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Electromagnetic analyses of Single and Double Null configurations in DEMO device

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The DEMO design has to face a number of challenges. According to the DEMO device limitations, the power load impinging on the Plasma Facing Components (PFCs) in the plasma Single Null (SN) magnetic configuration (which is the reference configuration in ITER) clearly underlines the need to explore alternative divertor concepts. In this paper, a comparison between the Single and Double Null (DN) configurations is proposed. In particular, a comparative electromagnetic analysis of the magnetic configurations is performed in terms of vertical stability (VS) and disruptions in the 2D axisymmetric case.

Keywords: DEMO, tokamak, MHD, vertical stability analysis.

1. Introduction

The development of a conceptual design for a demonstration fusion power plant (DEMO) is a key priority of the recent European fusion program [1]. Compared to ITER, the DEMO design has to face an even higher challenge since it has a fusion power four times higher than the ITER one with a major radius only 1.5 times larger. From a first review of the wall loads and the associated limits in DEMO, the power load impinging on the Plasma Facing Components (PFCs) in the plasma SN configuration clearly underlines a significant challenge that requires substantial engineering efforts as well as the need to explore alternative divertor concepts. Within this framework, an exploration of double null configurations in DEMO seems to be mandatory. In this paper, a comparative electromagnetic analysis of single and double null plasma magnetic configurations is proposed in terms of vertical stability (VS) and disruptions. Indeed, the plasma vertical stability properties and disruptive events are highly relevant to the protection of the PFCs. The comparison between SN and DN configurations is itself not simple requiring a comparable optimization of the machine design. Therefore, a dedicated optimization of the DEMO machine design has been devoted to the DN plasma configuration. Only then, the assessment of the plasma performance for both the plasma configurations has been possible. The proposed electromagnetic analysis, performed in the 2D axisymmetric case, focuses on the plasma vertical stability, with particular emphasis on the plasma passive and active stability parameters, and on the assessment of the plasma behavior in case of major disruption.

2. Plasma magnetic configurations definition

The design of a fusion device is usually performed using systems codes able to assess the engineering and economic viability of a hypothetical fusion power station using simple models of all parts of a reactor system. For DEMO device, the systems code PROCESS [2] is used to identify the relevant parameters assuming a net-electric power output of 500MW. Table 1 reports the main parameters defined by PROCESS for the DEMO Single Null and Double Null baseline 2017 configurations.

Table 1. Main parameters of DEMO SN and DN baseline 2017 defined by PROCESS.

Geometrical parameters		SN	DN
Major radius	R_0 (m)	8.938	8.939
Minor radius	a (m)	2.883	2.883
Aspect ratio	A	3.10	3.10
Elongation	k_{95}	1.65	1.66
Triangularity	δ_{95}	0.33	0.34
Volume	V (m^3)	2266	2350
Magnetic field on axis	B_0 (T)	4.89	4.89
Plasma physics parameters			
Plasma current	Ip (MA)	19.07	19.08
Poloidal beta	β_{pol}	1.141	1.141
Internal inductance	l_i	0.8	0.8

Starting from the systems code run, a 2D device geometry is developed and optimized according to the procedure proposed in [3]. However, a comparison between SN and DN configurations is not simple since the machine design needs to be optimized to a comparable level. Indeed, whilst the DEMO SN baseline design is largely based on ITER and hence already optimized in terms of vertical stability, special attention has been given to reducing the distance between toroidal conducting structures and plasma in the DN configuration. Figure 1 shows both the SN and DN baseline 2017 plasma configurations.

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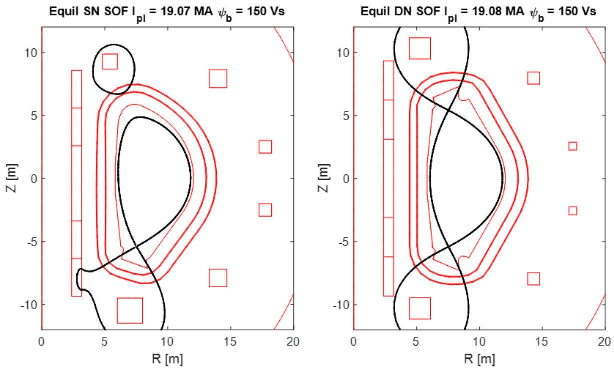

Fig. 1. DEMO SN and DN baseline 2017 plasma configurations.

