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# Magnetic configurations and electromagnetic analysis of the Italian DTT device

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The Divertor Tokamak Test (DTT) facility has been launched to investigate alternative power exhaust solutions for DEMO. DTT should offer sufficient flexibility to be able to incorporate the best candidate divertor concept (e.g. conventional, snowflake, super-X, double null, liquid metals). In this paper, the revised up-down symmetric DTT device is presented. The up-down symmetrisation of the device allows the introduction of an additional divertor and the realization of double-null configurations with a plasma current up to 5.5MA and, at the same time, it has an impact on the costs, for which a slight revision of the main parameters has been considered. The DTT alternative magnetic configurations, such as Double Null, SnowFlake, Super-X, Double Super-X and Single Null with reverse triangularity, guarantee suitable constraints on the plasma-wall distance and the plasma elongation. The feasibility of the configurations is evaluated in terms of maximum vertical forces and currents on the PF coils along the scenarios.

Keywords: tokamak, plasma magnetic scenarios, alternative divertor concepts

## 1. Introduction

The main objective of the Divertor Tokamak Test (DTT) facility is to host experiments addressed to the solution of the power exhaust issues in view of DEMO [1]. This derives from the need to develop integrated and controllable exhaust solutions including plasma, PFCs, control diagnostics and actuators, using experiments, theory and modelling, so as to mitigate the risk that conventional divertor might not be suitable for DEMO [1]. The DTT project has been proposed in 2015 by about one hundred scientists from several Italian institutions with the support of scientists from various international labs with the publication of the DTT facility proposal [2] and a special issue on Fusion Engineering Design [3].

In the last year the DTT Team has refined the project, also in the light of suggestions of EUROfusion, defining an up-down symmetric DTT device so as to allow for an additional, upper divertor and, thereby up-down symmetric configurations. The revision process necessitated a slight reduction of the major and minor radius (currently of 2.10m and 0.65m, respectively) and plasma current (presently 5.5 MA) leaving the magnetic field unaltered (6.0 T).

Starting from a reference DTT scenarios in [2]-[6], conventional Single Null (SN), Double Null (DN) and SnowFlake (SF) plasma scenarios for the symmetrized DTT device have been produced optimizing the plasma shape and the currents on the PF coils. Flat-top snapshots for Double Super-X (DSX) and Single Null with negative triangularity (SN-NT) have been also investigated in order to demonstrate the flexibility of the machine and its PF coil system to achieve different alternative divertor concepts.

The paper is organized as follows: in Section 2 a description of the DTT PF coil system is proposed; in Section 3 the reference single null and alternative DTT plasma scenarios are presented. Section 4 illustrates the main conclusions of the paper.

## 2. Machine configuration and constraints

The last version of the DTT device has been designed with a major radius $R_0 = 2.10$ m and an aspect ratio $AR = 3.2$. Two stainless steel vessel shells of 1.5 cm have been assumed with two toroidally discontinuous stabilizing plates of 3 cm placed between the first wall and the in-vessel Vertical Stability (VS) coils (*InVessVSU-InVessVSL*), as illustrated in Figure 1.

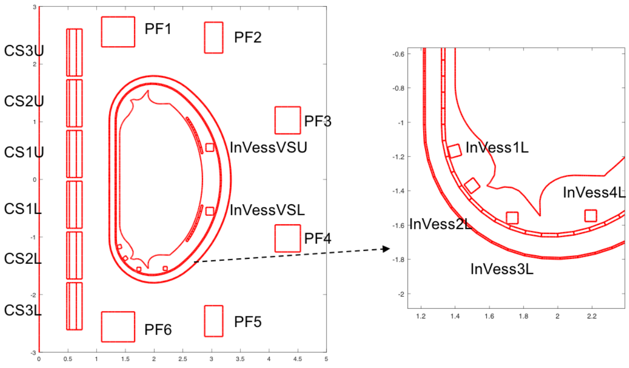

Fig. 1. Poloidal section of the DTT device.

### 2.1 PF coil system

The DTT PF coils system, illustrated in Figure 1, is composed of six independent CS coils with a graded solution *CS3U – CS2U – CS1U – CS1L – CS2L - CS3L;* six independent PF coils *PF1 – PF6*, four independents lower divertor coils *InVess1L – InVess4L* and two

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independents in-vessel (VS) coils *InVessVSU – InVessVSL*.

