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Novel divertors based on manipulation of poloidal field structure

D.D. Ryutov

Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

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Contributions of my many colleagues are gratefully acknowledged:

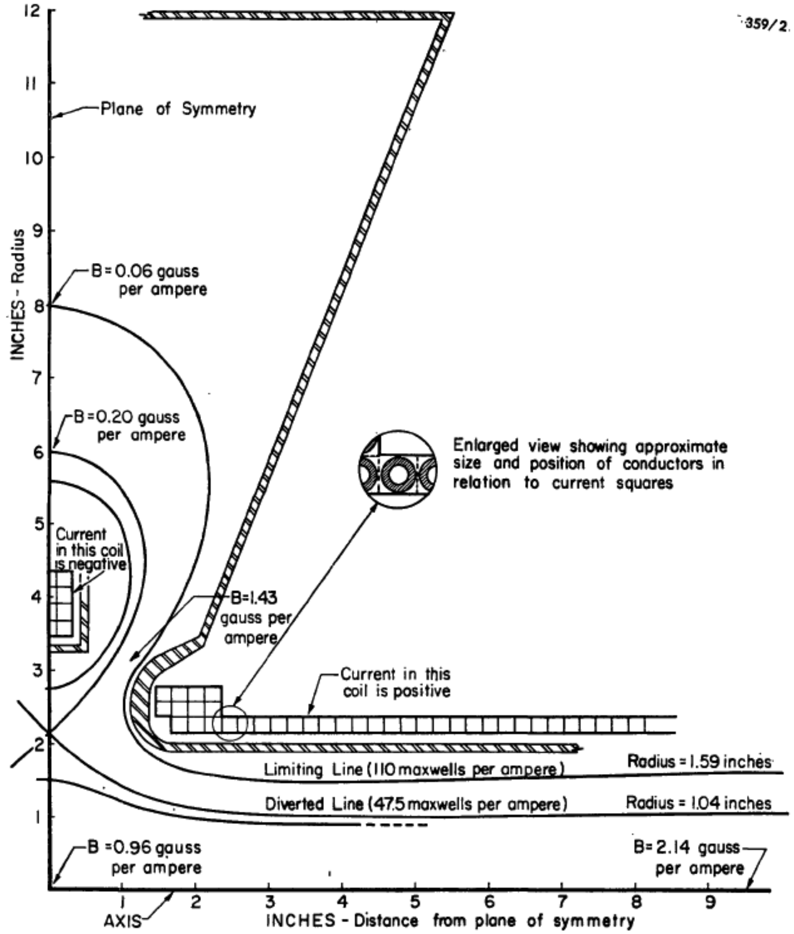
LLNL: R. Cohen, B. Cohen, D. Correll, I. Joseph, L. Lodestro, T. Rognlien, V. Soukhanovskii, M. Umansky…

PPPL: E. Kolemen, J. Menard…

TCV: G. Canal, B. Labit, F. Piras, H. Reimerdes, W. Vijvers …

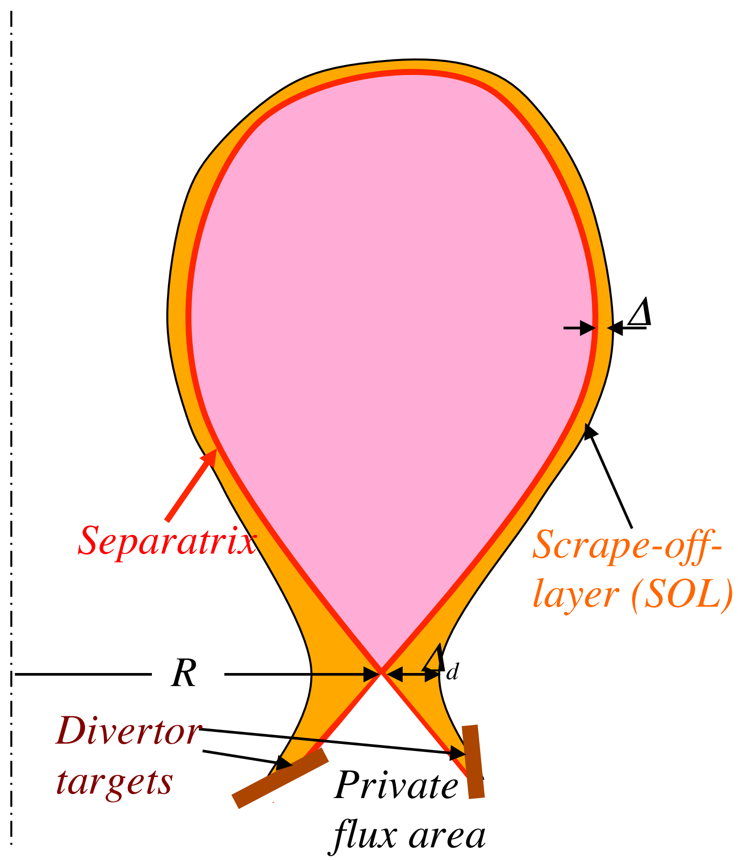
……

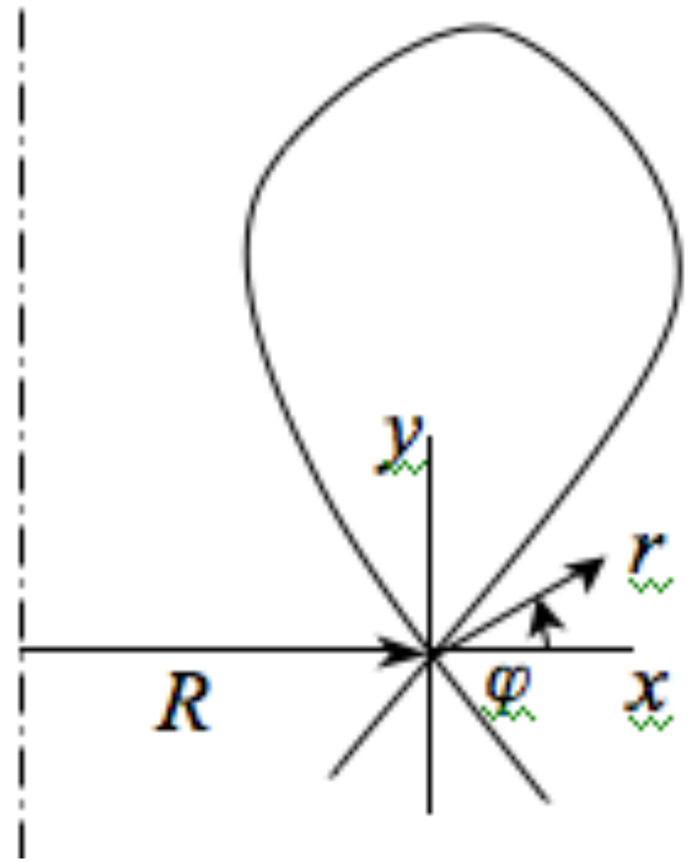
"The divertor is a device, first proposed by L. Spitzer [A Proposed Stellarator, AEC Report No. NYO-993, PM-S-1, 1951], for averting contact between the hot ionized gas and the wall of the main discharge tube"*



*C. R. Burnett, D. J . Grove, R. W. Palladino, T. H. Stix and K. E. Wakefield, P/339, 1958 Geneva Conference

Poloidal divertor notations and divertor coordinates





The divertor performance is determined by the processes occurring both inside and outside the separatrix; they cannot be reduced to just the energy and particle transfer along the SOL to the divertor targets.

The X-point geometry creates an intimate link between the plasma inside and outside the separatrix. It affects q and magnetic shear divergence just inside the separatrix (germination of ELMs); prompt ion loss; neoclassical orbits, etc., etc.

The X-point geometry generates a private flux region, which cannot be left out in any realistic divertor assessment. A cross-talk between two (or multiple) divertor legs is important.

One has to consider both strike points (or multiple strike points as in a snowflake and cloverleaf divertors); one cannot limit the analysis to the outer strike point only.

