# General Atomics Perspective on the US MFE Program in the 2020s

By
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Presented to
**Fusion Power Associates**
Washington, DC

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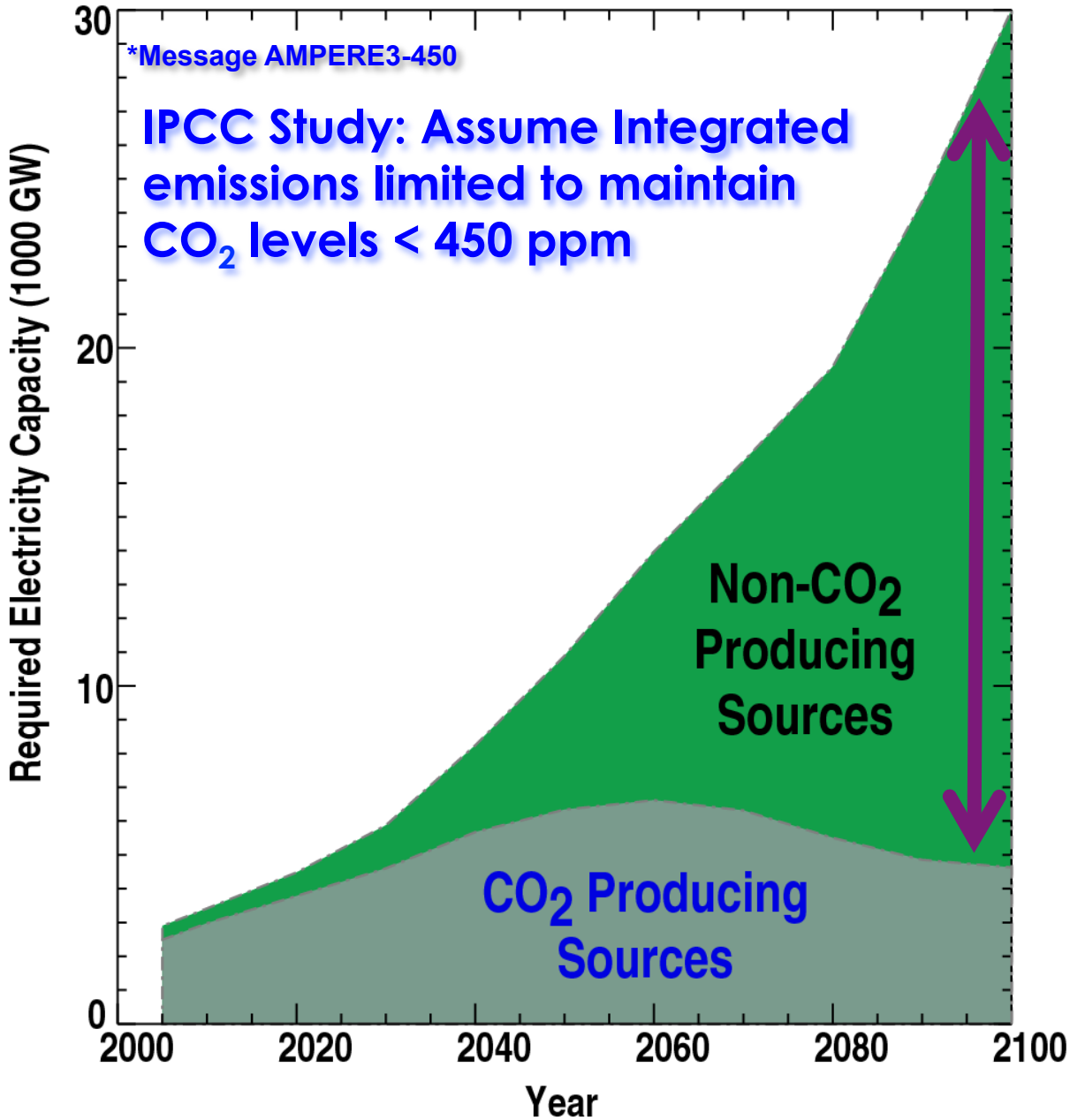
# Exploding Energy Demand in Coming Decades Provides Significant Motivation for Urgency in Fusion Development



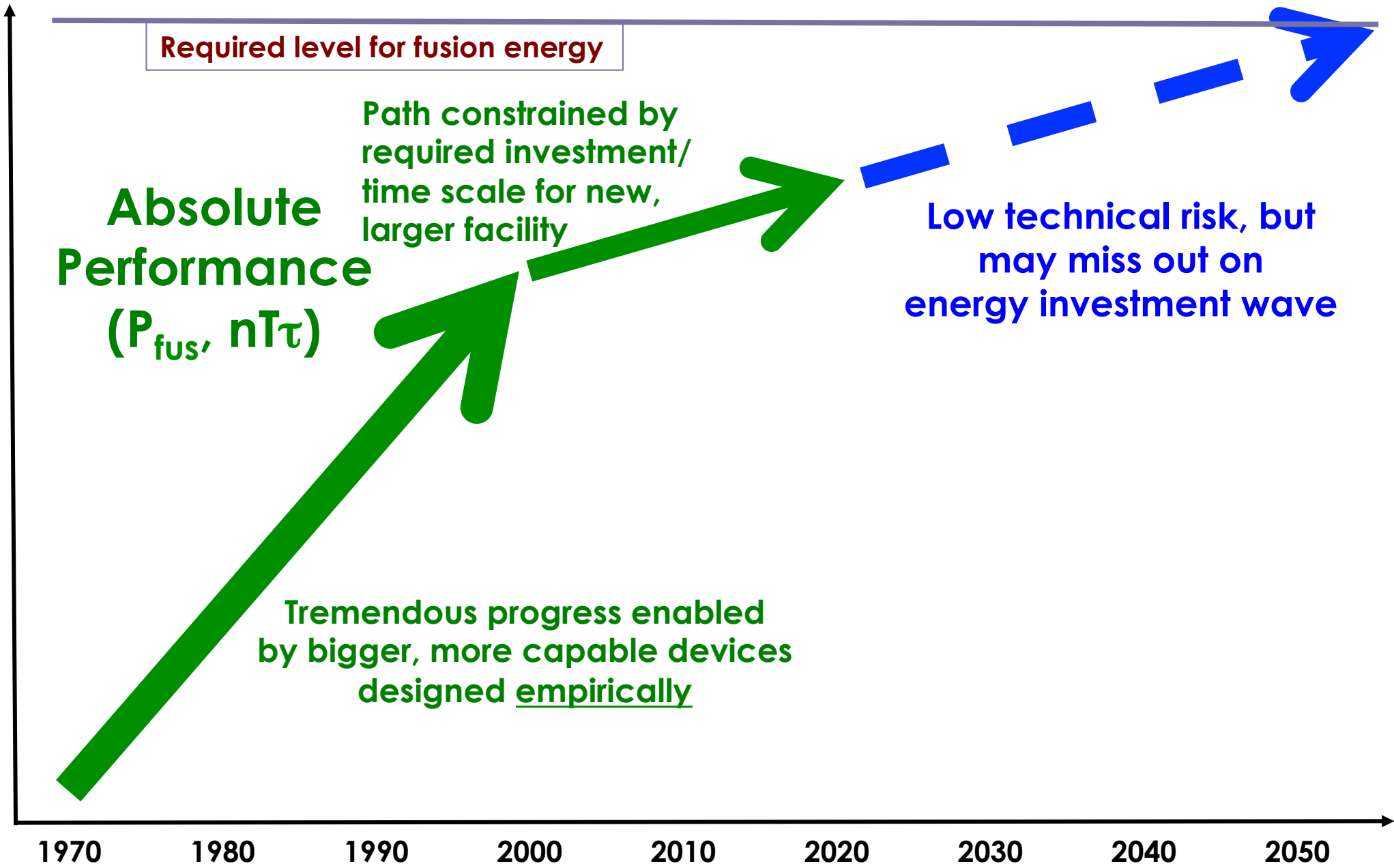

- **Projected need for ~ 25,000 GW from non-CO2 producing sources**

**25,000 1 GW-e plants !!!**

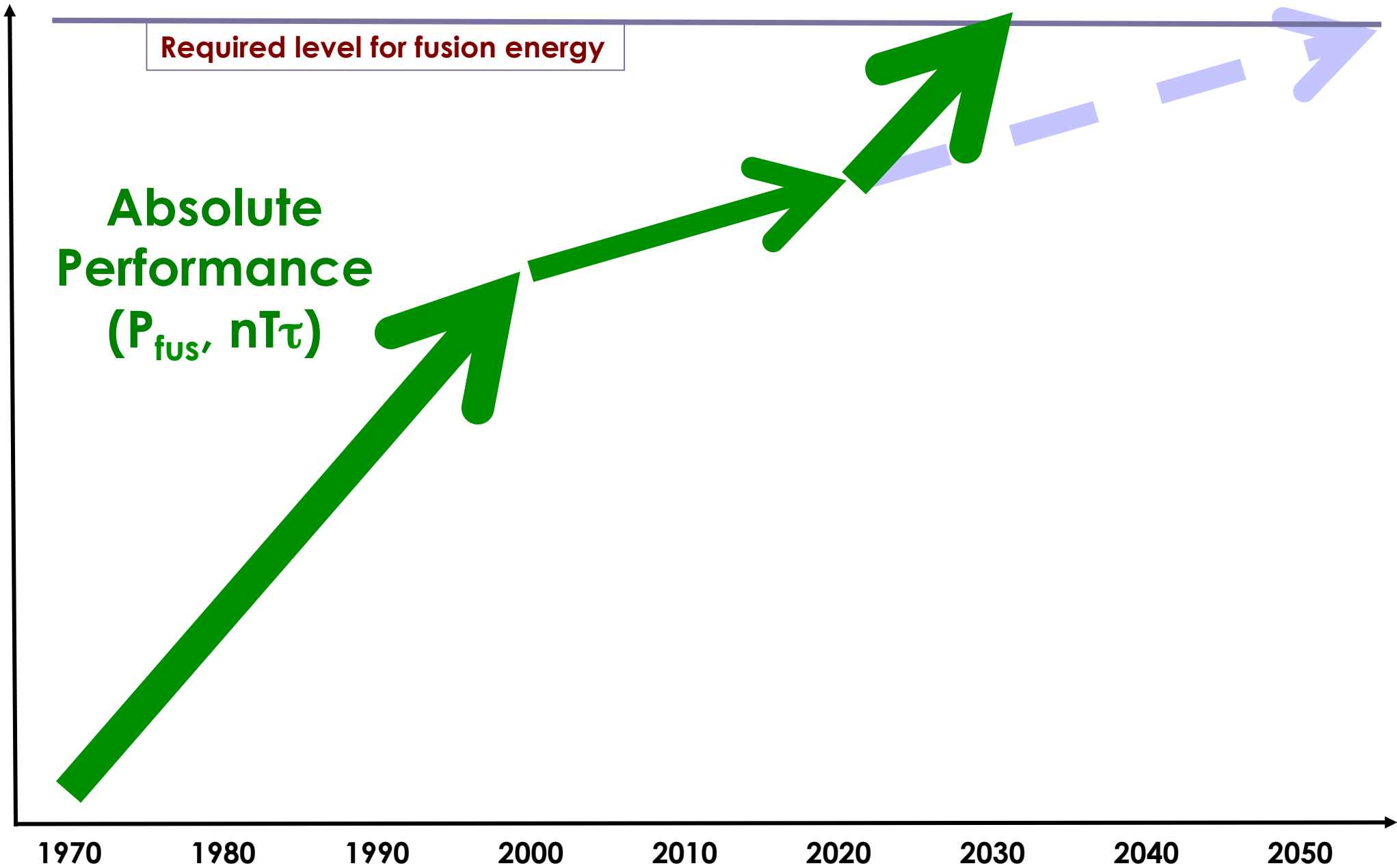
- **Consequently, annual investment in energy projected to explode**
  - $0.8 T by 2050
  - $2.5 T by 2100

→ ***Timely positioning is key***

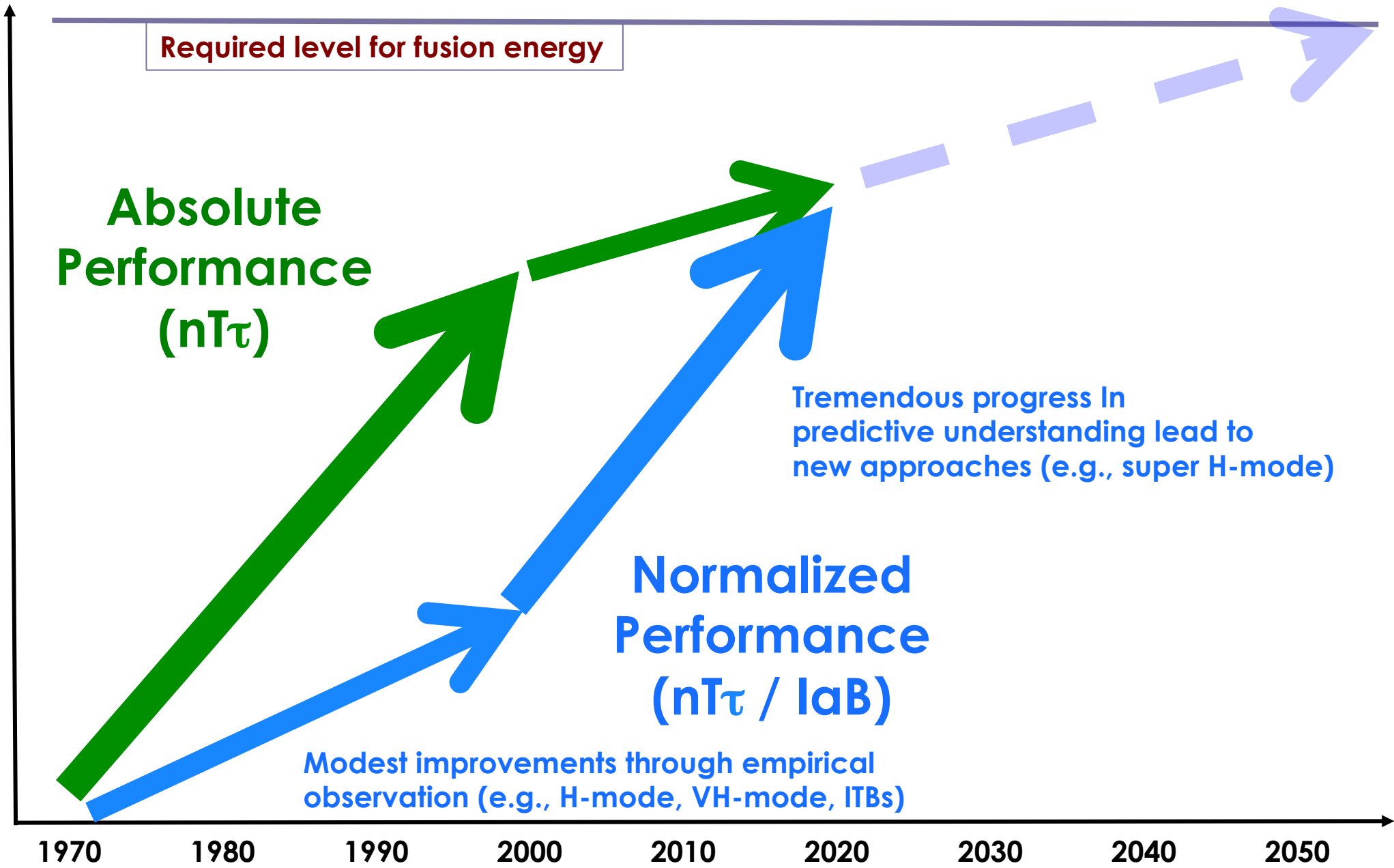
# Present Plan Provides Low Technical Risk Path that is Likely to Succeed But Perhaps Too Late



