Snowflake divertors for power plants

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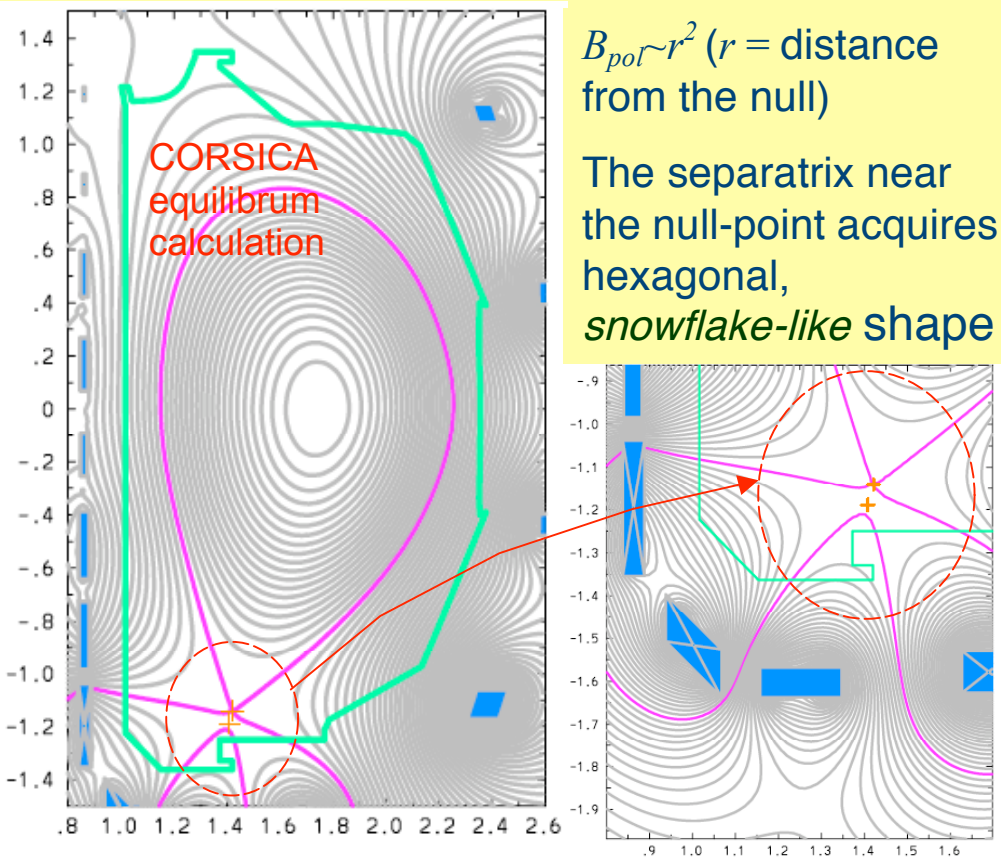
OUTLINE

- What is a snowflake (SF) divertor?
- Effect of a SF on
  - Radiation and detachment
  - Divertor power loads
  - ELMs
  - Blobs
- SF divertor for a power plant

Contributions by R. Cohen, F. Piras, T. Rognlien V. Soukhanowski and M. Umansky are gratefully acknowledged

“SNOWFALKE”: USING SECOND-ORDER NULL OF POLOIDAL FIELD TO IMPROVE DIVERTOR PERFORMANCE



$B_{pol} \sim r^2$ (r = distance from the null)

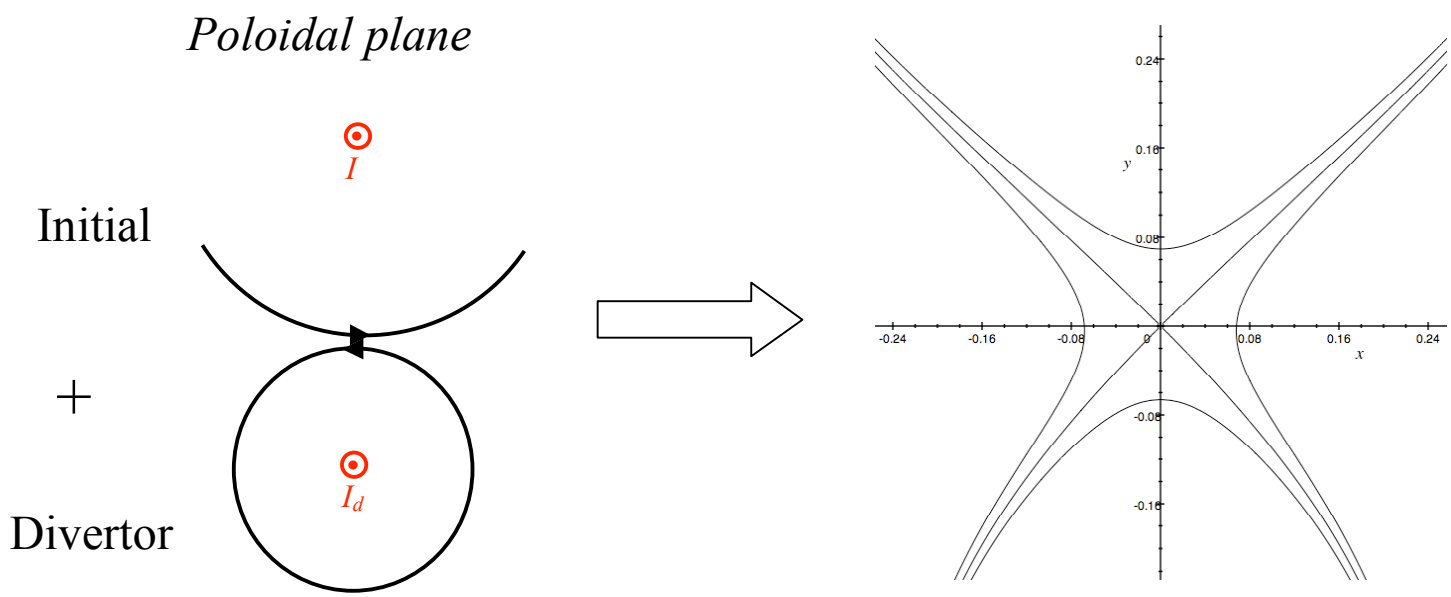
The separatrix near the null-point acquires hexagonal, *snowflake-like* shape

DIII-D, existing set of PF coils, $I_{plasma} \approx 1$MA

Features of snowflake divertors

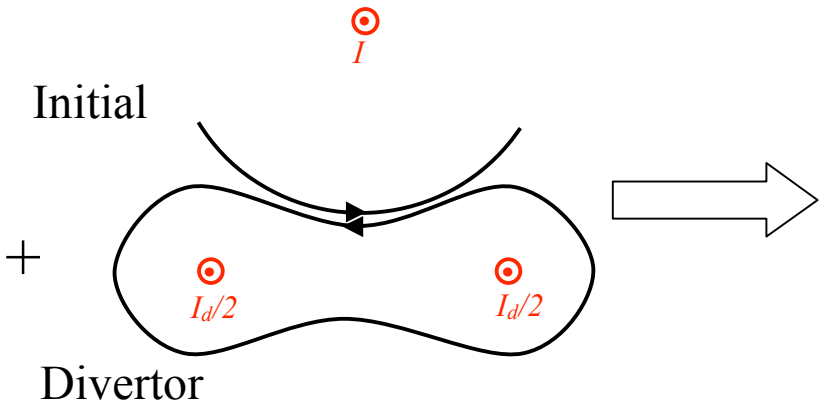
- Larger flux-expansion near the PF null
- Increased connection length
- Increased magnetic shear in the pedestal region (ELM suppression)
- Modified blob transport (stronger flux-tube squeezing near the null-point)
- Possibility to create this configuration with existing set of PF coils on the existing devices (TCV, NSTX, DIII-D….)
- Possibility to create “snowflake” in ITER-scale machines with PF coils situated outside TF coils

