Insights from Systems Code Analysis on Power Exhaust Requirements for Future Fusion Power Systems

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General Impression is that Power Exhaust Requirements Place Significant Constraint on Minimum Size of Fusion Power Systems

- Divertor Heat Flux: \( q_{div} \propto (1 - f_{rad}^{core})P_{heat}/2\pi R\lambda_q \)

- General Impression:
  - \( P_{heat} \) set by need to produce requisite electricity
  - \( f_{rad}^{core} \) limited by need to stay above L-H transition power threshold
  - \( \lambda_q \) set by core performance requirements (choice of \( I_p \) drives \( B_p \))
  - Primary “control” is device size \( R \)

- In certain cases (especially at ITER-level of confinement, \( H_{98y2} = 1 \)), this impression is accurate
  - Places increased importance on R&D to address this issue

- However, this is not universally this case...
Power Exhaust Requirements are Strongly Linked to the Achievable Core Confinement

- Tendency to think power exhaust is roughly independent of confinement
  .... Fusion power needed for electricity sets boundary power flow

- But it's a bit more complicated...

\[ P_{\text{fus}} \propto p_{\text{th}}^2 \propto (P\tau_E)^2 \propto (PHP^{-\alpha_p})^2 \]
\[ P \propto P_{\text{fus}}^{1/2(1-\alpha_p)} / H^{1/(1-\alpha_p)} \]

\[ \rightarrow \text{For } H_{98y2}, \alpha_p = 0.67 \rightarrow P \propto P_{\text{fus}}^{1.5} / H_{98y2}^3 \]
\[ \text{For } H_{89}, \alpha_p = 0.5 \rightarrow P \propto P_{\text{fus}} / H_{89}^2 \]

- Additionally, the required \( P_{\text{fus}} \) increases as confinement quality decreases

\~ {\text{factor of two decrease in }} P_{\text{SOL}}
Outline

• Introduction/Motivation

• GA systems code (GASC) and Compact Fusion Pilot Plant (CFPP)

• Impact of Power Exhaust and Confinement on CFPP cost

• Insights on Important R&D for CFPP Cost Attractiveness

• Summary
Based on a Set of Assumptions and Constraints, GASC-Opt Finds Optimal Solution to Minimize Chosen Optimization Parameter

**Set of Assumptions (e.g.)**
- Magnet Type (REBCO)
- Tritium Breeding Ratio (1.0)
- TF Bucking (Free TF)
- Thermal Efficiency (0.4)
- Blanket Power Mult. (1.2)
- Pulse Length (8 hr)

**Set of Constraints (e.g.)**
- $P_{\text{net}} = 200$ MWe
- $q_{\text{div}} < 10$ MW/m²
- $f_{GW} < 1$
- $f_{\text{rad,core}} < 0.75$
- $f_{BS} < 0.9$
- TF Stress $< 667$ MPa
- $J_{TF,sc,\text{limit}}/J_{TF,sc} > 2$
- $\beta_N/\beta_{N,\text{limit}} < 0.75$

**Outputs (e.g.)**
- Major Radius
- Aspect Ratio
- Plasma Ratio
- Toroidal Current
- CD Power
- Toroidal Field
- Fusion Power
- CD Power
- $\beta_T$, $\beta_P$, $\beta_N$
- $f_{BS}$, $f_{\text{non-ind}}$, $f_{\text{ind}}$
- $f_{GW}$, $q_{\text{div}}$
- $\Delta_{TF}$, $\Delta_{CS}$, $\Delta_{BI}$
- Tritium Inventory
- $\$\$_{TF}$, $\$\$_{Bl}$, $\$\$_{BOP}$
- COE

**Single Optimization Parameter (e.g.)**
- Cost of Electricity
- Capital Costs
- Operating Costs
- Major Radius

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Power Exhaust Models in GA System Code (GASC)

