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Control of ITER-like Plasmas by Pellet Injection

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Introduction

The goal of ITER-FEAT is the investigation of high-Q scenarios for inductive operation as well as long-pulse scenarios and steady-state scenarios. Steady state advanced scenarios with internal transport barrier (ITB) for next generation tokamaks have been studied e.g. by Refs.[1] and [2]. In those predictive scenarios the non-inductive current has been generated by a combination of fast wave current drive (FWCD), lower hybrid current drive (LHCD) and bootstrap current (BS). The temporal evolution of the plasma discharge is controlled by four actuators. These are the outer loop voltage, the LH power the FW power and the density. Density control can be effected by pellet fuelling as it has been shown in parameter studies See Ref.[3]. In this reference the injection frequency has been used as an actuator of the control system. In order to apply such results for ITER-FEAT many assumptions on which the results of Ref.[3] are based must be carefully examined. Furthermore it is necessary to compare the requirements for pellet penetration with available technology. For this reason a pellet code must be used where the dependence of penetration on the launching position is taken into consideration [4].

Method

In the present simulations we use a combination of neutral beam injection and pellet injection. Gas puffing is a further option. NBI has been used in place of LH in order to avoid the enhancement of the ablation rate due to the high-energy tail of the electron population.

All simulations have been accomplished using the well-known plasma transport code ASTRA [5]. We have used a mixed Bohm/gyroBohm model as it has been employed in Refs. [1] to [3]. In addition to the heat balance, fluid equations for ions and electrons the continuity equation for ions is solved, where the source term includes the pellet source and the NBI-source, eventually also a boundary source to model gas puffing. The thermonuclear helium is taken into consideration by two-group continuity equations for fast helium and helium ash..

The plasma parameters have been taken from Ref.[6].

The maximum additional power which can be supplied to the plasma is a ramp with a plateau of 40 MW (7 MW RF and 33 MW NBI). The actual heat power is equal to the maximum power as long as a prescribed maximum central temperature is not exceeded. Otherwise the additional power is reduced at prescribed time steps by prescribed amounts.

The density control works as follows. We prescribe a nominal alpha power by a ramp with a plateau with 80 MW. At prescribed time steps (which are variable and can be defined by a function) it is asked if the actual alpha power is higher than the nominal power. If this is not the case a pellet is injected. The injection is suppressed if the nominal power exceeds the actual alpha power or if the density approaches Greenwald density.

It is also possible to derive the injection frequency from comparison of nominal and actual fusion power. This option is preferable if we investigate long-pulse or steady state scenarios where thousands of injections could be necessary.

Results

ASTRA has been combined with the PELDEP code. Fig.1 shows the source profiles of a pellet which has been injected with a velocity $\upsilon_p = 1500 m/s$ from the low field side ($\theta = 0$) and from the high field side ($\theta = \pi$). We recognise the higher penetration and the improved fuelling efficiency. In Fig. 2 the source profiles due to HFS injections for different pellet velocities are shown.

Now we present a typical scenario where the plasma starts with prescribed auxiliary power and nominal fusion power. By the control system the nominal alpha power $P_{\alpha 0}(t)$ ramp should be approached by the actual fusion power $P_\alpha(t)$. A pellet has been launched from the HFS with a velocity of 2000 m/s into the ITER plasma. The barycenter of the source density is near 0.6 of the normalised radius. In that case it is not difficult to reach the nominal alpha power. We never approach the Greenwald limit. The prescribed additional power ramp is equal to the actual power ramp because we never approach the maximum central electron temperature of 25 keV. The average equilibrium temperatures are in agreement with Ref.[6]. It is remarked that the power oscillations due to pellet injection are quite acceptable, even in the high-Q regime. The temporary evolution of helium concentration is also in agreement with ITER-FEAT design [6]. The time evolution of the Greenwald factor may be recognised in Fig.5. In Fig. 6 we compare the time evolution of the alpha power for three pellet sizes. Each of them lead to acceptable scenarios. Of course in the case of larger pellets the power oscillations are heavier and the frequency is lower. In Fig. 7 the total number of injected pellets is shown for three pellet sizes.

Fig.8 opposes a scenario with deep penetration, ρ=0.5, to a shallow penetration scenario, $\rho = 0.9$. In the latter case the scenario discharge breaks down without failing the high-Q regime.

The main problem consists in attaining the necessary penetration depth. According to our studies it is highly likely that the necessary penetration can be achieved, if the pellets are launched from the top. Based on experimental evidence further studies are necessary.

Conclusions

We conclude that high-Q ITERFEAT plasmas can be fuelled and controlled by pellet injection. Pellet injection frequency can be used as an actuator. The contribution of NBI to the ion source is small. Pellet size and required launching frequency can be obtained by applying available technology. Using improved transport and pellet models, it should be investigated if the necessary penetration can be reached. It is highly probable that this penetration can be reached at leas from the top.

