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A new concept for a higher burn-up fraction improvement in DEMO reactor

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Abstract— **The possibility of improving the fuel burn-up fraction (of reducing the pumped-out fraction) by re-circulating part of He and fuel particles and separating helium atoms from fuel atoms in the DEMO conventional divertor is investigated. It is shown that the burn-up fraction can be considerable improved in case of recycling and He separation in the divertor.**

Index Terms— DEMO reactor; DEMO divertor; Fuel burn-up fraction; He enrichment; He recycling**.**

I. INTRODUCTION

One of the key challenges for a fusion power plant is the need to increase the fuel burn-up fraction significantly at least above 5% [1]. For 2GW DEMO fusion power the fuelling rate necessary to replenish the burnt fuel is rather small (~ 2.7 Pa-m^3/s) compare with the estimated fuel throughput (~200-350 Pa-m3/s) needed mainly for the replenishment of collateral fuel lost due to He ash removal [2]. Therefore, the fuel burn-up fraction is rather small (~ 1%), indicating the need to maintain the lowest possible fuel throughput for reducing the required tritium inventory.

Different methods have been discussed to improve the burn-up fraction and helium ash exhaust. The use of helium retention in the first wall to keep the helium accumulation below an admissible level is limited because of the wall saturation, erosion, blistering, etc. Usually for nonmetallic wall-plasma interaction helium recycling with the wall is large enough so that under such high-recycling conditions, the exhaust of several percent of the recycling helium particles is sufficient to keep the helium concentration in the main plasma below a permissible level. In DEMO with the all-tungsten wall under high wall temperature operation is, however, unrealistic. The sufficient pellet fuelling in the hot high density active reactor zone to increase the effective particle confinement time is still an open issue. As for the helium ash exhaust, it is shown by Monte-Carlo simulation that helium particles could be enriched in the divertor region and the ash exhaust can be achieved by a relatively moderate pumping speed [3]. The degree of enrichment is, however, not so high that a considerable amount of fuel particles would be pumped out simultaneously. Furthermore, experiments with detachment regimes show that the plasma density in the divertor region is fairly high. In this case, the enrichment is further reduced [3] and the amount of fuel pumped out may become much larger. Another suggestion of He separation is to use the palladium alloy membrane in the pumping port for selective pumping [4]. However, the erosion of the membrane during the long term operation could be a problem.

In this paper we propose a new concept which is based on the organization of a recirculation between the divertor plenum and the SOL for the He and fuel recirculation in order to reduce the amount of fuel pumped out. The reduction can be achieved by employing the fact that the helium atoms after neutralization on the divertor plate readily penetrate into PFR thus increasing the He enrichment in divertor. This will mitigate the load on the pumping system and reduce the circulating fuel amount (especially reducing the tritium inventory).

The divertor configuration with the vertical plates and particle bypassing loop connecting the plenum with the SOL area at the baffle region is suggested for facilitating the He removal with moderate pumping flow and, consequently the tritium inventory.

II. FUEL BURN-UP FRACTION

The fuel burn-up fraction, defiined as a ratio of burn-up fuel rate Φ_b to the particle throughput Φ_{in}, $f_b \equiv \Phi_b / \Phi_{in}$, where the particle throughput equal the sum of the burning rate and the pumping rate: $\Phi_{in} = \Phi_b + \Phi_{pump}$. The burn-up rate can be expressed as $\Phi_{burn} = nV_a/\tau_F$ and the pumping rate as $\Phi_{pump} = nV/\tau^*_p$, where τ_F is the burning time $\tau_F = 1/ n <\sigma_{dt}v>$ and $\tau^*_p = \tau_p/(1-R)$ is the effective particle confinement time, consequently. Here τ_p is the particle loss time related to the particle transport and R is the recycling coefficient. The values are averaged over the plasma volumes V and the volume of active zone V_a, where a stable fuel burn occurs. Using the temperature and density radial profiles from [5] the active zone for DEMO can be defined from inequolity: $n_p(r)\tau_E \leq 12T(r)/E_\alpha <\sigma v>_F$, here E_α=3.5 MeV, $\tau_E \sim 4$ s and $<\sigma v>_F$ is the DT burning rate averaged over the active zone, which is for DEMO reactor in the range $0 \leq r \leq 0.7 \cdot a$, where a is the minor radius (~2.8 m). Then $V_a \sim 1100$ m^3 and is almost half of the plasma volume 2252 m^3. The fuel burn-up fraction is inverse proportional to the throughput flux and exceeds 5% for $\Phi_{in} < 50$ Pa-m^3/s. (see Fig.1)

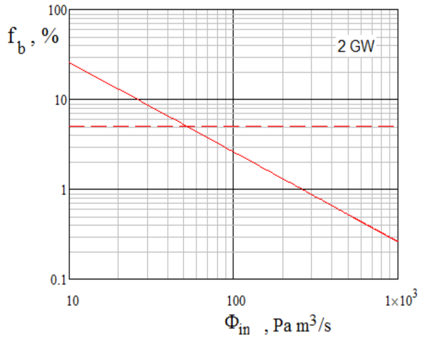

Fig. 1 Fuel burn-up fraction versus fuel throughput; 2GW fusion power.