- **Core**: Standard power balance assuming coronal equilibrium emissivity

- **Divertor → Two-point model with impurities**

  \[
  q_{\text{div}} = P_{\text{Sol}}(1 - f_{\text{rad,div}})/A_{\text{wetted}} \\
  q_{\text{rad,div}} = n_{e,\text{mid}}T_{e,\text{mid}} \left( 2\kappa_0 f_{z,\text{core}}\eta_{z,\text{div}} \int_{T_{e,\text{mid}}}^{T_{e,\text{div}}} L_z(T_e) T_e^{0.5} Z_{\text{eff}}^{-0.3} dT_e \right) \\
  A_{\text{wetted}} = 2\pi N_{\text{div}} R \lambda_q F_{\text{exp}} \sin(\theta_{\text{div}}) \\
  F_{\text{exp}} = F_{\theta,\text{exp}} F_{\phi,\text{exp}} \\
  f_{\text{rad,div}} = q_{\text{rad,div}}/q_{||} \\
  \theta_{\text{div}} = \sin^{-1}\left[(1 + 1/\alpha_{\text{div}}^2) \sin \beta_{\text{div}}\right] \\
  \alpha_{\text{div}} = F_{\text{exp}} \sin\left(\tan^{-1}(B_{p,\text{mid}}/B_{T,\text{mid}})\right)
  \]

- **Typical assumptions:**
  - Number of Divertors: \( N_{\text{div}} = 2 \)
  - Heat Flux Width: \( \lambda_{\text{int}} = \lambda_{q,Eich} + 1.64S_{\text{Scarabosio}} \)
  - Flux Expansion: \( F_{\theta,\text{exp}} = 5; \ F_{\phi,\text{exp}} = 0.75 \)
  - Divertor Impurity Enrichment: \( \eta_{z,\text{div}} = n_{z,\text{div}}/n_{z,\text{core}} = 3 \)
  - Angle of Incidence Between Field Line and Target: \( \beta_{\text{div}} = 2.5^\circ \)

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Costing Model in GASC

• Costing model adapted from Sheffield et al. 1986, updated by Sheffield et al 2016 (includes all core components and balance of plant)

• We Include cost of tritium required to run facility for 2 years in the capital cost
  – Initial Inventory + (Consumption – Breeding - loss/decay) at $30M/kg

• GASC configured to minimize the capital cost given a set of assumptions
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Technical Requirements for a Compact Fusion Pilot Plant (CFPP)

- At present, no agreed upon technical requirements for a CFPP
- My assumptions for those requirements:
  1) **Produce 200 MW-e** (provide sufficient headroom that if device doesn’t perform as projected, can still produce net electricity)
  2) **Produce (or purchase) its own tritium** (not required to produce tritium for follow-up facilities)
  3) **Produce power continuously for a 2-year calendar lifetime** (balance between demonstrating feasibility of fusion electricity and introducing significant set of materials issues) – can be pulsed
  4) **Capital costs to construct should be minimized**; operating costs is secondary consideration; COE not important at all
- Note that these assumptions significantly reduce or even eliminate potential impact of material lifetime and RAMI requirements
### Analysis of Cost Drivers for a CFPP Indicate Importance of Both Physics and Technology Towards Attractiveness

- Independently vary assumptions to determine cost sensitivity to each parameter → tornado chart
  - Identifies risk/reward of potential R&D developments (or lack thereof)

- Aggressive baseline w/ $H_{98y2} = 1.6$, REBCO magnets, Plug-Bucked TF/CS

- Evident that physics and technology constraints are both critical to cost attractiveness

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#### Tornado Chart

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Risks</th>
<th>Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement Quality ($H_{98y2}$)</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tritium Breeding Multiplier</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Efficiency</td>
<td>0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Divertor Heat Flux (MW/m²)</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron Wall Loading (MW/m²)</td>
<td>6.0</td>
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<tr>
<td>Pulse Length</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density Limit</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF Bucking Solution</td>
<td>Plug Bucked</td>
<td></td>
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</tr>
<tr>
<td>Magnet Type</td>
<td>REBCO</td>
<td></td>
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</tr>
<tr>
<td>Stability Limit</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactivity Multiplier</td>
<td>1.5</td>
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</tbody>
</table>

#### Baseline Case

- Estimated Capital Cost ($B$): 12210.16

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#### Risks

- Net Power (MW): 200.0
- $H_{98y2}$: 1.6
- Magnet Type: HTS
- $R$ (m): 3.7
- $A$: 3.0
- $P$ (MW): 649.6
- PCD (MW): 33.9
- $I_p$ (MA): 8.6
- $B_T$ (T): 5.89
- $B_{Tcoil}$ (T): 13.4
- $a_{95}$: 5.53
- $I_{fs}$: 0.76
- $f_{rad} (\%)$: 0.23
- $P_{oil/plh}$: 2.59
- $TBR$: 0.98
- $\gamma$: 1.8
- Capital Cost: 4215.3
- $I_{case}$: 4.2
- $I_{case}$: 12210.16
On its own, power exhaust capabilities provide modest leverage on cost attractiveness

