A Fusion Program Strategy for Timely Fusion Energy Deployment

By

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Presented to

NAS Committee for a Strategic Plan for U.S. Burning Plasma Research

February 26, 2018

*With input from C. Greenfield, H. Guo, D. Hill, J. Menard, C. Petty, W. Solomon, and T. Taylor and revised based on comments to accompanying white paper by P. Ferguson, R. Hawyrluk, D. Whyte, and M. Zarnstorff

General Comments

- **The strategic plan outlined here is my personal view on a potential path forward to <u>realize fusion energy in the next several decades</u>**
  - Takes onboard what I have learned from the community workshop but does not represent a community perspective

- **The plan is based on my assessment of the opportunities and attempts to focus resources on areas that would provide distinctive US leadership**
  - It's not comprehensive for what is required for fusion energy
  - It could be more aggressive

Key Points for this Panel

- **Because of its unique positioning in the world program, the US has an opportunity to take a distinctive pathway to fusion energy**
  - ➢ Distinct opportunities for US leadership
- **Technically, the US is well positioned to extend world leadership in key physics areas with continued investment:**
  - Burning plasma science
  - High performance tokamak operation
  - Theory & computation
- **Additional investment is required to establish world leadership in key technology areas going forward**
  - Materials
  - HTS magnets
- **Success in these individual areas can converge in ~ 2040 time scale for a leadership-class next-step device beyond ITER**
  - ➢ Cost-attractive pilot plant/DEMO/FNSF

Outline of Talk

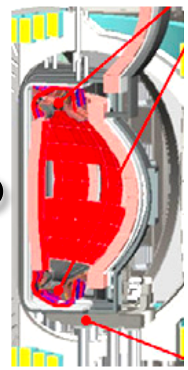
- **Introduction/Background**
- **Heart of the Plan**
- **Other Considerations of Plan**
  - Blanket R&D Plan
  - ‘Without ITER’ Plan
  - Secondary Pathways
  - Reduced Funding Implications

World is Moving Aggressively Forward with Fusion Energy

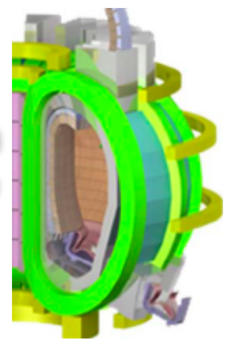
- **To date, worldwide fusion energy R&D has had the common goal of demonstrating the feasibility of fusion energy**
  - ITER project embodies, at a grand scale, this partnership
- **World program is considering major facilities beyond ITER that are based on *existing or high-confidence approaches***

EU DEMO

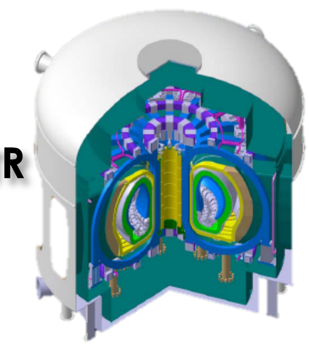
K-DEMO



Japan DEMO



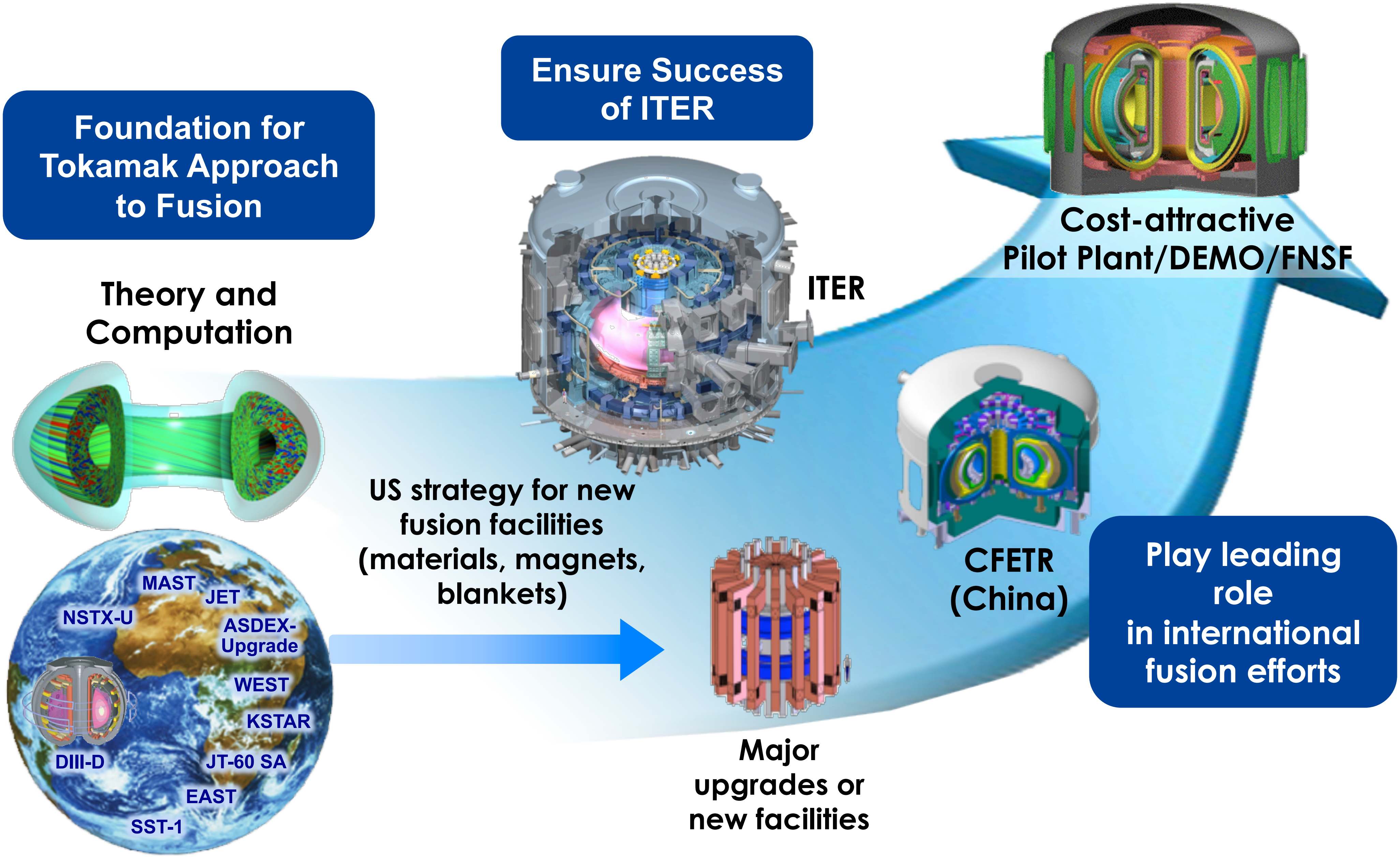
CFETR



- **Looking beyond ITER, nations are likely to view fusion energy R&D quite differently due to unique strategic needs for energy supply**

U.S. program has an opportunity to take a distinctive approach that significantly improves the cost-attractiveness of both the pathway to fusion energy AND the end product

Envisioned Strategy Leverages U.S. Scientific Excellence to Deliver Timely Fusion Energy



Underlying Features of the Strategy

- **This plan develops the U.S. pathway through the tokamak line**
  - Performance metrics and maturity level of physics basis exceed all other lines
  - Enables leverage of significant investment worldwide in tokamaks
  - Requisite time scale demands urgency → next several decades
- **A strong theory, modeling, and computation program is foundational to the plan**
  - Exascale and high-capacity computing are key enabling capabilities
- **Plan assumes U.S. remains a participant in ITER**
- **Required funding was not a significant consideration**

Key Objectives of the Plan

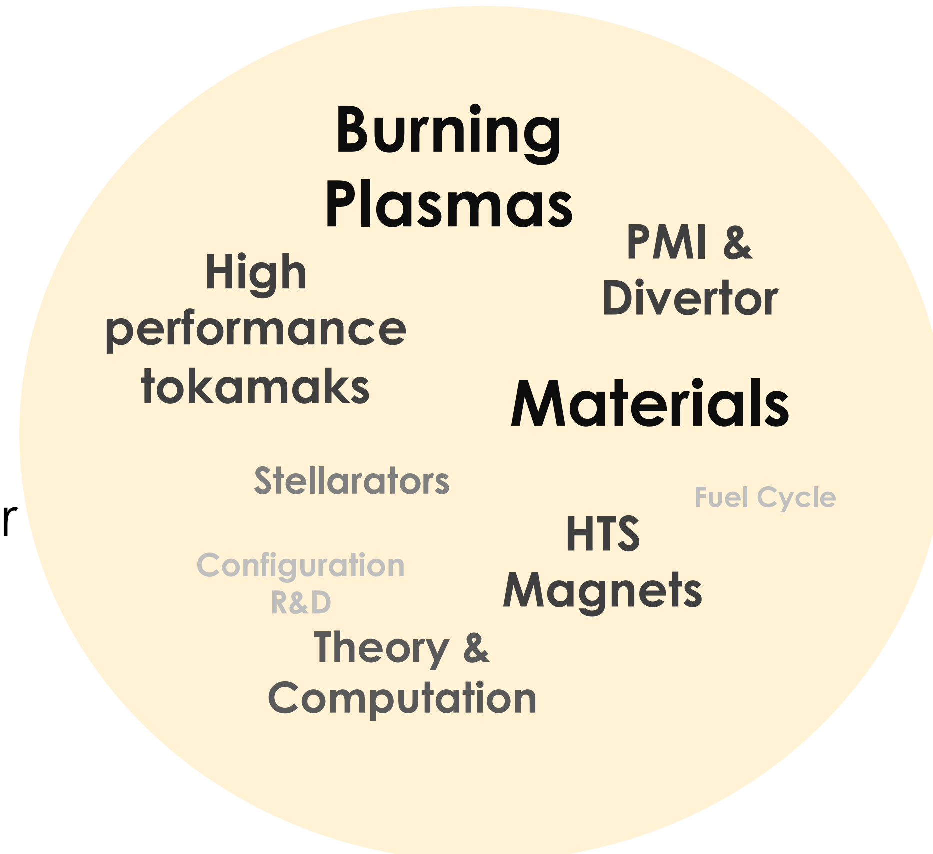
- **Establish U.S. leadership in critical physics and technological areas**
  - ➢ Strategically position the U.S. with critical expertise that will be needed by other nations in their pursuit of fusion energy
- **Deliver world-class research platforms in a timely manner**
  - ➢ Enable excellent science leading to key knowledge & breakthroughs
- **Utilize the most cost-attractive approaches to establish this leadership**
  - ➢ Wisely invest available resources to enable broader set of pursuits
- **Broaden the constituency base to enable strengthened technical and political support**
  - ➢ Promote pathways that broaden the required scientific disciplines and institutional engagement
- **Provide compelling 2040 goal for program direction and resourcing**
  - ➢ Identify the destination to clarify technical objectives

