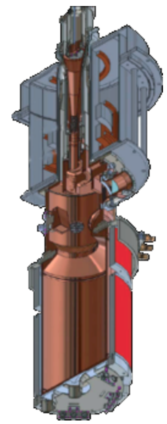
DIII-D 10-Year Vision: Developing the Scientific Basis for the Burning Plasma Era and Fusion Energy Development

by
M.R. Wade on behalf of DIII-D Team

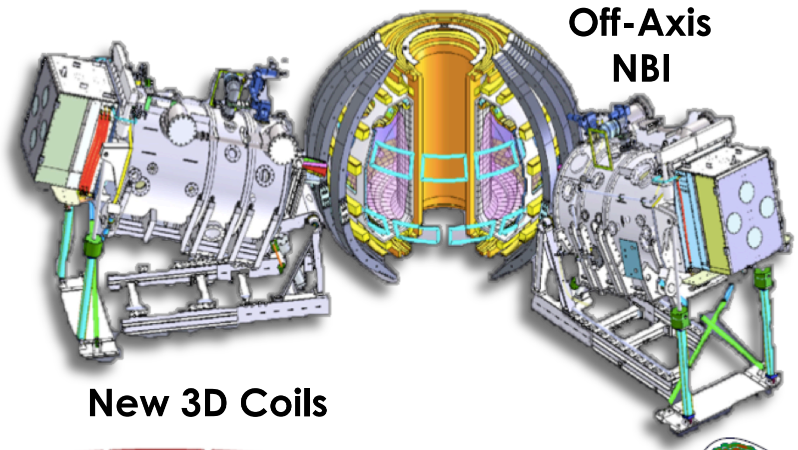
Presented to the
FESAC Strategic Plan Subpanel
Gaithersburg, MD

July 8, 2014

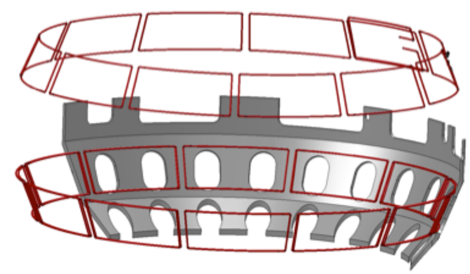
Electron Cyclotron



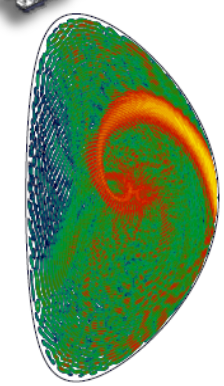
Off-Axis NBI



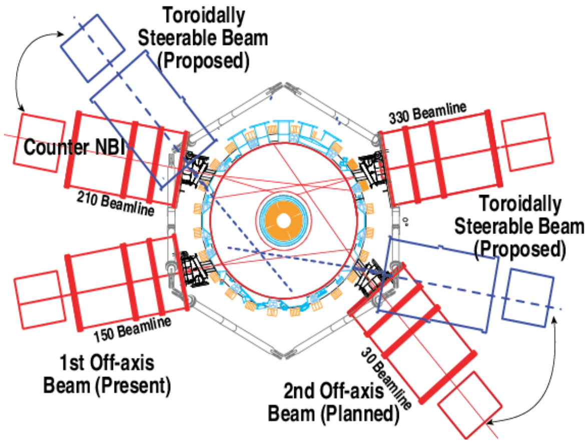
New 3D Coils



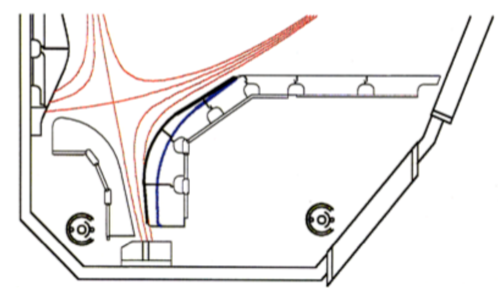
Helicon Current Drive



Co/Counter/Balanced NBI



Advanced Divertor



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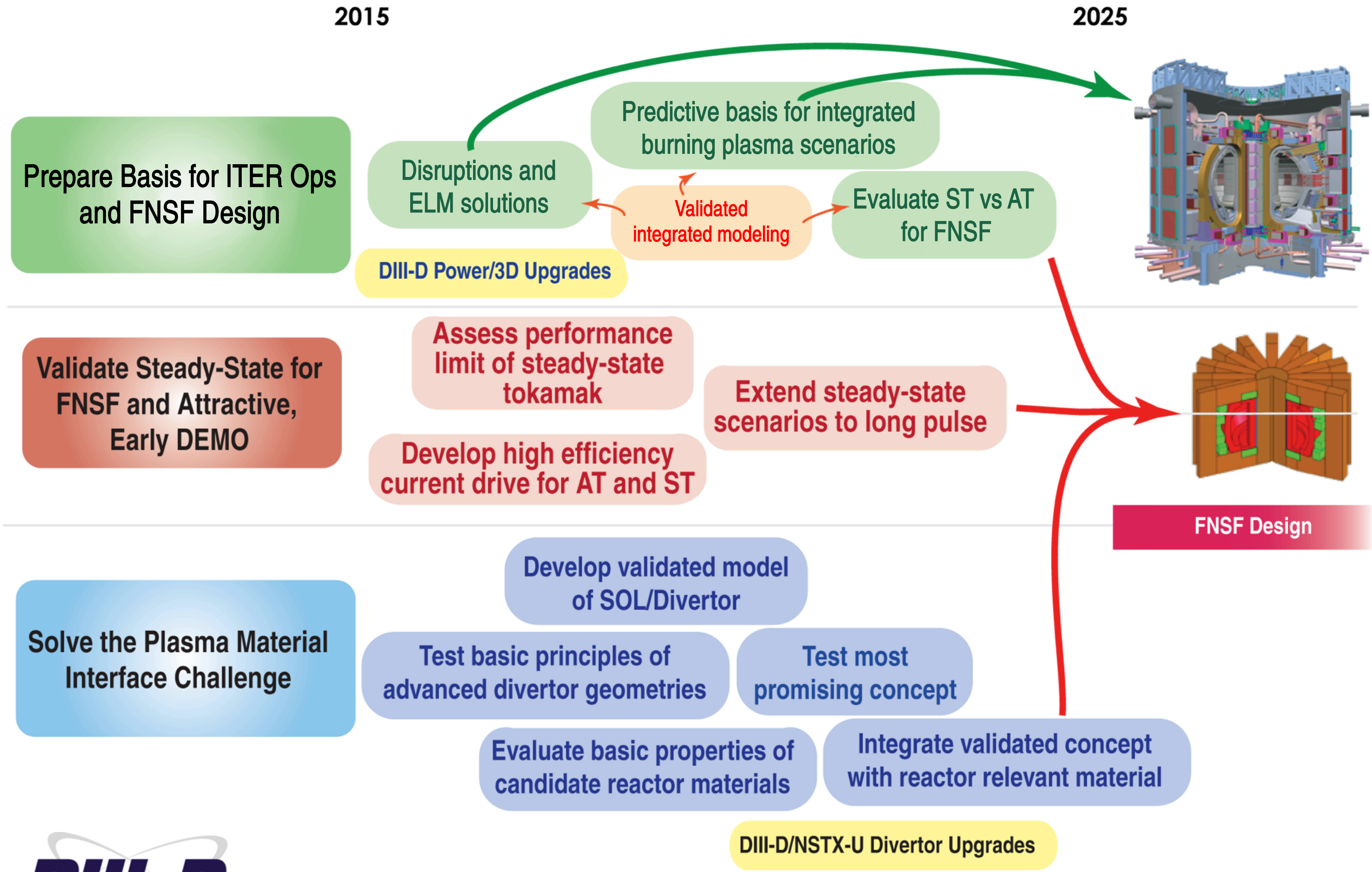
GENERAL ATOMICS

