A strategy to develop power exhaust solutions for tokamaks beyond ITER

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ORNL

IAEA Divertor Concepts Meeting

Nov 7, 2019

Vienna, Austria

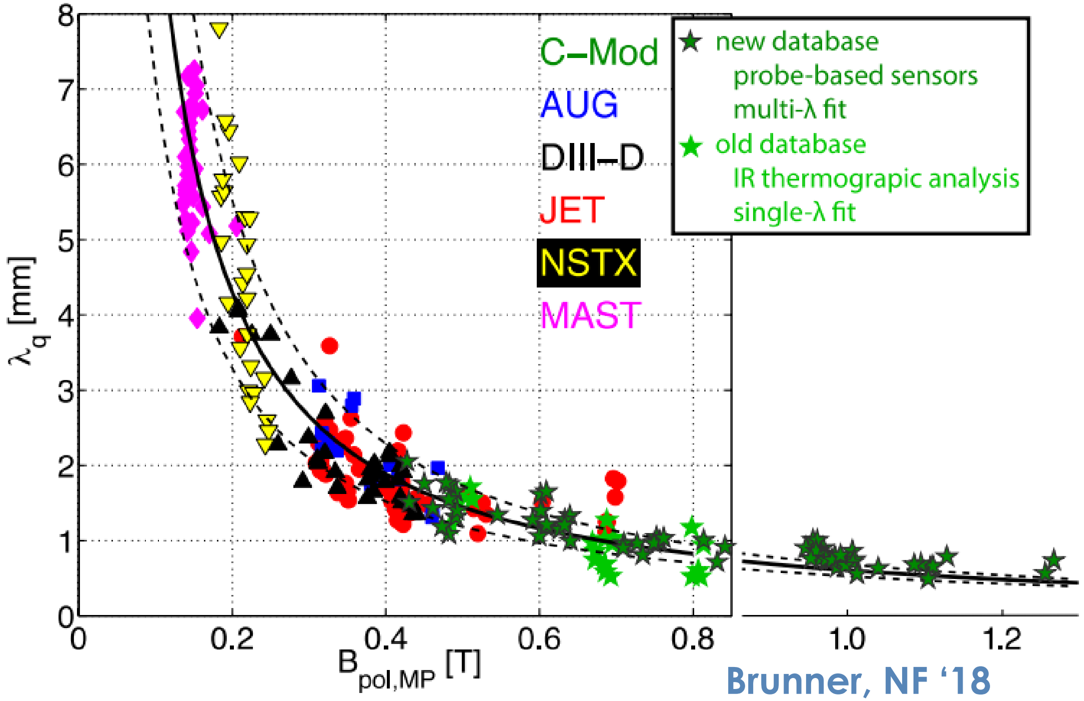
The challenges behind heat exhaust are well known

- Combining scaling for λ_q (Eich NF '13) with L-H threshold scaling (Martin JPCS '08) yields very strong scaling with B

$$q_{||} \sim 0.112 \boxed{B^{2.52}} f_{LH} \left(\frac{f_{GW}}{q_*}\right)^{0.72} R^{0.16} \epsilon^{0.52} (1+\kappa^2)^{1.19}$$

Reinke, NF '17

- Strong dissipation typically coincides with reduced T_e^{ped}, H_{98}
  - Loss of confinement (and back-transition to L-mode) sets the practical limit of dissipation
  - Contamination of the core by impurities seeded for divertor radiation will likely set another limit



Brunner, NF '18

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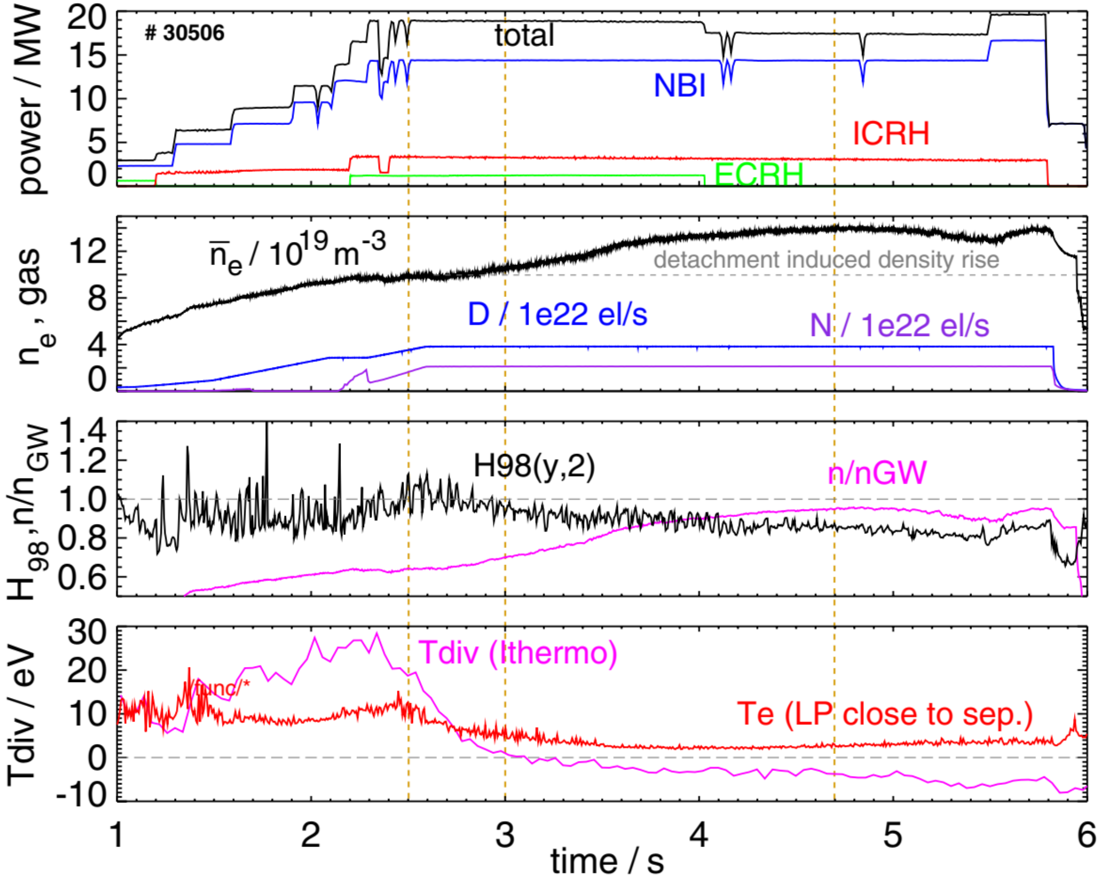
Kallenbach, NF '15