I will concentrate on the poloidal field (PF) structures created *by remote coils*, situated outside the divertor region

The plasma current in the divertor area is small; use vacuum equations; consider a zone of a size small compared to the major radius (full-blown Eqs. see PoP, **14**, 064502, 2007; PoP, **15**, 092501, 2008)

$$B_x=B_x(x,y);\ B_y=B_y(x,y);$$

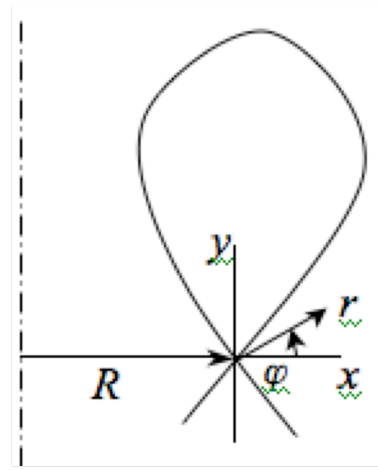
Divergence-free:

$$B_x = -\partial\Phi/\partial y; B_y = \partial\Phi/\partial x$$

Curl-free (*r*<<*R*):

$$\partial B_y/\partial x - \partial B_y/\partial y = 0$$

(very low beta, negligible plasma currents)



Laplace equation:

$$\partial^2\Phi/\partial x^2 + \partial^2\Phi/\partial y^2 = 0$$

Polar coordinates *r*, φ in the (*xy*) plane: $\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\Phi}{\partial\varphi^2}=0$

Properties of the field created by distant conductors

If the poloidal field in some area is created by the far-away currents, the field distribution in this area *is smooth* and can be presented as a power-law series in *x* and *y* or, alternatively, as a multipole expansion

$$\Phi = const + \underbrace{A_0 r\cos(\varphi + \psi_0)}_{\boxed{\text{Uniform}}} + \underbrace{A_1 r^2\cos(2\varphi + \psi_1)}_{\boxed{\text{X-point}}} + \underbrace{A_2 r^3\cos(3\varphi + \psi_2)}_{\boxed{\text{Snowflake}}} + \underbrace{A_3 r^4\cos(4\varphi + \psi_3)}_{\boxed{\text{Cloverleaf}}} + \ldots$$

If no special measures are taken, then the coefficients are on the order of $A_n \sim B_{pm}/a^{n+1}$.

A successife elimination of coefficients A_0, A_1, A_2... leads us to standard X-point → snowflake → cloverleaf ….

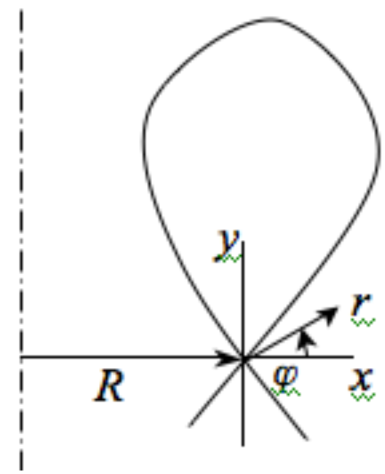
Higher-order poloidal field nulls

Standard divertor: $|\boldsymbol{B}_p| \sim r$, $\Phi \sim r^2$ (r is the distance from the null)

Snowflake divertor: $|\boldsymbol{B}_p| \sim r^2$, $\Phi \sim r^3$

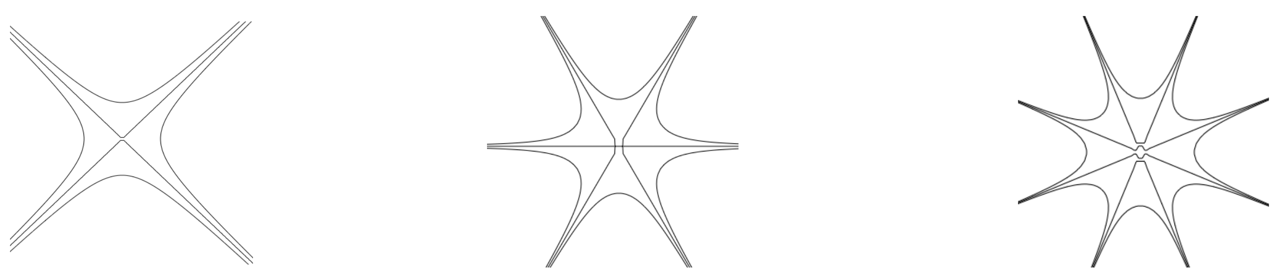
Cloverleaf divertor: $|\boldsymbol{B}_p| \sim r^3$, $\Phi \sim r^4$

The power-law dependence of the flux function on r, $\Phi \sim r^{n+1}$, corresponds to a harmonic dependence of Φ on φ:



$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \Phi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \varphi^2}=0 \qquad (n+1)^2\Phi+\frac{\partial^2 \Phi}{\partial \varphi^2}=0 \qquad \Phi = A r^{n+1}\cos[(n+1)\varphi+\psi]$$

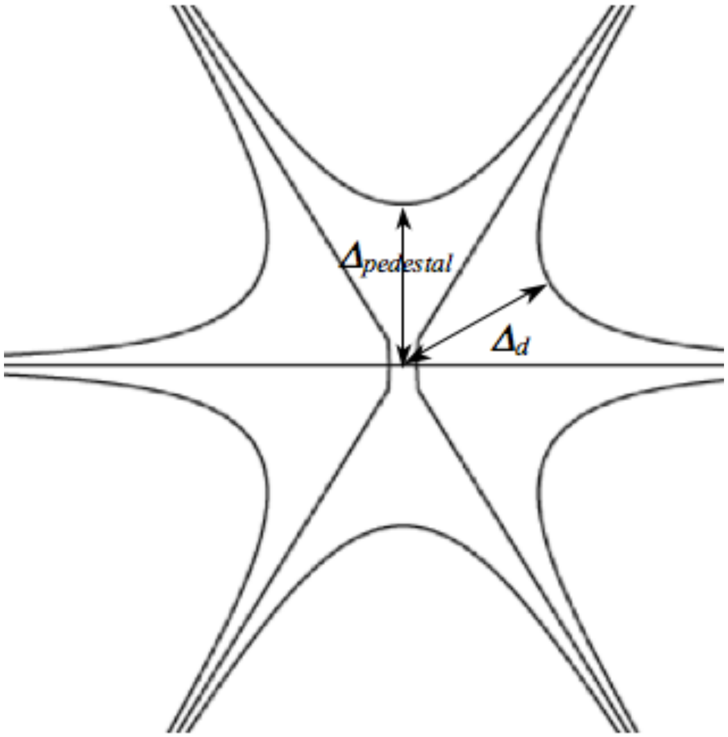
Yields the separatrices and flux surfaces (field lines) near the null



Standard, n=1   Snowflake, n=2   Cloverleaf, n=3

Consider an exact snowflake

Compared to the standard divertor, characteristics of the SF poloidal field change *both inside and outside the separatrix*



$\Delta_d = Ka(\Delta/a)^{1/3}$ (~15-20 cm for DIII-D)

Δ=distance from the separatrix to the chosen flux surface in the midplane; K~1 is a form-factor

The same scaling inside, for $\Delta_{pedestal}$

For the standard X-point, $\Delta_d = K_1 a(\Delta/a)^{1/2}$ (~4 cm for DIII-D)

A strong flux expansion both inside and outside the separatrix

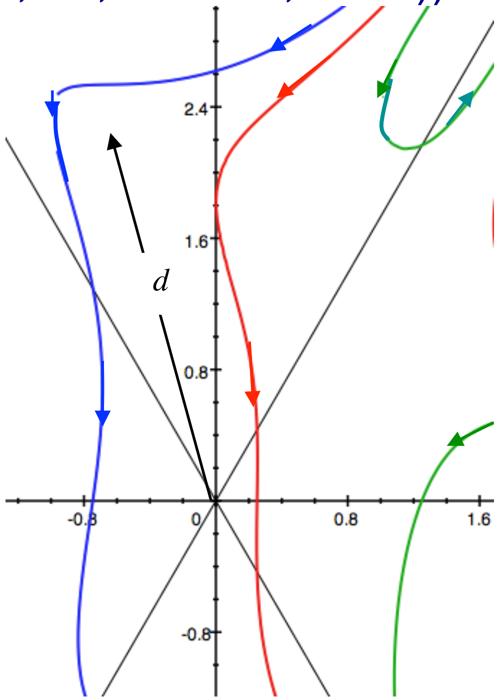
What else is different between the standard and the snowflake divertors?