References

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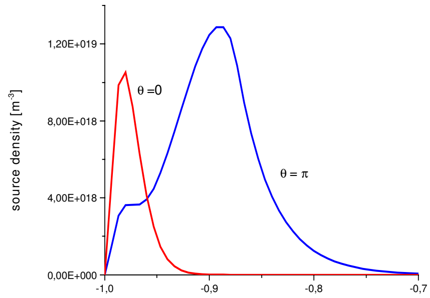


Fig. 1: Source profile vs. normalised plasma radius

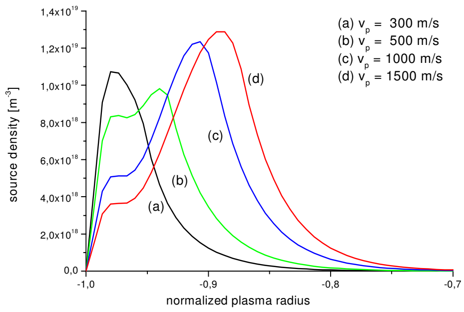


Fig. 2: Source profiles for different injection velocities

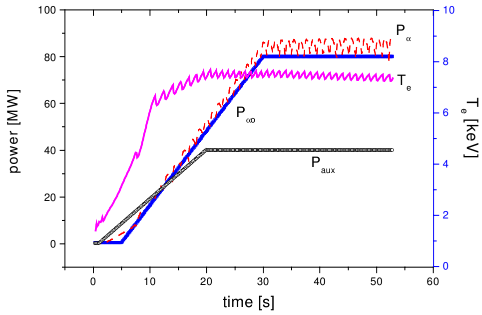


Fig. 3: P_α, $P_{\alpha0}$, P_{aux} and $\langle T_e\rangle$ vs. time

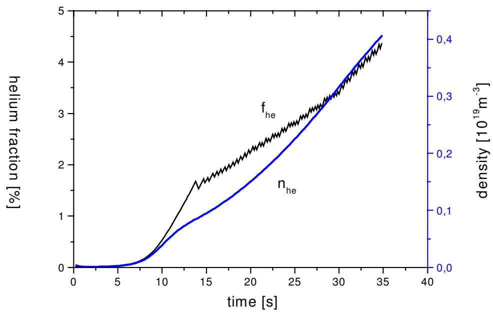


Fig.4: helium density and helium fraction vs. time

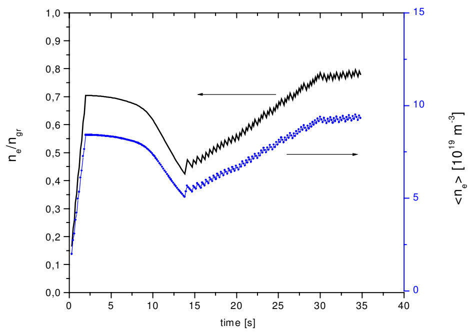


Fig.5: Greenwald factor $\langle n_e\rangle$ vs. time

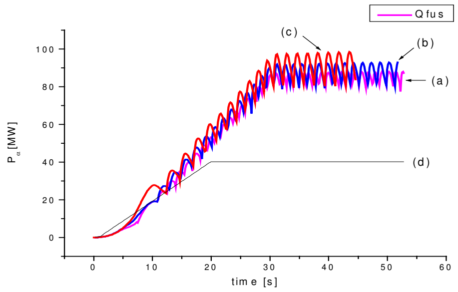


Fig.6: Evolution of P_α for different pellet sizes N_p (a) 3 x (b) 4 x (c) 5 x 10^{21} m^{-3}, (d) P_{aux}

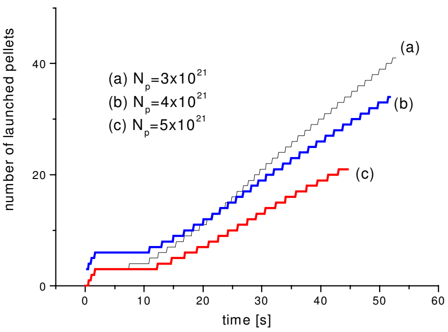
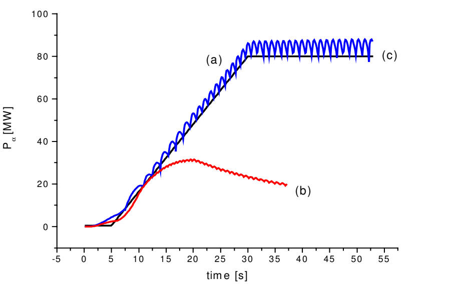


Fig.7: Number of injected pellets for different sizes N_p (a) 3 x (b) 4 x (c) 5 x 10^{21} m^{-3},



temporal evolution of alpha power
(a) shallow injecion (b) deep injection (c) nominal power

Fig.8 temporal evolution of alpha power (a) shallow and (b) deep injection (c) P_{a0}