LLNL-PRES-668162

Divertor theory: plasma transport in complex geometries

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Presented at 2015 Sherwood Fusion Theory Conference

New York University
March 16-18 2015

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences.

Contributions of my many colleagues are gratefully acknowledged:

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

PPPL: E. Kolemen, J. Menard…

UCSD: S. Krasheninnikov

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

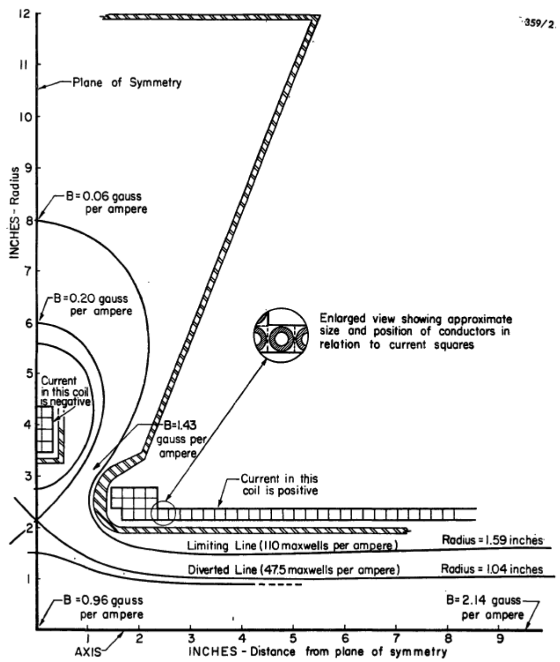
HL-2M: G.Y. Zheng…

……

Why divertor?

A burning plasma is not a perfectly controlled, static object: it is more like a burning flame, continuously flickering, with occasional tongues of flame darting from its surface…

One cannot let a burning plasma "lean" on a conformal wall of the confinement vessel: the plasma would immediately burn a hole in it.

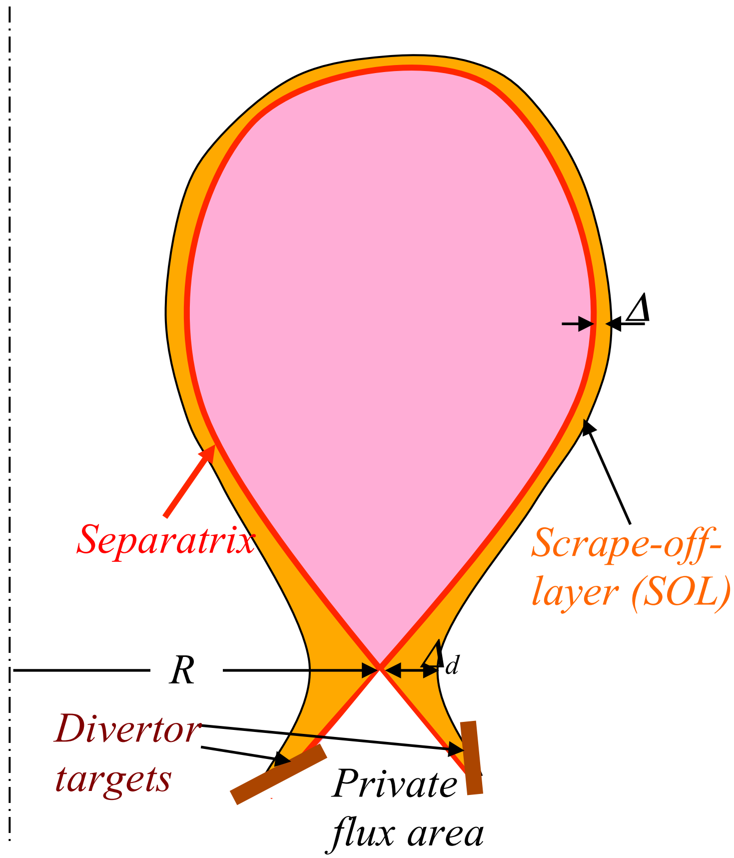


A solution: "magnetic divertor"

"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



This is a vertical cross-section; the toroidal field (large) is normal to the screen

Having solved a problem of protecting the reactor chamber, divertors create a problem of too high heat fluxes on the divertor components

In some of the ARIES reactor studies (F. Najmabadi and the ARIES team) the divertor power flux is comparable to that on the surface of the Sun, 60 MW/m^2 (!)

The problem is that the scrape-off layer is too narrow, giving rise to too narrow “wetted zone” on the divertor plates (divertor targets)

A possible solution: increase the width of the “wetted zone(s)” by manipulation of the poloidal field structure – the subject of this talk

A “Dream” Divertor

Heat flux on the absorbing surfaces is below a few MW/m^2

The plasma is “detached” from the divertor surfaces

The presence of divertor does not lead to confinement degradation (and, perhaps, reduces or eliminates ELMs)

The field is generated by PF coils situated *outside* the TF coils

The divertor volume is a small fraction of the total volume inside the vacuum chamber

Several ideas of improving the divertor performance by modifying the poloidal field structure have appeared during the last decade

Cusp divertor (H. Takase, 2001)

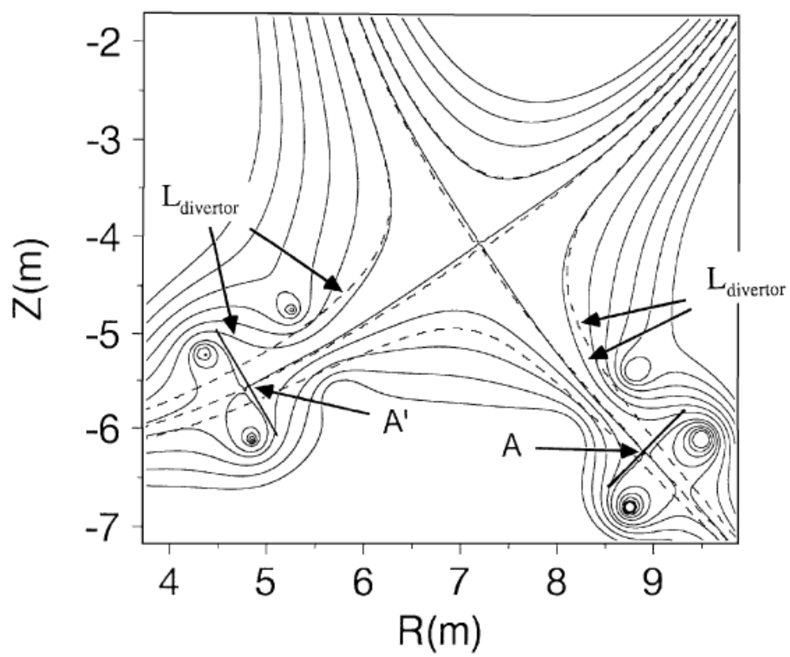


Fig. 3. Example of magnetic configuration generated by using parameters in Table I. Original divertor channels and separatrix are represented by dotted lines.

"The proposed configuration utilizes an additional cusp-like magnetic field generated by four poloidal coils for expanding the divertor channels. This not only allows a significant reduction of the heat load due to expansion of the divertor channels but also hardly affects the original magnetic configuration of the core plasma."

H. Takase, Journal of the Physical Society of Japan, **70**, 609, 2001

X-divertor (M. Kotschenreuther et al, 2004)

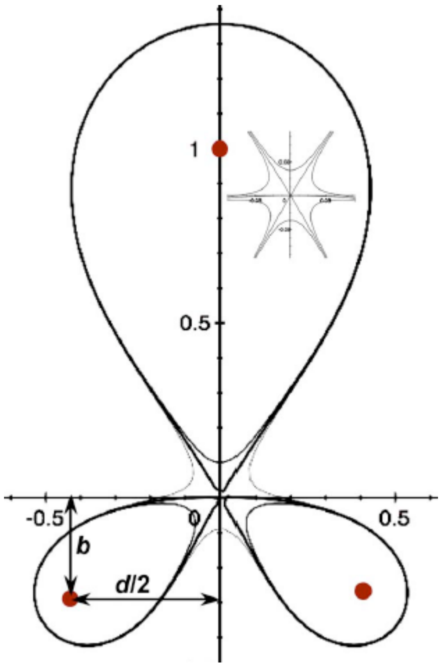
It is similar to the cusp divertor:

> "This extra downstream X-point can be created with an extra pair of poloidal coils… Each divertor leg (inside and outside) needs such a pair of coils. …The distant main plasma is hardly affected because the line flaring happens only near the extra coils."
>
> M. Kotschenreuther, P. M. Valanju, S. Mahajan, J. Wiley. "On heat loading, novel divertors, and fusion reactors." Phys. Plas. 14, 072502 (2007)

An elegant solution of bringing the coils closer to the divertor by inserting segmented coils between TF coils was proposed.

