Advanced Divertor Test Facility – Alcator DX

- Motivation
- Snowflake, XD, SXD and XPT concepts
- Possible implementations of SXD and XPT in an Alcator package

Presented by Brian LaBombard
for the Advanced Divertor Team

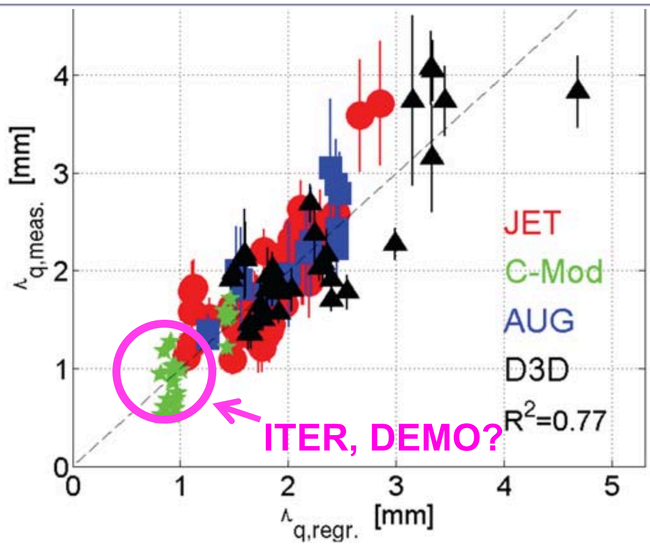
Motivation#1: Magnetic fusion is facing a potential power-handling roadblock

Alcator DX

Recent results from a multi-machine database project to extremely narrow heat flux channel widths in a reactor (caveat: *low divertor recycling*, H-mode conditions)

Heat flux power channel width appears to be independent of machine size – depends only on B_{pol}

$$\lambda_q(mm) = (0.7 \pm 0.2) \cdot B_{tor}^{-0.8\pm0.1} \cdot q_{95}^{1.05\pm0.2} \cdot P_{SOL}^{0.1\pm0.1} \cdot R_{geo}^{0\pm0.1}$$



Eich, *et al.*, IAEA, 2012

→ **λ_q ~ 1 mm in ITER? (!)**
1/5 of 'planned' value

λ_q ~ 1 mm also in DEMO?
with x4 power exhaust!

Even if ELMs are eliminated, standard divertor solutions, employing high poloidal flux expansion, do not look credible for a reactor – just on power density considerations alone.

Note: Scaling implies that C-Mod has same λ_q (B_p) as ITER/DEMO.
C-Mod can also achieve P/S ~ 1 MW/m², similar to a DEMO.

Motivation#2: Magnetic fusion is facing a potential material erosion roadblock

Even if the power handling challenge could be met with a conventional divertor, the requirements for material erosion/ redeposition control is nearly impossible to meet.

~10 MW/m^2 SS heat removal requires < ~5 mm thick armor plate.

This restricts net tungsten erosion < 1 mm/year (Γ_W ~ 2x10^{18}/m^2/s).

But plasma ion flux is high ($\Gamma_{i,\perp}$ ~ 1-2x10^{24}/m^2/s) requiring **$\Gamma_W/\Gamma_{i,\perp} < 10^{-6}$**.

B. Lipschultz, PSFC IAP 2013

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

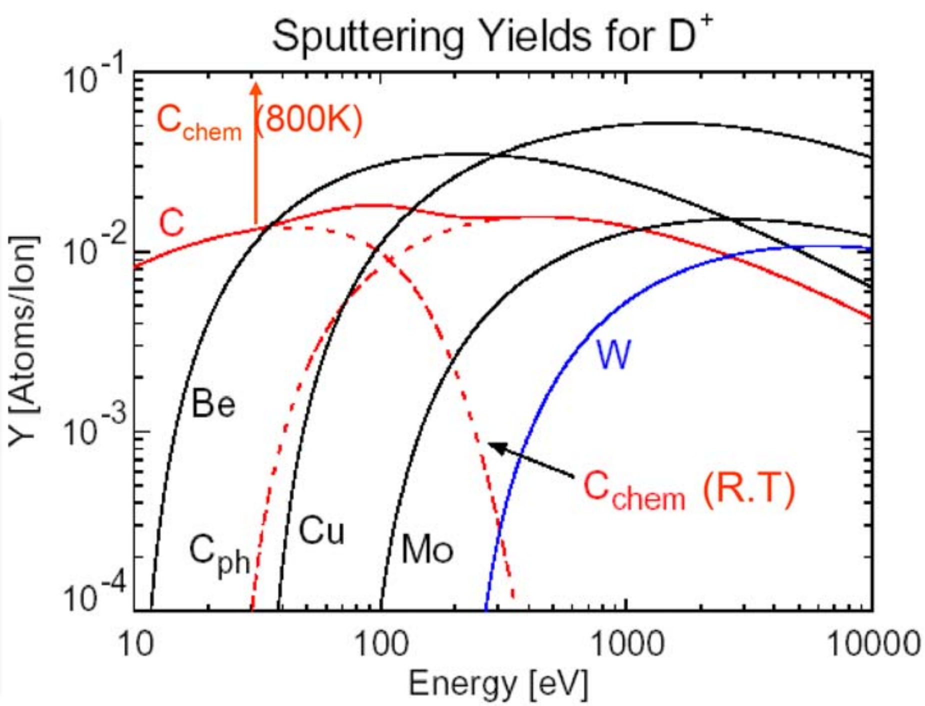
- Efficient prompt redeposition > ~ 99%
  (but redep. material is probably crud!)

