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

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Presented to
IAEA Divertor Concepts Meeting
Vienna, Austria

November 6, 2019

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
  - λ_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

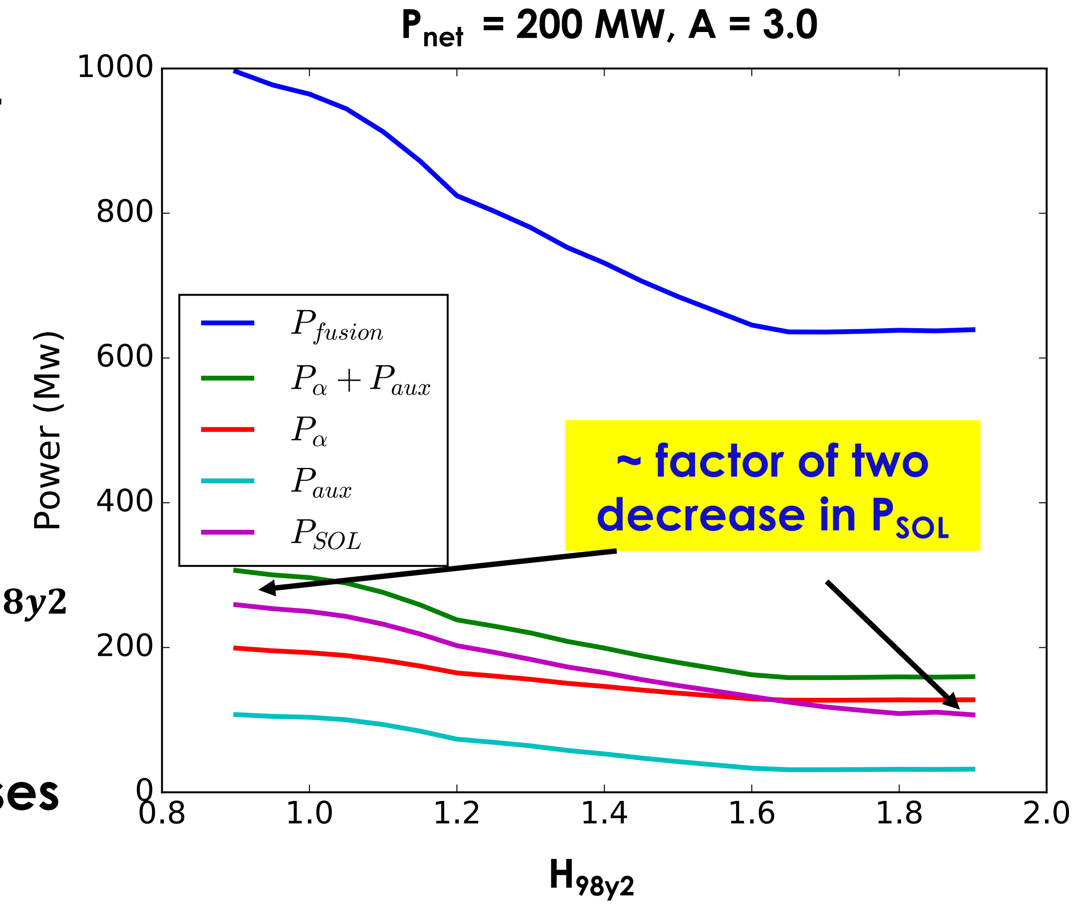
- **But it's a bit more complicated…**

$$P_{fus} \propto p_{th}^2 \propto (P\tau_E)^2 \propto \; (P\; H\; P^{-\alpha_P})^2$$
$$P \propto P_{fus}^{1/2(1-\alpha_P)} \;/\; H^{1/(1-\alpha_P)}$$

→ **For** H_{98y2} , $\alpha_p = 0.67 \;\rightarrow P \propto P_{fus}^{1.5}/H_{98y2}^3$

For H_{89} , $\alpha_p = 0.5 \rightarrow P \propto \;\; P_{fus}/H_{89}^2$

- **Additionally, the required P_{fus} increases as confinement quality decreases**



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

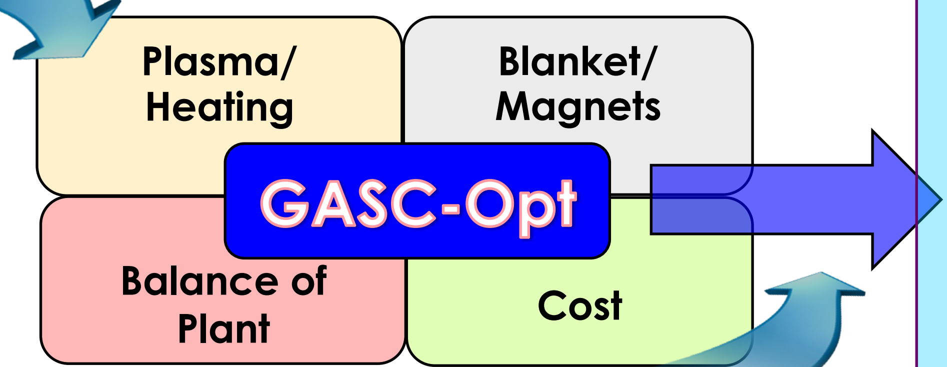
Based on a Set of Assumptions and Constraints, GASC-Opt Finds Optimal Solution to Minimize Chosen Optimization Parameter

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_{net} = 200 MWe
- q_{div} < 10 MW/m2
- $f_{GW} < 1$
- $f_{rad,core} < 0.75$
- $f_{BS} < 0.9$
- TF Stress < 667 MPa
- $J_{TF,sc,limit}/J_{TF,sc} > 2$
- $\beta_N/\beta_{N,limit} < 0.75$



Single Optimization Parameter (e.g.)

- Cost of Electricity
- Capital Costs
- Operating Costs
- Major Radius

Outputs (e.g.)

