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Benchmarking of Codes for Spatial with Account of Plasma

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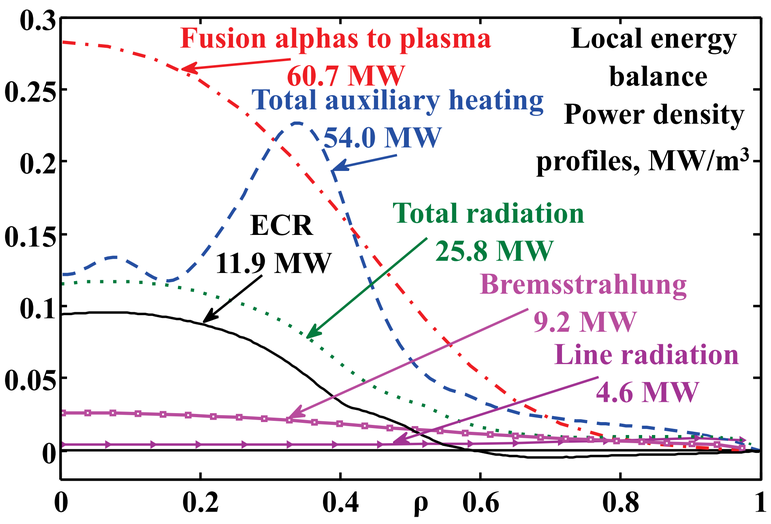
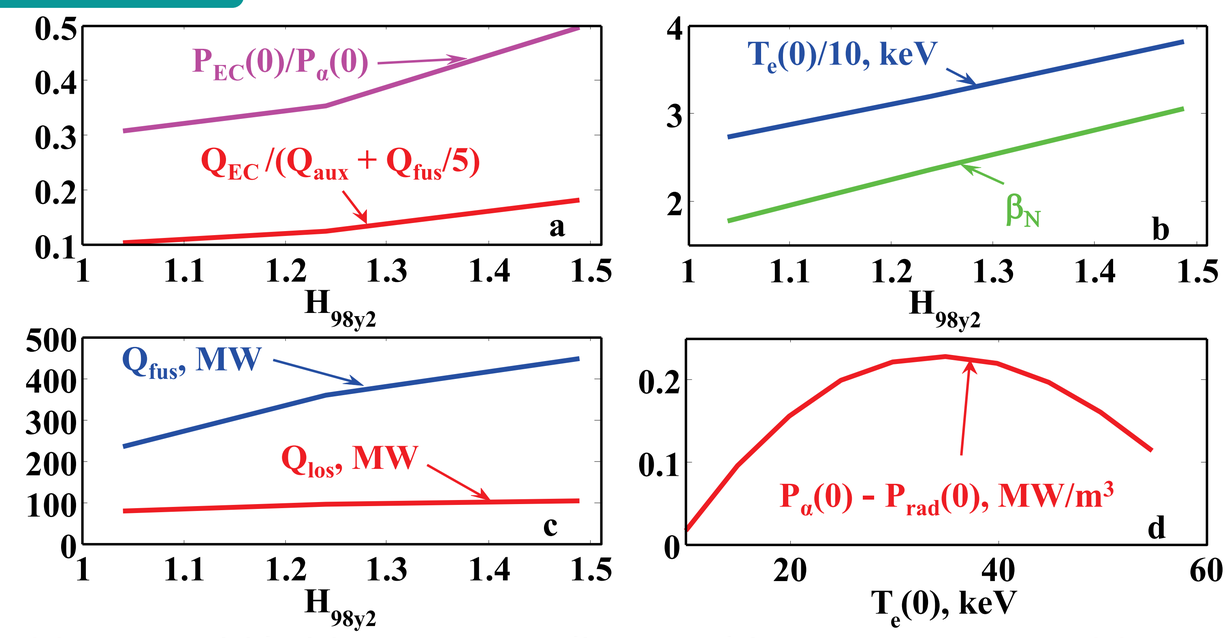
MOTIVATION

