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Evaluation of feasibility and costs of alternative magnetic divertor configurations for DEMO

R. Ambrosino[1,2], A. Castaldo[1,2], S. Ha[3], V.P. Loschiavo[2], S. Merriman[3], H. Reimerdes[4]

[1]*University of Naples Federico II, via Claudio 21, I-80125, Napoli, Italy*
[2]*CREATE-ENEA, via Claudio 21, I-80125, Napoli, Italy*
[3]*CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*
[4]*Ecole Polytechnique Federale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland*

The European roadmap to the realisation of fusion energy has identified a number of technological and scientific challenges towards the development of a DEMO reactor. Mission 2 'Heat-exhaust systems' includes the investigation of alternative divertor configurations such as the snowflake, X and super-X divertors as a reliable solution for the power exhaust problem. This paper, starting from the geometrical description of a conventional European DEMO scenario with an aspect ratio of 3.1 and a reference Single Null configuration, firstly illustrates the objectives, the figure of merits and the constraints considered in the design of alternative configurations. DEMO descriptions for Double Null, Snowflake, X-divertor and Super-X configurations optimizing the plasma shape, the machine geometry and the PF coil system will be proposed. A comparison of costs and benefits of the various configurations is given, with particular reference to the power exhaust issues.

Keywords: DEMO tokamak, alternative divertor concepts, optimization problem

1. Introduction

The development of a reliable solution for the power and particle exhaust in a reactor is recognized as a major challenge towards the realization of DEMO [1]. To mitigate the risk that the conventional divertor solution adopted for ITER will not extrapolate to a robust fusion power plant, the European fusion consortium (EUROfusion) has identified a number of technical challenges and defined eight different missions to face them. Mission 2 'Heat-exhaust systems' addresses the challenge of reducing the heat load on the divertor targets. Part of this mission is an assessment of several alternatives to the conventional divertor concept, including 'Alternative Magnetic Configurations' such as Double Null, Snowflake, X and Super-X divertors.

The Double Null (DN) configuration produces a second first order null point in the poloidal magnetic field in the upper part of the main chamber. This diverts a significant fraction of the heat load to the inner divertor of a SN to a second target at larger radius, which increases the wall interaction area and decreases the peak heat load reaching the targets (compared to the SN case). However, it also decreases the connection length to the target.

The X divertor (XD) concept [2] seeks to flare the flux surfaces near the divertor targets. The flaring is obtained by decreasing the poloidal magnetic field and, hence the poloidal flux expansion at the target, f_{exp}, typically using two dedicated divertor coils for each target.

The Super-X divertor (SXD) concept seeks to increase the total flux expansion towards the target. This is achieved by increasing the major radius of the divertor targets, R_t [3]. The maximum value is usually limited by the toroidal field coils. Increasing R_t allows for an increase of the wetted area, without decreasing the grazing angle of the field lines at the target.

The Snowflake divertor (SFD) concept seeks to decrease the poloidal field in the vicinity of the null point by introducing a second order null point [4]. This splits the separatrix around the null into six legs with two enclosing the confined plasma and four divertor legs. Since the exact SFD is only a point in the operational plane any real configuration is characterized by two nearby first null-points (x-points). The resulting configuration may have different topologies referred to snowflake plus (SFD+) and snowflake minus (SFD-) depending on whether the second x-point is located in the private or common flux region of the primary, active x-point, respectively.

In this paper, DEMO descriptions for Double Null, Snowflake, X-divertor and Super-X configurations will be proposed optimizing the machine geometry (first wall, divertor structure, vessel and TF coil shells) and the PF coil system to reduce forces on the coil system to tolerable values. The feasibility of Alternative Configurations (ACs) on DEMO is analysed in terms of possible engineering solutions to build such a device and their costs. This study distinguishes between constraints that must be met and costs that are compared to the costs of the reference DEMO divertor solution.

Our study shows that ACs such as Double Null, Snowflake, X and Super-X divertors, while being more demanding on the PF coil system and generally more expensive than a standard single null, can be realized on DEMO provided that the magnetic configuration, the machine geometry and the PF coil system are optimized.

This paper is organized as follows: Section 2 illustrates the constraints and the design procedure of the DEMO descriptions for the ACs and Section 3 describes the main features of the optimized ACs on DEMO. Finally, some conclusions are drawn in Section 4.

