Innovation is Key from ITER to DEMO

Miklos Porkolab

in collaboration with
L. Bromberg, P.T. Bonoli, M. Greenwald, A. Hubbard,
B. Labombard, E. Marmar, J. Minervini, D. Whyte
and PSFC Graduate Students

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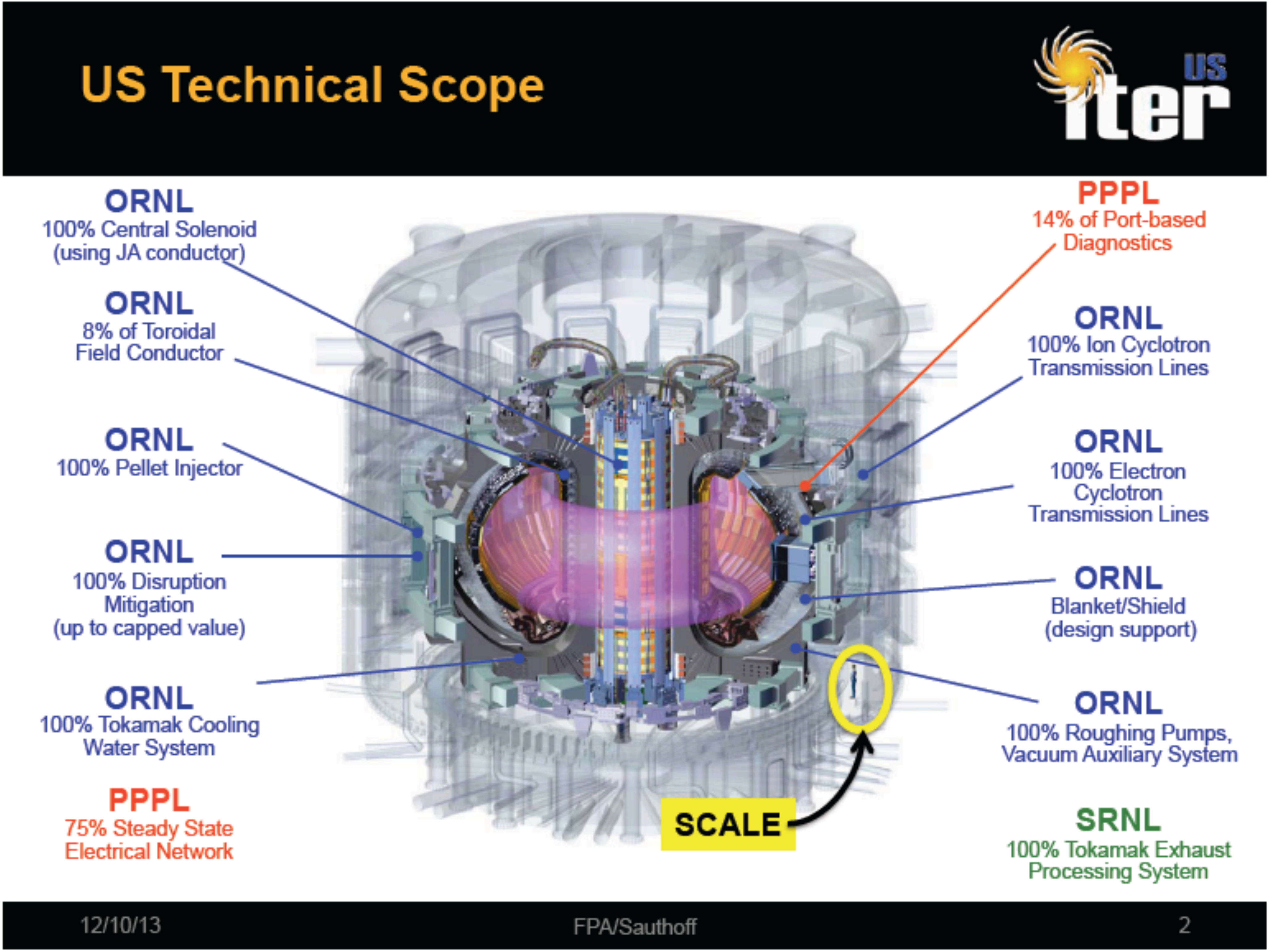
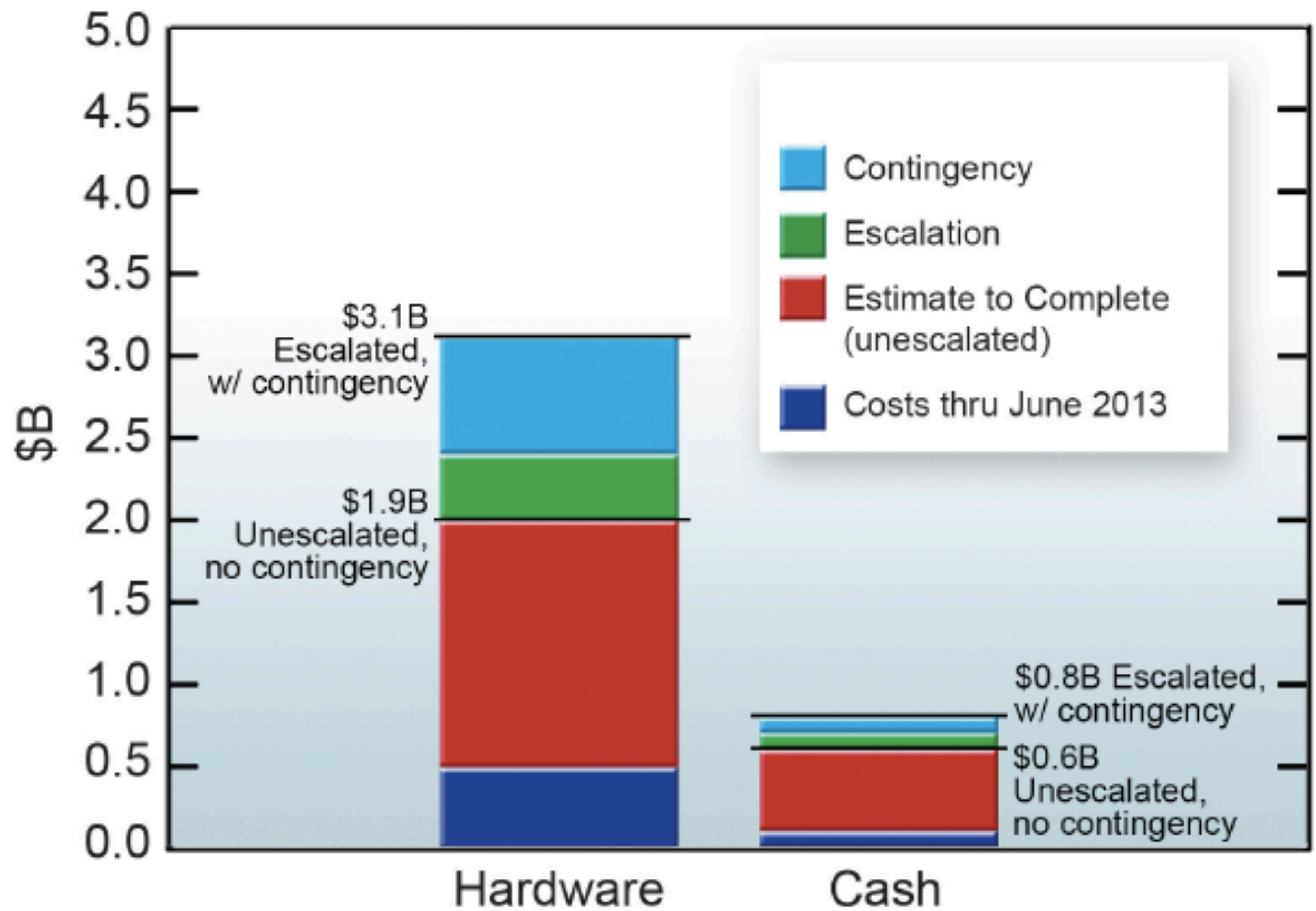


