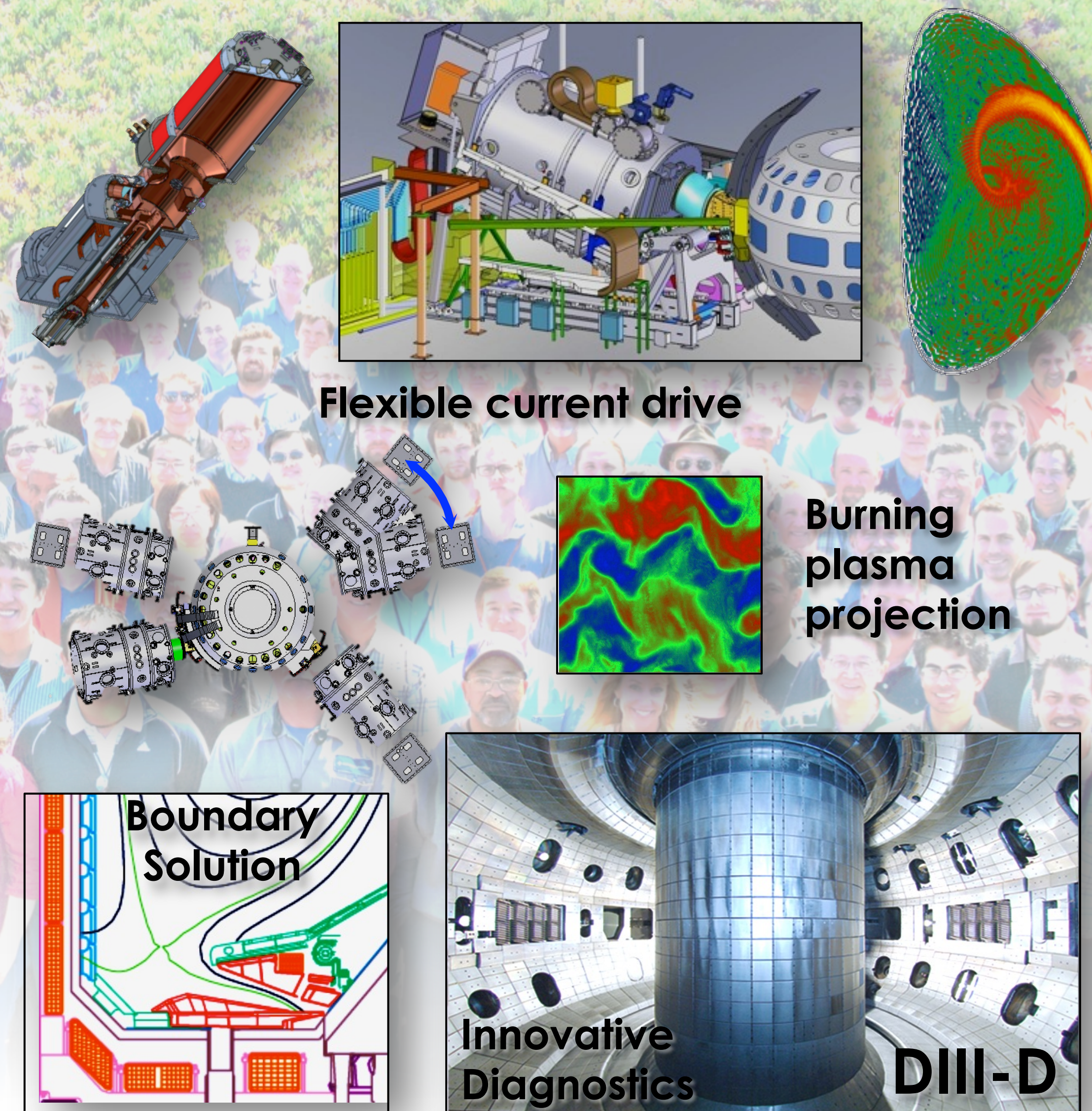
Establishing the Physics Basis for Sustaining a High β Burning Plasma in Steady-State

by

R.J. Buttery



Presented at the

FESAC 10 Year Program Planning Meeting

Gaithersberg

June 3rd 2014

GENERAL ATOMICS

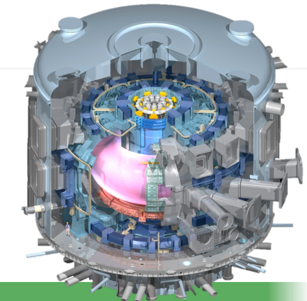
Our Vision of the 10-Year U.S. Program to Enable Success in ITER and the Start of an FNSF Design in the Early 2020's

