ADVANCED DIVERTOR GEOMETRIES FOR NEXT GENERATION TOKAMAKS- POSSIBLE SOLUTIONS FOR DIVERTOR ISSUES

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OUTLINE

- ***Brief tutorial on advanced divertor geometries***
  - →The problem they must solve
  - →Physics mechanisms by which they intend solve it
  - →Experiments
- ***Surprisingly: potentially possible to implement an advanced divertor on ITER with NO hardware changes from baseline***
  - →Characteristics and issues
- ***Implementations on future devices***
  - →DEMO studies
  - →Experimental test devices

Power exhaust: a fundamental challenge of fusion energy

- ***Formidable in burning plasmas (inter-ELM)***
  - →ITER: difficult
  - →Beyond ITER: universal agreement among DEMO design teams – *very demanding*
    - Not just heat flux, but also divertor erosion for high duty cycle

- ***Recent projections of SOL width (width ~ 1/ B_{pol}): sobering***
  - →Unfavorable extrapolation to burning plasmas
  - →May be only a narrow operating window for ITER* (according to present divertor simulations- SOLPS code)

- ***Beyond ITER, power exhaust is arguably the most difficult plasma challenge***

*Kukushkin, Pacher, et. al., Journal Nucl. Mat **438** S203 (2013)

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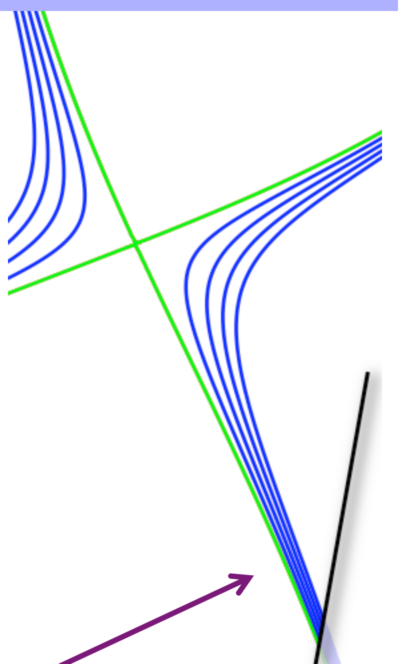
Advanced Divertor Geometries

"Ancient times"

Standard divertor

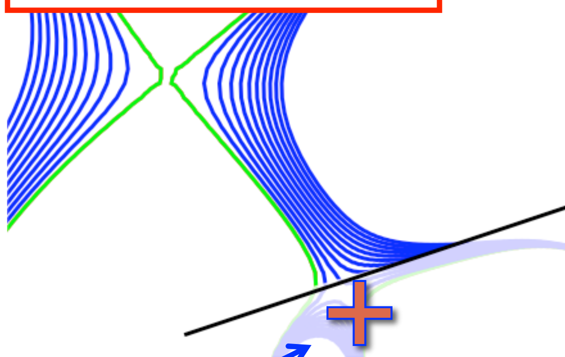


SOL contracts

2004

X-divertor (XD)

Flared SOL (poloidal)



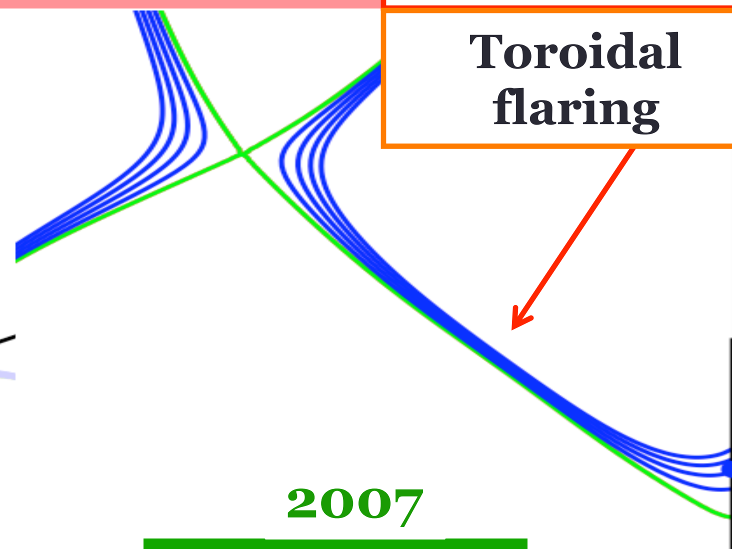
XD: "creating an extra X-point near the divertor plate; the magnetic field in the open field line region is flared to increase the area ….higher degree of detachment"

2007

Super-XD

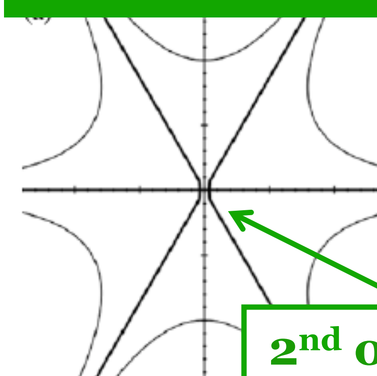
Higher major R

Toroidal flaring



2007

Snowflake



2^{nd} order null

High flux expansion near core X-pt

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Advantages of Advanced Divertors

- **Obvious: higher flux expansion**
  - → **Spread the heat out**
  - → **Experiments have shown this works**