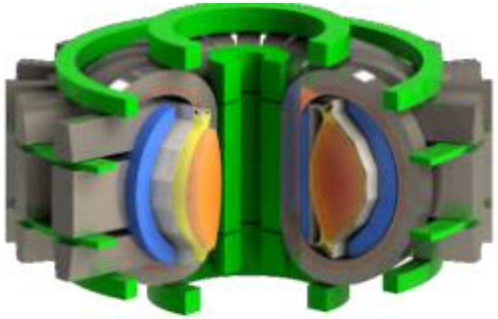
Recent strategic planning within the US has advocated a strong push to fusion

- Two high-level recommendations US National Academy of Science and Engineering strategic plan for fusion*
  - "First, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant."
  - "Second, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost."
- NAS report has in part triggered a community planning activity, which is discussing the scope for a possible new U.S domestic facility
- Two general directions: high-confinement high-beta sustained tokamaks (AT), and high magnetic field tokamaks (possibly pulsed)
- Accelerated timeline compared to previous discussions, with aggressive research in parallel with ITER

*Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research
https://www.nap.edu/catalog/25331/final-report-of-the-committee-on-a-strategic-plan-for-us-burning-plasma-research

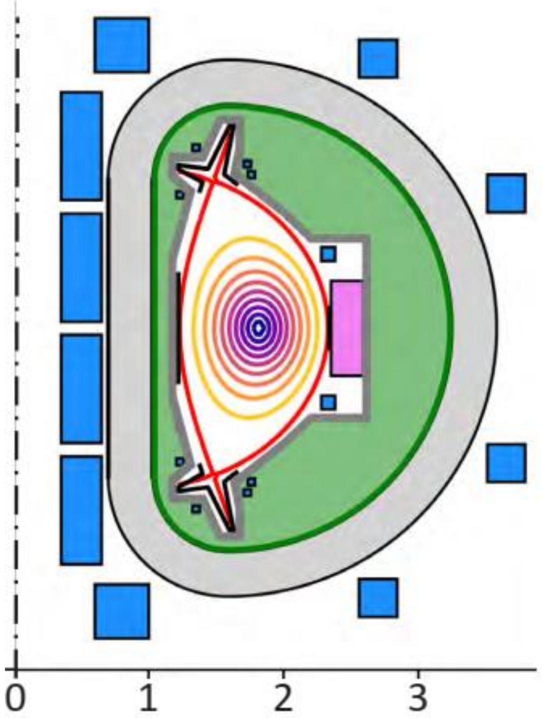
Example of the aggressive timeline and steps towards compactness

- New private company in US—Commonwealth Fusion systems—is pursuing high field path
- Very aggressive timeline
  - Large HTS coil in 2021
  - First plasma in Q>2 device in 2025
  - ‘Demo’ reactor in 2030’s
- Unique challenges to power exhaust
  - High field leads to higher heat fluxes than ITER
  - Timeline means R&D needs to happen faster than we’re used to



Prototype: SPARC
Q>2, P_{fusion}>50MW

SPARC V1C
September 2019 – Present



Version	V1C
B_0 [T]	12.5
R_0 [m]	1.78
I_p [MA]	8.65
ε	0.31
κ_a	1.75
δ_{95}	0.45

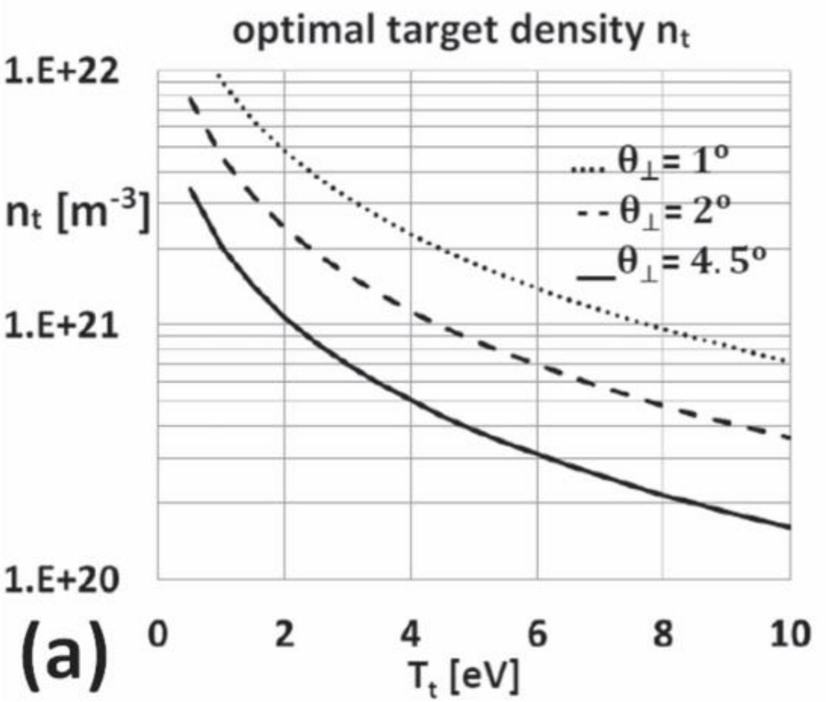
ORNL has been considering a strategy that pursues R&D to enable a CPP as quickly as possible

- Starting assumption: solid (high-Z) materials with strong radiation via impurity seeding represents the fastest path to a power exhaust solution for some visions of a CPP
  - Highest TRL among divertor concepts, with physics and engineering basis developed over decades of tokamak research (incl. ITER)
  - → An aggressive program is needed to prepare a divertor scenario for CPP based on the highest TRL technology, or establish it will not work

- Elements of a strategy to develop a divertor solution
  - Develop predictive physics basis for heat flux and detachment
  - Develop high-performance core scenarios that lessen the demand on the divertor
  - Study divertor-pedestal integration at-scale through next step near-reactor plasma experiments
  - Advance the TRL of alternative divertor configurations as risk mitigation beyond ITER

Use engineering limits at PFCs to build required divertor solution, extend to requirements on upstream parameters

