Advanced divertor equilibrium calculations with finite current density on the plasma boundary.

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Introduction

The high exhaust power fluxes that are expected to reach critical values in the narrow wetted area on the ITER and DEMO divertor plates (implying the need for a large core radiation fraction for the latter) have motivated the development of the X-divertor (XD) [1] and Snowflake (SF) [2] advanced divertor configurations. The aim of the XD is to expand the poloidal flux in the proximity of the target plates. Expansion of the flux surfaces, primarily around the X-point (XP), can also be achieved by the SF, where a second order null in the poloidal magnetic field (both the field and its first derivatives vanish) results in a configuration exhibiting local six-fold symmetry. The benefits of strong flaring in the SF configuration are conditional on the divertor plates being in the vicinity of the SF origin, however the increased scrape-off layer (SOL) volume associated with the SF will independently have the beneficial effect of increasing radiative losses. Here we focus on the ideal snowflake and its variants already introduced in [2], namely the 'snowflake plus' (SF^+) and 'snowflake minus' (SF^-) where the second order null is replaced by two closely positioned conventional X-points. In the case of the SF^+ the secondary XP lies in the private flux region (PFR) of the primary XP, while for the SF^- the XP lies in the primary SOL. In what follows we consider (i) the effect of finite current density on the ideal SF configuration, (ii) the fitting of decay lengths for currents in the SOL and PFR and (iii) SF^- configurations that are experimentally feasible on ASDEX Upgrade.

Snowflake calculations with finite current density on the plasma boundary

Since its introduction in [2], work on the SF configuration reported so far (e.g. [3]) has assumed a vanishing toroidal current density at the separatrix, although Ryutov et al. [4] have considered finite j_ϕ in the SOL for SF^+ and SF^- cases. More recently, the volume of the scrape-off layer has been proposed as a new figure of merit for advanced divertor configurations [5]. The predictive/interpretive CLISTE equilibrium code [6] has added functionality to calculate snowflake-like equilibria under the realistic assumption that the current density profile extends across the separatrix into the SOL and PFR. CLISTE can compute an ideal snowflake at any feasible location by assigning values to four of the poloidal field coil currents so as to satisfy four conditions at the specified location of the SF origin:

$$\psi_R = \psi_Z = \psi_{RR} = \psi_{RZ} = 0 \tag{1}$$

where $\psi_R = \partial\psi/\partial R$, etc. and the condition $\psi_{ZZ} = 0$ is redundant provided the toroidal current density vanishes on the plasma boundary. For the realistic case of $j_{\phi,boundary} \neq 0$ where at a first order null the Grad Shafranov equation simplifies to

$$\psi_{RR} + \psi_{ZZ} = -\mu_0 R j_\phi \tag{2}$$

a second order null and hence an ideal snowflake is not possible. To study the transition in the SF configuration from $j_\phi = 0$ to $j_\phi \gg 0$ the condition $\psi_{RR} = 0$ in (1) is replaced by $\psi_{RR} - \psi_{ZZ} = 0$ which imposes a second order null for $j_\phi = 0$ where the poloidal flux takes the form $\psi(R,Z) - \psi_{XP} = a((R-R_x)^2 - (Z-Z_x)^2)$ (in suitably rotated coordinates) at the location R_x, Z_x of a single null, while at the same time allowing a circular current density distribution ($\psi_{RR} = \psi_{ZZ} \neq 0$) for $j_\phi > 0$. Contour plots for a $20 \times 20\,\text{cm}^2$ region centred on the (nominal) SF origin for three cases using the ASDEX Upgrade coil configuration are shown in figure 1.

