5MA/1.8T helium H-mode ITER scenario with increased outboard plasma-wall gap

V.E. Lukash[1], A.A. Kavin[2], Y. Gribov[3], M.L. Dubrov[1], R.R. Khayrutdinov[1], A. Loarte[3]

[1]*NRC Kurchatov Institute, Moscow, Russia,*
[2]*Joint Stock Company "D.V. Efremov Institute of Electrophysical Apparatus" Saint Petersburg, Russia*
[3]*ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France*

1. Introduction

For reduction of the toroidal field (TF) ripple in ITER, some plates of the vacuum vessel outboard neutron shielding blocks, located in the planes of the TF coils, are made from ferritic steel SS430 [1]. At the nominal TF (5.3 T at 6.2 m), these plates, called Ferromagnetic Inserts (FI), reduce the maximum value of the TF ripple on the plasma nominal boundary from 1.16% (without FI) to 0.34% (in the regular sectors of the vacuum vessel) [1]. At a half of the nominal field (2.65 T at 6.2 m), the FI overcompensate the "vacuum" TF ripple and the TF ripple becomes negative with the maximum value on the plasma nominal boundary -0.54% [2]. At a third of the nominal field (1.8 T at 6.2 m) the TF ripple overcompensation becomes even higher and the maximum value of the TF ripple increases to -1.28% [2].

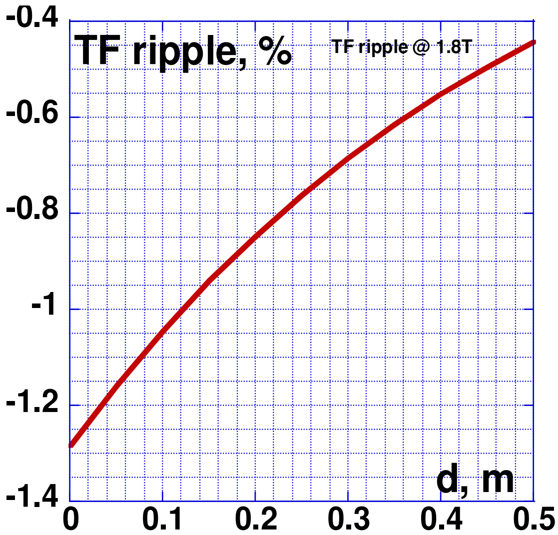

Fig. 1. Maximum value of the TF ripple on the plasma boundary at 1.8 T vs. inward displacement of the plasma outermost point [2].

Initial ITER scientific exploitation considers H-mode operation in helium plasmas at 5MA/1.8T with 20 MW of ECRH heating to allow early H-mode exploration and development of control schemes. These plasmas will have a maximum TF ripple of -1.28% at the plasma nominal boundary which could have a significant detrimental effect (~20-30%) on their energy confinement [3]. Therefore, we have performed a study of such plasma scenario with increased outboard plasma-wall gap (to reduce the TF ripple, see Fig. 1) using the DINA code [4]. Fig. 1 shows the maximum value of the TF ripple on the plasma boundary at 1.8 T vs. inward displacement of the plasma outermost point [2]. Here $d = R_{\max}^{nom} - R_{\max}$, where $R_{\max}$ is the radial co-ordinate of the plasma outermost point (see Fig. 2) and $R_{\max}^{nom}$ = 8.2 m is the value of this parameter for plasma with the nominal position and shape. The DINA code comprises a two-dimensional free boundary plasma equilibrium solver with a one-dimensional model describing transport of the poloidal magnetic flux and the plasma temperatures (electrons and ions), taking into account eddy currents in the vacuum vessel and models of the power supplies. The scenario simulations were performed with feedback and feedforward control of the plasma current, position and shape, and using the in-vessel coils for stabilization of plasma vertical displacements. In the simulations, a low frequency noise with a given Root Mean Square (RMS) value in the frequency band [0, 1 kHz] was added to the "diagnostic" signal of plasma vertical speed, *dZ/dt*, used for feedback stabilization of the plasma vertical displacements. Six parameters (plasma-wall "gaps") characterizing plasma position and shape, which were controlled in the simulations of divertor phases of the plasma scenarios, are shown in Fig. 2.

