Integrated Modeling of DEMO Advanced Scenarios with the CRONOS Suite of Codes

J. Garcia, G. Giruzzi, J.F. Artaud, V. Basiuk, J. Decker, F. Imbeaux, Y. Peysson, M. Schneider

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

e-mail contact of main author: jeronimo.garcia@cea.fr

Abstract. A performance analysis of a DEMO design with relative small size is carried out with the CRONOS suite of codes and the GLF23 theory-based transport model. The aim of this study is to analyze whether the main goals of a DEMO device can be attained in the case of a scenario with moderate inductive current, high bootstrap current fraction, relatively small major radius R=7.5m and minor radius a=2.5m and high elongation and triangularity. It is shown how it is possible to obtain a high fusion power of 2600 MW and high fusion gain Q=26.5 by adding 98 MW Off-Axis Neutral Beam at a moderately high Greenwald fraction of 1.2. A non-inductive current fraction of 88% is mainly obtained from the bootstrap current at the plasma edge, where a high pedestal of 7.8 keV has been considered in order to optimize the alpha power. It is also shown how by adding more NBI power, a non-inductive fraction of 100% can be obtained, however, this approach leads to a significant drop of the fusion gain and the instability of the q profile. The possibility of steady-states scenarios based on Internal Transport Barriers is also discussed.

1. Introduction

The final goal of nuclear fusion research is to develop a fusion reactor capable of providing electrical power continuously. For this purpose, ITER will be built as first experimental demonstration device which will explore the physics of burning plasmas. However, ITER, will not show that producing enough electrical power in steady-state will be possible, since energy generation in ITER is downscaled to a fusion gain of Q=5-10, which would correspond to roughly 160 MW of electrical power. That is the reason why the next-step after ITER, i.e. the demonstration reactor (usually called DEMO), will be built with the clear goal of demonstrating the viability of burning plasmas and their engineering related aspects as an electrical generation source.

DEMO, with respect to the commercial power plant, is downscaled to an electrical power production of the order of 1 GW. In order to study the plasma behaviour in a machine like DEMO in detail, a key ingredient is the elaboration of scenarios of operation, by means of 0-D tools as done in the European framework which have led to a final report on Power Plant Conceptual Study (PPCS) [1], or integrated modelling by 1.5-D codes, including 2-D magnetic equilibrium, predictive transport calculations, detailed description of heating, current, particle and momentum sources, as well as impurity transport and radiation losses.

Several conceptual studies of commercial fusion power plants have been carried out in [1]. This report has shown a wide range of possibilities for the power plant design: from a full inductive scenario, which 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 (labelled as A in [1]) to an advanced scenario with less inductive current, smaller toroidal magnetic field and size, but with a higher bootstrap fraction (labelled as C in [1]). In this last configuration, longer or even steady-state discharges can be expected, but the large amounts of non-inductive current necessary can be a drawback.

However, the 1.5-D integrated modelling of burning plasmas is an essential step to solve the equations obtained from physical theories, without neglecting too many important ingredients. 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 a more realistic way. With this motivation, the CRONOS suite of codes [2] has been developed and it has been applied to this study [3].

The aim of this paper is to analyze the critical physics issues of these advanced scenarios from the 1.5-D simulation point of view by means of the CRONOS suite of codes and by avoiding optimistic assumptions (very high Greenwald limit fraction for having enough alpha power, high density peaking to obtain high bootstrap current fractions or artificially boost confinement factors) which could be difficult to justify from present day experiments. Therefore, the Greenwald limit fraction in this paper has the relatively low (compared with [1]) value of 1.2, the density profile considered is rather flat and the pedestal height has been chosen as a sensitivity parameter.

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 [4]. 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 [5] 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 [6,7]. The Electron Cyclotron Heating and Current Drive (ECH/ECCD) is calculated by means of REMA [8] (ray-tracing and relativistic damping of electron cyclotron waves), with a linear estimate of the ECCD efficiency [9] and LUKE [10] for Lower Hybrid Current Drive (LH). The fusion reactions are calculated by means of the Bosch–Hale formulation [11]. The core plasma line and bremsstrahlung radiation are computed with a model based on coronal equilibrium. EXACTEC module is used to calculate synchrotron radiation. This module is based on the exact solution for the radiative transfer equation for plasmas in a cylinder with circular cross section [12], corrected for elongated geometry and inhomogeneous magnetic field.