  or

- **Fully detached divertor with ion energies below sputtering threshold**

  or

- Liquid metal targets? …



High-level reports are calling for aggressive research on innovative divertor solutions

Gaps 1 & 2 (among others) are impacting fusion development plans. Solving the heat exhaust problem is being ranked as #1 …

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

High-level reports are calling for aggressive research on innovative divertor solutions

Independent of the recent λ_q results, 'taming the plasma-material interface' is widely recognized as one of the most critical research areas for magnetic fusion energy development.

Research Needs for Magnetic Fusion Energy Sciences

Report of the Research Needs Workshop (ReNeW)

Bethesda, Maryland – June 8-12, 2009

We don't like what we are finding!

Theme 3: Taming the plasma-material interface

- **Thrust 9: Unfold the physics of boundary layer plasmas**
- **Thrust 10: Decode and advance the science and technology of plasma-surface interactions**
- **Thrust 11: Improve power handling through engineering innovation**
- **Thrust 12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma**

Requirement	Research Thrust to Address Requirement
Innovative divertor concepts and testing	9 and 11
Antenna and launcher development	10
Integrated demonstration of taming plasma materials interactions	12
…	…

http://burningplasma.org/web/ReNeW/ReNeW.report.web2.pdf

Recent 'Rosner Panel Report' prioritizes ReNew thrusts 9 and 10 as among 'highest priority thrusts' (of 18)

Alcator DX

Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program

Written in Response to Dr. William Brinkman's charge letter to FESAC of April 13, 2012

Thrust 9: Unfold the physics of boundary layer plasmas

Mid-term (3-5 years)

→ • Innovative ideas for improved divertors

• Explore the detailed effects of RF heating on the boundary plasma

Mission of Advanced Divertor Test Experiment

=> *Identify and demonstrate solutions to these problems!*

The ultimate divertor solution will be one that produces a controlled, <u>fully-detached</u> divertor condition (~no plasma sputtering) while maintaining high plasma temperatures 'upstream' at the last-closed flux surface – at the parallel heat flux density of an FNSF/DEMO.

This vision should be the target of a US high-performance divertor development program.

The Alcator platform – compact, high-field, high power density – is an ideal R&D platform for an Advanced Divertor Test Facility

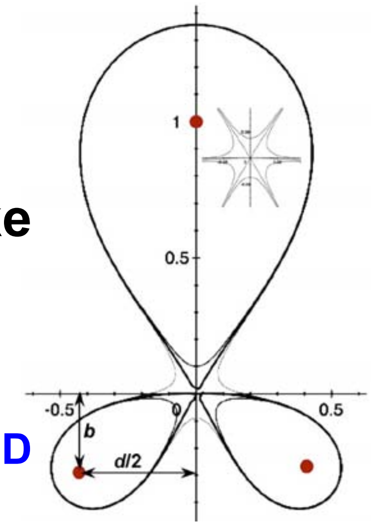
- **Reactor level heat fluxes and divertor conditions (n, T_e, n_0)**
- **Small size ($), rapid turn-around for innovation**
- **World-class tokamak and divertor physics teams**
- **Capitalize on existing C-Mod infrastructure (~$200M)**

... an opportunity for the US to take the lead in this critical area.

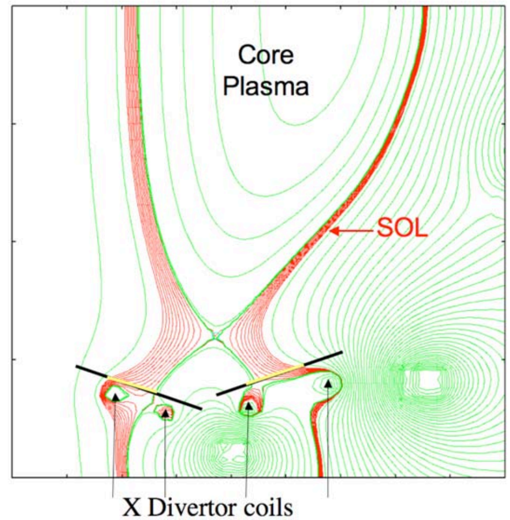
Some advanced divertor concepts are well developed. Potential high-performers have not yet been tested.

