Overview of Activities in Steady State Integration

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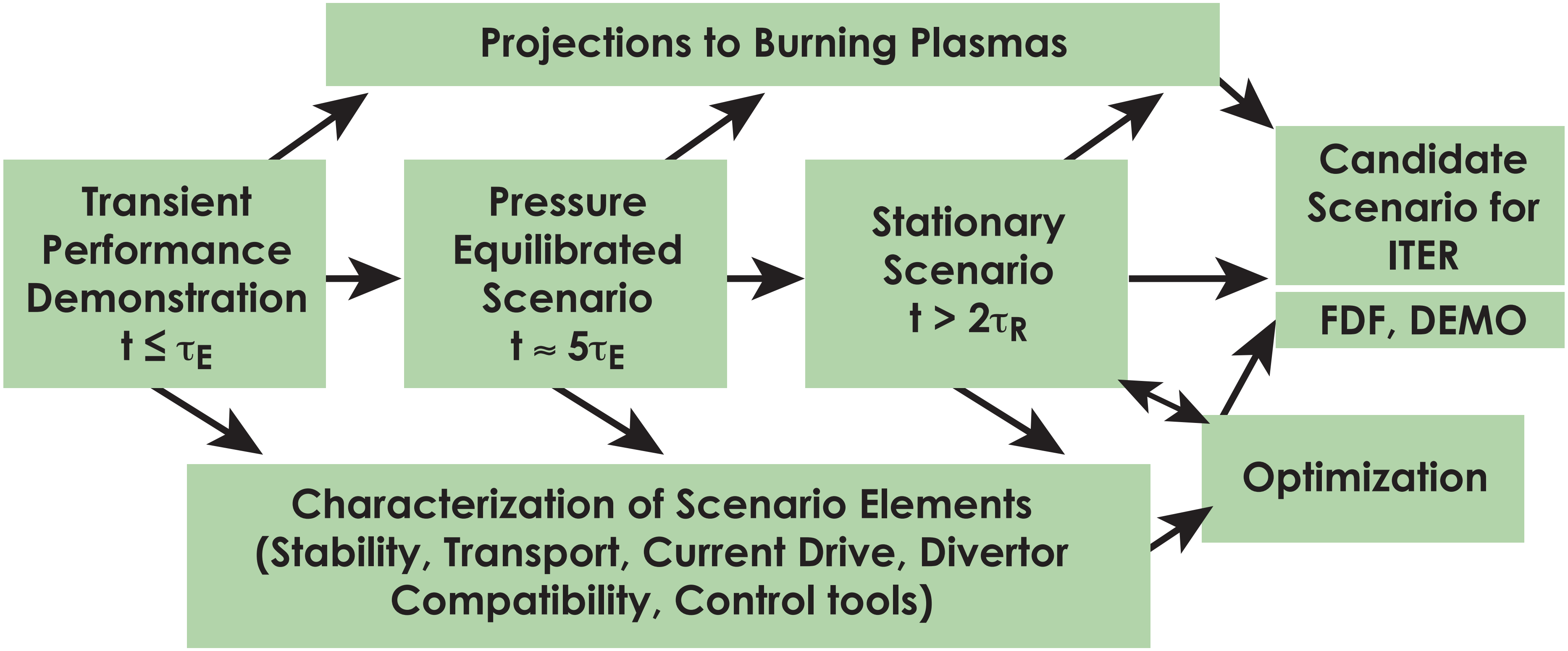
DIII-D
NATIONAL FUSION FACILITY