Strategic Plan Includes Community-Identified Elements but Relative Emphasis Varies Significantly

Strategic Elements from recent USMFRSD Community Workshops:

- Burning plasma science
- HTS magnets for fusion applications
- Configuration research
- Stellarators
- Theory/computation
- Plasma-material interactions & divertor
- Fusion nuclear materials
- Tritium fuel cycle
- Sustained high performance

Relative Emphasis* in this Plan



*Relative emphasis denoted by size of label

Timing of Transitions Must Balance Desire for Change and Time Scale Required to Implement Effective Change

- **Strong desire in the community for a strategic plan that disrupts the status quo**
  - Sooner rather than later

- **Impactful, lasting change requires deliberate thought and planning**
  - Small changes in direction (small rudder changes) will produce large change in target/goal

- **This strategic plan attempts to address this tension by calling for definitive changes in program makeup but over a time scale in which the implementation can realistically (and non-disruptively) be done**

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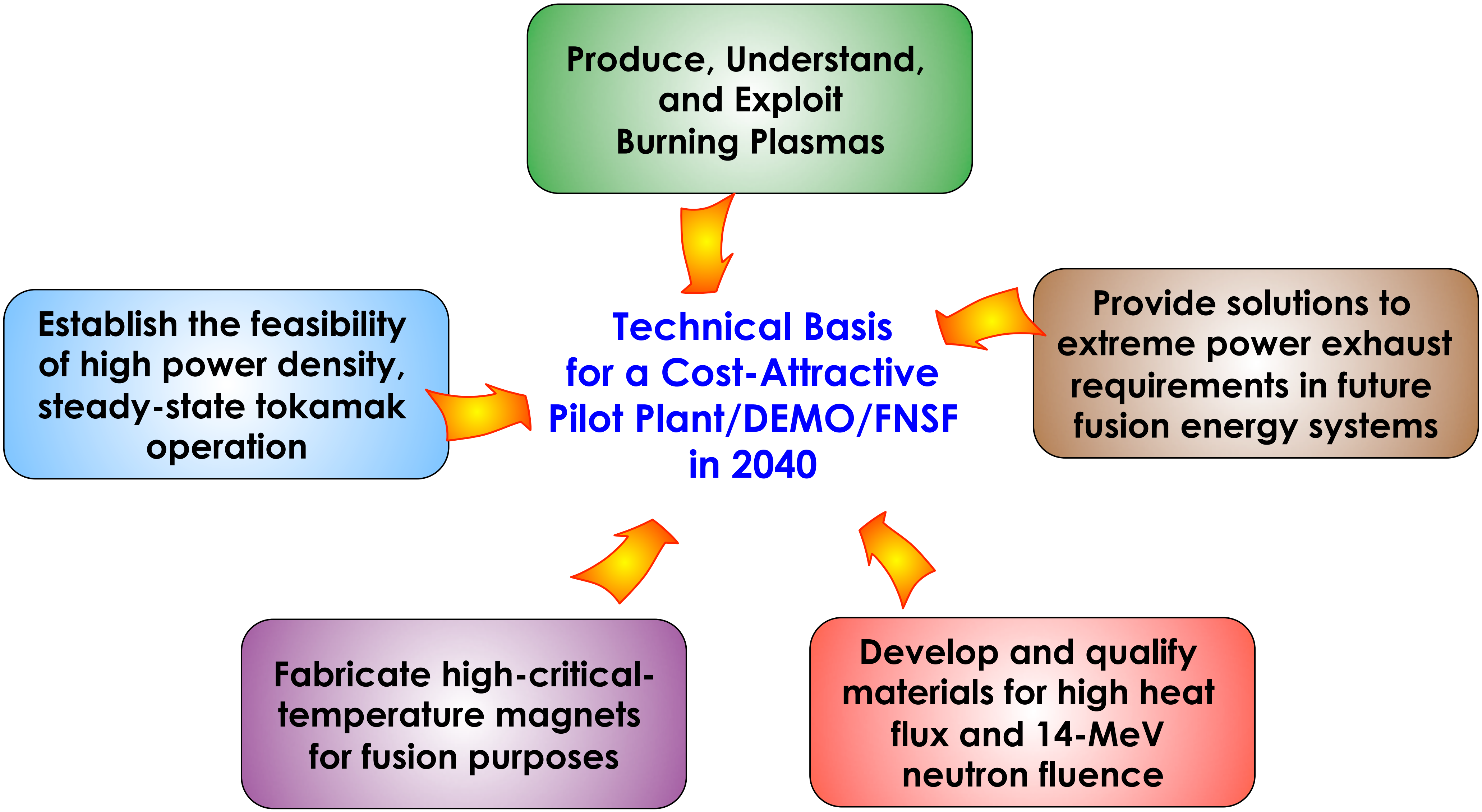
Overall Objective of Strategic Plan is to Converge R&D Elements in ~ 2040 for Design of Cost-Attractive Next Step



Overall Objective of Strategic Plan is to Converge R&D Elements in ~ 2040 for Design of Cost-Attractive Next Step

Produce, Understand, and Exploit

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- **Plan will likely require significantly increased funding**
- **Tough choices will be required if these funding levels fall short of these requirements**
- **Choices depend on expected funding and assumption on what is the most important deliverable (e.g., first to fusion, leadership in specific areas, …)**
  - ➢ Possibilities outlined at end of talk

temperature magnets for fusion purposes

flux and 14-MeV neutron fluence

Access and Understanding of Burning Plasmas is Foundational to Fusion Energy R&D – US Leads in This Effort

Produce, Understand, and Exploit Burning Plasmas

Importance:

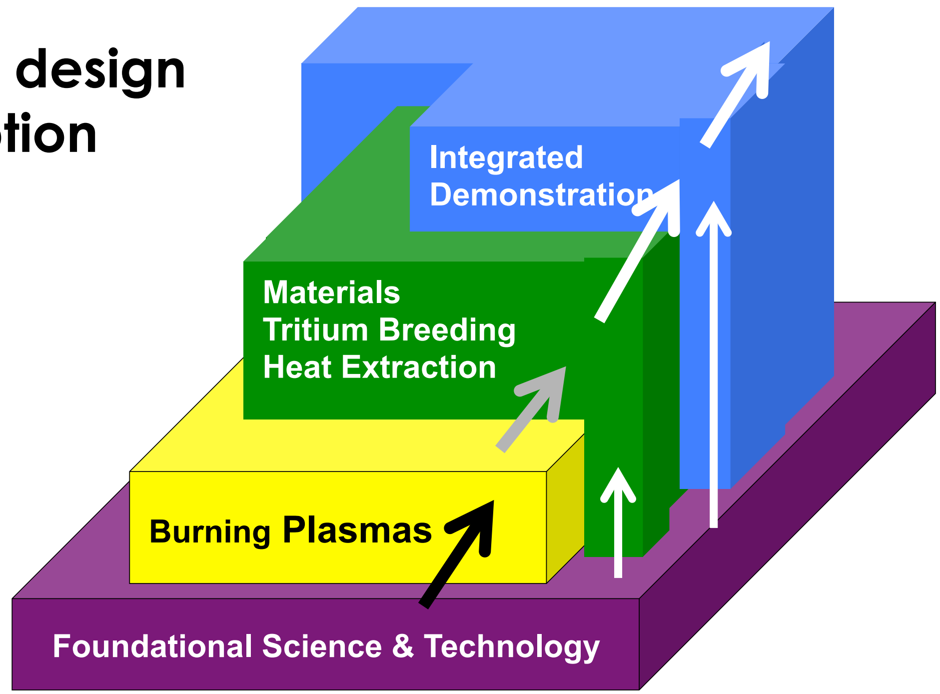
- Fundamental building block of entire plan → Motivates and enables all other areas

U.S status:

- Key contributor to physics basis for ITER design and operation (ELM suppression, disruption mitigation, scenarios,…)
- DIII-D well positioned for future impact

International context:

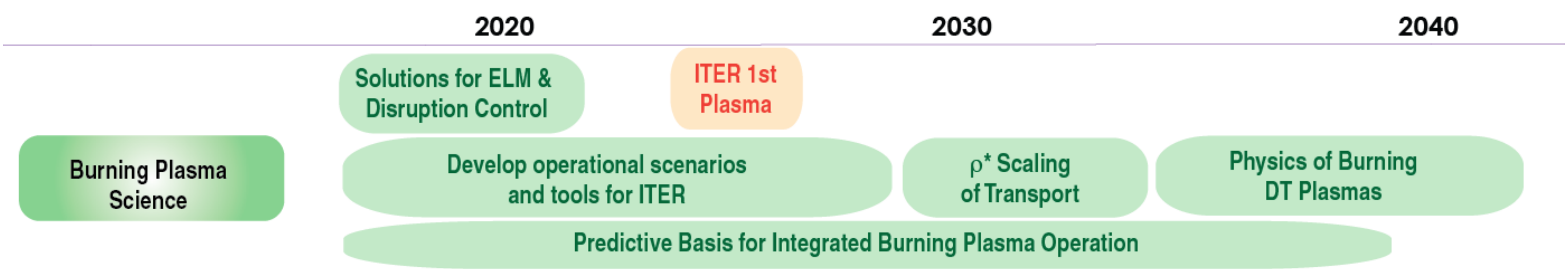
- All ITER partners have programs that support burning plasma science
- 100% of ITER R&D output will be available to the U.S. (if we remain a partner)



Burning Plasma R&D Focused on Demonstrating ITER Q=10 Operation and Exploiting ITER for Future Aspirations