- Major Radius
- Aspect Ratio
- Plasma Current
- Toroidal Field
- Fusion Power
- CD Power
- β_T, β_p, β_N,
- f_{BS}, $f_{non\text{-}ind}$, f_{ind}
- f_{GW}, q_{div}
- Δ_{TF}, Δ_{CS}, Δ_{BI}
- Tritium Inventory
- $\$\$_{TF}$, $\$\$_{BI}$, $\$\$_{BOP}$
- COE

Power Exhaust Models in GA System Code (GASC)

- **Core: Standard power balance assuming coronal equilibrium emissivity**
- **Divertor → Two-point model with impurities**

$$q_{div} = P_{SOL}(1 - f_{rad,div})/A_{wetted}$$

$$f_{rad,div} = q_{rad,div}/q_{\parallel}$$

$$q_{rad,div} = n_{e,mid}T_{e,mid}\left(2\kappa_0 f_{Z,core}\eta_{Z,div}\int_{T_{e,div}}^{T_{e,mid}} L_Z(T_e)\,T_e^{0.5}Z_{eff}^{-0.3}\,dT_e\right)^{0.5}$$

$$A_{wetted} = 2\pi N_{div}R\lambda_q F_{exp}\sin(\theta_{div})$$

$$\theta_{div} = \sin^{-1}[(1 + 1/\alpha_{div}^2)\sin\beta_{div}]$$

$$F_{exp} = F_{\theta,exp}\,F_{\phi,exp}$$

$$\alpha_{div} = F_{exp}\sin(\tan^{-1}(B_{p,mid}/B_{T,mid}))$$

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

T. Eich et al. Nucl. Fusion 53 (2013) 093031
A. Scarabosio et al., J. Nucl. Mater. 463 (2015) 49

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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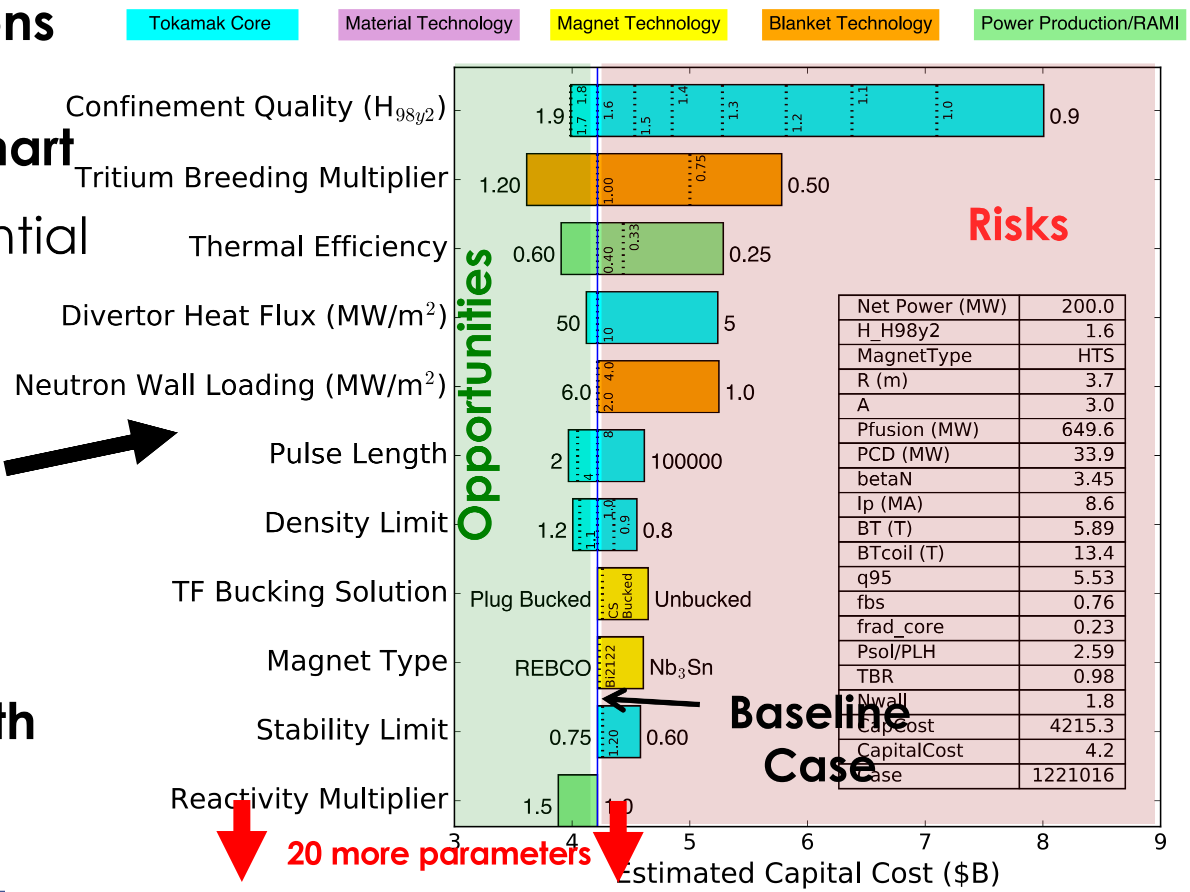
Technical Requirements for a Compact Fusion Pilot Plant (CFPP)

- **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**

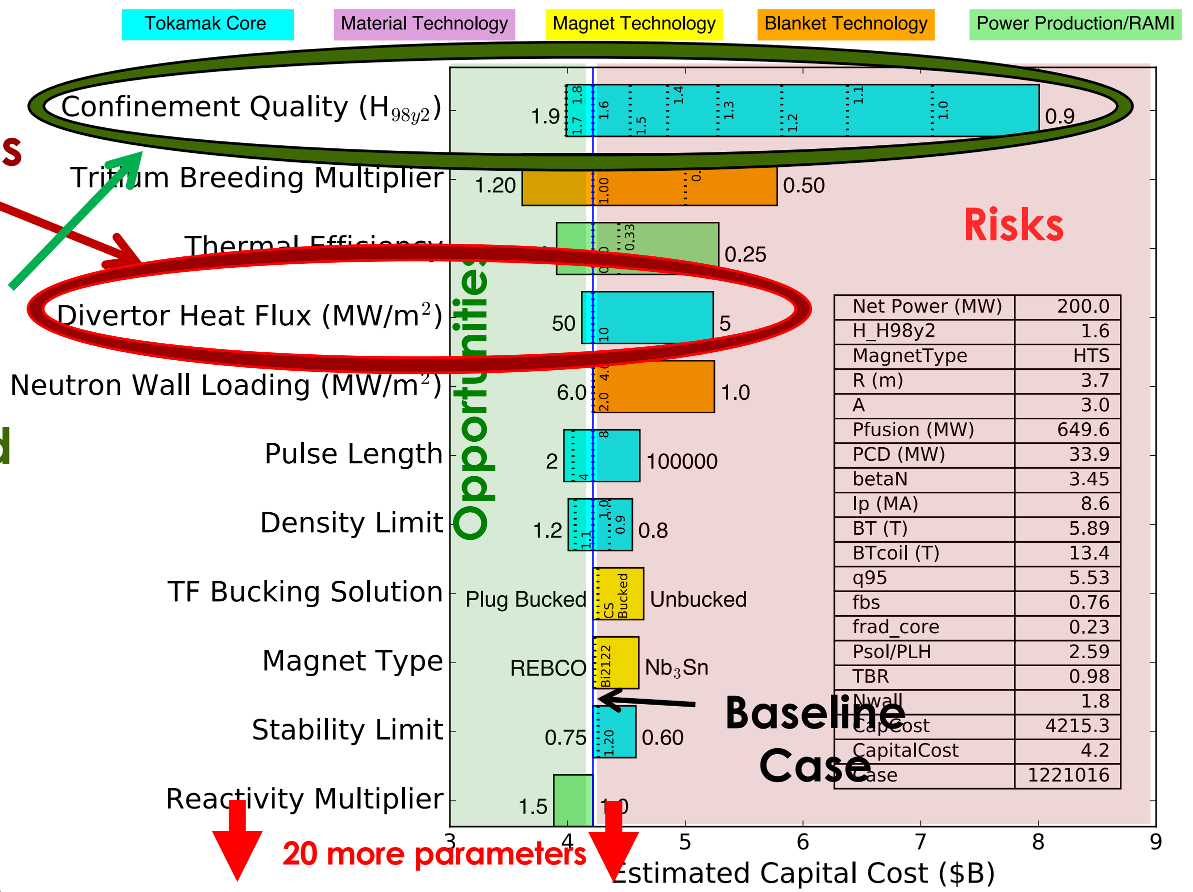
Analysis of Cost Drivers for a CFPP Indicate Importance of Both Physics and Technology Towards Attractiveness

