the ULs.
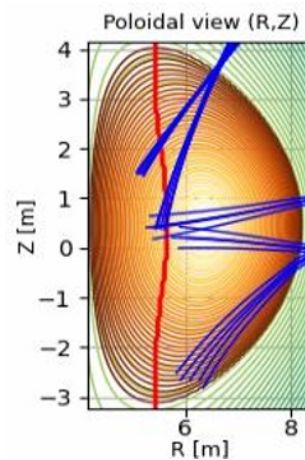

Fig. 6. EC rays read from the *waves* IDS generated by the TORBEAM code [3], for an ITER DT baseline 15MA/5.3T scenario; the cold resonance layer is displayed in red.

3.2.2 EC in standalone and within Integrated Modelling contexts

In IMAS, EC modelling can be carried out 1) as a standalone program, or 2) within the IMAS H&CD workflow where all H&CD sources can be combined together including synergetic effects [8], or 3) within a transport suite of codes. The best way to insure modularity and self-consistency of a scenario computation is to run EC modelling inside the H&CD workflow within a transport solver. This is the case with the JINTRAC transport suite of codes [9] into which the H&CD workflow has been integrated to provide the *core_sources* IDS used as heating sources for the transport equations. The ultimate goal is to combine such a transport suite with a free-boundary equilibrium code, including control algorithms to adjust the H&CD waveforms (e.g. the EC power allocation among launchers and mirrors and their steering angles, e.g. for NTM control) according to the signals (simulated and later measured during ITER operation) from the (synthetic) diagnostics. Such a suite will enable high fidelity plasma simulations which is one of the ultimate goals of IMAS.

When EC modelling is carried out as a standalone simulation, it takes its input from an existing scenario

and from the machine description. In ITER, we have developed and populated two databases to provide the necessary input:

- **The Scenario database**, from which *equilibrium*, *core_profiles* and possibly other IDSs can be read; note that all the key scenarios of the ITER Research Plan for the various values of magnetic field foreseen during ITER operation are available in the IMAS scenario database.
- **The Machine Description (MD) database** which contains the geometry of the various ITER plant systems. The geometry of the ITER EC system is stored in the *ec_launchers* IDS which is read from this database.

As an example, Fig. 7 shows ECCD profiles from X2 resonance, applying 13.3 MW on the EL and 6.7 MW on one of the ULs, for an ITER 7.5 MA / 2.65 T scenario in hydrogen as simulated by the JINTRAC transport suite (scenario 104103/22/public/ITER). Note that following the IMAS sign convention, negative ECCD means co-current. Fig. 7 then shows that EL/TSM is the only mirror injecting in the counter-current direction.
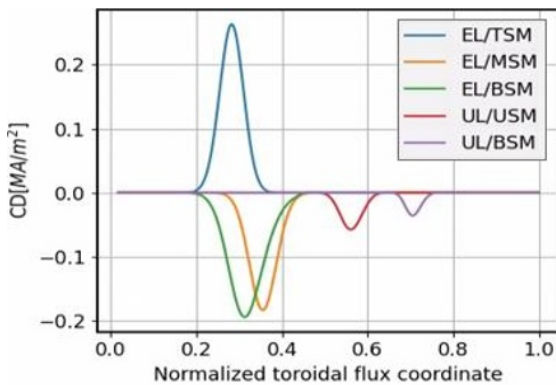

Fig. 7. ECCD profiles from X2 absorption simulated by TORBEAM for a JINTRAC 7.5 MA / 2.65 T H scenario.

The EC waveforms, as mentioned earlier, are part of the *ec_launchers* IDS, which contains both the static data (geometry of the system) and dynamic data (time evolution of the power, polarization, steering angles, etc.) configured for a given scenario. For the time being, this dynamic data is configured in the *ec_launchers* IDS via a waveform editor, but it will ultimately be read from the *pulse_schedule* IDS, including the system latency time along with some operational variations, as illustrated in Fig. 8.

In its current version, the geometry of the EC launchers stored in the MD database is described at the level of the steering mirrors. However, to model the whole flexibility and capabilities of the EC system, each of the 56 beamlines of the five launchers will soon be defined in the MD database instead. Another aspect to later consider is to account for the coordinate change of the beam launching points at the steering mirrors w.r.t. to the chosen steering angles. In ITER, as illustrated in Fig. 3, from the exit of the waveguides the beams first encounter three static mirrors (M1, M2 and M3), then the M4 steering mirror.
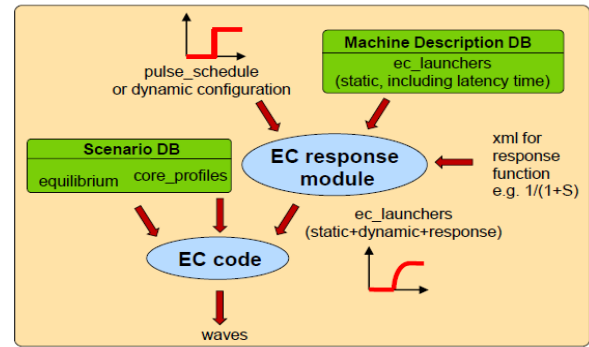

Fig. 8. EC modelling using Scenario and Machine Description data combined with dynamic waveforms configured by a pulse scheduler.

So far the geometry of the EC system was stored considering a fixed position of the launching point of the beams at M4, but this approximation will be replaced by a proper calculation of the actual position of the beams with respect to the steering angle configuration.

4 Conclusion

The installation of the EC system has started but part of it is still under design finalisation. Zemax OpticStudio modelling supports the optimisation of optical design, but will also be used during the preparation of plasma operation. Several EC codes (beam and ray tracing codes) are available within the IMAS Integrated Modelling and Analysis suite and are used to assess the ECRH and ECCD capabilities for the various scenarios of the ITER Research Plan. Those modelling capabilities are under permanent development and will support the definition of an EC system upgrade if required.

Acknowledgments

References

1. ITER Research Plan, Tech. Rep. ITR-18-03 (2018)
2. D. Farina, Nucl. Fusion 58 (2018) 066012
3. E. Poli et al, Comp. Phys. Com. (2018) 225 36–46
4. M. A. Henderson, Phys. Plasmas 22 (2015) 021808
5. B. Plaum et al. this workshop (2022)
6. F. Imbeaux et al, Nucl. Fusion 55 (2015) 123006
7. D. Farina Fusion Sci. Technol. 52 (2007) 154
8. M. Schneider et al, Nucl. Fusion 61 (2021) 126058
9. M. Romanelli et al, Pl. Fus. Res. 9 (2014) 3403023