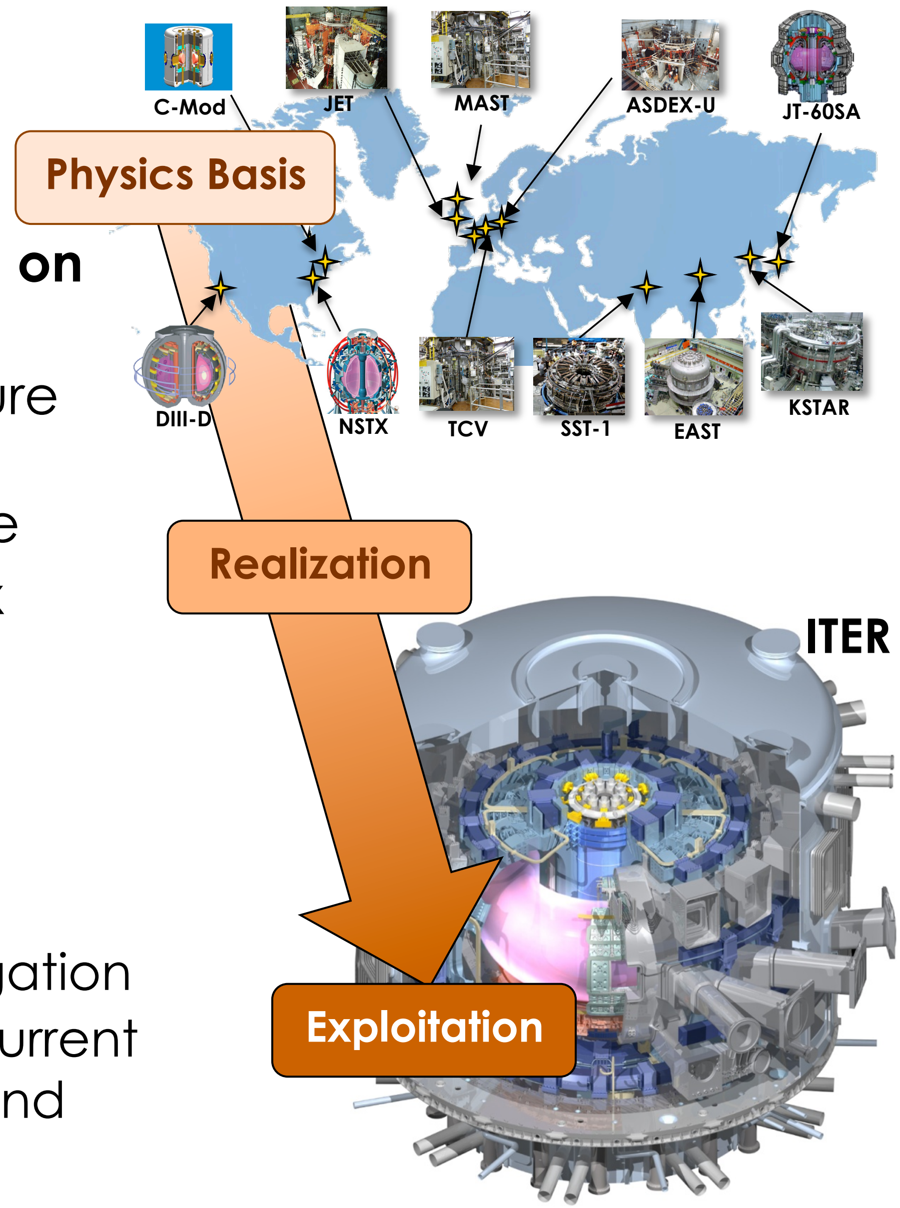
Key Elements of R&D Plan:

- **Establish credibility for cost-attractive Pilot plant/DEMO/FNSF**
  - ITER achieves it technical mission (Q=10, 500 MW for 400 s)
  - Robust solutions for disruption and ELM control
  - Predictive understanding of the physics of burning plasmas
- **Inform design of Pilot plant/DEMO/FNSF**
  - Identification/qualification of burning plasma operational scenarios that offer best integrated performance
  - ρ^* (size) scaling of transport



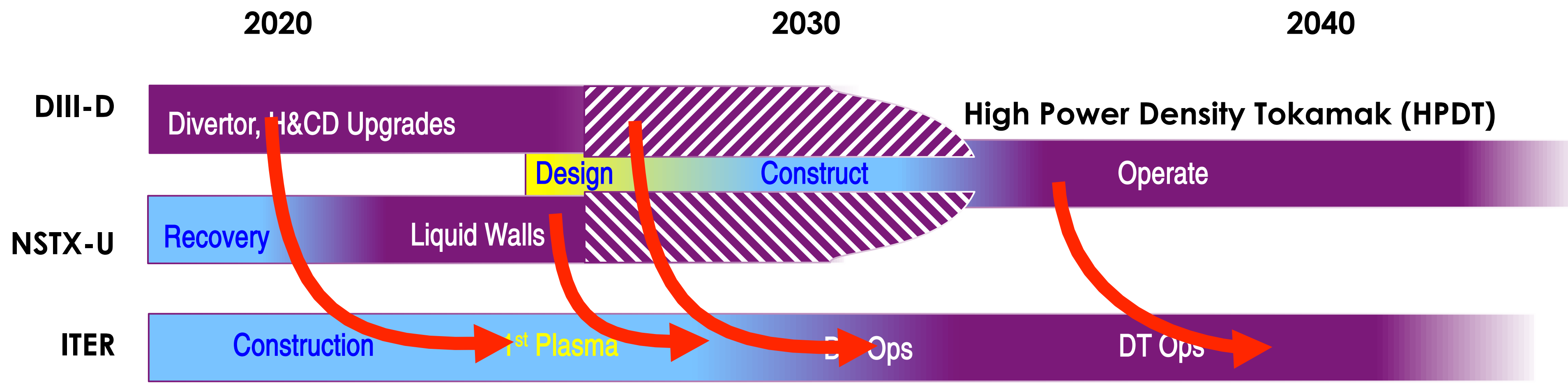
ITER is the Center Piece of Burning Plasma Science R&D, Both Motivating and Enabling Cutting Edge Research

- **ITER capabilities are far beyond anything the US could do on its own**
  - 500 MW for 400 s
- **ITER participation motivates vigorous R&D on key challenges for fusion**
  - Achieve necessary density/ temperature confinement (n T τ)
  - Operate safely at high plasma pressure
  - Handle concomitant heat/particle flux
  - Minimize/Eliminate effect of transients
- **… and will enable new opportunities**
  - Alpha-particle physics
  - Transport and MHD at low ρ*
  - Fusion burn stability, control, and propagation
  - Strong, non-linear coupling of heating, current drive, turbulent transport, MHD stability and boundary plasma



U.S. Domestic Facilities Are Essential to Prepare for ITER Operation and Subsequent Exploitation

Facilities Plan:



- **Preparation for ITER**
  - Improved physics basis for robust solutions for disruption/ELM control
  - Improved ITER scenarios (Q = 10 at lower I_p)
  - Better predictive understanding
- **Exploitation of ITER**
  - Explore means for very high gain operation in ITER
  - Detailed investigations of physics phenomena observed in ITER but require enhanced diagnostic capabilities

Targeting High Power Density, Steady-State Systems is a Hallmark of US Program and Should Remain a Key Strength

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

Importance:

- Cost attractiveness of future fusion systems improved by power density and steady-state capability

U.S status:

- World leader in developing physics basis of high-performance, steady-state
- No long-pulse capability

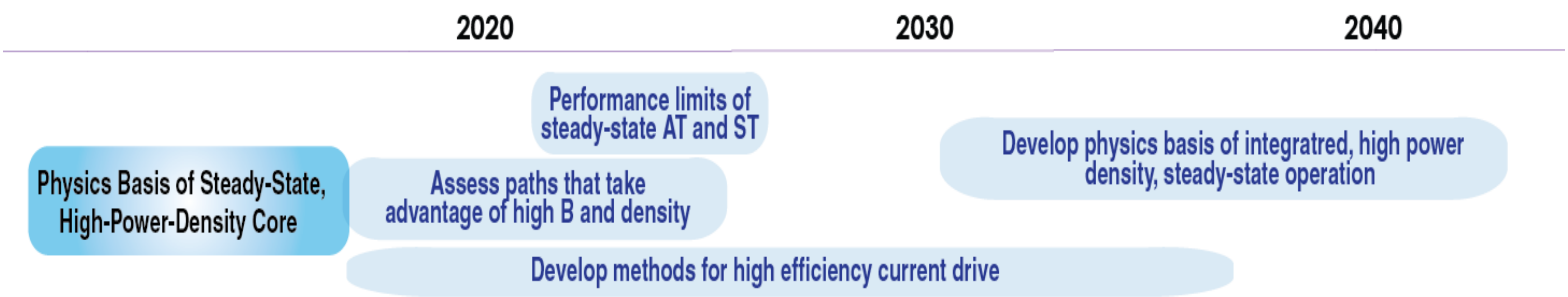
International context:

- New superconducting devices (EAST, KSTAR, JT-60SA) have advantage in extending to true steady-state
- Planned DIII-D/NSTX-U upgrades will maintain U.S. leadership in advancing performance envelope and establishing physics basis

R&D Plan Focused on Demonstrating and Providing the Physics Basis for Design of Future Steady-State Devices

