LLNL-PRES-56280

# A snowflake divertor: solving a power exhaust problem for tokamaks

D.D. Ryutov

*Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*

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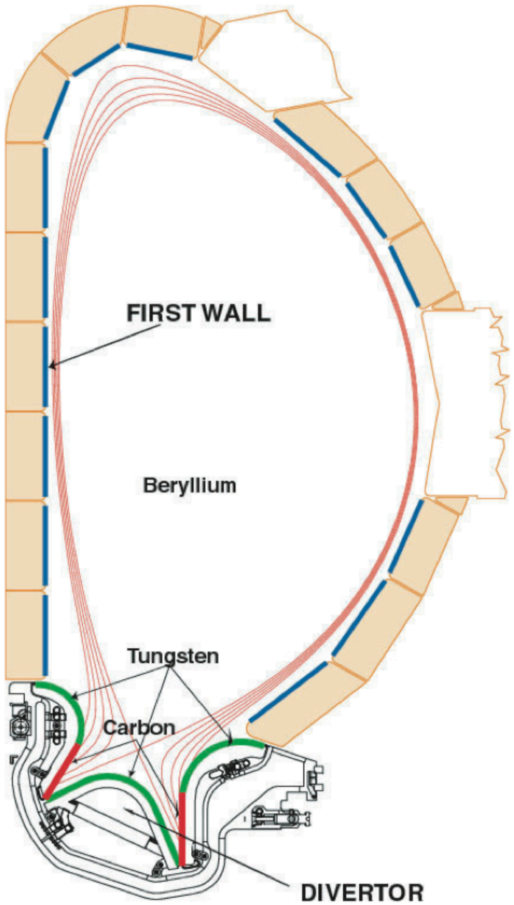
In collaboration with R.H. Cohen, T.D. Rognlien, M.V. Umansky (LLNL)

Contributions of V.A. Soukhanovskii (NSTX), B. Labit (TCV), H. Reimerdes (TCV), W. Vijvers (TCV), V. Pericoli (FAST) and G. Calabro (FAST) are greatly appreciated

Snowflake posters:

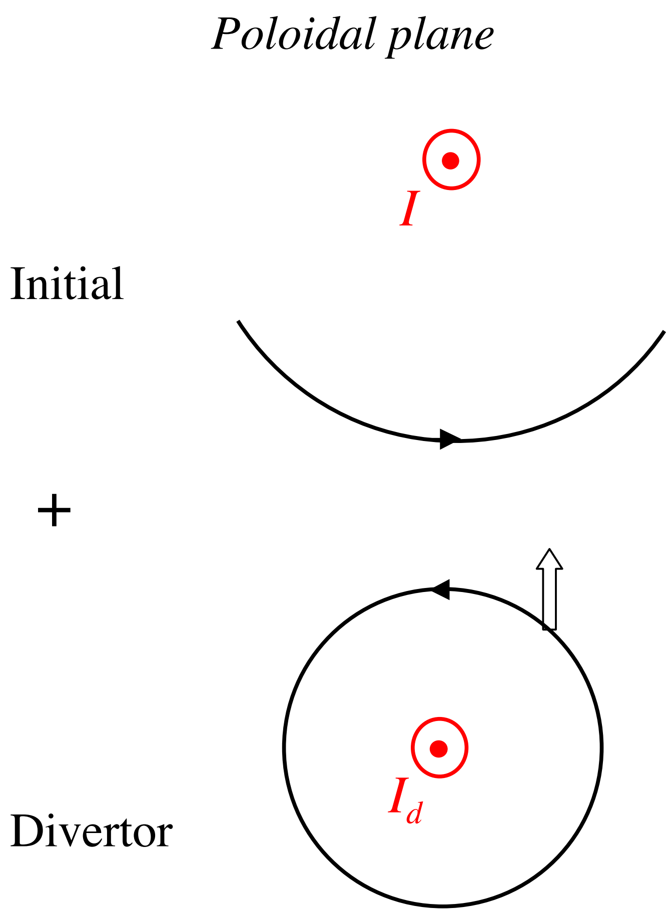
P1 029 (G. Y. Zheng),
P1 056 (S. Medvedev),
P5 049 (V. Soukhanovskii),
P5 091 (B. Labit)

The power that has to be accommodated inside the vacuum vessel of a fusion reactor is more than 20% of the fusion power (alpha particle heating + current drive, etc)