	Standard	Snowflake
B_p variation with r	r	r^2
q just inside the separatrix	$\sim\ln(a/\Delta)$	$\sim(a/\Delta)^{1/3}$
Shear just inside the separatrix	$\sim(a/\Delta)/\ln(a/\Delta)$	$\sim(a/\Delta)$
SOL connection length	$L\sim L_0+a\ln(a/\Delta)$	$L\sim L_0+a(a/\Delta)^{1/3}$
Specific flux-tube volume, $\delta V/\delta\Phi$	L/B_T	L/B_T
# of strike points	2	4

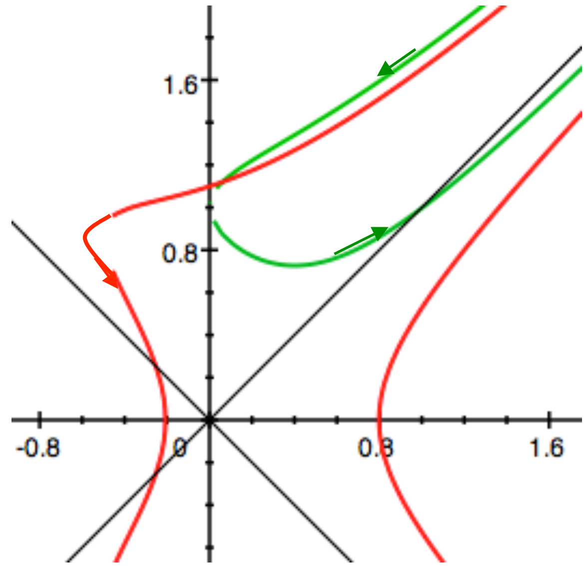
Conclusions:

1. Side-by-side comparison of the SF vs SN can be effective research tool
2. Switching to the SF may have a favorable effect on the divertor performance

An example of the effects produced by the SF inside the separatrix:
the zone affected by the prompt ion loss is 3 times larger than in a standard divertor (PoP, **17**, 014501, 2010)).



Snowflake
[affected zone: $(d/a)<(q_0\rho_i/a)^{2/5}$~0.2]



X-point (C.S. Chang)
[affected zone: $(d/a)<(q_0\rho_i/a)^{2/3}$~0.07]

Expressly non-quasineutral → effect on the radial field in the pedestal → effect on ELMs

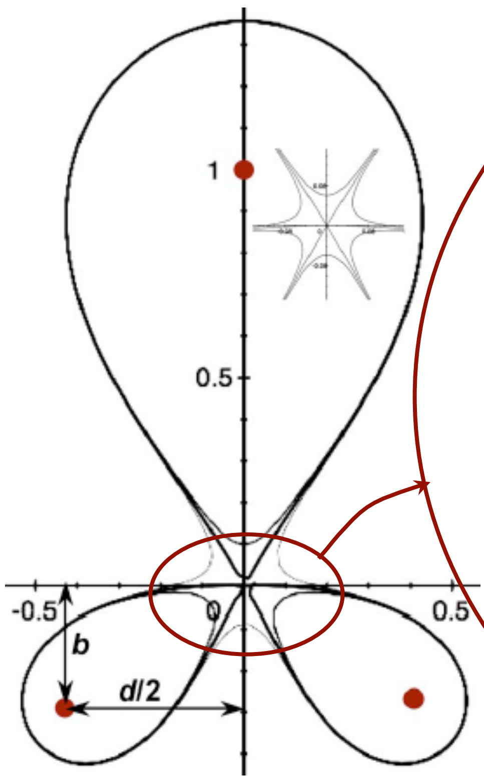
A “near-snowflake”

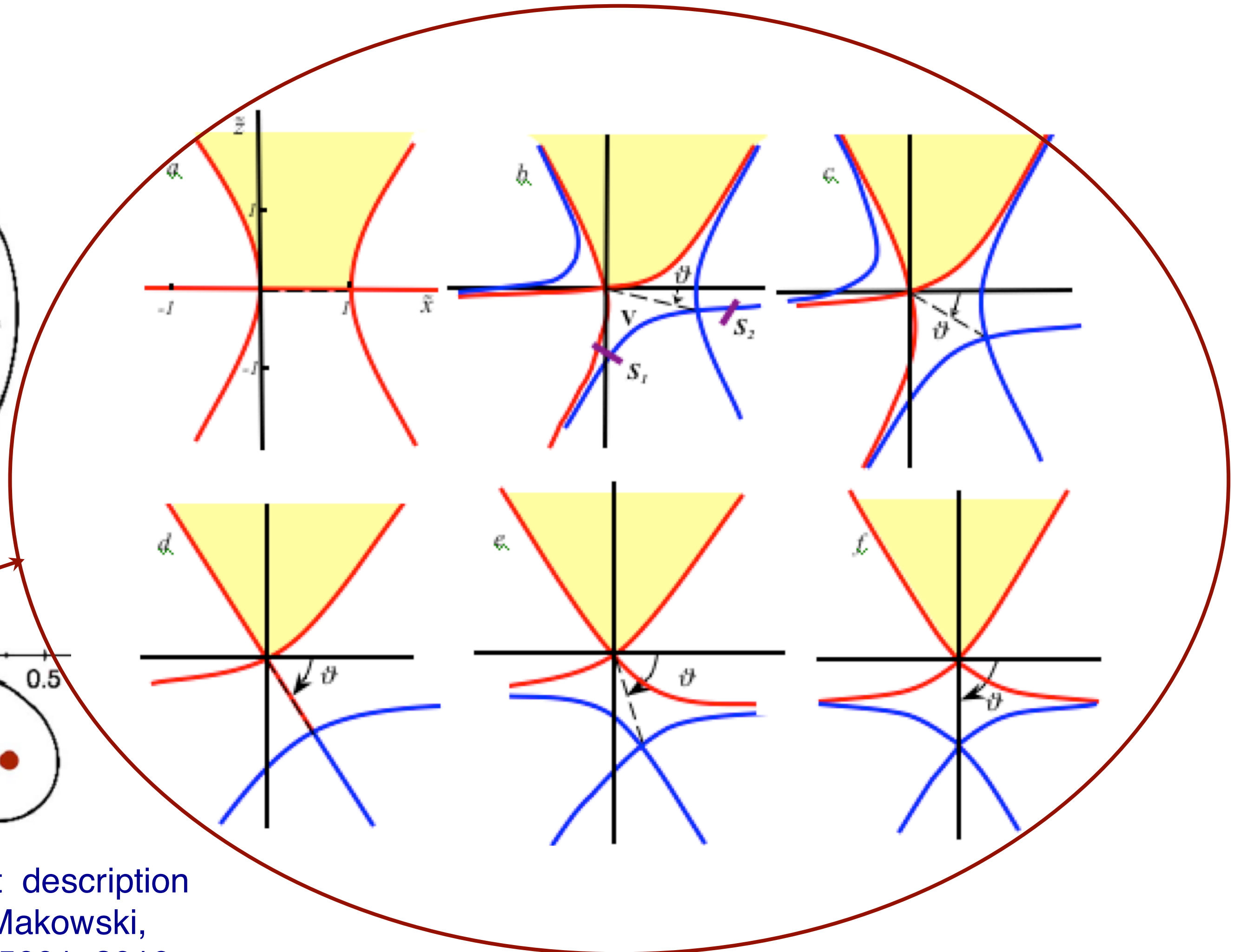
$$\Phi = const + \underbrace{A_0 r \cos(\varphi + \psi_0)}_{\boxed{Uniform}} + \underbrace{A_1 r^2 \cos(2\varphi + \psi_1)}_{\boxed{X\text{-}point}} + \underbrace{A_2 r^3 \cos(3\varphi + \psi_2)}_{\boxed{Snowflake}}$$

- A second-order null can be created by making $A_0=A_1=0$, with A_2 remaining of order 1.
- If the matching condition is not satisfied by some small amount ε, one has $A_0 \sim \varepsilon B_{pm}$, $A_1 \sim \varepsilon B_{pm}/a$. The flux function is a cubic function of coordinates (PoP, **15**, 092501, 2008; PPCF, **52**, 105001, 2010);
- The magnetic field is a quadratic function of the coordinates; *one second-order null therefore splits into two (and only two) first-order nulls.*
- The *snowflake expansion* can, therefore, be also called *“two-null” expansion*
- This expansion is valid until distance between the two nulls is smaller than distance to the coils.

A field structure in the divertor area can be controlled by remote coils!