Potential importance of electron cyclotron (EC) wave emission in the local electron power balance in the steady-state regimes of ITER operation with high temperatures (see, e.g., [Albajar F., et al. // Nucl. Fusion, 2005]), and in DEMO reactor, suggested accurate calculations of the local net radiated power density, $P_{EC}(\rho)$. When central electron temperature increases to ~30 keV the local EC power loss can become a substantial part of heating from fusion alphas and is close to the total auxiliary heating [Kukushkin A.B., P.V. Minashin, A.R. Polevoi //Plasma Phys. Reports, 2012]



Comparison of components of the local energy balance in ITER steady state scenario [Polevoi A.R., et al. Proc 37th EPS Conf., 2010] (R_0=6.2 m, a=2 m, k_{elong}=1.9, R_w=0.6, B_0=5.3 T, $T_e(0)$=35 keV, $T_e(1)$=3.3 keV, $n_e(0)$=0.7 10^{20} m^{-3}, $n_e(1)$=0.5 10^{20} m^{-3}, I_p=9 MA)



(a) Local $P_{EC}(0)/P_\alpha(0)$ and total $Q_{EC}/(Q_{aux}+Q_{fus}/5)$ fraction of EC loss, (b) Central electron temperature and normalized beta (c) Fusion power Q_{los} and loss to the SOL $Q_{los} = Q_\alpha + Q_{aux} - Q_{rad}$ from 1.5D simulations of scan of plasma confinement, H_{98y2}. (d) Temperature scan of central power balance from 1.5D simulations with $T_i=T_e$ at low density, <n> ~ 6 10^{19} m^{-3} in ITER-like configuration

Goal Verification of numerical codes for EC losses in the frame of self-consistent simulations of 2D plasma equilibrium and 1D transport for tokamak-reactors ITER and DEMO

BENCHMARKING OF CODES FOR ECR LOSSES 2008

The first benchmarking of the codes for calculating the spatial profiles of EC power losses was carried out in [Albajar F., Bornatici M., Engelmann F., Kukushkin A.B. // Fusion Sci and Tech., 2009] with the codes SNECTR, CYTRAN, CYNEQ, EXACTEC.

Comparison of results for the following cases was made:

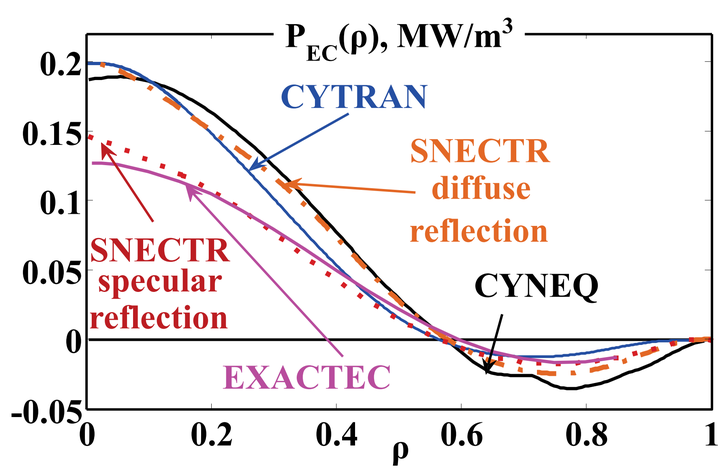
(A) Specular reflection of the EC waves from the wall of the vacuum vessel, a cylinder with circular cross-section (EXACTEC and SNECTR),

(B) (1) Diffuse reflection in a circular cylinder (SNECTR),

(2) Diffuse reflection in any geometry or any reflection in a noncircular toroid (CYTRAN and CYNEQ)