A favourable effect on the divertor detachment has been emphasized

Snowflake divertor (D. Ryutov, 2007)

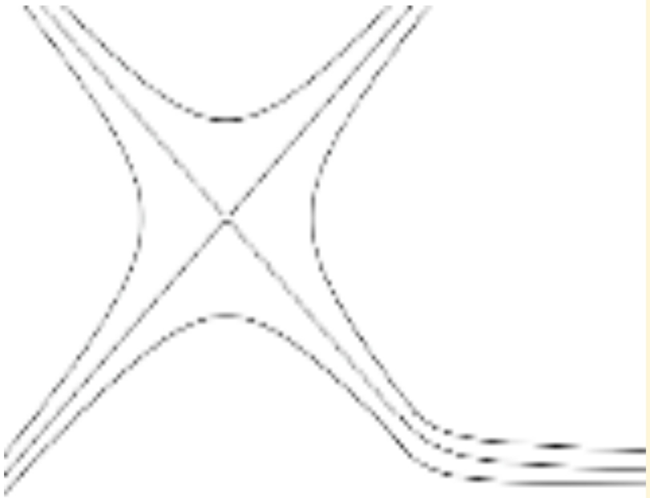


"Using a simple set of PF coils, one can reach the situation in which the null of the poloidal magnetic field in the divertor region is of second order... Then, the separatrix in the vicinity of the null point splits the poloidal plane… into six sectors, making the whole structure look like a snowflake - hence the name. This arrangement allows one to spread the heat load over a much broader area than in the case of a standard divertor." (D. Ryutov, PoP, **14**, 064502, 2007)

From the outset, the distance to the coils was assumed to be large compared to the divertor size.

To beat the "topological instability" (splitting the second-order null into two closely-spaced first-order nulls) it was proposed to use the divertor current somewhat above or below the "ideal" one, giving rise to SF+ or SF- geometry

Super-X divertor (M. Kotschenreuther et al, 2008)



The Super-X Divertor (SXD), a robust axisymmetric redesign of the divertor magnetic geometry … is presented. With small changes in poloidal coils and currents for standard divertors, the SXD allows the largest divertor plate radius inside toroidal field coils. This increases the plasma-wetted area by 2–3 times over all flux-expansion-only methods, e.g., plate near main X point, plate tilting, X divertor, and snowflake, decreases parallel heat flux and hence plasma temperature at plate, and increases connection length by 2–5 times.

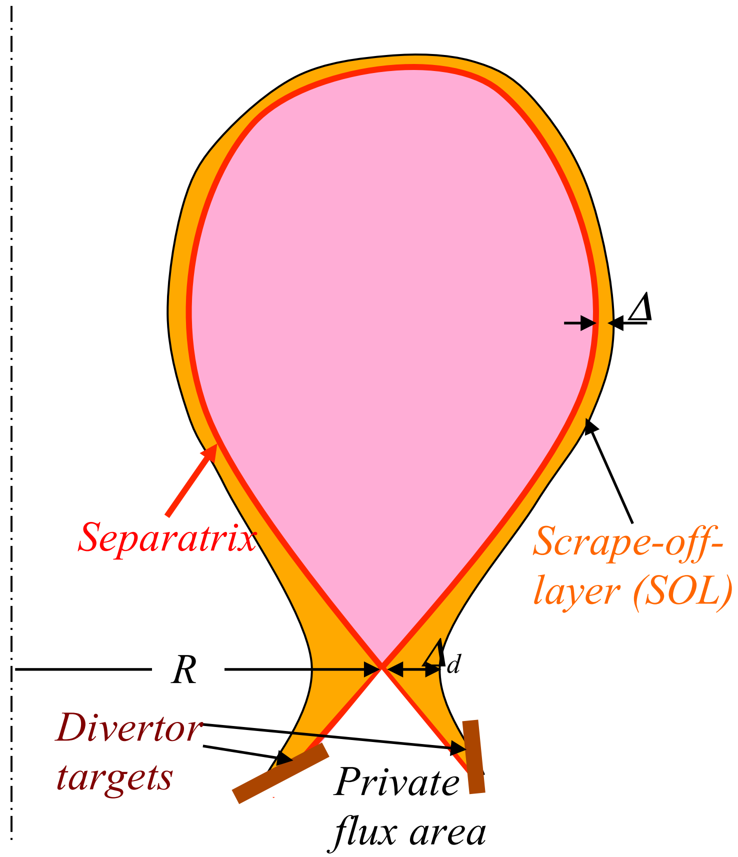
P.M. Valanju, M. Kotschenreuther, S.M. Mahajan, J. Canik. Phys. Plas. **16**, 056110 (2009)

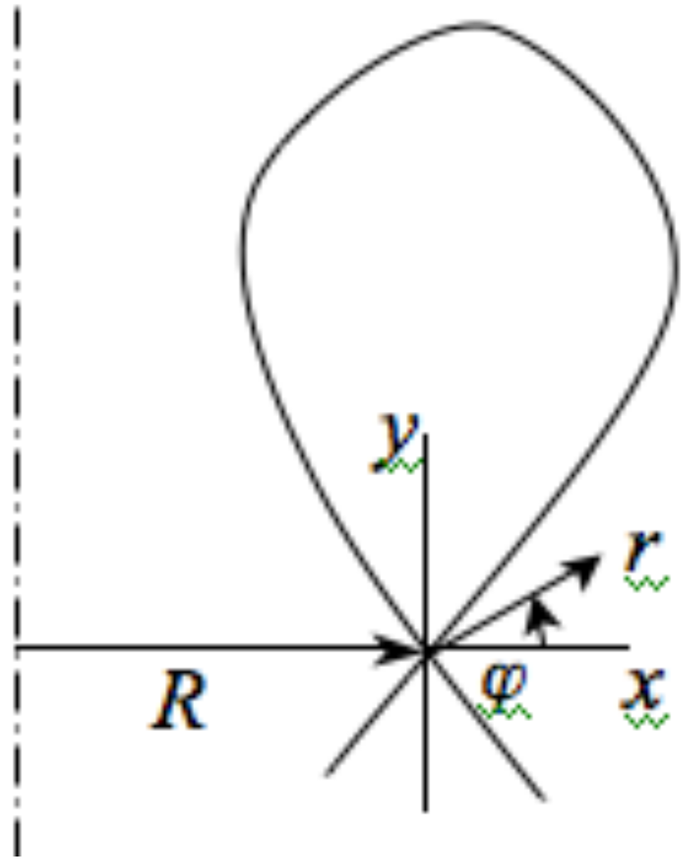
An idea: pulling an outer divertor leg as far as possible in the radial direction, to utilize the factor *R* in the surface area of the wetted zone.

Long leg may facilitate detachment.

Inspired magnetic design of the MAST-Upgrade

Poloidal divertor: notation and divertor coordinates





This is a vertical cross-section; the toroidal field (large) is normal to the screen

In the spirit of the “dream divertor” approach, I assume that the currents creating the divertor field are situated far away from the divertor area

This allows us to use the power-law expansions for the magnetic field

Assume also that the divertor size D is small compared to the major radius, $D \ll R$ (if needed, the analysis can be improved by adding $1/R$ corrections; typically small even for spherical tokamaks)

$$\Downarrow$$

The poloidal field can be considered as a planar field

General properties of the planar field ($B_x(x,y)$, $B_y(x,y)$)

For a planar field, the condition $\nabla \cdot \boldsymbol{B} = 0$ reads as:

$$\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \quad . \tag{1}$$

This equation generates a flux function $\Phi(x,y)$ such that

$$B_x = -\partial \Phi / \partial y; B_y = \partial \Phi / \partial x \, . \tag{2}$$

The condition $\Phi(x,y)$=const describes poloidal flux surfaces.

Toroidal current in the divertor area is small, and the field is curl-free, i.e.

$$\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = 0 \quad . \tag{3}$$

This equation then generates a scalar potential Ψ,

$$B_x = -\partial \Psi / \partial x; B_y = -\partial \Psi / \partial y \quad .$$

Substituting Eq. (2) into Eq. (3), one finds that the flux function satisfies Laplace equatuion,

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} = 0 \, .$$

(the same is true for the scalar potential).

The planar curl-free magnetic field can be conveniently described by the machinery of the complex variables*

$$\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \quad (1)$$

$$\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = 0 \quad (3)$$

The complex position

$z=x+iy$,

The field can be represented by a complex function $F(z)$:

$\mathrm{Re}F=B_x$, $\mathrm{Im}F=-B_y$.

Equations (1) and (3) constitute the Cauchy-Riemann conditions for the complex function F, which is therefore, a regular function.

The complex potential $G(z)= \Psi+i\Phi$

It is related (by virtue of the Cauchy-Riemann conditions) to the field function:

$F=-dG/dz$,

so that

$B_x=-\mathrm{Re}(dG/dz)$, $B_y=\mathrm{Im}(dG/dz)$.

