Integrated Modelling of DEMO Scenarios by the CRONOS Suite of Codes

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Abstract. The CRONOS suite of codes, developed at CEA-Cadarache, is used to make a first 1.5D analysis of the DEMO design. Since high temperatures are expected in these plasmas, the electron synchrotron (ES) radiation may be an important cooling mechanism, and therefore, a model which takes into account the non-local effects of this radiation, i.e. emission and re-absorption by the plasma itself, has been specially coupled to the code.
Two simulations have been performed with plasma parameters similar to those obtained in the European final report on Power Plant Conceptual Study (PPCS) [1] in the case of the full inductive mode, labelled as A in [1], and an advanced scenario with lower inductive current and higher bootstrap current fraction, labelled as C in [1]. It is shown as the inductive DEMO scenario is well simulated leading to similar results to those obtained by means of 0-D simulations in [1], whereas in the case of the advanced regime the fusion power and the bootstrap current fraction are not comparable to the 0-D studies due to the lack of high enough confinement.
In spite of the fact that in these scenarios the operating density is slightly above Greenwald density, n_e/n_{gw}~1.0, and that bremsstrahlung radiation is enhanced in this regime owing to relativistic effects, ES radiation tends to be the main radiation cooling mechanism for the electrons in the plasma core, even when the optimistic reflection coefficient R_w=0.7 is used throughout the simulation. In fact, a local treatment of ES wave power losses based on Trubnikov formulae, as is generally adopted, does not correctly account for the ES radiation profile, since it underestimates the central power density losses, which can lead to an increasing of the central electron temperature, and the re-absorption of the outer part of the plasma, which leads to a net energy transfer from the core to the edge.

1. Introduction

The ultimate goal of magnetically confined fusion research is to develop commercial fusion reactors. In order to achieve this objective, several conceptual studies of commercial fusion power plants have been carried out. In the European framework, these studies have finally led to a European final report on Power Plant Conceptual Study (PPCS), which has shown a wide range of possibilities for the power plant design. In this report, four main designs for the commercial fusion power plant have been selected, primarily on the basis of 0-D modelling. These main options can also be used to design the demonstration reactor (usually called DEMO) which, with respect to the commercial power plant, is downscaled to an electrical power production of the order of 1 GW. A vigorous programme has now been started in Europe aiming at a more and more refined selection of the various options of the DEMO design. A key ingredient of this programme is the elaboration of scenarios of operation for DEMO, by means of far more sophisticated tools than the 0-D analysis, i.e., integrated modelling by 1.5-D codes, including 2-D magnetic equilibrium, predictive transport calculations, detailed modelling of heating, current, particle and momentum sources, as well as impurity transport and radiation losses.
The integrated modelling of burning plasmas is an essential step to solve the equations obtained from physical theories. Moreover, from the analysis of the results obtained, the experimental data can be better understood, the experiments may be improved and the

performance of future fusion magnetic devices can be predicted in an easier way. With this motivation, the CRONOS suite of codes [2] has been developed.
This paper will report simulations of DEMO scenarios performed by means of the CRONOS suite of codes and including, for the first time, essential reactor physics ingredients such as i) self-consistent kinetic computation of the fusion-born alpha particle distribution; ii) time evolution of the various current sources (bootstrap, rf-driven, NBI-driven); iii) precise calculation of radiation losses, in particular the synchrotron loss, which is expected to be significant in DEMO, not only as a global loss, but also as a mechanism for substantial electron energy redistribution.

