Physics of divertor power exhaust beyond ITER

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- Introduction: from ITER to DEMO and FPPs
- Radiative Core Solutions
- Alternative Divertor Geometries: Physics Principles
- Alternative Divertor Geometries: Experimental Results
- Summary and Conclusions

Presented at 10th ITER International School, Daejeon, Korea, January 22, 2019

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From ITER to DEMO and FPPs

ITER:

- Q=10 for P_α = 2 x P_{ext}, study of ‘burning plasma physics’
- T-breeding tested in ‘Test Blanket Modules’ but not self-sufficient

DEMO and Fusion Power Plants (FPPs):

- T self-sufficiency from breeding
- demonstration of net electricity generation

$\Rightarrow$ Q_{fus} has to be substantially higher than in ITER:

$$Q_{el} = \frac{P_{el}}{P_{el,AUX}} = \frac{P_{fus}\eta_{TD} - {P_{AUX}}/{\eta_{AUX}}}{{P_{AUX}}/{\eta_{AUX}}} \approx Q_{fus}\eta_{TD}\eta_{AUX}$$

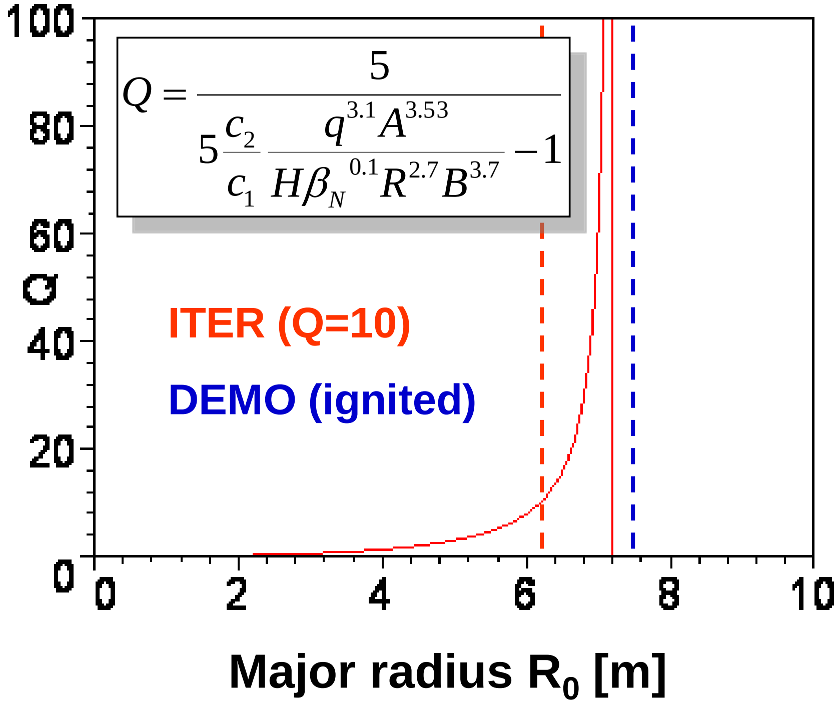
(η_{TD} = thermodynamic efficiency, η_{AUX} = efficiency for auxiliaries)

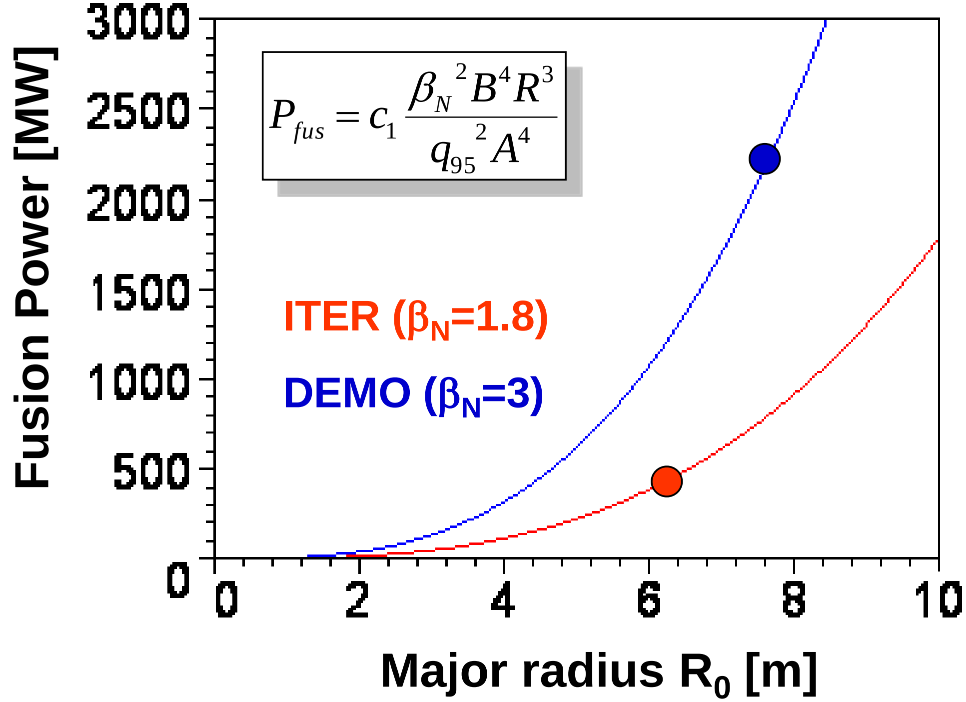
- typical values of ≥ 50 are projected for FPPs

(assuming that P_{AUX} dominates internal electricity needs)

DEMO and FPPs will be ‚larger' than ITER

H. Zohm, Fus. Sci. Technology 2010

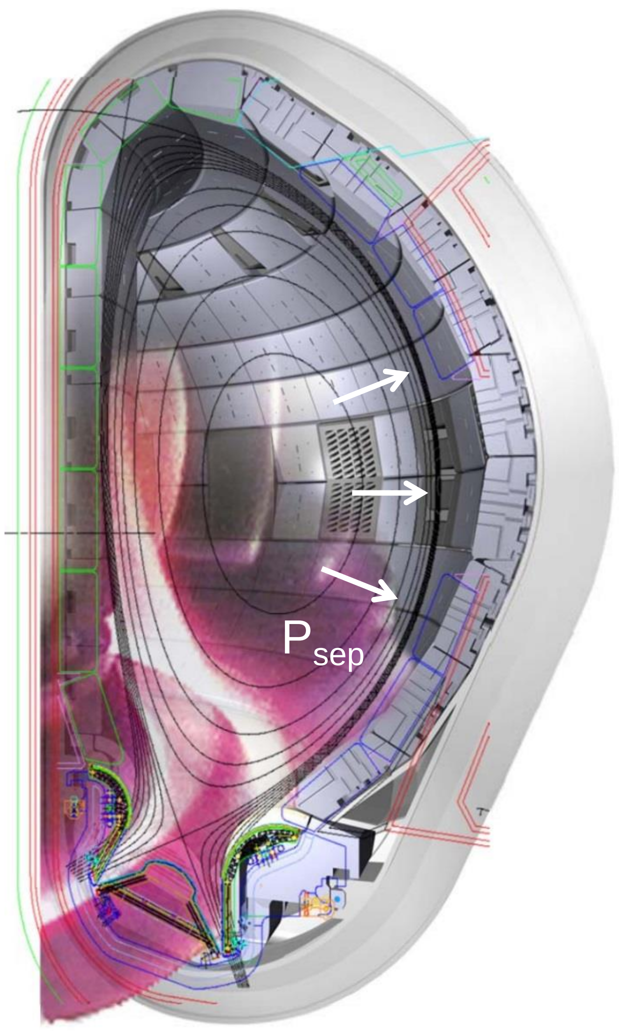




Example: assuming same physics and technology as in ITER

- ignition will be reached at *R* around 7.5 - 8 m
- producing power comparable to large nuclear fission plants will need higher normalised plasma pressure β than foreseen in ITER

Exhaust problem aggravated in DEMO and FPPs



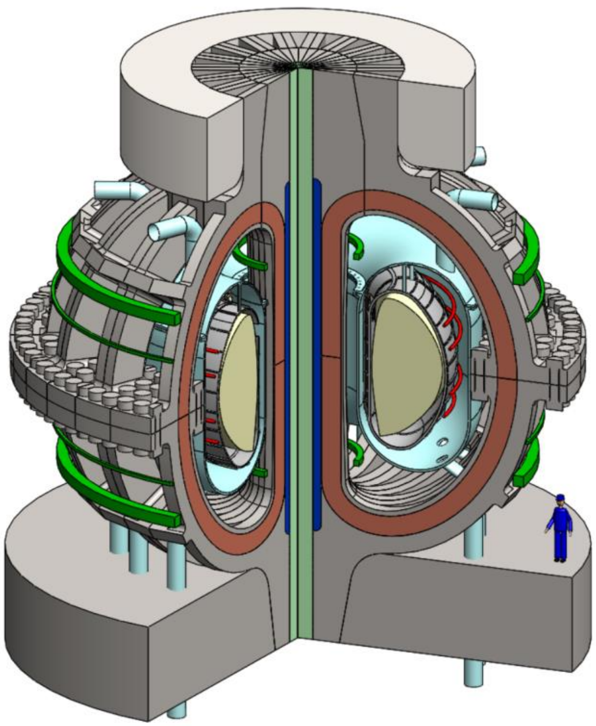
Very simple scaling arguments:

- P_{fus} is ~ 5 x larger than in ITER
- R is ~ 1.3 x larger than in ITER
- λ_q will be roughly constant
- unmitigated heat flux on target increases by factor 5/1.3 ~ 4(!)

Note in addition that

- neutral flux higher, too, so even ion surface recombination flux might become a problem
- ELMs will probably not be tolerable at all (larger, higher β plasma will have larger W_{th}).

Possible solutions (i): compact high field devices



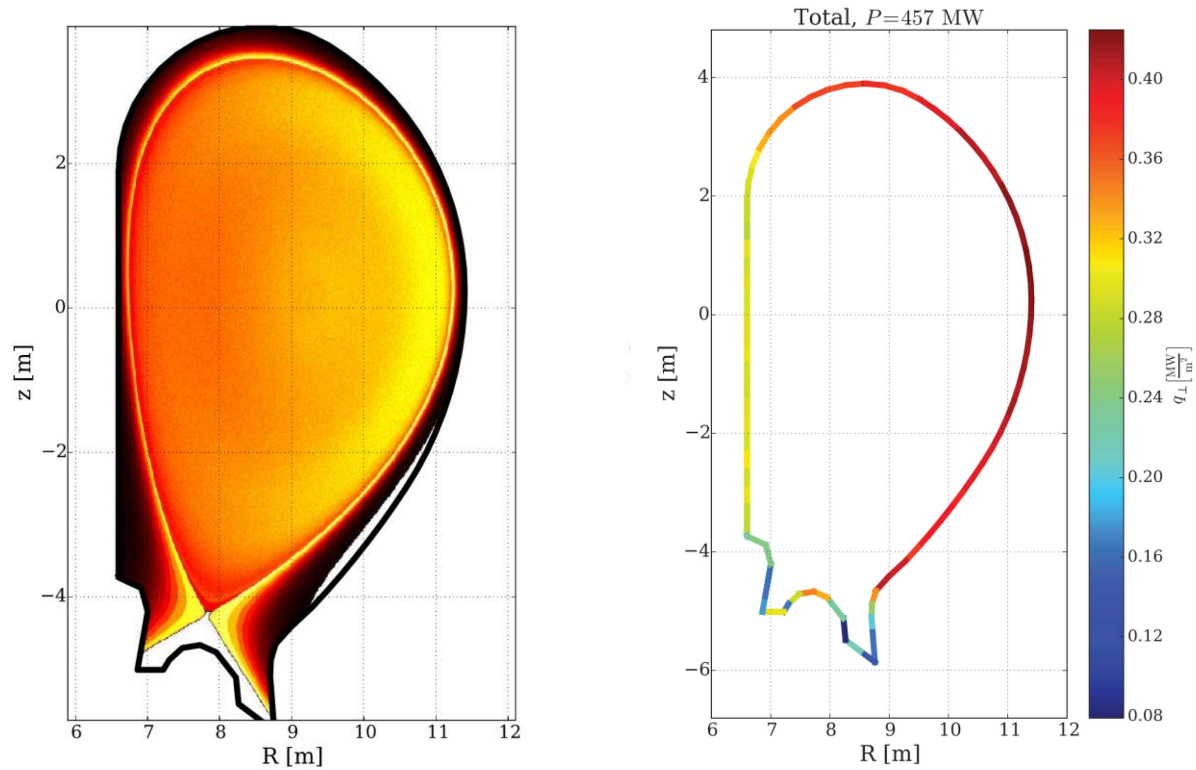
B. Sorbom et al., Fus. Eng. Des. 2016

ARC (MIT)
- **$B_{inner\ leg}$ = 21 T**
- **demountable TF coils**
- **FLiBe blanket**
- **H = 1.8**
- **P_{fus} = 525 MW**
- **$P_{el,net}$ = 190 MW**

Assuming substantial progress in technology and physics, FPPs could be smaller units than envisioned today

- however, required steps in physics and technology forward very large
- will not be treated in the remainder of the talk

Possible solutions (ii): increasing core radiation



(a) Radiation distribution. (b) First wall heat load.

Example:

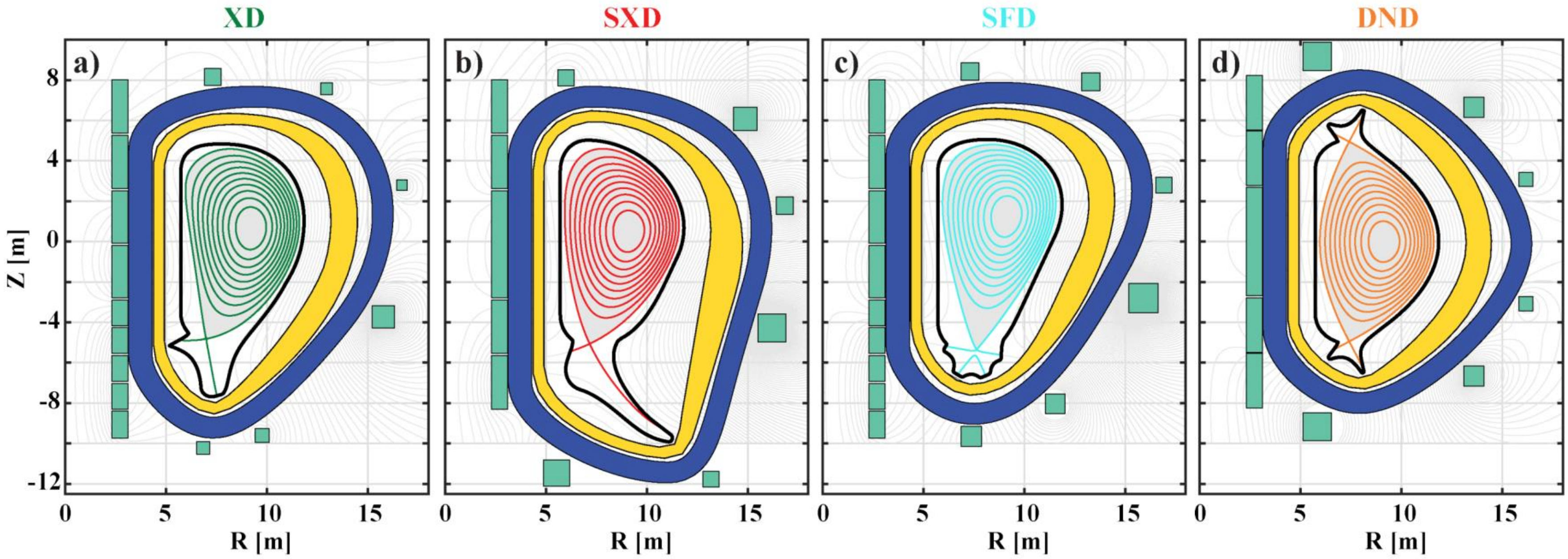
wall load if 100% of P_α+P_{AUX} were radiated from core & SOL

R. Wenninger et al., Nucl. Fusion 2017

Increase the radiated power fraction in the core

- adding ('seed') impurities can increase the core radiation
- radiative losses go into 4π – benign heat loads

Possible solutions (iii): alternative divertors



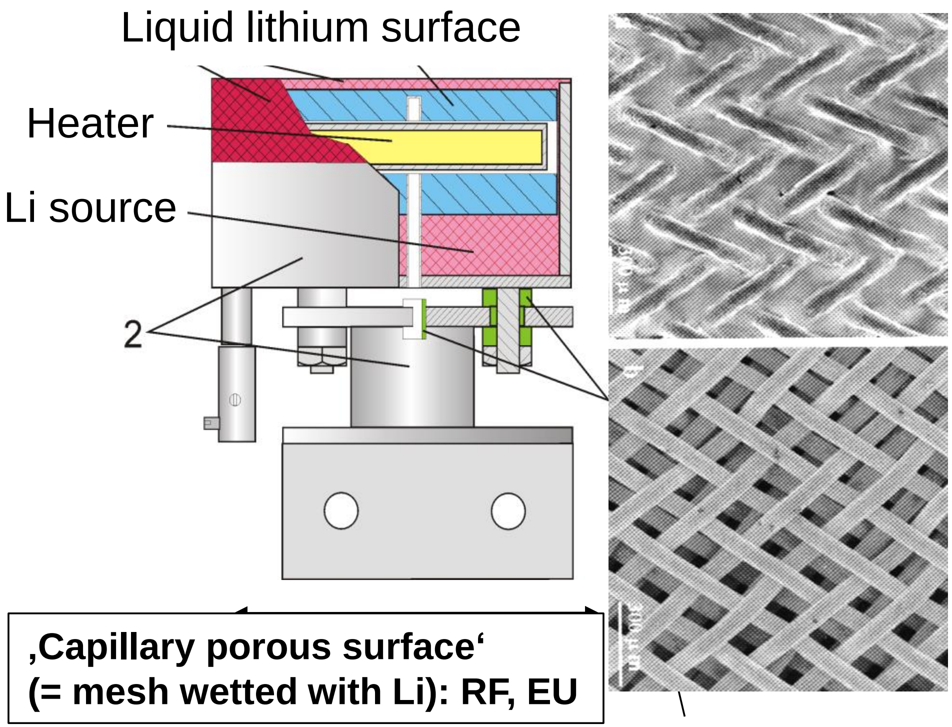
Alternative divertor geometries may lead to higher allowable P_{sep}

- increase (dissipative) divertor volume
- increase wetted area on target plate
- stabilise detachment front…

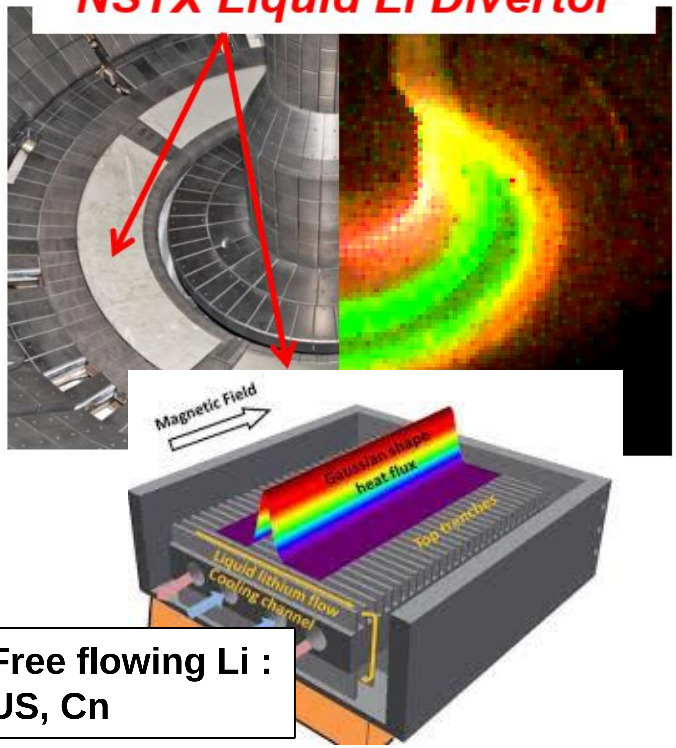
H. Reimerdes et al., 27th IAEA Fusion Energy Conference (2018), TH/P7-18

Has become a very active research field across the globe

Possible solutions (iv): alternative materials



‚Capillary porous surface‘
(= mesh wetted with Li): RF, EU



Free flowing Li :
US, Cn

Alternative (liquid) materials may lead to higher allowable P_{sep}

- avoid leading edges, self-healing of local deviations
- circulation of plasma facing part effectively increases wetted area
- will be treated on Friday in the talk by D. Andruczyk, stay tuned…

