Requirements for Pellet Injection in ITER Scenarios with Enhanced Particle Confinement

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Abstract

Requirements for pellet injection parameters for plasma fuelling are assessed for ITER scenarios with enhanced particle confinement. The assessment is based on the integrated transport simulations including models of pedestal transport, reduction of helium transport and boundary conditions compatible with SOL/divertor simulations. The requirements for pellet injection for the inductive H-mode scenario ($H_{H98y,2} = 1$) are reconsidered taking account of a possible reduction of the particle loss obtained in some experiments at low collisionalities. The assessment of fuelling requirements is carried out for the hybrid and steady state scenarios with enhanced confinement with $H_{H98y,2} > 1$. A robustness of plasma performance to the variation of particle transport is demonstrated. A new type of steady state (SS) scenario is considered with neutral beam current drive (NBCD) and electron cyclotron current drive (ECCD) instead of lower hybrid current drive (LHCD) to extend the range of stable operation and to avoid the reduction of the edge LHCD efficiency caused by pellet injection.

1. Introduction

High Field Side (HFS) pellet injection is proposed as a main candidate for core fuelling to provide high plasma core density $n_e \sim 8-10 \cdot 10^{19} m^{-3}$ required for target ITER operation with the fusion power $P_{fus} \sim 400$ MW, and power multiplication $Q \sim 10$ [1]. Gas puffing and particle recycling are probably inadequate for core fuelling, since the neutral particle influx across the separatrix and the separatrix density saturate at comparatively low levels: $\Gamma_{core} \sim 13-18$ Pa-$m^3 s^{-1}$, $n_s \sim 3-4 \cdot 10^{19} m^{-3}$ [2,3]. Pellet injection parameters required for fuelling depend on the core and edge pedestal particle transport. Pellet injection is also considered for ELM loss mitigation in tokamak plasmas. Requirements for an ELM control system depend on the pedestal plasma parameters.

In this paper, the requirements for pellet injection parameters for plasma fuelling and ELM mitigation are assessed for ITER scenarios with enhanced particle confinement. The assessment is based on integrated transport simulations described in section 2 including modeling of pedestal transport, reduction of helium transport and boundary conditions compatible with SOL/divertor simulations.

The requirements for pellet injection [1] for the inductive H-mode scenario ($H_{H98y,2} = 1$) are reconsidered in Section 3 taking account of a possible reduction of the particle transport obtained in some experiments at low collisionalities [4, 5].

An assessment of fuelling requirements is carried out in section 3 for the hybrid and steady state scenario with enhanced confinement with $H_{H98y,2} > 1$. A new type of SS scenario is considered with NBCD and ECCD instead of LHCD to extend the range of stable operation and to avoid the reduction of the edge LHCD efficiency caused by pellet injection.

2. Transport model

In experiments with low effective collisionalities $\nu^* \sim 0.01$, similar to those expected in ITER, particle transport can be well described with the neoclassical pinch velocity $V = V_W$ provided the particle diffusivity D in the zone of turbulent transport is low. In this case, $D = 0.1$ ($\chi_{e,turb}$ + $\chi_{i,turb}$) in ASDEX-Upgrade [4], $D = 0.2$ $\chi_{e,turb}$ in JET [5] with $\chi_{e,turb} = 0.5$ $\chi_{i,turb}$. The particle diffusivity at the edge pedestal is uncertain (up to a factor of 10) [5]. Moreover, the main part of the edge pedestal zone is beyond the applicability of the present-day theory based models.

For expected ITER parameters with neutral beam injection (NBI) and edge gas fuelling, the particle source in the turbulent zone is estimated to be much smaller than that obtained in present-day experiments. The reduction of the particle transport in this core region will mainly affect the plasma contamination by helium ash rather than core fuelling. The particle source in ITER, produced by gas puffing, will be located within the good confinement zone of the edge pedestal. Thus, parametric analysis of particle transport in both core and edge areas is of interest to assess the operational window for $Q > 10$ and requirements for the core fuelling by pellet injection.