* See divertor-relevant examples in: D.D. Ryutov, M.V. Umansky. Phys. Plasmas, **20**, 092509, Sept. 2013

General representation of the field function:

$F = A_0 + A_1 z + A_2 z^2 + A_3 z^3 + \ldots.$

The corresponding complex potential G ($-dG/dz = F$):

$-G = A_0 z + (A_1/2)\, z^2 + (A_2/3) z^3 + (A_3/4) z^4 + \ldots.$

The coefficients A_n depend on the currents in a plasma and PF coils

We will place the origin at the field null lying on the main separatrix (A_0=0).

The scale of the global field variation is $\sim a$, so that

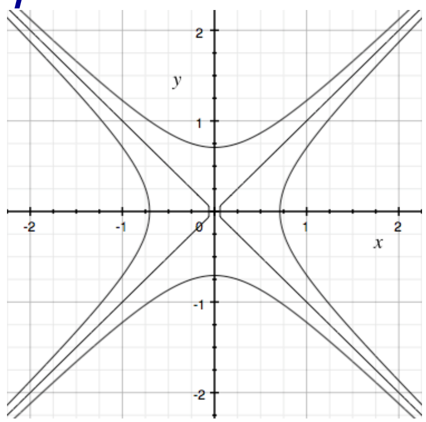
$$A_n = B_{pm} \frac{K_n e^{i\eta_n}}{a^n},$$

where B_{pm} is a poloidal field *at the midplane* and K_n are dimensionless coefficients of order 1 (both real and positive).

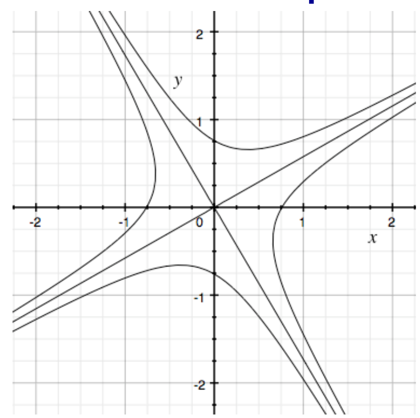
The “standard” first-order null: $K_1 \sim 1$ $\Longrightarrow$ In the divertor area ($D << a$) one can neglect the higher-order terms:

$$F \approx B_{pm}(e^{\eta i}K_1/a)z; \qquad G \approx - B_{pm}(e^{\eta i}K_1/2a)z^2$$

The coefficient η determines the orientation of the separatrix



$\eta = \pi/2$



$\eta = -\pi/3$

Flux function for $\eta = \pi/2$:

$$\Phi = \operatorname{Im} G = B_{pm}(K_1 / 2a)\left(x^2 - y^2\right)$$

The field strength near the null does not depend on the direction:

$$\left|\boldsymbol{B}_p\right| = |F| = \left|B_{pm}K_1\right| r / a \; ; \quad dB_p / dr = B_{pm}K_1 / a \;\; (the \;\; field \;\; "flatness")$$

If the plasma and coil currents change by some small amount $\sim\varepsilon$, then the constant A_0 reappears, $A_0=\varepsilon B_{pm}$, with ε complex. This leads to a small shift of the null from the initial position:

$F=A_0+A_1z$;

$F=0$ at $z=-A_0/A_1=\varepsilon a/K_1$

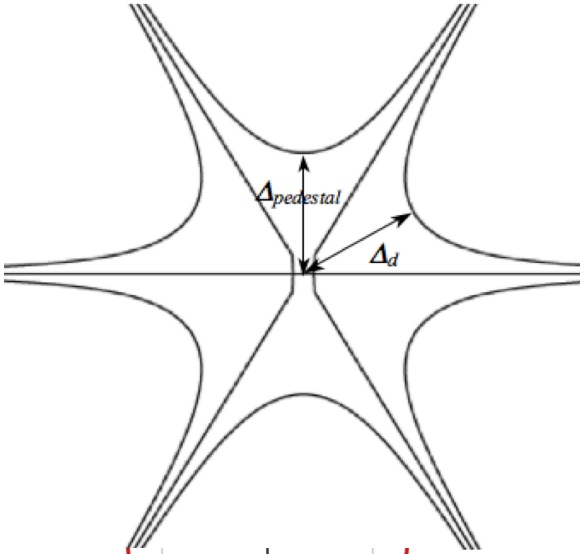
(also, some small $\sim\varepsilon$ tilt may occur).

The standard divertor is topologically stable

Let us adjust the PF currents so as to make both A_0 and A_1 zero

$$F \approx A_2 z^2; \qquad A_2 = B_{pm} K_2 e^{i\eta_2} / a^2$$

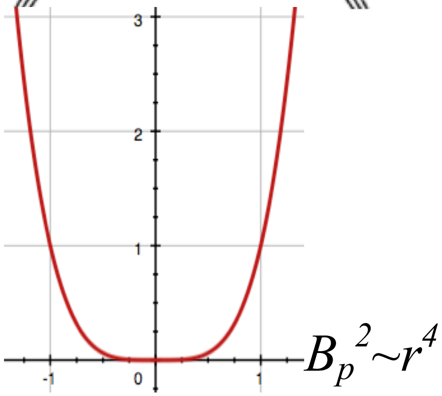
$$G \approx -A_2 z^3 / 3$$



The flux function (for η_2=0):

$$\Phi = \operatorname{Im} G = B_{pm}\left(K_2 / a^2\right)\left(\frac{y^3}{3} - x^2 y\right)$$

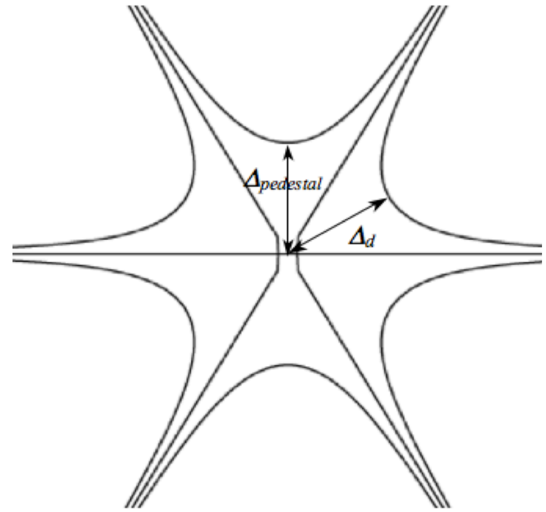
$$\left|\boldsymbol{B}_p\right| = \left|A_2\right|\left|z^2\right| = B_{pm} K_2 \left(r^2 / a^2\right)$$



A snowflake field! A very strong SOL broadening compared to the standard divertor. A zone of a very low poloidal field near the null.

Other features caused by the B_p~r^2 dependence:

- Large connection length
- Large specific volume of the flux tube
- Power-law divergence of the safety factor q
- Stronger shear



May have repercussions for both the SOL and pedestal physics

Yu. Medvedev et al. “Edge Stability and Pedestal Profile Sensitivity of Snowflake Diverted Equilibria in the TCV Tokamak,” Contrib. Plasma Phys. **50**, 324, 2010; M.V. Umansky et al, “Edge Plasma in Snowflake Divertor,” Contrib. Plasma Physics, **50**, 350, May 2010; T.D. Rognlien et al. “Comparison of ELM heat loads in snowflake and standard divertors” Journ. of Nucl. Mat., **438**, S418, 2013.

Consider now the effect of an imperfect adjustment of the currents in PF coils

$$F=A_0+\cancel{A_1 z}+A_2 z^2$$

$A_0=\varepsilon B_{pm}$; $A_1=\varepsilon_1 B_{pm}/a$

The crossed term is small for small $|z|/a$.

One sees that now the second-order null splits into two first-order nulls. The system is topologically unstable.

By shifting the origin to the null lying on the main separatrix (the one that encloses the confined plasma), one can present the field function as

$$F= A_2 z(z-z_1),\ \ z_1=2(A_0/A_1)^{1/2}\sim\varepsilon^{1/2};$$

Obviously, for $|z|>>|z_1|$ one recovers a snowflake structure

Some general properties of the two-null representation

We use notation $z_1 = de^{-i\theta}$

The absolute value of the field:

$$B_p = |F| = |A_2||z||z - z_1|$$

In the vicinity of each of the nulls the field behaves as a first-order null,

$$B_p = |A_2| rd$$

where *r* is the distance to the corresponding nulls.

The field "flatness" near each null is the same,

$$dB_p / dr = B_{pm} K_2 d / a^2$$

and proportional to the distance *d* between them*

* 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.." NF, **49**, 075005, 2009.
  D. Ryutov, M. Makowski, M. Umansky, PPCF, **52**, 105001, 2010

The two nulls are "talking" to each other via the magnetic field structure. The field flatness in the location of one of them "knows" of the presence of the other.

