

Effect of Helium Ash on Advanced ITER-Scenarios

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1. Introduction

One of the principal goals of the international efforts in fusion research is the construction of a tokamak (ITER or ITER-light) operating at least a thousand seconds in the ignited regime or at least in a regime with high power amplification factor Q .

It is highly desirable to operate fusion reactors in a steady-state regime. Long-pulse experiments at Tore Supra [1] based on non-monotonic (flat or hollow) profiles of the safety factor q produced by LHCD (Lower Hybrid Current Drive) have encouraged the investigation of scenarios for a steady-state operation of the next generation tokamaks. See Refs.[2] to [4].

The problem of generation and removal of helium ash plays an important role in long-pulse and steady-state tokamak discharges Refs.[5] to [7]. In Refs.[6] and [7] it has been shown that the dilution of the hydrogen fuel as a consequence helium ash accumulation could lead to heavy oscillations of fusion power and plasma temperature if no appropriate control system is available. The numerical simulations presented in these latter references have been performed using a 1/2D-code. To obtain more realistic results - taking into consideration transport and profiles of temperatures and densities - we investigated again the helium problem by means of the 1-1/2 dimensional Astra-code [8]. Our interest is focussed also on the effect of helium accumulation on auxiliary power needed to produce the nominal fusion power.

2. Advanced Scenarios

We investigated advanced scenarios for steady state operation with full non-inductive current drive like Ref.[4]. In this reference the strategy leading the plasma from the ohmic equilibrium to a steady-state high- Q fusion plasma is described in detail. In the first phase a hollow current profile is set up and an ITB (Internal Transport Barrier) is generated. The second phase is characterized by an increase of the plasma volume and a change in the plasma shape (elongation, triangularity) together with an increase of the current to 12 to 13 MA. This is achieved by proper combination of ohmic power and external off-axis power, i.e. LH-heating. During the third phase the plasma is directed to nominal fusion power by increasing the density. During this phase the transition to a steady-state regime takes place.

By means of a density control loop the nominal fusion power is approached. The shape of the optimized safety factor profile $q(r)$ is maintained by the combined control of the off-axis LHCD and the central FWCD. The profile of total plasma current is determined by the plasma geometry, by the FW and LH power deposition profiles and from the pressure profile. The latter determines the bootstrap current.

3. Transport Model

The numerical simulation results to be presented have been obtained by means of the Astra-code [8] based on the numerical solution of a transport equations consisting of the electron continuity equation, the energy balance equation for electrons and ions and on the equation of the diffusion of the electric field. The structure of magnetic surfaces is obtained from a simplified solution of Grad-Shafranov equation.

The evolution of the discharge towards a steady-state regime critically depends on the electron temperature determined by the energy balance equations for electrons

$$\frac{3}{2} \frac{\partial(n_e T_e)}{\partial t} = P_{tot} + \text{div}(\chi_e n_e \nabla T_e) \quad [1]$$

and ions, where $P_{tot}(\vec{r}, t)$ is the total power injected into the electron component of the plasma. For this reason the transport model must be chosen carefully. The energy balance equation of the ion component is an analogue to Eq.[1]

In Ref. [9] it has been demonstrated that a linear combination of mixed Bohm/gyroBohm transport model has proved successfully in simulation of L-mode plasmas In Refs. [3] and [4] the transport model has been upgraded to H-mode plasmas with RS (Reversed Shear) to obtain

$$\chi_e = \alpha_B^e \chi_B^F + \alpha_{gB}^e \chi_{gB} + \chi_{e,neo} \quad [2]$$

χ_B is the Bohm heat conductivity, χ_{gB} the gyroBohm conductivity and $\chi_{e,neo}$ the neoclassical heat conductivity. The function $F_{s,e}$ is the semi-empirical shear function Refs. [3,4] accounting for the transport barrier. The constants α_B^e and α_{gB}^e have been taken from Ref. [4]. For ion conductivity we have used a similar expression.

4. Model for Helium Ash

The alpha particles produced by fusion reactions are represented by a two-group model. The particle balance equation of the fast alpha group is given by

$$\frac{\partial n_\alpha}{\partial t} = \nabla \cdot (D_\alpha \nabla n_\alpha) + S_\alpha - \frac{n_\alpha}{\tau_s} \quad [3]$$

n_α denotes the fast alpha particle density. S_α represents the thermonuclear fusion source.

The third term at the right side of Eq.[3] denotes the slowing down losses of the fast group to the slow group referred to as helium ash group. τ_s is the slowing down time.