Using definitions for Φ_{pump} and Φ_b , the fuel burn-up fraction can be expresses as

$$f_b = \frac{1}{1 + \tau_F \cdot (1 - R)/\tau_p} \qquad (1)$$

Dependence of the burn-up fraction on recycling coefficient R for the DEMO steady state burn with $\tau_E \sim 4$ s , and $\tau_p = \alpha\ \tau_E$ is shown in Fig. 2 for two different values of α.

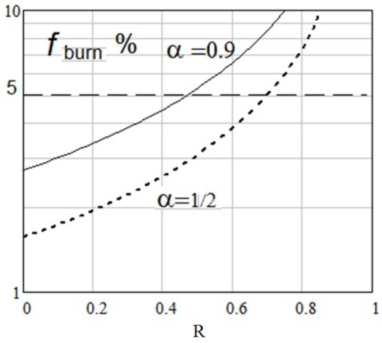

Fig. 2 Fuel burn-up fraction versus recycling coefficient R for different values of the particle confinement time $\alpha = 0.5$ ($\tau_p \sim 2$ sec) and $\alpha = 0.9$ ($\tau_p \sim 3.6$ sec).

To increase the burn-up fraction, a large fraction of particles flowing into the divertor chamber must be returned to the main plasma. The critical value of fuel burning fraction can be exceeded for R values above 0.5-0.7 (for different τ_p).

III. THE HELIUM ENRICHMENT

The helium ash produced in the reactor with the rate $\Phi_\alpha \equiv \Phi_{burn} = 2P_\alpha/E_\alpha = 1.42 \cdot 10^{21}$ 1/sec must be exhausted from the divertor at the same rate. Analysis shows that the He concentration in the core is limited due to fuel dilution $c_{He,core} \leq 5\%$ and the helium flux equal to Φ_α must be removed from the core to the divertor. The dt fuel losses $\Phi_{dt,He}$ pumped out together with He depend on He concentration in divertor pumped gas $c_{He,div}$ and can be expressed as $\Phi_{dt,He} = \Phi_\alpha/\eta_{He}\, c_{He,core}$, where $\eta_{He} \equiv c_{He,pump}/c_{He,core}$ is the He enrichment factor in divertor. The fuel replenishment due to He removal strongly depends on He enrichment factor at the divertor. For example, for $\eta_{He} \geq 5$ % the fuel dt particles, which must be replaced during steady state reactor production of 2GW fusion power must be ≤ 100 Pa-m^3/s in molecules (~3.8 t/yr) (see Fig. 3).

The helium ash profile in DEMO reactor will probably drop to the edge, because the He ash will be removed with confinement time and recycling from the wall will be small. Therefore, without wall recycling the efficient He ash exhaust will require large D/T flows.

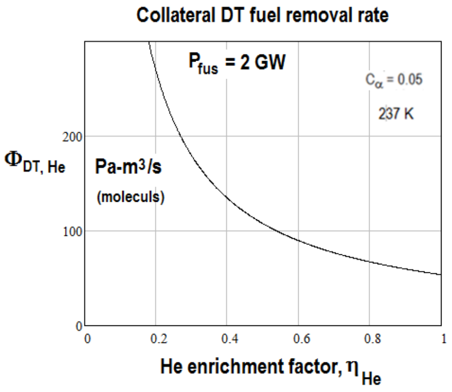

Fig. 3 Fuel removal rate collateral to the He evacuation from the plasms versus He enrichment in divertor; 2 GW DEMO reactor with He ash concentration c_α =0.05 in the core.

The way to remove effectively the He ach is to organize a strong particle bypassing in the divertor, thus to replace the particle recirculation from the wall to the divertor region. The He de-enrichment in the divertor can also be expected [6]. If this were actually the case, the reduction of the absolute amount of pumped-out fuel would become a much more urgent problem. The degree of improvement in the fuel burn-up fraction brought about by our method is larger when helium is de-enriched. The absolute amount of pumped-out fuel can thus be greatly reduced so that our method can alleviate this problem substantially.