GENERAL ATOMICS

Scenario Development Roadmap



Projections to Burning Plasmas

Transient Performance Demonstration $t \leq \tau_E$

Pressure Equilibrated Scenario $t \approx 5\tau_E$

Stationary Scenario $t > 2\tau_R$

Candidate Scenario for ITER

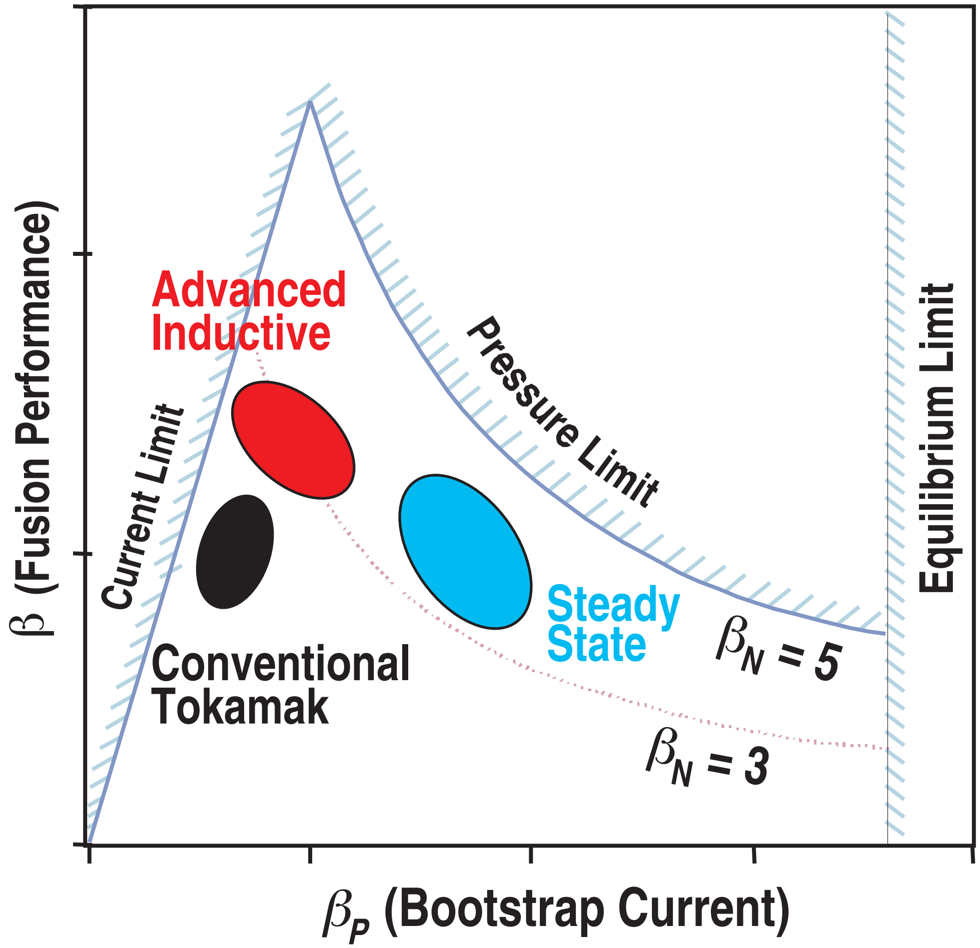
FDF, DEMO

Optimization

Characterization of Scenario Elements (Stability, Transport, Current Drive, Divertor Compatibility, Control tools)

