A nationally organized, advanced divertor tokamak is needed to demonstrate plasma exhaust and PMI solutions for FNSF/DEMO.

A compact, high field, advanced divertor tokamak (ADX) is the most physically relevant and cost-effective facility for this mission.

Brian LaBombard for the ADX Team

MIT Plasma Science and Fusion Center

Presentation to FESAC Strategic Planning Panel, June 5, 2014

Alternative divertor solutions must be found for FNSF/DEMO.

"A reliable solution to the problem of heat exhaust is probably the main challenge towards the realisation of magnetic confinement fusion ... an aggressive programme on alternative solutions for the divertor is necessary ..."

"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."

EFDA

Fusion Electricity

A roadmap to the realisation of fusion energy

http://www.efda.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf?5c1bd2

"If ITER shows that the baseline strategy [with a conventional divertor] cannot be extrapolated to DEMO, the lack of an alternative solution would delay the realisation of fusion by 10-20 years."

Priorities, Gaps and Opportunities:

Towards A Long-Range Strategic Plan For

Magnetic Fusion Energy

Major Gaps for DEMO:

"*G-2. ...* ***first wall and divertor interactions****.*"

"*G-7. ...* ***RF launching structures and wave coupling****...*"

"*G-9. ...* ***environment for and behavior of plasma facing and other internal components****...*"

http://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf

U.S. DEPARTMENT OF ENERGY

Office of Science

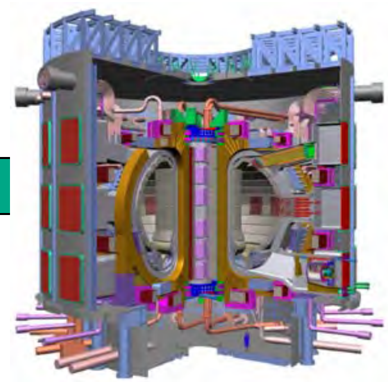
Burning Plasma Science

Foundations

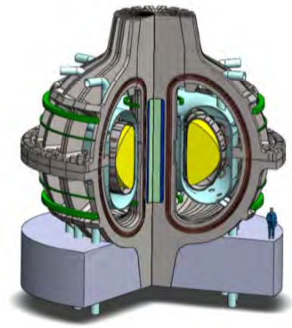
Long Pulse

Key power exhaust, PMI and RF technology milestones to demonstrate readiness for *long-pulse*, FNSF/DEMO.

ITER

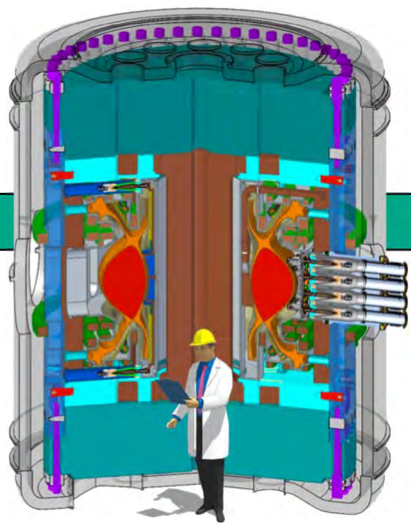


FNSF/ DEMO



Research performed in parallel with ITER

ADX



1. **Demonstrate robust divertor power handling solutions**
2. **Demonstrate ~complete suppression of divertor erosion**
3. **Demonstrate low PMI, efficient, RF current drive and heating technologies**
4. **Achieve 1, 2, 3 with core plasma performance *compatible with obtaining burning plasma***

http://www.psfc.mit.edu/~labombard/FESAC-SPpaperPriorities-LaBombard.pdf

http://www.psfc.mit.edu/~labombard/FESAC-SPpaperInitiatives-LaBombard.pdf

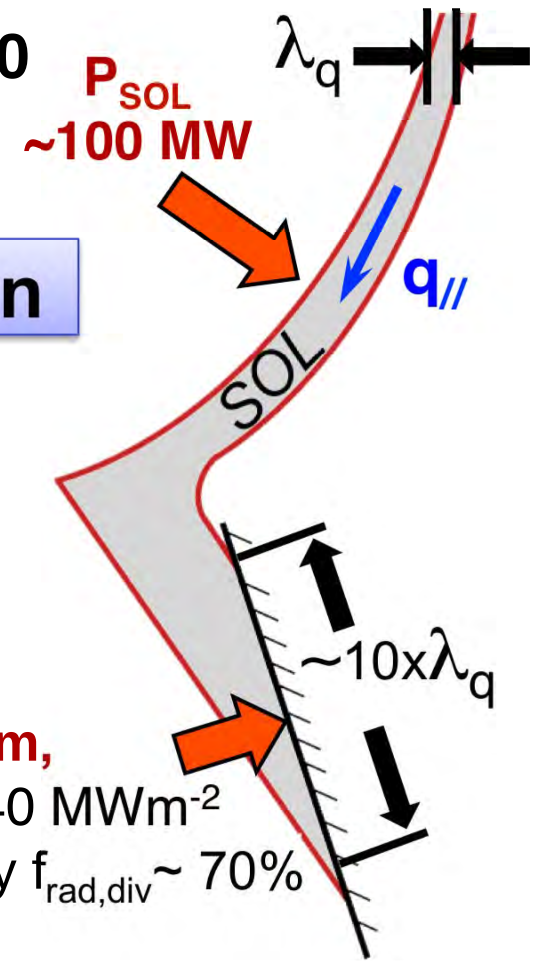
A high-field, Advanced Divertor Tokamak Experiment (ADX) is the right tool for this mission, well-aligned with FES priorities

ITER power exhaust challenge...
...more difficult than originally planned

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

ITER, Q_{DT}=10

ITER plan



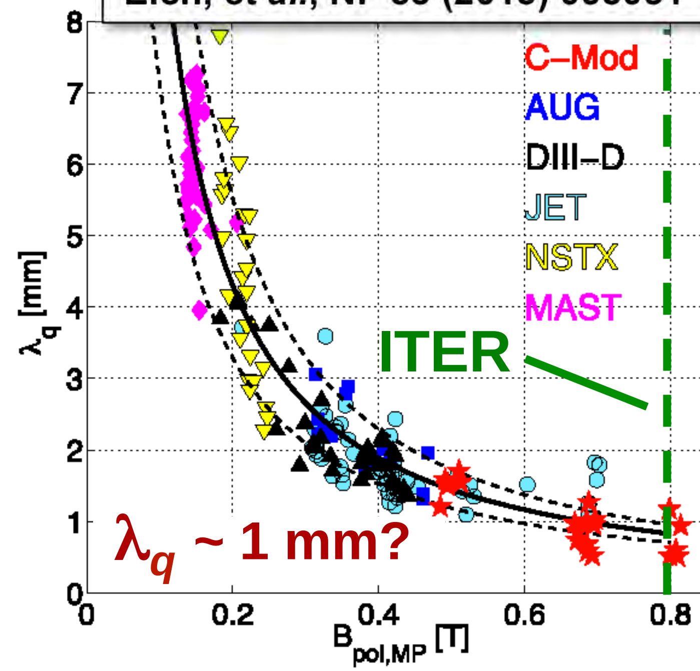
λ_q = 5 mm,
$q_{\perp,max}$ ~ 40 MWm^{-2}
=>must apply $f_{rad,div}$~ 70%

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

New results from multi-machine database:

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

Eich, *et al.*, NF 53 (2013) 093031



=> 1/5 of 'planned' value

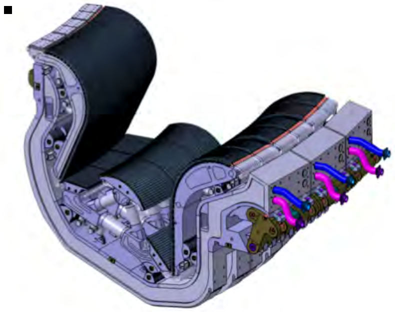
(caveat: *low divertor recycling*)

DEMO Challenge: Power exhaust

A conventional divertor will not work for a DEMO.

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

$H_{98} > 1$ requires $P_{SOL} > \sim P_{LH}$



	$f_{rad,core}$	$P_{SOL}B/R$
ITER, Q_{DT}=10	33%	90
with $P_{SOL}=P_{LH}$	66%	45

Divertor demonstration experiments ($H_{98} > 1$, $q_{target} < 5$ MW/m^2, ITER-like div.)

AUG: $P_{sol}B/R$ =18 Kallenbach, NF 52 (2013) 122003

C-Mod: $P_{sol}B/R$ =25 Loarte, PoP 18 (2011) 056105

Max demonstrated $P_{SOL}B/R$ with is only ~1/2 of ITER $P_{LH}B/R$

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

FNSF/DEMO: *Extreme values of $P_{SOL}B/R$*

ACT1, ACT2 from ARIES design studies
http://aries.ucsd.edu/ARIES/DOCS/bib.shtml

Power entering SOL should be reduced (but may not be possible)

	$f_{rad,core}$	$P_{SOL}B/R$
ACT1	33%	260
with $P_{SOL}=P_{LH}$	85%	57
ACT2	33%	380
with $P_{SOL}=P_{LH}$	80%	114

Power handling of divertor must be improved by factor of 3 to 10 for FNSF/DEMO.

