
ADX

A concept for a high-power density, advanced divertor tokamak test experiment

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for the ADX development team

MIT Plasma Science and Fusion Center

Presentation at PPPL, May 12, 2014

Alternative solutions for the divertor are necessary.



EFDA

Fusion Electricity

A roadmap to the realisation of fusion energy

A solution for the heat exhaust in the fusion power plant is needed.

A reliable solution to the problem of heat exhaust is probably the main challenge towards the realisation of magnetic confinement fusion. The risk exists that the baseline strategy pursued in ITER cannot be extrapolated to a fusion power plant. Hence, in parallel to the programme in support of the baseline strategy, an aggressive programme on alternative solutions for the divertor is necessary. Some concepts are already being tested at proof-of-principle level and their technical feasibility in a fusion power plant is being assessed. Since the extrapolation from proof-of-principle devices to ITER/DEMO based on modelling alone is considered too large, a dedicated test on specifically upgraded existing facilities or on a dedicated Divertor Tokamak Test (DTT) facility will be necessary.

http://fire.pppl.gov/EU_Fusion_Roadmap_2013.pdf

Alternative solutions for the divertor are necessary.



A solution for the heat exhaust in the fusion power plant is needed.

We must recognize the possibility that a design window for an electricity producing fusion reactor may not exist based on power and PMI considerations alone.

We are therefore obligated to identify and test, ASAP, solutions that demonstrate a plausible pathway forward.

Plasma confinement facilities: ITER – \$5B (US)

Advanced divertor R&D facility: \$100M

Test (DTT) facility will be necessary.

http://fire.pppl.gov/EU_Fusion_Roadmap_2013.pdf

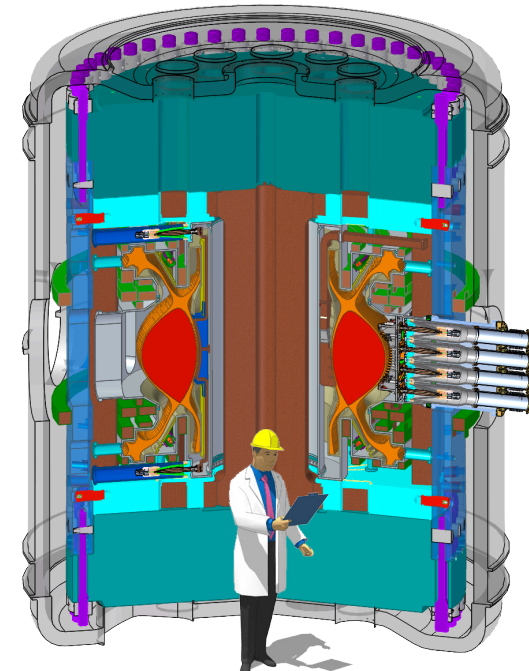
Background



- The MIT Plasma Science and Fusion Center and collaborators are considering a concept for an ADX – a tokamak facility specifically designed to address critical gaps in the world research program on the pathway to DEMO.

Idea

- Build a flexible, advanced divertor R&D facility to develop solutions for divertor and RF challenges that scale to steady-state reactor operation (FNSF/DEMO); produce divertor conditions that are nearly identical to reactors with a high-performance core plasma
- Build a national facility, with input, advice and direct participation from experts in the plasma fusion community – *i.e., input from you*



Advanced Divertor Experiment

Background



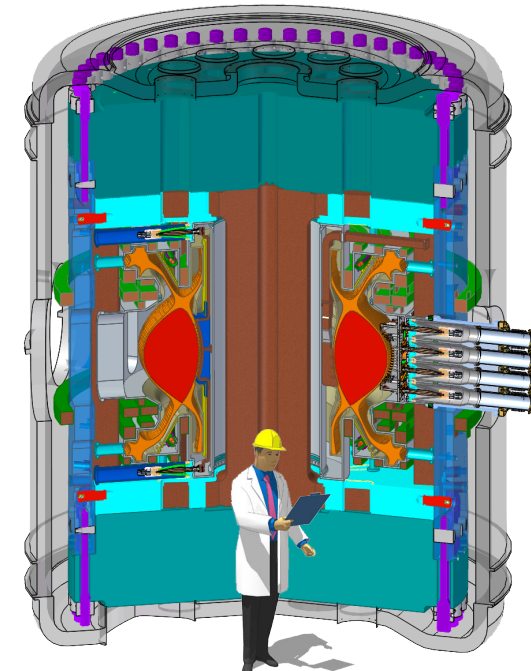
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ADX development team

E. Marmor, J. Irby, R. Vieira, D.G. Whyte, J. Terry, G. Wallace, S. Wolfe, S. Wukitch, W. Beck, P. Bonoli, J. Doody, R. Ellis, D. Ernst, C. Fiore, R. Granetz, M. Greenwald, Z.S. Hartwig, A. Hubbard, J.W. Hughes, I.H. Hutchinson, C. Kessel, M. Kotschenreuther, R. Leccacovi, Y. Lin, B. Lipschultz, S. Mahajan, J. Minervini, R. Nygren, R. Parker, F. Poli, M. Porkolab, M.L. Reinke, J. Rice, T. Rognlien, W. Rowan, S. Shiraiwa, D. Terry, C. Theiler, P. Titus, M. Umansky, P. Valanju, A. White, J.R. Wilson, S.J. Zweben, ...

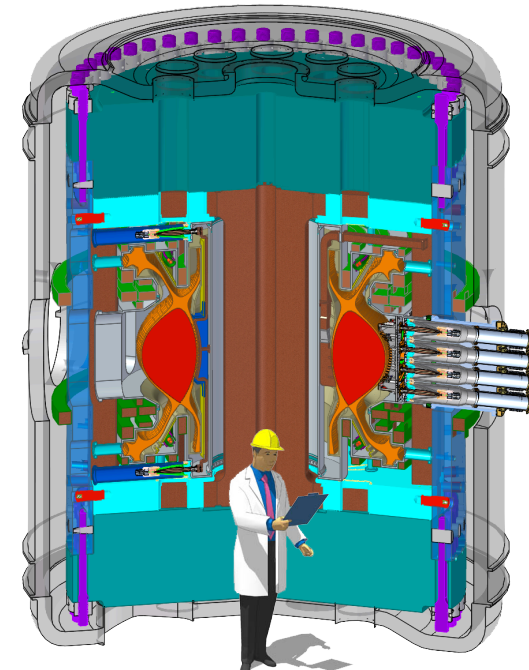


Advanced Divertor Experiment

Outline



- **Motivation & Mission for ADX**
- **Power & particle exhaust challenges**
 - ITER
 - DEMO
- **Potential solutions – advanced magnetic divertors, ...**
- **Potential solutions – double-null + high-field side launch RF**
- **Requirements for a divertor test tokamak**
- **ADX concept – version 1.0**

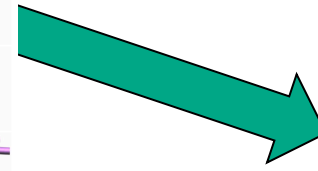
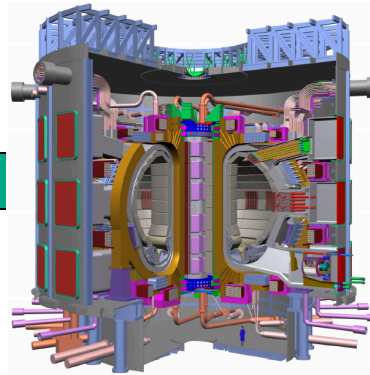


Advanced Divertor Experiment

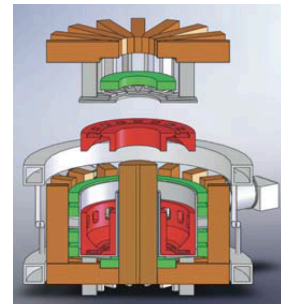
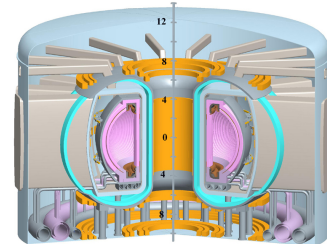
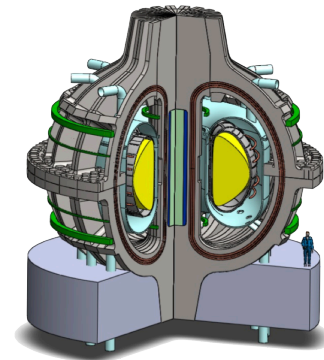
Motivation: Five milestones must be attained to demonstrate readiness for FNSF/DEMO.

ITER

Research performed in parallel with ITER



FNSF/
DEMO

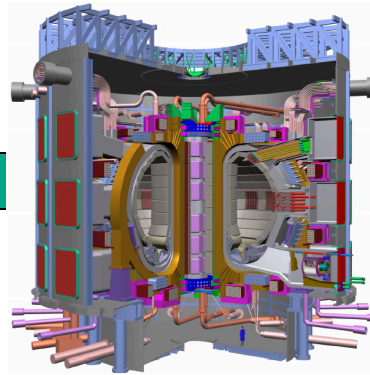


1. Demonstrate robust divertor power handling solutions *at DEMO divertor plasma parameters*
2. Demonstrate suppression of divertor erosion *at DEMO parameters*, sufficient for SS ($\sim 5 \times 10^7$ s)
3. Achieve 1 and 2 with core plasma performance *compatible with burning plasma*
4. Demonstrate low PMI, efficient, RF current drive and heating technologies that scale to SS
5. Determine *high-temperature* PMI response of candidate divertor target materials (tungsten and liquid metals) *at DEMO divertor parameters in a high performance tokamak*

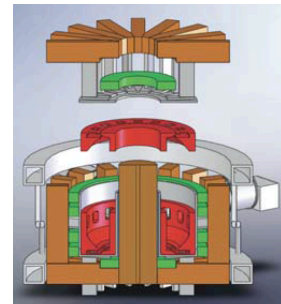
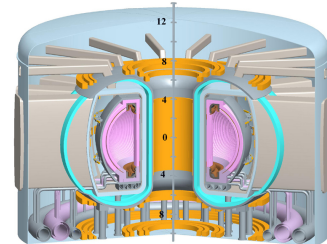
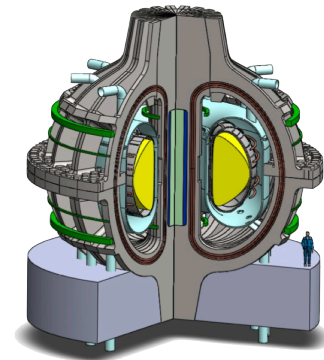
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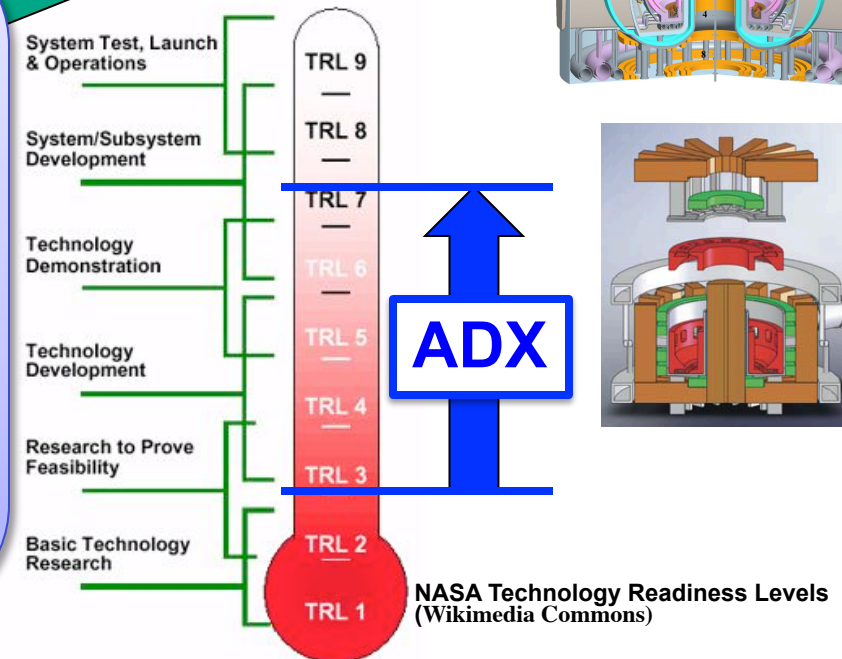
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FNSF/DEMO



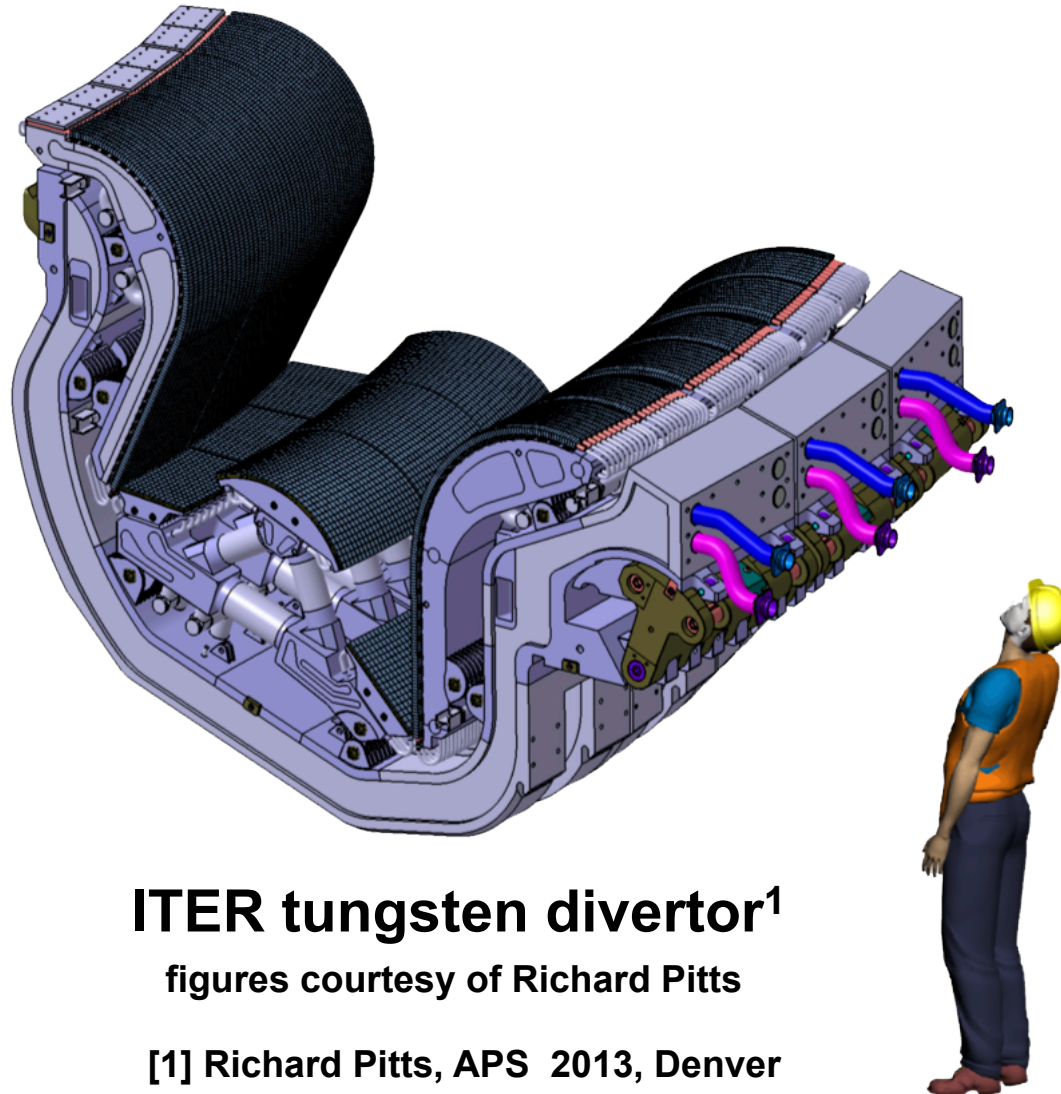
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- ★ 5. Determine *high-temperature* PMI response of candidate divertor target materials (tungsten and liquid metals) *at DEMO divertor parameters in a high performance tokamak*



★ **ADX** mission is aimed at achieving these milestones...

What is required?

Research in support of ITER is revealing the magnitude of the power exhaust challenge ...



ITER tungsten divertor¹

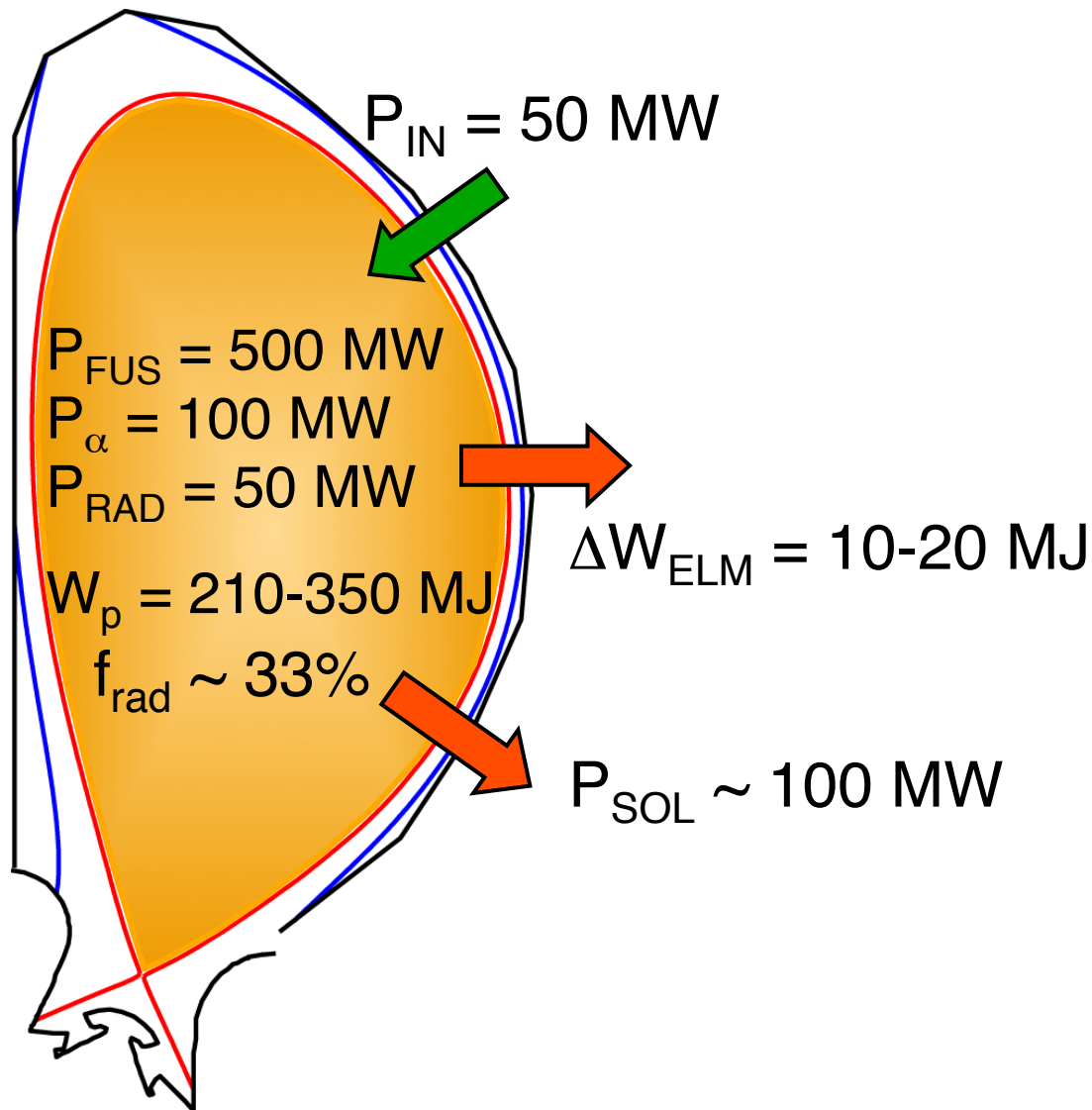
figures courtesy of Richard Pitts

[1] Richard Pitts, APS 2013, Denver

Power exhaust challenges for ITER

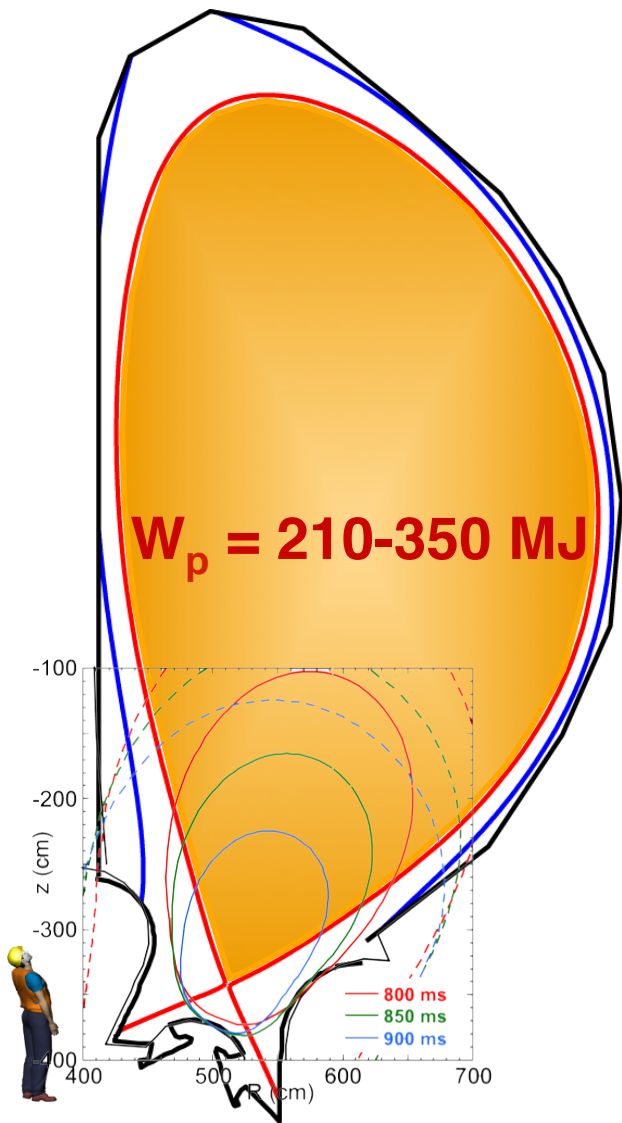
ITER $Q_{DT} = 10$; $t \sim 400$ s
Type I ELMing H-mode

- Disruptions
- ELMs
- Power exhaust



ITER (and DEMO) disruptions –must be avoided/mitigated!

ITER $Q_{DT} = 10$; $t \sim 400$ s
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- ~~Disruptions~~
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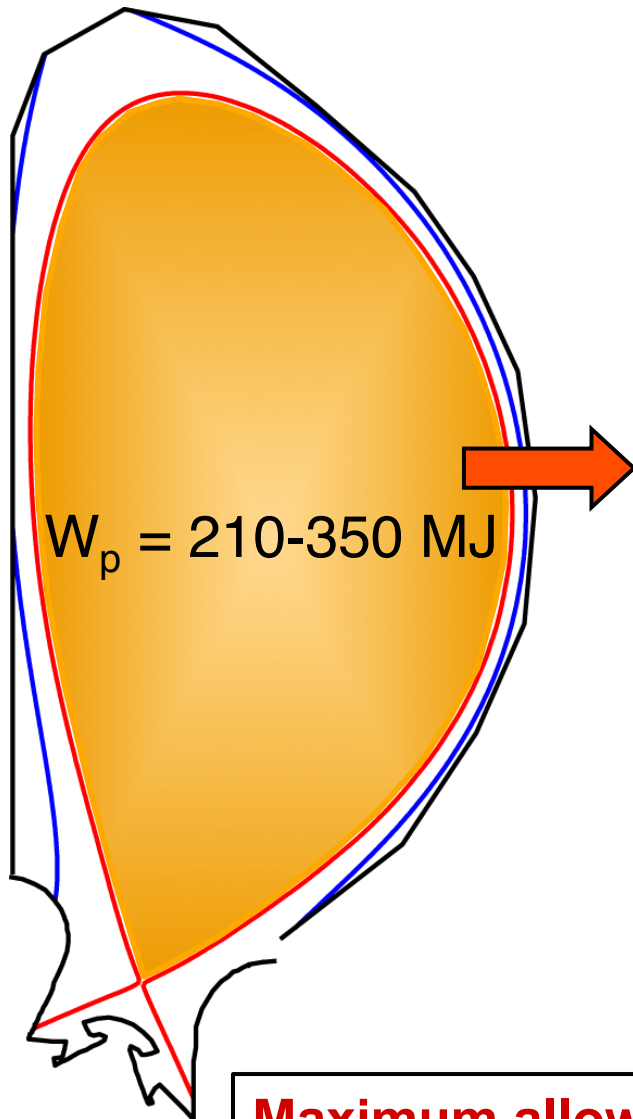
Potential solutions:

- Operate far from instability boundaries
- Disruption mitigation systems

ITER (and DEMO) ELMs –must be suppressed!