- **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**



Cost Sensitivity Studies Suggest a Potential New Emphasis for Divertor Research

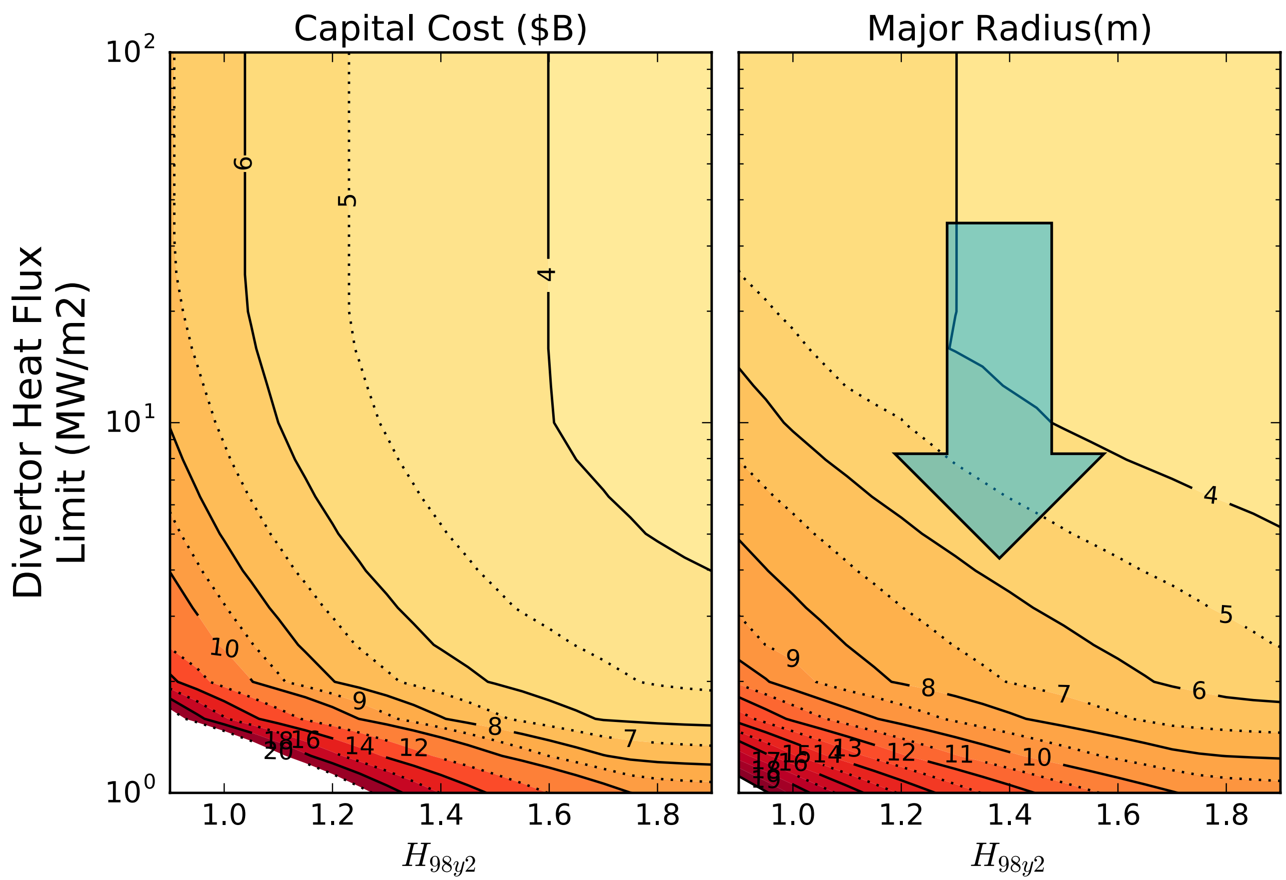
- **On its own, power exhaust capabilities provide modest leverage on cost attractiveness**
  - q_{div} = 5-50 MW/m²
- **However, cost is extremely sensitive to confinement quality, which is strongly linked to edge/divertor**
- **→ A new direction for R&D focused on integrated performance**
  - Rather than just simply divertor performance