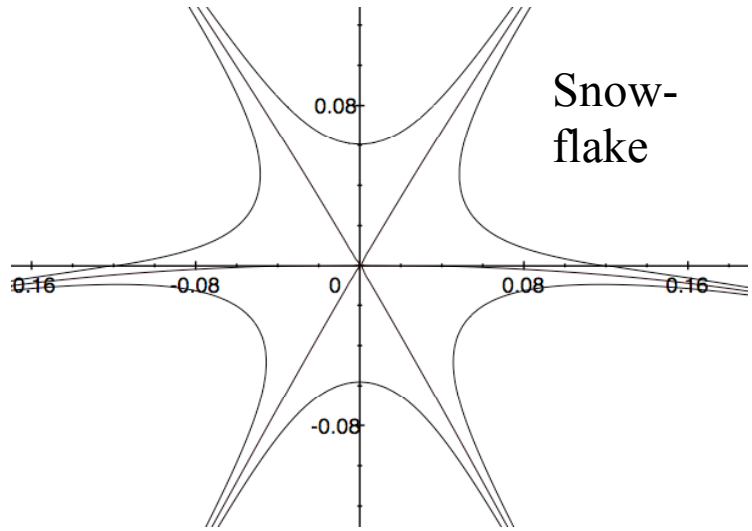
A “standard” X-point divertor requires creating a first-order null of the poloidal magnetic field



If one wants to make a second-order null of the poloidal magnetic field at a chosen point, one should design the divertor coils in such a way as to satisfy two conditions:

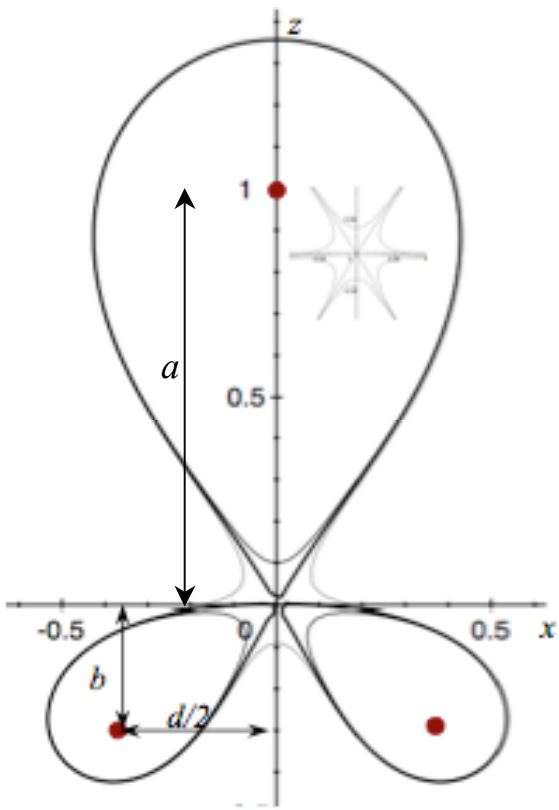
1. The magnetic field of divertor coils at the chosen point is equal in magnitude and directed oppositely to the “initial” field
2. The curvature of the field lines generated by the divertor coils in the chosen point is equal to the curvature of the field lines of the initial field





There occurs significant flux expansion

3-wires model



Snowflake divertor in symmetric 3-wire configuration.

Two conditions must be satisfied:

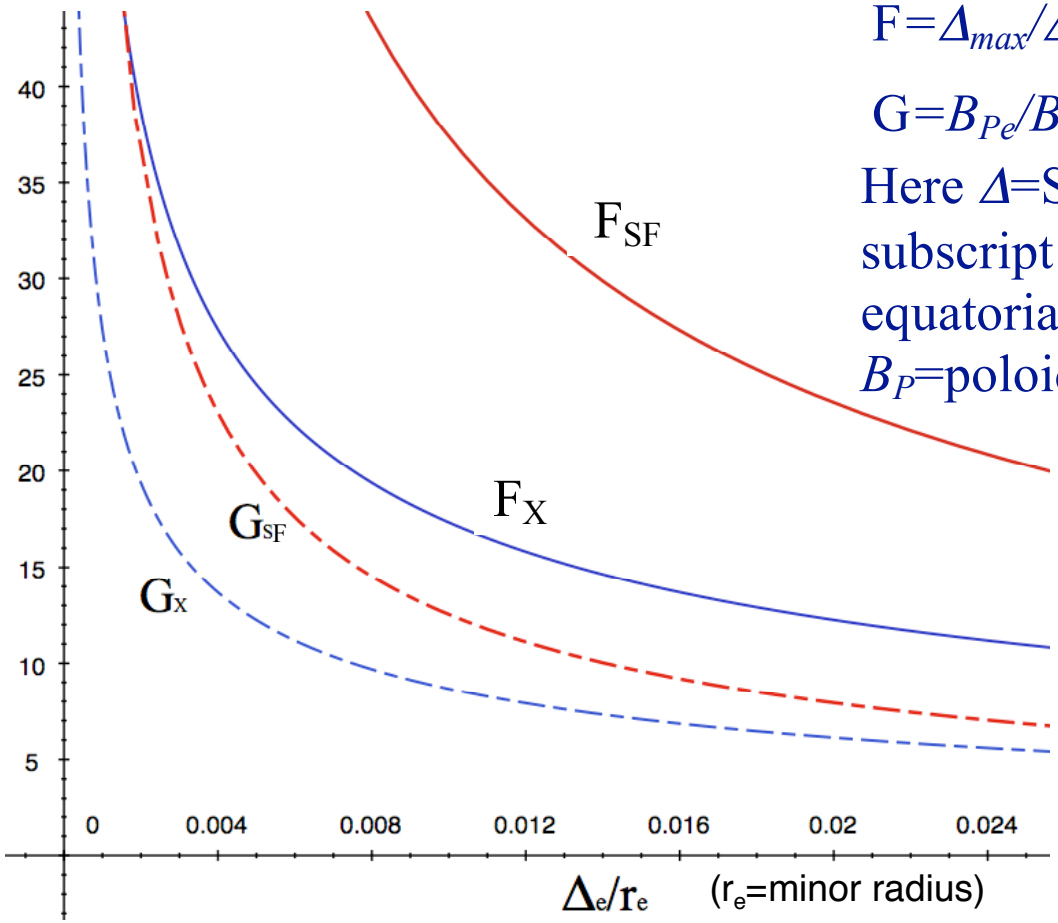
$$I_d = I_{d0} \equiv I\frac{2b}{a-b}; \; d = 2b\sqrt{\frac{a+b}{a-b}}.$$

For $b=0.3a$, the total current in both divertor coils is $I_d=0.9I$. For a=5m, the divertor coils are situated at a distance 2.5 m from the null point