Additional challenge for long-pulse, DEMO:
~complete suppression of material erosion and damage

Erosion

- Gross sputtering yield on tungsten divertor target must be suppressed to less than 10^{-6} to achieve < 1mm/year erosion rate

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

Damage

- Helium implantation (E_{He+} > 20 eV)

Solutions?

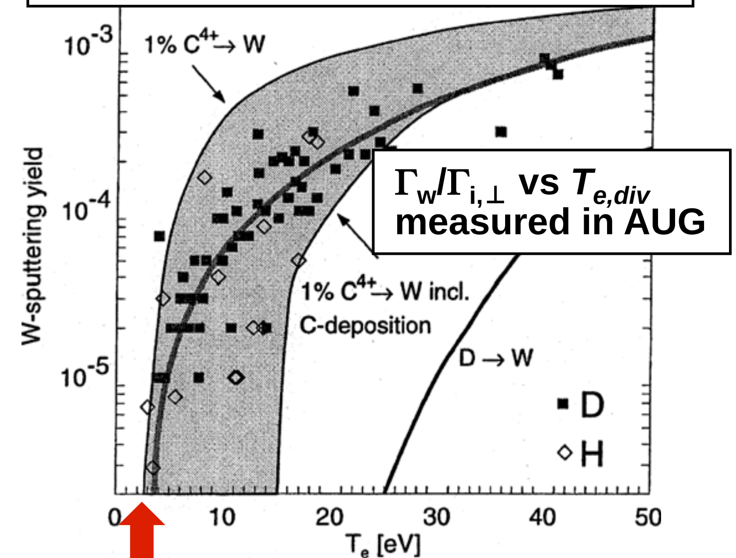
- *Ion impact energies below sputtering and damage thresholds* – cold ('fully detached') divertor plasma required

or

- Liquid metal targets?

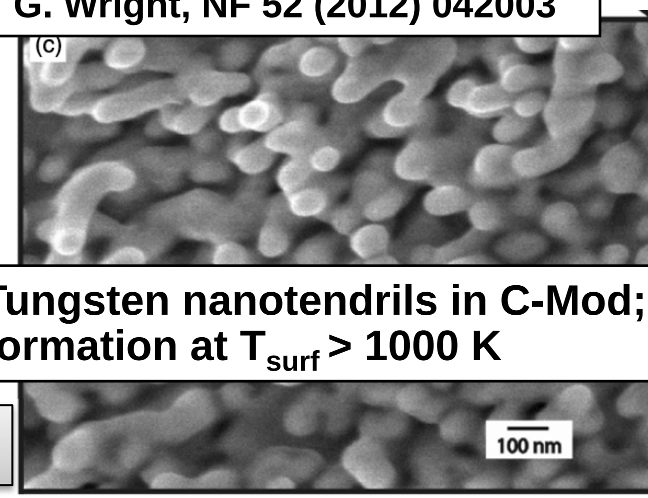
Advanced materials alone will not solve this problem.

K. Krieger, JNM 266-269 (1999) 207



suppress sputtering: T_e < 5 eV

G. Wright, NF 52 (2012) 042003



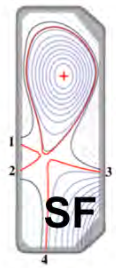
Tungsten nanotendrils in C-Mod; formation at T_{surf} > 1000 K

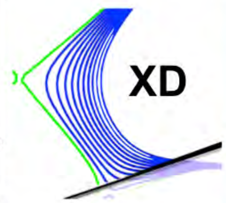
To avoid "fuzz": E_{He+} < 20 eV, T_e < 7 eV

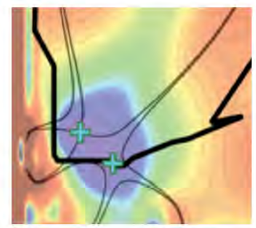
Alternative solutions for the divertor are necessary.

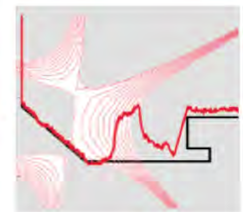
Advanced Divertors

Use magnetic topology and divertor physics to solve heat & PMI problems



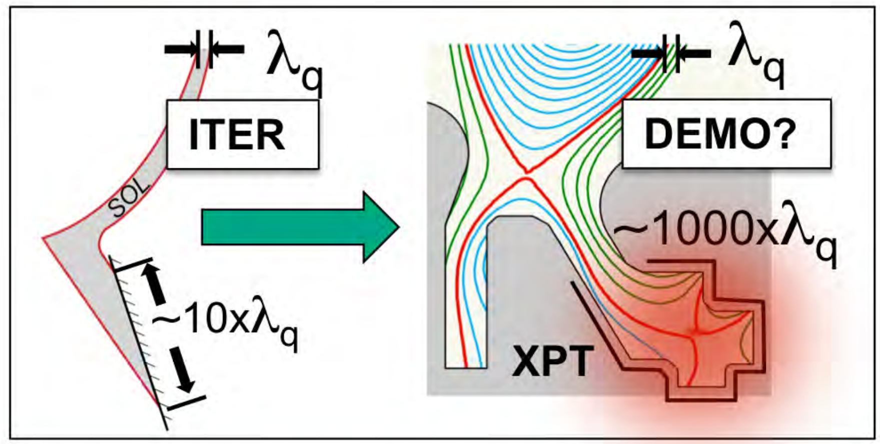






- **enhanced power handling**
- **cold ('fully detached') divertor possible**
  => suppress erosion
- **synergy with liquid metals**

Some proof-of-principle tests at low power are now being performed with non-optimal PF coil sets.



Integrated tokamak performance testing at high power density is required.

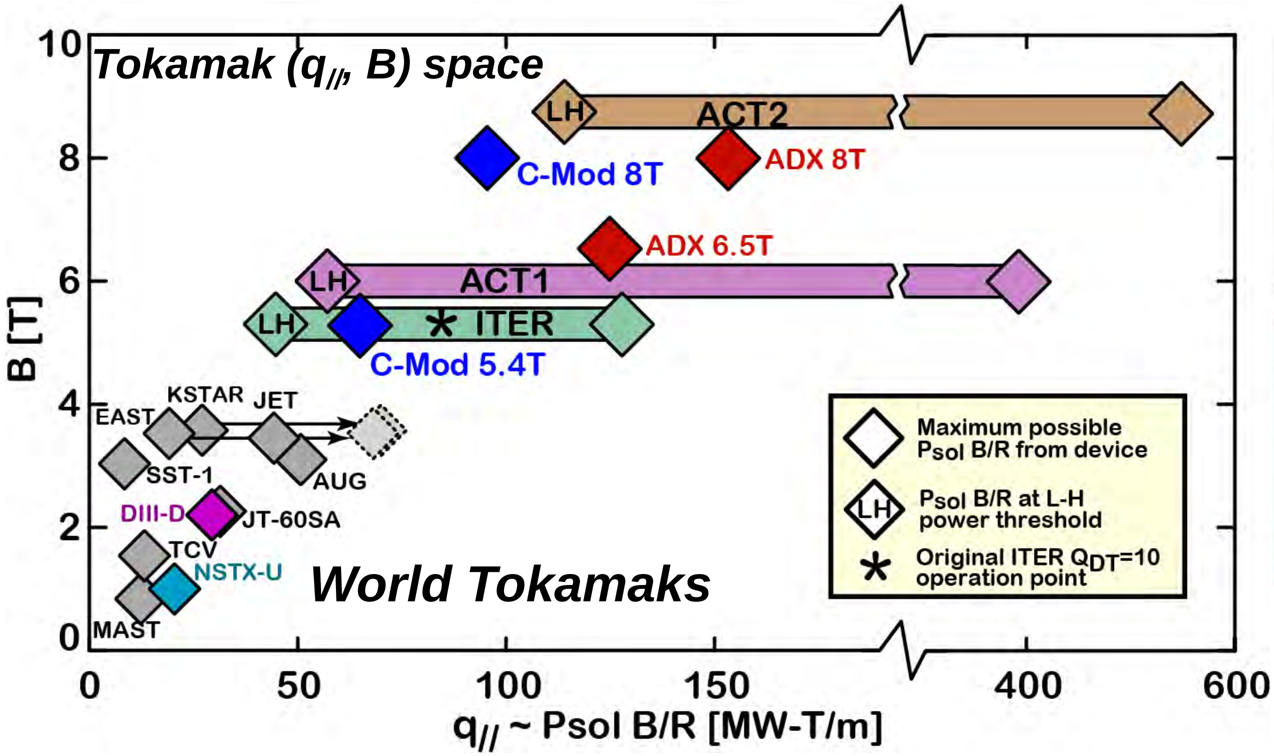
Q: *What is required to test a divertor idea for FNSF/DEMO*?