The effect of the second null may be substantial even if the null is outside the vacuum chamber

The splitting of the second order null to two first-order nulls may occur both due to the imperfections in the control system and "by design"

Flux surfaces for a two-null system

$$F = A_2 z(z - z_1); \quad G = A_2\left(\frac{z^3}{3} - \frac{z^2 z_1}{2}\right)$$

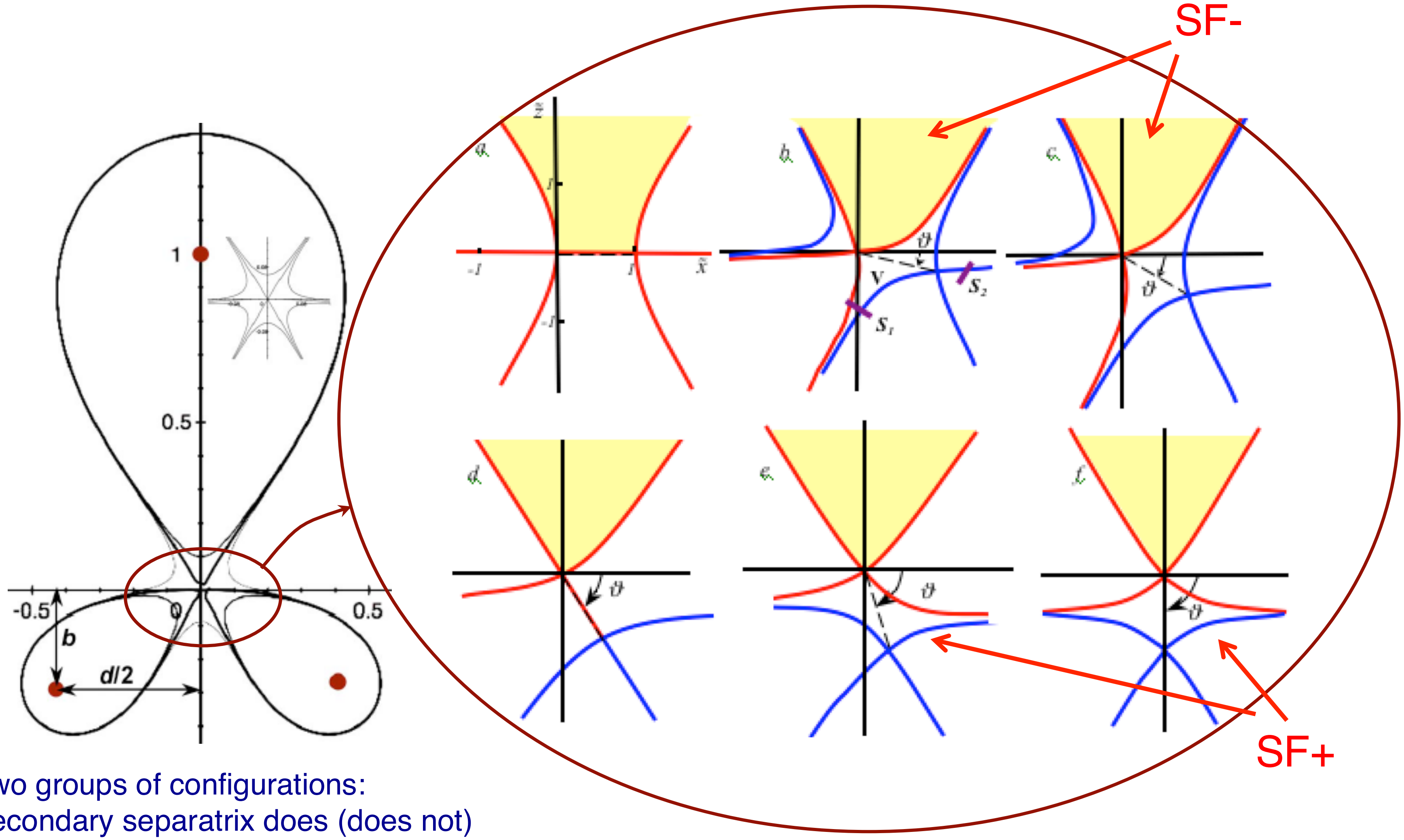
Two separatrices:

$$\mathrm{Im}\left(\frac{z^3}{3} - \frac{z^2 z_1}{2}\right) = 0 \quad and \quad \mathrm{Im}\left(\frac{z^3}{3} - \frac{z^2 z_1}{2} + \frac{z_1^3}{6}\right) = 0$$

Recalling that $z_1 = de^{-i\theta}$ and normalizing all the distances by d, we find that the whole panoply of the field structures is characterized by a single parameter, θ.

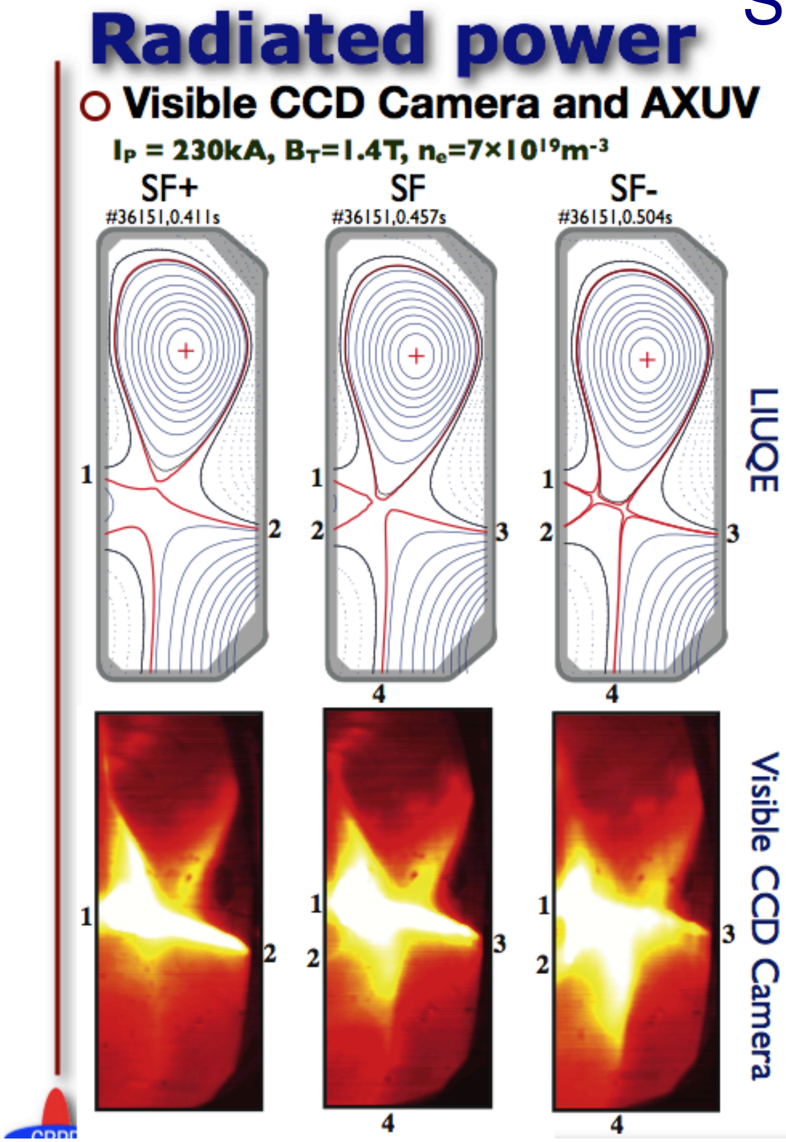
A field structure in the divertor area is controlled by remote coils

"Dance of the two nulls"



Two groups of configurations:
Secondary separatrix does (does not) enclose the primary one: SF- (SF+)

Snowflake on TCV (Lausanne)