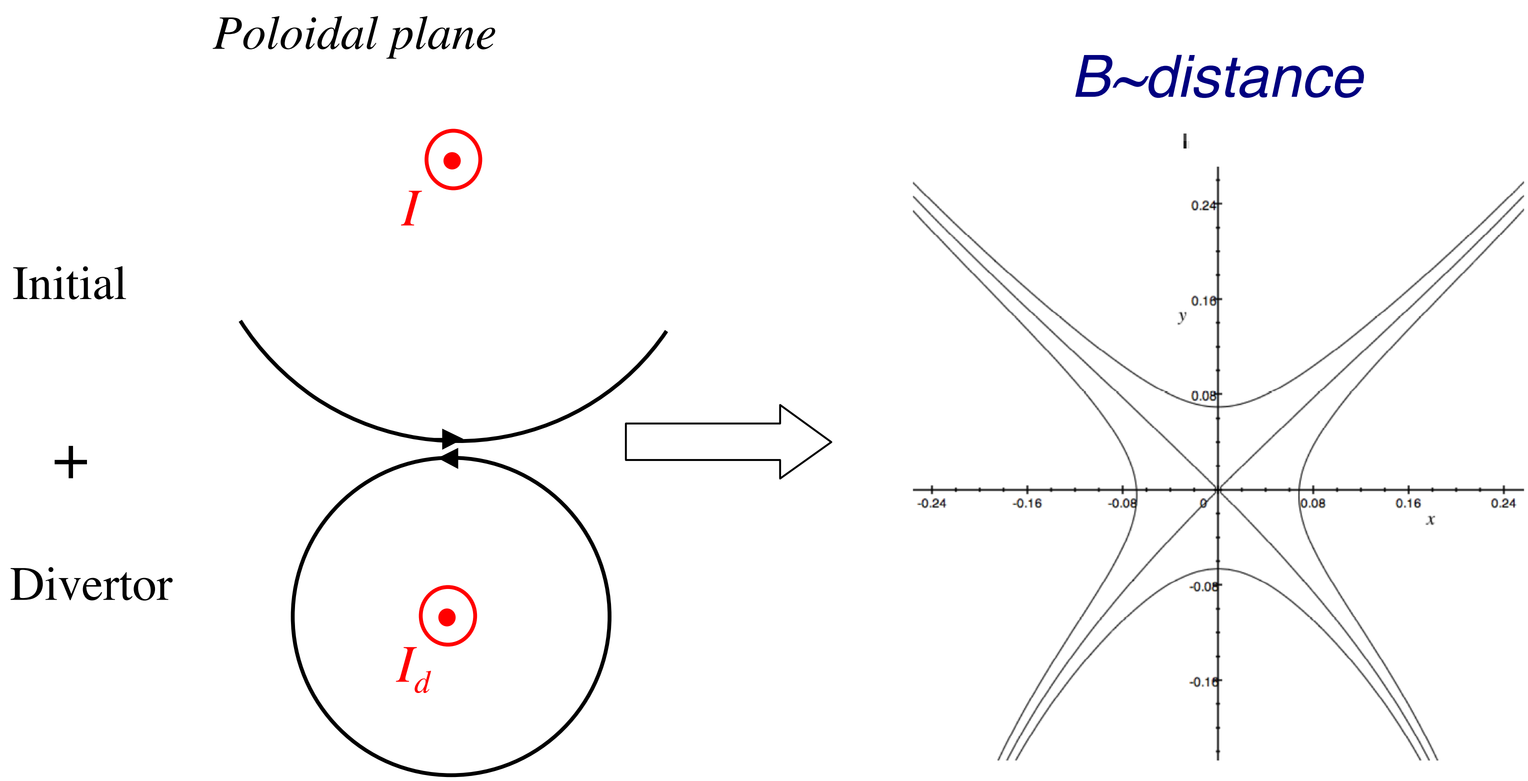



For 1 GW(electric) power plant this will be about 0.5 GW (!)

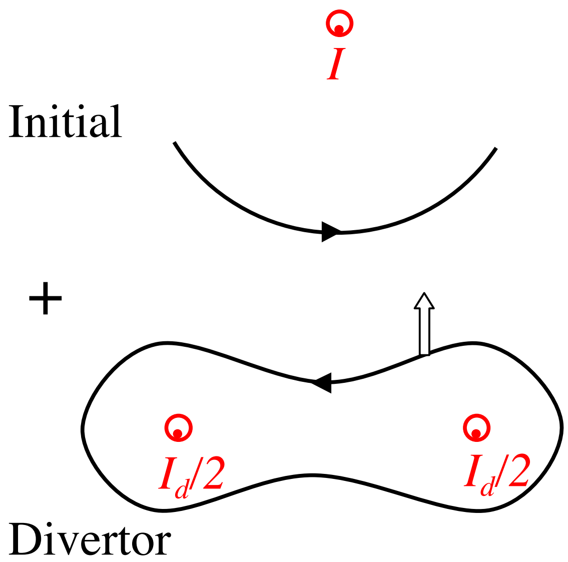
# A "standard" *X-point* divertor is based on a poloidal field configuration with a first-order null of the magnetic field



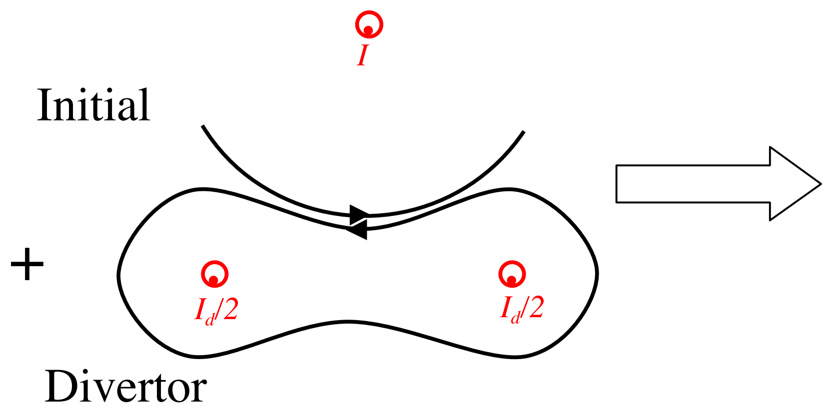
## A “standard” *X-point* divertor is based on a poloidal field configuration with a *first-order* null of the magnetic field

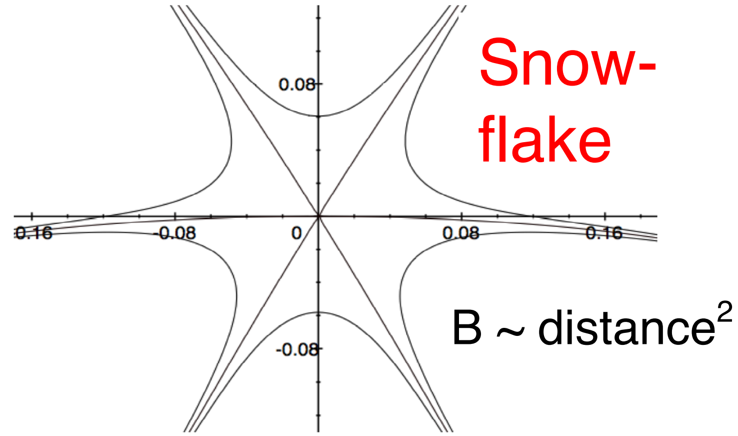


If one wants to make a second-order null of the poloidal magnetic field in a chosen point, one should design the divertor coils in such a way as to match the curvature of the initial field



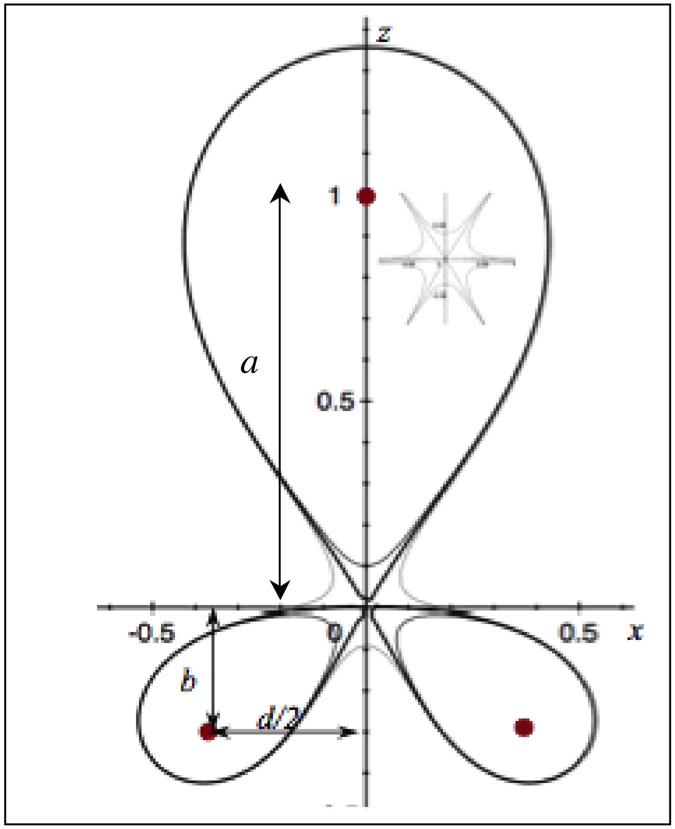
2. If one wants to make a second-order null of the poloidal magnetic field in a chosen point, one should design the divertor coils in such a way as to match the curvature of the initial field




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

# A snowflake divertor: not only $B_p$ but also its first spatial derivative are zero at the null-point ($B_p \sim r^2$ vs $B_p \sim r$ in the standard case)




Snowflake divertor in symmetric 3-wire configuration.