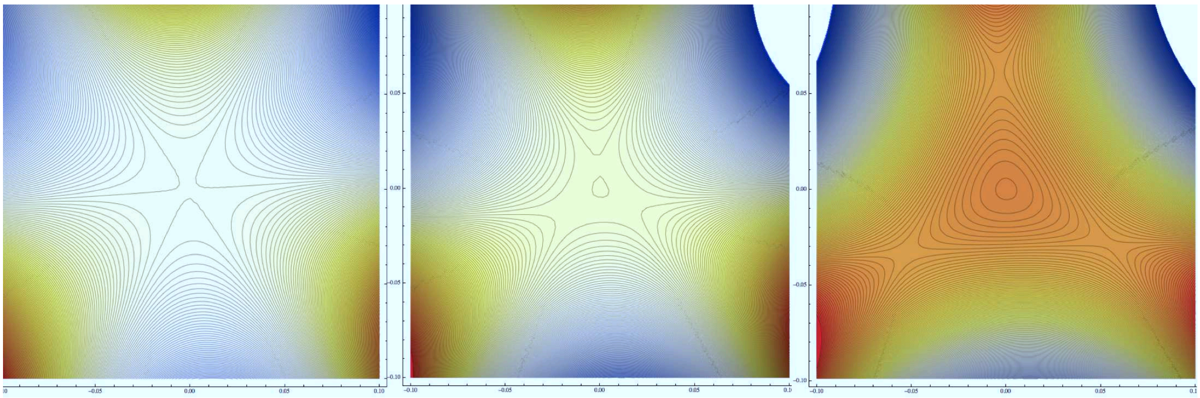

FIG. 1: Contour plot detail (20 cm × 20 cm centred on nominal SF origin) of poloidal flux for three $I_p = 800\,\mathrm{kA}$ SF calculations; (a) ideal SF with $j_\phi = 0$ at the origin, (b) $j_\phi = 25\,\mathrm{kA\,m^{-2}}$, (c) $j_\phi = 100\,\mathrm{kA\,m^{-2}}$.

As j_ϕ increases, the second order null of the ideal SF is replaced by a triangular region bounded by three X-points and an O-point corresponding to a shallow extremum in flux. In the right-hand plot in figure 1 this region is (approximately) an equilateral triangle of side 10 cm where the O-point is at $\rho_{pol} = 1 - 0.00015$ and j_ϕ is approximately constant (∼5% variation) taking a value ($\simeq 100\,\mathrm{kA\ m^{-2}}$) which is ∼ 5% of the maximum j_ϕ value in the plasma core.

Experimental determination of current density decay lengths in the SOL and PFR

A prerequisite for the potential experimental relevance of the finite j_ϕ SF-like configurations is that current density in the PFR should have a sufficiently long decay length. ASDEX Upgrade is well equipped with robust divertor tile current measurements of SOL poloidal currents whose dependence on plasma parameters has previously been reported [7]. The resolution and bandwidth for individual tile signals was improved in 2012, and subsequent discharges which include a slow horizontal sweep of the separatrix very occasionally generate data where a tile extremity transits from well outside the SOL (in the deep PFR) to well inside the SOL under quasi stationary plasma conditions (I_p, $\bar{n}_e$, W_{mhd}). Two such discharges were analyzed, and an exponential decay in Ipol (and, by assumption, j_ϕ) versus $\delta\rho_{pol}$, the separation of the separatrix from the tile extremity, was found to fit the data extremely well for the first discharge (#29779, $I_p = 1\,\mathrm{MA}$, $\bar{n}_e = 2.7 \times 10^{19}\,\mathrm{m^{-3}}$, $W_{\mathrm{mhd}} = 100\,\mathrm{kJ}$, L-mode/I-phase) and reasonably so for a second discharge (#29729, $I_p = 1\,\mathrm{MA}$, $\bar{n}_e = 5.5 \times 10^{19}\,\mathrm{m^{-3}}$, $W_{\mathrm{mhd}} = 750\,\mathrm{kJ}$, H-mode) where averaging over high frequency ELMs was necessary. Separate regressions of $\mathrm{Ipol_{tot}} - \mathrm{Ipol_{roof}}$ vs. $\delta\rho_{pol}$ were made for time points with positive $\delta\rho_{pol}$, and of $\mathrm{Ipol_{PFR}}$ vs. $\delta\rho_{pol}$ for negative $\delta\rho_{pol}$, where $\mathrm{Ipol_{tot}}$ is the total Ipol flowing in the inner divertor. The results shown in figures 2 and 3 indicate decay lengths (expressed in terms of ρ_{pol}) for Ipol in the PFR of $\lambda_{\mathrm{PFR}} = 0.0007$, 0.0011 for #29779 and #29729, in both cases comfortably exceeding the range of $\delta\rho_{pol}$ in the SF-like triangular region in figure 1(c). The corresponding SOL values are $\lambda_{\mathrm{SOL}} = 0.0046$, 0.0071 which equate to outer midplane spatial decay lengths of 3.2 and 4.4 mm, respectively.