2. The CRONOS code. Models applied

The suite of codes CRONOS solves the transport equations for various plasma fluid quantities (current, energy, matter, momentum). This is done in one dimension (the magnetic flux coordinate associated with the minor radius) self-consistently with magnetic equilibrium which is calculated by means of HELENA module [3]. The neoclassical terms, and in particular the bootstrap current which is essential for the correct simulation of the steady-state regimes, are determined using the NCLASS [4] code. The sources are computed by external modules coupled with the main transport equations. The Neutral Beam Current Drive is calculated by means of the SINBAD module [5,6], PION [7] for Ion Synchrotron Resonance Heating and DELPHINE [8] for Lower Hybrid Current Drive. The alpha power deposition profile and distribution function are computed with the module SPOT [9] which is a Monte-Carlo code for computing the fusion alpha products, including finite orbit width effects. The core plasma line and bremsstrahlung radiation are computed with a model based on coronal equilibrium. According to [10], synchrotron radiation can be the main cooling mechanism for electrons in the plasma core when temperature is high and the fusion device size is large. Therefore, in order to simulate DEMO, a new module for the calculation of the synchrotron radiation called EXATEC has been recently coupled to CRONOS. This module is based on the exact solution for the radiative transfer equation for plasmas in a cylinder with circular cross section [11], corrected for elongated geometry and inhomogeneous magnetic field. It takes into account the non-locality characteristic of this radiation, i.e. emission and reabsorption by the plasma. The absorption coefficients used along the simulation can be found in reference [12].
Two classes of models for the heat transport are available in CRONOS, the first principles models, based on the linear growth rates of the various instabilities which are the source of plasma turbulence, as the Weiland ITG/ETG model [13] and the gyro-Landau-fluid GLF23 [14], as well as the more empirical models, based on global scaling laws, as the Kiauto [15]. In this paper, the GLF23 model has been applied for the DEMO simulations in the plasma core, however, since the pedestal can not be obtained by means of this model, the Kiauto scaling has been used to define the pedestal height and width. Finally, the density profiles are prescribed and fixed during the time evolution, and the helium concentration is obtained by imposing $\tau_{He}/\tau_E=5$.

3. DEMO device parameters

With the aim of analyzing the performance of DEMO for different plasma regimes, two different configurations have been chosen as representative, respectively, of the full inductive scenario with low bootstrap fraction, and of one more advanced which can be close to the steady state regime with lower inductive current. The global characteristics of the operation scenarios considered for DEMO as well as some of the main global parameters obtained in the simulation are shown in table 1. In fact, the full inductive scenario is just an extrapolation of the expected ITER inductive regime, with a high amount of external current, large major and minor radius and small elongation and triangularity. Unlike the inductive case, the advanced scenario tends to decrease the inductive current, the toroidal vacuum magnetic field and major and minor radius, whereas the bootstrap fraction increases. In this configuration longer or even steady-state discharges are expected, however, the large amounts of non-inductive current necessary can be a drawback.

TABLE I: GLOBAL CHARACTERISTICS OF THE DEMO OPERATION SCENARIOS

Parameter	**Inductive**	**Advanced**
Major radius R (m)	9.55	7.5
Minor radius a (m)	3.15	3.0
Elongation/Triangularity	1.7/0.25	1.9/0.47
B_t (T)	7.0	6.0
I (MA)	30.5	20.1
$n_{e,0}$/ $<n_e>$ (10^{19} m^{-3})	12/10.3	11/10.1
n_e/n_{gw}	1	1
$T_{e,0}$ (keV)	42	36
$T_{i,0}$ (keV)	60	41.5
P_{fus}/ P_{add} (MW)	4300/246	2000/103
P_{ES}/ P_{bremms} (MW)	120/156	26/72
f_{BS} (%)/ Q	28/17.5	38/19.4
q_0/q_{95}	0.81/3.4	0.55/4.5

4. Analysis of full inductive DEMO

The electron and ion temperature profiles as well as the current density profiles obtained for the inductive DEMO when t=1500s are shown in figure 1(a) and 1(b) respectively. The central ion temperature, $T_{i,0}\approx 60$ keV, is higher than the central electron temperature $T_{e,0}\approx 40$ keV, although the pedestal is similar $T_{ped}\approx 6$ keV. Related to plasma density currents, the NBI heating moderately contributes to the current in the plasma core, whereas bootstrap current completely determines the total current at the edge, as expected from the existing pedestal. The fusion power obtained is 4.3 GW, leading to 1 GW net electrical power. From the 0-D analysis carried out in reference [1] the expected fusion power for DEMO-A is 5 GW, which means that the simulation performed with CRONOS is close to that value. In this scenario the steady-state operation is made possible by a large amount of injected power (= 246 MW), which implies a rather low Q = 17.5. As shown in figure 2(a) the boostrap current contributes moderately to the total current $f_{BS}\approx 28\%$. The alpha, radiated and input power evolution are shown in figure 2(b). After 250s, the simulation is stabilized leading to an scenario with 860 MW alpha power. In addition, high levels of radiated power (=300MW) are obtained in this simulation and this feature can strongly determine the difference between the ion and electron temperature.