Model/code extrapolation to untested regimes is unreliable.
Divertor test experiment should match divertor physics regimes in a reactor...

Reactor divertor conditions can be matched ($T_{e,div}$, n_{div}, **key dimensionless parameters) if $q_{//}$, B and divertor geometry are matched.**

Stangeby, NF 51 (2011) 063001; Whyte, FED 87 (2012) 234.

A: *A tokamak that produces DEMO-like $q_{//}$, B and geometry*



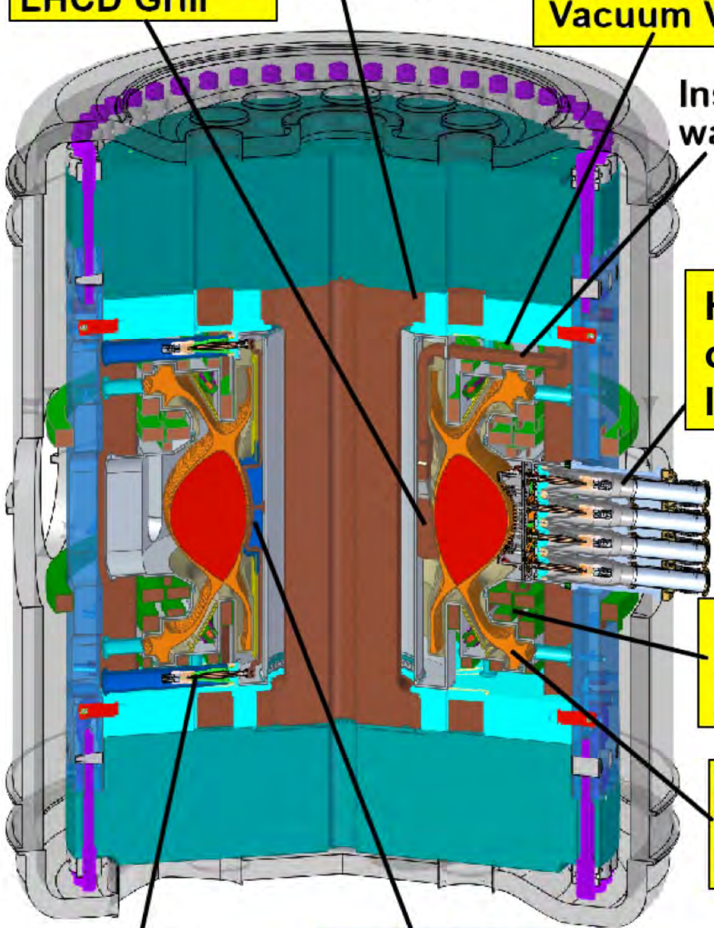
Reactor-like divertor regimes are already being accessed by *C-Mod* -- high-field, compact, high power density.

A similarly constructed *ADX* would be cost-effective platform for an *advanced divertor test experiment.*

Plasma pulse lengths of 3-5s are ideal for this mission.

ADX -- example: a high-power, advanced divertor test facility, using Alcator magnet technology

Advanced Divertor Experiment



Infrastructure presently supporting C-Mod is valued at $200M

- Development platform for Advanced Divertors
- Reactor-level $q_{||}$, B, plasma pressures

  P_{sol} *B/R* ~ *125*
  => above ITER, Q_{DT}=10 operating point (90)

- Development platform for low PMI, efficient RF
  - Inside launch LHCD
  - Inside launch ICRF

Cost estimate with reuse of Alcator C-Mod components and siting at MIT:
$3M design (2 yr)
$36M hardware
+$32M construction (4 yr)
$71M

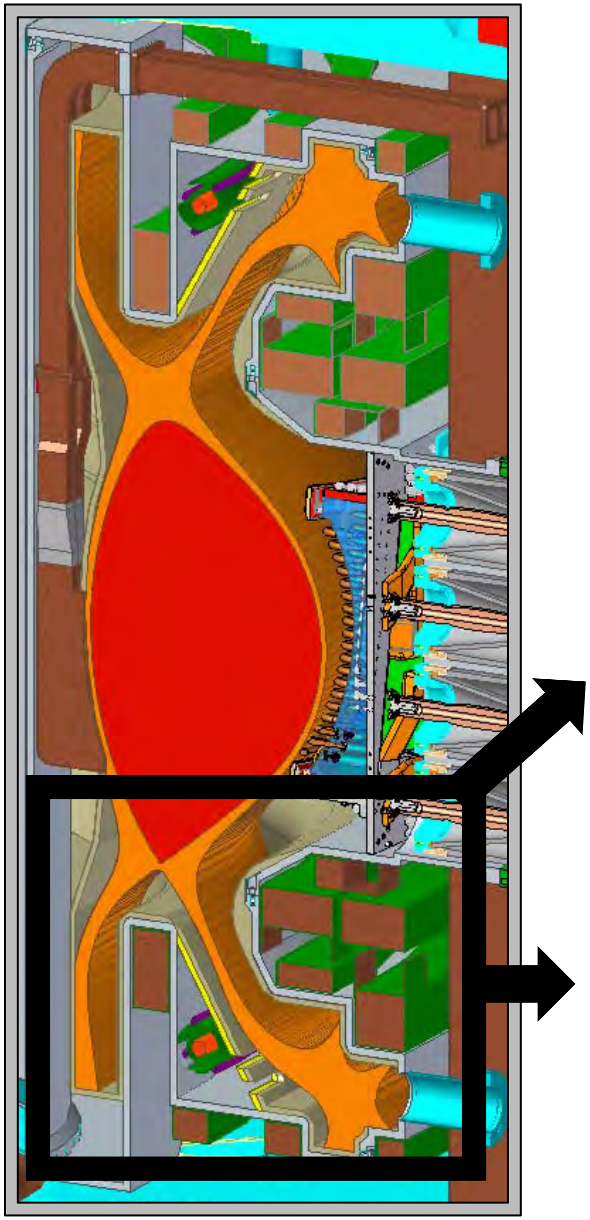
ADX	
Major/ Minor Radii	0.73 / 0.2 m
Elongation	1.7
Magnetic Field	6.5 Tesla (8 Tesla)
Plasma Current	1.5 MA (2 MA)
P_{AUX}	10 MW ICRF 4 MW LHCD
Surface Power Density	~ 1.7 MW/m^2
P_{AUX} *B/R*	125 MW-T/m
Advanced Divertor Concepts	Vertical target; Snowflake; Super-X; X-point target; Liquid metal target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

