Possibility of Q > 5 Stable, Steady-State Operation in ITER with Moderate β_N and H-factor

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Abstract. A possibility of steady state stable operation in ITER with Q > 5 and moderate requirements for plasma confinement is investigated. It is shown that there is some parametrical space for such operation where the ideal kink modes could be stabilised by the first wall. It is found that operational space where the ideal kink modes can be stabilised by the conducting wall could be noticeably extended by a relatively small reduction of the pressure peaking factor. The resistive wall mode stabilisation in ITER is discussed.

1. Introduction

The demonstration of steady-state (SS) operation with Q > 5 is one of the aims of the ITER project [1]. Such operation would require high $\beta_N > 2.5$ and low internal inductance $l_i \sim 0.5$-0.7 with high fraction of the bootstrap current (~50%), off-axis maximum, and reversed magnetic shear (RS). Therefore, the required $\beta_N > 2.5$ is close to or above the no-wall stability limit [2] $\beta_{N,no\text{-}wall} = 4\ l_i$. The ideal modes can be stabilised by a conducting wall located near the plasma boundary [3]. For this case resistive wall mode (RWM) stabilisation would be required. Thus, the wall position and conditions of RWM stabilisation imply restrictions on the possible SS operational range. The range of stable SS operation in ITER is discussed here.

2. Steady-State Plasma Performance

Plasma transport is simulated by the ASTRA transport code [4] with 2D arbitrary-shape, fixed-boundary equilibrium solver SPIDER. The ideal MHD stability analysis is performed for global kink modes with the KINX code [5]. We consider here SS RS scenarios with plasma current $I_p = 9$ MA similar to the scenario described in [1]. It is possible to provide the SS operation with different current profiles by variation of the lower hybrid (LH) current drive. For ITER simulations, we consider a reduced set of 1D fluid like equations, which describe the evolution of electron and helium densities (n_e, n_{He}), toroidal rotation velocity ($V_{\phi i}$), electron and ion temperatures (T_e, T_i), and poloidal magnetic flux (ψ). The helium content is controlled by pumping to keep $\tau^*_{He}/\tau_E = 5$, where τ_E and $\tau^*_{He} = \int n_{He}dV/\int S_{He}dV$ are the energy confinement time and effective helium confinement time respectively. Other impurity species are assumed to be known fractions of the electron density $n_{zk} = f_k n_e$, and the fuel density n_D+n_T is calculated from the quasineutrality condition. Evolution of ψ is calculated taking into account the bootstrap current (j_{bs}) [6] and the externally driven current (j_{CD}). To calculate the auxiliary heating and current drive (CD) we simulate the neutral beam (NB) injection using a Fokker-Planck solver taking account of real geometry, multistep NB stopping cross sections, orbital losses, and neo-classical effects [7]. We consider also the LH with high CD efficiency of $\gamma = 0.3\times10^{20}\ AW^{-1}m^{-2}$ [8] at the plasma periphery to provide a RS configuration in the SS regime. Unfortunately, there is no comprehensive transport model for enhanced confinement with ITB. Here we assume that in the good confinement zones the plasma transport coefficients would reduce to the ion neoclassical level. We simulate the SS scenarios with an internal transport barrier (ITB) using equal thermal, toroidal momentum and particle diffusivities:

$$\chi_e = \chi_i = \chi_\phi = D_{He} = D_e = f(x)\,h(x)\,F(s) + \chi_i^{neo}, \tag{1}$$

where $f(x) \sim 1 + 3x^2$ describes the radial dependence of the transport coefficients [9], $x = r/r_a$, $h(x) = 1$ for $x < 0.9$ and $h(x) = 0$ for $x > 0.9$ (corresponding to the H-mode edge pedestal transport improvement). Factor $F(s) = (1 + \exp(7(1-s)))^{-1}$ provides the fast drop of transport coefficients to the ion neoclassical diffusivity χ_i^{neo} in the optimised and reversed shear zone, $s = rq'/q < 1$. At the separatrix the electron density is prescribed and temperatures are chosen on the basis or parameterisation of the B2-EIRINE calculations [9]. For simplicity we assume zero rotation velocity at the boundary.