- Divertor plasma in a reactor is reasonably fixed by power exhaust and erosion limits
  - Maximum steady state heat removal sets q_{dep} (~5MW/m^2)
  - Plasma temperature must be <~10eV to eliminate net erosion
  - Angle of B wrt PFC surface then set $q_{||}$ and hence n_t
- This also sets minimum upstream pressure
  - Must be several x P_{div} for low T_t operation
- CPP-like $q_{||}$ are needed to test high f_{rad} physics
  - And matching of n, T distribution in the divertor
- Required impurity concentration f_Z for detachment should approach CPP values
  - Important part of compatibility with the pedestal/core
  - Make sure unphysically high f_Z is not required



Recent analytic f_Z scalings using Lengyel model:

$$f_Z = 0.014 \frac{B_T^{0.88} f_{LH}^{1.14} q_\star^{0.32} R^{1.33} \varepsilon^{0.59}}{f_{SEP}^2 f_{GW}^{1.18} (1+\kappa^2)^{0.64} \hat{l}^{0.86} m_L(Z, n_e\tau)}$$

Reinke, NF '17 Goldston, NF '17

The worldwide tokamak program is well positioned to address many of the needs in power exhaust physics

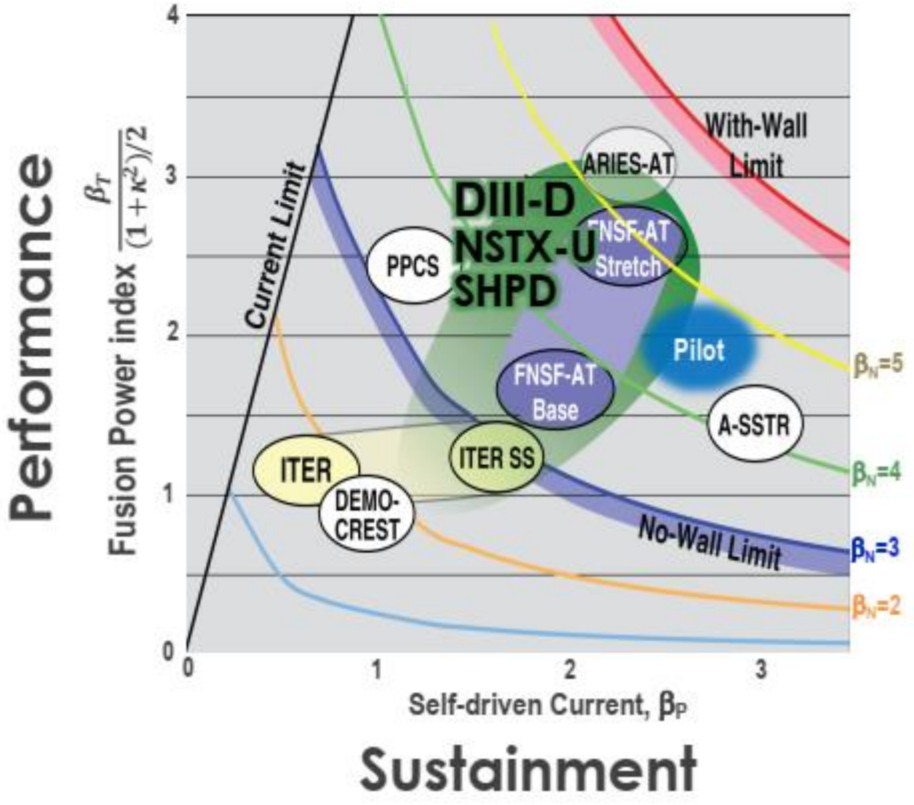
	[T]	[m]	[GW/m2]		
Facility	**BT**	**R**	**q||**	**fZ/ARC**	**OPS**
TCV	1.4	0.88	0.3	0.03	***presently operating***
DIII-D	2.2	1.66	1.0	0.11	
JET	3.5	2.96	3.4	0.37	
WEST	3.7	2.50	3.8	0.31	
AUG	2.8	1.65	1.8	0.14	
KSTAR	3.5	1.80	3.2	0.19	
EAST	3.5	1.85	3.2	0.20	
C-Mod	5.4	0.68	8.1	0.08	---
JT-60SA	2.3	2.96	1.2	0.26	FY23
Comp-U	5.0	0.90	6.9	0.10	FY23
SPARC	12.0	1.65	69.5	0.50	FY26
DTT	6.0	2.15	12.6	0.39	FY26
ITER	5.3	6.20	11.0	1.42	FY28
LLDRP	10.0	1.00	40.5	0.22	FY26
ARC	9.2	3.30	39.7	1.00	TBD
CAT	7.0	4.00	20.6	1.02	TBD
EU-DEMO	5.2	9.00	11.1	2.30	~2050

Reinke, NF '17

- First step in developing exhaust solution: build physics basis for heat flux and detachment projection
  - Focus of present experimental and theory/modeling activities
  - Wide range facilities contributing to developing and confirming predictions of, e.g., heat flux, f_Z
- Existing and planned (I-DTT, ITER, SPARC) tokamaks will ~meet CPP divertor exhaust parameters
- Main capability gap is geometry: more later

Further development is needed of edge-friendly sustained scenarios

- Present assumption within US program is that reactor must be steady-state
- For a tokamak power spent driving current should be kept to minimize recirculating power
- Advanced Tokamak is the mainline path
- Sustainment achieved through high bootstrap fraction
  - $f_{BS} \sim q\beta_N$
  - Has to go hand-in-hand with confinement improvement ($H_{98}>1$; ~1.5-1.8)