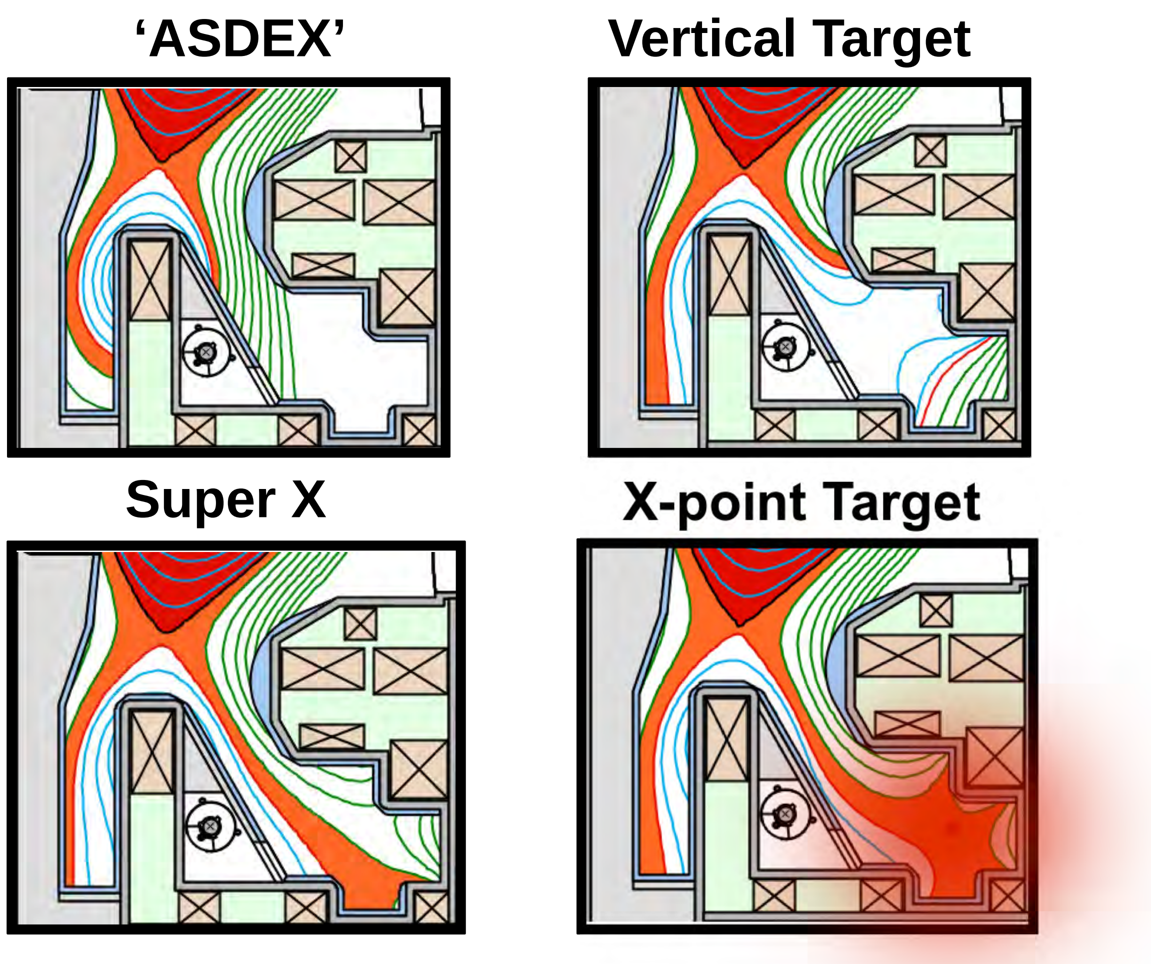
First plasma 2020

ADX

Advanced Divertor Experiment

Configure internal PF coils to *test multiple magnetic geometries and divertor targets*.





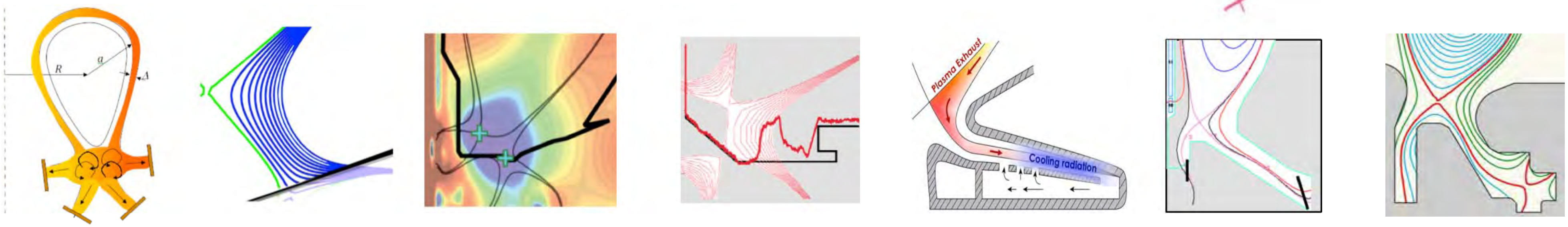
PF coils may be configured for other geometries: snowflake, x-divertor, ...

Also design for testing high temperature target and liquid metal options

Nationally organized ADX *-- a US leadership experiment*

- ***US is a world leader/innovator*** **-- divertors, advanced divertors and liquid metal target concepts**

IFS · Lawrence Livermore National Laboratory · MIT PSFC · PPPL · Sandia National Laboratories · DIII-D NATIONAL FUSION FACILITY · NSTX · Alcator C-Mod · LTX · OAK RIDGE National Laboratory

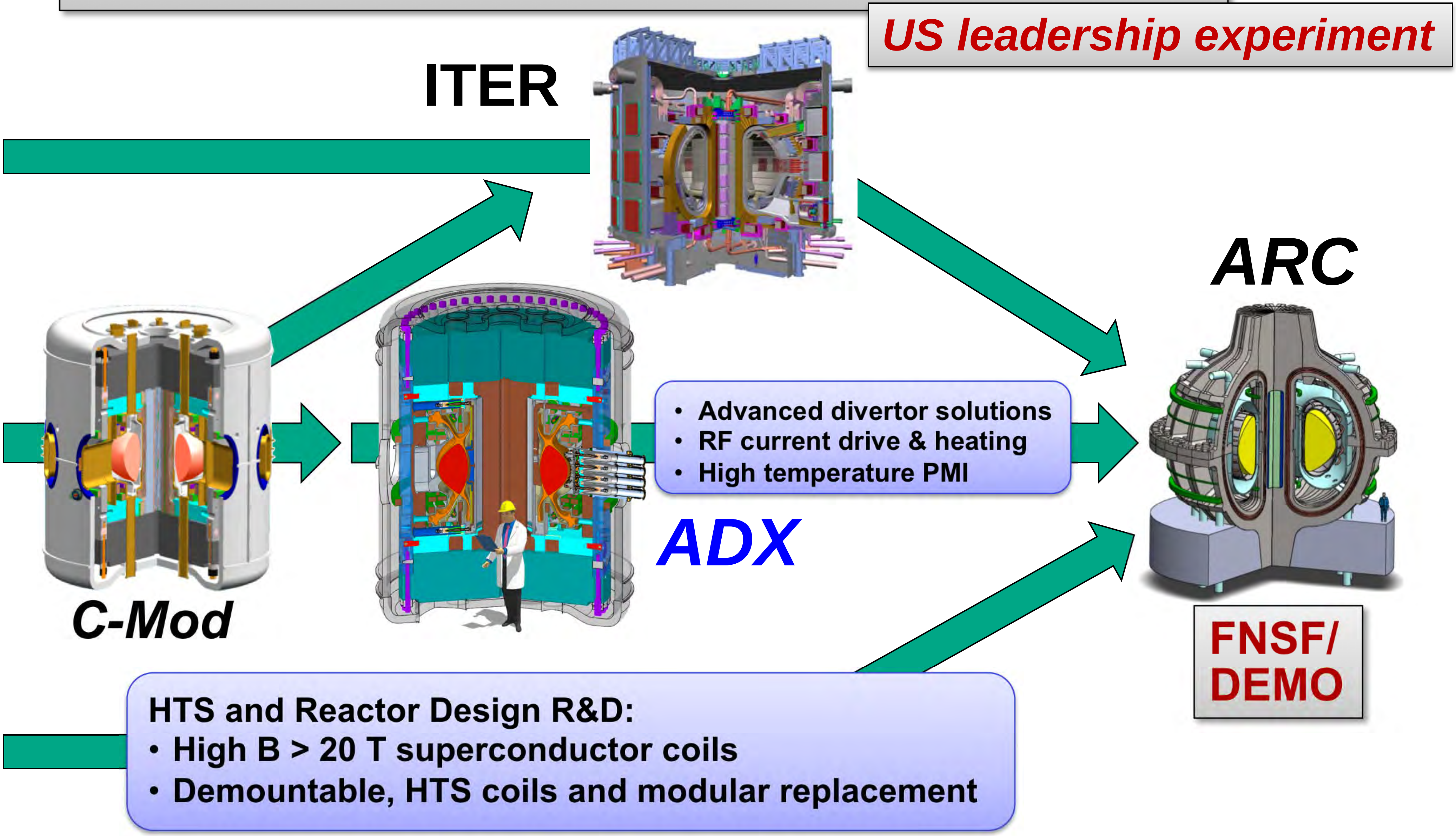


- ***US has the enabling technology and expertise*** **-- demountable, high-field magnets and RF systems developed for the Alcator program; RF wave physics expertise and high power-density RF systems**

Critical need + unique expertise + unique facilities + timeliness
=> US leadership experiment

Through academic connections (MIT and collaborating universities), ADX would help train the next generation plasma physicists for ITER and DEMO eras.

ADX – an essential element on a pathway to an attractive high field, compact FNSF/DEMO



Inform the conceptual development and demonstrate technology readiness for FNSF/DEMO.

backup slides

ADX -- Cost and schedule estimate (subject to revision)

Advanced Divertor Experiment

FY15 | FY17 | FY21

Schedule: ADX Design → Construction → Operations

Alcator C-Mod operations

First Plasma 10/1/2020

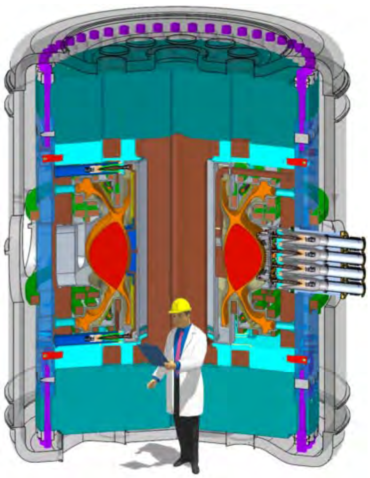
Operations

Establish operations
P_{ICRF} = 5 MW (LFS)
Advanced div expts

Upgrades

P_{ICRF}=> 10 MW (LFS)
HFS LHCD prototypes
HFS ICRF prototypes
Adv. div. optimization
….