IV. EFFECT OF BYPASSING

The required He enrichment can be achieved by increasing recycling in the divertor, when some fraction R of helium atoms and fuel molecules before being eventually pumped out from the pumping system is diverted to a bypassing tube, which is connected with the plasma in the SOL region close to the baffles. Neutrals can easily penetrate the SOL, since the SOL plasma is almost an ideal pump (neglecting a small charge exchange effect). He atoms and fuel molecules ionized and return back to the divertor plate, where after neutralization and escaping the ionization in the plasma fan, falling again in the PFR as a neutral particles. The model of bypassing is shown in the Fig. 4, where the DEMO conventional divertor configuration with vertical plates is shown. Also on the right hand side a schematic drawing of the recirculating fluxes are shown

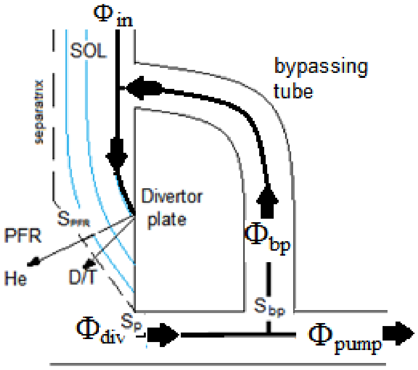

Fig. 4. DEMO configuration of poloidal divertor systems with bypassing loop in the law field side of divertor

A certain fraction of fuel and helium atoms penetrate into the PFR trough the opening S_{pfr} after being neutralized on the divertor plate.

These fluxes build up the density and pressure in the divertor region and form the divertor flux Φ_{div}. According the flow conservation $\Phi_{div} = \Phi_{bp} + \Phi_{pump}$. In steady state operation the particle throughput equals to Φ_{pump}. Due to flow recirculation Φ_{div} will increace as $\Phi_{div} = \Phi_{pump} / (1- R)$, where $R = \Phi_{bp} / \Phi_{div}$ is a fraction of particles recirculating in the divertor loop and $\Phi_{bp} = R \cdot \Phi_{pump} / (1 - R)$. R varies from no recirculation case $R = 0$ and a full recirculation $R \rightarrow 1$, when particels are not pumped out and not fueled in. The pumping flux drops with increasing of recycling $\Phi_{pump} = (1- R) \cdot \Phi_{div}$. However, recycling doesnot change the He concentration in the divertor $c_{He,\ div}$ and, therefore, the collateral fuel pumping flux $\Phi_{dt,\ He} = \Phi_\alpha / c_{He,\ div}$, remains unchanged. Separation of He atoms and increase of $c_{He,\ div}$ in divertor region an occure due to the difference in electron ionizaton rates of He atoms and DT atoms (see Fig 6). The fuel atoms ionization rates are almost order of magnitude high than ionization of He atoms for temperatures ≤ 30 eV, which are expected in the SOL for detach regimes.

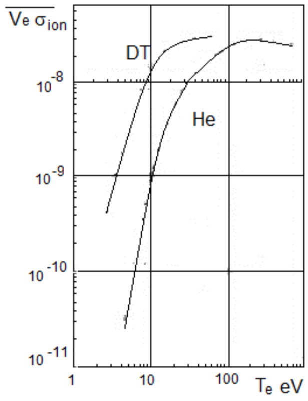

Fig. 5. Electron ionization rate σv of He and D/T atoms versus electron temperature.

Before reaching the private flux region (PFR) He and fuel neutrals passing through the plasma fan in the SOL region and undergo the ionization due to collisions with electrons. Helium atoms can preferentially penetrate into the PFR, while deuterium/tritium atoms are ionized within the plasma fan. Therefore, the helium density increases in the PFR and the density at the separatrix is less affected, because the He atoms mainly passing through the hot SOL width $\Delta \sim 15 \div 20$ cm at electron temperatures ≤ 10 eV without being ionized ($\lambda_{He,\ ion} \geq \Delta > \lambda_{DT,\ ion}$). This selective penetration increases the He enrichment in the PFR and decreasing the DT flux which is removed with the He atoms. He atoms can also concentrate in the outer cold SOL region where the friction between He and dt ions dominates over thermal force (in attached case) and can be preferably pumped out in divertor configuration with properly inclined plates. Preferential penetration of He atoms into PFR occurs at each recycling turn, thus increasing the He concentration in divertor $C_{He,div}$. Therefore, the DT fuel losses due to He removal can be reduced. The collateral fuel pumping flux can be written as $\Phi_{dt,div} = \Phi_\alpha / C_{He,div} = \Phi_\alpha / \eta_{He} C_{He,core,}$ where $\eta_{He} \equiv C_{He,div} / C_{He,core}$ is the helium enrichment factor. The helium concentration in the divertor due to preferable penetration of He atoms will increase proportional to $\lambda_{He}/\lambda_{dt}$ and after η turns of recirculation the enrichment factor grows as $f_b\ (R) \sim (\lambda_{He}/\lambda_{dt})^{1/(1-\eta)}$. Here λ is the ionization mean free pass of neutrals. Assuming that the throughput is mainly detemined by the need of the fuel replanishment due to He removal, e.g. $\Phi_{pump} \sim \Phi_\alpha / \eta_{He} C_{He,core}$, the burn fraction can be expresses as

