Effect of Multi-Pass Absorption of Electron Cyclotron Heating Wave on Initial Stage of Discharge in ITER-like Tokamak

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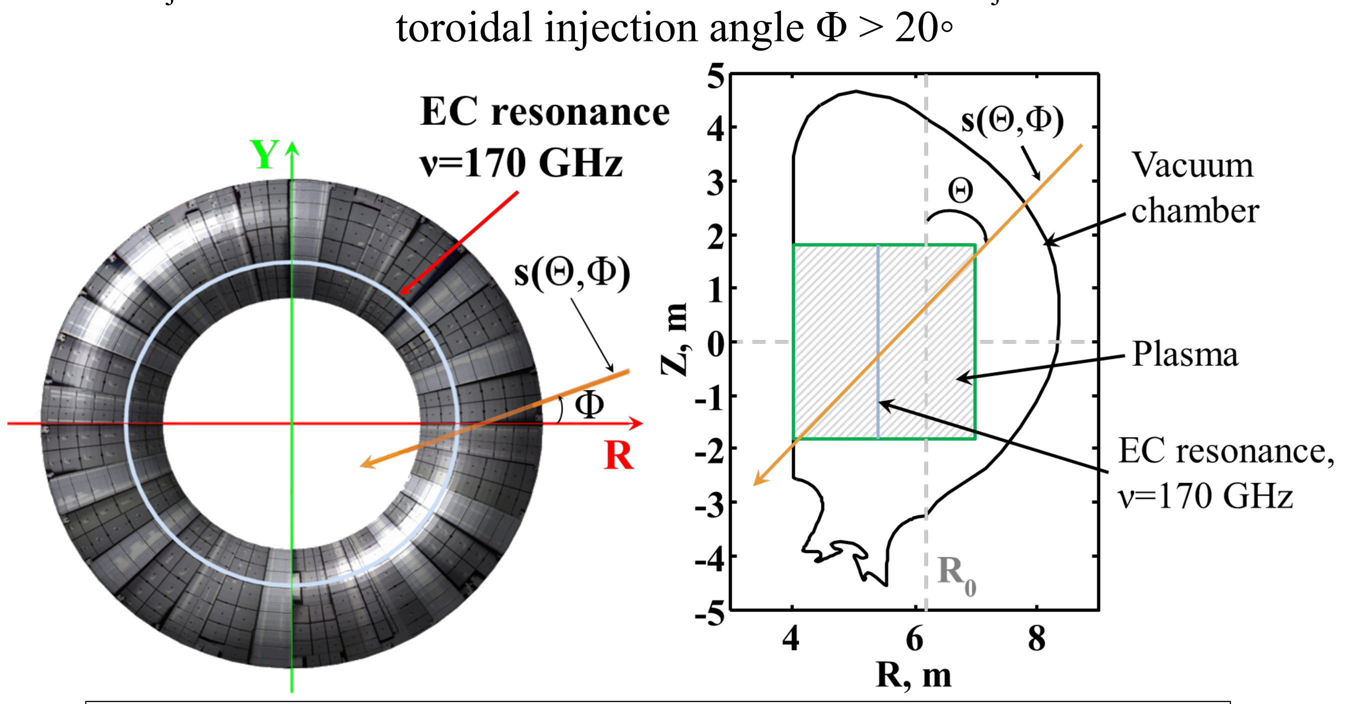
1. Introduction