We performed simulations of ITER scenarios using 1.5-D transport code generated with the help of Automatic System for Transport Analysis ASTRA [6]. In our simulations we used a semi-empirical approach for the transport coefficients [7]. For the simulations of ITER performance, thermal, toroidal momentum and particle diffusivities, χ_e, χ_i, χ_ϕ, D_{He}, D_e of similar form are chosen:

$$\chi = C\, f(x)\, h(x) + (1 - h(x))\, \chi_{ped}.$$

where $h(x) = 1$ for $x < 1 - \Delta$ and $h(x) = 0$ for $x > 1 - \Delta$ (corresponding to the H-mode edge pedestal transport improvement to neoclassical value), $x = r/r_a$ is the normalised radius, connected with the toroidal magnetic flux Φ ($r = (\Phi/\pi B)^{1/2}$ and B is the toroidal magnetic field). For ITER scenarios this simplified description of the edge pedestal gives a pedestal pressure gradient within the ballooning limit, which is consistent with the ELM-Type-I operation considered. Argon and beryllium densities are prescribed.

The width of the edge pedestal, Δ, in our modelling is calculated using the approach proposed in Ref. [8] based on the suppression of the ITG turbulence by the **ExB** shearing rate:

$$\gamma_{ITG}/(1+S^2) < \omega_E = |R\,(B_\theta/B)\,(E_r/RB_\theta)'|,$$

where ω_E is the **ExB** shearing frequency, R is a major radius, B_θ is a poloidal component of the magnetic field B, E_r is the radial electric field determined from the radial ion pressure balance

$$E_r = p_i'/en_i - V_{\theta i}B_\phi + V_{\phi i}B_\theta.$$

$$\gamma_{ITG} = 0.3c_s a^{-1} (aT_i/RT_e)^{1/2}|a/L_{Ti}+ a/L_{ni}|^{1/2},$$

is the linear growth rate of the ITG instability in the absence of sheared rotation [9], $S = xq'/q$ is a magnetic shear, $L_{Ti} = 1/(lnT_i)'$, $L_{ni} = 1/(lnn_i)'$, and c_s is the ion sound speed.

At the edge pedestal we considered $\chi_{i,ped} = \chi_{i,neo}$, where $\chi_{i,neo}$ is the ion neoclassical heat diffusivity. For the electron heat diffusivity we consider the expression which corresponds, according to [10], to the minimum of the electron anomalous transport, $\chi_{e,ped} \sim (c/\omega_{pe})^2 v_e \varepsilon^{3/4}/qR$, and has the following form in the dimensional units [11]:

$$\chi_{e,ped} = 158 (T_e/A_i)^{1/2}(r/R)^{3/4}/qRn_e ,$$

where $\chi_{e,ped}$ is in m^2s^{-1}, T_e, keV is a local electron temperature, q is a local safety factor, R, m is a major radius, A_i, is the atomic mass of plasma ions, R/r is a local aspect ratio, n_e, $10^{19}m^{-3}$ is a local density. It is useful to note that in present day experiments usually $\chi_{e,ped}/\chi_{i,neo} \ll 1$, meanwhile for ITER pedestal parameters $\chi_{e,ped}/\chi_{i,neo} \sim 1$.

In our modelling the boundary conditions at the separatrix are calculated from interpolation of the B2-Eirene (B2E) calculations for SOL/DIV heat, charged and neutral particle transport. In this approach, the densities, temperatures of charged particles, as well as neutral fuel and impurities influxes are calculated self-consistently as functions of power output, and the outflows of DT, He and impurity ions: $\Gamma_{DT,s}$, $\Gamma_{He,s}$, $\Gamma_{imp,s}$. Proper control of plasma parameters is provided by realistic actuators: such as gas puffing rate Γ_0, pumping speed S_p, deep fuelling rate Γ_{core} (neutral beams (NB) [12], pellet injection), tritium fraction in the fuel and auxiliary heating power P_{aux}. For the reference $P_{fus} = 400$ MW inductive operation with loss power $P_{LOSS} < 100$ MW, this interpolation predicts rather low boundary density $n_e(a) \sim 3$-$4x10^{19}m^{-3}$, temperature $T(a) \sim 200$ eV and He atomic influx $\Gamma_{He,0} \sim 0.5$-$0.6 \Gamma_{He,s}$. For ITER parameters in our analysis the core fuelling from the edge puffing followed from this parameterisation does not exceed 15 Pa-m^3s^{-1}. The particle source from the NBI is small. Thus, the required fuelling is assumed to be provided by the high field side (HFS) pellet injection, which is modelled as described in [13].