Two conditions must be satisfied:

$I_d = I_{d0} = 2Ib/(a-b)$; $d = 2b(a+b)/(a-b)^{1/2}$

where $I$ is the plasma current

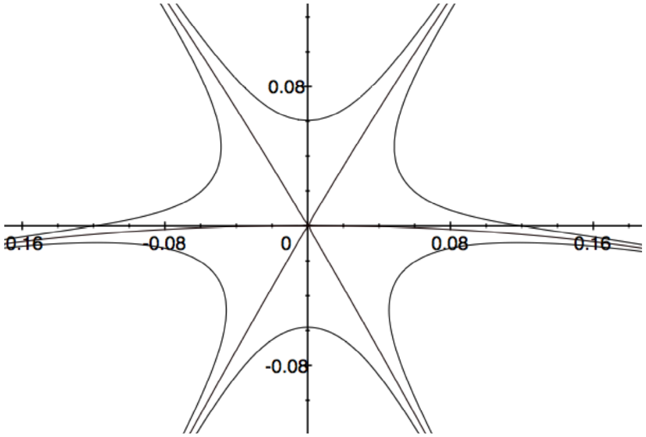
For $b=0.3a$, the total current in both divertor coils is $I_d=0.9I$ . For $a$=5m, the divertor coils are situated at a distance 2.5 m from the null point

Divertor coils can be situated outside TF coils!

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

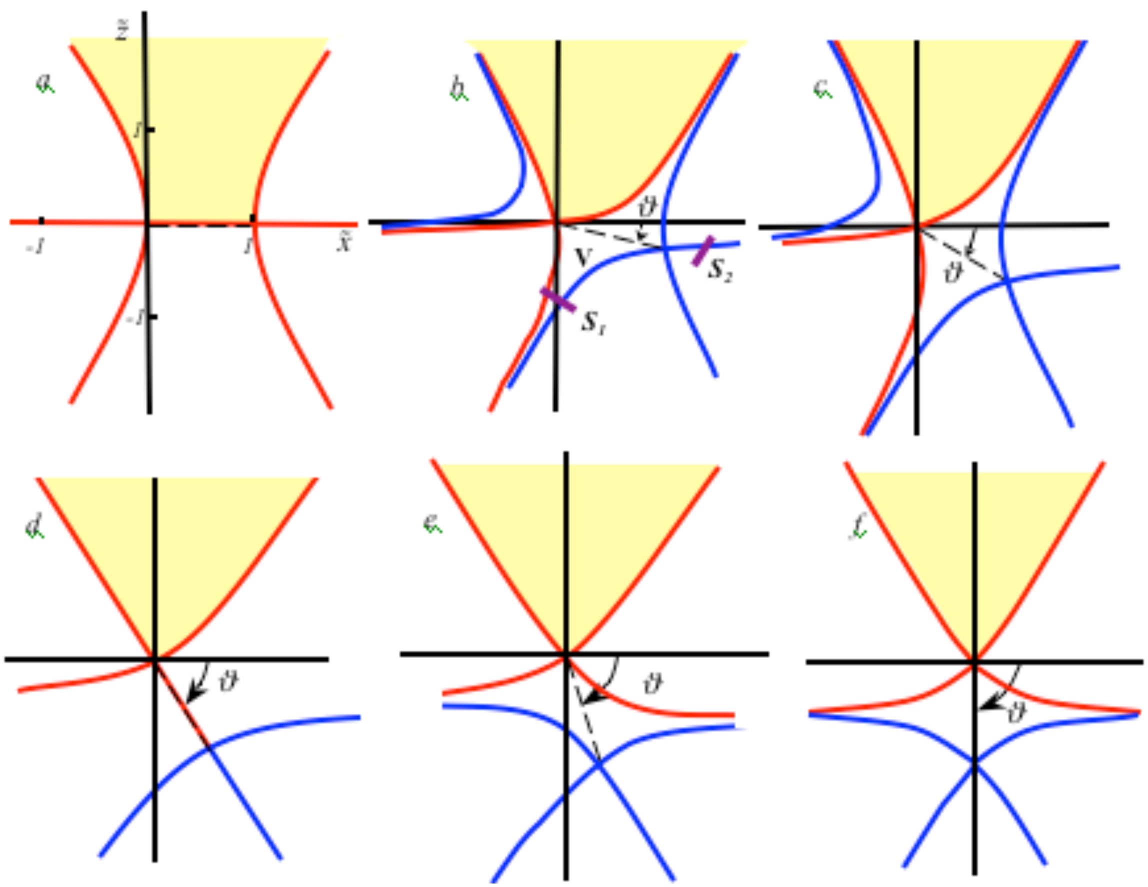
# Attractive features of the snowflake configuration

- Larger flux-expansion ratio
- Increased magnetic shear in the pedestal region (potentially better control of ELMs)
- Increased connection length
- Increased non-quasineutral ion transport, leading to stronger shear flows in the pedestal region
- Control over blob transport (stronger flux-tube squeezing near the null-point)
- Possibility to create this configuration with existing set of PF coils on existing devices (TCV, NSTX, DIII-D ….)
- Possibility to create “snowflake” in ITER-scale machines with PF coils situated outside TF coils




D.D. Ryutov, R.H. Cohen, T.D. Rognlien, M.V. Umansky. Phys. Plasmas, **15**, 092501 (2008)
M.V. Umansky, R.H. Bulmer, R.H. Cohen, T.D. Rognlien. D.D. Ryutov..” Nuclear Fusion, **49**, 075005, 2009.
D.D. Ryutov, M.V. Umansky. “Phys. Plasmas,” **17**, 014501, 2010.
M.V. Umansky, T.D. Rognlien, D.D. Ryutov, P. B. Snyder. Contrib. Plasma Physics, **50**, 350, 2010.
S. Yu. Medvedev, A. A.Ivanov, A. A. Martynov, et al Contrib. Plasma Phys. **50**, 324 – 330, 2010.