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- ~~Disruptions~~
- ~~ELMs~~
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$W_p = 210-350$ MJ

$\Delta W_{ELM} = 10-20$ MJ

Potential solutions:

- Operate far from instability boundaries
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Potential solutions:

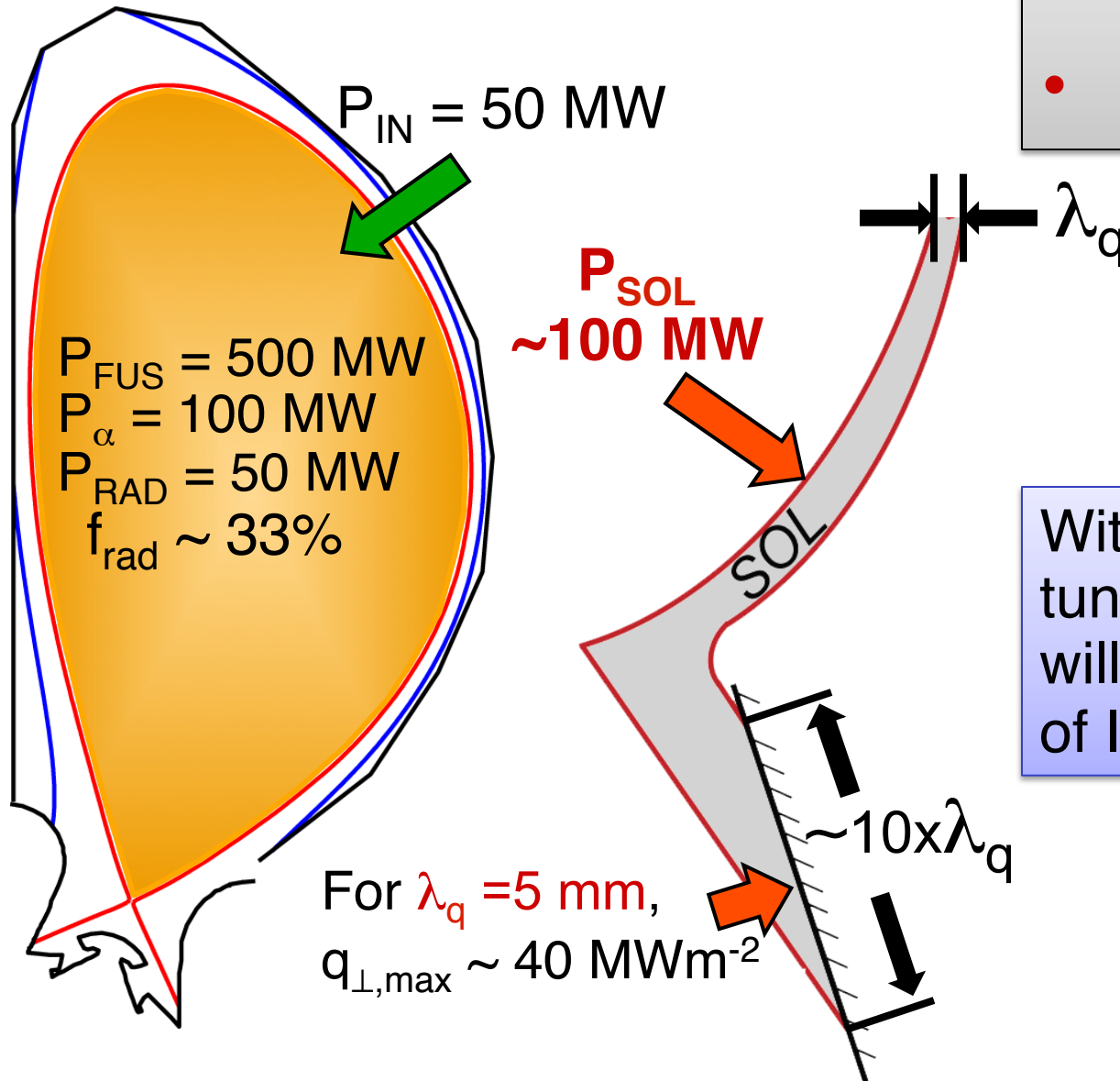
- ELM-free regimes (QH, I-mode, ...)
- RMP, pellet pacing, external excitation of edge modes/turbulence

Maximum allowed ELM size is $\Delta W_{ELM} \sim 0.7$ MJ, $1/20^{\text{th}}$ natural Type I

Power exhaust challenge

ITER $Q_{DT} = 10$; $t \sim 400$ s
Type I ELMy H-mode

- ~~Disruptions~~
- ~~ELMs~~
- **Power exhaust?**

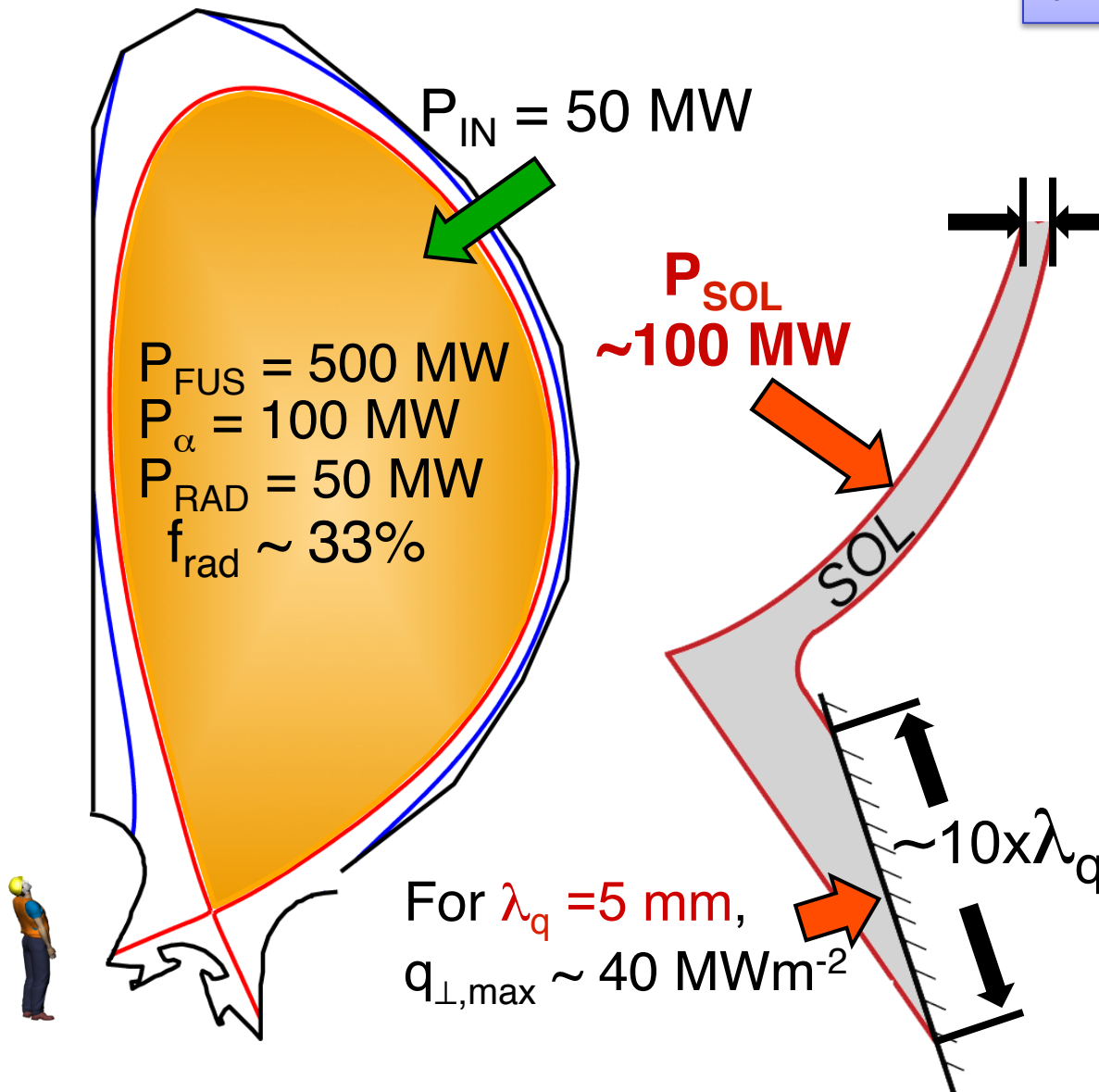


Without divertor dissipation, tungsten divertor surface will be damaged in only ~ 1 s of ITER operation.

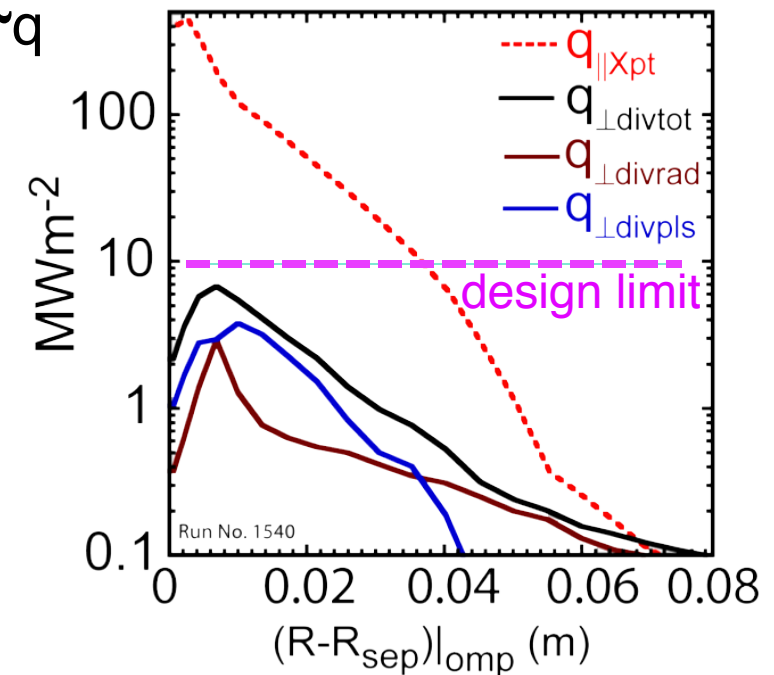
Power exhaust challenge

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ITER solution relies on partial
divertor detachment (circa ~1994)



B2-Eirene, A. Kukushkin, pre 2010



Require $f_{rad, div} \sim 0.7 \rightarrow$ **partial divertor detachment** to reduce $q_{\perp, max}$ to ~ 10 MWm⁻²

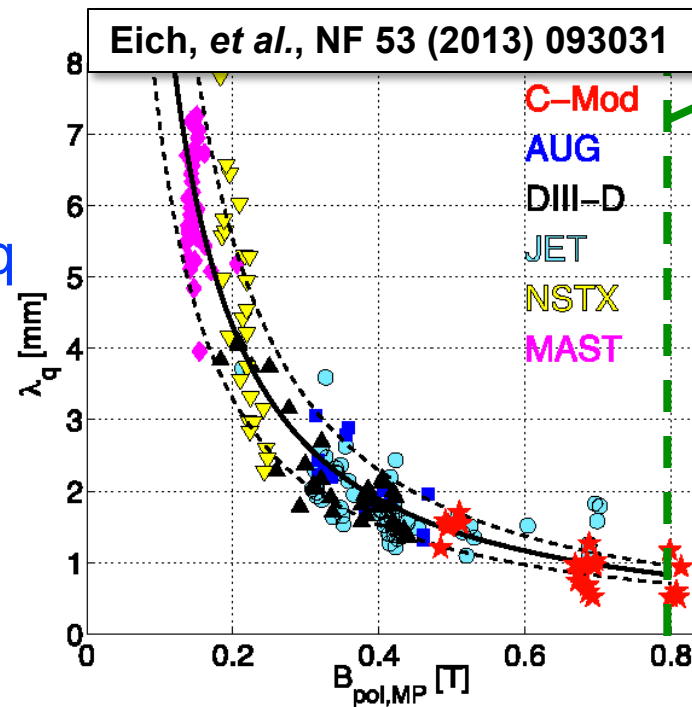
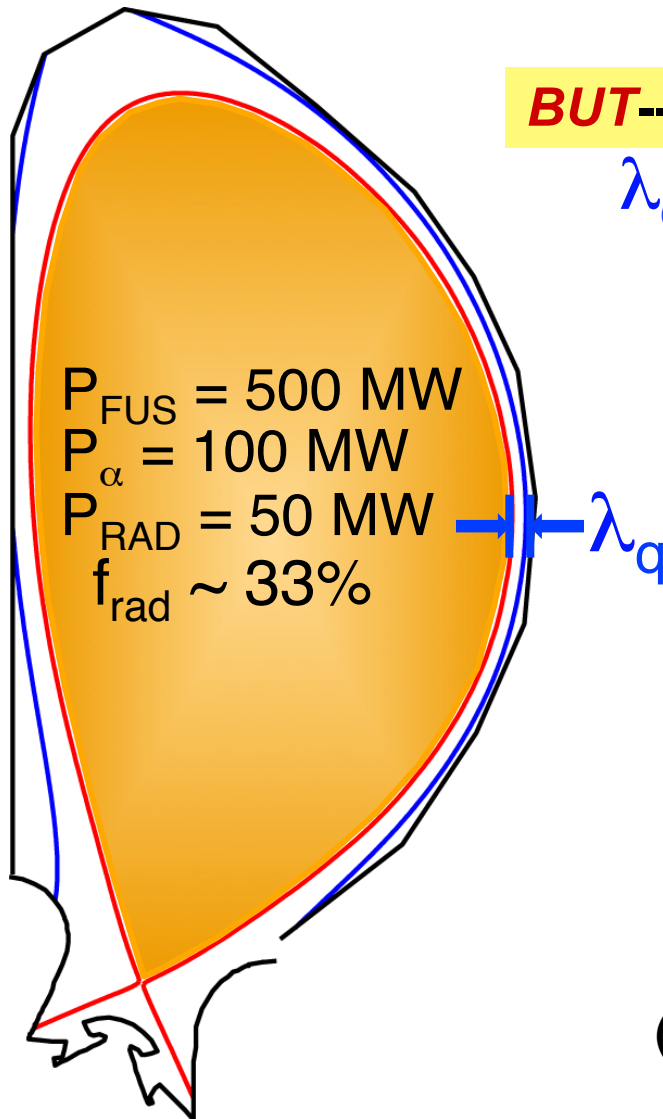
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BUT--New results from multi-machine database (2010+):

λ_q appears to be independent of machine size...
...depends only on B_{pol}



ITER $\lambda_q \sim 1$ mm?
1/5 of 'planned' value

(caveat: *low divertor recycling*, H-mode conditions)

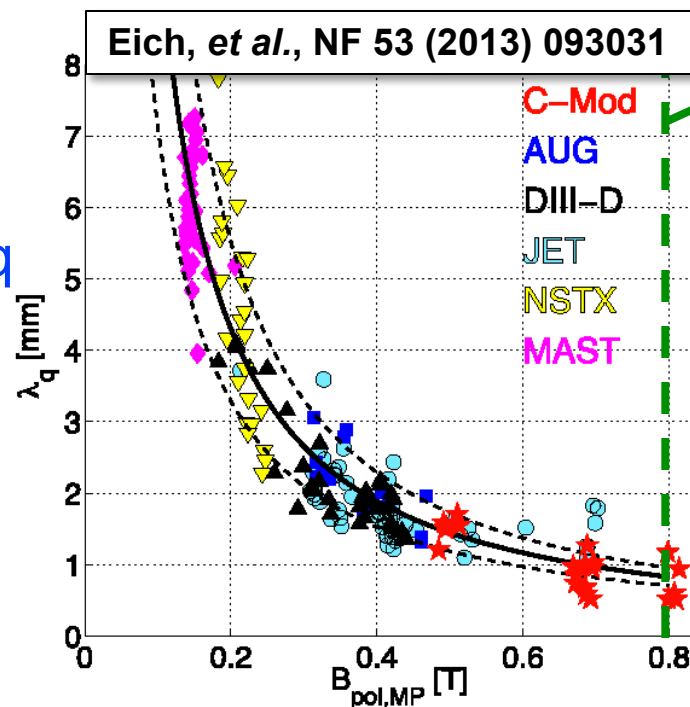
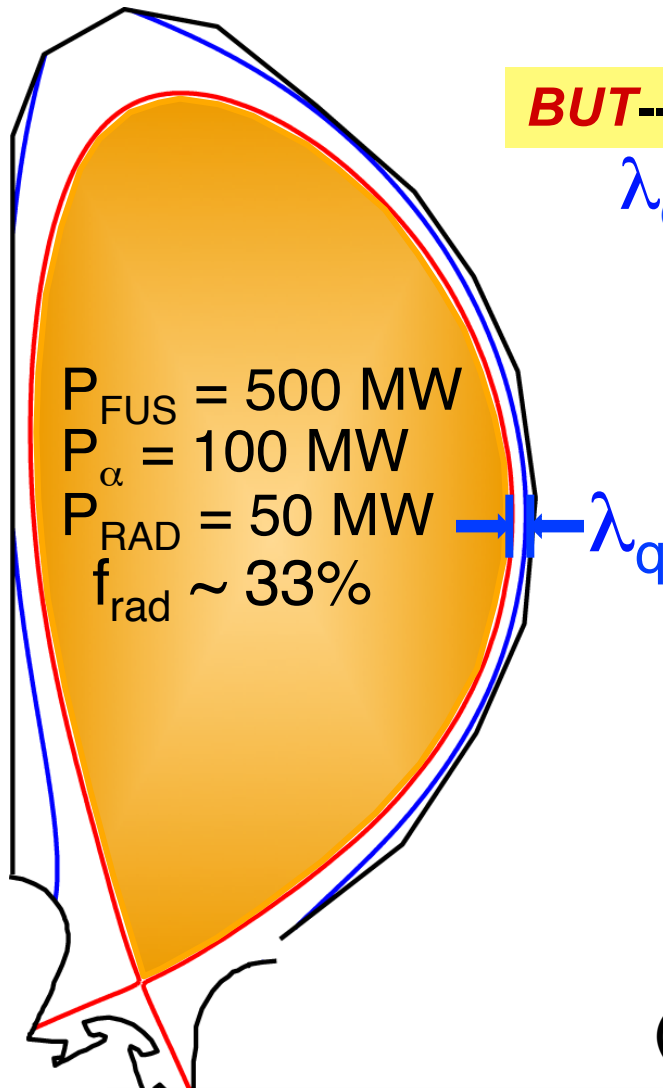
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$$q_{\theta} = P_{SOL} / \lambda_q 2\pi R$$

$$q_{||} = q_{\theta} B / B_{\theta}$$

$$\lambda_q \propto 1 / B_{\theta}$$

$$\Rightarrow q_{||} \propto P_{SOL} B / R$$

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New Result: $\sim P_{SOL} B / R$ is scale parameter for $q_{||}$ into divertor

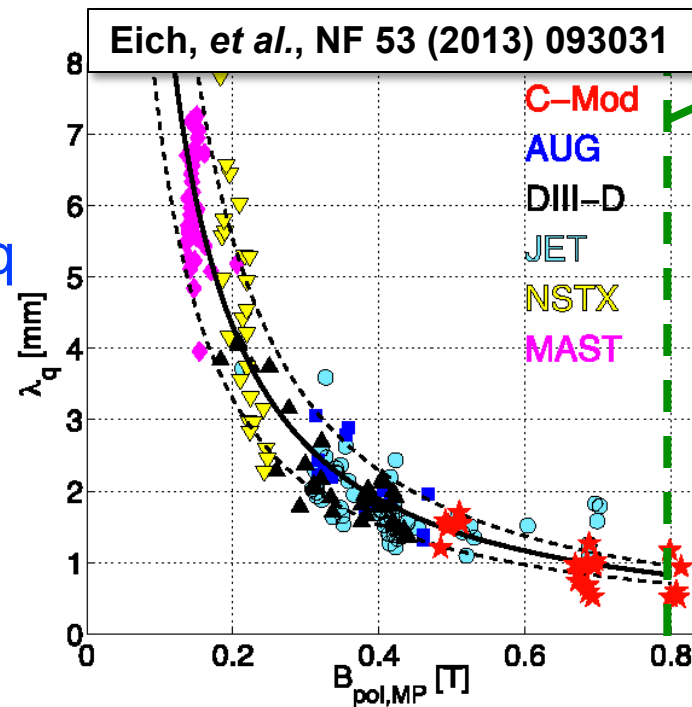
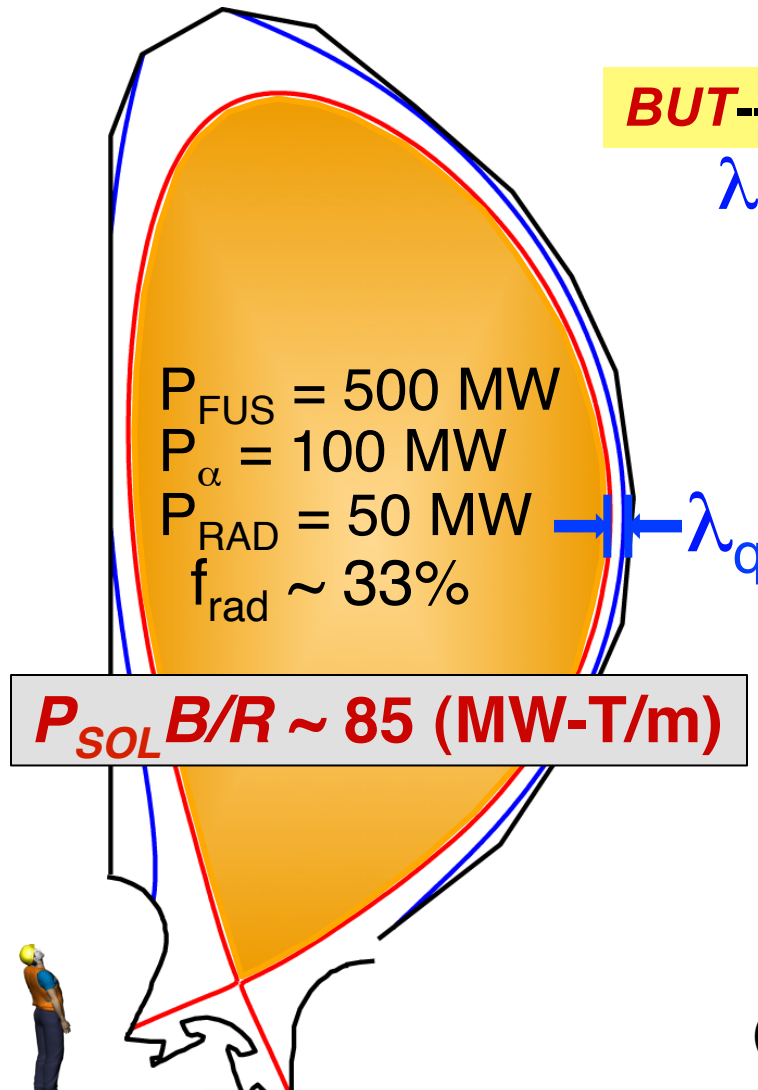
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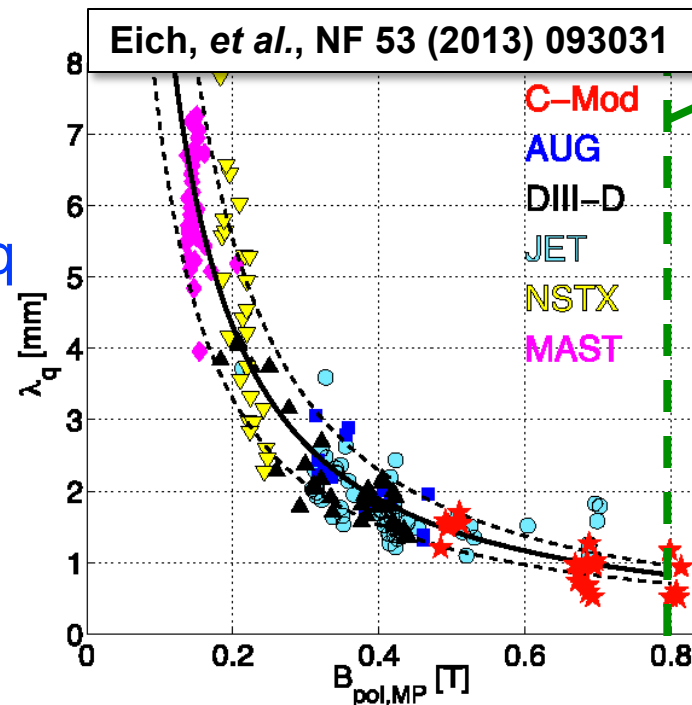
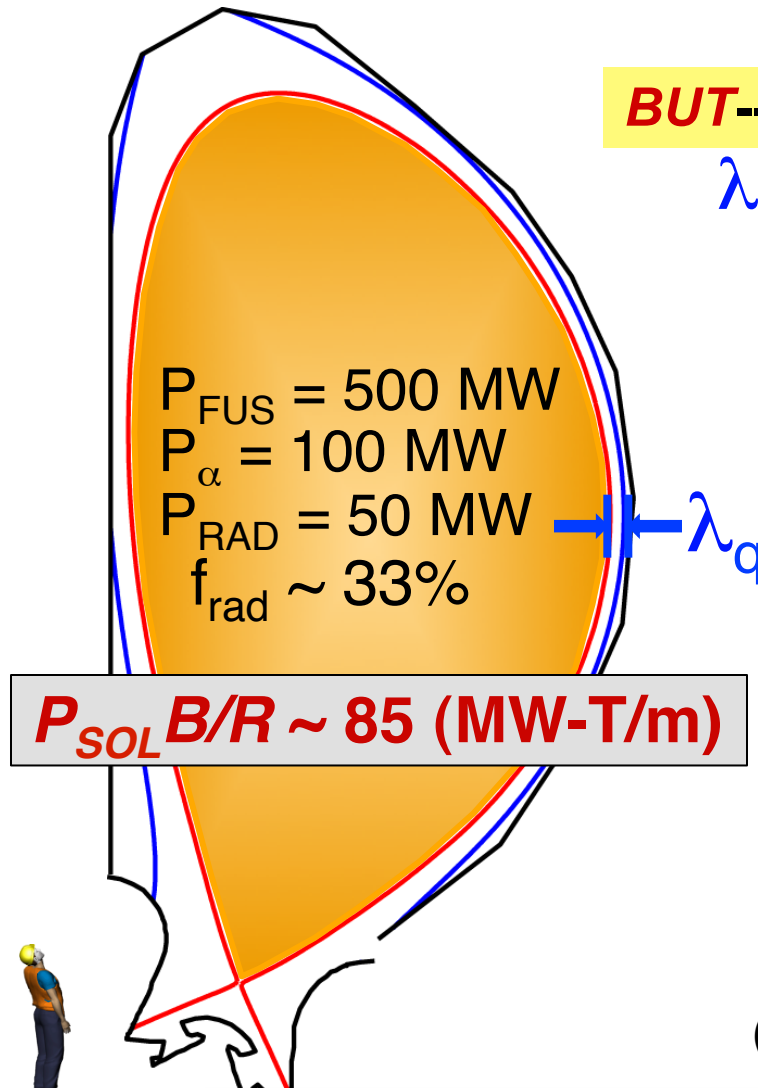
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Increase $P_{rad,core}$?
Increase $P_{rad,div}$?

Yet, must avoid
full detachment ...

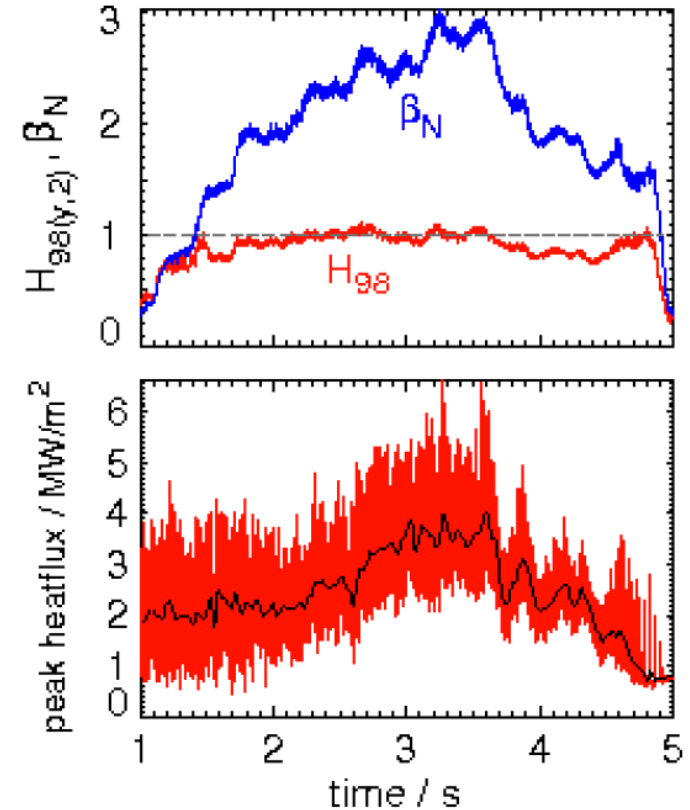
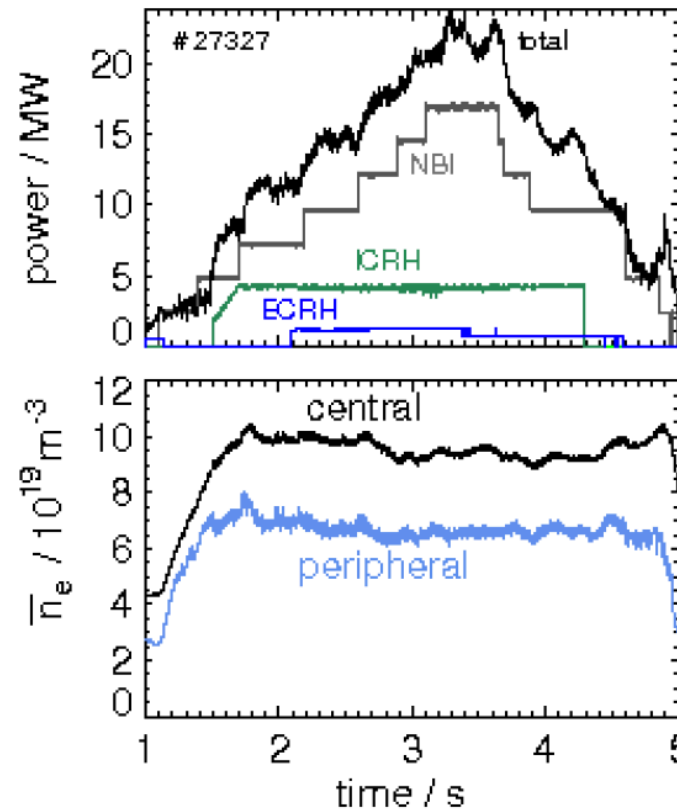
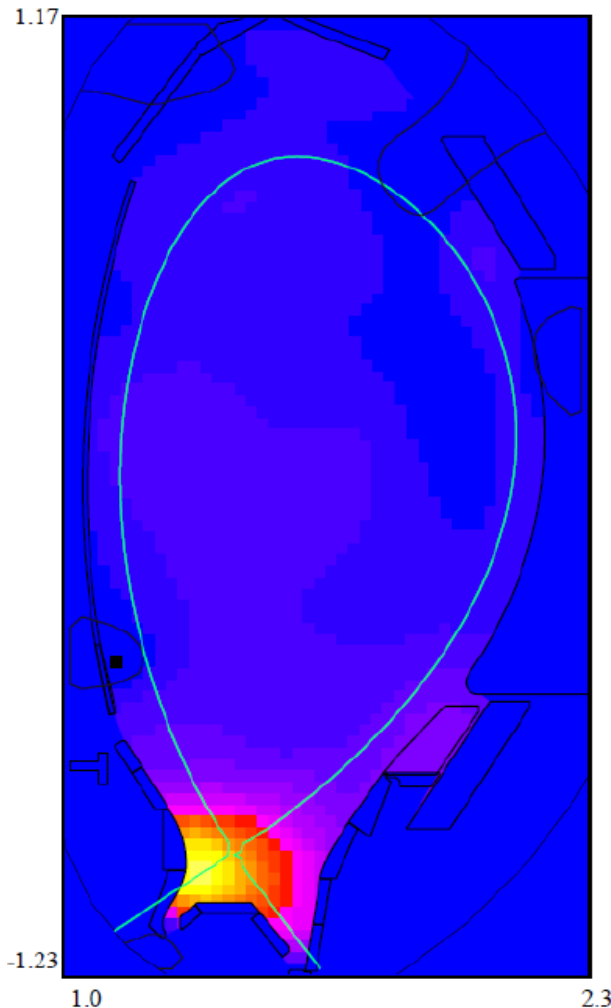
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New Result: $\sim P_{SOL} B/R$ is scale parameter for $q_{||}$ into divertor

Experiments are seeking a mix of **core & divertor radiation** to demonstrate a power-handling solution for ITER's W divertor.