The relation between normalisation constants is chosen on the basis of experiments: $\chi_i/\chi_e = 2$, correspondently to [5], and $\chi_i/\chi_\phi = 1$, $D_{He}/D_e = 1$. The normalisation is fitted to provide the prescribed behaviour of the energy confinement time τ_E according to the experimental scaling, i.e. $H_{H98(y,2)} = 1$ [14]. In present simulations it was chosen in the simple form approximating a radial dependence of the transport coefficients observed in experiments: $f(x) = 1 + 3 x^2$.

The ratio $D_e/\chi_e = d_c$ in the core area is considered as a parameter used for the assessment of fuelling requirements in the range $d_c = 0.75$ - 0.2 as is required to fit the experimental data. The neoclassical particle pinching $V = V_w$ has been suggested. For assessment of the edge pedestal transport we introduced another independent variable parameter $d_e = D_e/\chi_{e,ped}$ at the pedestal.

The semi-empirical model used for ITER has been validated with the experimental data from the international profile data base [15]. The subset of experimental data from JET and DIII-D with $H_{H98} \sim 0.9$-1.35, high density, $n/n_G > 0.4$, was chosen for such validation. The range of

collisionality at the mid radius x = 0.5 is rather wide ν_i^* (0.5) ~ 0.01 - 0.7. The boundary conditions and input power and NBI particle source profiles are taken from experiments. Heat and particle transport is simulated. In all the experiments considered $\chi_{e,ped} \ll \chi_{i,neo}$,

The simulations reveal satisfactory agreement between the proposed semi-empirical model predictions and the experimentally measured temperature and density profiles. For the considered data subset the minimal average values of the standard deviation ($\Delta A_{std} = (\Sigma (A_s - A_x)^2)/(\Sigma A_x^2))^{1/2}$) for plasma density predictions is 10-15% for $d_c = 0.75$ and $d_e = 0.2$, where A_s is the result of simulation, A_x is the experimental value (summation is performed over the radial point positions). For lower core diffusivities the deviation increased to 20-30%. Thus, in our analysis of ITER we also considered the case of high core diffusivity $d_c = 0.75$.

3. Assessment of ITER inductive scenarios

The reference inductive scenarios in ITER were simulated with a conservative particle transport model [7] with the following diffusivities in the core: $D_e = D_{He} = \chi_e = 0.5 \chi_i \gg \chi_{i,neo}$ and $D_e = D_{He} = \chi_e = \chi_i = \chi_{i,neo}$ at the edge pedestal. In this case, in the core region, the ratio of diffusivity to the effective heat conductivity, $\chi_{eff} = 0.5 (\chi_e + \chi_i)$, $D_e = 2\chi_{eff}/3$ is 2.5 - 3 times higher than that reported in some experiments [4,5] with low collisionalities similar to ITER meanwhile the central contamination by helium is rather low $n_{He}(0)/n_e(0) \sim 2\%$. Let us note that $D_e/\chi_e = 0.3$ corresponds to $D_e/\chi_{eff} = 0.1$ reported in [4] provided $\chi_e = 0.5 \chi_i$ as we consider in ITER.

In all cases we considered a full bore plasma with aspect ratio R/a (m/m) = 6.2/2.0, elongation, $\kappa_x/\kappa_{95} = 1.85/1.7$, triangularity, $\delta_x /\delta_{95} = 0.48/0.33$ and vacuum toroidal magnetic field, B_T (R=5.2) = 5.3 T with beryllium and argon impurities $n_{Be}/n_e = 2\%$, and $n_{Ar}/n_e = 0.12\%$. All scenarios were calculated with tangential NBI of two 1 MeV deuterium beams with total power $P_{NB} = 33$ MW. The results of calculations are summarized in Table 1.

For expected ITER parameters, the neoclassical convective term is found by analysis to be a small fraction of the particle flux Γ: $\Gamma(nV_w)^{-1} \gg 1$ in the entire region x > 0.5. In the inner part of plasma $\Gamma(nV_w)^{-1} \sim 1$, even for strong diffusivity $d_c = 0.75$ and $\Gamma(nV_w)^{-1} \ll 1$ for $d_c = 0.2$. This agrees formally with analysis based on the theoretical transport modelling in the range of low effective collisionality $\nu^* < 0.1$ [16].

