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Divertor configuration with two nearby poloidal field nulls: modelling and experiments for EAST and JET tokamaks

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Abstract. Alternative magnetic configurations may enable tokamak operation with a lower peak heat load than a standard Single Null (SN) divertor. This papers reports on the modelling, creation and control of one of such alternatives for EAST and JET tokamaks: a divertor configuration with two nearby poloidal field nulls. The secondary null could be moved around to change its distance from the first null and to form a magnetic configuration that features either contracting or flaring geometry near the plate. Preliminary experiment with the second null forming a configuration with significant distance between the two nulls and a contracting geometry near the target plates have been performed for both tokamaks. Experimental results of ohmic (JET) and low/high confinement (EAST) two-null divertor and SN discharges will discussed. Future experiments will be devoted to vary the distance between the two nulls in high confinement (H-mode) seeded discharges for both tokamaks.

1. Introduction

Heat and particle loads on the plasma facing components are among the most challenging issues to be solved for a reactor design [1, 2]. One approach to handling the heat exhaust power is to use alternative magnetic configurations, such as Snowflake Divertor (SF) [3] and recently described divertor with a strong flux flaring in a single divertor leg [4, 5]. A divertor with a strong flux flaring in a single divertor leg [4, 5] places the second x-point near plate, causing flared field lines there, which spreads the heat over a larger area and increases the line connection length. The SF configuration is characterized by a second-order null (x-point) in the poloidal magnetic field (B_P), where both B_P itself and its and its spatial derivatives vanish. This splits the separatrix near the null into six segments: two of them enclose the confined plasma and four lead to the machine wall (the divertor legs). The poloidal cross-section of the obtained magnetic flux surfaces with a hexagonal null-point has the appearance of a snowflake. Theoretical studies indicate that the SF magnetic geometry may lead to both higher power losses during scrape-off layer (SOL) transport and an increased plasma wetted area of the wall [6]. As it was realized in the first assessment of the SF [3], an exact SF configuration is topologically unstable: any imbalance of the Poloidal Field (PF) coil currents, splits the second-order null in two first-order nulls, leading to a variety of the topologically-stable SF-like configurations [6]. Indeed, here, we will discuss the modelling, creation and control of a divertor configuration with two nearby nulls for the EAST and JET tokamaks. The secondary null could be moved around to change its distance from the first null and to form a magnetic

[1] See the appendix of B. Wan et al., 25th IAEA FEC, St. Petersburg, Russia, 2014
[2] See the appendix of F.Romanelli et al., 25th IAEA FEC, St. Petersburg, Russia, 2014

configuration that features either contracting or flaring geometry near the plate [3-6]. The linear dependence of the gradient of magnetic field B_P in the primary null on the distance between the two nulls is described in [7, 8] and characterizes the interdependence of the field structures of both nulls. This feature will be analyzed for EAST and JET tokamaks. It should be noted that in EAST, on the contrary of JET, the divertor coils, which could be used to shape the local flux distribution within the divertor region, are outside the Torodial Field Coils (TFCs). However, for both tokamaks, the flaring of the magnetic flux (characterized by the magnetic field gradient) in the primary null is affected by the presence of the secondary null. This flaring could be then directly translated to the increased wetted surface area and reduced heat flux [5, 6]. Experimental results of ohmic (JET) and low/high confinement (EAST) two-null divertor and SN discharges supported by edge modelling will be also discussed.

