Innovation is Key from ITER to DEMO

**M. Porkolab, L. Bromberg, M. Greenwald, A. Hubbard,
B. Labombard, E. Marmar, J. Minervini, D. Whyte**

Plasma Science and Fusion Center

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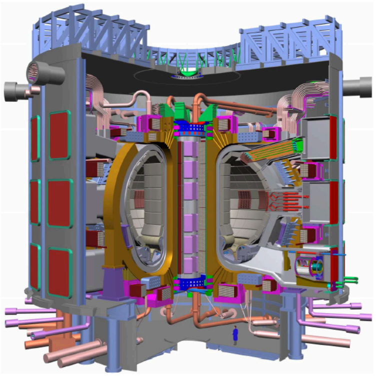
Plasma science and technology innovation on the path to DEMO

ITER

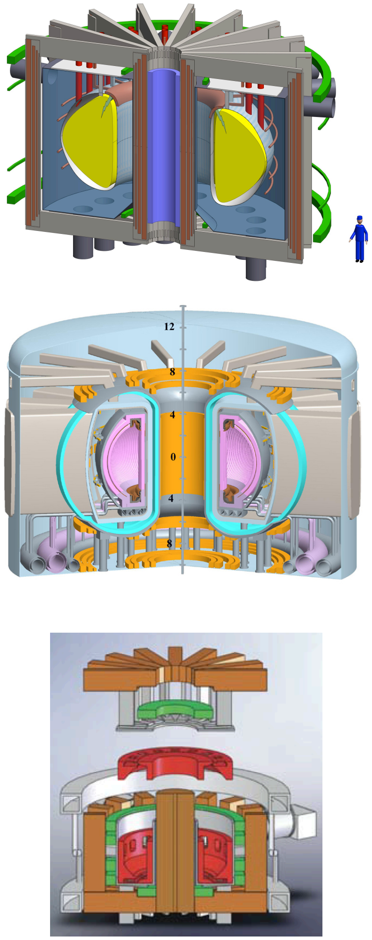


parallel pathways

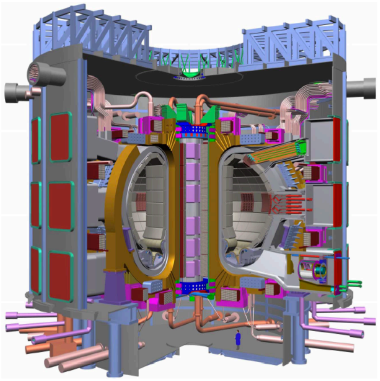
FNSF/ DEMO

R&D + innovation required for steady state:
- Power exhaust, transients, wall lifetime
- High temperature tungsten PMI in tokamak
- SS current drive & heating
- Divertor solution compatible with core

R&D + innovation required for reduced cost DEMO:
- Demountable, high temperature superconductors
- High-field, compact, modular reactor designs



For PMI, the step from ITER to DEMO will be enormous.



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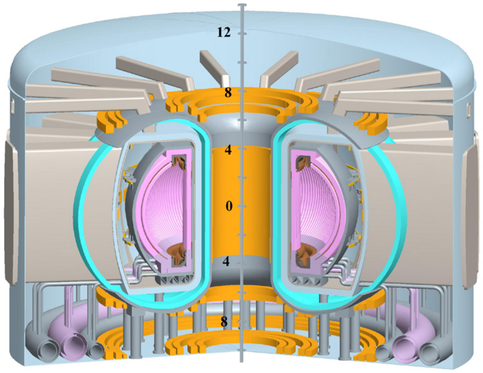

ARIES-ACT1

	ITER	ARIES-ACT1	ARIES-ACT2
R(m)	6.2	6.25	9.75
B(T)	5.3	6.0	8.75
P_α (MW)	100	360	520
P_{fusion}(MW)	500	1800	2600
$P_\alpha B/R$	85	350	810

http:www-pub.iaea.org/MTCD/publications/PDF/ITER-EDA-DS-22.pdf
http://aries.ucsd.edu/ARIES/DOCS/bib.shtml

Factor of 4 to 10 times higher $P_\alpha B/R$ than ITER

Factor of 10^5 increase in pulse length

High temperature (1000 C) tungsten divertor/wall

-- while survival of divertor and wall in ITER is already a concern.[1]

Innovative solutions to critical PMI challenges – *beyond those the fusion community is now pursuing* – must be explored and demonstrated on existing and/or upgraded facilities.

