Conclusions

The understanding and modelling of heat and radiation transport in tokamak plasmas is essential in order to progress in the development of thermonuclear fusion towards a practical energy source which meets all the future needs of environment, safety, and fuel inexhaustibility. This activity enables prospective studies and design to be carried out for next step tokamaks.

Due to the complexity of the exact calculation, synchrotron losses are usually estimated in such studies, with expressions derived from a plasma description using simplifying assumptions on the geometry, radiation absorption, density and temperature profiles. In this thesis, a complete formulation of the transport of synchrotron radiation has been performed for realistic conditions of toroidal plasma geometry with elongated cross-section, using a quasi-exact method for the calculation of the absorption coefficients, and for arbitrary shapes of density and temperature profiles.

As a result of this formalism, which allows an accurate calculation of synchrotron losses without wall reflections for realistic tokamak plasma conditions, the effects of toroidicity and of advanced temperature profiles on synchrotron radiation losses are analysed for the first time. In particular, when the electron temperature profile is almost flat in the plasma centre, as for example, in internal transport barrier confinement regimes, synchrotron losses are found to be much stronger (around 20-40%) than in the case where the profile is represented by its best generalized parabolic approximation, though both cases give approximately the same thermal energy content.

A reasonable agreement has been found with previous studies of synchrotron losses when using the same set of assumptions for the plasma geometry, profiles, and absorption phenomena description. When all toroidal effects are taken into account and the plasma self-absorption of synchrotron radiation is accurately calculated, our results agree again with the presently used expressions (including a correction factor for the toroidal inhomogeneity of the magnetic field) for aspect ratios $A \sim 3$. The explanation is that the errors introduced with the description simplified phenomena and geometry are compensating each another for these intermediate aspect ratios. However, our results differ substantially from the previous ones for larger or smaller aspect ratios, which can be of interest for a commercial reactor.

Considering the quantitative importance of the above effects, which are not included in present approximate expressions, a new fit for the fast calculation of the synchrotron radiation loss has been proposed. This fit, which gives a good accuracy for the entire range of plasma parameters of interest for the thermonuclear energy problem, has been included in a precise thermal equilibrium code using a correction factor for the estimation of the wall reflection effect. This results in a unique tool for predicting plasma performance, for design, and for isolating the key issues which limit the performance of the next step tokamak and of a commercial fusion reactor.

This model is of high value specially in advanced high-temperature plasmas envisaged for a steady state D-T commercial reactor, for which the synchrotron loss is found to represent approximately 20% of the total losses and is therefore significant in the global plasma power balance. This important conclusion is different from that of previous studies. Moreover, it has been shown for the first time that the plasma performance is quite sensitive to the value of the wall reflection coefficient for synchrotron radiation.

Prospective studies have been performed for future tokamak projects (ITER-FEAT and the European Commercial Reactor), for which the inductive mode of operation is evaluated using the global energy confinement time empirically deduced from the analysis of a large dataset of H-mode discharges from present-day tokamaks. This is the reference confinement regime for ITER-FEAT. The non-inductive (continuous) mode of operation is analysed by means of a new tool, the current drive diagram, where the thermal equilibrium is solved self-consistently for each point taking into account the current drive efficiency, the bootstrap generation, and the helium fraction calculated from an imposed ratio of the apparent helium particle confinement time to the energy confinement time.

We have shown that, in non-inductive steady-state operation, advanced tokamak regimes are required to achieve relevant thermonuclear plasma performance for next step tokamaks and for a commercial reactor. In these regimes, the confinement is significantly improved by the creation of internal transport barriers characterized by peaked density and temperature profiles, in which the bootstrap current generation is enhanced. As a second common result from these prospective studies, we have shown that the most restrictive constraint for achieving higher plasma performance is the peak heat flux on the divertor plates, which is the most critical plasma facing element in a tokamak.

The objective of ITER-FEAT in terms of plasma performance in the inductive mode of operation ($Q = 10$) is reproduced with the reference H-mode confinement regime, as well as the fusion power and divertor heat loads. Sensitivity studies for this device indicate that, in inductive operation, the ITER-FEAT device has good margins with respect to the MHD stability limits. Even in the case of a softly mixed (L and H-mode) scaling for the energy confinement time, where pure H-mode is obtained only if the power crossing the separatrix is twice the H-L power threshold, the $Q = 10$ operating point (alpha heating power roughly double the external power heating) is still reached. This result is a new contribution of this thesis. In non-inductive operation, and considering an advanced regime, the objective of ITER-FEAT ($Q = 5$) is reproduced.

In a different multi-step strategy towards a commercial reactor, which would lead to significantly increasing the overall cost and the time frame to arrive at a demonstration reactor compared to the ITER-type strategy, a superconducting European next step tokamak has been optimized. An original algorithm has been derived to determine the smallest machine, for a given aspect ratio, generating a $Q = 5$ plasma (corresponding to an alpha power heating which is roughly equal to the external heating power) in inductive mode of operation with a burn duration of about 500 seconds, meeting the physical and technological requirements. In order to carry out this study, the thermal equilibrium code for the modelling of plasma physics has been coupled with a code for the magnet system design. The optimized machine has a major radius of about 5 meters, about 200 MW of fusion power, and its cost has been estimated at 1.7 billion Euros, which should be compatible with the European budget possibilities.

The analysis of the performance of the European Commercial Reactor shows that in order to achieve its objectives and requirements at the same time, first of all, it is required to consider high current drive efficiencies, and secondly, the physics and technology of the divertor should be significantly improved with respect to the ITER-like one. In particular, when increasing the current drive efficiency from the one in agreement with present-day experiments to the other one which is considered in other reactor studies, the highest electrical power into the network meeting the stability requirements goes from about 1.3 to 1.5 GW (the nominal value), and the plasma amplification factor goes from 18 to 23 (giving a global power plant efficiency of about 33%).

Due to synchrotron losses (increased in the “advanced” profiles required for achieving reasonable thermonuclear plasma performance) and to the experimentally observed conservation of the ratio of the apparent helium particle confinement time to the energy confinement time, we show that there is an optimal value for the confinement enhancement factor which maximizes the Q plasma performance, for a given (and also for the highest) electrical power into the network. This highest electrical power meeting the stability requirements steadily decreases with the confinement enhancement factor. This effect, shown in this thesis for the first time, is crucial because both a high plasma performance and a high enough electrical power into the network are required to minimize the cost of electricity, and consequently to make fusion energy more competitive.