- Due to technological issues the ohmic plasma breakdown in tokamak-reactor ITER is only possible over a narrow range of plasma pressure and magnetic field errors [*Lloyd B., Plasma Phys. Controlled Fusion, 1996*].
- For the reliable plasma start-up in ITER it is planned to use electron cyclotron resonance heating (ECH, ECH-assisted start-up) [*Omori T., Fusion Eng. Des., 2011*]. The ECH is a standard way for plasma start-up in stellarators and already showed to be an effective method for plasma breakdown in tokamaks [*Stober J., Nucl. Fusion, 2011*].
- Modelling of the initial stage of plasma discharge in ITER with the 0D model [*Lloyd B., Plasma Phys. Controlled Fusion, 1996*] showed that in a wide range of initial conditions, taking into account beryllium impurities, the 3 MW of absorbed external EC radiation is needed to achieve the plasma breakdown (for the carbon impurities even 5 MW of absorbed power is not enough). However, in [*Lloyd B., Plasma Phys. Controlled Fusion, 1996*] **the efficiency of EC absorption was not calculated**.
- Recent 1D simulations [*Khayrutdinov R.R., Kuyanov A.Y., Lukash V.E., EPS-2011*] of the ECH start-up in ITER with the help of the OGRAY code [*Zvonkov A.V., Kuyanov A.Y., Skovoroda A.A., Timofeev A.V., Plasma Phys. Rep., 1998*] for the ECH calculations showed that the planned EC power could be not enough for plasma breakdown because of **low efficiency of the single-pass** ECH power absorption.

2. ECRH in ITER

ν_{inject} = 170 GHz, O-mode, injected EC power P_{inject} = 24 MW, toroidal injection angle $\Phi > 20°$



Major torus radius, R_0 = 6,2 m, minor torus radius, a = 2 m, toroidal magnetic field on geometrical axis $B(R_0) \equiv B_0$ = 5.3 T.

The main functions of the ITER ECH&CD system are as follows [*Omori T., et al., Fusion Eng. Des., 2011*]

1. ECH-assisted plasma start-up: assistance to initial breakdown and the heating during the current ramp-up.
2. Auxiliary heating to achieve the H mode and the fusion energy gain factor Q = 10.
3. Steady state on-axis and off-axis current drive.
4. MHD instabilities control by the localized current drive.

3. Modelling of ECRH

RAY-TRACING	Kinetic codes	Analytical models
Solution of geometrical optics equations • GENRAY [*Smirnov A.P., Bull. of the American Phys. Society, 1994*] • TORBEAM [*Poli E., Comp. Phys. Commun., 2001*]	Solution of Fokker-Planck equation • OGRAY [*Zvonkov A.V., Kuyanov A.Y., Skovoroda A.A., Timofeev A.V., Plasma Physics Reports. 1998*], • CQL3D [*Harvey R.W., IAEA TCM, 1992*]	• [*Bae Y.S., England A.C., J. of the Korean Phys. Soc., 2007*] • [*Hada K., Japan-Korea Workshop on Phys. & Techn. Heating & Current Drive, Busan, Korea, 2013*],

Single-pass absorption model is used in all calculations, while when the high power ECRH is injected at initial stage of discharge (low density plasma), we have to allow for multi-pass absorption

4. Single-pass absorption of EC radiation

$$P_{absorp} = P_{inject}\left(1 - f_O e^{-\tau_{O,eff}} - f_X e^{-\tau_{X,eff}}\right)$$

$f_{O,X}$ coefficient determines the fractions of radiation of O- and X-mode respectively, $\tau_{(O,X),eff}$ – effective optical thickness of the plasma column

