LLNL-PRES-406499

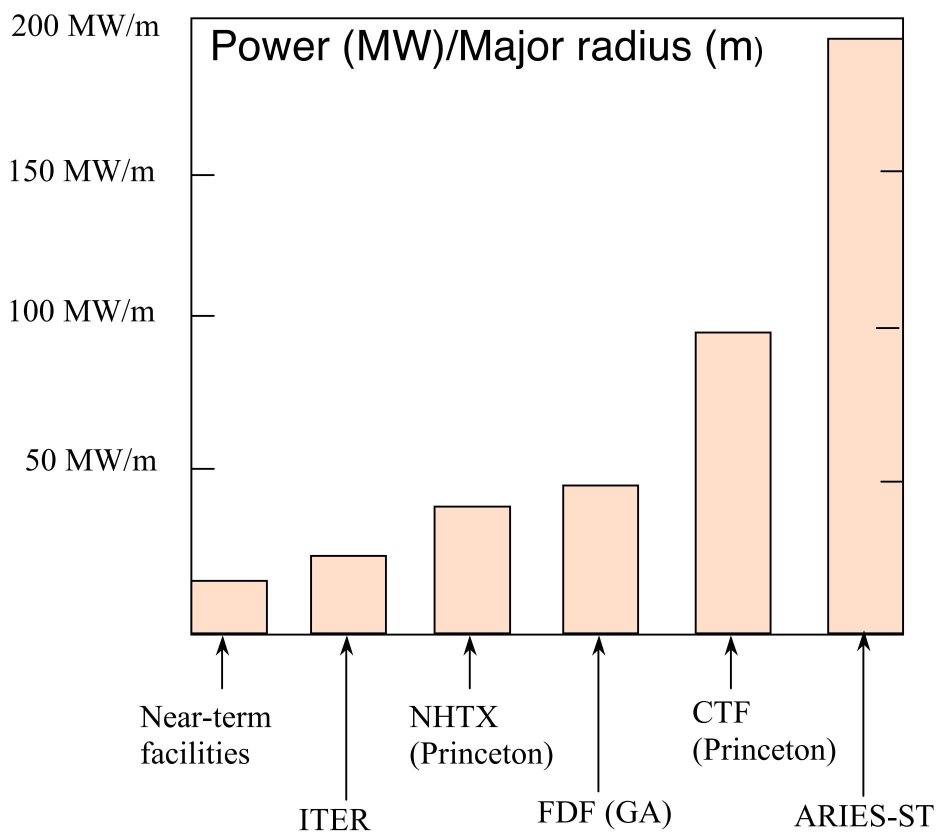
A Snowflake Divertor - an Attempt to Solve the Heat Load Problem for Future Tokamaks*

D.D. Ryutov,
in collaboration with R. Bulmer, R.H. Cohen, T.D. Rognlien, M.V. Umansky

International Workshop "Theory of Fusion Plasmas"
(Varenna, August 25-29, 2008)

*Prepared by LLNL under Contract DE-AC52-07NA27344.

The divertor heat load problem becomes very severe for future fusion facilities based on tokamaks



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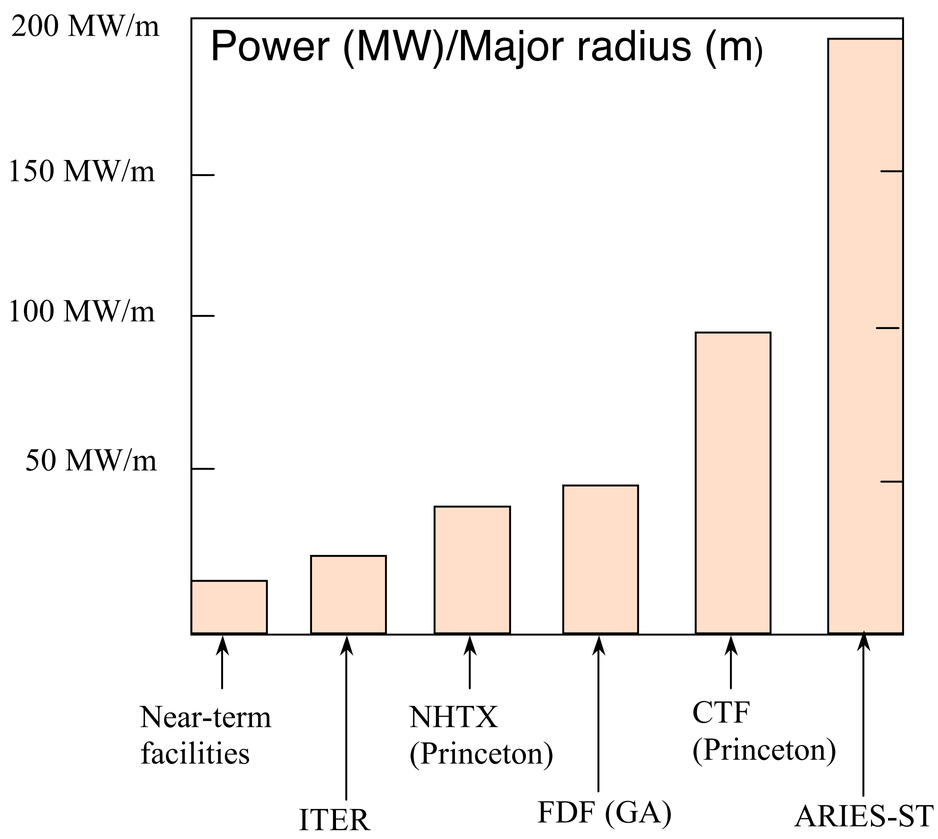

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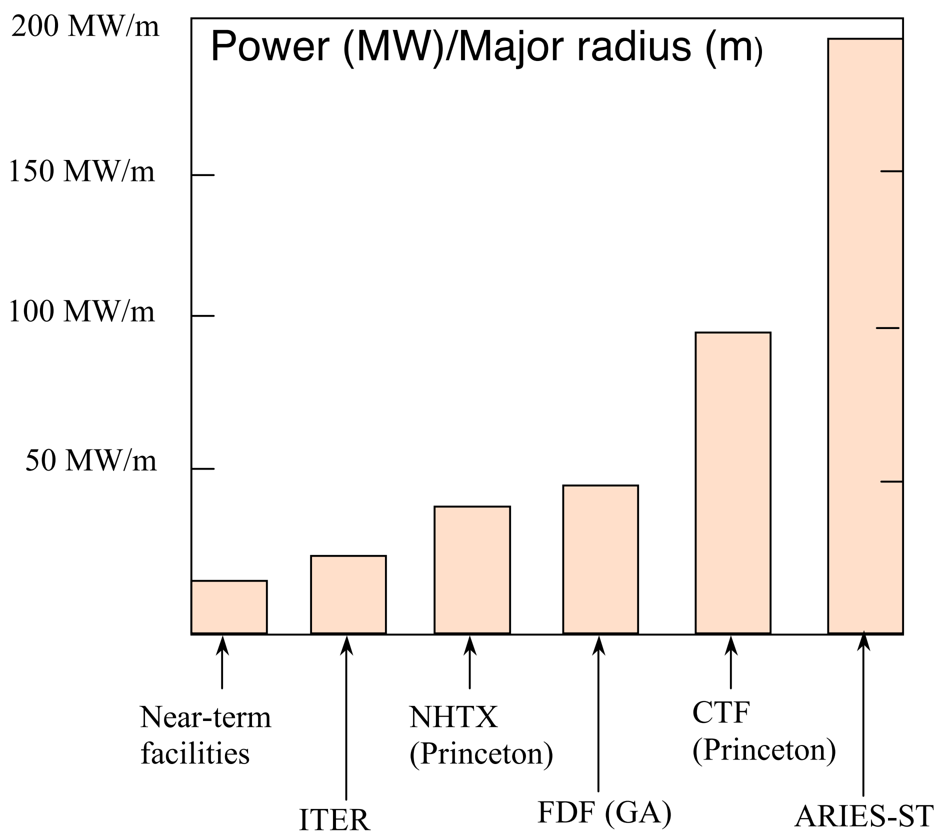

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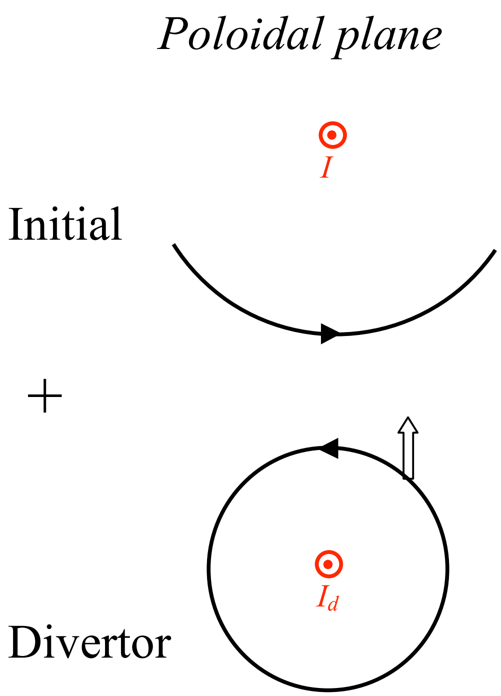
New approaches needed!