# What are the Prospects for Accelerating this Timeline?



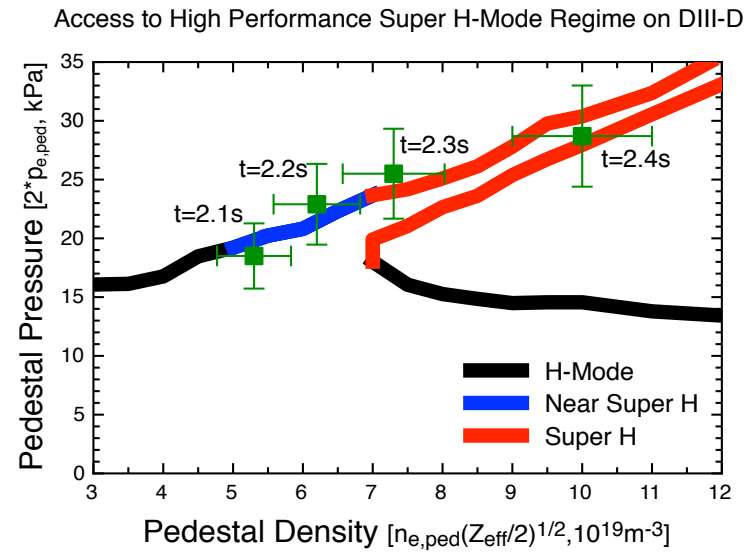
# Recent Progress in Physics Understanding Has Enabled Significant Improvements in Underlying Fusion Metrics

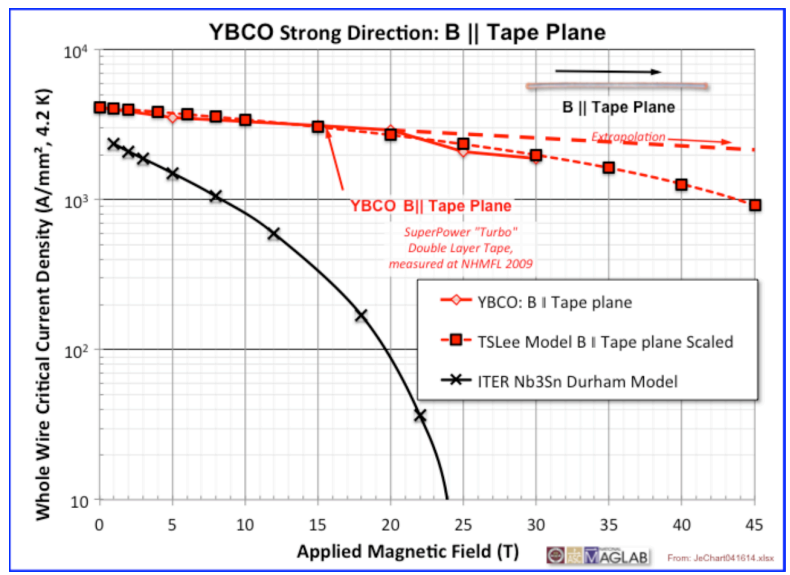


# A Confluence of Developments Have Positioned Fusion Development for a Major 20-year Push

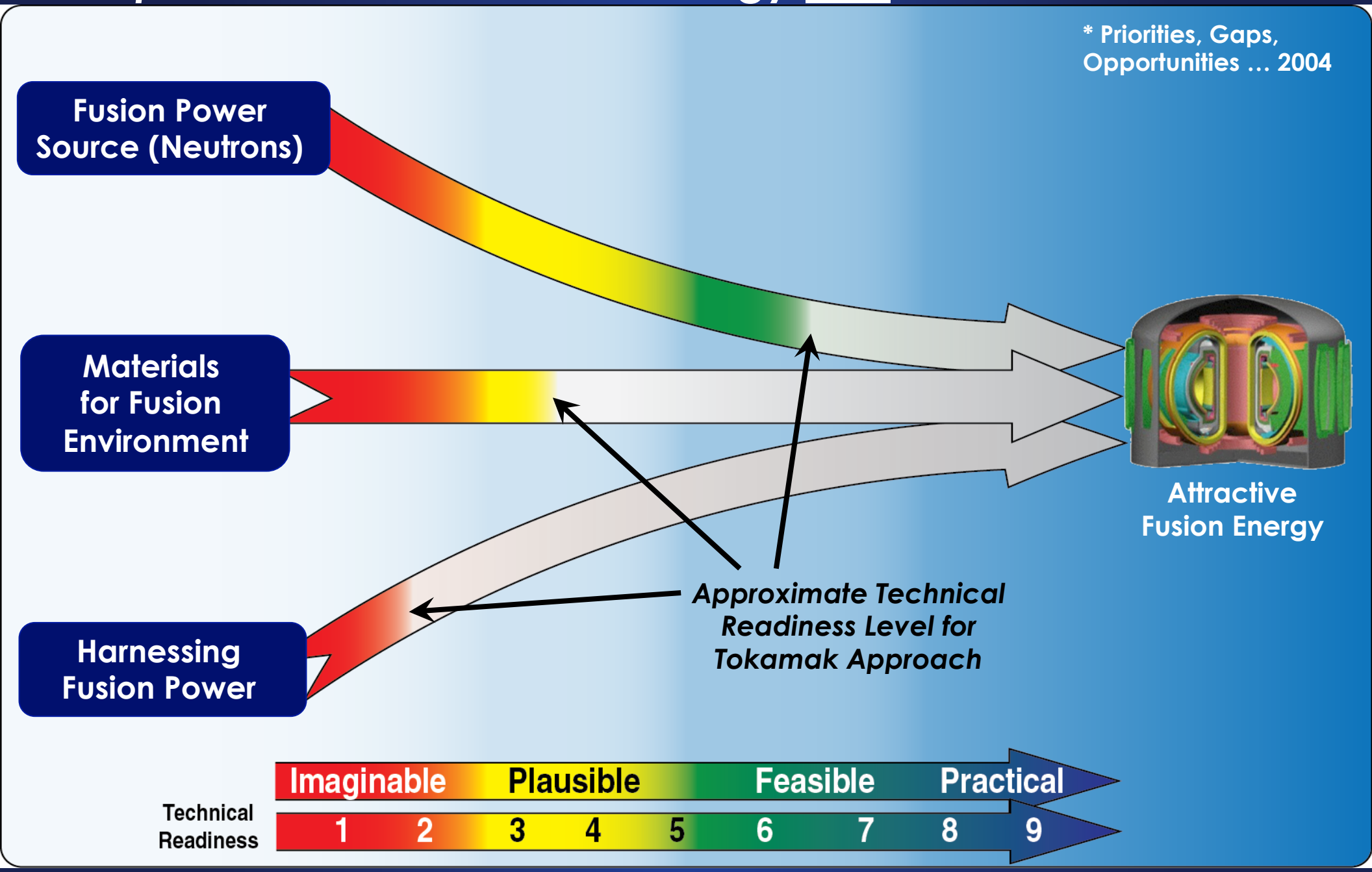
## Recent Developments:

- **Extensive predictive tools for optimizing performance**
  - Example: Super H-mode → record performance on C-Mod and DIII-D
- **Emerging technologies to push boundaries of absolute performance at smaller scale**
  - Example: HTS magnets → record magnetic fields
- **Significant escalation in investment in clean energy → new $$$ to make push possible**



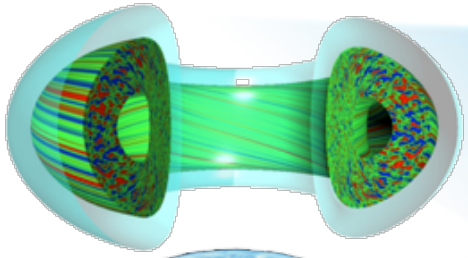
# Any Plan Must Recognize Several "Heavy Lifts" are Still *Required* to Realize Fusion Energy and Make it Attractive*



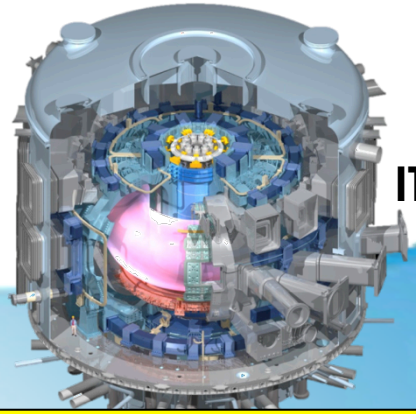
# Facility to Enhance Attractiveness of Pathway is Key to Accelerating Path to Pilot Plant/FNSF

**Develop Foundation for Tokamak Approach to Fusion**

**Theory and Computation**




**Secure Benefit of ITER Construction and Operation**



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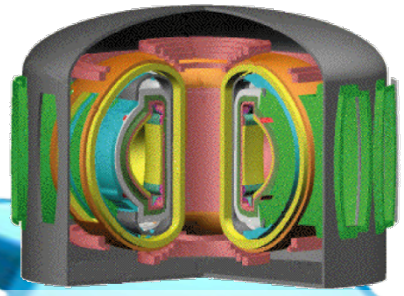
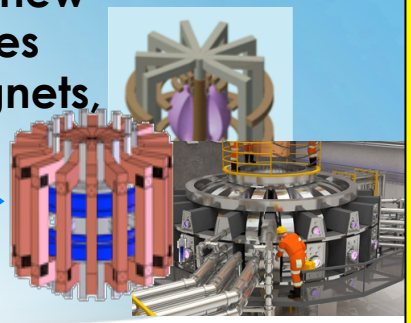


**Cost-attractive Pilot Plant/DEMO/FNSF**

**CFETR (China)**

**US strategy for new fusion facilities (materials, magnets, blankets)**



**Enhance Attractiveness of Pathway and/or End Product**

**Leverage major international efforts**

# GA Systems Code (GASC) Has Been Extended and Utilized to Inform Priorities for the Path Forward

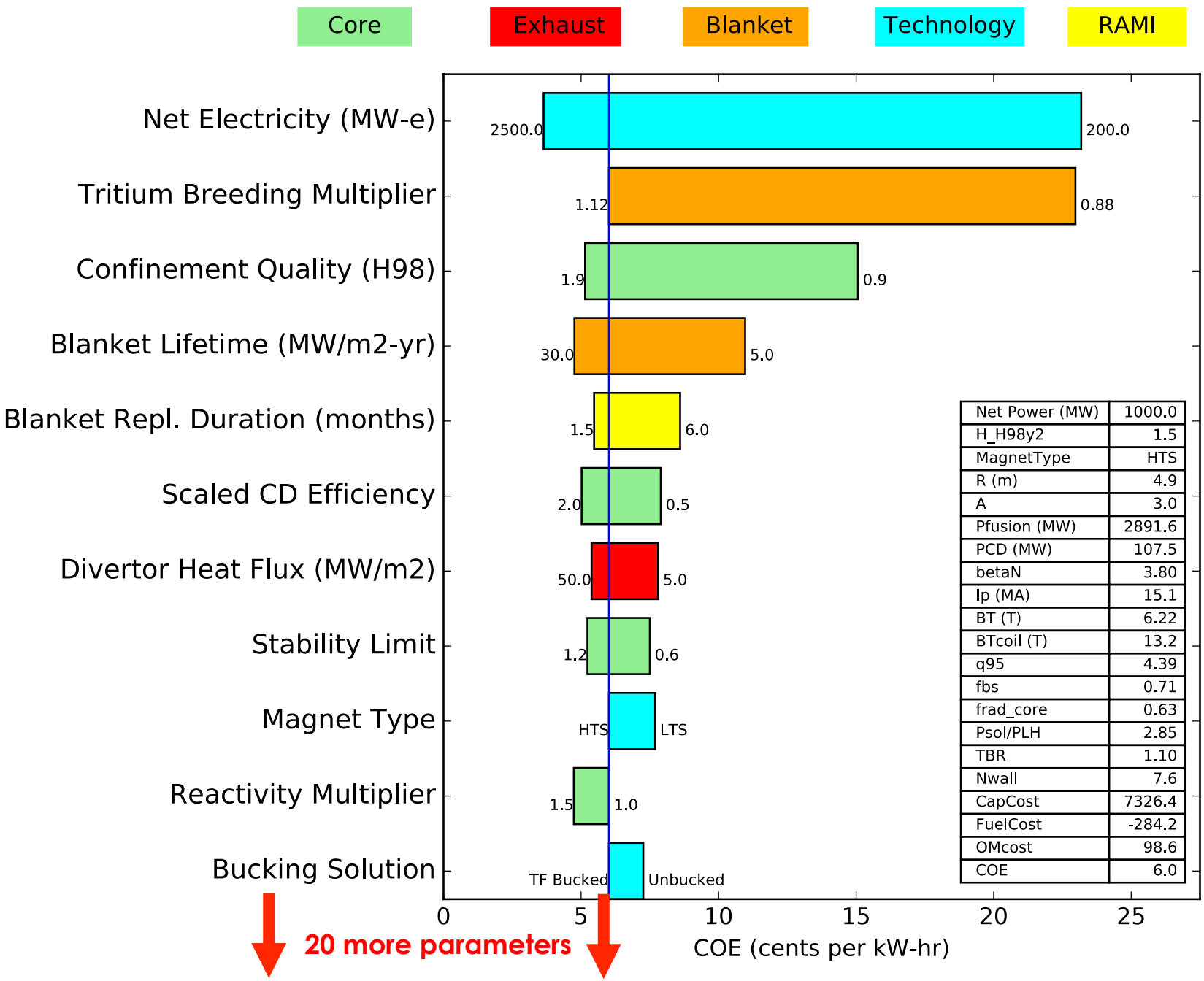
- **GASC extended to include:**
  - Potential transformative physics/technology capabilities (magnet technology, blanket tech., CD physics, power exhaust, maintenance)
  - Cost model based on Sheffield FST 2016

- **GASC-Opt produces an optimized solution based on a set of assumed capabilities**
  - Example optimization parameters: device size, COE, capital cost, …

- **Utilized to conduct sensitivity studies to identify most important R&D on path to fusion energy**