Email address: antonio.castaldo@unina.it

2. Problem definition

A conventional DEMO design based on a SND configuration serves as a reference, which the alternative solutions are compared against. The systems code PROCESS [5] is used to identify DEMO relevant parameters for a device with a net-electric power output of 500MW. In Fig.1 the poloidal layout of the SND reference has been reported while key machine and plasma parameters are given in Table 1 [6].

Table 1: DEMO SN reference scenario for a net-electric power output of 500MW.

Machine parameters		
Major radius	R_0 (m)	8.77 m
Aspect ratio	A	3.10
Elongation	κ_{95}	1.55
Volume	V	2214 m^3
Magnetic field on axis	B_0	5.80 T
Plasma current	I_P	20.3 MA

In the following we describe the constraints and the proposed optimization procedure that, starting from a reference SN configuration, is able to produce ACs reducing the PF currents and the mechanical loads to acceptable values.

2.1 Optimization procedure

The optimization procedure, which is carried out for each AC, is an iterative procedure composed of two main steps. In the first step, given a reference plasma shape that features the main characteristic of an alternative divertor concept, the geometry of the machine (first wall, vessel and TF coil) is optimized by means of the NOVA optimization code. In the second step an optimization of the PF coil system (number, position and current in the PF coils) is performed in order to find a finite set of PF coils able to maximize the flat top flux swing of the respective alternative configuration until the reference value of 330Vs imposed for the SND baseline is reached while satisfying the PF coil currents and vertical forces constraints [7]-[8].

2.2 Constraints

PF coil current

Poloidal coils cross-sections shall be determined assuming a current density limit of 12.5 MA/m^2.

Magnetic field

The maximum field at the location of the PF and CS coils shall not exceed 12.5 T.

Vertical Forces

- Maximum vertical force on a single PF < 450 MN.
- Maximum vertical force on the CS < 300 MN.
- Maximum separation force in the CS < 350 MN.

TF coils

- A 18 TF coil cage shaped to keep ripple below 0.6%.
- Presence of TF shells not up-down symmetric.

Divertor

- Distance between divertor plates and X-point > 1m.
- Minimum grazing angle of magnetic field lines at the target 1.5 deg.

The assumed constraints are not inevitable engineering limits and may vary depending on design details and technologies that are used. They should be understood as reasonable numbers and enable a fair comparison of the alternative concepts with the conventional divertor solution.

3. Alternative divertor configurations

In this section the optimized alternative configurations for DEMO are illustrated. The alternative configurations, designed with the same major radius, aspect ratio, elongation and at the same plasma current parameters as the reference single null, feature the main characteristic of each alternative divertor concept, as shown in Figure 2. The configurations have been designed with external coils only. The PF coil systems of the SN, DN and SX configurations are composed of 11 independent coils while for the XD and the SF a redundant segmentation of the central solenoid has been imposed to increase the flat top flux swing.

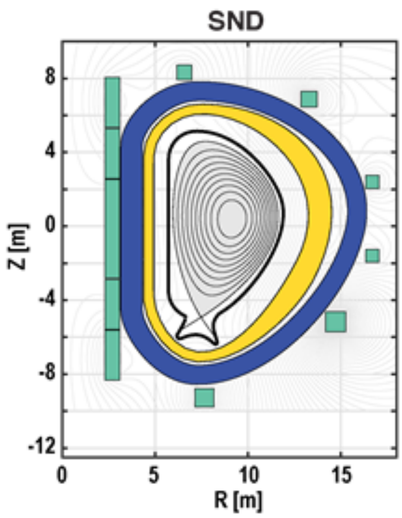

Fig.1 DEMO Single Null reference.

Table 2 reports the main geometric characteristics of the ACs, evaluated at Start of Flat-top (SOF), divided in:

Shape parameters

- $\kappa_{95\%}$: plasma elongation at 95% of the flux difference between the axis and the separatrix.
- $\delta_{95\%}$: plasma triangularity at 95% of the flux difference between the axis and the separatrix.
- V_{pl} : plasma volume.
- V_{TF}/V_{pl} : the ratio of the volume inside the inner shell of the TF coil and the plasma volume.

X-point parameters

R_{xpt}: major radius of the X-point.