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**

Δt_{pulse} = 8 hours



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

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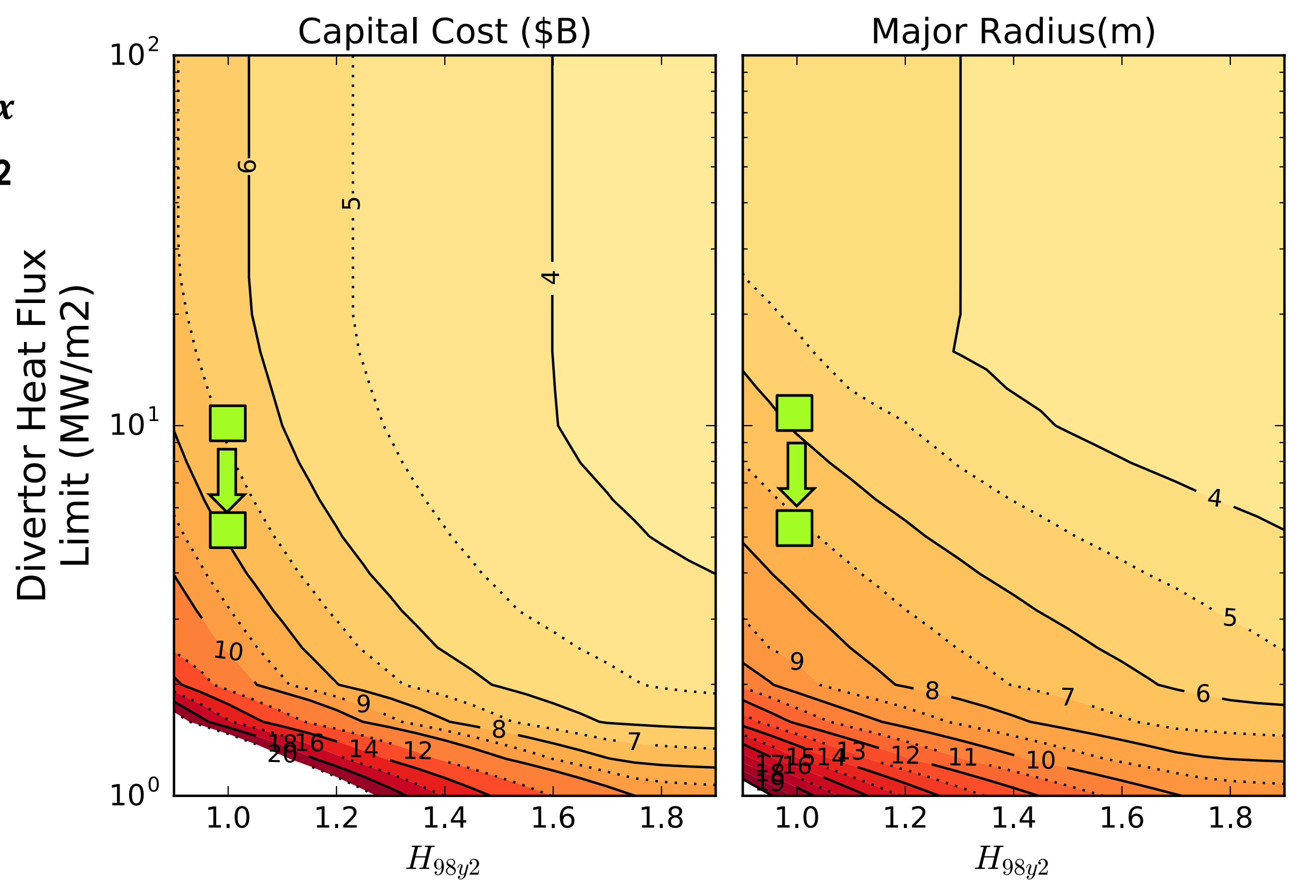

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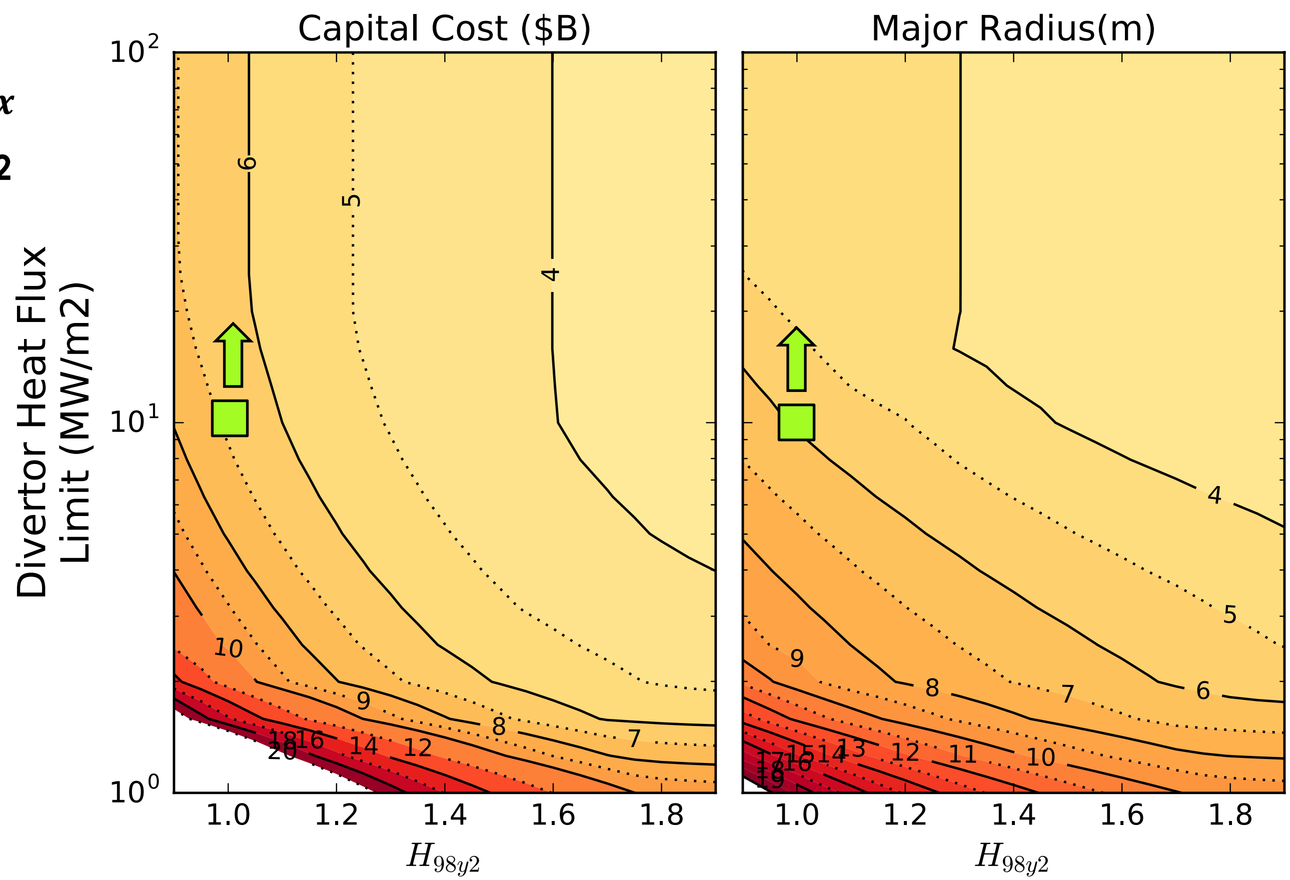
  - **R_o: 5.8 m → 7.2 m**
  - **Capital Cost: ↑ 30%**
- **Some advantage to increasing q_{div}^{max} but only up to ~ 15 MW/m^2**