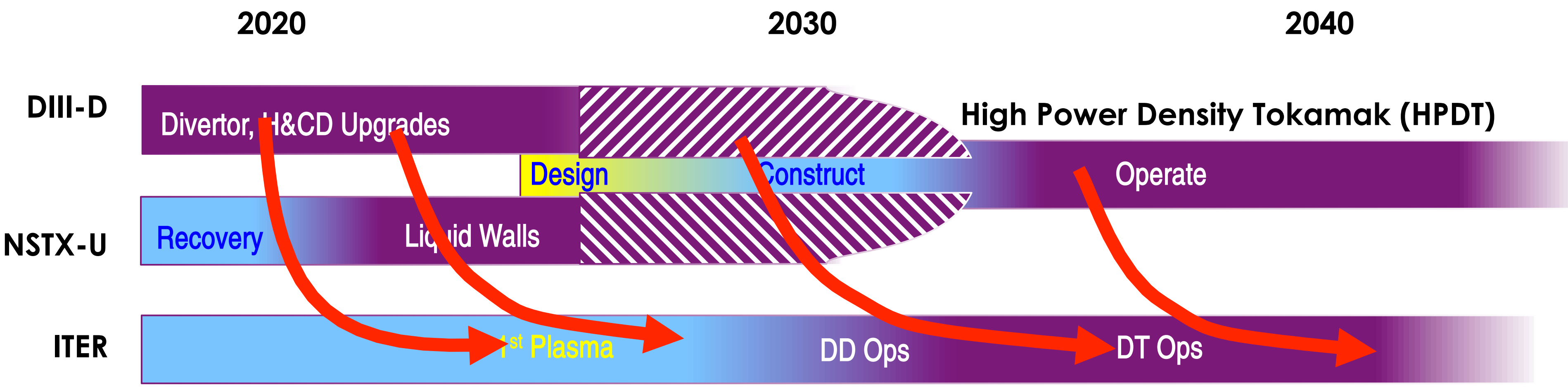
Key Elements of R&D Plan:

- **Establish credibility for cost-attractive Pilot plant/DEMO/FNSF**
  - Demonstrated capability of fully non-inductive, high β operation
  - Physics/technology basis for high efficiency current drive tools
- **Inform design of Pilot plant/DEMO/FNSF**
  - Quantification of performance limits for AT and ST along with optimal current profile to achieve those limits
  - Impact of high toroidal field and density on confinement, current drive, and core-edge integration



DIII-D/NSTX-U/HPDT/ITER Provide a Powerful Combination for Developing Basis for High Power Density, Steady-State

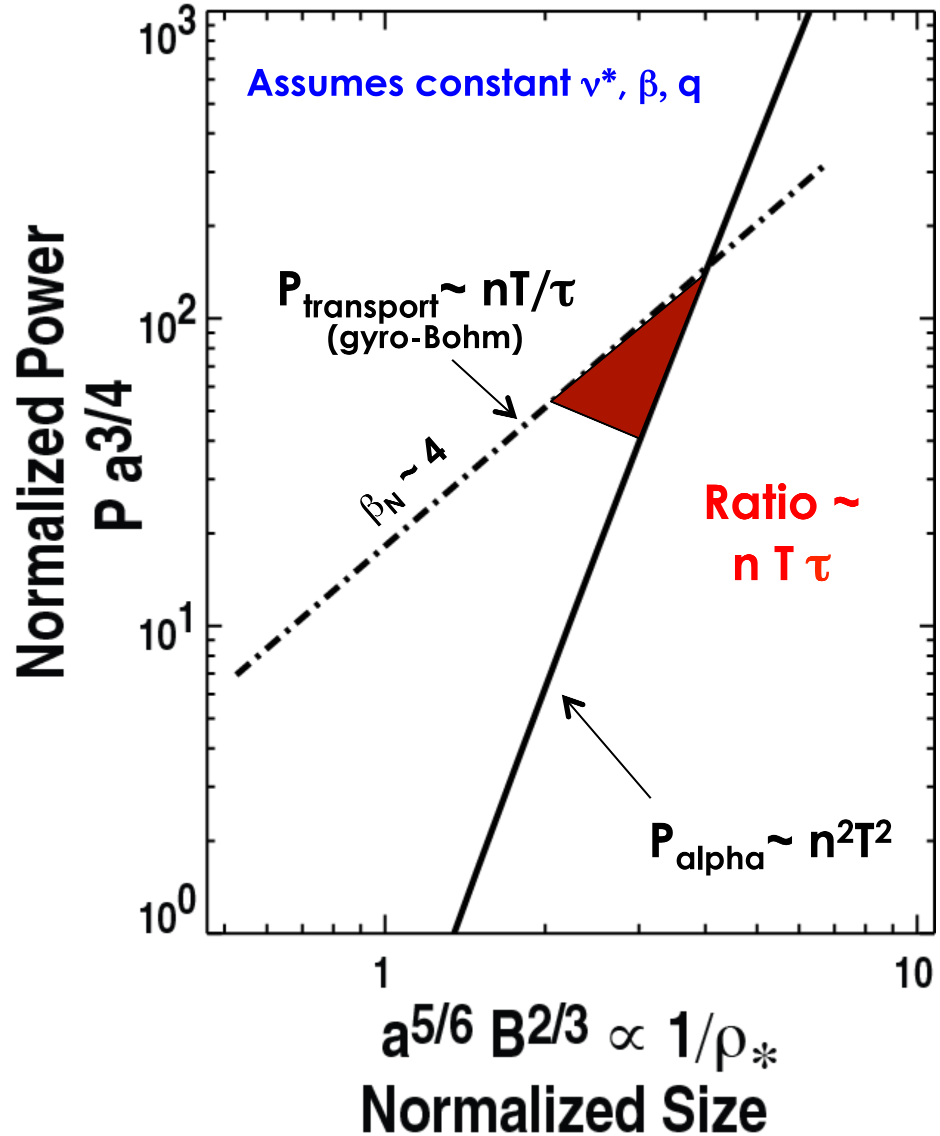
Facilities Plan:



- **Establish physics basis for high power density, steady-state**
  - DIII-D/NSTX-U upgrades will provide access to steady-state regimes
  - HPDT enables exploration of unique operating space (see next slide)
- **Inform next steps**
  - DIII-D/NSTX-U current profile sustainment → ITER H&CD upgrades for Q=5
  - DIII-D/NSTX-U performance limits → HPDT design (R/a, size, CD tools)
  - HPDT/ITER steady-state regimes → Pilot plant/DEMO/FNSF physics basis and design

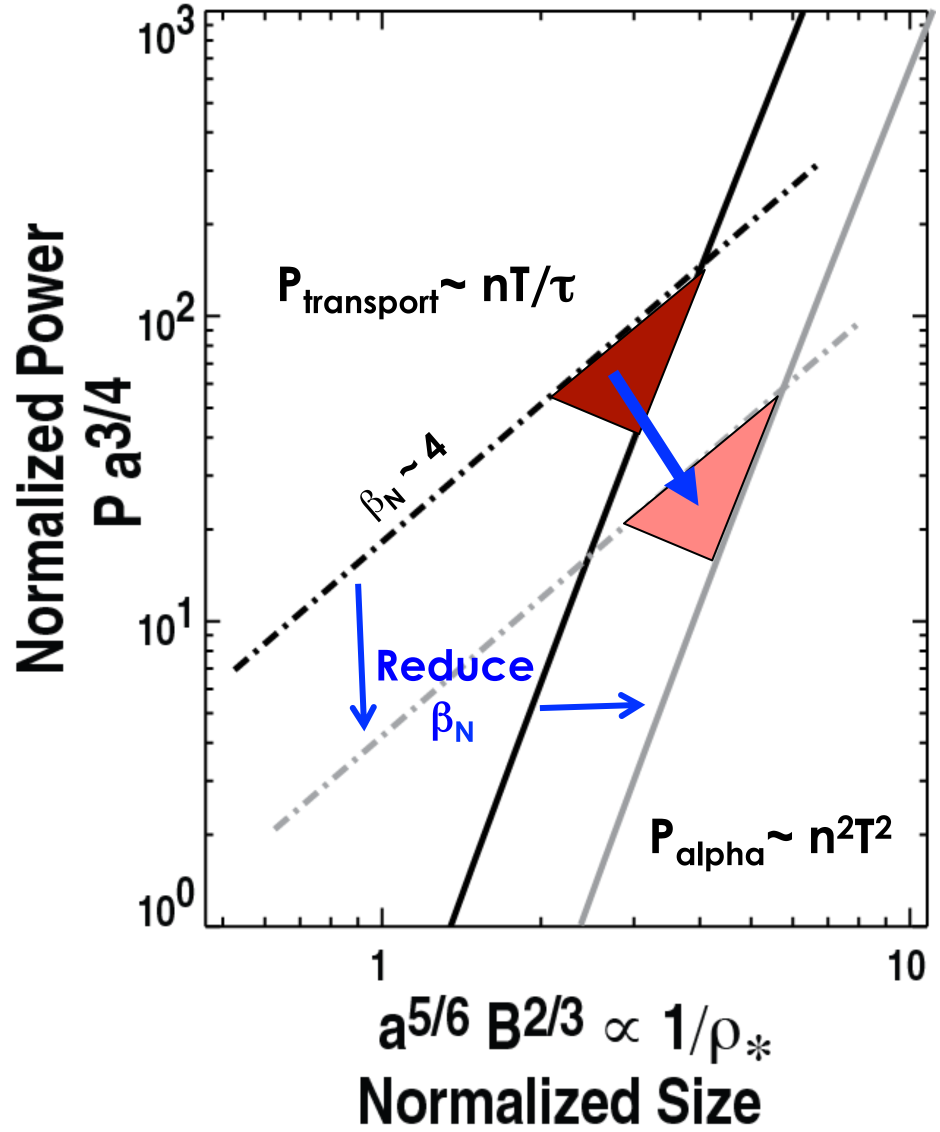
Moderate Sized, High Field Device Needed to Test Important Regime for Compact Tokamak Approach

- **High β_N is highly favorable for compact, high gain, high power density approach**



Moderate Sized, High Field Device Needed to Test Important Regime for Compact Tokamak Approach

- **High β_N is highly favorable for compact, high gain, high power density approach**
  - Decrease in β_N increases device size and reduces nominal output power
  - $f_{BS} \sim q\ \beta_N \rightarrow$ reduced CD requirements