2. Interdependence of the field structures of two nearby divertor field nulls

Two-null divertor configuration have been designed and optimized by means of CREATE-NL code (non-linear plasma evolution code), described in [9]. The procedure proposed for the design and optimization of the equilibria using the CREATE-NL code exploits the linearized relation between the plasma-wall gaps and the PF currents in two steps: the first step allows to have a first cut of the two-null equilibrium starting from a standard SN configuration: a new equilibrium with a second null point within a limited distance from the SN x-point is obtained, forcing the plasma boundary to be almost unchanged, apart from the region in the vicinity of the null point; the second step refines the plasma shape and possibly reduces the PF coil currents while fulfilling the machine technological constraints. The objectives of the two-null configuration design and optimization procedure consists in the definition of a set of equilibria, at low (0.1) and high β_p (0.45) with the secondary x-point close or far from the vessel structures maximizing the plasma current (~500kA for EAST, ~2.5MA for JET) . The linear dependence of the gradient of magnetic field B_P in the primary x-point on the distance between nulls is described in [7] as criterion of interdependence between them. A self-explanatory way to show the aforementioned dependence is to plot the iso-contours of $|R \cdot B_P|/|R \cdot B_P|$midplane = const around the nulls, as discussed in [7, 8], with const=0.01–0.1 and R is the radial coordinate, for both the optimized ‘far nulls’ and ‘close nulls’ configuration (Figs. 1-2).

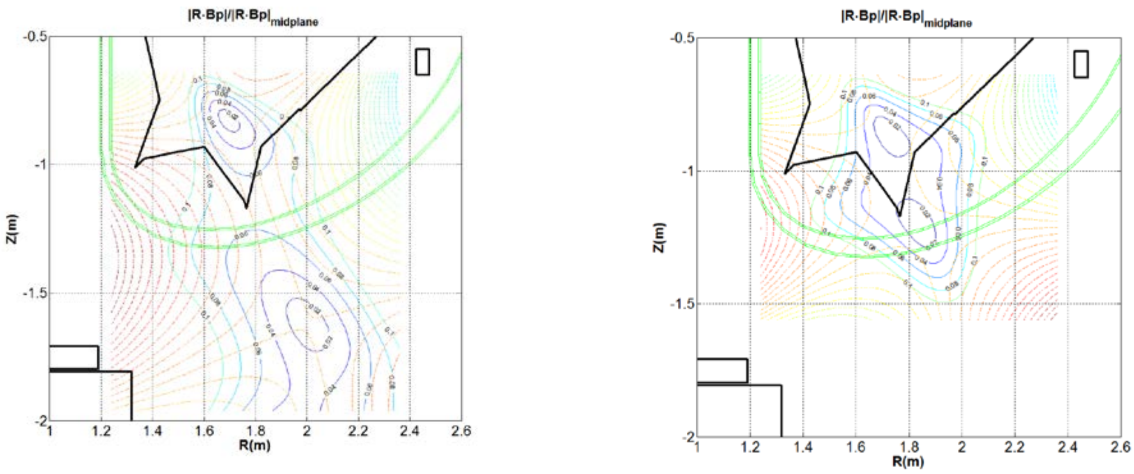

Figure 1. EAST: (a) Iso-contours $|R \cdot B_P|/|R \cdot B_P|_{midplane}$ = const for the two ‘far’ nulls configuration. (*b*) Iso-contours $|R \cdot B_P|/|R \cdot B_P|_{midplane}$ = const for the two ‘close’ nulls configuration.