Δt_{pulse} = 8 hours



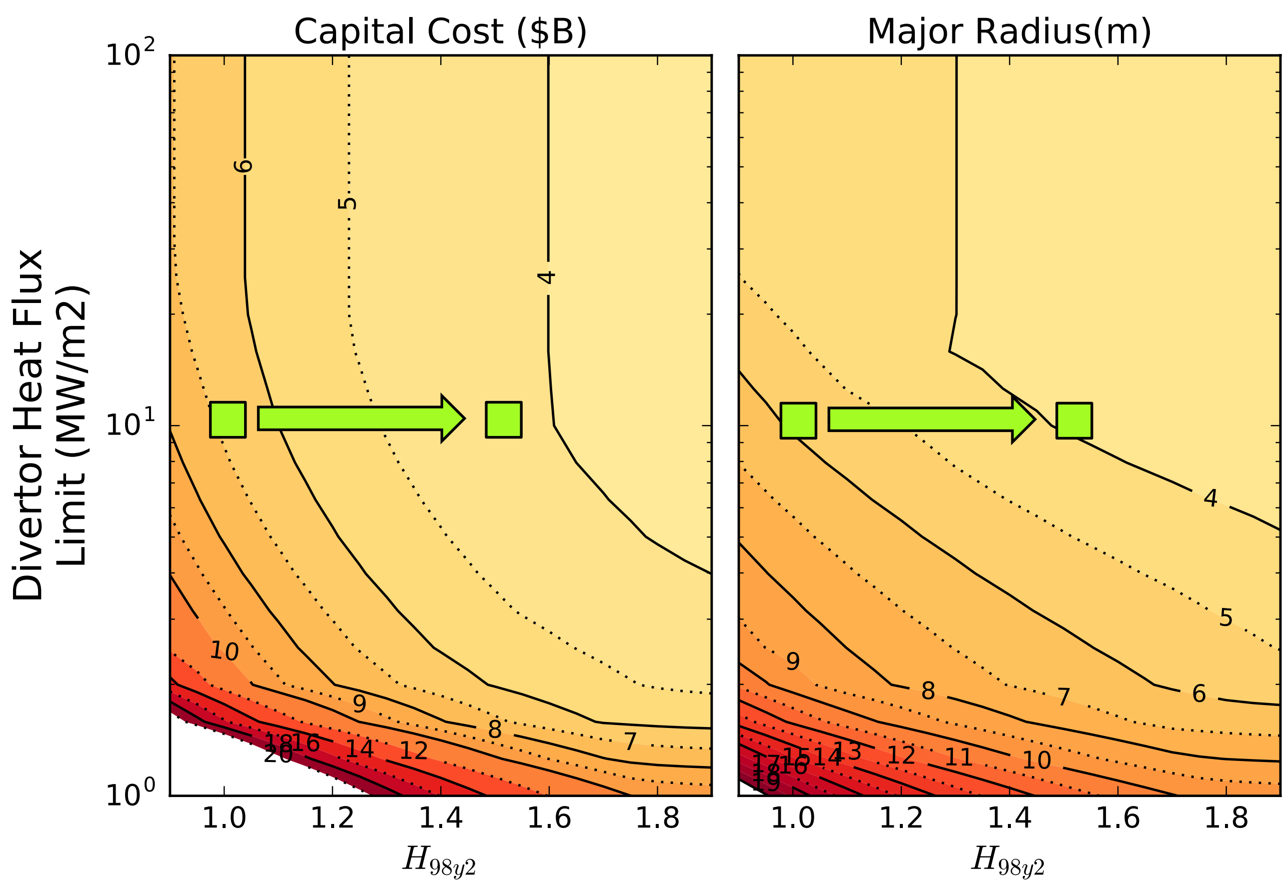
At q_{div}^{max} = 10 MW/m², Increasing Confinement Leads to Significant Reduction in Device Size (and Capital Cost)

- **Increasing H_{98y2} from 1.0→1.5 yields significant benefit**
  - **R_o: 5.8 m → 4.0 m**
  - **Capital Cost: ↓ 35%**

- **Similar improvements at all values of q_{div}^{max}**

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

Δt_{pulse} = 8 hours



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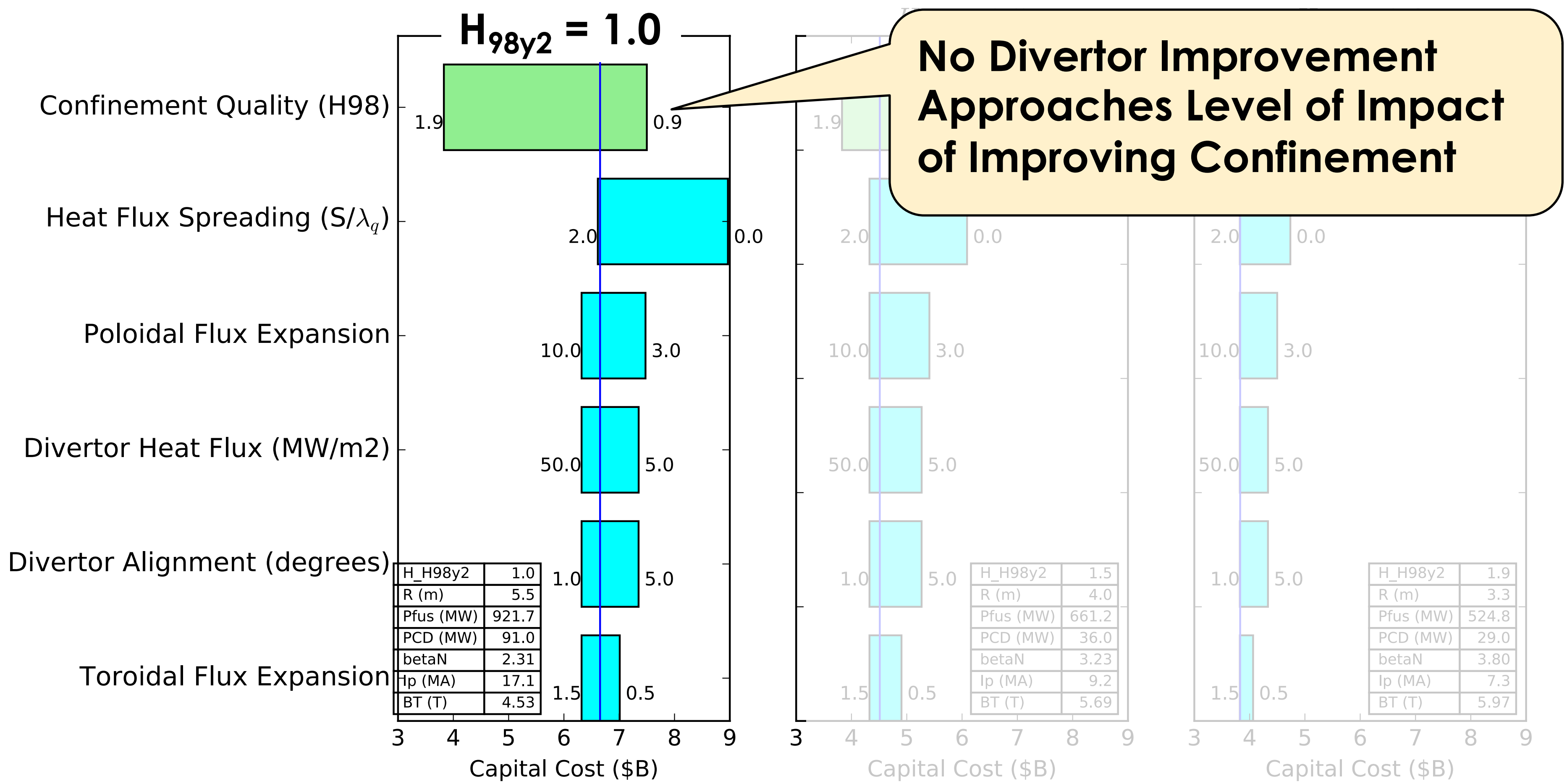
Analysis of Confinement and Divertor Assumptions Reveal Important R&D Needed to Reduce CFPP Capital Costs