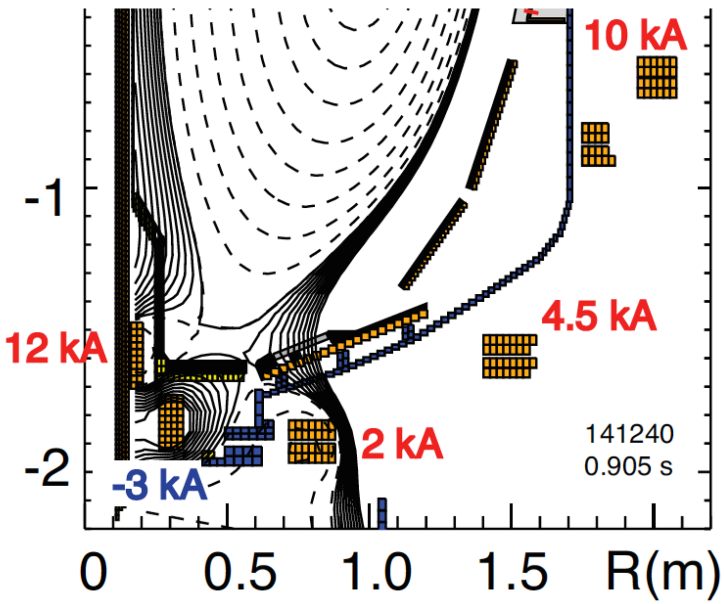


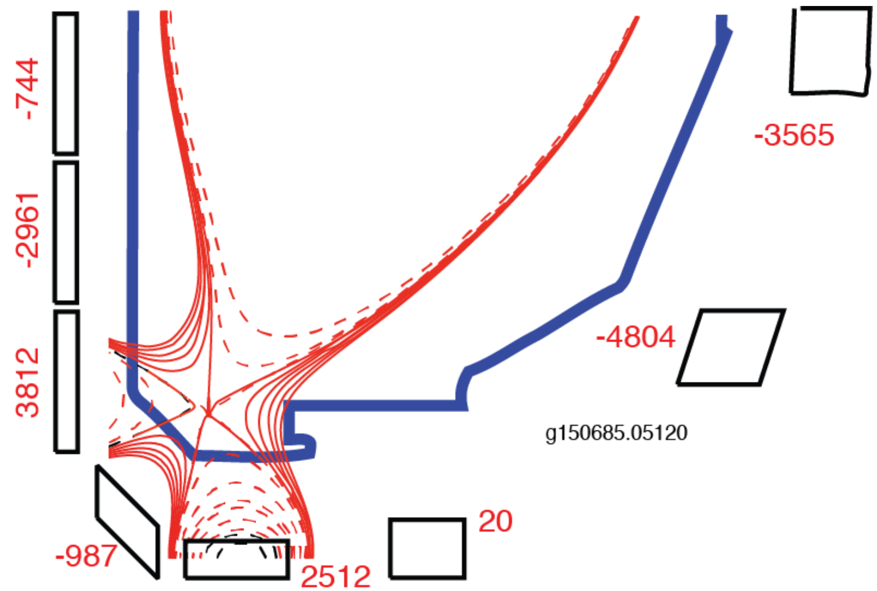
Piras F, Coda S, Furno I, Moret JM, Pitts RA, Sauter O, Tal B, Turri G, Bencze A, Duval BP, Felici F, Pochelon A, Zucca. "Snowflake divertor plasmas on TCV", *Plasma Physics and Controlled Fusion,* **51,** 055009, 2009,

A term "quasi-snowflake" was coined by Italian researchers in 2012 to designate all these snowflake-like configurations

A qualitative identifier: four outgoing divertor "legs"

Snowflake configurations have been realized and studied on NSTX and DIII-D





Courtesy V. Soukhanovskii

See also: V. A. Soukhanovskii, et al "Taming the plasma-material interface with the 'snowflake' divertor in NSTX," Nucl. Fus., **51**, 012001, 2011; V. A. Soukhanovskii, et al, Radiative snowflake divertor studies in DIII-D, Journ. Nucl. Mat., 2015, http://dx.doi.org/10.1016/j.jnucmat.2014.12.052

Other examples of recent configurations of the snowflake family:

R Albanese, R Ambrosino and M Mattei. "A procedure for the design of snowflake magnetic configurations in tokamaks" PPCF, 56, 035508, 2014. *Examples of coil structures for DEMO-scale facilities.*

G. Calabro, S.L. Chen, Y. Guo et al. EAST Snowflake Experiment: Scenario Development and Edge Simulations. Paper EX/P3-4 at the 2014 IAEA FEC, St. Petersberg, Russia. *Quasi-snowflake configurations realized on the EAST Facility*

G.Y. Zheng, X.Q.Xu, D.D. Ryutov, Y.D. Pan, T.Y. Xia. "Magnetic configuration flexibility of snowflake divertor for HL-2M." Fusion Engineering and Design, **89**, 2621, 2014. *A detailed characterization of the SF configurations that can be produced on the HL-2M Facility.*

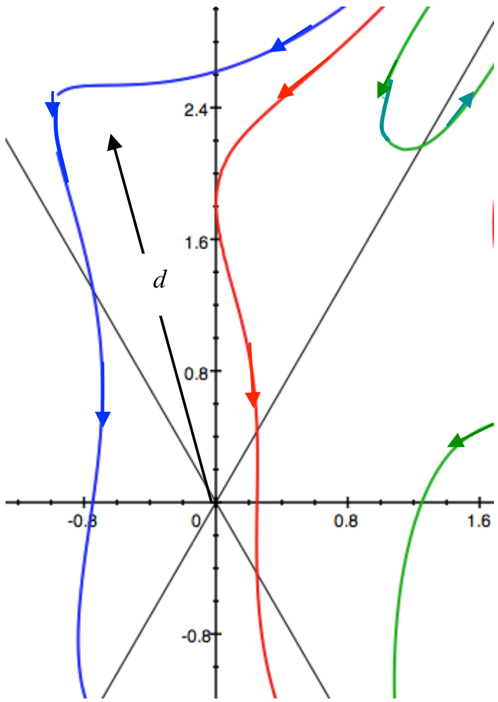
S.F. Mao, Y. Guo, X.B. Peng et al, "Evaluation of target-plate heat flux for a possible snowflake divertor in CFETR using SOLPS", JNM, 2015, http://dx.doi.org/10.1016/j.jnucmat.2014.11.078. *Contains information on the plasma shape and PF coil structure for the reactor-scale facility*

Key experimental findings (TCV, NSTX, DIII-D):

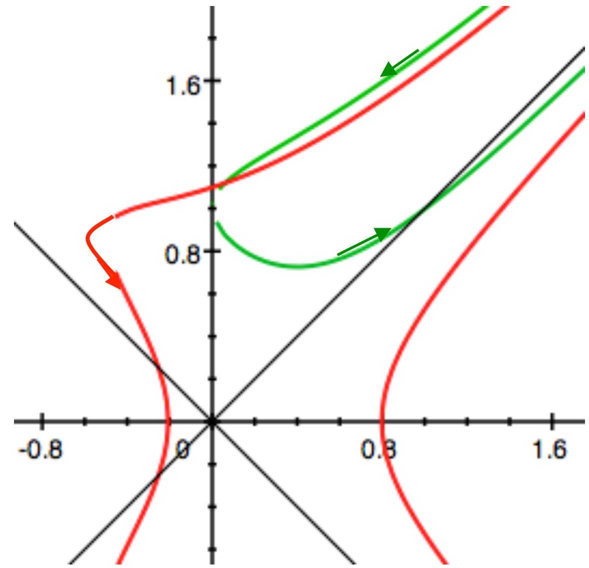
- The snowflake (SF) configurations can be created and maintained for seconds
- There is no significant confinement degradation with transition to SF
- Heat fluxes are reduced more strongly than by the poloidal flux expansion only
- There exists significant power sharing between the four divertor legs
- SF facilitates transition to the detached regimes

Switching back to the SF theory

Prompt particle losses in a snowflake (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 *Not assessed yet*

The SF geometry should have a significant effect on the general neoclassical orbits, including those that penetrate to SOL: important for Goldston's SOL model (R. Goldston, "Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks." NF **52**, 013009, 2012).

Not assessed yet

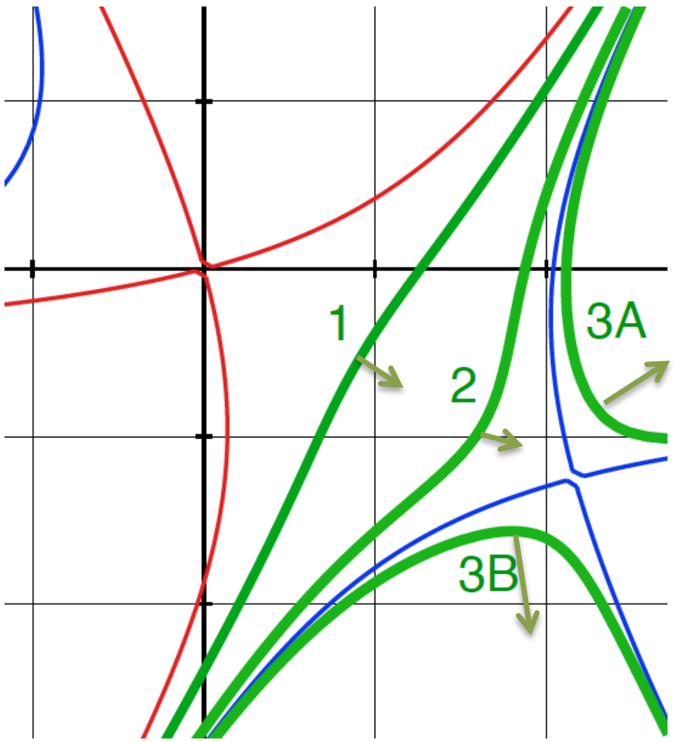
Stochastic effects in the zone of a second-order PF null

Even for quite small perturbations the field lines may become fully stochastic (we are dealing with essentially toroidal field, no poloidal field in a wide zone)

I am not aware of any analyses

(except for a very preliminary discussion in: S.S. Abdullaev, M. Jakubowski, M. Lehnen, O. Schmitz, B. Unterberg. "On description of Magnetic Stochasticity in Poloidal Divertor Tokamaks." Phys. Plas., 15, 042508 2008)

Blob propagation in a SF- geometry



The blob (shown in green) is propagating in the outboard direction in the snowflake-minus configuration

1 → 2 → 3

When passing through the secondary null it has to split into two independent structures, A and B.