Strategy for Optimizing Tokamak Performance

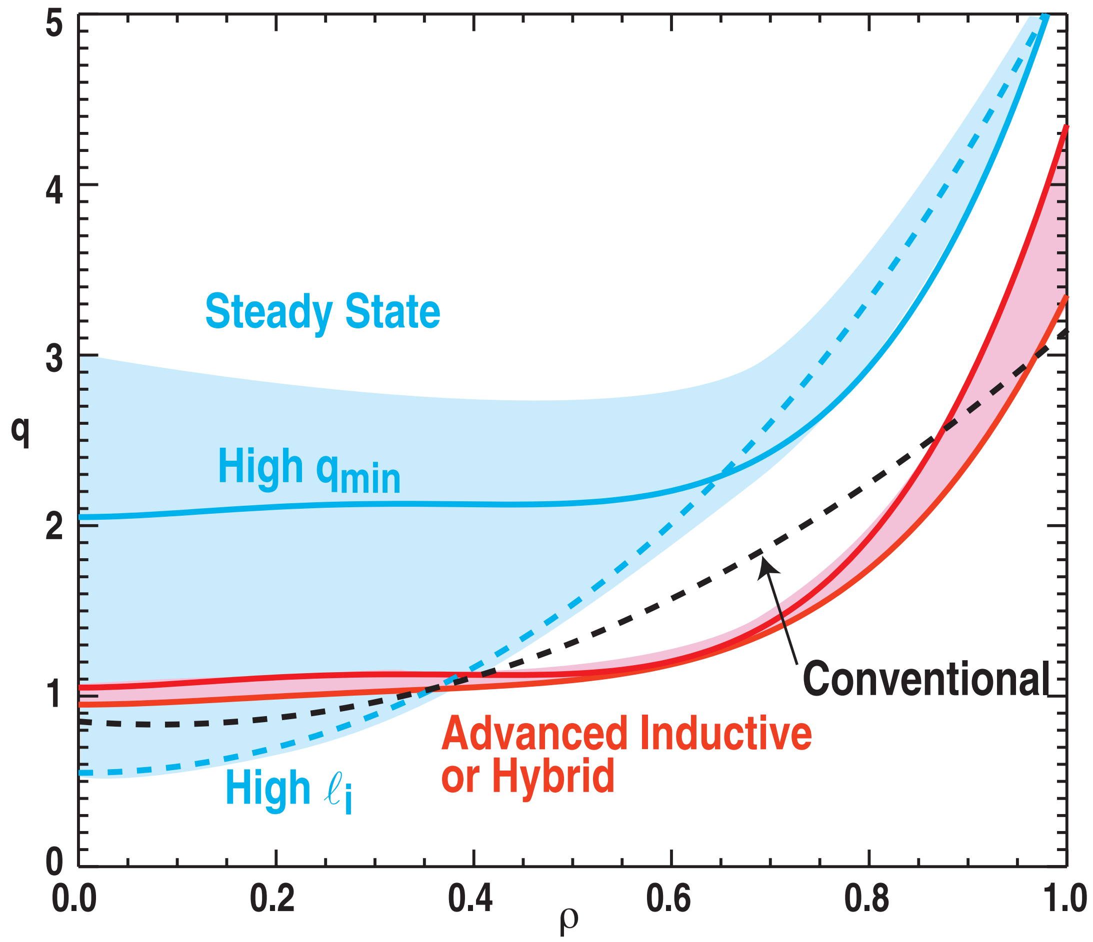
The DIII–D program strategy is to determine the operational limits and establish the scientific basis for design choices in future tokamaks



- Conventional tokamak scenarios (like the ITER baseline scenario) run at relatively low pressure near the current limit
- Advanced inductive scenarios have higher pressures, but still are close to the current limit
- Steady-state scenarios move away from the current limit to maximize the self-driven bootstrap current and push toward the pressure limit to maximize fusion performance without current drive

Advanced Scenarios Under Development in DIII–D Are Uniquely Associated with Distinct Current Profiles

The ultimate goal of advanced scenario development is a fusion powerplant solution with high power density, low circulating power, and high availability