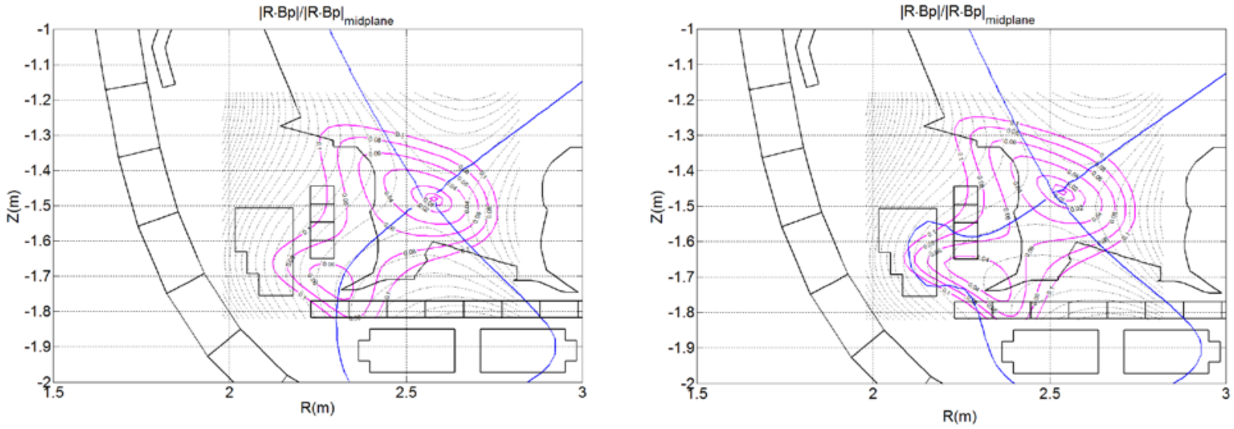

Figure 2. JET: (a) Iso-contours $|R \cdot B_P|/|R \cdot B_P|_{midplane}$ = const for the two 'far' nulls configuration. (*b*) Iso-contours $|R \cdot B_P|/|R \cdot B_P|_{midplane}$ = const for the two 'close' nulls configuration.

A direct manifestation of the interdependence between the nulls is that the flux flaring (characterized by the magnetic field gradient) in the main null is affected by the presence of the second null. Indeed, as it may be judged from the Figs. 1-2, the gradient of magnetic field B_P is proportional to the distance between the nulls. This flaring is then directly translated to an increase of the main magnetic divertor geometry parameters (flux expansion, connection length, etc.), and consequently, to an increased wetted surface area and reduced heat flux [6, 7].

3. EAST experimental results

Initial ohmic and low confinement (L-mode) two-null experiments with the second null forming a configuration with significant distance between the two nulls and a contracting geometry near the target plates have been performed in EAST tokamak [8]. In this experiments (plasma current I_P=250kA, toroidal field B_T=1.8T, ~500kW of NBI heating at low plasma electron density n_e~$1.2x10^{19}m^{-3}$) the simplest form of plasma current and position (i.e. both horizontal and vertical plasma centroid position) control has been used, the so-called RZIP control [10]. An increase of the connection length by ~30% and the flux expansion in the outer strike point (SP) region by a factor of ~4 has been obtained (Table I), as discussed in [8].

Table I. Main magnetic geometry parameters and peak heat load for two-nulls and SN discharges (considering a SOL width of λ_q=2 mm)

	L-mode Two nearby nulls (#48971) at 4.5s (x_1-x_2 distance=79cm)	**L-mode SN (#47038) at 4.5s**
SOL volume [m3]	0.389	0.260
Connection length [m]	189.91	144.38
Magnetic flux expansion at inner SP $f_{exp,in}$	4.71	2.34
Magnetic flux expansion at outer SP $f_{exp,out}$	8.22	2.01
Peak heat load [MW/m^2]	0.1	0.21

A peak heat load reduction observed in Infrared (IR) and Langmuir Probes (LPs) measurements for the two-null configuration has been confirmed by interpretive simulations by using EDGE2D-EIRENE [11] in combination with TECXY [12] code (Table I). This reduction has been mainly considered due to the higher flux expansion [8] of two-null with respect to the standard SN configuration. Indeed, a strong mitigation of the peak deposition power is expected to appear at the higher density, as a combination of the flux expansion which dominates at low density, and of the enhanced dissipation processes, which dominates at the higher densities, as discussed in [8]. Recently [13], an ISOFLUX/PEFIT Single-Input Single-Output (SISO) shape feedback controller has been developed in order to guarantee a stable two-null configuration and explore the operational space and effective heat load reduction under various plasma conditions and shape parameters. The ISOFLUX control aims at controlling the overall plasma shape by controlling the position of the primary x-point and by regulating to zero the flux error on a set of control segments. Long pulse (up to t_{pulse}~19s in discharge #56603) and high confinement (H-mode) discharges in EAST have shown heat flux reduction once operating in two nearby nulls divertor configuration with a contracting geometry near the target plates [14]. Time evolution of main plasma parameters and heating systems for well controlled two-null H-mode discharge #57239 are shown in Fig. 3, whilst the magnetic configuration at 6s is shown in Fig.4.