In the ITER scenarios under consideration $\chi_{e,ped} = \chi_{i,neo}$. In our previous modelling [1] we suggested $D/\chi_e = 1$, at the core and $D/\chi_e = 1 - 0.25$ at the pedestal with $\chi_{e,ped} = \chi_{i,neo}$. That analysis in terms of present consideration corresponds to the case $d_c = 1$, $d_e = 1 - 0.25$ with $S_{pel} = 100 - 36$ Pa-m^{3}s^{-1}. In the simulations of the ITER scenarios with reduced particle diffusivities in the core, $D_e/\chi_e = D_{He}/\chi_e = 0.2-0.3$ becomes lower at the top of the pedestal than the ion neoclassical heat diffusivity. Thus, the natural suggestion in the transport estimates is the appropriate reduction of the pedestal diffusivity $d_e < 1$ ($d_e = 0.2$ is considered in the table). As it follows from calculations the extra core fuelling by pellet injection is still required even for the extreme case with $d_c = d_e = 0.2$. For the case $d_c = 0.75$, $d_e = 0.2$, which provides the best fit of the analysed experimental data, the required pellet fuelling rate is 32 Pa-m^{3}s^{-1}.

Table 1. Dependence of the ITER plasma performance on the ratio $d = D/\chi_e$ in the core and edge pedestal areas d_c/d_e

Parameter	Inductive				Hybrid		Steady State
d_c/d_e	0.75/1	0.75/0.2	0.3/1	0.2/0.2	0.75/1	0.2/0.2	0.75/1
Plasma current, I_P (MA)	15.0	"	"	"	12.0	"	9
Confinement time, τ_E (s)	3.7	3.57	3.95	3.92	2.9	5.6	2.93
$H_{H98(y,2)}$	1.03-1	1.01-0.99	1.01-0.99	1.01	1.22-1.17	1.2-1.19	1.67
Normalised beta, β_N	1.83	1.83	1.7	1.75	1.93	1.9	2.76
Inductance, l_i3	0.77	0.86	0.75	0.87	0.85	0.955	0.87
Electron density, $\langle n_e \rangle$ (10^{19}m^{-3})	9.65-10.8	9.78-10.2	9.56-10.3	9.8	7.27-8.23	7.64-7.81	5.35-5.66
n/n_G	0.85-0.91	0.84-0.86	0.85-0.89	0.85	0.81-0.87	0.84-0.85	0.77-0.8
$f_{He, axis}$ (%)	2.0	3.9	3.3	9.2	2.9	9.4	3.3
$\langle f_{He} \rangle$ (%)	0.92-0.83	1.6-1.5	1.3-1.2	3.2	1.1-0.99	3.2-3.1	1.3-1.2
Helium pumping, τ_{He}^*/τ_E	1.13	2.2	1.9	4.7	1.44	5.0	1.56
Fusion power, P_{FUS} (MW)	441	447	375	392	318	290	275
Energy multiplication, Q	13.5	13.5	11.4	11.9	9.6	8.8	5.15
Burn time, τ_{BURN} (s)	420	406	317	307	1442	1464	inf.
Radiated power, P_{RAD} (MW)	39.4	41.4	38.	41.6	26	28	22
Alpha-particle power, P_α (MW)	88	89.5	75	98	63.6	58	55
P_{los}/P_{L-H}	1.65	1.67	1.41	1.45	1.68	1.47	2.5
Plasma thermal energy, W_{th} (MJ)	338	330	318	320	273	267	261
Z_{eff}	1.61-1.63	1.62-1.63	1.61-1.63	1.64	1.6	1.65	1.64
S_{pel}, Pa-m^{3}s^{-1}	85	32	55	20	64.6	13.7	49

The effect of particle transport on the plasma performance appears to be moderate. Fusion power is varied by 10-15% with Q > 10 in spite of the increase of the core helium content $n_{He}(0)/n_e(0)$ from 2 to 4-9%.