A "standard" X-point divertor is based on a poloidal field configuration with a first-order null of the magnetic field



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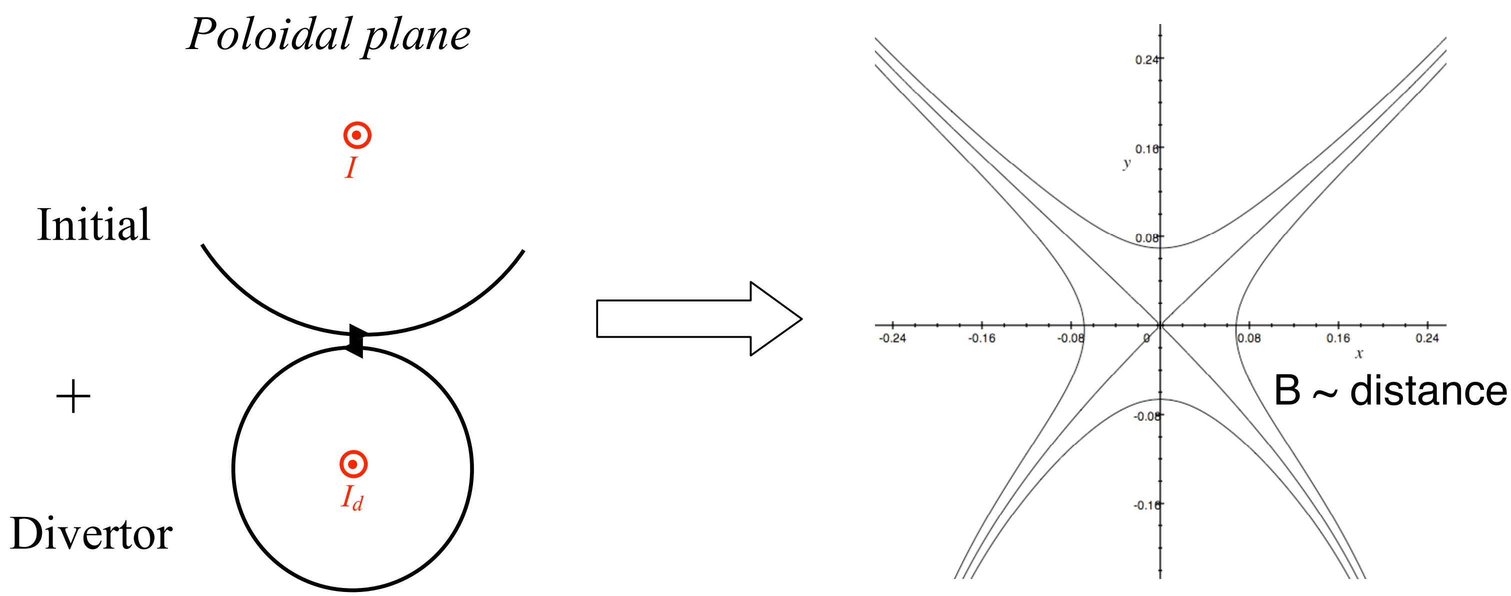
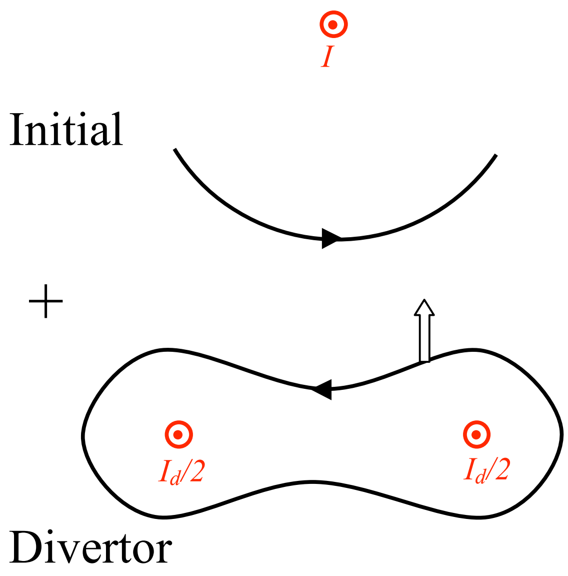


If one wants to make a second-order null of the poloidal magnetic field in a chosen point, one should design the divertor coils in such a way as to satisfy two conditions:

1. The magnetic field of divertor coils in 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



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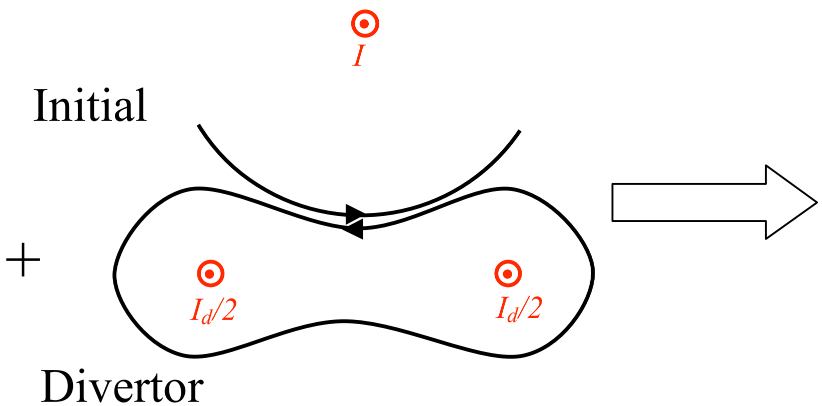

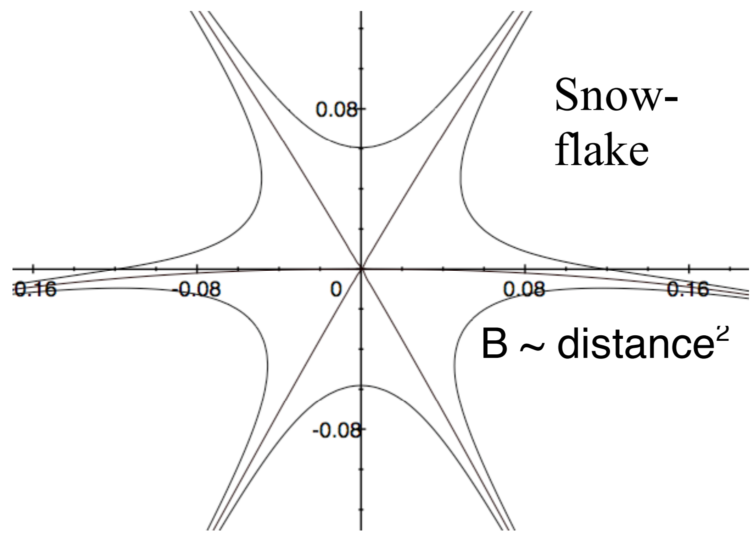

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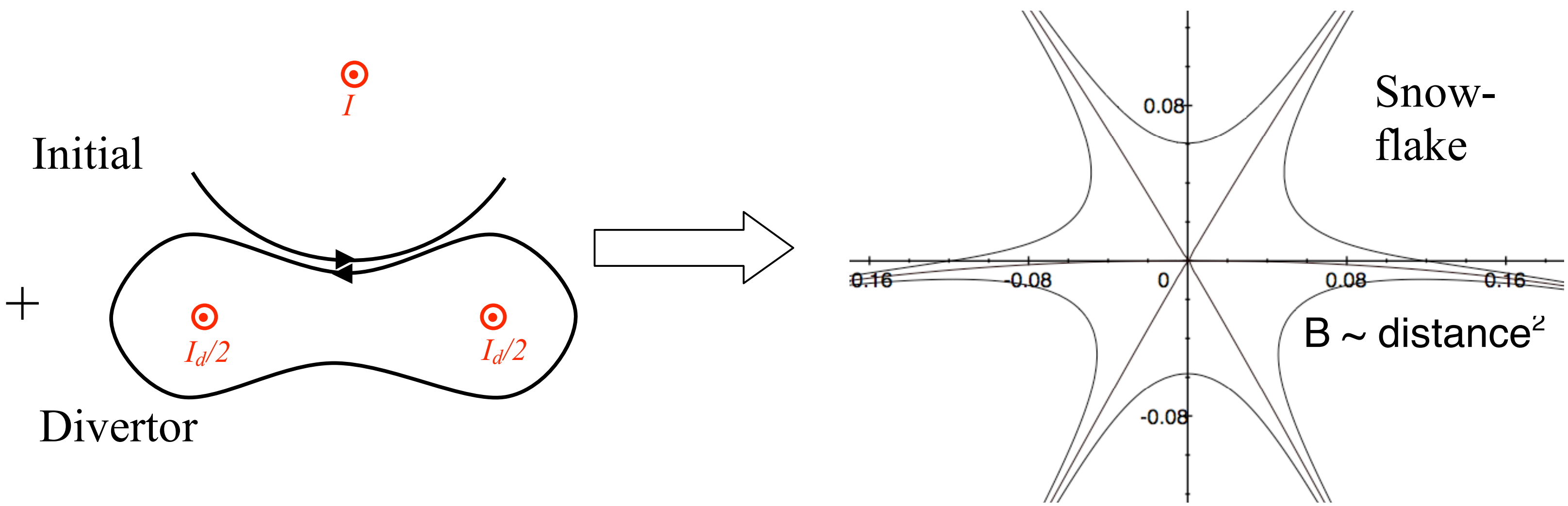
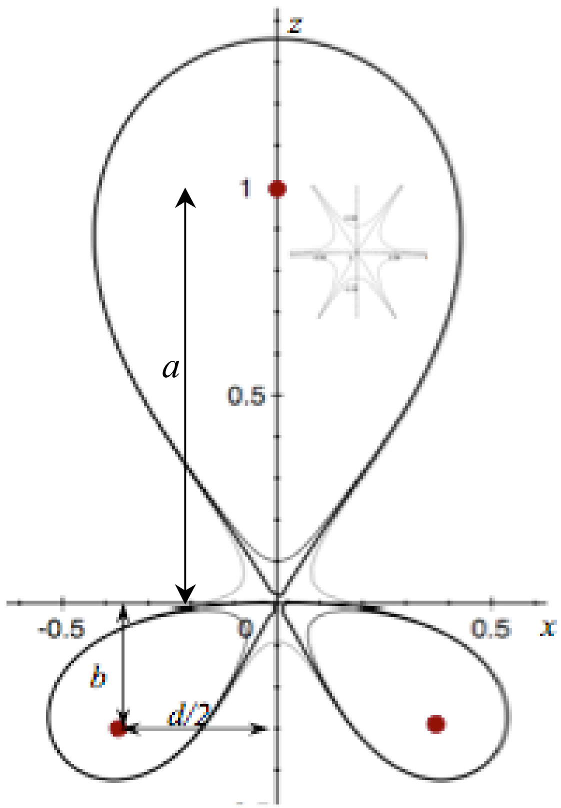