Search for feasible SF$^-$ configurations for ASDEX Upgrade

Transport simulations and experimental results on TCV [8] indicate that the SF$^-$ configuration is more promising than the SF$^+$ for reducing the power flux at the divertor plates. Most ASDEX Upgrade coils are remote from the plasma, requiring large currents to generate SF configurations which generally require a substantial reduction in the plasma current to avoid exceeding coil current and/or vertical force limits. CLISTE in predictive mode has the facility to search parameter space using Monte Carlo methods and hence identify optimal configurations satisfying pre-specified criteria. Two such configurations are shown in figure 4. The $I_p = 800\,\mathrm{kA}$ case, with a spatially remote secondary XP, does not differ strongly from the standard XP configuration even though it satisfies the SF$^-$ criterion of magnetic proximity: the outer midplane equivalent separation is $\sim 1\,\mathrm{mm}$. The second configuration exhibits large flux expansion at the divertor plates, but at the price of a much reduced plasma current of 300 kA.

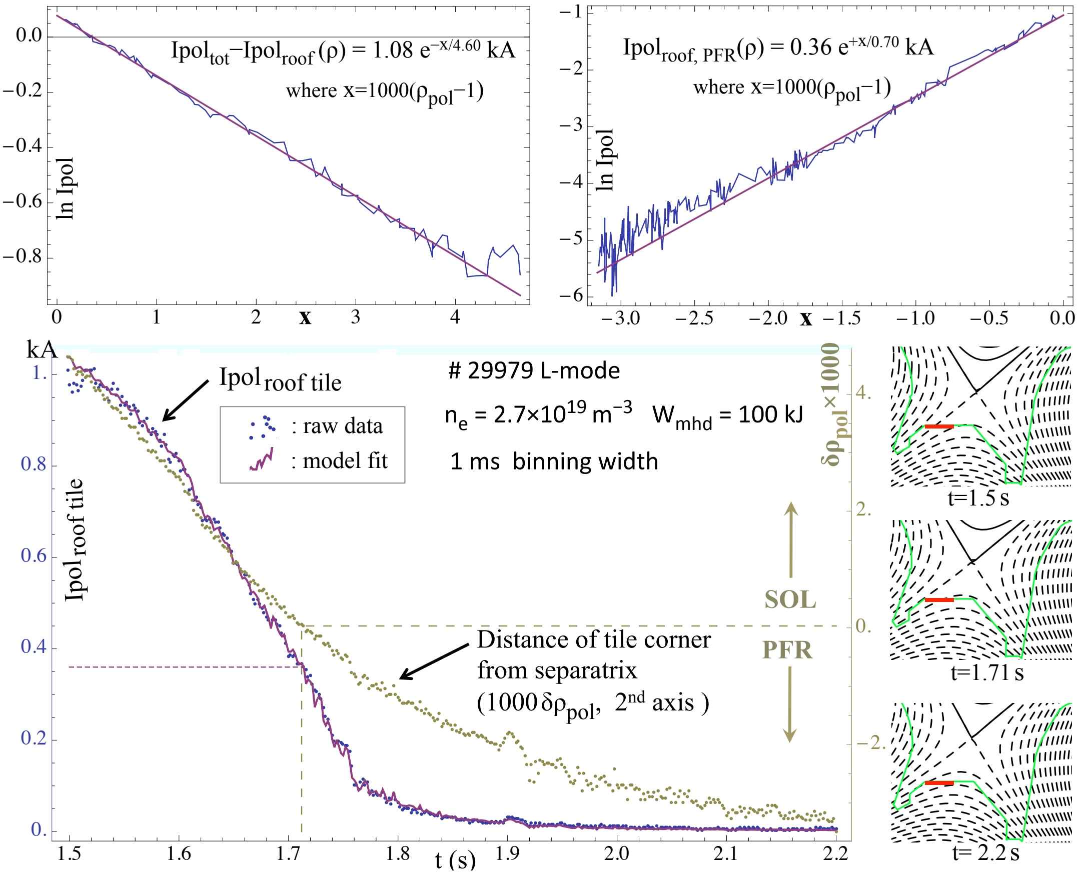

FIG. 2: Fits to poloidal current through roof baffle tile 14DUMoi in ASDEX Upgrade L-mode/I-Phase shot #29779 versus $\delta\rho_{pol}$ distance from separatrix. The upper plot pair show $\ln(\mathrm{Ipol}_{\mathrm{tot}} - \mathrm{Ipol}_{\mathrm{roof}})$ vs. $\delta\rho_{pol}$ data and regression line for $\delta\rho_{pol} > 0$ (left) and $\ln \mathrm{Ipol}_{\mathrm{roof,\,PFR}}$ vs. $\delta\rho_{pol}$ for $\delta\rho_{pol} < 0$ (right). The lower plot shows the raw (blue points) and fitted (wine-red curve) data vs. time. The light brown dots are the values (2nd axis) of $1000\,\delta\rho_{pol}$ obtained from CLISTE equilibrium fits to magnetic data *not* including the tile currents. The separatrix leg departs from the tile at $t = 1.71$ s (dotted lines). The tile geometry (red) and flux surfaces at the sweep extremes and the crossing point are shown on the right.