"Dance of the two nulls"





There exist a convenient description of these fields: Ryutov, Makowski, Umansky, PPCF, **52**, 105001, 2010

The whole concept of the Snowflake divertor is based on the "conversation" between the two nearby PF nulls

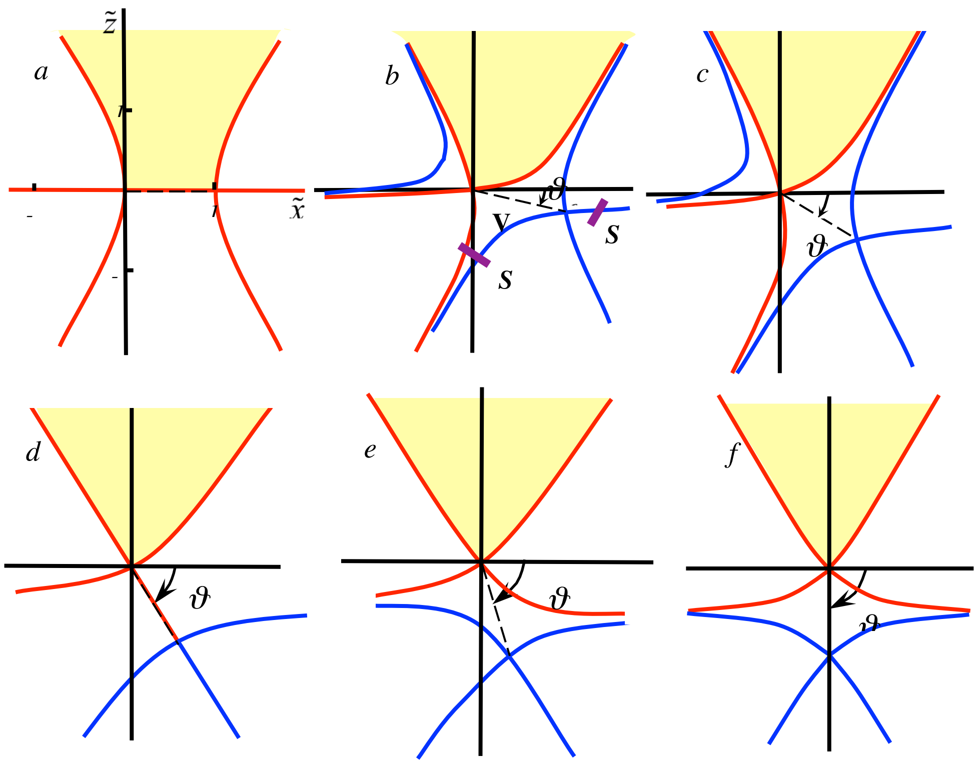
Effect or parameter	Proximity constraint
Flux expansion; Connection length; Specific volume; Magnetic shear; RMP Blob connectivity.	$D < \Delta_d = Ka(\Delta / a)^{1/3}$
Prompt ion loss	$D < D_{prompt} \equiv a\varepsilon^{2/5};\ \varepsilon = \frac{\rho_i}{a}\frac{B_T}{B_{pm}}\sqrt{\frac{a}{R}}$
Plasma convection	$D < D_{\beta_p} \equiv r^*$

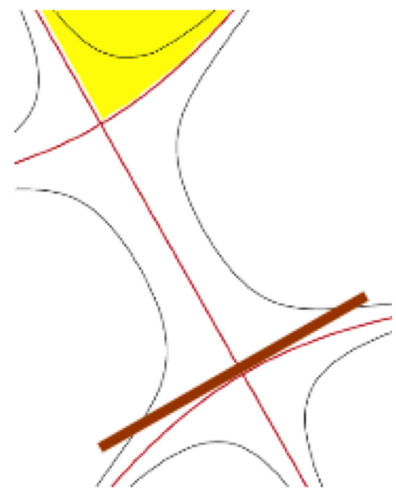
D = distance between the nulls; Δ = SOL midplane thickness (for the SOL effects); Δ = distance from the separatrix (for the effects on the pedestal, etc)

A qualitative identifier: 4 divertor legs

If the two nulls are far away from each other (in terms of the proximity constraints), we get a standard X-point configuration, with the second null becoming one of many other nulls lurking around (although it is still within the SF expansion domain)

One exception: a configuration *"d"* (tilted symmetric snowflake): two nulls are lying on the same separatrix





When the distance between the nulls is large, one gets a true cusp configuration near the target; LLNL group calls it "trident" configuration

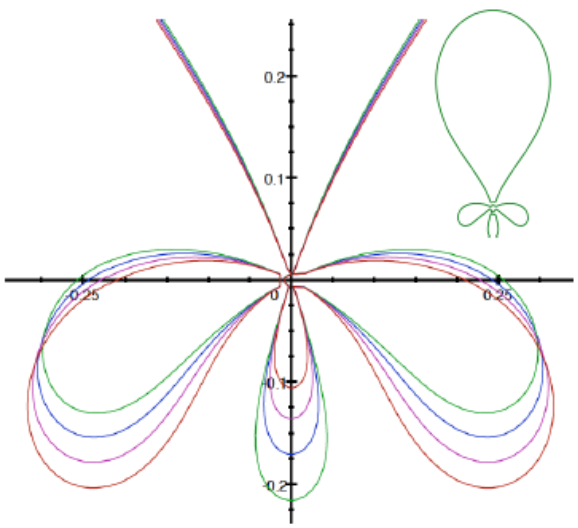
INTERMEDITE SNOWFLAKE SUMMARY

- Manipulation of the currents in remote coils allows one to create configurations with higher-order nulls of the poloidal field (snowflake = second-order null)
- In the case of a snowflake, if matching conditions are not exactly satisfied, the second-order null splits into two nearby first-order nulls
- The characteristic properties of the snowflake are maintained if the distance between the nulls is small-enough; specific “proximity constraints” are different for different physical effects (SOL geometry; finite beta poloidal effects; prompt ion loss; RMP and ELM control, etc)

Cloverleaf divertor: third-order null created by remote coils*

(Overall shape of the magnetic surfaces is reminiscent of a four-petal cloverleaf)

Table 1 $d=0.5l$ in all cases (l is a vertical plasma size)



color	b	c	I_1 (current per conductor)	I_2	K
red	0.14	0.0954	0.2369	0.0183	12.86
purple	0.12	0.1222	0.2197	0.0384	10.62
blue	0.10	0.1522	0.1987	0.0688	8.96
green	0.08	0.1899	0.1747	0.1129	7.54

Parameter K characterizes the "flatness" of the magnetic field near the null: $B_p = K(2r/l)^3 B_{pm}$, where B_{pm} is the poloidal field in the midplane.

A large zone of a very weak poloidal field is formed near the null.

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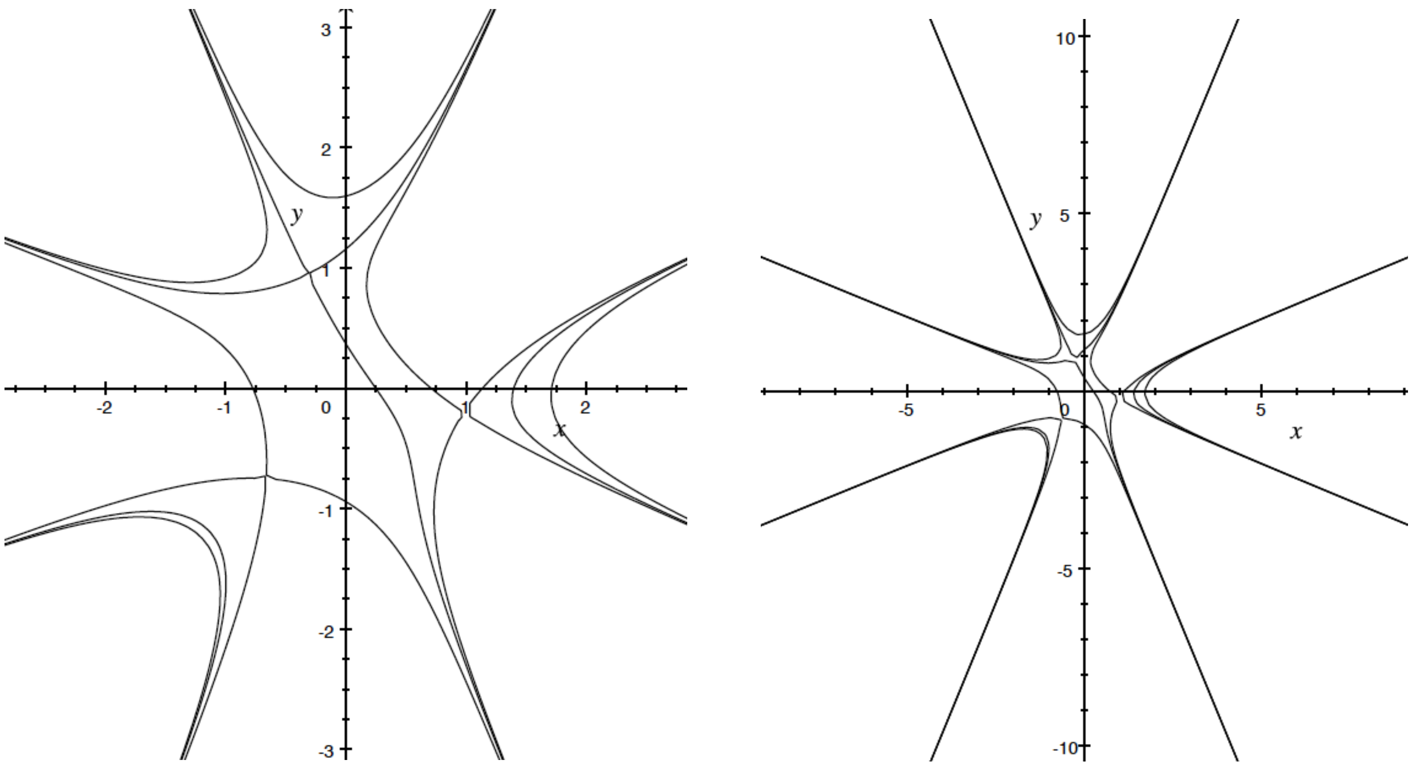
* PoP, **20**, 092509, 2013