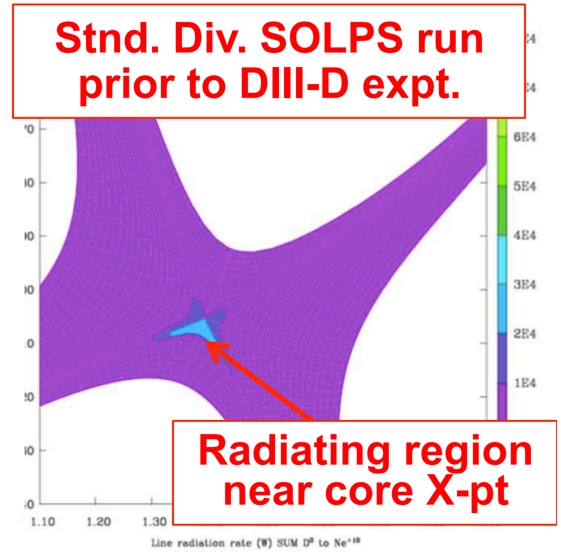
- **Not as obvious: effects of geometry on detachment**
  - → **Advanced geometries: predicted to reduce plate temperature and increase plasma radiation**
  - → **Increase detachment (compared to standard geometries)**

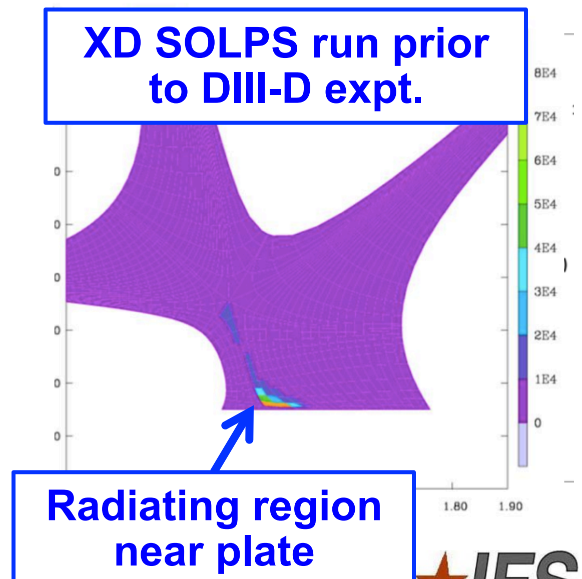
- **Most relevant: potentially increased *acceptable* detachment**
  - → ***Acceptable detachment* is the *maximum degree of detachment before unacceptable H-mode degradation* sets in**
  - → **H-mode degradation is the *practical* limiting factor for the degree of detachment possible on standard divertors**

- **Higher *acceptable detachment* predicted**
  - → ***This is the area where further experiments are needed***
  - → **Different mechanisms proposed for XD/Super-XD and snowflake**

Why are *Flared* Geometries Predicted to Enable Higher *Acceptable Detachment?*

- ***In experiments with standard divertors: very strong detachment degrades H-mode confinement***
  - →By bringing a cold radiating region to the edge of, and ultimately into, the transport barrier
- ***Flared geometries (XD and Super-XD) tend to keep the radiating region away from the barrier***
  - →**Tend to "Isolate" cold radiating region from the barrier**
  - →Greater advantage for Super-XD than the XD
    - Theoretically, toroidal flaring is much more efficacious than poloidal flaring for this





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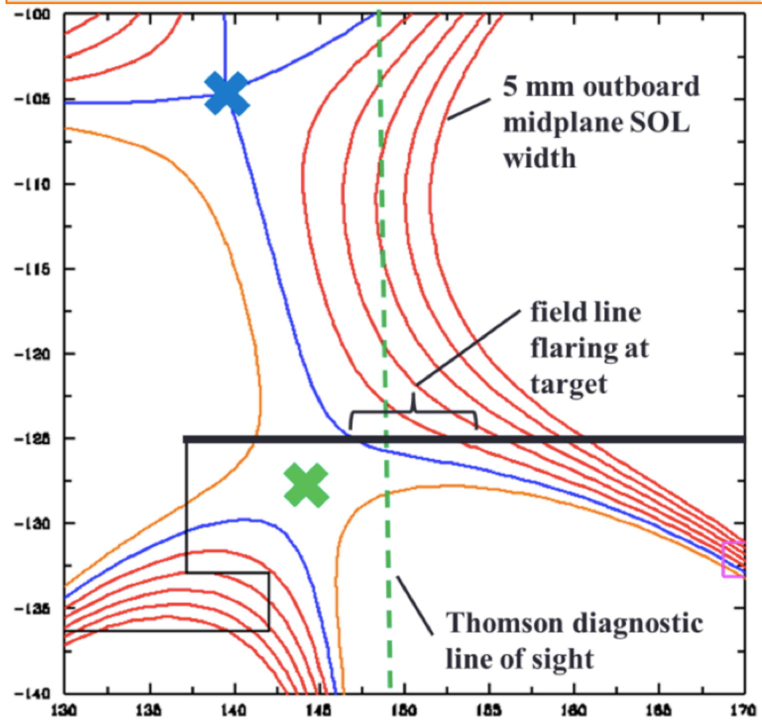
Experimental Comparison of Detachment in XD and Standard Divertor (on DIIID)

- ***Experiment (two weeks ago)***
  - →Experiments emphasized effect of geometry ***on detachment***
    - Unique DIII-D Thompson diagnostic
  - →First impressions: in qualitative direction expected for XD
- ***Hopefully, more matched comparisons in future of***
  - →Degree of detachment
  - →Ease of detachment
  - →H-mode confinement
- ***MAST, NSTX-U, C-Mod, TCV, HL-2A, EAST, …..***