ASDEX-Upgrade

High P_{rad} seeding experiment¹ $P_{\text{SOL}} B/R \sim 18$



[1] H. Zohm, APS 2013 invited talk

Feedback controlled N-seeding; $P_{\text{SOL}} \sim 12 \text{ MW}$, $q_{\text{div}} < 5 \text{ MW/m}^2$, $H \sim 1$, $\beta_N \sim 2.8$

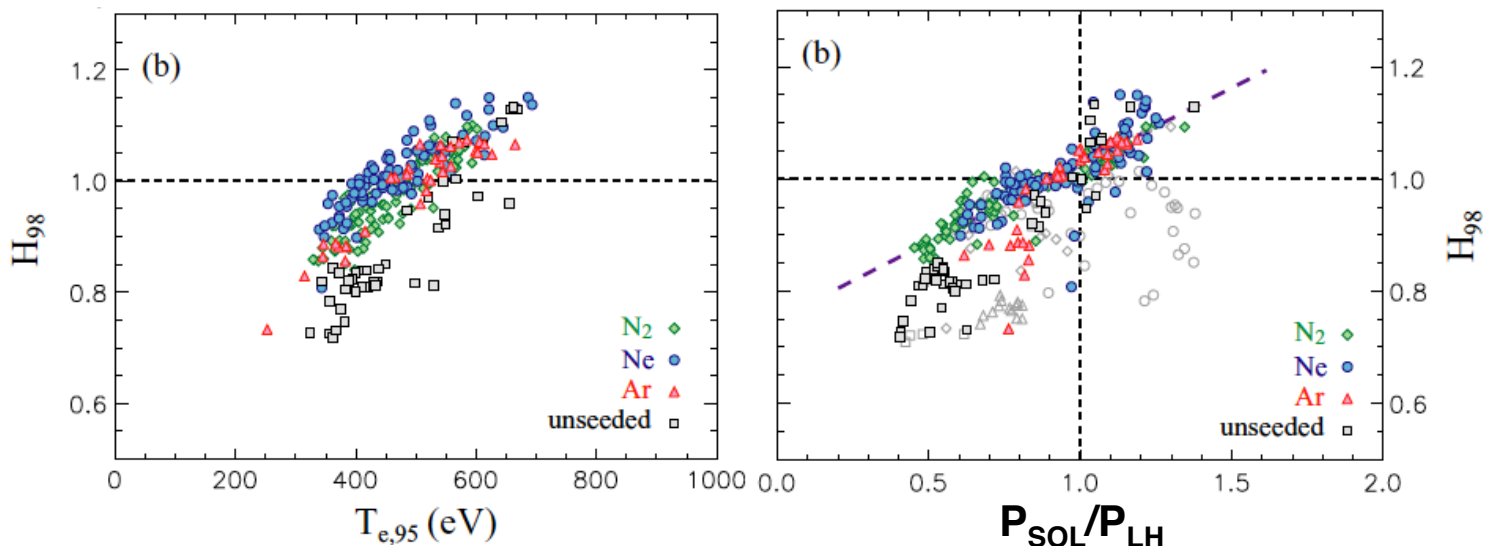
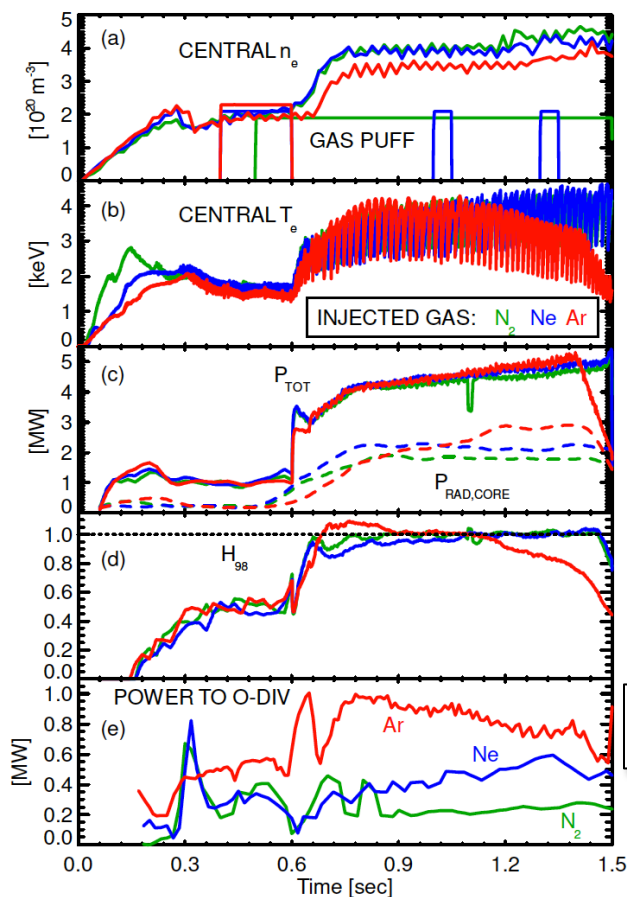
But $P_{\text{SOL}} B/R \sim 18$ is only $\sim 1/5$ value required for ITER $Q=10$: $P_{\text{SOL}} \sim 100 \text{ MW}$, $f_{\text{rad,core}} \sim 33\%$

Experiments are seeking a mix of **core & divertor radiation** to demonstrate a power-handling solution for ITER's W divertor.

Alcator C-Mod

High P_{rad} seeding experiments^{1,2} $P_{\text{SOL}} B/R \sim 16$

Comparison of N_2 , Ne, and Ar seeding



Good confinement requires $P_{\text{SOL}} > \sim P_{\text{LH}}$ (LH thres. power)

$P_{\text{SOL}} B/R \sim 16 \Rightarrow$ only 1/3 of ITER $P_{\text{LH}} B/R$

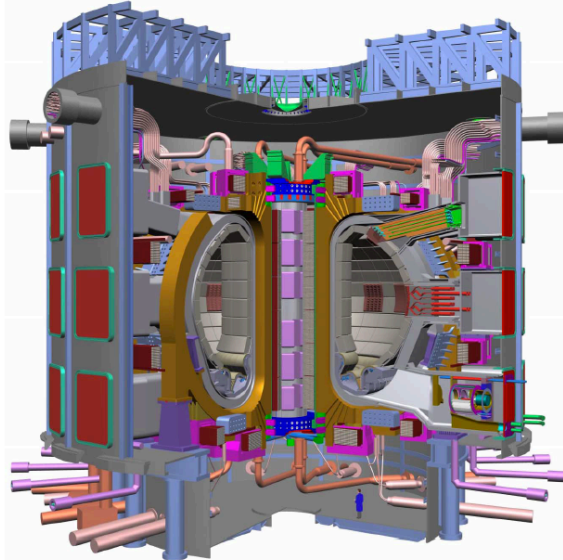
[1] Loarte, PoP 18 (2011) 056105 [2] Hughes, NF 51 (2011) 083007

Game: *trade-off core performance* (H_{98} , Z_{eff}) for reduced P_{SOL} and P_{div} .

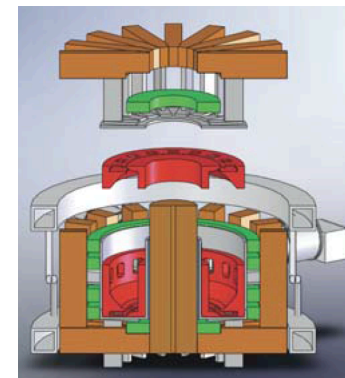
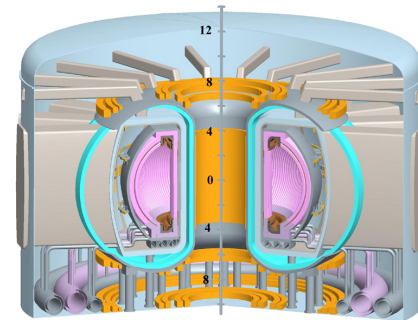
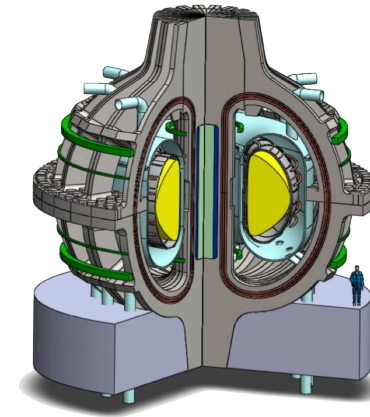
Not yet known what performance will be attained in ITER, compatible with div.

Power & particle exhaust challenges for FNSF/DEMO

ITER

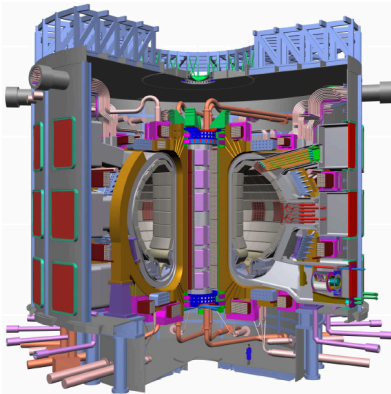


FNSF/
DEMO

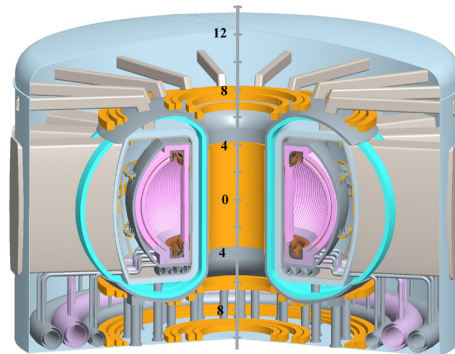


★ Challenge #1: Power exhaust

‘ITER solution’ for power handling -- does not apply for DEMO



ITER



ARIES-ACT1

ACT1, ACT2 have
3 to 4 times higher
 $P_{\alpha+aux}$ B/R than ITER

Conventional divertor
(assuming P_{sol} B/R ~ 48!)
requires extreme levels
of core radiation.

Risk that core plasma may
not maintain H-mode

Noted by Kotschenreuther¹
as motivation to consider
X-divertor (and super-X
divertor) options

	ITER	ARIES-ACT1	ARIES-ACT2
R(m)	6.2	6.25	9.75
B(T)	5.3	6.0	8.75
$P_{\alpha+aux}$ (MW)	150	402	625
P_{fusion} (MW)	500	1800	2600
$P_{\alpha+aux}$ B/R	130	390	560
P_{LH} B/R	~45?	~60?	~120?
$f_{rad,core}$ (P_{sol} B/R~48)	63%?	~88%?	~91%?

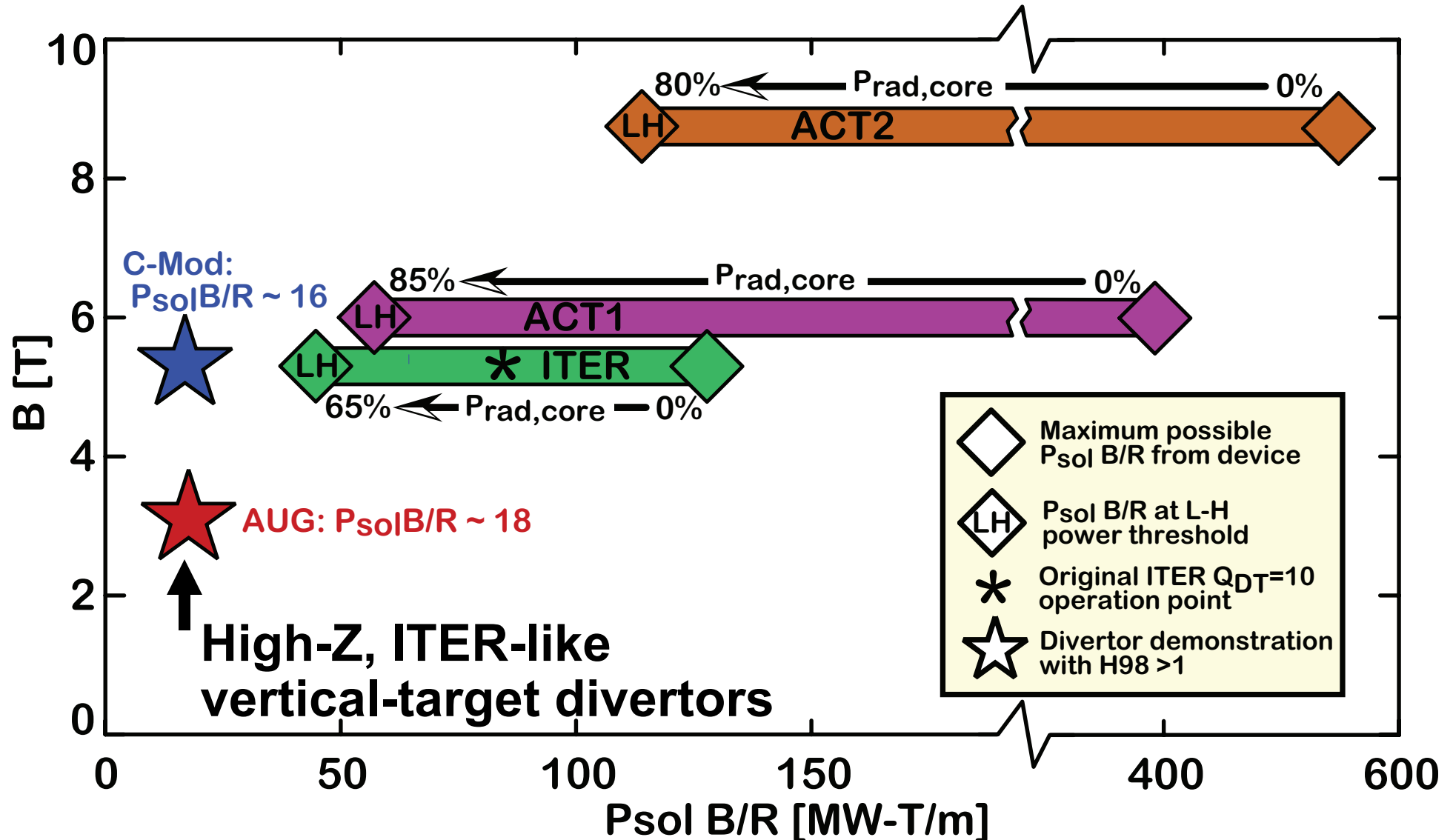
<http://www-pub.iaea.org/MTCD/publications/PDF/ITER-EDA-DS-22.pdf>

<http://aries.ucsd.edu/ARIES/DOCS/bib.shtml>

[1] Kotschenreuther, M., et al., IAEA 2004.

★ Challenge #1: Power exhaust

- Power entering SOL must be reduced (may not be possible)
- Power handling of divertor must be increased to accommodate it



★ Challenge #2: Material erosion

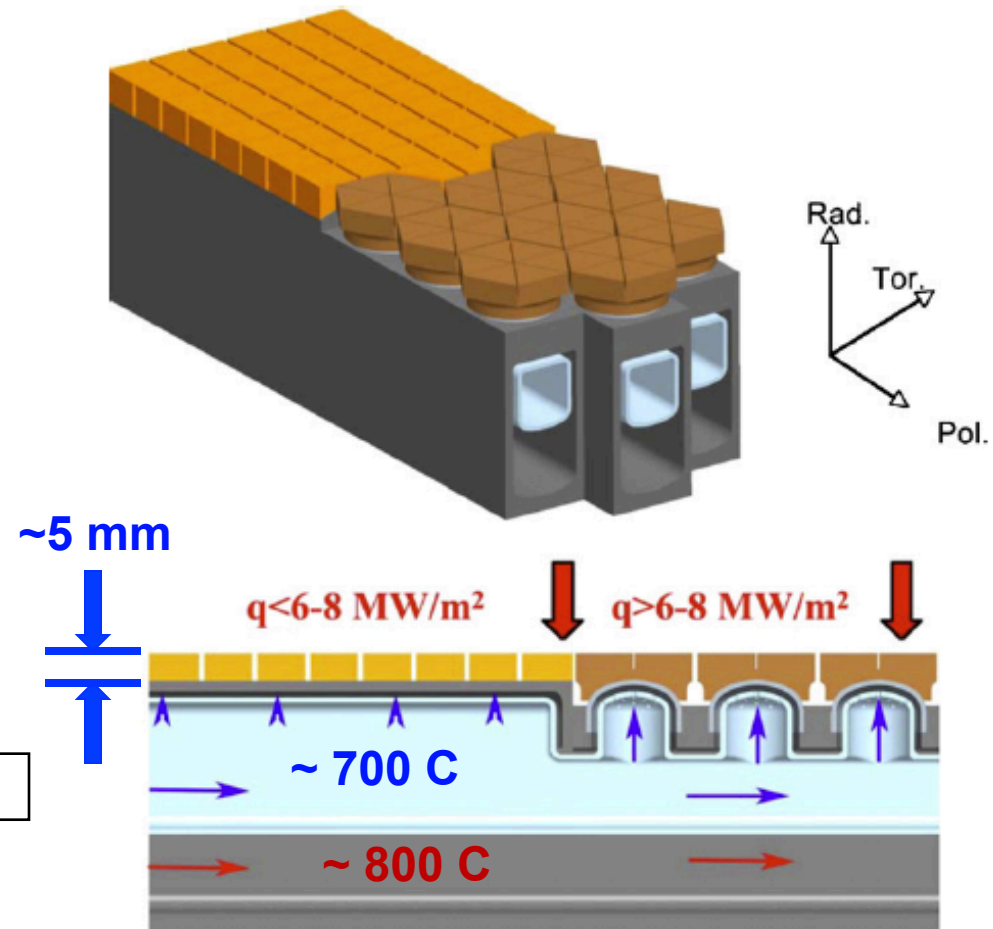
Steady state operation (FNSF/DEMO) imposes a new challenge on divertor operation: ~complete suppression of material erosion & PMI damage at the target plates is required.

~10 MW/m² SS heat removal requires < ~5 mm thick armor plate.

This restricts net tungsten erosion < 1 mm/year ($\Gamma_w \sim 2 \times 10^{18}/\text{m}^2/\text{s}$).

But divertor ion flux is high ($\Gamma_{i,\perp} \sim 1\text{-}2 \times 10^{24}/\text{m}^2/\text{s}$) requiring $\Gamma_w/\Gamma_{i,\perp} < 10^{-6}$.

D.G. Whyte, APS 2012; Stangeby, NF 51 (2011) 063001



He-cooled tungsten divertor plate with integrated finger units

M. Tillack, et al., FED 86 (2011) 71

90,000 to 500,000 'finger units' in a reactor

★ Challenge #2: Material erosion

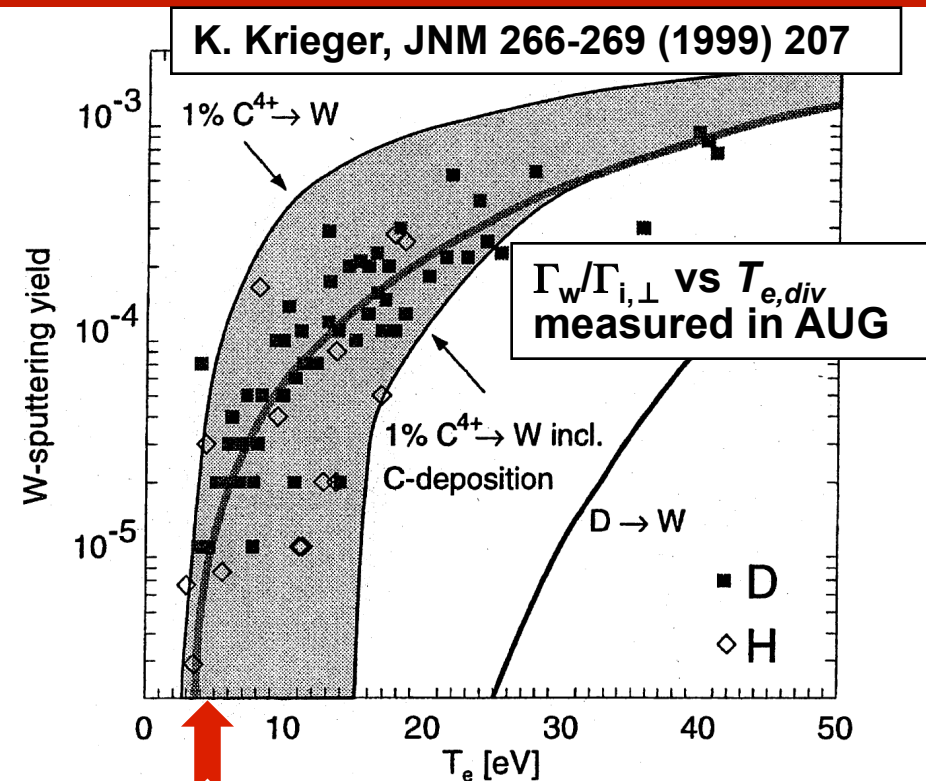
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D.G. Whyte, APS 2012; Stangeby, NF 51 (2011) 063001



suppress sputtering: $T_e < 5$ eV

Factor of $< 10^{-6}$ net yield requires:

- Efficient prompt redeposition $> \sim 99\%$ (*redep. material is mixed ~ poor quality*)

or

Doerner NF 2012: redep. sputters at x10 rate of bulk (Be)

- Fully detached divertor with ion energies below sputtering threshold, i. e., $T_e < \sim 5$ eV (with impurity ions)

or

- Liquid metal targets?

★ Challenge #2: Material erosion

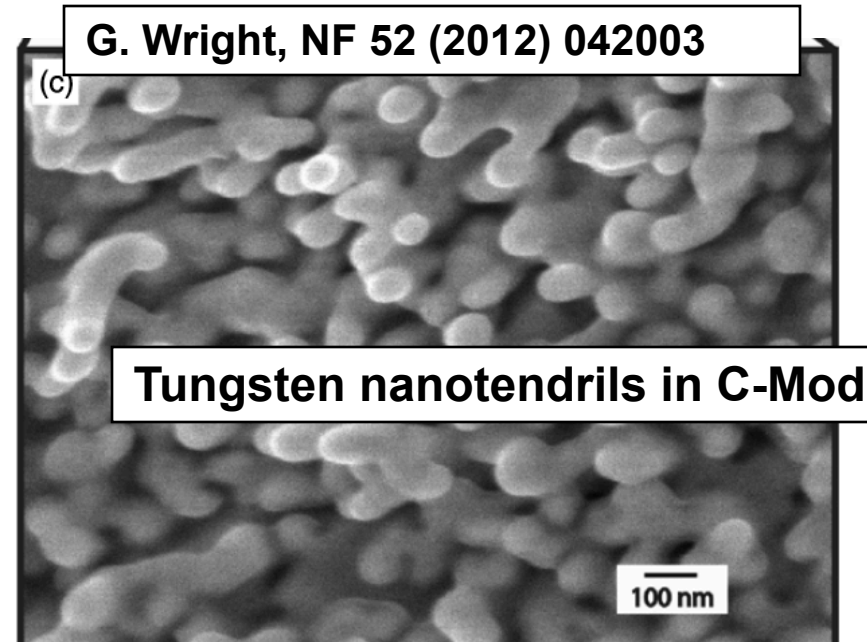
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D.G. Whyte, APS 2012; Stangeby, NF 51 (2011) 063001



To avoid “fuzz”: $E_{\text{He}^+} < 20 \text{ eV}$, $T_e < 7 \text{ eV}$

Factor of $< 10^{-6}$ net yield requires:

- Efficient prompt redeposition > ~ 99% (*redep. material is mixed ~ poor quality*)

or

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★ Challenge #2: Material erosion

The divertor “slag” problem

If $T_e = \sim 10\text{eV}$ at all plasma-wall contact areas, gross material erosion rates would exceed $\sim 30,000\text{ kg/yr}$ for tungsten in DEMO.

Device	P_{heat} (MW)	Annual run time (s/year)	Fluence of D/T ions to surfaces (TC/yr) ^a	Beryllium circulation rate (kg/yr)	Boron circulation rate (kg/yr)	Carbon circulation rate (kg/yr)	Tungsten circulation rate (kg/yr) [*]
DIII-D	20	10^4	0.0007	2.8	1	0.5	0.7
JT-60SA	34	10^4	0.0017	4.8	1.7	0.9	1.2
EAST	24	10^5	0.01	34	11	5	8
ITER	100	10^6	0.4	1680	580	270	410
FDF	100	10^7	3	13 400	4600	2100	3300
Reactor	400	2.5×10^7	40	141 000	50 000	22 000	31 000

^a(tera-coulombs/year).

Strangeby, NF 51 (2011) 063001

* Tungsten yield based on 0.5% N seeding.

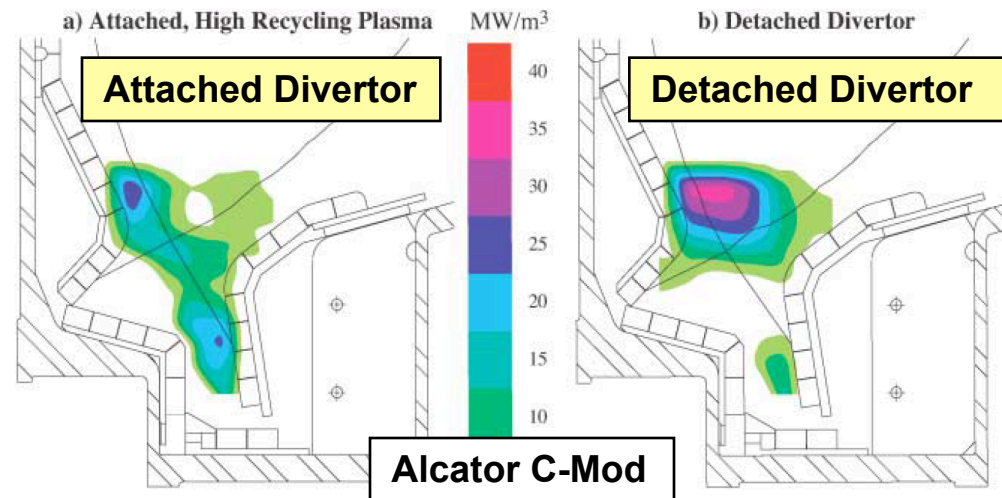
A fully-detached divertor would largely eliminate this problem. But, erosion from first wall surfaces will remain, perhaps at $\sim 1/1000$ the rate.

Wall-eroded material will end up as ‘slag’ in the divertor. A means to continuously remove it must be devised.

Q: Why not just operate with a conventional divertor in a fully detached regime?

A: The ‘thermal front’ of divertor detachment tends to intrude into the X-point region (‘X-point MARFE’) leading to...