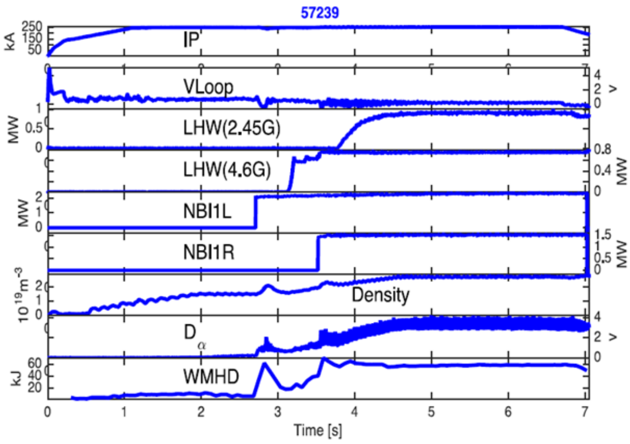

Figure 3. Time evolution of main plasma parameters and heating systems for two-null H-mode discharge #57239

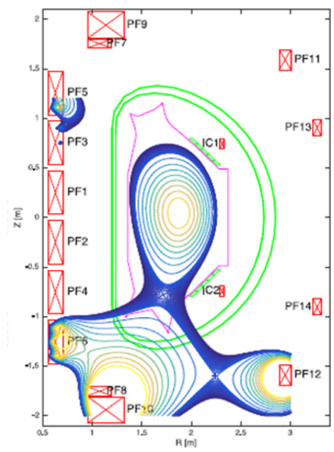

Figure 4. Magnetic configuration for two-null H-mode (P_{LH}~1.7MW, P_{NBI}~3.8MW) discharge #57239 at 6s.

From 0.2-2.7s the plasma is moving from limiter two-null configuration under the simple RZIP controller, then SISO ISOFLUX/PEFIT controller is used to achieve a stable H-mode. It should be noted that the nulls distance is kept constant all along the H-mode phase. An upgrade of ISOFLUX controller has been developing based on an eXtreme Shape Controller (XSC)-like [15] approach (i.e. model-based multivariable magnetic control architecture) that is suited for integrated control of both plasma and exact position of secondary x-point and consequently the flux expansion at inner and outer SP region, as discussed in [16]. This will permit to increase the additional heating power and to easily vary some of the features of the topological configuration in the H-mode discharges at low and high plasma current, i.e moving from a contracting to flaring geometry near the target plates with the second null located on the vessel.

4. JET experimental results

Initial ohmic two-null experiments (I_P=1.8MA) with the second null forming a configuration with a distance of ~37cm between the two nulls and a contracting geometry near the inner target plate have been recently achieved at JET tokamak. Here, an additional procedure has been developed to design the two-null configuration by optimizing the in-vessel divertor coil currents, and reported in [17]. First, a linearized model of the equilibrium is calculated, by CREATE-NL – XSC tools [18], in order to turn the non-linear relation between the coils current and the figures of merit to achieve into a linear one, described by an influence matrix. In order to calculate the additional currents contribution to add to that of the reference equilibrium, a constrained quadratic programming optimization procedure is then employed. The proposed procedure is applied to a conventional single null equilibrium, considering a SOL width of λ_q = 2 mm, accordingly with the length-decay of the thermal power in the SOL in JET tokamak [2]. Two different experimental flux expansions have been calculated: the flux expansion on the inner/outer target is the distance between the strike points of the SOL boundary and of the separatrix along the target tile on the poloidal plane. The flux expansion at the primary x-point is the expansion of the flux tube on the x-point horizontal plane. The increase of both the two flux expansion in the optimized equilibrium, as illustrated in Table II, for the experimental ohmic discharge #90541 at 61sec (reference SN) and 65sec (two-nulls) is shown in Fig. 5 (a). Magnetic field topology, with B_P varying from 0-0.045T, is shown in Fig.5 (b,c), as magenta iso-lines for both the configurations in order to highlight the magnetic field 'flatness' region, that is then translated into flux flaring in the main null and finally could lead to a decrease of thermal load, as previously discussed.