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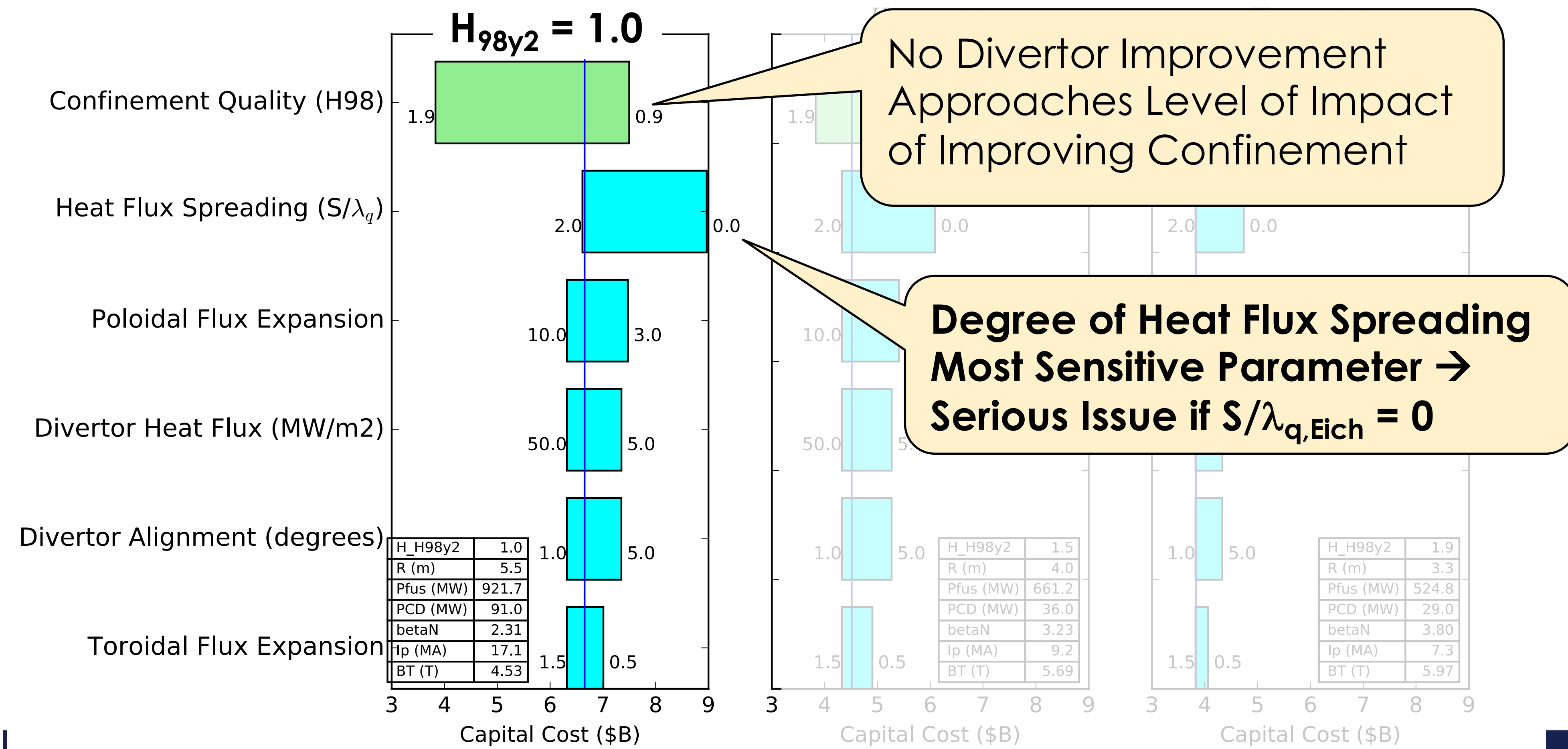

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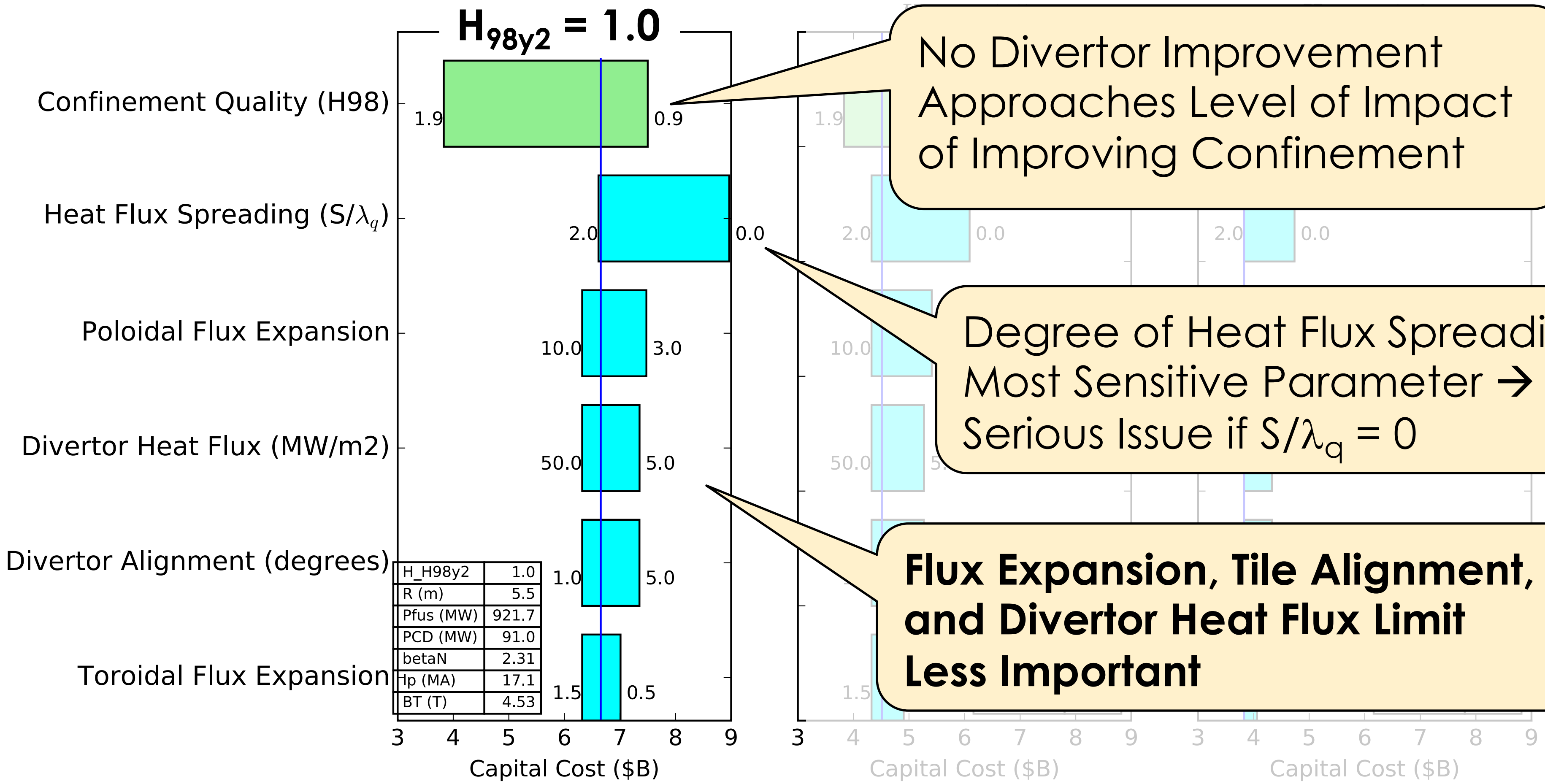