Related to radiation, the synchrotron and bremsstrahlung power density profiles are shown in figure 2(c). Due to the high temperatures obtained in this simulation, the electron synchrotron losses are enhanced being 4 times higher in the plasma core than bremsstrahlung losses. The synchrotron radiation profile is strongly peaked and therefore it leads to almost negligible losses outside the plasma core; the total bremsstrahlung and synchrotron radiation are similar,

P_{ES}=120 MW and P_{bremms}=156 MW. In spite of the fact that in these scenarios the operating ratio n_e/n_{gw} is close to 1 being n_{gw} the Greenwald density, and that the ratio of synchrotron to bremsstrahlung losses scales as $(n_e/n_G)^{-3/2}$, ES radiation tends to be the main radiation cooling mechanism for the electrons in the plasma core, although the reflection coefficient R_w = 0.7 is used throughout the simulation. Note that bremsstrahlung losses are enhanced in the plasma core of about 20% owing to relativistic effects in this simulation. Thus, synchrotron radiation can be as important as bremsstrahlung in this scenario in both senses, the profile and total losses. However it is worth to point out that this feature can highly be determined by the reflection coefficient $R_{w.}$ This point will be clarified in next sections.

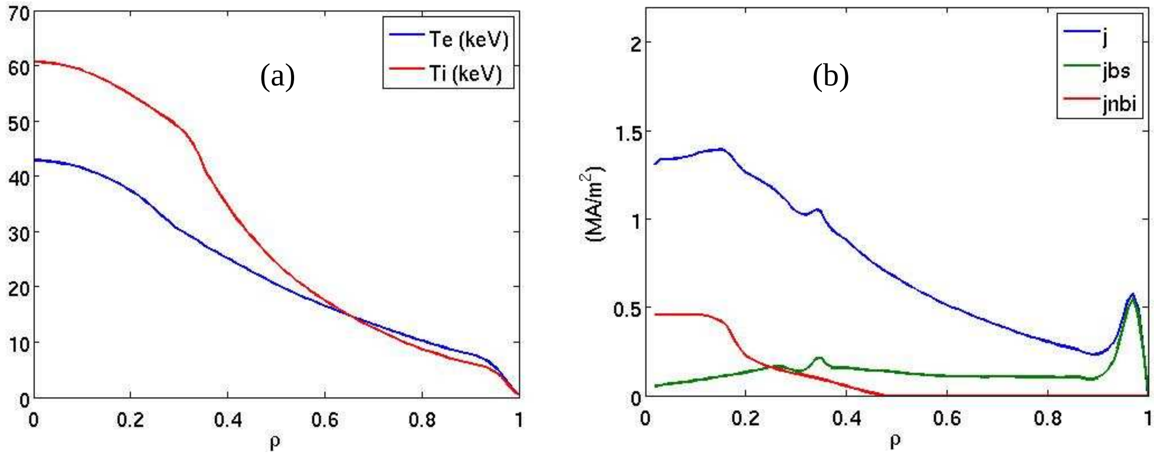

FIG.1. Electron and ion temperature profiles for DEMO inductive scenario obtained with CRONOS when t=1500s (a). Current density profiles for DEMO inductive scenario when t=1500s (b).