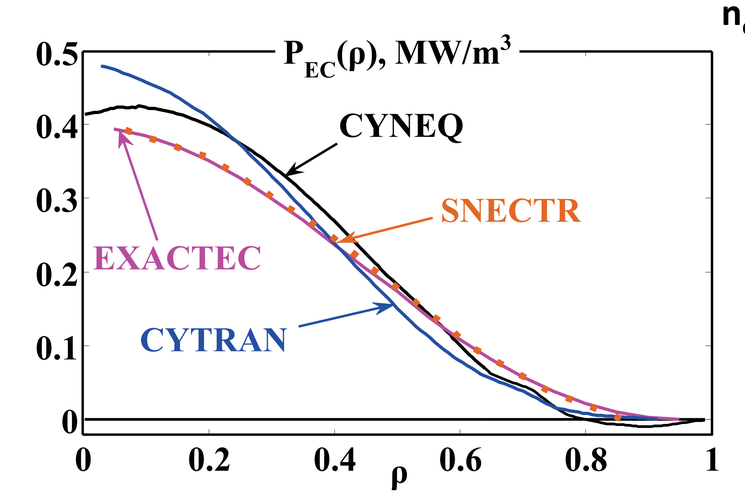
- The benchmarking [Albajar F., Bornatici M., Engelmann F., Kukushkin A.B. // Fusion Sci and Tech., 2009] has shown good agreement of results within the cases A and B.
- The results have confirmed the expectation that for large enough reflectivity of the vacuum vessel wall, R_w (>~0.5), the cases A and B provide, respectively, the lower and upper bounds for spatial profile of EC power losses, $P_{EC}(\rho)$.

Benchmarking 2008 was made in a wide range of temperature and density profiles expected in reactor-grade tokamaks, but for a homogeneous magnetic field, $B(\rho)$ =const= $\langle B\rangle_V$



Strong wall reflection, R_w=0.98

R_0=6.2 m, a=1.77 m, B(ρ)=5 T
$n_e(\rho)$= $(1-\rho^2)^{0.5}$ 10^{20} m^{-3},
$T_e(\rho)$=50(1- ρ^2) keV,



No wall reflection
R_w=0

EXTENDING THE BENCHMARKING 2008

1. Addition of new code RAYTEC (2009) [Albajar F., et al. // Nucl. Fusion. 2009]

2. Inhomogeneous profile of the effective magnetic field, calculated with allowance for plasma equilibrium

Comparison for various dimensionality of magnetic field:
CYNEQ-B(0D), CYNEQ-B(1D), CYNEQ-B(2D) versions of the code

Comparison of CYNEQ with RAYTEC, CYTRAN, EXACTEC, for plasma profiles, obtained in the frame of self-consistent 1.5D transport simulations:
(1D transport + 2D equilibrium)