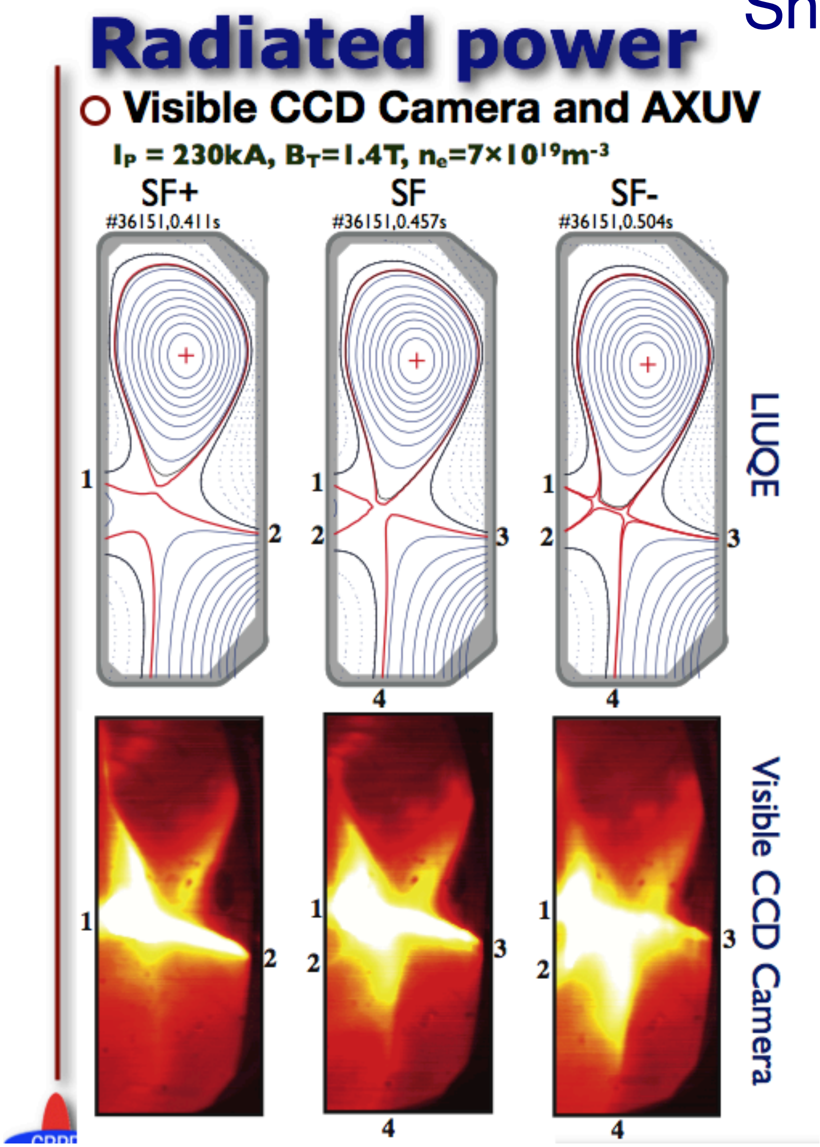
If the currents are different from the “exact match”, two near-snowflake (SF) configurations appear: SF+ or SF-



This broad variety of configurations can be controlled by PF coils situated far away from the nulls

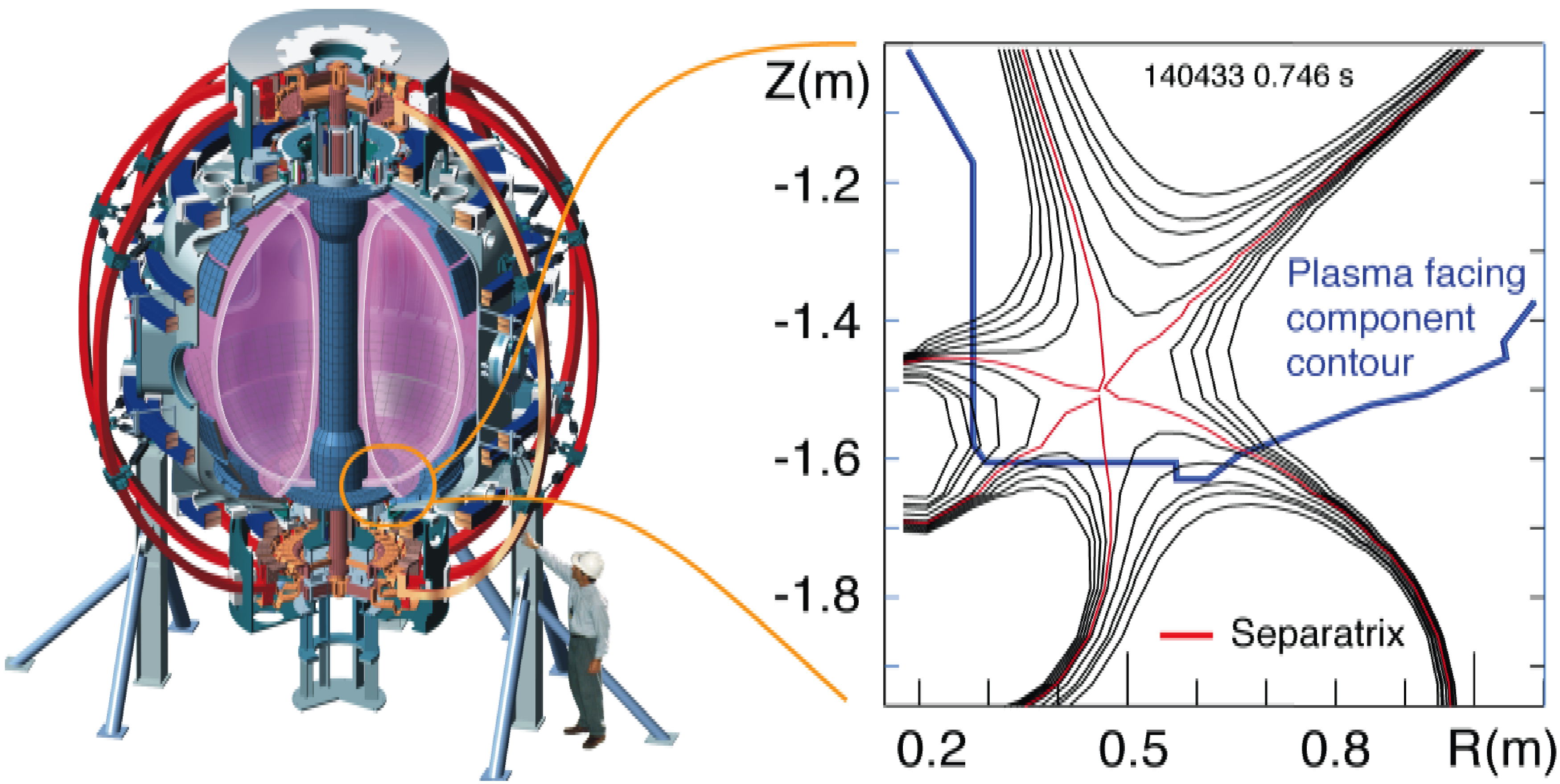
D.D. Ryutov, M.A. Makowski, M.V. Umansky. “Local properties of the magnetic field in a snowflake divertor,” PPCF, **52**, 105001, Oct. 2010.