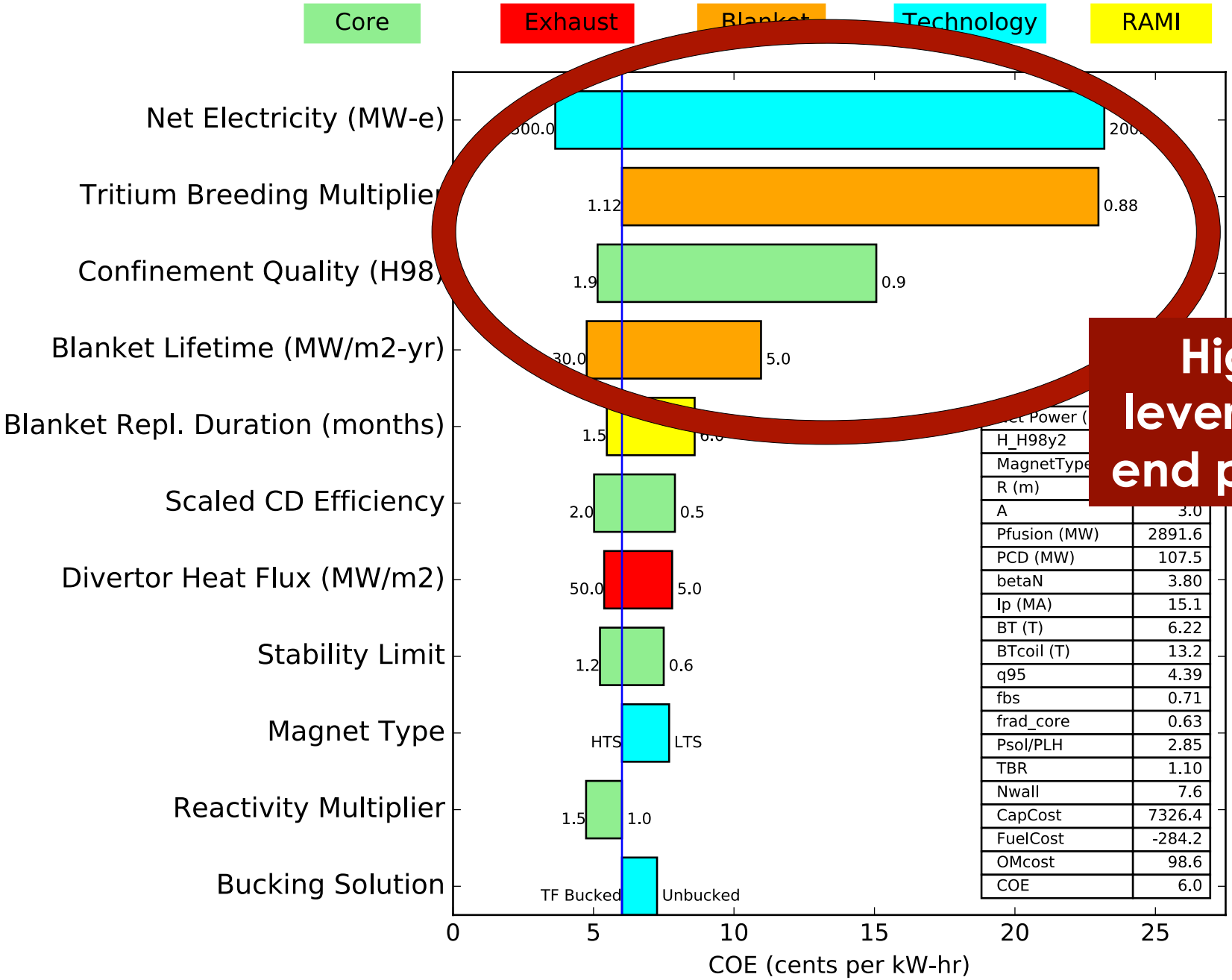
  → "Tornado" charts

# Example of COE Sensitivity Analysis: 1 GW-e Reactor Assuming H98y2 = 1.5, A = 3.0




| | |
|---|---|
| Net Power (MW) | 1000.0 |
| H_H98y2 | 1.5 |
| MagnetType | HTS |
| R (m) | 4.9 |
| A | 3.0 |
| Pfusion (MW) | 2891.6 |
| PCD (MW) | 107.5 |
| betaN | 3.80 |
| Ip (MA) | 15.1 |
| BT (T) | 6.22 |
| BTcoil (T) | 13.2 |
| q95 | 4.39 |
| fbs | 0.71 |
| frad_core | 0.63 |
| Psol/PLH | 2.85 |
| TBR | 1.10 |
| Nwall | 7.6 |
| CapCost | 7326.4 |
| FuelCost | -284.2 |
| OMcost | 98.6 |
| COE | 6.0 |

# Most Sensitive Parameters for COE: Power Output, Tritium Breeding, Confinement, and Materials Lifetime

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**Highest leverage on end product***

** Although this is tokamak specific, the importance of these 3 parameters is likely generic to all D-T fusion systems.*

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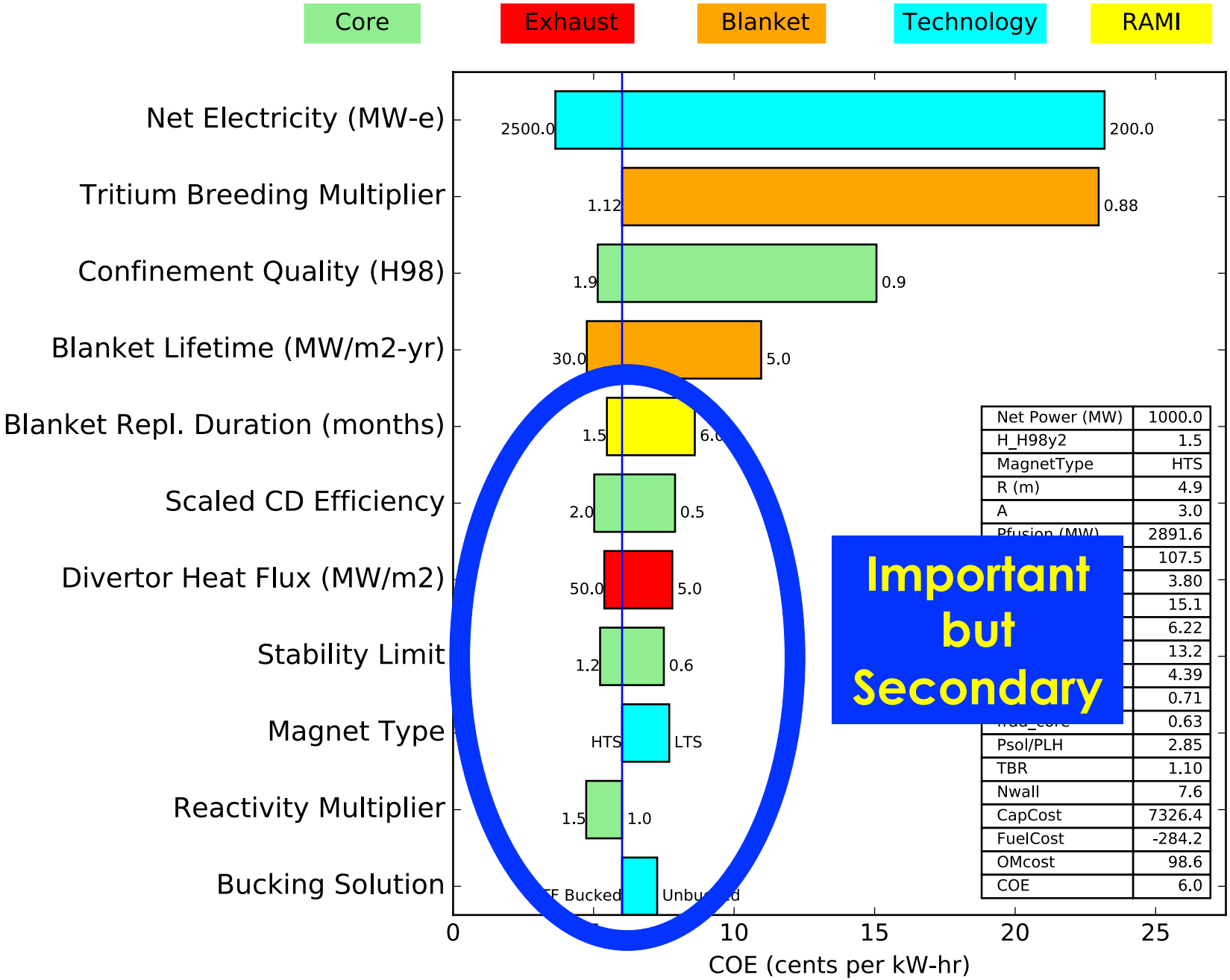


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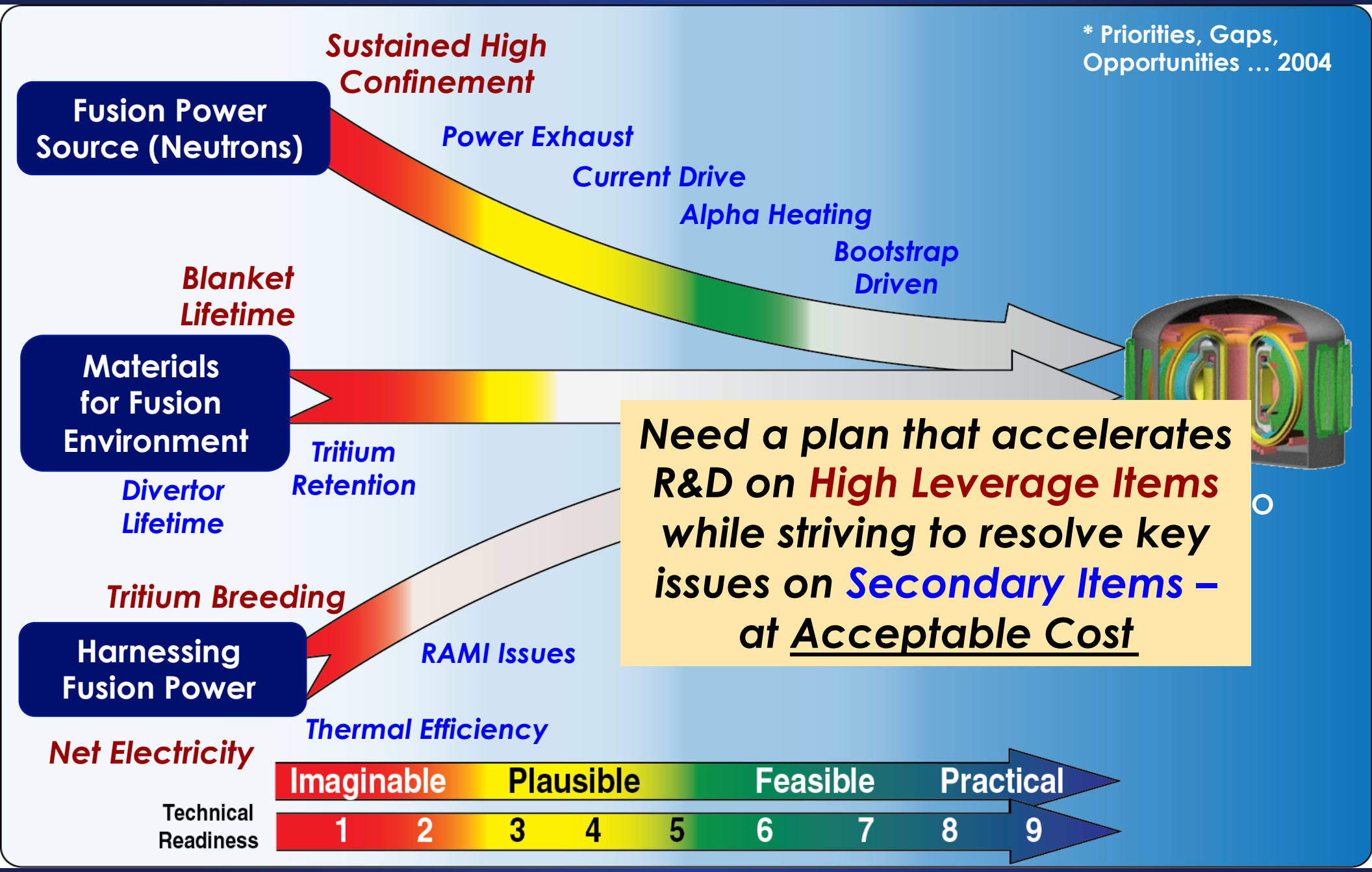
# Populating our Roadmap with This Information….



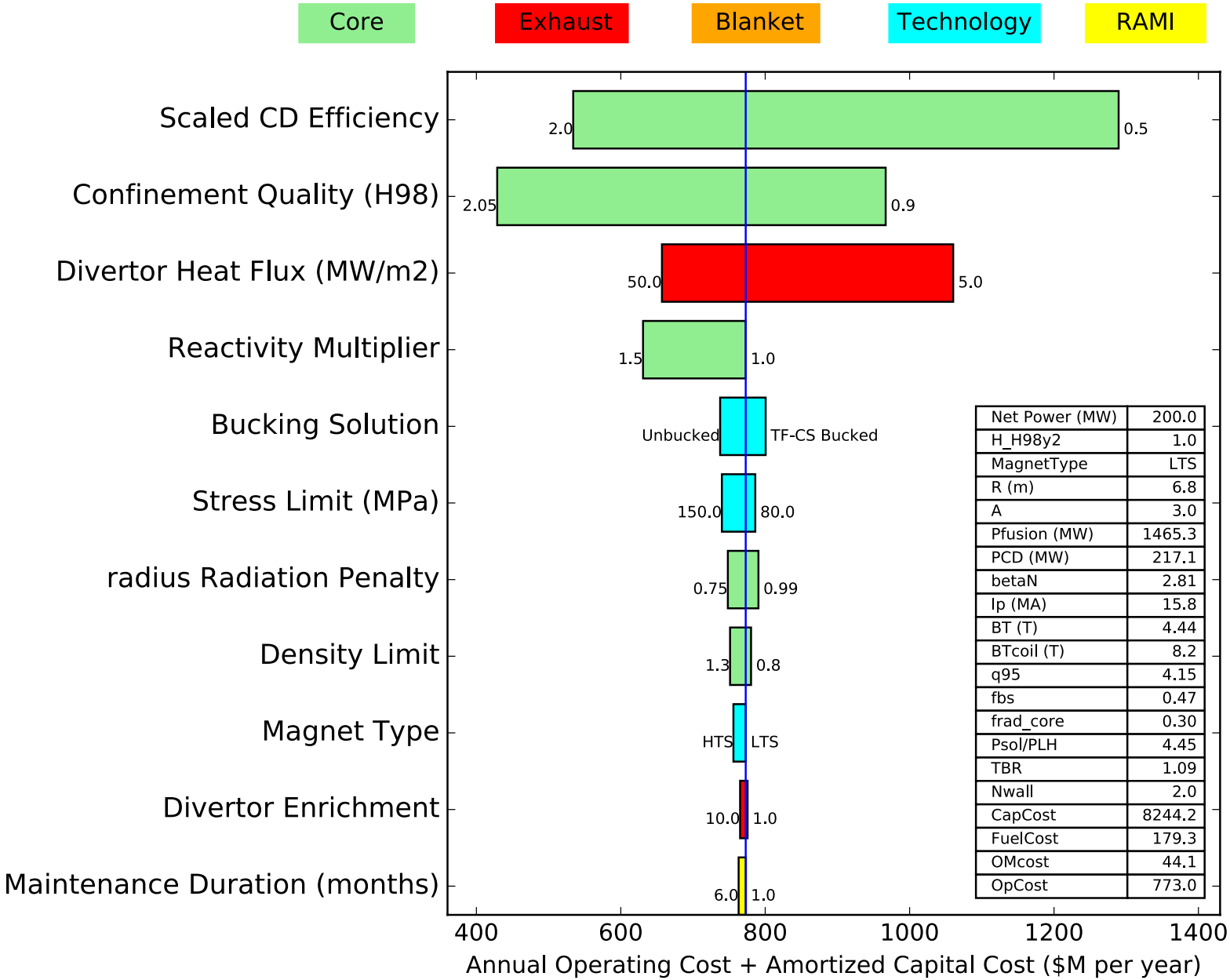
# Let's Look Ahead to a Pilot Plant/FNSF that would Address the Fusion Nuclear Science and Technology Issues

- **Assume facility has combined missions**
  - Provide fusion nuclear test bed for blankets and materials
    - Neutron wall loading = 2 $MW/m^2$
  - Net electricity
    - $P_{net}$ = 200 MW-e
  - Establish the technical and safety basis for rapid deployment of future fusion energy products
- **Q: What parameters provide greatest leverage in minimizing the cost of producing/operating this class of facility?**
  - Optimization parameter: Annual operating cost + amortized capital cost (assuming 5-year construction and 10-year lifetime)
  - Start with conservative physics/technology and see where the cheese leads us