$$f_b(R) \approx \frac{1}{1 + \frac{const.}{c_{He,core}} \cdot \left(\frac{\lambda_{dt}}{\lambda_{He}} \right)^{1/(1-R)}} \qquad (2)$$

where $c_{He,\ core} \sim 0.05$ [5], const ≈ 15 was chosen so that at $R = 0$, $f_b \approx 0.01$. Fig. 6 shows the burn fraction increase due to the recycling of particles in the divertor $\eta \neq 0$ and selective penetration of He atoms to the PFR.

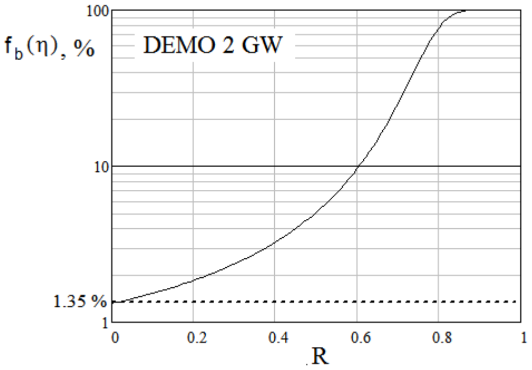

Fig. 6 Dependence of the burning fraction on particle recycling coefficient in the pumping zone; $T_e \sim 30$ eV $n_e \sim 3\ 10^{18}$ m^{-3}, the SOL width, $\lambda_{He} \geq \Delta \sim 0.2$ m, $\lambda_{dt} \sim 0.05$ m; the dashed line indicates the burning fraction without recycling.

For the SOL temperatures smaller than 30 eV , the electron density ~ 3 10^{18} m^{-3} and the SOL width $\Delta \sim 0.2$ m, the mean free pass $\lambda_{He} \geq \Delta$ and $\lambda_{dt} \sim 0.05$ m. The ratio $\lambda_{He}/\lambda_{dt}$ increases strongly at low electron temperatures and e.g. for ~5 eV reaches 50. Therefore, at low temperatures expected at the divertor plates in detachment the selective penetration of particles to the PFR will increase and enrichment of He can exceed the value, at which the fuel pumping will drop and the burning fraction increases.

Preferential penetration of He atoms into the PFR occures at each turn of recirculation, thus increasing the concentration of He atoms in the divertor. According [2] the burning fraction in DEMO reactor is expected on the level about 1%. As it seen from Fig.6 it can exceed 10% for R ≥ 0.6. The remaining fraction of fuel particles 1- R is pumped out by the actual pumping system. Since the He concentration increase at every recycling turn the enrichment η_{He} grows with recycling and can be expressed as

$$\eta(R)\approx\frac{1}{const.}\left(\frac{\lambda_{He}}{\lambda_{dt}}\right)^{1/(1-R)} \qquad (3)$$

and the fuel pumped flux drops with R, $\Phi_{dt,div} = \Phi_{\alpha} / (c_{He,core} \cdot \eta_{He}(R))$. Fig. 7 shows the dependence of the He enreachment in the divertor and the fuel pumping flux associated with the He removal as a function of recycling (fraction of the bypassing particles to the divertor flux). It is seen that for high recycling R ≥ 0.6 (the ratio of the bypassing flux Φ_{bp} exceeds 60% of the flux in the divertor Φ_{div}), the enreachment factor $\eta_{He} \geq 2$ and the pumping flux drops down to ≥25 Pa-m^3/s. The burn-up fraction $f_b \geq 10\%$.