We considered scenarios when the value of R_{max} was decreased by the plasma control system just after the start of current flattop ($t = 20$ s) from $R_{max} = R_{max}^{nom}$ to a given lower value during $\Delta t = 5$ s. To provide the likeness between the nominal separatrix and the separatrix with decreased R_{max}, during the same time Δt we increased, in an appropriate way, the target value of gap g4 (see Fig. 2). The target values for R_{min}, other gaps (g1, g2, g5) and the coil currents, used in the feedback control of the plasma shape, were not changed, which leads to increasing plasma elongation when d and g4 are increased.

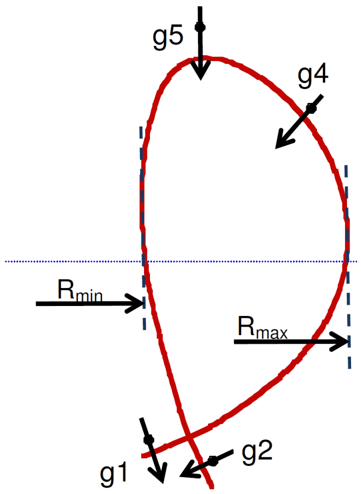

Fig. 2. Six plasma shape and position parameters (plasma–wall "gaps") feedback controlled in divertor magnetic configuration in DINA simulations of plasma scenarios.

The goal of the study was to find the minimum value of the outermost radius R_{max} (maximum value of d) at which the plasma for a given RMS value the noise in *dZ/dt* would maintain vertical stability.

The scenario simulations include the following phases of PF system operation: initial magnetisation of the CS, gas breakdown and inboard plasma initiation, plasma current ramp-up with early formation of the divertor configuration, plasma current flattop, plasma current ramp-down in the divertor configuration until 1 MA, followed by a "disruption" and final termination of the currents in the CS and PF coils (without plasma). In the scenarios design and simulations, the currents in the CS coils were limited to 20 kA at the initial magnetization and at the end of the current flattop.

2. Plasma transport model

During the plasma current ramp-up and ramp-down performed without the ECRF heating, the energy confinement time is described by the JET Ohmic scaling [5]. When 20 MW of ECRF heating is switched on (at t = 30 s), the L to H mode transition happens and the plasma confinement is then described by the Coppi-Tang scaling [6], adjusted to an H-mode confinement level typical of Helium H-modes (H_{98} = 0.8), as seen in experiments [7]. It was assumed that the plasma is in H-mode, when the power loss through the plasma boundary due to conductivity and convection, P_{cond}, is higher than the power threshold value [8]:

$$P_{cond} > P_{H\ to\ L} = 0.0488 \cdot C \cdot n_e^{0.72}(10^{20} m^{-3}) \cdot B_t^{0.8}(T) \cdot S^{0.94}(m^2), \quad MW \ .$$

Here $P_{cond} = P_{heat} - P_{rad} - dW_{th}/dt$, P_{heat} is the total heating power, P_{rad} is the total power of the radiation, W_{th} is the plasma thermal energy $C = \sqrt{2}$ (for helium plasmas), n_e is the volume averaged electron density, B_t is the toroidal magnetic field and S is the plasma surface area.

The radiation model takes into account line radiation of beryllium and tungsten using the model described in [9].

3. Simulation results

The study performed has shown that, assuming the RMS value of noise in the dZ/dt signal is 0.2 m/s, the value of R_{max} that can be achieved without loss of the plasma vertical stability is 7.8 m (d = 0.4 m, which corresponds to the maximum value of TF ripple on the plasma boundary -0.55%). Waveforms of the plasma parameters in a scenario with R_{max} = 7.8 m are shown in Fig. 3. Fig. 4 shows waveforms of errors in the control of plasma-wall “gaps” during the divertor phase of this scenario.