Snowflake Divertor (SF)

Operated on TCV, NSTX, D3D



D. Ryutov, PoP 14 (2007) 064502.



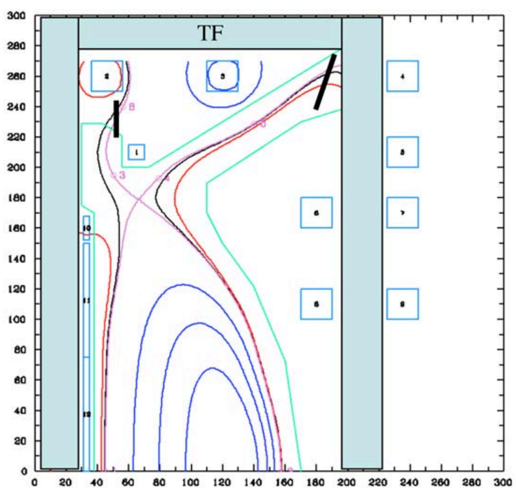
X Divertor (SD)

Not tested

M. Kotschenreuther, PoP 14 (2007) 072502.

Super X Divertor (SXD)

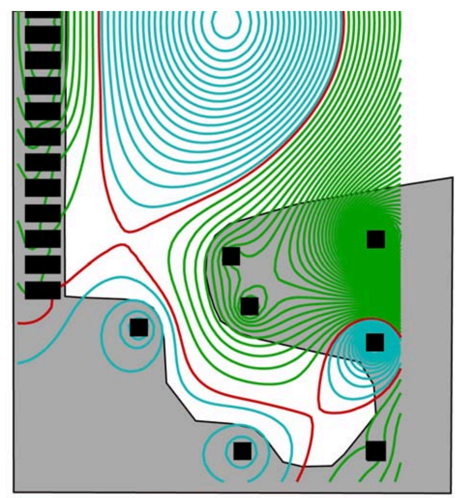
Not yet tested (MAST 2015)



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

X-point Target Divertor (XPT)

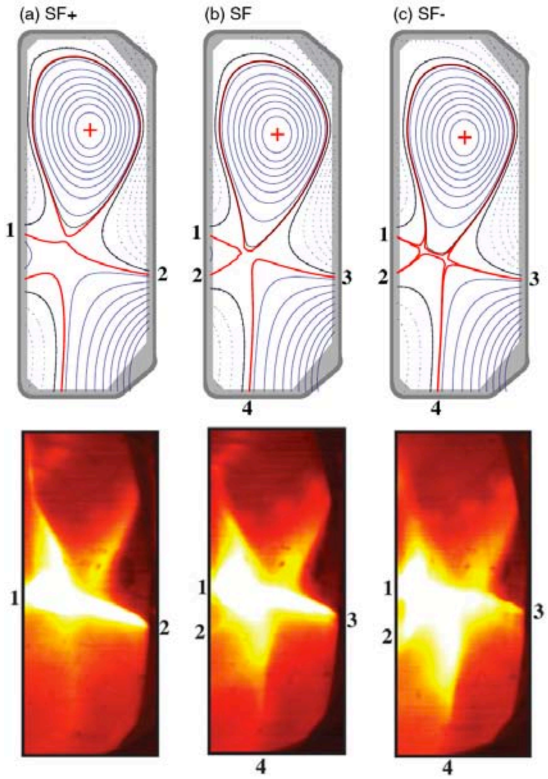
Not tested



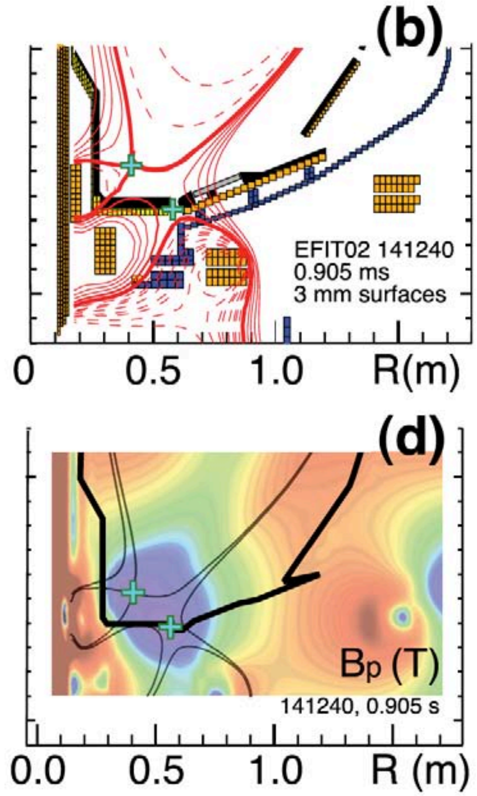
B. LaBombard, PSFC Brainstorming Session, Jan. 2013.

