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Assessment of Independent Fuelling and ELM Pace Making by Pellet Injection in ITER.

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Abstract. The possibility of independent plasma fuelling by high field side (HFS) DT pellet injection and ELM pace-making by low field side (LFS) D pellet injection is considered for ITER. The model used in the analysis takes into account the outward drift of the ablated pellet substance. The simulations show that the residual fuelling efficiency from the LFS injection is a non-monotonic function of the pellet size. It is shown that it can be possible to use the pellets of similar size, speed and frequency for HFS fuelling with ELM pace-making and for LHS ELM pace-making with low residual core fuelling to keep particle fluxes to the divertor on the same level. The relations between pellet size and speed and frequencies for the HFS and LFS pellet injection, which provide desirable residual fuelling and tolerable divertor loads are determined.

Introduction.

Gas puffing and particle recycling can be inadequate for core fuelling in ITER, since the neutral particle influx across the separatrix saturates at a comparatively low level: $S_{fuel,e} \approx 15$ Pa m^3 s^{-1} (Fig. 1) [1, 2]. HFS pellet injection is proposed as a main candidate for core fuelling to provide the high plasma core density $n_e \sim (8–10) \times 10^{19}$ m^{-3} required for target ITER operation with a fusion power $P_{fus} \sim 400$ MW, and power multiplication Q ~ 10 [3]. Pellet injection is also considered as a possible tool for ELM mitigation to a tolerable level to provide long life of the divertor target plates. It is shown that HFS pellet injection with frequency, f = 4-5 Hz and pellet speed, $v_p \sim 300 - 500$ m s^{-1}, can provide in ITER both core fuelling ($S_{pel} \sim 20\text{-}100$ Pa m^{3}s^{-1}) and ELM pace-making [1,2] to reduce the energy load on the divertor target plate caused by ELMs to the level $\Delta W_{ELM} < 5$ MJ. To avoid erosion of the divertor plate material the requirement for ELM energy reduction can become more stringent. It can require an increase of the pellet pace-making frequency independently of the core fuelling. Plasma density control can require to reduce or to stop pellet fuelling keeping the frequency of the ELM pace-making to keep the similar tolerable loads. For ELM pace-making independent of core fuelling LFS injection is considered in our investigations (Fig.2).

Pellet pace-making requirements.

In present day experiments [6] it is observed that ELM triggering starts when the pellet penetrates deeper that one half of the pedestal width,

$$\lambda/\Delta_{ped} > 0.5 . \qquad (1)$$

In our analyses we consider equation (1) as a necessary and sufficient condition for ELM pace-making. For the ELM energy loss, ΔW_{ELM} we consider experimental dependence on the ELM frequency, f_{ELM}, total stored energy, W_{tot} and the energy confinement time, τ_E, to be [7]:

$$\Delta W_{ELM}/W_{tot} = 0.2\, (\tau_E\, f_{ELM})^{-1}. \qquad (2)$$

Maximal tolerable ELM energy loss can be derived from the requirements to keep good material properties in the divertor plate, $P_{pl} < 0.5$ MJ/m^2 [8]. Taking into account the possible 2:1 asymmetry of the energy deposition between inner and outer plates for the inner plate with area of the energy deposition, $S_{pl} = 1.6$ m^2, we have:

$$\Delta W_{ELM,\,max} = 1.2\ \mathrm{MJ}, \qquad (3)$$

which gives the requirement for the pellet pace-making frequency for W_{tot}/τ_E = 80 -100 MW, expected in ITER in the H-mode operation as:

$$f_{pel} = 0.2\ W_{tot}/\Delta W_{ELM,\,max}\,\tau_E = 13\text{ -}17\ \mathrm{Hz}. \qquad (4)$$