There occur both significant flux expansion and increase of the connection length

A snowflake divertor



Snowflake divertor in symmetric 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

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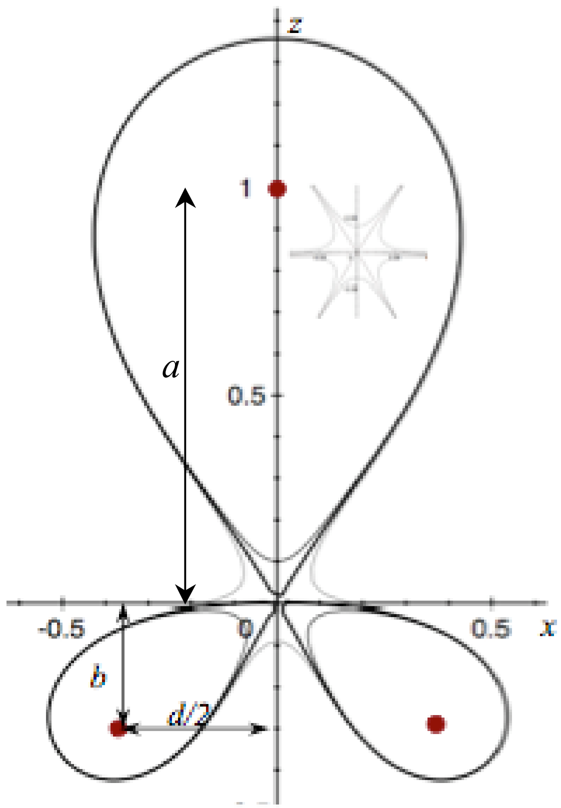

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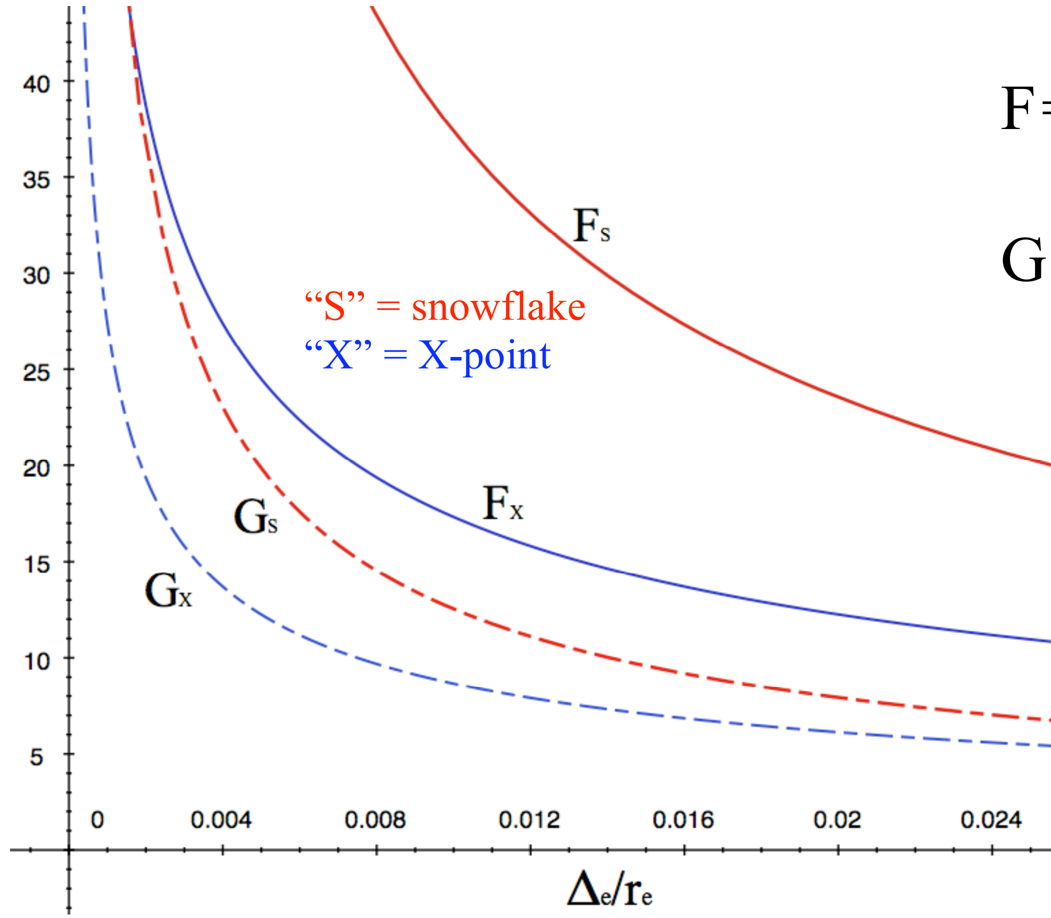
Divertor coils can be situated outside TF coils!

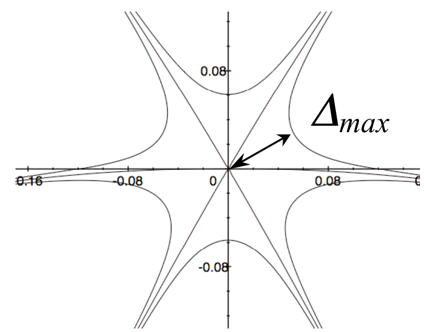
More details in: D.D. Ryutov. Phys. Plas, **14**, 064502, 2007; D.D. Ryutov, R.H. Cohen, T.D. Rognlien, M.V. Umansky. Phys. Plas, **15**, #8, 2008

Flux expansion in the snowflake divertor is 2-3 times stronger than in a standard X-point divertor



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

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



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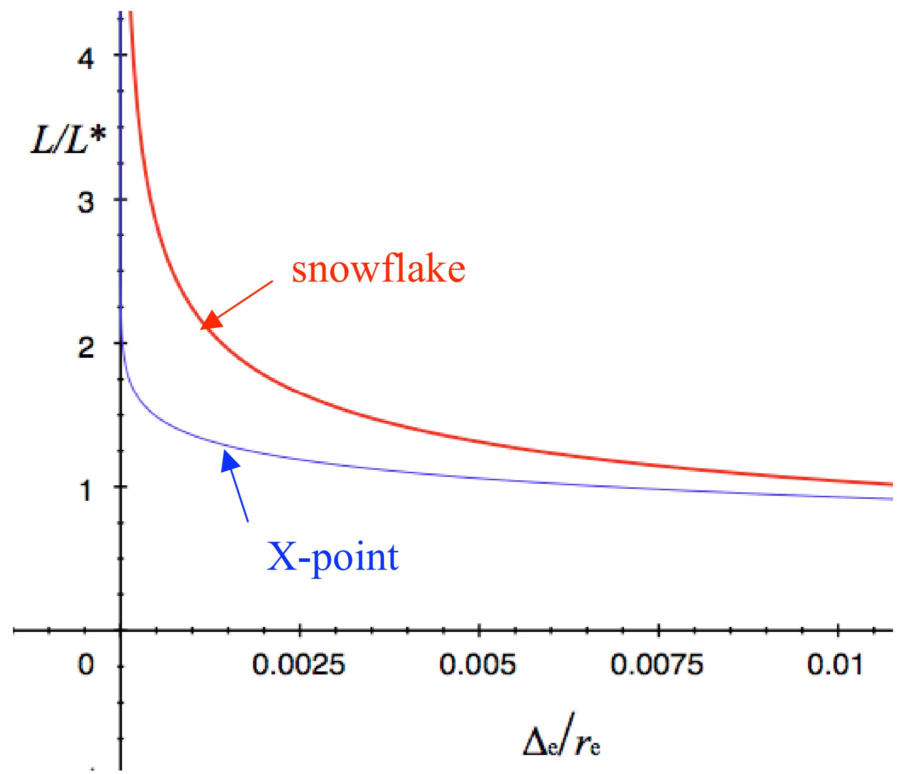
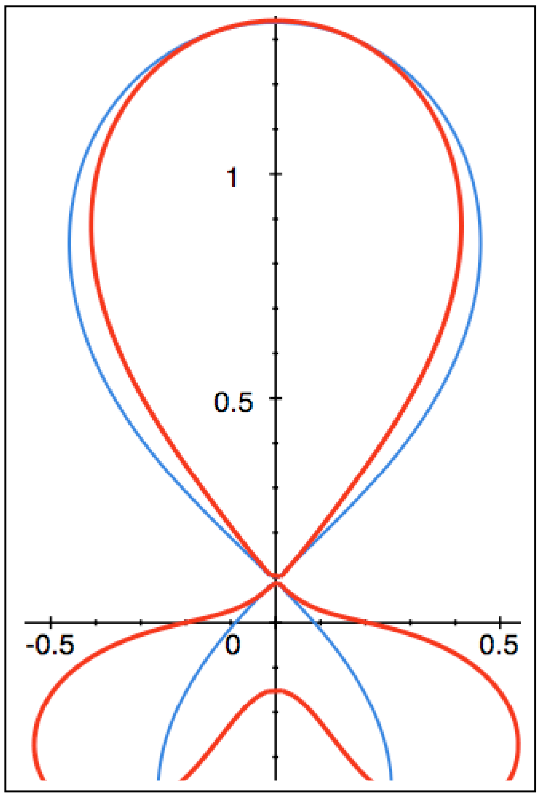
In the vicinity of the separatrix, connection length between the equatorial plane and the divertor zone is significantly larger in the snowflake divertor