Snowflake divertor (SF)

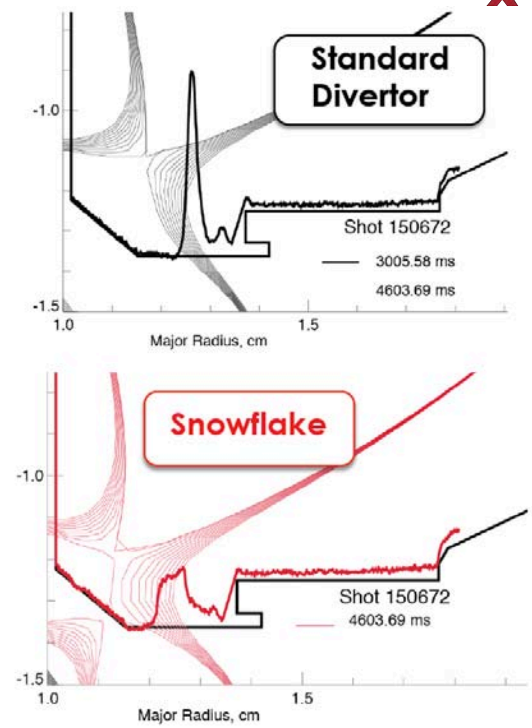
TCV F. Piras, PPCF 51 (2009) 055009.



NSTX V.A. Soukhanovskii, PoP 19 (2012) 082504.



DIII-D S. Allen, IAEA, 2012.



Advantages:

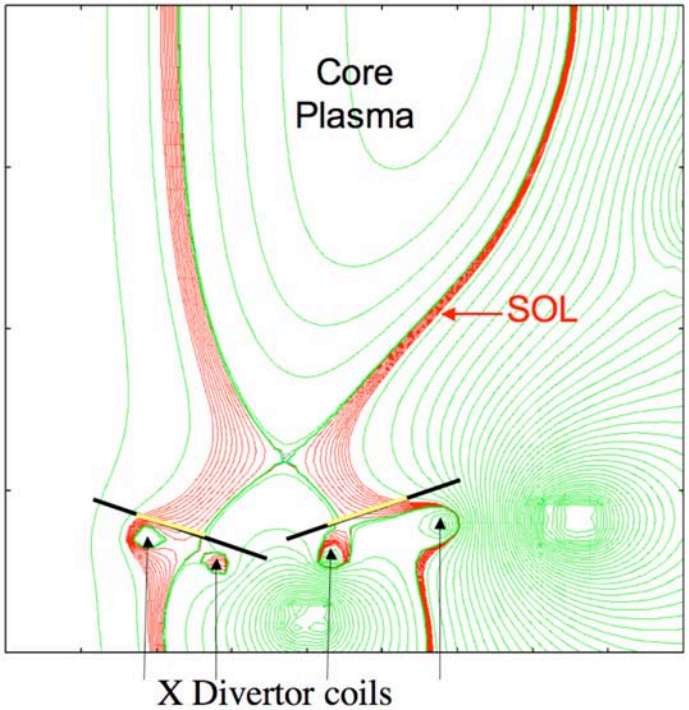
Poloidal flux expansion; increased $L_{||}$; multiple strike points; increased x-pt shear (stabilizes BMs?); lower detachment threshold; ELM resilient? Easy to implement

Disadvantages:

PMI near core plasma; full detachment not allowed? (X-pt MARFE)

X divertor (XD)

M. Kotschenreuther, PoP 14 (2007) 072502.



Advantages:

Poloidal flux expansion; increased $L_{||}$; lower detachment threshold?

Disadvantages:

PMI near core plasma; full detachment not allowed? (X-pt MARFE); Not easy to implement.

X divertor (XD)

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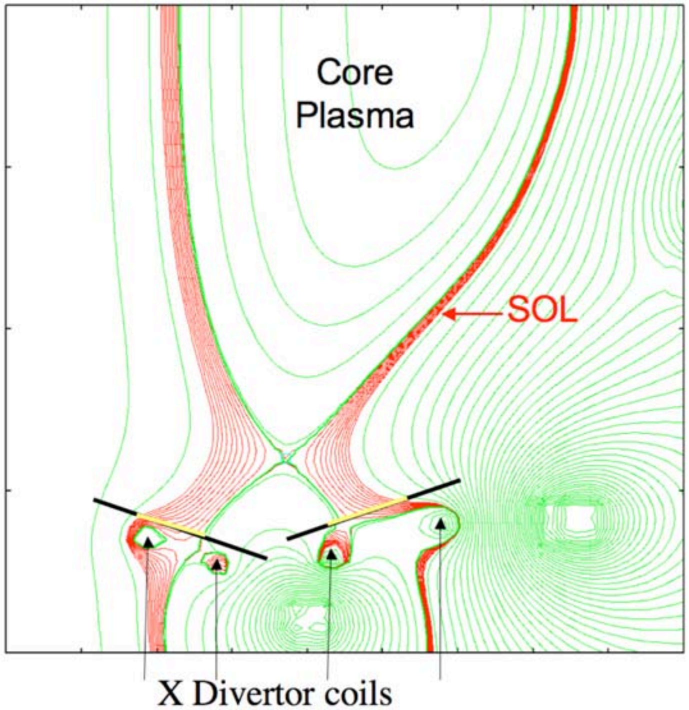
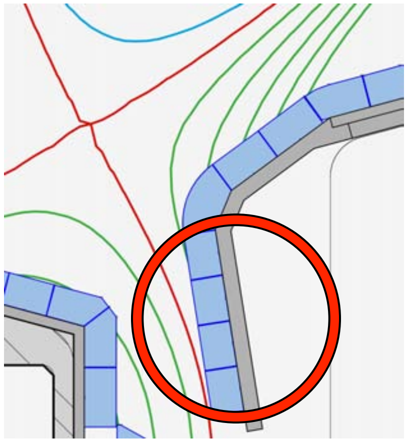


Note:
Poloidal flux expansion using PF coils is similar to the poloidal flux expansion obtained by a tilted target plate (but with no $L_{//}$ increase).