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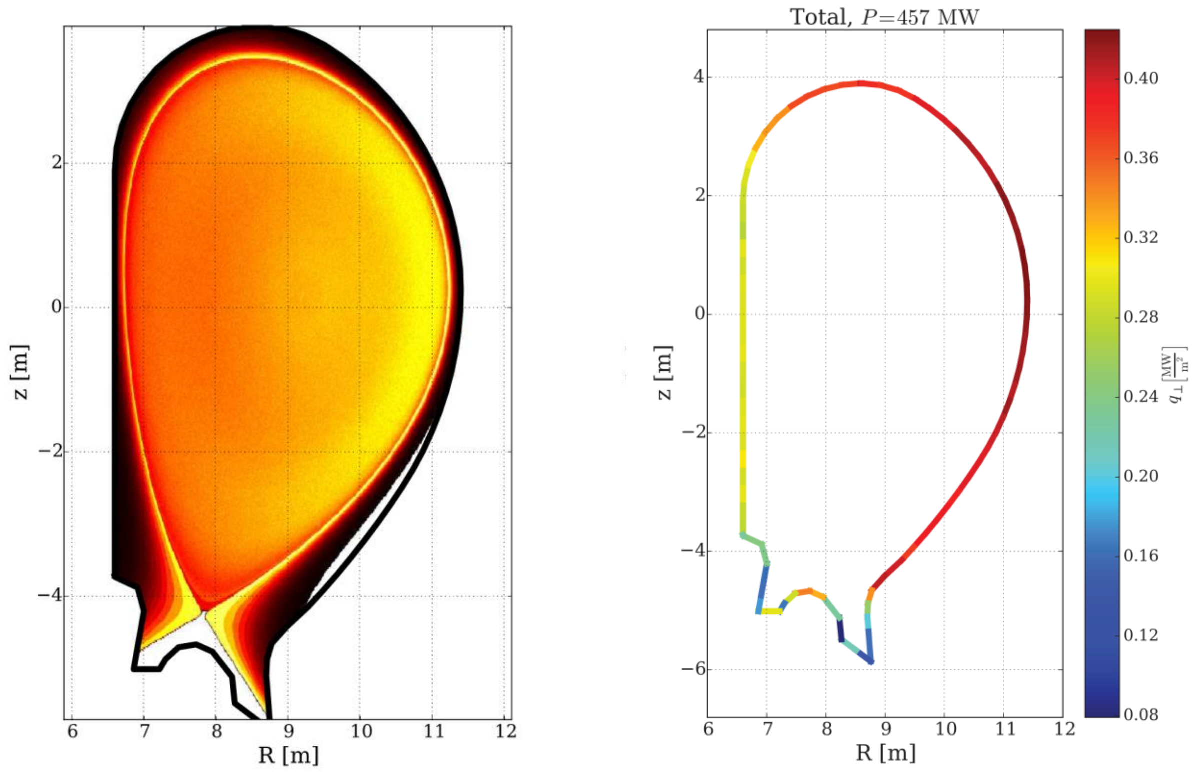

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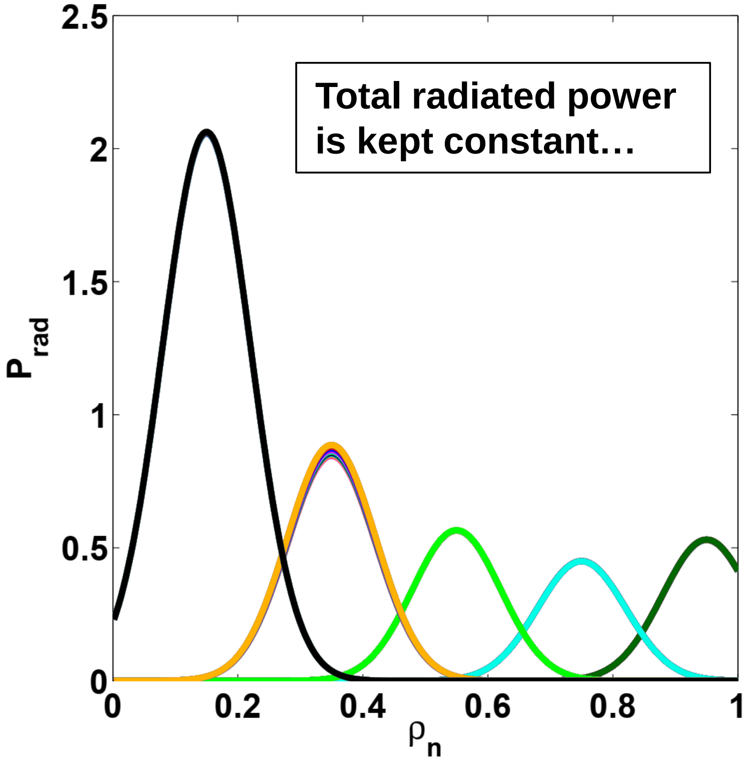
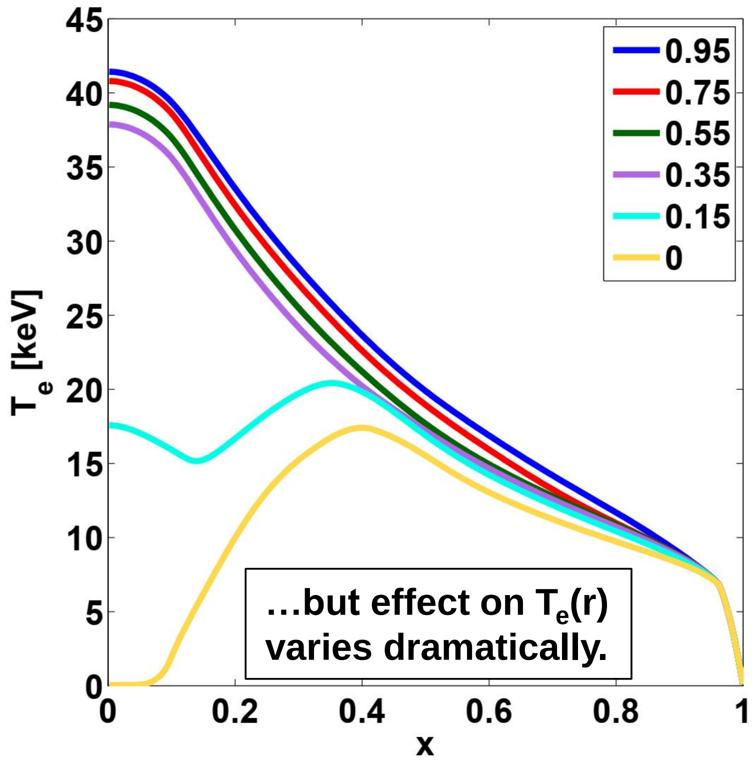
Core radiation: importance of radial distribution





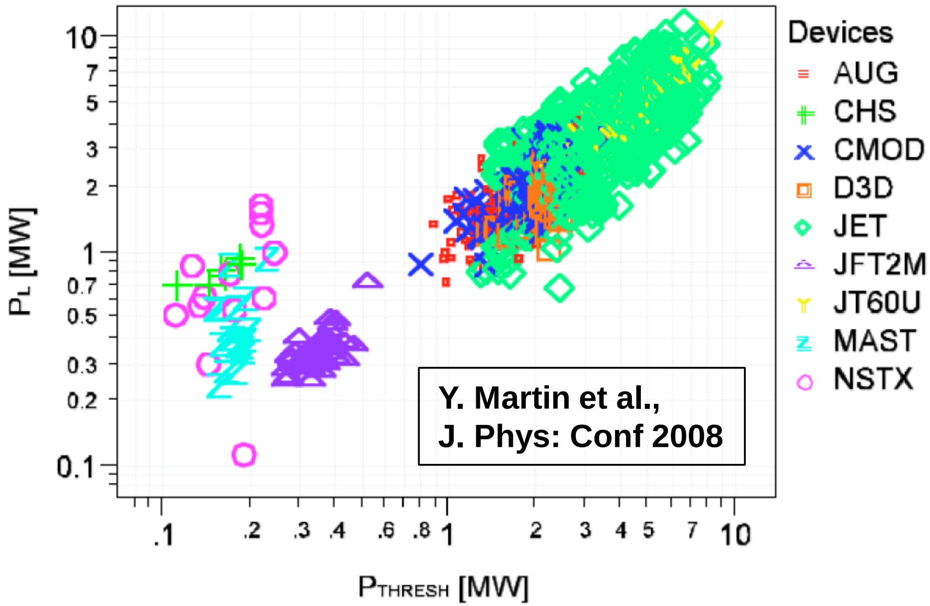
100 % radiation would be great, but…

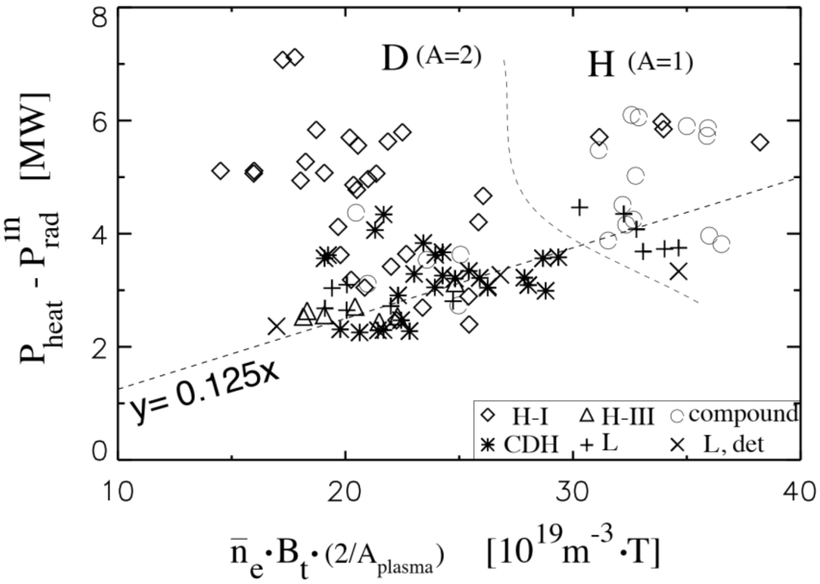
E. Fable et al., Nucl Fusion 2016

- must not lose the central heating by α-particles

$\Rightarrow$ overlap between $P_{rad}(r)$ and $P_{\alpha}(r)$ must be minimised!

Core radiation: compatibility with H-mode operation





Radiative H-modes:
A. Kallenbach et al.,
Nucl. Fusion 1996

Increase the radiated power fraction in the core

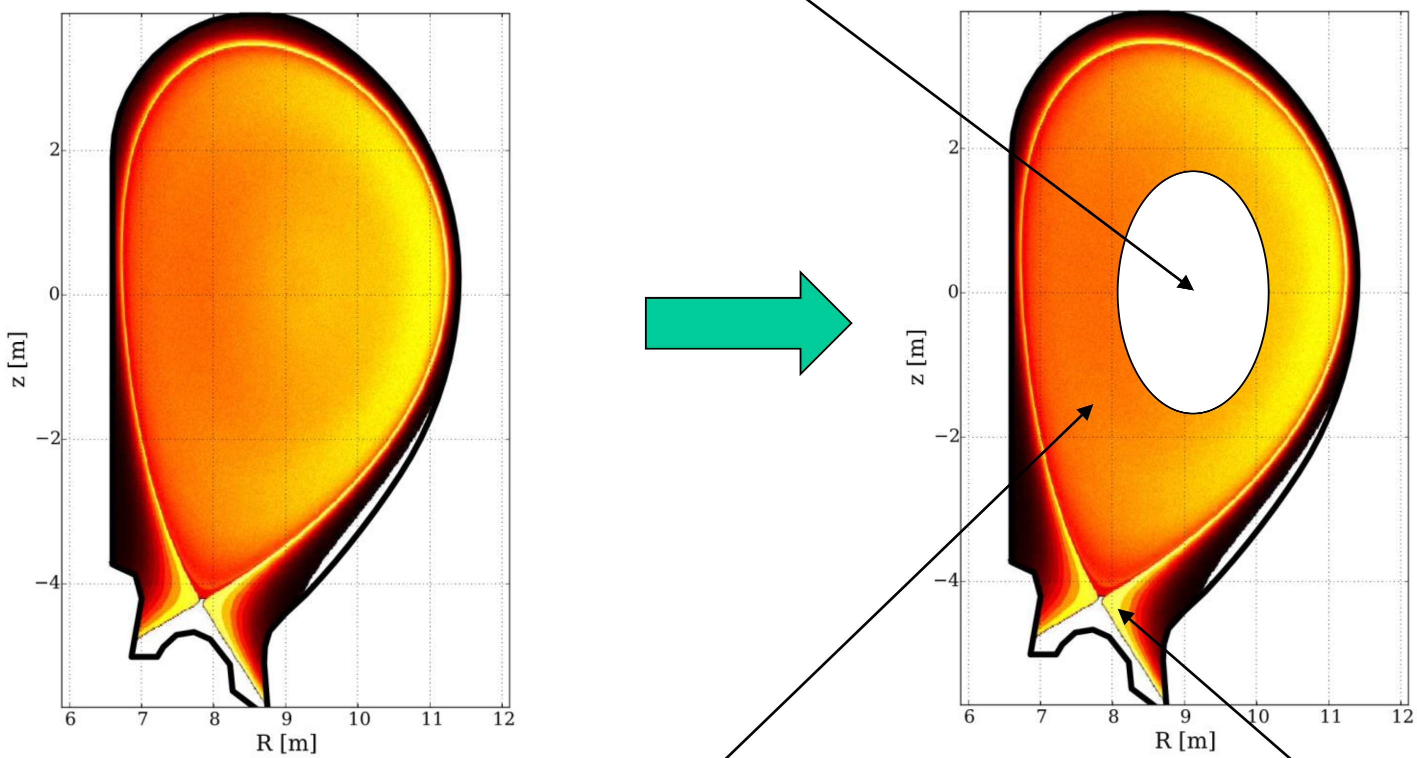
- radiated power limited by the need to stay in H-mode
- P_{LH} should be expressed in $P_{sep} = P_{heat} - P_{rad}$
- $P_{sep,min} = f_{LH}\, P_{sep,LH} \propto n_e^{0.7}\, B_t^{0.8}\, R^2$

Unmitigated power load will ‘only’ go up by $P_{LH}/R \sim R$

Note: a scenario different than H-mode may relax this substantially (not so much the total radiation, but separation between core and SOL&divertor!)

The ideal radiation distribution

No additional radiation from plasma core (just bremsstrahlung and synchrotron radiation)



In outer part of confined plasma, additional radiation such that $P_{rad,tot}(core) = P_\alpha + P_{AUX} - f_{LH} P_{sep,LH}$

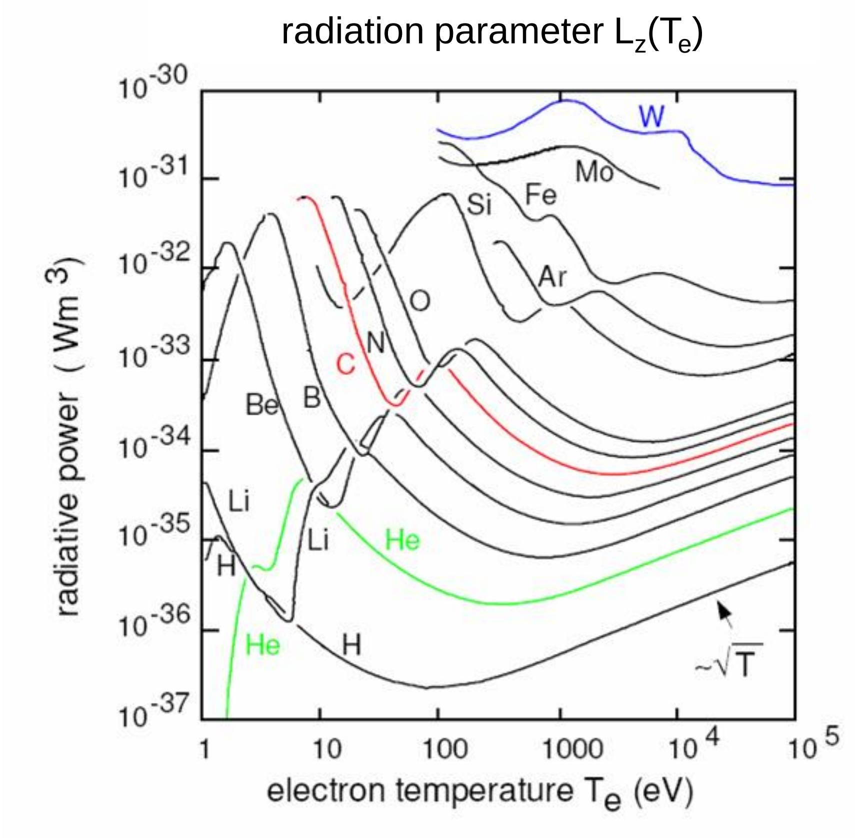
In SOL and divertor, $f_{LH}\, P_{sep,LH}$ is largely dissipated (radiated)

DEMO and FPPs will need larger $f_{rad,core}$ than ITER

	ITER	EU-DEMO
R [m]	6.2	8.5
P_{fus} [MW]	500	2500
P_{heat} [MW]	150	550
P_{sep} [MW]	85	120
$f_{rad,core}$	43%	78%

(assume f_{LH} = 1.2 for ITER, f_{LH} = 1.1 for EU-DEMO, λ_q = 5 cm on the target for both)

How well can we tailor the radiated power?



Total radiation power of element with charge number *Z:*

$$P_{rad} = n_Z \, n_e \, L_z(T_e)$$

- line radiation from different ionisation stages (shell structure)
- bremsstrahlung from fully stripped ion (proportional $T^{1/2}$)
- note: ‚corona‘ approximation (neglect radial transport)

Use of different ‘seed’ impurities allows a tailoring of $P_{rad}(r)$

- localisation of radiation by $L_Z(T_e(r))$
- usually, seed impurity has to be ‘puffed and pumped’

$\Rightarrow$ noble gases are usually favoured (chemistry complicates flux pattern)

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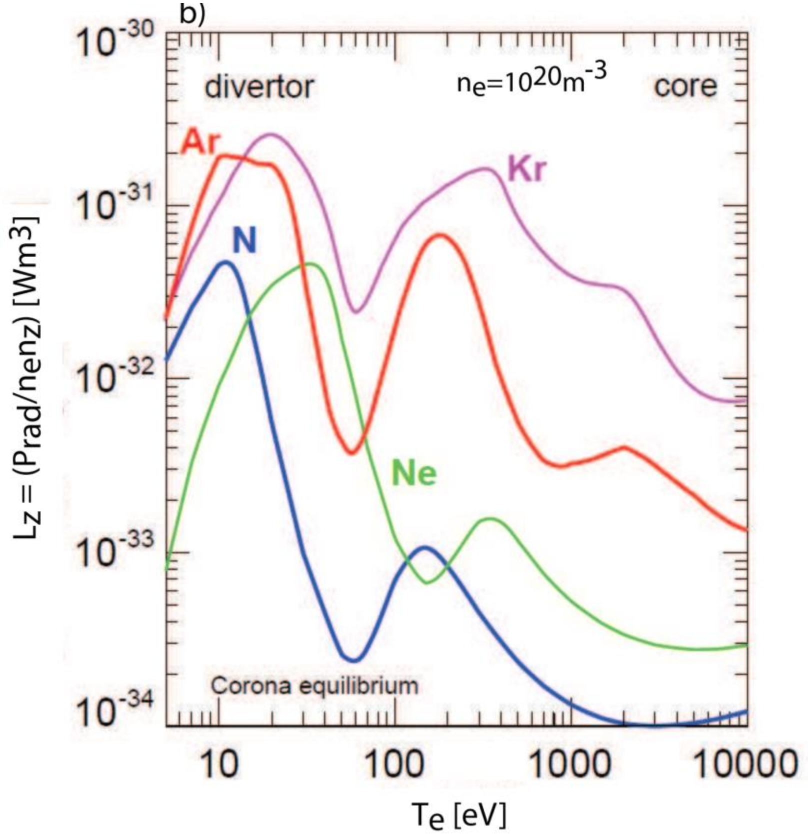