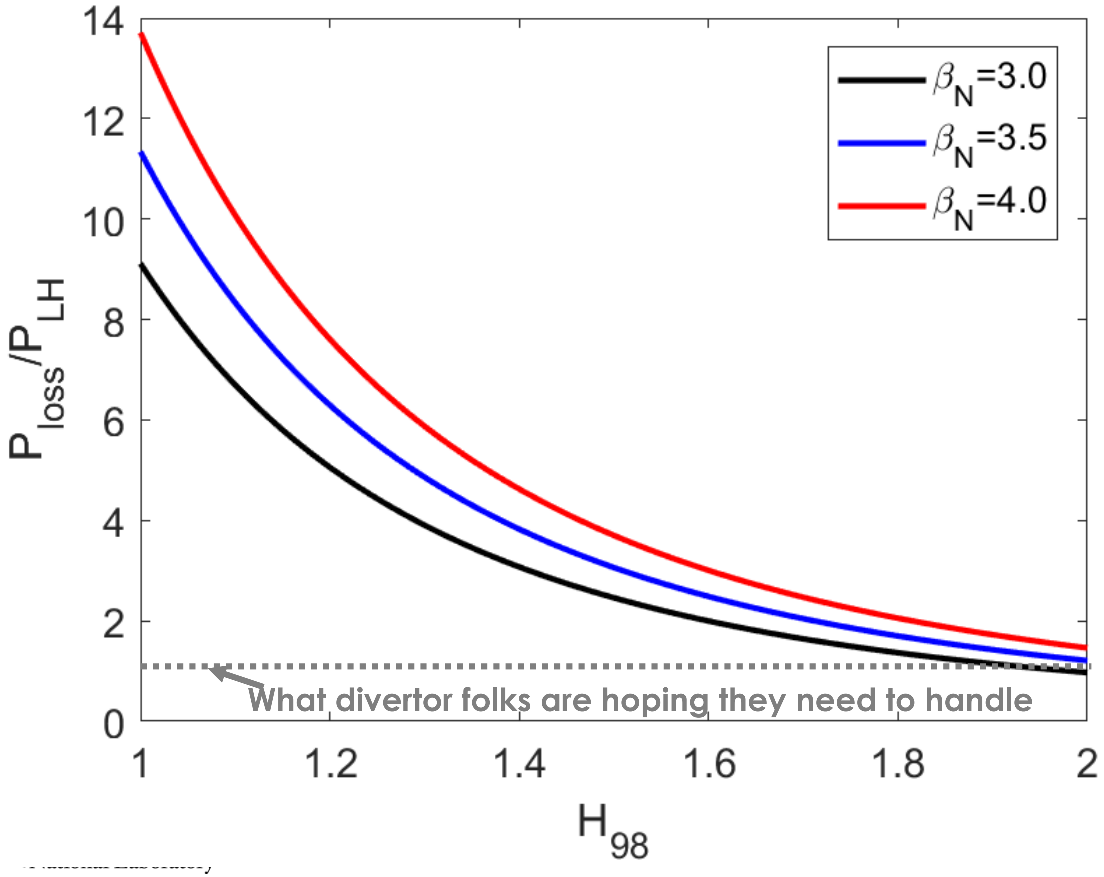


Buttery, DPP-CPP '19

CPP core scenarios need to be developed that minimize the burden on the divertor

$$\frac{P_{loss}}{P_{LH}} = 1.6H^{-3.23}\boxed{\beta_N^{1.42} f_{BS}^{1.81}}B^{0.14}R^{0.49}f_G^{-2.04}$$

For ε=0.33, κ=1.8, A=2
R=1.7m B=2.2T, f_{BS}=0.9, f_G=1.0



- High β_N, high f_{BS} plasmas imply strong heating unless very high confinement achieved: P_{heat} ~ several x P_{LH}
- Divertor exhaust scenarios aim for P_{SOL}~f_{LH}*P_{LH} with f_{LH} as close to 1 as possible

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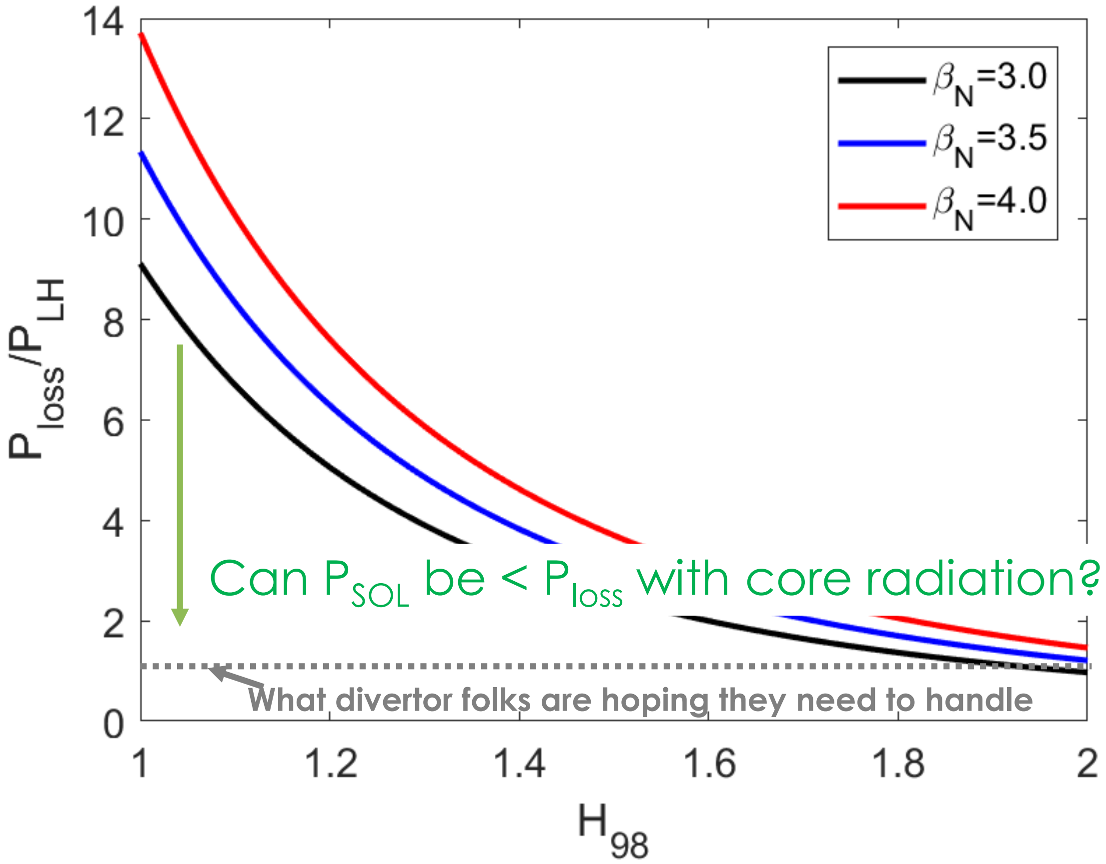
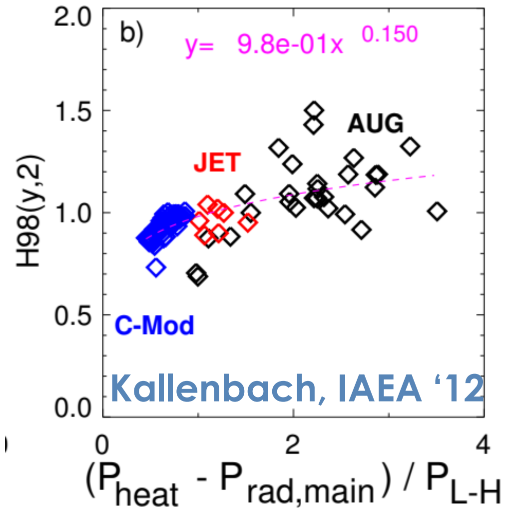
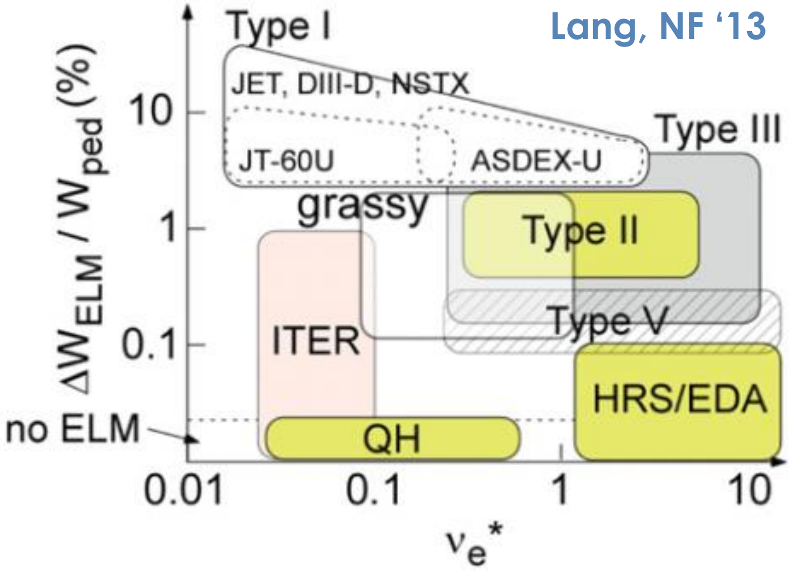