- reduced radiation in divertor volume
- reduced screening of impurities
- increased radiation in X-point region
- cooling of LCFS and pedestal region
- reduced plasma confinement
- near thermal collapse (H-L transition, density limit disruption)



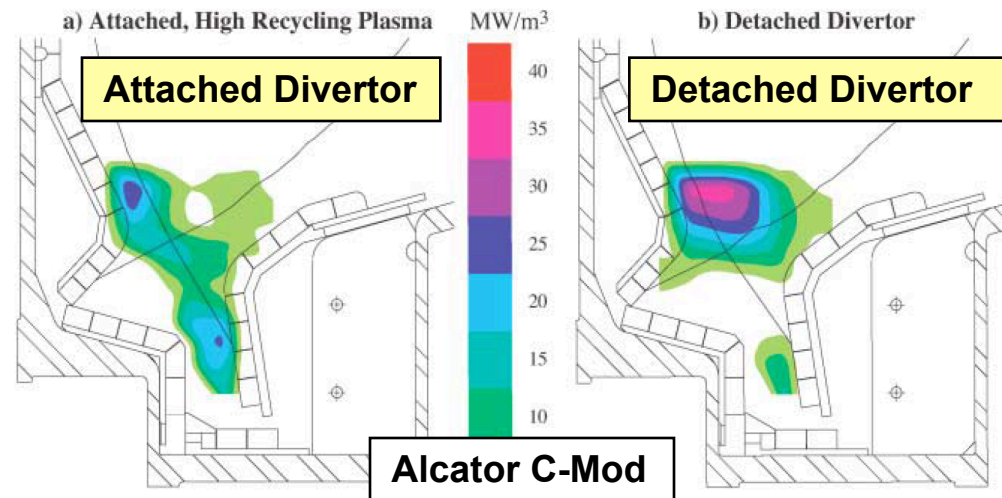
J. Goetz, PoP (1996) 1908.

... i.e., the core performance degradation problem.

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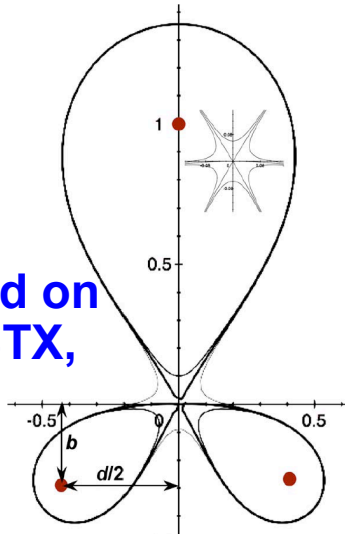
A different approach is required for FNSF/DEMO.

- Motivation & Mission for ADX
- Power & particle exhaust challenges
 - ITER
 - DEMO
- **Potential solutions –
advanced magnetic divertors, ...**
- Potential solutions –
double-null + high-field side launch RF
- Requirements for a divertor test tokamak
- ADX concept – version 1.0

Advanced Magnetic Divertor Ideas

Snowflake

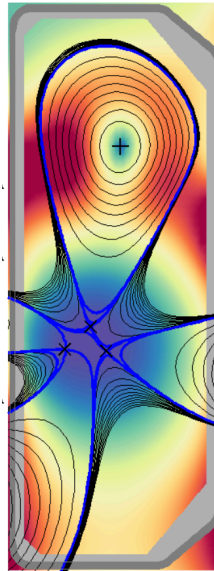
Operated on
TCV, NSTX,
DIII-D



D. Ryutov, PoP **14** (2007) 064502.

Cloverleaf

Scenario
developed
for TCV

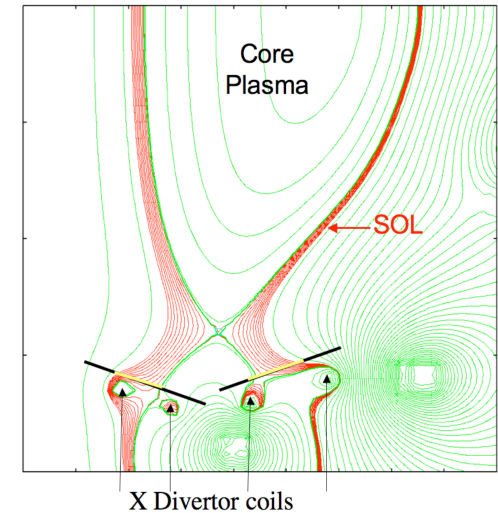


W. Vijvers APS 2013, D. Ryutov, 2013

X Divertor

Produced
on TCV

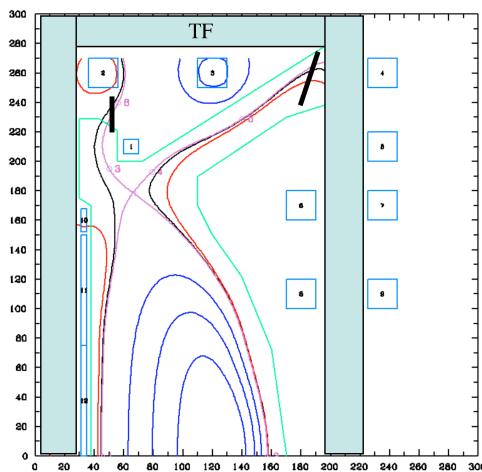
Secondary
x-point
near target
operated
on NSTX,
DIII-D



M. Kotschenreuther, PoP **14** (2007) 072502.

Super X

Not yet
tested
(MAST
2015)

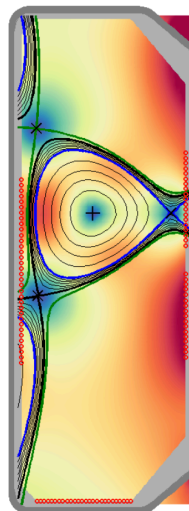


P. Valanju, PoP **16** (2009) 056110;
M. Kotschenreuther, NF **50** (2010) 035003.

Triple-X

Produced
on TCV

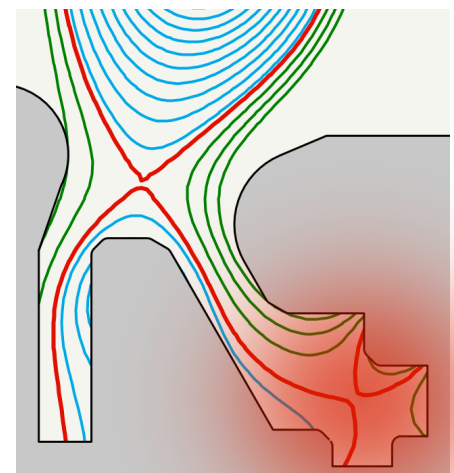
Similar to
old JT-60



J. Kesner NF 1990, W. Vijvers APS 2013

X-point Target

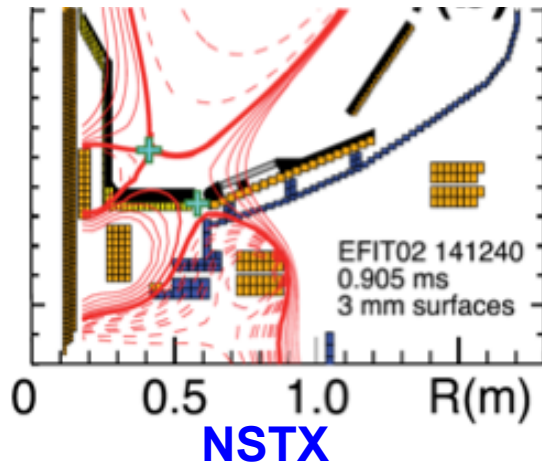
Not
tested



B. LaBombard, *et al.*, Bull. Am. Phys. Soc. **58** (2013) 63.

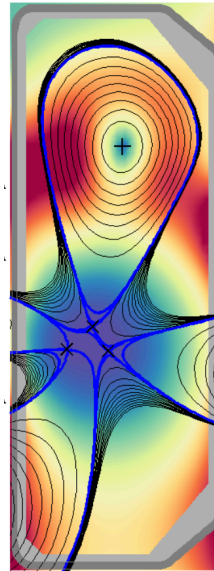
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V.A. Soukhanovskii, PoP 19 (2012) 082504.
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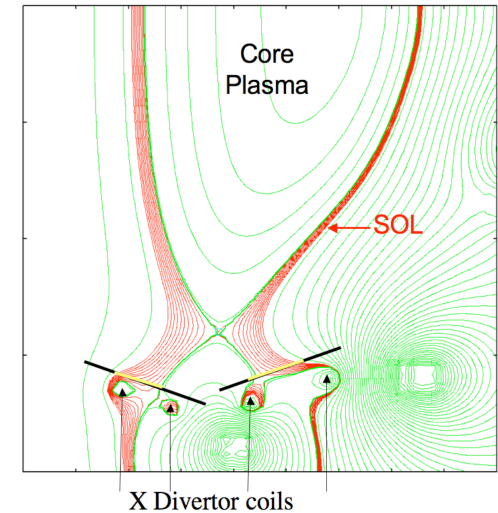
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**Produced
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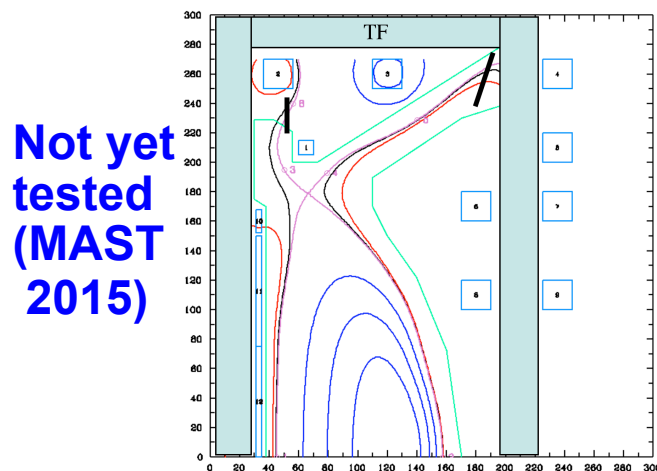
**Secondary
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near target
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DIII-D**

X Divertor



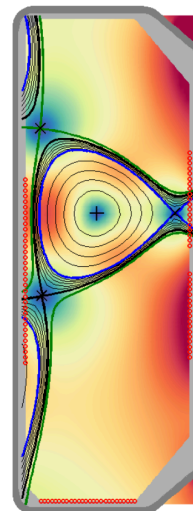
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Triple-X



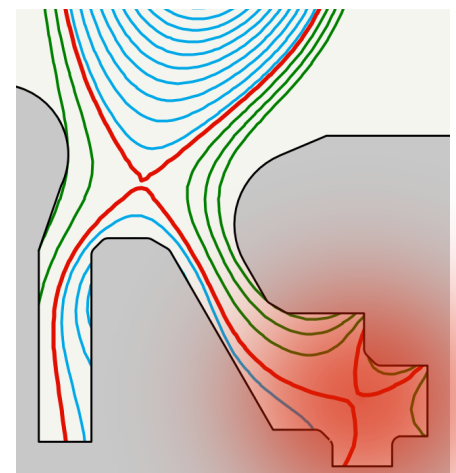
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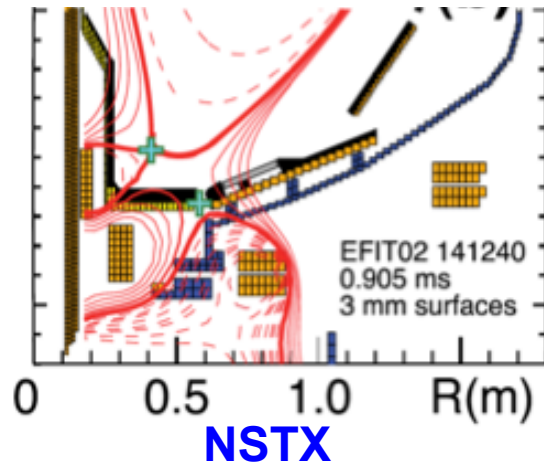
X-point Target



B. LaBombard, *et al.*, Bull. Am. Phys. Soc. 58 (2013) 63.

Advanced Magnetic Divertor Ideas

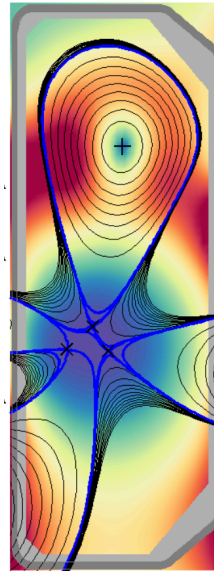
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Cloverleaf

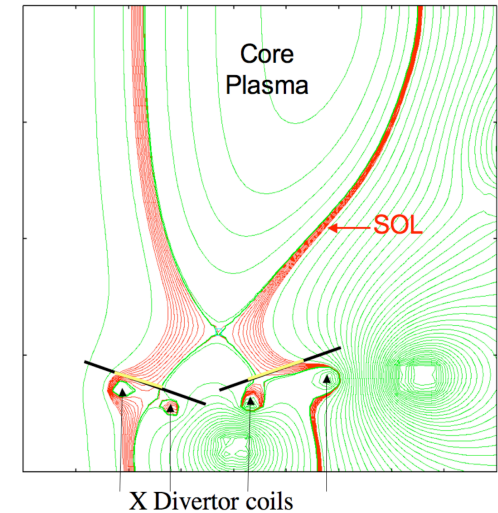


W. Vijvers APS 2013, D. Ryutov, 2013

Produced on TCV

Secondary x-point near target operated on NSTX, DIII-D

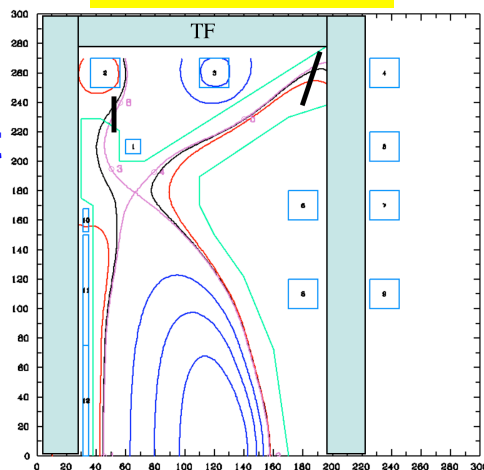
X Divertor



M. Kotschenreuther, PoP 14 (2007) 072502.

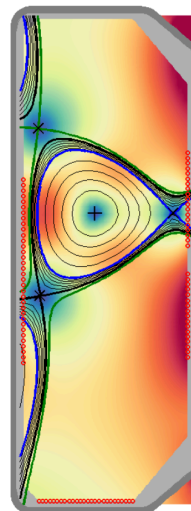
Super X

Not yet tested (MAST 2015)



P. Valanju, PoP 16 (2009) 056110;
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Triple-X

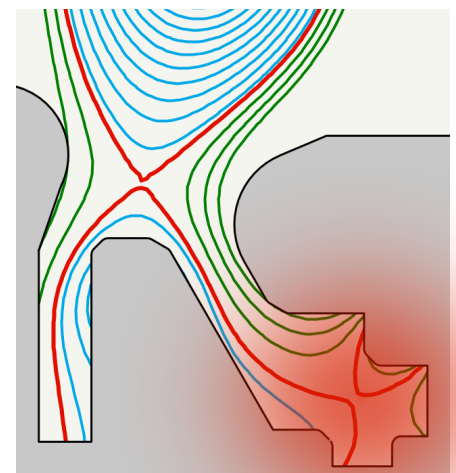


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Not tested

B. LaBombard, et al., Bull. Am. Phys. Soc. 58 (2013) 63.

How might advanced magnetic divertors help?

Super X¹ and X-point Target²

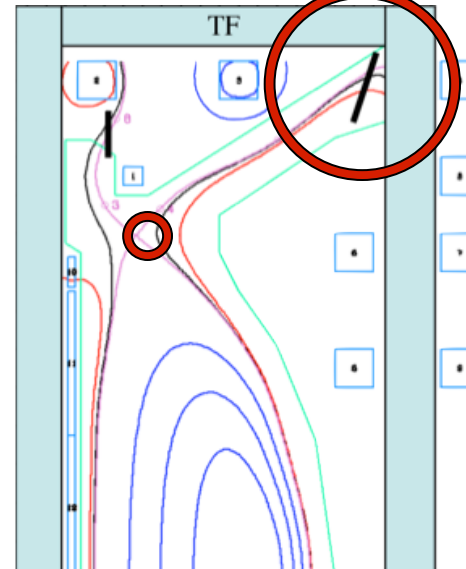
Locate targets at large major radius relative to primary x-point

Exploit total flux expansion

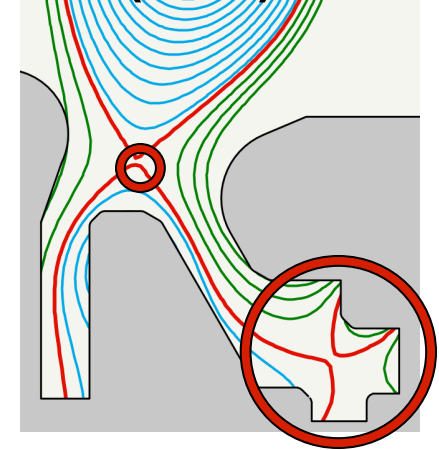
B at target plate is decreased $\sim 1/R$;
heat flux density at target is decreased $\sim 1/R$:

$$q_{//t} \propto n_t T_t^{3/2} \propto \left(\frac{R_{OMP}}{R_t} \right)$$

Super X (SXD)



X-point Target (XPT)



[1] P. Valanju, PoP **16** (2009) 056110;

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[2] B. LaBombard, *et al.*, Bull. Am. Phys. Soc. **58** (2013) 63.

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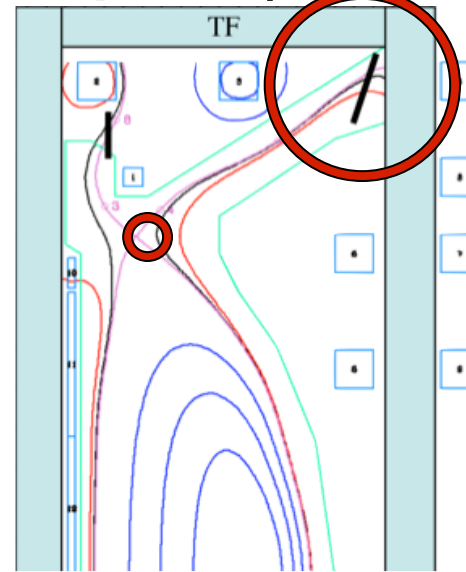
$$q_{//t} \propto n_t T_t^{3/2} \propto \left(\frac{R_{OMP}}{R_t} \right)$$

For fixed upstream pressure and $q_{//}$,

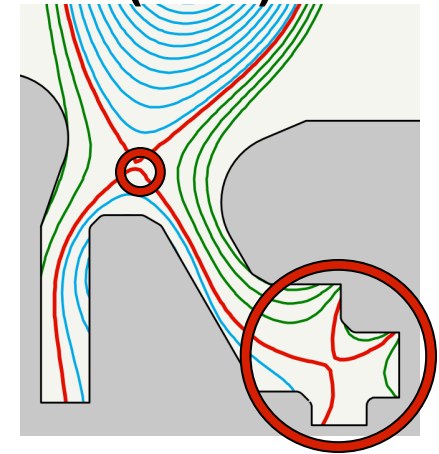
$$T_t \propto \left(\frac{R_{OMP}}{R_t} \right)^2 \downarrow \quad n_t \propto \left(\frac{R_t}{R_{OMP}} \right)^2 \uparrow$$

promoting earlier onset of detachment.
Large increase in $L_{||}$ also contributes.

Super X (SXD)



X-point Target (XPT)



[1] P. Valanju, PoP **16** (2009) 056110;

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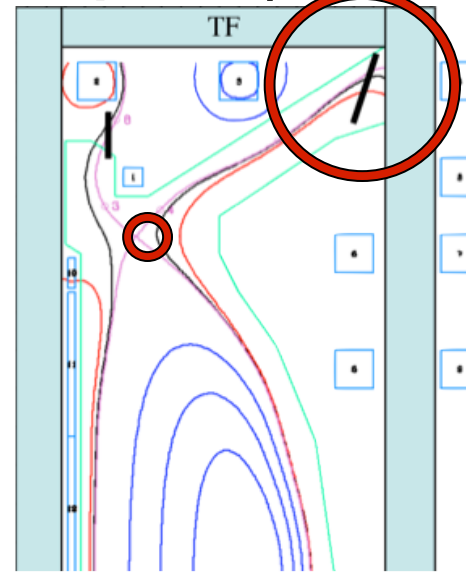
Poloidal flux expansion can also applied at target plate.

[1] P. Valanju, PoP **16** (2009) 056110;

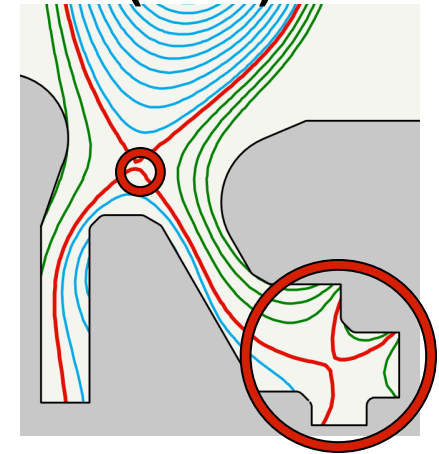
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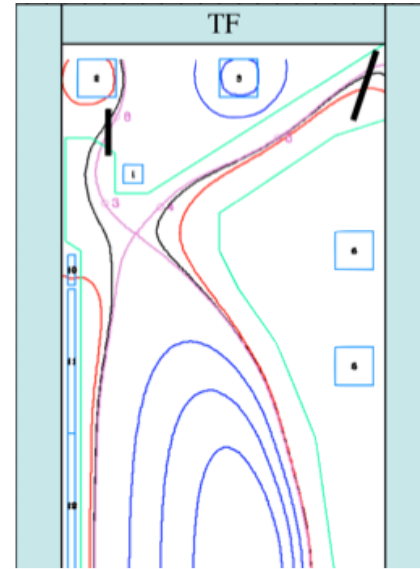
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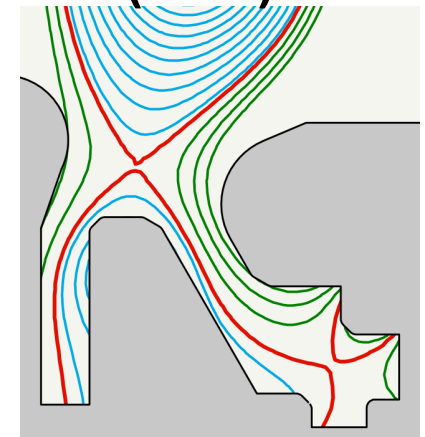
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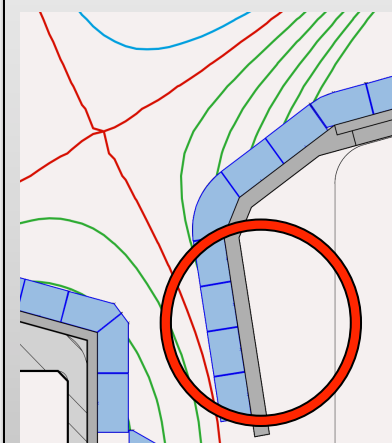
Super X (SXD)



X-point Target (XPT)



Note: Poloidal flux expansion using PF coils is similar to that obtained by a tilted target plate



For attached plasmas, field line angles must be greater than ~ 1 degree

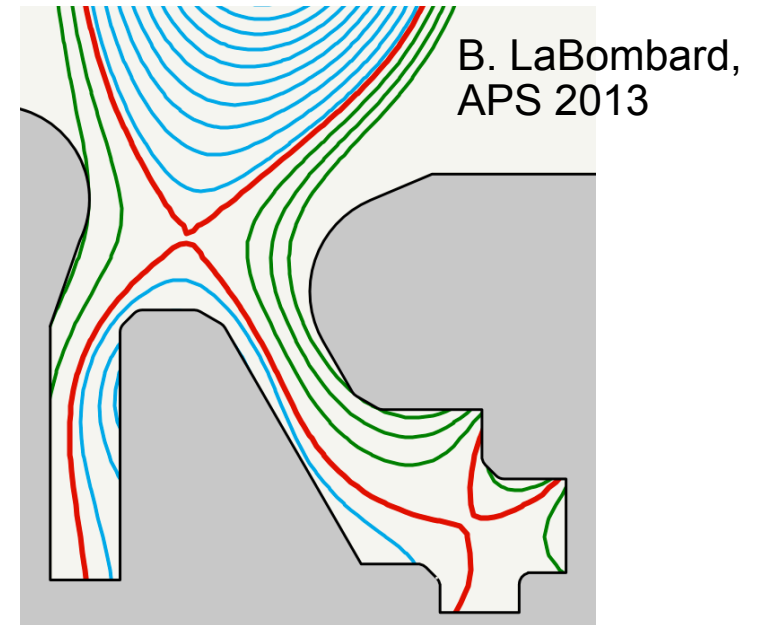
This sets max poloidal flux expansion for all concepts.

How might advanced magnetic divertors help?

X-point Target Divertor¹ – a refinement of SXD topology

Idea: Use a remote X-point to produce a fully detached, radiating plasma (local X-point MARFE) as a virtual target

X-point Target (XPT)



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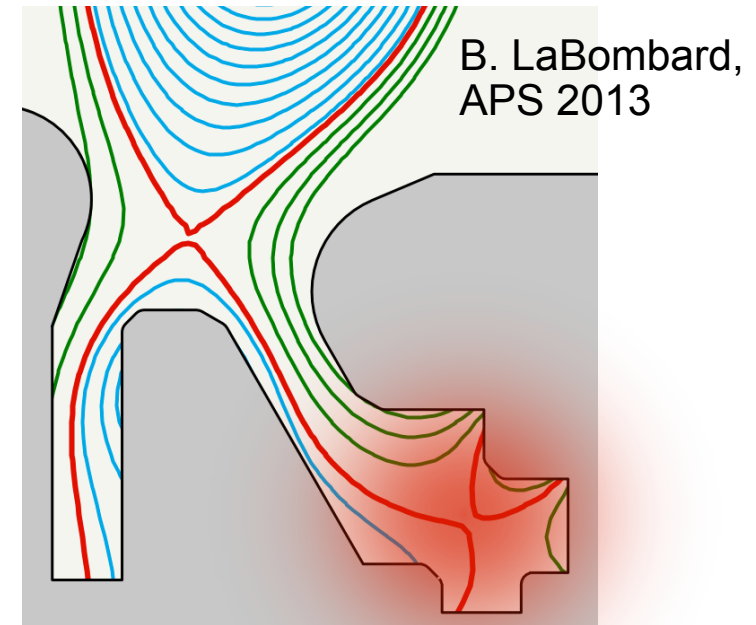
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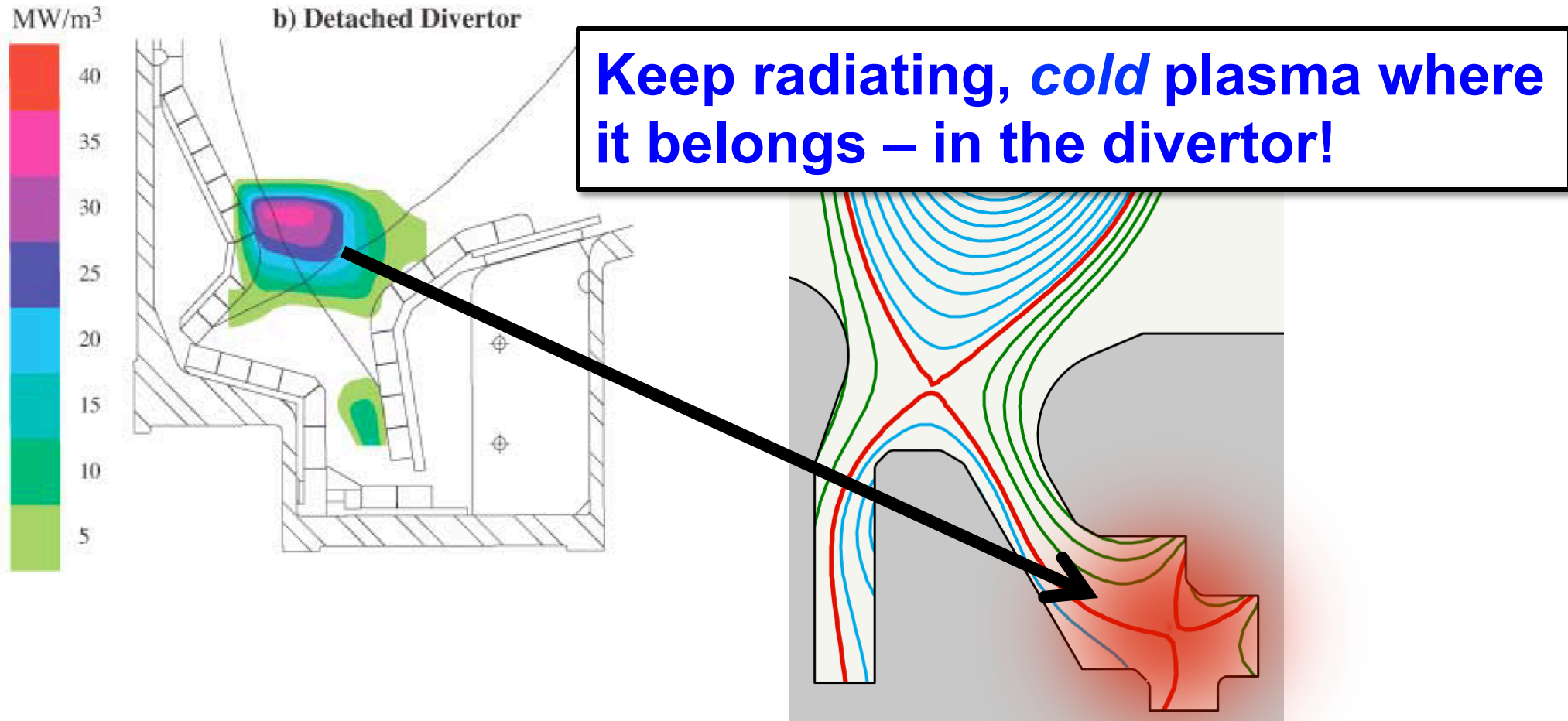
- $L_{\parallel}$ set to infinity on flux tube carrying peak heat flux (adjusting target X-point flux).
- *No field line shadowing at target plate; attack angles everywhere > 1 degrees*
- Tight baffling for high neutral pressures in divertor – gas target divertor.
- Employ feedback control (seeding) for a stable ‘divertor X-point MARFE’

X-point Target (XPT)



[1] B. LaBombard, *et al.*, Bull. Am. Phys. Soc. **58** (2013) 63.