3. Vertical stability analyses

The electromagnetic analysis of Single and Double Null configurations has been carried out firstly in terms of vertical stability. Indeed, plasma vertical stability parameters are highly relevant for the design of the machine plasma facing components determining the expected vertical displacement of the plasma during transients. Moreover, these parameters fix the maximum tolerable elongation of the plasma for a given geometry and so the performance (i.e. net electric power) of the device for a fixed major radius. The vertical stability analysis of the SN and DN configurations has been performed in terms of passive and active stability parameters. Furthermore, the comparison between SN and DN configurations has been performed at different phases of the plasma scenario, i.e. at the Flat Top (FT) at the reference internal inductance (l_i) value of 0.8 and at the most critical case of l_i=1.

3.1 Passive stability parameters

The main passive stability parameters are the growth rate γ and stability margin m_s [4]. To estimate the effects of the ports, 1/3 of the vessel shells has been removed in correspondence of the port locations.

Table 2 shows that, comparing SN and DN configurations with the same nominal k_{95} and δ_{95}, the stability margins m_s, for which we assume a lower constraint of 0.3, as suggested by the recent TCV H-mode experiments on SN configurations [5], are significantly higher for SN whereas the growth rate is lower. Experiments on a lower bound for the H-mode DN configurations are ongoing and possible reductions of the limits are attended due the lower coupling of the DN with the vertical mode.

Table 2. Passive stability parameters.

	γ	m_s
SN FT @ l_i=0.8	3.19	0.924
SN FT @ l_i=1	6.05	0.583
DN FT @ l_i=0.8	7.34	0.453
DN FT @ l_i=1	7.16	0.492

This is due to the fact that, despite the geometrical optimization for the geometries, in the DN configuration the average distance between plasma and toroidally conducting structures in relevant poloidal regions is higher due to the presence of two divertors. Table 2 also shows that the growth rate of the SN doubles when l_i is increased while in the DN case is kept constant. An interpretation of this is that, in the DN case, an increase of l_i with a fixed plasma shape, turns out in a reduction of the elongation at 95% of the flux at the separatrix (from 1.65 to 1.62). This effect is less evident in the SN configuration.

3.2 Active stability parameters

The main active stability parameters considered here are the maximum vertical displacement of the plasma current centroid Z_{MAX} and the power request on the vertical stabilization systems P_{VS} in case of disturbances.

Three types of disturbance have been considered:

- VDE (an uncontrolled Vertical Displacement Event of 5 cm);
- ELM (Edge Localised Mode, modeled as step variations of β_{pol} and l_i: $\Delta\beta_{pol} = -0.1$,$\Delta l_i = 0.1$);
- MD (Minor Disruptions, modeled as step variations of β_{pol} and l_i: $\Delta\beta_{pol} = -0.1$, $\Delta l_i = -0.1$).

Linear (in case of VDE) and nonlinear (in case of ELMs and MDs) simulations of the plasma response are performed, respectively, with CREATE-L [6] and CREATE-NL [7] codes. In the present analysis, we impose a constant voltage αV_0 on the imbalance circuit, where V_0 is the minimum voltage able to stop the plasma vertical unstable mode for $t \rightarrow \infty$ and $\alpha \in R$ is a constant value, usually fixed equal to 5 or 10. This choice allows to provide also an estimation of the power request in case of best achievable performances.

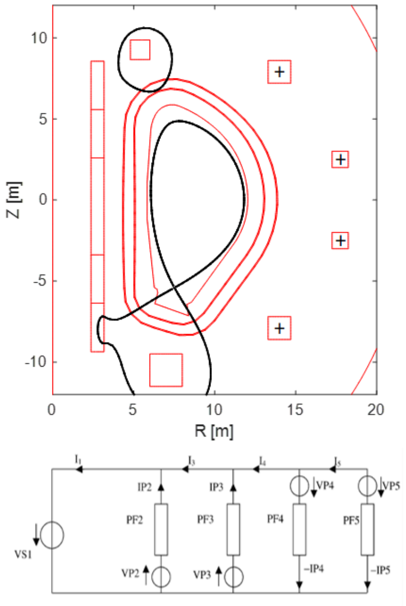

Fig. 2. Vertical stabilization system.

The vertical stabilization system, as ITER VS1 circuit [VS_{SYSTEM}], is a differential (imbalance) circuit composed by the outer equatorial coils PF2, PF3 and PF4, PF5, which varies the radial component of the magnetic field.

Figure 2 highlights the coils of interest in the SN configuration and illustrates the vertical stabilization system.