## Snowflake on TCV




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,

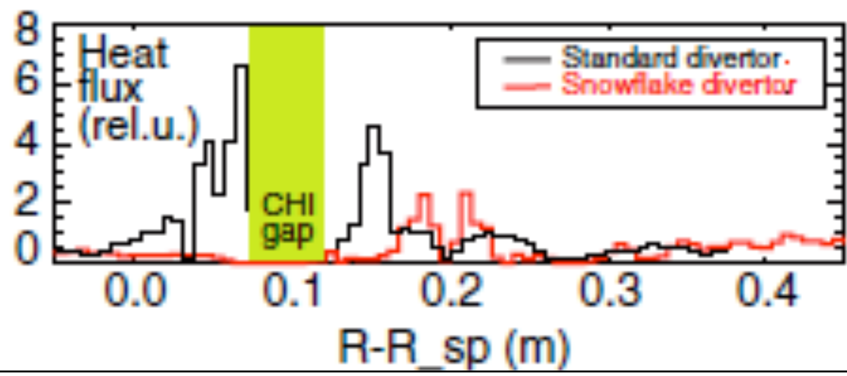
# Snowflake on NSTX (Princeton)

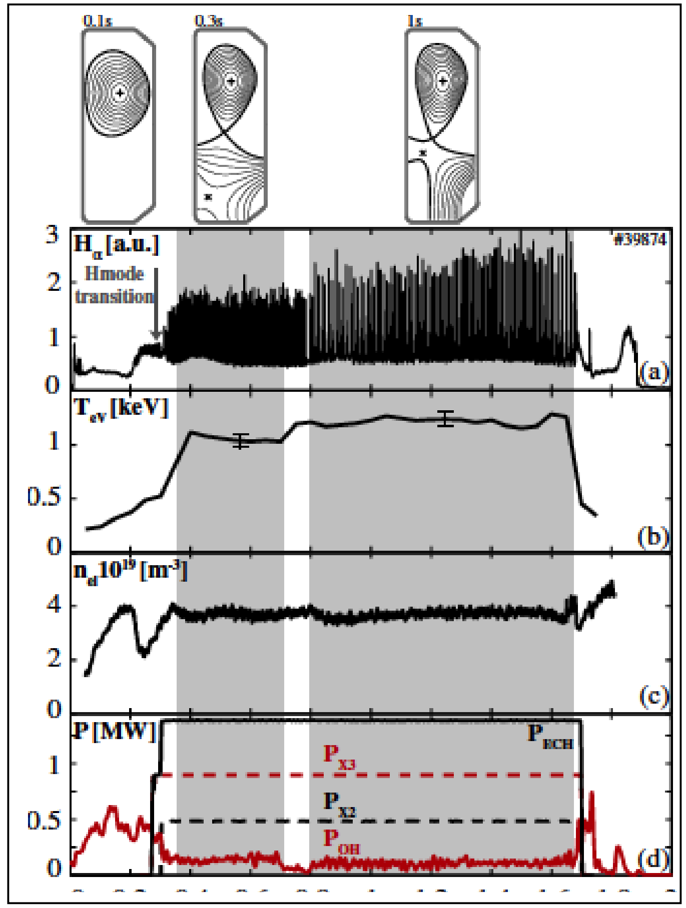


# Exciting results from two tokamaks: NSTX and TCV

NSTX: factor of 3 heat-flux reduction on the divertor plate (V.A. Soukhanovskii et al, Nucl. Fusion, **51**, 012001, 2011)

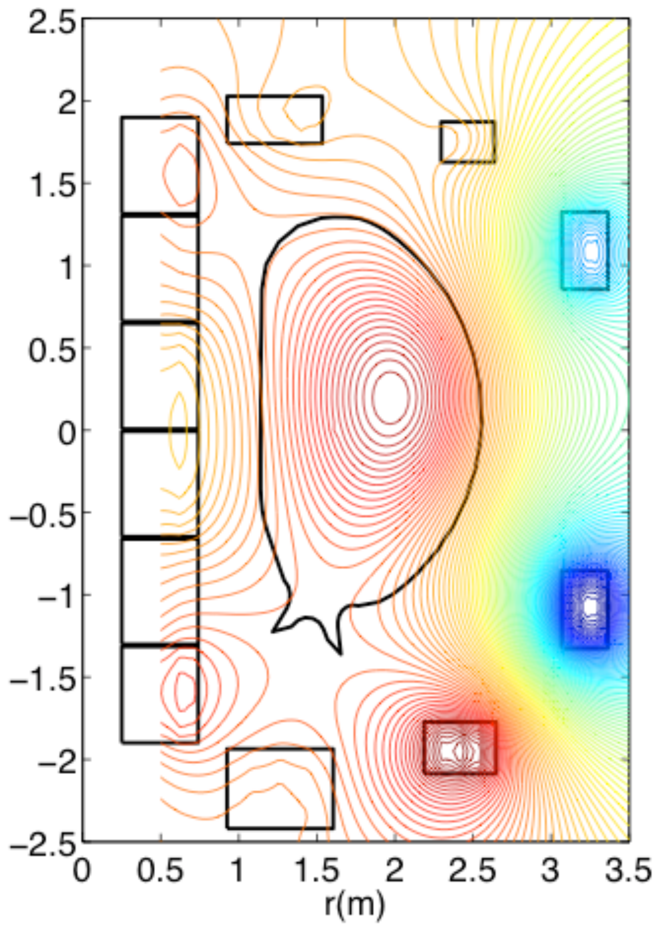
TCV: strong effect on ELMs: 3 times lower frequency, only 30% increase of the amplitude (F. Piras et al, PRL, **105**, 15503, 2010)




Easier detachment (no need for 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