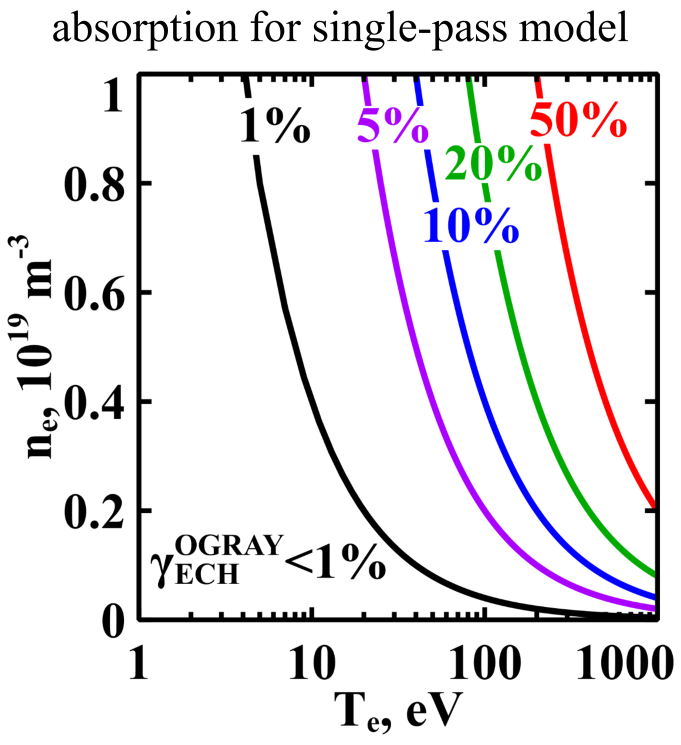
OGRAY scaling formula for single pass EC radiation absorption efficiency in ITER [*Khayrutdinov, et al., EPS-2011*] (O-mode)

$$\gamma_{ECH}^{OGRAY} = \frac{P_{absorp}}{P_{inject}} = \frac{T_e[eV]\cdot n_e[10^{19}\,m^{-3}]}{400} \qquad 10 \le T_e\,[eV] \le 1000,\quad 10^{17} \le n_e\,[m^{-3}] \le 10^{19}$$

where distortion of electron velocity distribution function by a strong EC wave absorption is not taken into account

For plasma parameters at initial stage of discharge $n_e \le 0.1\cdot10^{19}$ m^{-3} and $T_e \le 100$ eV the efficiency of ECRH in ITER (O-mode) will by **less than 1-5 %**

Level lines of the efficiency of ECRH absorption for single-pass model



5. Multi-pass absorption of EC radiation

- Multiple reflection of the EC wave from the wall of the vacuum chamber.
- Isotropy/uniformity of the injected EC radiation intensity in plasma (semi-analytical solution of radiative transfer problem for the case of multiple reflection of radiation from the wall)
- The model modifies the approach of the CYTRAN [*Tamor S., Report SAI-023-81-189LJ/LAPS-72, 1981*] and the CYNEQ code [*Kukushkin A.B., IAEA-1992*], [*Kukushkin A.B. , Minashin P.V., IAEA, FEC-2012*], developed for the plasma-produced EC radiation transport at moderate and high EC harmonics and verified in the benchmarking [*Albajar F., Bornatici M., Engelmann F., Kukushkin A.B., Fus. Sci&Tech, 2009*], [*Kukushkin A.B., Minashin P.V., Polevoi A.R., Plasma Phys. Rep, 2012*].
- We use OGRAY scaling for single pass absorption of injected EC wave (O-mode) and the above model for multi-pass absorption after first reflection of EC wave from the wall.EC mode mixing in wall reflections.

$$P_{absorp} = P_{absorp}^{Single} + P_{absorp}^{Multi} \qquad P_{absorp}^{Single} = P_{inject}^{O}\left(1 - \exp\left[-\tau_O^{(kin)}(P_{inject}^{O})\right]\right)$$

We assume the isotropy/uniformity of the injected EC radiation intensity

$$P_{absorp}^{Multi} = \sum_{\varsigma = X,O} 4\pi \int dV d\omega\, I_\varsigma(\omega) \left\langle \kappa_\varsigma(\mathbf{r},\mathbf{n},\omega)\right\rangle_\Omega, \quad \kappa_{X,O} \text{ is absorption coefficient}$$

$$\left\langle \kappa_\varsigma(\mathbf{r},\mathbf{n},\omega)\right\rangle = \frac{1}{4\pi}\int d\Omega\, \kappa_\varsigma(\mathbf{r},\mathbf{n},\omega).$$

k is wave vector, **n**=**k**/k is wave direction

From energy balance equation one can obtain (for all $R_{\varsigma\varsigma'}$=const):

$$I_X = \frac{C_O 4\pi\int dV\langle q_X\rangle + \pi S_{tot} R_{OX} 4\pi \int dV \langle q_O\rangle}{C_X C_O - (\pi S_{tot})^2 R_{XO} R_{OX}},$$