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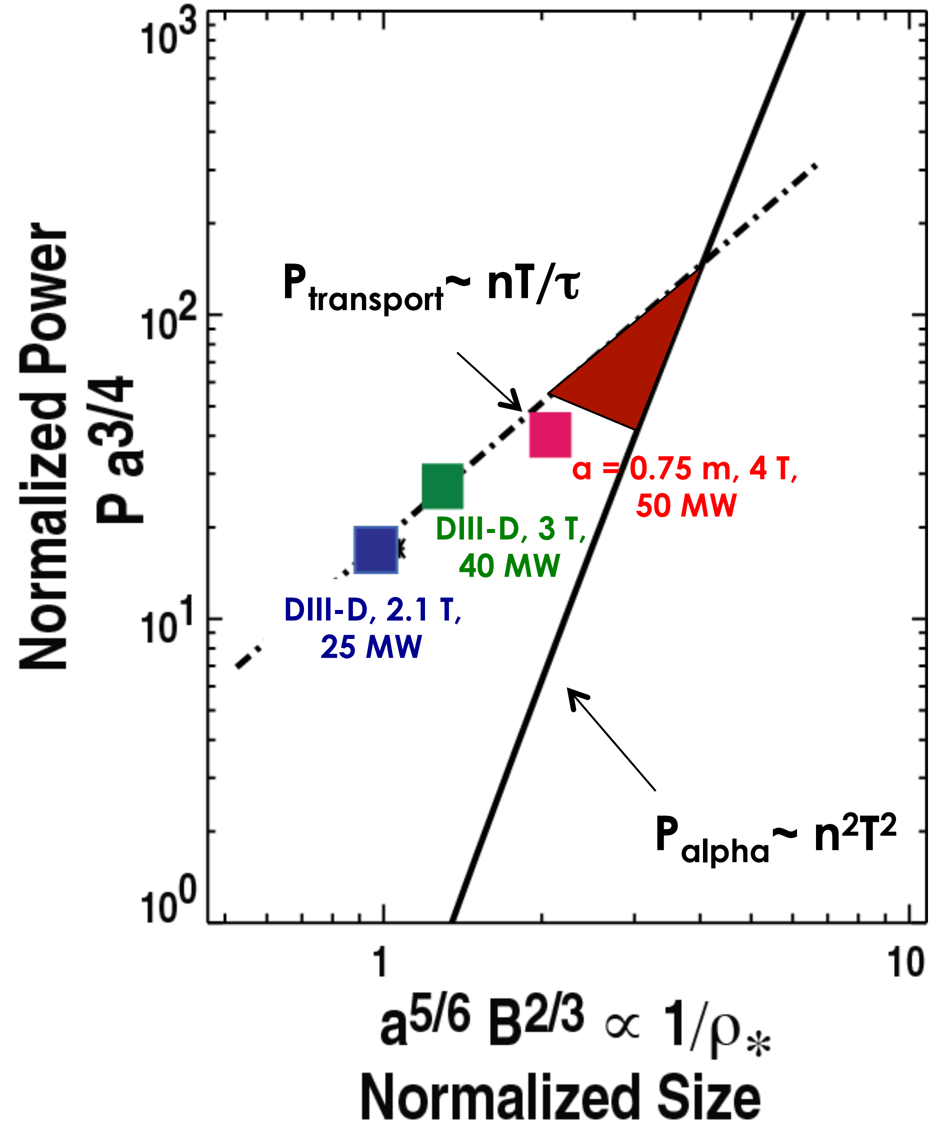
- **High β_N is highly favorable for compact, high gain, high power density approach**
  - Decrease in β_N increases device size and reduces nominal output power
  - $f_{BS} \sim q\ \beta_N \rightarrow$ reduced CD requirements
- **Progressive set of new capabilities would enable a detailed assessment of this approach. (example from the R/a ~ 3 path)**
  - Presently planned upgrades of DIII-D
  - DIII-D scale device at 3 T, 40 MW
  - New device with increased size, field, and power (could be a substantial upgrade of an existing facility)
- **Resultant high power density device would also enable exploration of:**
  - High pressure pedestals
  - Power exhaust solutions (later in talk)



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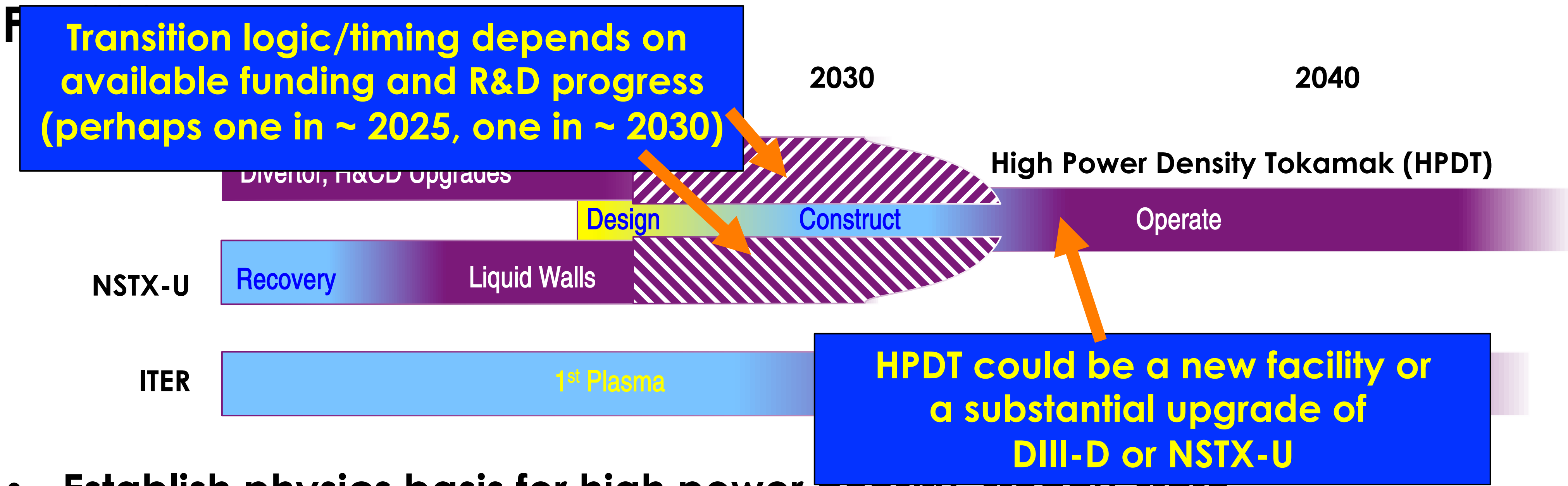

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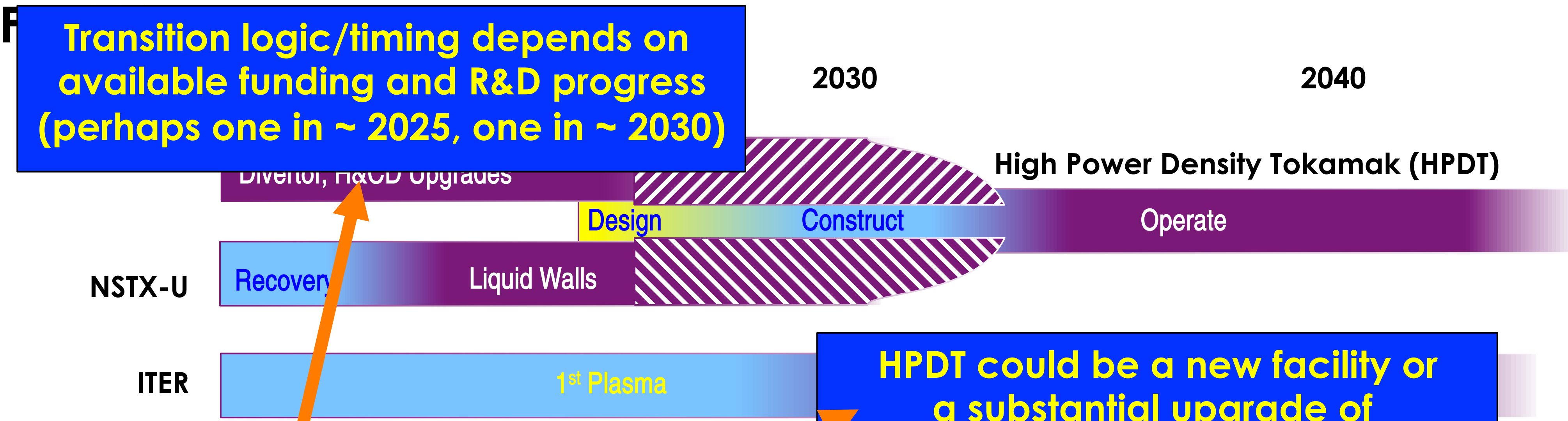


- **Establish physics basis for high power density, steady-state**
  - …provide access to steady-state regimes
  - …f unique operating space (see next slide)

Decided through a community process that engages all stakeholders and FES

- **Inform next steps**
  - DIII-D/NSTX-U current profile sustainment → ITER H&CD upgrades for Q=5
  - DIII-D/NSTX-U performance limits → HPDT design (R/a, size, CD tools)
  - HPDT/ITER steady-state regimes → Pilot plant/DEMO/FNSF physics basis and design

Power Exhaust Solutions are Essential for High Power Density Systems – Recent Renewed Emphasis in R&D

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

Importance:

- **Fundamental limitation on achievable power density of future fusion systems is handling the concomitant heat flux**

U.S status:

- **World leader in divertor/SOL measurements**
- **Wide range of capabilities to change divertor geometry and conditions**

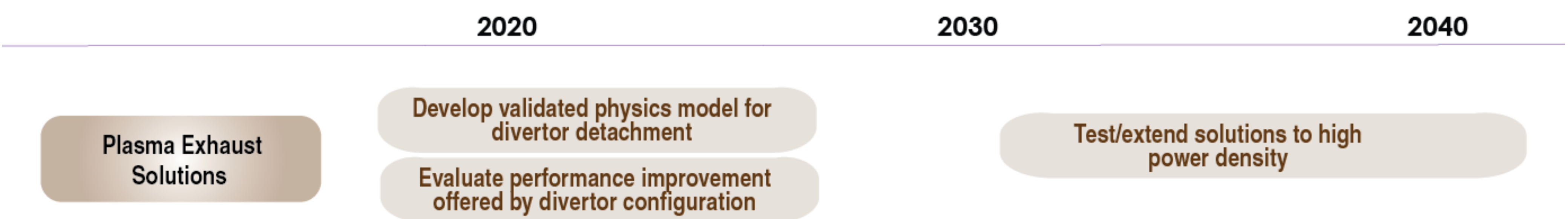
International context:

- **Capabilities exceed those of US in important areas**
  - Metal walls/divertors (AUG, JET, EAST, WEST)
  - Long pulse (EAST, KSTAR, WEST, JT-60SA)