The simulations have been performed assuming an axisymmetric vacuum vessel with two shells. For the both the SN and DN plasma configurations the vertical stability parameters have been evaluated taking into account the presence of the ports. Table 3 reports the maximum vertical displacement of the plasma current centroid (Z_{MAX}) and the maximum power needed by the vertical stabilization system (P_{VS}) in case of a 5 cm VDE with a constant voltage on the imbalance circuit V=10 V_0.

Table 3. Best achievable performance in case of 5 cm VDE.

Configuration	Z_{MAX} (cm)	P_{VS} (MW)
SN FT @ l_i=0.8	5.31	25.8
SN FT @ l_i=1	5.33	98.0
DN FT @ l_i=0.8	5.52	237.2
DN FT @ l_i=1	5.58	276.7

It is worth to notice that the performances of the SN are much better than the DN configuration due to the lower growth rate. On the other hand, the 5cm VDE is much less likely to happen in a DN, due to up-down symmetry that decouples the radial to the vertical movement. Moreover, the increase of the internal inductance affect marginally the performances of the DN due to the similar values of growth rates of both the DN configurations.

Table 4 shows the results of the nonlinear simulations in case of ELM and MD. The parameters of interest are the initial displacement of the plasma current centroid (Z_0) together with Z_{MAX} and P_{VS}. It is important to underline the difference between Z_0 and Z_{MAX}. Z_0 is the displacement of the plasma current centroid occurring when the disturbance, modeled in terms of plasma parameters step variation, is applied. Once the plasma current centroid has been displaced, a constant multiple of the V0 voltage (in this analysis we use a value of α=10) is applied to the imbalance circuit modeled as a feed-forward control system. In this way, it is possible to evaluate the Z_{MAX}, which is the maximum displacement of plasma current centroid during the whole simulation.

Table 4. Active stability parameters for ELM and MD case.

		SN @ l_i=0.8	SN @ l_i=1
ELM	Z_0 (cm)	1.75	1.62
	Z_{MAX} (cm)	2.29	2.02
	P_{VS} (MW)	17.3	51.6
MD	Z_0 (cm)	-3.15	-1.72
	Z_{MAX} (cm)	-5.23	-2.28
	P_{VS} (MW)	55.6	52.2

The parameters of interest are reported in Table 4 only for the SN configuration since, whereas in the previous VDE case the 5cm initial displacement of the current centroid was imposed, in the latter cases the inherent up-down symmetry of the DN configuration causes a negligible initial displacement of the plasma current centroid despite the presence of the ports. Finally, Figure 3 shows the initial (black) and maximum displaced (magenta) equilibria for the SN configuration with li=0.8 and li=1 only in case of MD.

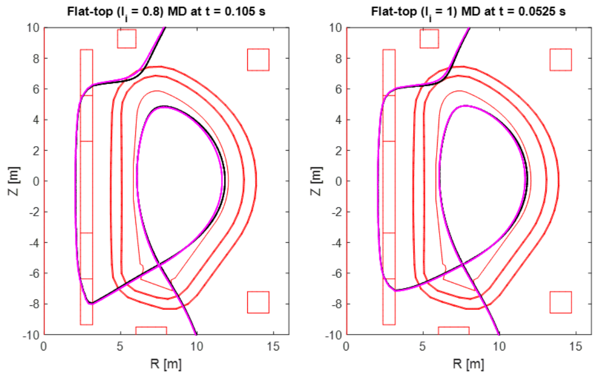

Fig. 3. Initial (black) and maximum displaced (magenta) equilibria for the SN configuration with li=0.8 and li=1 in case of MD.

4. Major disruptions

2D nonlinear simulations of a major disruption have been performed for SN and DN configurations using the CREATE-NL simulation code. The major disruption has been modeled as two sequential phases:

STEP 1: a small vertical kick has been applied to the plasma in order to excite the vertical unstable mode;

STEP 2: an open loop evolution has been performed until $q_{boundary}$ reaches the value of 2 then a thermal quench of 4ms and a current quench of 74ms, modeled in terms of I_{pl}, β_{pol} and l_i variations, have been applied.

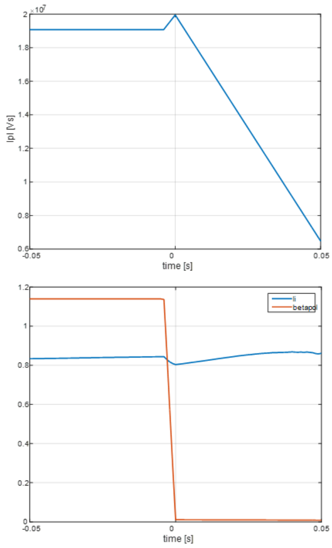

Fig. 4. Time evolution of I_{pl}, β_{pol} and l_i for the SN and DN configurations.