GLF23 transport model is applied in this paper since it is widely used for ITER studies and for specific code benchmark [13] and in fact it is one of the transport models which yields the best results compared to experimental data when the pedestal is fixed. The main pedestal features are critical for this type of simulation, therefore, instead of using some of the scaling laws available for their calculation (which leads to average errors of around 30%), the pedestal is fixed to attain the main requirements of the advanced scenarios considered in this paper, i.e high fusion gain together with high bootstrap current fraction. In the following sections a sensitivity study on this parameter will be carried out.

No particle transport is considered and therefore the density profiles are prescribed and fixed during the time evolution, and the helium concentration is obtained by solving a purely diffusive transport equation for the Helium, while imposing $\tau_{He}^{*}/\tau_{E} = 5$.

Finally, since the role played by flow shear rate on the final confinement in ITER is unclear, it seems more realistic (and conservative) not to include these effects in these simulations until major advances are made at least in the ITER physics development.

3. DEMO device parameters

The DEMO scenarios considered in this paper are inspired by the Model-C scenario in [1], which is based on advanced physical assumptions, i.e. it is characterised by a high β and high confinement, MHD stabilisation by strong plasma shaping, a high bootstrap current fraction and low Zeff (≈2.2). The choice of this type of machine seems convenient for an advanced scenario [14] since it is an intermediate design between the pure extrapolation of the ITER inductive scenarios, labelled as model-A in [1] and the extremely advanced machine model-D in [1] with a size similar to that of ITER. In particular, the D machine would need a very strong Internal Transport Barrier (ITB) or a large density peaking factor to provide the necessary bootstrap current fraction.

TABLE I: GLOBAL CHARACTERISTICS OF THE DEMO OPERATION SCENARIOS

Parameter	Value
Major radius R (m)	7.5
Minor radius a (m)	2.5
Elongation/Triangularity	1.9/0.47
B_t (T)	6.0
I (MA)	19.0
$n_{e,0}$/ $<n_e>$ (10^{19} m^{-3})	11.0/10.1
n_e/n_{gw}	1.20

In order to clarify such scenarios from the 1.5-D simulation point of view, two different regimes have been studied in this work. Scenario 1 has the aim of maximizing the fusion gain and minimizing the number of external heating systems, just by using Neutral Beam Injection (NBI). Two versions of this scenario will be analyzed: one with non-inductive current fraction below 100%, f_{NI}<100%, which could be used as a pulsed scenario and another one with f_{NI}=100%. Scenario 2 is designed to approach a full non-inductive current steady-state regime by adding an ECH/ECCD system in order to create an ITB.