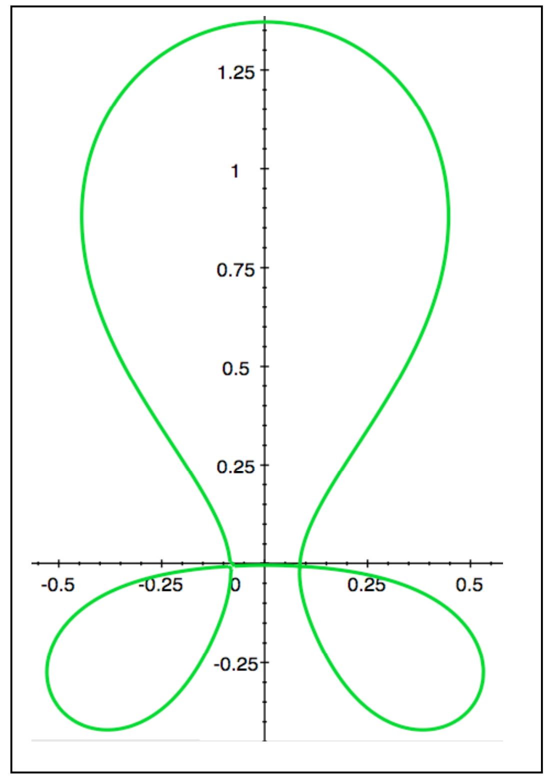
A problem: the *exact* snowflake configuration is topologically unstable

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).

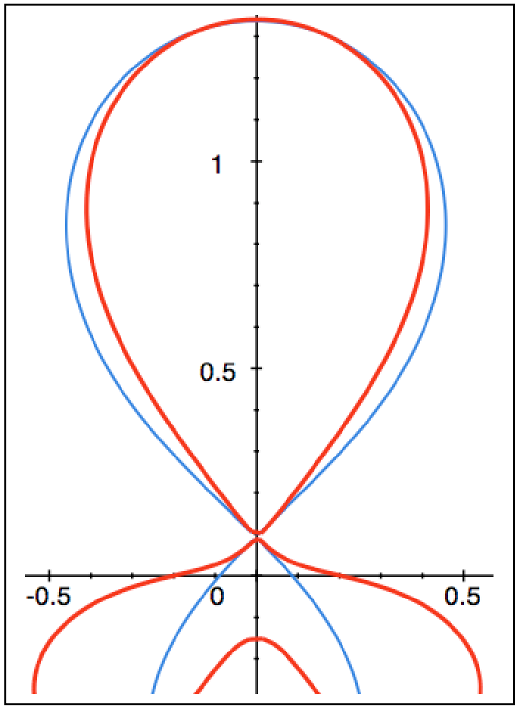


The divertor current is 5% higher than I_{d0}. We call this configuration "snowflake-plus"

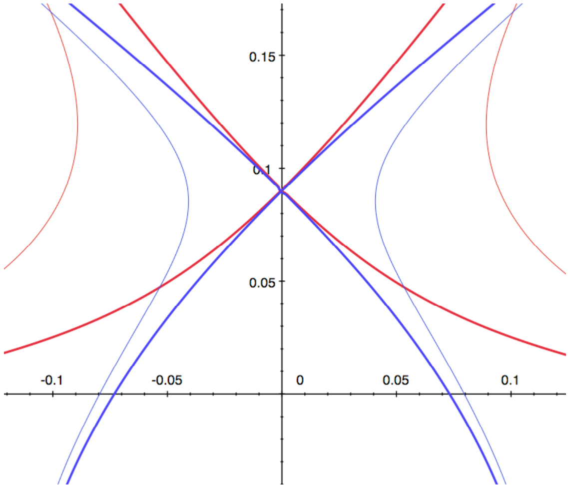
The divertor current is 5% lower than I_{d0}. We call this configuration "snowflake-minus"



We choose the snowflake-plus configuration as our prime candidate, $I_d = I_{d0}(1+\varepsilon)$

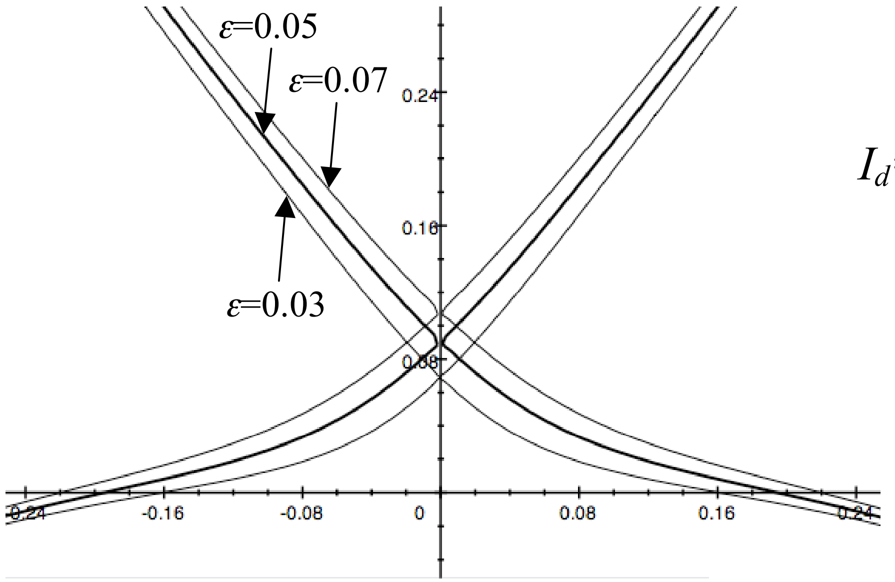


Shown in red is the configuration with ε=0.05; the blue curve shows a "standard" X-point configuration with almost the same shape of the separatrix above the X-point. We use it as a reference.



The 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 2.5 times higher for the snowfake-plus configuration

The snowflake-plus configuration is remarkably robust!



$I_d=I_{d0}(1+\varepsilon)$

Change of the separatrix shape in the vicinity of the null point with the change of the divertor current. The central (bold) line corresponds to a reference case of ε=0.05. The upper thin line corresponds to ε=0.07, whereas the lower thin curve corresponds to ε=0.03. With this variation, the motion of the separatrix is insignificant.

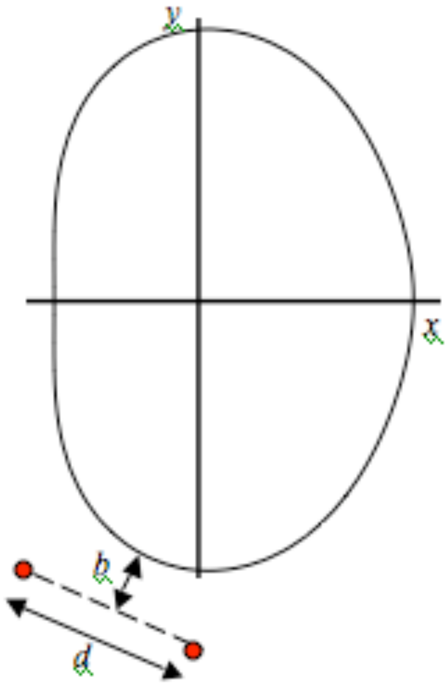
The snowflake configuration exists in the toroidal geometry

(see derivation in Ryutov, Phys. Plasmas, **14**, 064502, 2007)

For a given initial magnetic field, two divertor coils do the job: they allow one to create second-order null at a chosen point.

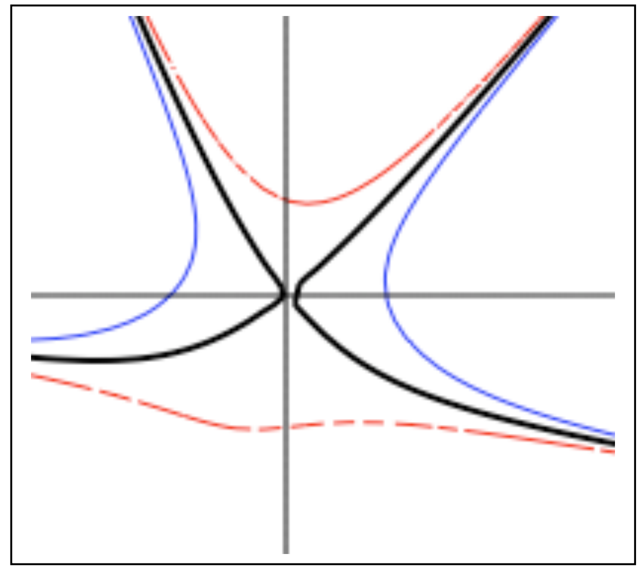
2 coils = 6 parameters (2 currents, 4 coordinates), with 4 constraints; 2 parameters remain free and determine the orientation of the snow-flake and the rate of the spatial variation of the field.