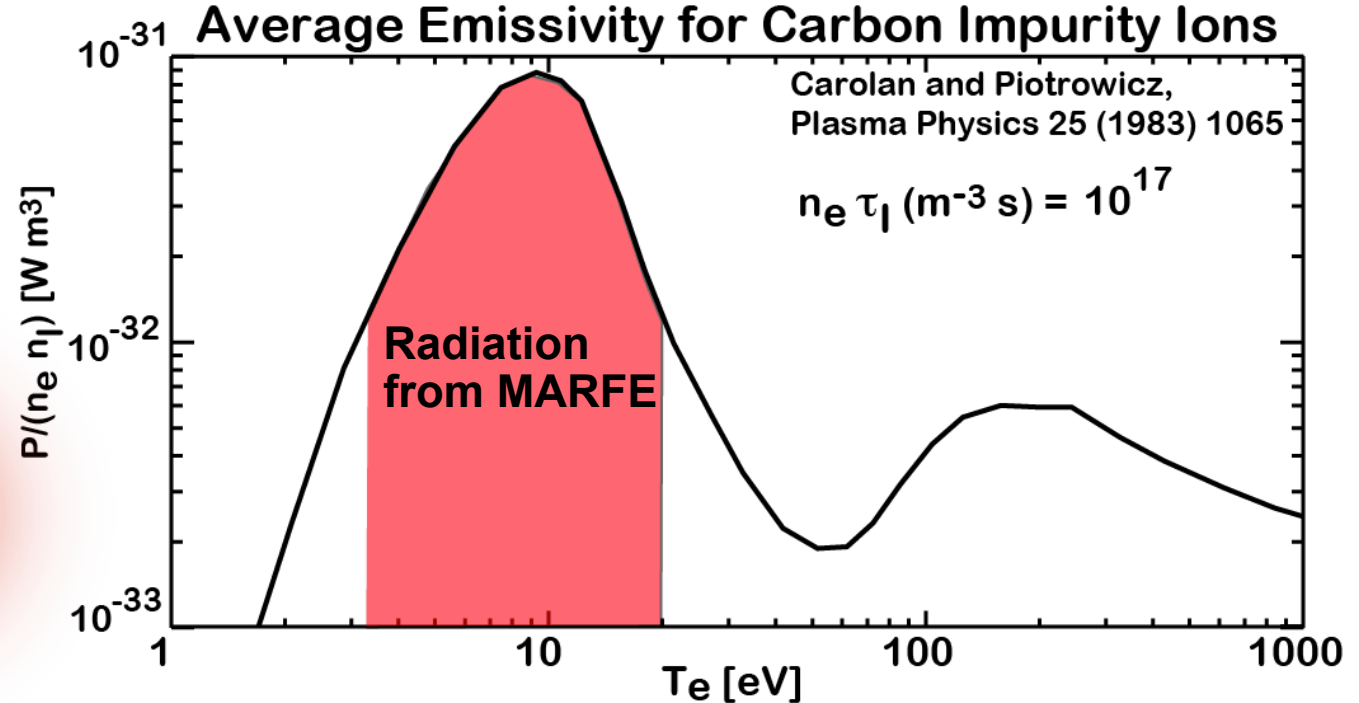
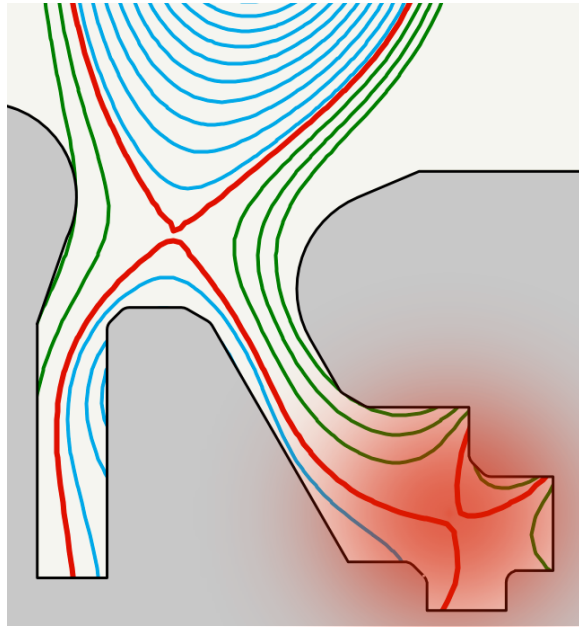
Important goal for any advanced divertor concept: *Control/suppress X-point MARFE onset*



★ **Challenge #3:** that achieve full detachment with minimal impact on core plasma

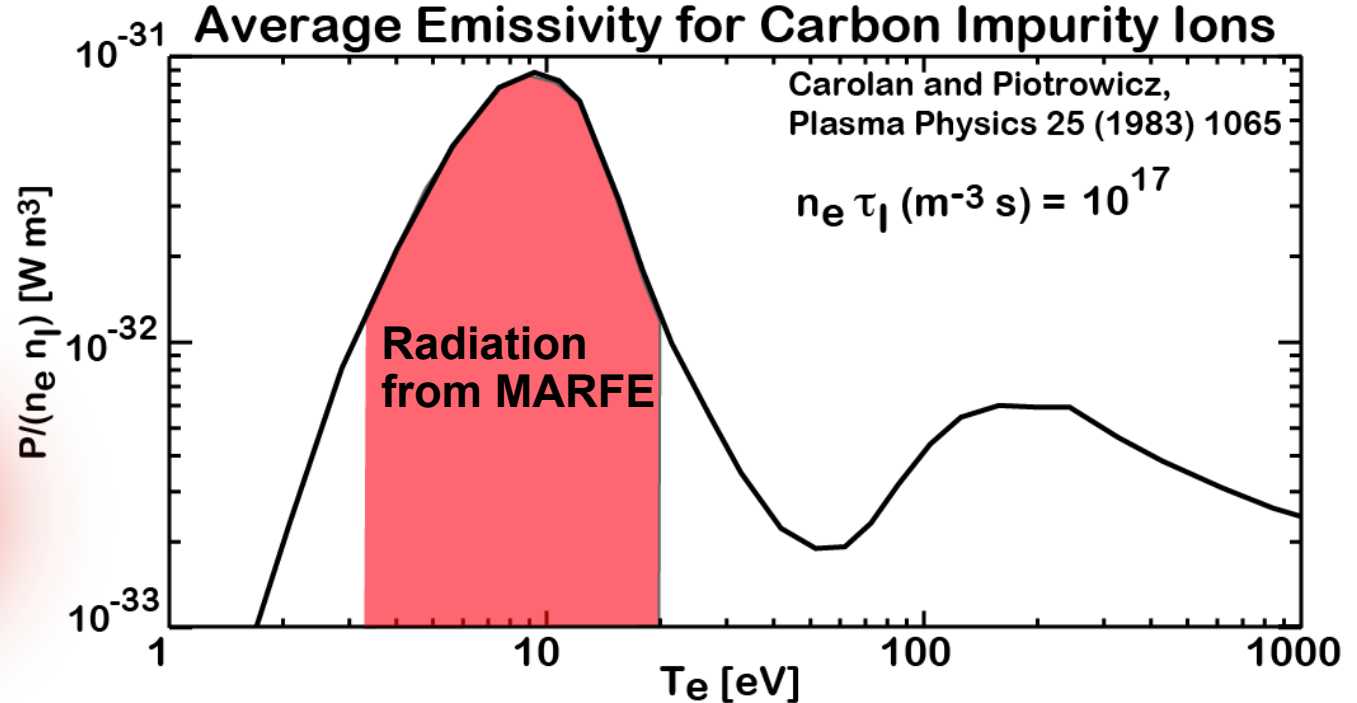
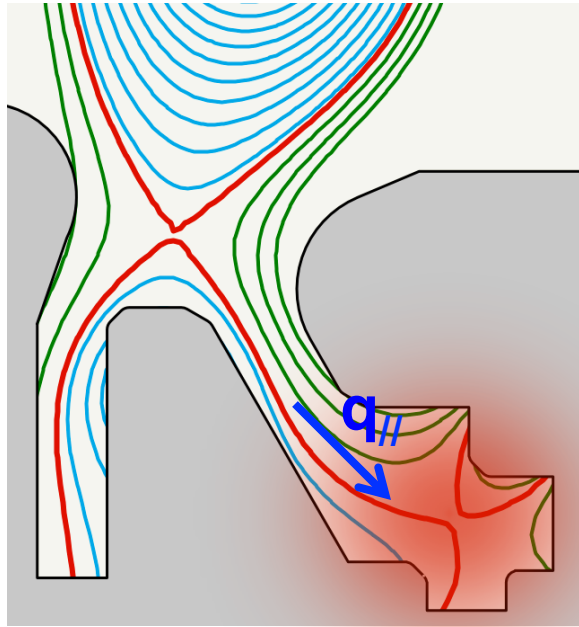
Develop robust, advanced divertor solutions

Important Goal: *Control/suppress X-point MARFE onset*



MARFEs (“*thermal fronts*”) form when impurity radiation affects local power balance in flux tube. For C impurity ions: $\sim 3 \text{ eV} < T_e < \sim 20 \text{ eV}$

Important Goal: *Control/suppress X-point MARFE onset*



Thermal fronts accommodate a maximum value of incident $q_{//}$ that depends on **plasma pressure**, nT_e and **impurity fraction**, f_I

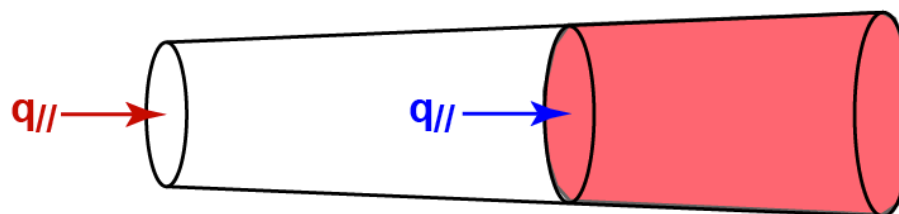
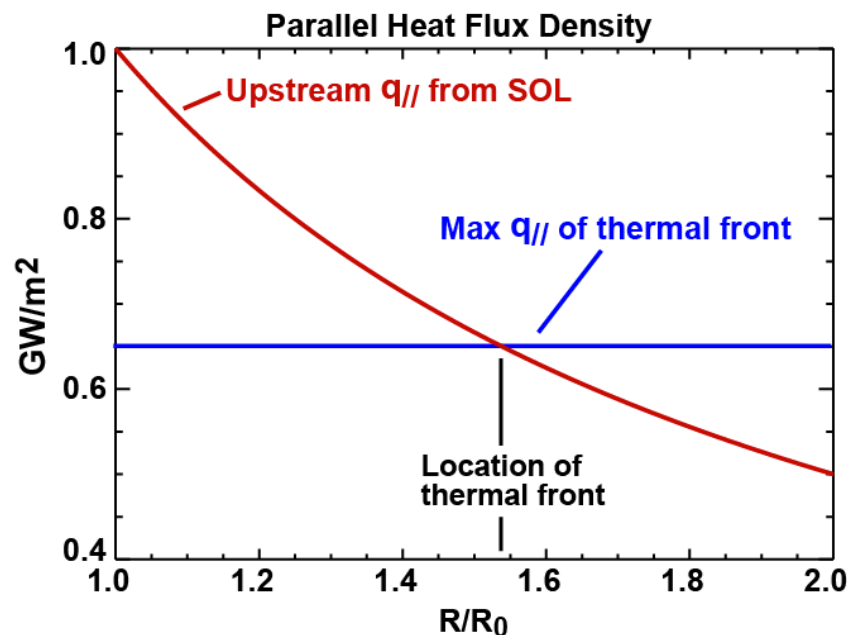
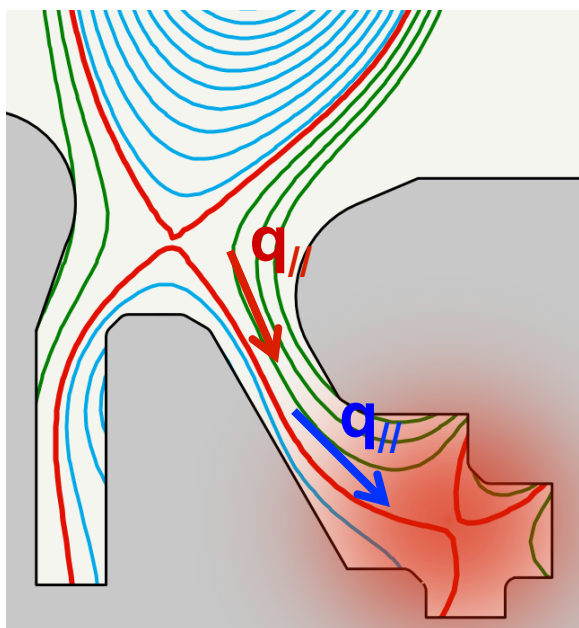
Example Carbon¹:

$$f_I \approx 4\%; \quad n \approx 10^{20} \text{ m}^{-3}; \quad T_e \approx 100 \text{ eV}$$

$$q_{//} \approx 30 f_I^{1/2} \frac{nT_e}{10^{20} \text{ m}^{-3} \text{ eV}} [\text{MW} / \text{m}^2] \Rightarrow q_{//} \approx 0.6 \text{ GW} / \text{m}^2$$

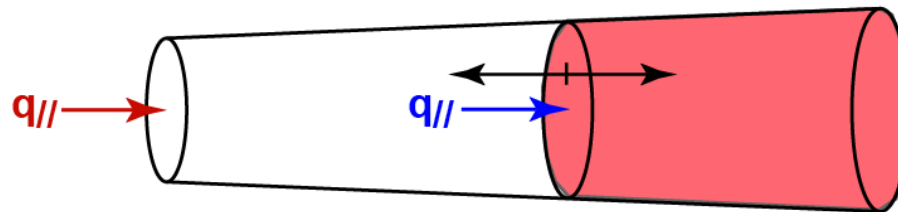
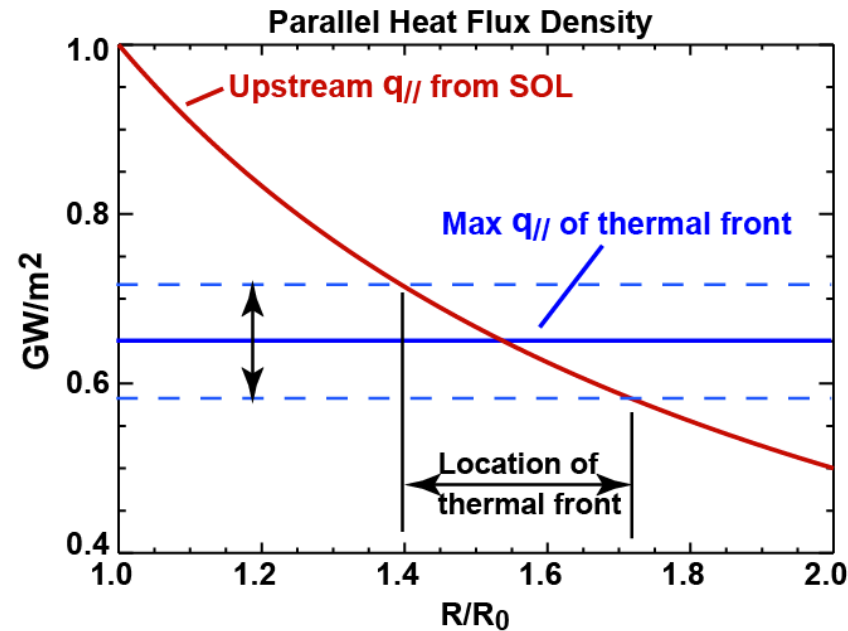
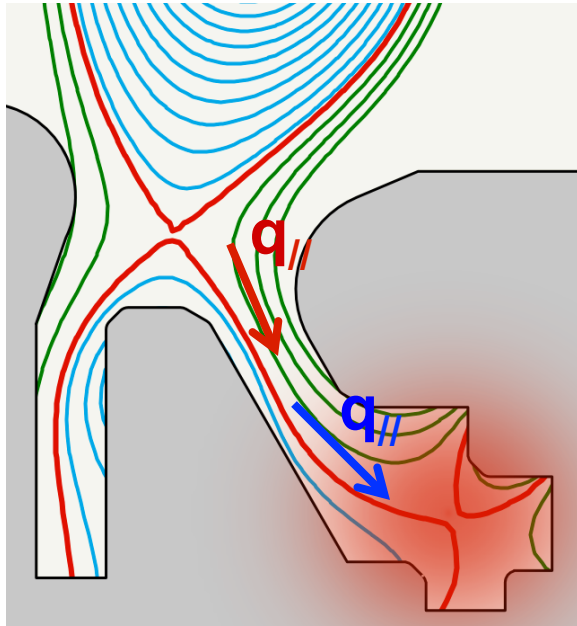
[1] I. Hutchinson, NF 34 (1994) 1337.

Large major radius of divertor target plate may provide natural control of thermal front (MARFE) location



Upstream $q_{||}$ decreases as $\sim 1/R$ along divertor leg.

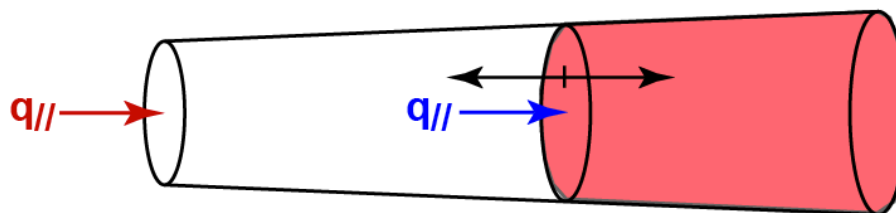
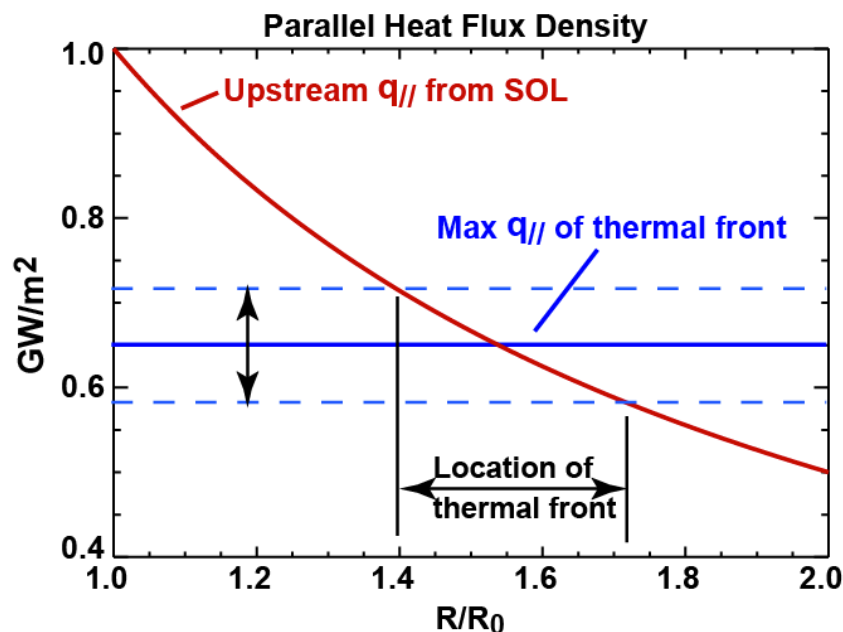
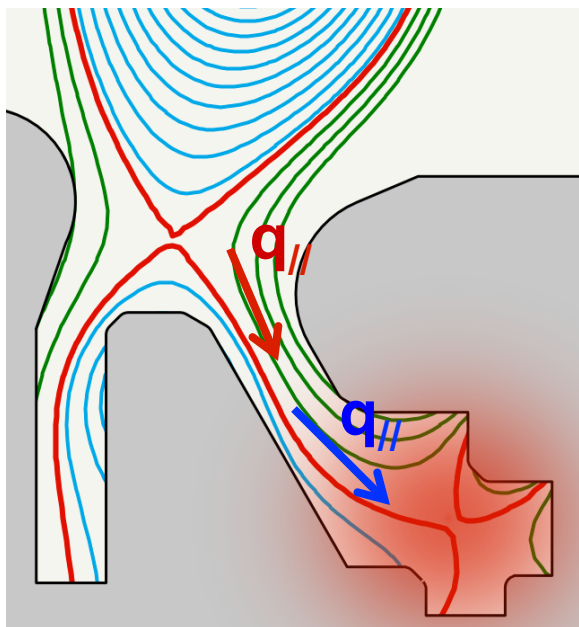
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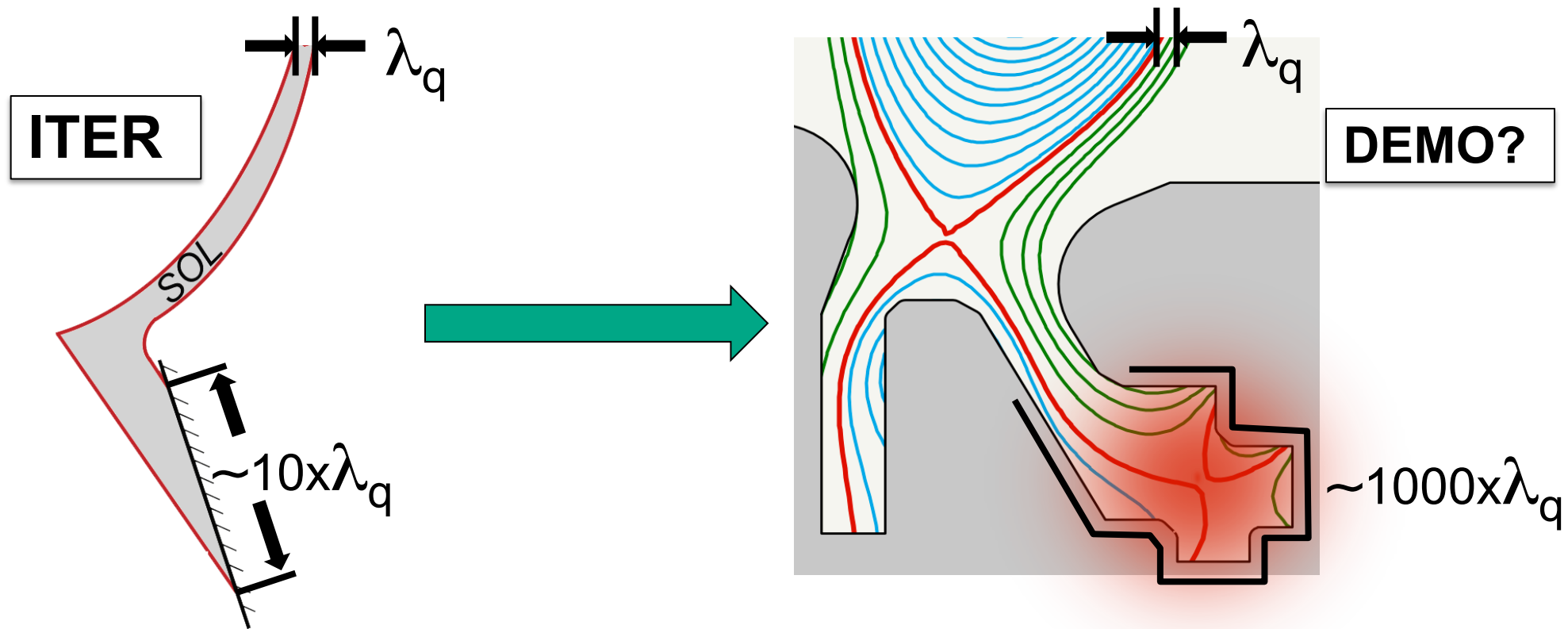
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**Caveats: cross-field transport, neutral interactions also play role.
Need to optimize geometry, poloidal and total flux expansion...**

Message: Magnetic geometry is a powerful tool that has not yet been fully explored to tackle the divertor problem

Spread heat exhaust over a large surface area in a divertor chamber by tailoring magnetic geometry and radiation/neutral interaction zone



- **Cold, fully detached divertor = $\sim$ zero erosion**
- **Hot separatrix and pedestal regions = good core performance**

What if advanced magnetic divertors alone can't do it?

Liquid metal targets may be the only hope.

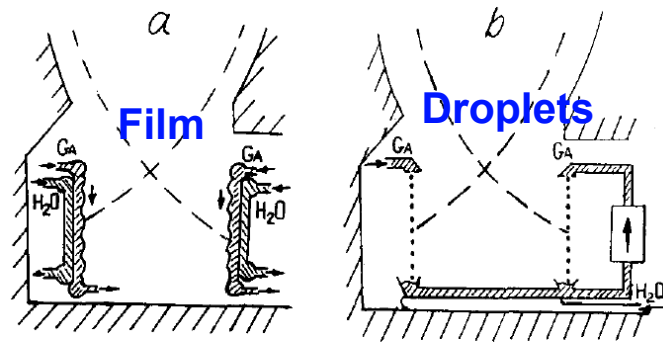
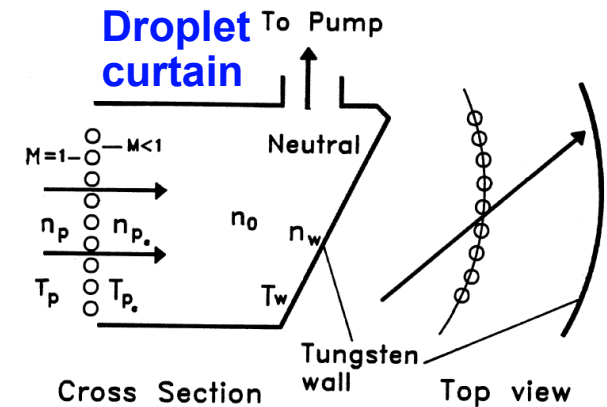
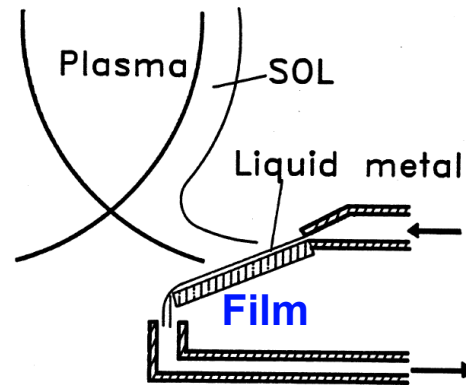


Fig. 1. Principal scheme of the sheet (a) and jet-drop curtain (b) divertor plates; (I) MHD pump.