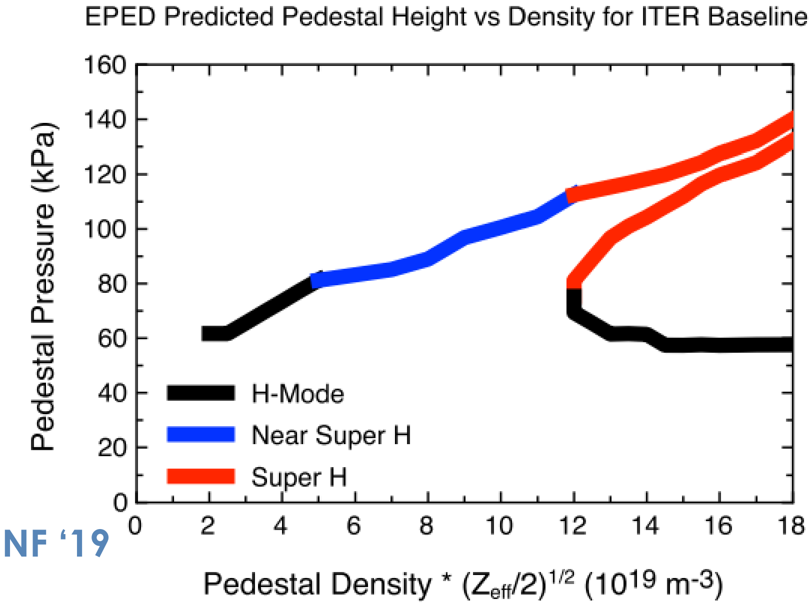
- Development of core scenarios that minimize power flow into SOL is needed
  - Can high confinement be maintained at high f_{rad}^{core}?
  - Can confinement be made so high this isn't an issue?
  - Will elevated Z_{eff} affect sustainment path?

Divertor solution needs to be integrated with pedestal which is strongly impacted by collisionality

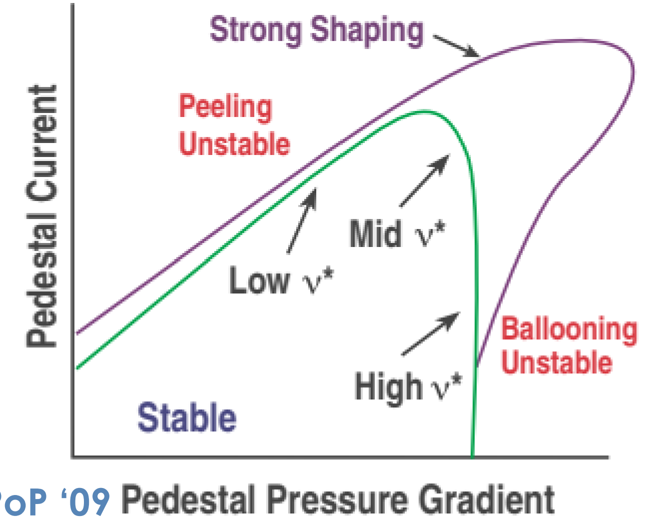
- Affects ELM regime and ELM size, as well as pedestal structure/height
- Physics thought to be understood via location of operating point in peeling-ballooning stability space
- High collisionality can lead to running on low-pressure-limit branch
- Present facilities challenged to produce detached divertor with low collisionality pedestal
- So far no evidence of strong ρ* dependence, will that hold?