For attached plasmas, field line angles must be > ~1 degree, otherwise shadowing will occur. This sets maximum flux expansion.

Advantages:

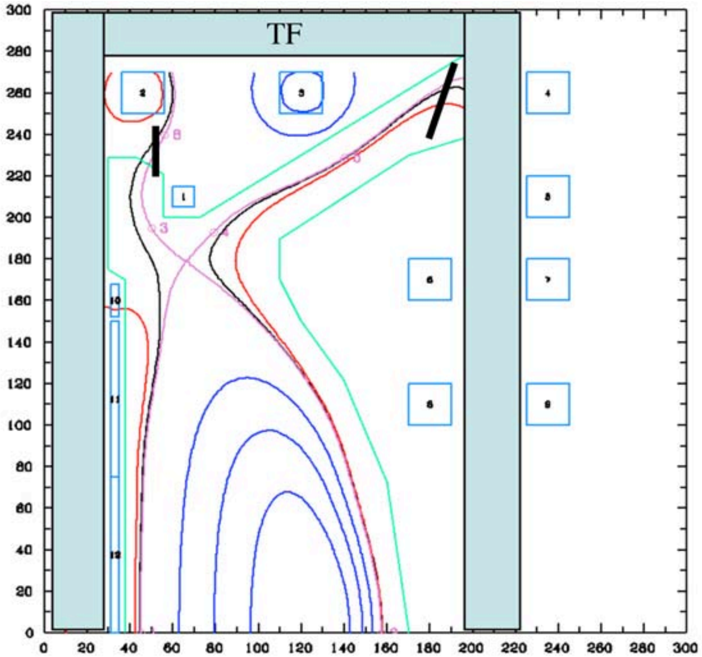
Poloidal flux expansion; increased $L_{||}$; lower detachment threshold?

Disadvantages:

PMI near core plasma; full detachment not allowed? (X-pt MARFE) ; Not easy to implement.

Super X divertor (SXD)

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



Key concept: Major radius of target plate is increased; B at target plate is decreased; heat flux density at target decreases. 2pt model yields:

$$T_t \propto \left(\frac{R_{t\,arg\,et}}{R_{OMP}}\right)^{-2} \quad \text{and} \quad n_t \propto \left(\frac{R_{t\,arg\,et}}{R_{OMP}}\right)^{2}$$

Stangeby notes, 2011

Increased $L_{||}$ also helps.

Idea of possibility operating with a fully detached, radiative divertor not developed. => field line angle (>1^0) requirement?

Advantages:

Increased $L_{||}$; reduce target $q_{||}$ & T; increased target n; much lower detachment threshold expected; PMI away from core plasma.

Questions:

Operation with completely detached divertor plasma?

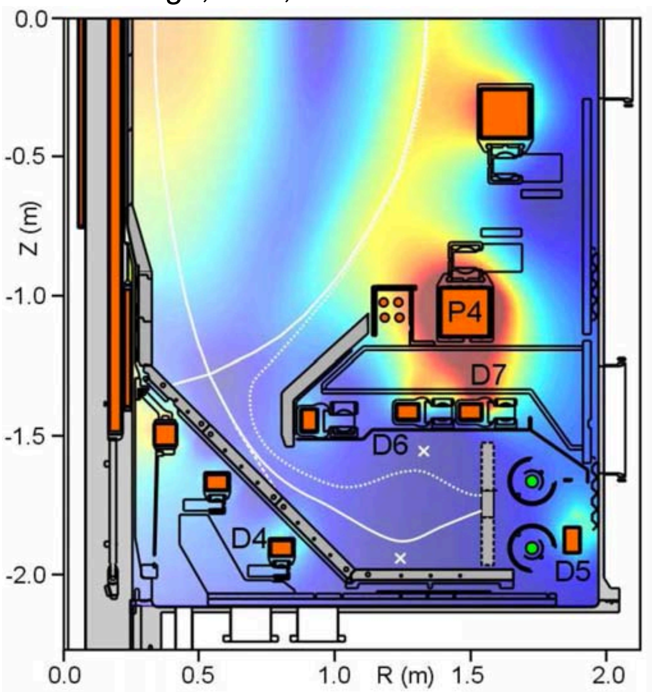
Stability against X-pt MARFES?