Our Vision of 10-Year US Program Plan Targets ITER Operation and Start of FNSF Design in First of Half of 2020



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SAN DIEGO

DIII-D Initiatives Target Critical Gaps in Physics Foundations Needed to Enable ITER and FNSF Success

- ITER design finalized; need to prepare for the burning plasma regime
- FNSF performance elements demonstrated; critical gaps remain to begin design activity

DIII-D Initiatives:

1. Prepare for Burning Plasmas

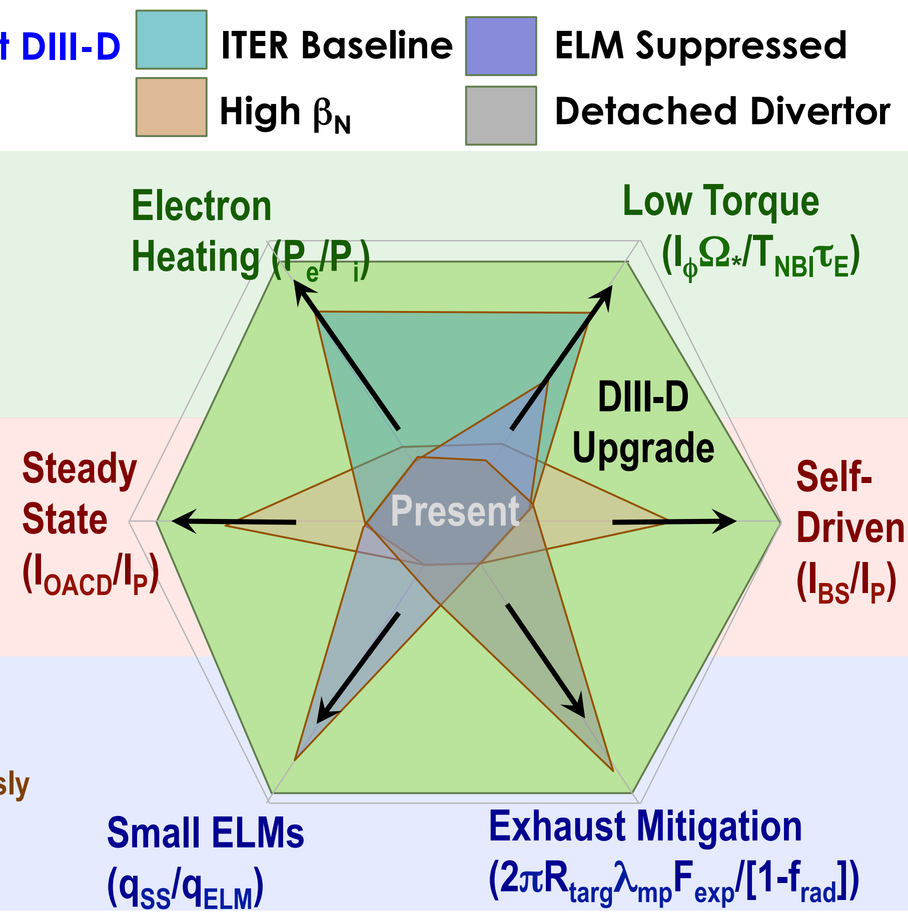
Deliver predictive understanding of the impact & optimization of burning plasma conditions on plasma performance

2. Determine Steady-State Path

Provide requirements for achieving efficient, high performance, steady-state operation in FNSF

3. Develop PMI-Boundary Solution

Develop and validate solutions for heat flux control including transients in FNSF and future devices



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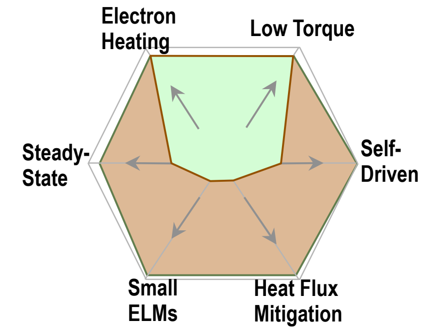
DIII-D upgrades will provide a unique capability to individually AND simultaneously develop the science of performance-defining features of steady-state, burning plasma operation

High Power EC and Configurable NBI Will Provide Platform to Assess Physics of the Burning Plasma Regime