Since the neoclassical diffusivity in the RS zone increases with q, the current profile variation affects the confinement. The increase of q(0) and q_{min} reduces the pressure peaking (Fig.1). The same effect could be achieved in our simulations by increasing the impurity content in the central zone (Z_{eff}). That reduction of the pressure peaking factor (PPF), $p_0/\langle p\rangle$, the ratio of central to average pressure, improves stability, although it reduces the power multiplication factor Q. Here we consider SS scenarios in the range q_{min}= 2.12-2.43 to identify possible operational limits of $\beta_{N,ITER\ wall}$ which are determined by the ITER wall position, $a_{w,ITER}/a \approx 1.375$ for a = 1.85 m, R = 6.35 m, and the requirement Q > 5. A high fusion full-bore scenario is also considered (a = 2 m, R = 6.2 m, $a_{w,ITER}/a \approx 1.35$). The results of calculations are presented in Table I.

TABLE I: ITER PLASMA PARAMETERS FOR THE SS SCENARIOS

Scenario N	1	2	3	4	Scenario N	1	2	3	4
a,m	1.85			2.0	$\langle T_e\rangle/\langle T_i\rangle$,keV	10.5/11	10.8/11.7	11/12	15.5/18
δ_{95}	0.41			0.39	$\langle n_e\rangle, 10^{19}m^{-3}$	6.74			8.02
κ_{95}	1.84			1.76	n/n_G	0.83			0.86
R,m	6.35			6.2	W_{th}/W_{fast}, MJ	255/50	264/53	273/60	474/99
B(R),T	5.17			5.3	$H_{H98\,(y,2)}$	1.3	1.36	1.41	1.53
I_p,MA	9			12	Q	5	5.42	5.7	8
q_{95}	5.13	5.14	5.16	4.14	P_{NB}/P_{LH}, MW	34/33.7	34/31	34/29	47/40
q_{min}	2.43	2.25	2.12	2.16	P_{fus}, MW	338	352	361	699
β_N	2.56	2.7	2.82	3.6	P_{los}, MW	97	94.5	93	155
p(0)/<p>	2.7	2.9	3.1	2.55	τ_E, s	2.32	2.44	2.54	2.73
li	0.63	0.69	0.72	0.58	$\langle Z_{eff}\rangle$	2.17	2.22	2.2	2.5

3. Ideal Mode Stability in the Steady-State Plasma

To analyse the operational space where ideal modes and RWMs could be stabilised by the first wall and plasma rotation we introduce the following parameterisation for the toroidal plasma current density j_{tor} in the vicinity of SS operational points from the Table I:

$$j_{tor} = j_n\left\{\frac{r}{R}\alpha G(\psi) + \frac{R}{r}\left[H(\psi) - \alpha G(\psi)\right]\right\}, \tag{2}$$

Functions $G(\psi)$, and $H(\psi)$ with $\alpha = 1$ correspond to self-consistently calculated SS points from the Table I. We scan the parameter α near the SS operational point ($\alpha = 1$) keeping constant the total plasma current. Only one point of this scan ($\alpha = 1$) corresponds to the SS operation. Such a scan simulates possible relatively fast (on the energy confinement time scale) pressure and β_N excursions ($\beta_N \sim p' \sim \alpha G(\psi)$) from the self-consistent SS operational points with nearly constant PPF. The analysis reveals that the most dangerous mode is an external n = 1 kink mode coupled to internal modes. The marginal ideal-wall position, a_w, needed for its stabilisation is determined with KINX code [5] in a series of equilibria (see Fig.2) with β_N changed as a result of scan Eq.(2). In this scan we prescribe the conformal ideal wall by $\mathbf{r}_w = \mathbf{r}_p + (\mathbf{r}_s - \mathbf{r}_p)\, a_w/a$, where $\mathbf{r}_s = \mathbf{r}(R,Z)$ is a plasma boundary and $\mathbf{r}_p = \mathbf{r}(R_p,Z_p)$ is a plasma centre position. The best approximation of the real first wall position in ITER for considered equilibrium corresponds to $a_w/a = 1.375$ for a = 1.85 m, R = 6.35 m, and to a_w/a =