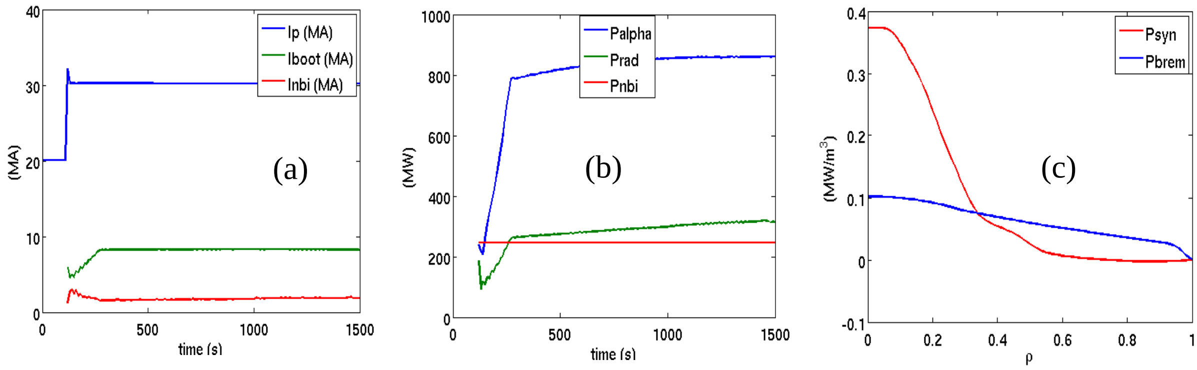

FIG.2. Evolution of the total current (Ip), bootstrap current (Iboot) and NBI current drive (Inbi) (a). Alpha, radiated and NBI power evolution (b) Comparison between synchrotron and bremsstrahlung radiation profiles when t=1500s (c).

5. Analysis of advanced DEMO

With the aim of analyzing a regime with higher bootstrap current fraction and less inductive current, close to the so called "steady-state" regimes of ITER, a scenario with the characteristics shown in table 1 has been chosen as reference. The electron and ion temperature profiles as well as the current density profiles obtained for this regime when t=1500s are shown in figure 3(a) and 3(b) respectively. Both, ion and electron central temperatures are lower than in the previous case, $T_{i,0}$≈42 keV and $T_{e,0}$≈36 keV, although the pedestal is similar T_{ped}≈6 keV. These temperature profiles have not any Internal Transport Barrier (ITB) feature which can be expected for an advanced scenario. This fact leads to a low fusion power of 2GW and low Q=19.4, which is higher than in the previous scenario, but far from the 0-D analysis performed in [1] for DEMO-C, but close to the 1GW electrical power version of that scenario. The on-axis NBI heating contribution to the current is similar to the previous case, however, the bootstrap current fraction is larger in this scenario, i.e. f_{BS}≈38%. Anyway, the total non-inductive current fraction, 45%, is still far from the one expected from a steady-state scenario, which confirms the lack of ITB in this simulation. The evolution of the q profile, given in figure 4(a), shows as the operation regime tends to have a rather low q_{0}, which finally degrades the confinement after a long time of operation. In order to improve the confinement, a scenario with no or very little sawteeth would be desirable by pushing the central safety factor close to 1 or even higher. Therefore, it is expected to follow with the analysis of the advanced DEMO by adding off-axis NBI and Lower Hybrid current drive to finally get a flattened q profile with q_0 above 1.