Mirnov JNM 1992



C. Lao, MIT 1992

Lithium in Capillary Porous Structure

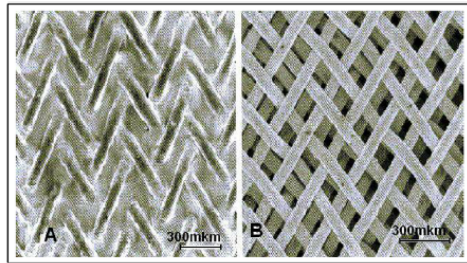
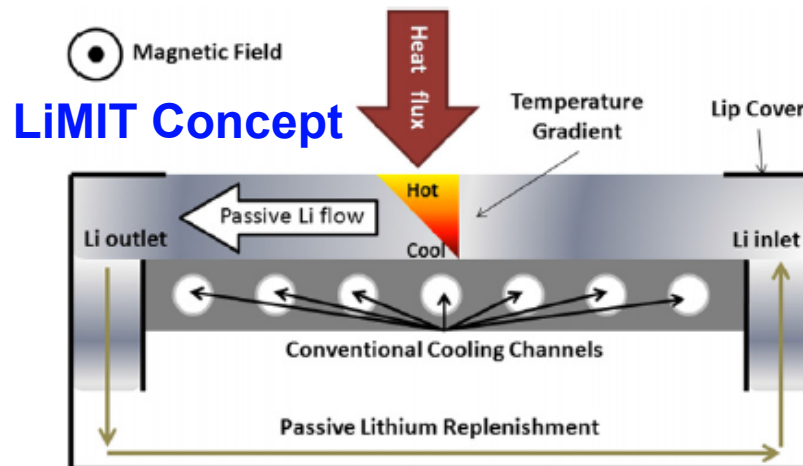


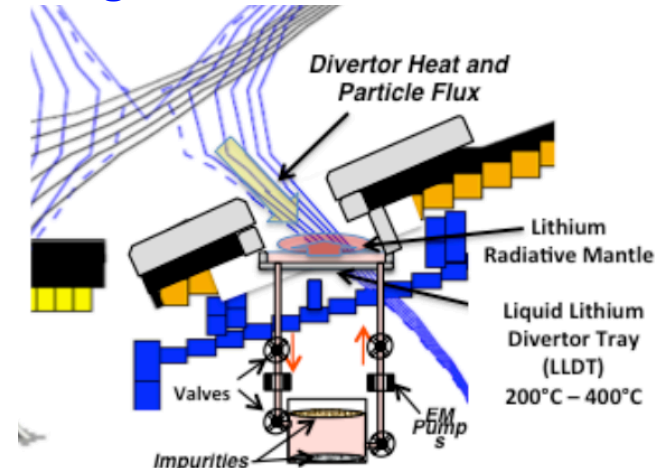
Figure 1. View of the 100 μm (mkm) CPS with (A) and without (B) Li filling (top).

Mirnov PPCF 2006



Ruzic NF 2011

Lithium vapor target NSTX



Ono FED 2012

Advantages:

Self annealing, good transient thermal response, ...

Disadvantages:

Extra complexity, pumping, temperature limits, corrosion, core impurities, ...

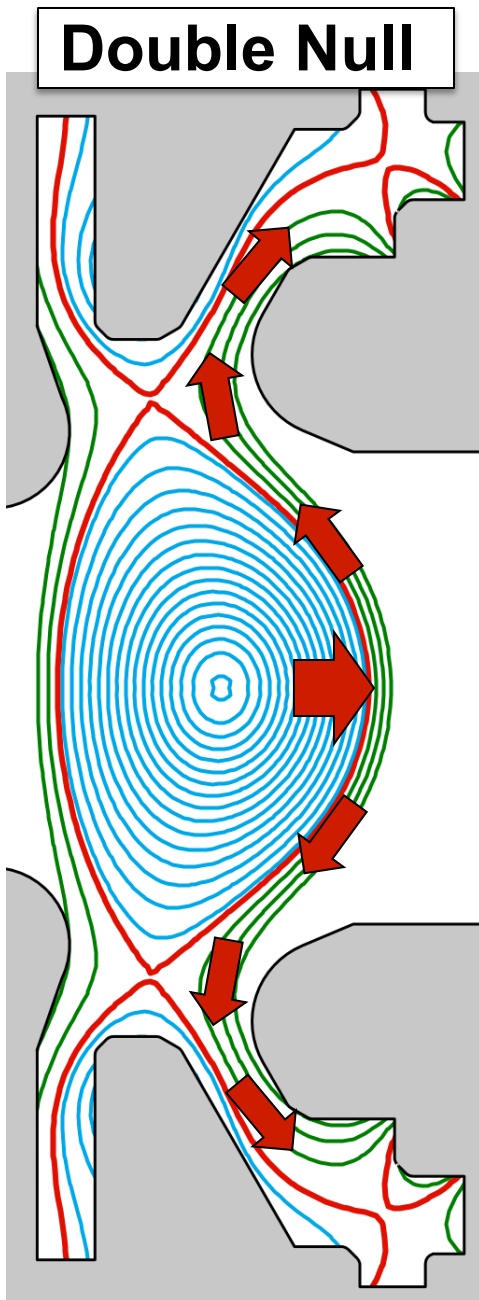
A divertor tokamak test facility is required to assess these ideas.

- Motivation & Mission for ADX
- Power & particle exhaust challenges
 - ITER
 - DEMO
- Potential solutions –
advanced magnetic divertors, ...
- **Potential solutions –
double-null + high-field side launch RF**
- Requirements for a divertor test tokamak
- ADX concept – version 1.0

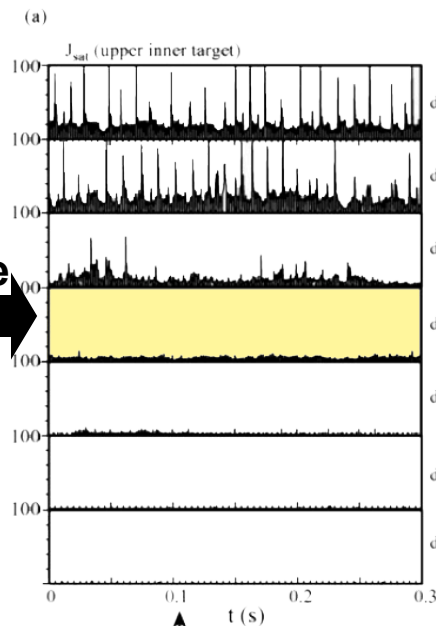
How else might magnetic geometry help?

=> Exploit the advantages of double null

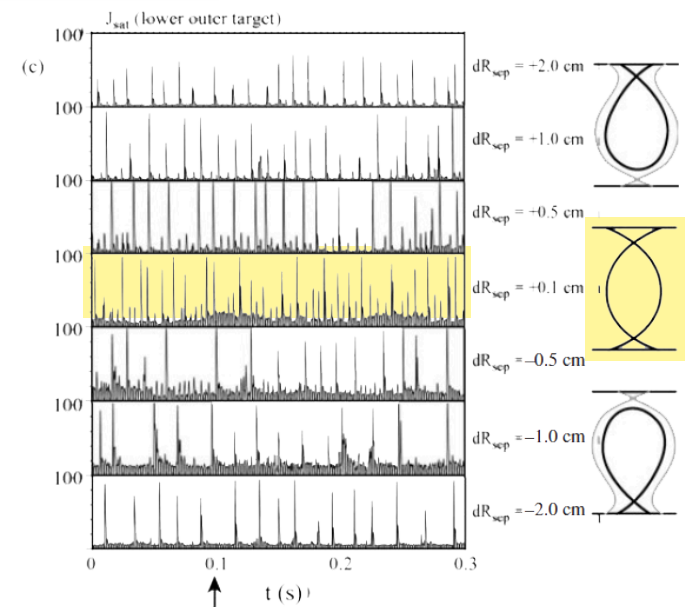
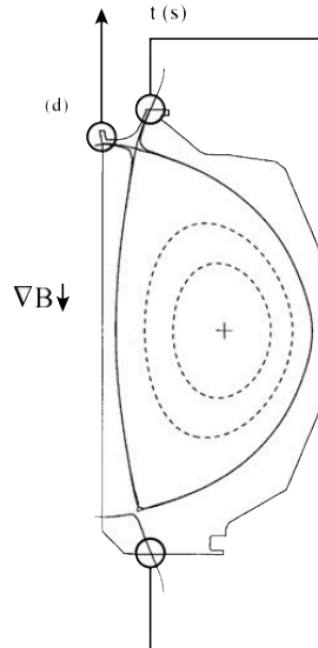
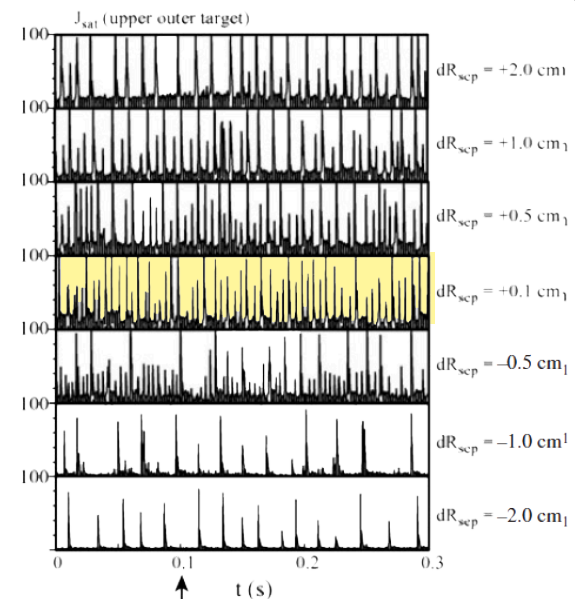
ELMs do not appear at high-field SOL in double null.



Double
null
case

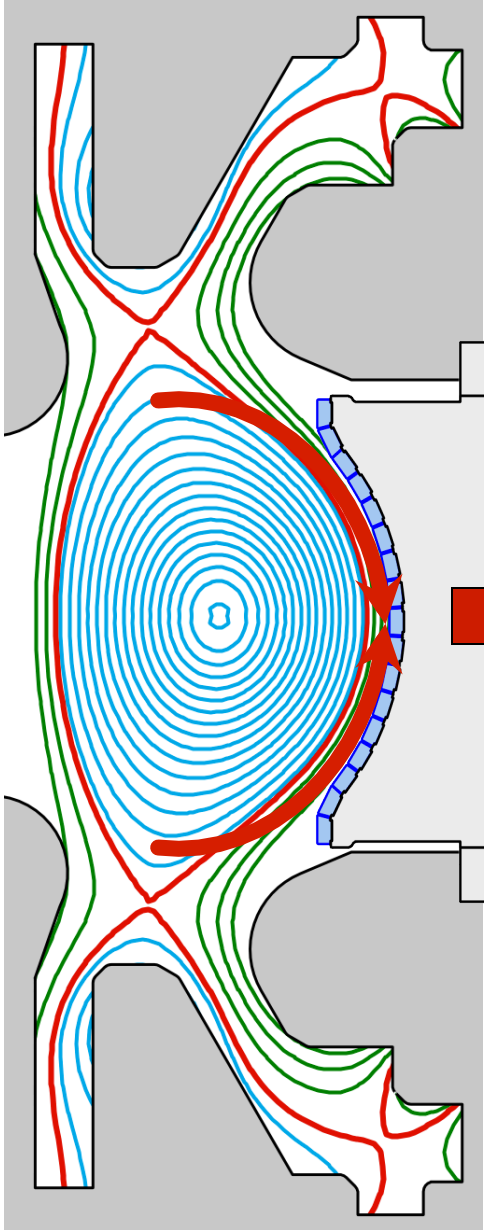


DIII-D – Petrie, NF 43 (2003) 910



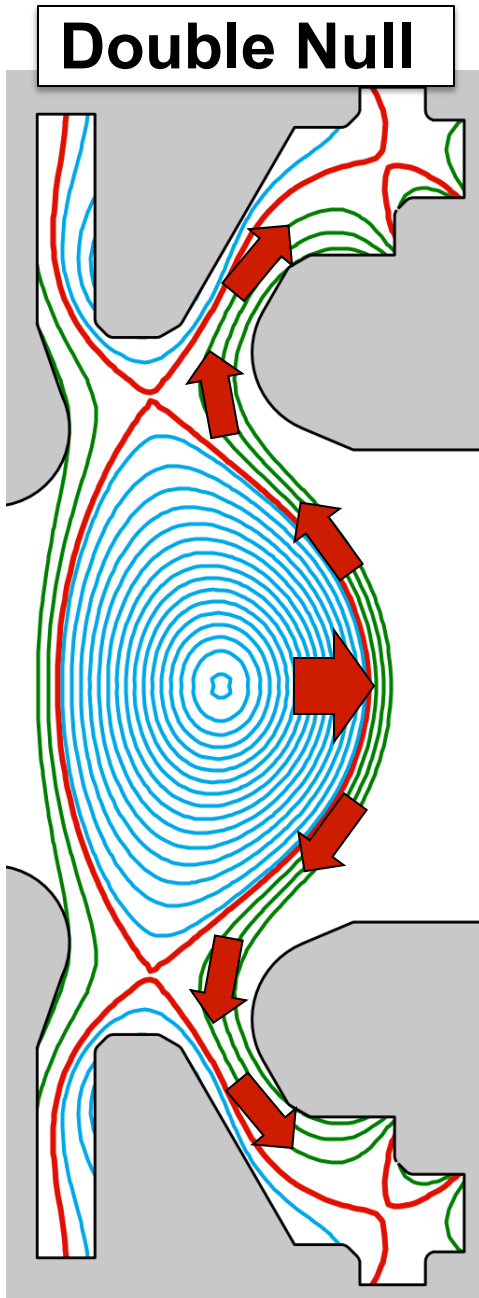
Energetic ion drift orbits enter low-field side scrape-off layer – damage to wall/antenna structures

Can be a serious problem for outboard limiters and ICRF antennas.



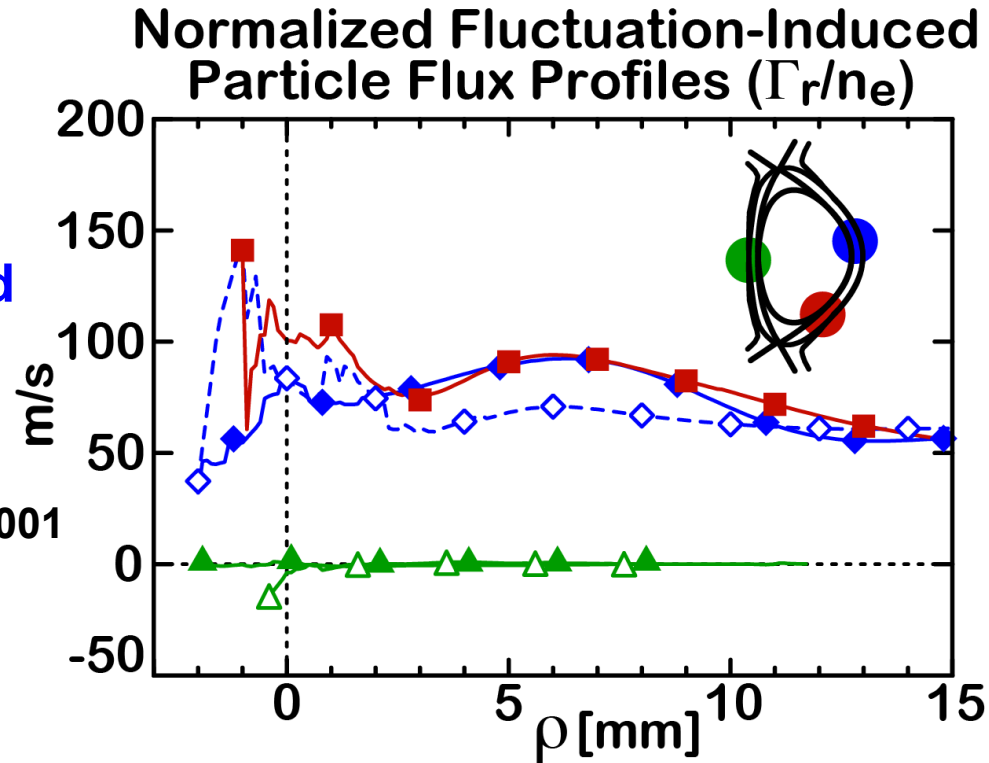
Alcator C-Mod G-H Limiter

High-field side SOL is quiescent. Radial transport is $\sim$ zero.
No 'blobs', ELMs or energetic ion loss.



Fluctuation-induced
radial transport is
essentially zero on
high field side.

Smick NF 53 (2013) 023001



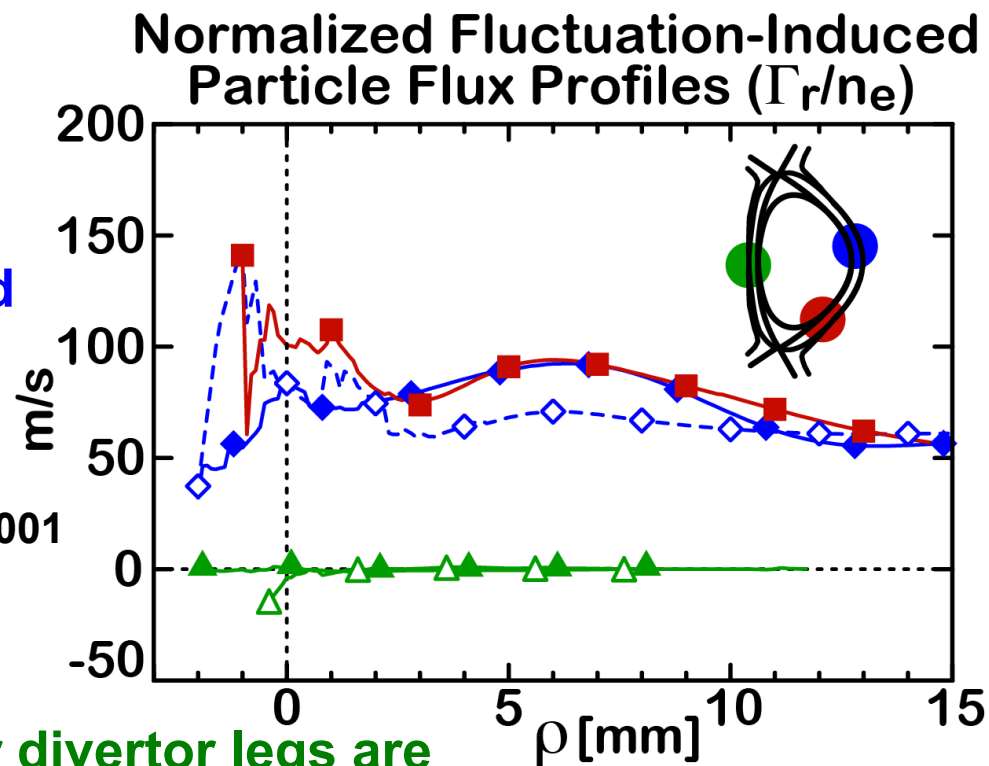
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Double Null

Fluctuation-induced radial transport is essentially zero on high field side.

Smick NF 53 (2013) 023001

Power-starved inner divertor legs are naturally detached at moderate and high core densities (with no x-point MARFE)



Double null topology: essential tool for power handling and plasma-material interaction control.

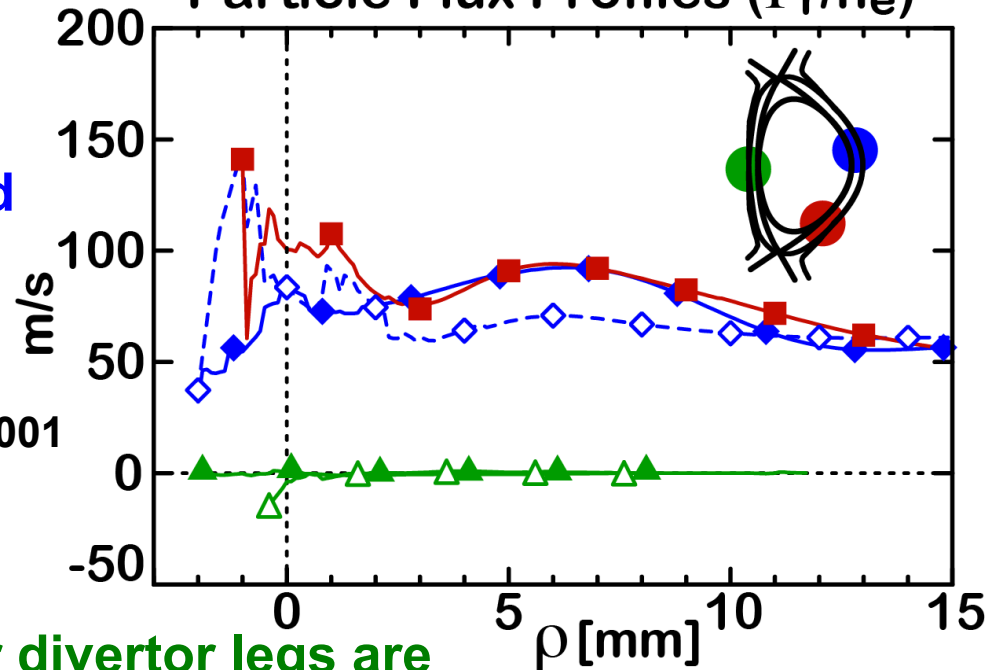
Double Null

Put RF antennas here

Fluctuation-induced radial transport is essentially zero on high field side.

Smick NF 53 (2013) 023001

Normalized Fluctuation-Induced Particle Flux Profiles (Γ_r/n_e)



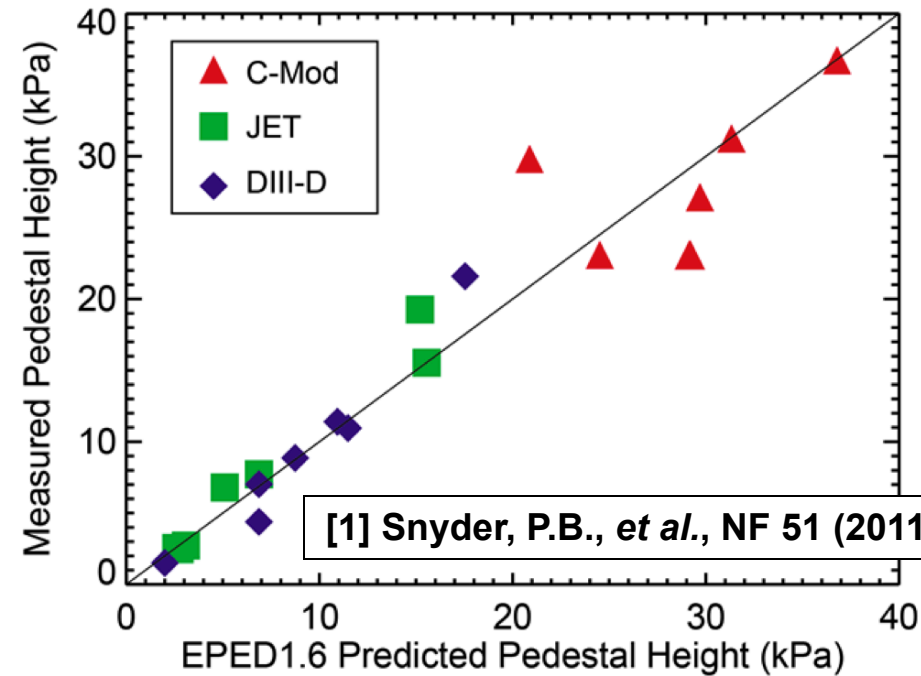
Power-starved inner divertor legs are naturally detached at moderate and high core densities (with no x-point MARFE)

Advantage:

- Solves heat exhaust for inner divertor legs
- Sends heat to the 2 divertor legs that can take it
- Creates low-PMI high-field SOL for RF actuators

- Motivation & Mission for ADX
- Power & particle exhaust challenges
 - ITER
 - DEMO
- Potential solutions –
advanced magnetic divertors, ...
- Potential solutions –
double-null + high-field side launch RF
- **Requirements for a divertor test tokamak**
- **ADX concept – version 1.0**

High magnetic field and power density are required to access reactor-level divertor conditions.



Edge plasma pressure is set by critical values of β_p , as demonstrated by the success of the EPED1.6 model¹ in simulating H-mode pedestal heights.

$$P_{ped} \sim B^2$$

Reactor-level SOL plasma pressures can be obtained only by operating at the same magnetic fields as a reactor (5 to 9 tesla).

Reactor-level SOL pressures facilitates reactor level divertor densities...

$$P = n(T_i + T_e); T_e \sim 10 \text{ eV}; T_i \sim T_e$$

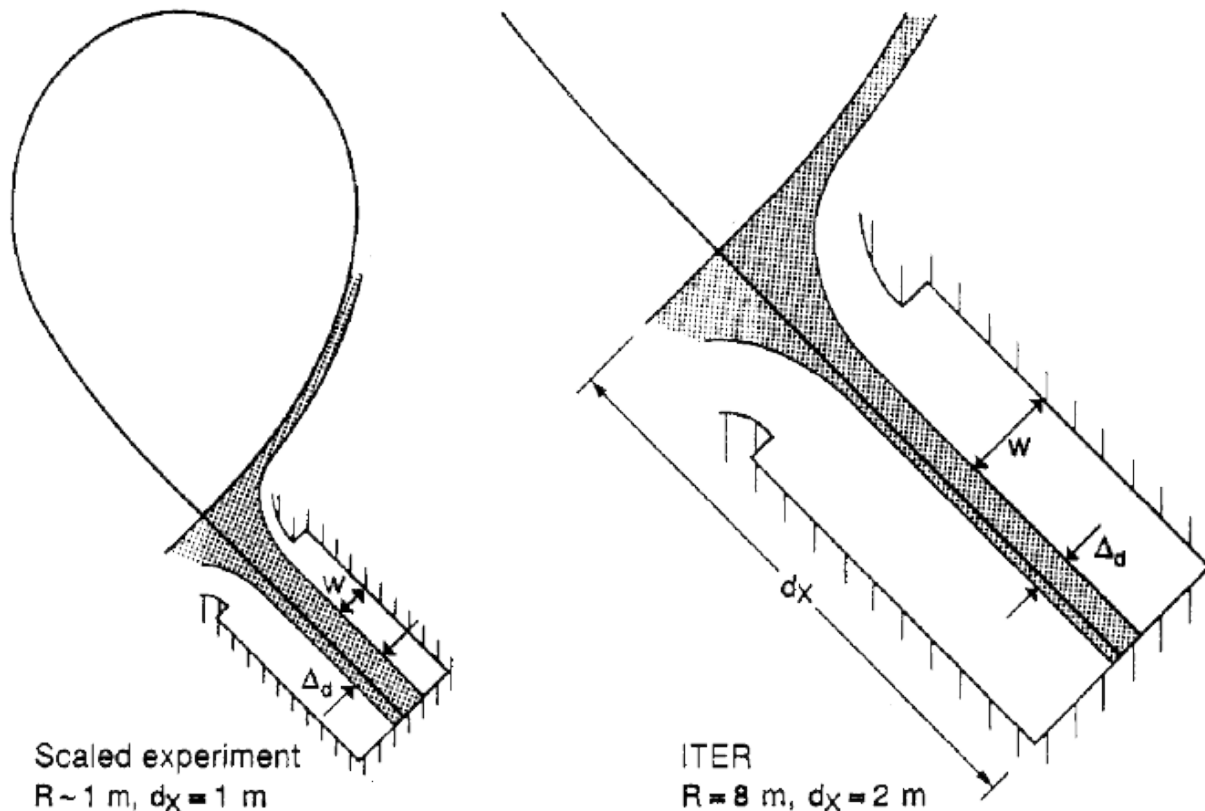
$$\Rightarrow n > \sim 10^{21} \text{ m}^{-3}$$

...which is required to access the relevant divertor and PMI regimes^{2,3}.