4. Analysis of Scenario1: Pulsed DEMO with only a NBI system

The possibility of a pulsed machine is studied first with the aim of analyzing a device without the strong constraints of having both a high Q with 100% non-inductive current. In this case, the plasma density, the electron and ion temperature profiles as well as the current density profiles obtained for scenario1 at t=3000s are shown in figure 1. Electron and ion temperature profiles are quite similar, with $T_{i,0}$=32.5 keV, $T_{e,0}$=31.7 keV. The current density profile structure is dominated by the 2 MeV off-axis NBI driven current at normalised radius ρ ≈ 0.3 due to the high peak obtained. On the other hand, the bootstrap current completely determines the current profile at the edge, and in fact, a large amount of the total bootstrap current, I_{boot}=10.0 MA, comes from that region. Therefore, it is shown that a high pedestal height, as the one used in this paper, T_{ped}≈7.8 keV, is necessary to both provide enough confinement, and enough bootstrap current fraction, H_{98}=1.1 and f_{boot}=52.6% respectively. The pedestal used in this study is similar to the one obtained in other similar DEMO studies performed with a different transport model [15]. The dependence of this advanced scenario on the pedestal height will be analyzed in the next section. Owing to its high CD efficiency, the NBI current is also very high, i.e., I_{nbi}=6.8 MA for an injected power of 98 MW. Therefore, in this scenario the total non-inductive current is large, I_{ni}=16.8 MA, and represents a high fraction of the total current, f_{NI}=88%, as shown in figure 2. In fact, although a high pedestal has been considered, the bootstrap current fraction is still somewhat smaller than in [1], where f_{boot}=63% has been assumed. The q profile and its evolution for different times is given in figure 2. According to the models applied in this paper, in this scenario the q profile is close to those obtained in ITER hybrid-like scenarios with zero or low negative magnetic shear in the plasma core. However, the q profile is not completely stable and q values in the region $0<\rho<0.2$ slowly decrease in time. Sawteeth in these high beta plasmas would trigger Neoclassical Tearing Modes, which then have to be controlled by a large amount of current drive with precise deposition (as foreseen in ITER with the ECCD system), which eventually lowers the Q.

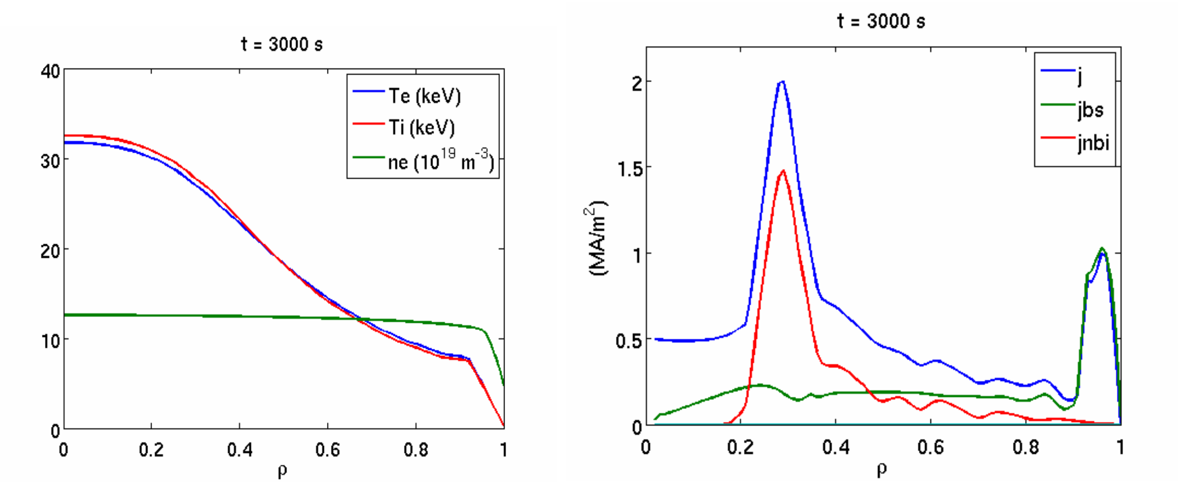

FIG. 1. Electron and ion temperature profiles for DEMO scenario1 obtained with CRONOS when t=3000s (left). Current density profiles for DEMO scenario1 when t=3000 s(right).