Summary

Ideal snowflake configurations are not possible when a finite current density flows on and outside the separatrix, as is observed experimentally. CLISTE computations of the evolution of the topology of the SF flux surfaces with increasing j_ϕ on the separatrix show that a triangular region with quasi-uniform j_ϕ and bounded by three X-points is established. Initial analysis of several divertor swept ASDEX Upgrade discharges with favorable geometry and information-rich tile current data yielded private flux region decay lengths for the poloidal current and, by assumption, j_ϕ of order $\Delta\rho_{pol} = 0.001$. Feasible SF^- configurations using the existing ASDEX Upgrade coils have been found by a Monte Carlo scan of parameter space.

[1] PM Valanju et al, Phys.Plasmas **16** 056110 (2009).
[2] DD Ryutov et al, Phys. Plasmas **15** 092501 (2008).
[3] K Lackner, H Zohm Fus. Sci. Tech. **63** (2012) 43-48.
[4] DD Ryutov, MA Makowski and MV Umansky, Plasma Phys. Control. Fusion **52** 015001 (2010).
[5] K Lackner, H Zohm, *private communication*, (2014).
[6] PJ Mc Carthy and ASDEX Upgrade Team, Plasma Phys. Control. Fusion **54** 015010 (2012).
[7] A Kallenbach et al., J. Nucl. Materials **290-293** (2001) 639.
[8] T Lunt et al., Plasma Phys. Control. Fusion **56** 035009 (2014).

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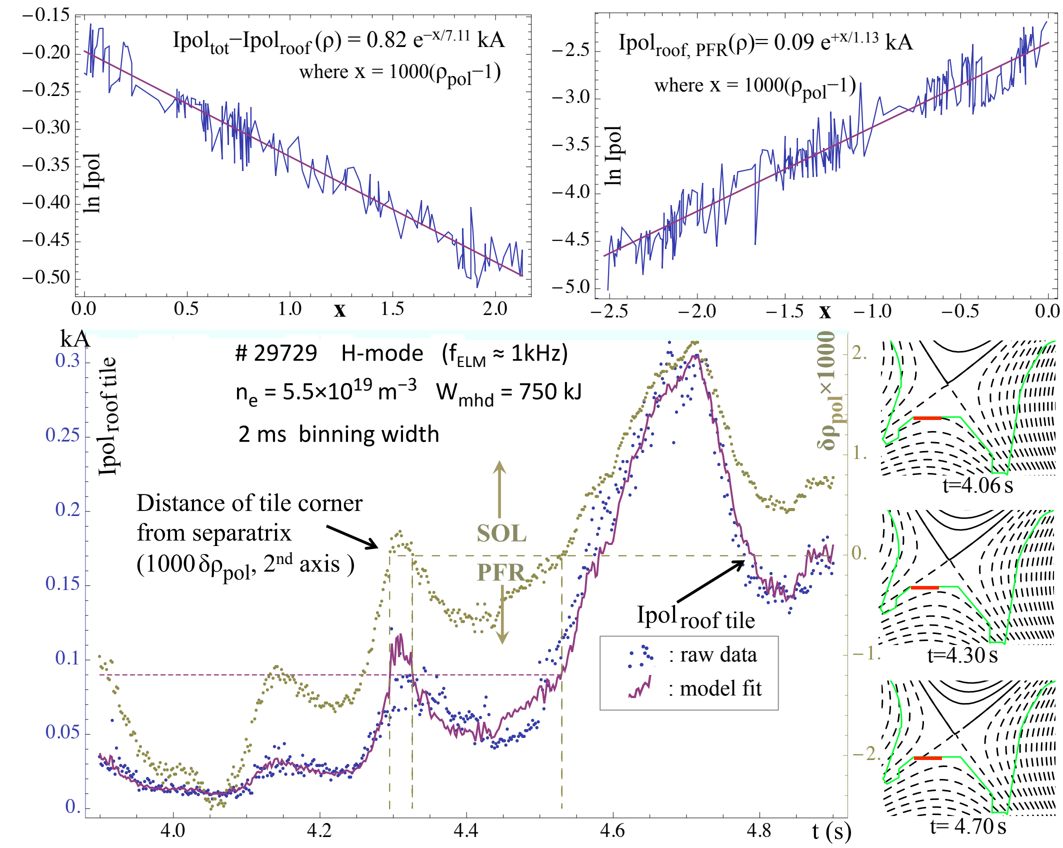
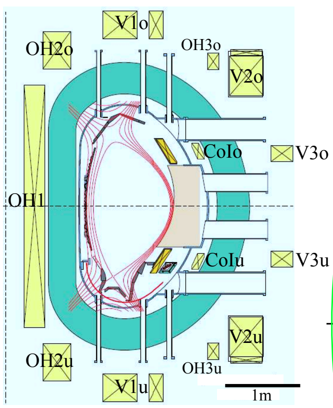
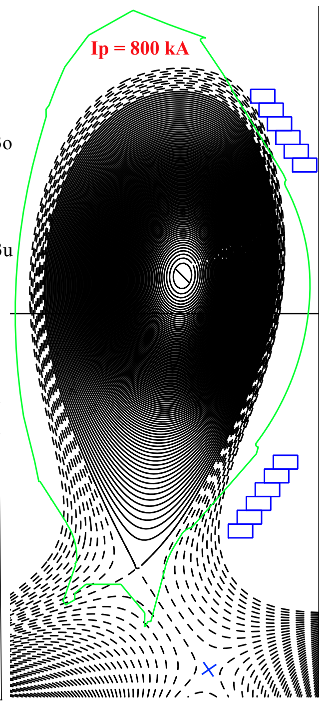