Each CS circuit is composed by the series of 3 coils at high, medium and low poloidal field. It allows to maximize the currents in the circuits up to 28 kA for the CS and 26.6 kA for the PF circuits.

## 2.2 Plasma Scenario Constraints

Hereafter we summarize the main specifications used for the design of the DTT plasma scenarios.

*Magnetic field*

The maximum magnetic field at the location of the CS coils shall not exceed ~ 14 T in the high field region, ~ 12 T in the medium field region and ~ 8 T in the low field region. The constraint related to the magnetic field on the PF is ~ 6 T.

*Vertical Forces*

The force limits on the PF coils are:

- The maximum vertical force on the CS stack in DTT should not exceed 17 MN;
- The maximum separation force in the CS stack should not exceed 30 MN;
- Maximum vertical force on a single PF coil should not exceed 40 MN at the low field PF coils (PF2-PF5) and it is 26MN for PF1 and PF6.

*Plasma*

- Minimum clearance of 30 mm between the plasma last closed surface and the first wall
- Maximum plasma current of 5.5 MA
- Plasma shape parameters similar to present EU DEMO: $R_0$+/a≈3.2, $k_{95\%}$≈1.65-1.7
- Flux swing at flat top compatible with a pulse duration of about 100 s
- Ripple limited to 0.5%, yielding $R_0$+a<2.75 m
- Vertical stability margin $m_s$>0.3, thus $m_s$>>0.3 at high poloidal beta

# 3. Magnetic plasma scenarios

## 3.1 Single Null

The scenario has been designed to form a X-point configuration in H-mode with a plasma current $I_P$ = 5.5MA with a discharge duration around 90s from the breakdown to the end of flat top and an X-point configuration sustained for around 70s (much longer than the plasma resistive time) equals to a flat top flux-swing of around 8.1 Vs.

Table 1 shows the main plasma parameters of the DTT reference Single Null scenario, obtained using the CREATE-NL code [4], as illustrated in Figure 2. The main plasma parameters of the SN flat top configuration are reported in Table 2.

After the breakdown, $I_P$ rises up to 3.0 MA in Δt = 15s; during this phase, the plasma evolves with a circular to elliptical shape, leaning on the inboard side of the first wall. Between t = 15s and t = 22s the plasma current ramps up to 4.3 MA achieving the X-point configuration. In this scenario the plasma remains limited for about 15s.

Between t = 22s and t = 27s, the plasma current achieves its target value of 5.5 MA, while $\beta_p$ remains very low. The boundary flux $\Psi_{SOF}$ at start of flat top (t = 27s) is calculated assuming an Ejima coefficient $C_{EJIMA}$ = 0.35 and a breakdown flux $\Psi_{BD}$ = 16.2Vs [5].

At t = 28s full additional heating is assumed, causing an increase of the internal kinetic energy on a time scale longer than the plasma energy confinement time. After t = 36s, all plasma physical parameters are assumed nearly constant up to the end of the current plateau at t = 90s.

At the end of flat top, the plasma is no longer heated and a controlled ramp-down phase similar to the JET tokamak follows, in which the plasma current decreases at the rate of ~100 kA/s (more than 400 kA/s if needed in emergency cases) while keeping a single null configuration at low beta, low elongation, and controlled density (no more than 50% of Greenwald limit) till about 200 kA.