[1] Richard Pitts, "Physics basis and design of the ITER full-tungsten divertor", APS 2013, Denver.

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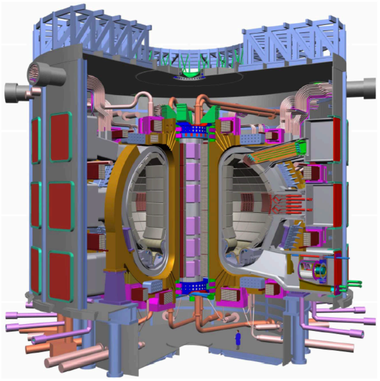
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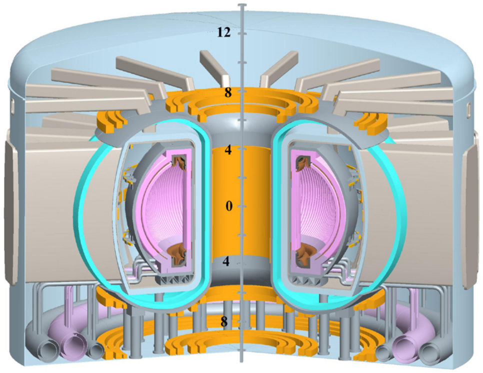

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Innovative solutions are also required to reduce the cost of DEMO.

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Six milestones must be included in the DEMO development pathway, along with facilities and R&D programs that will address them:

1. Demonstrate robust divertor power handling solutions at DEMO boundary plasma parameters

2. Demonstrate complete suppression of divertor erosion at DEMO parameters, scaling to SS operation (10^7 seconds)

3. Achieve goals 1 and 2 while attaining reactor-relevant core plasma performance

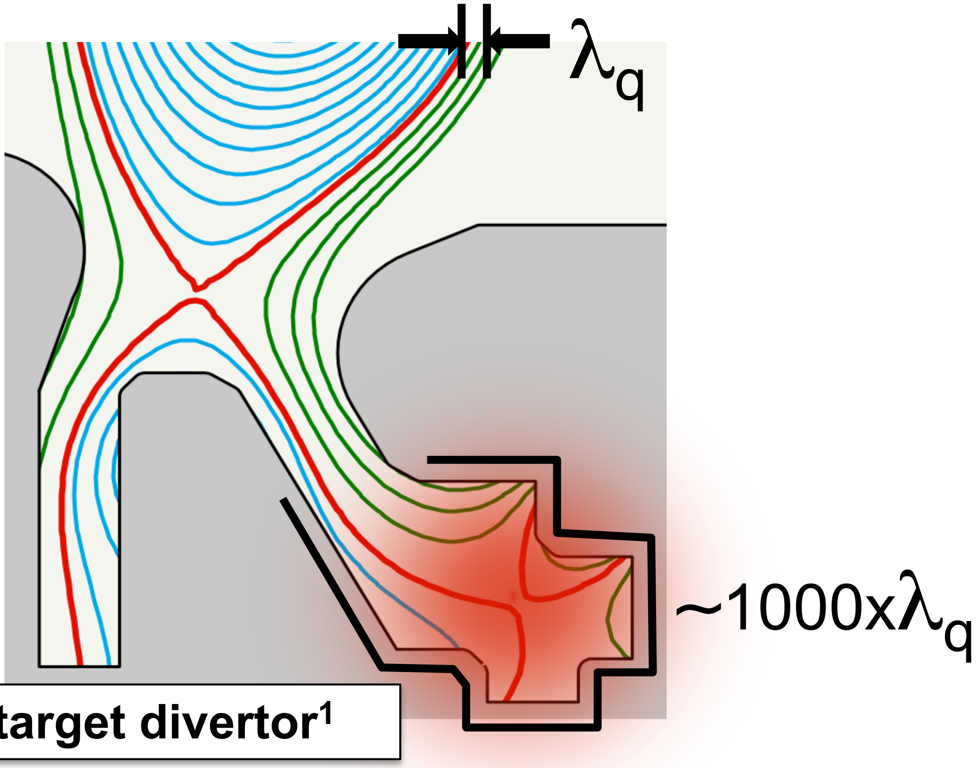
4. Demonstrate low PMI, reactor-compatible current drive and heating technologies