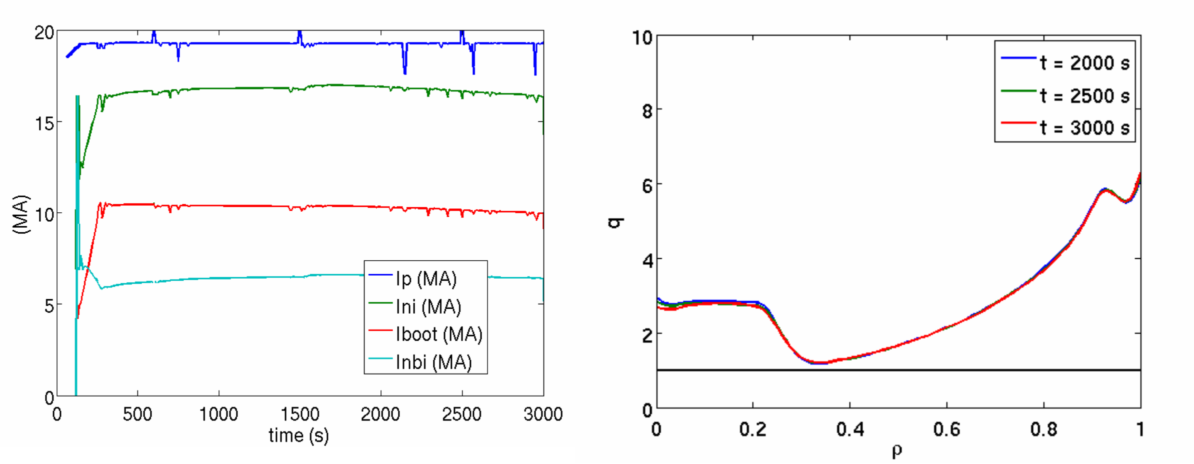

FIG. 2. Evolution of the total current (Ip), total non-inductive current (Ini), bootstrap current (Iboot) and NBI current drive (Inbi) (left). Alpha (Palpha), radiated (Prad) and NBI (Pnbi) power evolution (right).

The fusion power obtained is 2.6 GW, which means roughly 1 GW net electrical power (assuming a conversion efficiency ≈ 40 % as in [1]). Therefore, the analysis presented here downscales the electrical power from the 1.45 GW obtained in the 0-D analysis carried out in [1]. The main reason is that we have considered a conservative value on the Greenwald fraction, 1.2, compared to that used in [1], 1.5, with the aim of avoiding too optimistic results on the fusion power. Therefore, the normalized beta obtained, 3.0, is also lower than in [1], (3.4), although it is close to the upper values needed for a fusion reactor. In this scenario, long pulse operation is made possible by a low amount of injected power (= 98 MW) and the high pedestal considered, leading to a rather high Q = 26.5, which is one of the main goals of the DEMO design.

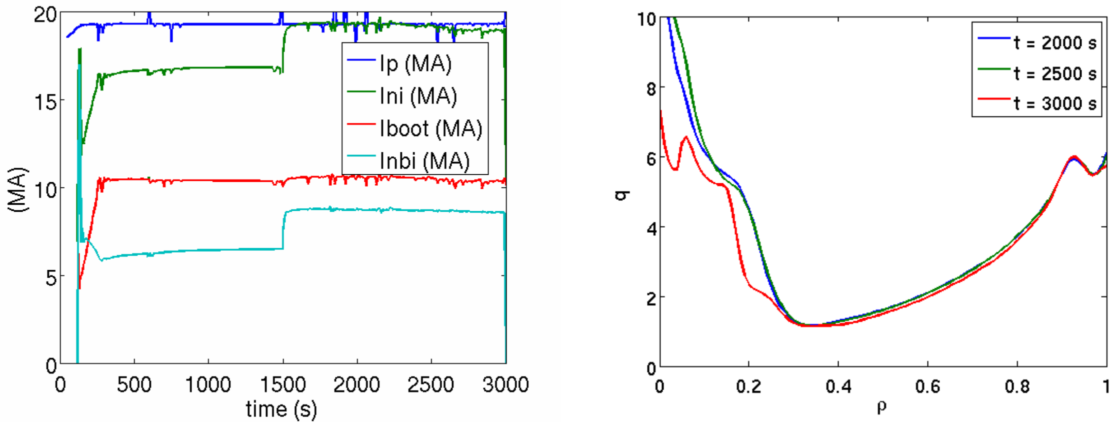

FIG. 3. Evolution of the total current (Ip), total non-inductive current (Ini), bootstrap current (Iboot) and NBI current drive (Inbi) (left). Evolution of the q profile for t=2000,2500,3000 s.