2014 — **2023**

Validated Integrated Modeling

Prepare Burning Plasma Physics Basis

- Disruption and ELM Solutions
- Assess & optimize behavior in BP relevant conditions



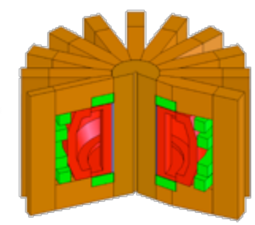
ITER Operation

Tokamak power & performance upgrades

Determine Steady State Path

- Develop self-consistent, self-sustaining regime & extend to long pulse
- High efficiency Current Drive

FNSF Decision



Divertor & Wall Upgrades

FNSF Design

Solve the Plasma Materials Challenge

- Develop Principles and Test an Optimized Divertor Solution
- Evaluate & assess integration of Reactor Materials

Nuclear Science & Enabling Technology

- Develop Nuclear Materials & Breeding Blankets
- High T Superconductors and high Thermal Efficiency

DEMO Design

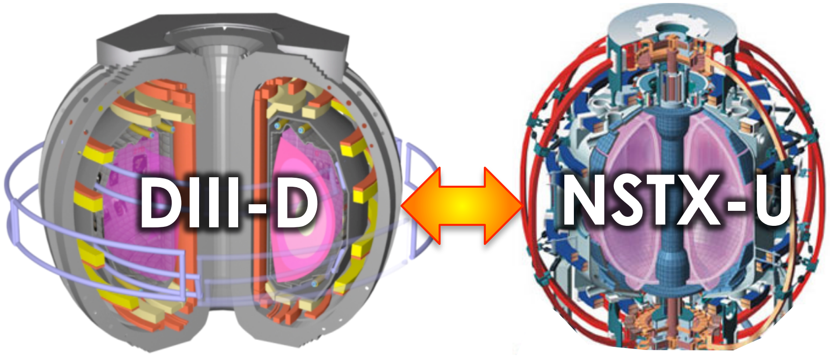
Need Steady State Initiative to enable FNSF decision in 10 years

Steady State Research is Critical to Fusion Energy Path, Requiring Continued AT and ST US Leadership

FNSF provides unique insights in path to fusion energy:
- ***Resolve Tritium breeding***
- ***Develop nuclear-hard materials and components***
- ***Extract high grade heat***

- **Steady state research required to:**
  – Resolve design point for FNSF
  – Determine optimization for ITER and other long pulse facilities
  – Identify the path to DEMO

- **DIII-D and NSTX-U provide world leading & complementary capabilities to resolve physics for fusion reactors**



  – Highly flexible, well diagnosed, reactor relevant solutions for > τ_R
  – Low vs high torque and ρ_e
  – Complementary current drive *(ECCD, Helicon vs HHFW, helicity injection)*
  – Complementary boundary approach *(cryopumping vs lithium)*

DIII-D and NSTX-U provide physics basis for steady state regime, additional validation from long pulse facilities abroad

Steady-State Operation Requires Demonstration of a Self-Consistent Operating Scenario

Physics need	FNSF Objective	Motivation
High pressure limit	High neutron flux	Tritium breeding
Fully non-inductive current sustainment	High neutron fluence	Materials testing
Dominant self-driven current & efficient non-inductive current drive	Low recirculating power	Minimize stress on heat handling systems Minimize size and operating cost

- **Self-consistent scenarios must meet these objectives simultaneously**
- **Both scenario demonstration and physics understanding are required for FNSF design start with high confidence**