# General Assumptions for Analysis

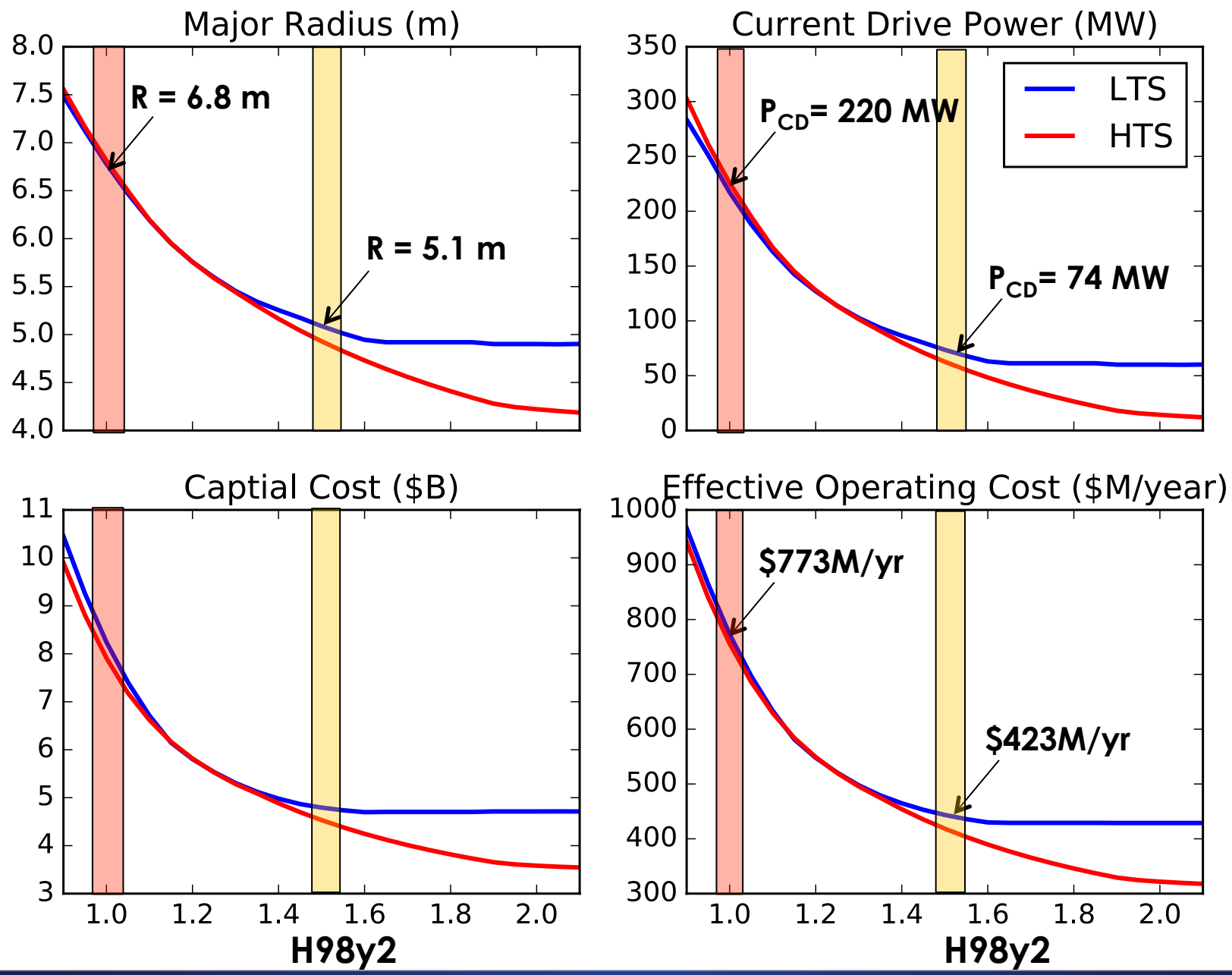
- **Mid-range assumptions for physics and technology as the baseline**
  - e.g., $\beta_N/\beta_{N,limit}$=0.75; $q_{div,max}$ = 10 MW/m$^2$; $\eta_{th}$ = 0.4
- **No cost difference in HTS and LTS magnets**
  - Assume HTS development will drive cost down to LTS levels
- **No credit given for selling electricity and tritium on open market**
  - Potential offset in operating cost of ~ $100M per year

# Baseline Case for Pilot Plant/FNSF: Use LTS Magnets, H98y2 = 1.0; $P_{net}$ = 200 MW, $N_{wall}$ = 2.0 MW/m2

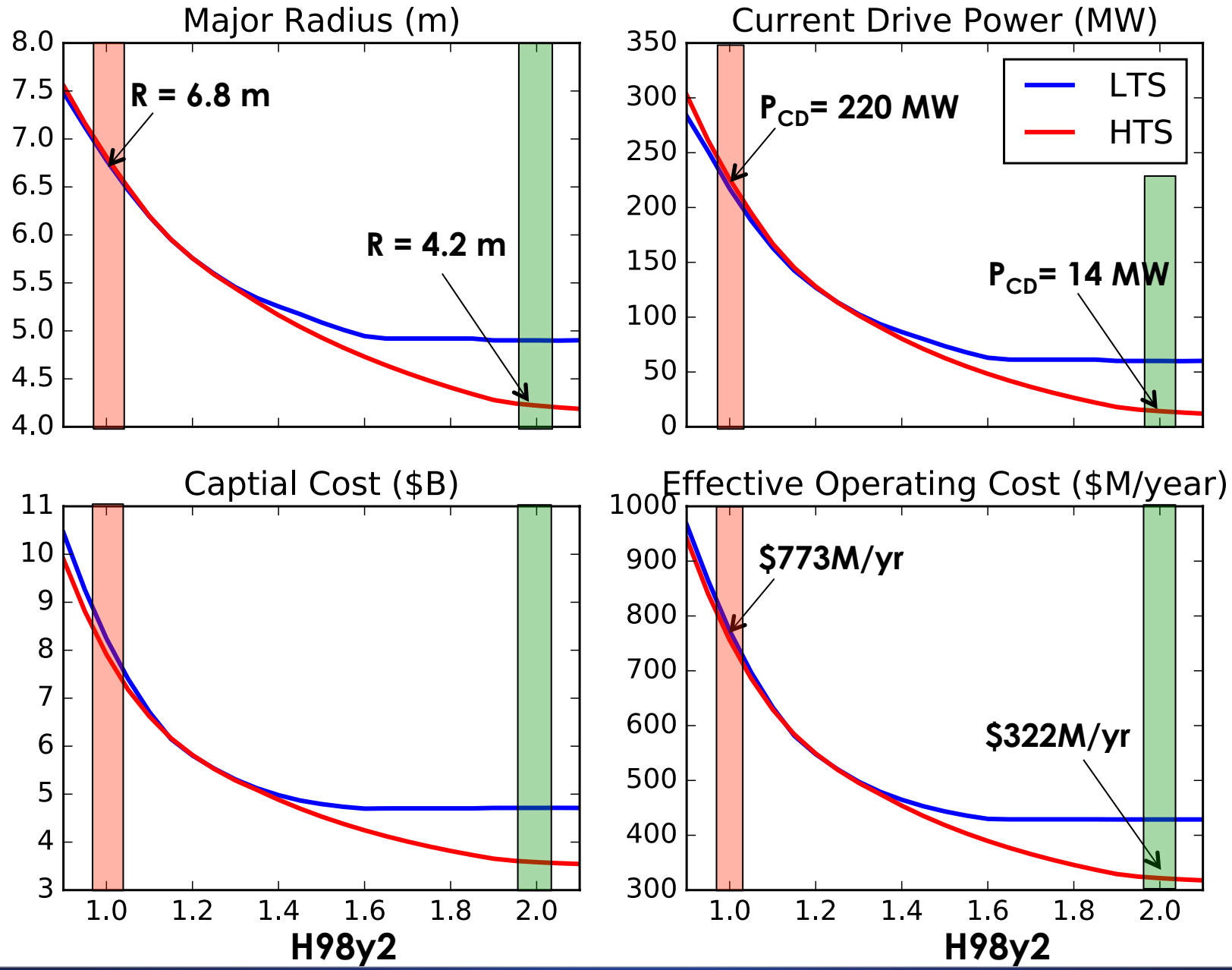



| | |
|---|---|
| Net Power (MW) | 200.0 |
| H_H98y2 | 1.0 |
| MagnetType | LTS |
| R (m) | 6.8 |
| A | 3.0 |
| Pfusion (MW) | 1465.3 |
| PCD (MW) | 217.1 |
| betaN | 2.81 |
| Ip (MA) | 15.8 |
| BT (T) | 4.44 |
| BTcoil (T) | 8.2 |
| q95 | 4.15 |
| fbs | 0.47 |
| frad_core | 0.30 |
| Psol/PLH | 4.45 |
| TBR | 1.09 |
| Nwall | 2.0 |
| CapCost | 8244.2 |
| FuelCost | 179.3 |
| OMcost | 44.1 |
| OpCost | 773.0 |

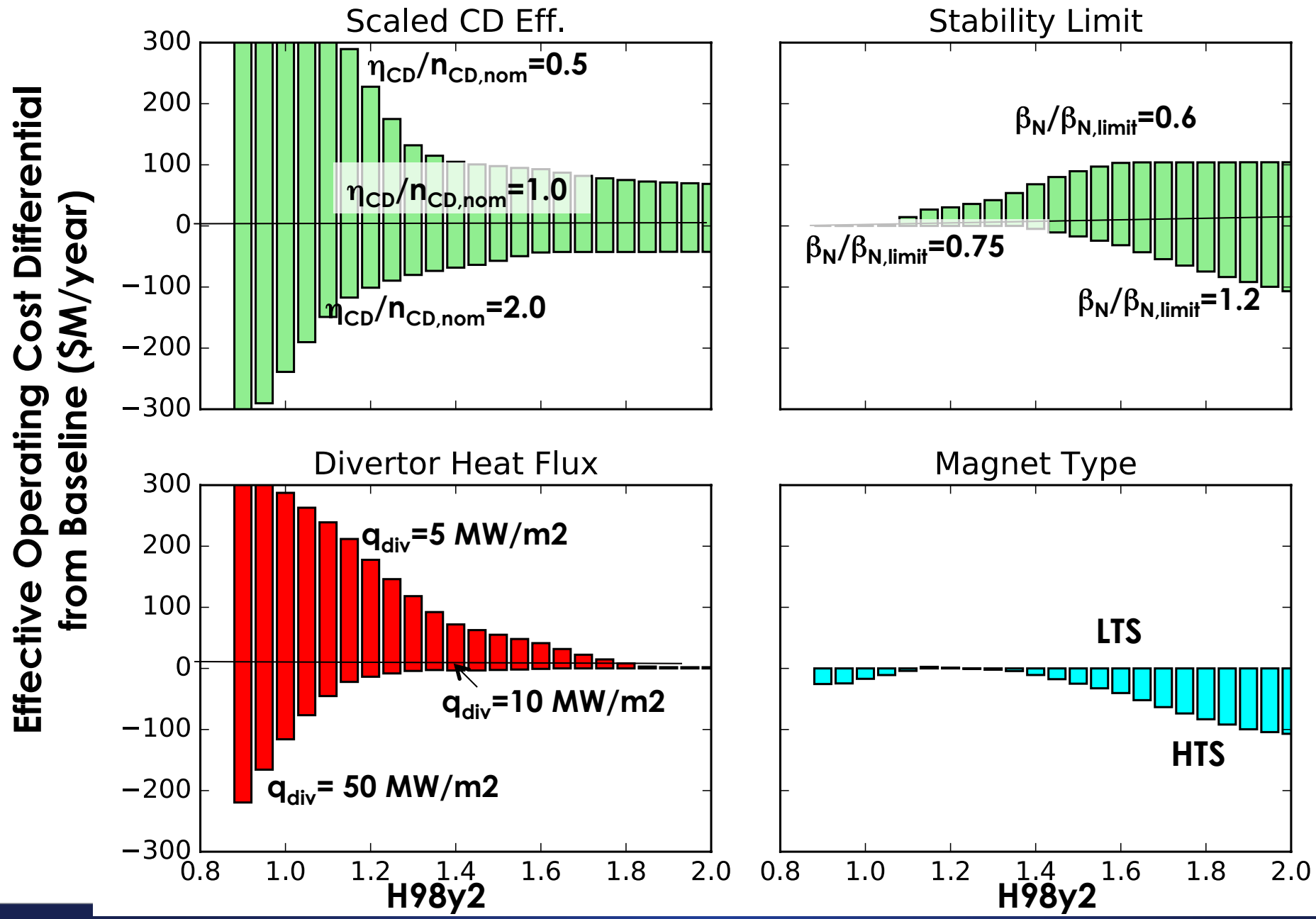
# Improved Confinement is Very Favorable for Reducing Cost of Building and Operating Pilot Plant/FNSF



# HTS Magnet Technology Provides Significant Potential Cost Reduction for $H_{98y2}$ > 1.5



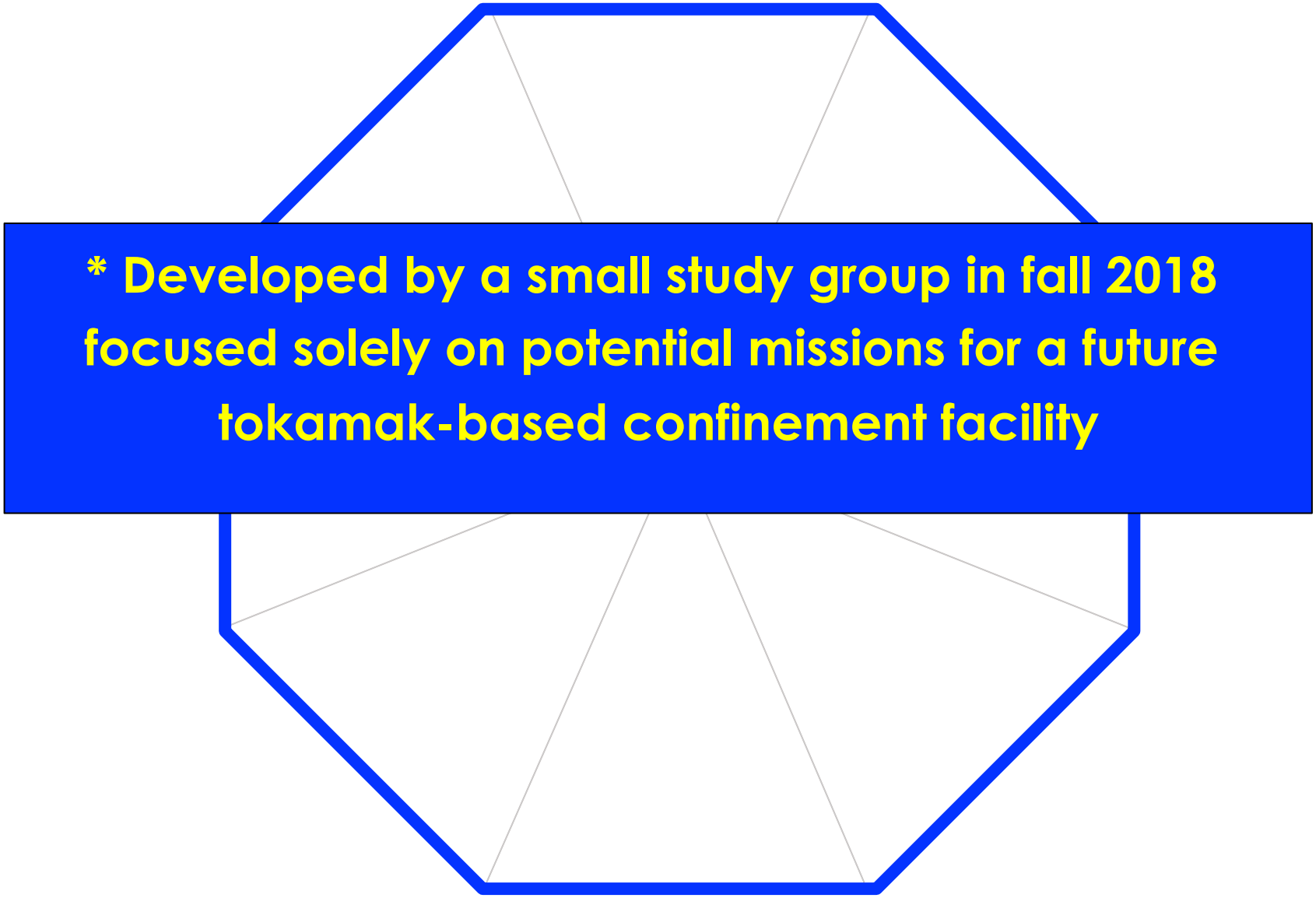
# Analysis Implies R&D Focus on Current Drive and Power Exhaust at $H_{98y2}$ = 1.0; Shifts to Stability/HTS at $H_{98y2}$ > 1.5