# FAST magnetic configuration for the snowflake

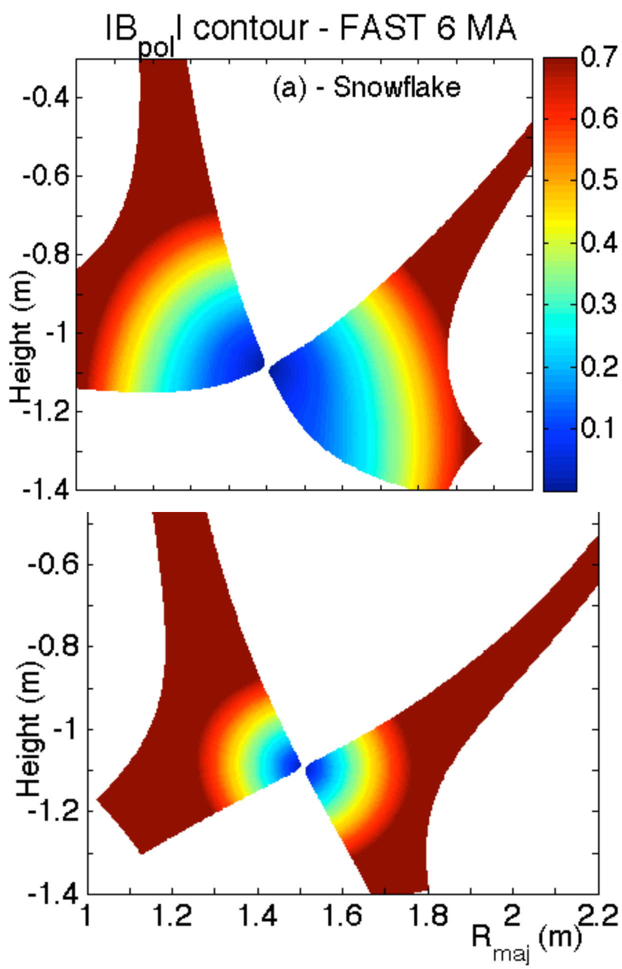


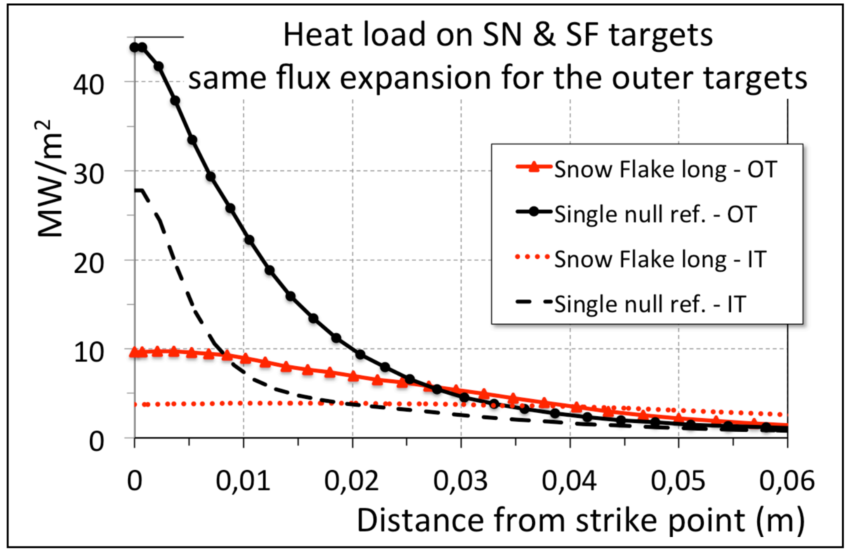

Courtesy G. Calabro and FAST team

FAST = Fusion Advanced Studies Torus (a design study, Frascati)

The coils are the same as designed for the initial standard-null divertor

# 2D transport simulations for FAST demonstrate significant reduction of the wall heat load for a snowflake case




## Courtesy V. Pericoli Ridolfini.

" Comparative study of a conventional and snowflake divertor for the FAST tokamak," V. Pericoli Ridolfini, R. Zagórski[1], G. Artaserse, G. Calabrò, F. Crisanti, G. Maddaluno, G. Ramogida and B. Viola, Paper presented at PSI Conference, Aachen, May 2012; to appear in J. Nucl. Mat.

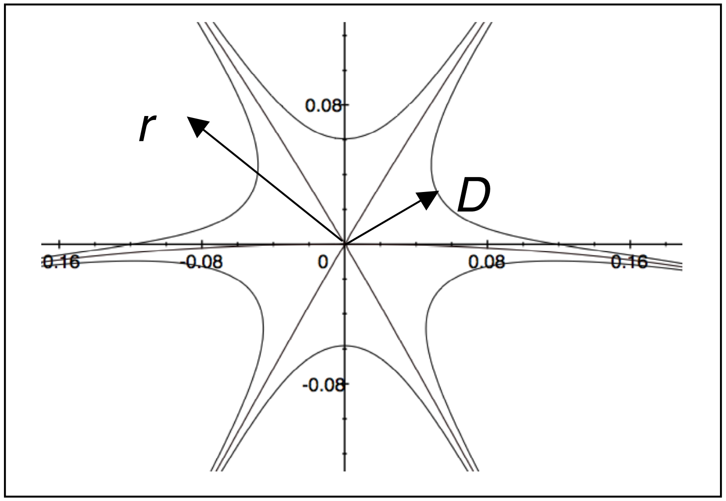
Recently, an additional favorable effect has been identified and studied for the SF configuration: *strong curvature-driven convection* in the high $\beta_p$ zone near the snowflake null(s)

The poloidal magnetic field strength near the null-point:

$$B_p \sim B_{pm} (r/a)^2; \ \beta_p \sim \beta_{pm} (a/r)^4$$

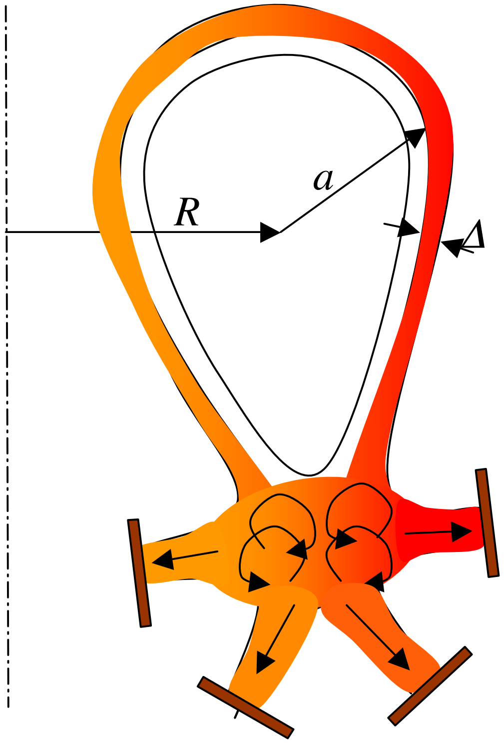
The poloidal beta is higher than 1 for

$$D<D^* \equiv a(\beta_{pm})^{1/4}$$




* D.D. Ryutov, T.D. Rognlien. Paper 3O3 at the Int. Sherwood Fusion Theory Conference, Austin, TX, May 2-4, 2011.
D. D. Ryutov, R.H. Cohen , T.D. Rognlien and M. V. Umansky. Contrib. Plasma Phys., **52**, No. 5-6, 539 – 543, June 2012.

# The curvature-driven convection is intense




Turn-over time

$\tau_{conv} \sim (\rho R / |p'|)^{1/2} \sim (D^* R)^{1/2} / c_s$

Parallel flow time $\tau_{||} \sim L / c_s$

If the second is longer than the first, the heat flux is distributed evenly between 4 strike points

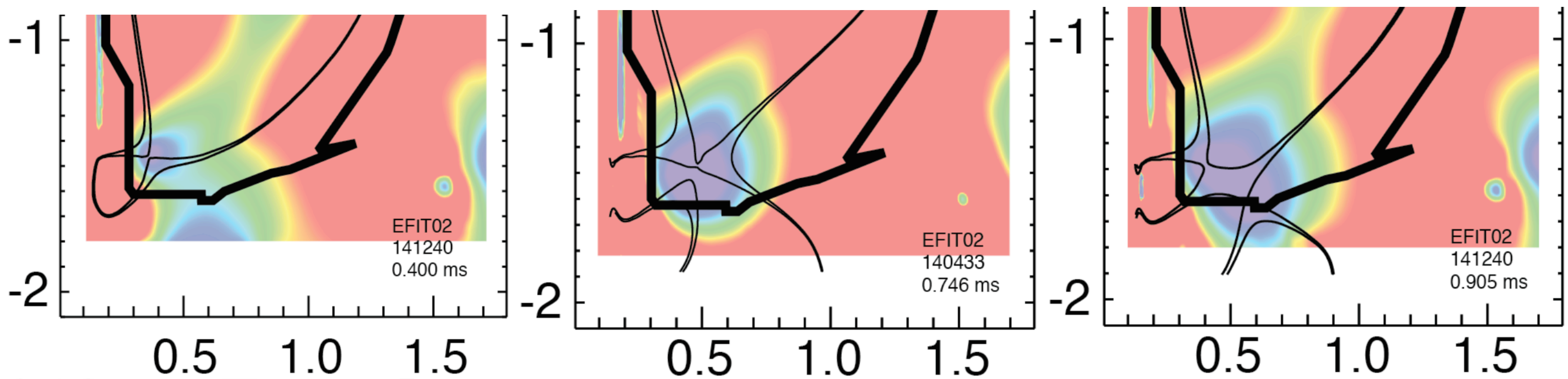
# Comparing a Snowflake and Standard X-point divertors