Divertor coils can be situated outside TF coils

D.D. Ryutov. Phys. Plas, **14**, 064502, 2007

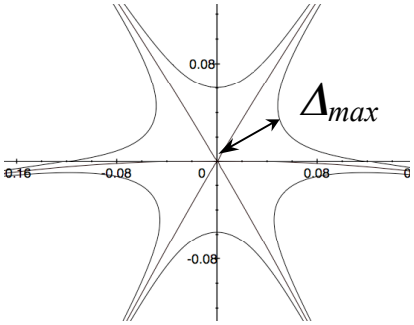
Flux expansion in the snowflake divertor is many times stronger than in a standard X-point divertor



$F=\Delta_{max}/\Delta_e$;

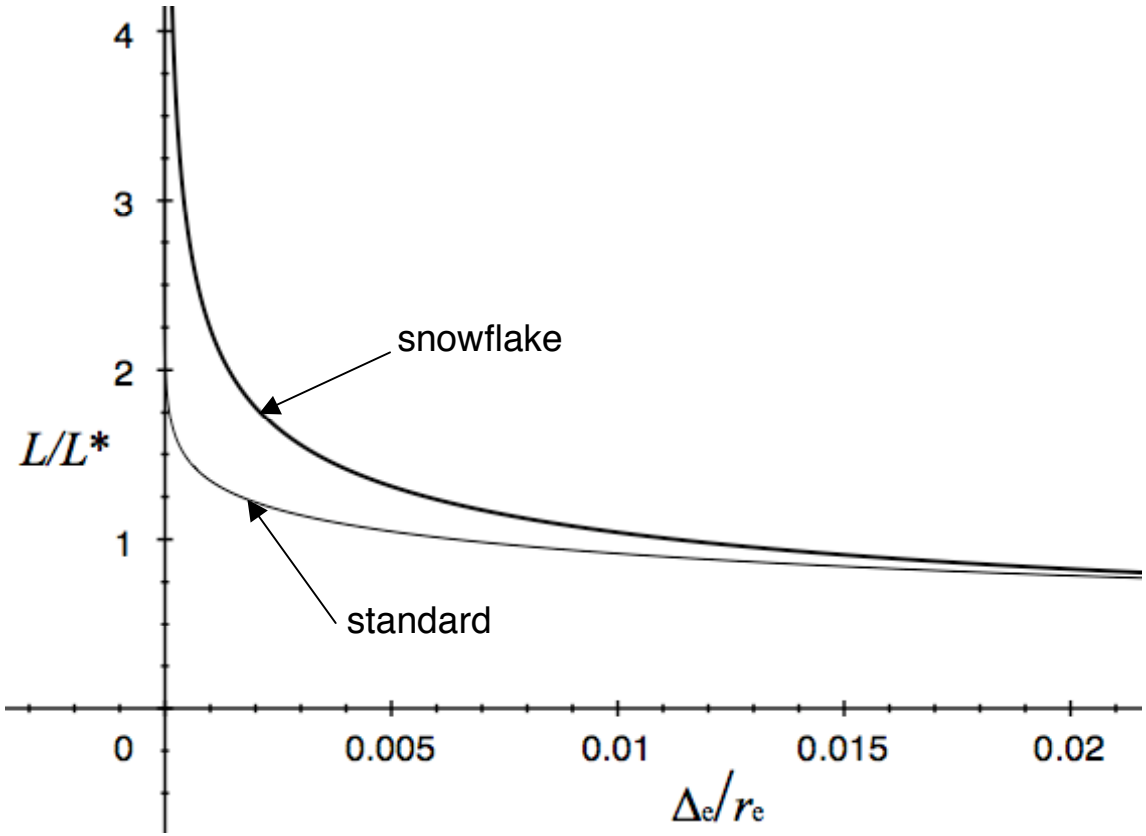
$G=B_{Pe}/B_{Pmin}$

Here Δ=SOL width; subscript "*e*" refers to the equatorial plane; B_P=poloidal field strength



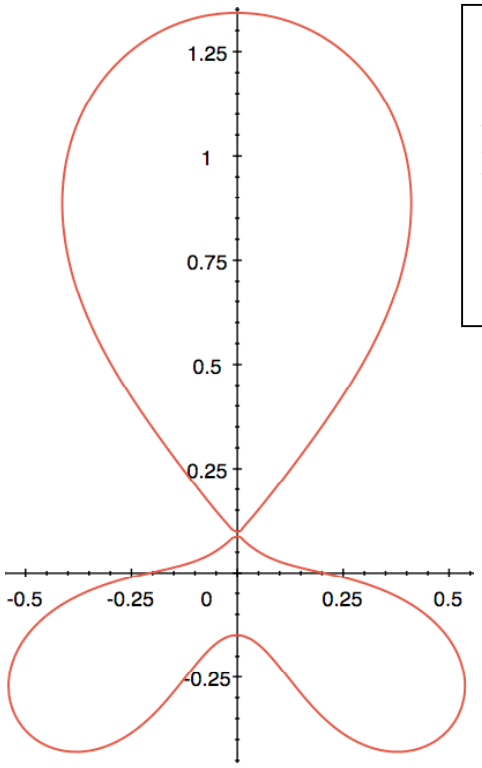
D.D. Ryutov, R.H. Cohen, T.D. Rognlien, M.V. Umansky. Phys. Plas. **15**, 092501, 2008.

The connection length between the midplane and the point nearest to the null-point is significantly longer for the snowflake divertor than for the standard x-point divertor



A problem: the *exact* snowflake configuration is topologically unstable

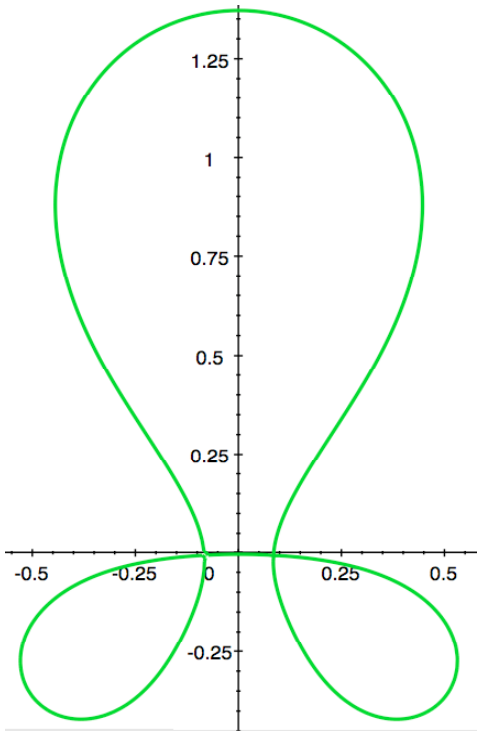
The configuration becomes either an X-point configuration (if the divertor current is higher than needed), or a double-X-point configuration (if the divertor current is lower than needed).