Figure 4 and Figure 5 report, respectively, the time evolution of the plasma parameters I_{pl}, β_{pol} and l_i and some snapshots of the plasma boundary time evolution during a simulated major disruption for both SN and DN configurations. The simulations take into account the presence of the ports.

The results of the simulations describing the evolution of the plasma boundary during a major disruption reported in Figure 5 are in good agreement with the disruption location prediction carried out in [8].

5. Conclusions

In this paper, an electromagnetic analysis of single and double null plasma magnetic configurations for the DEMO device is proposed. The comparison between the two configurations is carried out in terms of vertical stability (VS) and disruptions. In particular, the VS performances of the two plasma configurations are assessed comparing the passive and active stability parameters in the 2D axisymmetric case taking into account the presence of the ports. Linear and non-linear simulations are performed to evaluate Z_{MAX} and P_{VS} in case of VDE, ELMs and MDs. The results of the analysis show that in case of VDE the performances of the SN are much better than the DN case due to the lower growth rate even if the 5cm VDE is much less likely to happen in a DN, due to up-down symmetry that decouples the radial to the vertical movement. In case of ELMs and MDs the inherent up-down symmetry of the DN configuration causes a negligible displacement of the plasma current centroid but it would be necessary to analyze the disturbances response in case of non-ideal DN, as already agreed for the future DEMO activities. Finally, 2D nonlinear simulations of a major disruption are performed for both the SN and DN configurations in order to predict the dynamic plasma evolution and disruption location.

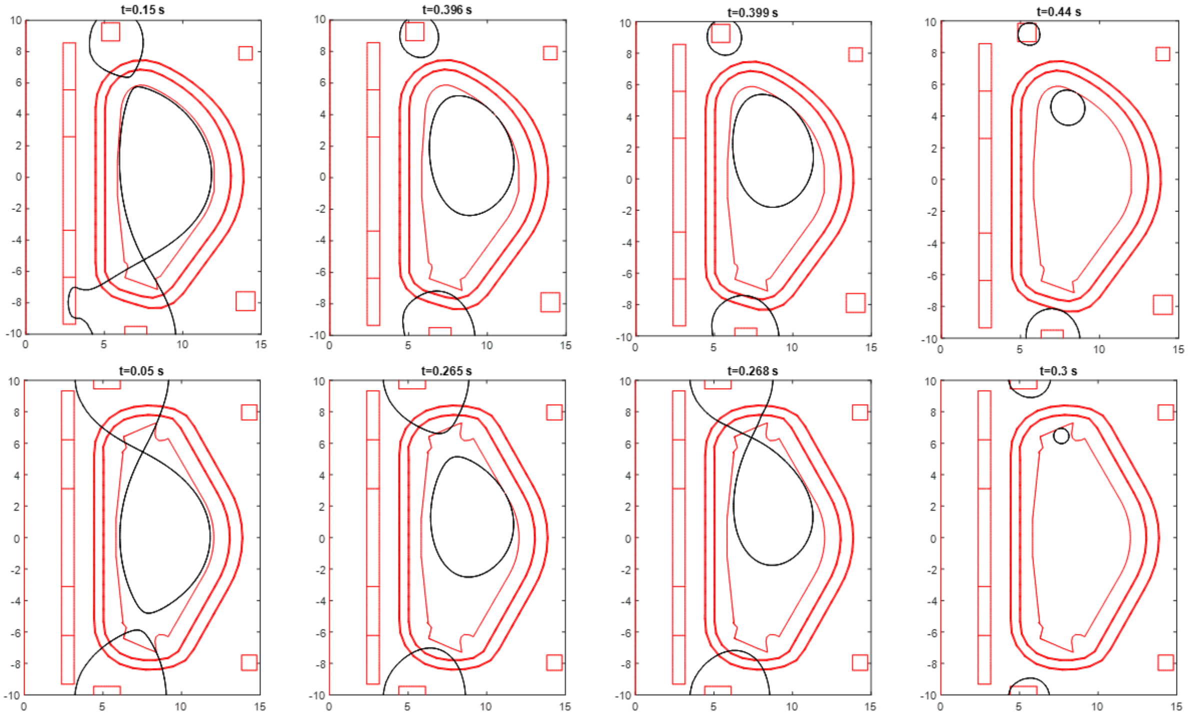

Fig. 5. Plasma boundary time evolution during a major disruption for both SN (upper) and DN (lower) configurations.

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