R&D Plan Focuses on Understanding, Predictive Capability and Solutions, Then Extending to High Power Density

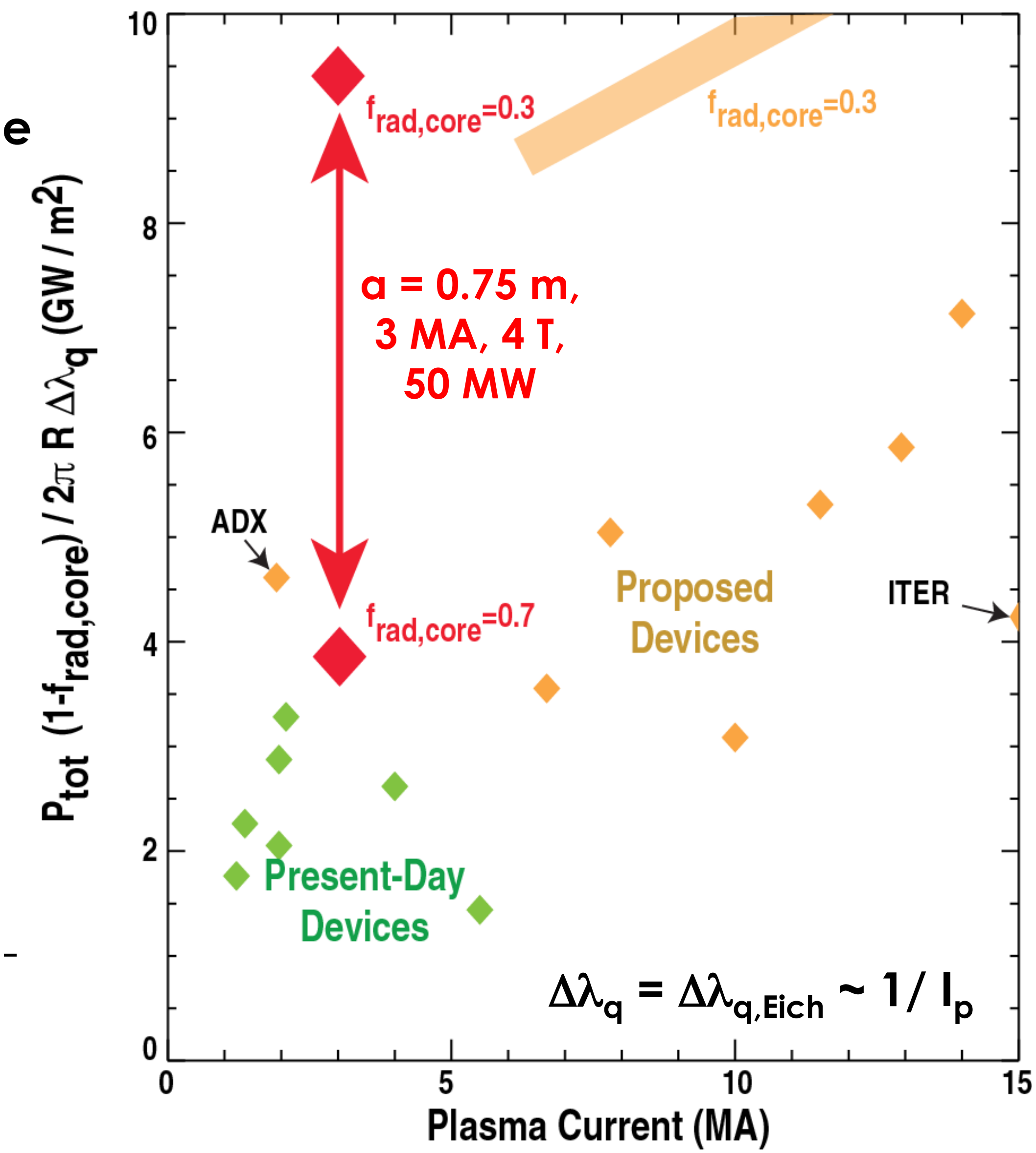
Key Elements of R&D Plan:

- **Establish credibility for cost-attractive Pilot plant/DEMO/FNSF**
  - Scientific understanding and demonstrated capability to dissipate very high heat heat flux without degrading core performance
  - Physics/technology basis for high accuracy divertor design
- **Inform design of Pilot plant/DEMO/FNSF**
  - Validated predictive capability in highly dissipative conditions for divertor/first wall design
  - Quantitative tradeoffs of impact of divertor design on core and divertor performance



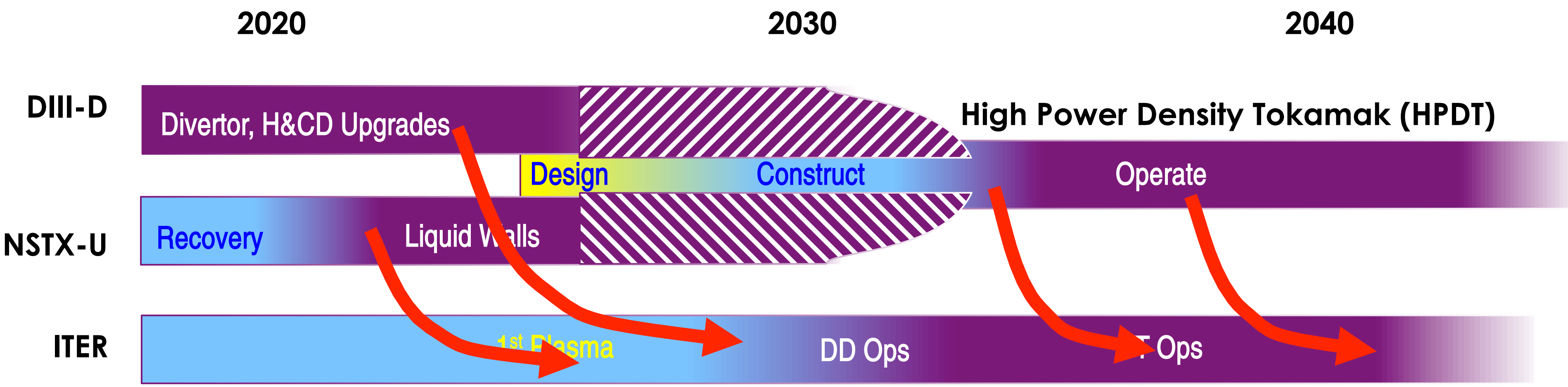
HPDT Would Provide Research Platform for Resolving Power Exhaust Solutions in High Power Density Systems

- **Combination of high power and modest size would naturally provide reactor-scale heat fluxes into SOL**
  - Higher that expected in ITER
- **Headroom above L-H power threshold enables development of core radiative solutions to augment boundary solutions**
  - As well as self consistency of those solutions
- **High field would enable decoupling of density and collsiionality**
  - $n \sim \nu_*^{1/2} B/a^{1/2}$ (at constant β and q)
  - Providing improved test bed for core-edge integration



R&D Plan Focuses on Developing Predictive Capability and Practical Solutions, Then Extending to High Power Density

Facilities Plan:



- **Establish physics basis for dissipative divertor operation**
  - Targeted upgrades/research on DIII-D/NSTX-U to close the predictive gap of dissipative divertor operation and assess impact of divertor geometry
  - ITER provides affirmation/test bed for physics basis established above
- **Extend to high power density**
  - ITER/HPDT provide unique combination of facilities to assess full radiative solutions (including both core and edge) at high power density

High-Critical-Temperature Magnets Have Potential for Improving Various Aspects of Fusion Magnet Systems

Importance:

Fabricate high-critical-temperature magnets for fusion purposes

- **Substantially increased operating space (critical field, operating temperature, current density) offer potential for several advantages**
  - Higher field operation
  - Jointed coils → potentially improved maintainability of system
  - Smaller radial build of coil → potentially smaller size system

U.S status:

- **Historically a world leader in magnet development for fusion; limited expertise with large HTS magnets**
- **Significant investment in other fields have led to rapid development of HTS conductors**

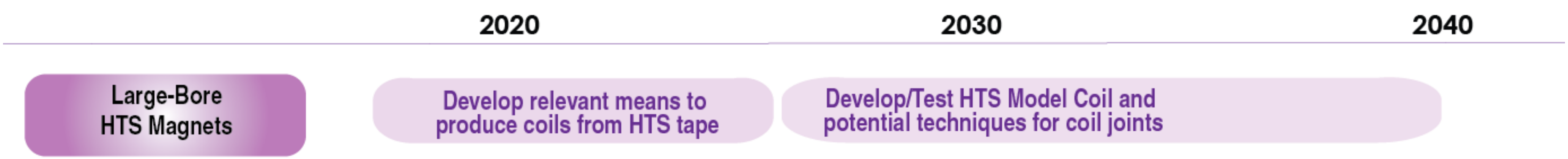
International context:

- **Due to the potential, many other countries pursuing this option also**
- **Due to competitiveness, openness of information not as readily available as most fusion technologies**

R&D Plan Targets Development of Relevant Technology, then Demonstration of Large-Bore HTS Magnets

Key Elements of R&D Plan:

- **Establish credibility for cost-attractive Pilot plant/DEMO/FNSF**
  - Demonstrated capability to build large-bore HTS magnets
- **Inform design of Pilot plant/DEMO/FNSF**
  - Ability to produce jointed HTS magnets
  - Performance variation of large-bore HTS magnets with:
    - Operating temperature (refrigeration costs)
    - Neutron fluence



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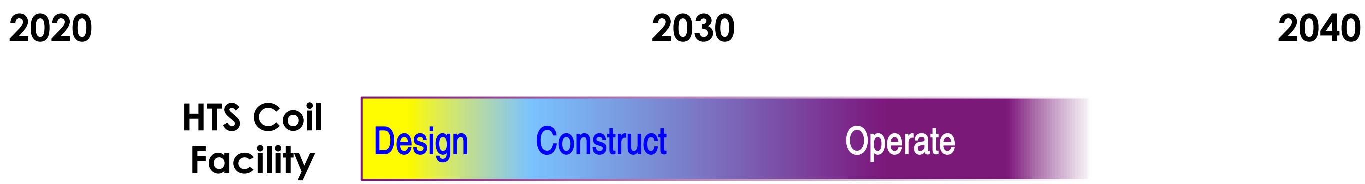