After Ned Sauthoff, FPA Meeting, Dec 10, 2013, Washington, DC USA

Cost Elements



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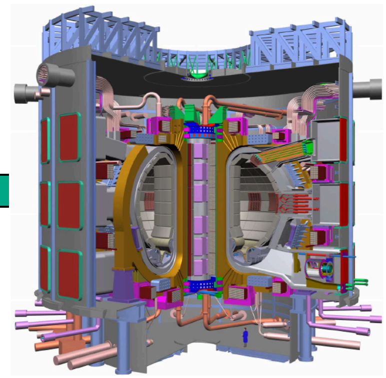
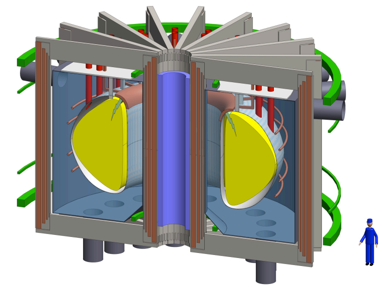
Plasma Science and Technology Innovation Essential on the Path to DEMO

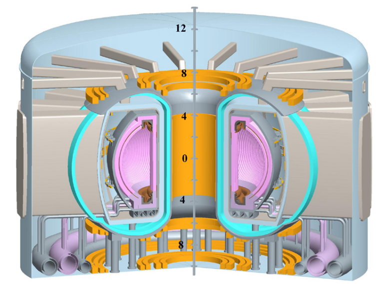
ITER

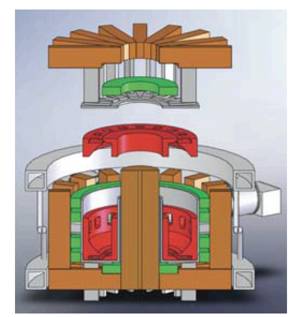


parallel pathways

FNSF/ DEMO







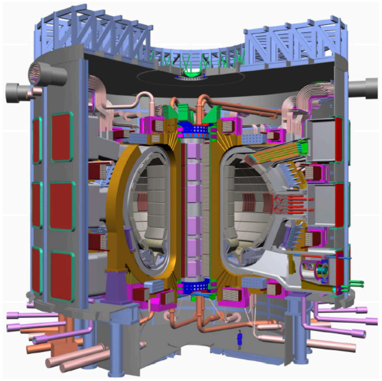
R&D + innovation required for steady state:

- 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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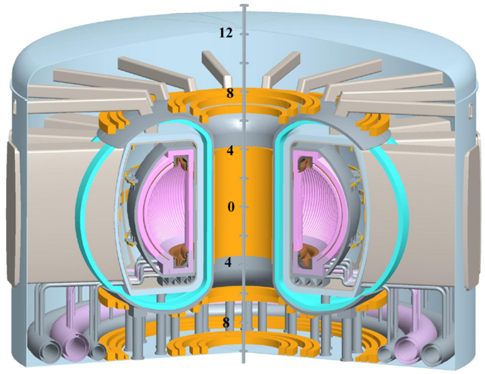


ARIES-ACT1

	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

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

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.

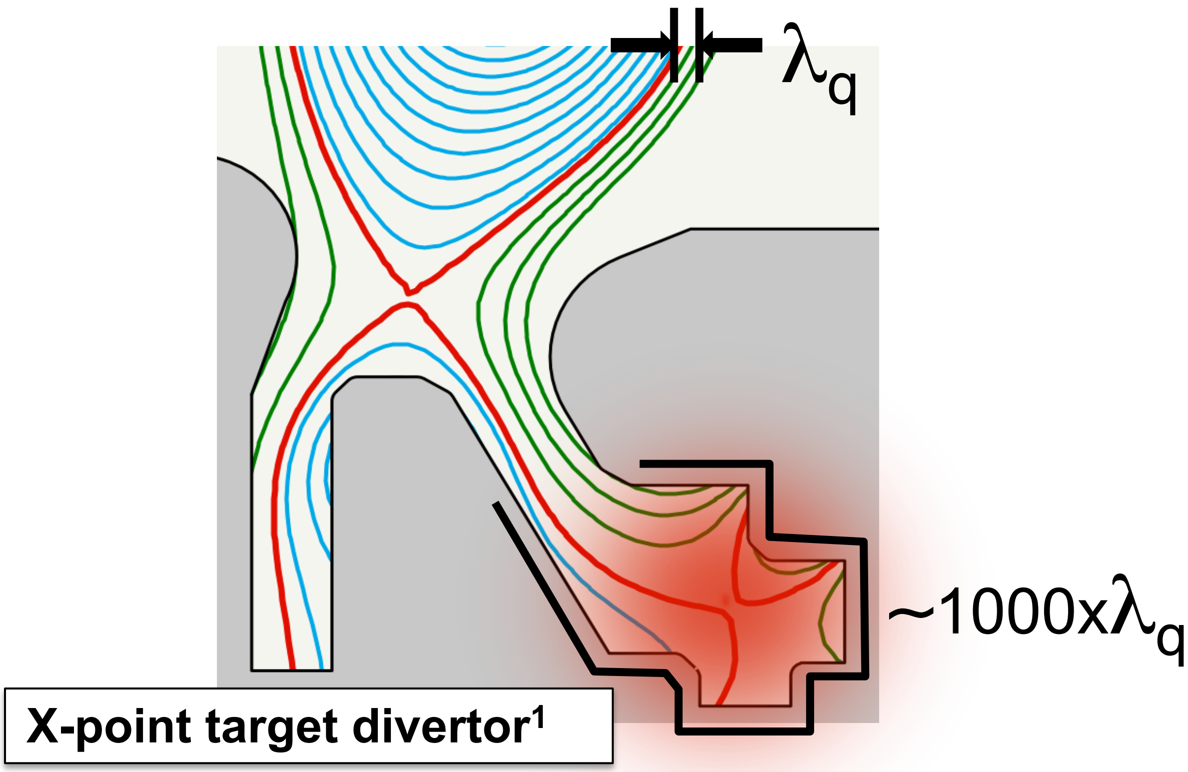
[1] Richard Pitts, "Physics basis and design of the ITER full-tungsten divertor", APS 2013, Denver.