This splitting will affect the further propagation of the structures 3A and 3B.

No theory yet

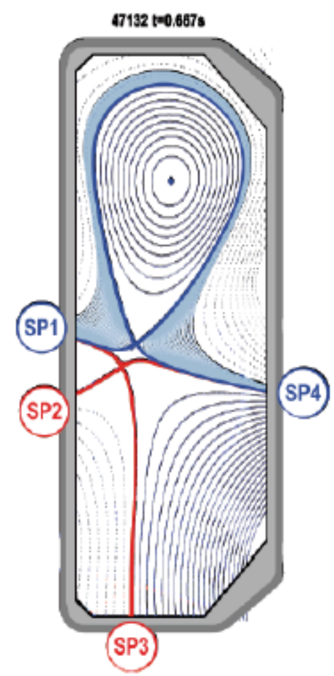
Heat and particle flux sharing between four divertor legs

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

In SF+ SOL is only directly connected to two strike points

SF+

- **Power has to cross the primary separatrix to reach secondary SPs**



CRPP

H. Reimerdes, EPS Conference, July 1-5, 2013

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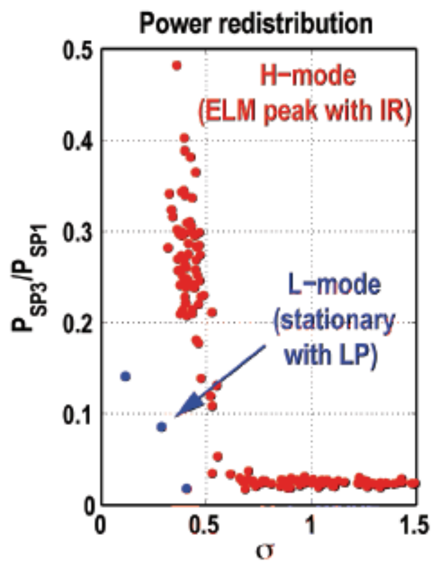
Power redistribution during ELMs significantly larger than in Ohmic L-mode

SF+



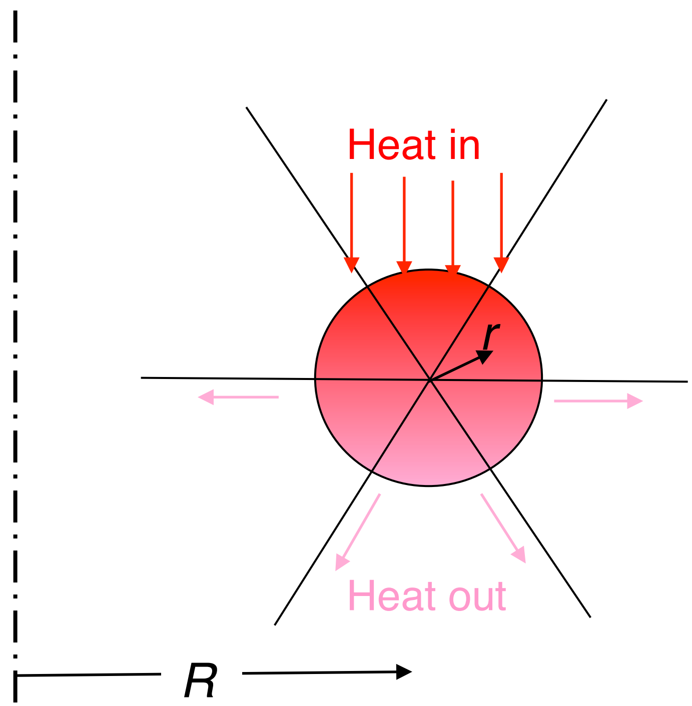
- **Larger redistribution during ELMs suggests the importance a beta poloidal driven transport channel, e.g.:**
  - Destabilisation of curvature driven, flute-like modes for $\beta_p >> 1$ **[D.D. Ryutov, et al., *Contrib. Plasma Phys.* 52 (2012) 539]**

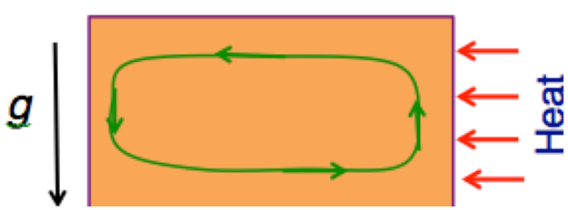
- **Alternatively, ELMs can cause transient changes of the equilibrium leading to smaller σ and/or a transition to a HFS SF-**
  - ELM resolved equilibrium reconstructions show a decrease of σ but not a transition to SF-

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

Courtesy H. Reimerdes

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)

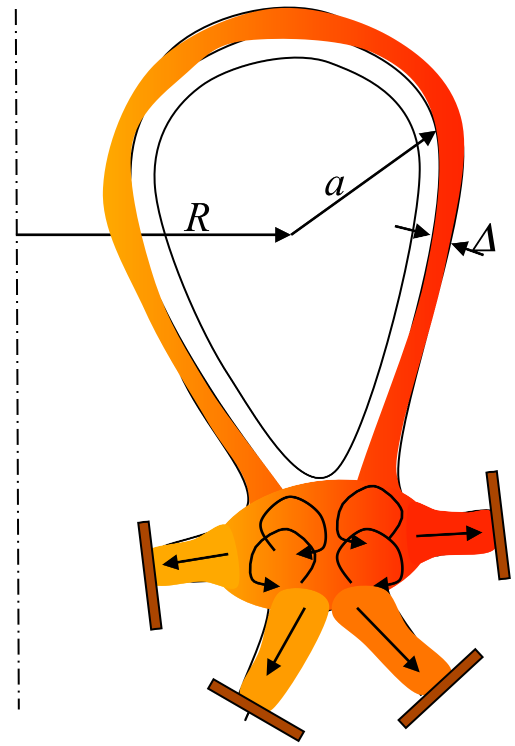
In the virtual absence of the poloidal field, there is no plasma equilibrium: the pressure gradient is non-collinear to the effective gravity force (directed along the major radius)

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

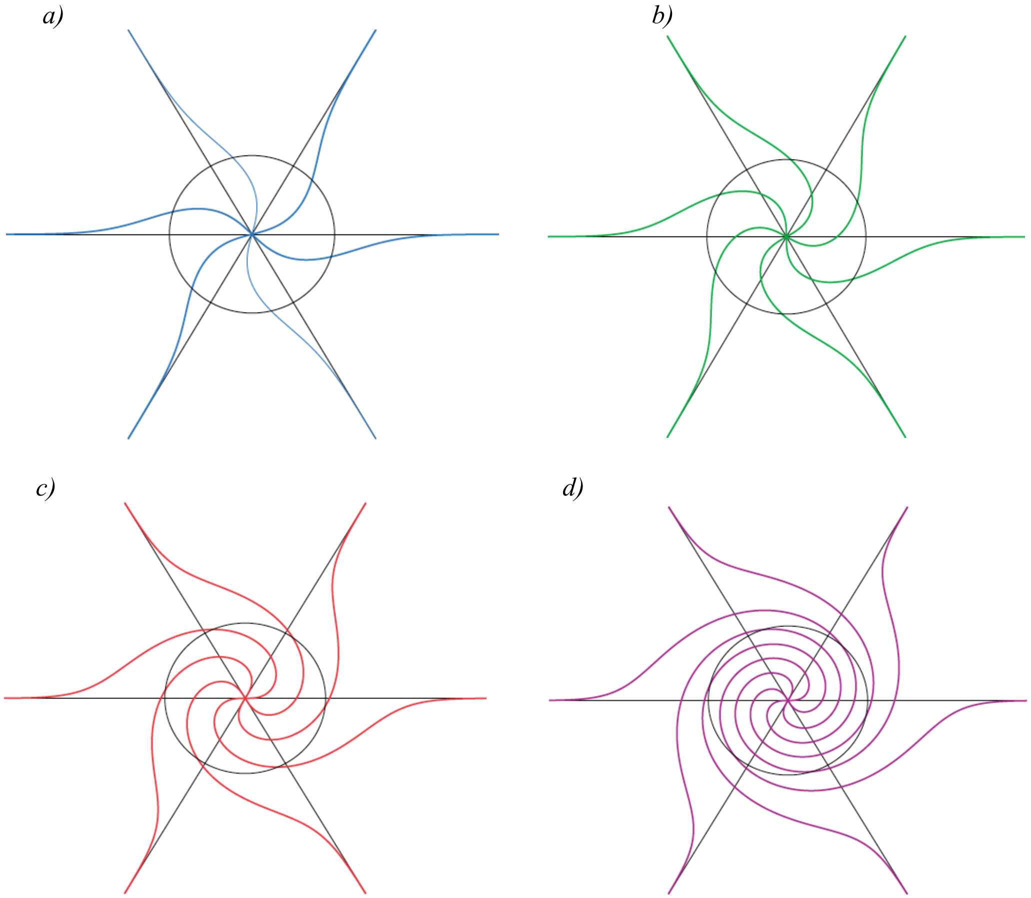
A typical setting for the baroclinic convection

A convective snowflake?

