Study of ELM triggering by axisymmetric in-vessel coils

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1. Introduction

Periodic vertical movements of the plasma have been used to trigger ELMs in a number of tokamaks and can be realized in ITER by the use of the in-vessel coils dedicated for plasma vertical stabilization (VS coils shown in Fig. 1 by the black filled circles). The upper and lower VS coils have 4 turns each. The maximum value of current in each turn is 60 kA and the maximum value of voltage produced by the power supply is 2.3 kV. Earlier studies [1] showed that the plasma periodic vertical movements has potential for ELM triggering to provide tungsten exhaust from the main plasma during the initial phase of ITER operation in H-mode plasmas for which the plasma current will be typically about 7.5 MA.

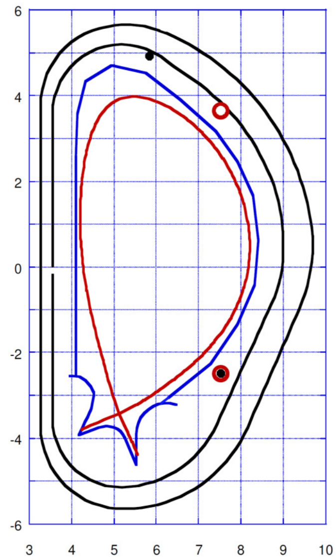

Fig. 1. Location of the VS coils: black filled circles –Baseline coils, red open circles – hypothetical Symmetric coils

On the basis that ELM triggering by vertical plasma position can be explained by the associated oscillation of the plasma current at the plasma edge [2], we use the following indexes to characterize the performance of the ITER VS coils for ELMs triggering:

1) $\Delta I_{ped} / I_{ped}$ -variation of the total current in the pedestal region $0.975 \le \rho \le 1$, where $\rho = \sqrt{\Phi/\Phi_b}$, Φ and Φ_b are the fluxes of toroidal magnetic field inside a given magnetic surface and inside the plasma boundary, respectively, and
2) $\Delta j_{tot}(\rho = 1) / j_{tot}(\rho = 1)$ - variation of the plasma current density at the separatrix.

2. In-vessel coils connected in anti-series (standard configuration)

Simulations of an ITER 7.5 MA / 2.65 T H-mode scenario, performed with the DINA code [3] with feedback and feedforward control of the plasma current, position and shape, have demonstrated promising results of ELMs triggering at a frequency of up to 20 Hz by oscillations of the plasma vertical position using the VS coils connected in *anti-series* (i.e. producing a magnetic field predominantly in the *radial* direction) [4, 5]. It has been shown that with the power supply voltage $V_{VS} = \pm 2.3$ kV, the displacement of the plasma current center, ΔZ_p, is about ±4 cm and this is sufficient to affect significantly the plasma current in the pedestal region leading to the triggering of ELMs. During the oscillations of the current in the VS coils, the plasma current in the region $0.975 \leq \rho \leq 1$ is changed by about 30% (index $\Delta I_{ped} / I_{ped}$) and the plasma current density at the separatrix $j_{tot}(\rho = 1)$ varies by about 60% (index $\Delta j_{tot}(\rho = 1) / j_{tot}(\rho = 1)$). The peak values of the coils current (40 kA) required to achieve this are within the engineering limits.

Two factors lead to the generation of plasma current in the pedestal region during the plasma vertical oscillations by the VS coils in ITER: 1) the up/down asymmetry of the ITER PF system, vacuum vessel and plasma, and 2) the up/down asymmetry of the VS coils in ITER, which are not located symmetrically with respect to the plasma midplane due to integration issues. Further DINA simulations have been carried out to determine to which degree these two factors contribute to the edge plasma induced current. The performance indexes calculated using the up/down asymmetric *Baseline* in-vessel coils adopted in the present ITER design (position shown in Fig. 1 by black filled circles) were compared with those calculated using a hypothetical up/down *Symmetric* in-vessel coils (position shown in Fig. 1 by red open circles). This comparison has shown that it is the up/down asymmetry of the PF system, vacuum vessel and plasma what dominates the generation of edge plasma current and not the asymmetry of the VS coils. For the *Symmetric* coils connected in *anti-series*, the index $\Delta I_{ped} / I_{ped}$ is about 20% and the index $\Delta j_{tot}(\rho = 1) / j_{tot}(\rho = 1)$ is about 50% to be compared with 30% and 50% respectively for the *Baseline* in-vessel coils.