1.35 for the full-bore plasma with a = 2 m, R = 6.2 m. The limits of $\beta_{N,no\text{-}wall}$ and $\beta_{N,ITER\ wall}$ for the α-scan near the SS operational points $\beta_{N,SS}$ are shown in Table II.

TABLE II: PLASMA OPERATIONAL LIMITS FROM STABILITY ANALYSIS

Scenario	SS operational point		α-scan		q=const scan	
N	p(0)/<p>	$\beta_{N,SS}$	$\beta_{N,no\text{-}wall}$	$\beta_{N,ITER\ wall}$	$\beta_{N,no\text{-}wall}$	$\beta_{N,ITER\ wall}$
1	2.7	2.56	2.5	3.55	2.5	3.85
2	2.9	2.7	2.51	2.97	2.4	3.25
3	3.1	2.82	2.34	2.72	2.1	2.6
4	2.55	3.6	2.7	3.8	2.7	4.0

For plasma diagnostic and control requirements it is important to know which parameter is the most important for the MHD stability. Therefore, to exclude the effect of the safety factor reduction with increase of pressure in the α-scan, we also consider a pressure scan with constant q profile (Fig.2) corresponding to the self-consistent SS operational scenario. The results of the stability analysis are compared in the Table II. The difference in the operational limits $\beta_{N,ITER\ wall}$ appeared to be relatively small, within 10%. Similar to [10,11], pressure peaking reduction increases $\beta_{N,no\text{-}wall}$. But the operational space for permitted pressure excursions from the SS operational point $\beta_{N,ITER\ wall}/\beta_{N,SS}$ is more sensitive to the PPF and q_{min} values than the no-wall limit $\beta_{N,no\ wall}$. For the equilibrium with $\beta_N = 2.82$, $q_{min} = 2.12$ and the highest $p_0/\langle p\rangle = 3.1$, the marginal stabilising wall should be located at $a_w = 1.3a$, closer to the plasma than the designed ITER first wall $a_w = 1.375$ a. Meanwhile for $p_0/\langle p\rangle = 2.7$ the range of pressure excursions permitted by ideal mode stabilisation is wide, $\beta_{N,ITER\ wall}/\beta_{N,SS} \sim 1.5$.

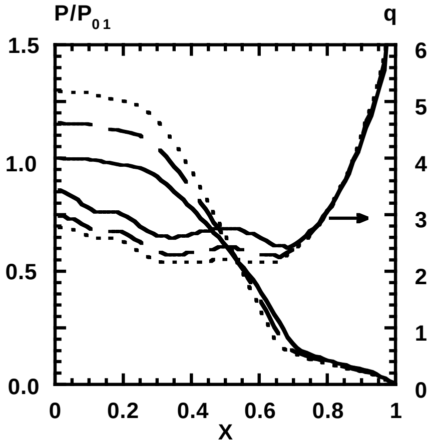

FIG.1. Normalised pressure P/P_{01} and safety factor q profiles for SS operational scenarios: solid line (N1): $q_{min}= 2.43$, $\beta_N = 2.56$, dashed line (N2): $q_{min}=2.25$, $\beta_N = 2.7$, dotted line (N3): $q_{min}=2.12$, $\beta_N = 2.82$. P_{01} corresponds to central pressure in the scenario N1.