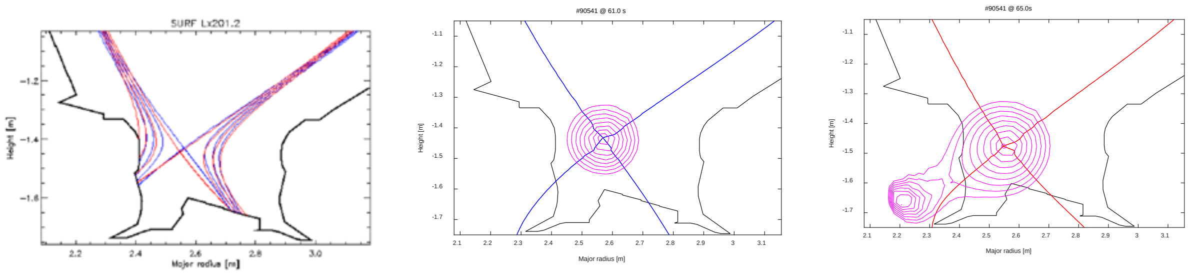

Figure 5. Reference (blue solid line) Vs, two-null (red solid line) equilibrium in terms of flux expansion (a) and magnetic field topology, shown as magenta iso-lines, for experimental discharge #90541 at (b) 61s (standard SN) and (c) 65s (two-null).

Table II. Flux expansion on the primary x-point and on the inner and outer targets

	$X_p\|_{IN}$	$X_p\|_{OUT}$	$\text{Target}\|_{IN}$	$\text{Target}\|_{OUT}$
Two-nulls	40.44	42.52	12.63	5.96
Standard SN	34.39	35.66	6.20	4.08

An experimental flux expansion increase by a factor of ~20% at primary x-point outwards and ~50% on the outer divertor target has been achieved, thanks to the generation of a second x-point close to the first wall. Next experiments will be devoted to investigate the two-null configuration with additional heating power and with/without nitrogen impurity seeding, in order to address the the physics of a possible dependence of radiative volume and total radiated power on the distance between the two nulls. Aim of this study will be the evaluation of the impact of main magnetic divertor geometry parameters, as the flux expansion and the connection length, on the radiation pattern disentangled by the change of recycling happening at the same time, focusing on bolometer and Langmuir probe measurements analysis supported by edge modelling. However, initial predictive EDGE2D-EIRENE code simulations, in combination with SOLEDGE code [19], have been set up for both reference and two-nulls configuration [20] shown in Fig. 5. The input power to the SOL used in the simulations is

P_{SOL}=8MW, with a plasma electron density (fixed puffing) of $4.5x10^{19}m^{-3}$ and feedforward N seeding (four steps of 0, 2.65, 6.4 and $1x10^{20}$ part/s). The preliminary results, discussed in [20], show an increase of total radiation power of ~30% for the two-nulls configuration.

5. Conclusions

The demonstration of the possibility of creating and controlling a two nearby poloidal field nulls SF-like configuration on a large superconducting tokamak, as EAST, and in JET tokamak, has been realized. Initial experiments with the second null forming a configuration with significant distance between the two nulls and a contracting geometry near the target plates have been performed for both tokamaks leading to an increase of the main magnetic divertor geometry parameters . First L-mode and recent long pulse and H-mode discharges at EAST have shown heat flux reduction once the shape moves from SN to a two nearby nulls divertor configuration with a contracting geometry near the target plates. Nitrogen seeded H-mode experiments are foreseen to be executed at JET in the near future, addressing the physics of the dependence of radiative volume and total radiated power on the distance between the two nulls.

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