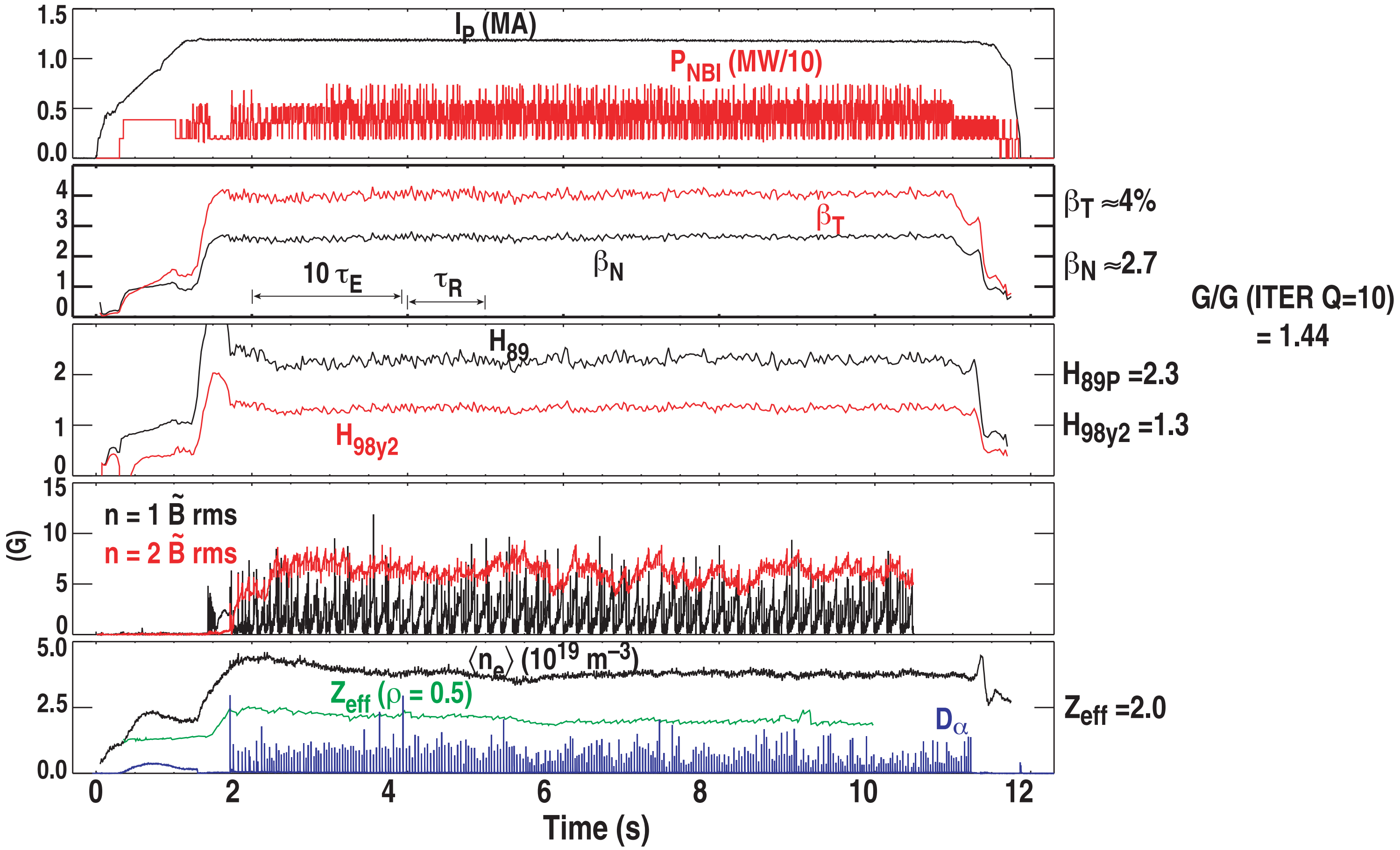


Optimization objectives:

- **Steady state**
  - True steady-state operation at high fusion energy gain
  - Two distinct approaches – high q_{min} and high ℓ_i
- **Advanced inductive or hybrid**
  - Maximum fusion power, maximum fluence per inductive pulse (increased duty cycle)

Outlook for Hybrid and Advanced Inductive Scenarios (3–5 Years)

- **Both hybrid (q_{95} ~4) and advanced inductive (q_{95} ~3) scenarios have been demonstrated to stationary conditions on the resistive timescale on DIII–D and other tokamaks**



Outlook for Hybrid and Advanced Inductive Scenarios (3–5 Years) (Cont.)

- **The focus now is on developing the physics basis for projection:**
  - Current profile evolution is not neoclassical – is there confidence that it will be realized in future tokamaks?
  - Present confinement data dominated by hot-ion cases with significant toroidal rotation – how do these effects change the projection to future tokamaks?
  - Solutions for transient and stationary heat exhaust need to be integrated into the scenario
- **ITER is the main customer for this scenario. The key design issue requiring near-term attention is the capability of the present first wall, limiter, and poloidal field coil set design to provide the target q profile at current flattop required to access this scenario.**
- **Optimization and projection studies will benefit greatly from pulse length and heating system upgrades, particularly FW and EC**
  - Equilibrated temperatures and low torque input from electron heating removes uncertainties in projection to ITER
  - Extended pulse length allows demonstration of stationary conditions with heat-flux and ELM mitigation solutions
  - More total power allows larger range of operating parameters to refine projections

Long-Range Vision for Steady-State Scenario Development in DIII–D Points to DEMO with Advanced Scenario