SNECTR	CYTRAN	CYNEQ	EXACTEC	RAYTEC
Author, year				
Tamor S., 1976 [S. Tamor, Nuclear Technology/Fusion 3, 293 (1983)]	Tamor S., 1981 [S. Tamor, Report SAI-023-81-189LJ/LAPS-72 (1981)]	Kukushkin A.B. 1992, 2004 [A.B. Kukushkin, IAEA 1992, K.V. Cherepanov, A.B. Kukushkin, IAEA FEC 2004] + Minashin P.V, 2009 [A.B. Kukushkin, P.V. Minashin, EPS 2009]	Albajar F., Bornatici M., Engelmann F. 2002 [F. Albajar, M. Bornatici, F. Engelmann, Nuclear Fusion 42, 670-8 (2002)]	Albajar F., Bornatici M., Engelmann F. 2009 [F. Albajar, M. Bornatici and F. Engelmann, Nuclear Fusion 49, 115017 (2009)]
Geometry, reflectivity				
Arbitrary axisymmetric magneto-plasma	Hot plasma $\langle T_e\rangle_V \geq 10$ keV, noncircular cross-section and moderate aspect ratio, A~3, multiple reflection $(1-R_w)$<<1		Cylindrical plasma, circular cross-section, A>>1	Toroidal plasma with noncircular cross-section
Solution of radiative transfer problem				
Monte-Carlo simulation of emission and absorption of EC-waves	Assumed angle isotropy of intensity, most of energy is carried at frequencies for which plasma is optically thin (nonlocal transport)		Analytical solution of transfer equation	Numerical integration along EC ray paths
	$P_{EC}(\rho\to 0)\to\infty$ (Corrected at ORNL)	Neglect of diffusive transport in the optically thick region in the core		
Electron velocity distribution function (VDF)				
Maxwellian		Non-maxw., anisotropic pitch-angle	Maxwellian	Maxwellian [F. Albajar et al., Nuclear Fusion (2009)], non-maxw. [F. Albajar et al., Proc. 16th Joint Workshop "ECE and ECRH" (2010)]
Calculation of absorption and emission				
Numerical calculation	Approx. formulas	Numerical calculation	Approximate formulas	
Magnetic field inhomogeneity				
2D field without plasma equilibrium	Homogen. B(ρ)=const	2D magnetic field with plasma equilibrium	2D magnetic field, without plasma equilibrium effects (Shafranov shift, etc.)	
Incorporation to self-consistent transport simulations				
No	Yes, in ASTRA [F. Albajar et al., Nuclear Fusion 45, 642-8 (2005)]	Yes, in ASTRA [A.B. Kukushkin, P.V. Minashin, A.R. Polevoi, Plasma Physics Reports 38, 211-20 (2012)]	Yes, in CRONOS [J. Garcia et al., Nuclear Fusion 48, 075007 (2008)]	No

Profiles of Electron Cyclotron Losses Equilibrium in Tokamak Reactors

P.V. Minashin

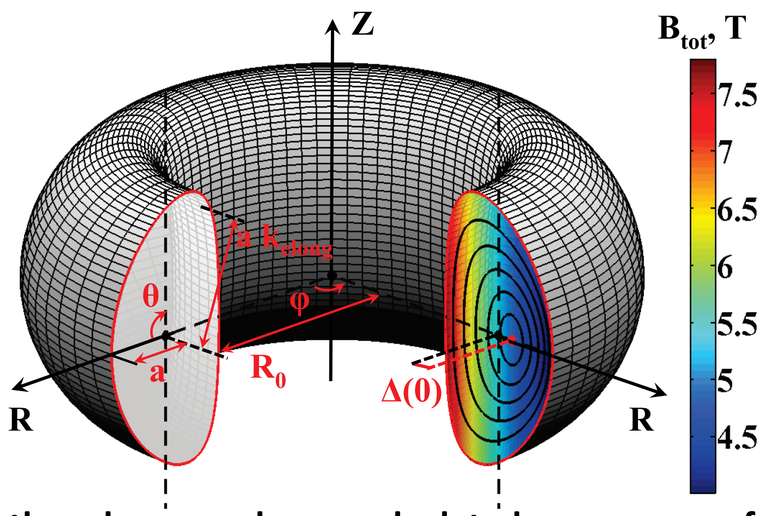
TH/P6-25

IAEA FEC 2012
24th IAEA Fusion Energy Conference

CYNEQ CODE

Electron Cyclotron radiation transport in Non-EQuilibrium hot plasmas

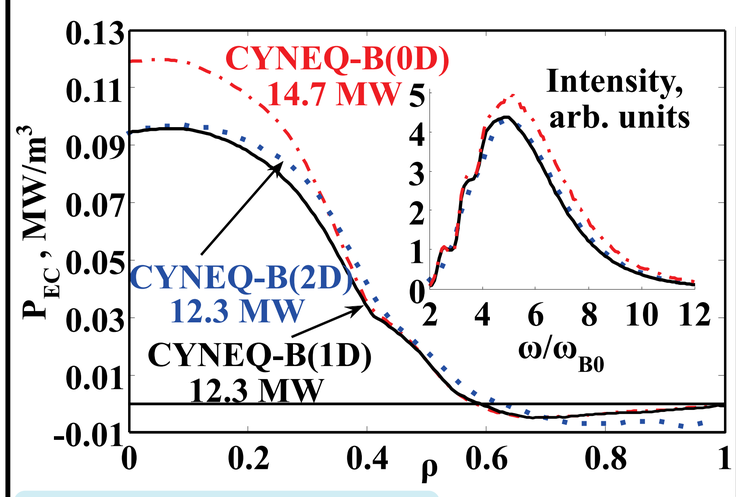
CYNEQ modifications to allow for 2D-magnetic field [Kukushkin A.B., Minashin P.V. // Proc. 36th EPS Conf. 2009]