The continuity equation of the helium ash is

$$\frac{\partial n_{He}}{\partial t} = \nabla \cdot (D_{He} \nabla n_{He}) + \frac{n_\alpha}{\tau_{SD}} \quad [4]$$

The loss term of Eq.[3] is the source of Eq.[4] The diffusion coefficients D_α and D_{He} are functions of the small plasma radius. In the first step we have taken these diffusion coefficients as constants. Their magnitudes have been selected to produce a helium ash fraction between 8% to 15 % as it is assumed for Iter-like plasmas [10]. In the second step we have used linear combinations of Bohm/gyroBohm transport for fast alphas as well for the helium ash.

$$D_{He} = \beta_B^{He} \alpha_B^e \chi_B^F + \beta_{gB}^{He} \alpha_{gB}^e \chi_{gB} + \chi_{i,neo} \quad [5]$$

The coefficients β_B and β_{gB} have been adapted to obtain the helium fraction in accordance with Ref. [10].

5. Results from Simulations

We are presenting the simulation of a typical discharge of an Iter-like tokamak plasma with the major radius $R_0 = 8.66$ m, the minor radius $a = 2.7$ m, the elongation $\kappa = 2$, the triangularity $\delta = 0.45$ and the magnetic field $B = 5.7$ T. The electron density profile is assumed as a parabola. The magnetic field $B_0 = 5.7$ T.

As a first step we investigated advanced scenarios with constant helium ash diffusion coefficients. We present scenarios adapting the diffusion coefficients in order to obtain helium fractions of 2%, 10% and 13% in agreement with the usual assumptions [10]. Fig.1 shows that the two group model predicts a relatively high LHCD-power to maintain the fusion power at 1500 MW. It can be seen that the LHCD power depends critically on the helium fraction. A fraction of 13% exceeds the available LH-heating power. For the same assumptions the evolution with time of electron density and helium ash density is presented (Fig.2). For a high helium fraction a high fuel density and therefore a high electron density is necessary to overwhelm the fuel dilution.

For the results presented in Figs. 3 to 6 we assumed a mixed Bohm/gyroBohm Diffusion coefficient. The open coefficients have been adjusted to obtain a helium fraction of about ten percent. The auxiliary power needed to reach the nominal fusion power is about 110 MW (Fig.3). Comparing the time evolution of the alpha power produced by fusion reactions and of the alpha power coupled into the plasma Fig.4 shows the fast alpha particle losses. The profiles of the fast diffusion coefficient caused by the hollow profile is demonstrated in Fig. 5. The influence of ITB on helium ash removal may be seen in Fig.6.

6. Conclusions

We have extended the Bohm/gyroBohm transport model to a two-group model for the fusion alpha particles. Qualitatively the results of an earlier work with constant diffusion coefficients have been confirmed. Qualitatively the experimental transport coefficients with reversed shear lead to a reduction of auxiliary power in the range of five to 10 MW. The ITB due to reversed shear reduces on the one side the power loss due to heat conduction and fuel removal. On the other side the existence of ITB reduces the removal of helium ash. We have found that the beneficial effect of RS is prevailing over the reduction of ash removal caused by this mechanism. The results are very sensitive even to small changes in the transport model emphasizing again the importance of upgrading transport codes with the most recent models.

7. References

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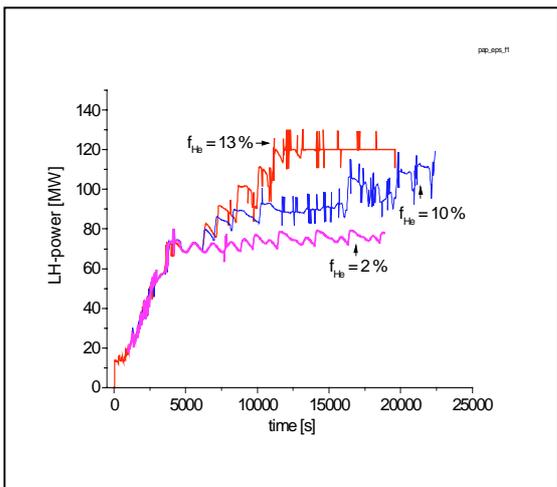