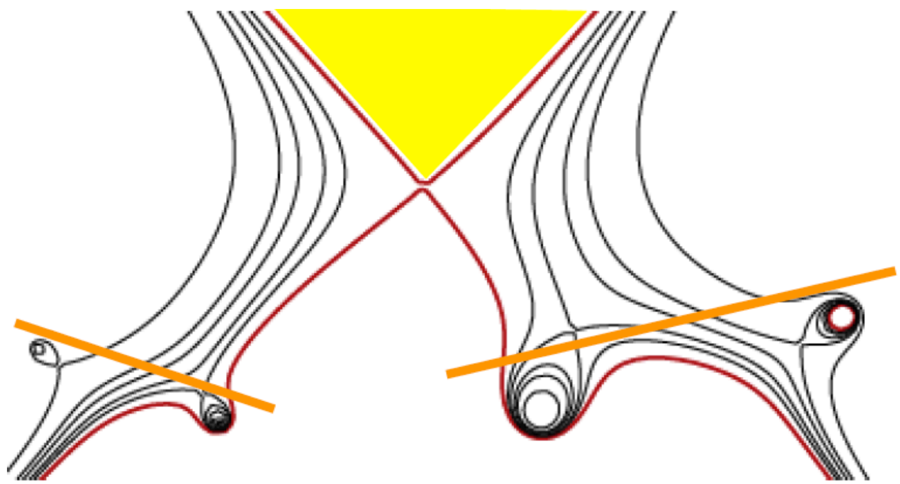
If the currents in the divertor conductors are slightly deviating from the exact match, a third-order null splits into three first-order nulls forming an equilateral triangle.

One of the configurations of a split-third-order null



X-divertor/Cusp divertor: create strong flux flaring at the target by putting coils just behind the target

This is an approach suggested in a cusp divertor (H. Takase, JPSJ, **70**, 609, 2001) and X-divertor (Kotshenreuther et al, 2004 IAEA FEC, IC/P6-43, http://www-naweb.iaea.org/napc/physics/fec/fec2004/papers/ic_p6-43.pdf)



A configuration of the X-divertor family

Advantages:

Heat-flux spreading by a clear and compelling mechanism

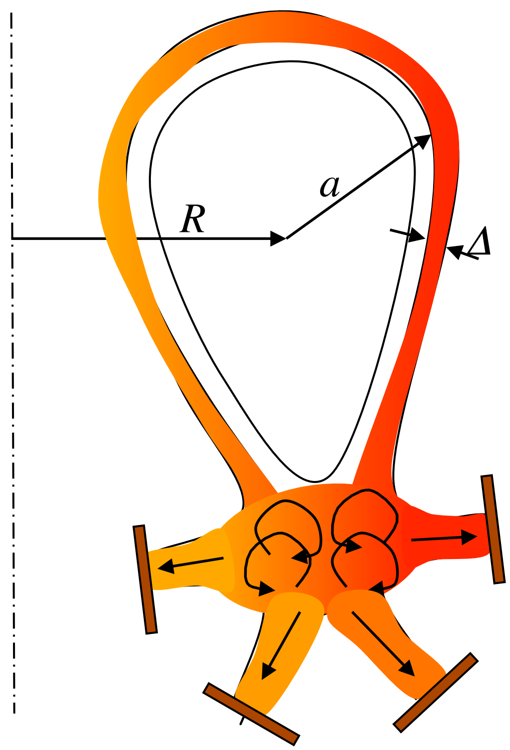
Affects both inner and outer strike-points

If properly designed may have no effect on the core plasma confinement

Disadvantage:

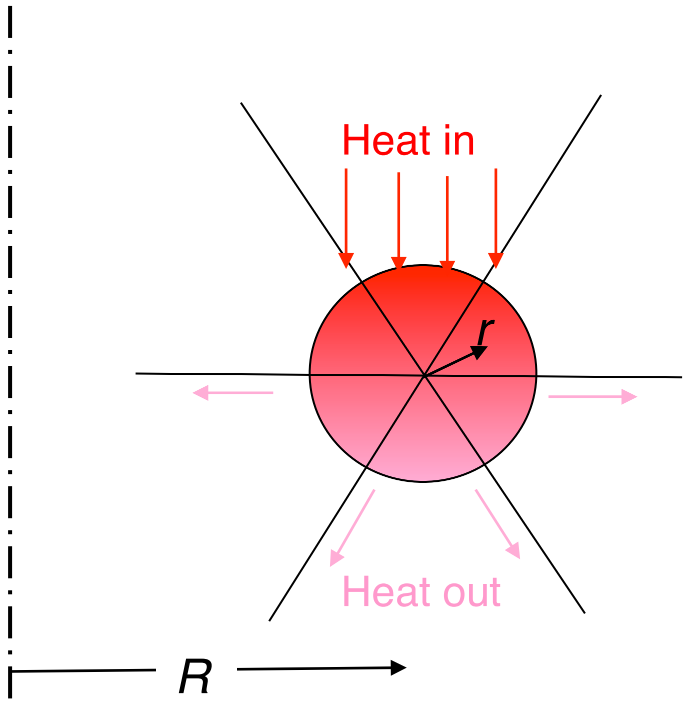
Needs nearby coils

Now I switch back to snowflake divertors and discuss a convective snowflake for the rest of my talk



An idea of this approach is based on the fact that there is a large zone of a very low poloidal field near the two closely-spaced nulls

A conjecture: the presence of a zone with a very low poloidal field near the second-order null point leads to a curvature-driven convection*



$$\frac{B_p^2}{8\pi} \approx \frac{B_{p,midplane}^2}{8\pi}\left(\frac{r}{a}\right)^4$$