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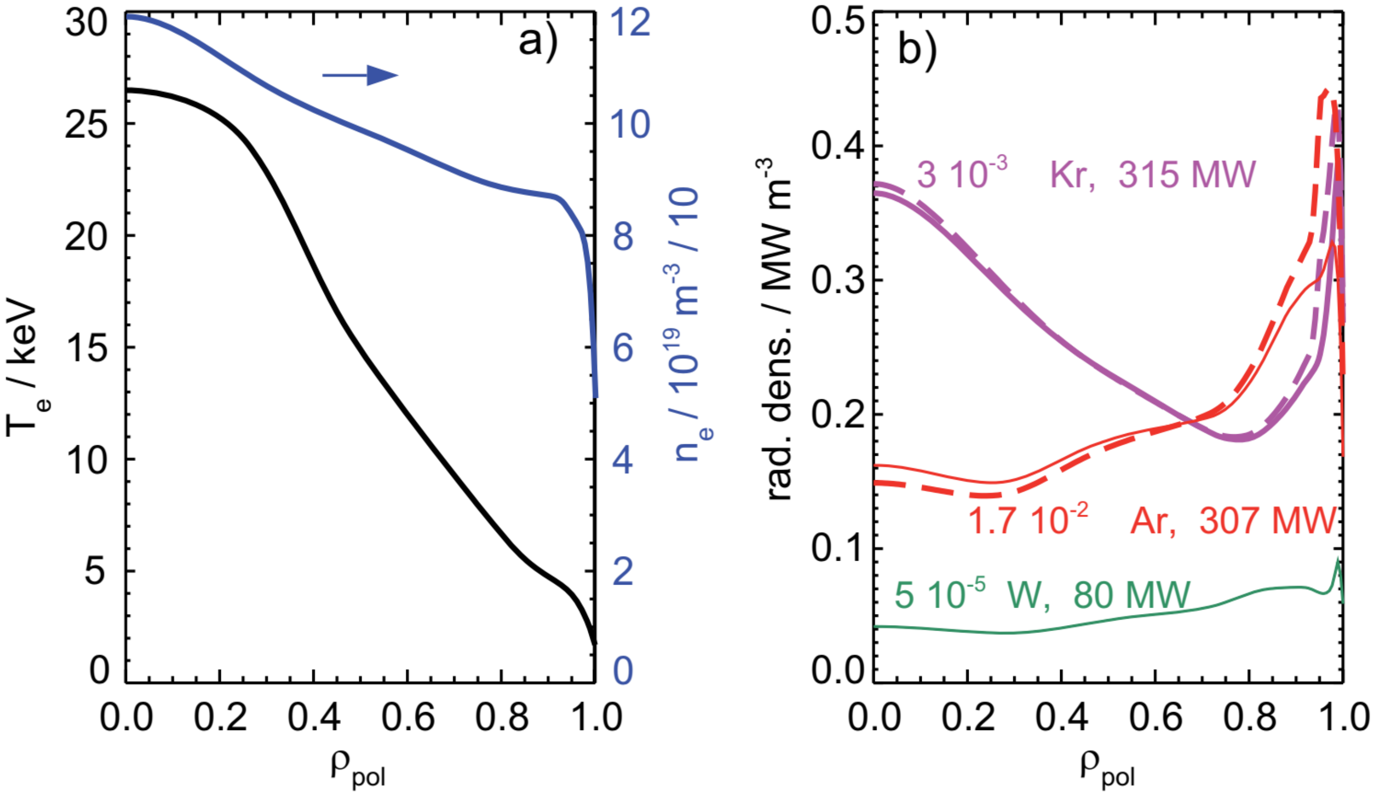
Modelling of impurity seeding



Forward modelling of Ar/Kr seeding in EU-DEMO

A. Kallenbach et al., Plasma Phys. Control. Fusion 2013

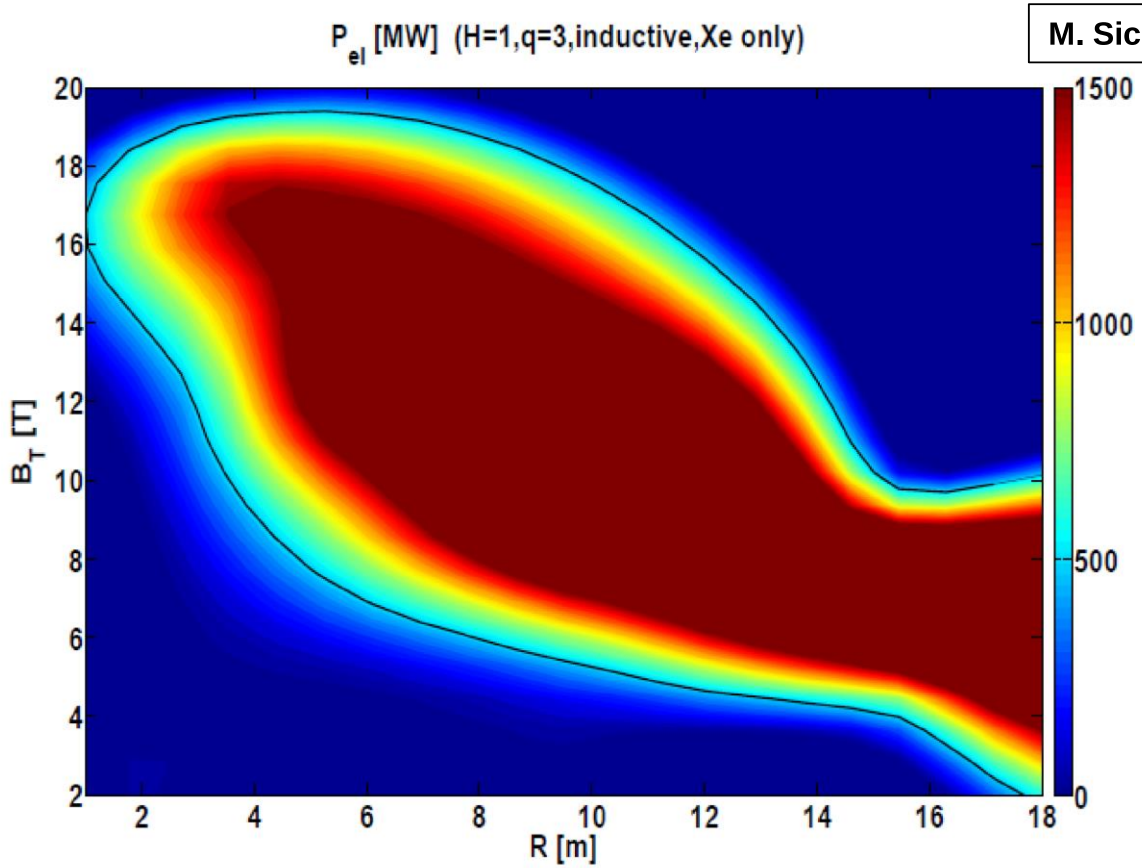
For given n_e, n_Z and T_e, radiation profiles can be calculated, but…

- radiative cooling will change kinetic profiles and hence P_α
- radial impurity transport may lead to deviation from corona equilibrium

Need self-consistent model (plasma transport code + radiation model)

Self-consistent modelling of impurity seeding

M. Siccinio, Nucl. Fusion 2018



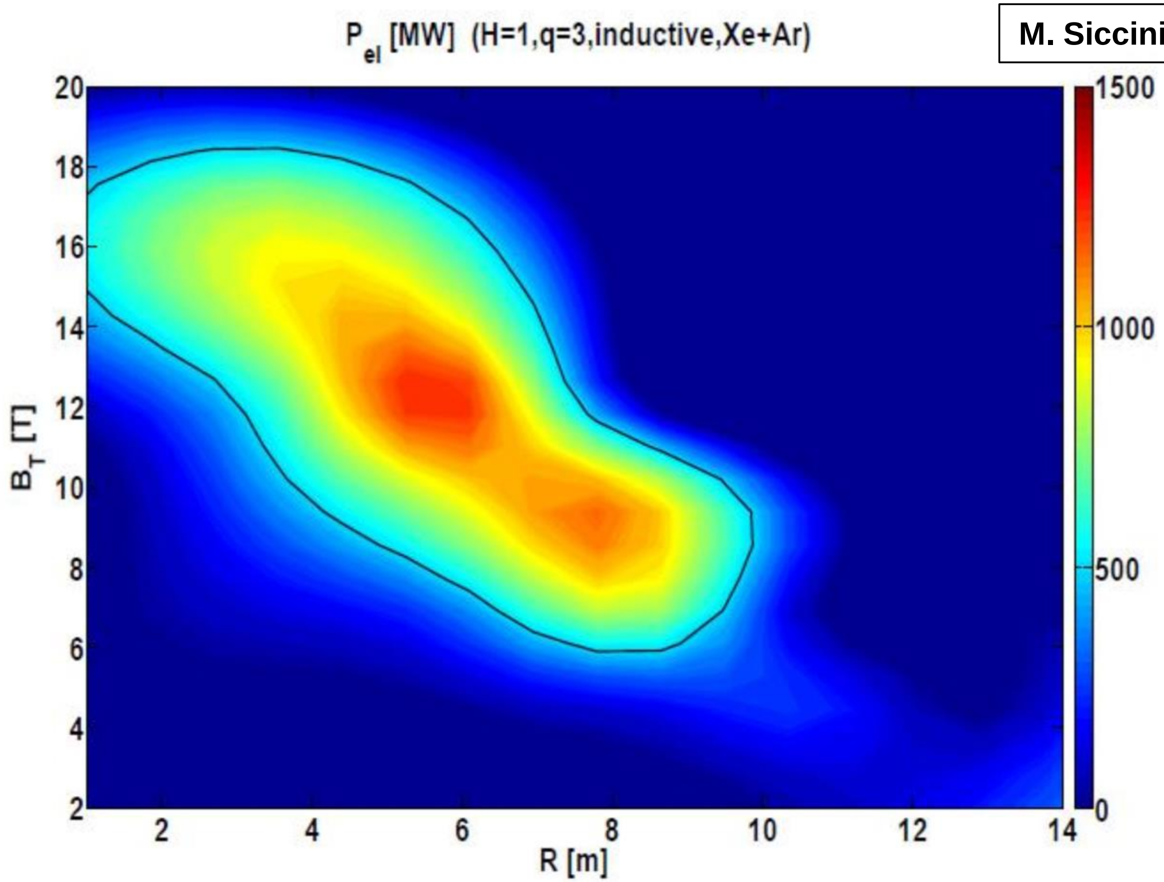
Coupled transport (ASTRA) and radiation (STRAHL) modelling of EU-DEMO:

Use Xe to stay at P_{sep}=1.1 P_{LH} and Ar to detach the divertor

- lines of constant electrical power lie in a ‚corridor' of B-R
- limited by ignition (lower left) and synchrotron losses (upper right)

Self-consistent modelling of impurity seeding

M. Siccinio, Nucl. Fusion 2018



Allowing Ar from divertor region to enter core plasma changes picture

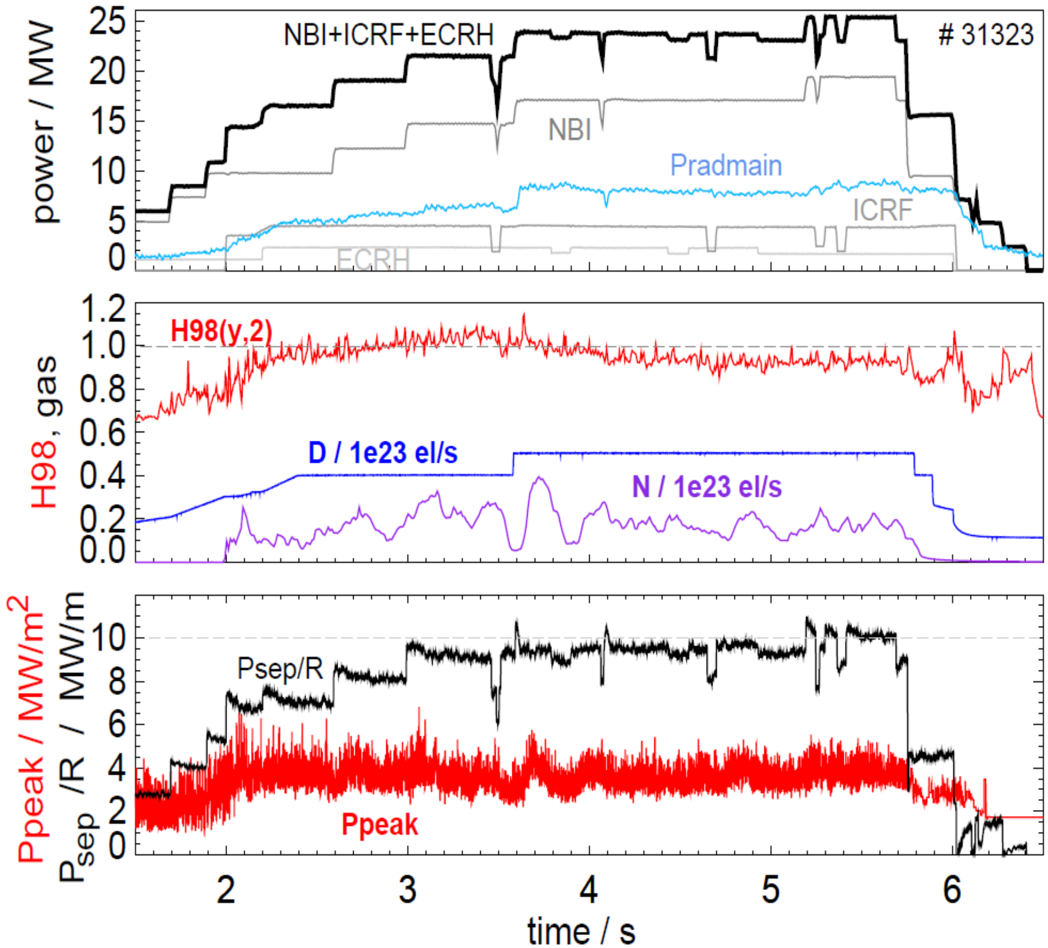
- region at low field, large radius is shut off due to excessive radiation
- essentially recovers the ‚Reinke scaling' $f_{Z,div} \sim B^{0.88} R^{1.33}$

M. Reinke, Nucl. Fusion 2017

Crucial role of ‚divertor enrichment' = ratio of Ar vs. D/T-compression

Reality check: experimental results (ITER case)

A. Kallenbach et al.,Nucl. Fusion (2013)

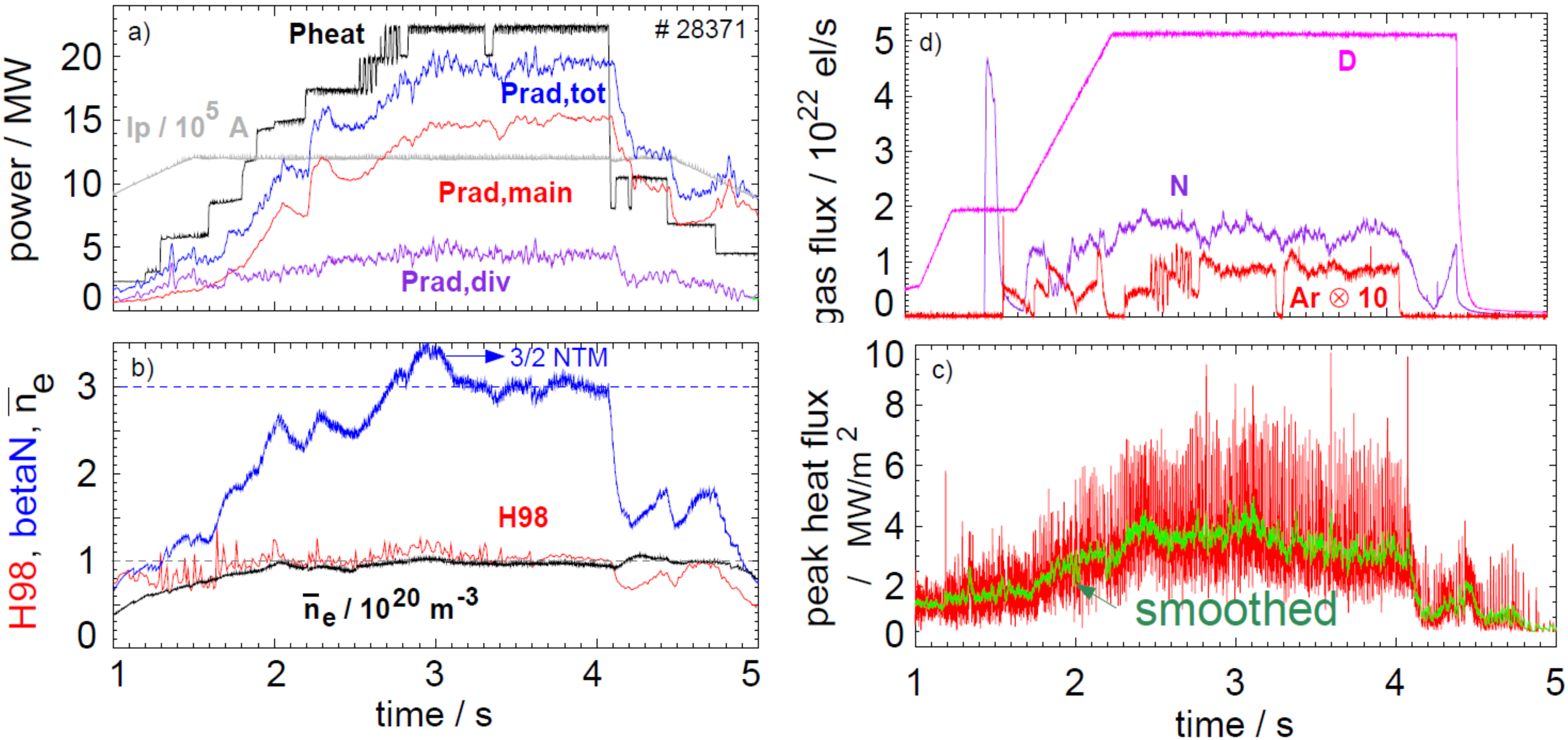


ASDEX Upgrade discharge applying N-cooling at 2/3 of Normalised ITER power flux (P_{sep}/R=10 MW/m)

With feedback-controlled N-seeding, divertor heat flux can be kept to very low level in ASDEX Upgrade (< 5 MW/m^2) at high P_{sep} (unmitigated divertor heat flux would be ~ 40 MW/m^2)

Reality check: experimental results (DEMO case)

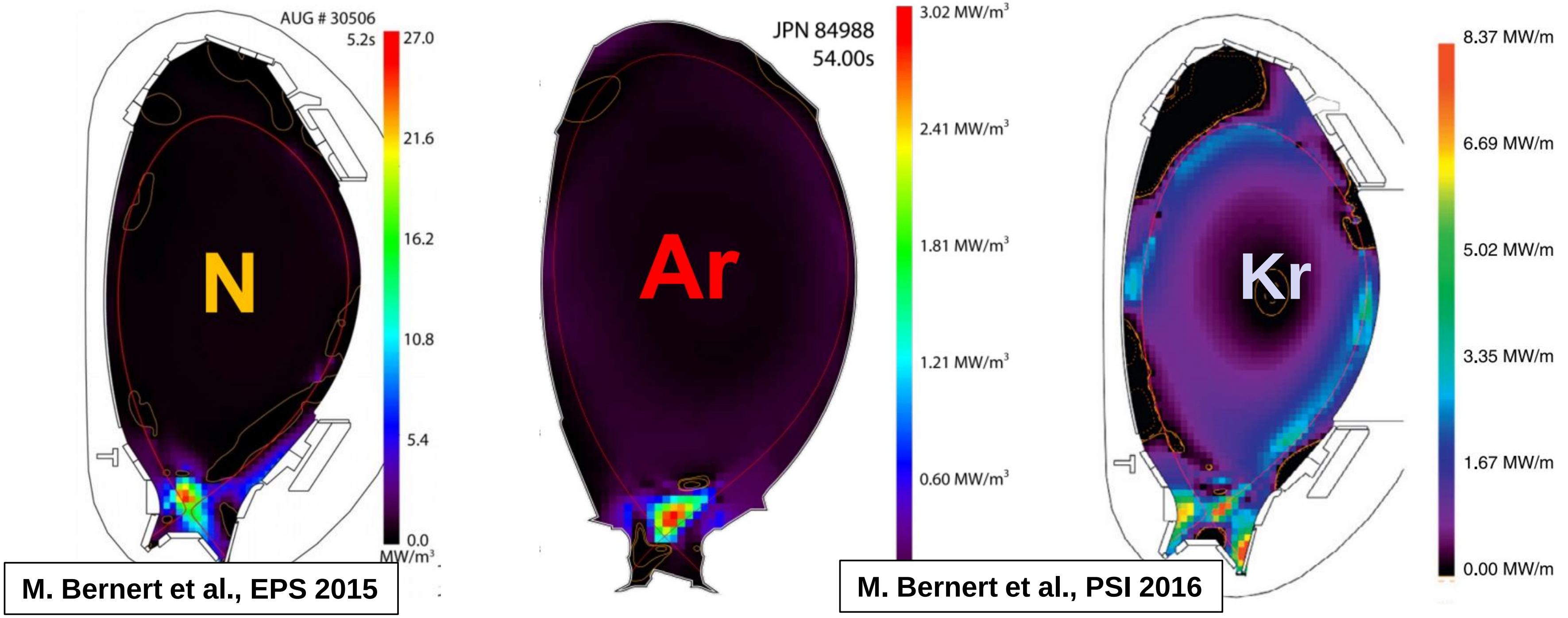
A. Kallenbach et al.,Nucl. Fusion (2013)



Double feedback control of $P_{rad,main}$ (Ar-seeding) and $P_{rad,SOL\&Div}$ (N-seeding)

- $P_{heat,tot}$ = 23 MW and $P_{rad,core}$ = 15 MW (67%), q_{div} < 5 MW/m^2
- close to P_{LH}, with good confinement $H \geq 1$ and stability $\beta_N = 3$

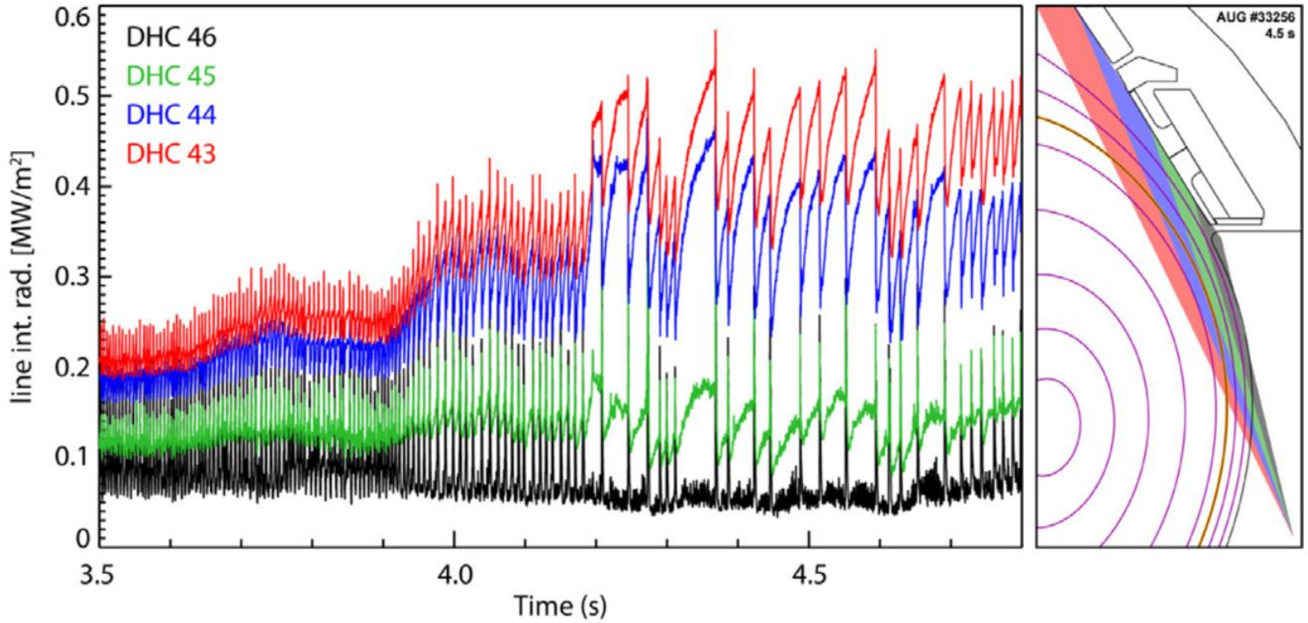
Core radiation: open challenges (choice of species)



Separation between core and SOL/divertor is not very strict

- radiative zone tends to pile up in X-point, independent of species
- points towards a stability of radiative zone at that location (minimum of heat flux due to flux expansion, see later)
- may lead to 'opening' of divertor and reduced pumping efficiency

Core radiation: open challenges



Impact of radiation on closed flux surfaces on H-mode pedestal makes control difficult (change of transport)

- interaction with ELMs in present day experiments
- compatibility with ELM-suppressed regimes not proven

Control of the (large) core radiation fraction has to be very precise

- at 80% core radiation, -10% excursion is a factor of 1.5 in P_{sep}(!)
- +10% will induce back-transition to L-mode, MARFE and disruption (?)