Total magnetic field in the plasma column calculated as a sum of toroidal field, with account of Shafranov shift, Δ, and poloidal field, may be represented as

Versions of the code

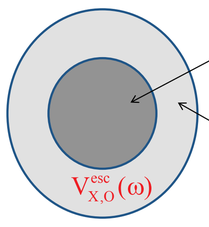
- **2D profile of magnetic field, B(ρ,θ), as a function of magnetic flux surface variable ρ (square root of normalized toroidal magnetic flux) and poloidal angle θ;** — CYNEQ-B(2D)
- **1D profile B(ρ), calculated by averaging B(ρ,θ) over θ;** — CYNEQ-B(1D)
- **flat profile, B(ρ)=const=<B>$_V$ volume–average magnetic field.** — CYNEQ-B(0D)



Local net radiated power density profiles predicted by CYNEQ code for 1.5 self-consistent simulation of plasma parameters for steady state ITER scenario [Polevoi, A.R., et al. Proc 37th EPS Conf., 2010] (R_0=6.2 m, a=2 m, k_{elong}=1.9, R_w=0.6, B_0=5.3 T, T_e(0)=35 keV, T_e(1)=3.3 keV, n_e(0)=0.7 10^{20} m^{-3}, n_e(1)=0.5 10^{20} m^{-3}, I_p=9 MA)

Basic equations

Plasma cross-section



X (eXtraordinary)
O (Ordinary) waves

Optically thick plasma, diffusion transport → **Intensity is local Planckian intensity, I_{BB}**

Optically thin plasma nonlocal transport → **Intensity is isotropic and homogeneous $I_{X,O}(\omega)$**

ρ – effective radial coordinate (magnetic surface label), θ_{pol} – poloidal angle, **k** – wave vector, **n** – wave direction, S_w – area of vacuum chamber inner surface, R_w – reflection coefficient of radiation from the wall, q – power density of ECR source, κ – absorption coefficient

$$\int d\Omega_{\vec{n}} \int_{V^{esc}_{X,O}(\omega)} dV\, q_{X,O}(\rho,\theta_{pol},\omega,\vec{n})$$

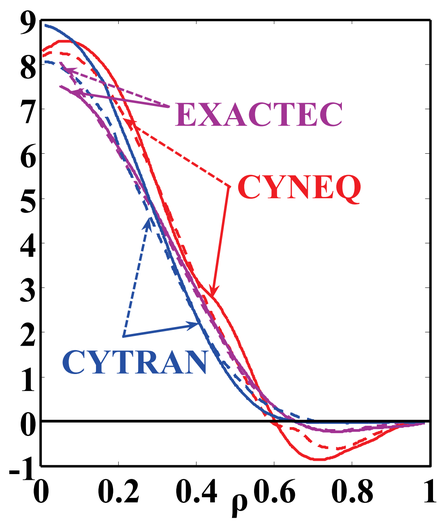
$$I_{X,O}(\omega) = \frac{\int_{\cap} d\Omega_{\vec{n}} \int_{S_w} (d\vec{S}\cdot\vec{n})(1-R_w) + \int d\Omega_{\vec{n}} \int_{V^{esc}_{X,O}(\omega)} dV\, \kappa_{X,O}(\rho,\theta_{pol},\omega,\vec{n})}{}$$