ADX



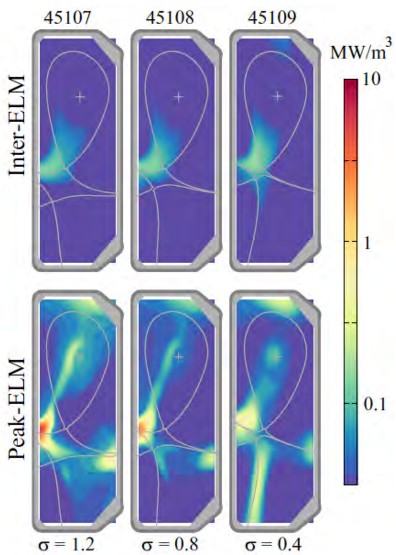
Design starting point:
Extensive reuse of C-Mod components (domes, TF arms, wedge plates,…) and siting at MIT

Cost:	$1.5M/yr 2 years	$17M/yr, 4 years Hardware - $9M/yr Construction Team - $8M/yr	$25M/yr including $5M/yr for collaborations

Opportunities for US leadership and international partnership

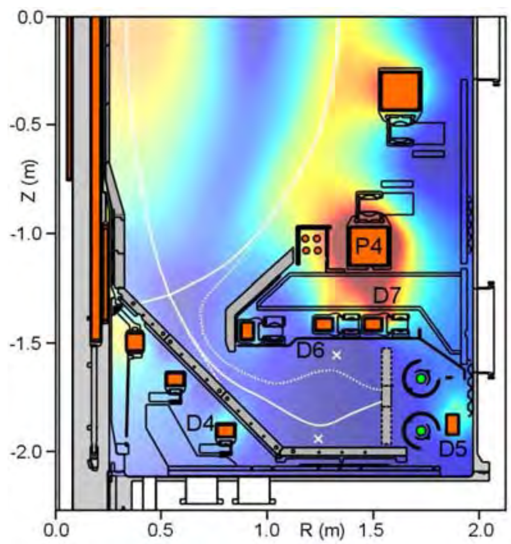
EFDA
Fusion Electricity
A roadmap to the realisation of fusion energy

TCV



Snowflake, X-divertor, Super-X, X-point target,…

MAST (2015)



Super-X

EU roadmap -- plans for advanced divertors:

- Near term focus: proof-of-principle concept testing

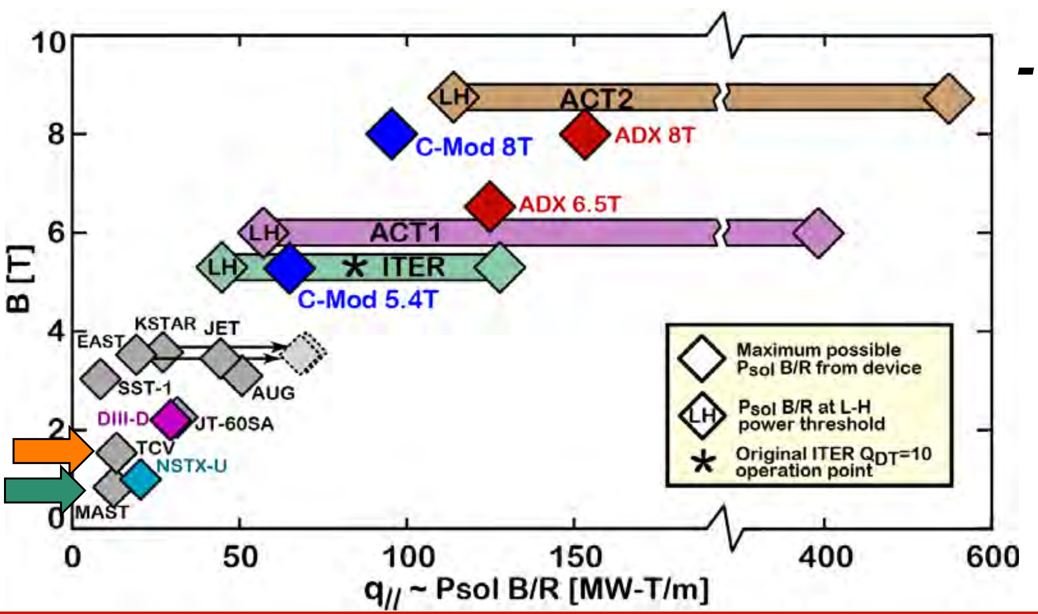
- Considering new facility, upgrade or international collaboration for DTT

- Decision for Divertor Test Tokamak (DTT) in 2016

- Seeking international collaborations

(page 54): "Europe should seek all the opportunities for international collaborations ….the following opportunities are underlined:"

"The collaboration on a joint DTT facility (US and Japan have also advocated the need for such a facility)"



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

Advanced Divertor Experiment

"But, ADX is a short-pulse experiment. How is that relevant for developing steady-state solutions?"

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

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

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

- Measure SS erosion/rep. and ion-induced material damage rates (divertor and RF actuators) at relevant PMI dimensionless parameters – E_{ion}/E_{thres}, L_{MFP}/ρ_i, ...

$\tau_{pulse} > \sim 5\tau_{L/R}$ – fully relaxed current profile

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

$\tau_{pulse} < \tau_{thermal}$ – first-wall components "inertially-cooled"

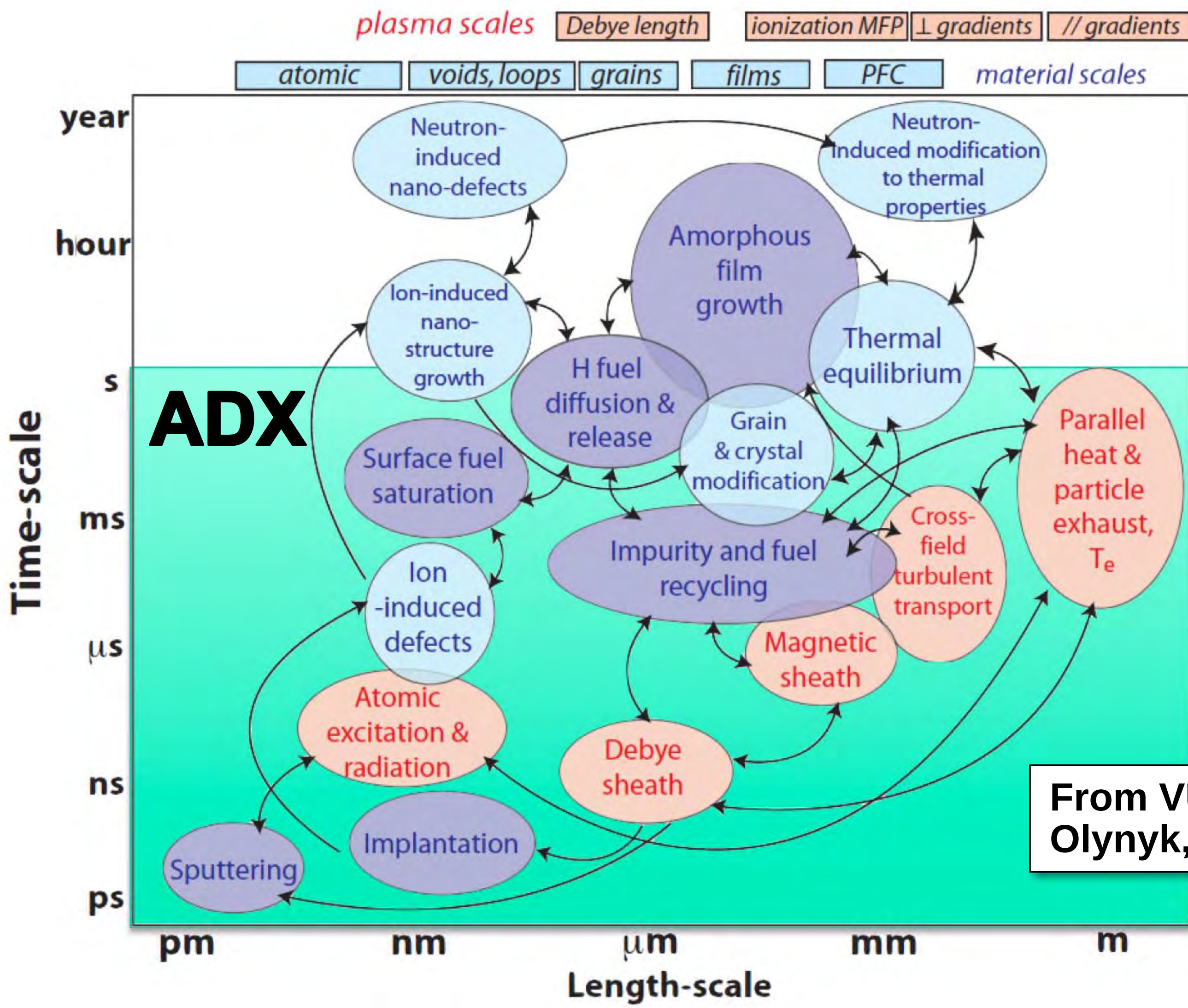
- *Advantage*: surface heating at ~40MW/m^2, 1 s pulse with *no damage*; avoids cost and complexity of SS cooling requirements