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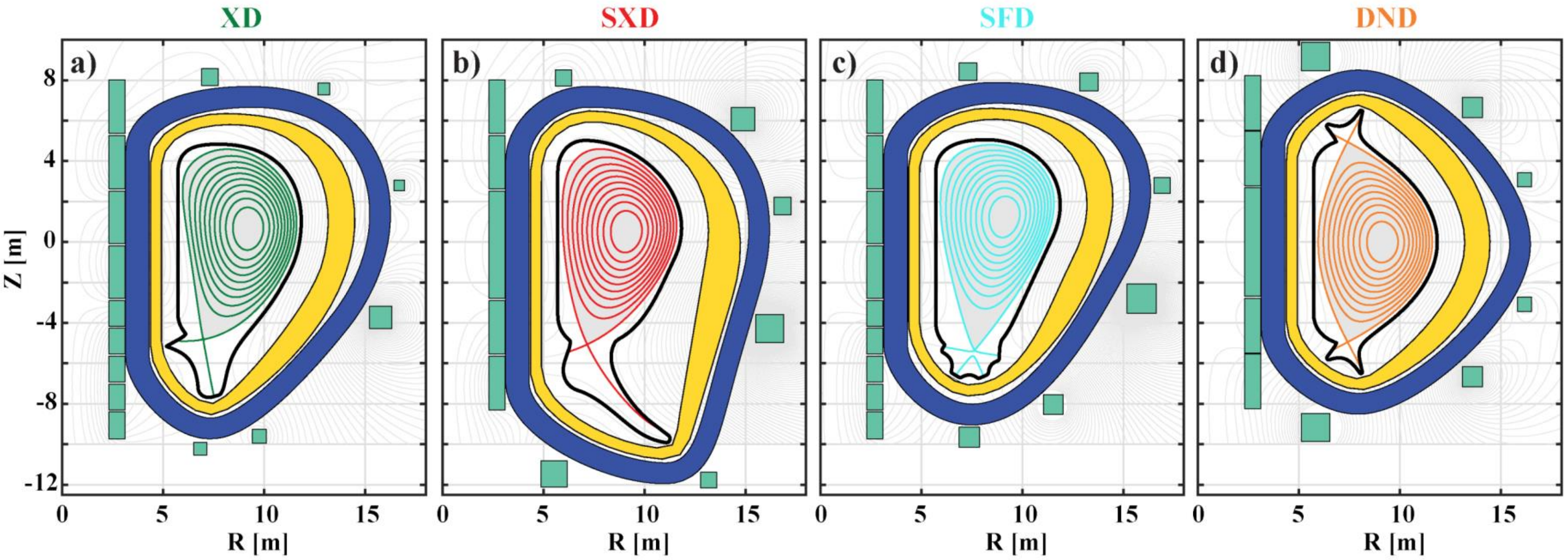

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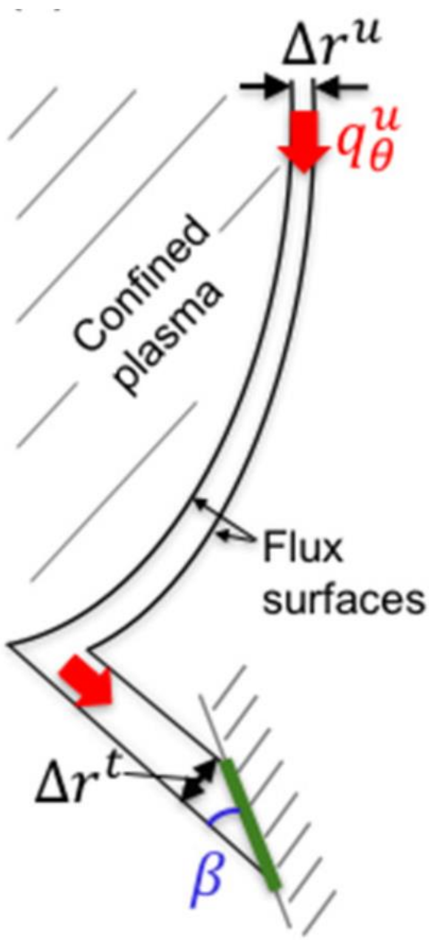
- increase (dissipative) divertor volume
- increase wetted area on target plate
- stabilise detachment front…

H. Reimerdes et al., 27th IAEA Fusion Energy Conference (2018), TH/P7-18

Has become a very active research field across the globe

How can we improve (power load on) divertors?

In a simple approach, the heat flux on the target can be expressed as



$$q_{t,\perp} = \frac{P_{target}}{wetted\ area} = \frac{P_{sep}(1-f_{rad})}{2\pi R_t \lambda_q f_x f_{tr} N_{div}} \sin\beta$$

P_{sep}: power flux across separatrix

f_{rad}: SOL/divertor radiated power fraction

R_t: major radius of target

λ_q: power width in the midplane

f_x: poloidal flux expansion

f_{tr}: increase of λ_q due to perp. transport

N_{div}: number of active divertors

β: poloidal target angle

Figure from C. Theiler et al., Nucl. Fusion 2017

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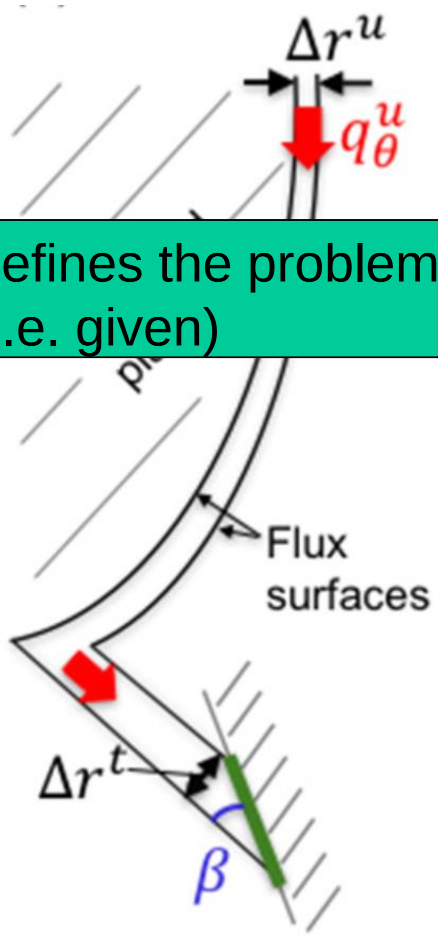

defines the problem
(i.e. given)

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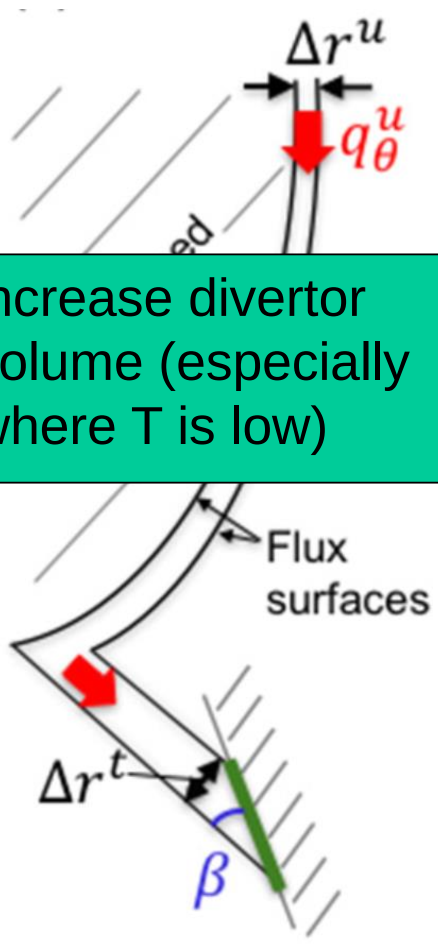

increase divertor volume (especially where T is low)

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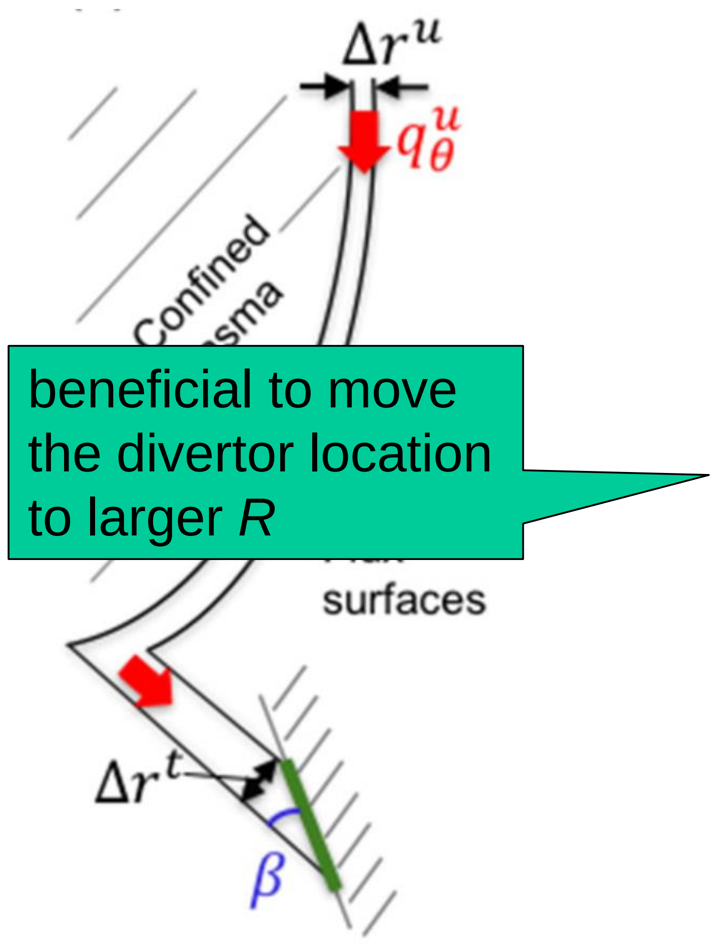

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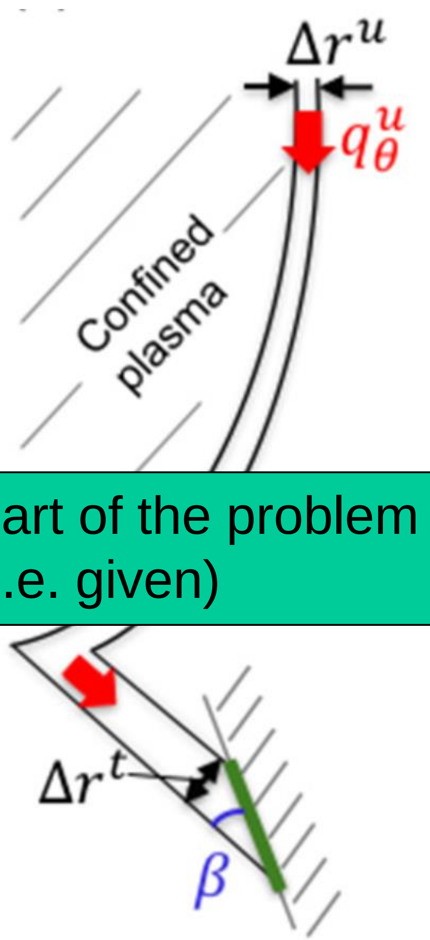

part of the problem (i.e. given)

Figure from C. Theiler et al., Nucl. Fusion 2017

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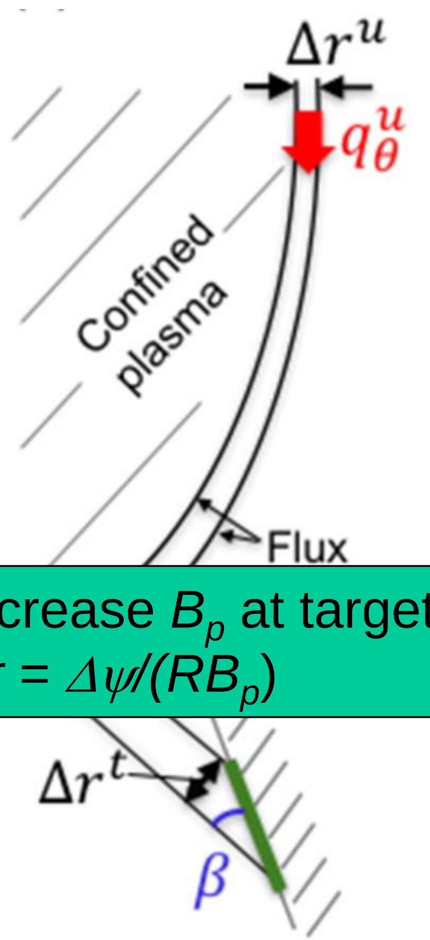

decrease B_p at target
($\Delta r = \Delta\psi/(RB_p)$)

Figure from C. Theiler et al., Nucl. Fusion 2017

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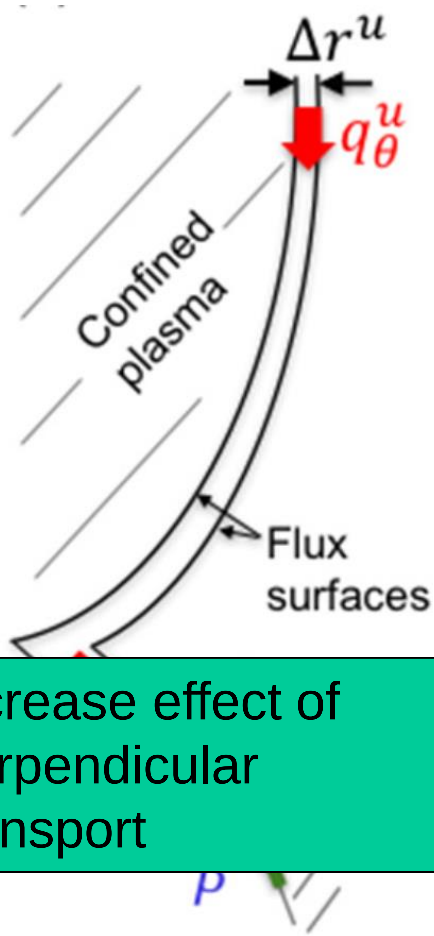

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increase effect of perpendicular transport

Figure from C. Theiler et al., Nucl. Fusion 2017

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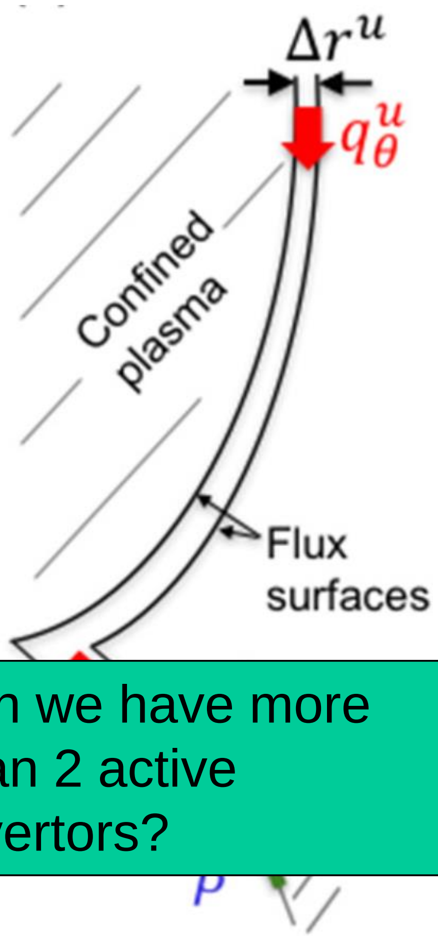

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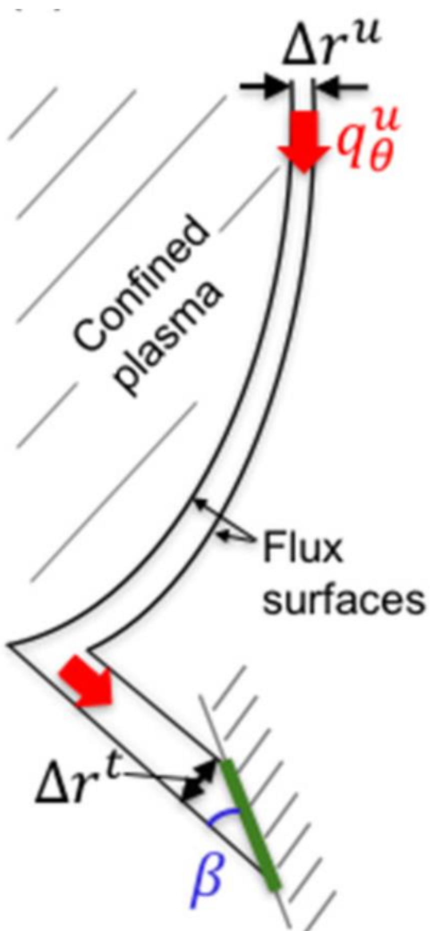
can we have more than 2 active divertors?

Figure from C. Theiler et al., Nucl. Fusion 2017

How can we improve (power load on) divertors?