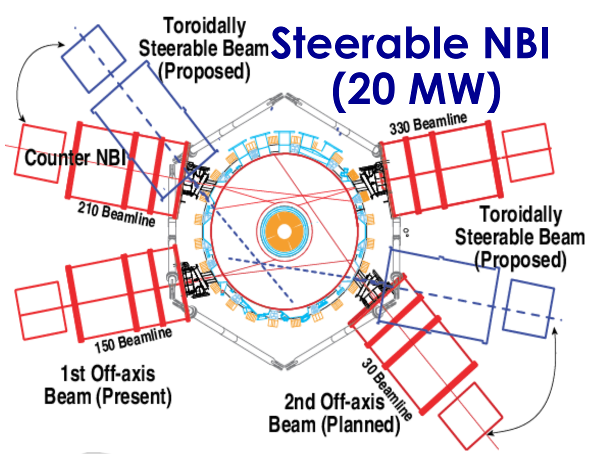
I. Prepare for Burning Plasmas

- **Challenge: Transport & stability predicted to change with significant α heating in burning plasmas**
  - Dominant electron heating, low torque and particle input
- **DIII-D Upgrade: High power electron heating and balanced NBI torque to access this physics at high β_N**
  - Physics evaluation and optimization of ITER & FNSF scenarios

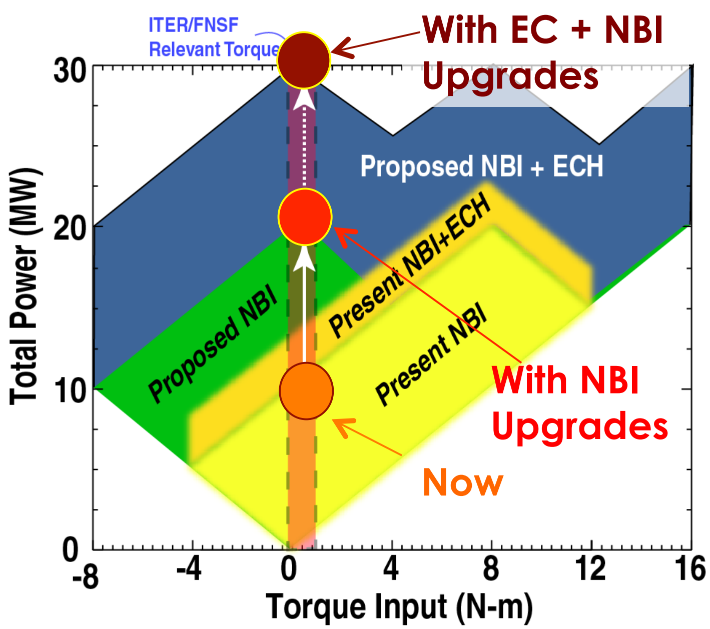


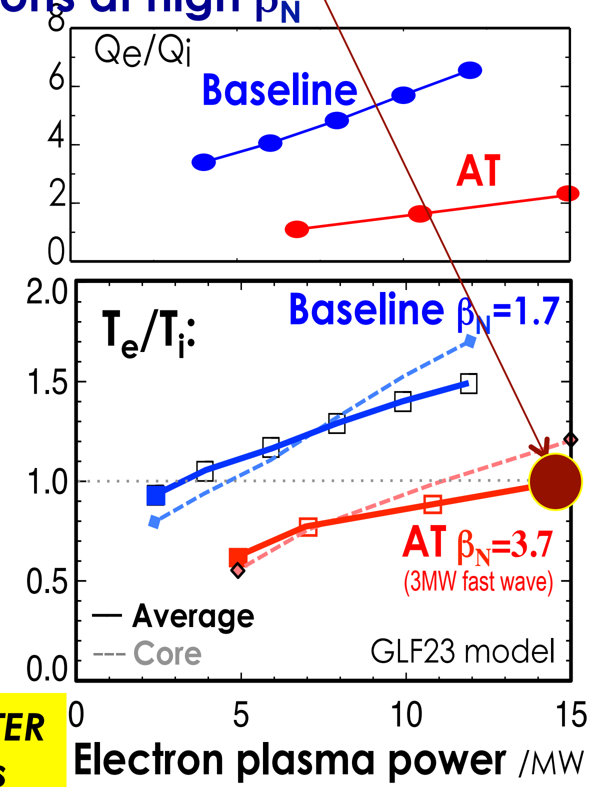
ECH: 3.5→10.5MW

Steerable NBI (20 MW)



➔ 30 MW of torque-free electron heating will enable access to burning plasma conditions at high β_N





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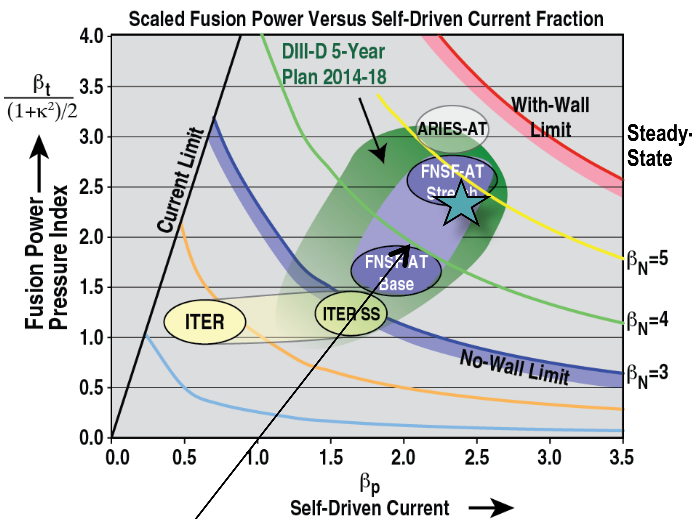
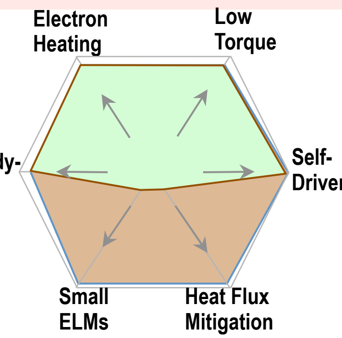
Gives the US a powerful scientific tool to prepare for ITER exploitation and train a new generation of scientists