The snowflake configuration can be used with strongly shaped plasmas



Generating SF-plus field for the highly shaped plasma. The distance between the divertor conductors (shown in red) is *d*.
Two conditions have to be satisfied:

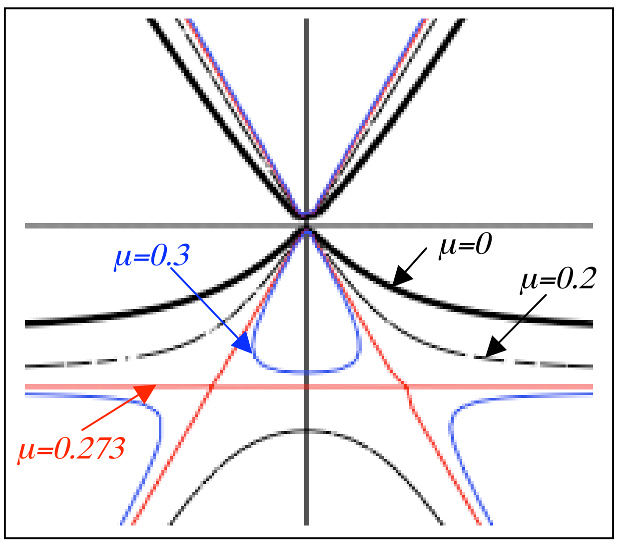
$$\frac{2I_d}{c}\frac{b}{b^2+(d/2)^2}=B_0;\ \frac{1}{b}\cdot\frac{(d/2)^2-b^2}{(d/2)^2+b^2}=\kappa_0$$



The shape of the separatrix and two adjacent flux surfaces in the vicinity of the null-point for the asymmetric case.

The effect of the toroidal current in the null-point region is minor, unless the toroidal current at the separatrix is excessively large

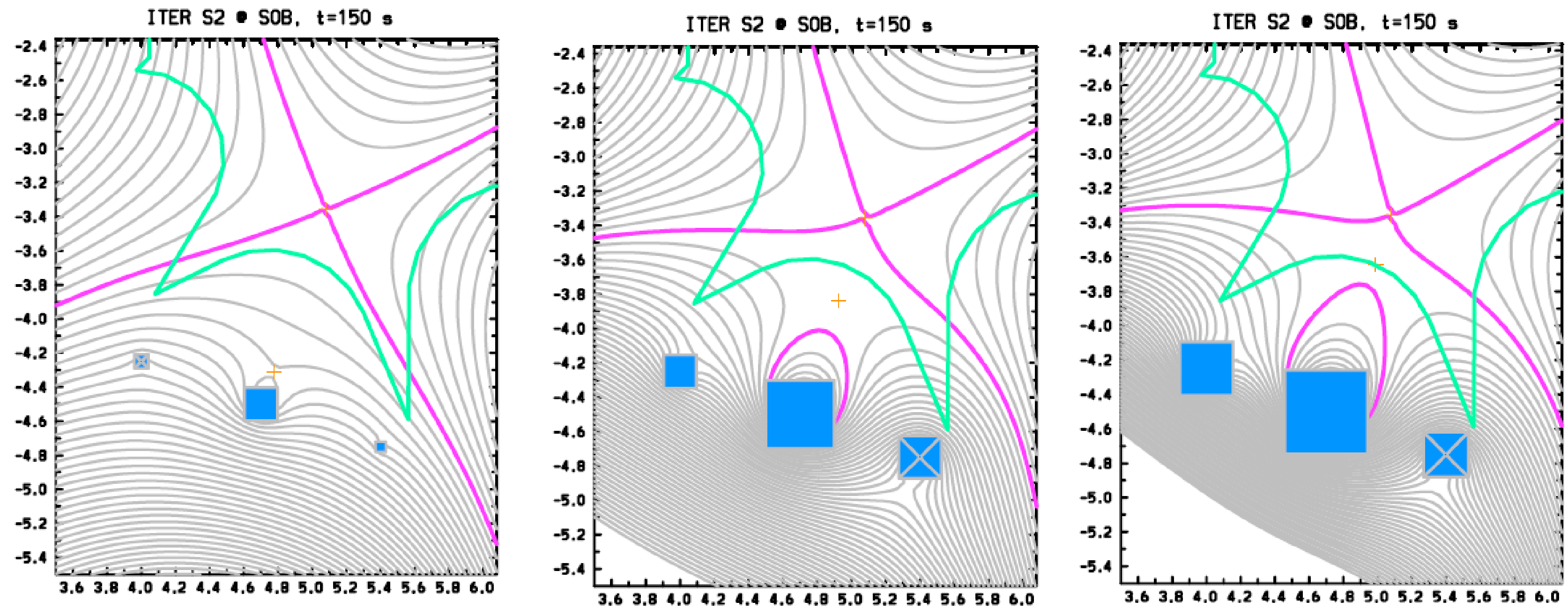
The shape of the separatrix for various values of the toroidal current density near the null-point: ε=0.05, $b\kappa_0$=0.2, (symmetric case)



$$\mu \equiv j_{zd} / \bar{j}_z$$

Thick black line corresponds to μ=0, thin black line to μ=0.2, red line to $\mu = \mu_{crit}$ =0.273, and blue line to μ=0.3. One sees that the effect on the separatrix is small even at the parameter μ as high as 0.2.

Snowflake configuration can be created in the ITER geometry (although not necessarily with the existing set of PF coils)



Corsica equilibria produced for the ITER configuration by M. Umansky and R. Bulmer

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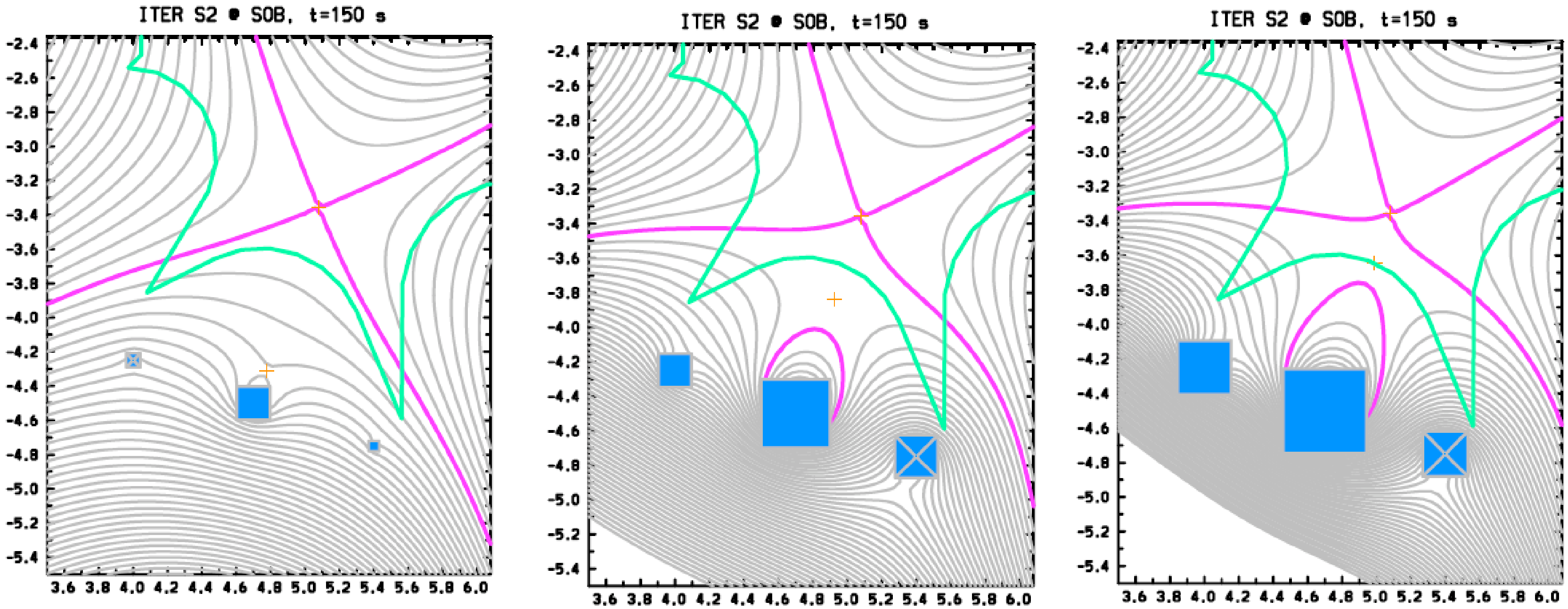

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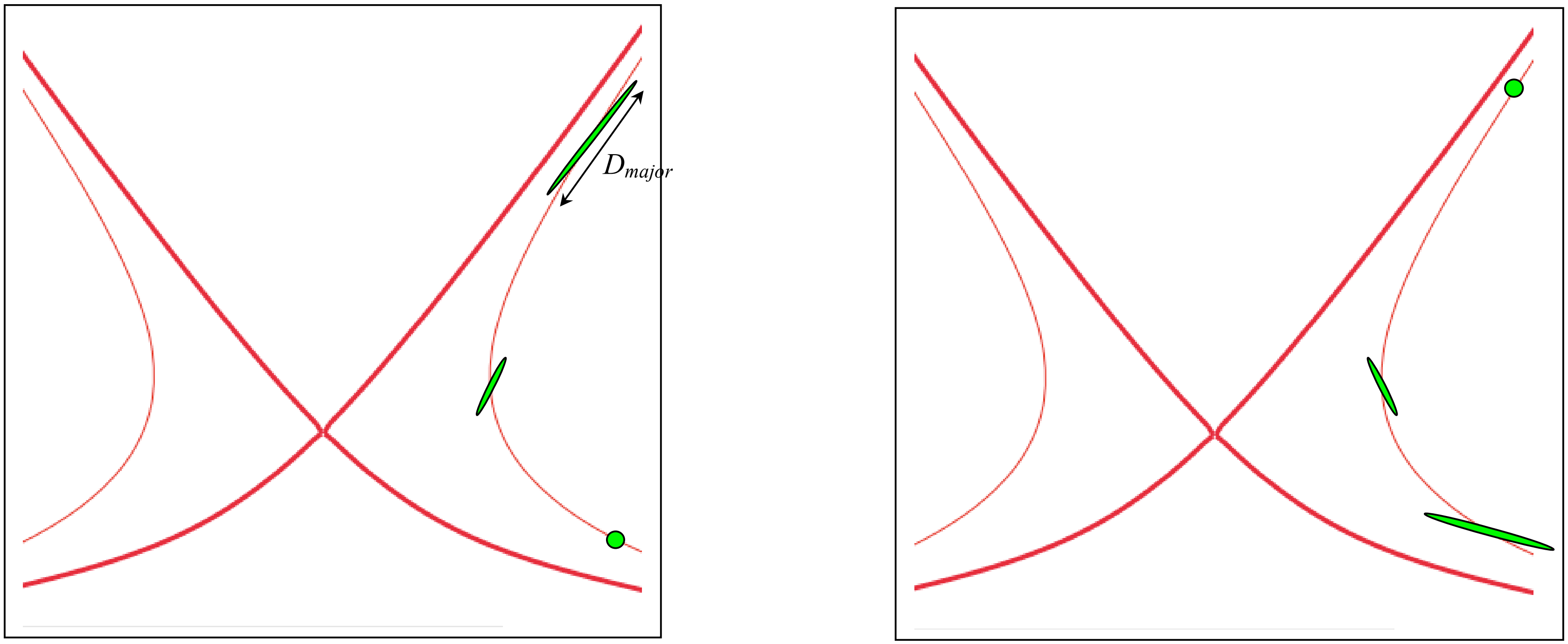
Snowflake configuration can be produced *with the existing set of PF coils* at DIII-D (Umansky, Bulmer), NSTX (Soukhanovsky), and NHTX (Menard)