With the aim of analyzing whether this kind of scenario can be extended to a steady-state regime, 30 MW of NBI power are added at t=1500s. With the new total NBI input power, 128MW, the current drive obtained is 8.5MA, which allows to obtain f_{NI}=100% as shown in figure 3. The addition of this power causes the bootstrap current to increase due to the negative magnetic shear and the increased temperatures. However, the higher alpha power obtained does not fully compensate for the new NBI power added and the fusion gain drops, compared with the pulsed regime, to Q=22, which is very close to the Q=20 limit desirable for a DEMO device. In addition, as shown in figure 3, there is a slow evolution of the q profile which finally leads to $q_0 \approx 6$ at t=3000s. Some of the bootstrap current gained is also lost due to this evolution, which eventually can lead to a degradation of the steady-state. Due to this evolution, the final fusion gain drops again to Q=21. Therefore, in spite of the fact that a NBI system is the heating system with highest current drive efficiency and that a high pedestal has been considered, the possibility of a steady-state with only NBI leads to a fusion gain close to the lower limit desirable for DEMO, Q=20, with the additional problem that the control of the q profile is difficult. In the future, a NBI system with multiple depositions at different radial locations will be considered to control the q profile, however, this possibility must be properly evaluated since other difficulties can appear due to the size and complexity of the NBI system (which means low flexibility for the plasma control [16]). Moreover recent experiments suggest that the off-axis current drive is not as localized as expected from theoretical models [17] (a feature needed to control the q profile). Finally, the issue of a high enough fusion gain remains, even with only a NBI heating system, in a DEMO device of the size considered in this paper.
The extension of scenario 1 to steady-state regimes by means of Radio Frequency systems (ECH/ECCD and LH) has been discussed in [3].

5. Sensitivity of the results to the pedestal height

The performance of the DEMO scenario 1 highly depends on the pedestal height, since the fusion gain and the total non inductive current (via the bootstrap current) are especially dependent on that parameter, at least for a stiff transport model such a GLF23. In order to check the impact of the pedestal height on scenario 1, several simulations have been carried out with the parameters of Table 1 but for different pedestal temperatures. As shown in figure 4, Q ranges from 26.5 to 17.5 if the pedestal height drops from 8 keV to 5 keV. In addition, the total non-inductive current fraction also falls from 88% to 63% due to the loss of bootstrap current as well as the normalized beta, 3.0 to 2.2 and the central q, 2.6 to 1.1. These facts show how such an important factor of the DEMO design as the fusion gain can strongly depend on a change of 2 keV on the pedestal height, which is in the uncertainty range for the currently available pedestal scaling [18]. In order to know whether a larger machine could strongly improve the previous results, the same scenario1 has been considered but with a larger major radius, R=8.1 m and minor radius, a=2.7 m. The results obtained are also shown in figure 6. In this case Q is increased by 2 units in the pedestal range 5-7 keV, which allows for a normalized beta of 3.0 with a pedestal of 7 keV, however, the total non-inductive current fraction might drop if a lower pedestal is used to obtain the same fusion gain. Moreover, the central q also depends on the pedestal height, being close to 1 for pedestals of 5 keV, which means that higher levels of input power may be necessary to control this issue, and therefore the Q can drop again. Thus, the increased size considered in this paper does not seem to strongly improve the previous results unless a much larger machine is considered (which would mean to abandon the advanced scenarios in [1] for the inductive ones). It seems that, in the case of 1.5-D simulations with GLF23 transport model, the proper calculation of the pedestal height can be more important for the correct determination of the performance than the machine size, in the case of advanced plasma regimes with relatively small device sizes.