*



The poloidal magnetic field is entrained by the churning motion



This mixing process causes "activation" of all four divertor legs and broadening of the plasma flow in each of them ("Physica Scripta," **89**, 088002, August 2014)

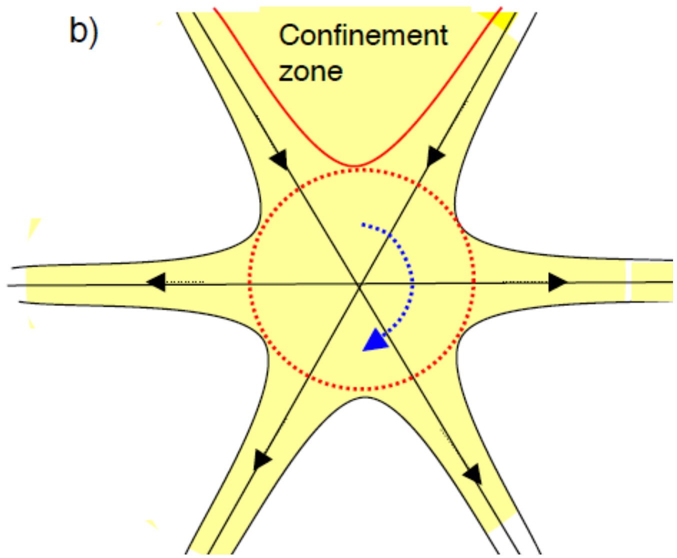
The size of the convective zone:

Standard $$\frac{d}{a} = 0.44\beta_p \frac{a}{R}$$

Snowflake $$\frac{d}{a} = 0.71\left(\beta_p \frac{a}{R}\right)^{\frac{1}{3}}$$

Cloverleaf $$\frac{d}{a} = 0.24\left(\beta_p \frac{a}{R}\right)^{\frac{1}{5}}$$

When projected to the midplane, the convection zone corresponds to a narrow layer near the separatrix



$$\frac{\Delta}{a} \approx 0.19\left(\frac{d}{a}\right)^3$$

No confinement degradation was observed experimentally. The convection zone may serve as a “smooth” limiter for the core plasma. [One more control of the pedestal?]

Much more has to be done in this area

Serious MHD equilibrium analysis (in the style of A. Cerfon and J. Freidberg "'One size fits all' analytic solutions to the Grad–Shafranov equation", Phys. Plasmas, **17**, 032502, 2010)

What is the role of magnetic reconnection?

Interplay with stochastic effects

Exciting physics problems exist for other divertor geometries

Detachment physics for strong flux flaring

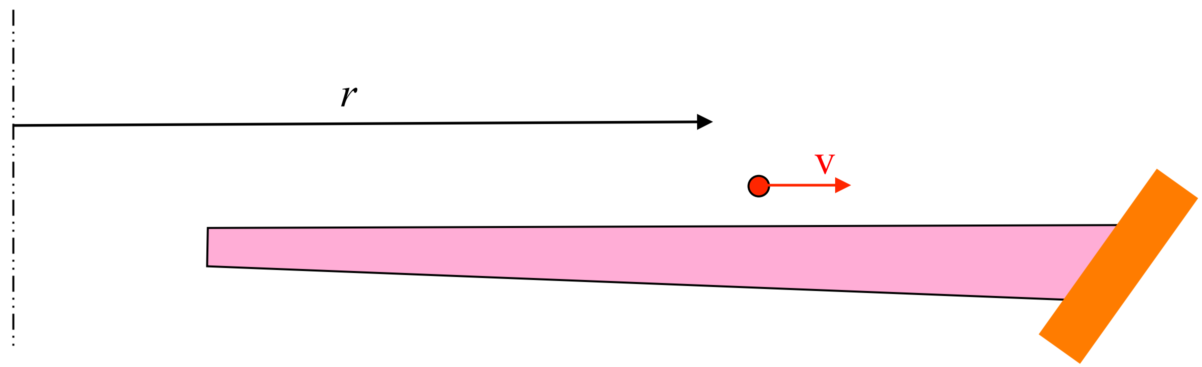
An important observation was made by B. Covele et al*:

In a fully detached regimes, the constraints on the waviness of the divertor target (and maximum field line flaring) are greatly relaxed, as the radiation and neutral particle fluxes are not following the magnetic field lines.

*B. Covele, P. Valanju, M. Kotschenreuther, S. Mahajan. NF, 54, 072006 (2014)

A very interesting research area

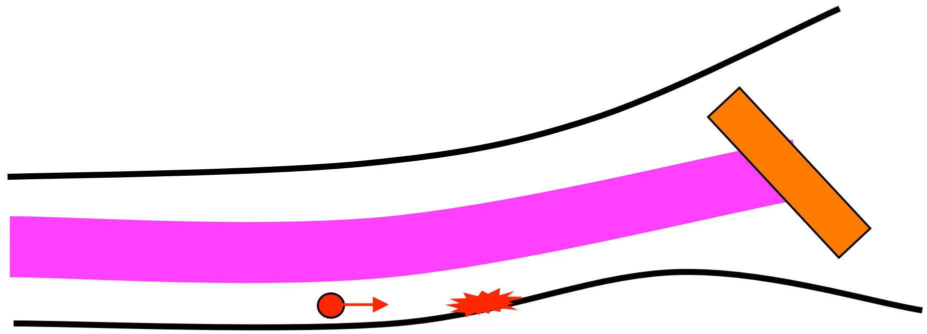
LONG DIVERTOR CHANNELS POSSESS INTERESTING FEATURES*



The blob, once formed, accelerates along the plasma surface.

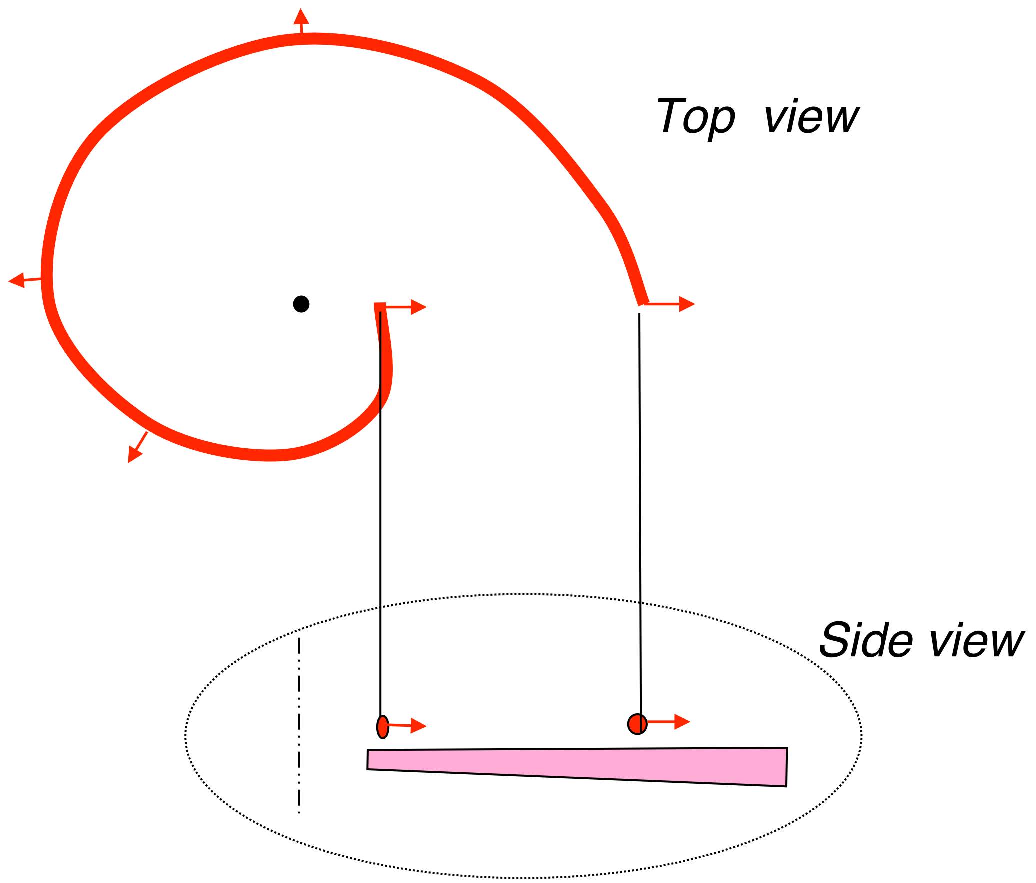
D.D. Ryutov, R.H. Cohen, I. Joseph, T.D. Rognlien, M.V. Umansky. “Instabilities and coherent structures in long-legged divertors.“ POSTER NP8.00120, APS DPP Annual Meeting, Atlanta, GA November 2-6, 2009

THE BLOB MAY BE INTERCEPTED BY WALL STRUCTURES, ESPECIALLY IN THE PRESENCE OF BENDS



This may be both detrimental (damage to the walls in the area where there is no adequate heat removal) and helpful (reducing heat load to the divertor plate proper) for the divertor performance.