5. Determine high-temperature tungsten PMI response in tokamak at reactor-relevant conditions

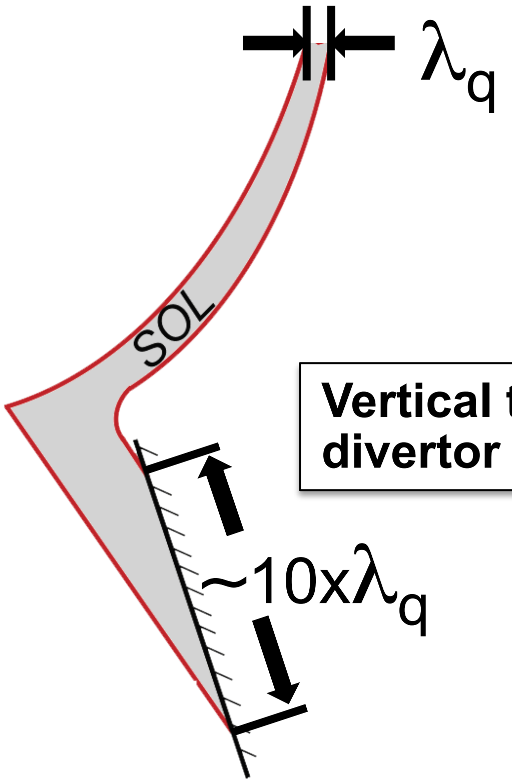
6. Develop demountable HTS technology to increase flexibility and higher high magnetic field for better stability and higher current drive efficiency to reduced cost of DEMO designs

Advanced divertors have the potential to the solve power handling and erosion problems – they must be pursued.

New Concept[1]: Use a remote X-point to produce a fully detached, radiating plasma as a *virtual target*.



X-point target divertor[1]



Vertical target plate divertor (ITER)