Spatial profile of EC power losses – distribution of losses over magnetic surfaces (ms)

$$P_{EC}(\rho) = \sum_{X,O} \int d\Omega_{\vec{n}} \int d\omega \left\langle q_{X,O}(\rho,\theta_{pol},\omega,\vec{n}) - I_{X,O}(\rho,\theta_{pol},\omega)\kappa_{X,O}(\rho,\theta_{pol},\omega,\vec{n}) \right\rangle_{ms}$$

SIMILARITY OF POWER LOSS PROFILES

$$P^{norm}_{EC}(\rho) \equiv P_{EC}(\rho) / (P^{tot}_{EC} / V_{tot})$$

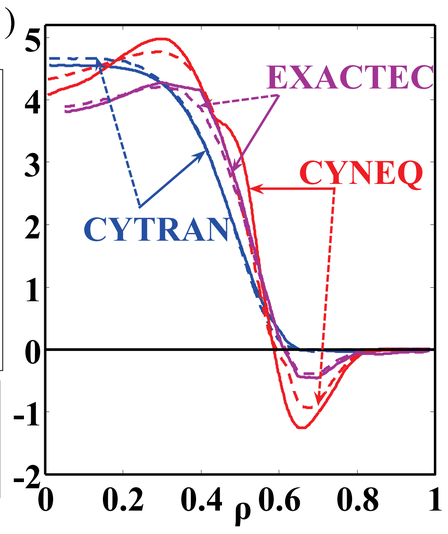


parabolic T_e (βT=2, γT=1.5)
T_e (ρ)=T_e (1)+(T_e (0)-T_e (1))(1- $\rho^{\beta T})^{\gamma T}$

The effects of plasma equilibrium (e.g., Shafranov shift), as shown in [P.V. Minashin, A.B. Kukushkin, Proc. 39th EPS (2012)] for the CYNEQ code, have a small impact upon above similarity.

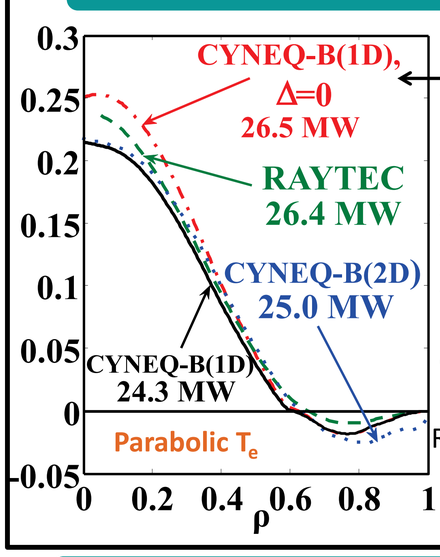
R_0=6.2 m, a=2 m, k_{elong}=1, B(R_0)=5.3 T, R_w=0.8, n_e(ρ)=1.1(1-ρ^2)$^{0.1}$ 10^{20} m^{-3}

T_e(0)=45 keV (dashed line)
T_e(0)=22.5 keV (solid line)
T_e(1)=0.01 keV



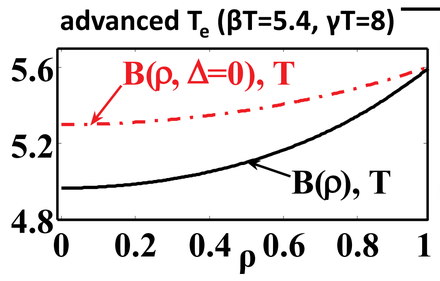
advanced T_e (βT=5.4, γT=8)

