Algorithm of Self-Consistent Calculation of EC Losses and Kinetics of ECRH/ECCD in Tokamak-Reactors

P.V. Minashin, A.B. Kukushkin

Tokamak Physics Institute, NRC "Kurchatov Institute", Moscow 123182, Russia

1. Introduction. In steady-state regimes of ITER operation [1], central electron temperature $T_e(0)$~30 keV may be attained. Under these conditions the electron cyclotron (EC) power losses can have a significant impact on the discharge evolution [2], [3], [4]. The transport of EC waves, emitted by plasma, produces an inward flux of energy, due to wave's reflection from the first wall, of ~20 MW total power, that is close to the planned power of injected EM waves for the EC resonant heating (ECRH) and the EC current drive (ECCD) (e.g., to suppress the neoclassical tearing modes and the sawtooth oscillations). The above requires the development of more accurate methods of calculation of all processes in ITER, related to plasma-produced EC radiation. There are several computational approaches to modelling separately the ECRH/ECCD at low harmonics (cf. benchmarking [5]) and the plasma-produced EC radiation transport at moderate and high harmonics of fundamental EC frequency (cf. benchmarking [6]). The first numerical calculation of partly self-consistent coupling of the above problems was carried out in [7], [8], [9] for studying the unilateral influence of ECRH on the EC losses with the help of the codes TORBEAM [10] (ray tracing) + RELAX [11] (ECRH/ECCD Fokker-Planck) and CYNEQ (power losses on plasma-produced EC radiation [12], [13]). Here we propose an algorithm that is the first attempt to combine existing EC radiation transport codes for fully self-consistent treatment of the above problems in a tokamak-reactor.

2. Algorithm of self-consistent calculation of EC radiation. A new algorithm (Fig. 1) is based on the iteration procedure for self-consistent coupling of a kinetic Fokker–Planck ECRH/ECCD code (e.g., OGRAY [14] or GENRAY [15]+CQL3D [16] (ray tracing + Fokker–Planck kinetics), or TORBEAM+RELAX) and CYNEQ. The iteration procedure includes the following data exchange between the codes. Both of the codes receive plasma parameters and profiles from a global transport code (e.g., ASTRA [17]). CYNEQ calculates the EC power loss profile, $P_{EC}(\rho)$, and the intensity of the EC radiation, J_{EC}, for given velocity distribution function (which is an output from the Fokker-Planck code) and 2D plasma profiles (electron density and temperature, magnetic field):

$$J(\omega,\xi)=\frac{\int\limits_{V_{esc}} dV\int d\Omega_{\vec{n}}\, q_{\xi}\left(\vec{r},\vec{n},\omega\right)}{\int d\Omega_{\vec{n}} \int\limits_{\left(\vec{n},d\vec{S}_w\right)\geq 0} \left(\vec{n},d\vec{S}_w\right)\left(1-R_w\right)+\int\limits_{V_{esc}} dV\int d\Omega_{\vec{n}}\,\kappa_{\xi}\left(\vec{r},\vec{n},\omega\right)}, \quad (1)$$

$$P_{EC}(\vec{r})=\sum_{\xi}\int d\omega\int d\Omega_{\vec{n}}\left[q_{\xi}(\vec{r},\vec{n},\omega)-\kappa_{\xi}(\vec{r},\vec{n},\omega)J(\omega,\xi,\vec{r})\right], \quad (2)$$

where ω and $\vec{n}$ are the frequency and propagation direction of the wave, respectively; the index ξ labels the type of EC wave (ordinary or extraordinary), q is the power density of EC radiation source, κ is absorption coefficient, S_w is the area of the inner (plasma-facing) surface of the first wall, R_w is the coefficient of wave reflection from the wall, $V_{esc}(\omega, \xi)$ is the projection of the optically thin outer zone of the phase space of plasma electrons onto its coordinate part.

The Fokker–Planck ECRH/ECCD code calculates the electron power deposition profile, $P_{ECRH}(\rho)$, and the effects of ECRH on the velocity distribution function. Usually the Fokker–Planck codes (e.g. OGRAY [14], CQL3D [16]) evaluate the quasi-linear diffusion operator for an externally injected EC power, J_{ECRH}, of a given frequency ω of the RF source (nearly monochromatic source). The coupling of the Fokker-Planck code with the CYNEQ code is performed by using in the Fokker-Planck code the EC quasi-linear operator in terms of the non-monochromatic spectral intensity of radiation (see, e.g., [18]) with allowance for emission of the plasma produced EC waves, according to eq. (1) for the intensity of this type of the EC radiation. On each iteration step the kinetic ECRH/ECCD code and the CYNEQ code solve their problems separately using as an input data the results from each other, obtained at previous iteration step. The iterative process stops when each of the calculated profiles, $P_{EC}(\rho)$ and $P_{ECRH}(\rho)$, at the current iteration step saturate with a given accuracy.

The proposed iterative procedure is an effective way to solve a complex system of integro-differential equations:

- the equation of radiative transfer in the geometrical optics approximation: ray-tracing codes for low harmonic radiation for ECRH/ECCD (e.g., GENRAY, OGRAY) and semi-analytic model for moderate and high harmonics of plasma-produced EC radiation, taking into account multiple reflection of radiation from the first wall (CYNEQ, eq. (1)),
- the Fokker-Planck kinetic equation (e.g., OGRAY, CQL3D).

The convergence of the iterative procedure for such a system of equations is not guaranteed. The first self-consistent calculation of the kinetics of superthermal electrons and plasma-produced EC radiation transport [19] under reasonable assumptions (isotropy of velocity distribution function in pitch angles, which allows the analytical solution [12]) by a similar iterative procedure (the code CYNEQ-KIN [19]) appeared to be converging very fast. That allows us to expect rapid convergence of proposed iterative procedure (Fig. 1).