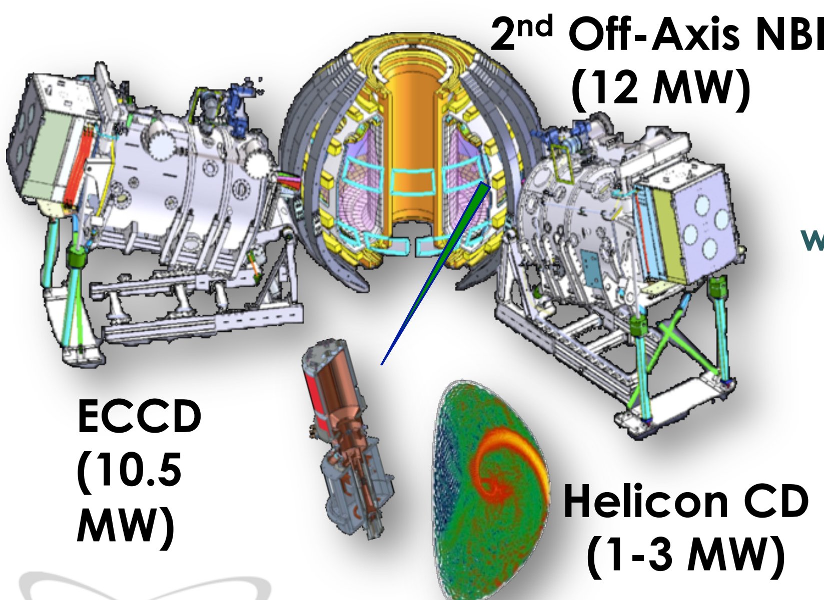
H&CD Upgrades Will Provide Sufficient Capability to Qualify Candidate Scenarios Required for FNSF Mission Objectives

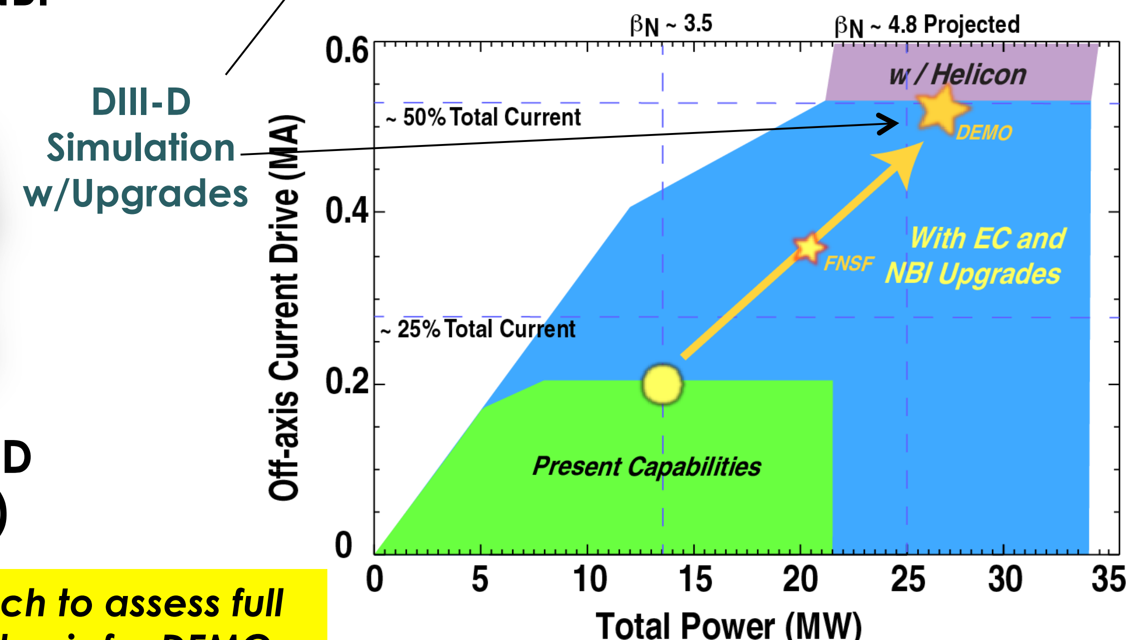
II. Validate Steady-State for FNSF

- **Challenge: Demonstrate physics basis for efficient, steady-state operation consistent with FNSF mission goals**
- **DIII-D Upgrade: Provide H&CD tools to run an FNSF scenario with $\beta_N > 4$ for $2\tau_R$**
  - Off-axis current drive (2.5x)
  - Total power (1.6x)
  - Pulse length (2x)









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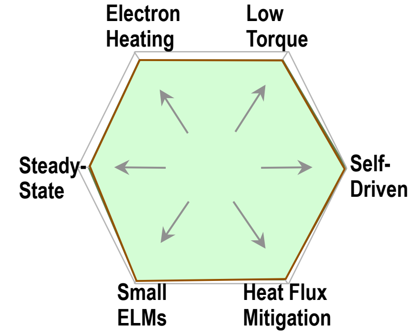
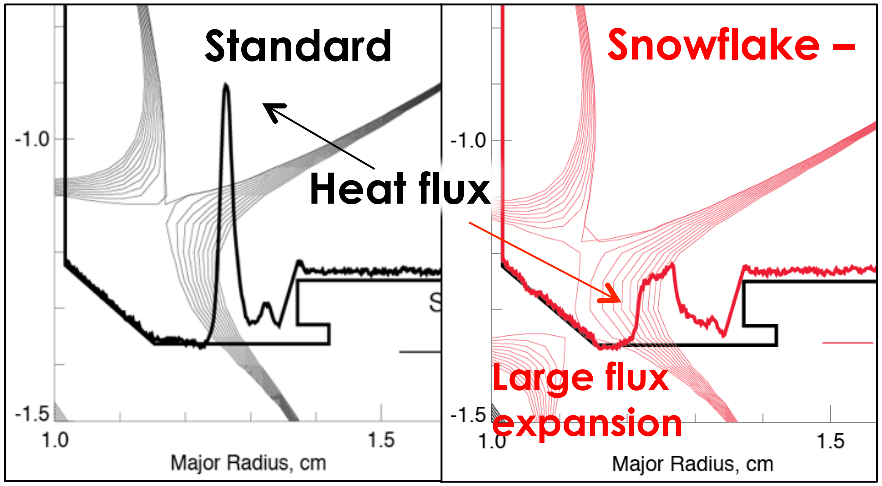
Provides technical reach to assess full potential of FNSF and basis for DEMO