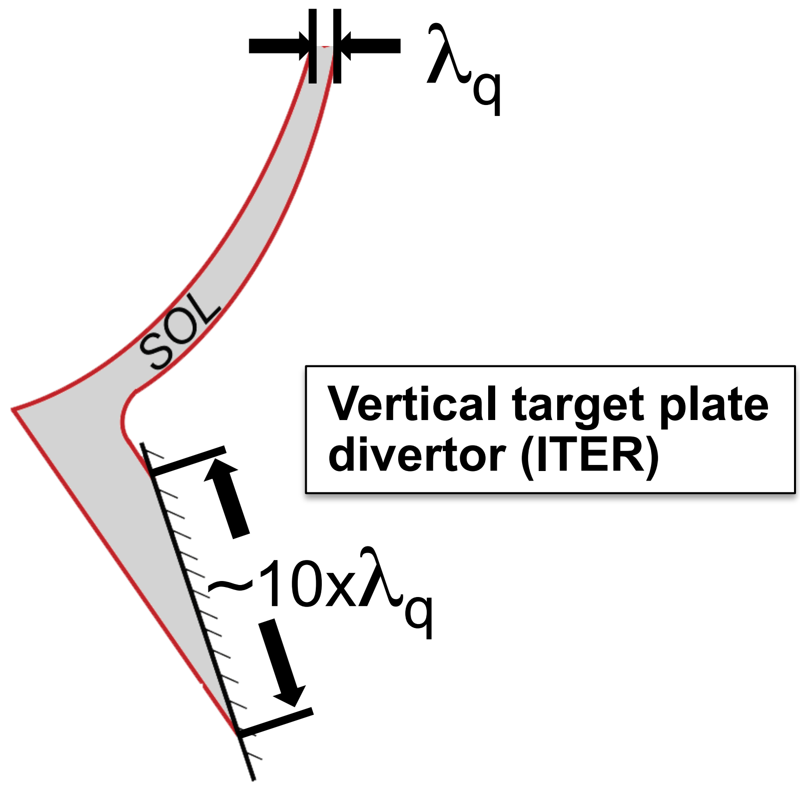
Six milestones for the DEMO development pathway, along with facilities and R&D programs

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 – must be tested experimentally

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





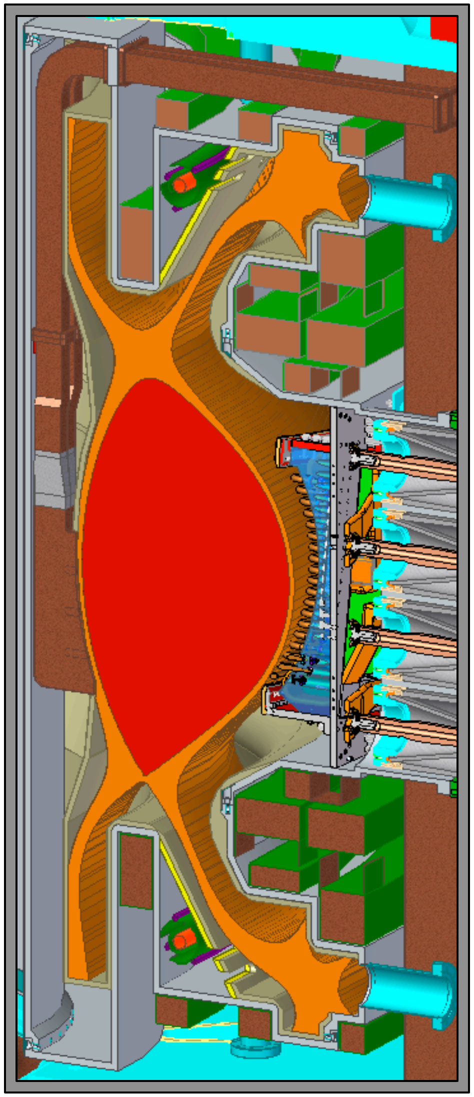
- ***Cold, fully detached divertor = ~ zero erosion***
- ***Hot separatrix and pedestal regions = good core performance***

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*

Alcator DX



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

  Advanced divertors -- low-field side SOL

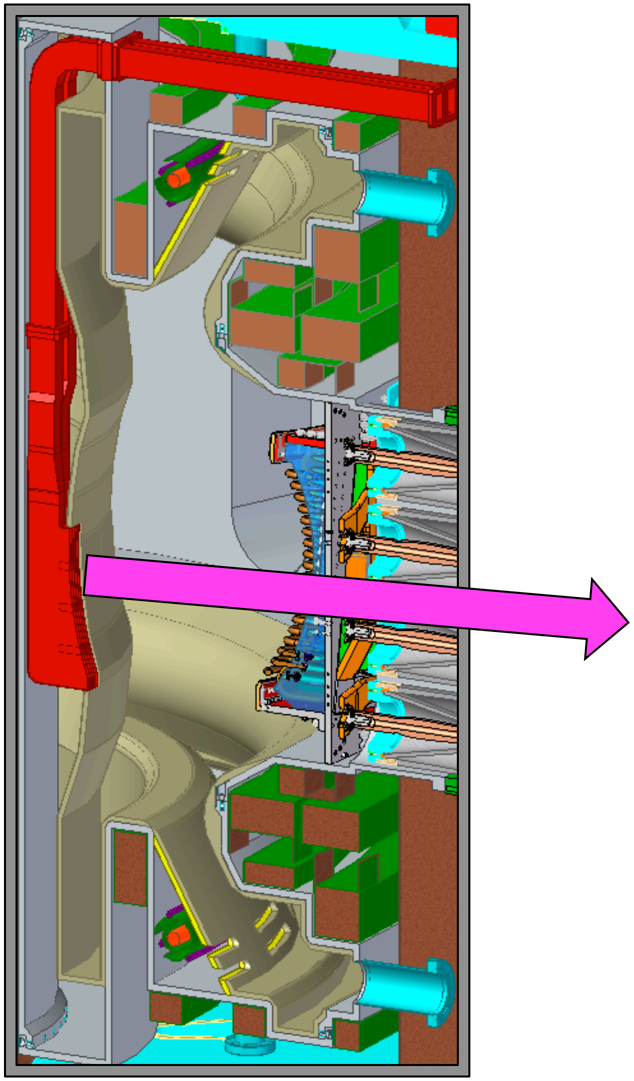
  Quiescent, low heat flux -- high-field SOL

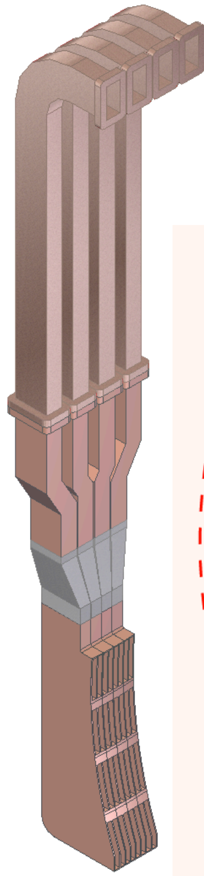
Double null + inside launch RF
=> potential game-changer for heating and current drive actuators

"Tame the plasma-material interface with plasma physics"

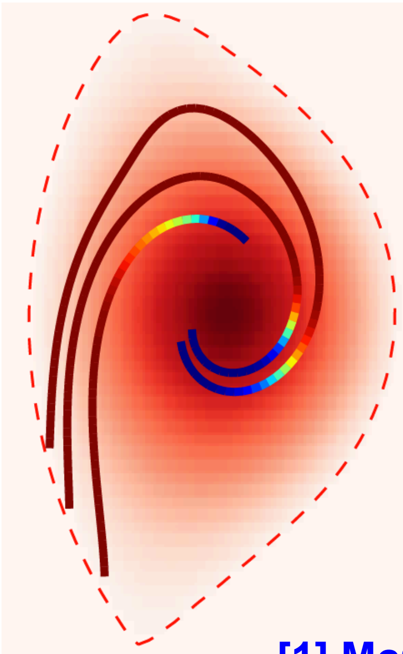
ADX -- an important innovation platform for low PMI, reactor compatible RF actuators