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

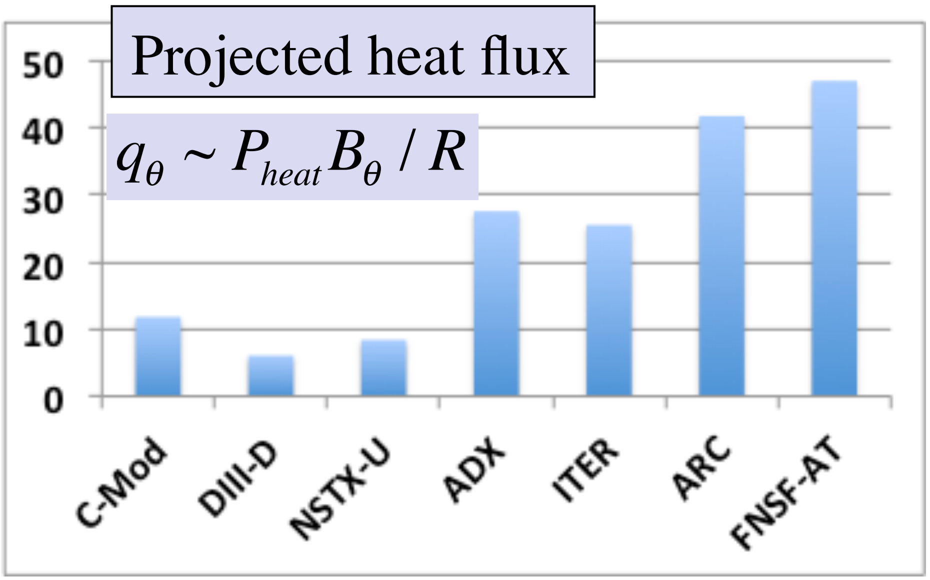


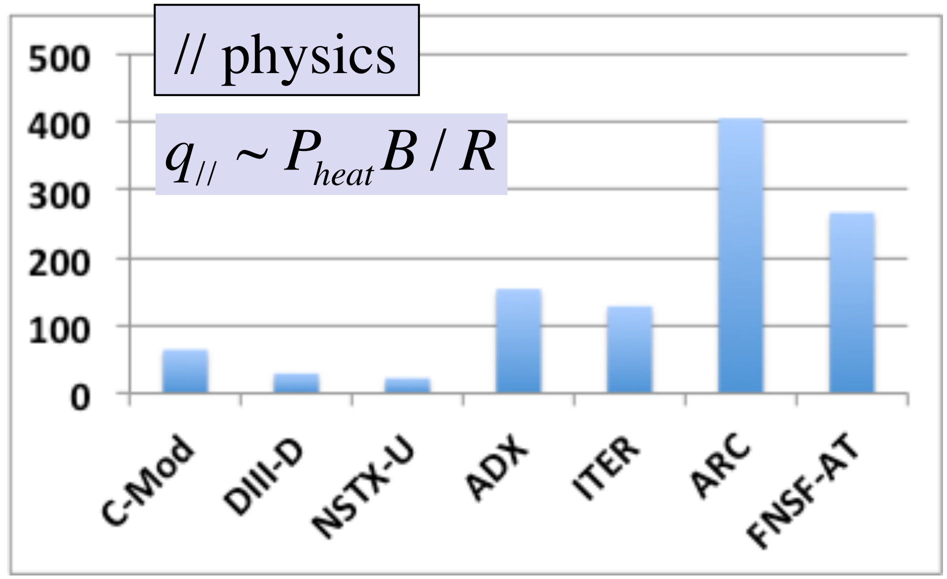
From VULCAN study:
Olynyk, *et al.*, FED 87 (2012) 224.

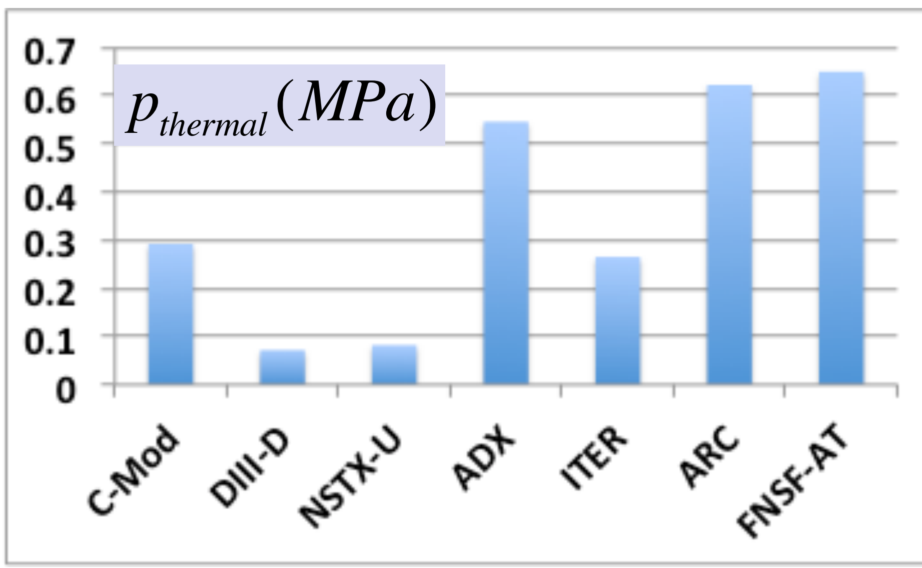
***Does not address*: thermal equilibrated materials, long-time film growth, surface modification at very large fluence, or neutrons ...**

ADX → develop *plasma physics solutions* that scale to SS

ADX provides a critically needed near-term, small-scale step into the ITER/FNSF heat exhaust & PMI parameter range

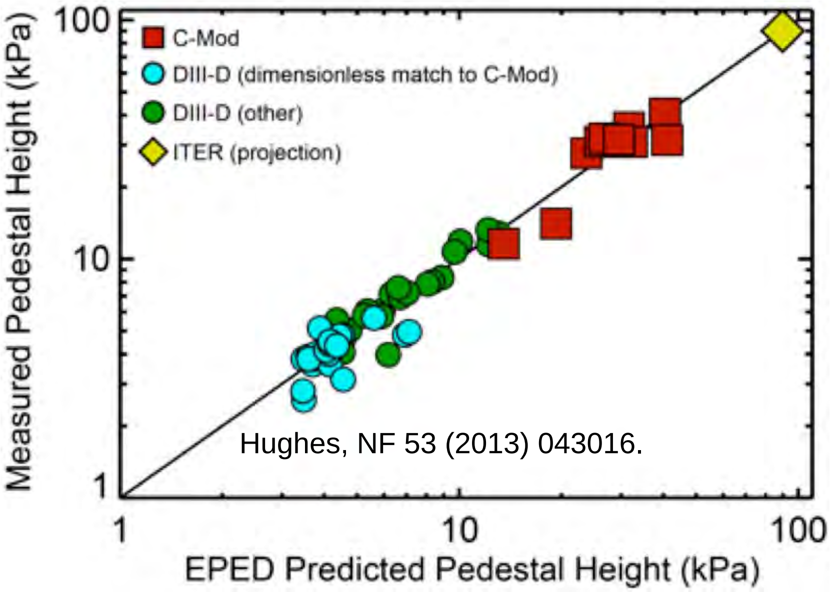






Atomic & PMI physics

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 model[1] 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 ($q_{//}$) facilitate reactor level divertor densities...

$$P = n(T_i + T_e);\ q_{//} \sim P\,T^{1/2};\ T_e \sim 10\text{ eV};\ T_i \sim T_e$$