VIEW FROM THE TOP ON THE BLOB MOTION

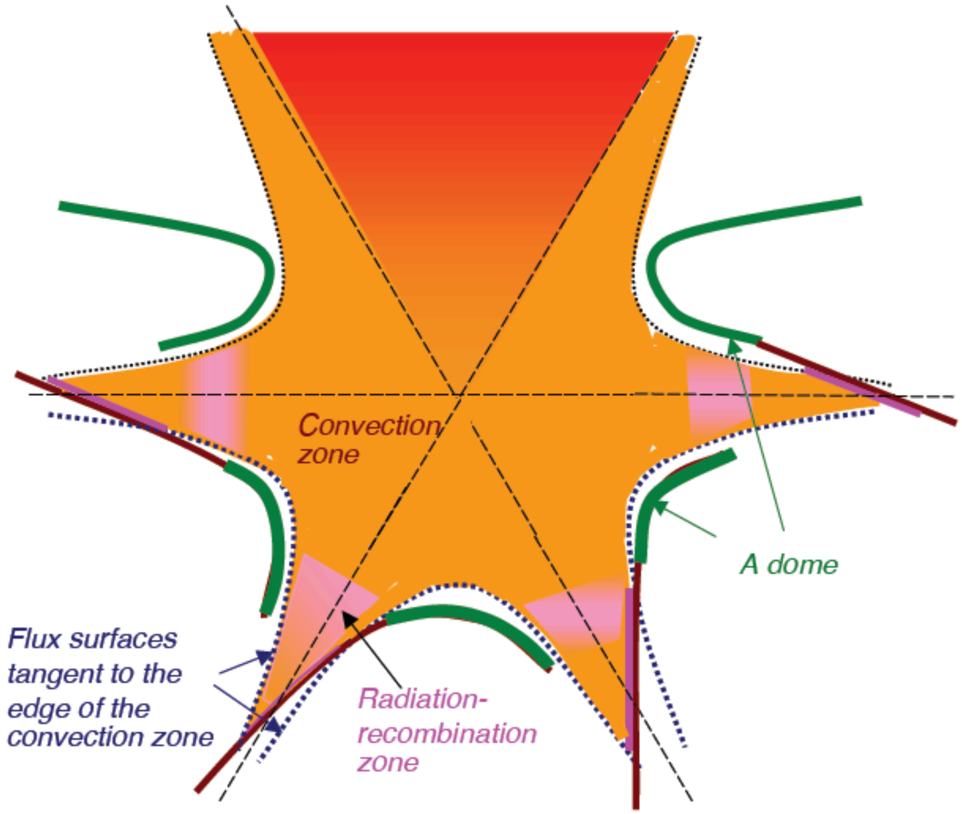


Plasma mesoscale instabilities and blobs in long-llegged divertors have been barely touched upon

Coming back to the “Dream Divertor”

A “Dream” Divertor = detached SF divertor???

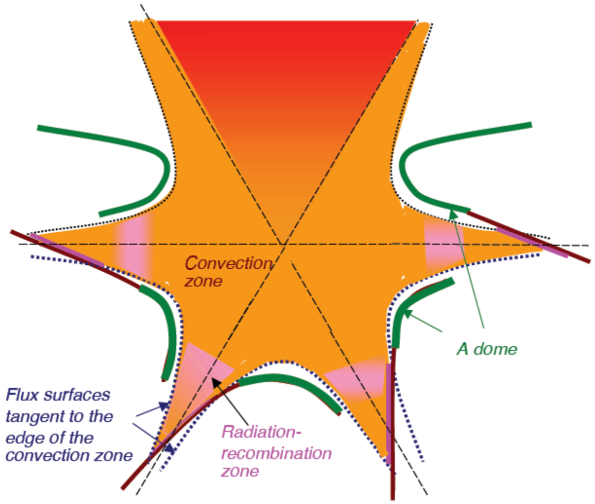
A sketch of what could become a detached SF divertor



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

*Ryutov, Krasheninnikov, Rognlien, Poster PP8.00028, 2013 APS DPP; T.D. Rognlien, 2014 APS DPP invited

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 by residual heat flux and radiation) ~ 1.5 MW/m^2

Convection zone is impermeable to the neutrals ($n_e \sim 10^{13}$ cm^3; $T_e \sim 30$ eV, $r \sim 40$ cm)

Conclusion:

Divertors based on manipulation of the poloidal field structure are a fascinating area for theory research

A number of important (and solvable!) problems, some clearly formulated, are ready for the first theory analyses

There is a lot of experimental information that can guide the theory

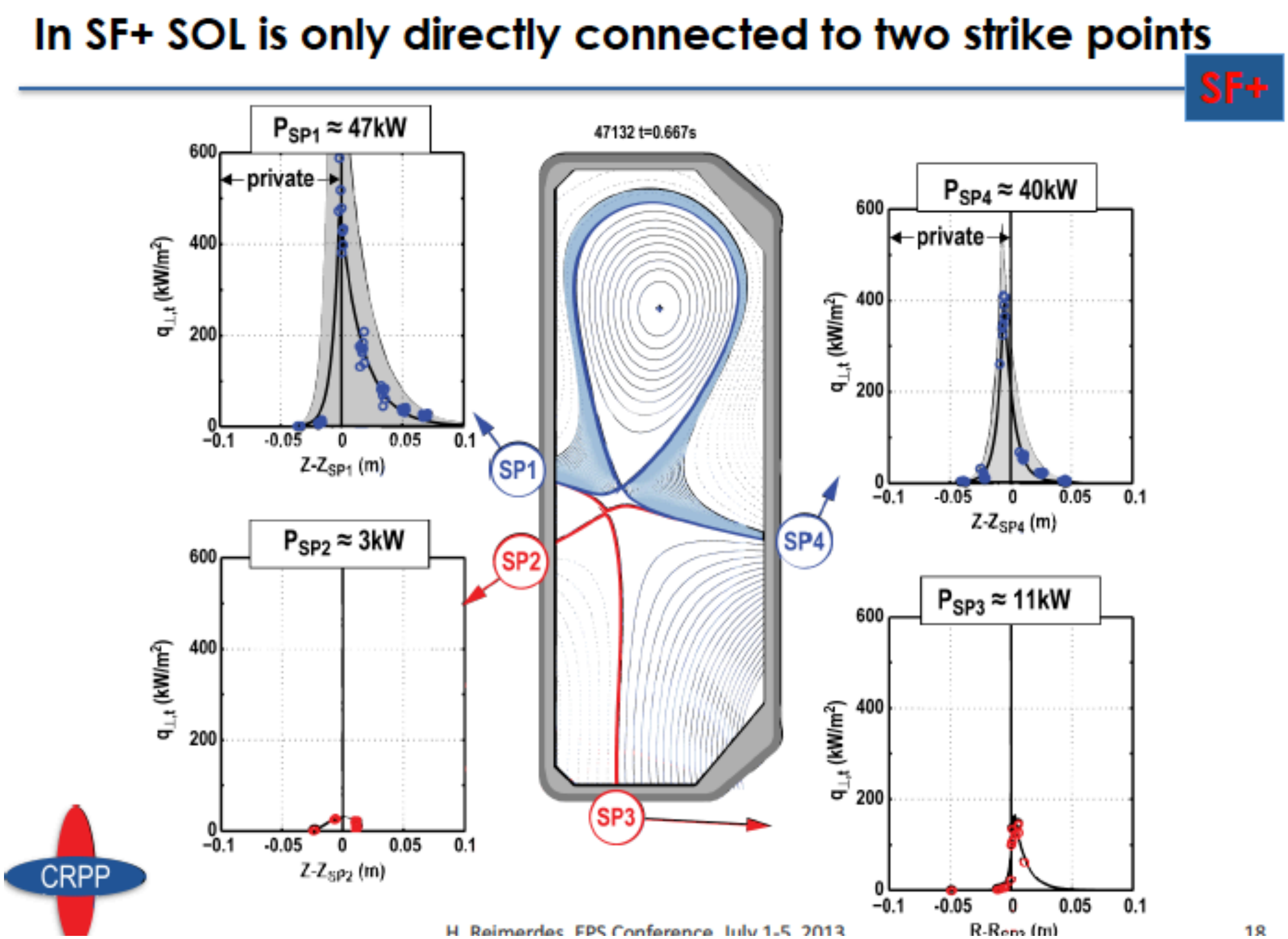
Naming exercise:

A Dream Divertor

A Wonder Divertor

A Wondervertor

BACKUP



Courtesy H. Reimerdes