CYNEQ vs. RAYTEC

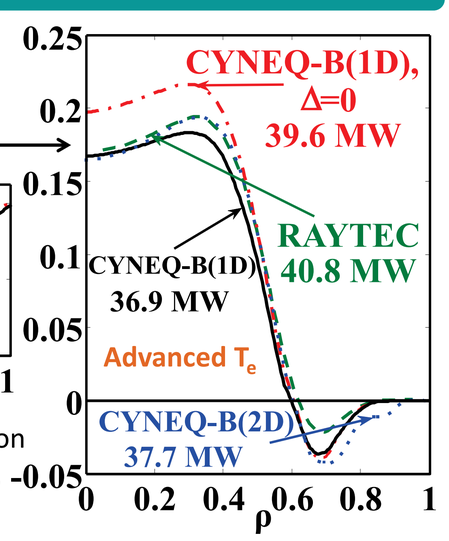


$P_{EC}(\rho)$, MW / m^3

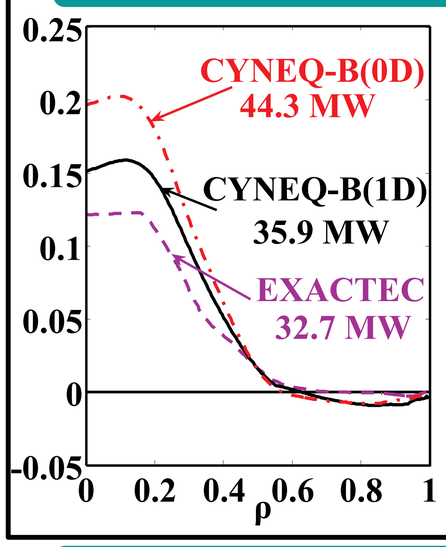
Parabolic T_e (βT=2, γT=1.5)
T_e (keV)=45(1- $\rho^{\beta T})^{\gamma T}$
advanced T_e (βT=5.4, γT=8)



R_0=6.2 m, a=2 m, plasma elongation k=1.7, triangularity δ=0, R_w=0.8, n_e(ρ)=1.1(1-ρ^2)$^{0.1}$ 10^{20} m^{-3}, T_i=T_e

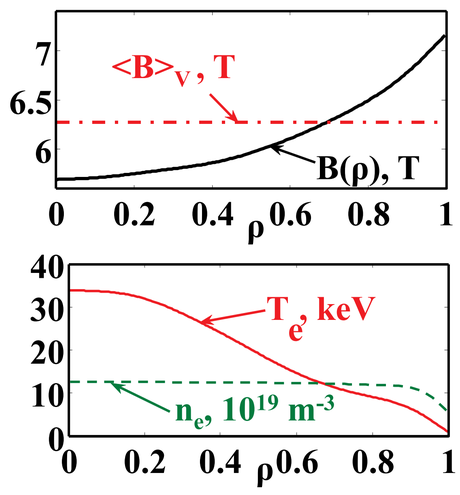


CYNEQ vs. EXACTEC

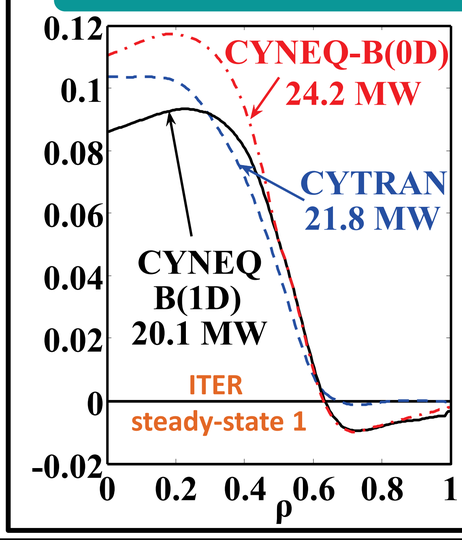


$P_{EC}(\rho)$, MW / m^3

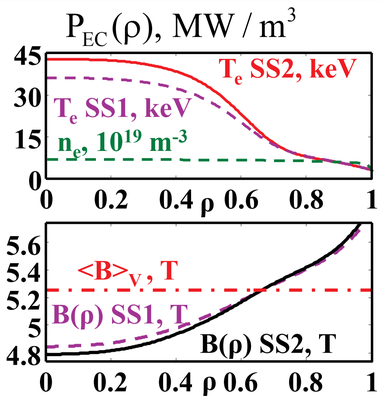
DEMO with ECH/ECCD, [Garcia J., et al. //Nucl. Fusion, 2008]
R_0=7.5 m, a=2.5 m, k_{elong}=1.9, δ=0.47, R_w=0.7, B_0=6 T, I_p=19 MA