# Takeaways from This Analysis on R&D Program in Preparation for Pilot Plant/FNSF/DEMO

- **Improved confinement is very favorable for reduced capital/operating cost solutions for a pilot plant/FNSF**
  - Factor of 2-3 reduction in cost
- **Low confinement (H98y2 < 1.3) solutions primarily constrained by power exhaust capabilities and current drive efficiencies**
  - R&D should focus on exhaust and CD; Little gain from HTS technology (EU-DEMO/JA-DEMO approach)
- **Mid-range confinement (1.3 < H98y2 < 1.6) solutions still limited by power exhaust but magnet capabilities and stability becoming important**
  - R&D focus: Core transport/stability, exhaust, CD, and HTS magnets
- **Very high confinement (H98y2 > 1.6) solutions constrained by stability limit, and magnet capabilities; little limitation posed by power exhaust or CD**
  - R&D focus: Core transport/stability, core-edge optimization, HTS magnets, and blanket technology

# Bottom-Up Approach from Physics Assessment Revealed Eight Potential Missions for Pre-Pilot-Plant Facility*



* Developed by a small study group in fall 2018 focused solely on potential missions for a future tokamak-based confinement facility

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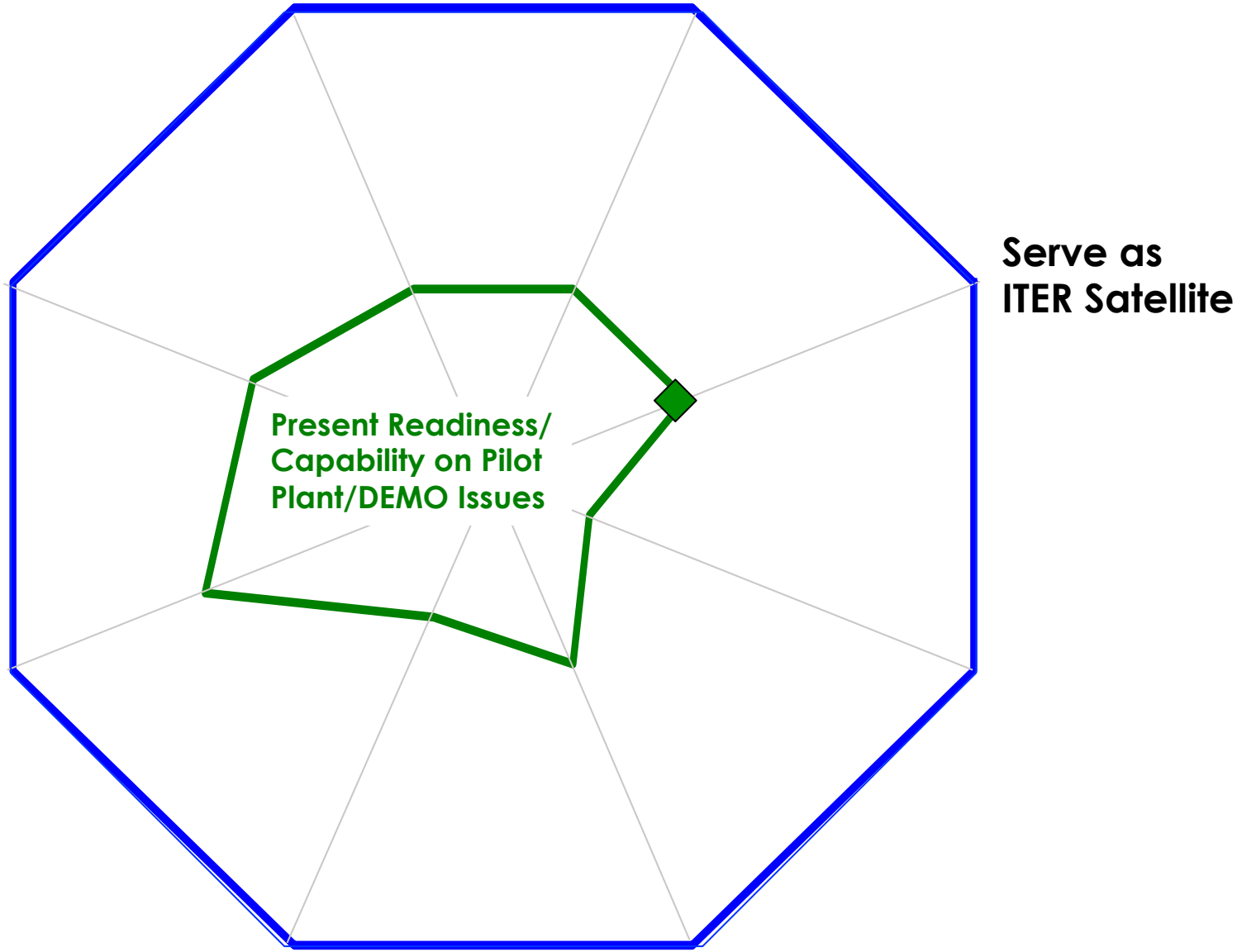

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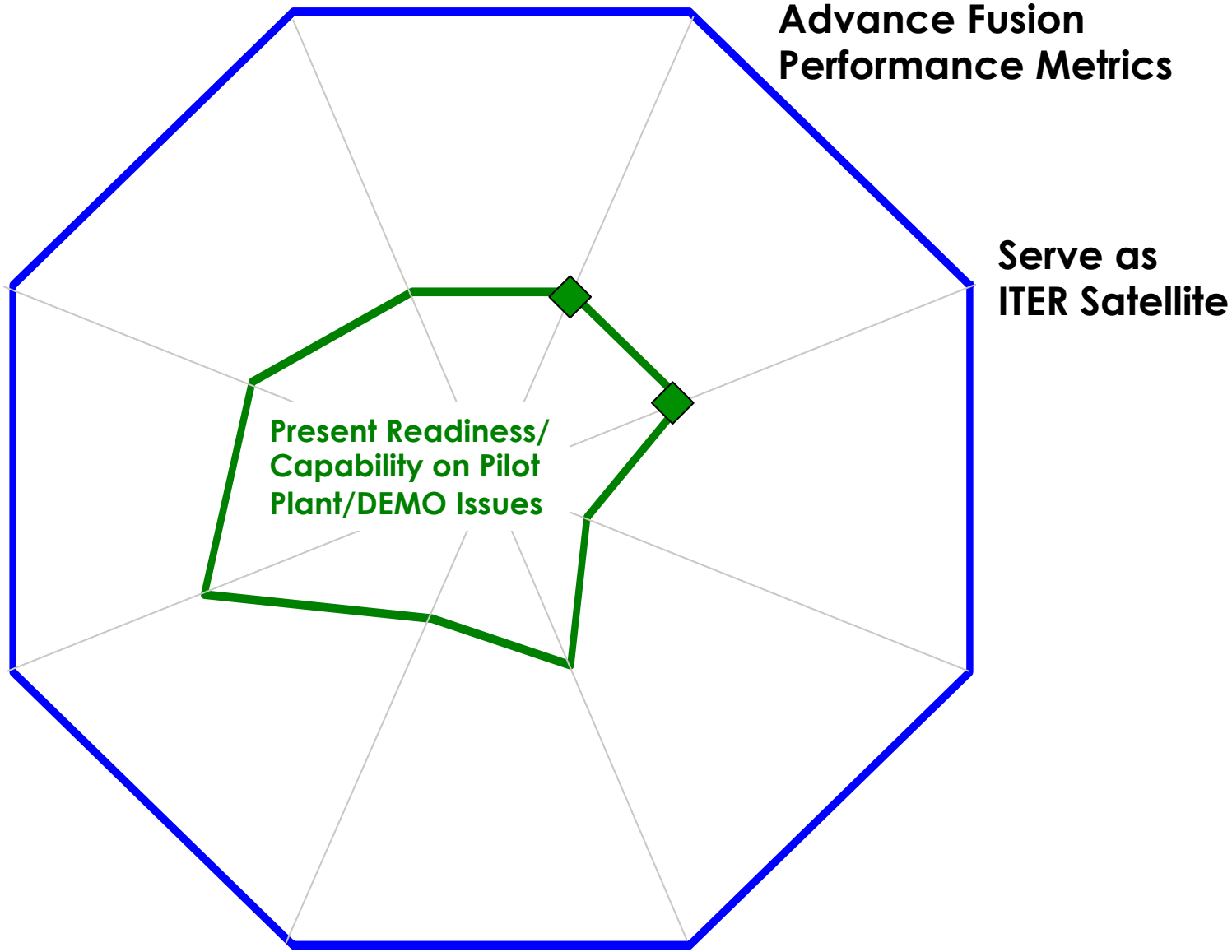

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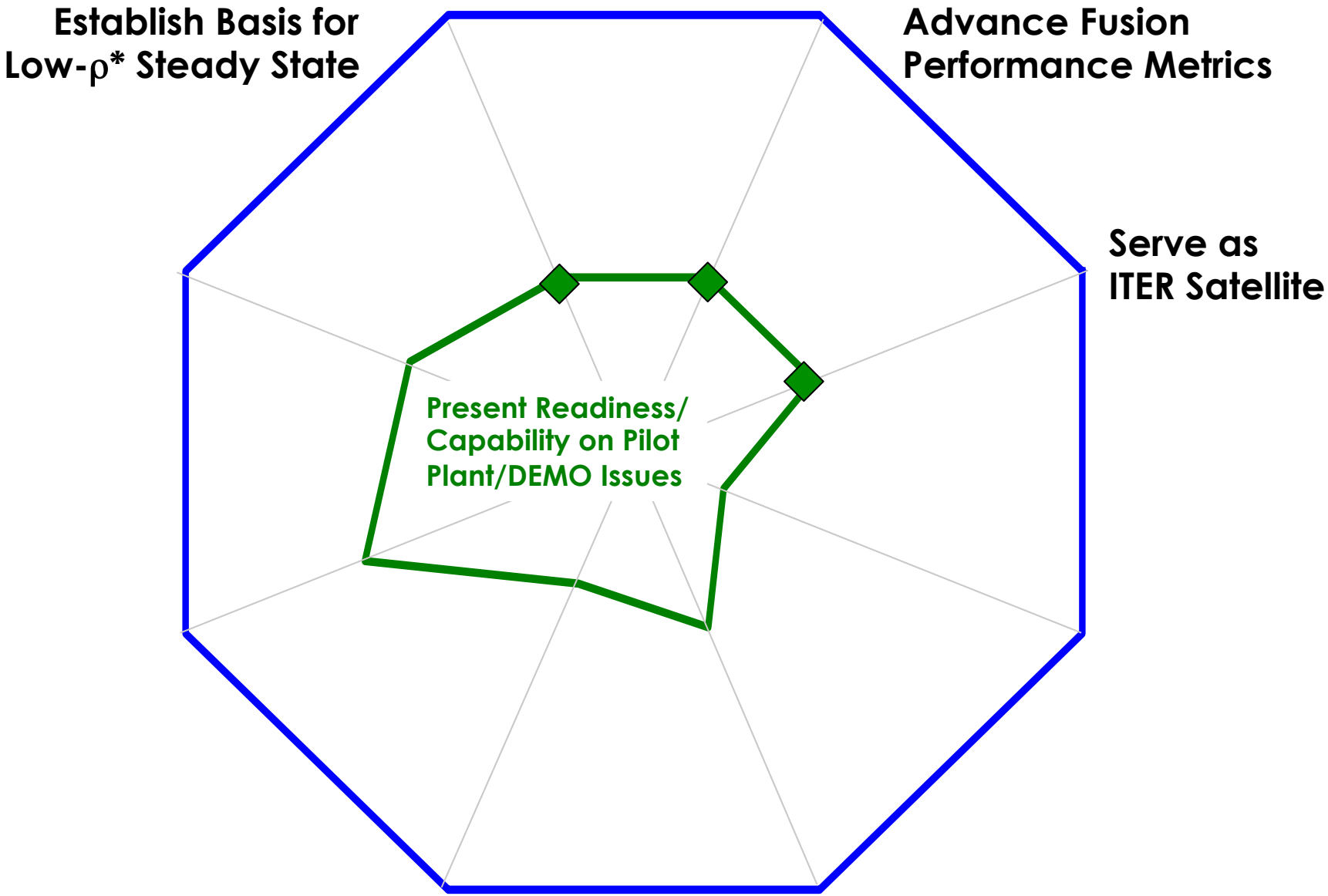

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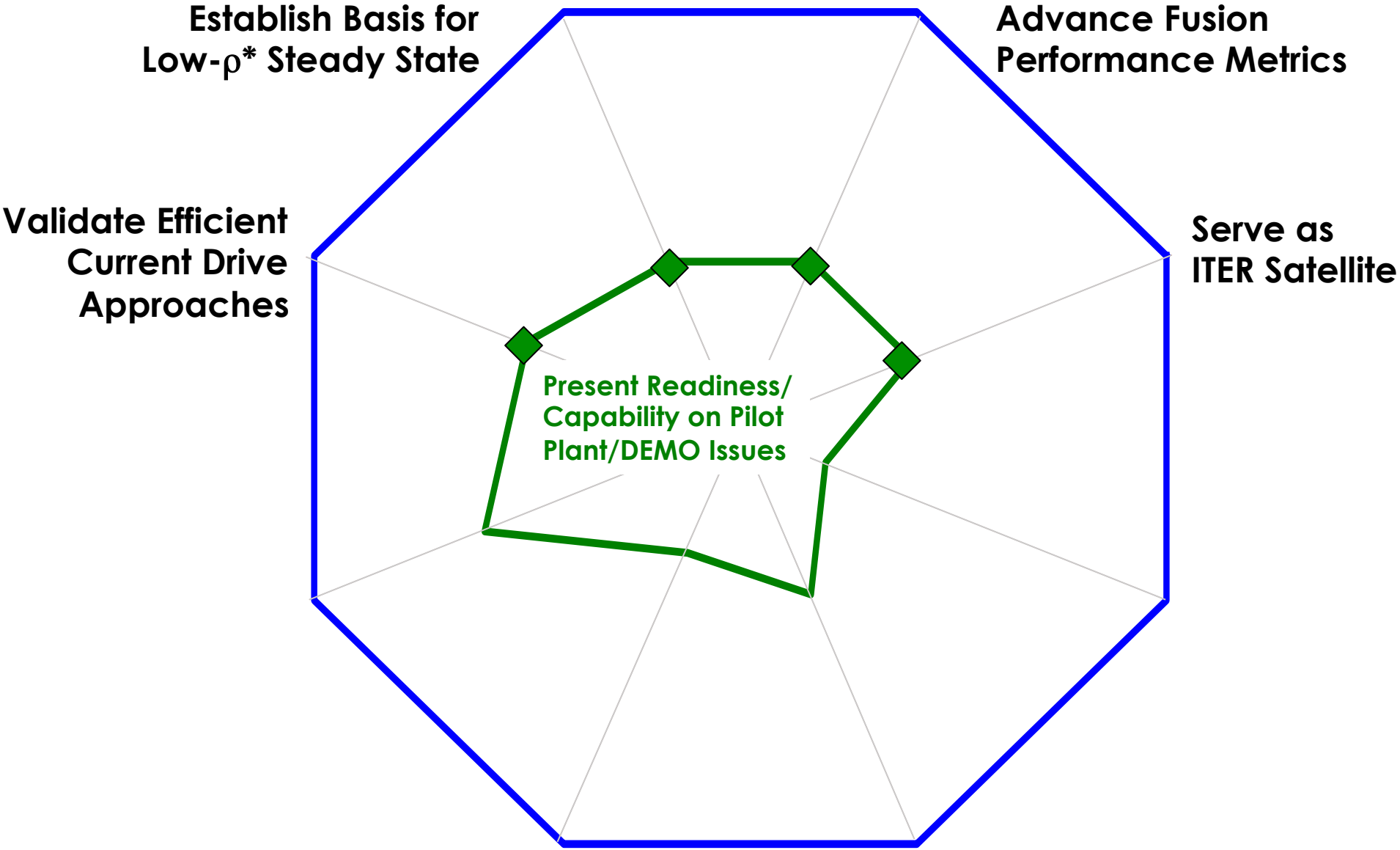