Lang, NF ‘13



Snyder, NF ‘19

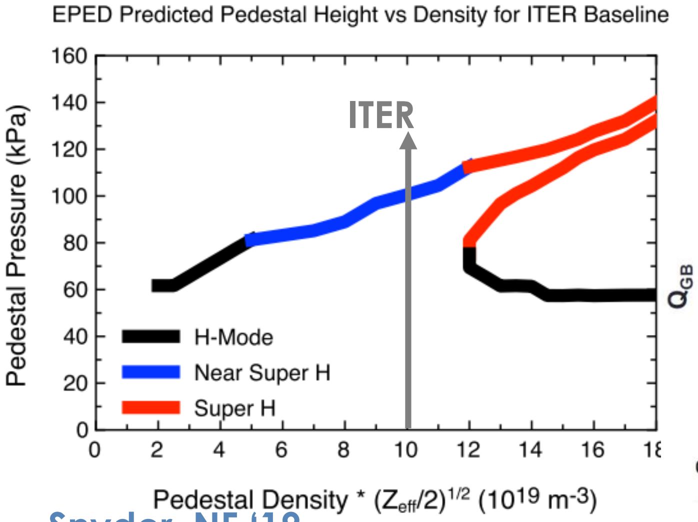


Snyder, PoP ‘09

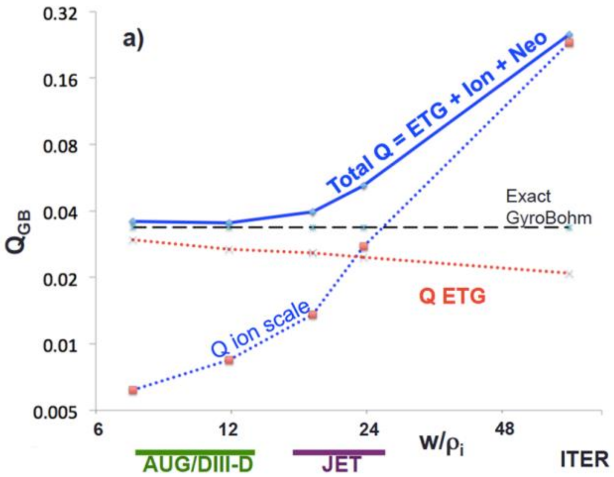
Oak Ridge National Laboratory

ITER and SPARC offer the opportunity to study pedestal-divertor integration at scale

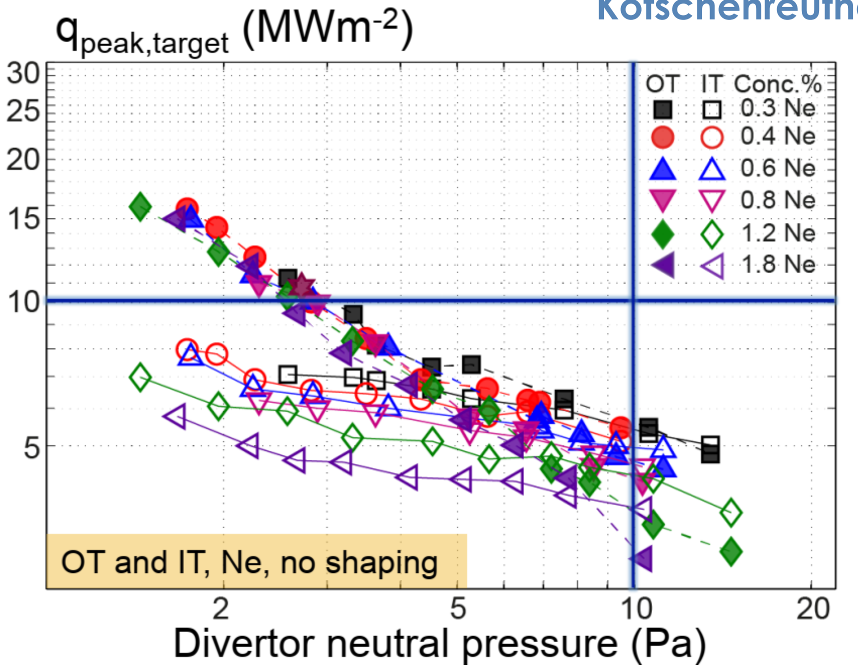
- Power exhaust must be achieved while maintaining high pedestal pressure
- Demonstrating pedestal-divertor compatibility in the end requires reactor-like parameters
  - ρ^*_{ped}, ν^*_{ped}, $q_{||}$, f_Z, p_{div}, etc simultaneously
  - Also for model validation
- Realizing reactor-like pedestal+divertor combinations are now on the horizon via ITER and SPARC
  - We should fully engage in the opportunity to study core-edge integration physics at-scale



Snyder, NF '19



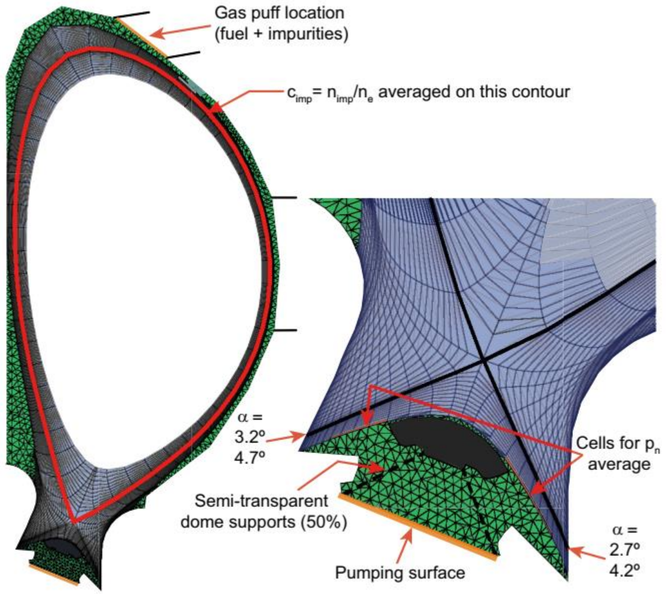
Kotschenreuther, NF '17



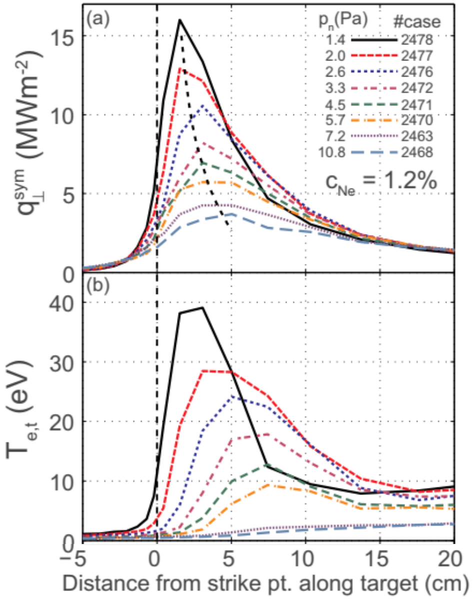
Pitts, PSI '18

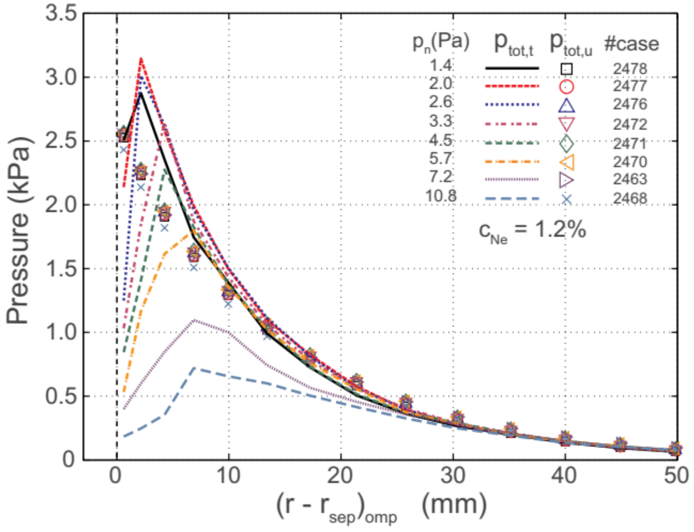
The ITER/SPARC divertor scenarios may not extrapolate to reactors