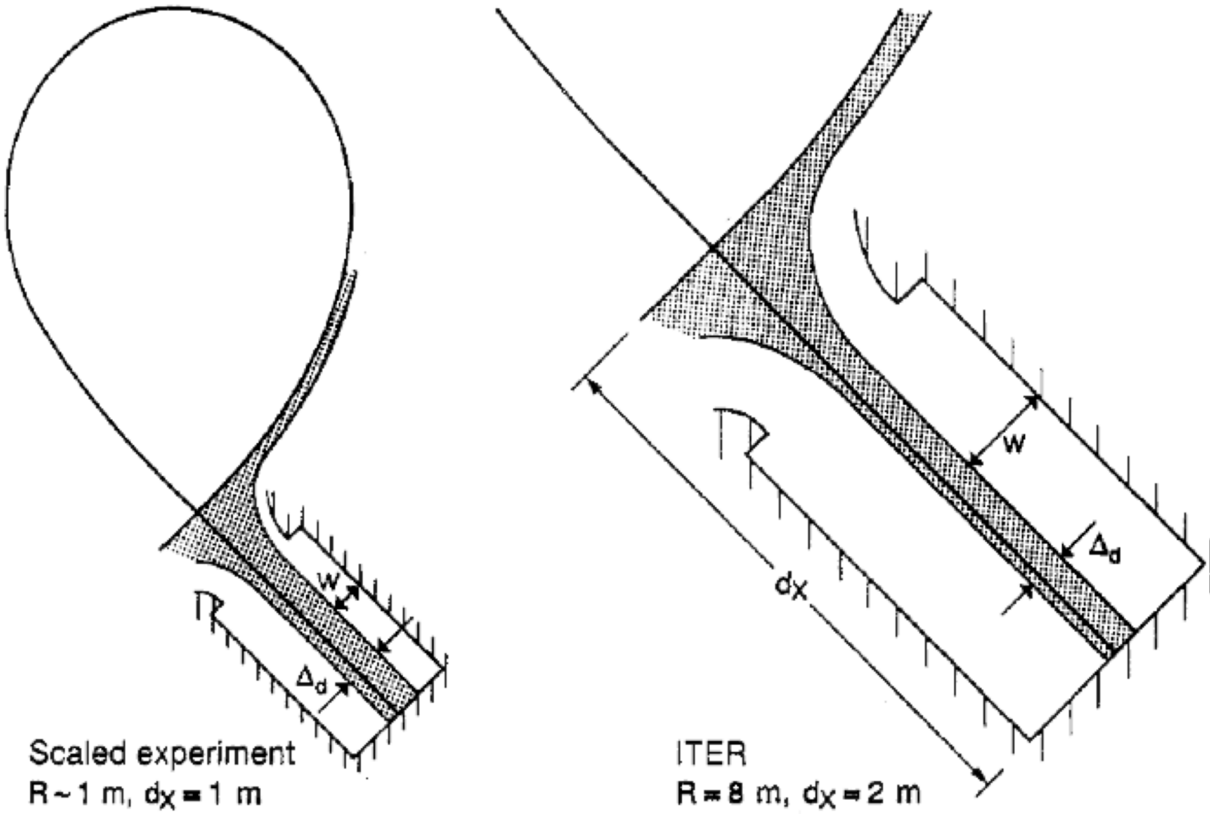
$$\Rightarrow n > \sim 10^{21}\ m^{-3}$$

This plus reactor level *B* is required to access the relevant divertor and PMI regimes[2,3]. Dimensionless parameters: ρ_z/λ_{ion}, $\lambda_{debye}/\lambda_{ion}$, …

[1] Snyder, P.B., *et al.*, NF 51 (2011) 103016; [2] Stangeby, NF 51 (2011) 063001; [3] 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, *divertor similarity with a reactor may be obtained.*[1]



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

$q_{//}$ = reactor
B = reactor
=> plasma and atomic physics dimensionless parameters in the divertor ...

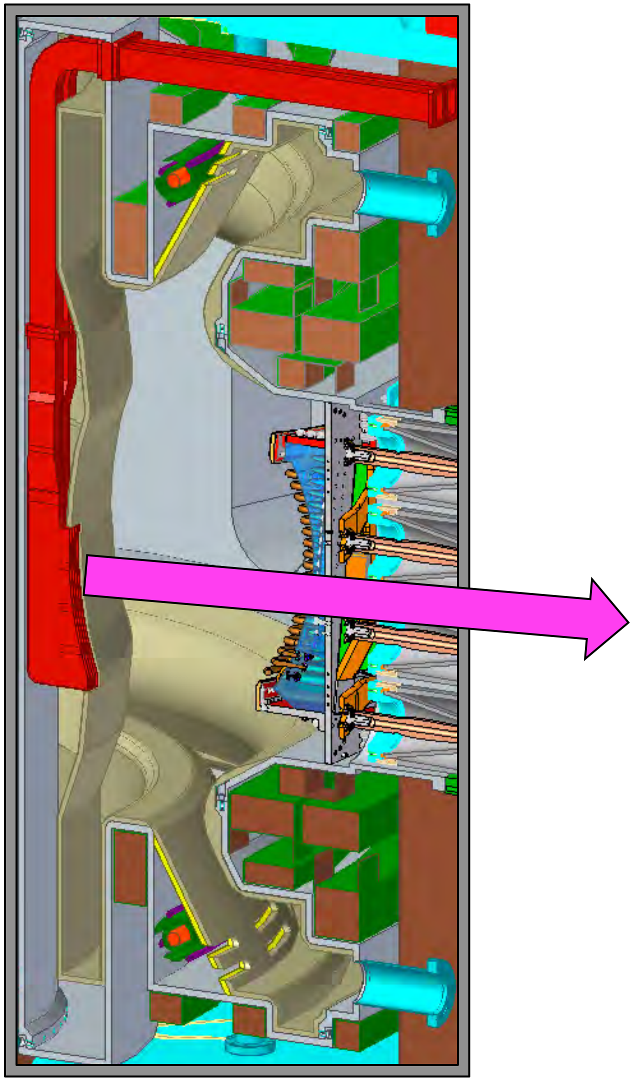
$$T_e, \nu^*, \rho^*, \beta, \lambda_0/\Delta_d$$

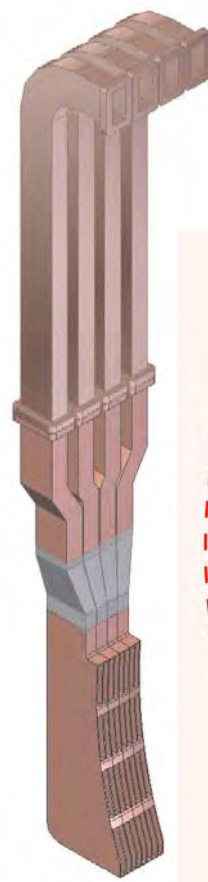
...may be made identical by adjusting poloidal flux expansion and divertor leg length.

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

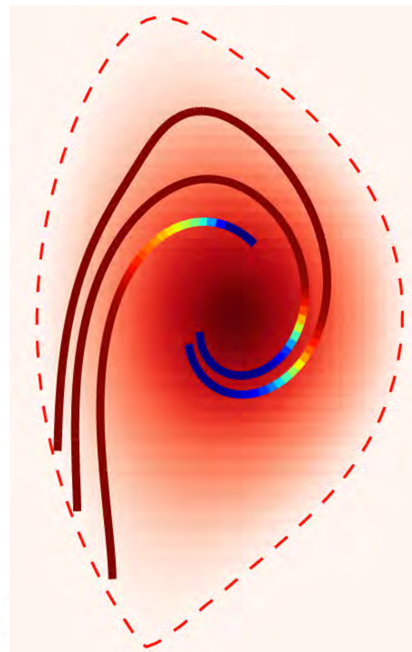
ADX -- an innovation platform for low PMI, reactor-compatible RF actuators

Advanced Divertor Experiment





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



- ***High B-field side***
  - *=> lower $n_{//}$*
  - *=> penetrating rays[1]*
  - *=> higher CD efficiency*
- ***Quiescent SOL***
  - *=> Low PMI*
  - *=> Excellent impurity screening[2]*

High field side launch is highly favorable for LHCD, as noted in VULCAN study[3].