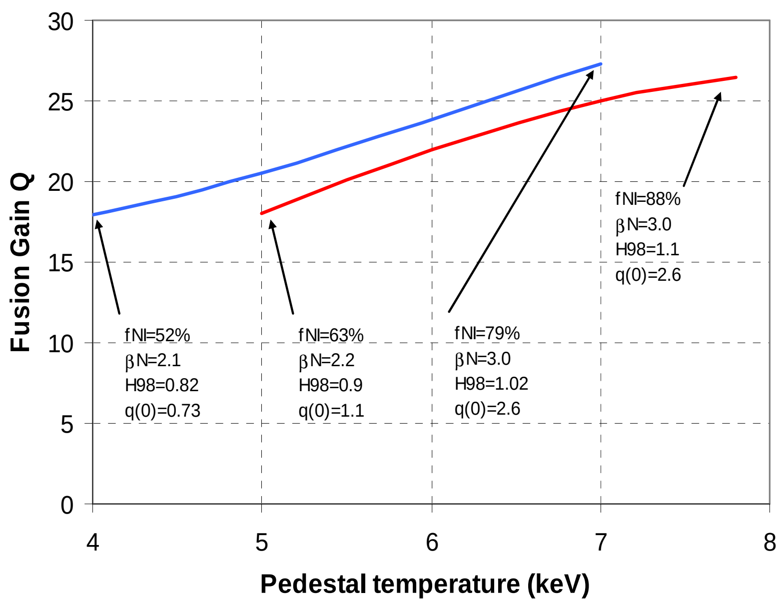

FIG.4. Fusion gain dependence on the temperature pedestal in the case of scenario1 (red) and in the case of the same scenario but with larger major and minor radius, R=8.1 m and a=2.7 m respectively (blue).

6. Analysis with scenario 2: ITB regime

The transport model and philosophy used for ITER steady-state simulations in Ref. [19], have been emplyed to study how a scenario with ITB might applied to the DEMO device studied in this paper. For this purpose, an ECH/ECCD heating and current drive system has been used to create negative magnetic shear and to lock the ITB foot in order to prevent the current shrinking. In addition, the total current has been downscaled to 14MA and the pedestal value to 4.5keV. However, since in this case the total current is still relatively high and the current drive by the ECCD system is very low (due to the fact that the density is high) it is necessary to add a NBI system to reach f_{NI}=100%, otherwise, the bootstrap current fraction needed would be around 90%, leading to a very difficult scenario from the stability point of view.

Therefore, 50MW of NBI and 30MW of ECH are added at ρ=0.25 and ρ=0.5 respectively. With this scheme, the current density profiles and the electron, ion and electron density profiles obtained are shown in figure 5. The maximum of the total current density profile is located at the maximum of the bootstrap current and the maximum of the ECCD current. This allows the formation of a region with negative magnetic shear which leads to high temperatures in the core, $T_{i,0}$=39.5 keV and $T_{e,0}$=35.5 keV, with flat profiles. In this scenario the fusion gain is high Q=25, but the total fusion power, 350 MW, does not attain the minimum desirable to have 1GW electrical power. In addition, as pointed out in [19], the inclusion of a NBI system leads to the shrinking of the ITB and the loss of bootstrap current as shown in figure 6.

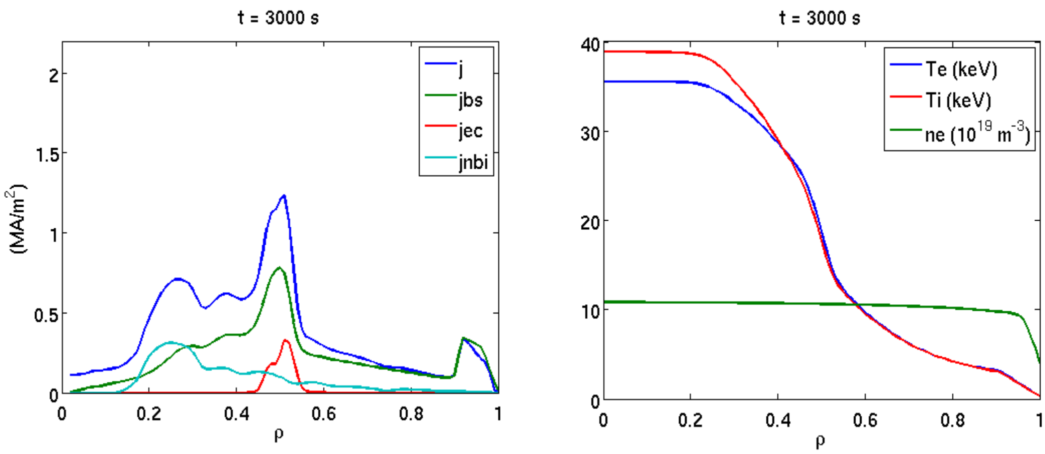

FIG. 5. Fusion gain dependence on the temperature pedestal in the case of scenario1 (red) and in the case of the same scenario but with larger major and minor radius, R=8.1 m and a=2.7 m respectively (blue).