Fig.1: LH-power for various He-fractions
Constant diffusion coefficient

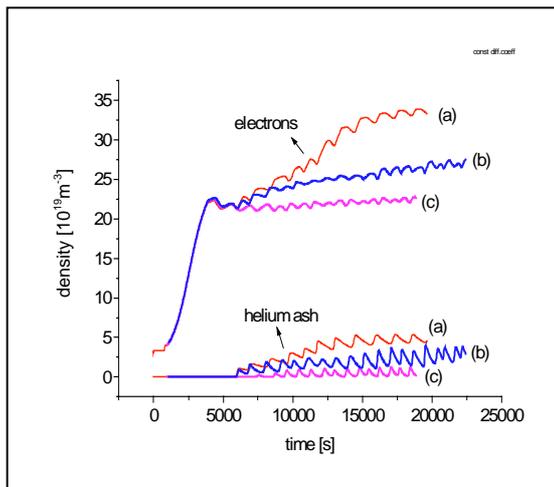


Fig.2: densities of electrons and He-ash vs. time, (a) 13%, (b) 10%, (c) 2% He ash

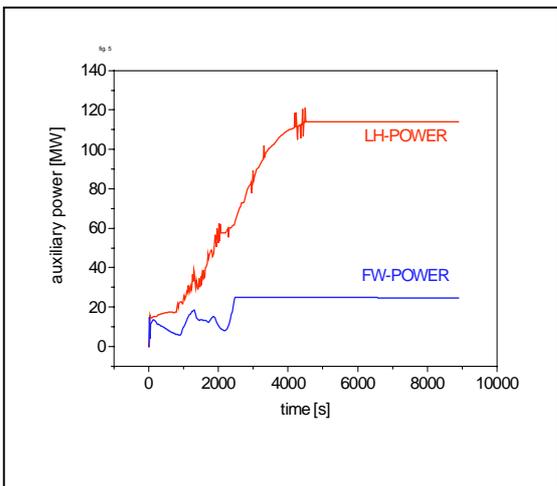


Fig.3: LH- and FW-power vs. time
Mixed B/gB transport, 10% helium

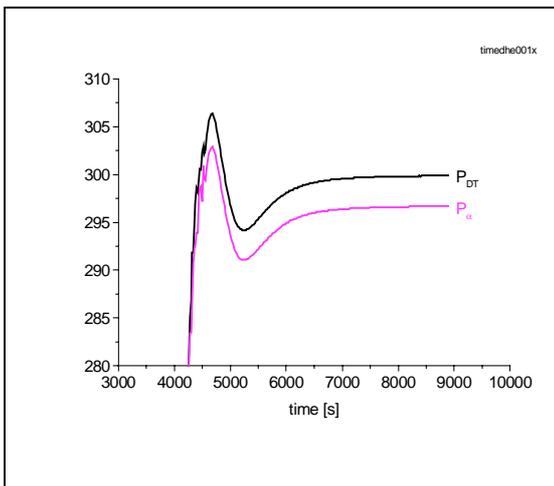


Fig.4: produced alpha power P_{DT} and alpha power P_{α} coupled into the plasma

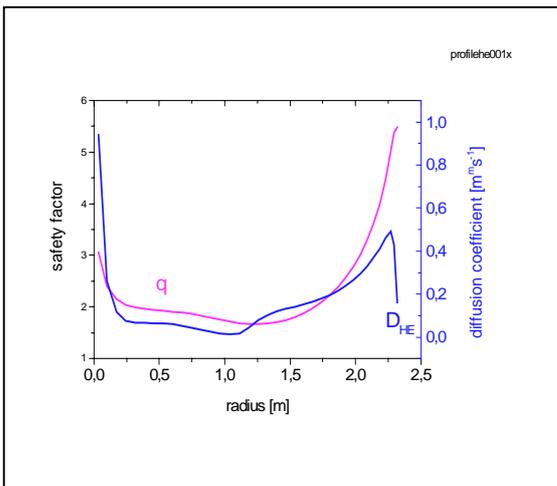


Fig.5: profiles of diffusion coefficient and safety factor in the quasi-steady state

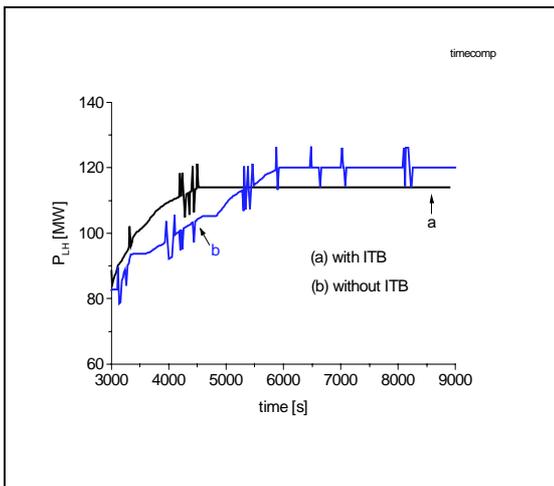


Fig.6: Evolution of LH-power for He-ash (a) with ITB, (b) without ITB