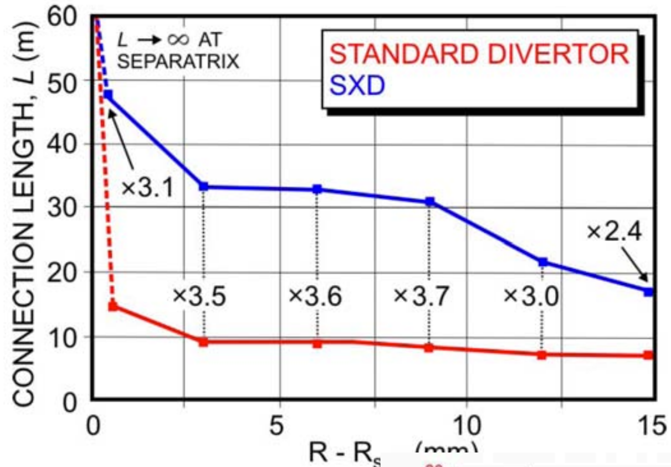
Disadvantages:

Not easy to implement; dedicated facility required.

MAST will operate with a SXD (2015)

S. Lisgo, EPS, 2009.





Increased $L_{||}$

Anticipated T_{div}, $q_{||}$ reduction

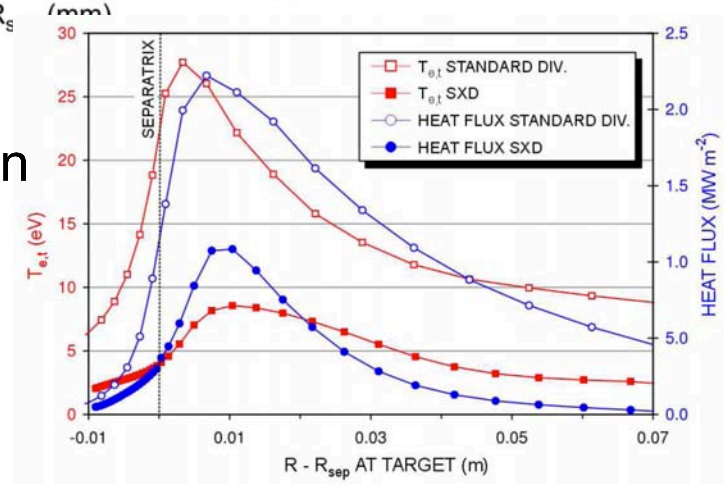


Figure 3: Preliminary SOLPS modelling results that illustrate the reduction in target temperature and heat flux with the SXD.

Input power upgrade (NBI) to be 7.5 MW (stage 1) => 12.5 MW (stage 2)

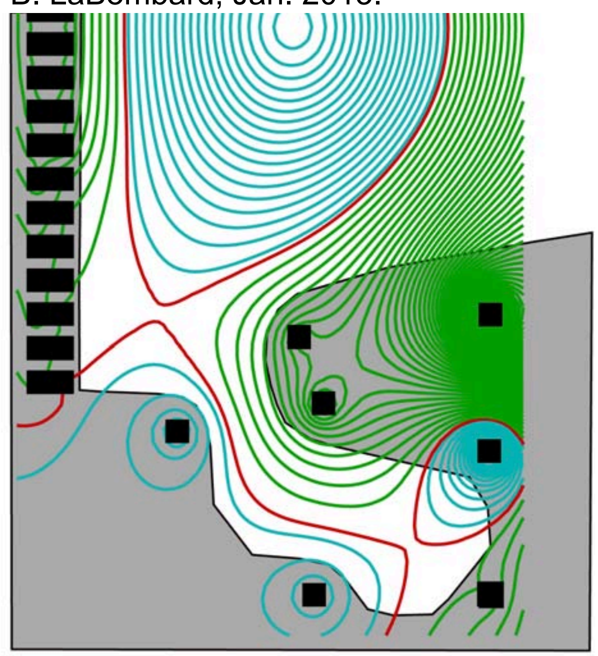
But MAST has λ_q ~ 7 mm (~5x C-Mod) with a similar major radius.

MAST will not be able to test the SXD at reactor-level $q_{//}$ values.

X-point target divertor (XPT)

Concept: Use a remote X-point to produce a fully detached, radiating plasma as the divertor target.

B. LaBombard, Jan. 2013.



Employ all tricks:

- Increase radius of target plate (~SXD)
- Set $L_{||}$ to infinity (via target X-point adjust) on flux tube carrying peak heat flux.
- Tight baffling for high neutral pressures of fuel plus seed gases (gas cushion concept)
- Feedback control (via seeding, gas puffs, power,…) for stable 'divertor MARFE'

Note: increased radius of target X-point provides thermal front stability.

I. Hutchinson, NF 34 (1994) 1337.

Potential Advantages:

Fully detached divertor maintained over a large operational space; PMI away from core plasma; divertor erosion problem solved.

Questions:

Stability against X-pt MARFES? Control requirements? …

Disadvantages:

Dedicated facility required.

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Concept: Use a remote X-point to produce a fully detached, radiating plasma as the divertor target.