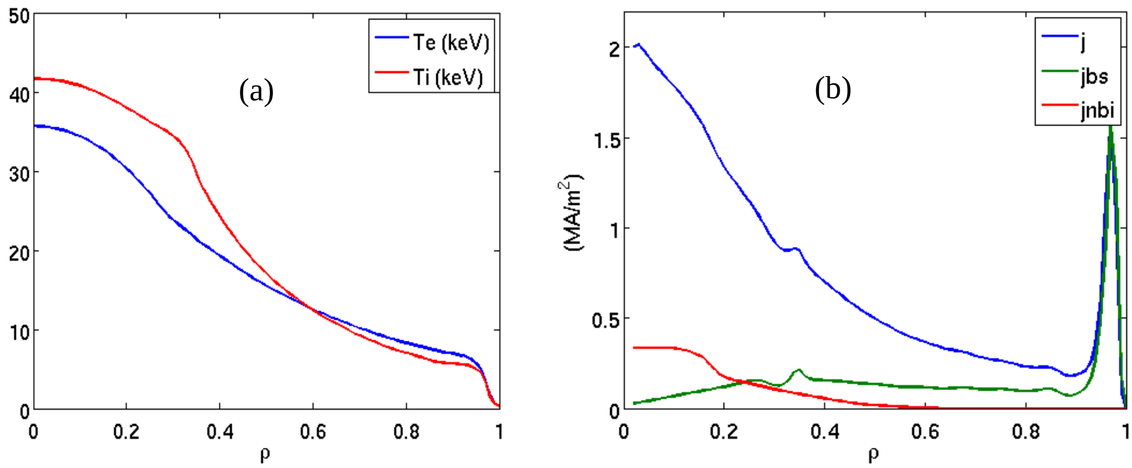

FIG.3. Electron and ion temperature profiles for DEMO advanced scenario obtained with CRONOS when t=1500s (a). Current density profiles for DEMO advanced scenario when t=1500s (b).

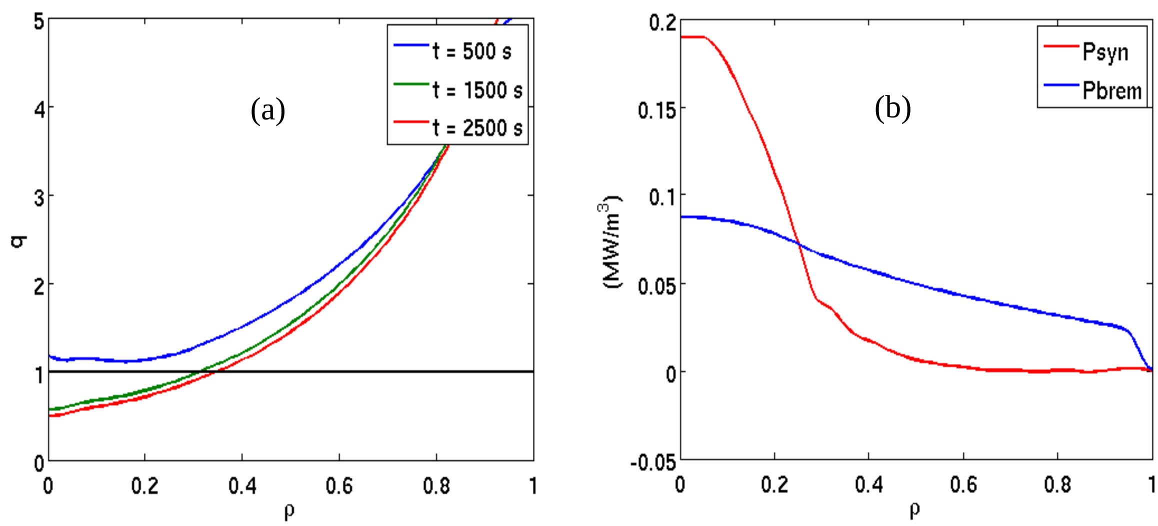

FIG.4. Evolution of the safety factor (a). Comparison between synchrotron and bremsstrahlung radiation profiles when t=1500s (b).

Since the electron temperatures attained in this scenario are lower to those obtained in the previous case, the relative importance of synchrotron radiation decreases, as shown in figure 4(b). In this case, the central synchrotron power density losses are just twice higher than bremsstrahlung ones. Moreover, since synchrotron losses are proportional to the confinement capability aB_t, which is much lower in this case, the total synchrotron losses reduce to 26 MW.