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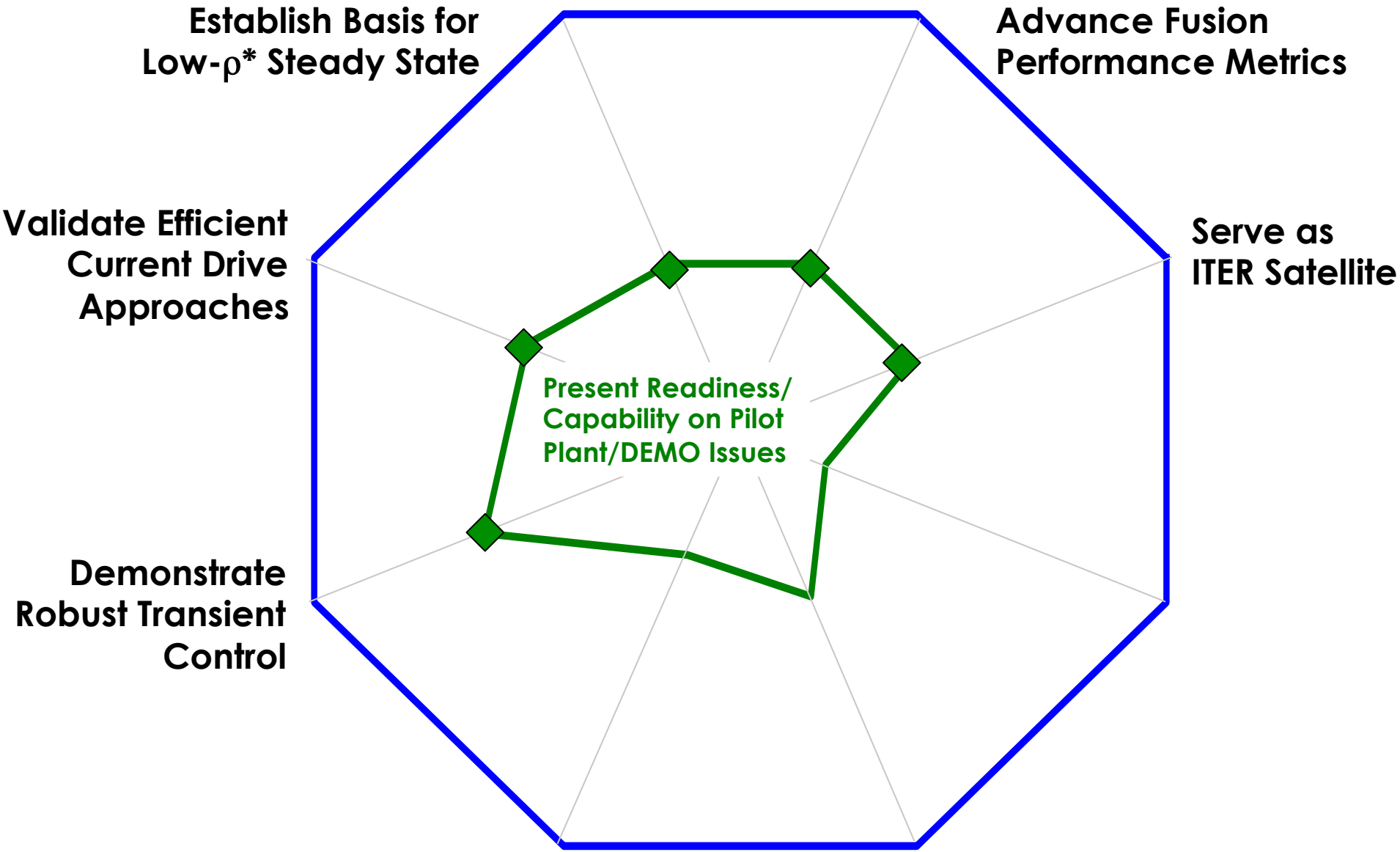

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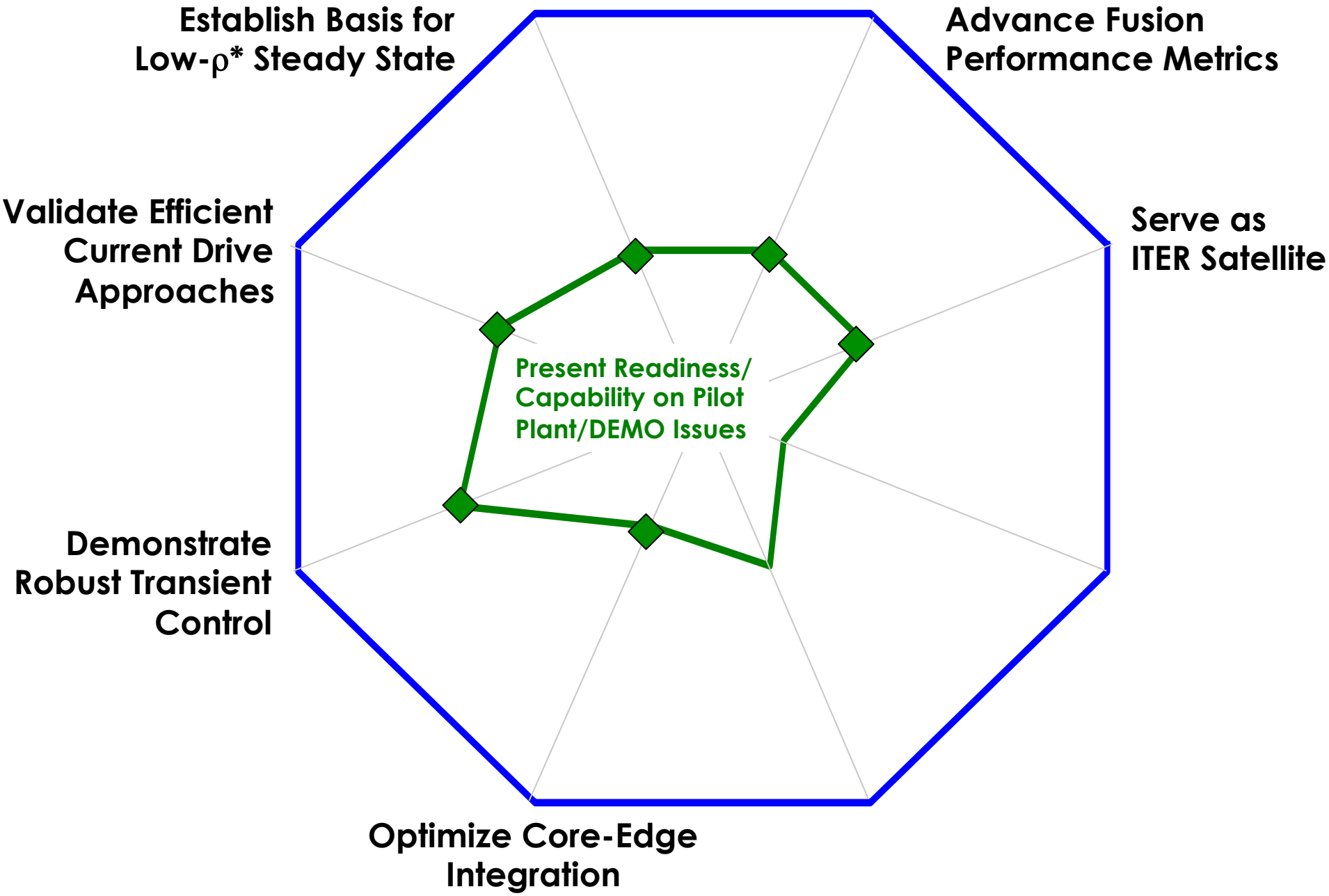

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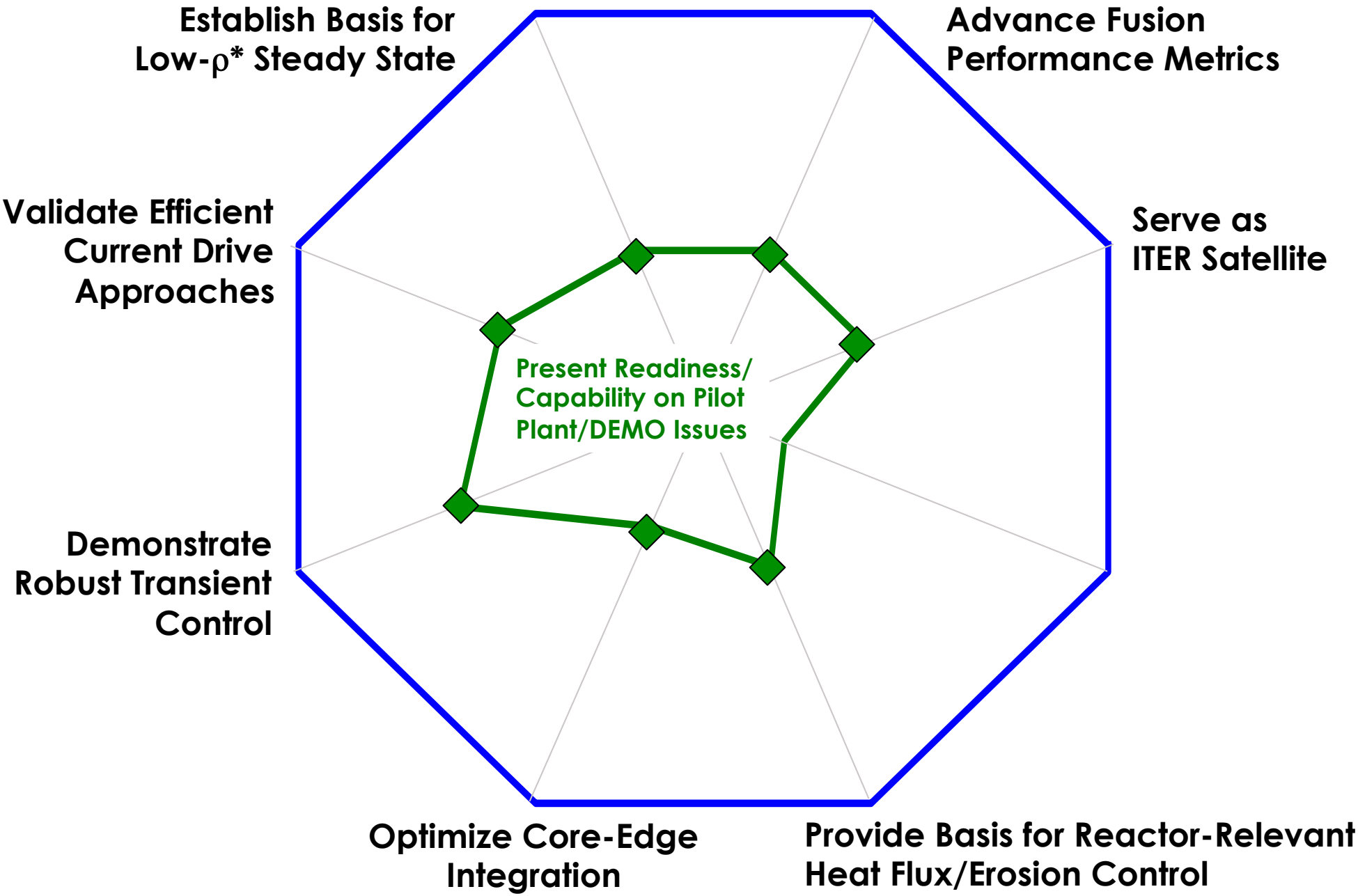