With the aim of stopping this process, more ECH power (up to 50MW) is added at t=1700s (which leads to a drop of the fusion gain to Q=20), however, since the NBI current drive is much higher and it is located inside the ITB, the scenario is finally destroyed due to the progressive loss of negative magnetic shear. Therefore, the difficulties of a scenario with ITB in a device like the one studied here are double. First, is difficult to get all the fusion power needed to have 1 GW electrical power. This issue could be solved by increasing the total current used, however, in this case, it would be difficult to have f_{NI}=100%. Another solution might be to increase the device size, which will be explored in future studies. And second, the inclusion of a NBI system with off-axis deposition tends to destroy the ITB after several current diffusion times.

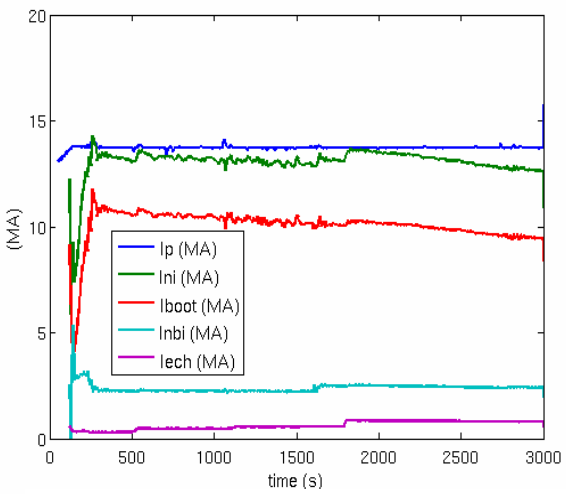

FIG. 6. Time evolution of the total current (Ip), total non-inductive current (Ini), bootstrap current (Iboot), NBI current drive (Inbi) and ECCD (Iech)

8. Conclusions

The CRONOS suite of codes has been applied to simulate and analyze the DEMO design in the case of a regime with high non-inductive current fraction. A large Q=26.5 is obtained in the pulsed scenario 1, which is possible due to the low injected power considered (=98 MW) and a high pedestal temperature, 7.8 keV, leading to a hybrid-like q profile with q_0>1. The non-inductive current fraction is rather high, 88%, with a high amount of bootstrap current, 10.0 MA mainly coming form the pedestal, and 6.8 MA of NBI current drive, which is possible due to the 2 MeV beam system considered In this

scenario, 30 MW more of NBI can be added to attain the steady-state regime with 100% non-inductive current. However, the alpha power obtained is not enough to compensate for the new NBI power added and the Q value drops to Q=22. In addition, the q profile is unstable which means that it can be difficult to control the sawteeth formation, since the control of the q profile becomes a problem due to the lack of precise current drive deposition.
The analysis of a scenario with ITB shows that the achievement of a fusion power corresponding to 1 GW electrical power is difficult due to the relatively small size of the machine. Moreover, the addition of NBI power, slowly degrades the ITB which leads to a strong reduction of bootstrap current in time.
Therefore, according to the models applied in this paper, the possibility of a DEMO device with advanced scenarios, i.e. high fusion gain with high bootstrap and non-inductive current fraction and relatively small size, will require strong physics performance: high density peaking, high pedestal height, Greenwald limit fractions much higher than 1 or strong ITB's lasting for very long times and no degradation. These features cannot be reached by the present day fusion devices. Thus, integrated modelling can provide important key points for the establishment of DEMO scenarios which could, in practice, be also worth for the research plan of ITER.

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