No Divertor Improvement Approaches Level of Impact of Improving Confinement

Degree of Heat Flux Spreading Most Sensitive Parameter → Serious Issue if S/λ_q = 0

Flux Expansion, Tile Alignment, and Divertor Heat Flux Limit Less Important

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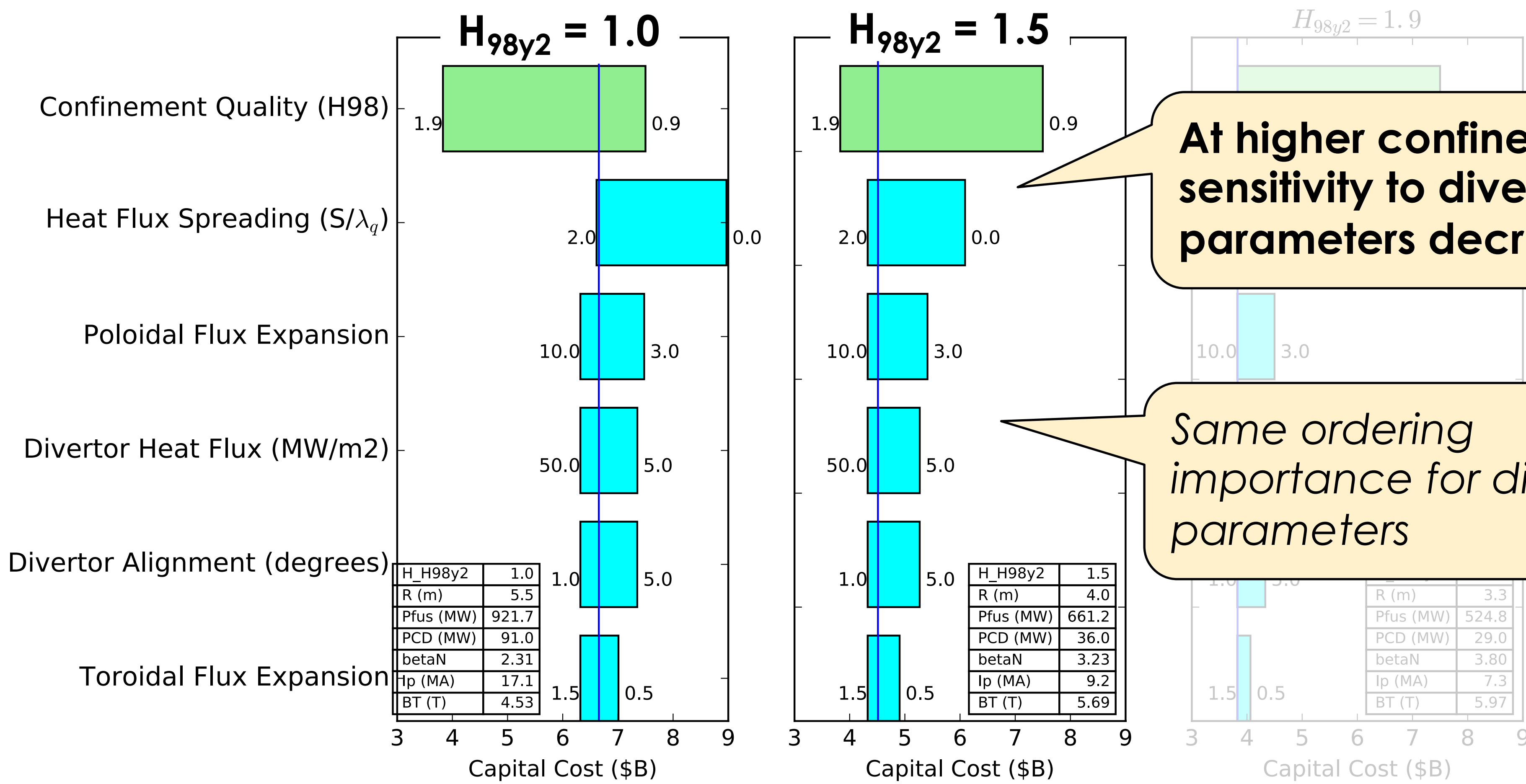