Snowflake causes a stronger squeezing of the fluxtube passing passes near the null-point (in SOL)

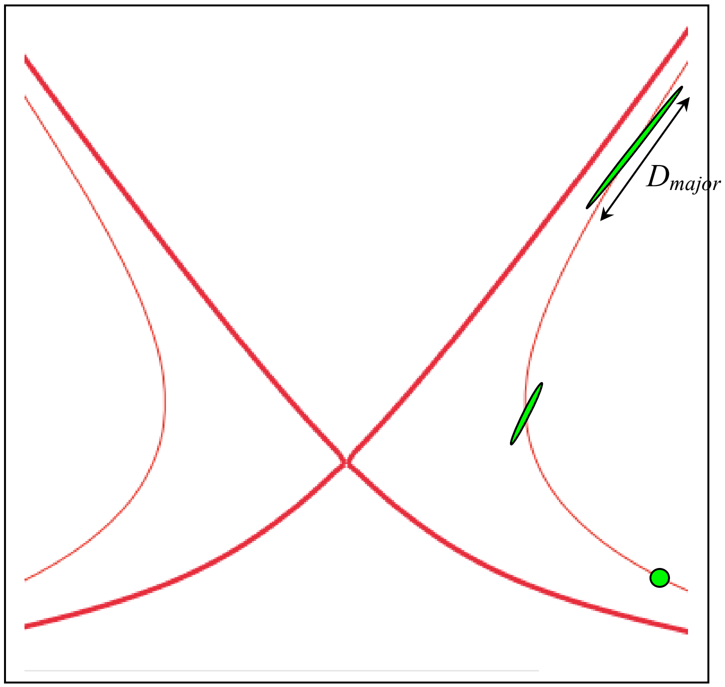


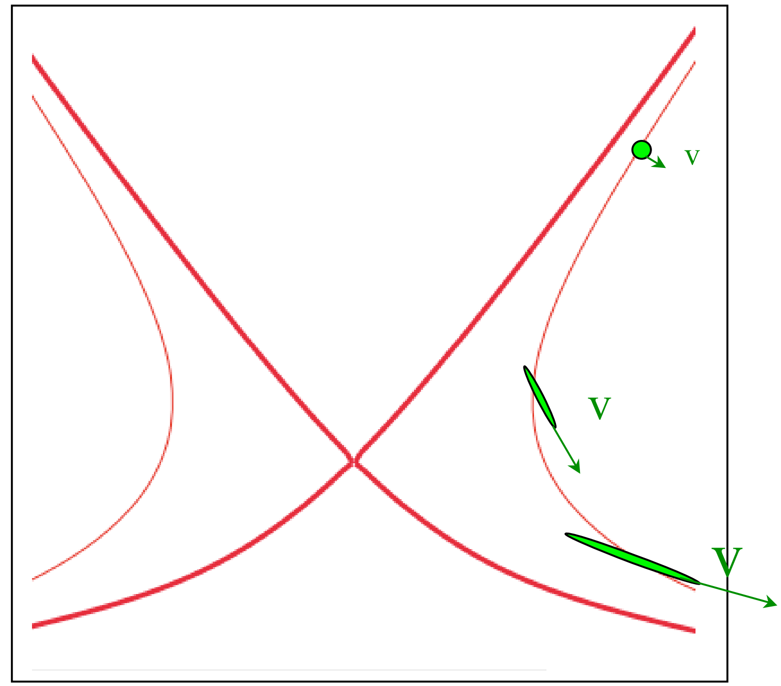
Elongation:

$$E_S \equiv D_{major}/D_0 \sim (r_e/\Delta_e)^{4/3}; \; E_X = r_e/\Delta_e$$

D_0= initial diameter of the fluxtube; Δ_e=SOL thickness in the equatorial plane; r_e ~ minor radius

Snowflake causes a stronger squeezing of the fluxtube passing passes near the null-point (in SOL)

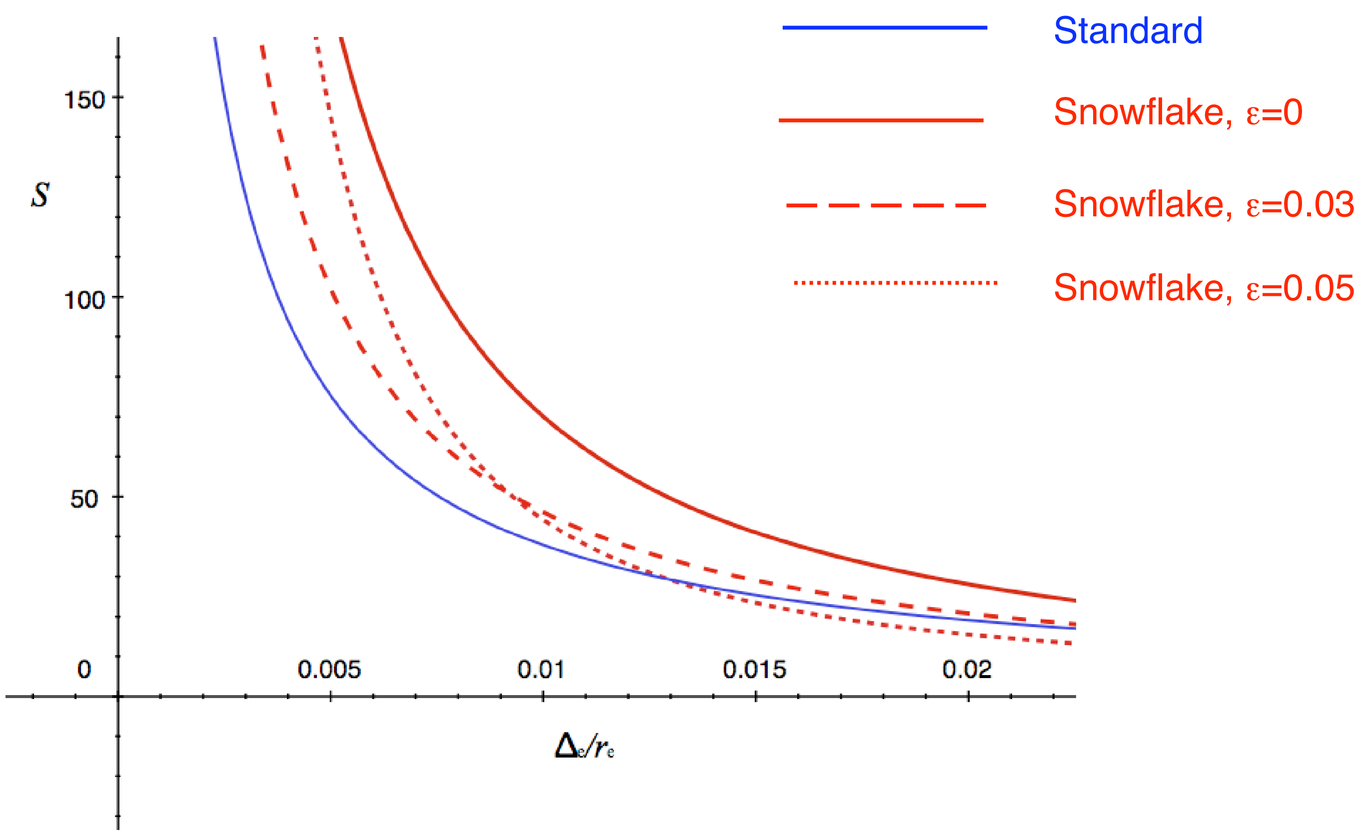




High elongation means:

1) Decoupling of the divertor convection/turbulence from the upper SOL
2) Slower convective ("blob") transport in the main SOL