Maximal DT throughput during plasma operation in ITER is suggested to be $S_{tot,max}$ = 120 Pa m^3/s [9]. This gives the maximal pellet size required for ELM pace-making in the absence of gas puffing as:

$$N_{pel} = S_{max}/f_{pel} = 7 – 9\ \mathrm{Pa\ m^3/pel}. \qquad (5)$$

We calculated pellet penetration, ablation and further drift of the charged particle cloud following a simplified mass ablation and relocation treatment SMART [5] for the reference ITER pedestal temperature, T_{ped} = 3.5 keV, density, $n_{ped} = 8\ 10^{19} m^{-3}$, and width Δ_{ped} = 10 cm. As can be concluded from Figures 3 and 4, pellets of a size d = 4.3 - 4.7 mm, injected from the LFS have rather small residual core fuelling S_{core}/S_{tot} < 10% due to the outward drift of the ablated particles. Such pellets penetrate deeper than one half of the pedestal width (see Fig. 5). Thus, they presumably can produce ELM pace-making. It is interesting to note that it is impossible to reduce the residual core fuelling from the LFS pellet injection by reducing the pellet size. For smaller pellets relocation of the ablated substance is also smaller. Thus, the smallest residual core fuelling from the LFS pellet injection can be evaluated as $S_{D+T,\,core} \approx$ 13 -17 Pa m^3/s, or $S_{D\text{-}fuel} = S_{T\text{-}fuel} \approx$ 6.5 – 8.5 Pa m^3/s. HFS pellets can penetrate deeper than half a pedestal width and therefore produce ELMs (Fig. 6). Unfortunately the pellet size of d = 4.3 - 4.7 mm is marginal for deep penetration λ: $\lambda/\Delta_{ped} > 0.5$ for the low HFS pellet injection speed v_p = 300 m/s. Taking into account the uncertainty of the assessment of the pedestal parameters it is necessary to have the possibility to inject intact pellets from the HFS with higher speeds.

Compatibility of ELM pace-making with core fuelling.

Core fuelling by HFS pellet injection additional to the edge fuelling, $S_{DT\text{-}fuel,e} \approx 15$ Pa $m^3\ s^{-1}$ required to keep density at the desirable level was estimated to be $S_{DT\text{-}fuel,p}$ = 20 - 85 Pa m^3/s for inductive scenario with $H_{y2,98}$ = 1. For hybrid scenarios with lower density and $H_{y2,98}$ = 1.2 the required additional core pellet fuelling should be $S_{DT\text{-}fuel,p}$ = 14 - 65 Pa m^3/s. For low densities in the steady state scenarios with $H_{y2,98}$ = 1.7 it should be $S_{DT\text{-}fuel,p}$ = 0 - 17 Pa m^3/s. The estimated range reflects the uncertainty of the particle transport [4]. This analysis suggested equal D and T fuelling from the pellets and that D:T = 1 from the edge fuelling. In general D and T core fuelling sources from the edge are not necessarily equal. Thus, in further analysis we will consider required core fuelling for each component separately, $S_{D\text{-}core} = S_{T\text{-}core} = S_{T\text{-}core,e} + S_{T\text{-}fuel,p} \approx$ 18 – 50 Pa m^3/s for the inductive scenarios, $S_{D\text{-}fuel} = S_{T\text{-}fuel} \approx$15 – 40 Pa m^3/s for the hybrid scenarios, and $S_{D\text{-}fuel} = S_{T\text{-}fuel} \approx$ 7.5 – 16 Pa m^3/s for the steady state scenarios. Thus, the frequencies of the HFS tritium and deuterium pellet injection, f_T, f_D,required to provide the desirable $S_{T\text{-}fuel}$, $S_{D\text{-}fuel}$ for appropriate scenario can be calculated from the particle balance:

$$S_{T\text{-}fuel} = N_{pel}\, f_T + S_{DT\text{-}fuel,e}\,(f_T + f_{T,LFS})/f_{pel} + N_{pel}\, f_{T,LFS}\, S_{core}/S_{tot}, \qquad (6)$$

$$S_{D\text{-}fuel} = N_{pel}\, f_D + S_{DT\text{-}fuel,e}\,(1 - (f_T + f_{T,LFS})/f_{pel}) + N_{pel}\, f_{D,LFS}\, S_{core}/S_{tot}, \qquad (7)$$