FIG. 3: Fits to poloidal current through roof baffle tile 14DUMoi in ASDEX Upgrade H-mode shot #29729 versus $\delta\rho_{pol}$ distance from separatrix. See previous caption for details.



Coil	Current	Limit	$F_v/F_{v,max}$
V1o	−14.4	59 kA	0.08
V1u	−9.0	59 kA	0.05
V2o	18.1	49 kA	0.43
V2u	16.6	49 kA	0.43
V3o	−46.4	55 kA	0.52
V3u	−46.4	55 kA	0.49
CoIo	1.9	30 kA	0.04
CoIu	−8.2	30 kA	0.20
OH1,3	0.0	47 kA	0.00
OH2o	29.6	47 kA	0.74
OH2u	41.9	47 kA	0.32



Coil	Current	$F_v/F_{v,max}$
V1o	−15.4 kA	0.06
V1u	−13.4 kA	0.07
V2o	11.0 kA	0.13
V2u	16.0 kA	0.25
V3o	−28.0 kA	0.16
V3u	−28.0 kA	0.25
CoIo	24.3 kA	0.29
CoIu	−23.7 kA	0.55
OH1,3	0.0 kA	0.00
OH2o	26.3 kA	0.66
OH2u	30.9 kA	0.32

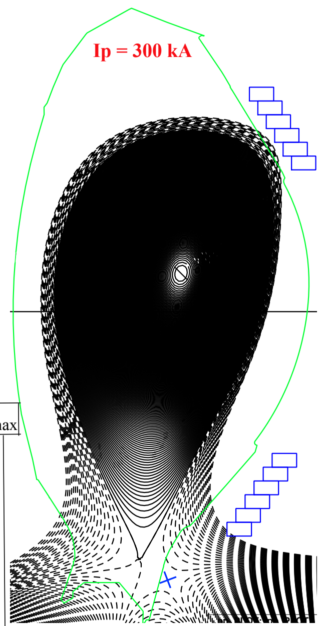


FIG. 4: Feasible SF$^-$ configurations for ASDEX Upgrade including a table of coil currents per turn, maximum values and vertical forces expressed as a fraction of the maximum permissible force on each coil for (a) remote and (b) close secondary X-points, in each case with magnetic separation equivalent to a gap of ~1 mm in the outer midplane. Case (b) is possible only at the cost of a reduced plasma current due to the greater demands on the coil currents to achieve closer proximity of the X-points and also relies on significant currents in the CoIo, CoIu position control coils.