- ITER employs conventional vertical target divertor geometry
- Targets 'partially' detached scenario
  - Te, pressure, heat flux reduced locally near the strike point, but remain high away
  - Sufficient for ITER's needs: heat flux mitigation while maintaining confinement
- CPP likely will require completely detached divertor
  - T_e low everywhere
  - ~Eliminate erosion, enhance heat flux mitigation
  - X-point radiation may be solution, but may not be compatible with core
  - → Advanced divertors should be pursued as risk mitigation



Pitts, NME '19

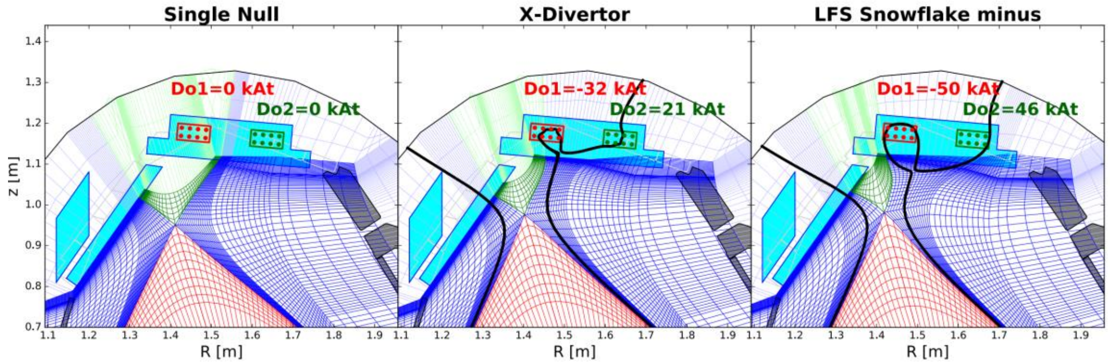


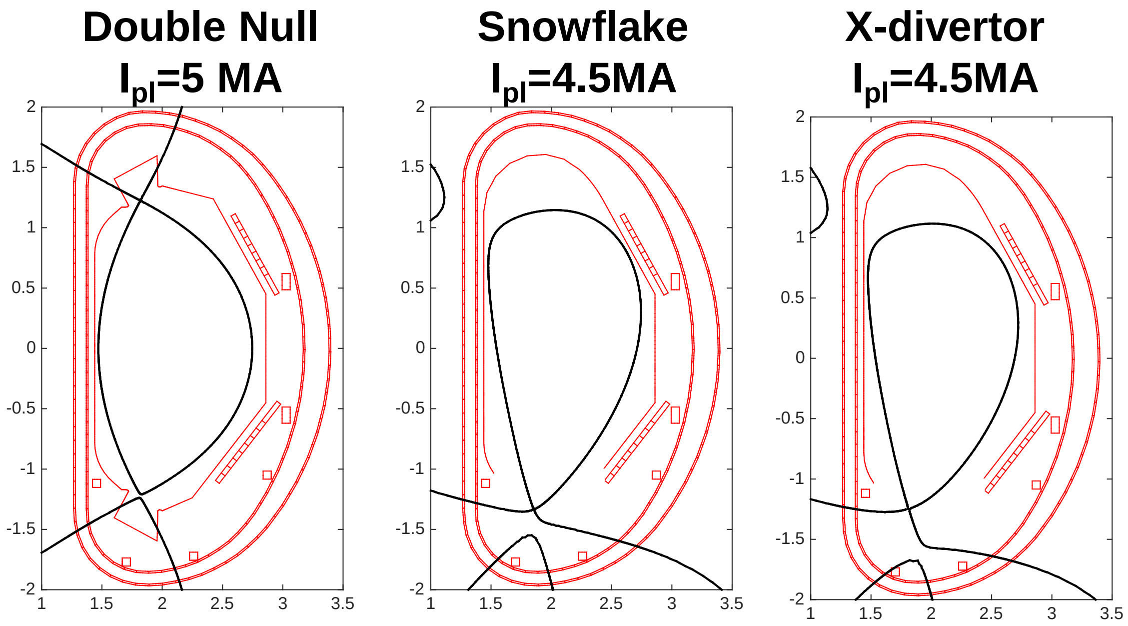


Planned upgraded and new facilities will test high poloidal flux expansion at more relevant conditions

- Upper divertor upgrade planned at AUG
  - Clean tests with metal walls + seeding
  - Moderate heat flux levels
- Italian Divertor Test Tokamak should also be capable of testing HPFX
  - ITER-like heat fluxes should be accessible
- These facilities will enable testing of high poloidal flux expansion divertors at conditions closer to CPP prototypic than otherwise available

Lunt, NME '17

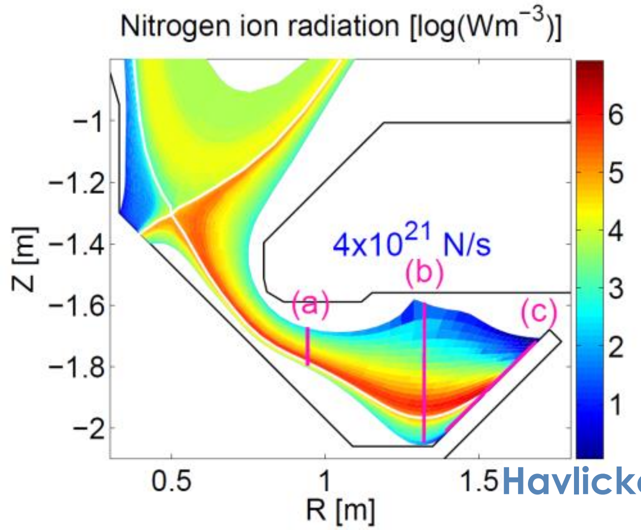




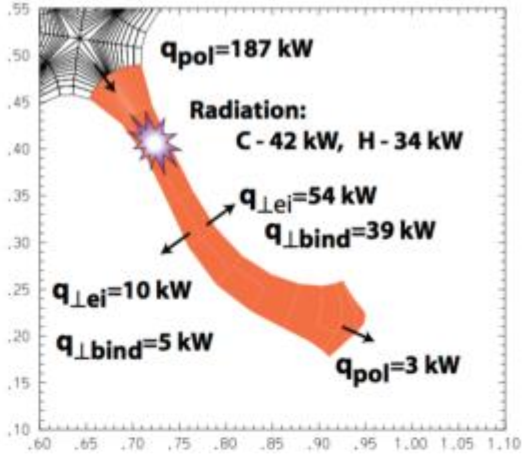
DTT Interim Design Report

Long-legged divertors are being pursued across the worldwide program at modest heat fluxes