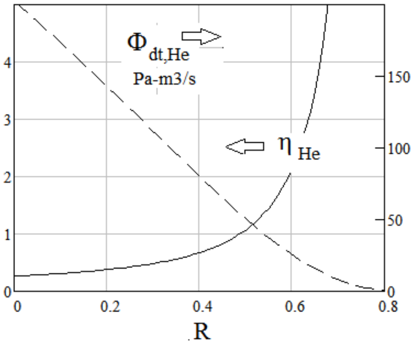

Fig. 7 He enrichment factor η_{He} in the divertor and the fuel pumping flux associated with the He removal versus recycling coefficient R, const. = 20 to keep the the burn-up fraction at R = 0 on the level of 1.35%.

The backflow fraction is the ratio of the particle flux flowing back to the main plasma from the divertor chamber through the entrance of the chamber to the particle flux flowing into the divertor chamber in steady state. The pumping fraction is the ratio of the particle flux actually pumped out by the pumping system to the particle flux flowing into the vacuum duct region through the gap separating the SOL region with the PFR. The pumping fraction for the helium particles $f_{pump,He}$ is defined as a ratio of He atoms pumped out to the He atoms entring to the PFR.

V. NUMERICAL CALCULATION

The Monte Carlo DIVGAS code [7] was applied to calculate the effect of recirculation and He enrichment on the fuel pumped-out flux required for He removal. Model of divertor with vertical divertor plates and He atoms and D_2 and T_2 molecules coming from the SOL region through the low and high field side gaps into the divertor region and with the pumping port located at the bottom of the diveror was used. He and the fuel (D_2 and T_2) particles are penetrating through the low and high field side gaps into the PFR. The boundary conditions for the particles reaching the PFR from the SOL after being neutralize on the vertical divertor plates are expressed through the average neutral pressure p and temperatures T at the entrance to the PFR. It is taken into account that the flux through the LHS twice exceeds the flux through the HFS gap and also assumed that the He flux about ten times less than the fuel flux. The temperatures are taken as 4060 eV for all species and pressure about 1/3 Pa for fuel molecules. These assessments based on scalings derived in [8] and are used here for estimation of the average divertor pressure p and the temperature T of D_2 and T_2 molecules at the side gaps. Helium partial pressure at the LFS increases due to preferential penetration of He atoms to the PFR and in calculations was varied. After hiting the plenum walls all neutrals are reflected backwards with Maxwellian distriburion fanction based on with the wall temperature T_{wall}=420 K. At the entrance to the pumping ports a pumping probability ξ for all species is assumed. Calculations show that the fraction of He pumped out increases with the increase of He pressure at the low field side gap side (see Fig. 8). The effect is more pronounced for the case of a strong pumping.

It should be noted that a self-consistent treatment of the scrape-off layer plasma is required to obtain a more precise evaluation of the reduction of the pumped-out fraction. An achievement of high recycling in the divertor can be limited by maximum plasma density attainable at the midplane. A higher plasma density in the divertor region of the reactor is more plausible in detach divertor operation, when the reverse plasma flows are rather seldom seen in experiments. Therefore, we believe that for high recycling in the divertor region the pumping fraction will become smaller as predicted from our simple model.

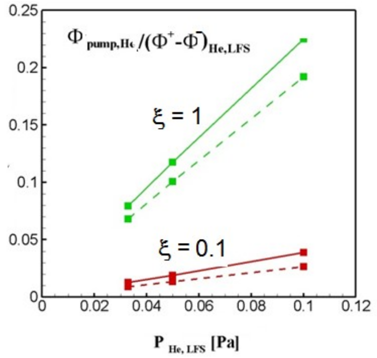

Fig. 8 Bypassing and He separation results to high He pressure at the LFS gap and to high pumping flux; the effect is more pronounced for high pumping efficiency, ξ =1 and for the case with dome (solid lines).Φ^+-Φ^- is the net He flux to the PFR.

CONCLUSIONS

The divertor configuration with bypassing loop from the plenum to the SOL is suggested as a divertor design which can facilitate He removal with moderate flow rates to be pumped out, low tritium inventory and high burn-up fraction in DEMO operation. The fuel burn-up fraction can be increased from ≤ 1% to at least above 5% in operation with particle bypassing. A small particle throughput (≤ 50 Pa m^3/s) corresponding to burning fraction above 5% will be consistent with the requirement of He removal by means of particle reinjection in the divertor /SOL region.

DT replenishment due to collateral losses associated with He removal depend on He enrichment factor at the divertor η_{He} and for $\eta_{He} \geq 0.3 \div 0.6$ correspond to $\Phi_{He,dt} \approx 170 \div 90$ Pa-m^3/s (see Fig. 3). For the fueling rate of about 50 Pa-m^3/s (when burning fraction is ≥ 5%) this implies ~30 times increase of the fuel flux in divertor due to bypassing.

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