$n$=2×10$^{13}$ cm$^{-3}$, $T_e+T_i$=50 eV, $B_{pm}$=0.6 T, $\beta_{pm}$=8×10$^{-4}$,

$R$=500 cm, $a$=200 cm, $\Delta$=0.6 cm

| | Snowflake | | Standard | |
|---|---|---|---|---|
| The size of a strongly convective zone | $D^*=a(\beta_{pm})^{1/4}$ | *35 cm* | $D^*=a(\beta_{pm})^{1/2}$ | *5.5 cm* |
| Turn-over time | $(\beta_{pm})^{1/8}(aR)^{1/2}/c_s$ | *10 μs* | $(\beta_{pm})^{1/4}(aR)^{1/2}/c_s$ | *5 μs* |
| Parallel transit time | $(B_T/B_{pm})\times(a/c_s)(a/D^*)$ | *800 μs* | $(B_T/B_{pm})\times(a/c_s)$ | *160 μs* |
| Affected width projected to the midplane | $\Delta^*\sim a(D^*/a)^3$ | *1.1 cm>Δ*<br>*Widening of the wetted zone* | $\Delta^*\sim a(D^*/a)^2$ | *1.5 mm<Δ* |

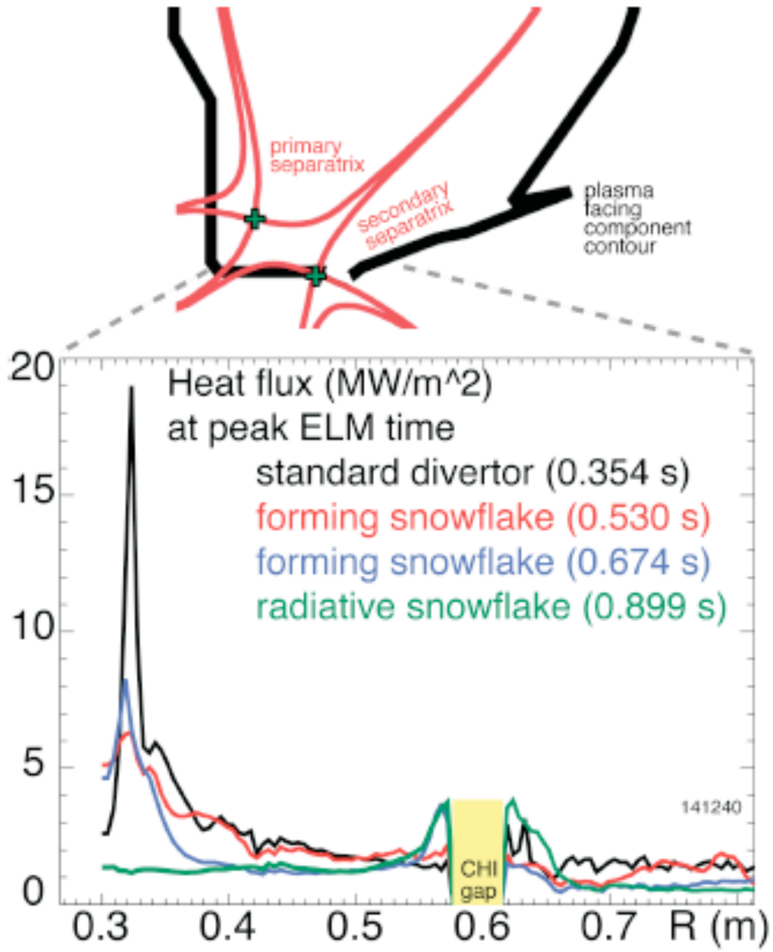
# The widening of a low $B_{pol}$ zone on NSTX (Courtesy V. Soukhanovskii)




*Standard* *Exact SF* *SF-minus*

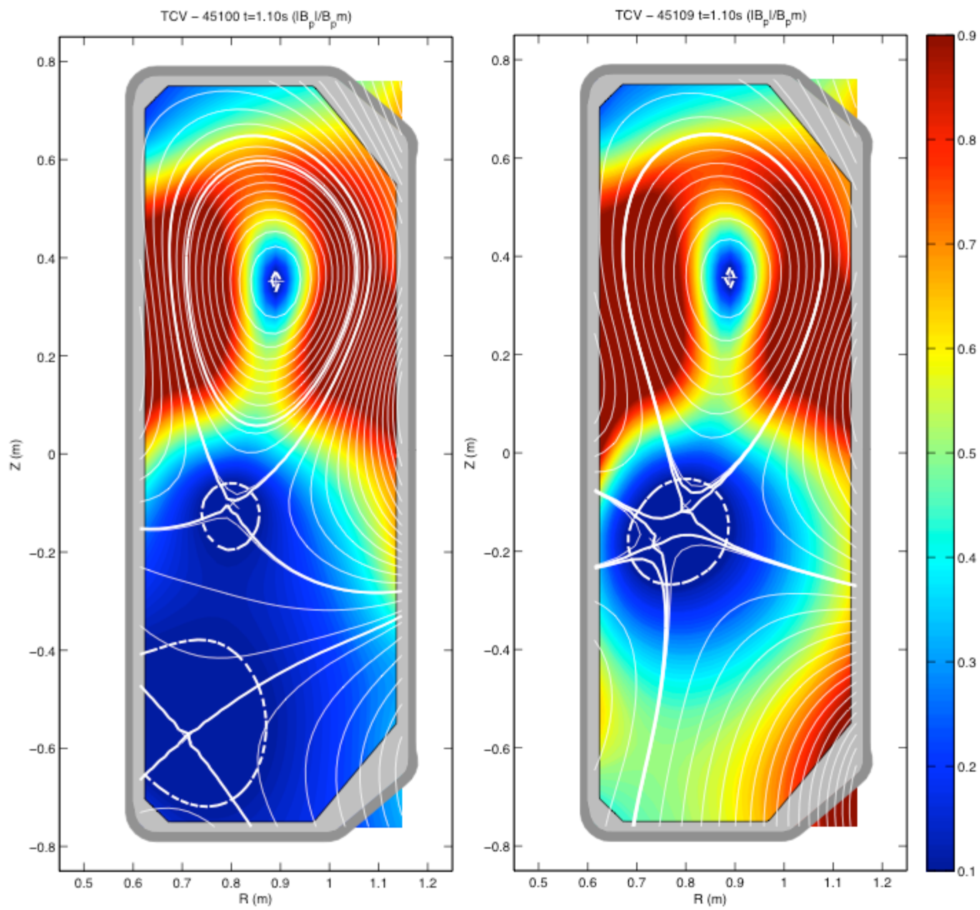
The purple corresponds to $B_{pol}<0.1B_{pol\ midplane}$. Note that the snowflake-minus (right panel) is as good as an “exact” snowflake (middle panel).