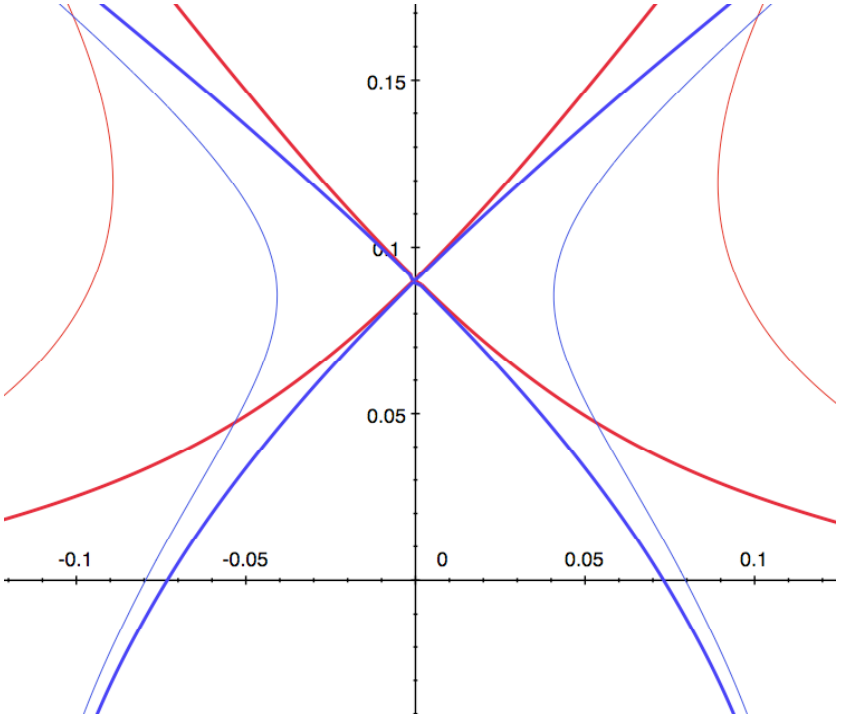
The divertor current is 5% higher than I_{d0}. We call this configuration "snowflake-plus"

The divertor current is 5% lower than I_{d0}. We call this configuration "snowflake-minus"

The "plus" and "minus" configurations are remarkably robust for $|\varepsilon|$ as low as 0.02, $I_d = I_{d0}(1+\varepsilon)$



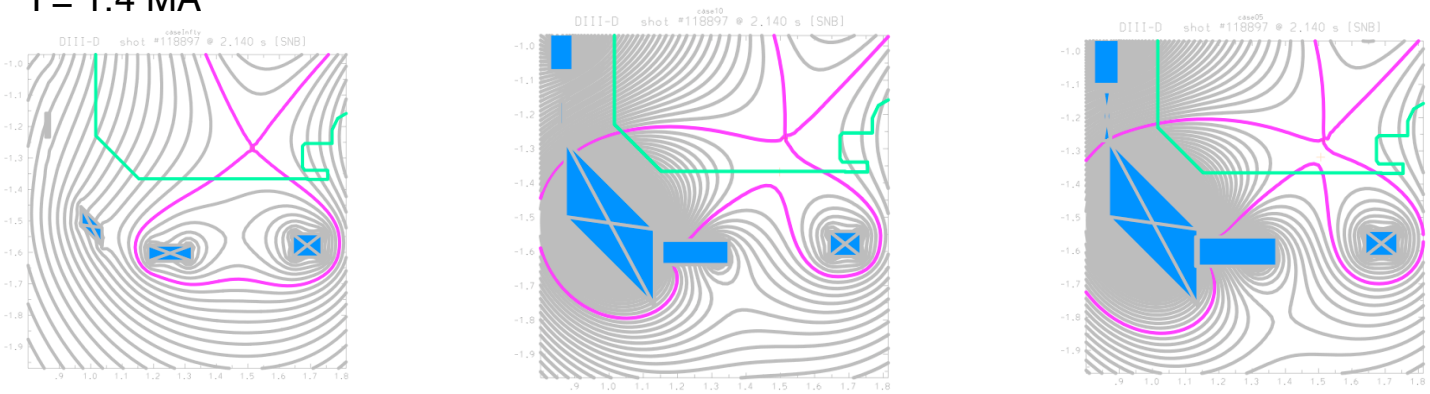
Comparison of the SOL geometry near the null point in the snowflake-plus divertor (red lines) and a standard X-point divertor (blue lines).



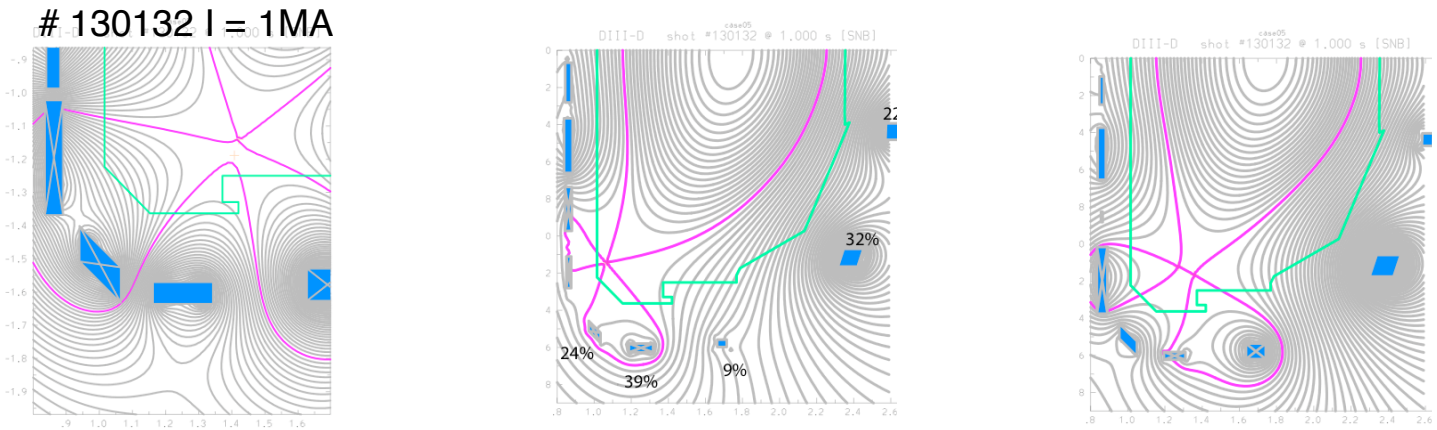
The flux expansion is 2-3 times higher for the snowfake-plus configuration (ε=0.05)

A broad variety of snowflake-like configurations can be produced on DIII-D (M. Umansky, 2008)

Standard x-point,
I = 1.4 MA



Similar to the shot
130132 I = 1MA

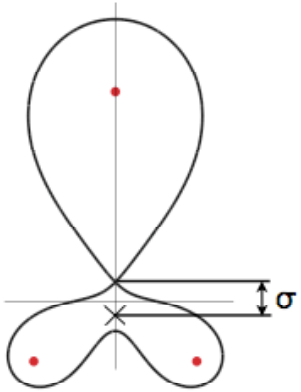


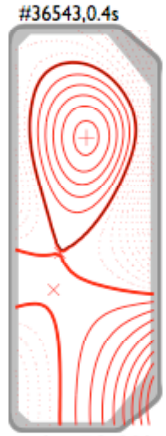
SF configurations on TCV

Equilibrium reconstruction

- Different SF configurations have been created in TCV and reconstructed using the LIUQE code

SF+ configuration:

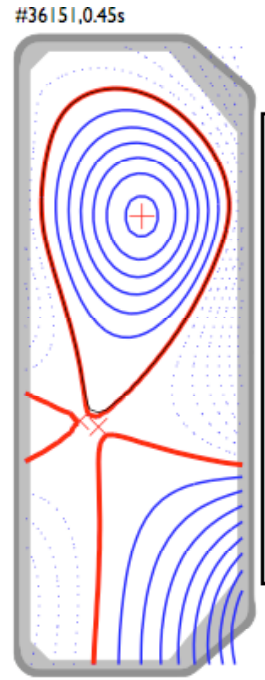




σ/a=58.8%

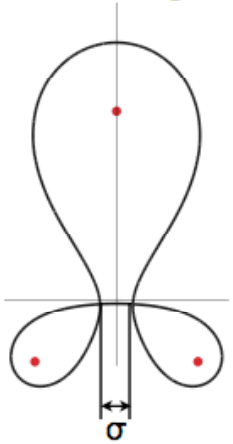
σ/a=32%

σ/a=20%

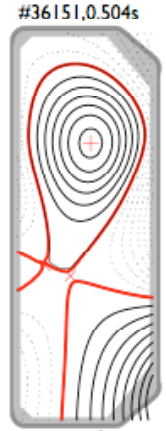


σ/a=15%

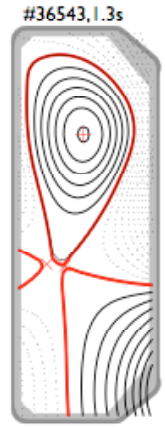
SF- configuration:



σ/a=78%, ΔRs=0.67



σ/a=43%, ΔRs=0.19



σ/a=29%, ΔRs=0.1

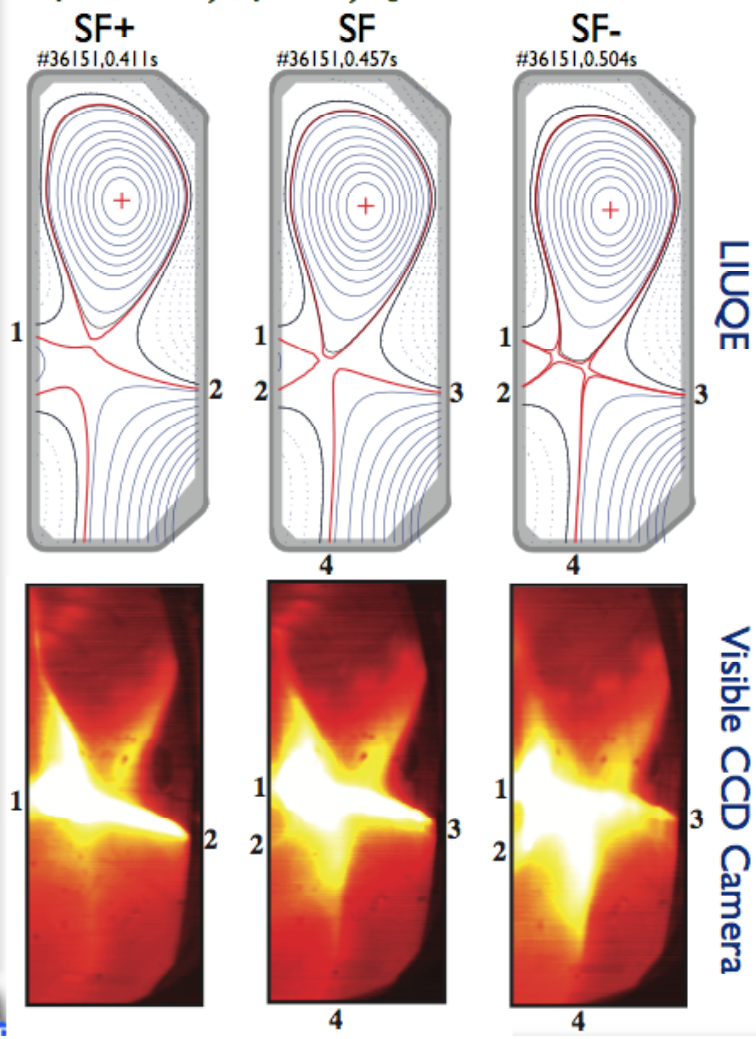
TCV SOL:

W=2-3cm
B_T=1.25T
T_e=7-40eV
n_e=0.3-30×10^{18} m^{-3}
ρ_e=10-20μm
ρ_i=0.5-1mm
λ_D=3-30μm

Radiated power

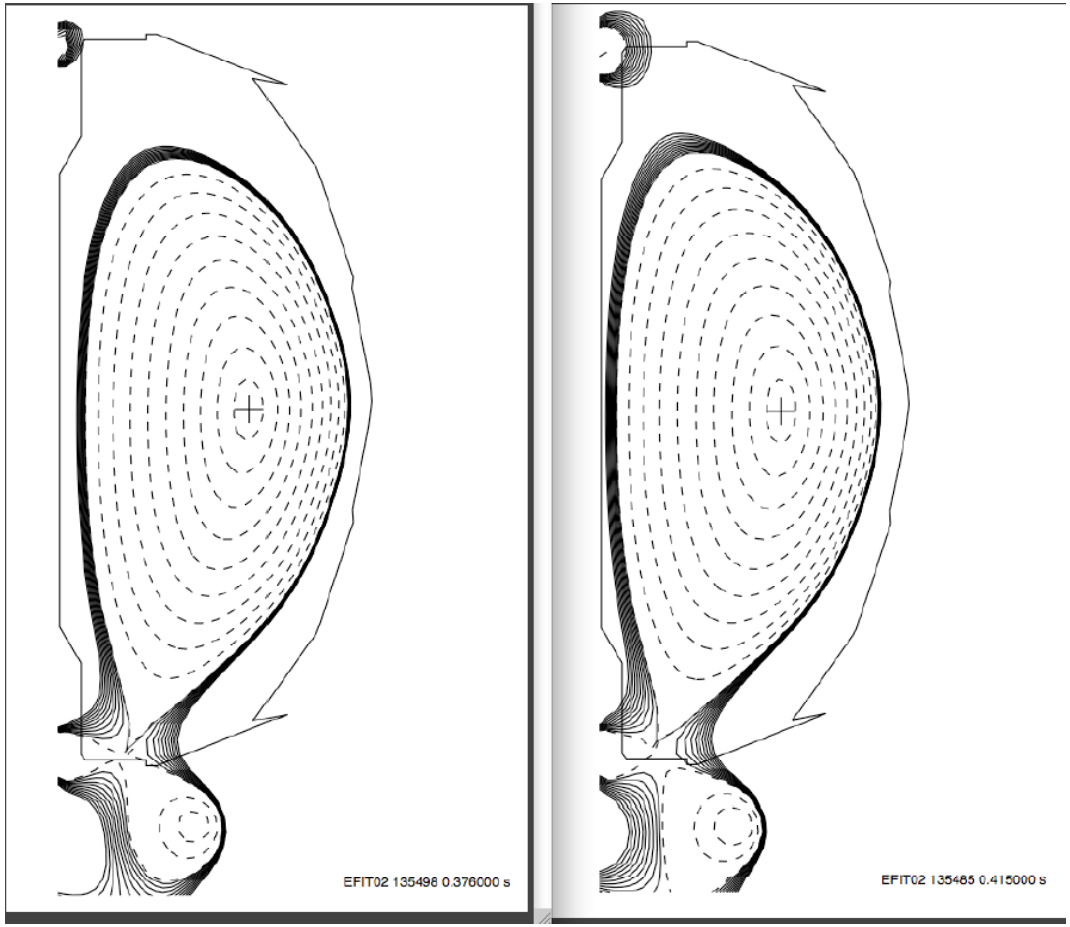
- Visible CCD Camera and AXUV

I_P = 230kA, B_T=1.4T, n_e=7×10^{19}m^{-3}



Piras F, Coda S, Furno I, Moret JM, Pitts RA, Sauter O, Tal B, Turri G, Bencze A, Duval BP, Felici F, Pochelon A, Zucca. "Snowflake divertor plasmas on TCV", *Plasma Physics And Controlled Fusion,* **51,** 055009, 2009,