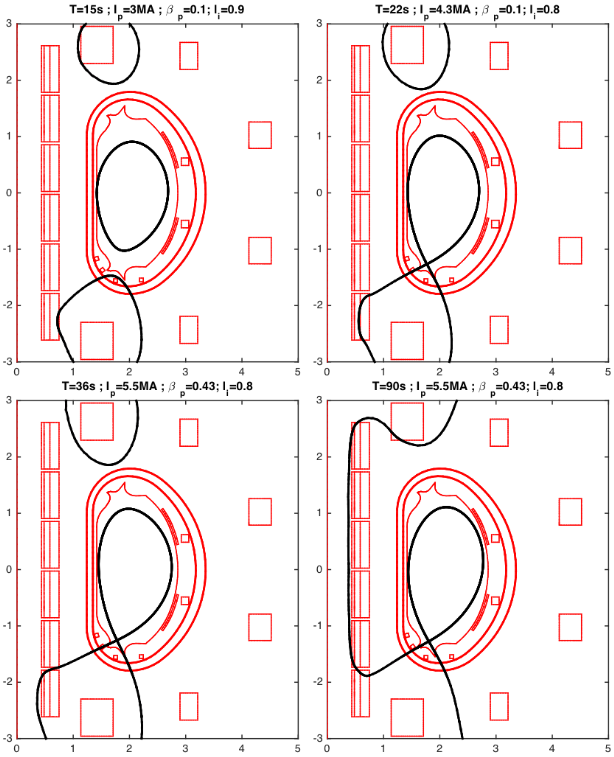

Fig. 2. Snapshots of the SN scenario at t=15s, 22s, 36s, 90s

## 3.2 Double Null

The up-down symmetrisation of the DTT device has made it possible to obtain a flat top DN configuration with $I_P$ = 5.5 MA and a flat top flux swing of 7.9 Vs. The reference DN scenario has been designed assuming the formation of both X-points at 22s with a plasma current of 4.3MA. The LH transition occurs in the time interval [28 – 36]s and the duration of the flat top is ~55s, similar to the SN scenario. In Figure 3 the DN scenario snapshots are illustrated while the main plasma flat top plasma are reported in Table 2.

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Table 1. Main plasma parameters of the SN scenario

| Time | 15 | 22 | 27 | 28 | 36 | 88 | 90 |
|---|---|---|---|---|---|---|---|
| **Ipl [MA]** | 3.00 | 4.30 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 |
| **Betapol** | 0.10 | 0.10 | 0.10 | 0.10 | 0.43 | 0.43 | 0.43 |
| **Li** | 0.90 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| **Boundary flux [Vs]** | 9.42 | 7.24 | 4.87 | 4.50 | 2.64 | -5.13 | -5.48 |
| **Raxis - node [m]** | 2.09 | 2.11 | 2.13 | 2.13 | 2.17 | 2.17 | 2.17 |
| **Zaxis - node [m]** | -0.02 | 0.00 | 0.02 | 0.02 | 0.04 | 0.04 | 0.08 |
| **Rbound - node [m]** | 1.42 | 1.78 | 1.80 | 1.80 | 1.78 | 1.80 | 1.80 |
| **Zbound - node [m]** | 0.00 | -1.26 | -1.24 | -1.24 | -1.26 | -1.27 | -1.27 |
| **R [m]** | 2.05 | 2.06 | 2.10 | 2.10 | 2.10 | 2.10 | 2.11 |
| **a [m]** | 0.63 | 0.63 | 0.65 | 0.65 | 0.65 | 0.65 | 0.67 |
| **Btor_tot at Mag. Axis [T]** | 6.29 | 6.35 | 6.38 | 6.38 | 6.22 | 6.23 | 6.20 |
| **q_95** | 3.54 | 3.12 | 2.50 | 2.50 | 2.54 | 2.47 | 2.57 |
| **elongation (k)** | 1.53 | 1.79 | 1.79 | 1.79 | 1.80 | 1.80 | 1.79 |
| **k_95** | 1.49 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.66 |
| **Triangularity (Delta)** | 0.13 | 0.28 | 0.34 | 0.34 | 0.33 | 0.21 | 0.23 |
| **Delta_95** | 0.11 | 0.19 | 0.24 | 0.24 | 0.23 | 0.13 | 0.14 |
| **Volume [$m^3$]** | 23.89 | 26.93 | 28.69 | 28.69 | 28.79 | 28.68 | 29.99 |