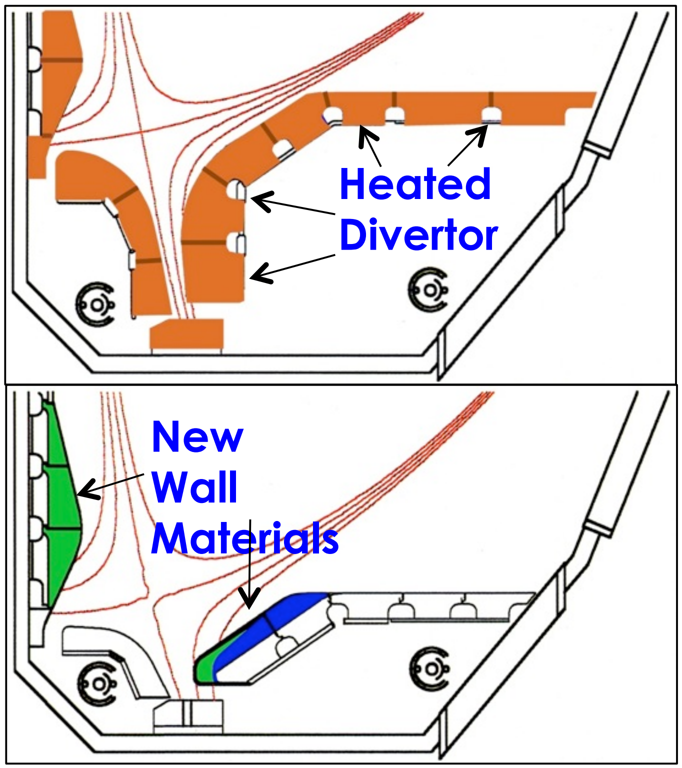
Advanced Divertor and New PFC Material Upgrades Will Provide Capability to Develop Core-Edge Solutions for FNSF

- **Challenge: Develop and qualify plasma dissipation and PFC solutions that achieve long component lifetime while maintaining acceptable core performance**
- **DIII-D Upgrade: Provide integrated capability to assess divertor geometry, hot wall operation, and innovative PFCs**
  - Advanced divertor: Achieve detachment at lowest possible density, highest possible β_N
  - Heated divertor: Assess impact of recycling dynamics
  - Reactor relevant materials: Test new solutions developed by US materials community





Advanced Divertor



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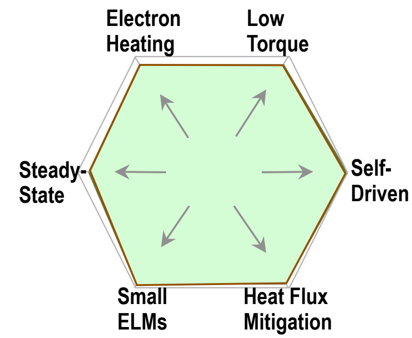
Provides potential to "leapfrog" state-of-the-art in plasma dissipation and PFC solutions

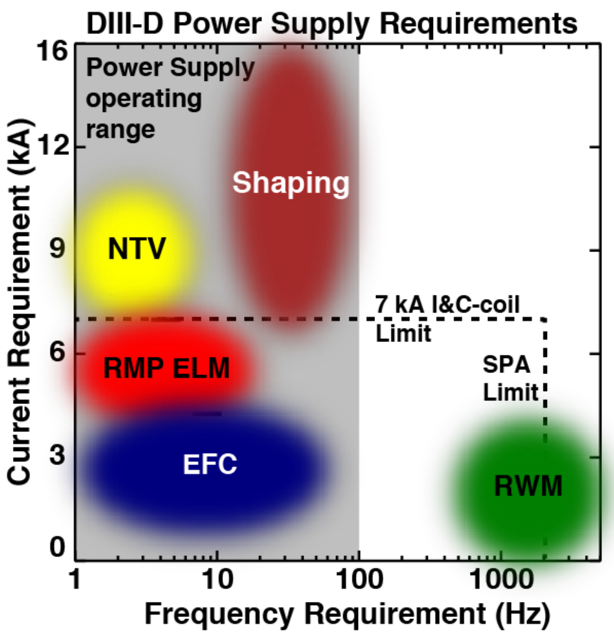
3D Upgrade will Enable Extension of ELM, Rotation, Error Field, and RWM Control to FNSF Conditions

I. Prepare for Burning Plasmas | II. Steady-State for FNSF | III. Boundary Solutions

- **Challenge: Deliver robust ELM control with minimal impact on stability and confinement**
  - Especially critical at low torque/rotation expected in ITER/FNSF
- **DIII-D Upgrade: Enhance spectral flexibility to identify critical spectral features and enable multi-harmonic application**



Enhanced 3D Power Supplies



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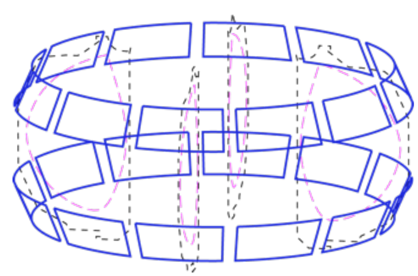
New 3D coil Set



Rotatable, Tunable to n=3,4

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Capability	n=1	n=2	n=3	n=4	n=6
RMP ELM Suppression		X	X	X	X
NTV Drive			X	X	
Error Field Correction	X	X	X		
RWM Control	X	X	X		
Simultaneous Optimization	X	X	X		

Provides basis for optimizing use of 3D fields for transient control simultaneous with high performance operation