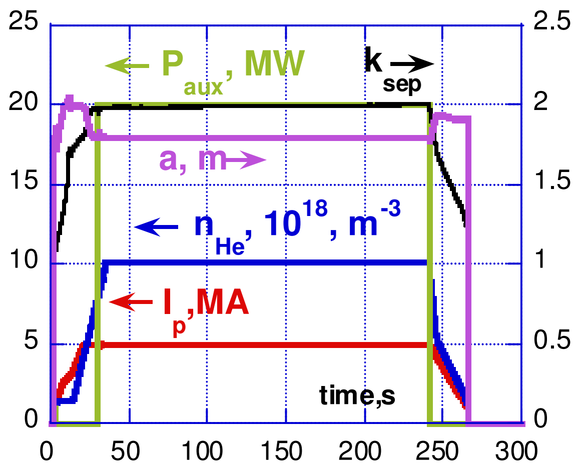

Fig. 3. Waveforms of the plasma parameters in scenario with R_{max} = 7.8 m.

An increase of the level of noise in dZ/dt leads to an increased amplitude of the plasma vertical oscillations, which may lead to the loss of plasma vertical stability. The simulations, performed assuming that the RMS value of noise in dZ/dt is 0.6 m/s, demonstrate unreliable plasma stabilization. The corresponding waveforms of errors in “gap” control, shown Fig. 5, are significantly higher than they are in the case illustrated in Fig. 4.

Calculations of the plasma vertical instability indexes, performed for the plasma considered (R_{max} = 7.8 m, $k \approx 2$), have shown that the instability growth time, τ, is 30 ms and the stability margin, m_s, is 0.17. The value of q_{95} of this plasma is slightly higher than that for the plasma with the nominal shape and position due to the increased elongation.

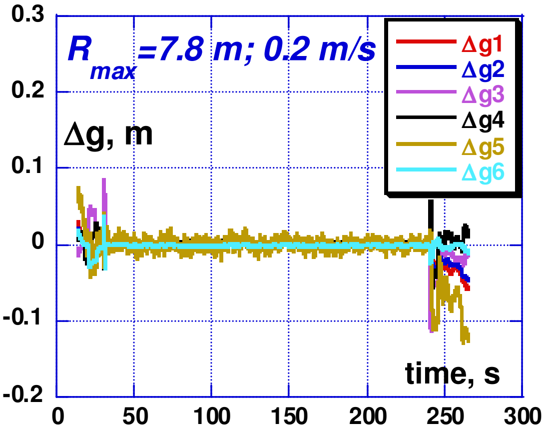

Fig. 4. Errors in gap control during the divertor phase for a scenario with R_{max} = 7.8 m and an RMS value of noise in the *dZ/dt* signal of 0.2 m/s.

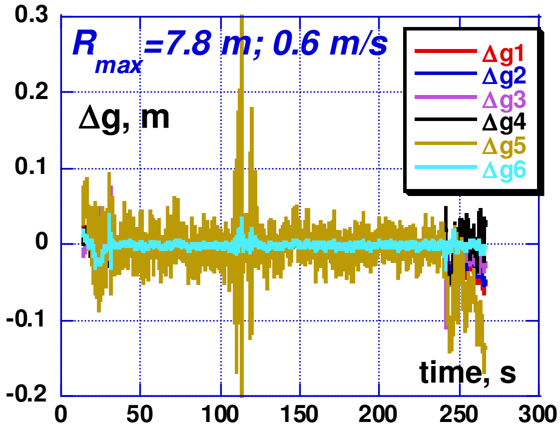

Fig. 5. Errors in gap control during the divertor phase for a scenario with R_{max} = 7.8 m and an RMS value of noise in the *dZ/dt* signal of 0.6 m/s.

4. Conclusions

In 5 MA/1.8 T helium H-mode ITER scenarios, the minimum value for the outermost plasma radius R_{max} that can be reached without loss of plasma vertical stability is R_{max} = 7.8 m ($k = 2$), if the RMS value of noise in the *dZ/dt* signal is less than about 0.2 m/s in the frequency band [0, 1 kHz]. The corresponding inward shift of the plasma outermost point relative to the nominal position by 0.4 m, reduces the maximum value of the TF ripple from -1.28% to -0.55%. The plasma has a vertical instability growth time of about 30 ms and a stability margin of about 0.17. The value of q_{95} of this plasma is slightly higher than that for the plasma with the nominal shape and position.

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