6. Impact of the synchrotron radiation on DEMO plasma conditions

The impact of the inclusion of a satisfactory model for the ES radiation for the correct analysis of DEMO scenarios is analyzed in figure 3(a) by comparing the synchrotron power density losses in the inductive DEMO obtained with EXATEC routine and the local approach based on Trubnikov's formula as it is usually applied. It appears that the local treatment does not correctly account for the synchrotron radiation profile, underestimating losses in the plasma core and underestimating the re-absorption of the outer part of the plasma. This fact has some impact on the ion and electron temperature profiles as shown in figure 3(b), leading to lower central temperatures and higher pedestal when EXATEC is applied, as expected from the power redistribution obtained using this routine. This feature has also effects on the fusion power and the total synchrotron power losses. When the local approach is applied, the fusion power drops from 4.3 GW to 4 GW, which represents almost 7%, and the total synchrotron losses rise from 120 MW to 225 MW. Therefore, the inclusion of a correct model for the synchrotron radiation losses calculation seems absolutely necessary when reactor operation conditions are simulated.

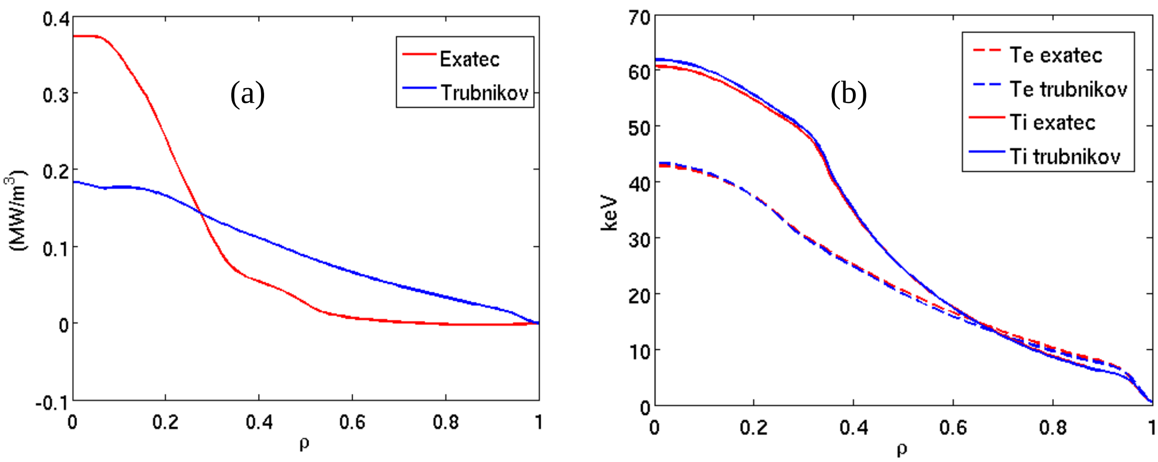

FIG. 5. Comparison between the synchrotron power density profile obtained using EXATEC routine and the local approach based on Trubnikov's formula (a). Comparison between the ion and electron temperature profiles obtained using EXATEC routine and the local applied Trubnikov's formula (b).

In order to analyze the influence of the reflection coefficient on the synchrotron radiation profile as well as in the global performance of DEMO inductive, two simulations have been performed with different reflection coefficients of R_w=0.7 and R_w=0.9. The temperature profiles obtained for each reflection coefficient are given in figure 6(a) and the synchrotron power density losses in figure 6(b). The electron temperature increases when the reflection coefficient increases, due to the reduction of synchrotron losses, mainly in the plasma core, as shown in figure 6(b). The ion temperature also increases, which means that a change in the wall reflection coefficient not only affects electrons but also ions. This fact leads to an increase of the fusion power from 4.3 GW for R_w=0.7 to almost 4.5 GW for R_w=0.9. Since the importance of synchrotron radiation is higher in regimes where the losses due to conductive-convective heat transfer are not dominant, i.e. in steady-state scenarios [10], the influence of synchrotron radiation in the overall performance of DEMO may be enhanced in the advanced regimes. This feature will be analyzed in the future.