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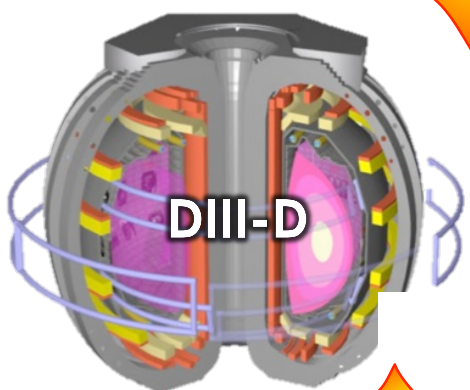
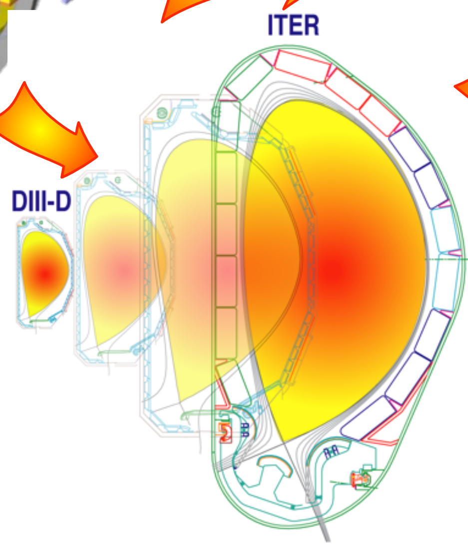
Physics Provided by New Capabilities Will Enable Strong US Partnership in International Programs

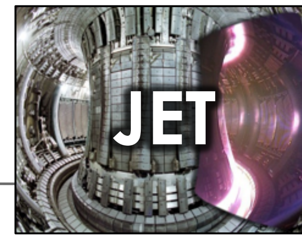
I. Prepare for Burning Plasmas	II. Steady-State for FNSF	III. Boundary Solutions

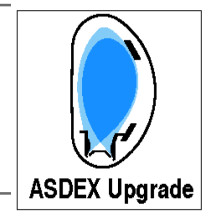
- DIII-D: New tools will enable development of solutions and physics basis
  - Flexibility to optimize
  - Technical reach to push frontier

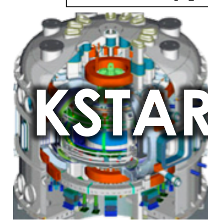


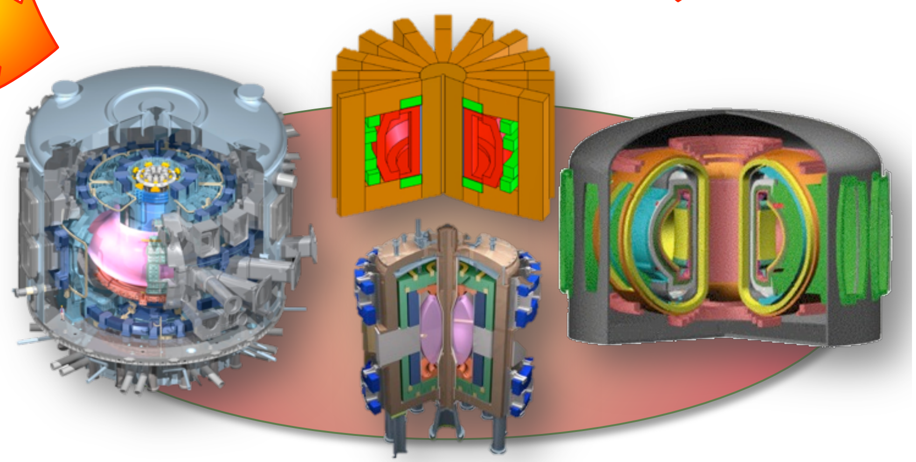


- Provides the foundation for effective US participation on international facilities
  - *Larger size (lower ρ*)*
  - *Metal walls*
  - *Long pulse*









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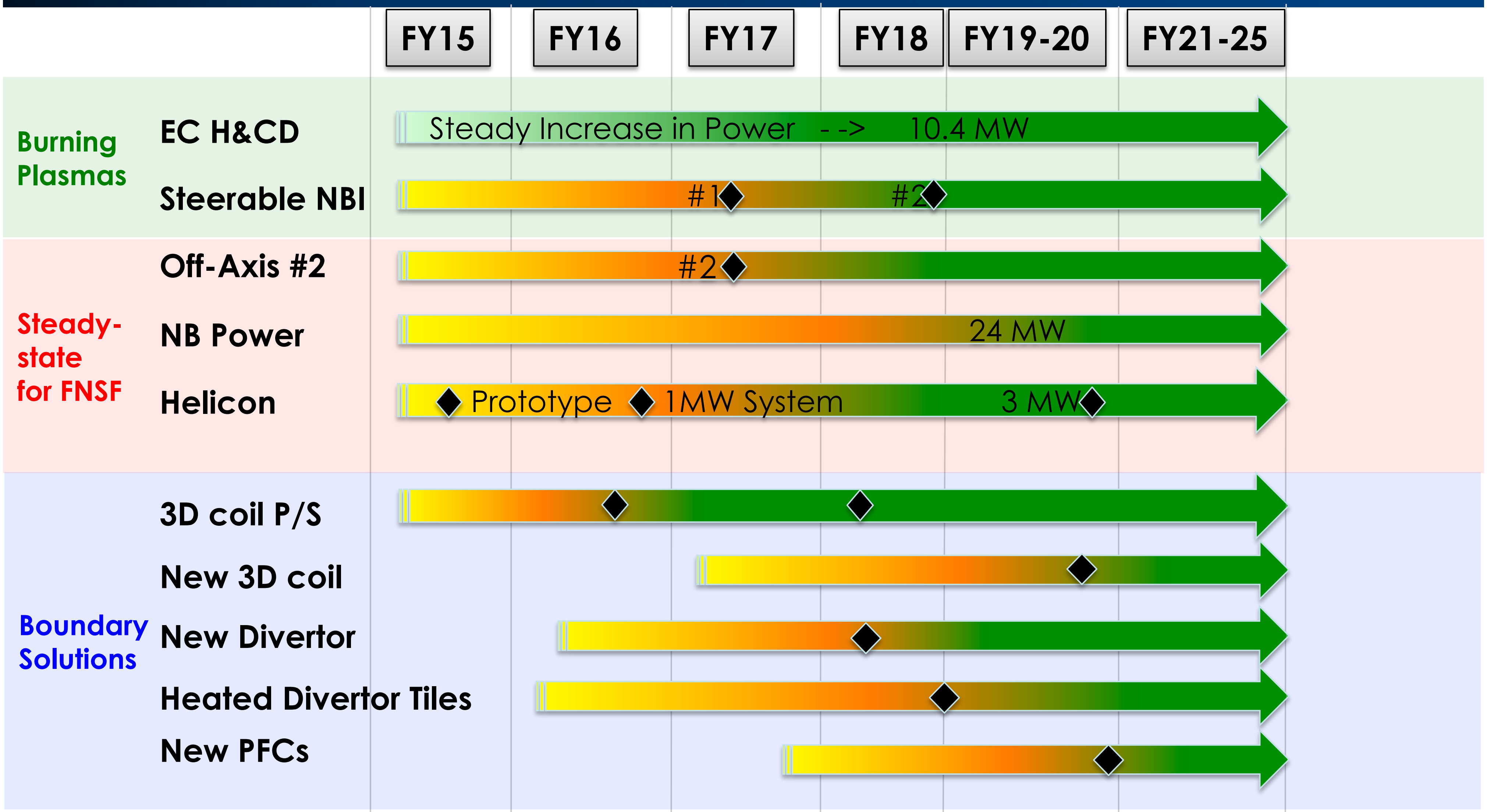
Schedule Targets Completion of Full Set of Upgrades In Time to Exploit for ITER Preparation and FNSF Design