- Cold, fully detached divertor = ~ zero erosion

- Hot separatrix and pedestal regions = good core performance

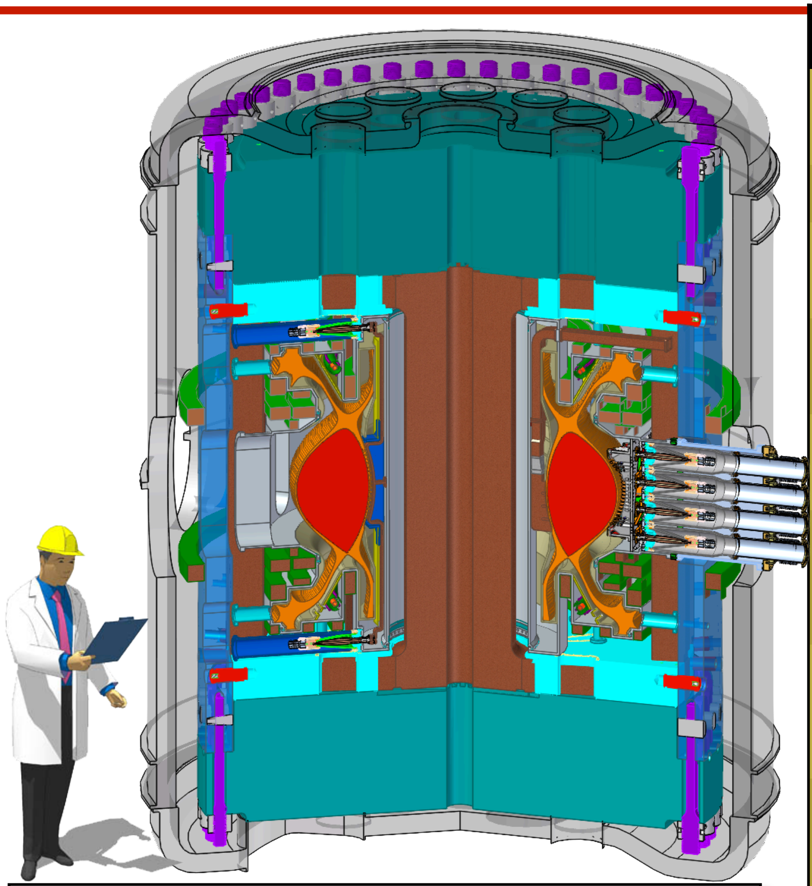
Spread divertor heat load over the large surface area of the divertor chamber by tailoring magnetic geometry and radiation/neutral interaction zone

[1] http://www.psfc.mit.edu/research/alcator/pubs/APS/APS2013/labombard_cont-oral_APS-13.pdf

ADX

*MIT PSFC is considering a concept for a high power density, advanced divertor test facility[1]**

Alcator DX



Alcator DX	
Major/Minor Radius	0.73 / 0.2 m
Elongation	1.7
Magnetic Field	6.5 Tesla (8 Tesla)
Plasma Current	1.5 MA
P_{AUX} (net)	8 MW ICRF 2 MW LHCD
Surface Power Density	~ 1.5 MW/m^2
SOL Parallel heat flux	$q_{\|\|}$ ~ 2 GW/m^2
Advanced Divertor Concepts	Vertical target; Snowflake; Super-X; X-point target; Liquid metal target
Divertor and first-wall material	Tungsten/ Molybdenum
Pulse Length	3s, with 1s flat-top

Proven Alcator Technology:

- *extremely strong super-structure*
- *sliding TF joints*
- *coaxial OH/PF coil feeds*
- *electro-formed terminals*
- *PF and OH coils supported by rigid vacuum chamber*
- *Reactor-relevant RF heating and current drive systems*

Key Elements:

- ***Demountable,*** LN$_2$ cooled, copper TF magnet
- Vertically-elongated VV
- Advanced divertor poloidal field coil sets (top and bottom)
- High power ICRF, 8MW
- Reactor-level *P/S*, SOL $q_{||}$ and plasma pressures

  => same and higher than Alcator C-Mod
- Development platform for low PMI RF actuators:
  - Inner-wall LHCD
  - Inner-wall ICRF

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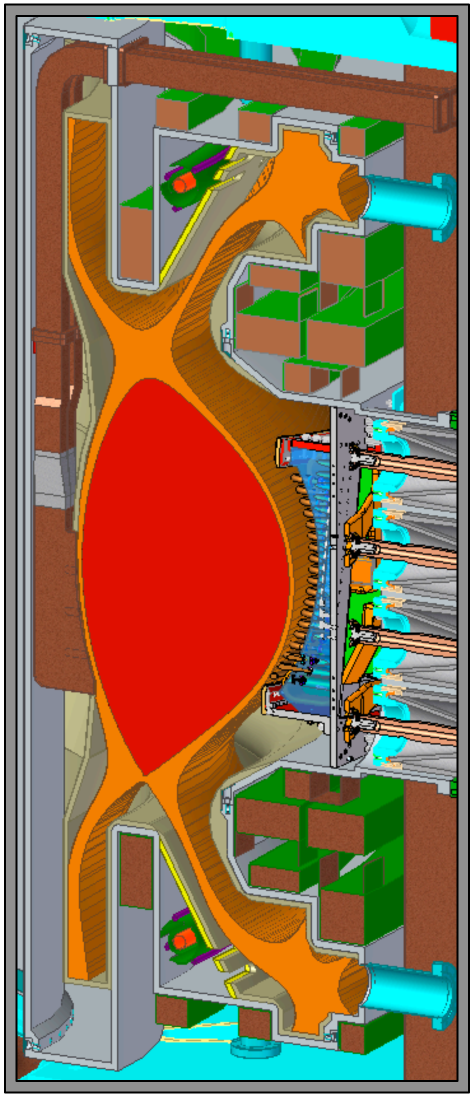
[1] http://www.psfc.mit.edu/research/alcator/pubs/APS/APS2013/Vieira_poster_APS-13.pdf