3. ITER scenarios with enhanced confinement

In addition to the inductive operation we have also considered hybrid and steady state operations with enhanced confinement. The first scenario considered is similar to the hybrid

scenario obtained at high triangularity $\delta \sim 0.43$ and high density $n/n_G = 0.83$ with $q \sim 4$ and $H_{H98y,2} = 1.2$ [17]. To increase the safety factor we consider the full bore plasma configuration with plasma current $I_p = 12$ MA.

The results of simulations of this scenario with the model described in section 2 are summarized in Table 1. In the considered case of the improved confinement $H_{H98y,2} = 1.2$, the particle diffusivity is only 1.5 times higher than the ion neoclassical heat diffusivity even for $d_c = 0.75$. Thus, we only consider two extreme cases, $d_c = 0.75$ and $d_e = 1$; and $d_c = 0.2$ and $d_e = 0.2$. Similarly to the inductive scenario, the plasma performance is not significantly affected by particle transport. Fusion power variation is within 10 %. Extra core fuelling by pellet injection, $S_{pel} \sim 15$ Pa-m^{3}s^{-1}, is required.

In the steady state operational scenario with the core fuelling provided by the edge gas puffing considered for ITER [1], the tangential NBI ($P_{NB} = 33$ MW) is planned for current drive near the central zone and LHCD at up to 40 MW is planned for the current drive near the plasma edge to keep $q_{min} > 2$ (SS scenario Type -I). In this scenario the operational points are above the no-wall ideal stability limit $\beta_N > \beta_{N,no-wal} \sim 4$ l_i due to low internal inductance l_i $\sim 0.5 - 0.7$. The stable operational space shrinks with the increase of the pressure peaking factor (the ratio of central to average pressure) $p_0/<p> > 3$. In the case of core fuelling by pellet injection, the plasma temperature and density will oscillate in the area of the LH wave absorption.

To extend the operational space and avoid oscillations of current drive (CD) location and efficiency, an alternative SS operational scenario is proposed for ITER (SS scenario Type-II). If the H mode improvement factor can be increased to $H_{H98y,2} \sim 1.5$-1.7 the required noninductive current can be achieved with the help of tangential NB injection (1 MeV 2 D-beams with total power $P_{NB} = 33$ MW) and ECCD ($P_{EC} = 20$ MW), which are planned to be installed for CD at the initial phase of ITER operation.

The SS scenario Type-II in ITER was investigated in [18] with plasma transport simulated by the ASTRA transport code [6]. The ideal MHD stability analysis was performed for external kink modes using the KINX code assuming the separatrix was at the plasma boundary [19].
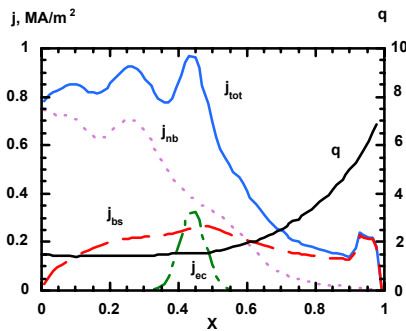

The reverse shear (RS) scenarios with different current profiles were provided by the variation of the lower hybrid (LH) current drive and the auxiliary heating and CD by the neutral beam (NB) injection. The ECCD calculations were performed on the basis of the OGRAY code [20]. Lower particle diffusivity and lower operational density required for such operation reduces the required fuelling by a factor of two, S_{ep} ~ 50 Pa-m^{3}s^{-1}, in comparison with the reference inductive operation [1].

Fig.1. Current density and safety factor profiles for the SS equilibrium with $\beta_N = 2.76$, $p_0/<p> = 3.5$, $l_i = 0.87$, $H_{H98y,2} = 1.67$, where x is a square root of a normalized toroidal magnetic flux.

The modeling of the SS scenarios with higher internal inductance $l_i \sim 0.8$ and lower $q_{min} \sim 1.5$ resulted in safety factor profiles with weak shear in the plasma center (Fig.1). As expected it gives an increase in the β_N limits against external $n = 1$ mode ($\beta_{N,no-wal} \sim 3$), but this configuration is unstable against the $n = 2$ mode if the resonant surface $q = 1.5$ is in the

plasma. For the case with q_{min} < 1.5, the n = 2 RWM stabilization and the NTM mode stabilization can be required for such profiles.