where we suggest that the edge fuelling is proportional to the ratio of tritium to deuterium for both fuelling and ELM pace-making. The frequency of the LFS pellet pace-making with tritium and deuterium pellets can be calculated as $f_{T,LFS} + f_{D,LFS} = f_{pel} - f_D - f_T$. For example, for a high additional core fuelling source, $S_{D-fuel} = S_{T-fuel} \approx 50$ Pa m^3/s for $f_{pel} = 13$ Hz, and $S_{core}/S_{tot} \approx 0.1$ the required frequencies are: $f_T = 5$ Hz, $f_D = 4$ Hz, $f_{D,LFS} = 4$ Hz without tritium pellet injection from the LFS for ELM pace-making, $f_{T,LFS} = 0$. If the particle source required for the core fuelling is small, $S_{D-fuel} = S_{T-fuel} \approx 15$ Pa m^3/s, then HFS injection can be stopped and the LFS injection with $f_{T,LFS} \approx f_{D,LFS} = 6 - 7$ Hz can provide the required core fuelling. Smaller core fuelling is not controllable if pellet pace-making is required, because the reduction of LFS pellet size for pellets which still penetrate deeper than half of the pedestal width will increase the residual core fuelling due to smaller drift of the ablated substance (see Fig. 3-5). The considered relations correspond to the ideal model of the core fuelling without abrupt loss of particles during an ELM event. Taking into account of the decrease of core fuelling efficiency due to such losses will require an increase in the maximum DT throughput above120 Pa m^3/s. It will decrease the residual core fuelling from the LFS pellets and help to extend controllability to the lower fluxes. According to our analysis 50% of the pellet substance for HFS pellet fuelling is absorbed in the pedestal area affected by ELMs. Therefore, the expected HFS fuelling efficiency is smaller than 100%.

Conclusions.

Long operation of the divertor plate with $P_{pl} < 0.5$ MJ/m^2 requires a reduction in the energy release per ELM in ITER to the level $\Delta W_{ELM, max} = 1.2$ MJ. For this purpose pellet injection frequency should be increased to $f_{pel} = 13 - 17$ Hz. For maximal total DT throughput of 120 Pa m^3/s high frequency will require small pellet size $d_p \sim 4.3 - 4.7$ mm. The modelling predicts that this size is marginally sufficient for pellet ablation deeper than half of the pedestal width necessary for ELM pace-making. Such small pellets can provide fuelling in the case of the ideal fuelling efficiency. From the modelling it follows that the reduction of the pellet fuelling efficiency to realistic values $C_{eff} < 1$ and robust penetration sufficient for ELM pace-making will require proportional increase of the total DT throughput, $S_{tot} > 120$ Pa m^3/s and increase of the pellet speed $v_p > 300$ m/s for HFS intact pellet injection, and increased tritium production $S_T > 50$ Pa m^3/s. However, to evaluate the quantitative implications of this analysis for the ITER pumping and fuelling system design parameters, specially dedicated experiments with shallow penetration of LFS and HFS pellets are required. The uncertainty of the particle transport and pedestal parameters predictions must be also taken into account. Further experiments are therefore necessary to determine the sufficient conditions of ELM pace-making and to understand plasma transport in the region in the vicinity of the plasma pedestal during ELMs and between ELMs.

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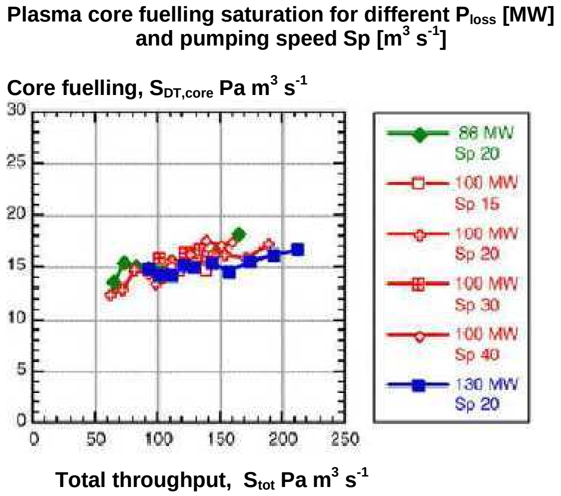