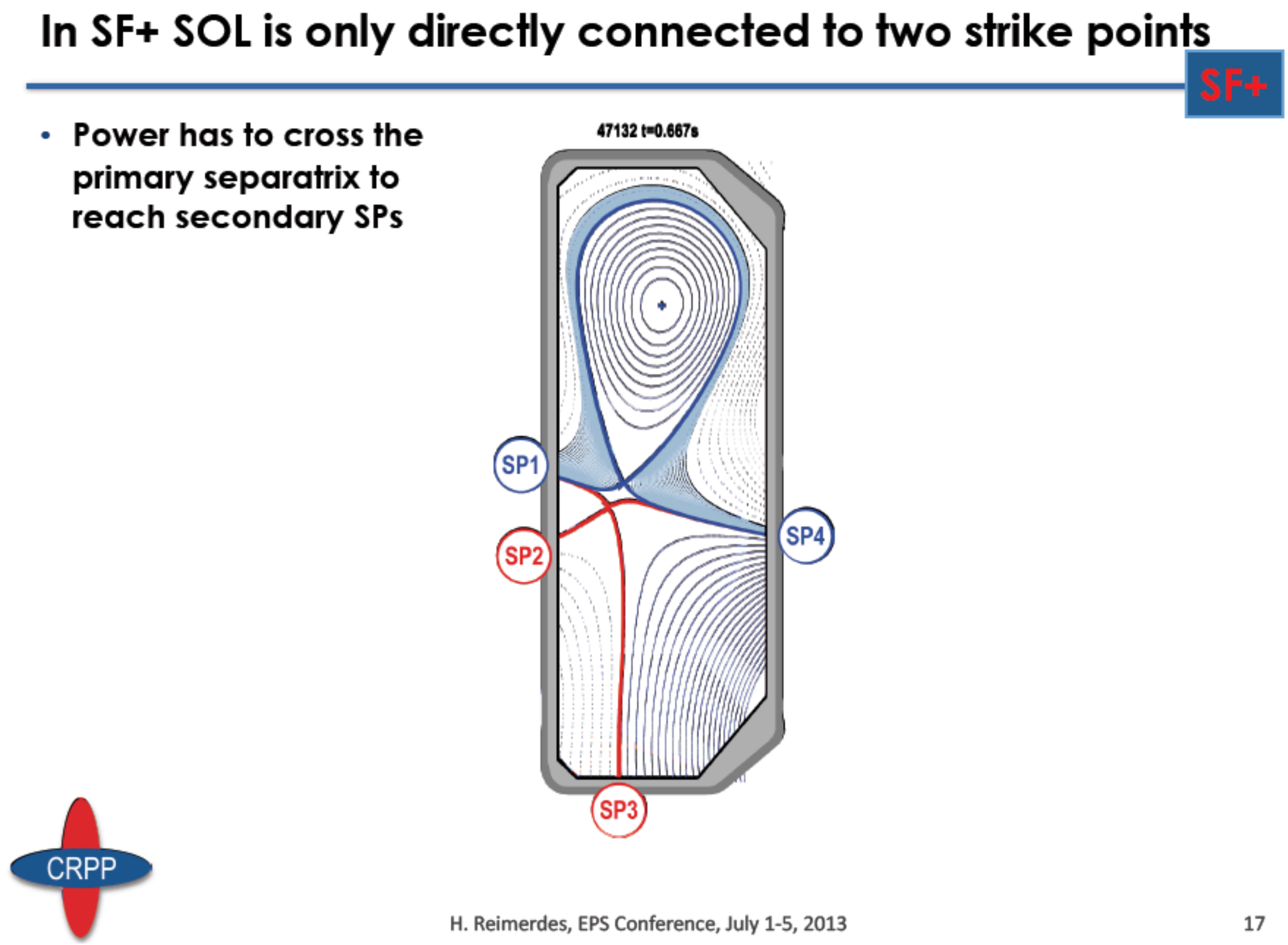
(a is a minor radius)

In the virtual absence of the poloidal field, there is no plasma equilibrium: the pressure gradient is non-collinear to the effective gravity force (directed along the major radius)

Outside the zone around the magnetic null, the poloidal field provides “stiffness” and equilibrium is robust

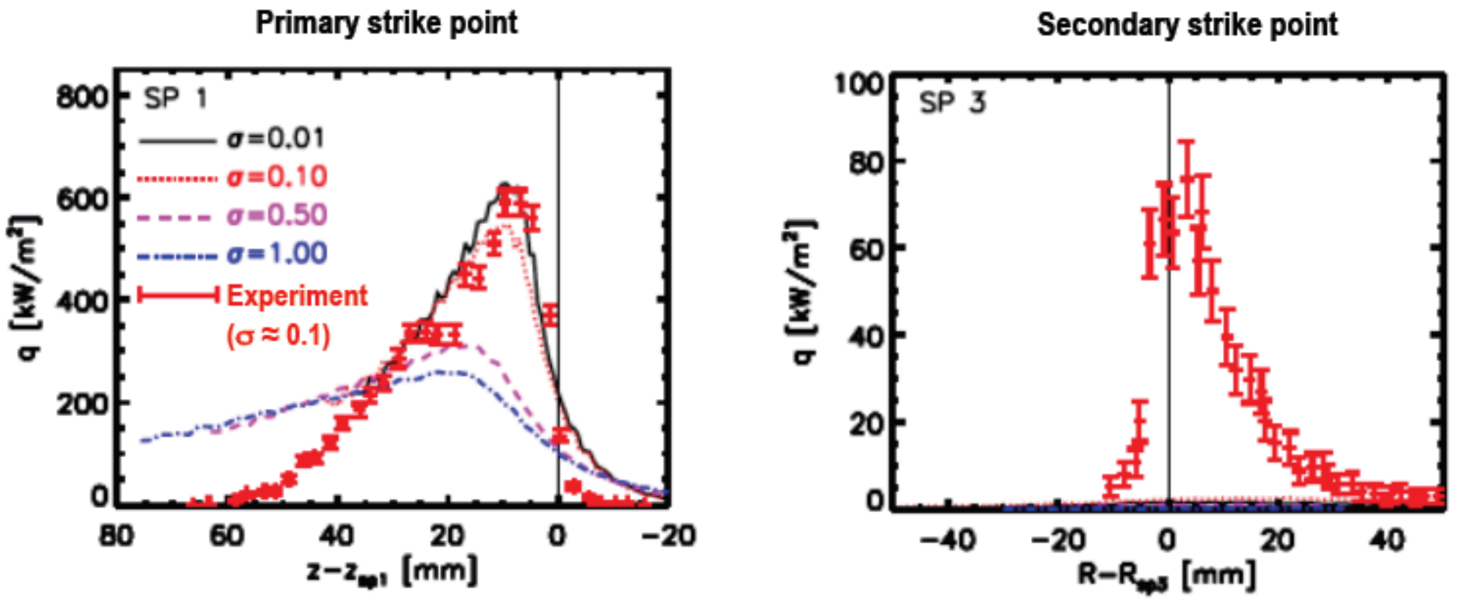
*D.D. Ryutov, T.D. Rognlien, Sherwood-2011; D.D. Ryutov, R.H. Cohen, T.D. Rognlien, M.V. Umansky, Contrib. Plasma Phys., **52**, 539, 2012; PPCF, **54**, 124050, 2012; D.D. Ryutov, R.H. Cohen, E. Kolemen, L. LoDestro, M. Makowski, J. Menard, T.D. Rognlien, V.A. Soukhanovskii, M.V. Umansky, X. Xu. “Theory and Simulations of ELM Control with a Snowflake Divertor” Paper TH/P4-18at 2012 IAEA Fusion Energy Conference, San-Diego, October 8-12, 2012; T.D. Rognlien, R.H. Cohen, D.D.Ryutov, M.V. Umanski, JNM, **438**, S418, 2013. W.A. Farmer, D.D. Ryutov. Phys. Plasmas, **20**, 092117, 2013 Experiment: V. Soukhanovskii, poster UP8.00032, W. Vijvers, poster PP8.00047, G. Canal, poster PP.800046

TCV: extensive studies of activation of additional strike points (Courtesy H. Reimerdes)



EMC3-Eirene modeling under-predicts power distribution into private flux region

- Adjust $D_\perp$ and $\chi_\perp$ to match target profiles at primary strike point



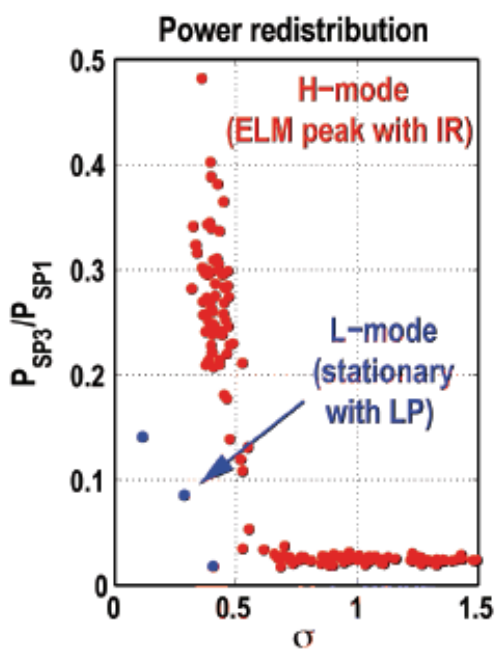
- Measured heat flux at SP3 is orders of magnitude larger than the modeled heat flux

→ Existence of another transport channel in addition to constant diffusivities

Courtesy H. Reimerdes, TCV (simulations by T. Lunt)