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

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



- **Internal PF coils to** ***test the most promising magnetic geometries and divetor targets.***
- **Double-null geometry:**

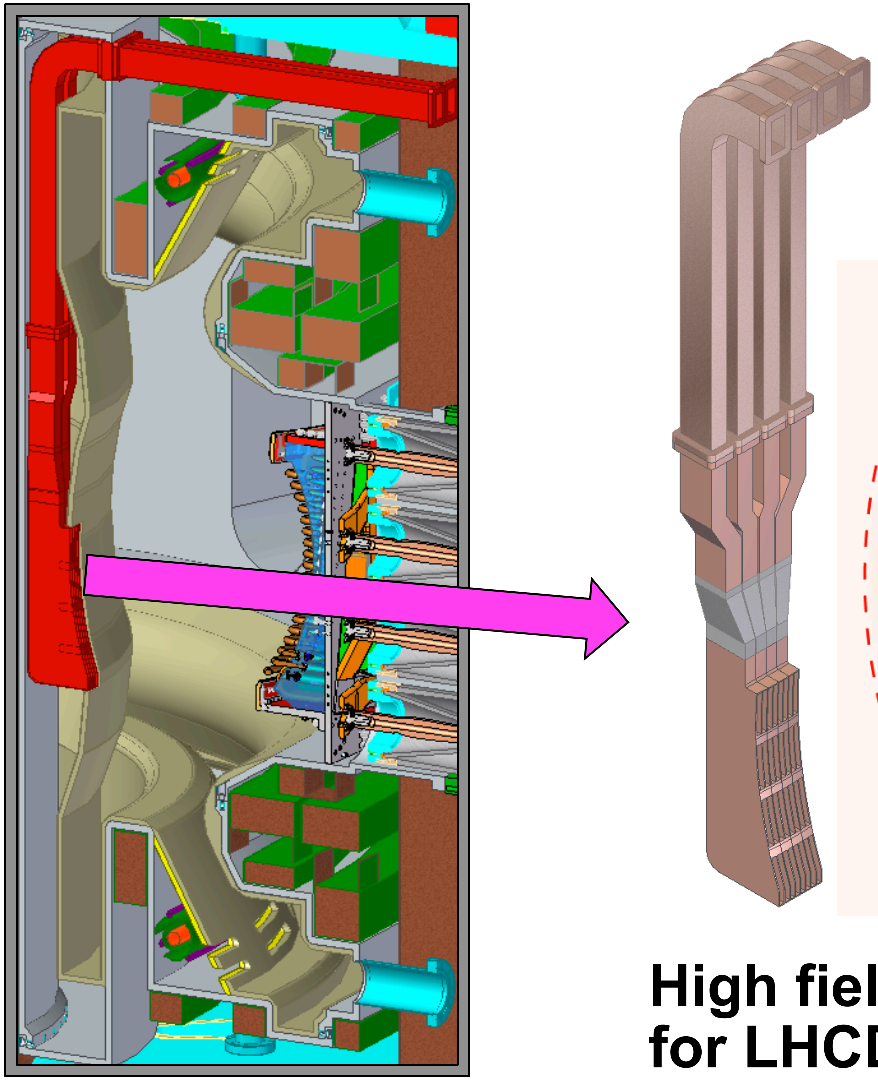
Advanced divertors -- low-field side SOL