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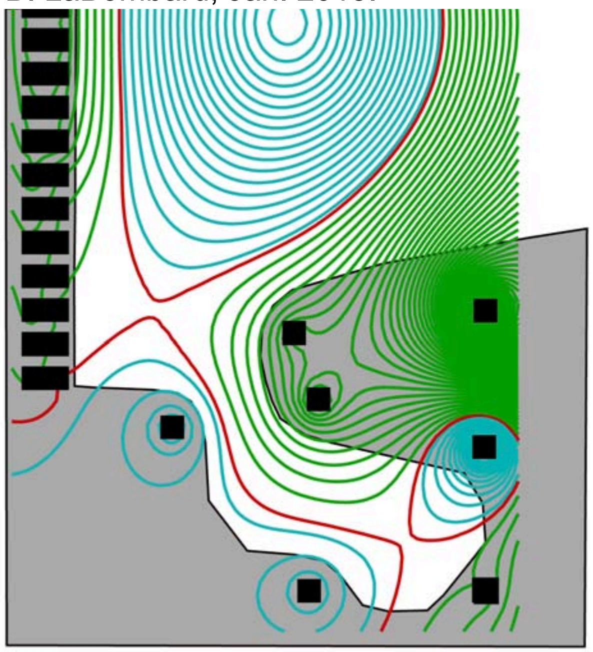
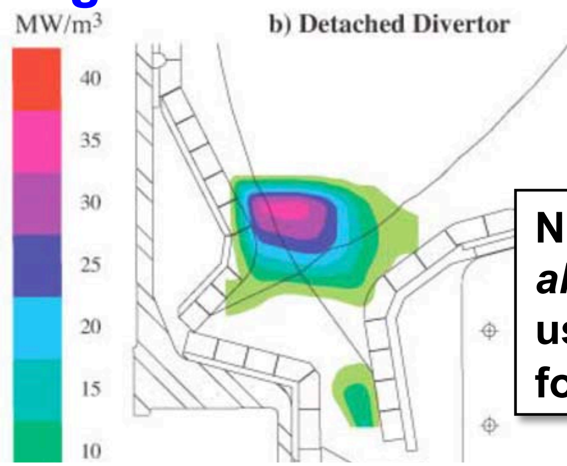


Put radiating, *cold* plasma where it belongs – in the divertor!



B. Lipschultz, FST 51 (2007) 369.

Note: Kotschenreuther *et al.* (IAEA 2004) advocated use of advanced divertors for this purpose.

Keep plasma *hot* near LCFS (and its X-pt) to maintain core plasma performance.

Potential Advantages:

Fully detached divertor maintained over a large operational space; PMI away from core plasma; divertor erosion problem solved.

Questions:

Stability against X-pt MARFES? Control requirements? …

Disadvantages:

Dedicated facility required.

More Questions for XPT (and SXD)

- What is required to maintain a stable fully detached divertor and over what 'upstream' operating conditions can it be maintained?

- What is needed to provide adequate helium pumping?

- How does XPT/SXD respond to off-normal events?
  Loss of feedback control, loss of ELM control, disruptions,…

- Tokamak operational issues – how does XPT/XSD affect:
  Density limit?
  Access conditions to H-mode and I-mode?
  Plasma fueling?

We may need to learn how to operate a tokamak all over again.

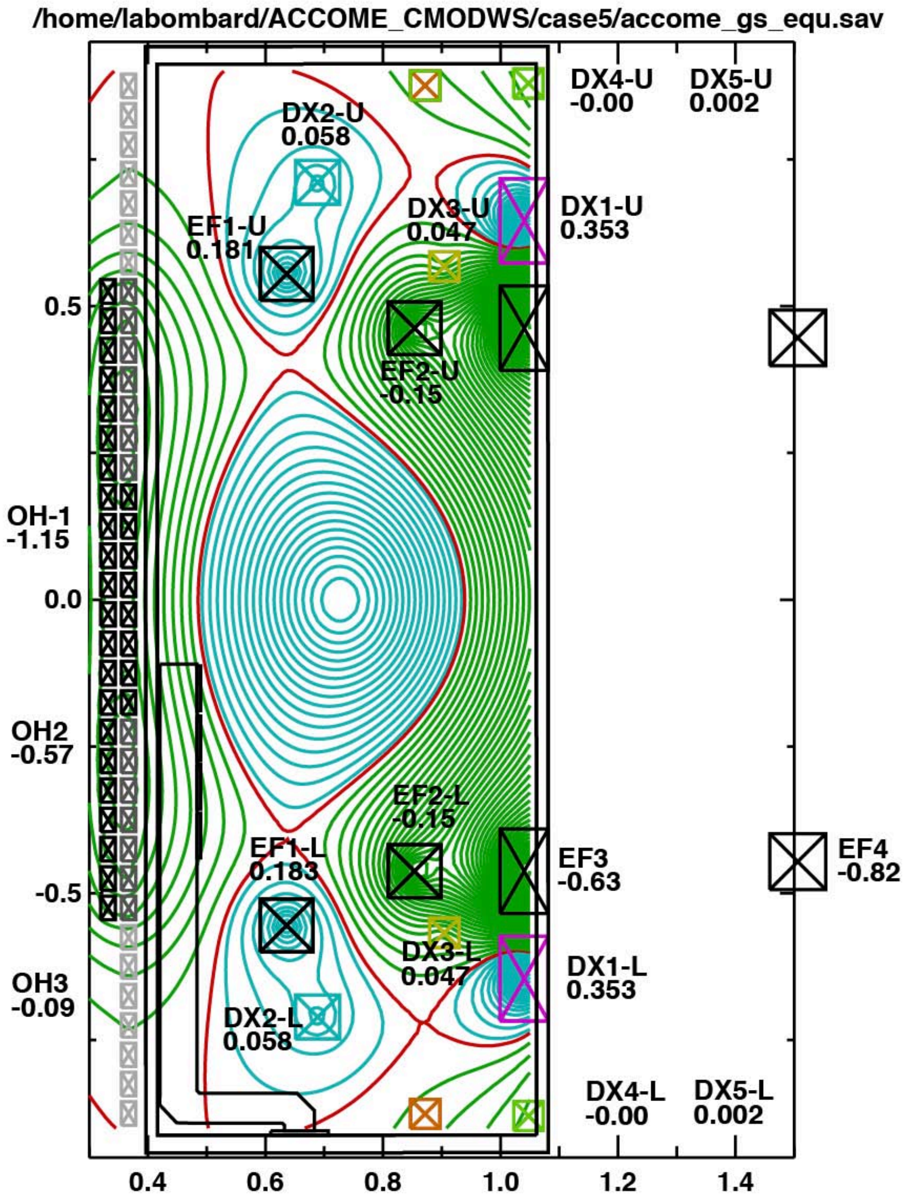
Initial scoping study for SXD & XPT in *Alcator DX*