Power redistribution during ELMs significantly larger than in Ohmic L-mode

SF+



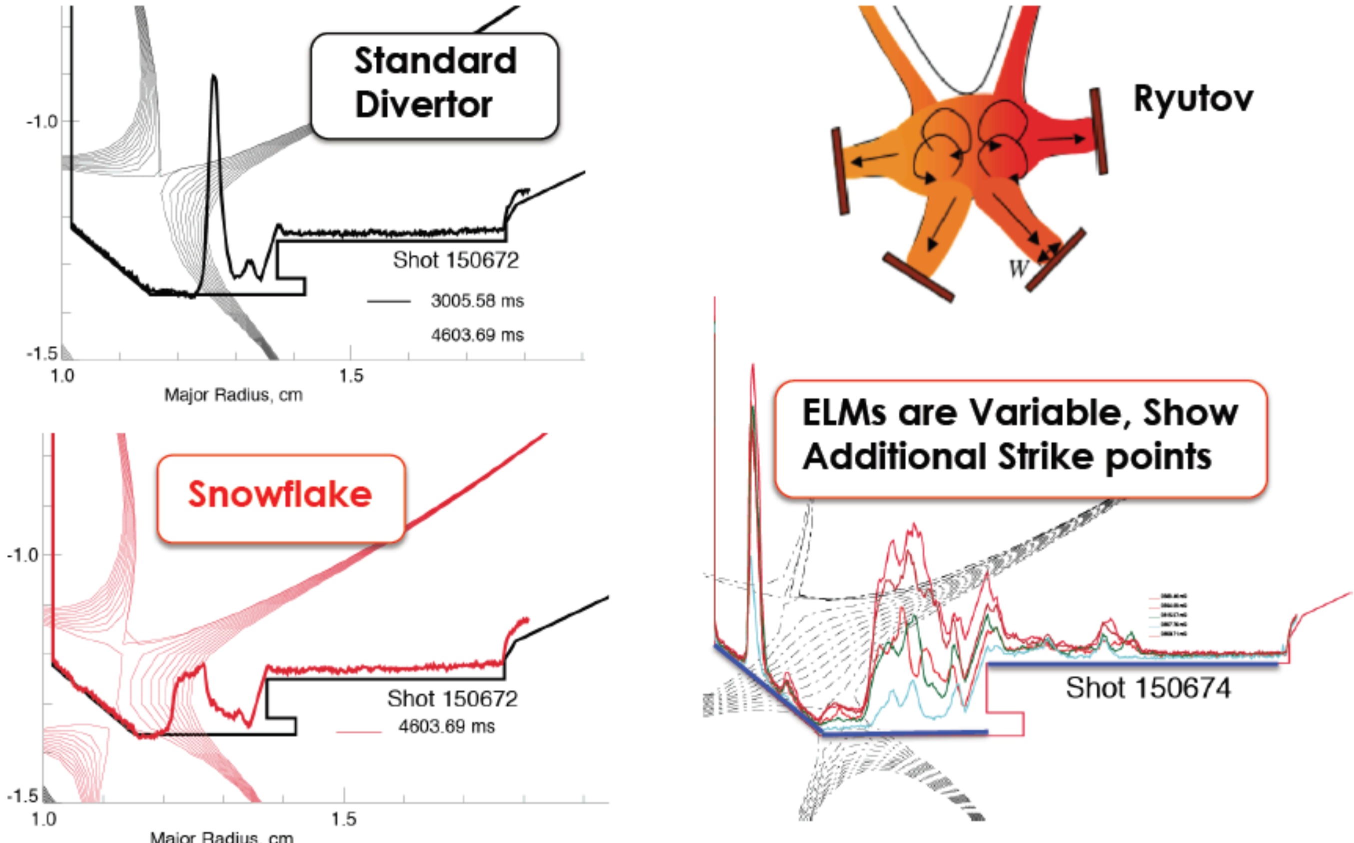
- **Larger redistribution during ELMs suggests the importance a beta poloidal driven transport channel, e.g.:**
  - Destabilisation of curvature driven, flute-like modes for β_p>>1 **[D.D. Ryutov, et al., *Contrib. Plasma Phys.* 52 (2012) 539]**
- **Alternatively, ELMs can cause transient changes of the equilibrium leading to smaller σ and/or a transition to a HFS SF-**
  - ELM resolved equilibrium reconstructions show a decrease of σ but not a transition to SF-

[W. Vijvers, et al, IAEA FEC 2012, EX/P5-22]

CRPP

Courtesy H. Reimerdes

New opportunity to study details of SOL transport in attached SF divertor; study ELMs



S.L. Allen/IAEA FEC/November, 2012

DIII-D NATIONAL FUSION FACILITY

14

S. Allen, IAEA 2012

Welcome to Brave New World!

A number of traditional assumptions breaks down:

The heat flux does not flow along poloidal flux surfaces to the divertor plates. It broadens significantly when passing near the null-point

Heat flux splits between all four divertor legs

Transport coefficients are not constant along the SOL, they may vary significantly

The plasma pressure becomes a significant player near the null-point, making the “vacuum” PF reconstructions unreliable

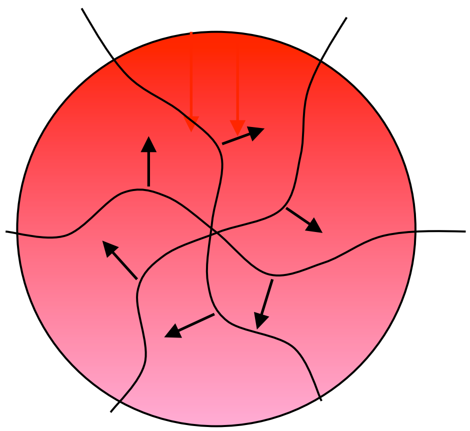
A “Churning Mode”*

In the earlier works, two modes of the power-partition between the divertor legs were considered: the loss of equilibrium caused by the continuous heating the upper part of the plasma in the vicinity of the null and the instability of an equilibrium state if such a state exist.

In this presentation we focus on large-scale convective mode driven by the heating. The largest-scale modes typicaly give main contribution to the convective transport between the differentially-heated surfaces

* D. Ryutov, R.H. Cohen, T. Rognlien, M. Umansky, YM10.00002, APS DPP – 2013)

More detail:



A mode of a toroidally-symmetric diferential rotation in the convective "blob"; the magnetic field is assumed to be frozen into the plasma;

This constraints the radial extent of the "churning" mode, as the poloidal magnetic field at large distances from the null becomes strong and, thereby, stiff.

So, beyond a certain distance, the poloidal field is unperturbed and the "churning" mode vanishes

A formal description: each fluid element is shifted by some angle $\psi(\varphi)$, while staying at the same radius *r*; the allowed dependence of $\psi(\varphi)$ is determined by the constraint that strong toroidal field is not perturbed. We use Lagrangian description:

$$\varphi = \varphi_0 + \psi(\varphi_0); \quad B_T(\varphi_0)d\varphi_0 = B_T(\varphi)d\varphi;$$

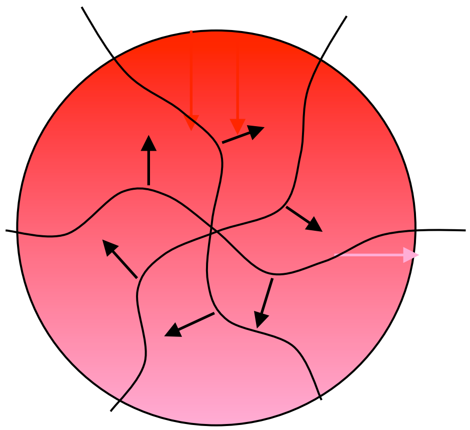
$$\psi = \chi + \Delta\varphi; \quad B_T(\varphi_0) = \frac{B_T\big|_{r=0}}{1 + \frac{r}{R}cos\varphi_0}$$

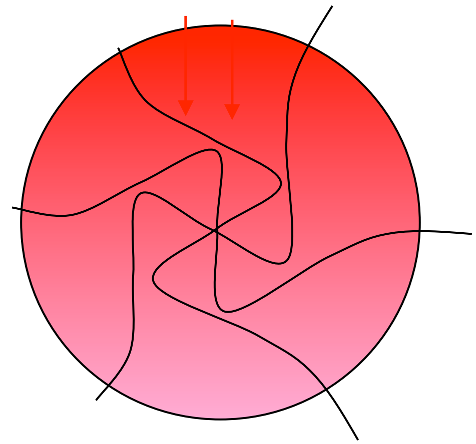
$$\frac{d\Delta\varphi}{d\varphi_0} \approx \frac{r}{R}\left[\cos\varphi_0 - \cos\left(\varphi_0 + \chi\right)\right]$$

$$\Delta\varphi = \frac{r}{R}\left[\sin\varphi_0 - \sin\left(\varphi_0 + \chi\right)\right]$$

Convection leads to formation of highly tangled magnetic field near the null

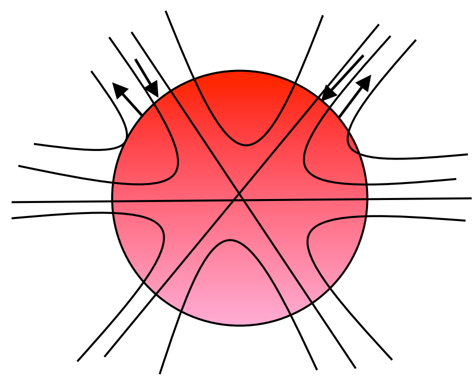
Convection leads to distortion of the poloidal field zone and strong magnetic field fluctuations.