In a simple approach, the heat flux on the target can be expressed as



$$q_{t,\perp} = \frac{P_{sep}(1 - f_{rad})}{2\pi R_t \lambda_q f_x f_{tr} N_{div}} \sin\beta$$

P_{sep}: power flux across separatrix

f_{rad}: SOL/divertor radiated power fraction

R_t: major radius of target

λ_q: power width in the midplane

f_x: poloidal flux expansion

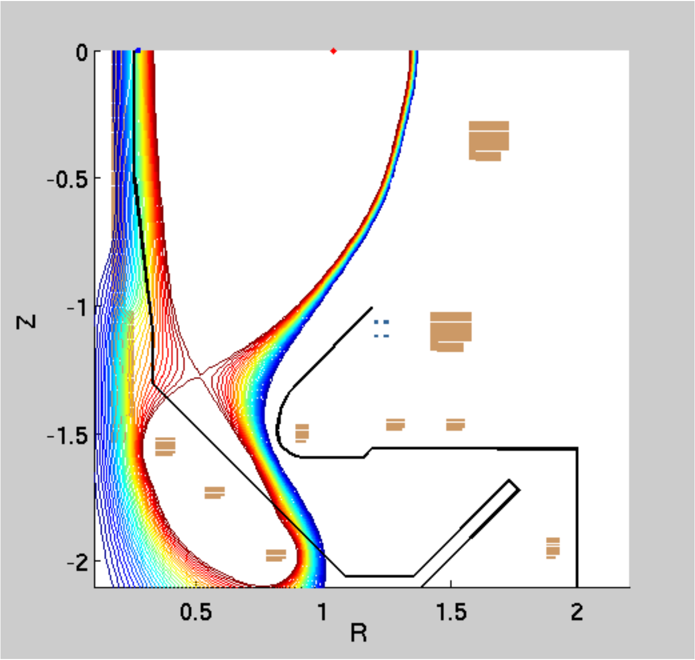
f_{tr}: increase of λ_q due to perp. transport

N_{div}: number of active divertors

β: poloidal target angle

increase poloidal target tilt angle

Increasing the radiated (dissipated) power fraction



‚Super-X divertor'

Proposed by Valanju et al., Phys. Plasmas 2009

to be tested in MAST-U (UK)

Animation courtesy of H. Meyer, CCFE

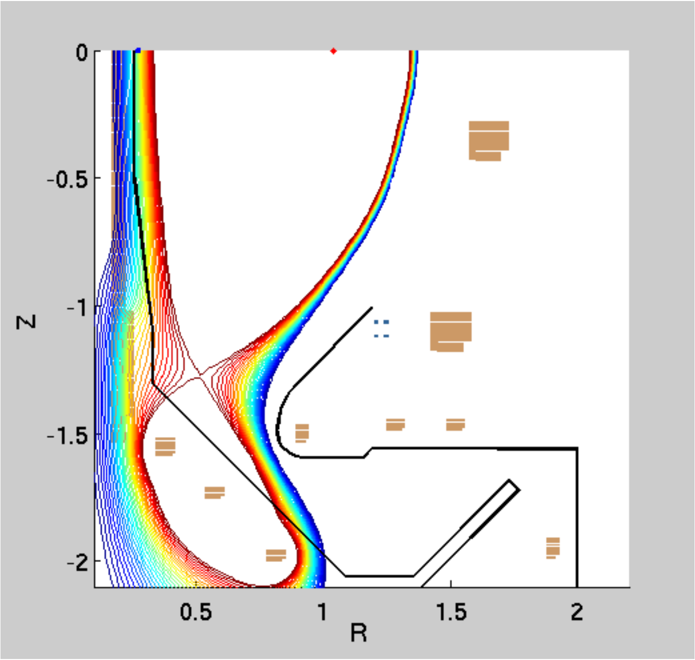
Remember 2-pt model: $T_{e,target} \propto \frac{q_{\parallel}^{10/7}}{n_u^2 L_c^{4/7}}$

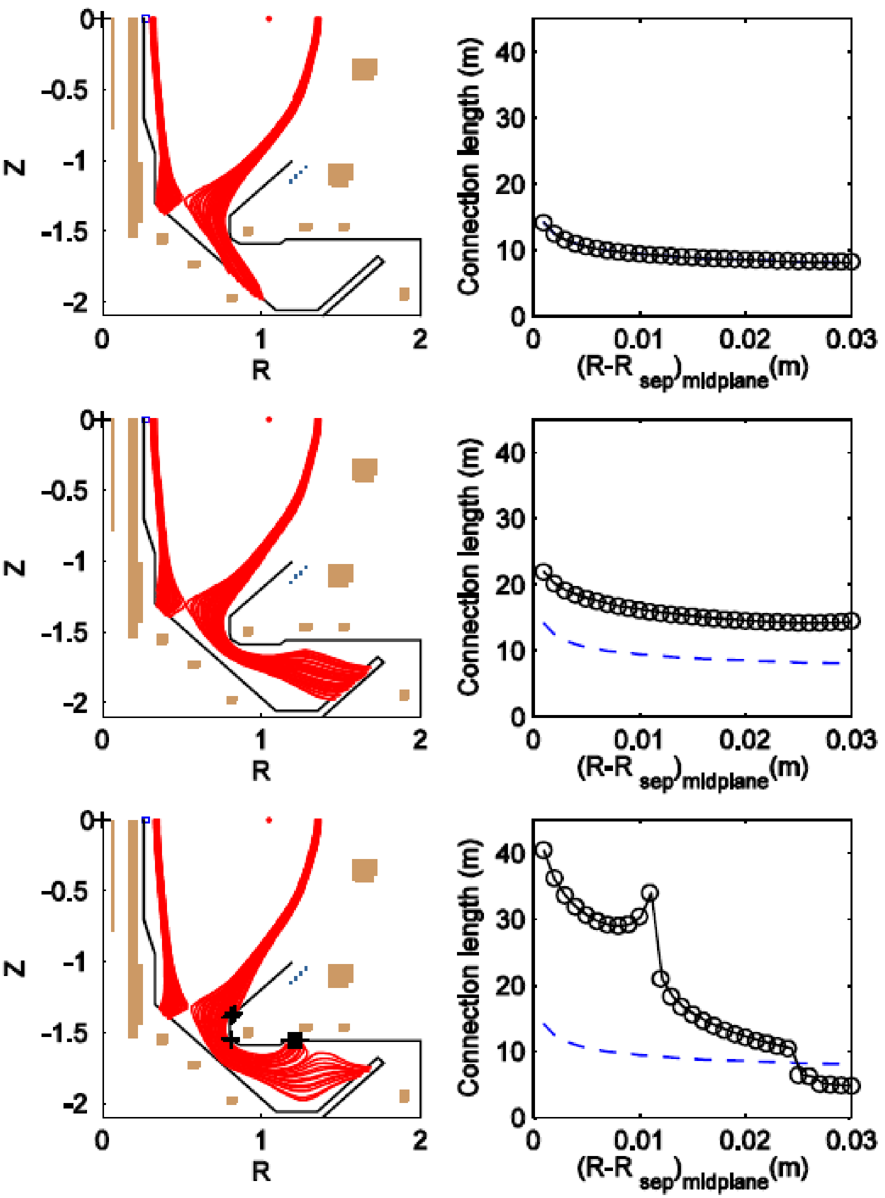
The physics of this is largely common with that of achieving detachment by radiative cooling along field lines

- need to make the connection length L_c long enough such that target temperatures are low and suited for additional radiation
- increased volume for radiation will also help, coupled to L_c by $V \sim R_X L_c$

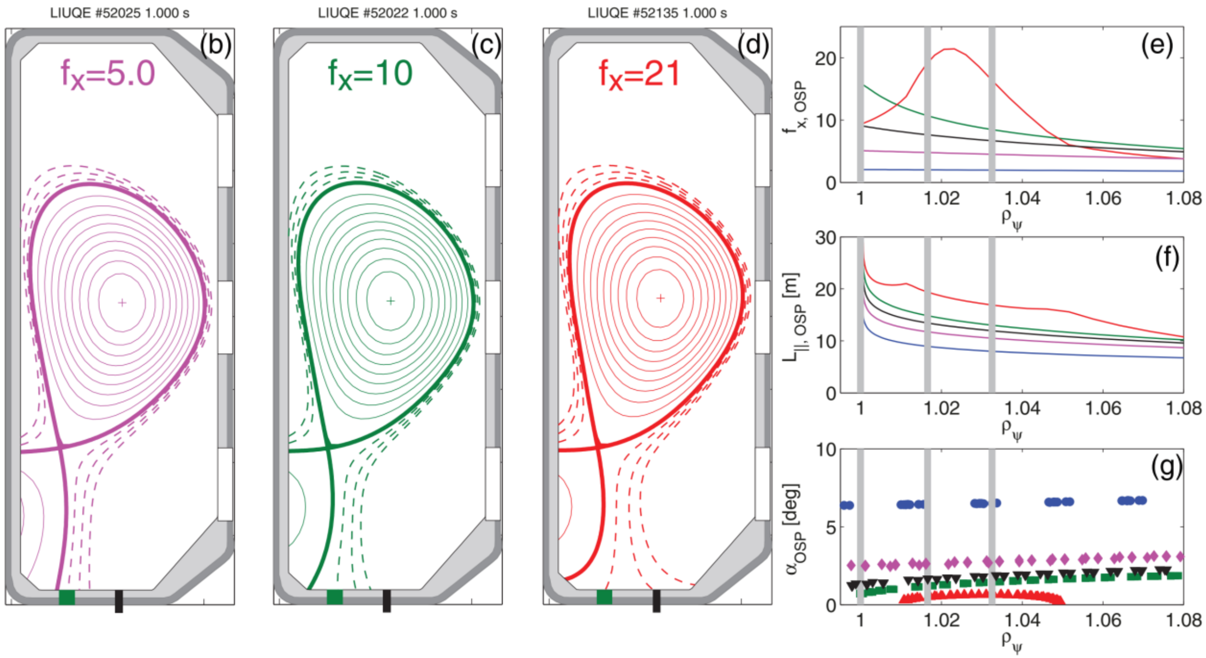
In addition to large poloidal divertor leg length, L_c can be increased substantially lowering the poloidal field (and hence the radiation volume)

Increasing the radiated (dissipated) power fraction





Increasing the wetted area (R_t, f_x and β)



X-divertor

proposed by
M. Kotschenreuther et al.,
Phys. Plasmas 2013

realised on TCV (CH)

C. Theiler et al.,
Nucl. Fusion 2017

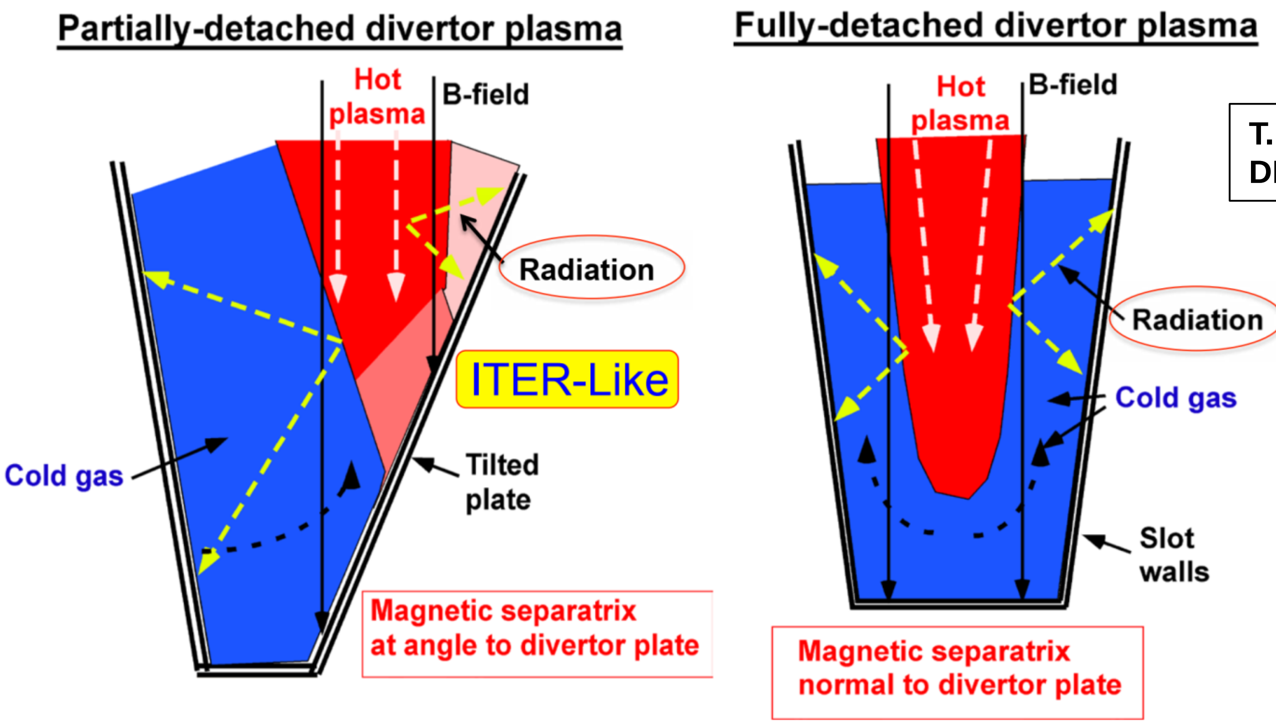
Increasing R_t increases wetted area in a straightforward geometric manner

Increasing f_x / decreasing β face a common problem:

- the increase in wetted area coincides with a decrease of the *total* field line incidence angle (for $B_p \rightarrow 0$ or $\beta \rightarrow 0$ lines become tangential)
- target tolerances limit incidence angle to 1-2 degrees due to leading edge heating and shadowing, at least under attached conditions

Note that increasing R_t decreases B_{tot}, compensating this effect by R_t/R_u

Plate tilt or poloidal flux expansion?



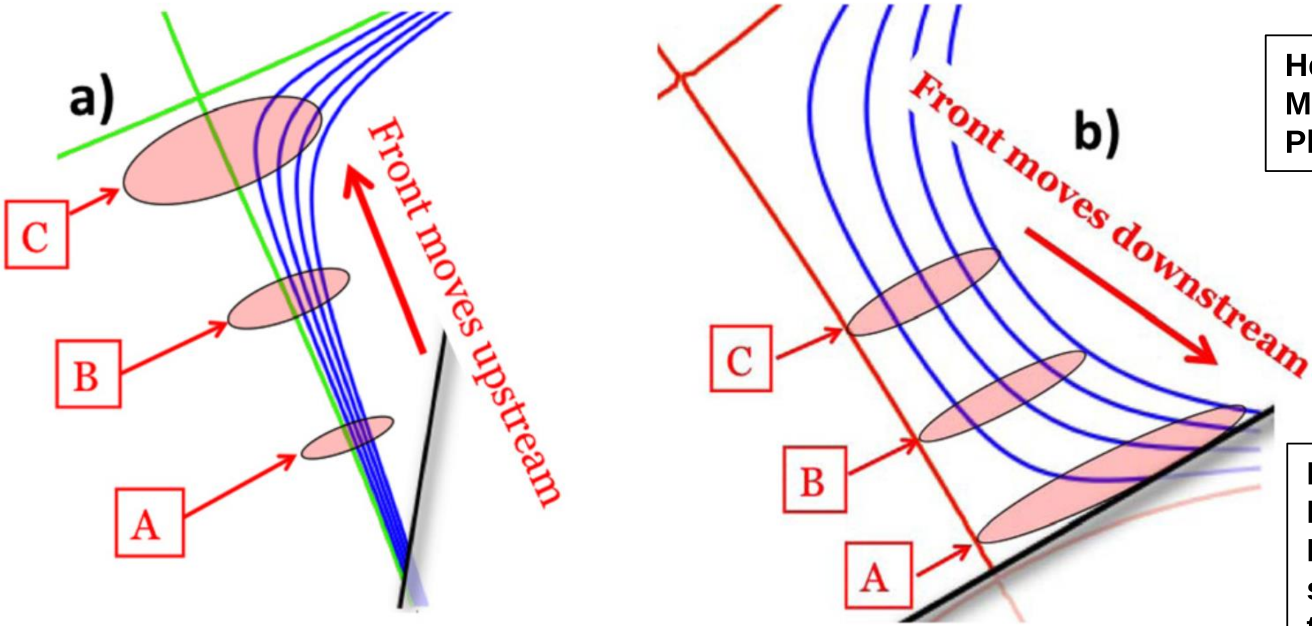
T. Rognlien et al. 2nd IAEA DEMO Workshop (2014)

Idea being realised in the DIII-D SAS (Small angle slot)

While equivalent in increasing wetted area, theory predicts at least two advantages of poloidal flux expansion

- near perpendicular poloidal angle should ease detachment by reflecting the recycling neutrals directly into the detachment front

Plate tilt or poloidal flux expansion?



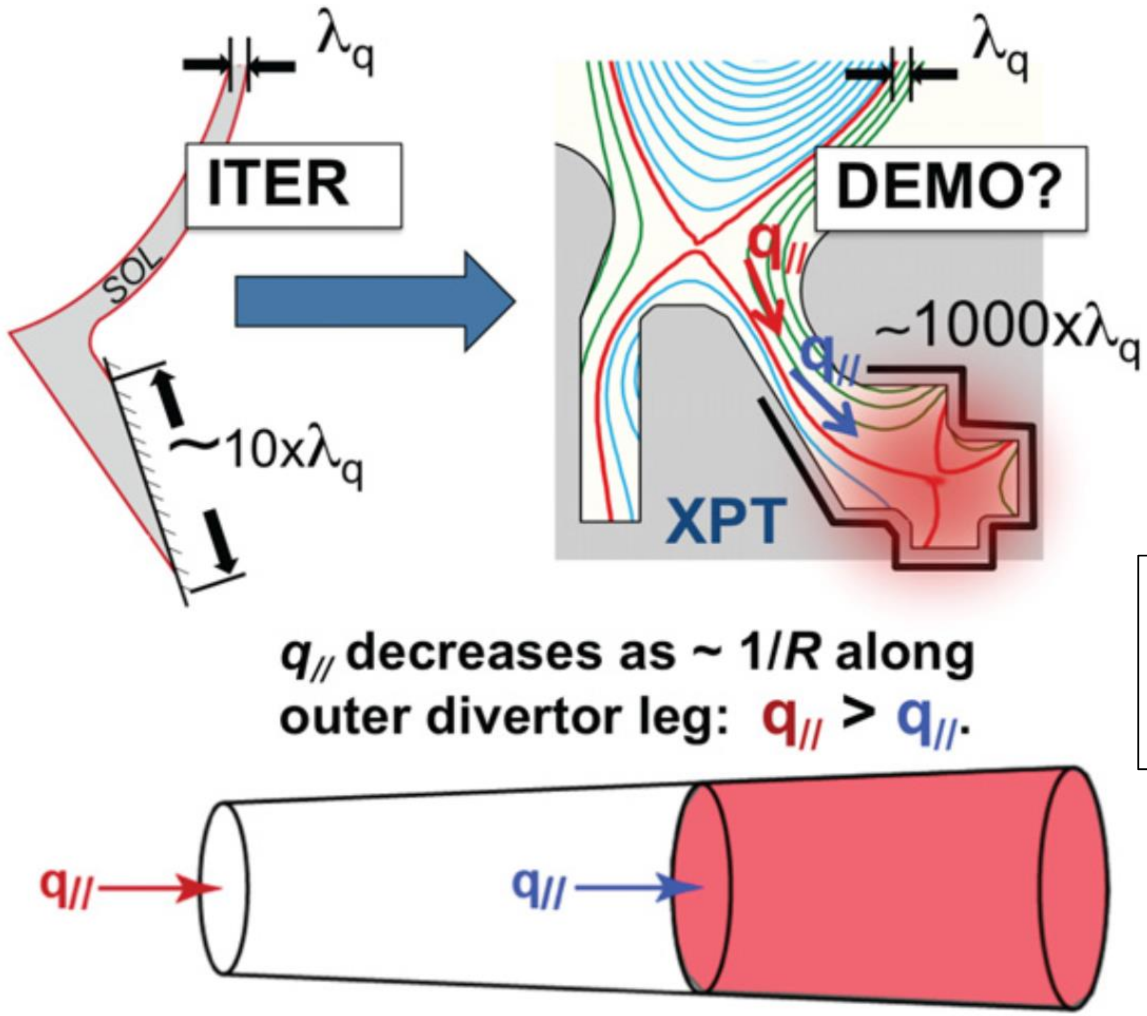
Heuristic argument:
M. Kotschenreuther et al.,
Phys. Plasmas 2013

Rigorous analytical theory:
B. Lipschultz et al.,
Nucl. Fusion 2016,
stresses the importance of
total flux expansion (B_t)

While equivalent in increasing wetted area, theory predicts at least two advantages of poloidal flux expansion

- near perpendicular poloidal angle should ease detachment by reflecting the recycling neutrals directly into the detachment front
- ‘flux flaring’ creates a local minimum in power flow that should stabilise the detachment front at the plate (similar to unwanted X-point radiation)

Plate tilt or poloidal flux expansion?