Quiescent, low heat flux -- high-field SOL

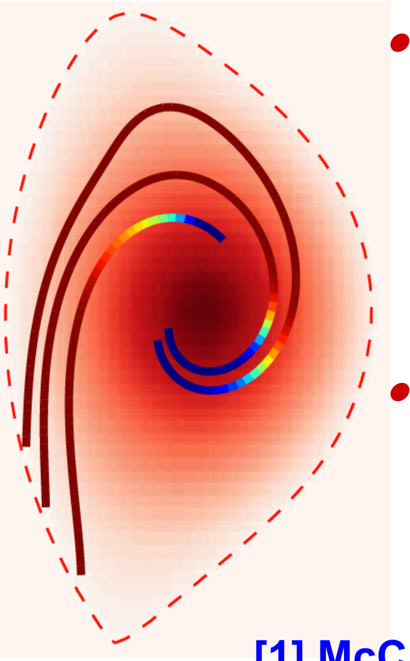
Double null + inside launch RF
=> potential game-changer for heating and current drive actuators

"Tame the plasma-material interface with plasma physics"

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



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



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

[1] McCracken, *et al.*, PoP 4 (1997) 1681.

High field side launch is highly favorable for LHCD, as noted in VULCAN study[2].

[2] VULCAN: Podpaly, *et al.*, FED 87 (2012) 215.

Milestone: *(for SS burning plasma)*	**Develop robust, reactor-compatible current drive & heating techniques**

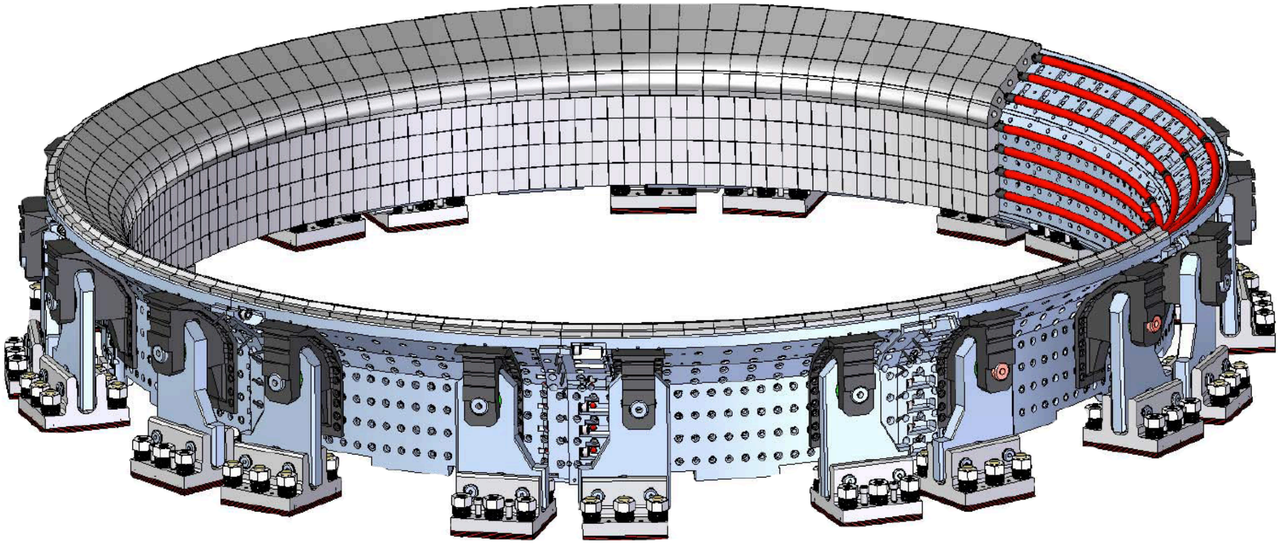
Alcator C-Mod *Can provide key information now on high temperature tungsten PMI for DEMO*