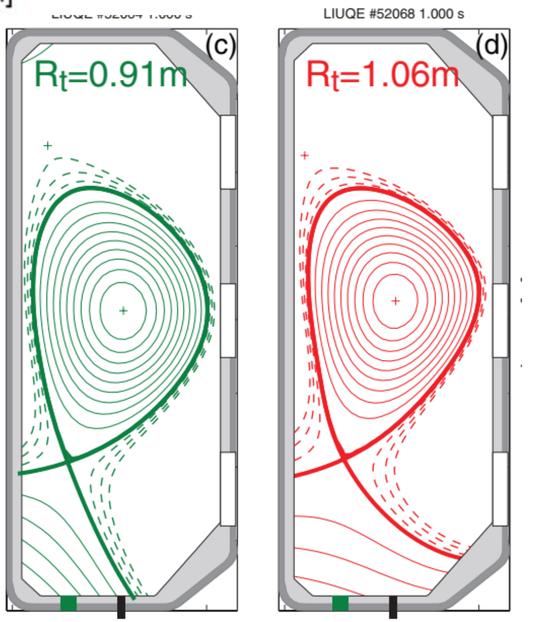
- Long-legged divertors have many predicted advantages
  - Reduction of $q_{||}$
  - Improved radiation stability
  - Stronger isolation of high neutral pressure divertor from main chamber
  - Enhanced turbulent spreading of flux
  - Enhanced buffering of ELMs?
  - →Need tests at high flux



Havlickova, PPCF '14



Umanksy NF '17

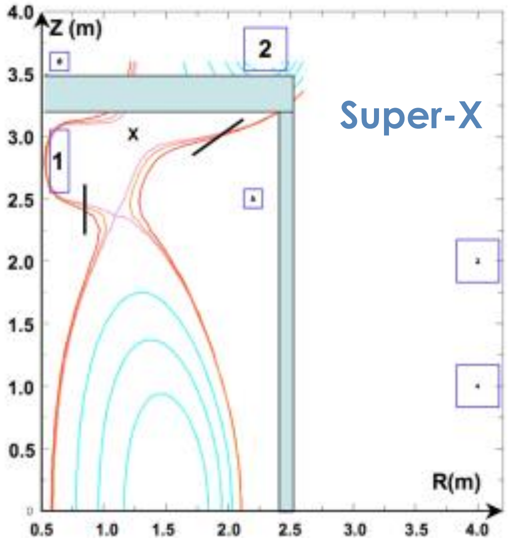


Theiler, NF '17

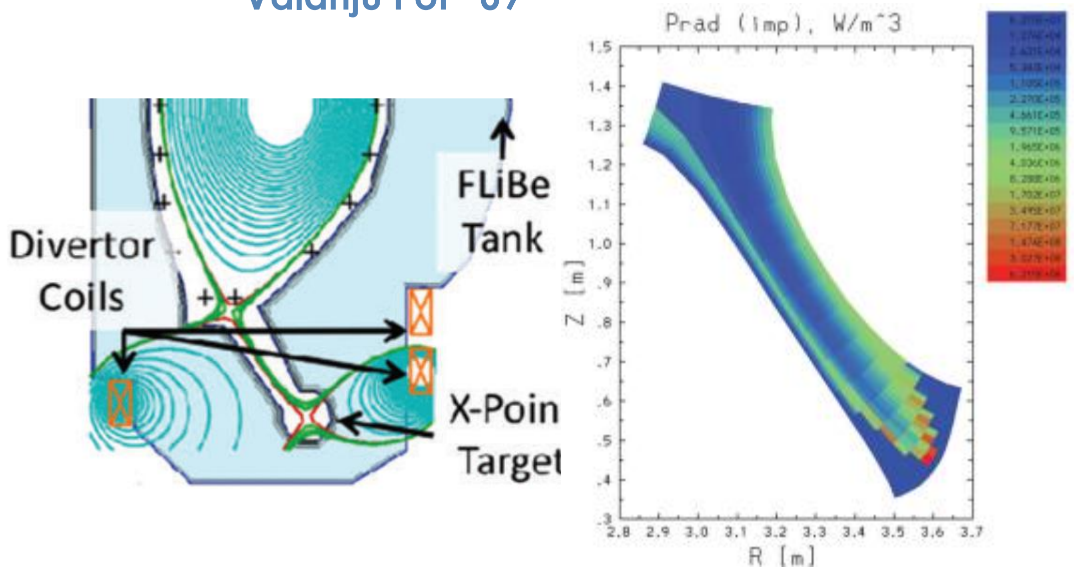
A new facility is needed with the limited mission of advancing long-legged divertor basis

- New Long-Legged Divertor Research Platform is needed to increase TRL of advanced geometry
  - Focus on capability gap within planned program
  - Operate on aggressive timeline to ensure possibility of connecting to industry

- Should also provide access to more CPP-like pedestal+divertor conditions than we have today
  - Absolute n,T at divertor
  - Absolute upstream pressure, $q_{||}$ and f_Z
  - Peeling-limited pedestal



Valanju PoP '09



Wigram CPP '18

Summary

- Looking for solutions to divertor challenge under constraints
  - High confinement, compactness emphasized
  - Accelerated timeline

- Elements of a program to establish CPP power exhaust solutions
  - Build predictive physics basis for challenge and solution
  - Develop high radiation core scenarios
  - Test core-pedestal integration at scale in next-gen devices
  - Explore innovative divertor concepts at reactor-level fluxes in a new, divertor-dedicated tokamak