Email address: antonio.castaldo@unina.it

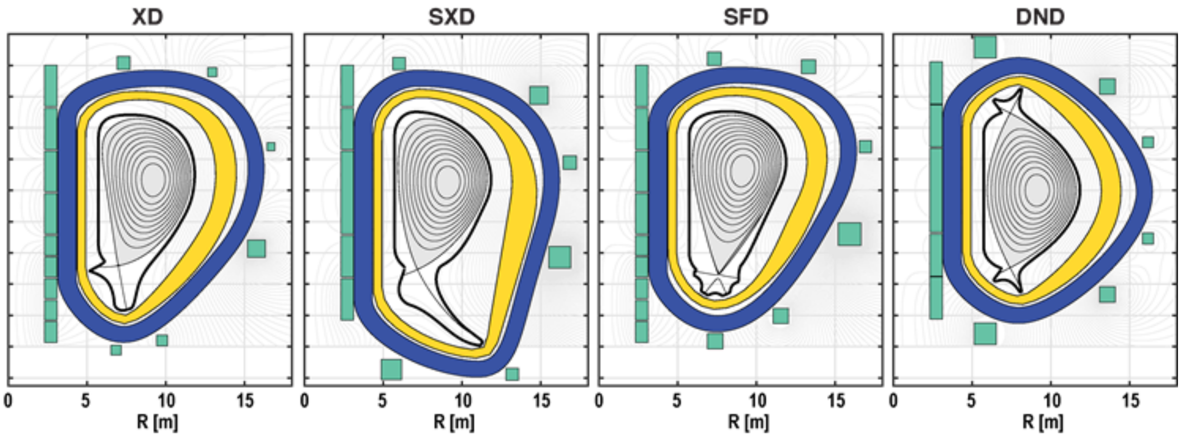

Fig.2 DEMO alternative divertor configurations

Table 2. Geometric parameters of the DEMO configurations

		SND		XD		SXD		SFD		DND
Shape	Elongation $\kappa_{95\%}$	1.55		1.57		1.56		1.55		1.55
	Triangularity $\delta_{95\%}$	0.34		0.27		0.34		0.25		0.34
	Volume V_{pl} $[m^3]$	2050		2100		2080		2060		2020
X-point	R_{xpt} [m]	7.47		6.98		7.17		7.64		7.4
	Gradient $\lvert\nabla B_{p,xpt}\rvert$ [T/m]	0.434		0.322		0.287		0.016		0.557
	V_{SOL} (ρ=1mm) [m]	5.62		8.05		7.33		17.3		3.78
	V_{SOL} (ρ =3mm) [m]	15.1		21.3		19.6		36.2		10.1
Targets		SN		XD		SXD		SFD		DND
		in	out	in	out	in	out	in	out	out
	L_p [m]	18.1	8.5	17.7	10.8	17.7	13.3	18.1	9.5	8.3
	$L_{\|\|}$ (ρ =1mm) [m]	215	125	237	236	238	217	464	344	104
	$L_{\|\|}$ (ρ =3mm) [m]	195	105	206	206	210	190	325	223	90
	$f_{x,t}/f_{x,min}$	1	1	1	1.29	1	1	1	1	1
	$f_{x,t}$	5.7	3.8	6.53	12.6	9.05	2.25	10.9	11.3	2.7
	R_t/R_x	0.85	1.11	0.81	1.08	0.87	1.51	0.8	1.16	1.1
	γ_t [Deg.]	1.5	1.7	1.5	1.5	1.54	1.58	1.52	1.54	1.51
	β_t [Deg.]	28.4	20.5	32.5	89	53	11.8	72.4	82.8	13

- **Gradient $\lvert\nabla B_{p,xpt}\rvert$:** gradient of the poloidal magnetic field at the X-point.
- $\boldsymbol{V_{SOL}}$**:** volume of the Scrape Off Layer (SOL) from the separatrix to the flux surface with an outboard midplane separatrix distance of $\rho = 1mm$ and $\rho = 3mm$.