"C-Mod operates at the right power and particle flux, right plasma pressure and density, right magnetic field, divertor geometry and materials."[1]

- Next: Right temperature ≈ Tungsten at >900˚K (Requirement for FNSF, Demo)

Solid tungsten tiles, divertor temperature controlled to 900°K

Toroidally continuous target, precision aligned, no leading edges



Designed and ready for fabrication

[1] http://www.psfc.mit.edu/research/alcator/pubs/APS/APS2013/Greenwald_invited_APS-13.pdf

Advantages of High Field for Fusion*

Operational limits in a tokamak all increase with field

- **Maximum plasma current (MHD kink limit) $I_P \approx\approx B$**
- **Maximum plasma pressure (MHD β limit) $p \approx B^2$**
- **Maximum plasma density (density limit) $n_e \approx I_P \approx B$**

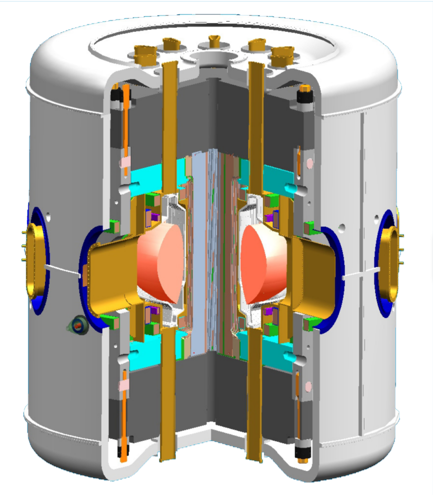
· **Fusion Power** $\propto \left(\frac{\beta_N}{q}\right)^2 R^3B^4$ **(Reactor Cost** $\propto R^3B^2$ **)**

3. The path to fusion energy would be much more attractive if the next nuclear steps had significantly lower costs

*Greenwald, APS DPP, Denver, November 2013

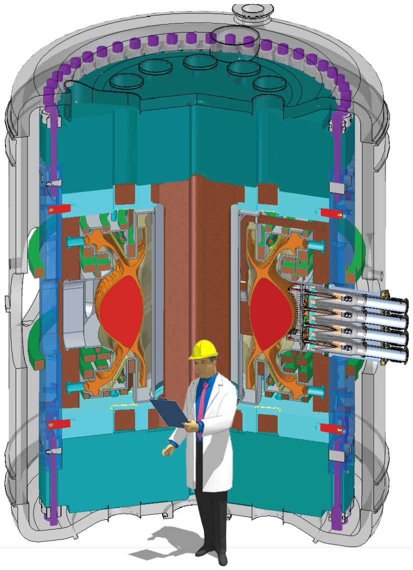
What might a high-field development path to DEMO look like?

Key Enabling Technology: demountable HTS magnetics[1]