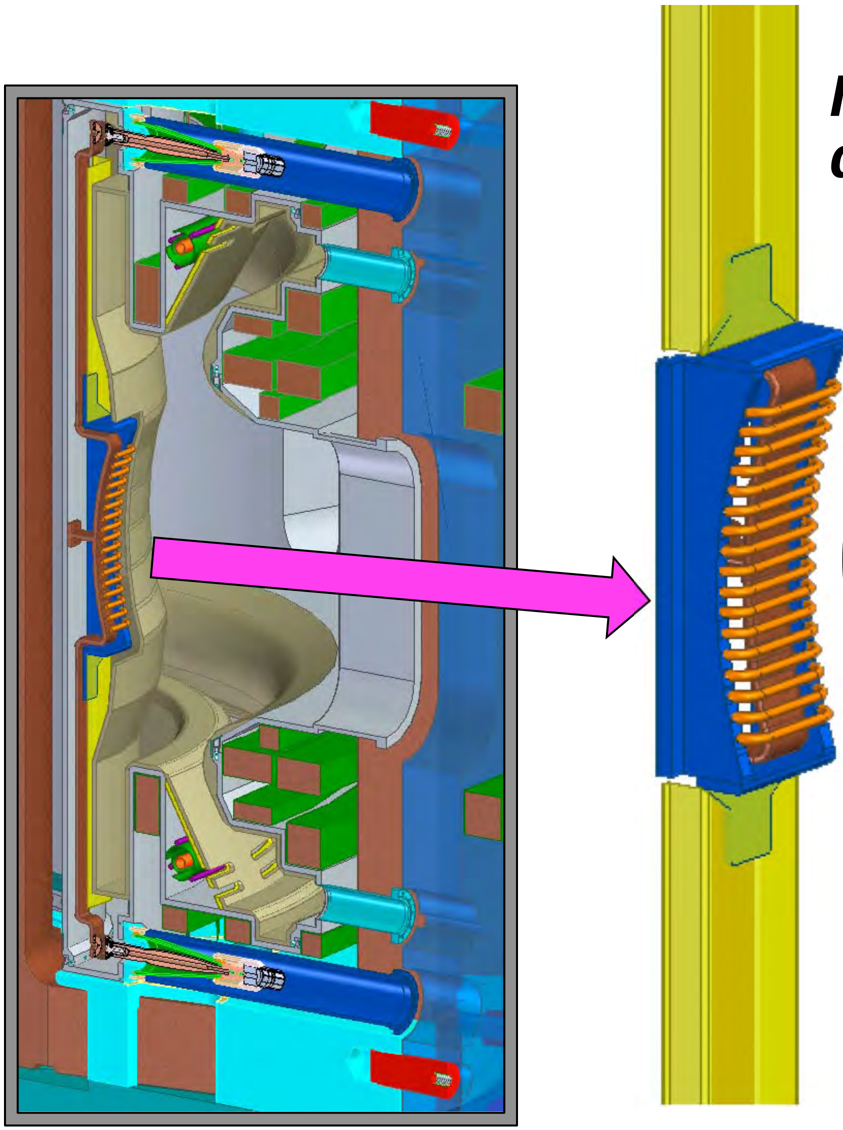
[1] GENRAY modeling by Syun'ichi Shiraiwa: $n_{//}$=1.6, Alcator C-Mod I-mode

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

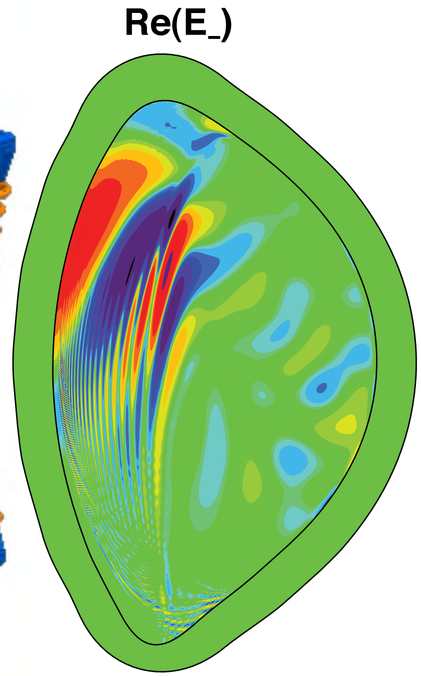
Demonstrate low PMI, reactor-compatible current drive and heating technologies

ADX -- an innovation platform for low PMI, reactor-compatible RF actuators

Advanced Divertor Experiment



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



- ***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 heating[1]

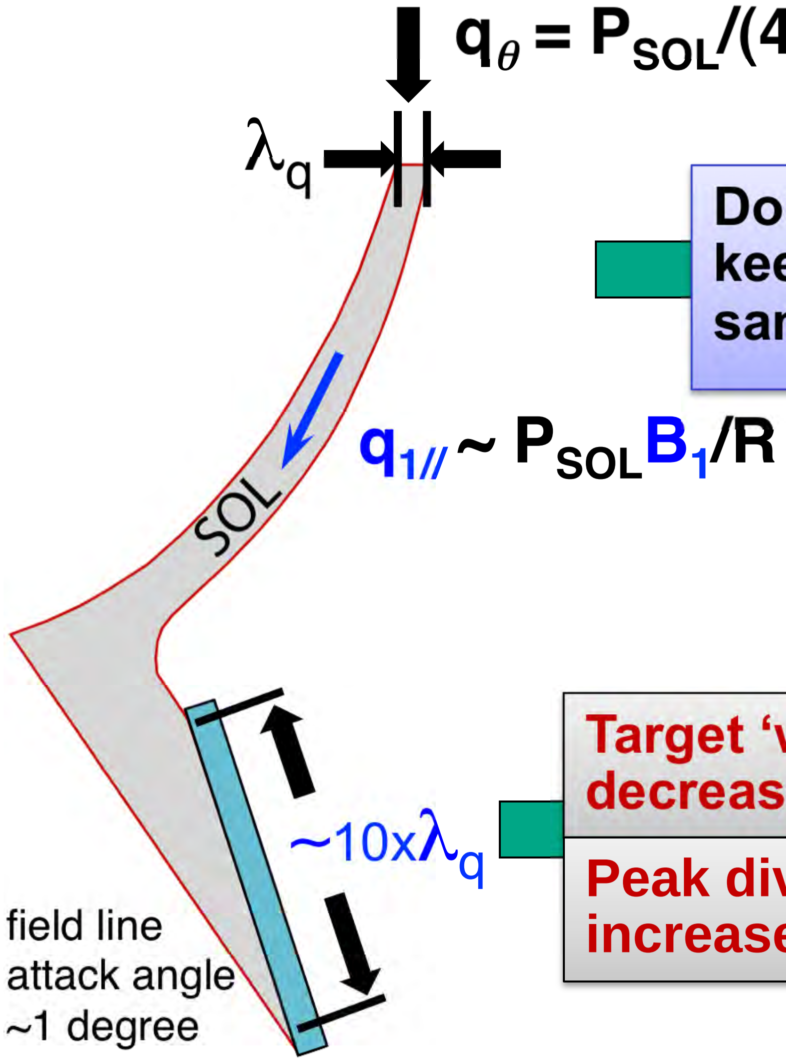
TORIC simulation: B = 5.4 tesla, f = 80 MHz, 15% H in D, n_ϕ = -10, 40% to electrons, 30% to H 1st harmonic and 30% to D 2nd harmonic

[1] TORIC modeling by Yijun Lin

Demonstrate low PMI, reactor-compatible current drive and heating technologies

Divertor heat flux challenge is set by $q_{//}$, not by q_θ

Thought experiment: double toroidal field



Double toroidal field, keeping all else the same: P_{SOL}, λ_q, B_θ, R

Target 'wetted area' decreases by a factor of 2

Peak divertor heat flux increases by a factor of 2

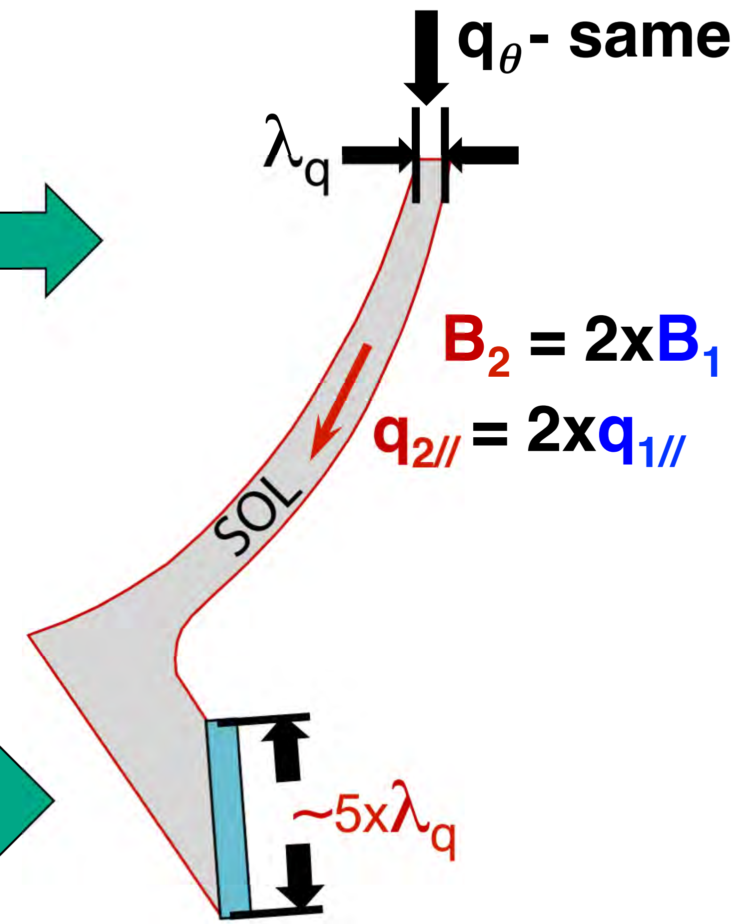


plate must be tilted to maintain field line attack angle ~1 degree

Maximum poloidal flux expansion is constrained by field line attack angle on target plate being greater than ~1 degree.