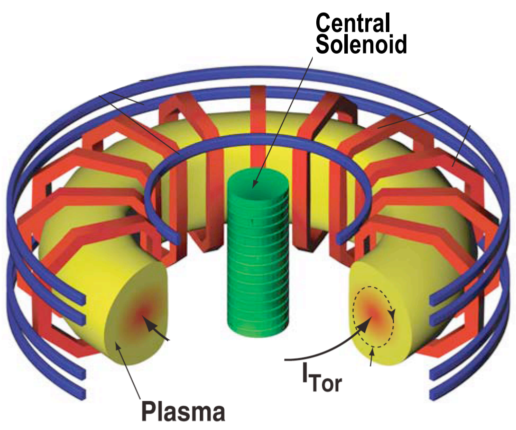
This talk will focus on AT side, anticipating similar talk on ST side

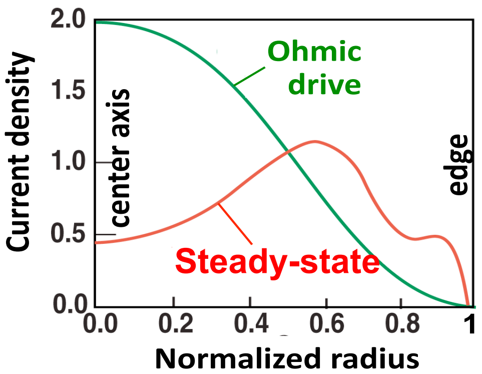
A Steady-State Burning Plasma Requires Both High Plasma Pressure and Self-Driven Plasma Current

- **Goal:** $\underbrace{\text{High pressure}}_{\text{Fusion power}} + \underbrace{\text{High self-driven current}}_{\text{Steady-state \& high energy gain}}$

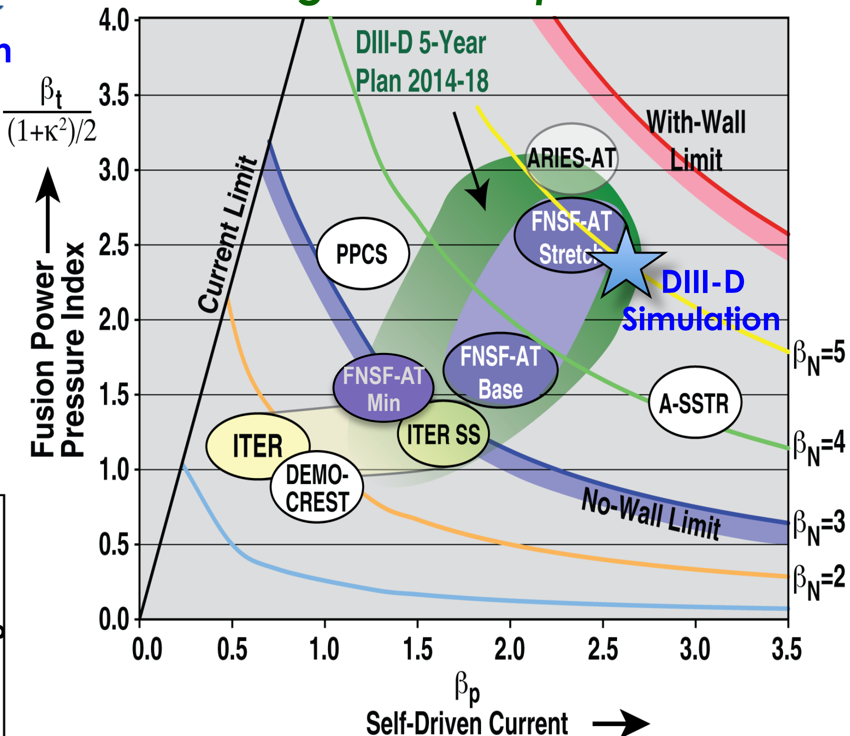
$$I_{\text{steady state}} = \cancelto{\sim 0}{I_{CS}} + I_{\text{self-driven}} + (I_{NBI} + I_{\text{waves}})$$

- **Heating & current must be driven off-axis for self driven current & high β stability**