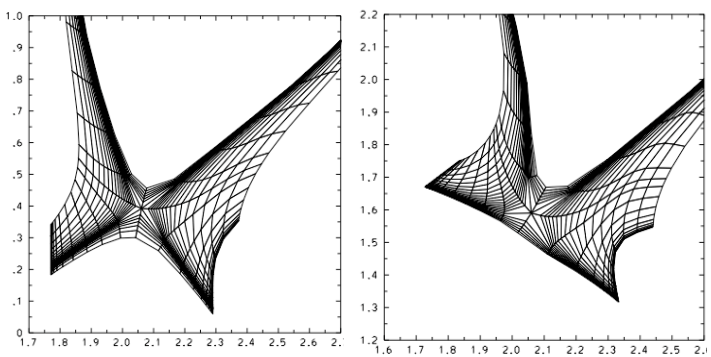
Snowflake on NSTX (courtesy V. Soukhanovskii, J. Menard)



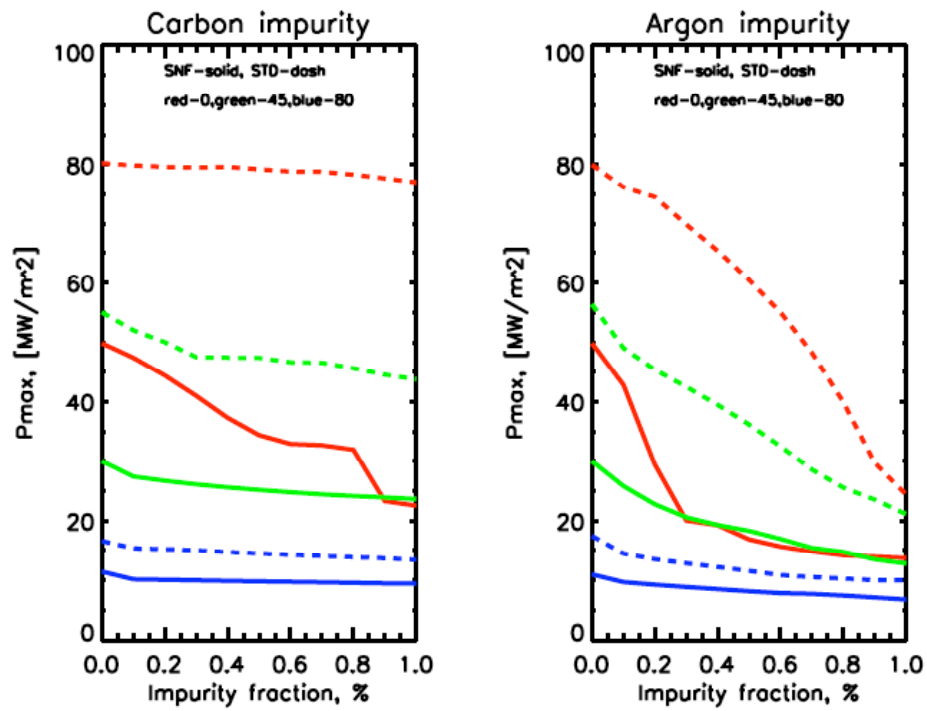
Increased flux expansion and connection length have a favorable effect on the divertor heat flux

UEDGE calculations predict significant difference for snowflake and standard divertor for otherwise same setup

Standard **Snowflake**



Maximum heat flux on plate



Umansky M V, Bulmer R H, Cohen R H, Rognlien T D, Ryutov D D *Nuclear Fusion* **49** 075005 (2009)

NSTX snowflake experiment

(V.A. Soukhanowski, USBPO E-News, #42, p. 3, 2010; V.A. Soukhanowski et al, PSI poster P1-28, Monday 24 May 2010)

Heat flux reduction by a factor of ~3

Easier detachment (no need in gas puff)

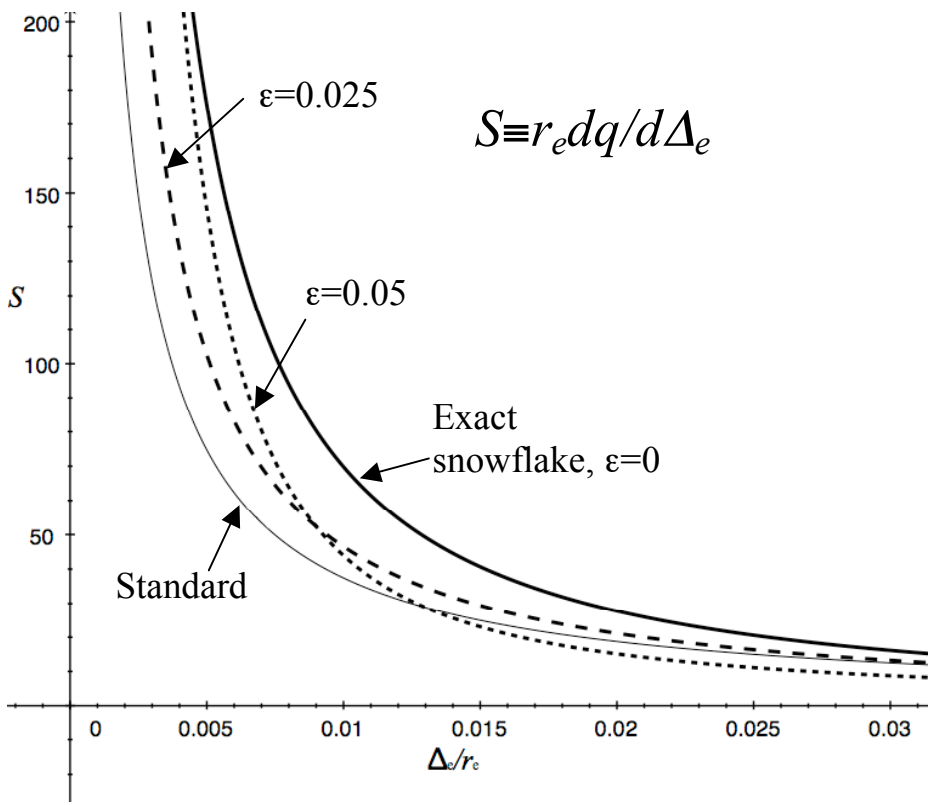
Carbon content in the core down by a factor ~ 2