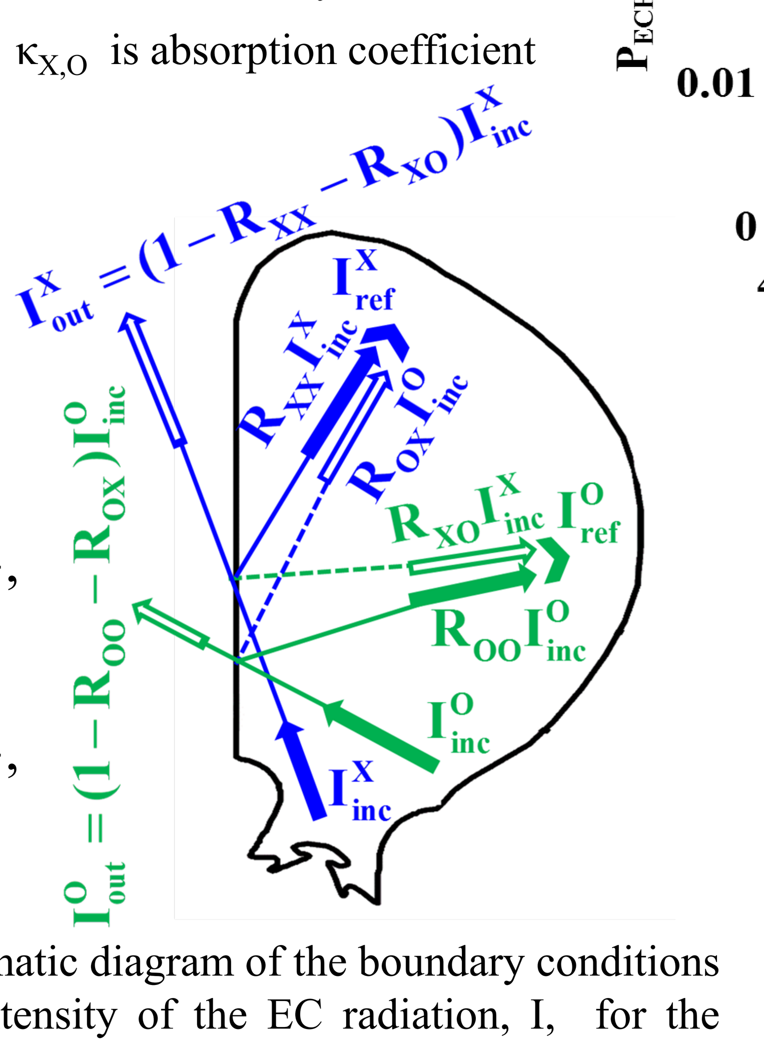
$$I_O = \frac{C_X 4\pi\int dV\langle q_O\rangle + \pi S_{tot} R_{XO} 4\pi \int dV \langle q_X\rangle}{C_X C_O - (\pi S_{tot})^2 R_{XO} R_{OX}},$$

$$C_\varsigma = 4\pi\int dV \kappa_\varsigma + \pi(1 - R_{\varsigma\varsigma}),\ \varsigma = X,O$$

$q_{X,O}$ is power density of ECR source

S_{tot} – area of vacuum chamber inner surface

$\mathbf{R}_{\varsigma\varsigma'}$ – wall reflection with ς to ς' mode conversion