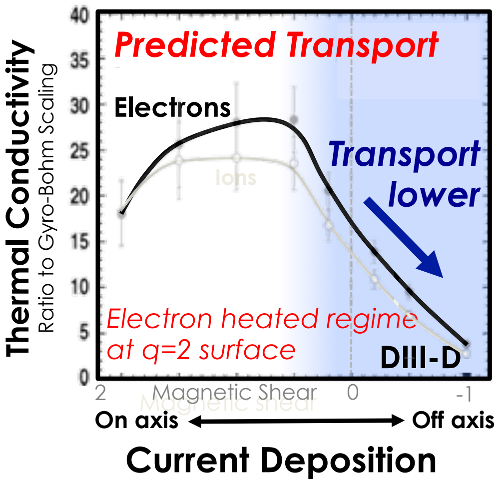


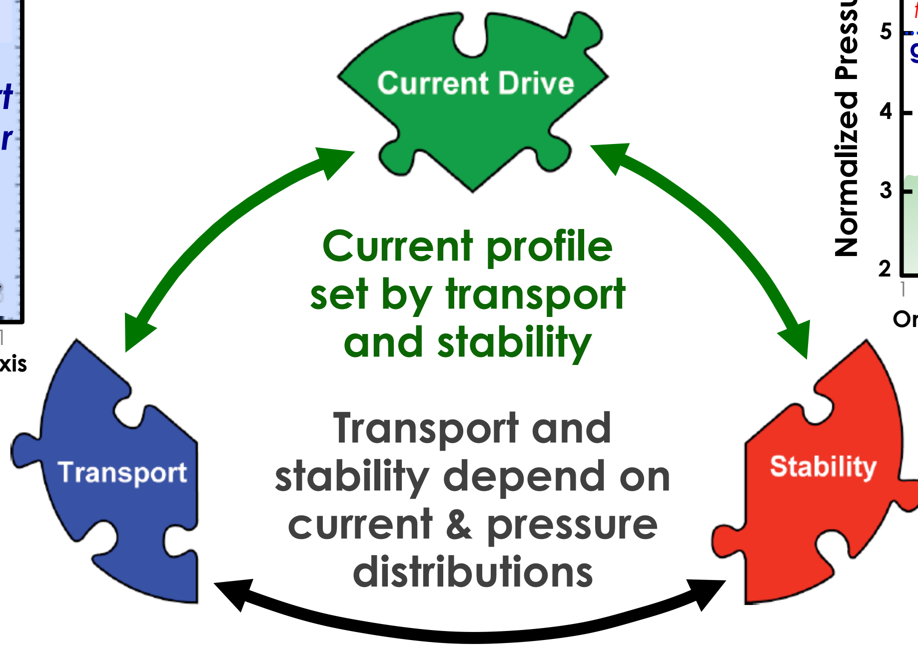
Range to be explored:

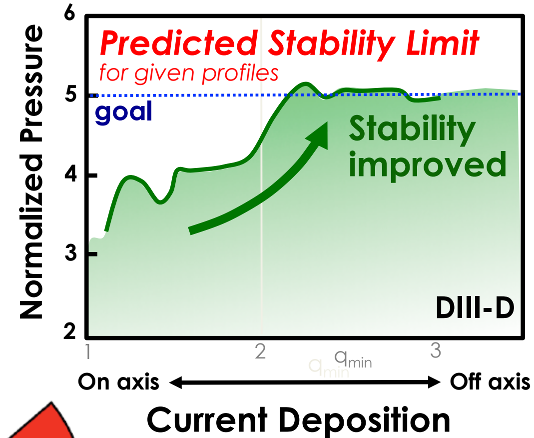


Tokamak steady state exploits a synergy between off-axis heating and current drive, and high β operation

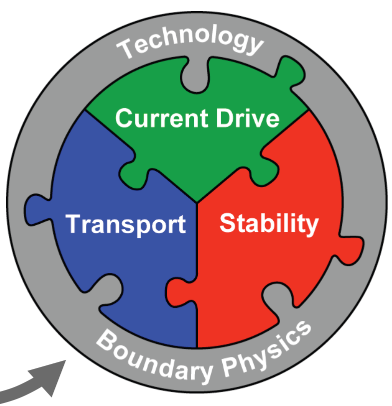
Transport, Current Drive & Stability are Tightly Coupled in Steady State Scenarios