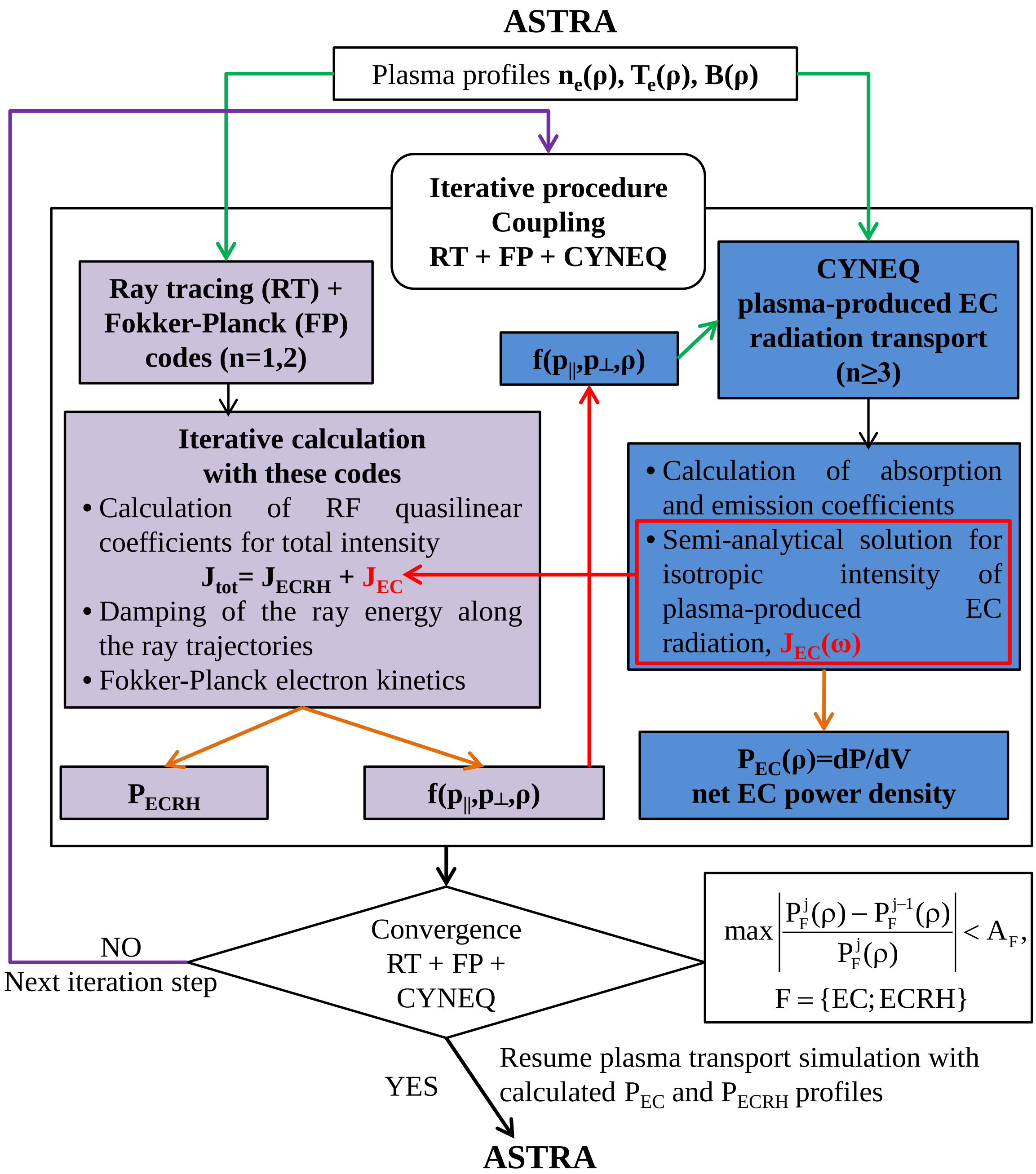

Fig. 1. Algorithm of self-consistent calculation of EC radiation transport in a tokamak-reactor in the entire spectral range, from low to high EC harmonics. Coupling of the CYNEQ code for EC radiation transport and the kinetic Fokker-Planck (FP) code is implemented on the platform of the plasma transport code (a suite of codes) ASTRA. The zero iteration step j=0 corresponds to the calculation of the kinetic code for given plasma parameters without taking into account plasma-produced EC radiation. The velocity distribution function calculated by the FP code, is used then in the CYNEQ code. Constants A_{EC} and A_{ECRH} (it is appropriate to take them equal to few-several percents) define the conditions of the convergence of the proposed iterative procedure.

3. Conclusions. We develop an algorithm for self-consistent calculation of the EC power losses and the kinetics of ECRH/ECCD in a tokamak-reactor. The proposed algorithm is based on an iterative self-consistent calculation of two basic components of the problem: (a) calculation with a kinetic ECRH/ECCD code of the electron space-velocity distribution function – for given external EC radiation at low harmonics of EC fundamental frequency (n=1, 2) and for spectral intensity of plasma-produced EC radiation at higher frequencies (harmonics n≥3), calculated by the CYNEQ code [13]; (b) calculations by the CYNEQ and ECRH/ECCD codes, respectively, of the EC power density losses and the EC external power density heating, using in both calculations a non-maxwellian electron velocity distribution function calculated by the kinetic code at previous iteration step, namely, when solving the problem "a"

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