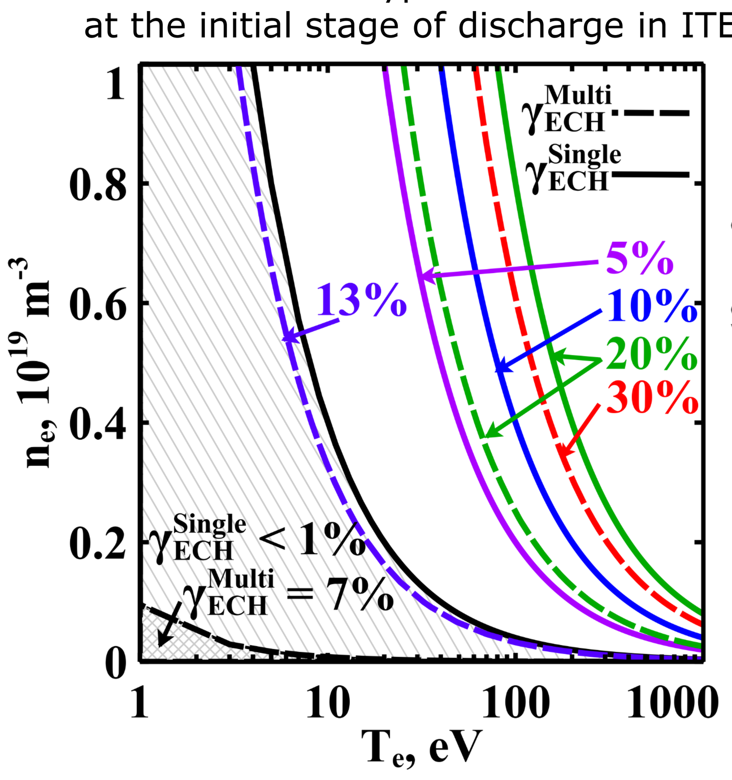
Schematic diagram of the boundary conditions for intensity of the EC radiation, I, for the case of mode-dependent reflection & polarization scrambling.

The subscripts 'inc' (incoming), 'ref' (reflected) and 'out' (outgoing), respectively

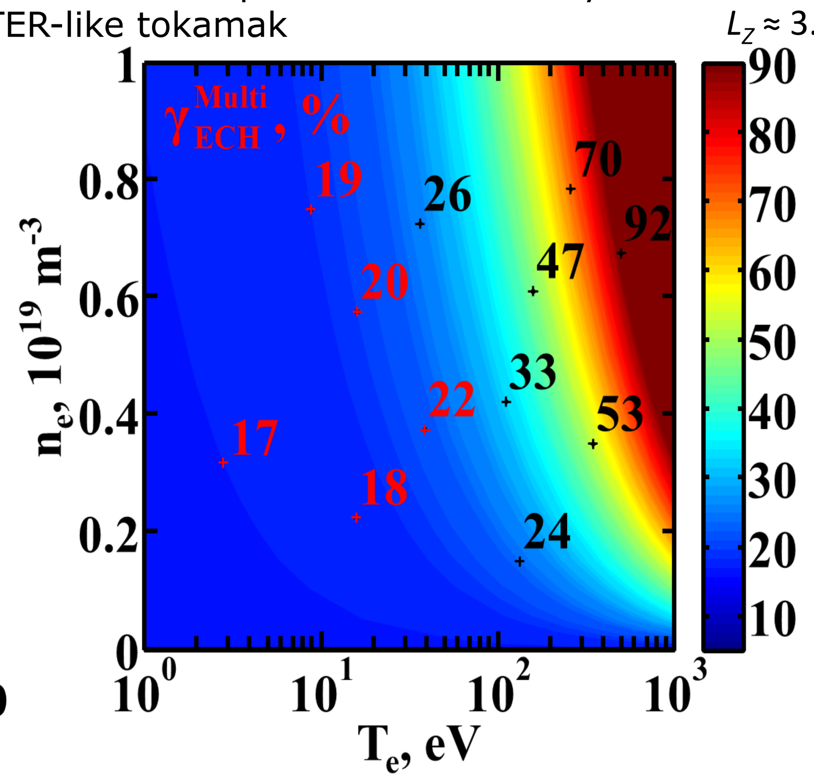
6. Main Results

Parametric analysis of the efficiency of multi-pass absorption of injected EC radiation for typical values of the electron temperature and density at the initial stage of discharge in ITER-like tokamak