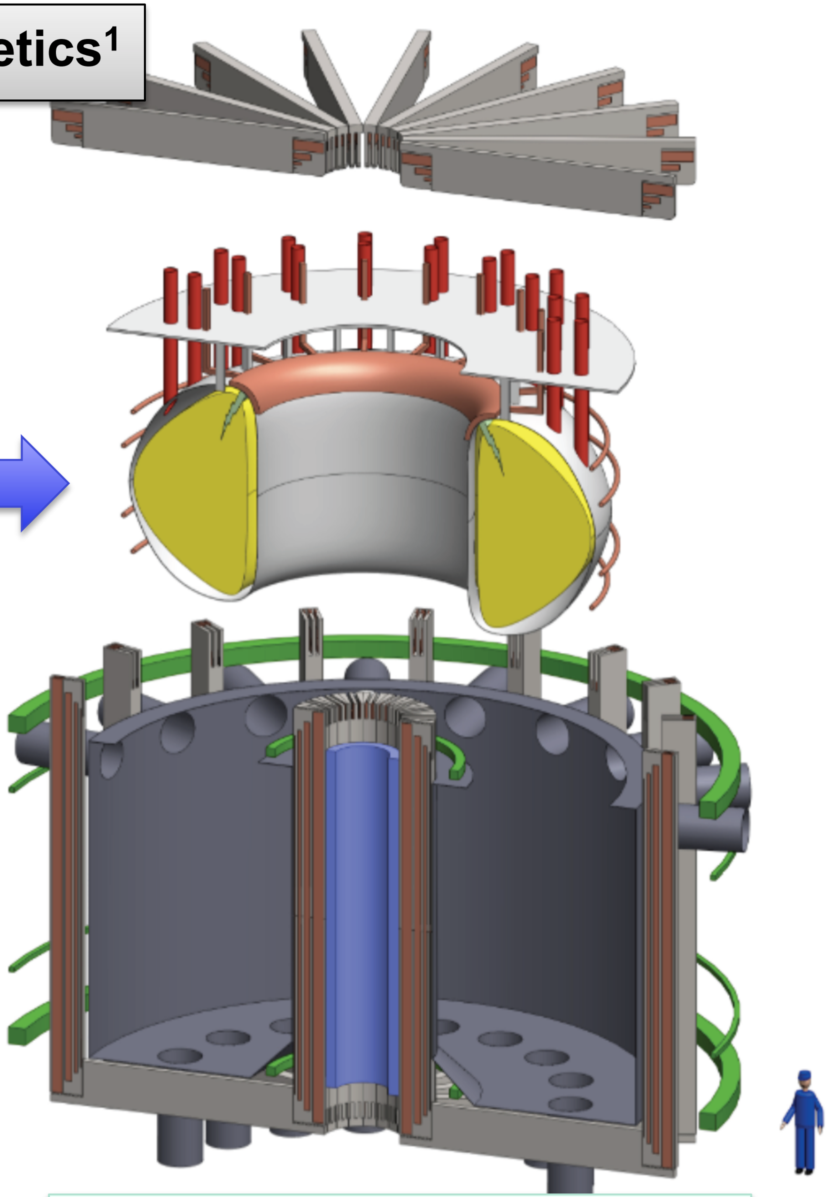
C-Mod (8 tesla)

- High-temp divertor at extreme $q_{//}$, tungsten PMI
- Advanced LHCD



ADX (8 tesla)

- Advanced magnetic divertors at reactor nT_e, $q_{//}$
- Divertor - core plasma optimization
- Reactor-relevant LHCD and ICRF



ARC[1] - High-field (9 Tesla) pilot plant

[1] http://fire.pppl.gov/FPA12_Whyte_SS.pdf

Need a HTS Development Program for Fusion

- Magnet technology for use in HTS magnets needs to be developed
- HTS offers a unique opportunity in fusion applications
  - ✧ Refrigeration of joint losses decreased because of operation at temperatures 40-60 K
  - ✧ Low electrical power requirements, good for long operation
  - ✧ Demountable, good for access (however, require external support structure)
  - ✧ Materials exist today, at costs that are not prohibitive
- R&D is required specifically for fusion applications:
  - ✧ Radiation effects on superconductor and insulating materials
  - ✧ Cable construction
  - ✧ Magnet cooling
  - ✧ Joints

SUMMARY: a Look to the Future

- Significant innovation needed to go beyond ITER, both in physics and technology
- Physics innovation calls for continuing experimental plasma research
- Technology innovations require development of better materials (test stands as well as FNSF) and nuclear materials testing (blankets and tritium breeding)
- High Temperature Superconducting Magnets shoul be developed (demountable magnets for ease of maintenance)
- High magnetic field magnets to reduce costs (more compact devices)
- Continuing education of scientists and engineers a priority