Alcator DX





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**

Higher Magnetic Field is a Winner

Fusion Power Density: $P \sim \beta^2 B_T^4 = (\beta/\varepsilon)^2(\varepsilon B_T^2)^2$

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

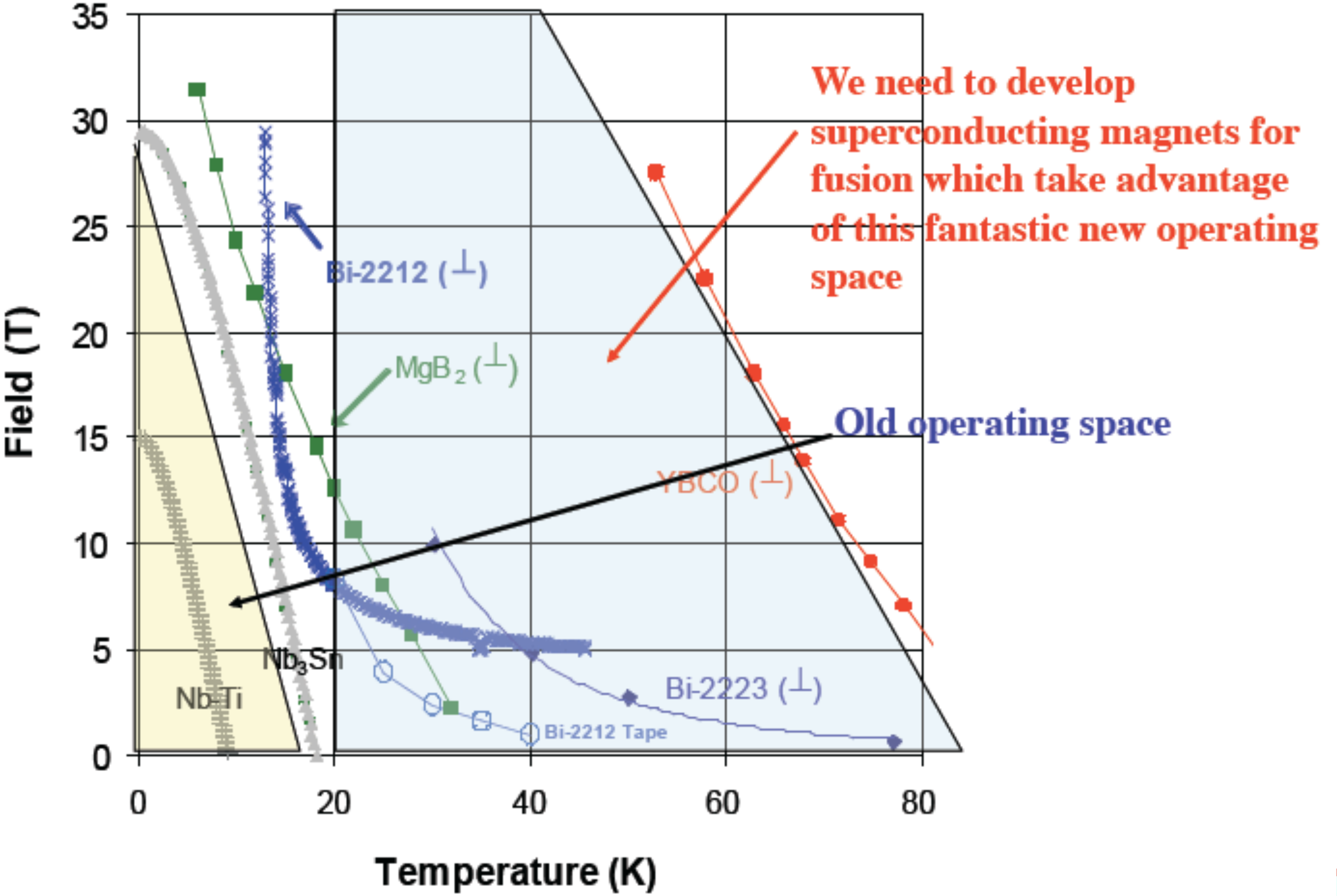
Greenwald, APS DPP, Denver, November 2013

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) $n_e \approx I_P \approx B$**

HTS Make Higher Magnetic Fields Accessible

L. Bromberg, J. Minervini, MIT PSFC



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

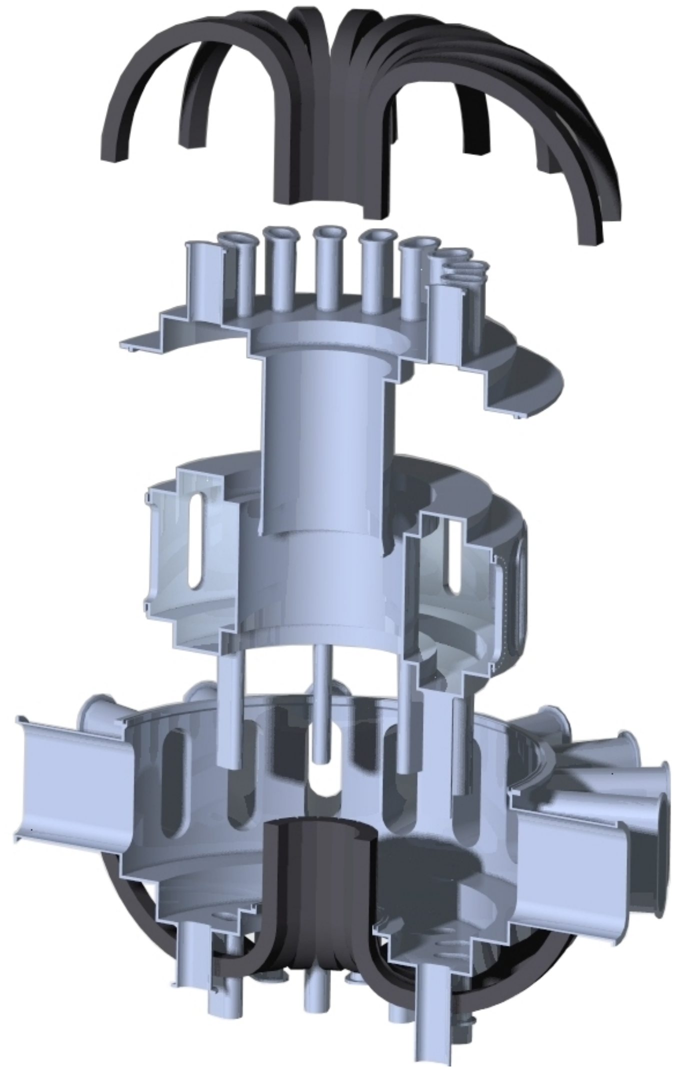
➔ *You know much more about this than I !!!*

The Vulcan concept: a steady-state tokamak for reactor-relevant plasma–material interaction science

D. Whyte et al Fusion Design and Engineering, 2012

Plasma major / minor radius (R_0 / a)	1.2 / 0.3 m
Magnetic field on axis (B_0)	7.0 T
Plasma current (I_p)	1.85 MA
Plasma elongation / triangularity (κ / δ)	1.7 / 0.7
Volume-averaged electron density ($\langle n_e \rangle$)	3.95×10^{20} m^{-3}
Volume-averaged electron temperature ($\langle T_e \rangle$)	2.7 keV
External lower hybrid current-drive power (P)	19.8 MW