Target parameters

- $\boldsymbol{L_p}$**:** poloidal connection length from the outer equatorial plane to the target.
- $\boldsymbol{L_{||}}$**:** parallel connection length from the outer equatorial plane to the target on the flux surface with an outboard midplane separatrix distance of $\rho = 1mm$ and $\rho = 3mm$.
- $\boldsymbol{f_{x,t}/f_{x,min}}$**:** the ratio of the flux expansion at the target and the minimum flux expansion along the divertor leg.
- $\boldsymbol{f_{x,t}}$**:** flux expansion at the target.
- $\boldsymbol{R_t/R_x}$**:** the ratio of the major radii of the target and the X-point.
- $\boldsymbol{\gamma_t}$ **:** grazing angle of the magnetic field line at the target plate.
- $\boldsymbol{\beta_t}$ **:** poloidal angle between the separatrix and the target plate.

A preliminary vertical stability analysis has been performed on the configurations at flat top showing

Email address: antonio.castaldo@unina.it

growth rate in the interval $[1.7\ 5]s^{-1}$ and a stability margin $\gg 0.3$.

Table 3 reports the main costs of the ACs. The main constraints for the definition of the alternative configurations are related to the vertical forces on the poloidal field coils and the central solenoid. While the margin with which the constraints are met will certainly affect the costs, the total current request and, hence, the volume of the required coil systems is assumed to be the main cost driver. The current is weighted with the radius of the coil to yield a proxy for the volume and, hence, cost of the coil system. The ratio of TF coil volume and the plasma volume is a proxy for the cost of the TF coils. The normalisation accounts for differences in the expected fusion power output of configurations with different plasma volume. Similarly, the flux swing that is available for the flat top will affect the (average) fusion power of a pulsed DEMO.

Table 3. Geometric parameters of the DEMO configurations

	SN	XD	SX	SF	DN
Flux Swing [Vs]	240	185	200	180	220
V_{TF}/V_{pl}	3.5	3.6	4.4	3.6	3.6
$\Sigma R_{PF/CS} \lvert I_{PF/CS} \rvert_{max}$ [$mMAturns$]	690	665	1016	970	744

4. Conclusion

In this paper it is shown that Double Null, Snowflake, X and Super-X divertors, while being more demanding on the PF coil system with respect to a standard single null, can be realized on DEMO as alternatives to the conventional single null divertor. Meeting constraints on magnetic fields and forces requires an optimization of the magnetic configuration, the machine geometry and the PF coil system. On the one hand a reduction of the flat top flux swing is noted is almost all the cases up to the 25% of the reference Single Null value. On the other hand, potential benefits of the ACs arise from the modified magnetic geometries, e.g. in terms of connection length and flux expansion.

It is important to remark that the presented set of configurations own all the physic features of the alternative configurations. However, additional engineering issues need to be considered in order to determine the engineering feasibility of the ADCs for DEMO. This includes the analysis of:

- port location and remote maintenance (RM).
- structural analysis of the TF coils.
- definition of the in-vessel components compatible with the Tritium Breeding (TB).
- thermal load analysis on the PFCs (first wall and divertor).
- vertical stability analysis
- sensitivity analysis and shape controllability of the configurations.

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References

[1] Fusion Electricity – A roadmap to the realisation of fusion energy, November 2012 (http://users.euro-fusion.org/iterphysicswiki/images/9/9b/EFDA_Fusion_Roadmap_2M8JBG_v1_0.pdf)

[2] M. Kotschenreuther, et al., *Phys. Plasmas* **14** (2007) 72502.

[3] P.M. Valanju, et al., *Phys. Plasmas* **16** (2009) 056110.

[4] D.D. Ryutov, *Phys. Plasmas* **14** (2007) 064502

[5] P.J. Knight, 'A user guide to the PROCESS systems code', CCFE report (2013).

[6] H. Reimerdes et al. 'Towards an assessment of alternative divertor solutions for DEMO', 3rd IAEA DEMO programme workshop, 11-15 May 2015, Hefei, China

[7] R. Albanese, R. Ambrosino, A. Castaldo, V.P. Loschiavo "Optimization of the PF coil system in axisymmetric fusion devices ", Fusion Eng. Des., Vol. 133, August 2018, pp. 163-172

[8] R. Albanese, R. Ambrosino, M. Mattei, "CREATE-NL+: A robust control-oriented free boundary dynamic plasma equilibrium solver", Fusion Eng. Des., 96-97, pp. 664-667(2015)