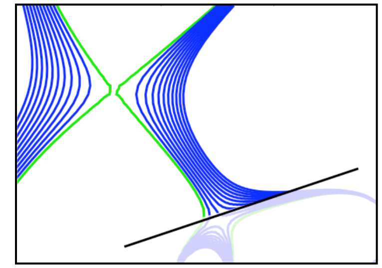
Close-up of DIII-D divertor in CORSICA



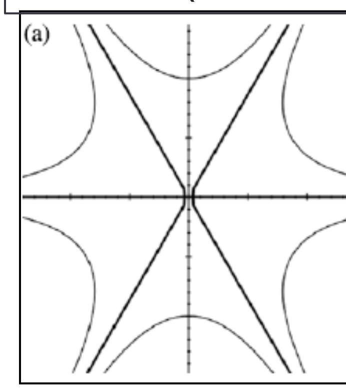
Quantifying Poloidal Flux Surface Flaring:
The Divertor Index DI*

- Flux surface flaring is a geometrical property of ***flux surfaces in the region of space where the divertor plasma lies***
  - →*Expected to be significant for detachment behavior*
- Define a precise mathematical quantity, the **Divertor Index, DI** to quantify this property
- DI = 1 for a standard divertor (***"REFERENCE"*** amount of flaring)
- DI > 1 for an XD: (***MORE FLARED*** surfaces than REF)
- DI < 1 for a Snowflake: (***MORE CONVERGING*** surfaces than REF)
- We believe: the **shape of flux surfaces in the divertor region is the most physically appropriate way to characterize divertors**
  - →*We believe some recent experiments labeled "snowflakes" have flared field lines and so are more properly considered XDs*

Flared field lines
DI > 1 (XD)



Converging field lines
DI < 1 (Snowfl.)



* Kotschenreuther, Valanju, Covele, and Mahajan, Phys. Plasma 102507(2013)

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Very Different Mechanisms Predicted for Snowflakes

- ***Convective cells argued to be present that induce detachment without degrading transport***
- ***2^{nd} order null has "fatter" SOL near core X-pt to buffer it from neutrals that help degrade confinement***
- ***The mechanisms predicted to lead to detached snowflakes with good H-mode confinement are quite different than for XDs***
- ***The geometrical differences in the divertor SOL region (value of DI) should be clearly distinguished to clarify the physics***

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SURPRISINGLY: X-Divertor can be Implemented on ITER WITHOUT ANY Hardware Changes*

- ***Without adding any new coils***
- ***Within current limits on present coils***
- ***With baseline divertor cassette and dome structure***

- ***Only because one must fit the plasma within the "preset" chamber shape (which wasn't designed for an XD):***
  - →**Minor radius must be reduced from 200cm to 183-186 cm to maintain 15 cm clearance form the wall**
  - →**With the same plasma height, elongation is increased from 1.8 to ~2**
  - →**H-mode confinement from ITER98(y,2) is *NOT* reduced**
  - →**NOTE: if ITER had been designed with an XD in mind, modest changes in chamber shape and/or modest increases in PF design limits could have allowed nominal elongation**

*B. Covelle, P. Valanju, M. Kotschenreuther, S. Mahajan, Nucl. Fusion **54** 072006 (2014)

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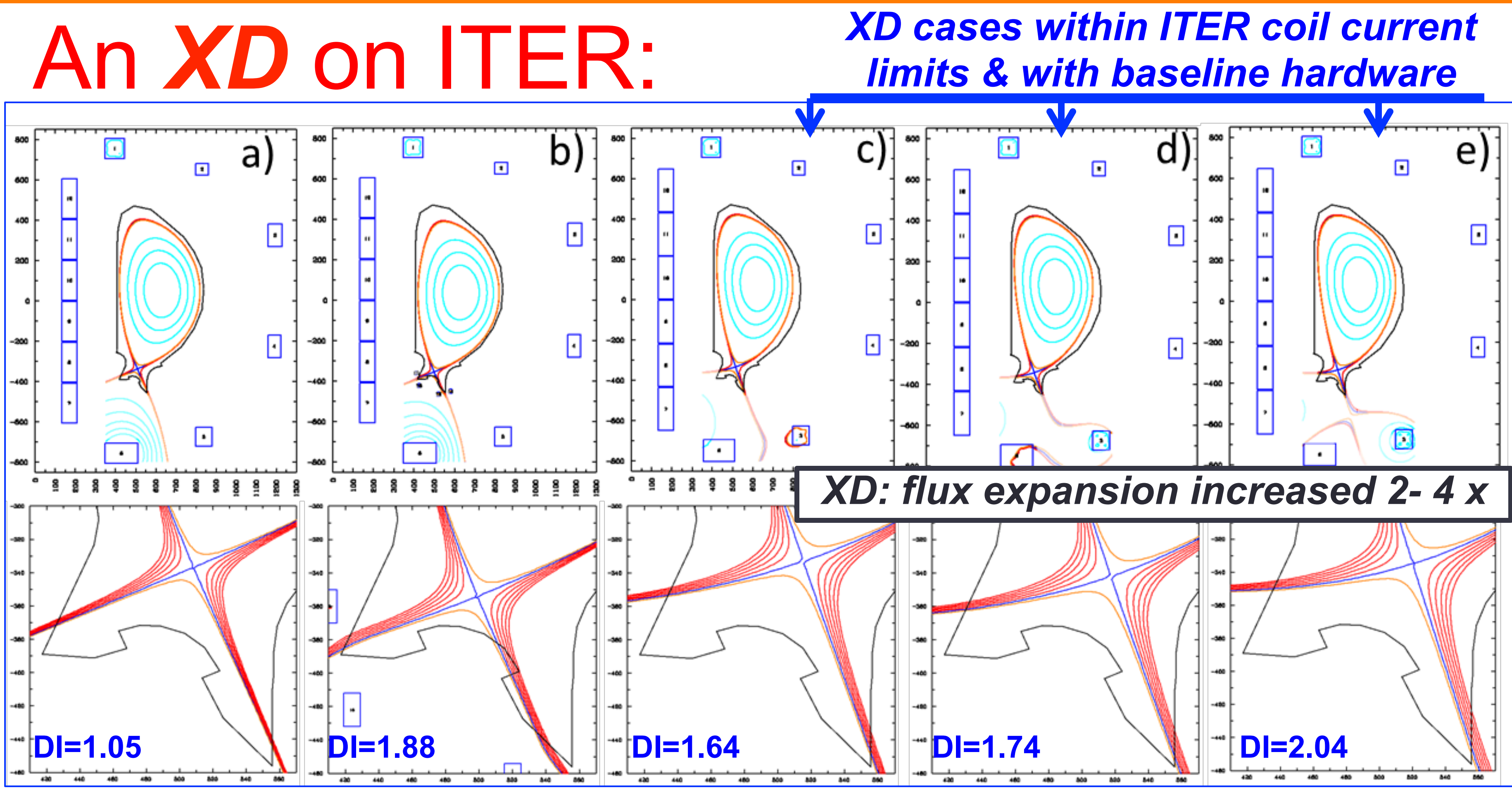
An *XD* on ITER:



ITER X-Divertors: (a) ITER baseline equilibrium. (b) Original 2004 version of the ITER XD with special PF coils near the targets. (c) –(e): sequences of equilibrium with increasing flux expansion, all within PF coil limits

It is possible to continuously go from standard divertors to XDs with the same PF coil set and practical currents

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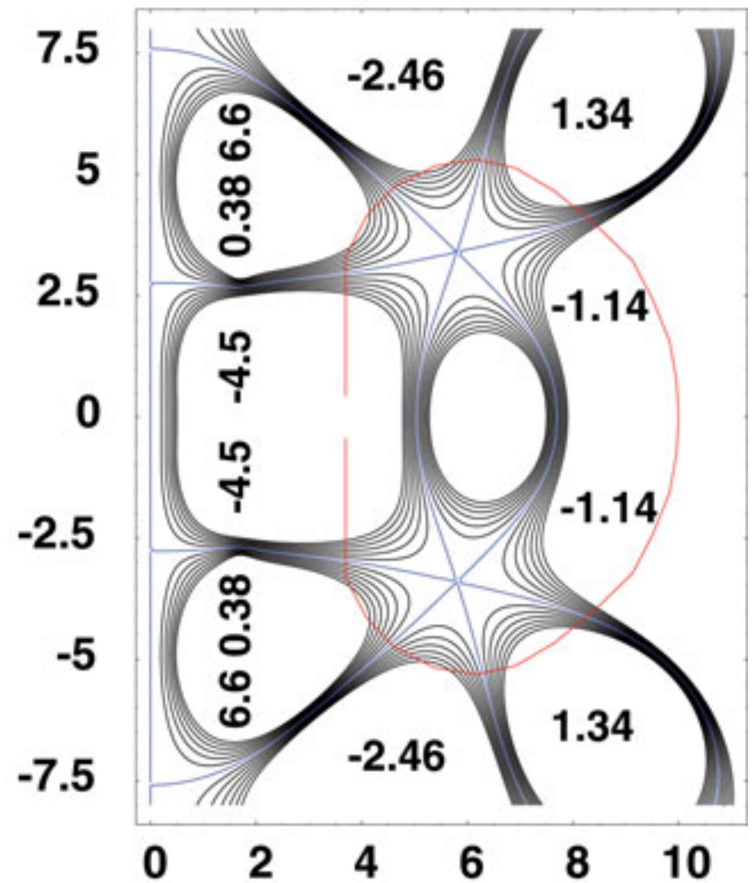
ITER Snowflake attempts -- Lackner and Zohm*

- **Lackner and Zohm tried to make a snowflake (2nd order null) with ITER coils.**
- **The PF currents were extremely high – *well beyond ITER design limits* & "a major technological challenge" for future tokamaks**
- **The ITER XD required far less PF current**



*K. Lackner and H. Zohm, Fus. Sci. and Technology **63**, 43 (2012).

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WHY was the ITER XD considerably easier to make than the snowflake?

- **The Second X-pt is *significantly* closer to the coils *so much less current is needed in the PF coils to make it***
  - →**About half the distance as the 2nd X-pt for a snowflake**

- **The second X-pt is *considerably* further from the plasma, *so it tends to perturb the outer boundary shape less***
  - →**Hence, the rest of the PF set doesn't have to "work" nearly as hard to maintain the same elongation and triangularity "against" this perturbation**

- **These considerations are likely general, at least qualitatively:**

X-divertor prescription is likely the "least expensive" way for a PF coil set to increase poloidal flux expansion at the plate