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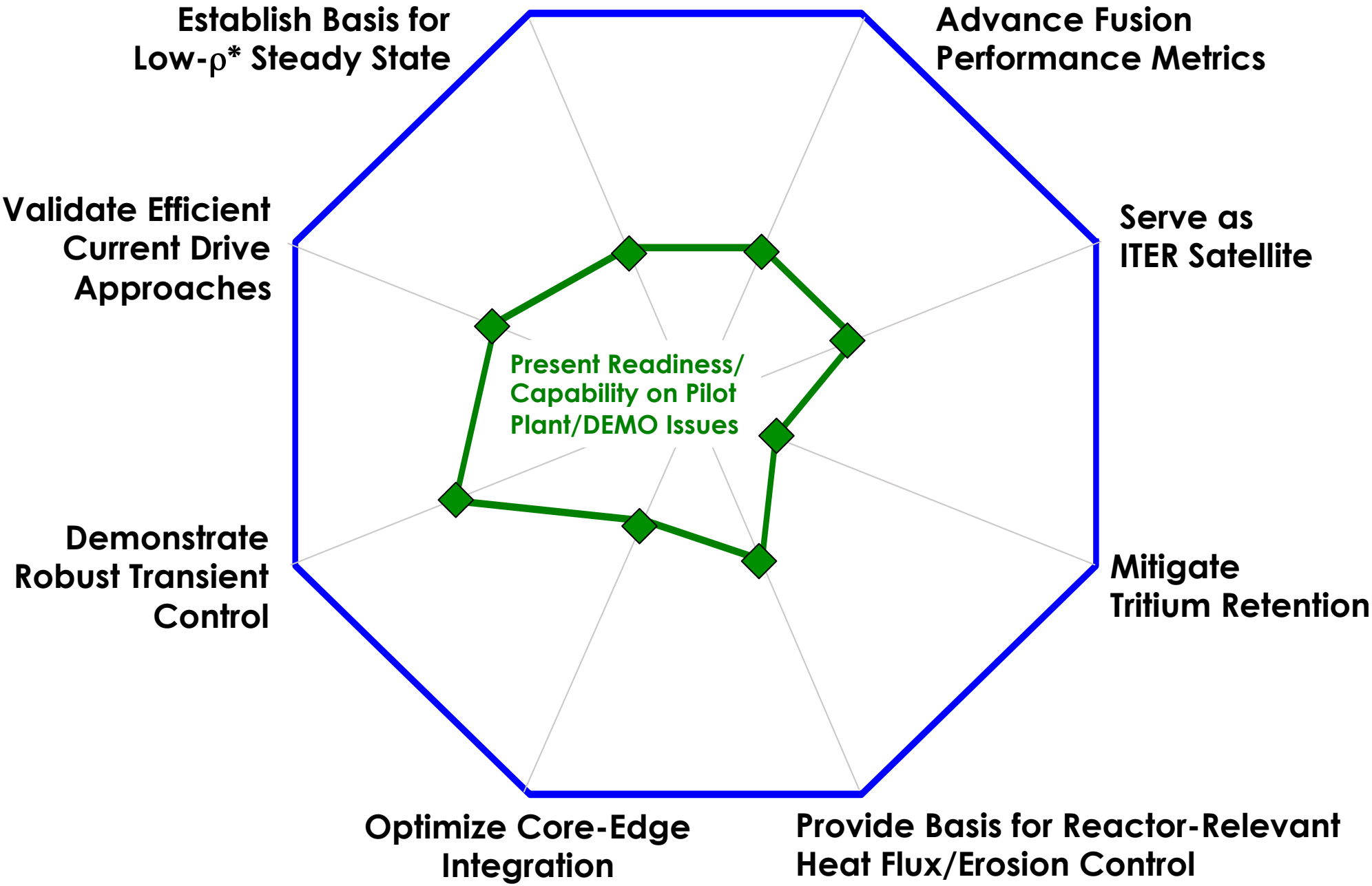
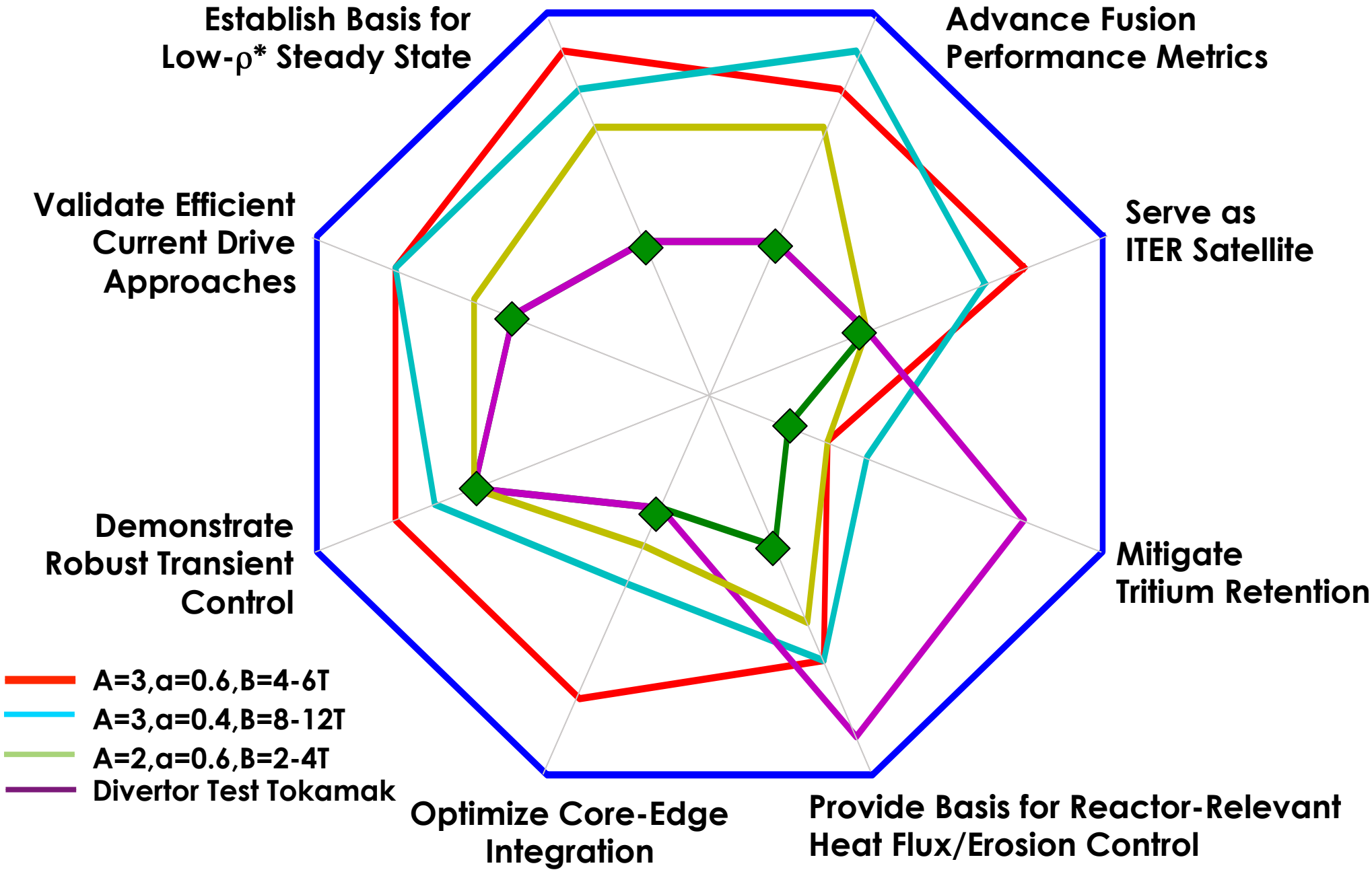


# Preliminary Assessment Suggests Largest Mission Breadth Provided by Modest Size, High Field Facility



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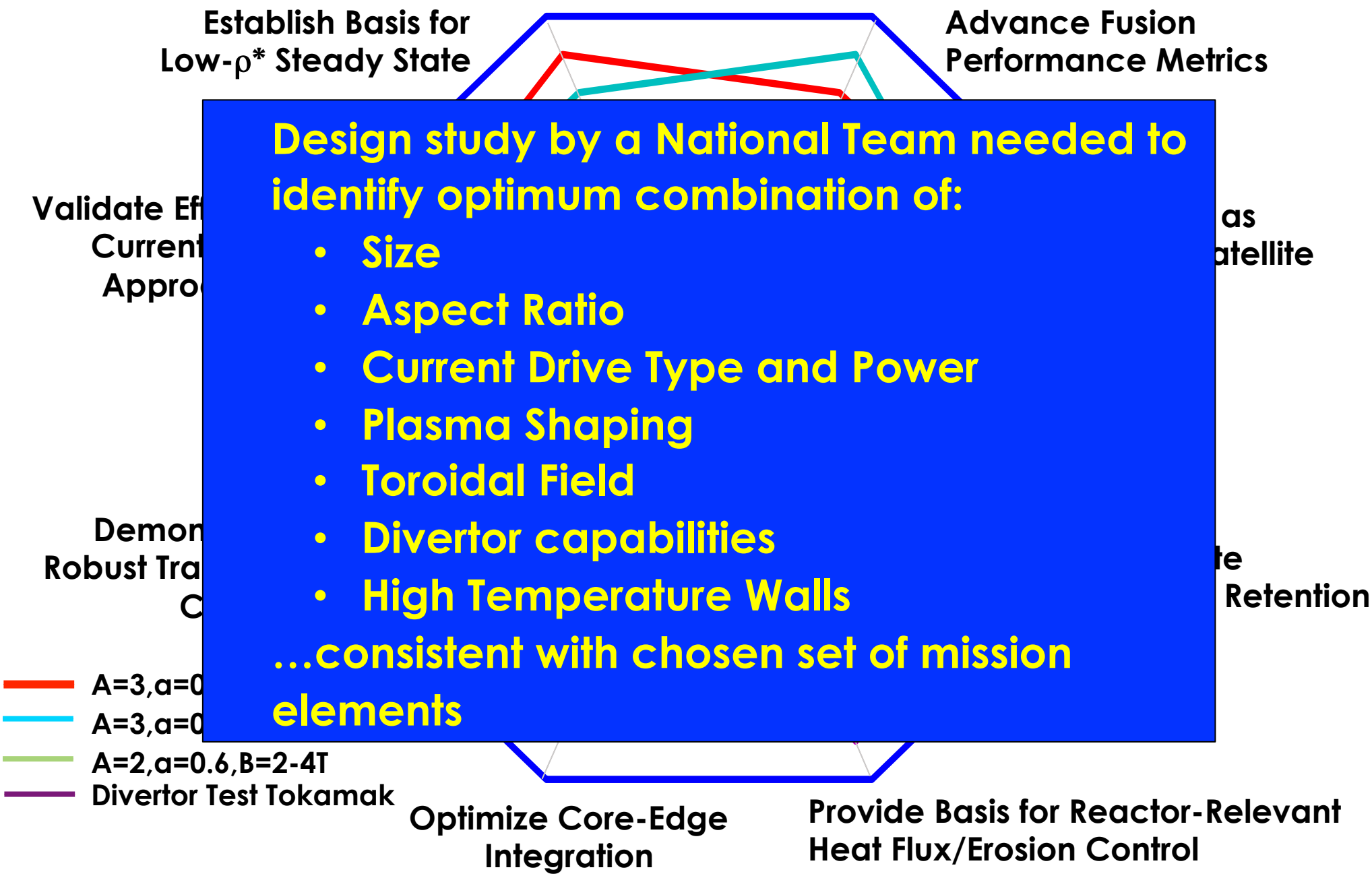



Design study by a National Team needed to identify optimum combination of:

- Size
- Aspect Ratio
- Current Drive Type and Power
- Plasma Shaping
- Toroidal Field
- Divertor capabilities
- High Temperature Walls

…consistent with chosen set of mission elements

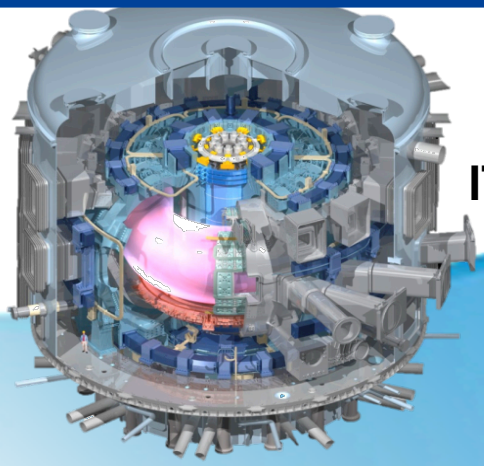
# Programmatic Priorities through the 2020s

- **Support ITER construction and ongoing physics basis**
  - Develop critically needed experience in building components/facilities
- **Develop and demonstrate HTS magnet technology**
  - As early as possible to enable design of new facility
- **Provide physics basis for projection of next-step device**
  - Targeted R&D on new facilities (MPEX) & upgrades (DIII-D, NSTX-U)
- **Design/construct/begin operation of new facility focused on key R&D efforts for enhancing cost-attractiveness of pilot plant/FNSF**
  - Likely require graceful transition from one or more of existing facilities
- **Begin fusion nuclear science program at modest scale; collaborate internationally on blanket technology**
  - Start developing the expertise needed for a US nuclear facility in 2040

# Overall Strategy is Straightforward and Timely… But Will Require a Few Bold Steps

**Develop Foundation for Tokamak Approach to Fusion**

**Secure Benefit of ITER Construction and Operation**



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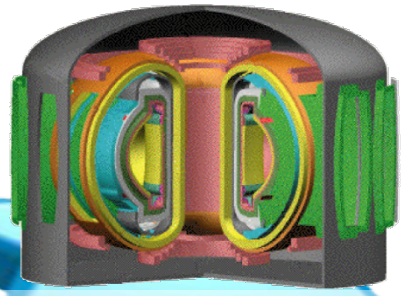

Cost-attractive Pilot Plant/DEMO/FNSF

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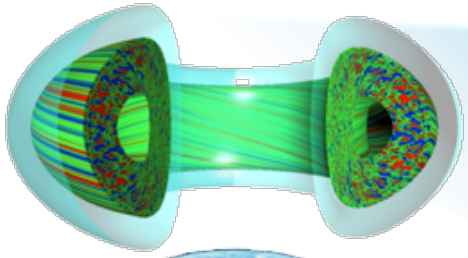
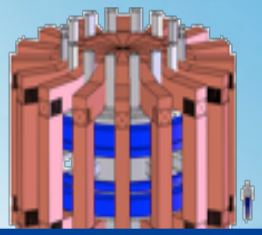



US strategy for new fusion facilities (materials, magnets, blankets)



CFETR (China)

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**Enhance Attractiveness of Pathway and/or End Product**

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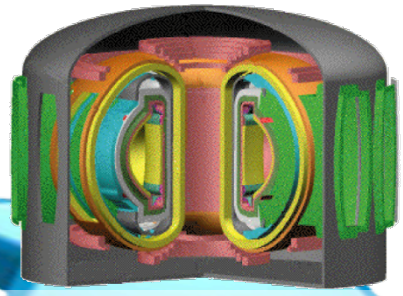
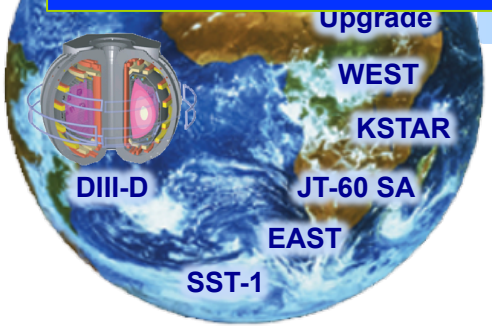


Cost-attractive Pilot Plant/DEMO/FNSF

History has conspired to bring us to this point of immense opportunity and grave threat.