[2] Stangeby, NF 51 (2011) 063001. [2] Whyte, FED 87 (2012) 234.

High magnetic field and power density are required to access reactor-level divertor conditions.

With $q_{//}$ and B being the same as in a reactor, complete divertor similarity with a reactor may be obtained.¹



[1] Hutchinson and Vlasses, NF 36 (1996) 783.

$q_{//} = \text{reactor}$

$B = \text{reactor}$

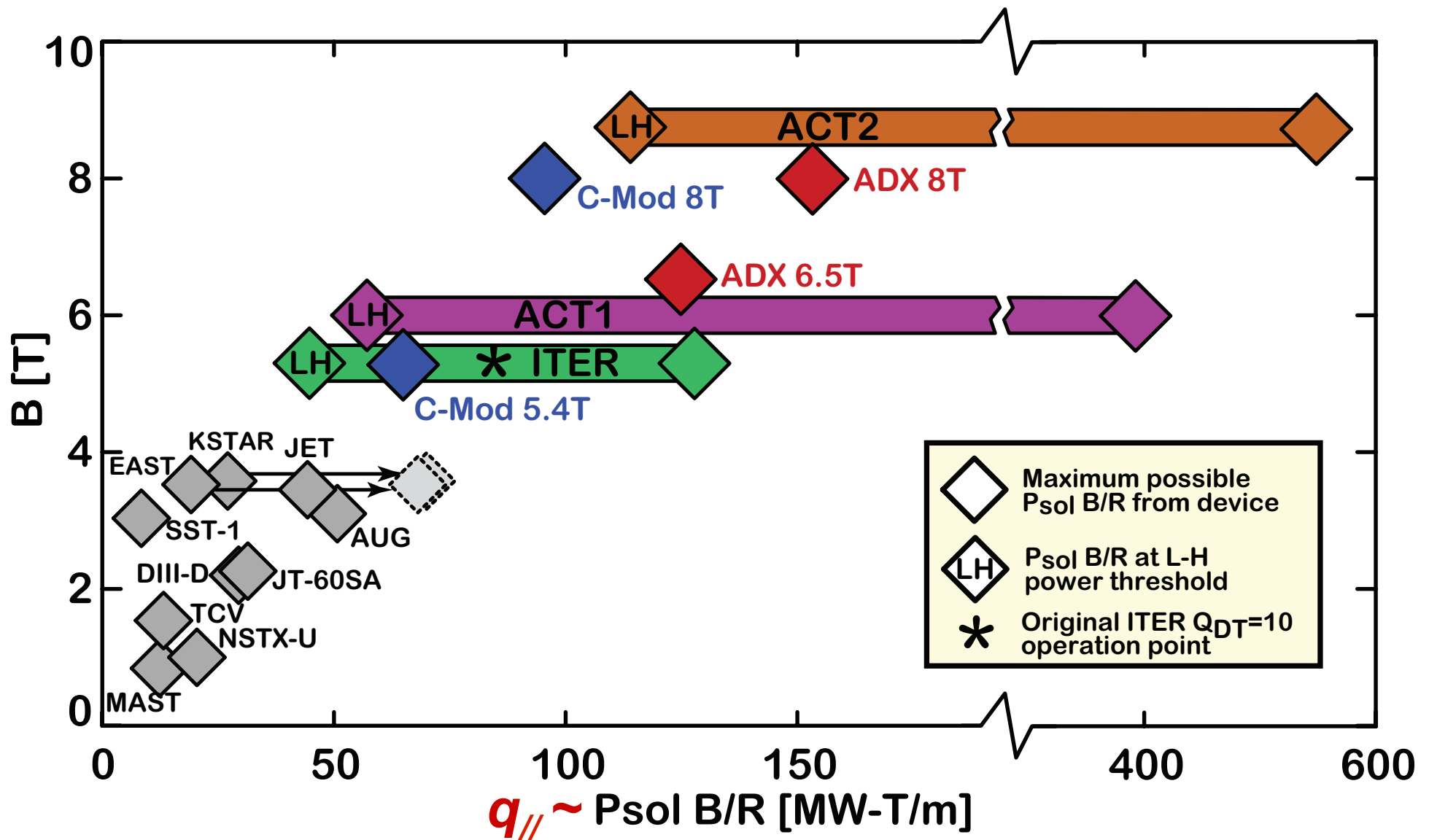
$\Rightarrow$ plasma and atomic physics dimensionless parameters in the divertor ...

$$T_e, \nu^*, \rho^*, \beta, \lambda_0 / \Delta_d$$

...may be made identical by adjusting poloidal flux expansion and divertor leg length.

Not a 'wind-tunnel' scaling experiment, but a simulation experiment

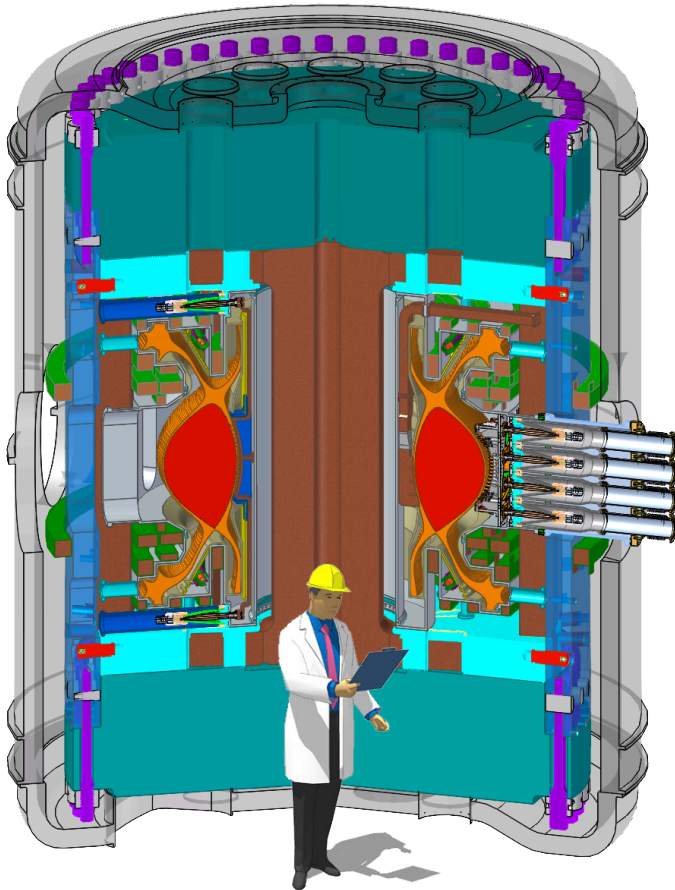
A high-field, compact, high power density tokamak is the ideal tool for the job



ADX -- the MIT PSFC is considering a concept for a high-power, advanced divertor test facility*



Advanced Divertor Experiment



ADX	
Major/Minor Radius	0.73 / 0.2 m
Elongation	1.7
Magnetic Field	6.5 Tesla (8 Tesla)
Plasma Current	1.5 MA (2 MA)
P_{AUX}	10 MW ICRF 4 MW LHCD
Surface Power Density	$\sim 1.7 \text{ MW/m}^2$
$P_{AUX} B/R$	125 MW-T/m
Advanced Divertor Concepts	Vertical target; Snowflake; Super-X; X-point target; Liquid metal target
Divertor and first-wall material	Tungsten/ Molybdenum
Pulse Length at max field	3s, with 1s flat-top

Key Elements:

- Demountable, LN₂ cooled, copper TF magnet

- Vertically-extended VV

- Advanced divertor poloidal field coil sets (top and bottom)

- High power ICRF

- Reactor-level, λ_q , $q_{||}$ and plasma pressures

$$P_{aux} B/R \sim 125$$

=> same as ITER, $Q_{DT}=10$

- Development platform for low PMI RF actuators:
 - Inner-wall LHCD
 - Inner-wall ICRF

*http://burningplasma.org/web/fesac-fsff2013/whitepapers/LaBombard_B.pdf

ADX

Advanced Divertor Experiment



“But, ADX is conceived as a short-pulse experiment. How is that relevant for developing steady-state solutions?”

ADX -- short pulse is the right R&D platform to identify solutions scalable to steady-state

Advanced Divertor Experiment

ADX

“But, ADX is conceived as a short-pulse experiment. How is that relevant for developing steady-state solutions?”

$\tau_{\text{pulse}} \gg \tau_E, \tau_p$ – SS power and particle exhaust established

- Develop/assess SS power & particle exhaust handling solutions, impurity behavior, feedback control, core performance,...

$\tau_{\text{pulse}} \gg \tau_{\text{PMI}}$ – SS erosion/redeposition fluxes established

- Measure SS erosion/rep. and ion-induced material damage rates (divertor and RF actuators) at relevant PMI dimensionless parameters – L_{MFP}/ρ_z , $L_{\text{MFP}}/L_{\text{Debye}}$, ...

$\tau_{\text{pulse}} > \sim 5\tau_{\text{CR}}$ – fully relaxed current profile

- Develop SS-relevant RF current drive, heating techniques and ops scenarios

$\tau_{\text{pulse}} < \tau_{\text{thermal}}$ – first-wall components “inertially-cooled”

- Advantage: surface heating at $\sim 40\text{MW/m}^2$, 1 s pulse with no damage; avoids cost and complexity of SS cooling requirements

ADX -- short pulse is the right R&D platform to identify solutions scalable to steady-state

Advanced Divertor Experiment



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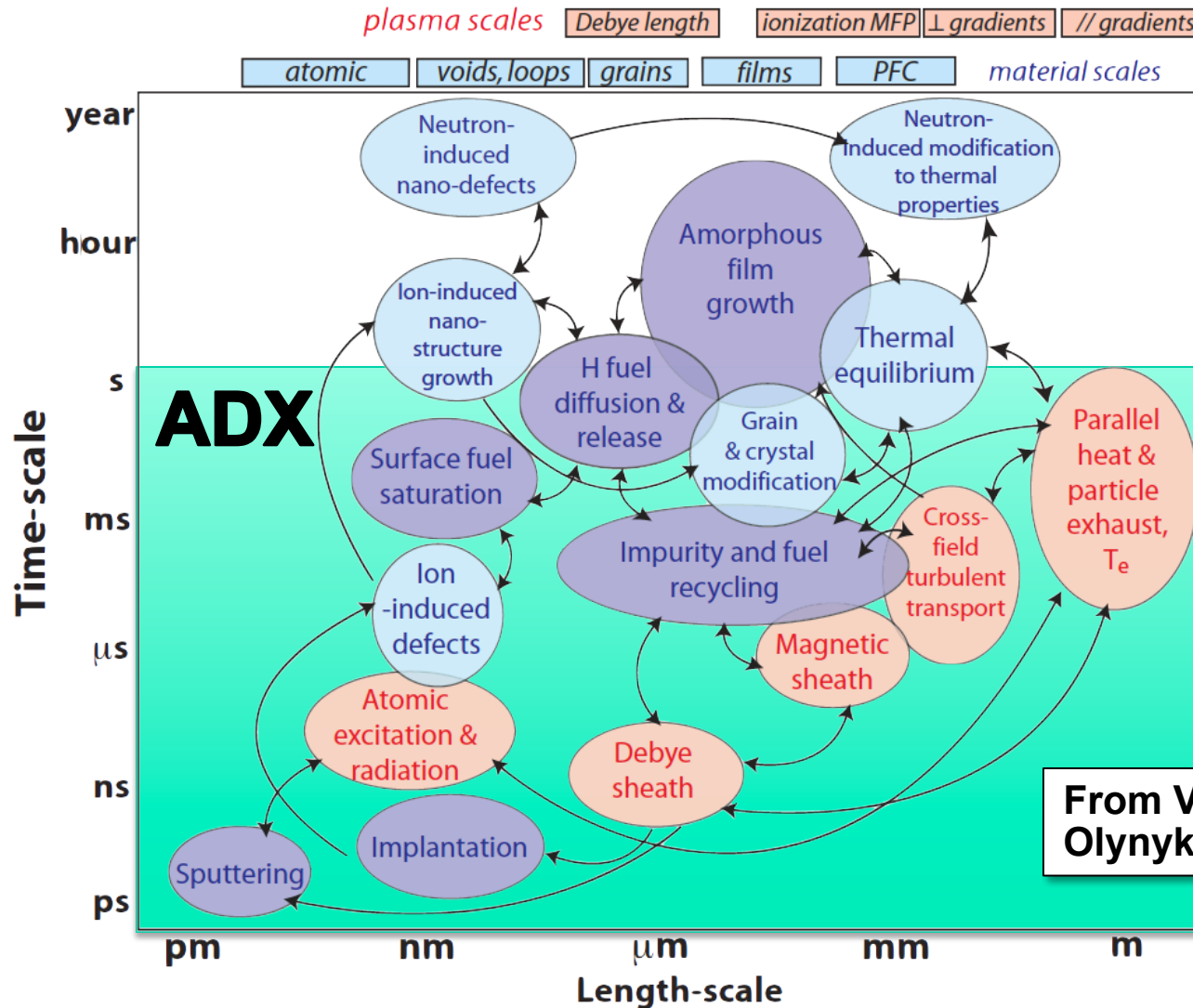
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Does not address: thermal equilibrated materials, long-time film growth, surface modification at very large fluence, or neutrons ...

ADX → develop plasma physics solutions that scale to SS

ADX -- short pulse is the right R&D platform to identify solutions scalable to steady-state

Advanced Divertor Experiment



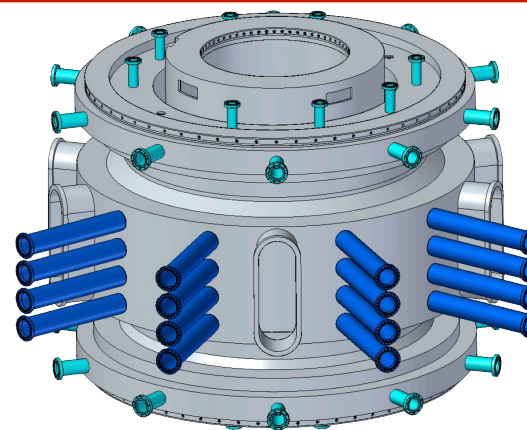
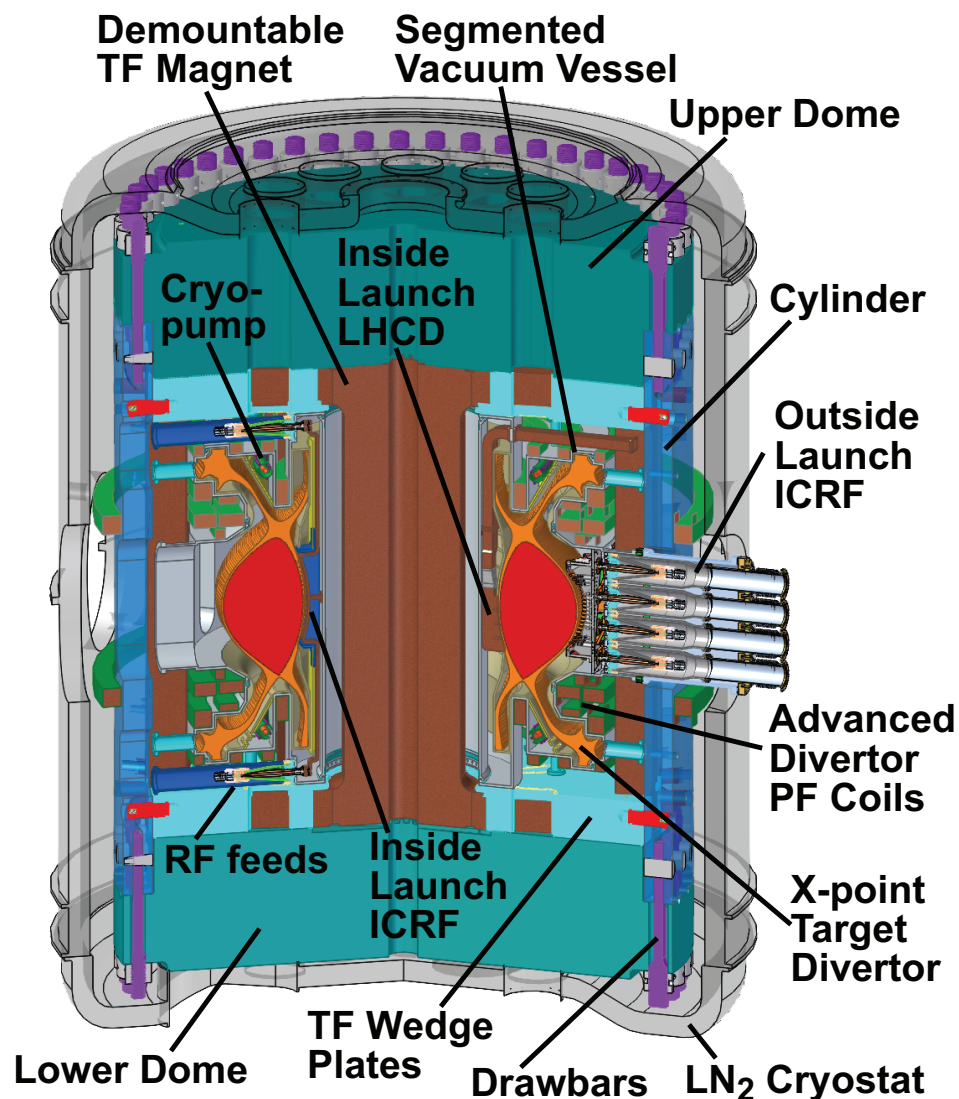
From VULCAN study:
Olynyk, et al., FED 87 (2012) 224.

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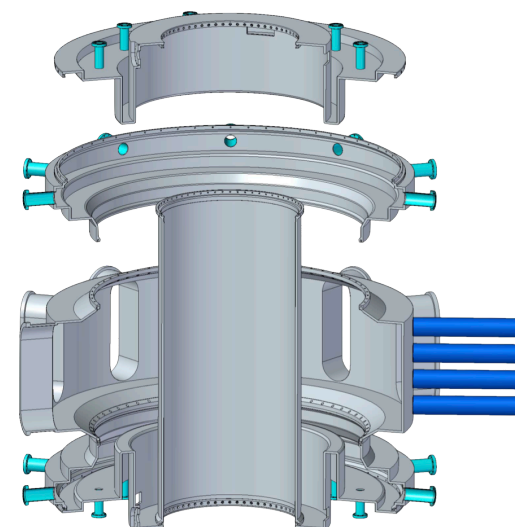
ADX → develop plasma physics solutions that scale to SS

ADX -- demountable, high-field TF magnet

Advanced Divertor Experiment is key enabling technology...



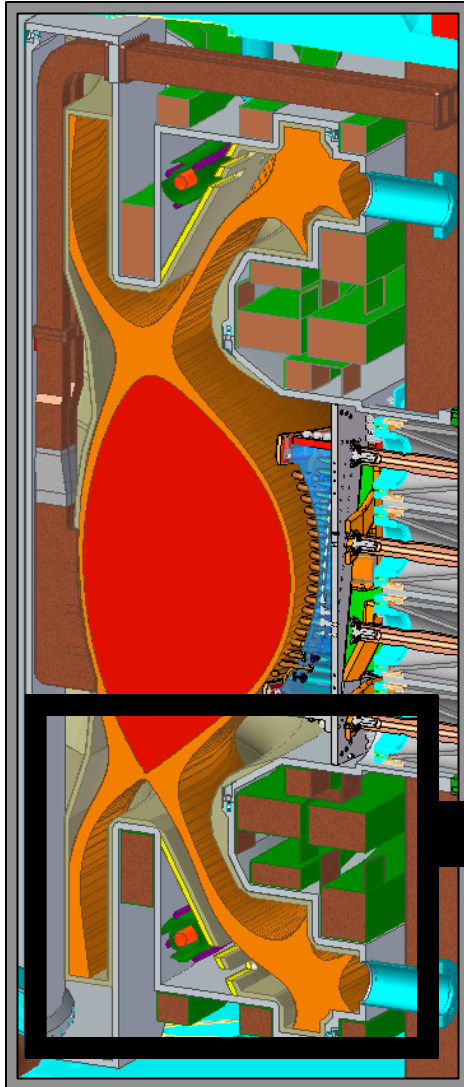
Reconfigurable, segmented VV, with PF coils inside TF magnet/superstructure



Most internal components (tiles, diagnostics, RF feeds, cryopumps) installed and tested off-line during assembly of integrated vacuum-vessel/PF coil unit.

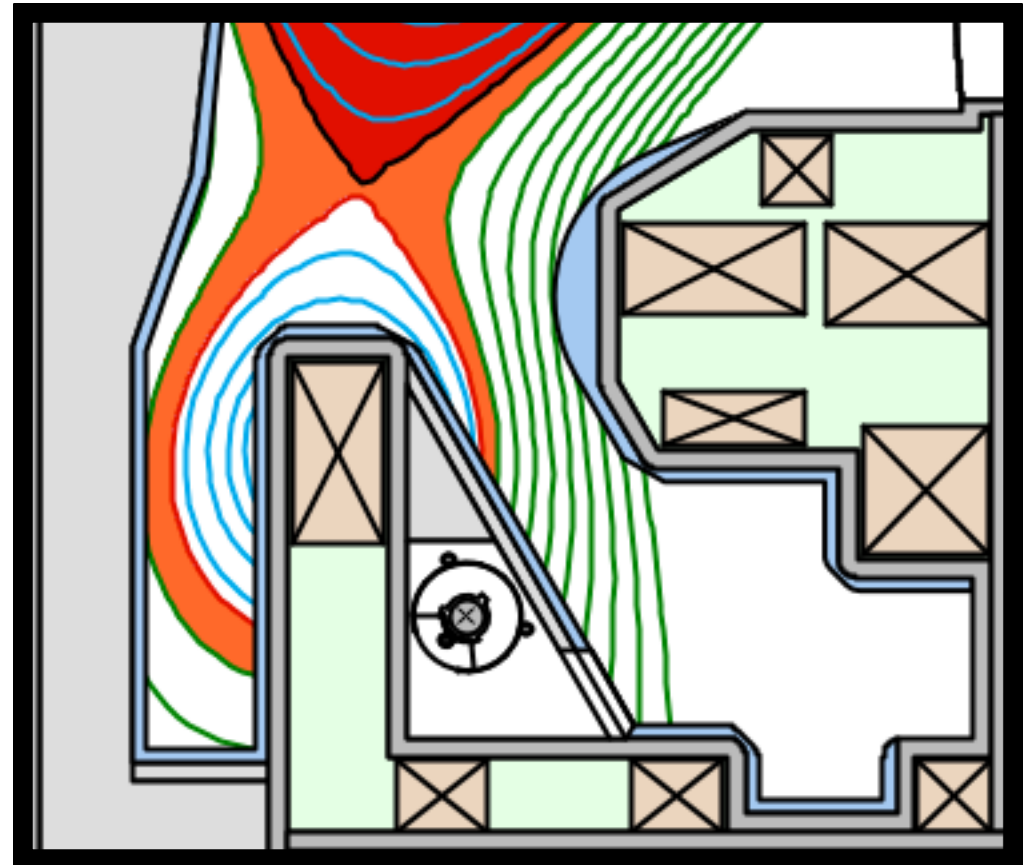
ADX -- vacuum vessel and PF coil set customized for physics/technology mission

Advanced Divertor Experiment



Configure internal PF coils to
*test the most promising magnetic
geometries and divertor targets.*

‘ASDEX’

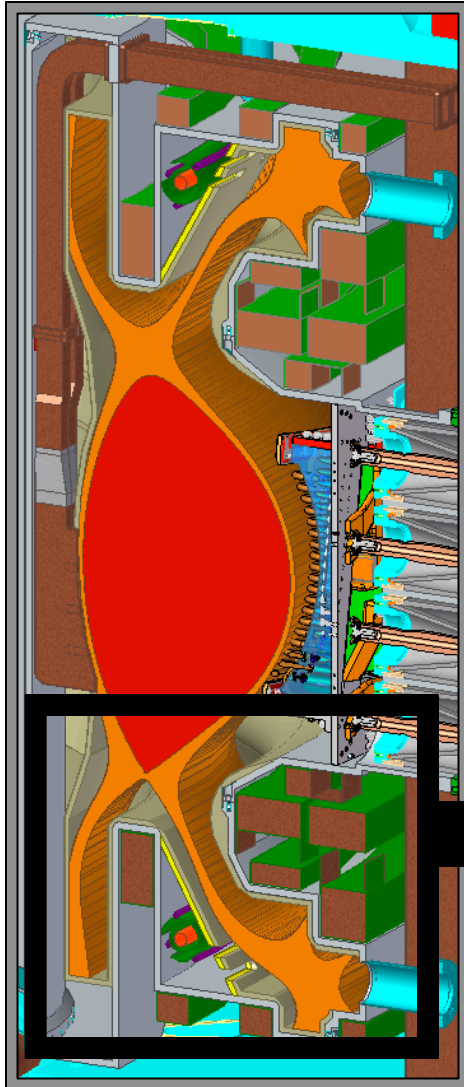


Grad-Shafranov equilibria
obtained using ACCOME (Selene)¹

[1] Tani et al., J. Comp. Phys. 98 (1992) 332.