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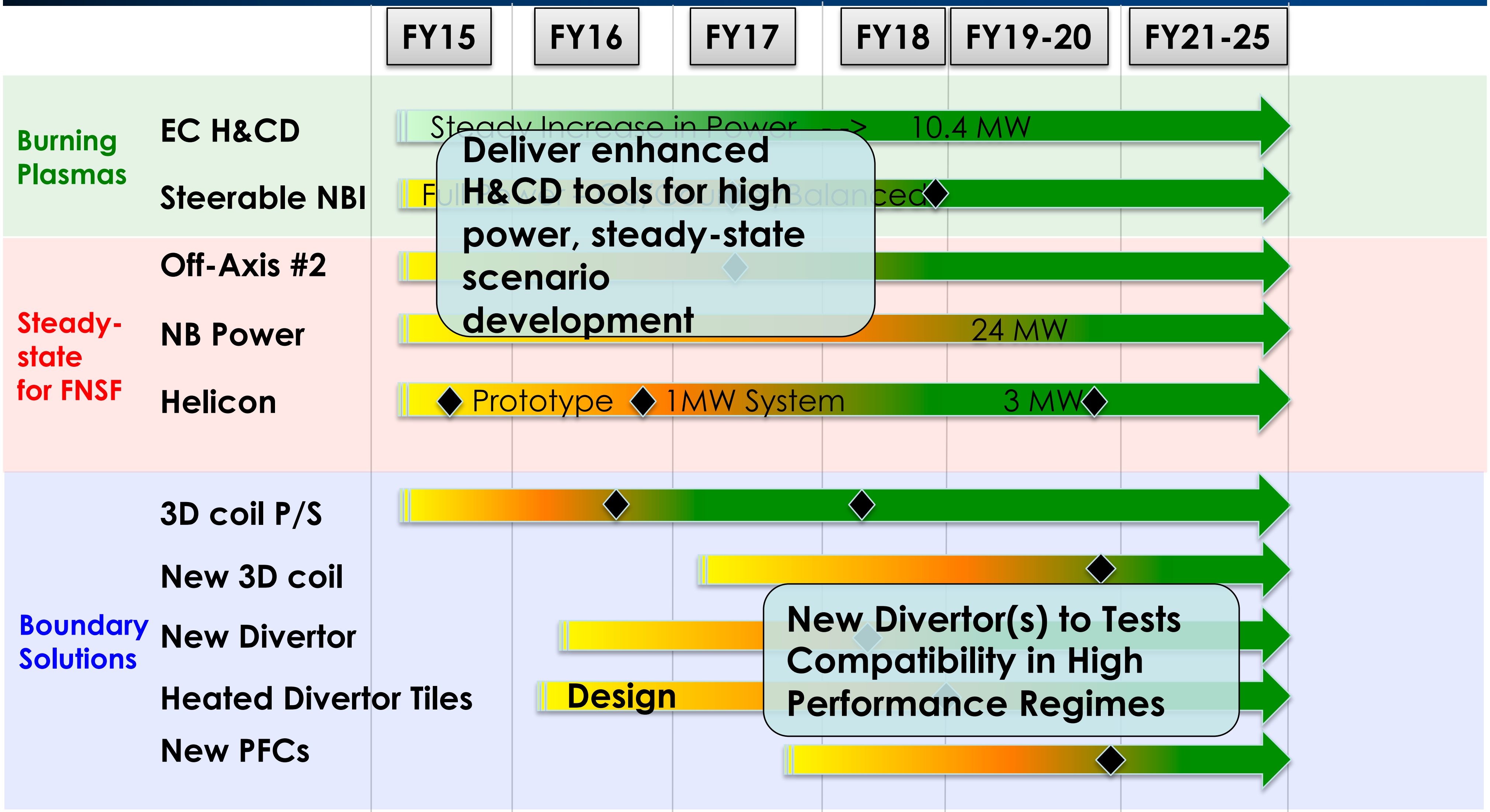
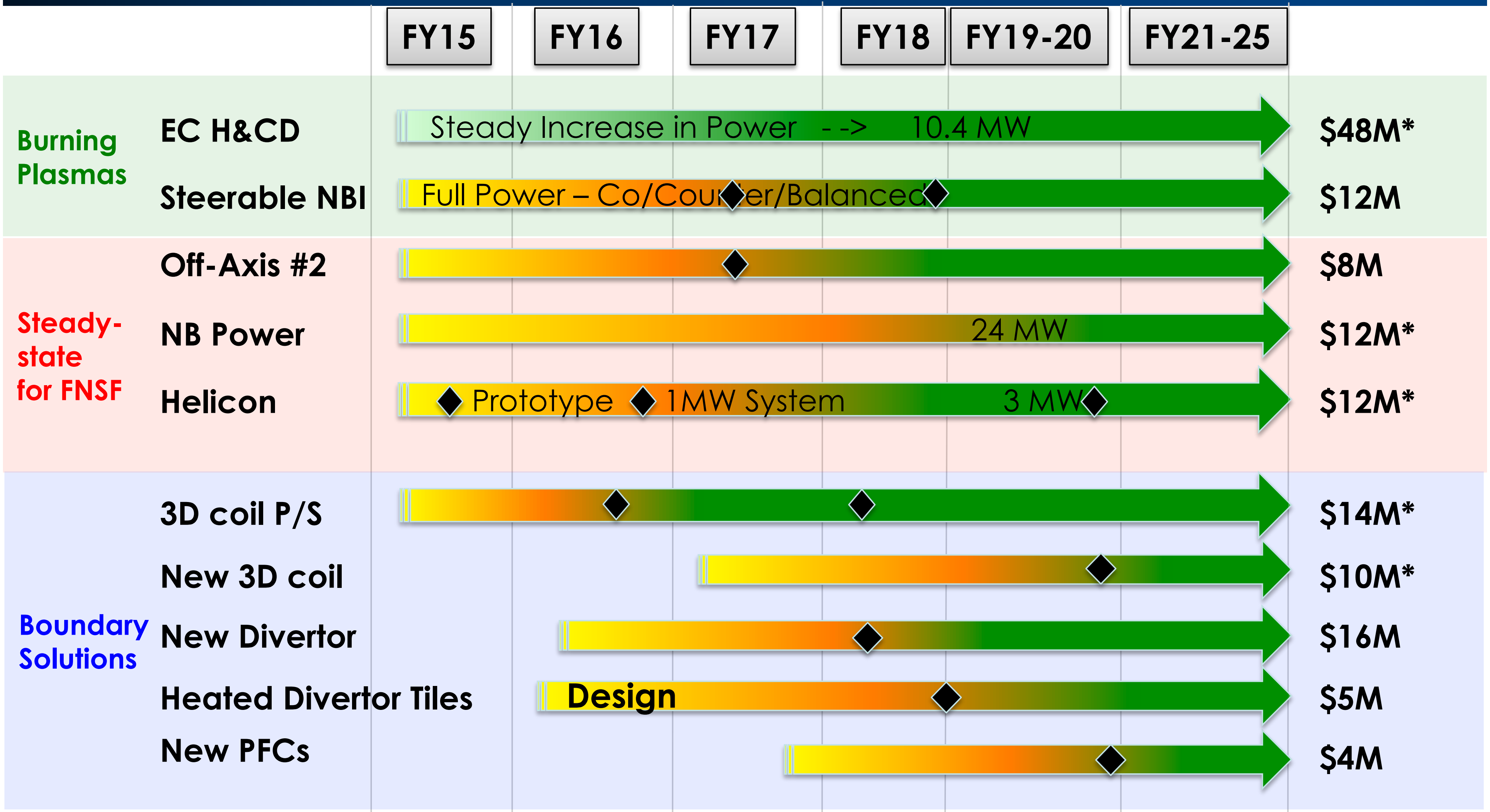
Phase I Focuses on Increasing Power/Flexibility for Core Scenario Development: Phase II on Core-Edge Coupling