History will judge us by how we respond…




(China)

efforts

Enhance Attractiveness of Pathway and/or End Product

# Extra Slides

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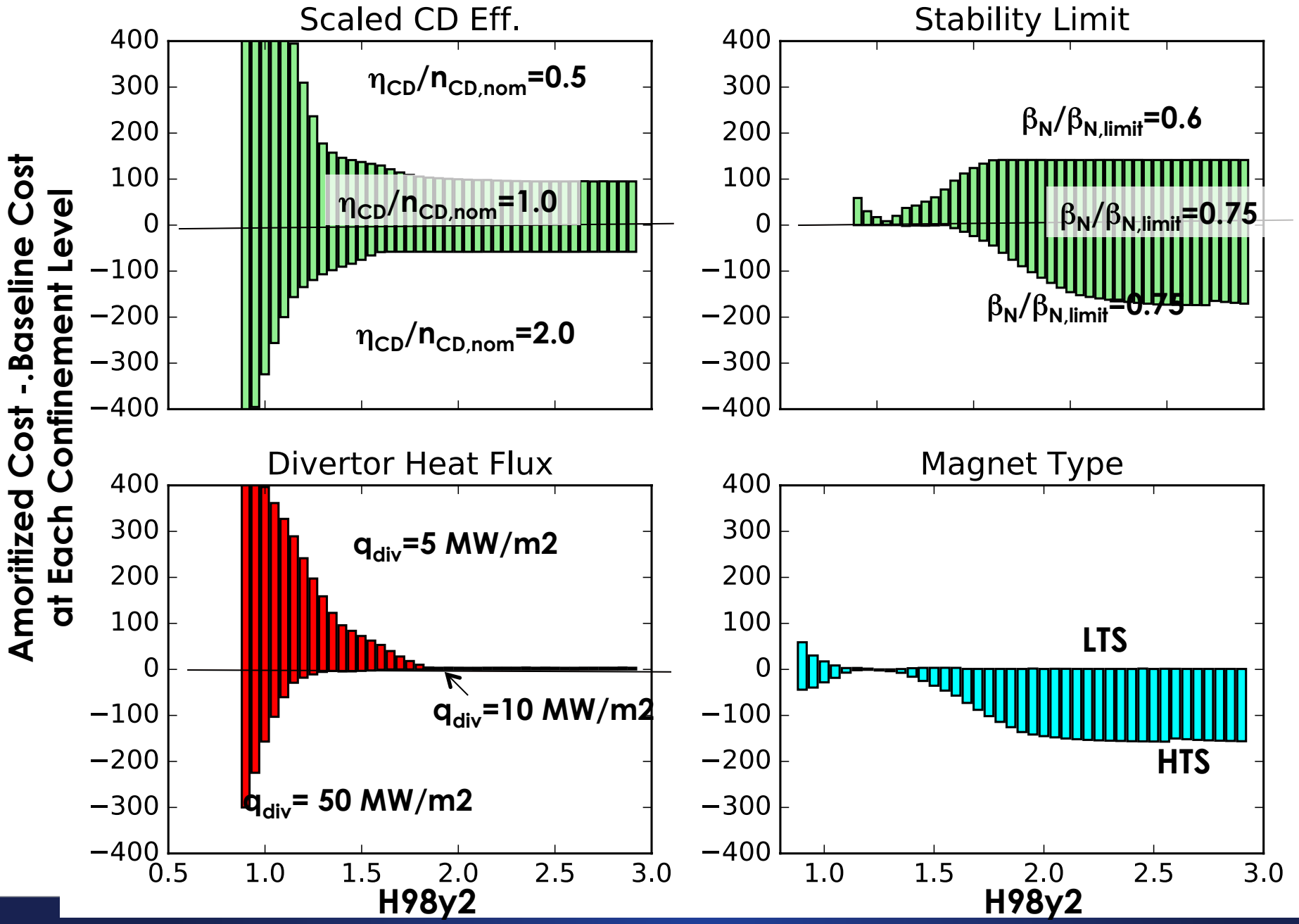
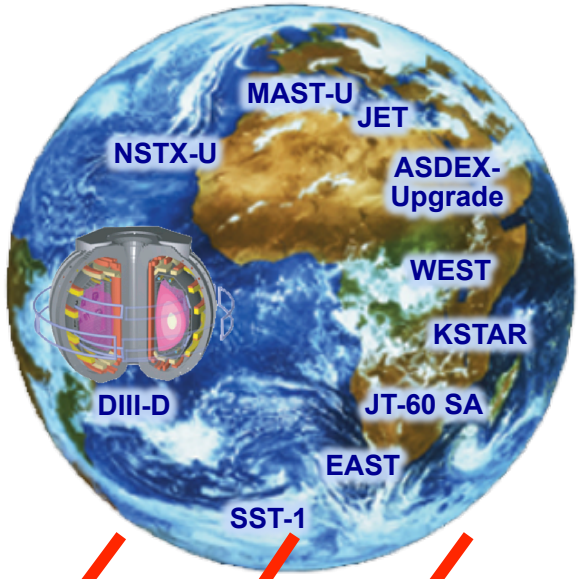
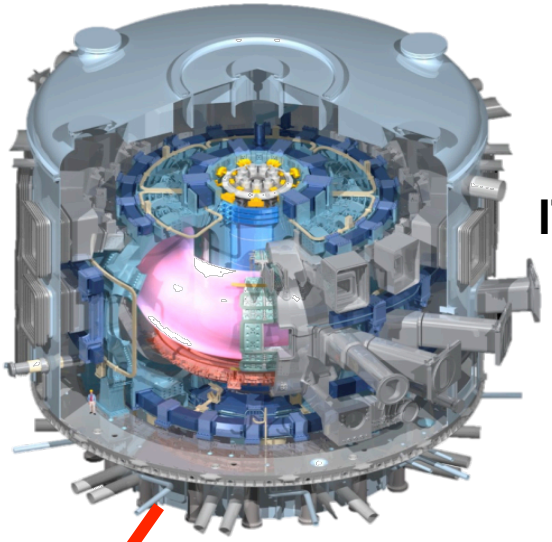


# Existing Programs Worldwide Will Drive Substantial Progress on Key Issues for Producing a Fusion Power Source




***Should provide solid basis for long-pulse burning plasma operation at modest confinement***

**Fusion Power Source (Neutrons)**

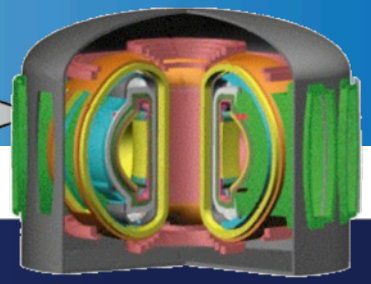
*Sustained High Confinement*

*Power Exhaust*

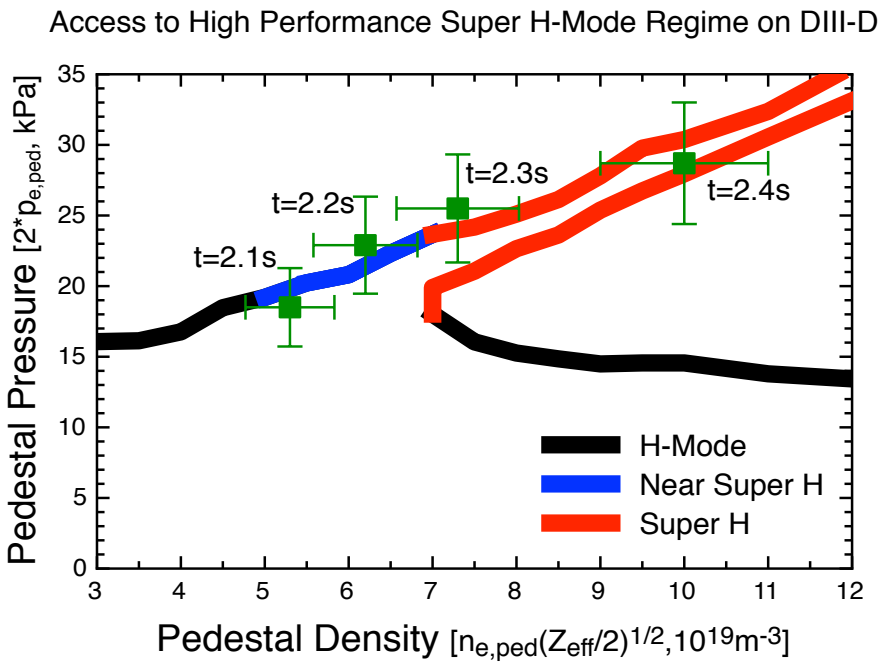
*Current Drive*

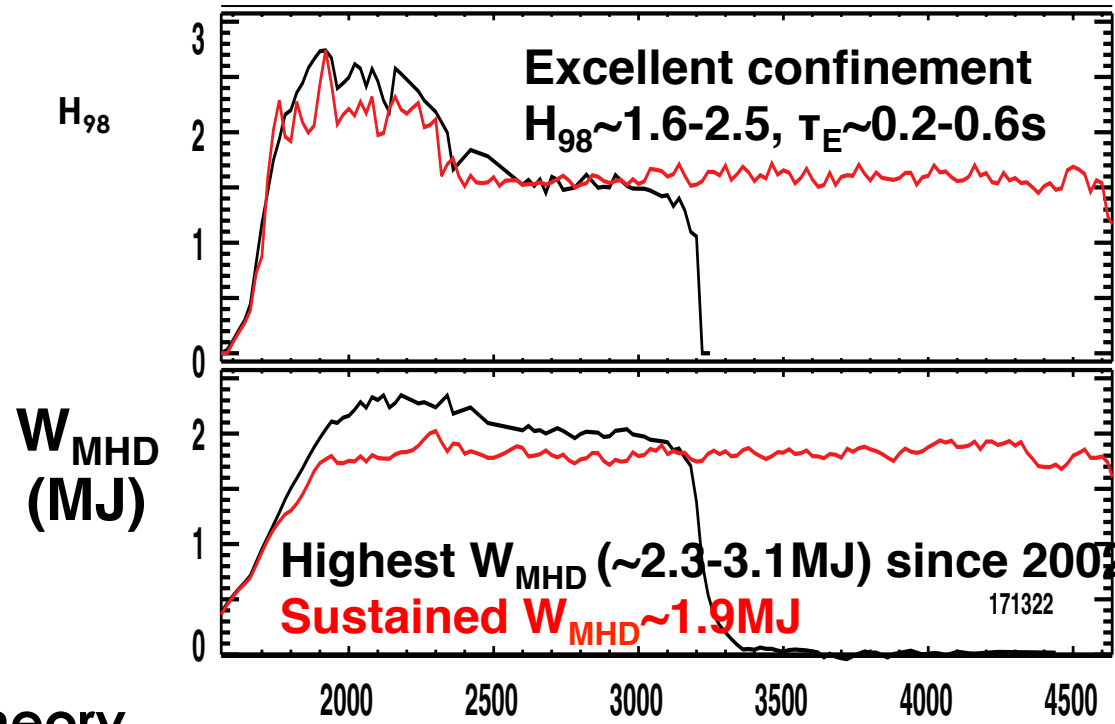
*Alpha Heating*

*Bootstrap Driven*

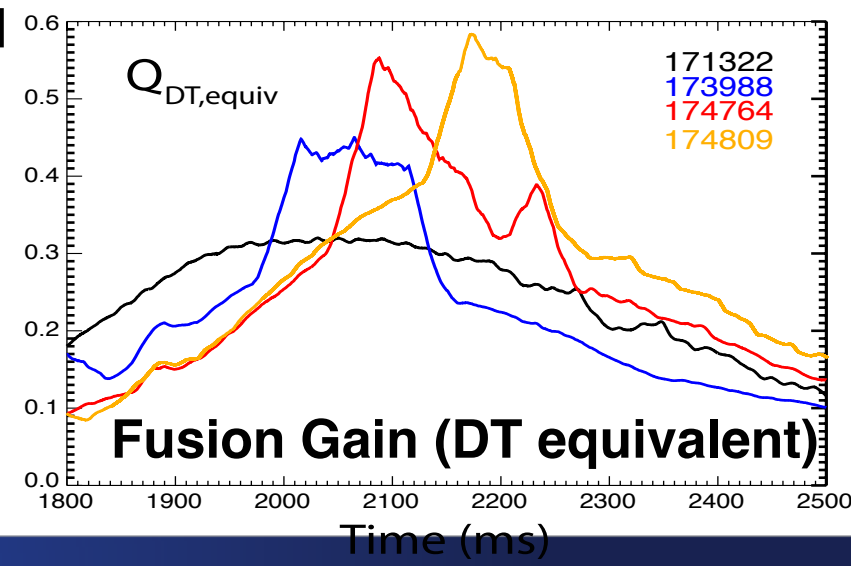


# Predictive Basis for Significant Enhancements in Performance Demonstrated and Now in Place to Optimize Future Devices



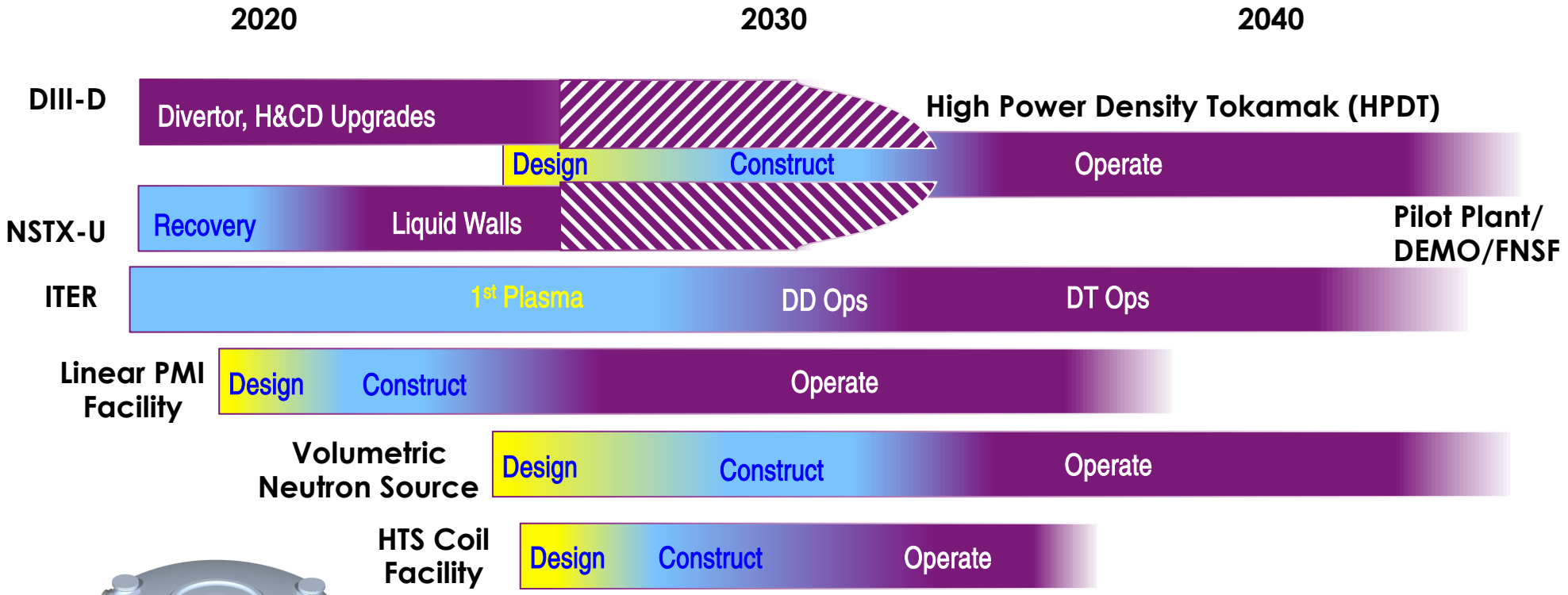

- Super H regime first predicted by theory (EPED), later discovered in DIII-D, then C-Mod
- Highest $Q_{DD}$ (or $Q_{DT\_equiv}$~0.5) on R<2m device. Record Q/IaB at high density




***While many open issues remain, can now optimize performance of existing and future machines with much greater confidence***

# Plan Presented to NAS Panel: Multiple Facility Transitions, Culminating with Three World-Class US Facilities

## Facilities Plan:

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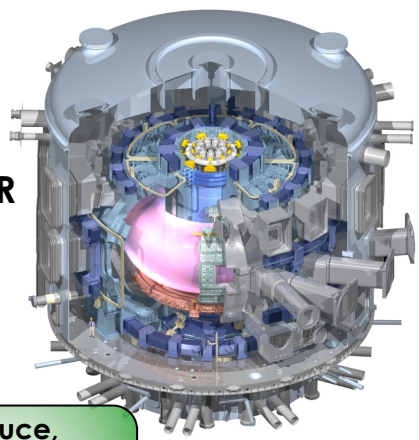
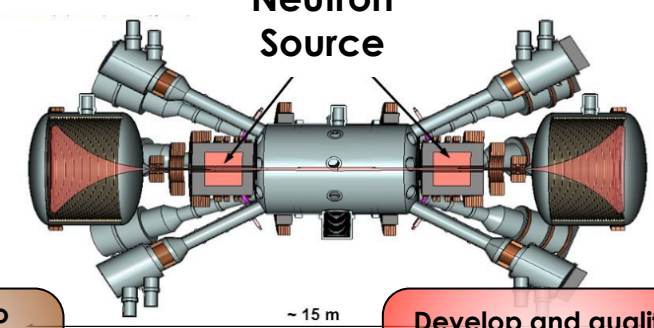


HPDT

Volumetric Neutron Source




Produce, Understand, and Exploit Burning Plasmas

Establish the feasibility of high power density, steady-state tokamak operation

Provide solutions to extreme power exhaust requirements in future fusion energy systems

Develop and qualify materials for high heat flux and 14-MeV neutron fluence