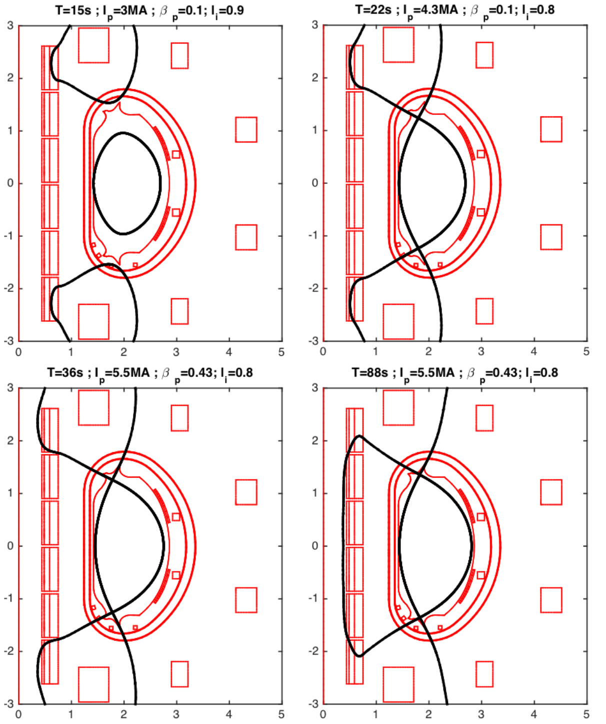

Fig. 3. Snapshots of the DN scenario at t=15s, 22s, 36s, 88s

### 3.3 Snowflake

The DTT geometry and PF coils system have made it possible to obtain a SF configuration at 4.5 MA with a flat top flux swing of ~8.5 Vs and a flat top duration ~45 s, due to currents and vertical forces limitations.

The reference SF scenario coincide with the SN case up to 22s. Then, a single null shape is maintained for the ramp up and the LH transition while creating a lower secondary X-point in the vicinity of the vessel shells. At 34s, after the LH transition, a migration towards a SF is imposed in a time interval of 3s. The flat top configuration is a $SF^-$ with a null points distance ~*30cm* and a poloidal magnetic flux difference within $15 mVs$. However, with the use of the internal coils is possible to locally modify the poloidal magnetic field in order to define ideal SF, $SF^+$ and X-divertor configurations within the limits of the accuracy of the diagnostic system [6].

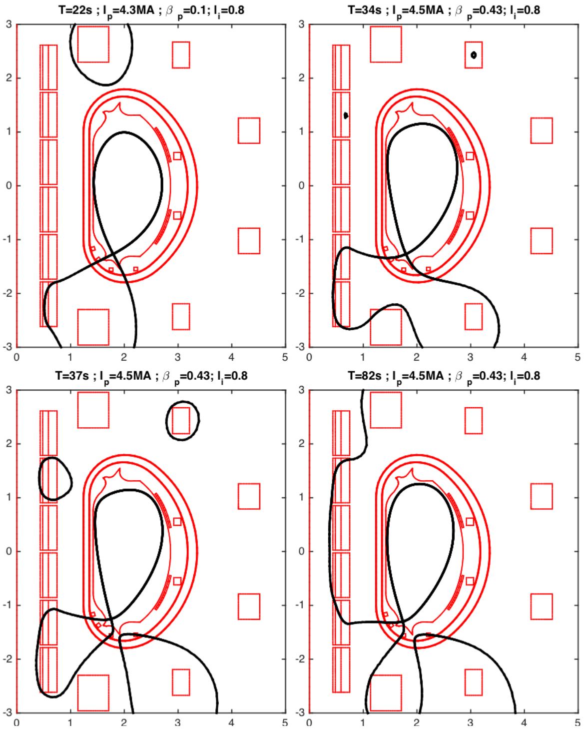

Fig. 4. Snapshots of the DN scenario at t=22s, 34s, 37s, 82s

In Figure 4 the SF scenario snapshots are illustrated while the main flat top plasma parameters are reported in Table 2. It is worth to notice that the $SF^+$ configurations illustrated in Figure 5, derived with slight PF current variations from the $SF^-$ scenario, can also be regarded as Super-X configurations provided the divertor plates are

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placed at a larger major radius $R_t$. Under these premises and in agreement with the space available in the divertor region, this DTT device can achieve a Super-X plasma scenario at 4.5MA with a flat top flux swing similar to the SF case and a maximum toroidal flux expansion $R_t/R_x \approx 1.35$ with an outboard leg length of $0.7m$. It is important to recognize that the high poloidal field at the target of the present configuration may annul part of the reduction of the toroidal field due to the major radius; hence a detailed analysis of the effect of the two close nulls on the total flux expansion will be considered.