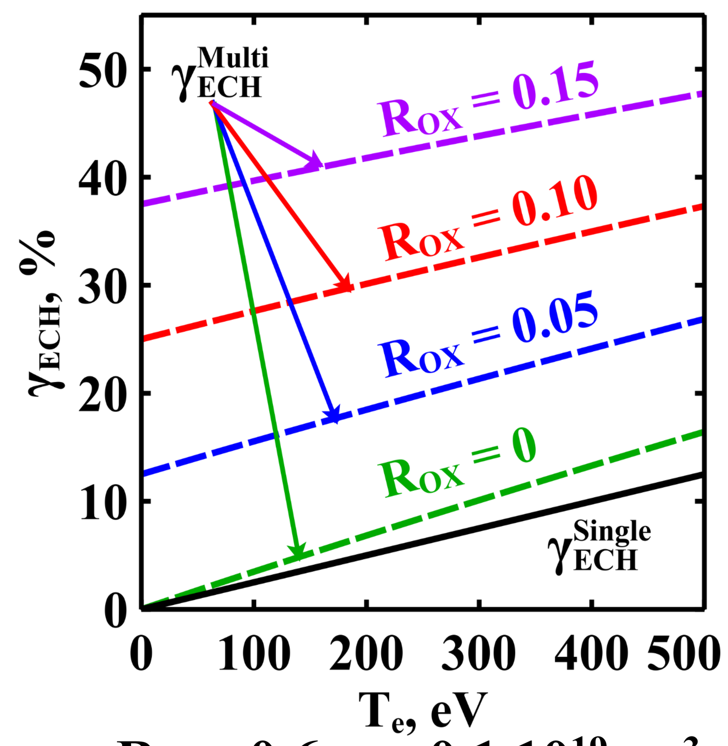
$R_{\varsigma\varsigma'}$ – wall reflection with ς to ς' mode conversion. Plasma shape in the torus mid-plane: vertical size $L_Z \approx 3.6$ m, radial size $L_R \approx 3$ m