- $q_{\text{div}} = 5-50 \text{ MW/m}^2$

However, cost is extremely sensitive to confinement quality, which is strongly linked to edge/divertor

- A new direction for R&D focused on integrated performance
  - Rather than just simply divertor performance

Cost Sensitivity Studies Suggest a Potential New Emphasis for Divertor Research
At $H_{98y2} = 1.0$, Divertor Heat Flux Capability Serves as A Primary Limitation on Device Size (and Capital Cost)

- For all $H_{98y2}$, device size must grow as $q_{div}^{max}$ is decreased.
At \( H_{98y2} = 1.0 \), Divertor Heat Flux Capability Serves as A Primary Limitation on Device Size (and Capital Cost)

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- At \( H_{98y2} = 1.0 \), reducing \( q_{div}^{\text{max}} \) from 10 MW/m\(^2\) to 5 MW/m\(^2\) increases size (and cost) significantly:
  - \( R_o \): 5.8 m \( \rightarrow \) 7.2 m
  - Capital Cost: \( \uparrow \) 30%

\[ \Delta t_{\text{pulse}} = 8 \text{ hours} \]
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- Some advantage to increasing $q_{\text{div}}^{\text{max}}$ but only up to $\sim$ 15 MW/m$^2$
At $q_{\text{div}}^{\text{max}} = 10 \text{ MW/m}^2$, Increasing Confinement Leads to Significant Reduction in Device Size (and Capital Cost)

- Increasing $H_{98y2}$ from $1.0 \rightarrow 1.5$ yields significant benefit
  - $R_o$: $5.8 \text{ m} \rightarrow 4.0 \text{ m}$
  - Capital Cost: $\downarrow 35$

- Similar improvements at all values of $q_{\text{div}}^{\text{max}}$

- Further improvements still possible at higher $H_{98y2}$

$\Delta t_{\text{pulse}} = 8 \text{ hours}$
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Analysis of Confinement and Divertor Assumptions Reveal Important R&D Needed to Reduce CFPP Capital Costs

No Divertor Improvement Approaches Level of Impact of Improving Confinement
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Degree of Heat Flux Spreading Most Sensitive Parameter → Serious Issue if \( S/\lambda_{q,Eich} = 0 \)
Analysis of Confinement and Divertor Assumptions Reveal Important R&D Needed to Reduce CFPP Capital Costs

- **Confinement Quality (H98)**: 1.9
- **Heat Flux Spreading (S/\lambda_q)**: 2.0
- **Poloidal Flux Expansion**: 10.0
- **Divertor Heat Flux (MW/m²)**: 50.0
- **Divertor Alignment (degrees)**: 1.0
- **Toroidal Flux Expansion**: 1.5

### Key Points
- **H_{98y2} = 1.0**: No Divertor Improvement Approaches Level of Impact of Improving Confinement
- **Degree of Heat Flux Spreading**: Most Sensitive Parameter.
- **Serious Issue if S/\lambda_q = 0**: Flux Expansion, Tile Alignment, and Divertor Heat Flux Limit Less Important

Capital Cost ($B$) vs. Parameter

- Flux Expansion, Tile Alignment, and Divertor Heat Flux Limit
- Less Important
Analysis of Confinement and Divertor Assumptions Reveal Important R&D Needed to Reduce CFPP Capital Costs

At higher confinement, sensitivity to divertor parameters decreases

Same ordering importance for divertor parameters
Analysis of Confinement and Divertor Assumptions Reveal Important R&D Needed to Reduce CFPP Capital Costs

At $H_{98y2} = 1.9$, little sensitivity to divertor parameters and negligible benefit gained from better divertor performance.
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At $H_{98y2} = 1.9$, little sensitivity to divertor parameters and negligible benefit gained from better divertor performance.

$S/\lambda_q = 0$ not as serious an issue!!!
Summary: Takeaways from this Analysis for Power Exhaust Research and Development

- Power exhaust constraints are important at ITER-like confinement
  - However, limited (no?) pathways to reduce device size with improved power exhaust methods

- Achieving higher confinement offers significant benefits in reducing power exhaust requirements and device size
  - *Aggressive R&D program in core-edge integration is needed to develop robust scenarios along this line*

- Regardless of assumption on confinement, highest leverage R&D effort in divertor R&D should be maximizing heat flux spreading $S/\lambda_q$
  - Flux expansion and divertor target angle offer some, but only modest, improvements