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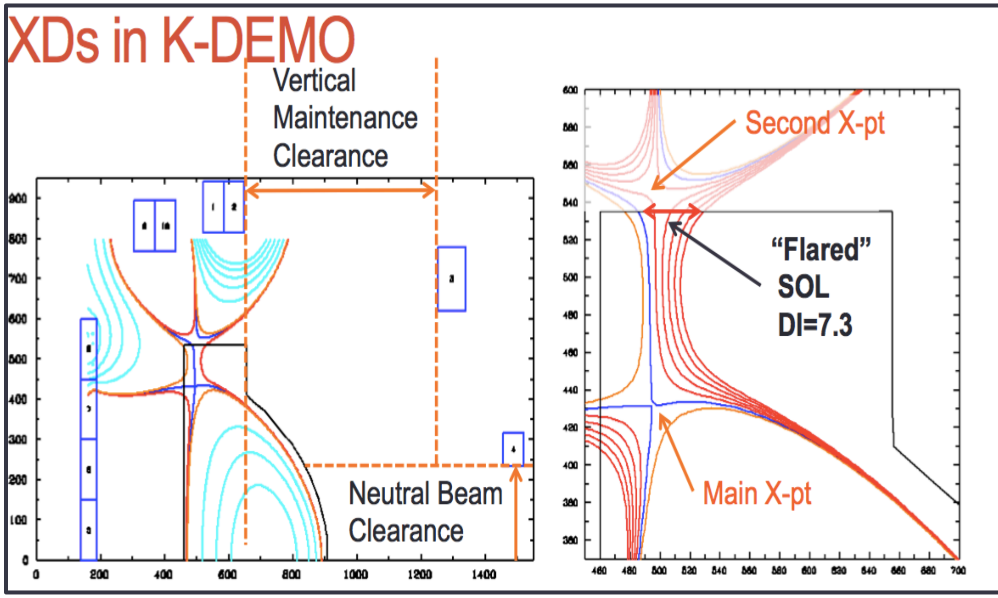
Issues for an ITER XD

- **Vertical control?**
  - →Higher elongation leads to stronger vertical instability
  - →Is this tolerable for the ITER control system?
  - →We emphasize, however, that higher elongation is a consequence of “retrofitting” an XD into the existing ITER design
- **Discharge evolution and volt seconds?**
  - →What is the Ohmic pulse length for the new configuration?
  - →What is a start-up/shut down sequence for the new PF currents?
- **Are coil forces acceptable in case of off-normal events?**
  - →E.g. unexpected superconducting coil failure

XDs on Next Step Devices



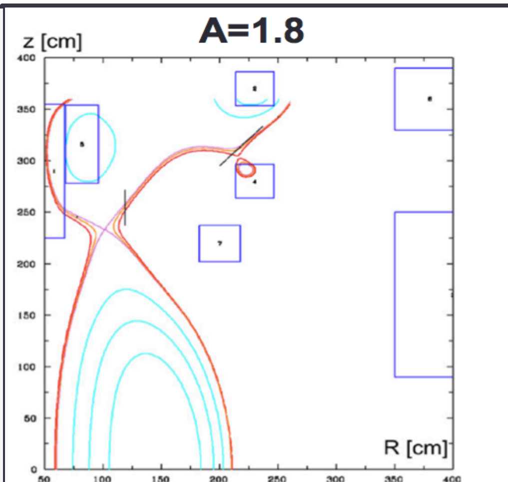
- **DEMO design studies examining advanced divertors: KDEMO, Slim-CS and CFETR**

K-DEMO:

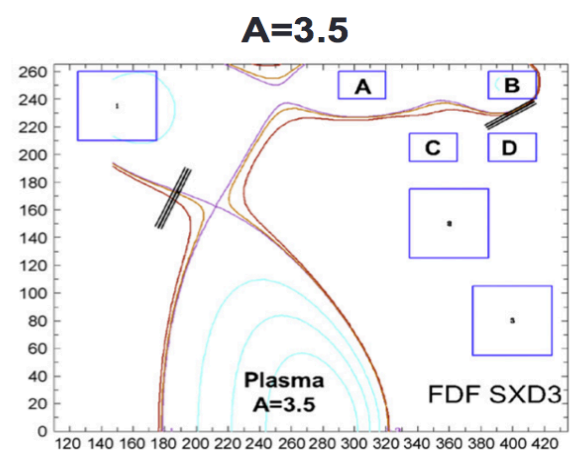
→**XDs can accommodate vertical maintenance**
→**PF currents practical**
→**Continuous transition: SD to XD**

FNSF

- ***For Cu coil FSNF options, have considered SXD designs spanning the range of aspect ratios***
- ***As FNSF designs evolve, will continue to develop coil designs for XD and SXD***



Kotschenreuther, Valanju, Mahajan, et. al., Nucl. Fusion **50**, 035003 (2010).



2010: Valanju, Kotschenreuther, Mahajan, Fus. Eng. Design **85** 46 (2010)

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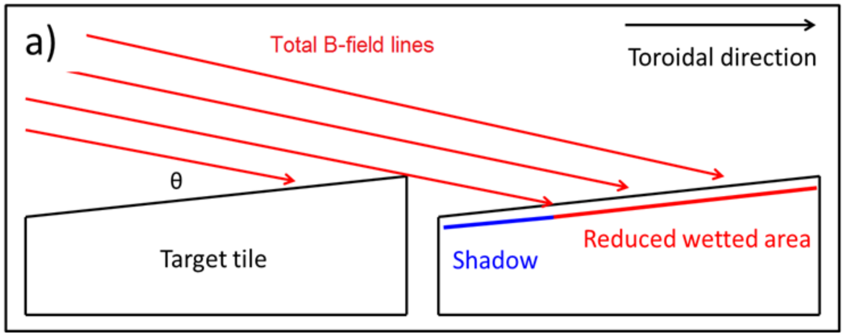
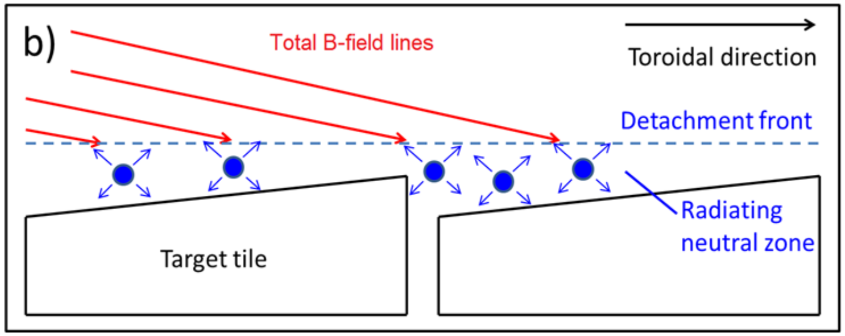
Deeper Detachment Also Makes High Flux Expansion More Utilizable