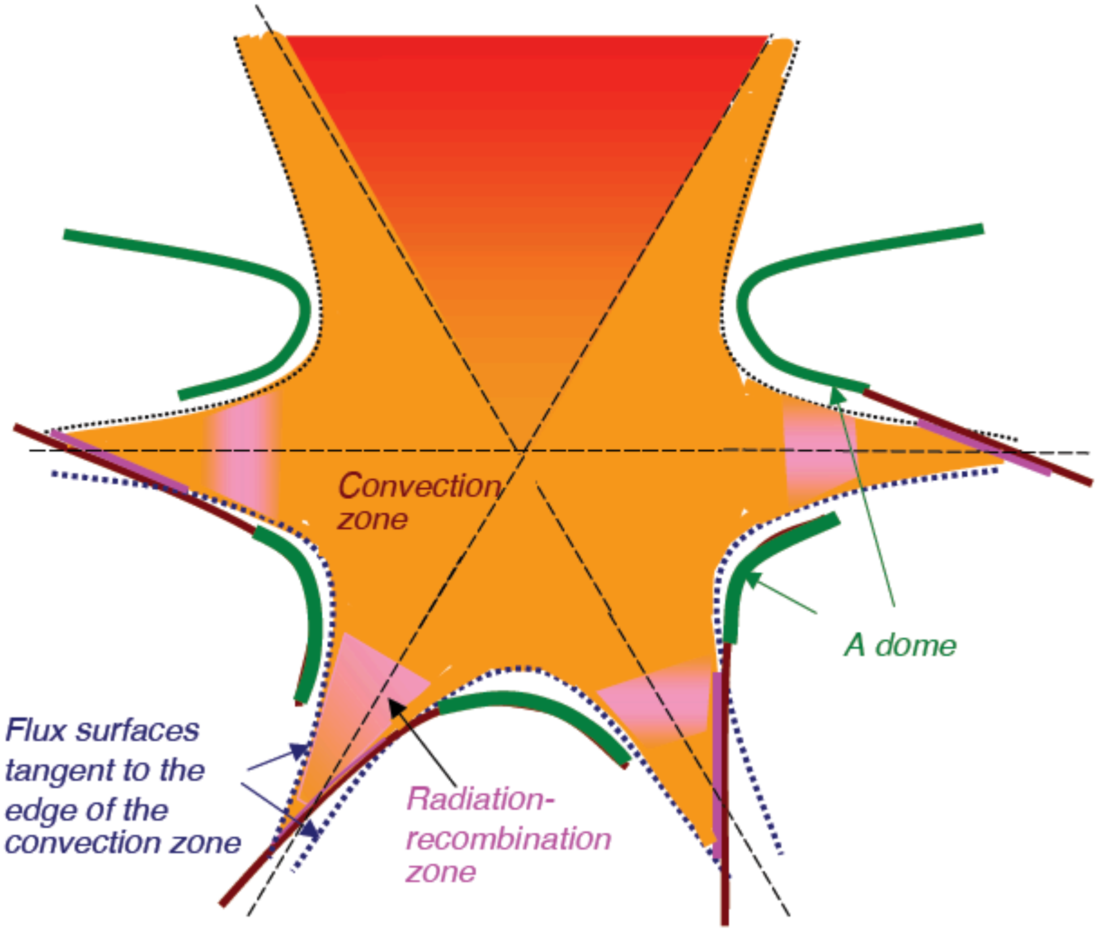
Current sheaths may form and lead to magnetic reconnection

Reversed plasma flow may form in the SOL if convection encompasses a larger area than the projection of the initial SOL



Attempting to develop a detached SF divertor*

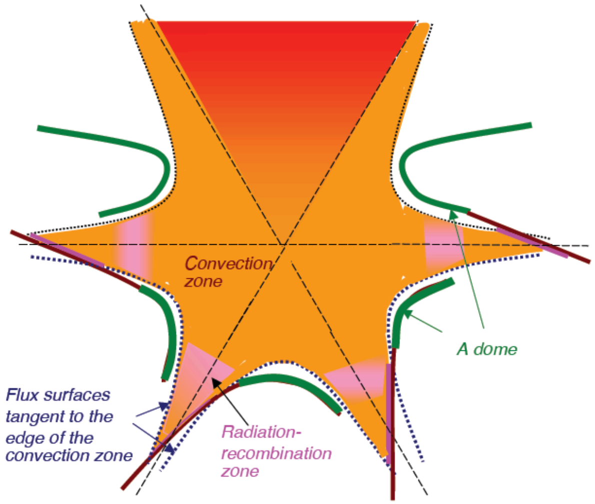
A sketch of what could become a detached SF divertor



This is just a general concept, the relative dimensions may change significantly

* Ryutov, Krasheninnikov, Rognlien, Poster PP8.00028, 2013 APS DPP

An approximate power balance for the hypothetical SF divertor



Total power reaching the divertor: 200 MW

Power radiated in each of the four radiative zones: 35 MW;

Power reaching each of the four wetted areas: 15 MW

The poloidal length of the absorbing zone on each of the domes: $l_{dome} \sim 50$ cm

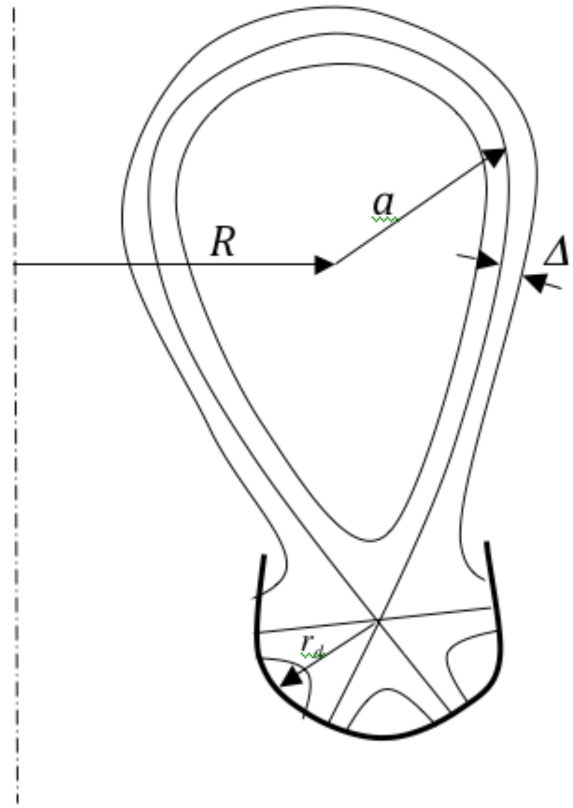
The poloidal length of each wetted zone: $l_{wet} \sim 30$ cm

The major radius $R \sim 5$ m

The power load on the domes (mostly radiation) ~1.5 MW/m^2

The power load on the wetted areas (surface heating, residual heat flux and radiation) ~ 1.5 MW/m^2

For spherical tokamaks, an "open" divertor may be a better option*



PPCF, **54**, 124050, 2012.

SUMMARY

- There exist two very different possibilities for the manipulation of the poloidal magnetic field in tokamak divertors:

  - Via far-away coils (as in snowflake or cloverleaf or trident divertors)

  - Via coils situated near or inside the divertor (as in cusp/X-divertor)

  Both approaches have their advantages and disadvantages

- In the area of snowflake divertor, during the last 5 years (2009-2013) the following fundamental experimental results have been obtained (TCV, NSTX, DIII-D):

  - No core confinement degradation when switching to the snowflake

  - Effects on ELMs

  - Activation of multiple divertor legs; the TCV experiments indicate order-one fraction of ELM energy getting to additional two strike-points

- Curvature-driven modes in a weak-field area around the SF null(s) have been identified as a possible candidate, in particular, a “churning mode”

- If this identification is correct, extrapolation to reactor-scale devices becomes promising; creating compact, detached “multi-leaf” divertors becomes possible

Winston Churchill, 1940:

“Gentlemen, we have run out of money; now we must think”