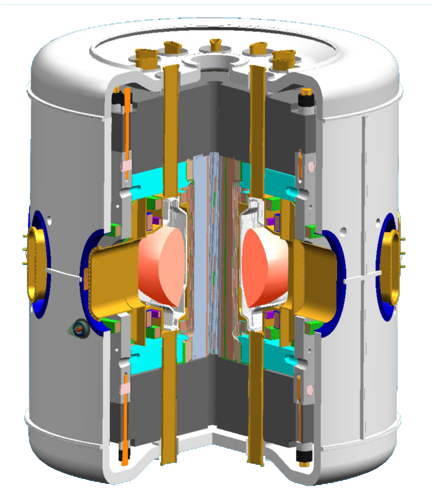
- High core density allows reactor similarity in divertor region while high external power allows full current drive
- Dual vacuum vessel design for thermal isolation
  - Rapid replacement of primary vacuum vessel and contained divertor components to test new PFC concepts
- High-temperature, helium-cooled divertor and first wall
- Demountable superconducting toroidal field coils
  - High-temp. superconductor (YBCO) tapes allow operation at higher temperature than metallic SC (e.g. ITER)
- Compact shielding ($Zr(BH_4)_4$) reduces nuclear heating & tape damage from gammas and D–D fusion neutrons
- Innovative high-field-side launch lower hybrid system
  - Accessibility at low $N_{||}$, enabling efficient current drive



The Vulcan concept incorporates demountable superconducting toroidal field coils, allowing vertical maintenance and rapid replacement of the vacuum vessel

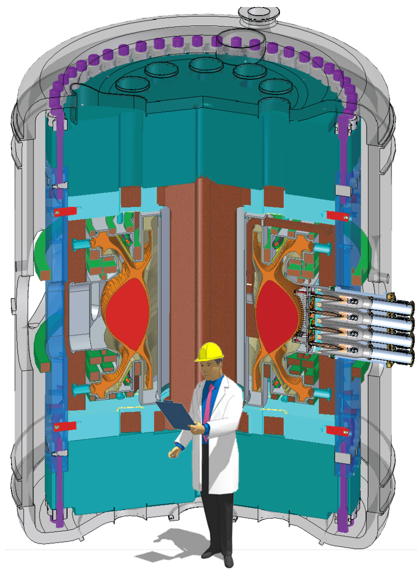
What might a high-field development path to DEMO look like?

Key Enabling Technology: demountable HTS magnetics[1]



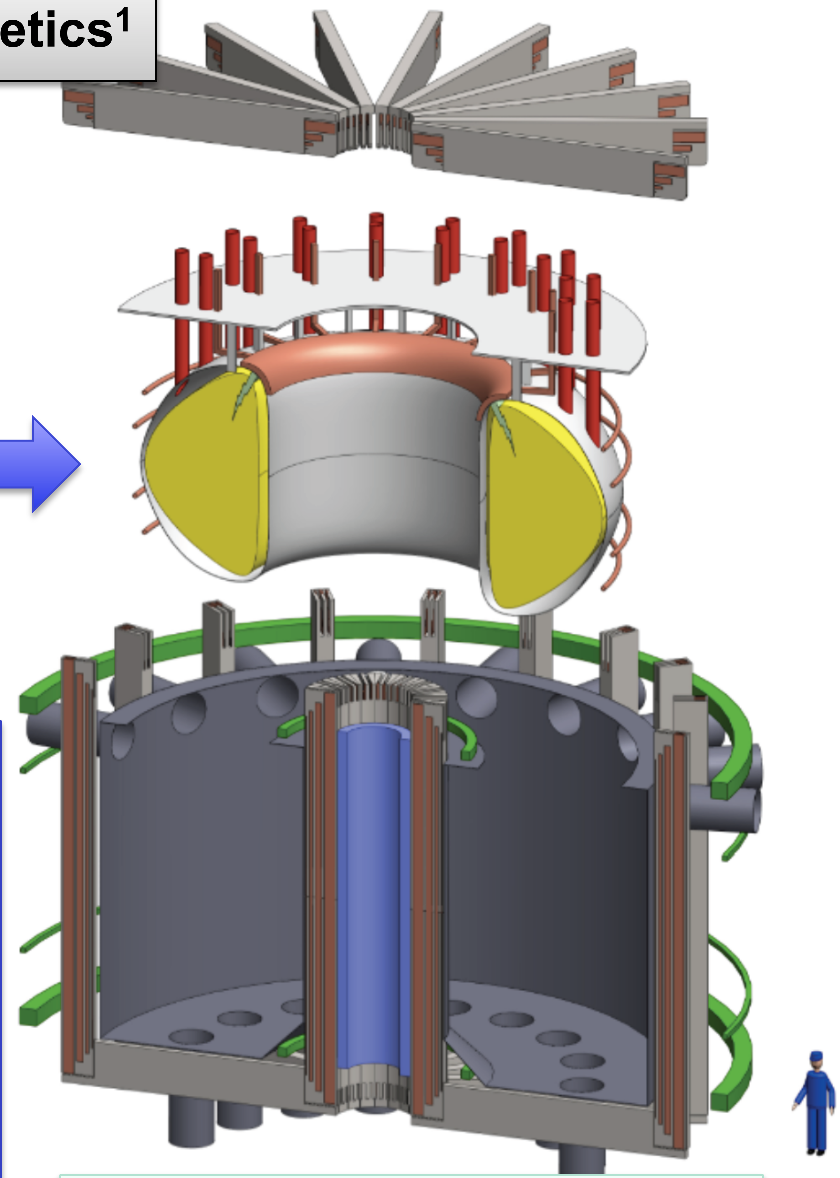
C-Mod (8 tesla)

- 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

ARC: A Compact, Disassemblable, High Field Fusion Nuclear Science Facility (After D. Whyte, the ARC Team, PSFC, MIT)

The ARC Magnet Concept

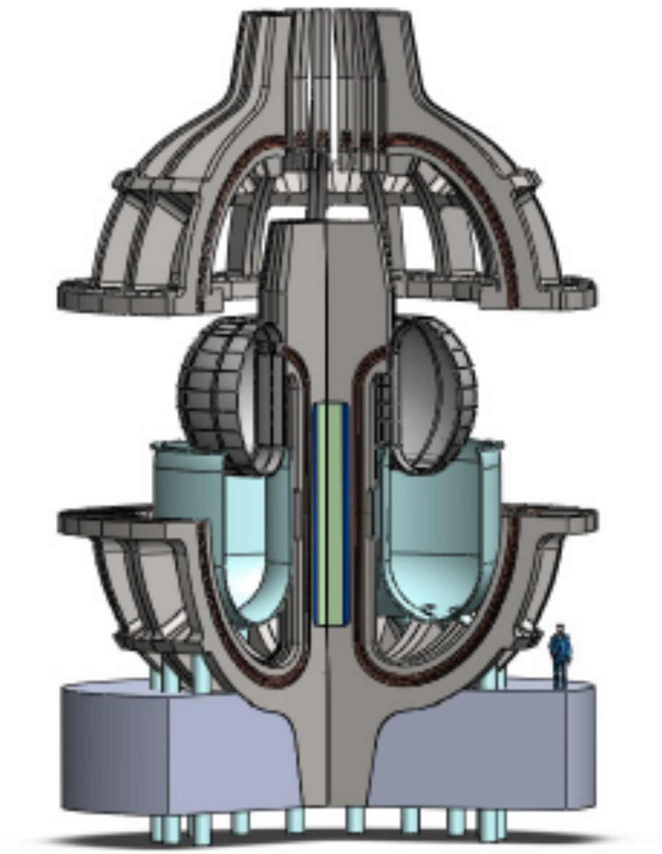


Figure 3: The upper half of ARC's superconducting coils can be removed, allowing the vacuum vessel to be removed from the blanket tank as a single piece and obviating sector maintenance.