- ***High poloidal flux expansion leads to nearly tangential field lines- shadows are cast***
  - →ITER tiles use chamfering to avoid exposure of leading edges => ***plasma-wetted area is reduced DUE TO THIS SHADOWING***
  - →Wetted area from high flux expansion is less desired
- ***Shadowing becomes less serious when T near the plate is low: then perpendicular transport can dominate parallel***
- ***Thus: deeper detachment should ameliorate shadowing***
  - →Parallel conduction is weak at low temperature
  - →At low enough temperature, most heat transferred to the plate **by perpendicular processes:**
    - →**radiation, neutrals, and perpendicular plasma transport**
  - →**In fact at 5 eV and 1 degree, classical perpendicular transport to plate > parallel**





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The Severity and Difficulty of the Exhaust Problem Fully Justifies New Devices

- ***Power exhaust is arguably the most worrisome plasma issue beyond ITER***
  - →Innovations in acceptable plasma SOL dissipation important- ***possibly crucial***

- ***Leadership shown by MAST is an example that should be emulated***
  - HL-2A another example, but only poloidal flux expansion (Snowflake & XD)

- ***High field, high power density divertor experiment (ADX)***
  - →**Parallel heat flux comparable to burning plasmas** ($q_{||} \gtrsim$ ITER level)
  - →Testing innovative geometries and concepts
    - Super-X
    - X-pt target divertor
    - Liquid metal targets
  - →***Examining compatibility of high confinement with strong detachment at high $q_{||}$, for these novel divertor concepts***

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CONCLUSIONS:

- ***Advanced divertors are a promising solution for burning plasma divertors***
- ***While initial experiments are promising, much more intensive investigation is needed (experimental, theoretical and simulations), focusing on high levels of detachment***
- ***XDs can be made on ITER without hardware modifications, within coil limits- further examination of important next order issues is needed***
- ***Initial design studies are being pursued on the feasibility of implementing advanced divertors on devices beyond ITER***
- ***Neutronic advantages of advanced divertors – including improved T breeding and reduced material damage on the plate- need more complete investigation***

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ADDITIONAL SLIDES:

Parameters of these ITER cases:

ITER X-Divertor Scenarios					
	Standard Divertor	2004 Dual XD	1-degree-limited XD	Max. expanded XD (15 MA)	Max. expanded XD (14 MA)
Plasma current (MA)	15.0	15.0	15.0	15.0	14.0
Minor radius (cm)	200	200	186	186	183
Elongation	1.84	1.86	2.02	2.05	2.06
Upper triangularity	0.44	0.37	0.48	0.49	0.54
Lower triangularity	0.52	0.59	0.47	0.48	0.48
Outer B-field angle (°)	2.3	1.2	1.0	0.7	0.5
Outer DI	1.05	1.88	1.64	1.74	2.04
Outer flux exp.	2.4	5.2	5.6	7.1	9.3
Outer conn. length (m)	86.1	97.8	118.5	128.1	147.0
Plasma volume (m^3)	832	834	786	794	777
Confinement time (s)	3.00	3.03	3.24	3.28	3.03
Min. wall clearance (cm)	12.5	8.0	15.1	15.0	15.0
Avg. wall clearance (cm)	26.5	26.2	32.6	31.6	33.9
* 2004 XD results (w/ special PF coils)			* 2013 XD results (ITER coils)		

Plasma and divertor parameters for the ITER X-Divertor equilibria. The minor radius was reduced in the 2013 XD plasmas to maintain 15 cm of clearance from the first wall. Confinement times are computed using the ITER98(y,2) scaling, with a density 80% of the Greenwald limit [21] and an assumed heating power of 120MW.

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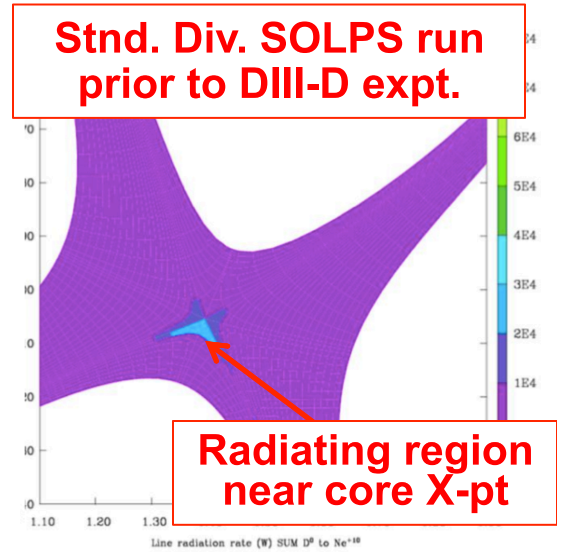
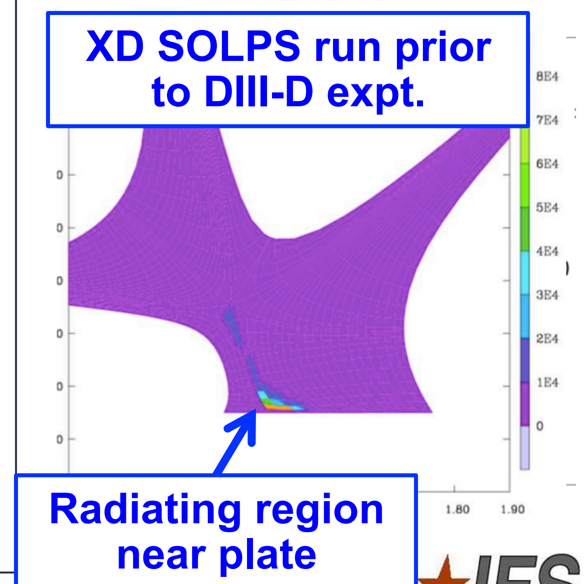
Why do flared geometries tend to give this isolation?