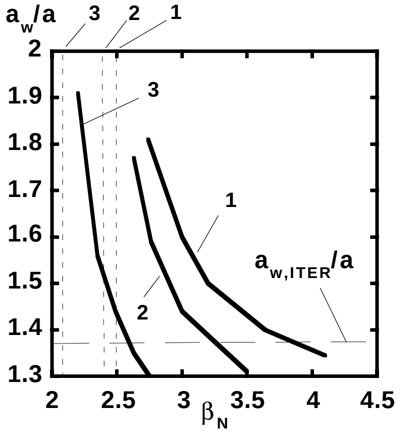

FIG.2. Stabilising wall position a_w/a vs. normalised beta β_N for q=const scan of SS operational points 1,2,3 from Table.I, and a = 1.85 m. The no-wall limits are shown by vertical dashed lines. $a_{w,ITER}/a \approx 1.375$.

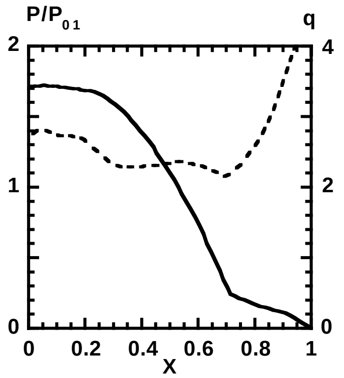

FIG.3. Normalised pressure (solid line) and safety factor (dashed line) profiles for SS scenario N4 from. P_{01} corresponds to central pressure in the scenario N1.

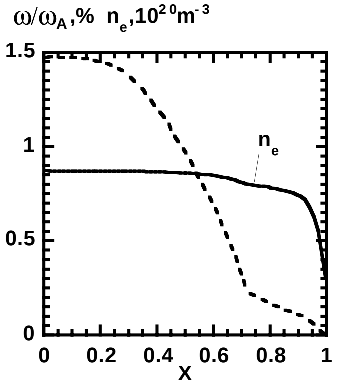

FIG.4. Ratio of plasma rotational frequency to Alfven frequency (dashed line) and electron density profile (solid line) for the SS ITER scenario N4.

In a power reactor with high pressures, limitations other than ideal stability, such as limit on the power loss to the divertor $P_{loss} < 100$ MW, will have to be faced. If extra power can be radiated outside of the core plasma, this limitation is relaxed and the high $\beta_N \sim 4$ SS operation with Q ~ 10 would become possible (scenario N4) under the assumptions used for SS operation cases 1,2,3. For high-Q operation with high enhancement factor we reduce PPF by increasing core contamination by seeding with argon. In the full-bore plasma with R = 6.2 m, a = 2 m ($a_{w,ITER}/a = 1.35$), with the lowest $p_0/<p> = 2.55$ the limits $\beta_{N,no\ wall} \sim 2.7$, $\beta_{N,ITER\ wall} \sim 3.8$ are noticeably higher than in the 9 MA scenario, in spite of rather low $q_{min} = 2.16$.

4. RWM Stabilisation

All considered SS cases have β_N above the no-wall limit $\beta_{N,no-wall}$. Therefore, RWM stabilisation is required. Such stabilisation can be provided by an active field control system and by toroidal plasma rotation. The possibility of the RWM stabilisation by plasma rotation in ITER-like plasma was analysed in [12] with the MARS code [13]. The calculated profile of the plasma toroidal rotation velocity caused by the tangential injection of 1 MeV NB with 34 MW of power used in the SS scenario for heating and current drive is shown in Fig.4. We may expect the RWM stabilisation by plasma rotation in the considered SS ITER scenarios since the profile is similar to that required for stabilisation of RWMs in ITER-like plasma in [12].