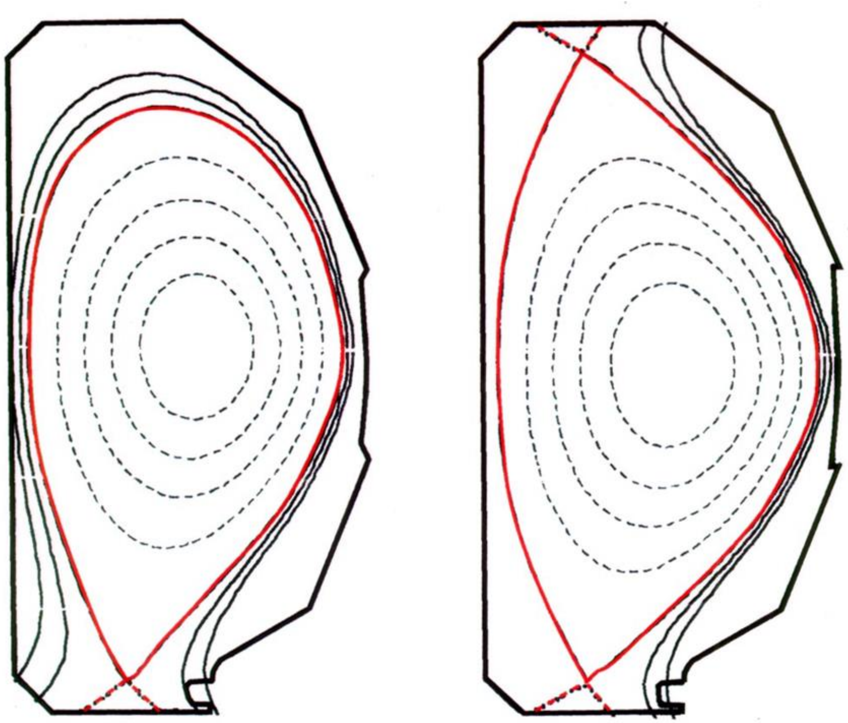


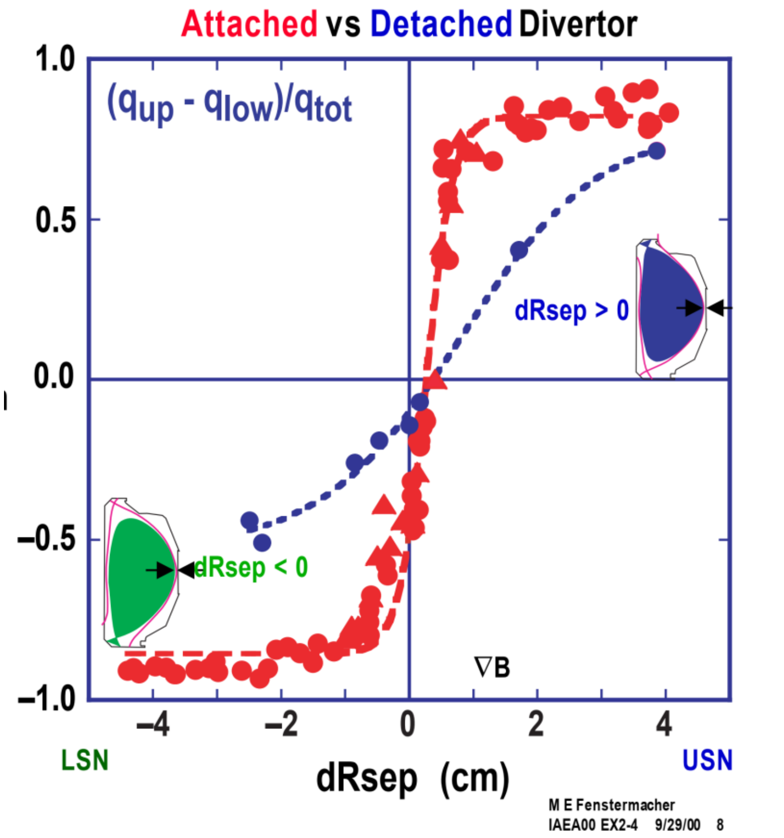
B. La Bombard et al.,
Nucl. Fusion 2015

Extreme case:
‚X-point target divertor'
in the ADX proposal

Increasing the number of divertors (N_{div})

‚Double null‘ configuration on DIII-D



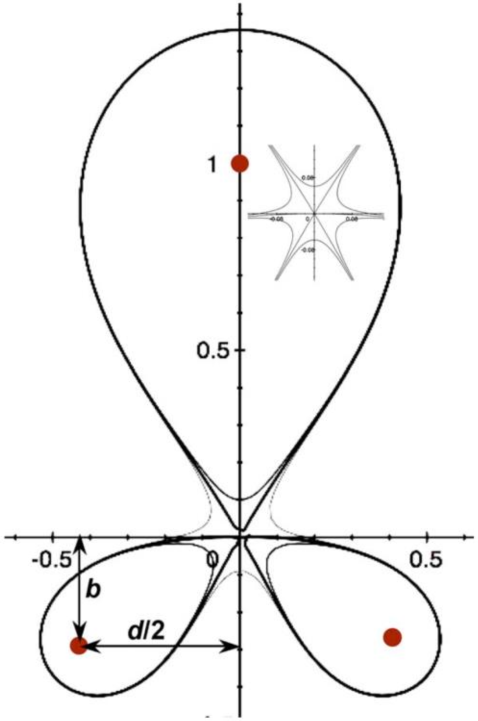


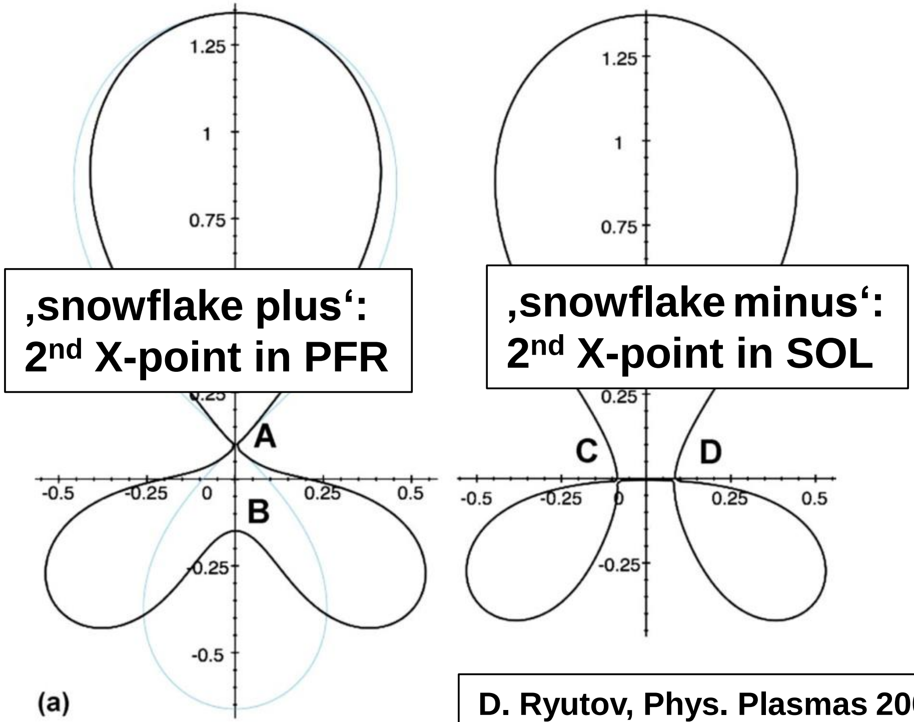
Introducing multiple X-points can lead to $N_{div} > 2$

- flux separation has to be less than power decay length: $\Delta\psi \leq R_u B_p \lambda_q$
- may become a delicate magnetic control problem!
- imbalance between inner and outer divertor(s) must be considered

Increasing the number of divertors (N_{div})

‚Snowflake': 2 X-points on top of each other (second order null in B_p)





D. Ryutov, Phys. Plasmas 2007

Introducing multiple X-points can lead to $N_{div} > 2$

- flux separation has to be less than power decay length: $\Delta\psi \leq R_u B_p \lambda_q$
- may become a delicate magnetic control problem!
- imbalance between inner and outer divertor(s) must be considered

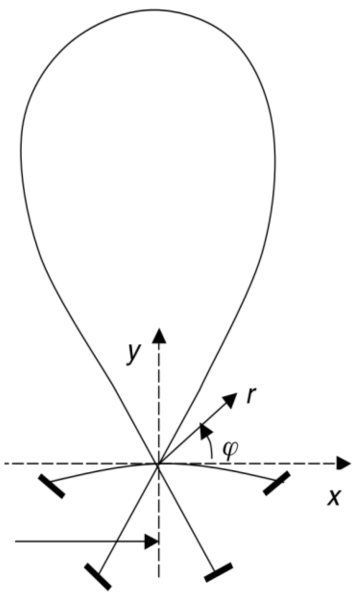
Increasing the power decay width (f_{tr})

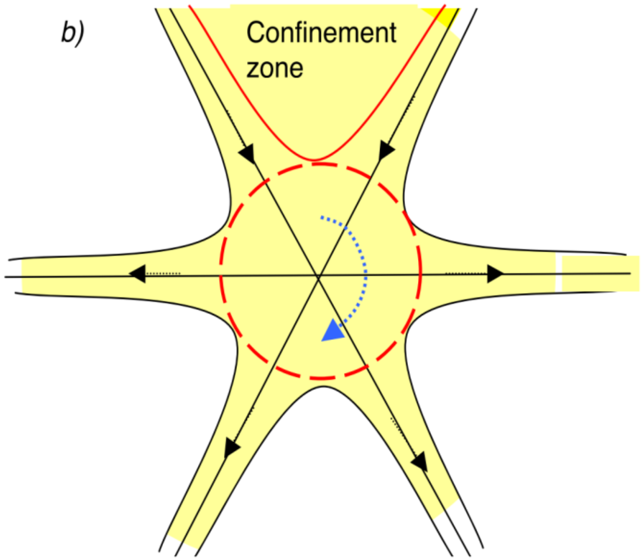
‚churning mode‘ in snowflake geometry(?)

$$\nabla \cdot q = -\nabla \cdot (\kappa_{\parallel} \nabla T + \kappa_{\perp} \nabla T) = 0$$

$$\Downarrow$$

$$\frac{L_{\perp}}{L_{\parallel}} \approx \sqrt{\frac{\kappa_{\perp}}{\kappa_{\parallel}}} \quad \Rightarrow \quad \Delta\lambda_q \approx \sqrt{\frac{\kappa_{\perp}}{\kappa_{\parallel}}} L_c$$





D. Ryutov et al., Phys. Scr. 2014

Broadening of the power decay length by perpendicular transport…

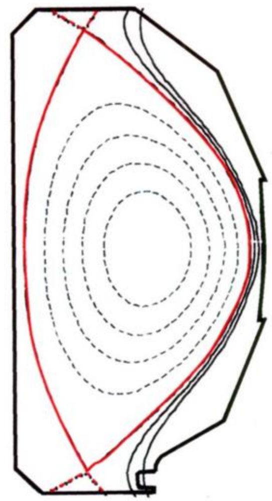
- will increase with connection length
- will be most efficient in the region of low T (due to $\kappa_{//} \propto T^{5/2}$)

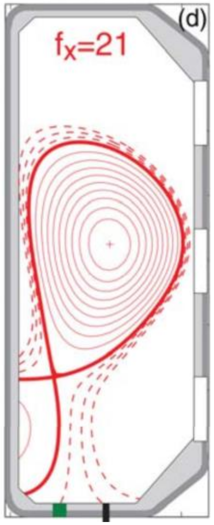
Note: region of low B_p might lead to additional perpendicular transport

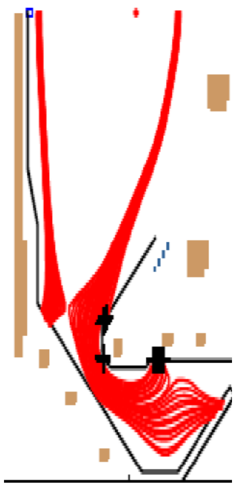
Different alternative geometries: overview

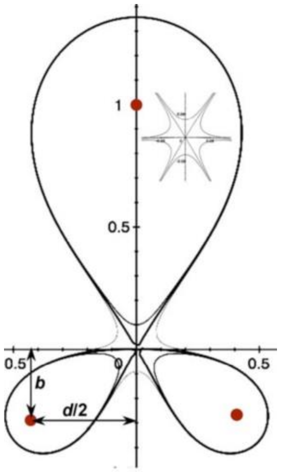
Different solutions combine different physics elements

Note: there are more than these (tripod, X-pt divertor, Small Angle Slot..)



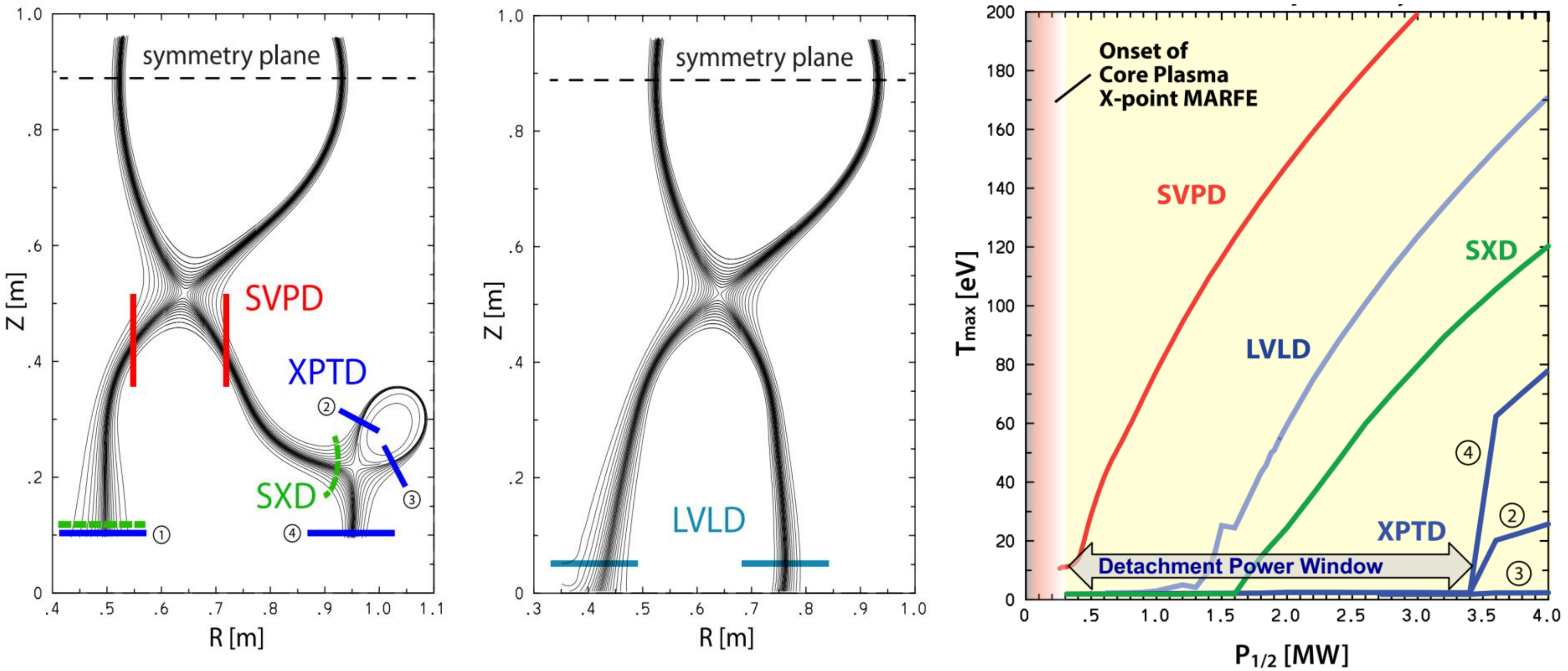






	Double Null	X-Divertor	Super-X	Snowflake
L_C / volume	/	√	√	√
N_{DIV}	√	/	/	√
poloidal flux expansion	/	√	√	/
total flux expansion	/	/	√	/
additional perp.transport	/	/	/	√

On paper, it works great!



Fluid code modelling of detachment onset

Umansky et al., Phys. Plasmas 2017

- long connection length eases detachment as expected
- stable large radiating volume in front of the target has largest window
- note: pumping / impurity compression should be addressed as well

The promise is large, let us see what experiments say

- Introduction: from ITER to DEMO and FPPs
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- Alternative Divertor Geometries: Experimental Results
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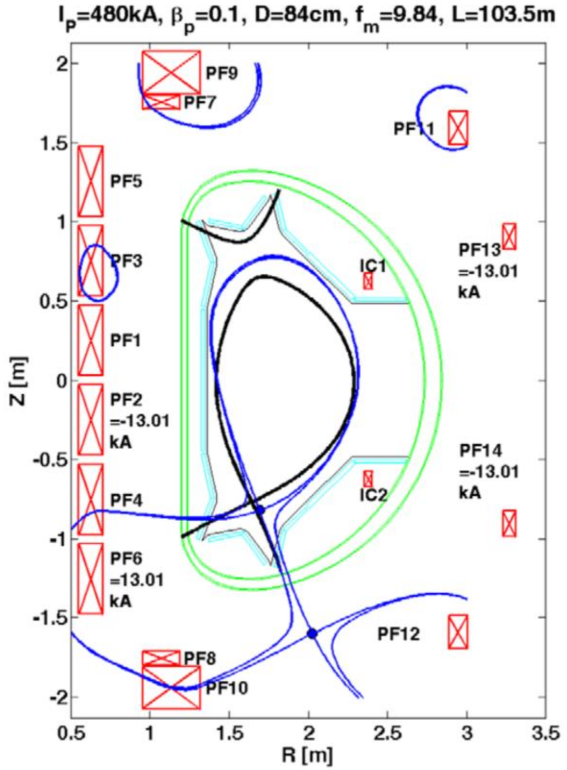
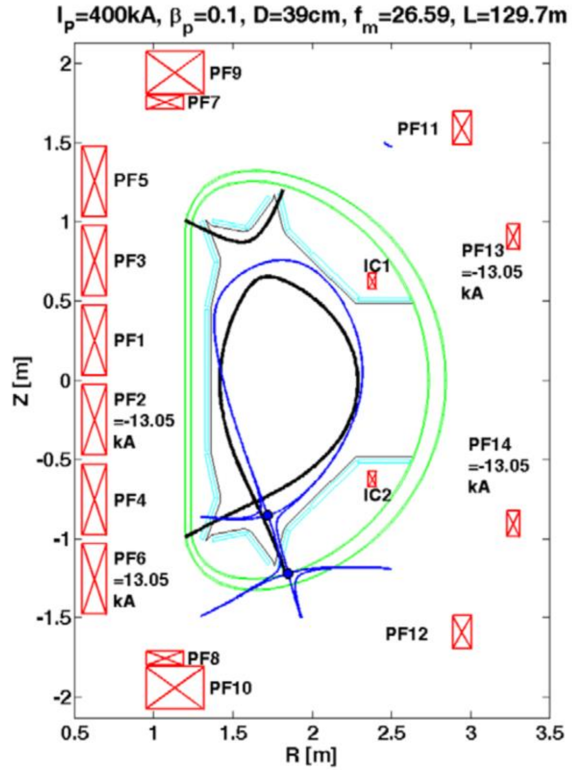
A word of caution…





‚Quasi-snowflake'
on EAST (Cn)

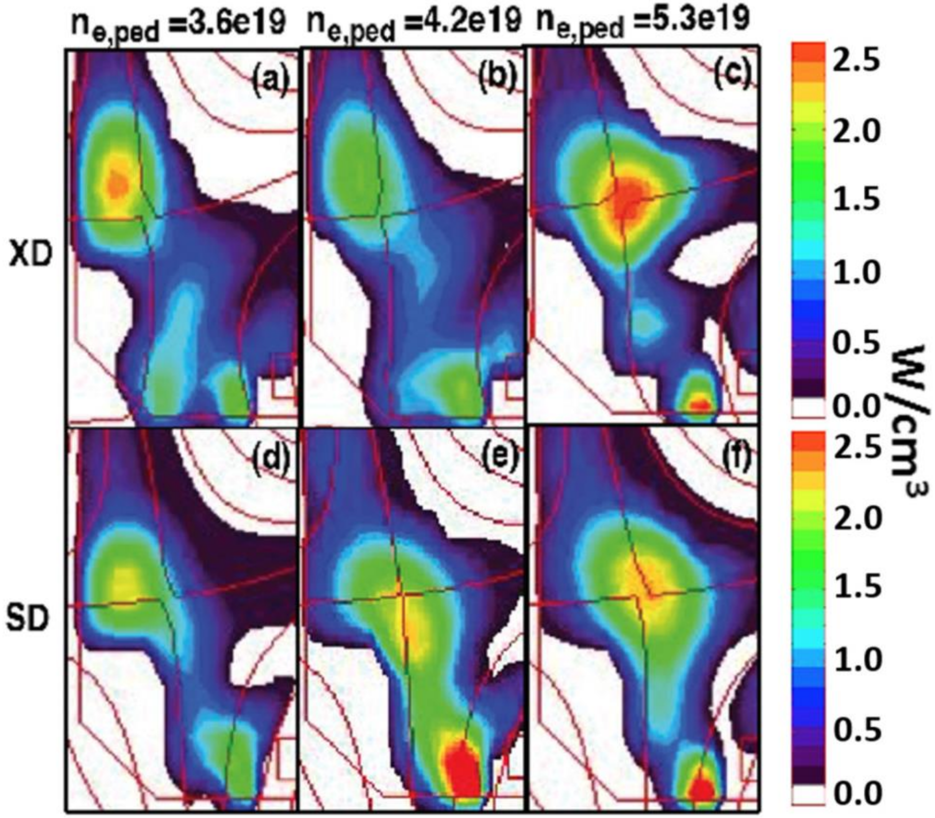
G. Calabro et al., Nucl. Fusion 2015

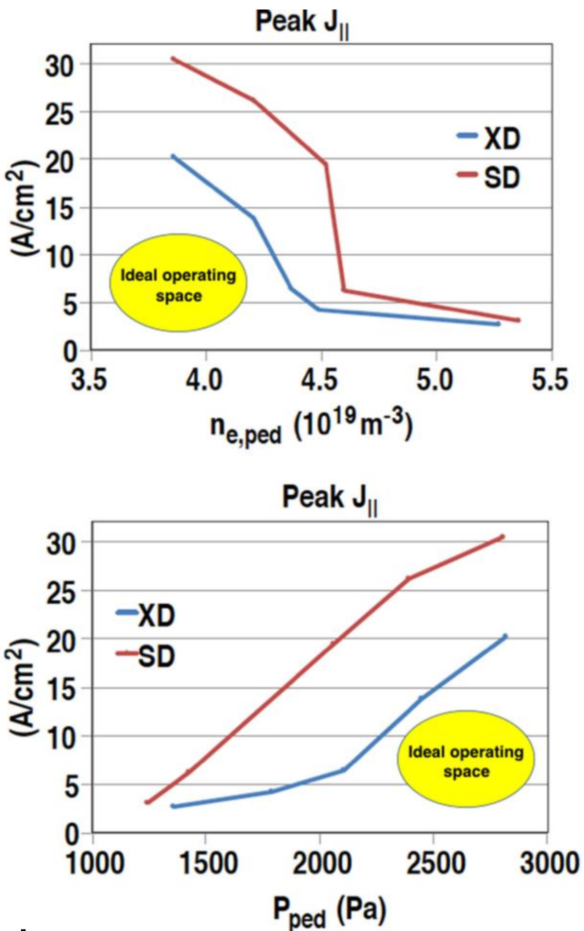
The field is very active, but experimental work has 'just started'

- machines are usually not designed for optimum geometry
- configurations in present machines are often a 'mix'
- important to clearly separate and validate the individual effects in future

Note: all experiments so far conducted at relatively low power

Does long connection length ease detachment?