Entire Upgrade Package Can Be Implemented on Modest Incremental Funding Over 6 Years



Total Estimated Upgrade Cost:	$ 141 M	
*Chinese/Russian Cost Sharing:	($ 22 M)	
DIII-D Ops → Project:	($ 25 M)	
Total Incremental DOE Funding:	$ 94 M	(~ $16M over 6 years)

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Upgrade Plan Will Enable The US to Remain the World Leader in Key Areas Identified by ReNeW

ReNeW Thrusts
(with Prioritization from 2012 Priorities Panel Report)

Anticipated DIII-D Position in 2020
A=Definitive World Leader; B=World Leader; C=Strong Contributor; D=Moderate Contributor

Area	# (Priority)	ReNeW Thrust	Present Capabilities	2020 with No Upgrades	EC 10.5 MW	Toroidally Steerable NBI	Off-Axis NBI	NBI Power	Helicon	3D Upgrades	Advanced Divertor	All Upgrades
Burning Plasmas	3 (Mid)	Understand the role of alpha particles in burning plasmas	B	C	B	B	B	B	B	B		B
Burning Plasmas	4 (Mid)	Qualify operational scenarios and the supporting physics basis for ITER	B	C	A	B				B	A	A
Burning Plasmas	6 (High)	Develop predictive models for fusion plasmas supported by theory and challenged with experimental measurement	B	C	B	B	B			B		B
Steady-State	5 (Mid)	Expand the Limits For Controlling and Sustaining Fusion Plasmas	A	B	A	A	A	A	A			A
Steady-State	8 (Low)	Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas	A	B	A	A	A	A	A	B		A
Boundary Solutions	2 (High)	Control transient events in burning plasmas	A	B		A				A		A
Boundary Solutions	9 (High)	Unfold the physics of the boundary layer plasma	B	C		B	B	B	B	C	A	A
Boundary Solutions	10 (High)	Decode and advance the science and technology of plasma-surface interactions	C	D				B		B	B	B
Boundary Solutions	12 (Low)	Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma	D	C	B	B	B	B		B	A	A

Where we are today (Present Capabilities)

Where we will be In 2020 w/ no Upgrades

Potential in 2020 with Full set of Upgrades

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	6 (High)	Develop predictive models for fusion plasmas supported by theory and challenged with experimental measurement	B	C	B	B	B			B		B
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Boundary Solutions	2 (High)	Control transient events in burning plasmas	A	B		A				A		A
	9 (High)	Unfold the physics of the boundary layer plasma	B	C		B	B	B	B	C	A	A
	10 (High)	Decode and advance the science and technology of plasma-surface interactions	C	D				B		B	B	B
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Where we are today

Where we will be In 2020 w/ no Upgrades

Potential in 2020 with Full set of Upgrades

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DIII-D Upgrade Is a Cost Effective Means to Deliver US Scientific Leadership in Critical Areas of Fusion Energy Development

- **Leverages $1B investment in existing world-class facility**
  - Extensive, flexible control tools
  - Comprehensive diagnostic set

Cost Effective

- **Delivers new capabilities that can transform the landscape of fusion science**
  - Burning plasma transport
  - Self-consistent high β steady states
  - Detached divertor with transients eliminated

Scientific Leadership

- **Provides the foundations for success in US next-step devices**
  - Burning plasmas in ITER
  - Long-pulse, high performance operation in FNSF

Critical to FES Mission

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→ A world-class US fusion user facility providing exciting research opportunities to scientists worldwide