We consider the RWM stabilisation with self-consistently calculated rotation for ITER SS scenarios as a subject of future studies. We formulate here a few conditions, which should be fulfilled to make such analysis with the MARS code relevant to ITER plasmas. The MARS code assumes up-down symmetry of the configuration. Therefore, to simulate ITER plasmas by the MARS code, we have to model the geometry as up-down symmetric while keeping the safety factor profile and ideal stability features the same as for the plasma with the real shape of the boundary and first wall. For this modelling of the 9 MA scenario we propose the following analytical expressions:

$$R = R_p + a_p (\cos(t) - \delta \sin^2(t));\ Z = Z_p + a_p k \sin(t), \qquad (3)$$

with $R_p = 6.35$ m, $\delta = 0.5$, $k = 1.9$, $a_p = a = 1.85$ m for the plasma boundary and $a_p = a_w = 1.375$ a for the conformal first wall parameterisation with a plane of symmetry at $Z_p = 0.47$ m. Calculations with KINX code demonstrated that such parameterisations reproduces the safety factor profile and ideal stability features (no-wall $\beta_{N,lim}$, and ITER wall $\beta_{N,max}$ limits) of the real shape plasmas within the accuracy of about 1%. Calculating the plasma rotation (Fig. 4), we suggested in Eq. (1), as observed in experiments [14], that toroidal momentum confinement is proportional to the energy confinement. Therefore, in the α-scans of β_N it is natural to scale the calculated rotation in the same way as calculated plasma pressure Eq. (2), $\omega_{tor} \sim \alpha\,\omega$, where ω corresponds to the originally calculated self-consistent SS operational point profile.

5. Summary

According to our analysis, the ITER wall position, $a_w/a = a_{w,ITER}/a$, implies a lower limit on q_{min} (upper limit pressure peaking and Q) for chosen global parameters. For the reference 9 MA scenario [1] we have found the possibility of stable SS scenarios with Q > 5 with moderate $\beta_{N,SS} \sim 2.5\text{-}2.6$ near the no-wall limit, moderate enhancement factor $HH_{98y,2} \sim 1.3$ and wide range of permitted pressure excursions $\beta_{N,ITER\ wall}/\beta_{N,SS} \sim 1.5$. To provide such operation in the long current skin time scale it is required to provide a q profile which maintains the SS operational point with appropriate low pressure peaking $p_0/\langle p\rangle \sim 2.6 - 2.7$. In the confinement time scale it would be necessary to control the pressure peaking with appropriate accuracy (~10% in our consideration) to avoid shrinking of the operational space. All considered SS cases have β_N above the no-wall limit $\beta_{N,no\text{-}wall}$. Therefore, RWM stabilisation is required.

References

[1] SHIMOMURA, Y., et al., PPCF **43** (2001) A385.
[2] STRAIT, E.J., Phys. Plasmas **1** (1994) 1415.
[3] TAYLOR, T.S., et al., Phys. Plasmas **2** (1995) 2390.
[4] PEREVERZEV, G.V., et al., Report IPP5/42 (1991).
[5] DEGTYAREV, L., et al., Comput. Phys. Comm. **103** (1977) 10.
[6] SAUTER, O., ANGONI, C., LIN-LIU, Y-R., Phys. Plasmas **6** (1999) 2834.
[7] POLEVOI, A., SHIRAI, H., TAKIZUKA, T., JAERI Data/Code 97-014, (1997).
[8] ITER Physics Basis, Nucl. Fusion **39** (1999) 2515.
[9] POLEVOI, A., et al., ITER Confinement and Stability Modelling , J. Plasma Fusion Research, SERIES Vol.**5** (2002), to be published.
[10] BONDESON, A., BENDA, M., PERSSON, M., CHU, M.S., Nucl. Fusion **37** (1997) 1419.
[11] TURNBULL, A.D., et al., Nucl. Fusion **38** (1998) 1467.
[12] CHAN, V.S., CHU, M.S., EVANS, T.E., et al., ITER-FEAT PHYSICS STUDY - ADVANCED TOKAMAK (AT) OPERATION CY01 IR&D PROJECT , GA Report GA-A23922, February 2002.
[13] CHU, M.S., MILLER, R.L., BONDESON, A., et al., Proceedings of 22nd EPS, Bournemouth, UK, Controlled Fusion and Plasma Physics, 19C, I-241 (1995).
[14] ITER Physics Basis, Nucl.Fus. **39** (1999) 2229.