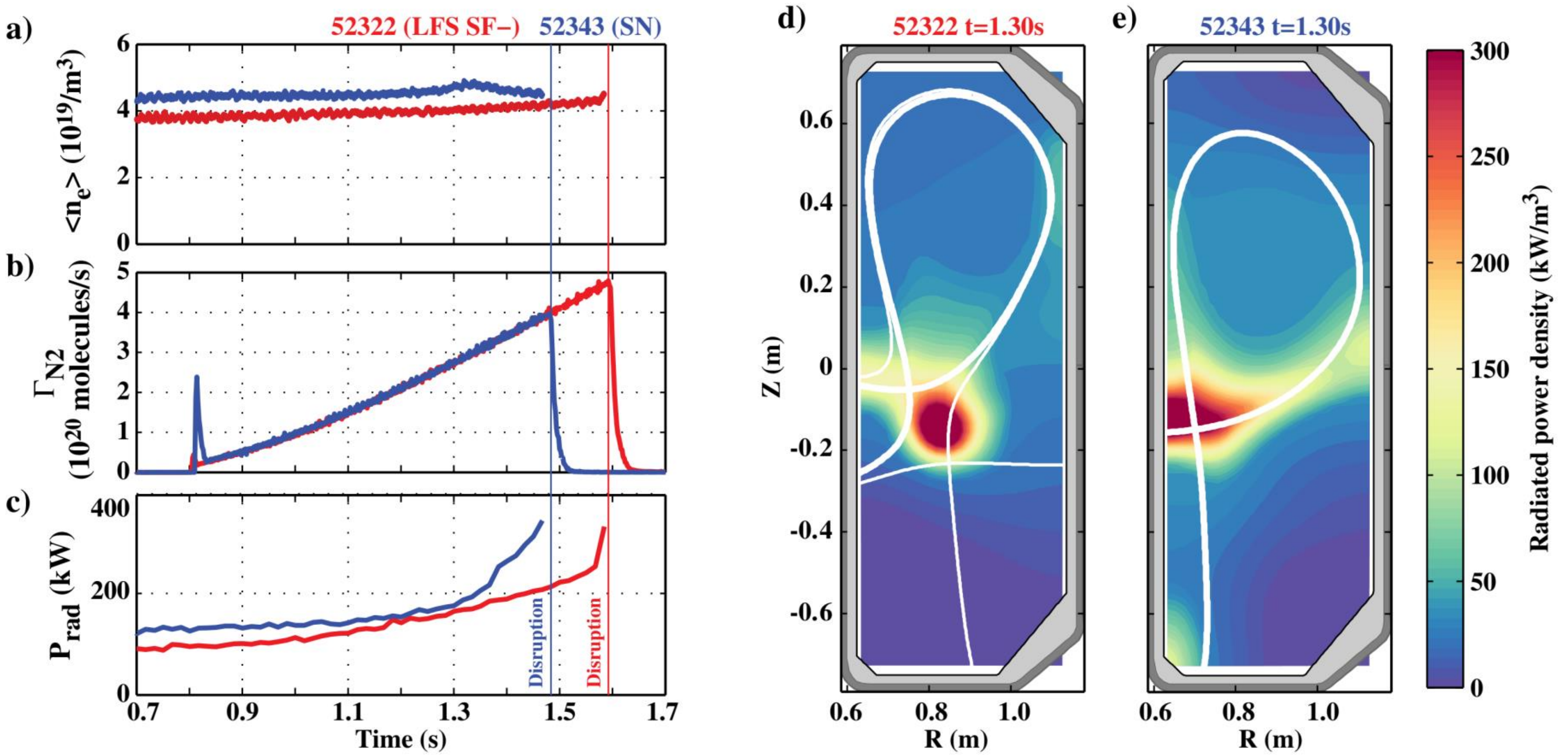


In DIII-D X-divertor, detachment at lower density

- due to coupling between V_{div} and L_c, hard to disentangle effects
- note that reduction in pedestal pressure also less severe with XD

B. Covele et al., Nucl. Fusion 2017

Does flux expansion stabilise radiative zone?

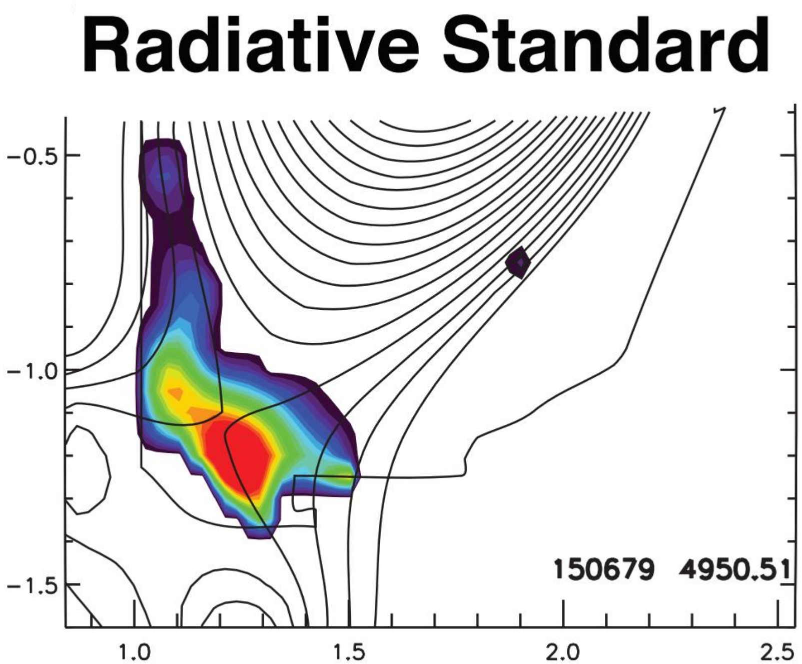


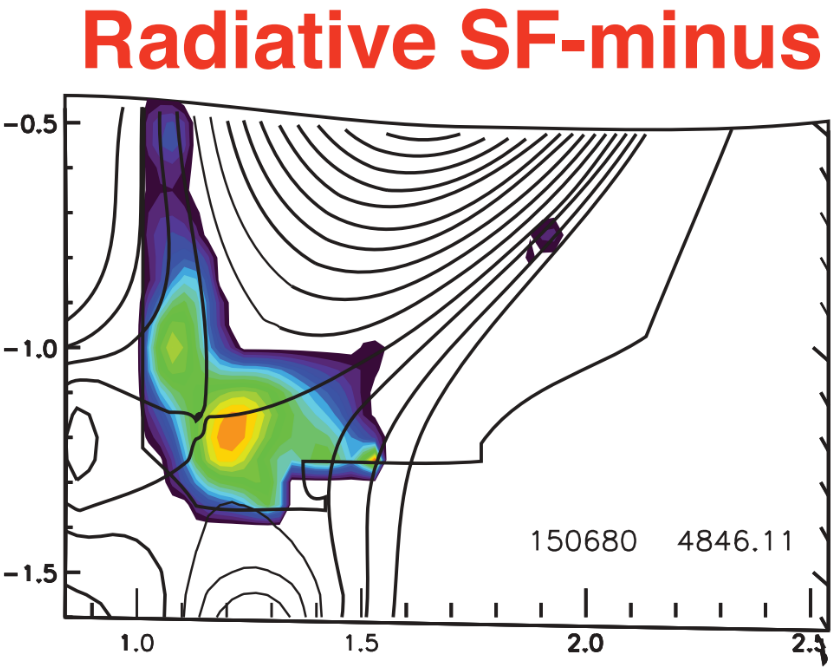
In N-seeded (ohmic) TCV discharges, radiative zone 'trapped' in SF$^-$

- ultimately, both configurations disrupt at same total radiated power when radiation extends into confined plasma region

H. Reimerdes et al., Nucl. Fusion 2017

Does flux expansion stabilise radiative zone?

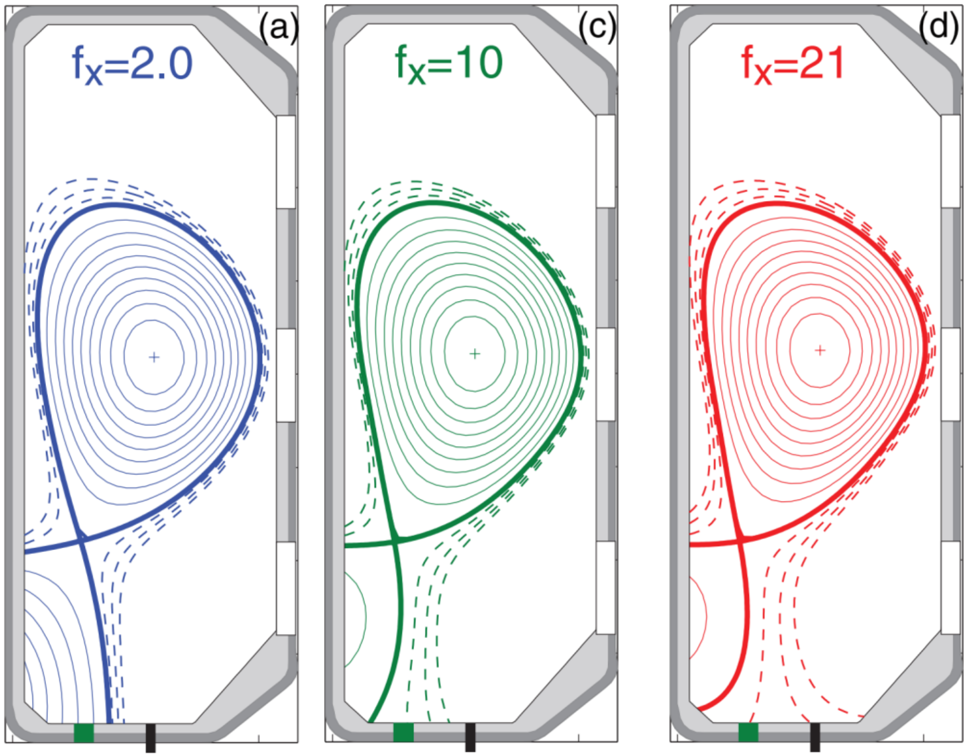


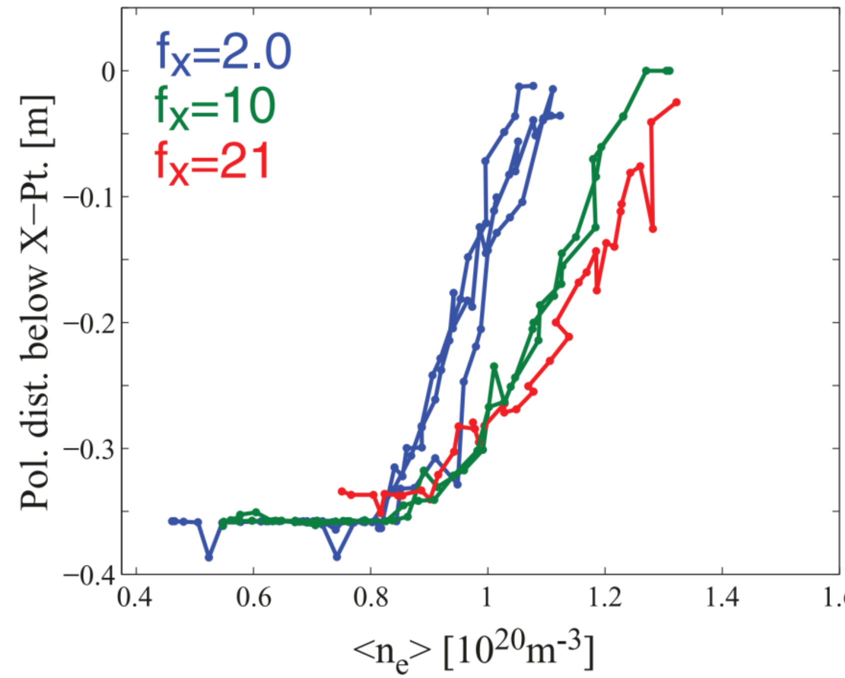


Somewhat similar findings in H-modes in DIII-D SF^{-}

V. Soukhanovski et al., IAEA FEC 2014

Does flux flaring stabilise radiative zone?





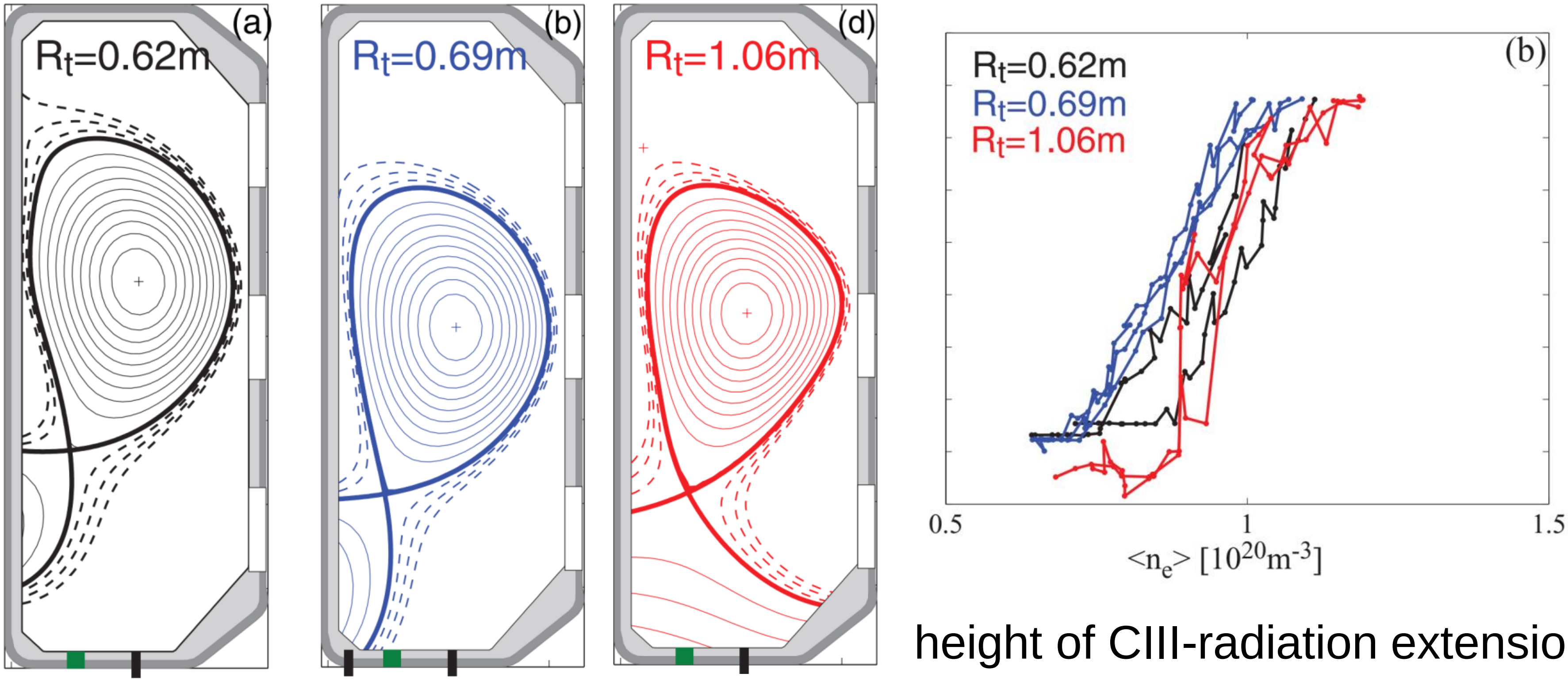
height of CIII-radiation extension

For the X-divertor in TCV, the transition of the detachment front from the target to the main X-point is delayed (= occurs at higher density)

- delay mostly in the zone where the flux surfaces expand
- indicative of a stabilising effect

C. Theiler et al., Nucl. Fusion 2017

Does flux flaring stabilise radiative zone?



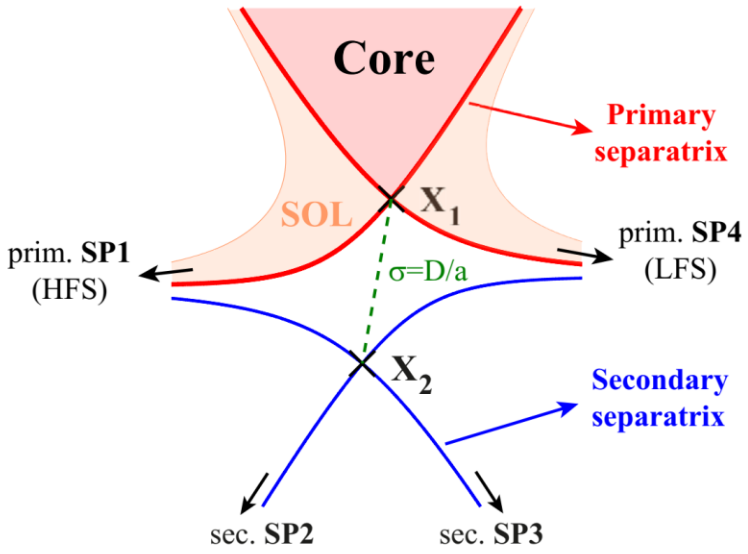
height of CIII-radiation extension

Surprisingly, moving the strike point outward (= increasing total flux expansion) does not show this effect

- while heat flux and temperature decrease as expected, density does not increase – further investigation needed

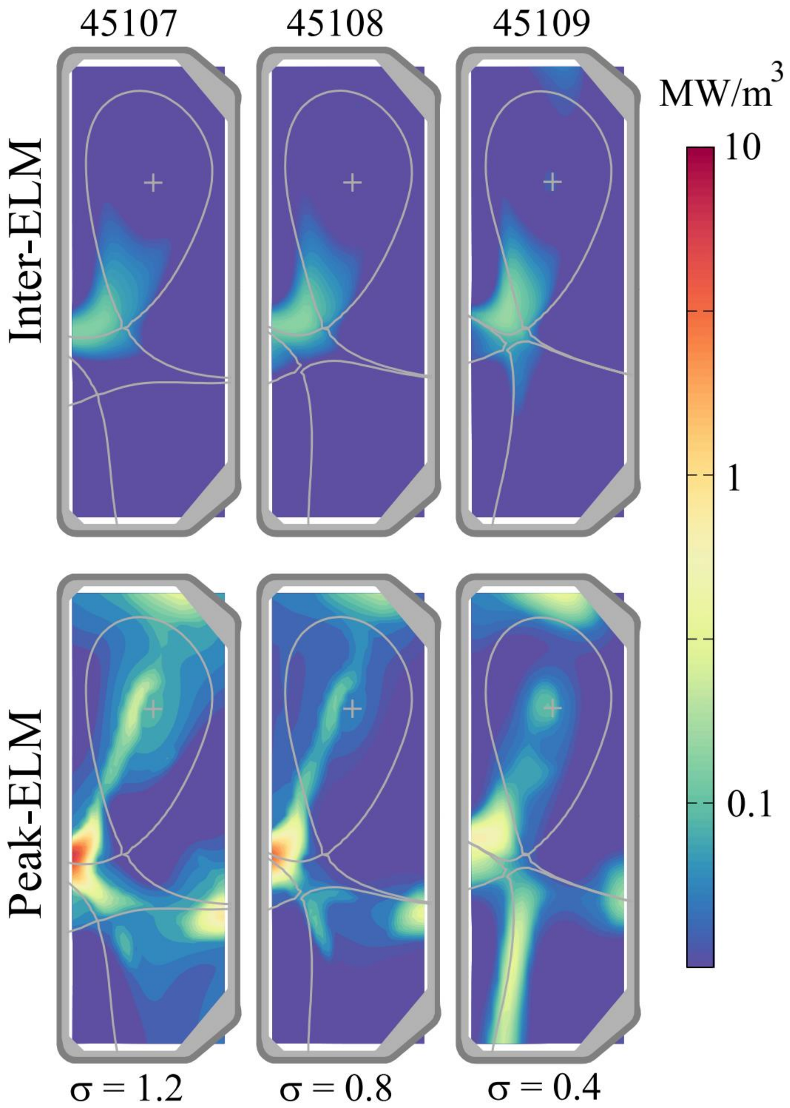
C. Theiler et al., Nucl. Fusion 2017

Can additional divertors be activated?