- **HTS conductor/coil development**
  - **Develop relevant means to produce either/both:**
    - High performance HTS conductor from strands to take advantage of ITER cable-in-conduit-conductor (CICC) technology
    - High performance, large-bore HTS magnets using HTS tapes

- **HTS magnet construction/testing**
  - Construct HTS magnet coil and quantify performance (possibly partner with China)

- **System studies with HTS**
  - Benefit of technology needs full assessment, especially as desired net electricity output increases above 500 MW

Solutions that Lengthen Materials Lifetime are a Critical R&D Need; Worldwide Effort is Modest

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

Importance:

- Maximizing materials lifetime is critical to cost-attractiveness of future fusion systems

U.S status:

- Very limited US effort
- Beginning new initiatives on plasma-material interaction (MPEX)

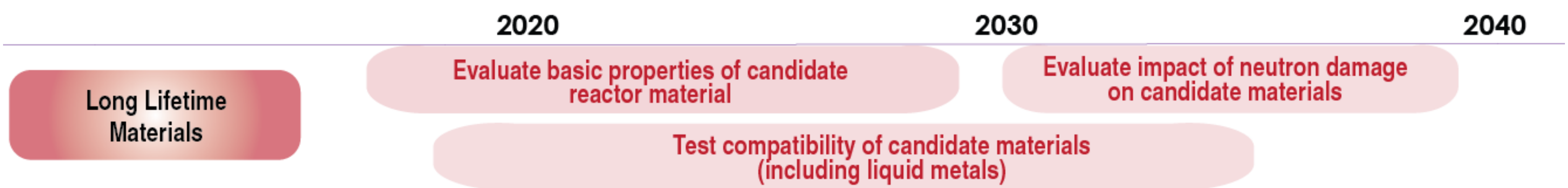
International context:

- Several plasma-material and high heat flux facilities worldwide, each with varying degrees of capability
- Little experimental effort worldwide on materials effects of 14-MeV neutrons

R&D Plan Targets Development/Qualification of Materials that Offer Long-Lifetime to Erosion and Neutron Damage

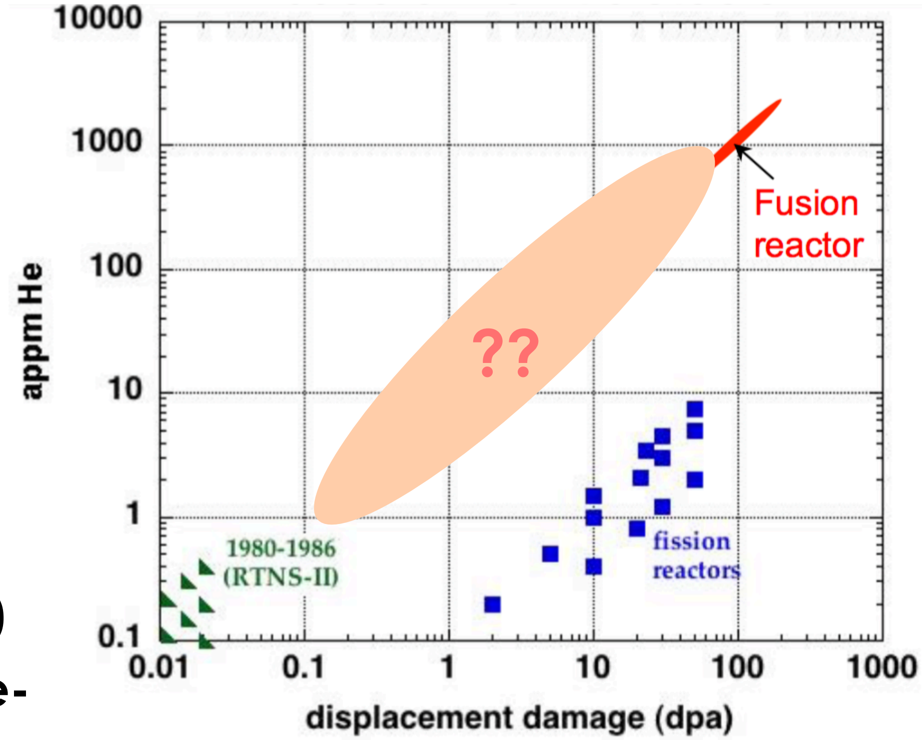
Key Elements of R&D Plan:

- **Establish credibility for cost-attractive Pilot plant/DEMO/FNSF**
  - Qualified long-lifetime materials for plasma facing and structural components
- **Inform design of Pilot plant/DEMO/FNSF**
  - Anticipated lifetime of materials → scheduled maintenance requirements
  - Performance limits of materials after exposure → engineering constraints on stresses, heat flux, …

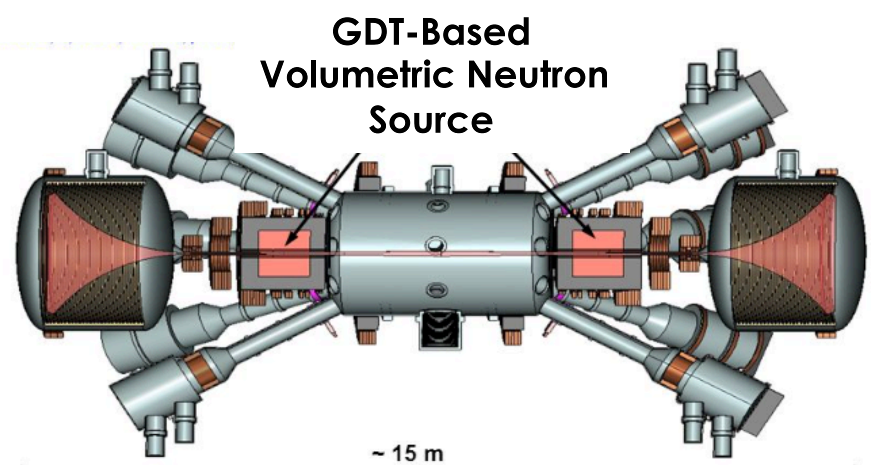


14-MeV Neutron Source Critically Needed to Fill Knowledge Gap on Impact of Neutron Damage

- **Evaluation of fusion radiation effects requires simultaneous displacement damage and He generation**
  - With He % above ~100 appm
- **Limited data available at He concentrations above 10 appm**
  - ➢ Facility critically needed to fill this gap

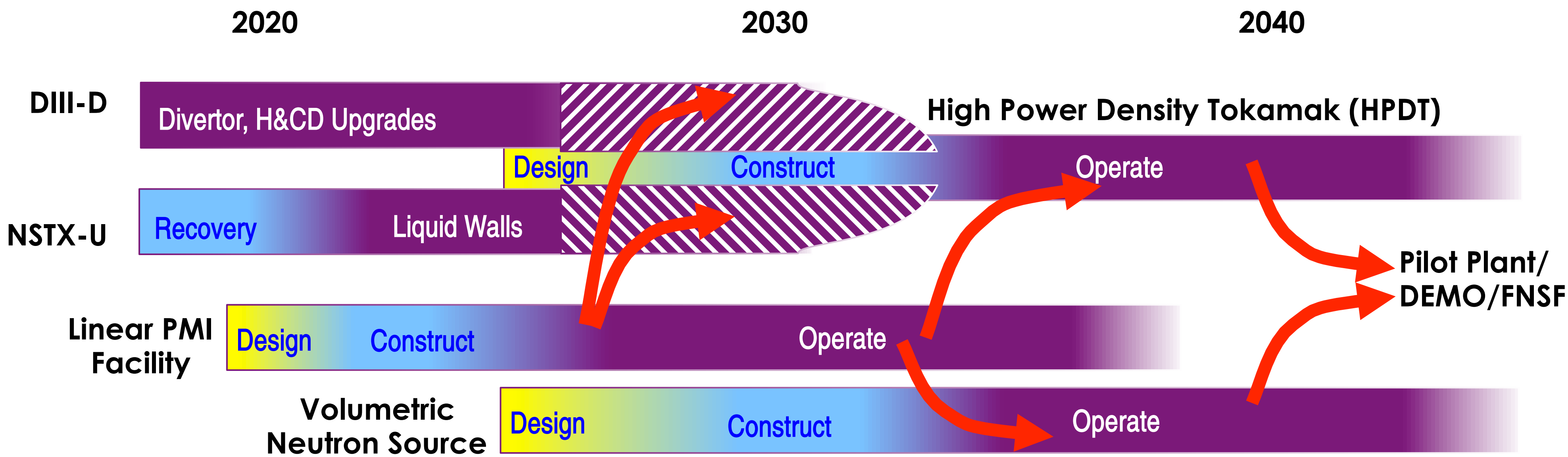


- **Proposed int'l facilities focus on small sample sizes for material exposure (e.g., IFMIF, DONES)**
- **U.S. developed capability to expose moderate-size samples would be world-leading**
  - Enabling tests of joints, welds, composites not possible in small samples
- **Recent developments in Gas Dynamic Traps may provide potential lower-cost option**
  - Eg.. Combining GDT with HTS magnet



R&D Plan Focused on Science-Driven Development of Materials for Fusion Application