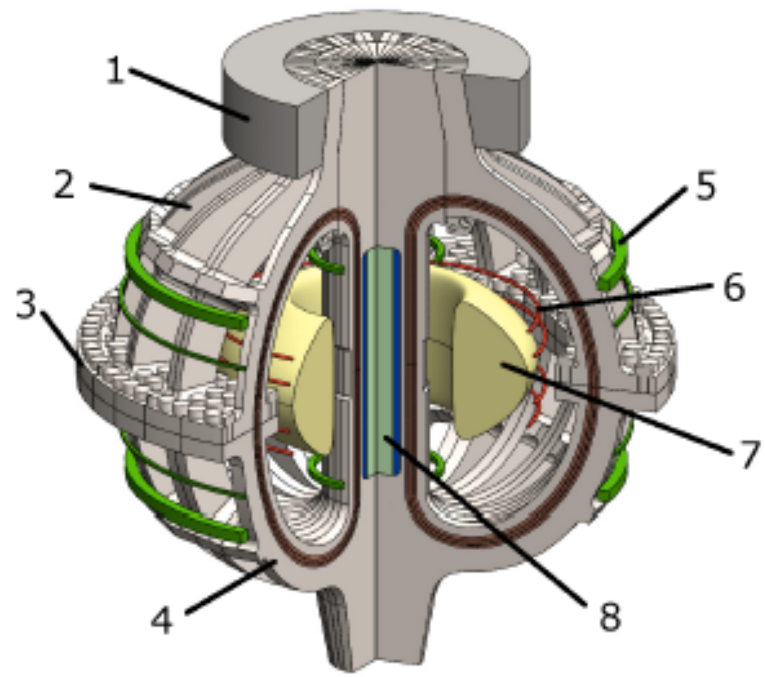
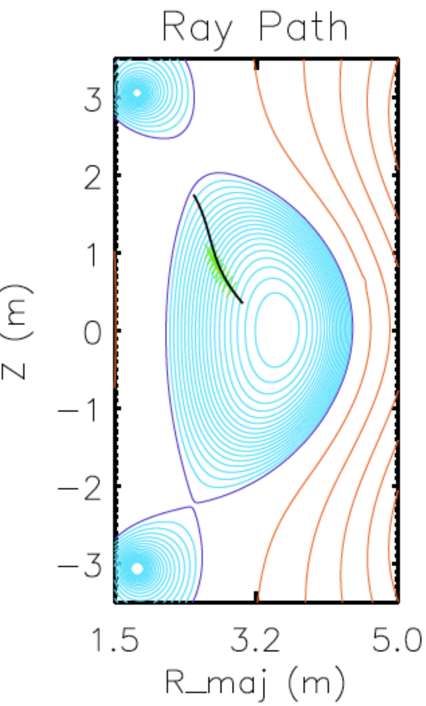
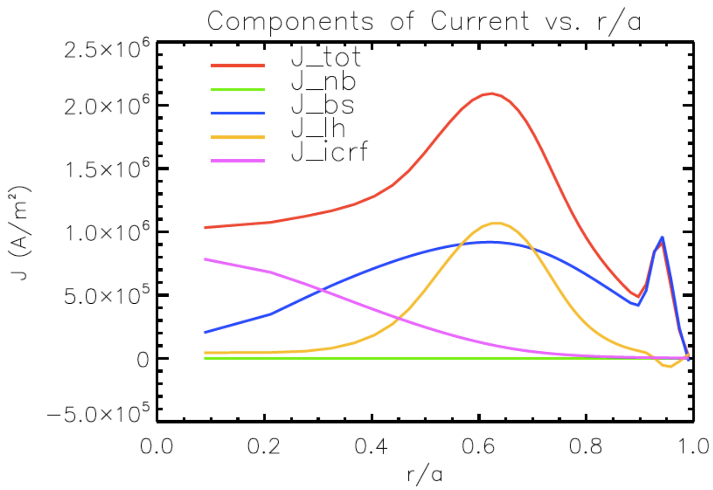


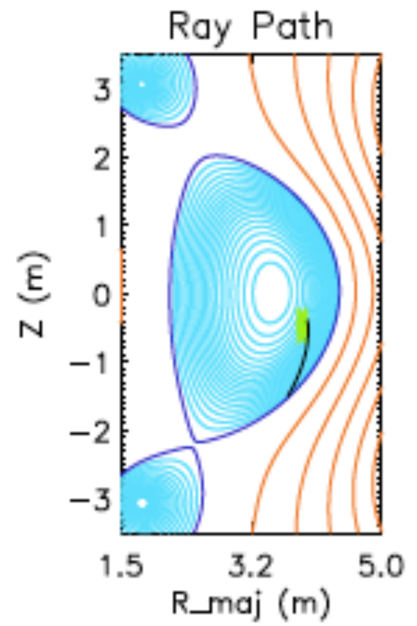
Figure 16: Schematic design of the coil systems, including: 1 – outward force support ring; 2 – top demountable leg of the TF coils; 3 – outer bolted joint between TF coil legs; 4 – bottom leg of the TF coils; 5 – PF coils (in green); 6 – AUX coils (in red); 7 – plasma; 8 – CS coil with epoxy plug reinforcement. The superconducting cables are shown in brown, within the steel support structure.

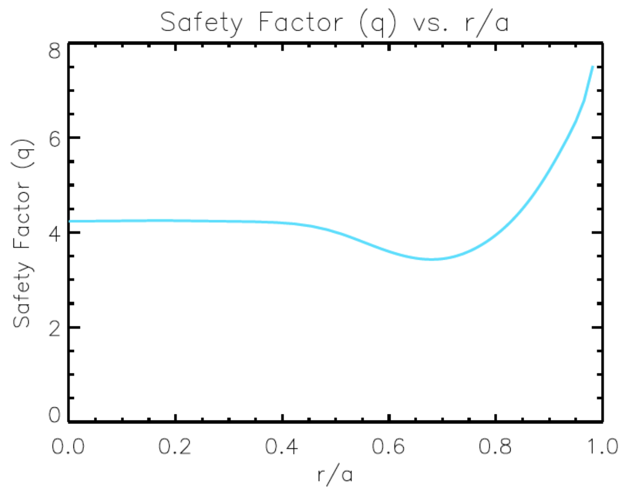
Lower Hybrid and ICRF Waves Give the Necessary Current Profile in ARC

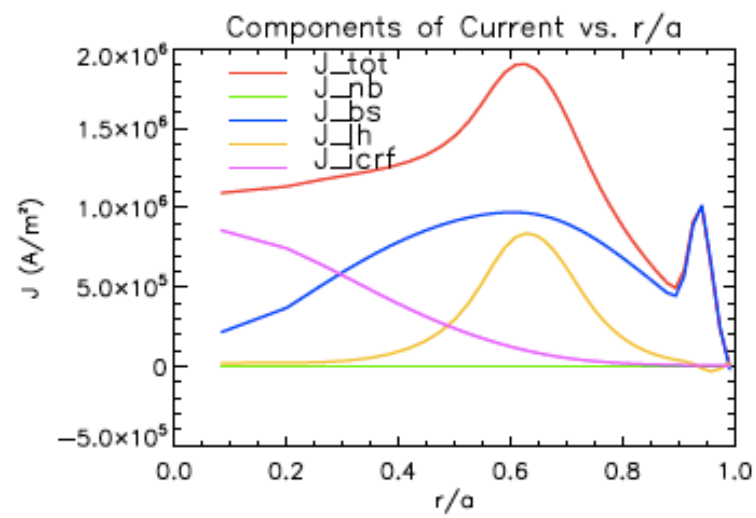
Physics Based on I-Mode in Alcator C-Mod (High T_e, T_i, Medium n_e)