Conclusions

The analysis reveal that even for reduced core and pedestal transport similar to the data obtained in some present-day experiments with low collisionalities, the extra core fuelling by pellet injection is needed for ITER to achieve the required performance. In the extreme case of $d_c = d_e = 0.2$ the rate of such fuelling (> 20 Pa-m^{3}s^{-1}) is still higher than the maximum level which can be provided by gas puffing (~ 15 Pa-m^{3}s^{-1}). Small pellets required for such fuelling can not significantly affect the collisionality at the top of the pedestal. Therefore, it may be necessary to consider a separate system for the ELM control by the LFS pellet injection, provided the ELM mitigation by pellet injection is connected with collisionality, rather than with frequency.

In the range of the considered parameters the effect of particle transport on the plasma performance appears to be moderate. The change in the fusion power is only ~10-15% with Q > 10.

The new possible steady state operational scenario looks attractive: replacement of the edge localised LHCD by more central ECCD will enable the extension of the operational space β_N < 4 l_i, and avoid oscillations of current drive location and efficiency if high confinement with $H_{H98y,2}$ ~ 1.5-1.7 can be reached in ITER. Further studies of the feasibility of scenarios such as this are required and their compatibility with pellet injection has to be determined.

Acknowledgement

References

[1] POLEVOI, A.R., SUGIHARA, M. , TAKENAGA, H., et al Nucl. Fusion **43** (2003) 1072.
[2] KUKUSHKIN, A.S., PACHER, H.D., Plasma Phys. Control. Fusion **44** (2002) 931.
[3] PACHER, H.D., KUKUSHKIN, A.S. , PACHER, G.W. , JANESCHITZ, G.J., Nuclear Mater. **313–316** (2003) 657.
[4] STOBER, J. , DUX, R. , GRUBER, O., et al. Nucl. Fusion **43** (2003) 1265
[5] VALOVIC, M. , BUDNY, R., GARZOTI, L. , et al, "Density peaking in low collisionality ELMy H-mode in JET", Submitted to Plasma Phys. Control. Fusion

[6] PEREVERZEV, G.V., et al., Report IPP5/42 (1991).

[7] POLEVOI, A.R. , MEDVEDEV, S.YU., MUKHOVATOV, V.S. , et al., J. Plasma Fusion Research SERIES, Vol.**5** (2002), 82

[8] SUGIHARA, M. , IGITKHANOV, Yu., JANESCHITZ, G. et al, Nucl. Fusion **40** (2000) 1743

[9] CRISANTI, F., et al Nucl. Fusion **41** (2001) 883

[10] KADOMTSEV, B.B., "Tokamak Plasma: A Complex Physical System", Institute of Physics Publishing Bristol&Philadelphia (1992) 178

[11] MEREZHKIN, V.G., MUKHOVATOV, V.S., POLEVOI, A.R., Sov. J. Plasma Phys., **14** (1988) 69.

[12] POLEVOI, A. , SHIRAI, H. , TAKIZUKA, T. , JAERI Data/Code 97-014 (1997).

[13] POLEVOI, A.R., SHIMADA, M., Plasma Phys. Control. Fusion **43** (2001) 1525.

[14] KARDAUN, O. , et al., 18th IAEA Fusion Energy Conference, Sorrento, Italy (2000) ITERP/04.

[15] ITER Physics Basis, Nucl. Fusion **39** (1999) 2215.

[16] ANGIONI, C., PEETERS, A.G., PEREVERZEV, G.V., et al., Phys. of Plasmas, **10** (2003) 3225

[17] SIPS, A.S. et al, Plasma Phys. Contr. Fusion, **44** (2002) B69

[18] POLEVOI, A.R., MEDVEDEV, S.YU., PUSTOVITOV, V.D., et al. Possibility of Q > 5 Stable Steady-State Operation in ITER with Moderate β_N and H-factor. IAEA-CN-94/CT/P-08, ITER Preprints, IAEA 18th Fusion Energy Conference, Lyon, France, 14-19 October 2002.

[19] DEGTYAREV, L. et al., Comput. Phys. Commun. **103** (1997)10

[20] ZVONKOV, A.V., KUYANOV, A.YU., SKOVORODA, A.A., and TIMOFEEV, A.V., Plasma Physics Reports **24** (1998) 389.