Magnetic shear inside the separatrix increases compared to the standard divertor



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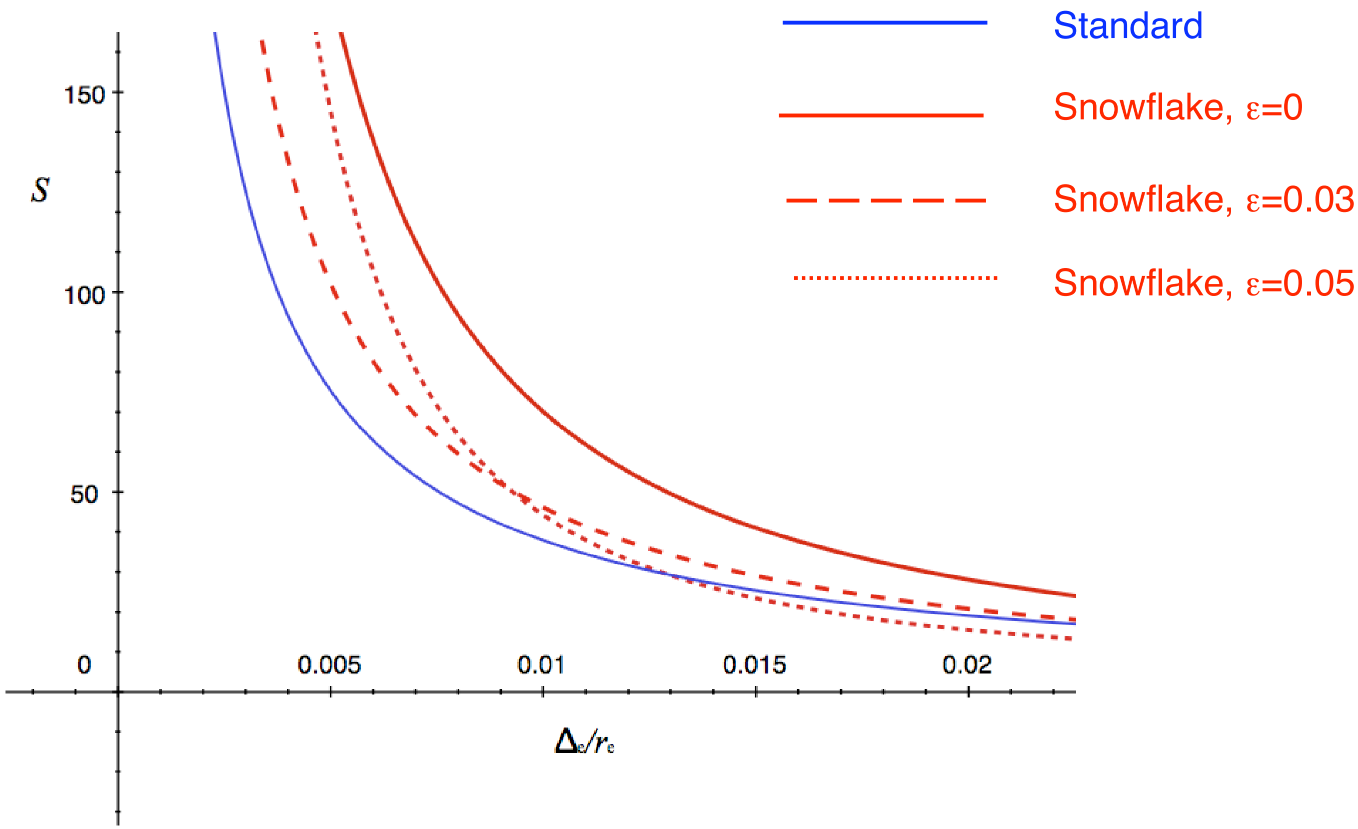
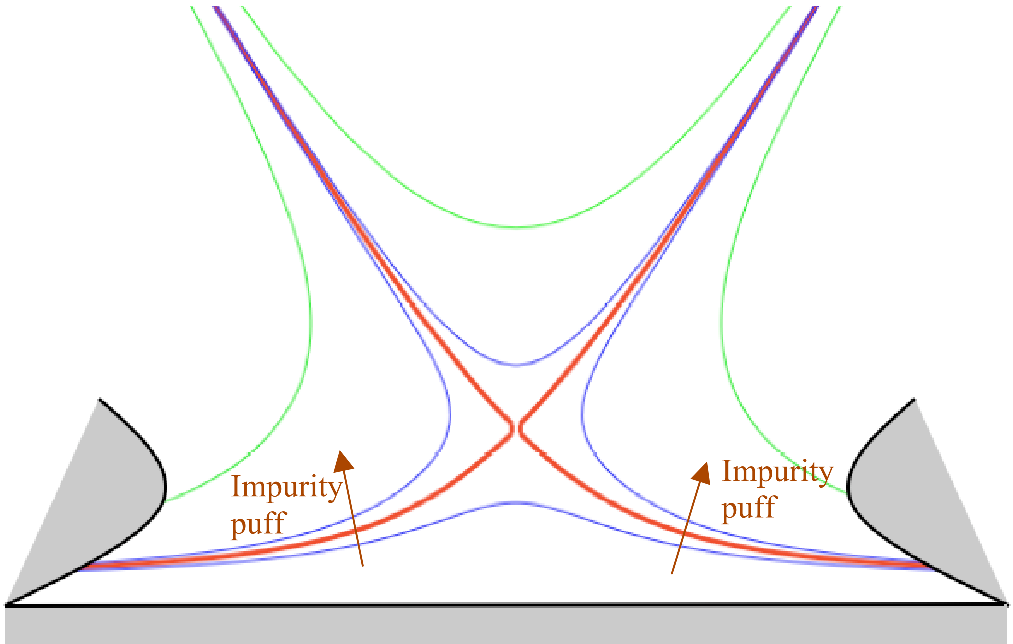


Control over shear means control over ELMs

P.B. Snyder, H.R. Wilson, J.R. Ferron, L.L.Lao, et al. Phys. Plasmas, **9**, 2037 (2002); A.J. Webster, C.G. Gimblett. Paper 3B03, International Sherwood Fusion Theory Conference, Boulder, CO, 31 March – 2 April 2008

The snowflake divertor is amenable to the radiation cooling technique (larger connection length, larger radiating volume)



Small amount of impurities is sufficient for significant cooling

One can puff them below the null point, to minimize their effect on the core plasma

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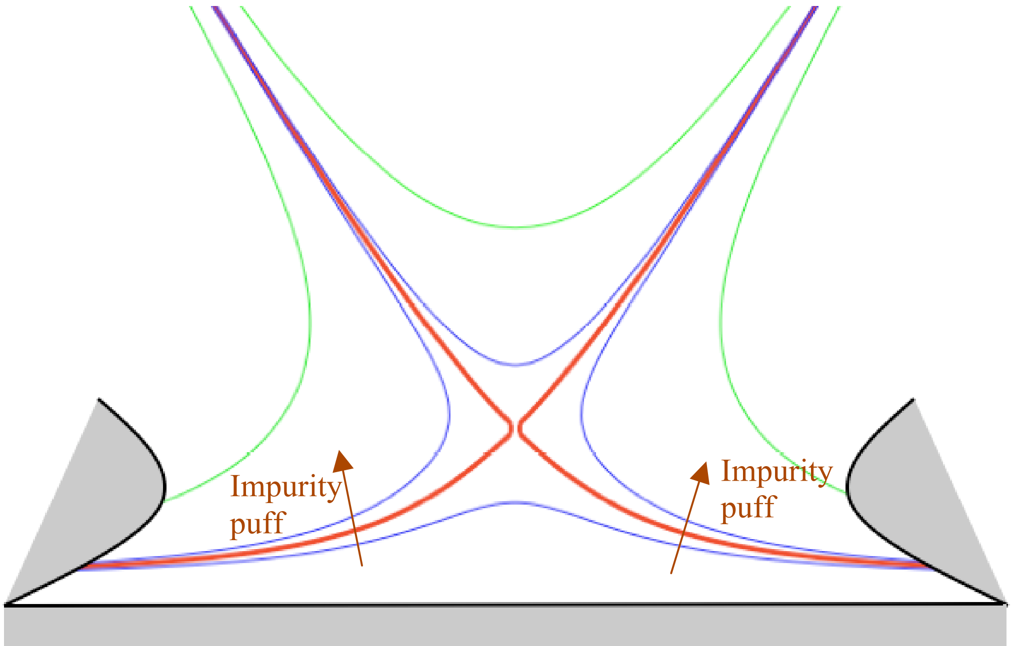

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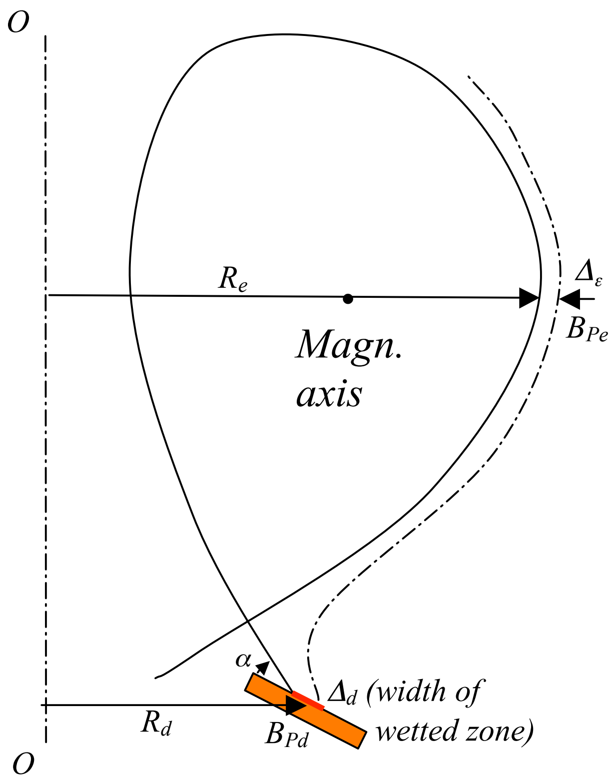
UEDGE simulations produce encouraging results (M. Umansky, T. Rognlien)