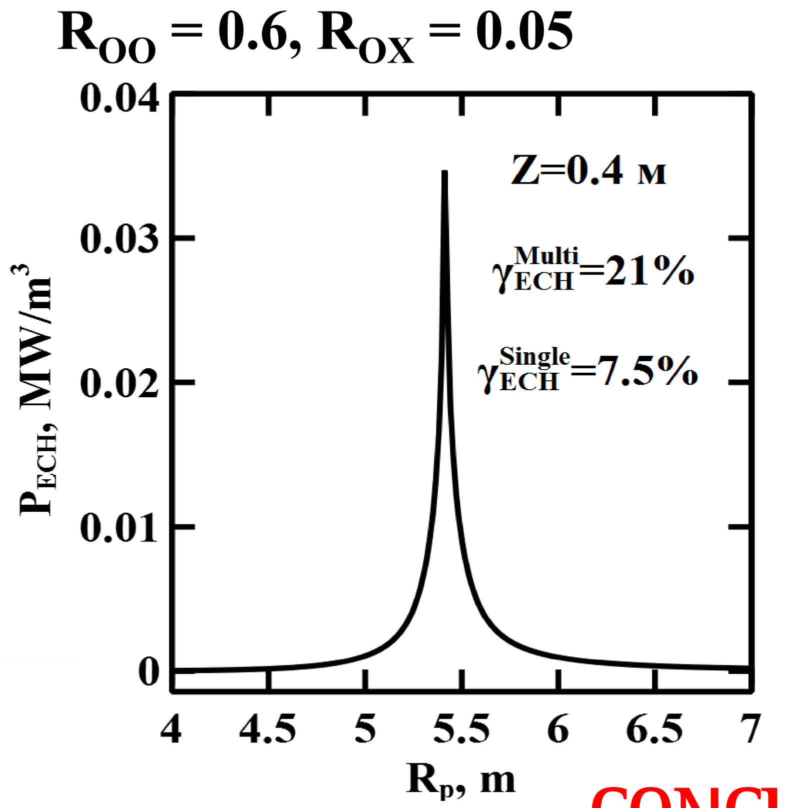
R_{OO} = 0.6, R_{OX} = 0.05



R_{OO} = 0.8, R_{OX} = 0.05

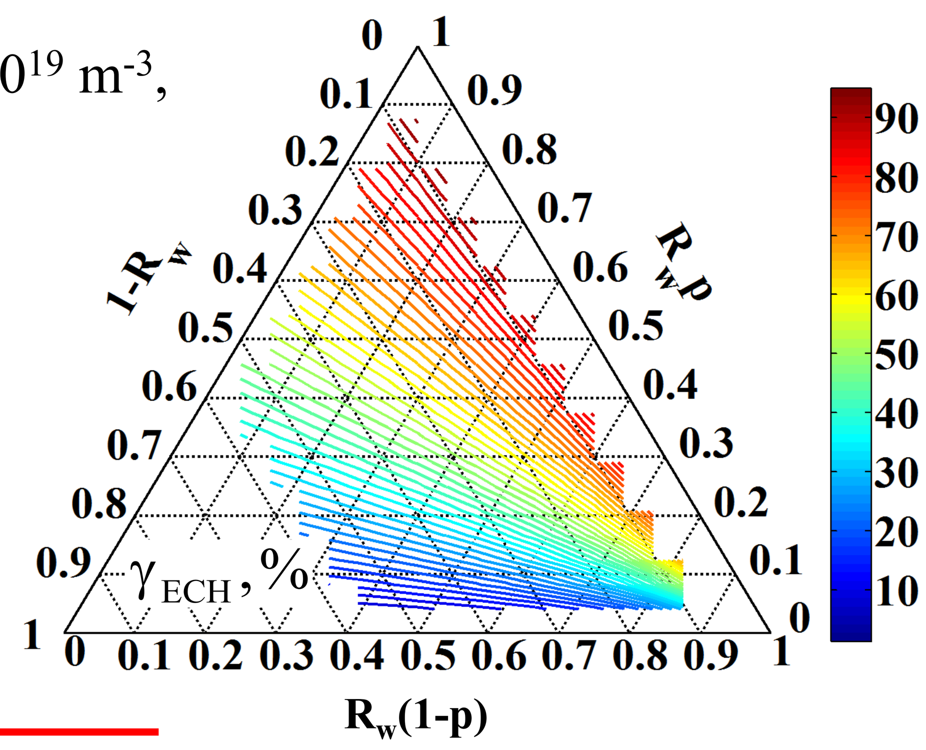


R_{OO}=0.6, n_e=0.1 10^{19} m^{-3}



T_e=300 eV, n_e=0.1 10^{19} m^{-3},
P_{inject}=5 MW,
R_{XX}=R_{OO}=0.6,
R_{OX}=R_{XO}=0.05

Plasma region
R=4 m÷7 m,
Z=-1.8 m÷1.8 m



T_e=10 eV, n_e=0.2 10^{19} m^{-3}

p – polarization scrambling parameter (percentage of radiation converted from one mode to another in the wall reflection)

CONCLUSIONS

- A model is suggested for calculating the efficiency of absorption of external EC power, γ_{ECH}, in tokamaks at initial stage of discharge. Results are given for ITER initial stage of discharge for the case:
  (a) multiple reflection of injected EC wave (O-mode) from the wall;
  (b) polarization scrambling in wall reflections;
  (c) full single-pass absorption of the X-mode.
- Parametric analysis for typical values of the electron temperature and density at the initial stage of discharge in ITER shows strong dependence of γ_{ECH} on the O-X conversion in wall reflections
- The proposed model of multi-pass absorption of ECH in tokamak-reactors is incorporated in DINA code for self-consistent simulation of plasma ECH-assisted plasma start-up scenarios in tokamak-reactors

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