Fig. 1

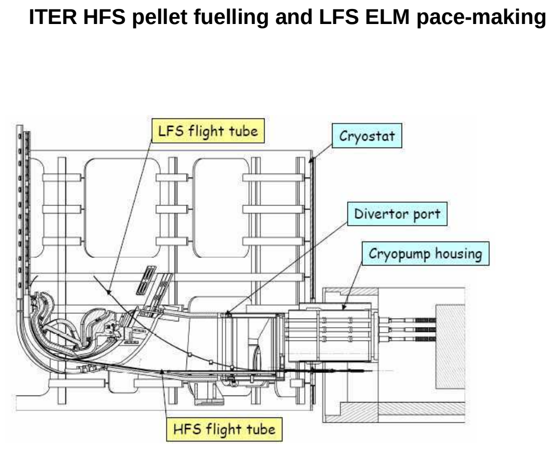

Fig. 2

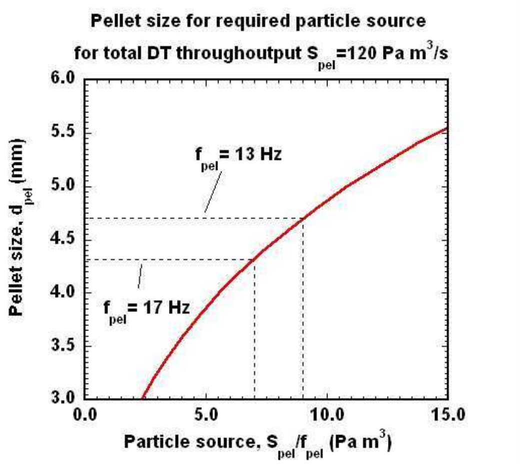

Fig. 3

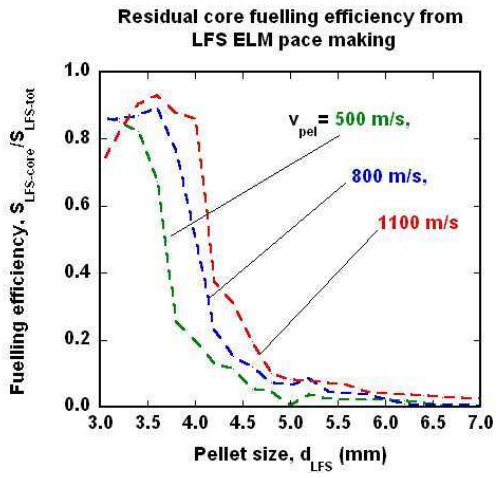

Fig. 4

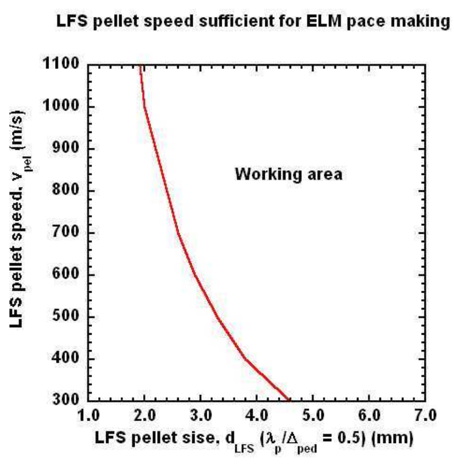

Fig. 5

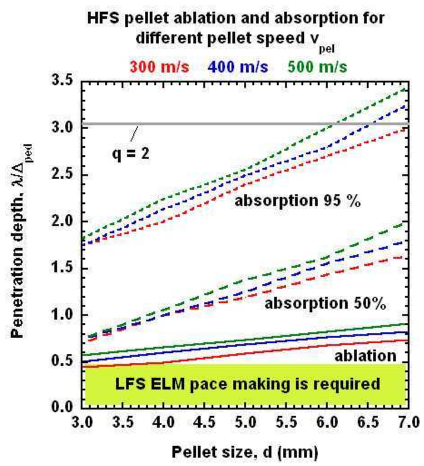

Fig. 6