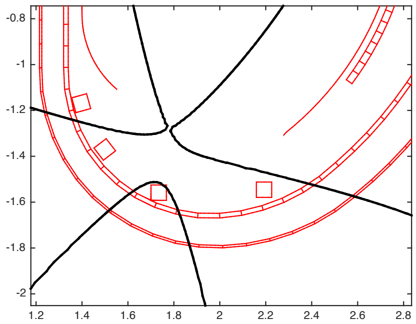

Fig. 5. SF plus configuration at 4.5MA

The design of proper divertors for the SF configuration and its possible variations is an ongoing activity.

Table 2. Main parameters of SN, DN and SF at flat top

| | SN | DN | SF |
|---|---|---|---|
| **Ipl [MA]** | 5.50 | 5.50 | 4.50 |
| **Rpl [m]** | 2.12 | 2.11 | 2.10 |
| **Zpl [m]** | 0.01 | 0.00 | 0.20 |
| **Raxis - node [m]** | 2.17 | 2.17 | 2.14 |
| **Zaxis - node [m]** | 0.04 | 0.00 | 0.25 |
| **Rbound - node [m]** | 1.78 | 1.78 | 1.75 |
| **Zbound - node [m]** | -1.26 | -1.26 | -1.25 |
| **R [m]** | 2.10 | 2.10 | 2.08 |
| **a [m]** | 0.65 | 0.65 | 0.63 |
| **Btor_tot at Mag. Axis [T]** | 6.22 | 6.22 | 6.21 |
| **betan** | 1.17 | 1.16 | 0.94 |
| **q_95** | 2.54 | 2.76 | 3.35 |
| **elongation (k)** | 1.80 | 1.94 | 1.91 |
| **k_95** | 1.67 | 1.72 | 1.72 |
| **Triangularity (Delta)** | 0.33 | 0.50 | 0.24 |
| **Delta_95** | 0.23 | 0.31 | 0.12 |
| **Volume [m$^3$]** | 28.79 | 29.26 | 28.08 |

### 3.4 Additional alternative configurations

The symmetrized DTT geometry allows the design of additional alternative configurations such as DSX and SN-NT, as illustrated in Figure 6.

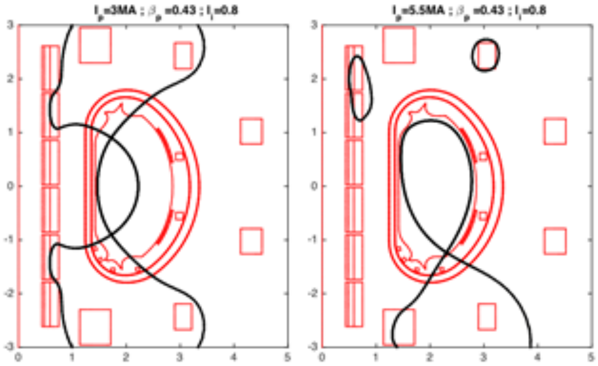

Fig. 6. DSX at 3MA and SNrev at 5.5MA

The SN-NT configuration at flat top can be achieved with a plasma current of 5.5 MA, a flat top flux swing of about 9.0 Vs and a lower triangularity of -0.26.

The DSX configuration can only be achieved with a maximum plasma current of 3 MA and a flat top flux swing of about 14 Vs. The need of having reasonably large values of the toroidal flux expansion $R_t/R_x \approx 1.36$ and the outboard leg length ($leg_{out} \approx 0.90$ m), forces the plasma to have a high elongation and a reduced value of the minor radius.

Such a plasma could not be stabilized vertically with the reference geometry of the passive structures. For this reason, we have envisaged the possibility of having a first wall closer to the plasma. This structure would also be accompanied by a proper divertor structure, which is not represented here.

## 4. Conclusions

In this paper the reference SN, DN and SF scenarios for the symmetrized DTT device have been presented. The possibility to realize SX, DSX and SN-NT has been also investigated. The presence of the stabilizing passive plates outboard connected to the vacuum vessel via sidewalls allows good breakdown and vertical stability performance [7]. A revision of the present results is under analysis in view of a detailed definition of the divertor structures.

## Acknowledgments

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