Radiation from the core down by a factor ~ 2

Radiation from divertor up by a factor of a few

No noticeable adverse effect on core plasma density and temperature

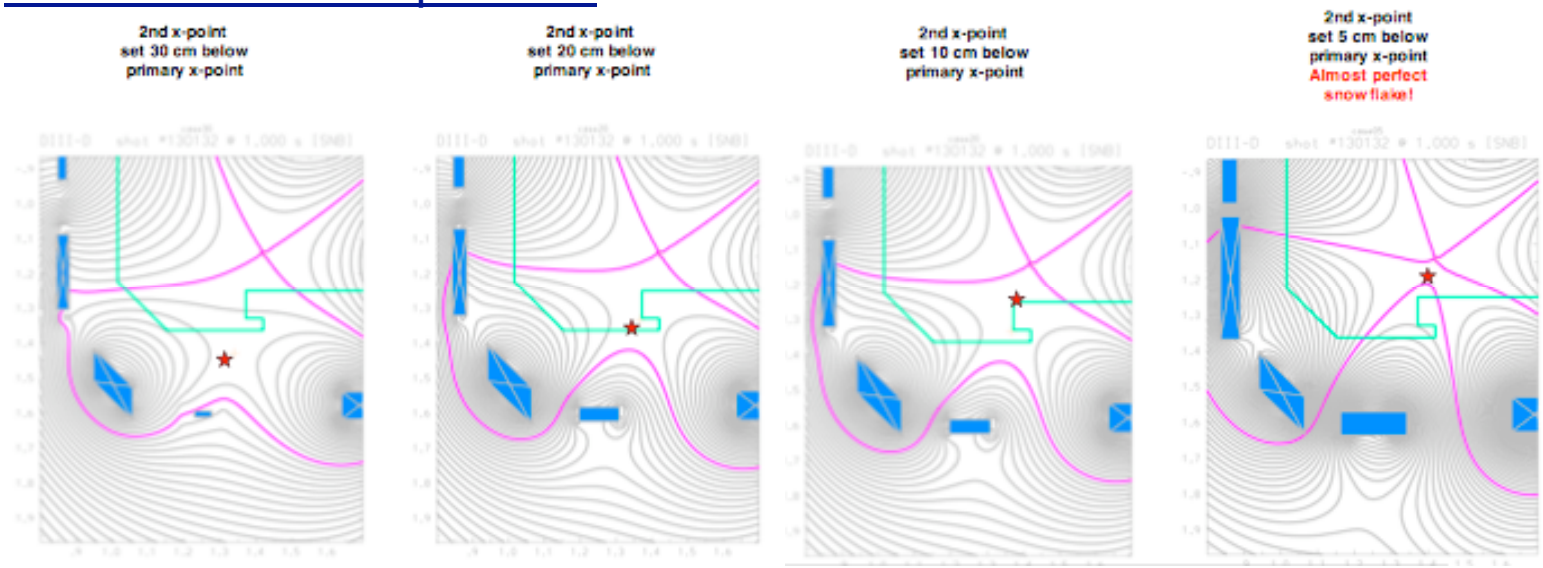
Magnetic shear *inside* the separatrix, in the pedestal region, can be controlled by changing the divertor current

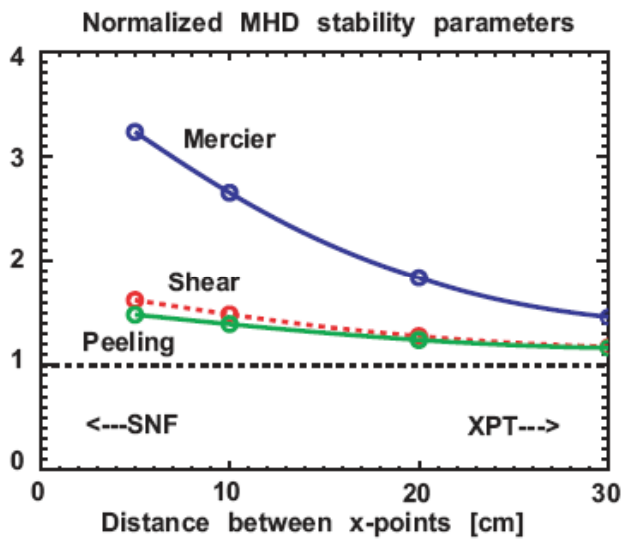


Magnetic shear for the standard X-point divertor (b/a=0.6), thin line, and for the snowflake-plus divertor (b/a=0.3), thick lines. Solid line: ε=0 (an exact snowflake), ε=0.025 (dashed line) and ε=0.05 (dotted line). Large values of the parameter S are related to the normalization. More important is the change of the S profile for the snowflake divertor compared to that of a standard divertor: in the immediate vicinity of the separatrix, the snowflake-plus divertor yields higher value of S, whereas at some distance from the separatrix, deeper into the pedestal region, S can become both larger and smaller than for the X-point divertor.

This may lead to significant degree of control over ELMs (P. Snyder et al, Phys Plasmas, 9, 2037 (2002).

Recent ELITE calculations have shown a stabilizing effect of the snowflake on MHD modes in the pedestal





M.V. Umansky, T.D. Rognlien, D.D. Ryutov, P. B. Snyder. "Edge Plasma in Snowflake Divertor," Contrib. Plasma Physics, **50**, 350, 2010.

Similar conclusion was reached in: S.Yu. Medvedev, A.A. Ivanov, A.A. Martynov et al, Contrib. Plasma Physics, **50**, 324, 2010

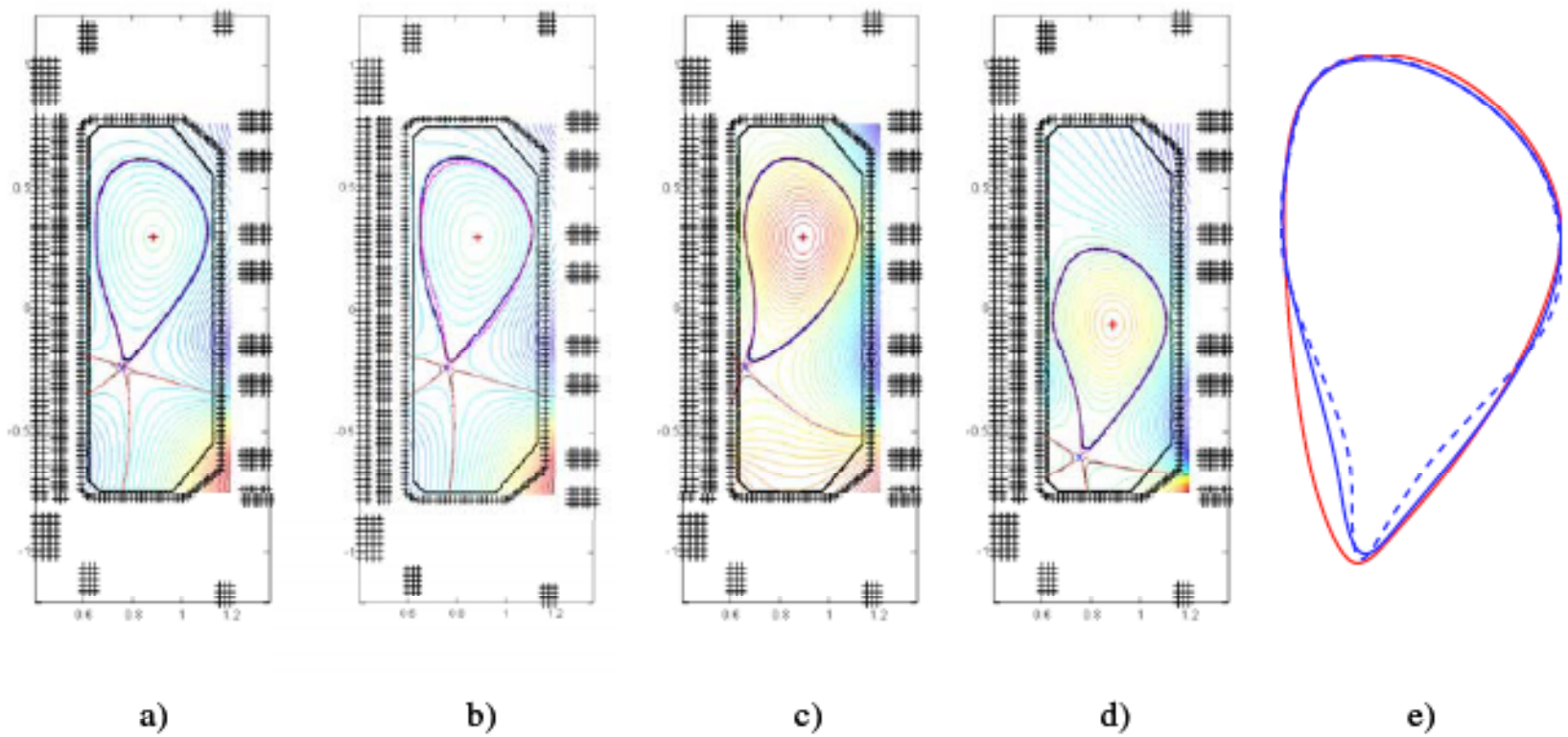
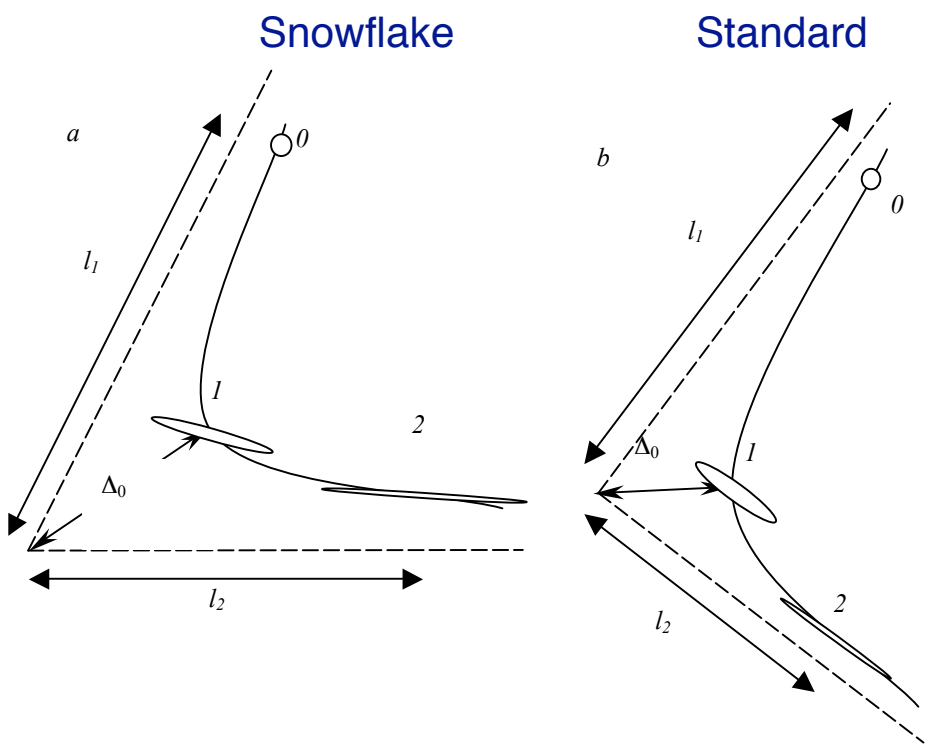