- **Requires development of a self-consistent solution**
  - Test convergence at reactor relevant parameters
  - Must project to burning plasma: e⁻ heating, low torque
  - Test and optimize with a **compatible boundary solution**

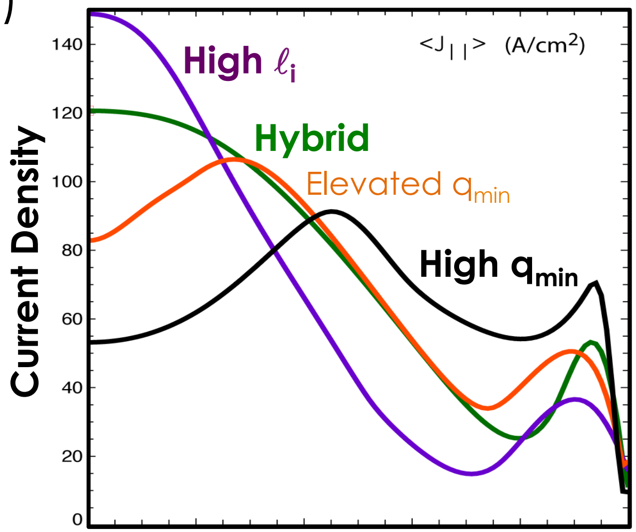


Existing tokamaks can resolve these physics issues

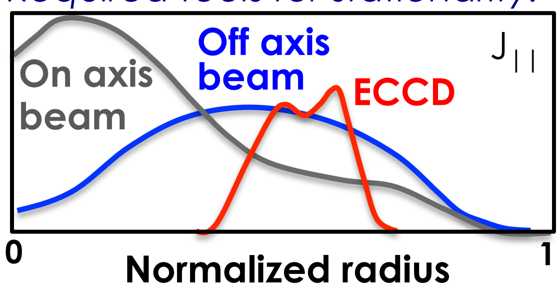
Heating and Current Drive Flexibility Required to Develop the Basis for High β Steady-State Operation

- **Challenge: Maintain non-inductive regimes at high pressure**
  - Solutions optimize with increasing pressure(β_N)
- **DIII-D off axis NBI & ECCD provide the tools needed to explore the solution**

Regime	Strength	Challenge
High q_{min}	β_N=5 potential. No disruptions	Fast ion transport
Hybrid	High confinement. Efficient CD	β limit
High ℓ_i	High confinement and β_N=5	Sustainment. n=0. Tearing modes



Required tools for stationarity:



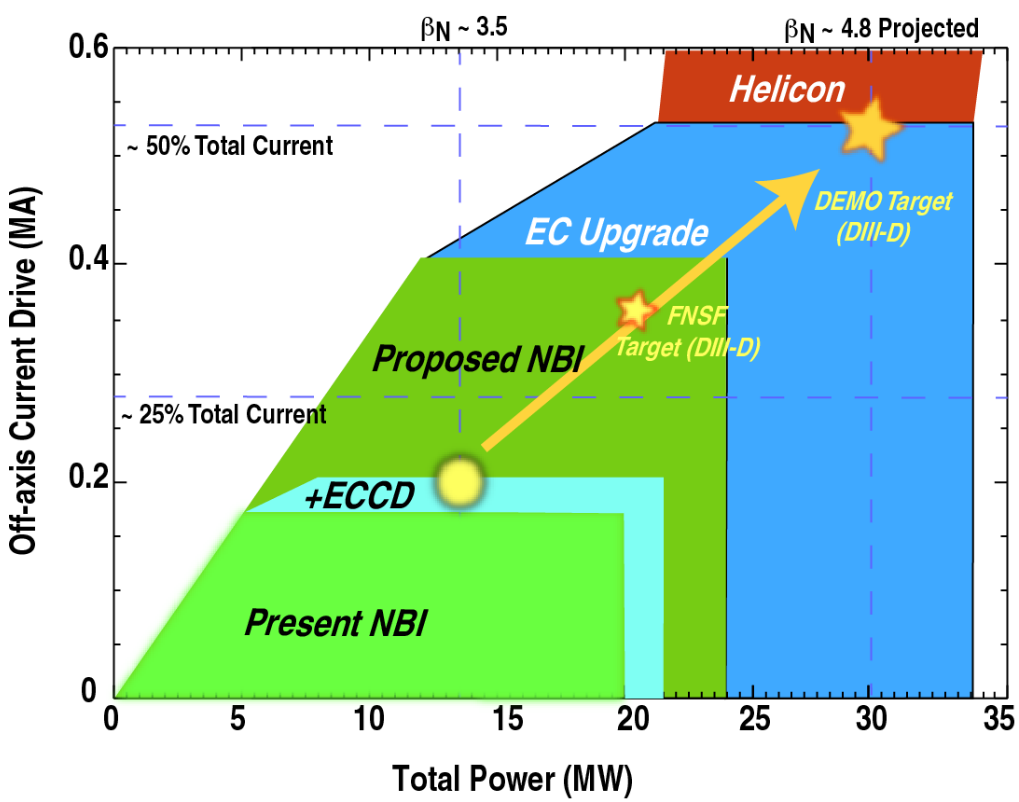
Directions needed:

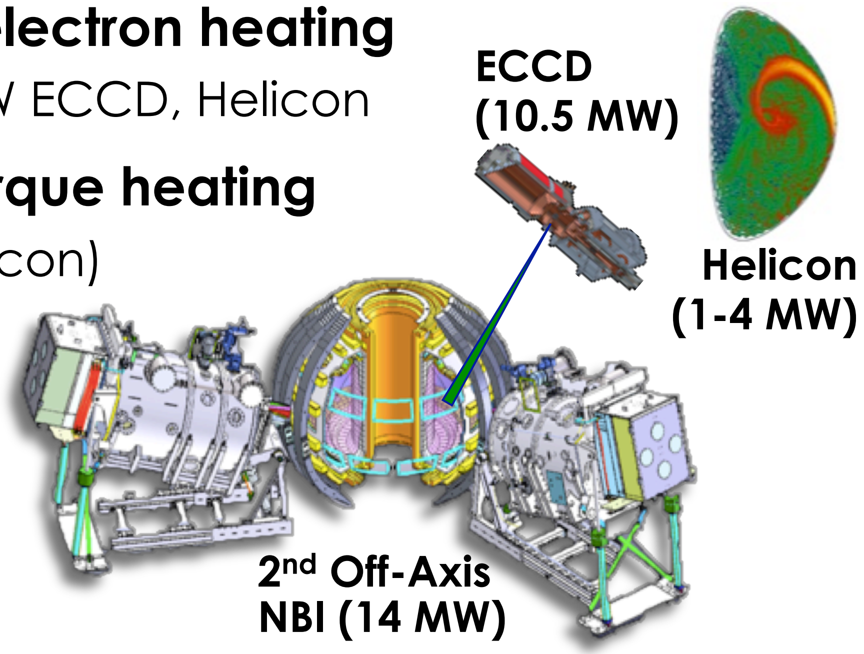
- Higher β & $J_{off\text{-}axis}$ for neutron flux and $I_{self\text{-}driven}$
- Increased electron heating and lower torque

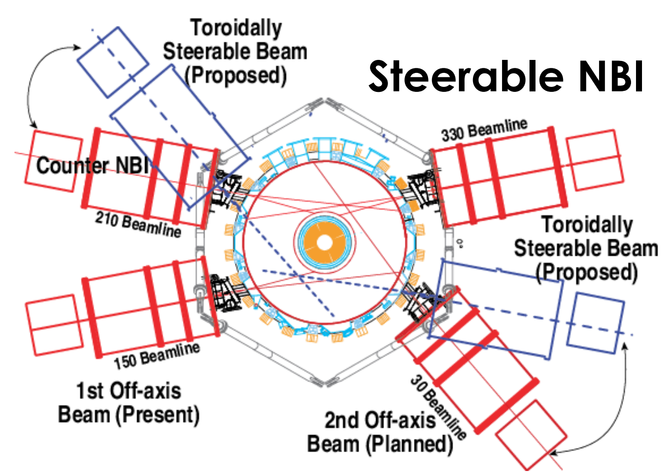
➔ Enable decision on FNSF & physics basis for DEMO

H&CD Upgrades Will Enable Detailed Assessment of FNSF Scenarios and Exploration of Attractive DEMO Solutions