At higher confinement, sensitivity to divertor parameters decreases

Same ordering importance for divertor parameters

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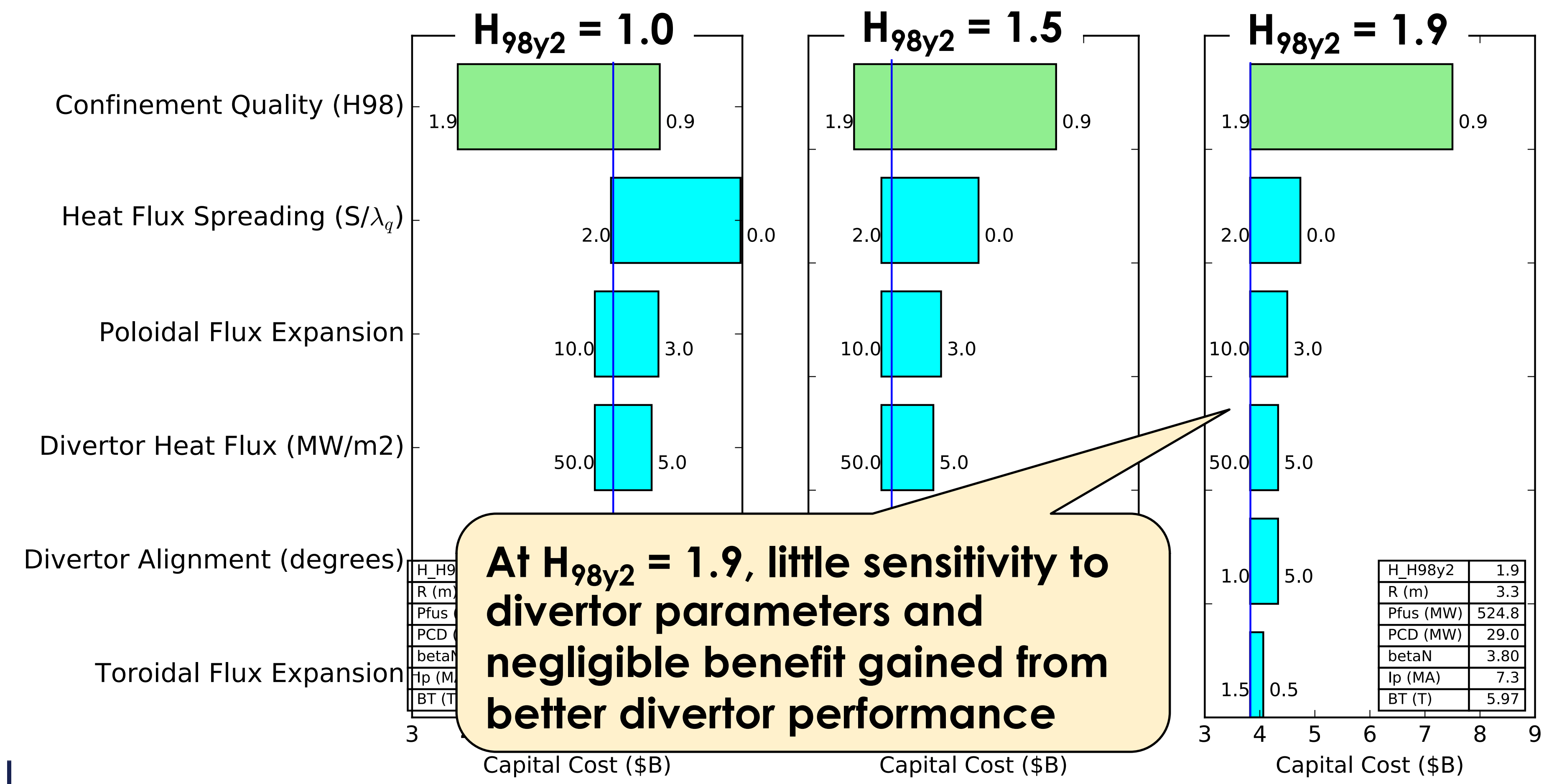

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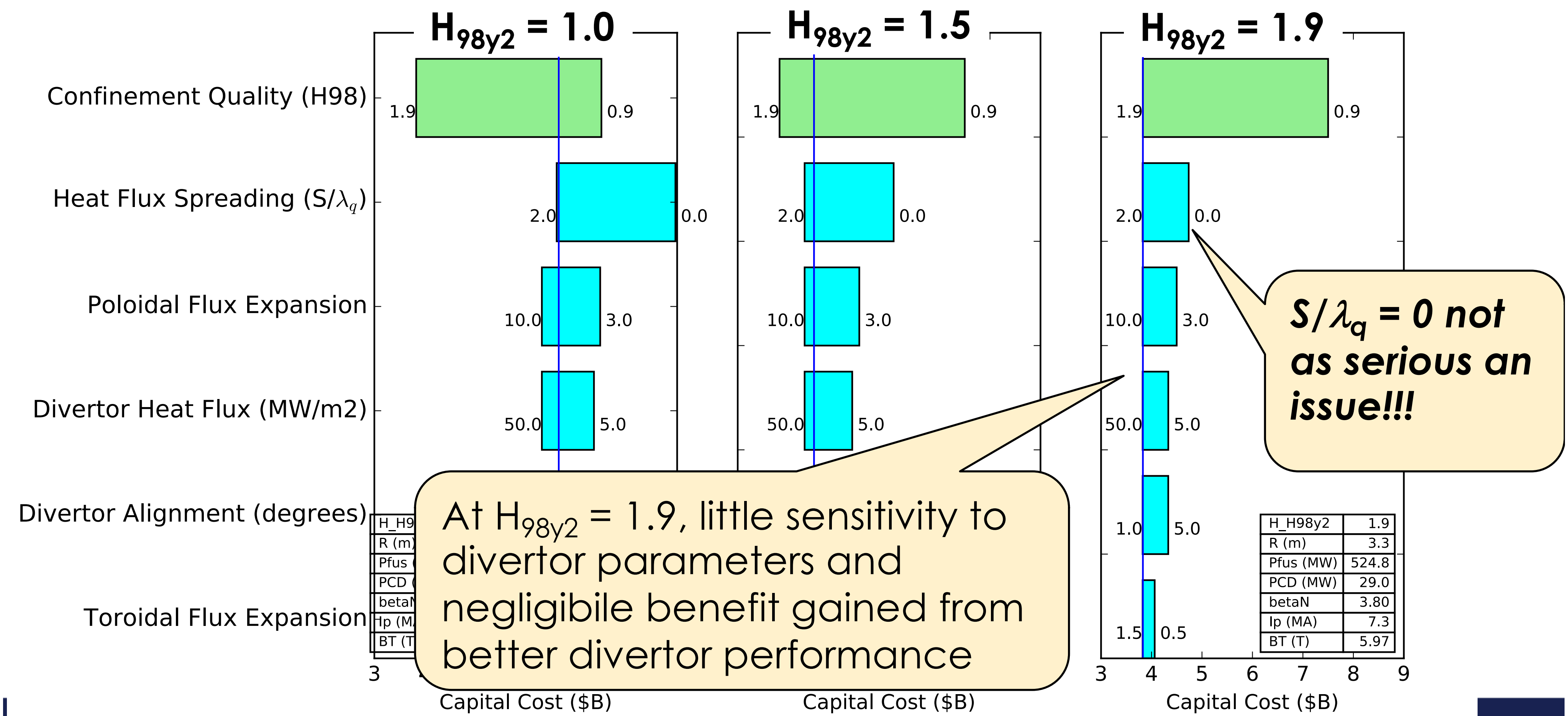

Summary: Takeaways from this Analysis for Power Exhaust Research and Development

- **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/λ_q**
  - Flux expansion and divertor target angle offer some, but only modest, improvements