Boundary conditions:
Reuse Alcator C-Mod upper and lower 'domes'
Allow vacuum vessel & PF coil set to grow in vertical height

Auxilary Goal:
Increase plasma-wall gap at inner wall to find a compatible divertor PF coil arrangement that provides for inside-launch LH and ICRH systems.

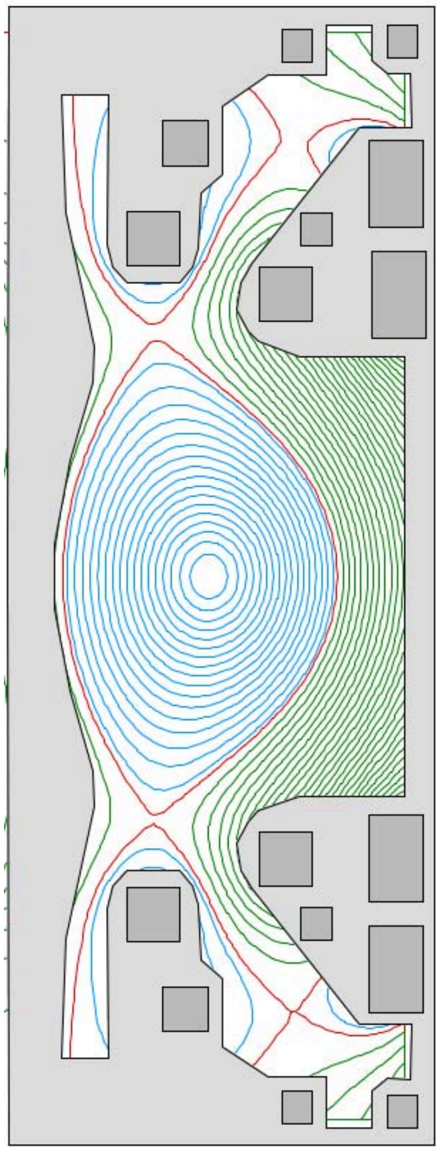
Tools:
ACCOME GS solver (SELENE) within an IDL wrapper
Find coil arrangements that produce SXD and XPT configurations, within boundary conditions

Possible XPT Divertor for Alcator DX



- Room for inner-wall launch LH WG
- Flux-expanded inner target (VP)
- VV height extended by 0.5 meters
- Reasonable coil currents

Possible XPT Divertor for Alcator DX



Room for inner-wall launch
LH WG

Flux-expanded inner target (VP)

VV height extended by 0.5 meters

Reasonable coil currents

Further refinement possible…

Mission for *Alcator DX*

Perform world-leading science in developing and testing advanced divertor concepts (SXD, XPT) at reactor level power densities; defining their limits with regard to power handling, material erosion control; developing/validating physics-based models to describe their behavior.

Determine compatibility with respect to burning plasma requirements: density limits, fueling behavior, impurity control, helium pumping, H/I-mode access, …

Exploit power handling capability of SXD/XPT to develop and test next generation, high-power LHCD and ICRF systems, synergistically exploring the highest performance possible in an Alcator-class device while testing the limits of SXD, XPT concepts.

Employ/test innovative, inside-launch techniques for LHCD and ICRF systems – potential game-changers that could yield efficient, reliable current drive and impurity-free steady-state auxiliary power.

Carry forward R&D required to inform next step devices (pre-FNSF, FNSF) in a timely manner on an affordable research platform.