There exist geometrical constraints on the achievable size of the wetted area

$$B_{Pe}R_e\Delta_e = B_{Pd}R_d\Delta_d \sin\alpha$$



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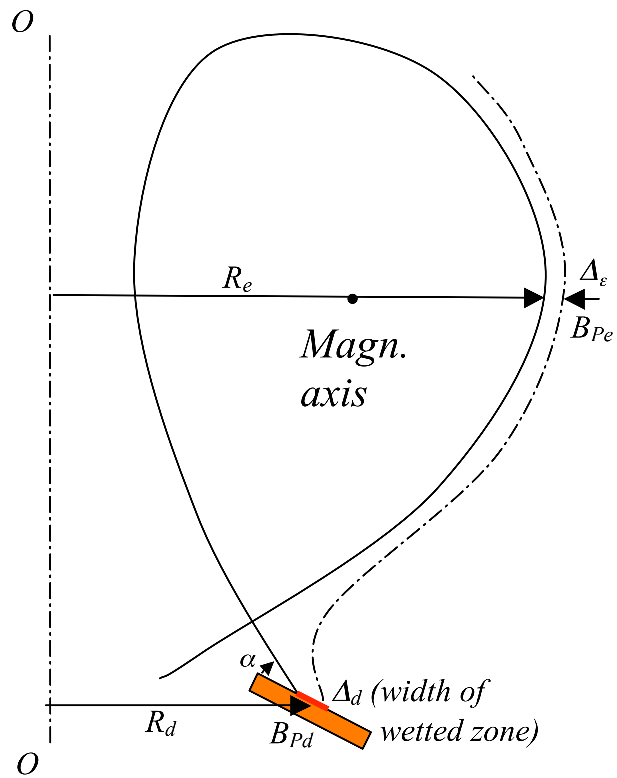

$B_{Pe} R_e \Delta_e = B_{Pd} R_d \Delta_d \sin\alpha$

Surface area of the wetted zone:

$2\pi R_d \Delta_d = (2\pi R_e \Delta_e)(B_{Pe}/B_{Pd} \sin\alpha)$

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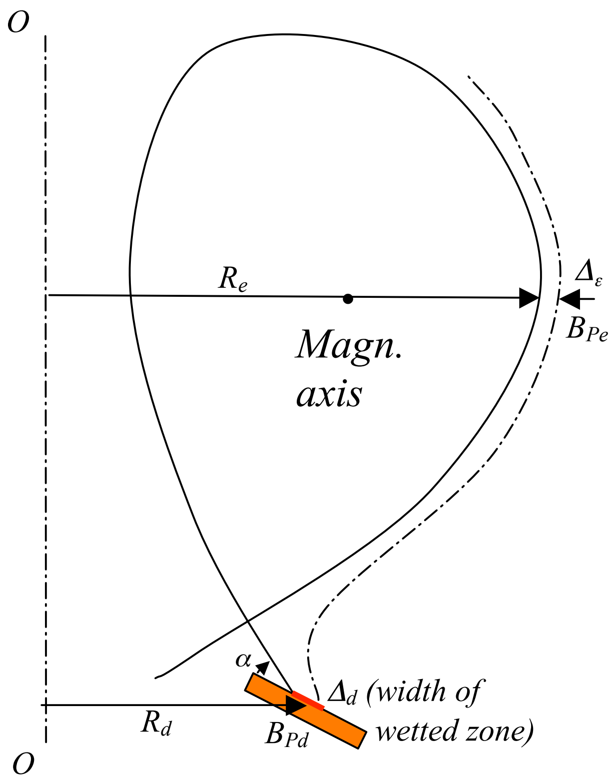

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$\gamma \approx (\sin\alpha) B_{Pd}/B_{Td}$

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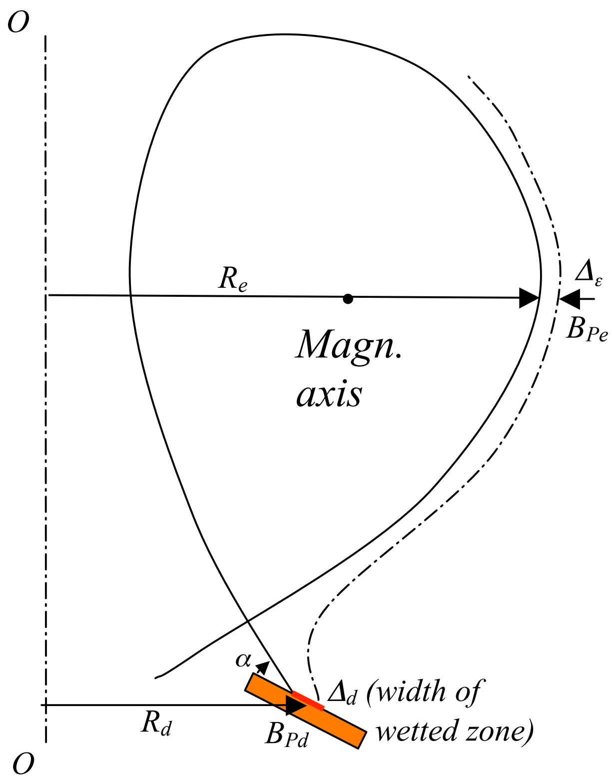

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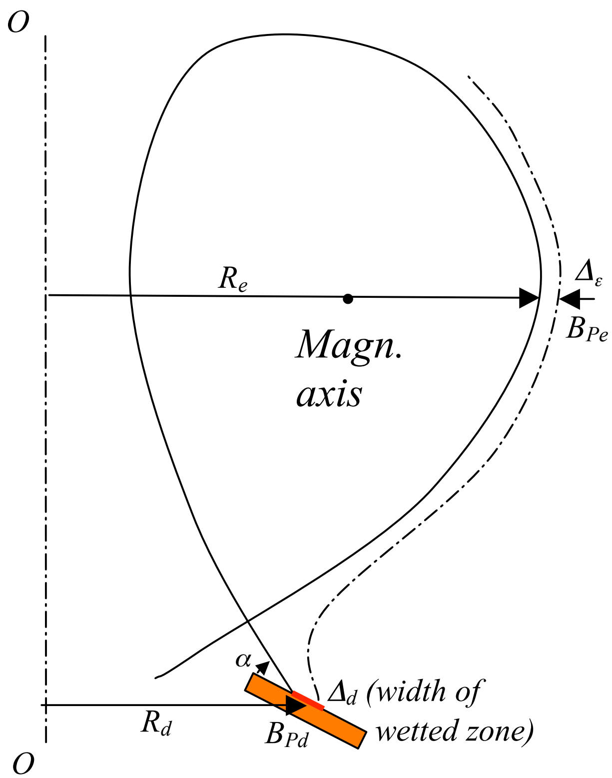

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$$2\pi R_d\Delta_d=(2\pi R_e\Delta_e)\ (B_{Pe}/\gamma B_{Td})=$$
$$(2\pi R_e\Delta_e)(B_{Pe}/\gamma B_{Te})(R_d/R_e)$$

General strategy of using snowflake divertor in future fusion devices

Use large flux expansion to enhance radiation (puff and pump*?)

Recompress flux and induce as strong turbulent transport in the divertor legs as possible

Use the strongest tilt compatible with engineering constraints

Fine tune the geometry near the null point to have the most favorable effect on ELMs

*Petrie TW, Wade MR, Brooks NH, Fenstermacher ME, Groth M, Hyatt AW, et al, Journal of Nuclear Materials, vol.363-365, 15 June 2007, pp. 416-20.

Physics issues for the future work:

- What are effects of the "snowflake" divertor geometry on the plasma stability in the pedestal region? What is its effect on ELMs? (Much higher *q*'s, stronger shear, possible effect on neoclassic orbits.)

- What is, quantitatively, effect of the divertor shear on various flute-like modes in the open-field-line region? (The shear is stronger now than in a standard X-point geometry).

- How will snowflake divertor operate in the radiative mode?

- Is there a merit of operating this divertor very close to the ideal snowflake mode (ε=0)?

- What would be the properties of a snowflake-minus configuration? Any advantages?

Engineering issues for the future analysis

- What is a reasonable constraint on the tilt angle γ?
- Can some of the PF coils be placed inside TF coils?
- Near plasma?

SUMMARY

- An approach based on the use of a snow-flake divertor opens up a promising new area of the operational space, an area characterized by:
    - strong flux expansion near the x-point
    - reduction of the convective ("blob") transport in the main SOL
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- Configuration is robust and can be used in strongly shaped plasmas, both with single-null and double-null configurations

Relevant references

R.H. Cohen, B. LaBombard, D.D. Ryutov, et al. Nucl.Fusion, **47,** 612, July 2007.

R.H. Cohen, D.D. Ryutov. Nucl. Fusion, **37**, 621 (1997).

G.F. Counsell, A. Kirk, R.H. Cohen, et al. Nucl. Fusion, **43** 1197-1203 (2003).

D.Farina, R.Pozzoli, D.D. Ryutov. Nuclear Fusion, **33**, 1315 (1993).

M. Kotschenreuther, P.M. Valanju, S.M. Mahajan, J.C. Wiley. Phys. Plasmas, **14,** 072502 (2007).
M. Kotschenreuther, et al, 2004 IAEA Fusion Energy Conference (Vilamoura, Portugal, 1-6 November 2004) paper IC/P6-43.

M. Kotschenreuther, P.M. Valanju, S.M. Mahajan. "High Power Density Experiment (HDPX) – A Next Step Device in the Age of ITER." Paper 1C presented at the 2008 Intern. Fusion Theory Conf, Boulder, CO, March 31-April 2, 2008.

S.I. Krasheninnikov. Phys. Lett. **A283**, 368 (2001).

F. Najmabadi and the ARIES team, Fus. Eng. Des., **38**, 3 (1997).

D.D. Ryutov. Phys. Plasmas, **13**, 122307 (2006)

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

D.D. Ryutov, R.H. Cohen, T.D. Rognlien, M.V. Umansky. Phys. Plasmas, **15**, #8 (2008).

P.B. Snyder, H.R. Wilson, J.R. Ferron, L.L.Lao, et al. Phys. Plasmas, **9**, 2037 (2002)