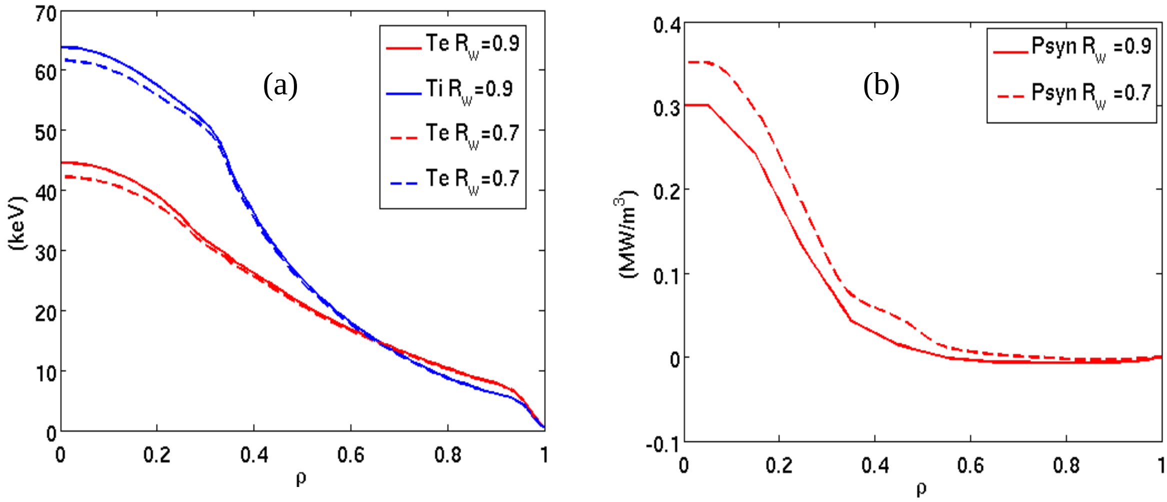

FIG. 6. Comparison between the electron and ion temperature profiles obtained for different wall reflection coefficients (a). Comparison between the synchrotron power density losses obtained for different wall reflection coefficients. (b).

7. Conclusions

The CRONOS suite of codes has been used to simulate and analyze the DEMO design in the case of full inductive operation and a more advanced regime with higher non-inductive current fraction.
An extrapolation of the inductive regime in ITER, with higher major and minor radius and 30 MA of inductive current, can lead to 4.3 GW fusion power, which means almost 1 GW electrical power. This result can be obtained by a large amount of injected power, which implies a low Q = 17.5 and low bootstrap fraction of 28%. These results are quite close to the ones obtained by means of 0-D studies carried out in [1]. In this scenario, the role played by the synchrotron radiation is enhanced due to the high electron temperatures achieved. In fact, synchrotron radiation is the main radiation mechanism in the plasma core, being almost 4 times higher in that zone than bremsstrahlung radiation, in spite of the reflection coefficient considered in this study is R_w = 0.7 and the density is close to the Greenwald limit The proper calculation of the synchrotron radiation losses profile by means of the EXATEC routine leads to important changes compared with the usual Trubnikov's approximation, since the non-local effects of this radiation are considered in this paper, obtaining higher losses in the core and smaller or even negative losses at the edge. This characteristic has an important effect on the main plasma variables, since a redistribution of the energy is obtained when the EXATEC code is applied, leading to lower temperatures in the core, and higher at the edge, which finally yields to a higher fusion power. All these effects are dependent on the reflection coefficient considered, being more important when it is high. In addition, as noted in [16], the reflection coefficient in the synchrotron wavelength range can depend of the wall temperature, therefore, the importance of the synchrotron radiation on the correct 1-D analysis of the fusion reactor conditions cannot be neglected, even when an inductive scenario is considered.

A study of a scenario with lower inductive current and vacuum magnetic field has been carried out in order to analyze the possibility of steady-state regimes in DEMO. A larger Q=19.4 is obtained in this scenario, which is possible due to the low injected power considered (=103 MW), however, no ITB is formed. This fact also leads to a low fusion power (2000 MW). The evolution of the q profile shows as the q_0 tends to be lower than 1, which finally leads to a degradation of the confinement. Therefore, in order to obtain higher contribution from the non-inductive currents and to obtain a flattener q profile, off-axis NBI and Lower Hybrid current drive will be considered in the future work in the DEMO advanced scenario.

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