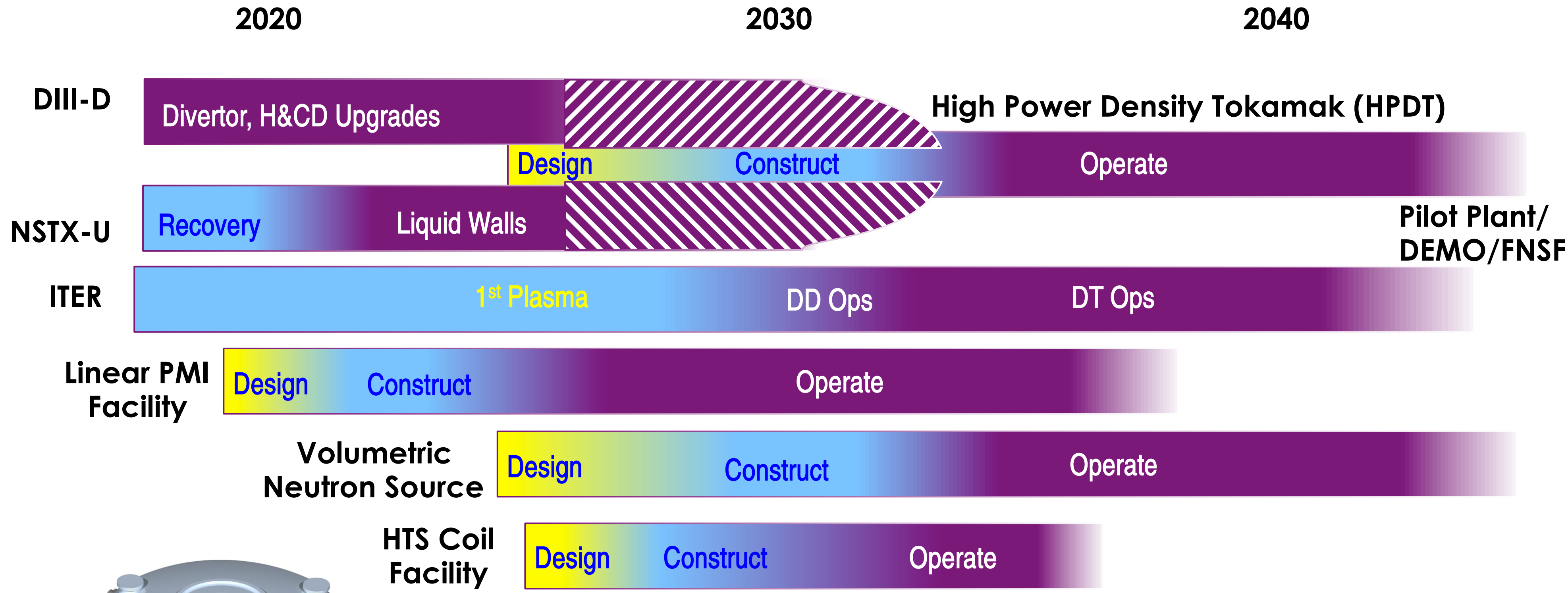
Facilities Plan:



- **Identification of best candidate materials**
  - Utilize theory and basic facilities to develop new materials that meet requirements
  - Asessmaterial evolution in dedicated test facilities (lifetime to erosion and neutron damage)
  - Followed by deployment in fusion systems for compatibility
- **Qualification of materials**
  - Utilize HPDT and VNS to test materials at near-reactor-level conditions

Plan Envisions Multiple Facilities Transitions, Culminating with Three World-Class US Facilities

Facilities Plan:



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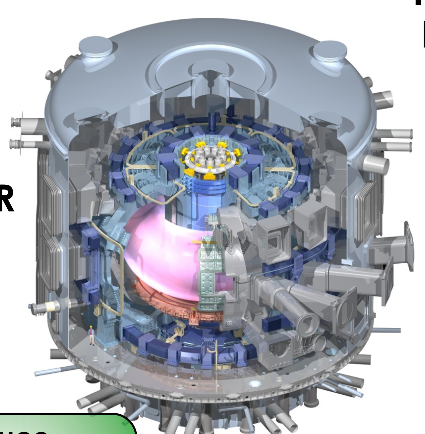
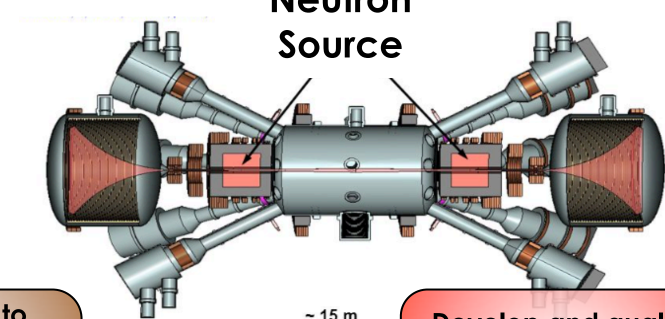


HPDT

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

Outline of Talk

- Introduction/Background
- Heart of the Plan
- **Other Considerations of Plan**
  - Blanket R&D Plan
  - ‘Without ITER’ Plan
  - Secondary Pathways
  - Reduced Funding Implications

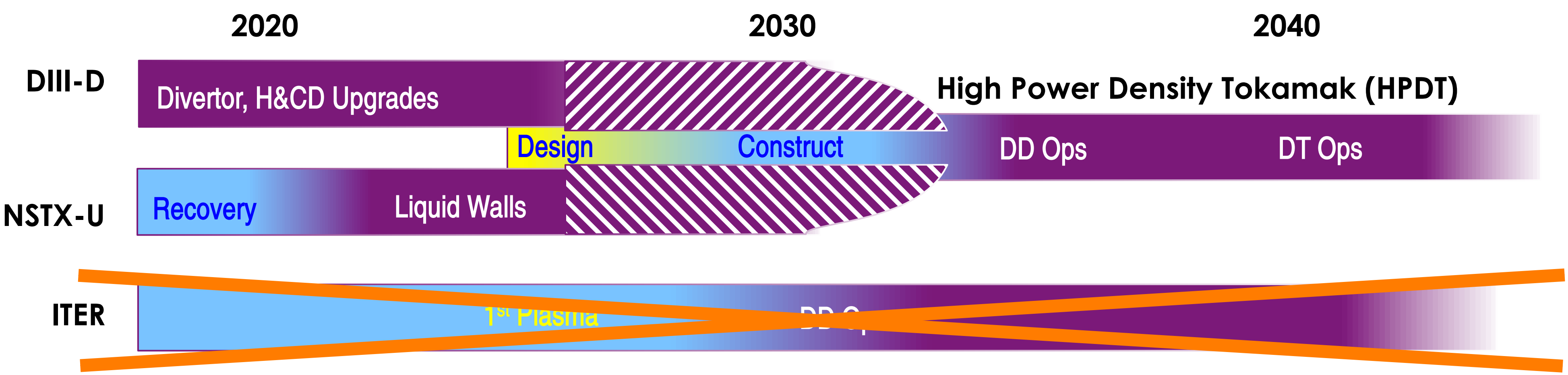
Blanket R&D Plan Relies on International Partnerships to Maintain Level of Expertise Required for Future Efforts

- **Efficient tritium breeding and power conversion is key requirement for cost-attractive fusion systems**
- **Demonstrative progress requires having a facility capable of both high neutron flux and power flow**
  - Likely requires a device with non-trivial fusion power

➢ **U.S. should invest sufficiently to leverage worldwide R&D while simultaneously developing U.S.-specific approaches that would benefit high-power density fusion systems. Program elements should include:**
  - Partnership with CFETR for blanket development/testing
  - High thermal efficiency blankets (e.g., He-cooled PbLi)

'Without ITER Plan': HPDT Mission Would be Expanded to Include Burning Plasma Science

- **Only significant change in the plan is to add DT capability to HPDT**

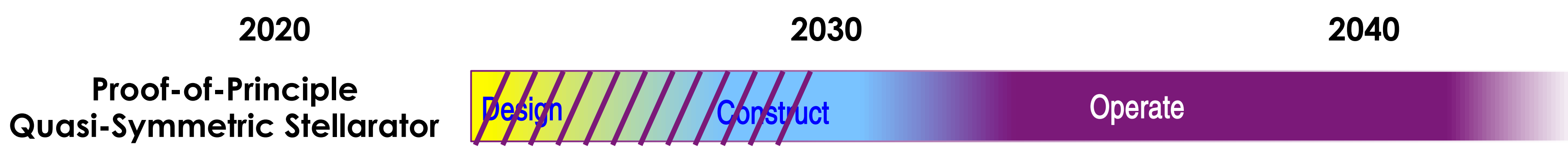


- **With further increases in field, HPDT-DT should be capable of Q = 5-10**
  - e.g., FIRE-AT: a = 0.6 m, B = 6.5 T, P = 50 MW
- **Impact on Plan:**
  - ↓ Costs more, takes more time, much shorter pulse length
  - ↑ <u>High β</u>, burning plasmas could be assessed
  - ↑ Logic of remainder of program would not change; however, cost difference would have to absorbed

A potential serious impact that is not taken into account here is the political impact (e.g., reduced funding, response of partners) of withdrawal.

Given Sufficient Funding, U.S. Should Strive to Develop A Non-Tokamak Configuration to Sufficient Maturity for Evaluation

- **Alternate configurations have long been a strength of the US program**
  - Scientific opportunities are abundant in this area
- **Furthermore, significant challenges remain for the tokamak (e.g., current sustainment, plasma disruptions)**
  - ➢ Compelling secondary pathways should be developed to reduce risk
- **Personal view: Quasi-symmetric stellarator represents the most compelling US option**
  - Based on emerging theoretical basis and recent results from LHD and W7-X
- **Proof-of-principle-scale quasi-symmetric facility would assess predictions of turbulence-driven ion thermal transport and energetic particle confinement**
  - Possibly in partnership with other countries



Inability to Attract Increased Funding Will Necessitate Tough Choices; Priorities Will Depend on Objective

Facility Priorities Based on Underlying Strategic Objective Strategic Objective	ITER	High Power Density Tokamak	Linear PMI Facility	Volumetric Neutron Source	Magnet Test Facility
Be the first to fusion	A	B	B	A	C
Distinctive path to fusion	B	A	C	A	B
Establish U.S. industrial leadership in key technologies	B	C	B	A	A
Establish U.S. leadership in physics design	B	A	A	B	C
Leverage international investment	A	C	C	A	B

Summary

- **With targeted investment, physics advances can continue to accelerate the US path to fusion energy**
  - Aggressively pursue burning plasmas, high performance tokamaks, and power exhaust solutions
- **Technology will ultimately be the mechanism through which world leadership is demonstrated in attractive fusion energy**
  - Lay down the foundations now to lead in distinctive technologies (e.g., neutron-resistant materials, HTS magnets, …)
- **Strategic plan outlined here simultaneously:**
  a) Enables resolution of critical issues for fusion development
  b) Provides compelling scientific opportunities to carry out cutting edge research
  c) Develops world-leading technical capabilities in fusion physics & technology
  d) Enables a pathway to a cost-attractive Pilot plant/DEMO/FNSF in ~ 2040

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Good luck on the development of the Final Report. Your task is not an easy one, but one that will have a lasting impact on the future of fusion research in the US and the world.