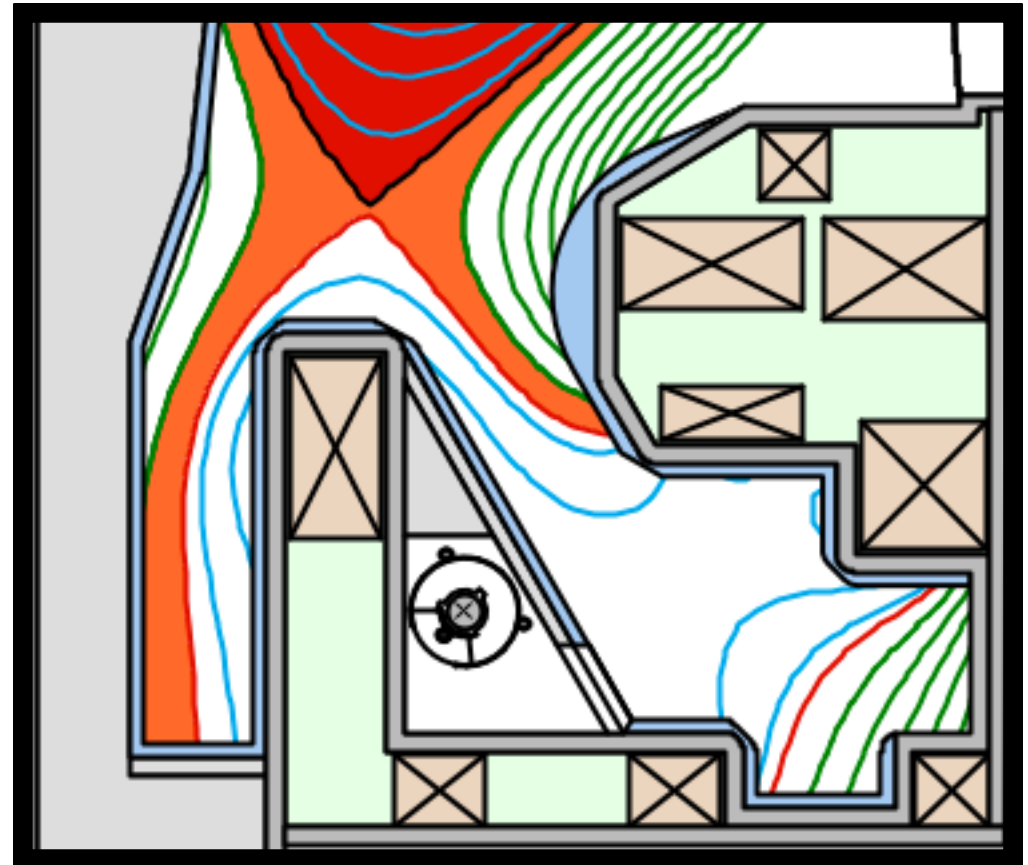
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Advanced Divertor Experiment



Configure internal PF coils to
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Vertical Target

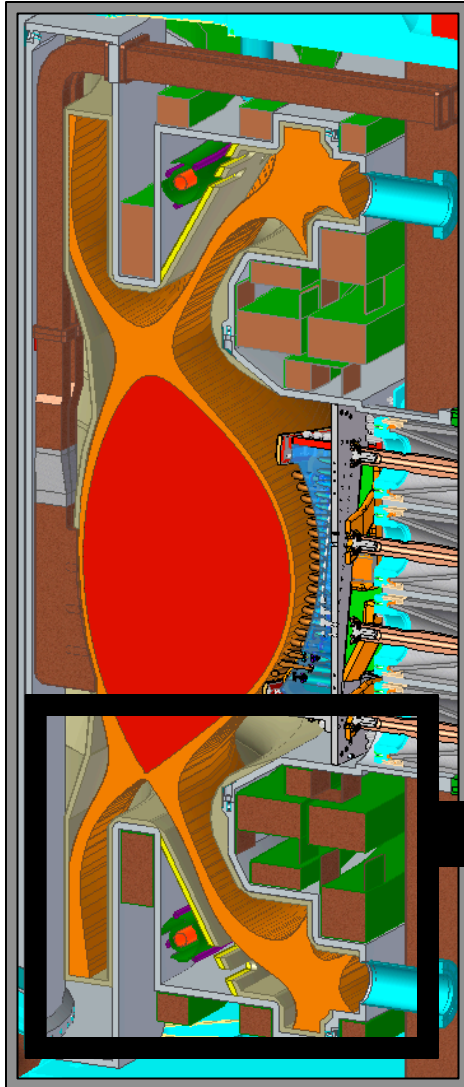


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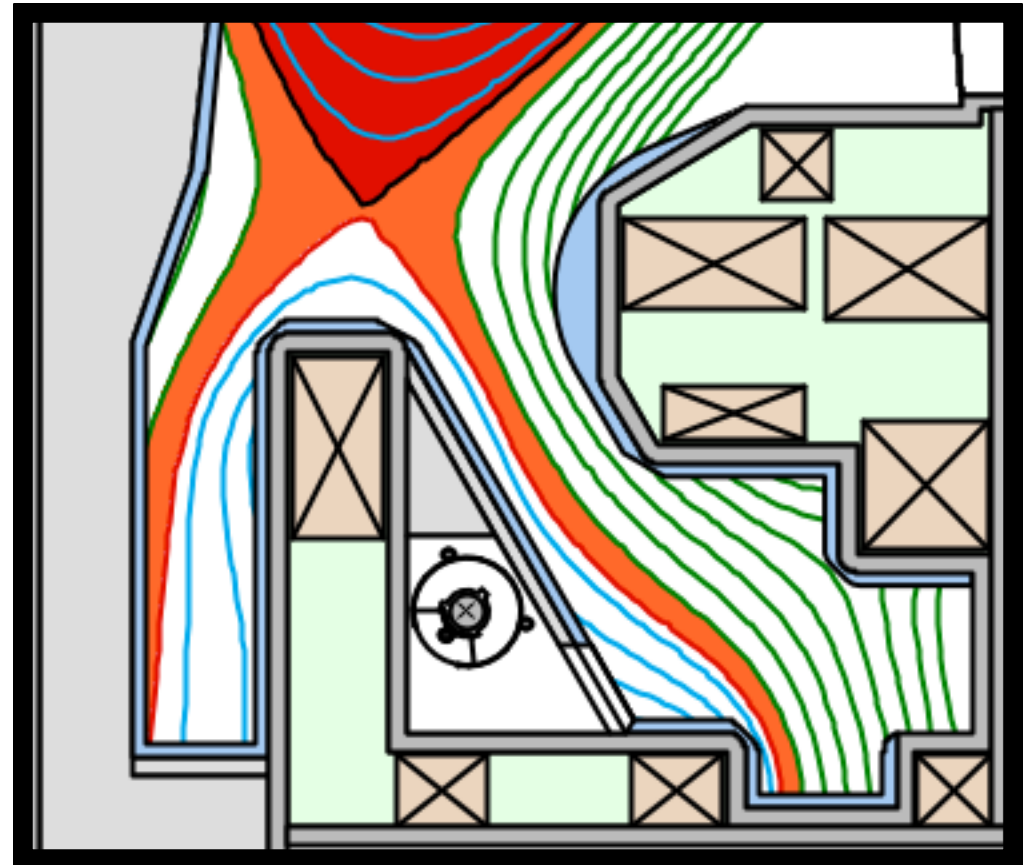
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Advanced Divertor Experiment



Configure internal PF coils to
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Long Leg

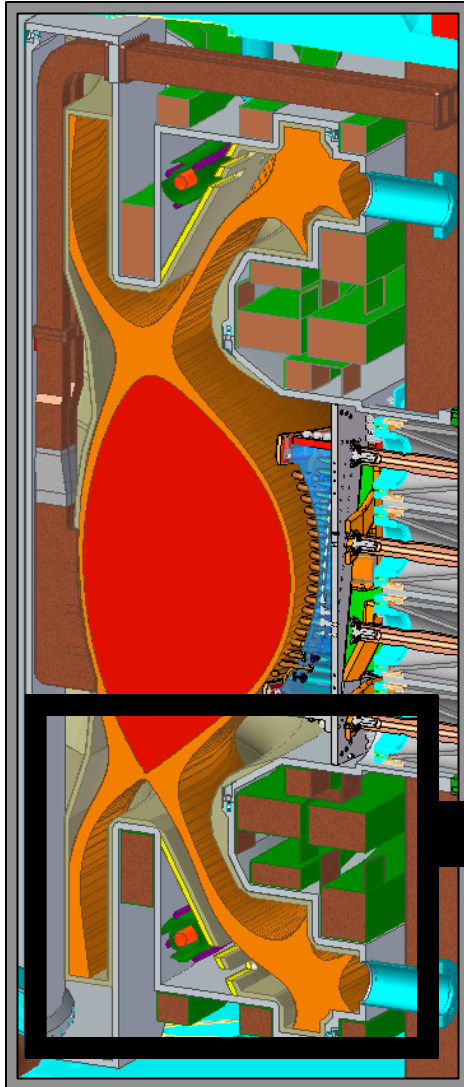


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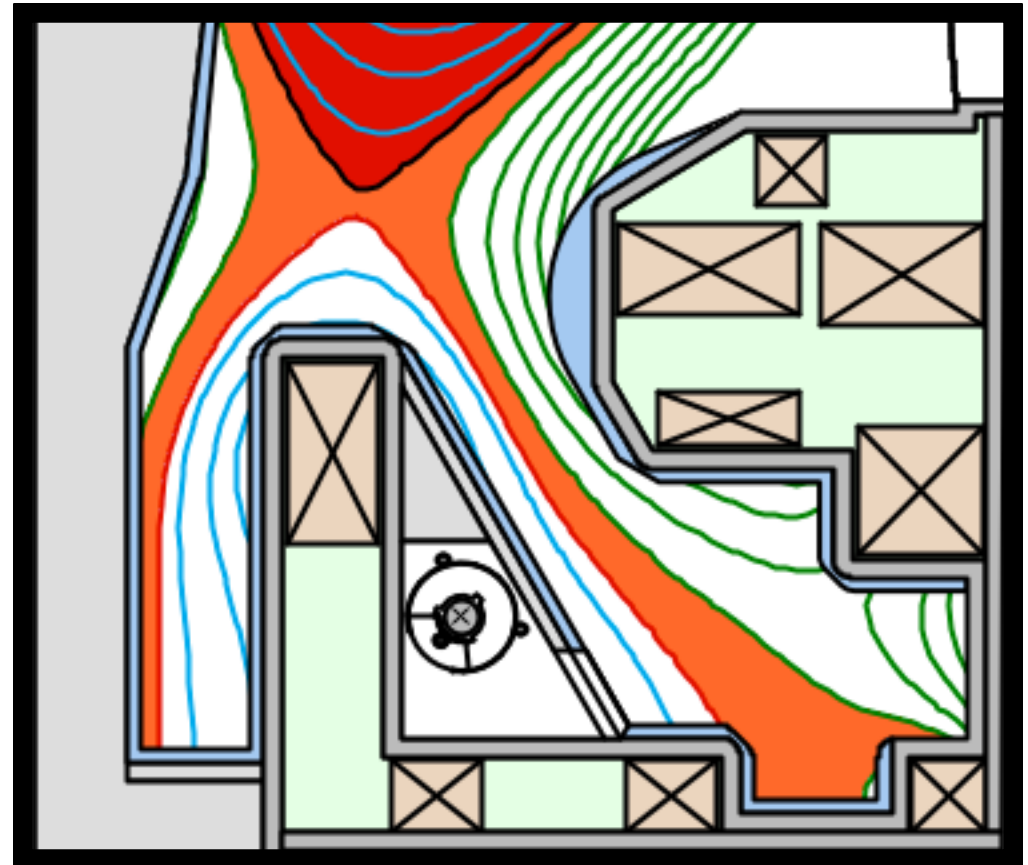
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Advanced Divertor Experiment



Configure internal PF coils to
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Super X

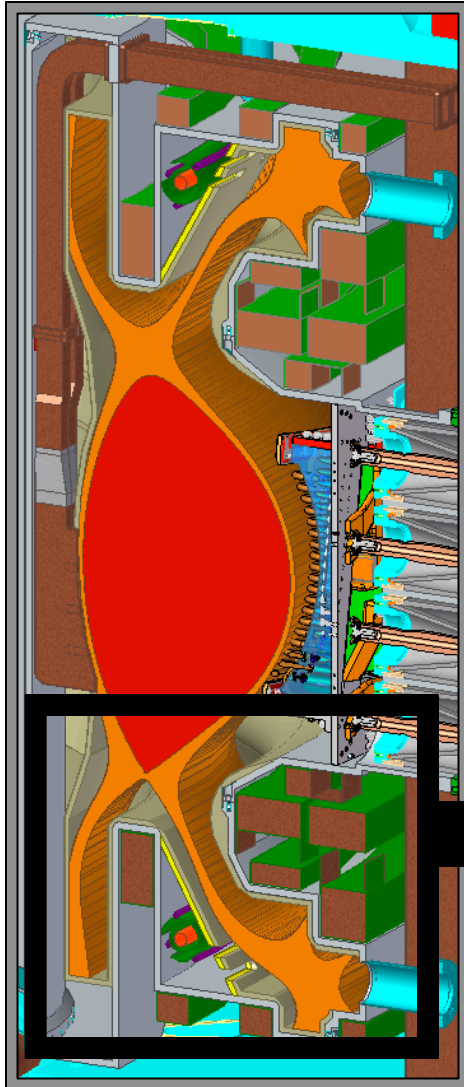


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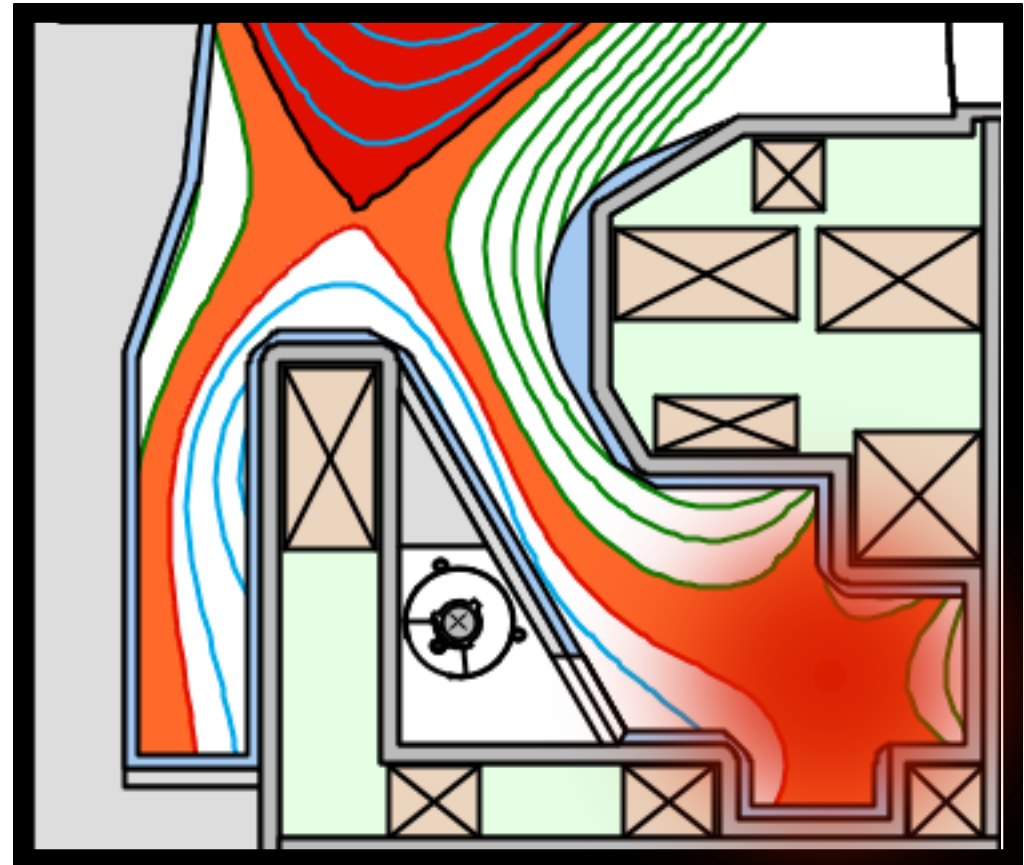
ADX -- vacuum vessel and PF coil set customized for physics/technology mission

Advanced Divertor Experiment



Configure internal PF coils to
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X-point Target



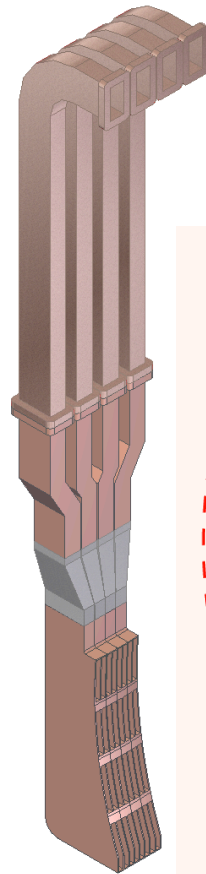
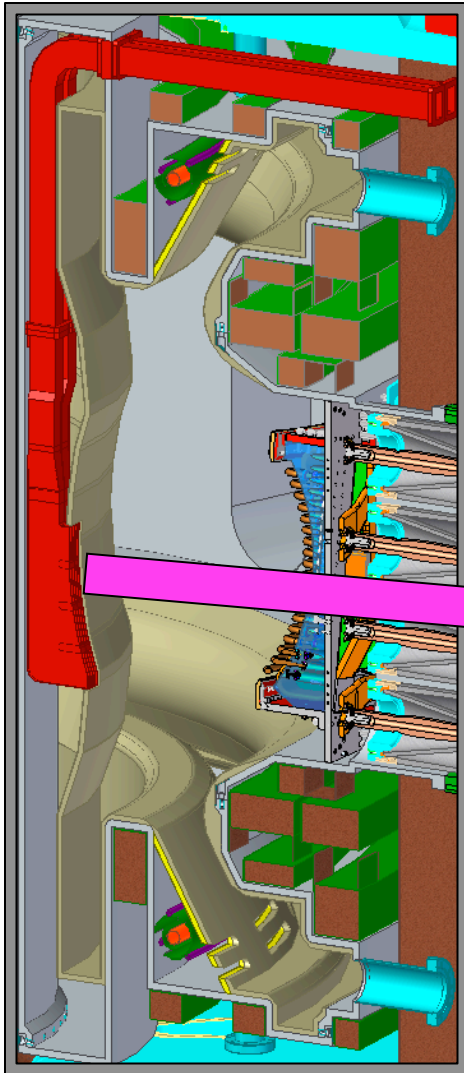
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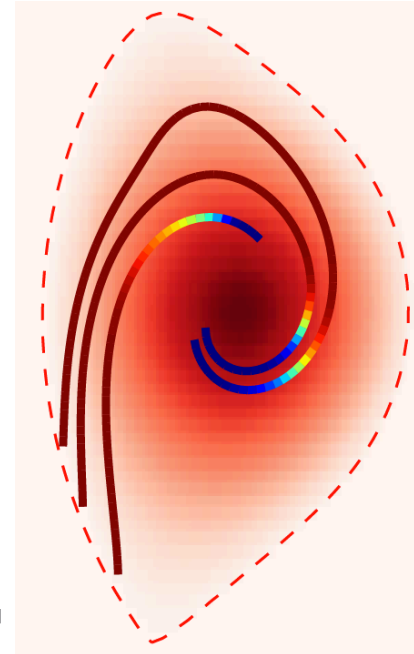
ADX -- provide integrated test platform for low PMI, reactor-compatible RF actuators

Advanced Divertor Experiment

ADX



Splitter and multi-junction fabrication techniques produce compact LHCD launchers that can fit on the inside wall.



- **High B-field side**
=> lower $n_{||}$
=> penetrating rays¹
=> higher CD efficiency (60% increase³)
- **Quiescent SOL**
=> Low PMI
=> Excellent impurity screening²

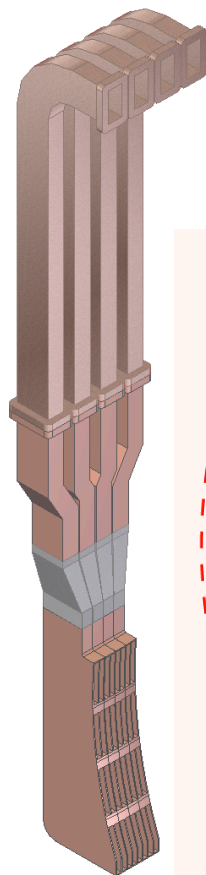
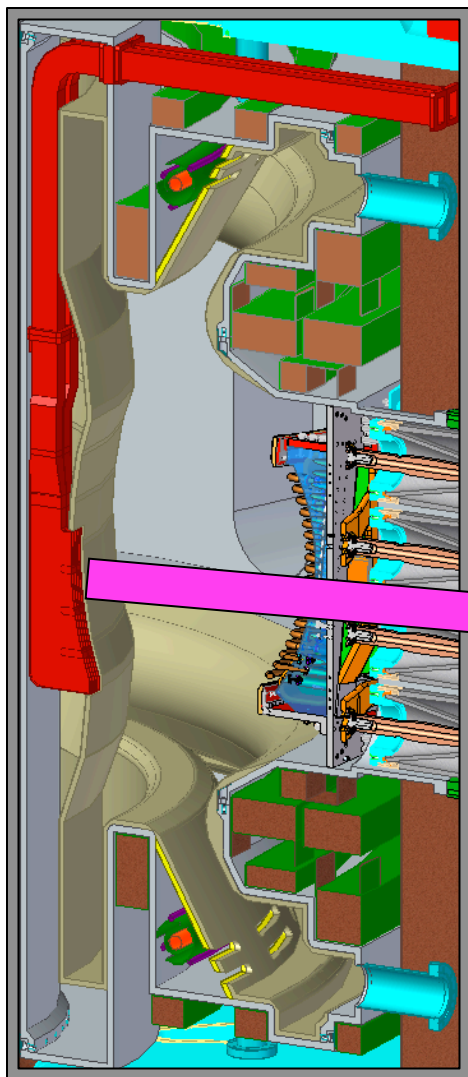
High field side launch is highly favorable for LHCD, as noted in VULCAN study³.

[1] GENRAY modeling by Syun'ichi Shiraiwa: $n_{||}=1.6$, Alcator C-Mod I-mode

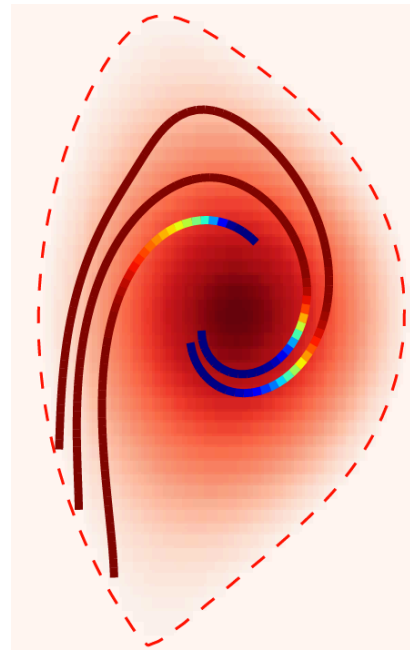
[2] McCracken, et al., PoP 4 (1997) 1681. [3] Podpaly, et al., FED 87 (2012) 215.

ADX -- provide integrated test platform for low PMI, reactor-compatible RF actuators

Advanced Divertor Experiment



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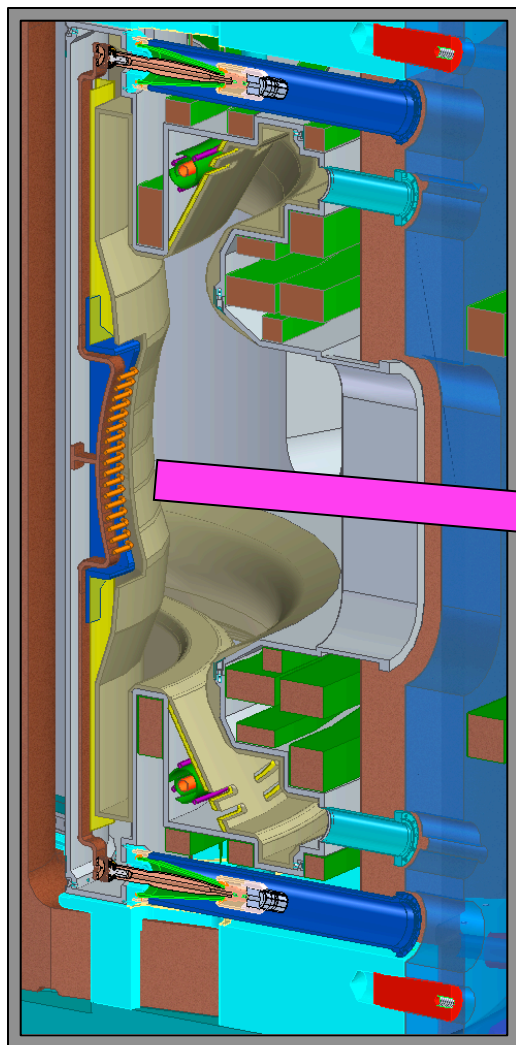
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★ **Challenge #4:** Demonstrate low PMI, reactor-compatible current drive and heating technologies

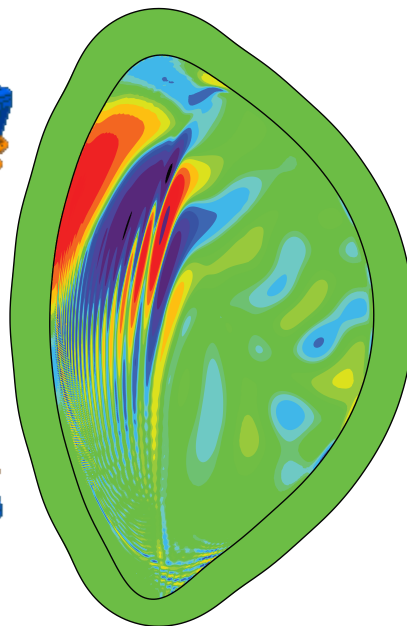
ADX -- provide integrated test platform for low PMI, reactor-compatible RF actuators

Advanced Divertor Experiment



**Integrated vacuum vessel,
designed for tests of inside-launch ICRF**

Re(E_z)



- **High B-field side**
=> Reduced energetic ion impact on antenna structures
- **Quiescent SOL**
=> Low PMI
=> Low neutral pressures
=> Excellent impurity screening

**FW mode-conversion to IBW with
efficient flow drive and heating¹**

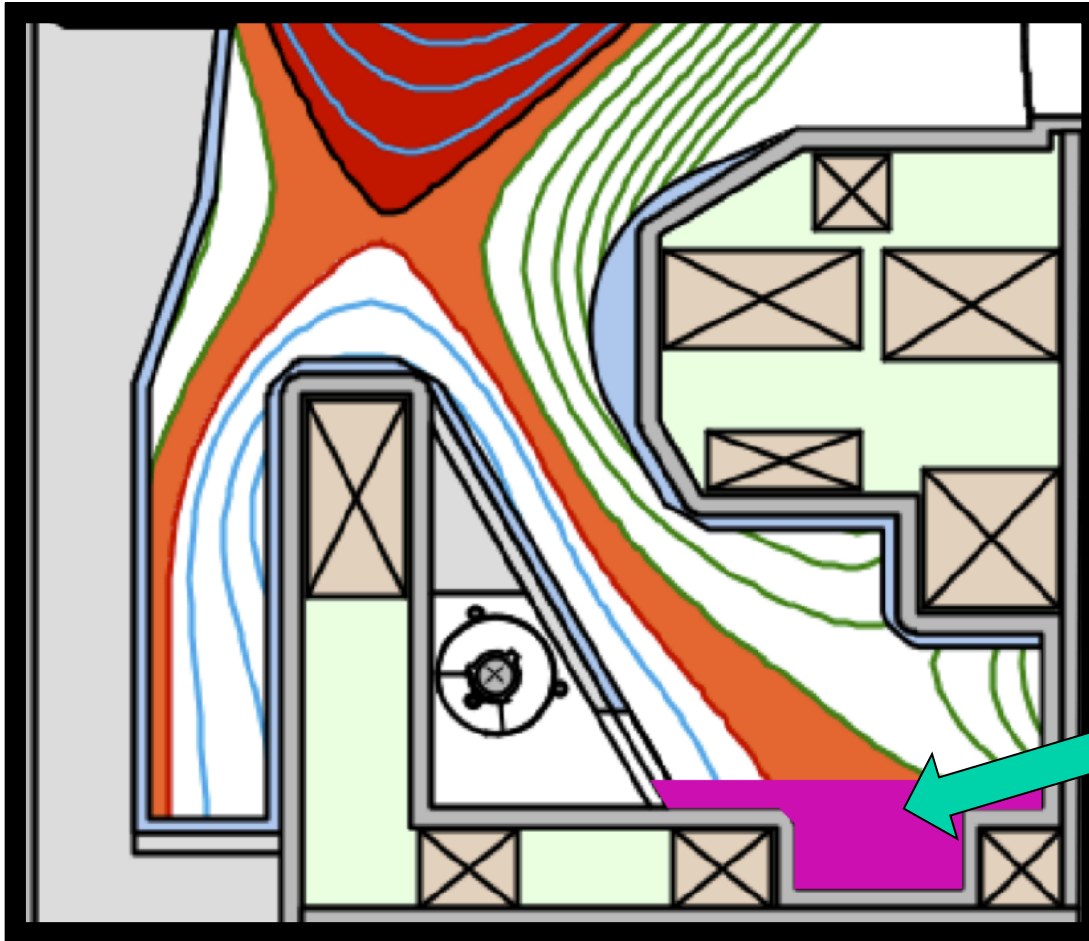
TORIC simulation: $B = 5.4$ tesla, $f = 80$ MHz, 15% H in D, $n_\phi = -10$, 40% to electrons, 30% to H 1st harmonic and 30% to D 2nd harmonic

[1] TORIC modeling by Yijun Lin

★ **Challenge #4:** Demonstrate low PMI, reactor-compatible current drive and heating technologies

ADX -- provide test platform for advanced target materials, including liquid metals

Advanced Divertor Experiment



PMI response of high temperature divertor targets (tungsten, liquid metals) may be tested.

Long-leg divertors work very well with liquid metal target concepts.

★ **Challenge #5:** Determine high-temp PMI response and core plasma compatibility of candidate divertor target materials at reactor-level parameters

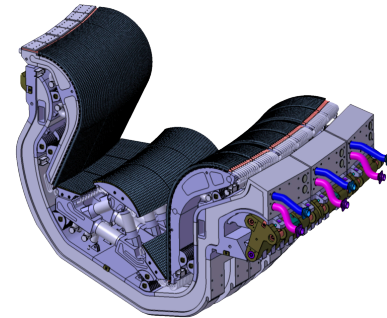
Summary



Boundary/divertor physics & PMI will ultimately determine the viability of a fusion reactor and its performance

Evidence: ITER is highlighting critical issues in power handling.

The jump from ITER to DEMO is extreme; plasma physics solutions must be found for power handling, material erosion issues and RF actuators compatible with burning plasma



Advanced magnetic divertors + geometry have potential to solve these problems.

A divertor test facility is critically needed to demonstrate plausible solutions at reactor conditions.

ADX can accomplish that mission.