- **Increased off axis current drive and electron heating**
  - 2nd off axis beam & energy rise, 10MW ECCD, Helicon
- **Increased total, "co-" & balanced torque heating**
  - Toroidally rotatable beams (+EC+Helicon)







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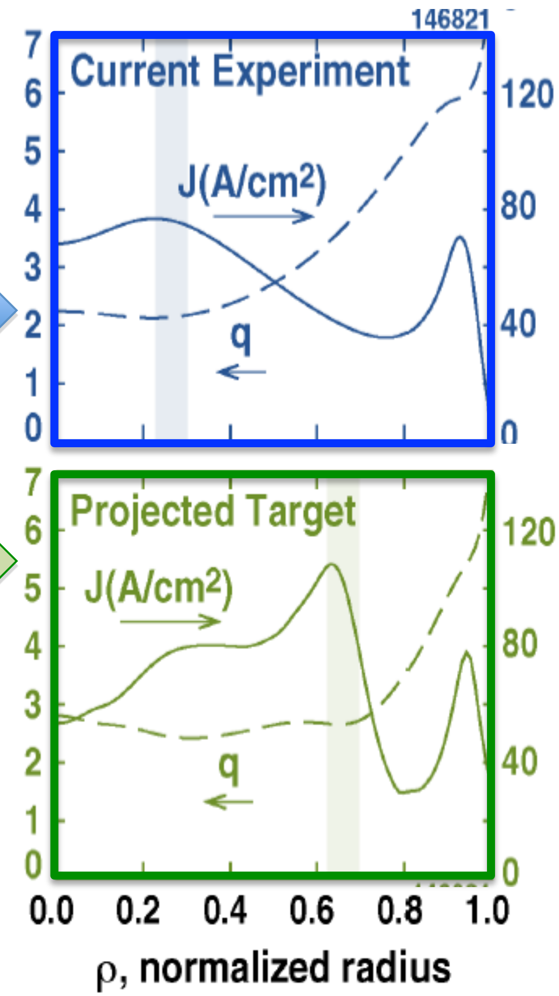
Higher Power NBI & ECH, and a 2nd Off-Axis Beamline Enable Access To Steady State Fusion Energy Conditions

- **Integrated modeling (transport, stability, CD) used to assess path to fully non-inductive β_N=5 with q_{min}>2 in DIII-D**
  - ECCD tuned to achieve $q_{min}=2+\varepsilon$

	On-Axis Power (MW)	Off-Axis Power (MW)	ECH Power (MW)	β_N Transport Limit	β_N Stability Limit
Present NBI@80kV + EC upgrade	10	5	9	4.0	4.5
Above + NBI@100 kV	14	7	9	5.2	4.4
Two OANB at 100 kV	7	14	9	5.1	4.9

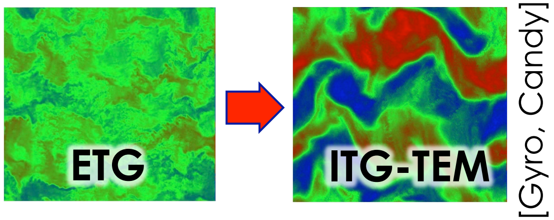


- **Pulse length extension to enable converged solutions for 2 current redistribution timescales**
  - $\tau_R \propto \beta_N^{3/2}$ ➔ increase pulse length x2 to 7s