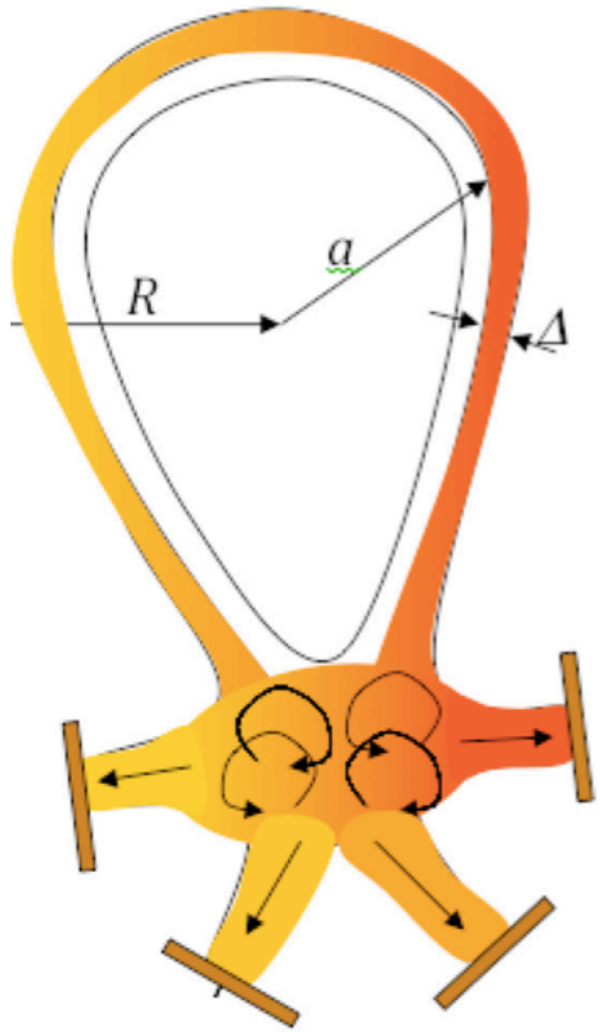
- ***High $Q_{||}$ and lower connection length $L_{||}$ IMPEDE detachment, so for isolation of detachment close to the plate:***
  - →Make $\mathbf{Q}_{||}$ increase away from the plate
  - →Make $\mathbf{L}_{||}$ strongly decrease away from the plate
- ***Super-X: directly geometrically modifies <u>both</u> $Q_{||}$ and $L_{||}$ in this way***
- ***XD: geometrically modifies $L_{||}$, relies on indirect radiation feedback from flaring to change $Q_{||}$***
  - →Radiation feedback indicated from physical arguments, simulations and experiments done to date
- ***Optimal combination of toroidal and poloidal flaring remains to be determined***
  - →MAST is has wonderful flexibility for this
  - →Further simulations and analysis also needed





SNOWFLAKE: LOW B_{POL} MAY LEAD TO LOCALIZED CONVECTIVE CELLS

- Approximate 2nd order null leads to region of weak poloidal field
- It is heuristically argued that this leads to a region of strong convection that broadens the SOL – "churning modes"
- TCV observations are consistent with this
- Instability calculations very heuristic



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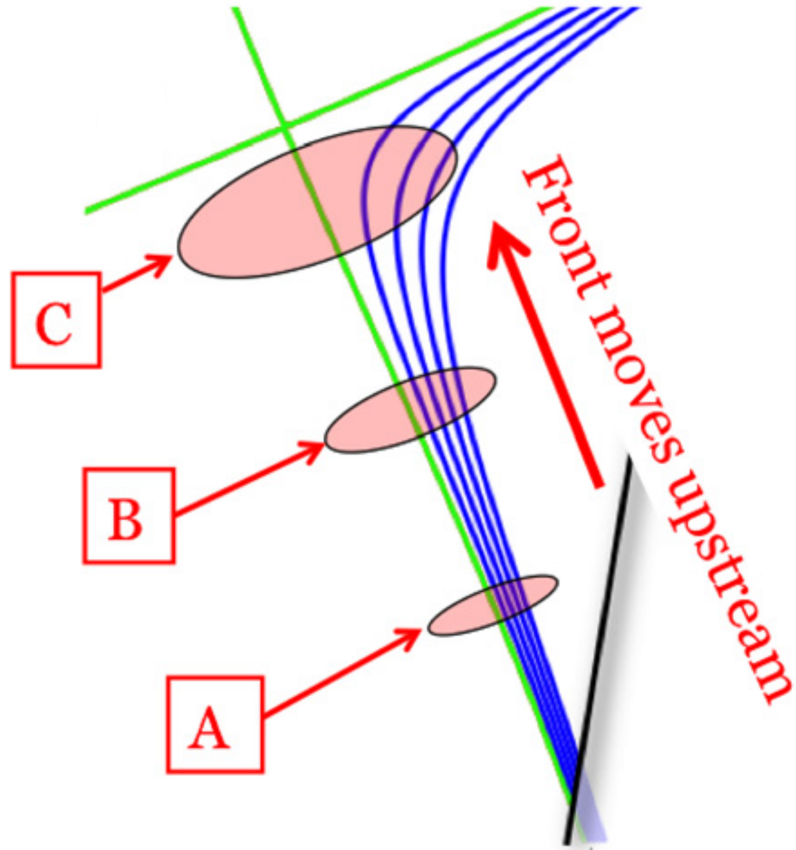
DETACHMENT CAUSED "INSTABILITY" IN STANDARD DIVERTOR (HEURISTIC EXPLANATION)

