A strategy to develop power exhaust solutions for tokamaks beyond ITER

J.M. Canik
ORNL

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The challenges behind heat exhaust are well known

- Combining scaling for $\lambda_q$ (Eich NF ’13) with L-H threshold scaling (Martin JPCS ’08) yields very strong scaling with $B$

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

Reinke, NF ’17

- Strong dissipation typically coincides with reduced $T_{e,\text{ped}}, H_{98}$
  - 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
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Kallenbach, NF '15

Reinke, NF '17
Recent strategic planning within the US has advocated a strong push to fusion

- Two high-level recommendations by the 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
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 $q_{\text{dep}}$ (~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 $P_{\text{div}}$ for low $T_t$ operation

- CPP-like $q_{\|}$ are needed to test high $f_{\text{rad}}$ 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:

$$f_Z = 0.014 \frac{B_T^{0.88} f_{\text{LH}}^{1.14} q_*^{0.32} R^{1.33} \varepsilon^{0.59}}{f_{\text{SEP}}^{2.18} f_{\text{GW}}^{1.18} (1 + \kappa^2)^{0.64} \lambda^{0.86} m_L(Z, n_c \tau)}$$

Reinke, NF '17  Goldston, NF '17
The worldwide tokamak program is well positioned to address many of the needs in power exhaust physics

- 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

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Reinke, NF ‘17
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 ($H_{98}>1; \sim 1.5-1.8$)

Buttery, DPP-CPP ‘19
CPP core scenarios need to be developed that minimize the burden on the divertor

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

For \(\epsilon=0.33\), \(\kappa=1.8\), \(A=2\)
\(R=1.7m\) \(B=2.2T\), \(f_{BS}=0.9\), \(f_G=1.0\)

- High \(\beta_N\), high \(f_{BS}\) plasmas imply strong heating unless very high confinement achieved: \(P_{\text{heat}} \sim \text{several} \times P_{\text{LH}}\)

- Divertor exhaust scenarios aim for \(P_{\text{SOL}} \sim f_{\text{LH}} \times P_{\text{LH}}\) with \(f_{\text{LH}}\) as close to 1 as possible
CPP core scenarios need to be developed that minimize the burden on the divertor

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For $\varepsilon=0.33$, $\kappa=1.8$, $A=2$, $R=1.7m$ $B=2.2T$, $f_{BS}=0.9$, $f_G=1.0$

- Development of core scenarios that minimize power flow into SOL is needed
  - Can high confinement be maintained at high $f_{\text{rad,core}}$?
  - Can confinement be made so high this isn’t an issue?
  - Will elevated $Z_{\text{eff}}$ 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 $\rho^*$ dependence, will that hold?
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
  - $\rho_{\text{ped}}^*, v_{\text{ped}}^*, q_{||}, f_z$, $p_{\text{div}}$, 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
The ITER/SPARC divertor scenarios may not extrapolate to reactors

• ITER employs conventional vertical target divertor geometry

• Targets ‘partially’ detached scenario
  – $T_e$, 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
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
Long-legged divertors are being pursued across the worldwide program at modest heat fluxes

- Long-legged divertors have many predicted advantages
  - Reduction of $q_{\parallel}$
  - 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
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
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