Fig. 1 Poloidal flux level lines for free boundary snowflake equilibria: (a) fit to the shot #36151 boundary $\delta_{up} = 0.2$; (b) increased upper triangularity $\delta_{up} = 0.4$, magenta dots show the target plasma shape; (c) large snowflake point triangularity $\delta_{down} = 0.8$; (d) snowflake on the floor of the TCV vacuum vessel; (e) snowflake boundary from Fig.1b (blue) compared to the x-point boundary (red) and to the snowflake boundary with large pedestal current density (dashed). (Online colour: www.cppjournal.org).

On the open field lines, the flux tube squeezing is much stronger in the snowflake than in a standard divertor



For a snowflake divertor

$$E_1 \approx 1.57 \frac{l_1^2}{\Delta_0^2} \qquad E_2 \approx 2.5 \frac{l_1^2 l_2^2}{\Delta_0^4}$$

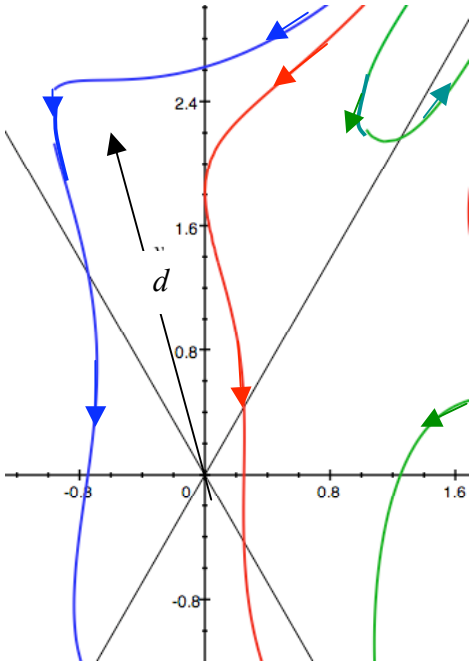
For a standard X-point divertor

$$E_{1X} = \frac{\sqrt{2} l_1}{\Delta_0} \qquad E_{2X} = \frac{2 l_1 l_2}{\Delta_0^2}$$

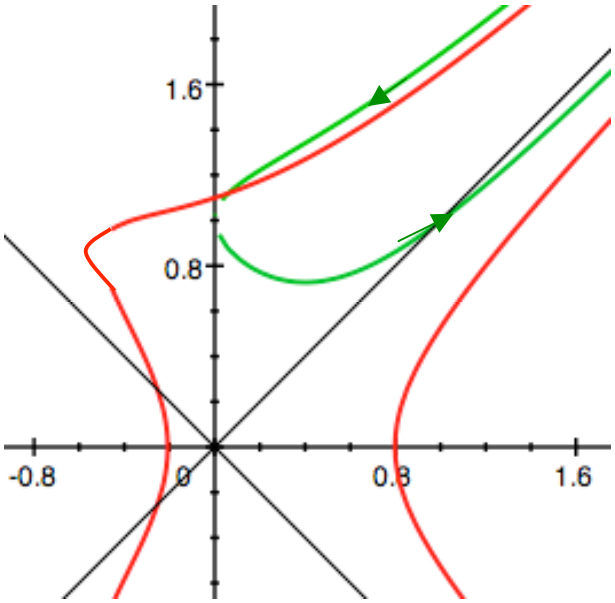
E = ellipticity of a squeezed, initially circular flux-tube (the ratio of the major semi-axis to the initial radius), see D.Farina et al, Nuclear Fusion, **33**, 1315 (1993).

A stronger squeezing leads to several changes in the blob behavior

ION DRIFTS IN THE VICINITY OF THE NULLPOINT LEAD TO STRONGER NON-AMBIPOLAR LOSS FROM THE PEDESTAL (STRONGER PEDESTAL SHEAR FLOW)



Snowflake
[affected zone: $(d/a)<(q_0\rho_i/a)^{2/5}$]



X-point (C.S. Chang)
[affected zone: $(d/a)<(q_0\rho_i/a)^{2/3}$]

D.D. Ryutov, M.V. Umansky. “Ion Drifts in a Snowflake Divertor.” “Phys. Plasmas,” **17**, 014501, 2010.

SNOWFLAKE DIVERTORS FOR POWER PLANTS

- Can be created by a set of PF coils situated outside TF coils

- Favorable effects of a snowflake, while having a global character, are caused by the changes of the poloidal field in a small volume near the null-point: no gross change of the plasma shape is needed.

- These effects include:

  - An easier detachment and reduction of the heat loads (big radiating “bulb”)

  - Control over ELMs (stronger shear inside; higher radial electric field in the pedestal)

  - Control over blobs

- Ongoing experiments with TCV and NSTX will provide a lot of information for the future engineering assessments of the snowflake