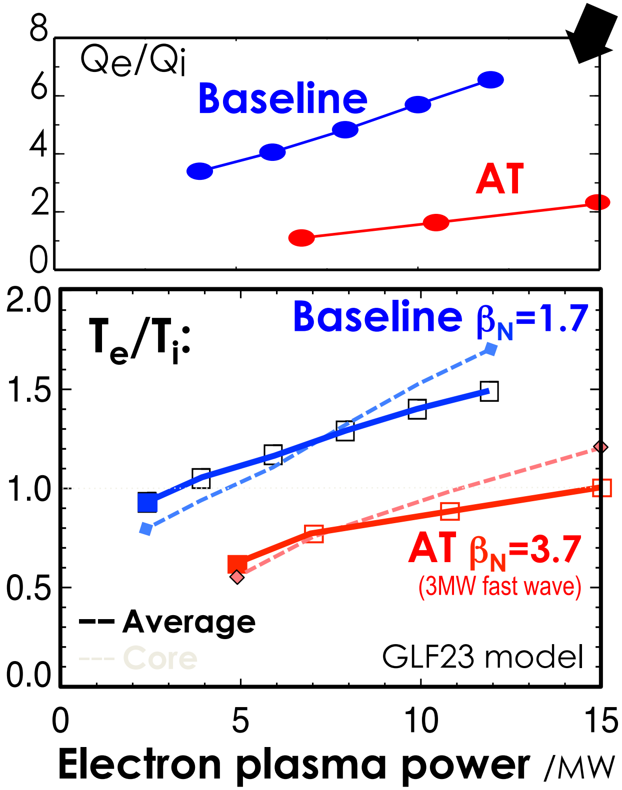
Enables DIII-D to explore reactor optimization

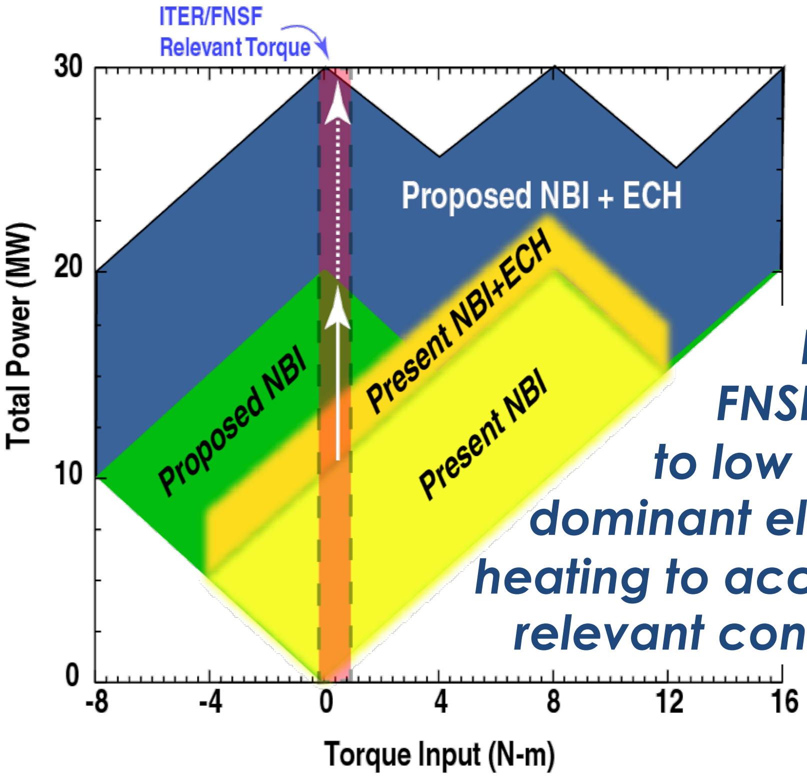
Increased Electron Heating Will Enable Projection of Steady State Scenarios to Burning Plasma Conditions

- **Transport altered with low torque e⁻ heating**
- **Increased ECH & E_{NBI} will heat like fusion α's**
  - Low torque, fuelling, ν^* & fast ion content



- **Enables model validation and optimization as T_e/T_i, ∇T_e, ∇T_i, & ExB shear varied over burning plasma relevant range**





Extend FNSF-base to low torque dominant electron heating to access BP relevant conditions

Initiative on Development of a Steady State Physics Basis is Critical to U.S. Path to Fusion Energy & an FNSF Decision

Delivering the basis for high β burning plasma steady-state will:

- *Provide exciting research opportunities at the frontier of fusion energy sciences*
- *Enable the US to extend its world leadership role in this key area and expand its influence worldwide through strategic partnerships with international facilities*
- *Develop validated fully non-inductive solution & projection to FNSF, and provide the basis for steady-state in ITER & DEMO*

This physics basis can be readily established with exploitation and reasonable development of the DIII-D and NSTX-U facilities

This Initiative is an Essential Element of the 10-Year U.S. Program