## Strong spreading of the heat flux during type-1 ELMs has been observed on NSTX in a SF-minus configuration



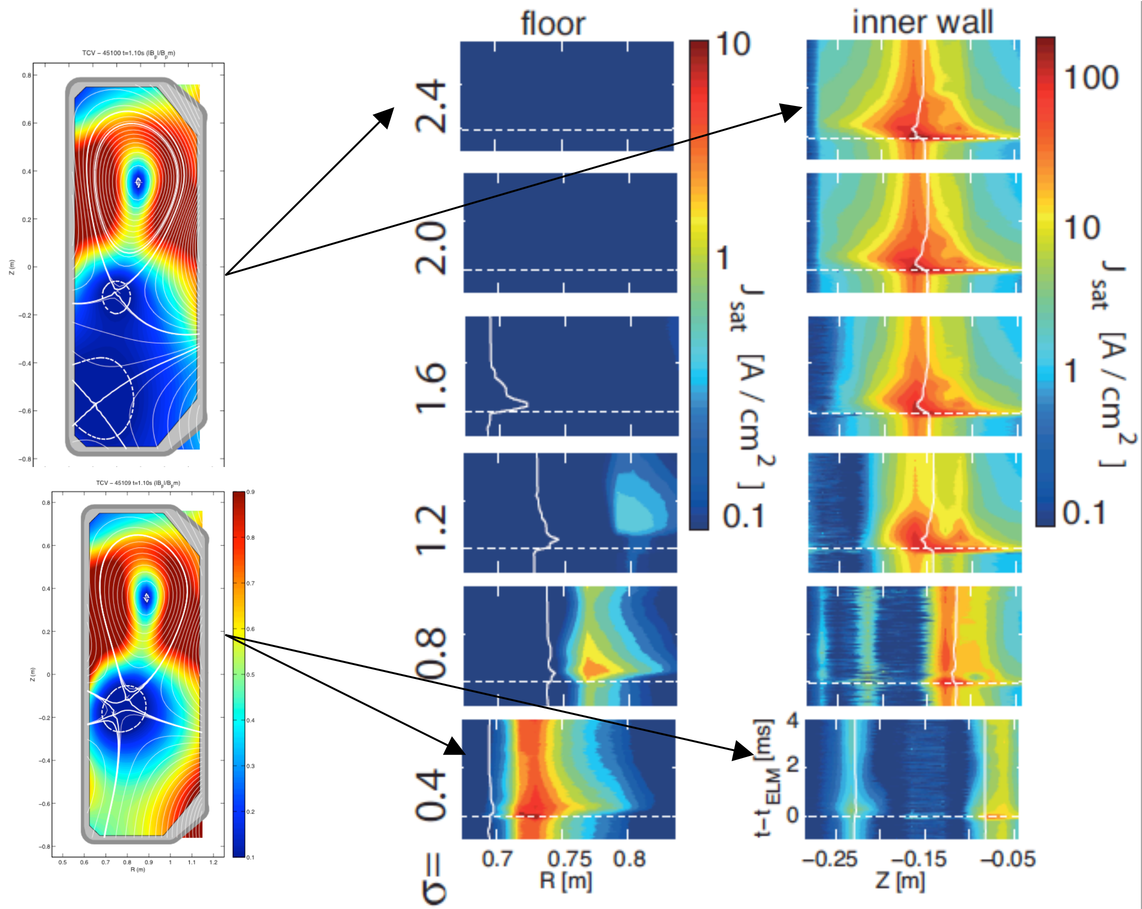

Courtesy V.A. Soukhanovskii, PPPL

For small distances between the two nulls, a zone of a weak $B_{pol}$ encloses both nulls




Courtesy W. Vijvers,
TCV (Lausanne)

# The closeness of the two nulls and the weakness of the poloidal magnetic field leads to "activation" of additional strike points




Courtesy B. Labit (see his poster on Friday)

# A concept for the divertor for a 1 GW (electric) fusion reactor (normal aspect ratio)

This divertor would have to accommodate the power of $W_{div}$~400 MW.

The required wetted surface has to be $W_{div}/P$, where $P$ is an allowable power load per unit surface area on the divertor target.

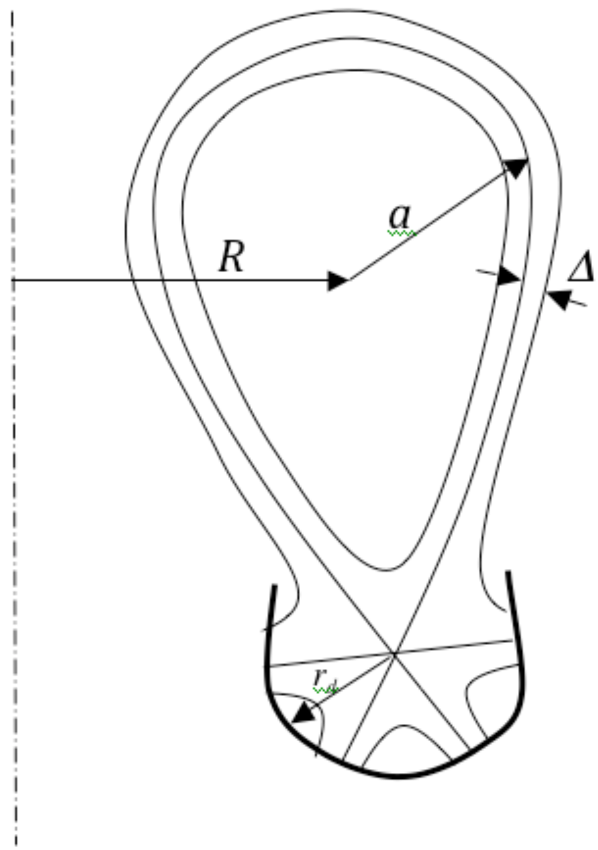
For $P$=5 MW/m$^2$, the required surface area is 80 m$^2$.

A divertor should allow for the convective spreading of the plasma flow at some distance from the target: this will then be a volume without internal barriers.

Approximating the poloidal cross-section of the divertor by a circle of a radius $r_{div}$ one finds the total surface area would be $S_{div}=(2\pi R)(2\pi r_d)$.

For $R$=5m, the surface area of 80 m$^2$ would be attained at modest radius $r_{div}$=40 cm.

# A possible model for the snowflake divertor for a 1 GWe fusion reactor (normal aspect ratio)



## SUMMARY

- The transition from the first-order magnetic null to the second-order null leads to profound changes in the plasma behavior in the divertor area.
- The most important cause of these changes is the formation of a much larger (than in a standard divertor) zone of a very weak poloidal magnetic field around the null-point.
- PF coils for the snowflake divertor can be situated outside the TF coils.
- Specifics of the snowflake divertor physics, when applied to a standard aspect ratio fusion reactor, favor a divertor without internal barriers which might have hindered the convection spreading.
- For fusion facilities based on spherical tokamaks, a better way of using the SF divertor could be an open divertor configuration employing strong flux expansion at the divertor targets and transition to the detached regimes facilitated by the flux expansion.