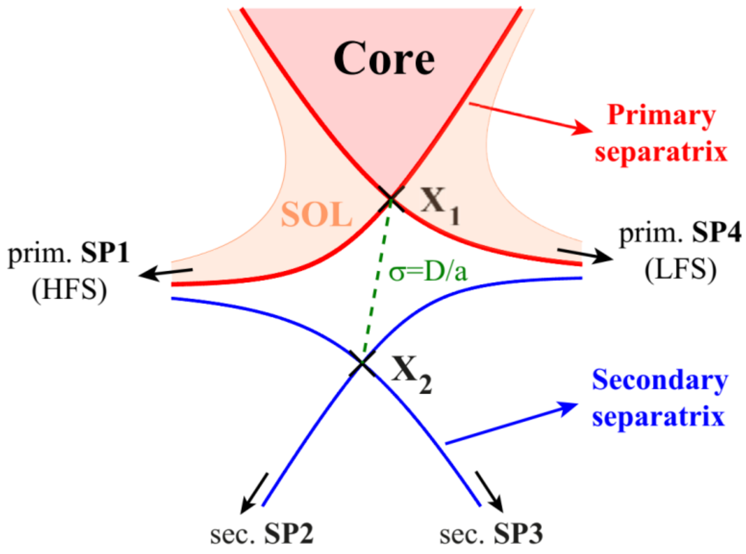
Scan of σ=D/a in TCV H-mode

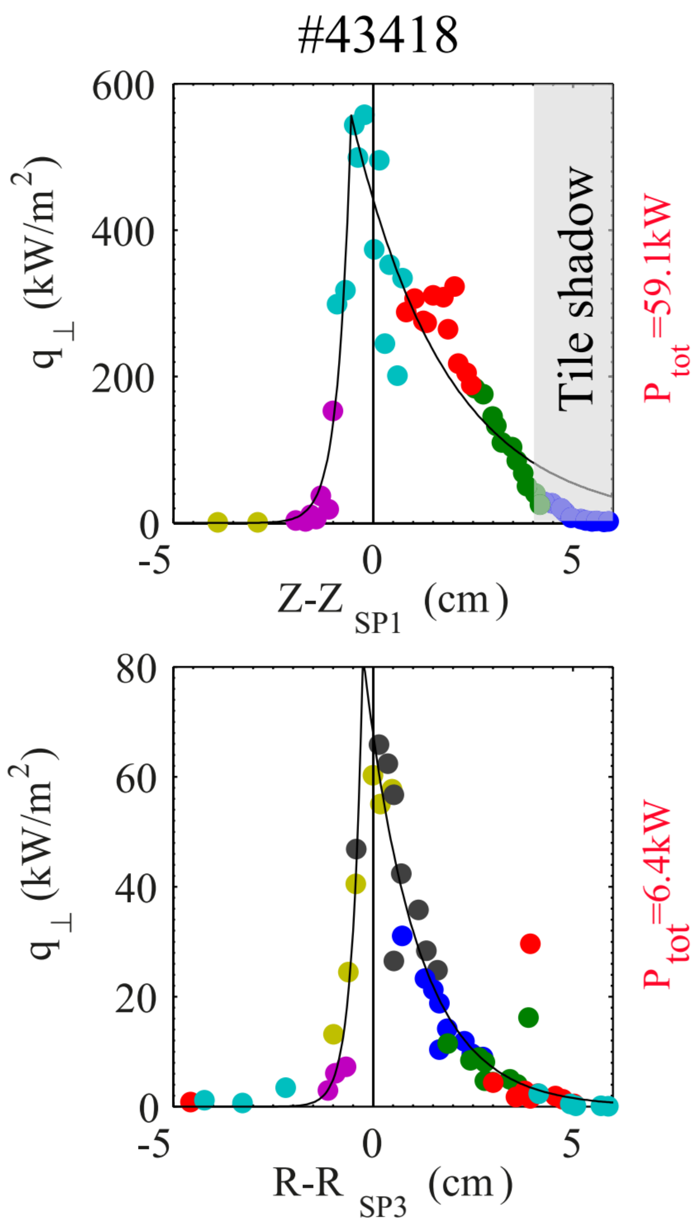
- σ=0.4-0.5 corresponds to λ_q
- additional strike points activated around this value
- more pronounced for ELMs (larger λ_q)



W. Vijvers et al., Nucl. Fusion 2014

Can additional divertors be activated?



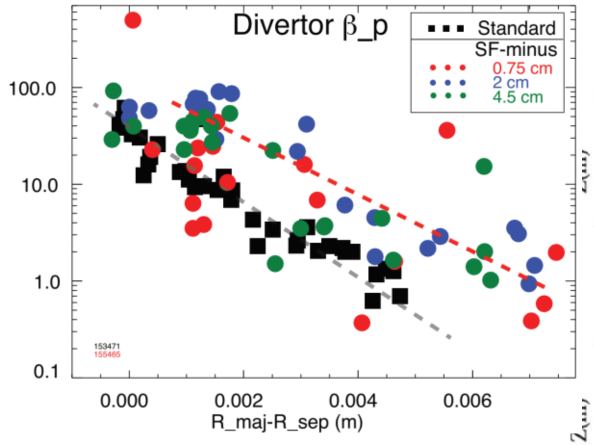


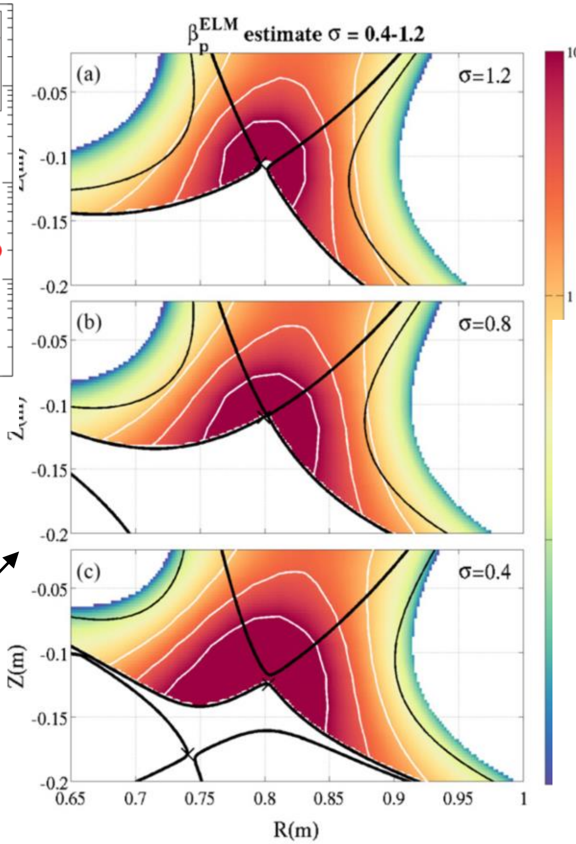
Note however that power load at secondary strike points is much lower than on primary even at σ=0.15 without ELMs (L-mode)

W. Vijvers et al., Nucl. Fusion 2014

Is perpendicular transport enhanced at low B_p?

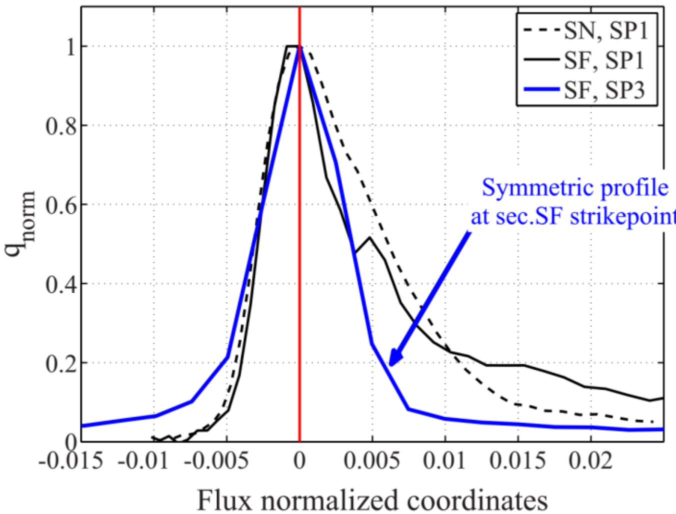
DIII-D: Soukhanovski et al., IAEA FEC 2014
TCV: W. Vijvers et al., Nucl. Fusion 2014





local β_p values

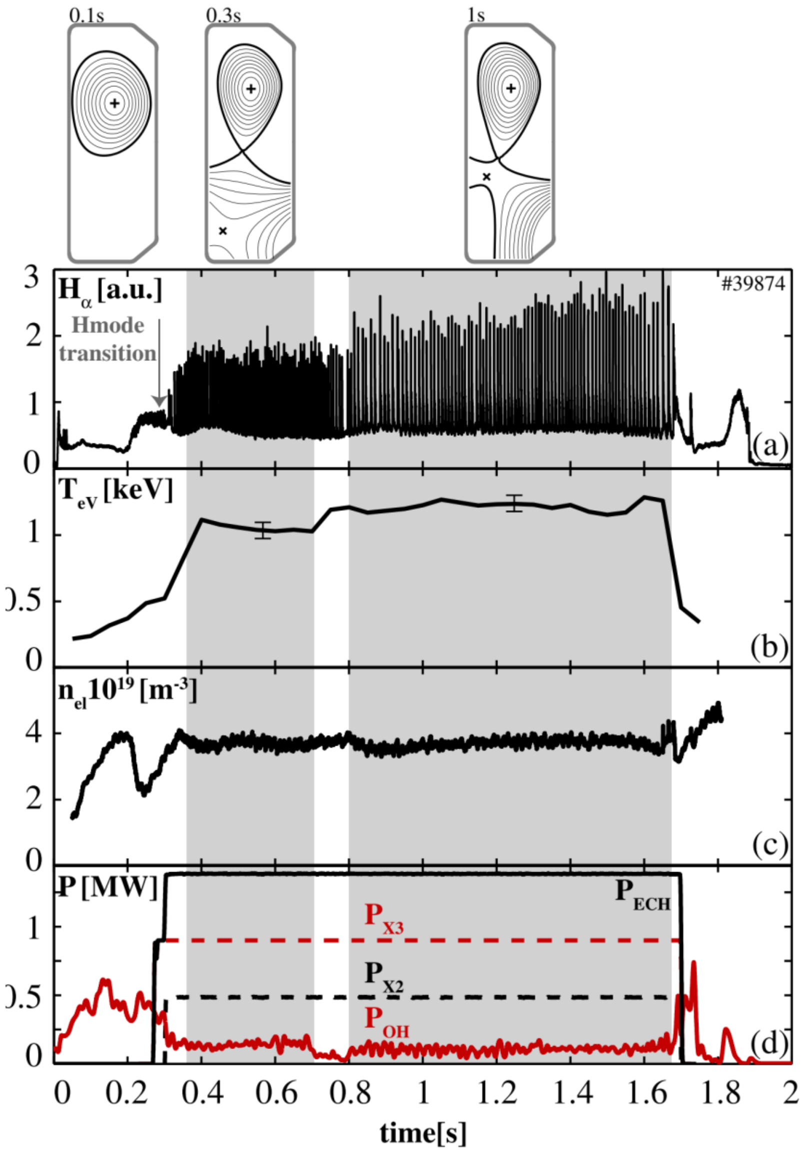
heat flux profiles

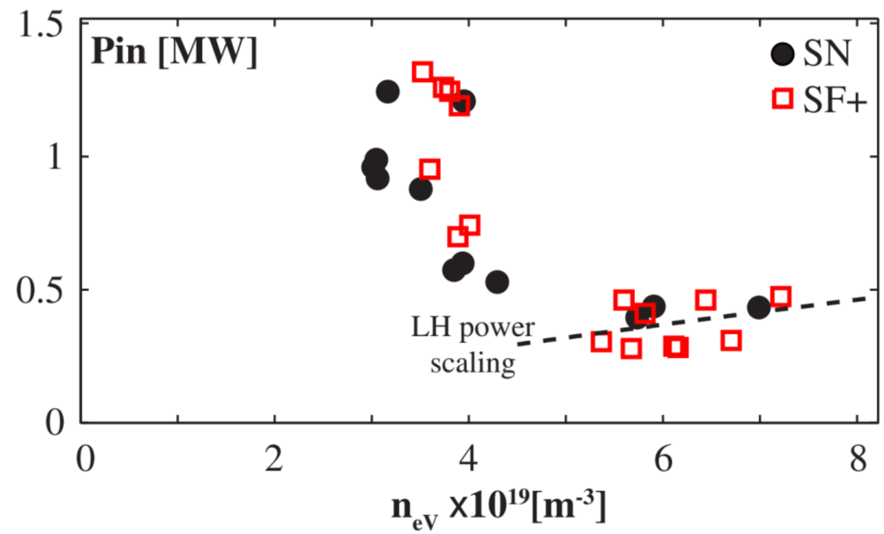


Both DIII-D and TCV diagnose extended zone of high β_p in SF

- values should be of the order needed to activate additional transport
- experimental evidence is however indirect (e.g. shape of power load)

Is the plasma core affected?





Shape change can change edge stability

- here: L-H threshold not affected
- ELMs become larger, consistent with linear stability
- will have to be taken into account in future designs

F. Piras et al., Phys. Rev. Lett 2010

What should future experiments show?

Due to the coupling of the different effects, it will be important to validate them separately as far as possible

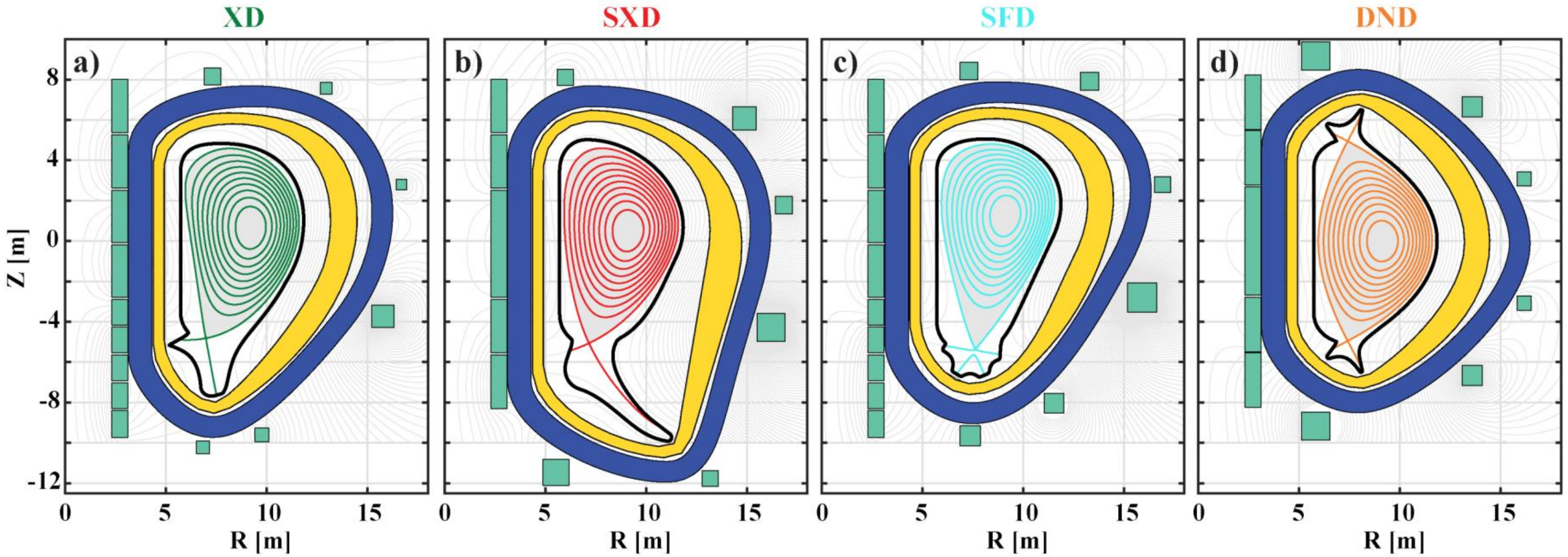
- design carefully not to compare ‘apples and oranges’
- validate physics effects, not particular configurations, in order to obtain predictive capability (extrapolation step is large, and no ‘ITER step inbetween’)
- put more emphasis on particle exhaust (at present, focus is on power exhaust)
- characterise better interaction with core plasma (e.g. impact on H-mode pedestal) – integrated solution needed

Present experiments are at relatively low power

- need to push to power levels comparable of present conventional divertor experiments (e.g. in P_{sep}/R)

Upgrades and new experiments are under way to adequately address these points (e.g. MAST Upgrade or Italian DTT)

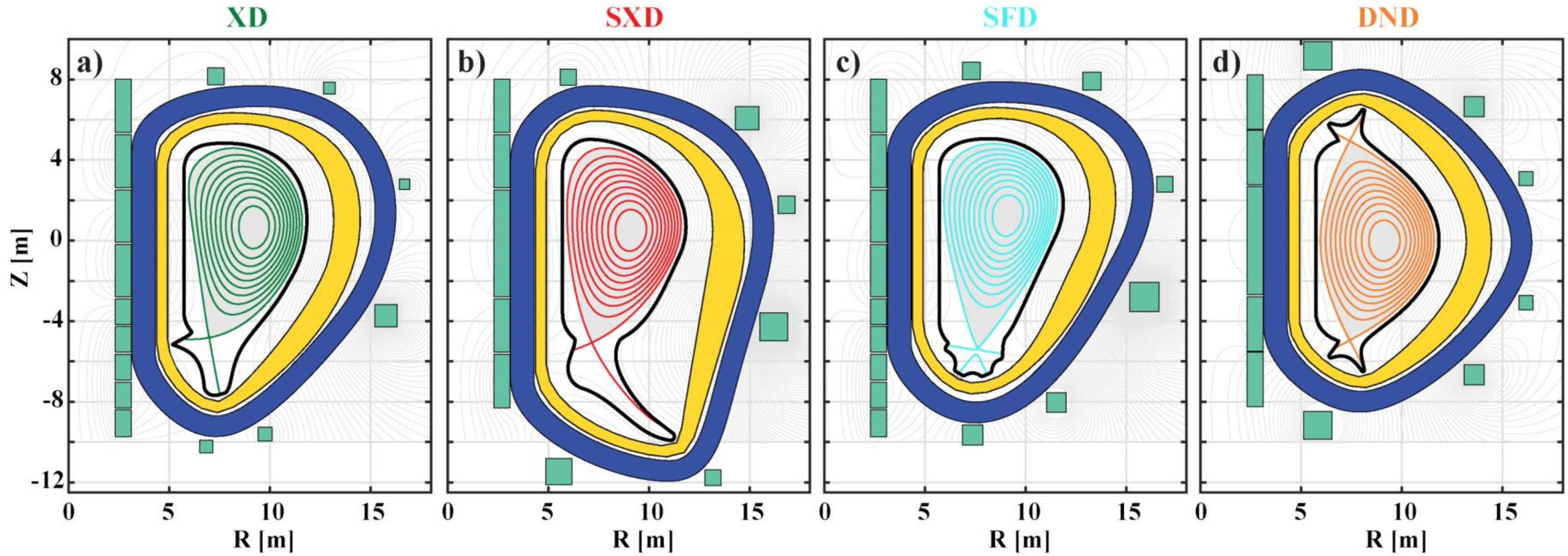
Challenges for alternative divertors



Present focus is on physics, but impact on technology will have to be addressed as well

- impact on coil system (forces, TF volume, internal coils…)
- control of strike points generally more challenging

Challenges for alternative divertors



		SND	XD	SXD	SFD(+)	DND
Cost	$V_{\mathrm{TF}}/V_{\mathrm{plasma}}$	3.50	3.61	4.42	3.57	3.60
	$\sum R_{\mathrm{PF}} I_{\mathrm{PF}}^{\mathrm{max}}$ [m·MA·turns]	690	665	1016	970	744
	Flux swing [Vs]	240	185	200	180	220

H. Reimerdes et al., 27th IAEA Fusion Energy Conference (2018), TH/P7-18

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Summary and Conclusions

DEMO/FPP exhaust problem more challenging than ITER – need additional elements

- higher core radiation fraction
- alternative divertor geometries
- alternative materials (c.f. D. Andruczyk)

Ultimate solution likely to contain a combination of these elements

Research in these areas has begun

- too early to single out the optimum solution
- need to understand the different physics elements in view of the large extrapolation and the absence of the ‘ITER-step’ in this area

This is an exciting area for future research (i.e. for *you*)