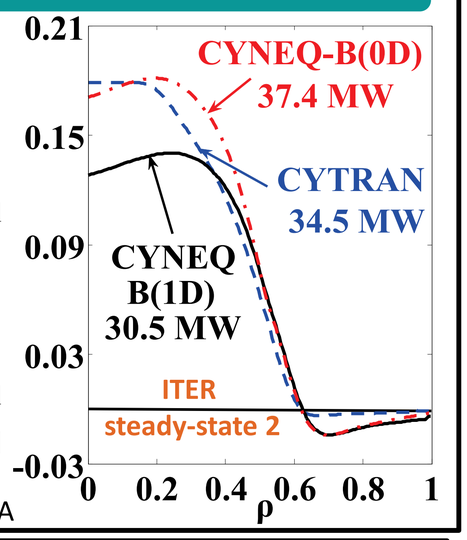
CYNEQ vs. CYTRAN



$P_{EC}(\rho)$, MW / m^3



[Albajar F., et al. // Nucl. Fus. 2005]
R_0=6.4 m, a=1.9 m, k_{elong}=1.9, δ=0.4, R_w=0.6, B_0=5.2 T, I_p=9 MA



CONCLUSIONS

The EC power loss density P_{EC}(ρ) predicted by CYNEQ has been benchmarked versus predictions of other modern codes (RAYTEC, EXACTEC, and CYTRAN) for the same plasma parameters and different approximations of magnetic field inhomogeneity.

- **For the parameters expected in the ITER steady state scenario, the difference between the profiles of the local EC power loss, P_{EC}(ρ), calculated by CYNEQ in 1D and 2D approximations of magnetic field appears to be less than a few percent in central plasma.**
- **The RAYTEC code takes into account the 2D inhomogeneity of the magnetic field and uses an EC transport model that differs from the model employed in the CYNEQ code and does not take into account the Shafranov shift Δ. For high elongations of k_{elong} = 1.7–2.0 and moderate aspect ratios of *A* ~ 3, expected for ITER and DEMO, both the maximum value of the local power loss density P_{EC}(ρ) in the central region of the plasma column and the volume integrated power losses coincide to within 15% with CYNEQ predictions**
- **Modified EXACTEC code still underestimates P_{EC}(ρ) profile near the center of the plasma column with a noncircular cross section. For the DEMO steady state scenario, the difference between EXACTEC and CYNEQ-B(0D) ~ 40% in the central region, while for CYNEQ-B(1D), the difference decreases to ~20%**
- **Benchmarking versus the CYTRAN code was carried out for the plasma parameters expected in the ITER steady state, obtained from self-consistent 1.5D transport simulations. For a small Shafranov shift agreement between the CYNEQ-B(1D) and CYTRAN predictions is within 10%, whereas for a large Shafranov shift, the difference between them increases to ~30%**

CYNEQ-B(1D) code is the most appropriate code for self-consistent 1.5D transport simulations of plasma evolution in tokamak-reactors, because it provides high accuracy and an increased computational speed.

Acknowledgements. *The authors are grateful to A.R. Polevoi (ITER Organization) for fruitful collaboration; A.Yu. Dnestrovskij (NRC "Kurchatov Institute"), for helpful discussions of the ASTRA code; F. Albajar (Fusion for Energy, Barcelona), for helpful comments on the results from the RAYTEC code. This work is supported by the RF State Corporation ROSATOM and the Council of the Russian Federation Presidential Grants for State Support of Leading Scientific Schools (grant no. NSh_65382.2010.2). Participation of P.V. Minashin in the 24th IAEA Fusion Energy Conference is partly supported by the travel grant from the IAEA.*