- As the cold detachment front moves upstream, the interaction area with neutrals increases
- Hence, the atomic dissipation increases, which causes the temperature to get colder
- This positive feedback moves the cold front from the divertor to core X-point
- This is the edge of the H-mode**- if the core boundary is cooled enough, H-mode barrier is degraded**



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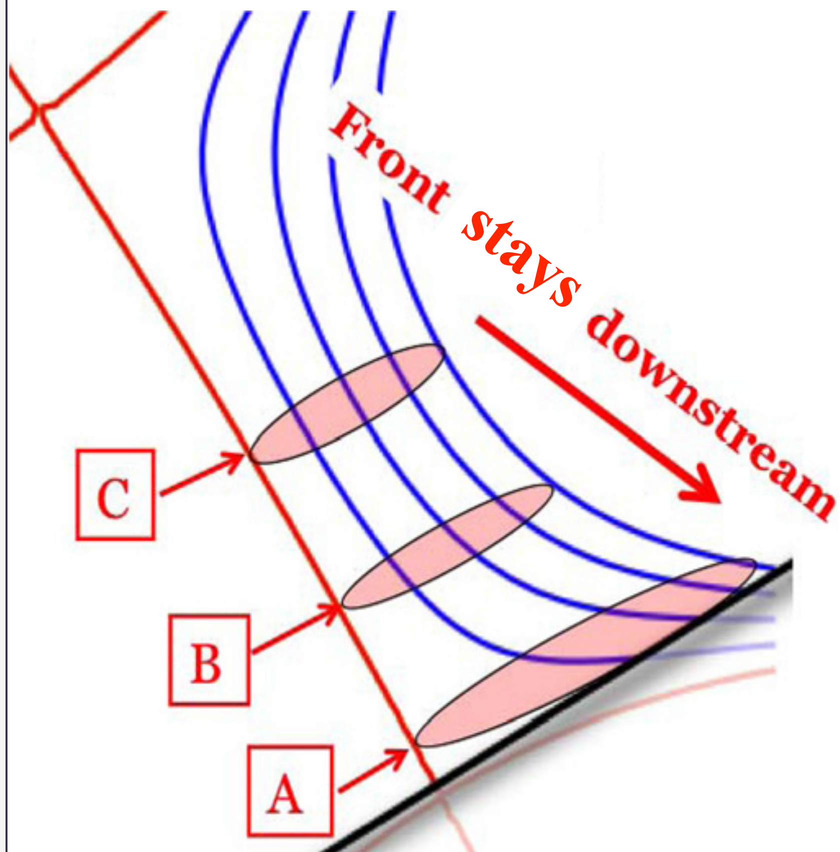
ENABLING "STABLE" FULL DETACHMENT: X-DIVERTOR PRESCRIPTION

- Create a 2nd x-point in the SOL downstream, increasing field line flaring at the target plates

- Change the feedback the detachment front "sees" if it migrates upstream

- Also, line length decreases greatly as the front moves away from the *plate*, adding further "stabilizing" feedback against front migration

- **With flared field lines, more of the radiating region stays away from the H-mode barrier- confinement degradation is avoided**



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Hence the Detachment Performance of Advanced Divertors is Crucial

- **Initial experimental results are *roughly consistent* with the picture that flaring/contracting SOL geometries influence the location of radiation:**
  - →TCV with near 2nd order null(highly contracting): radiation tends to concentrate near the core X-pt
  - →NSTX and DIII-D with flared geometries (misnamed snowflakes): radiation shows a tendency to be more localized near the plate

- ***But detailed comparisons of advanced geometries and standard geometries with strong detachment have not been systematically done***

IN ADDITION TO PLASMA PHYSICS, DIVERTORS WITH A LONG LEG HAVE NEUTRONIC ADVANTAGES

- ***Tritium breeding ratio****
  - →Breeding material can be in front of the divertor plate
  - →Neutrons captured on Li^6 to make tritium, rather than being parasitically lost to the divertor structure
  - →Effects in FNFS predicted to be significant
- ***Plate is neutron shielded*****
  - →**Up to an order of magnitude reduction in dpa on the plate**
  - →This could be extremely significant in reducing materials issues for high heat flux divertors being considered for FNSF/DEMO
    - Water cooled copper
    - Helium cooled Tungsten

*L. El-Geubaly (TOFE 2014)

P. Valanju et. al. Fus. Eng. Design **85 46 (2010)

Power exhaust: Solutions

- ***Advanced magnetic divertor geometries (tokamak):***
  - →2004 X-divertor
  - →2007 Snowflake
  - →2007 Super-X
  - →Recent innovations aiming to improve upon of these
    - X-pt target divertor (MIT)
    - “Double decker” divertor (Culham)

- ***New materials: liquid metals (1990s)***
    - Liquid lithium, including evaporative Li
    - Liquid metals likely highly synergistic with advanced geometries

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