$T_e(0) = T_i(0) = 26$ keV

$n_e(0) = 1.7 \times 10^{20} m^{-3}$

$P_{FUSION} = 500$ MW

$P_{LH} = 25$ MW

$P_{IC} = 14$ MW

$B_T(0) = 9.25$ T

$Q_{FUSION} = 12$

$f_{BS} = 63\%$

η_{IC} (10^{20} A/W/m^2) = 0.4

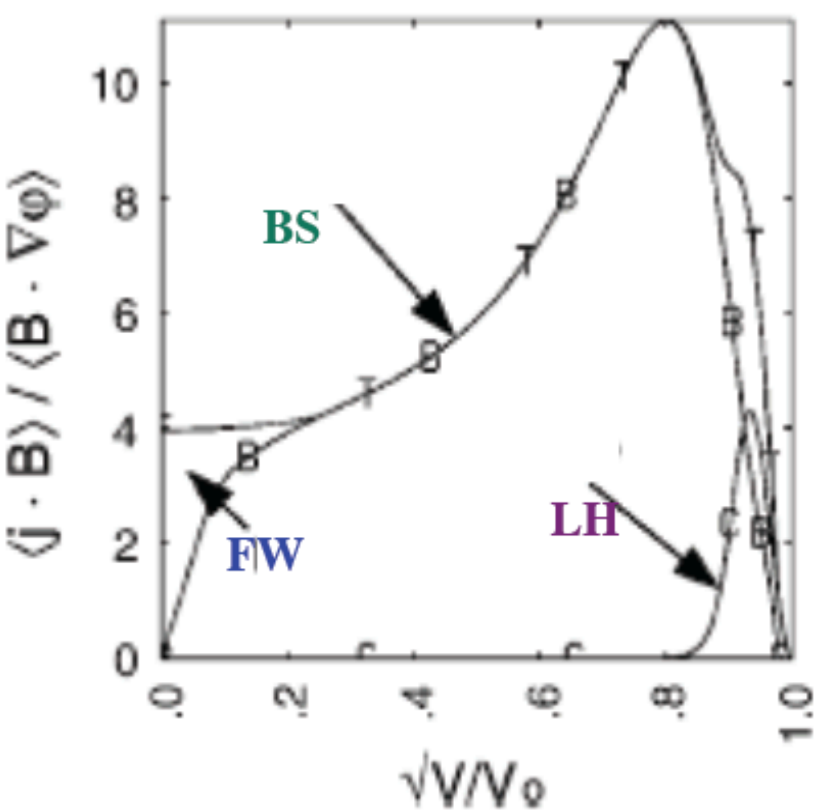
(After P.T. Bonoli)

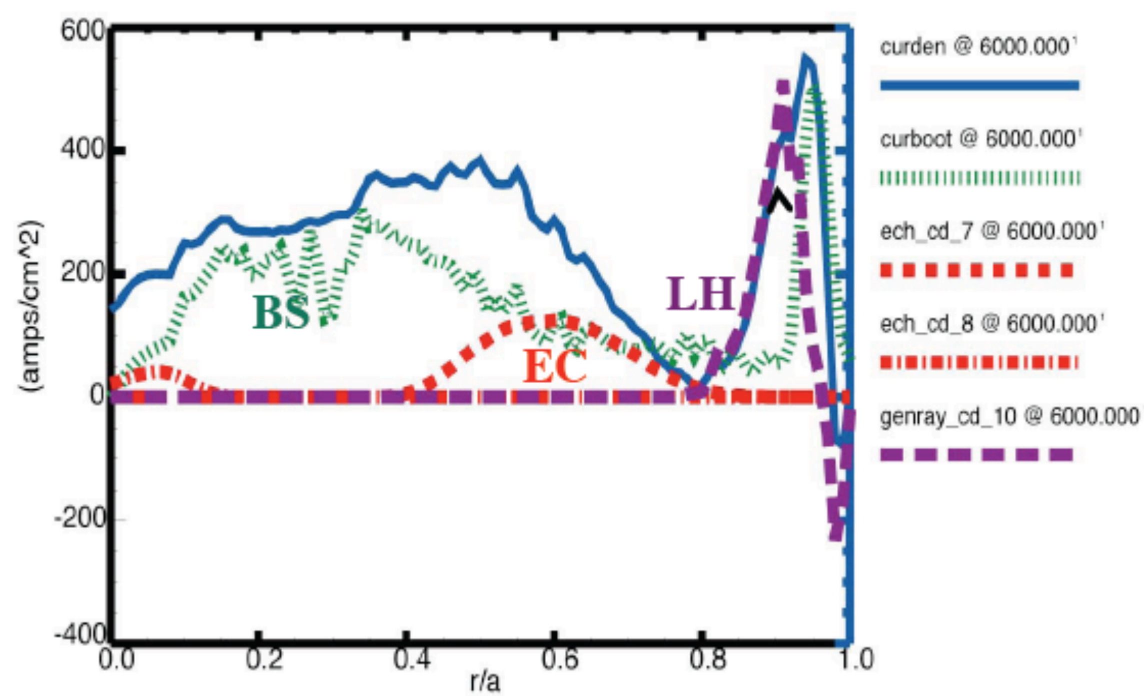
A Combination of RF current drive and BOOTSTRAP current in ARIES AT, RS and FDF, achieve reactor relevant performance

Current profiles in Aries AT :
F. Najmabadi et al, FED **80**, 3-23, (2006) **H_{98Y2} = 1.7, β_N = 5.4, f_{BS}=0.91, LHCD = 0.09, P_{LH} = 40 MW, P_{FW} = 10 MW (or P_{EC})**

Current profiles in FDF:

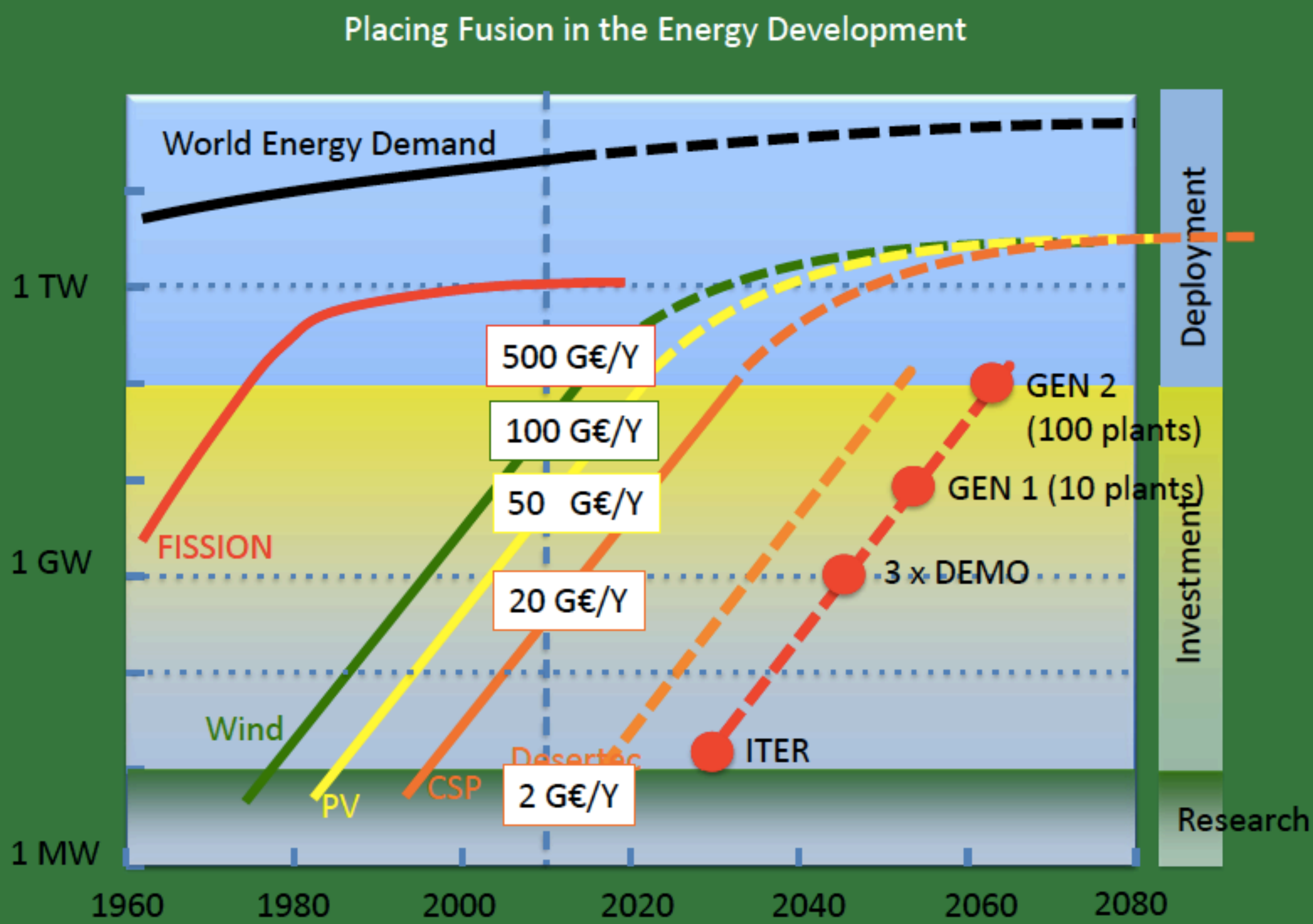
- 50 MW ECCD and 20 MW of LHCD, P_f = 198 MW, Q_{fus} = 2.8
- **f_{BS}= 0.65, (ECCD+LHCD) = 0.35, H_{98Y2} = 1.3, β_N = 3.8**
- (V. Chan, General Atomics, FDF poster GP8 – 2 , 2009 APS-DPP Atlanta)





Porkolab_FPA_2010

Niek Lopes Cardozo and Guido Lange, TU, Eindhoven, 2010



Assumptions on fusion output power (world roadmap)

- ITER: P_{fusion}= 500 MW.
  hypothetical $P_{electric}$=150 MW. Availability = 10%.
  → hypothetical power: 15 MW by 2026

- DEMO: 3 plants, 1.0 GW_e each, availability 30%
  → hypothetical power: 1.0 GW by mid 40ties

- Gen1: 10 plants, 1.7 GW_e each, availability 50%
  → hypothetical power: 8.5 GW_e by mid 50ties

From there: doubling in 3 years = tenfold growth in 10 years.

- Gen2: 100 plants, 1.7 GW_e each, availability 60%
  → hypothetical power: 100 GW_e by mid 60ties

Exponential growth phase: serious money involved!

During exponential growth, at 1 to 100 GWe total installed power, budget required: tens to hundreds Billion Euro/year!

Over entire exponential growth: 1000 – 2000 Billion Euro invested.

(cp Fusion: 100 Gen 2 plants @ 10 - 20 Billion each)

As no significant energy is produced yet:

This is tax payers money, invested in a future energy source.

No source has been developed without government support in one form or another.

This investment anticipates the payback by some 30 years or more.

How is fusion different?

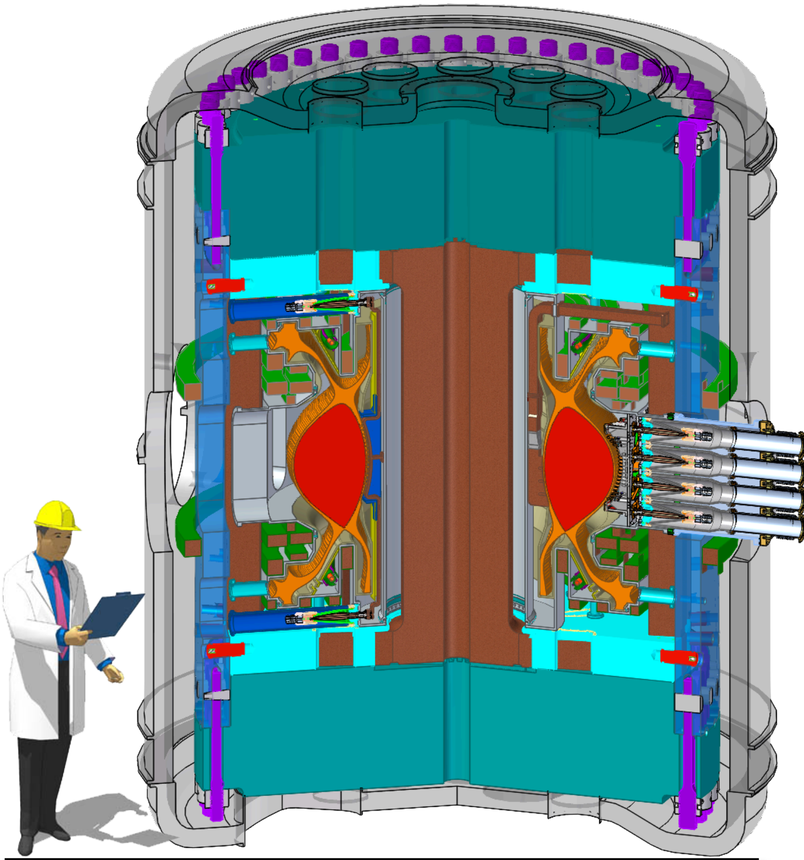
- Capital investment per unit is big.
  - This is a real problem, especially during exponential growth. *Valley of death* between Gen1 and Gen2?
  - To be balanced by promise of ‘clean, safe, for ever, for all’.
  - Need for a smart funding scheme. Crowd funding?

- Technology readiness level/uncertainty
  - Still early in the industrial development
  - ITER must make a big step here
  - But from ITER to DEMO is another big step
  - And from DEMO to 70% availability is yet another big step.

SUMMARY: a Look to the Future

- Significant innovation needed beyond ITER, both in physics and technology
- Physics innovation calls for continuing experimental plasma research (novel divertor designs, improved CD efficiency, ELM free modes of operation, eliminate disruptions, etc)
- Technology innovations require development of better materials (test stands as well as FNSF) and nuclear materials testing
- High Temperature Superconducting Magnets should be developed (demountable magnets for ease of maintenance - a game changer !)
- High field magnets to improve current drive efficiency (higher $Q = P_{fus}/P_{aux}$ and steady state) and lower beta for more robust stability
- More compact devices to speed up fusion's development at lower cost
- Continuing education of scientists and engineers a necessity

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



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*

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

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

[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