3. In-vessel coils connected in series

Oscillations of the edge plasma current can also be achieved by fast oscillations of the axisymmetric vertical magnetic field, which can be produced in ITER by the in-vessel coils, if they are connected in *series* (for production of a predominantly *vertical* magnetic field). Such oscillations result in oscillations of the poloidal magnetic flux linked with the plasma leading to the oscillations of the edge plasma current (skin current). Unfortunately, the oscillations of the vertical magnetic field lead also to plasma radial oscillations, which significantly reduce the amplitude of the oscillations of the poloidal magnetic flux linked to the plasma, leading to the reduction of the amplitude of the edge plasma current oscillations. In addition the in-vessel coils connected in *series* cannot provide the radial magnetic field required for vertical stabilization, which in this case of the DINA simulations was performed only by the VS1 circuit varying the differential currents in the PF2+PF3 and PF4+ PF5 coils [4, 5]. Taking into account that the plasma radial inward and vertical displacements, caused by the variation of current in the in-vessel coils connected in *series*, complicate plasma vertical stabilization, in the DINA simulations it was assumed a 9 kV engineering limit on the VS1 power supply. It should be noted that in the present design the voltage limit is 6 kV, although, if necessary, it can be increased to 9 kV within the insulation limit for the PF2 – PF5 coils.

Three configurations of the in-vessel coils connected in *series* were used in the DINA simulations:

1) the hypothetical up/down *Symmetric* configuration with 4 turns in the upper coil and 4 turns in the lower coil (position shown in Fig. 1 by red open circles).
2) the present *Baseline* configuration with 4 turns in the upper coil and 4 turns in the lower coil (position shown in Fig. 1 by the black filled circles),
3) the *Modified Baseline* configuration with 4 turns in the upper coil and 2 turns in the lower coil (position shown in Fig. 1 by the black filled circles),

The *Modified Baseline* configuration was chosen for this sensitivity study with the goal of maximization of the performance indexes with the present location of the in-vessel coils.

For a given frequency of the oscillations (20 Hz), the amplitude of the current in the in-vessel coils depends on the chosen voltage produced by the coils power supply (simulated as a chopper). In the DINA simulations the voltage produced by the in-vessel coils power supply was increased (taking into account the 2.3 kV limit) until the plasma vertical stabilization performed by the VS1 feedback circuit is lost. This maximum allowable value the voltage, V_{VS}, and the corresponding amplitude of the current in the in-vessel coils, I_{VS}, are shown in Table 1. Table 1 also shows the values of the performance indexes obtained in the simulations.

Table 1.
Performance indexes characterizing generation of current in the pedestal region (ΔI_{ped} / I_{ped} and $\Delta j_{tot}(\rho = 1)$ / $j_{tot}(\rho = 1)$), peak value of the coil currents (I_{VS}) and values of the applied voltages (V_{VS})

Coils configuration	$\frac{\Delta I_{ped}}{I_{ped}}$	$\frac{\Delta j_{tot}(\rho=1)}{j_{tot}(\rho=1)}$	I_{VS} kA	V_{VS} kV
Baseline coils connected in **anti-series**	30%	60%	40	±2.3
Symmetric coils connected in **anti-series**	20%	50%	35	±2.3
Baseline coils connected in **series**	9%	25%	25	±1.6
Modified Baseline coils connected in **series**	16%	40%	40	±1.15
Symmetric coils connected in **series**	8%	19%	40	±2.3

It should be noted that the oscillations of the vertical magnetic field leads to two effects: 1) oscillations of the plasma current density at *all* values of ρ due to the “frozen” profile of $q(\rho)$ caused by the associated radial plasma position oscillations, leading to periodic adiabatic compression of the plasma, and 2) oscillations of the plasma *skin* current – oscillations of the current in the pedestal region caused by the oscillations of the poloidal magnetic flux linked with the plasma.

The hypothetical up/down *Symmetric* in-vessel coils have the smallest value of the indexes $\Delta I_{ped} / I_{ped}$ and $\Delta j_{tot}(\rho = 1) / j_{tot}(\rho = 1)$ among the configurations with the coils connected in *series*. The present *Baseline* coils have higher values of these indexes than the *Symmetric* coils. The highest values of the indexes have the *Modified Baseline* coils, where the number of turns in the lower coil was reduced from 4 to 2. In this case the performance indexes "$\Delta I_{ped} / I_{ped}$" increases to 16% and the index "$\Delta j_{tot}(\rho = 1) / j_{tot}(\rho = 1)$" increases to 40%. However these values are lower than those obtained in the simulations when the *Baseline* in-vessel coils were connected in *anti-series* (the indexes are 30% and 60%, respectively).

4. Conclusions

The performance indexes characterizing generation of current in the plasma edge during oscillations of coil currents in the in-vessel VS coils have been calculated in DINA simulations of 7.5 MA / 2.65 T H-mode ITER plasmas with feedback control of the plasma current, position and shape, taking into account the design limits imposed on the engineering systems (coils, power supplies, etc.). The simulations have been performed for different configurations of the in-vessel coils for an oscillation frequency of 20 Hz. The highest values of the performance indexes are obtained for the *Baseline* configuration of the in-vessel coils connected in *anti-series* for plasma vertical stabilization: $\Delta I_{ped} / I_{ped} = 30\%$, $\Delta j_{tot}(\rho = 1) / j_{tot}(\rho = 1) = 60\%$. This indicates that the baseline configuration with its foreseen operational mode is optimum for ELM triggering by this technique for low current H-mode ITER operation.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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