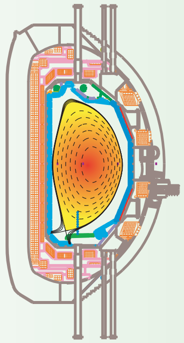
Steady-State Scenario for ITER

f_{BS} ~55%

β_N ~ 3.5

f_{NI} = 100%,

t_{DUR} ~5s

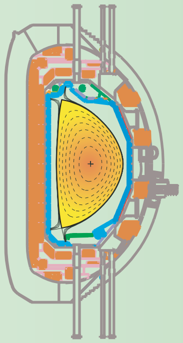


Steady-State Scenario for FDF

f_{BS} ~ 70%

β_N ~ 4

t_{DUR} ~ 10 s



Establish Physics Basis for Steady-State Powerplant Optimization

$f_{BS} \rightarrow 90\%$

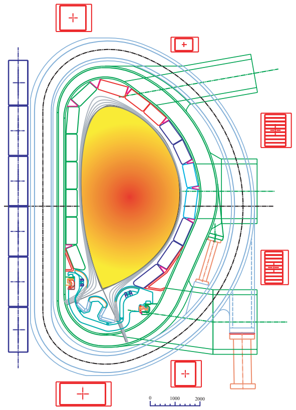
$\beta_N \rightarrow 5$

$t_{DUR} \rightarrow 10$ s

ITER

$Q \geq 5$

t_{DUR} ~1000s



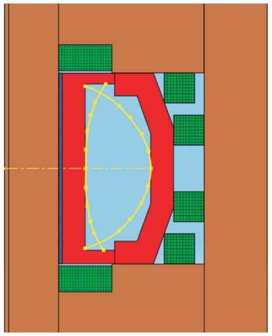
FDF

Net tritium

(1 kg/yr)

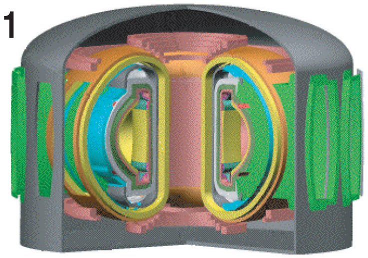
Blanket testing

(→ 1 MW yr/m^2)



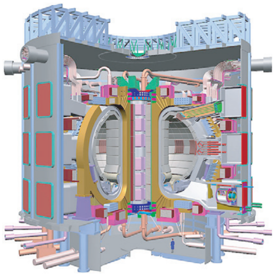
DEMO-AT

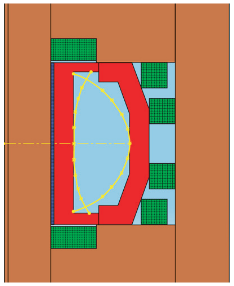
Plant Q > 1

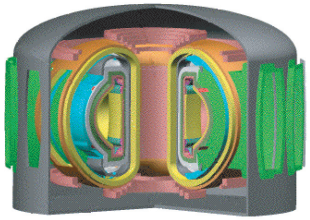


DIII–D Advanced Scenario Development Timeline (5 Year Perspective)

	1–2 years	3–5 years
ITER/ FDF Scenario	Demonstration of f_{NI} = 1 operation for > τ_R	Physics basis for projection operation > 2 τ_R β limit optimization Bootstrap optimization Integration of boundary solutions
DEMO-AT	Transient exploration of routes to β_N > 4	Demonstration of $\beta_N \Rightarrow 5$ for > 5 τ_E







Where Do We Want to Be in 5 Years?

ITER and FDF scenarios:

- Clear existence proof of an attractive scenario, including integration of boundary solutions
- Substantial physics basis for projection of ITER and FDF
- Reproduction of ITER scenario (or at least key elements) on JET or JT–60U
- Definition of requirements to reproduce FDF scenario on KSTAR and JT-60SA
- Determintion of control demands on heating and current drive systems

β_N = 5 Scenario:

- Achieve β_N = 5 for $>5\tau_E$
- Define upgrade path to $>2\tau_R$ in DIII–D (if possible)
- Define requirements to reproduce scenario in steady state on JT-60SA

What Will it Take to Reach These Goals?

- Significant increase in EC or FW power
  - Removing the uncertainties in the projection due to $T_i > T_e$ and rotation requires substantial central electron heating (hybrid and steady-state)
  - Maintaining $\beta_N = 5$ for 5 τ_E requires ~20 MW with little central current driven
  - Demonstration of control requires ~25% more power than the equilibrium condition
  - Based on 2:1 ratio of electron to ion energy transport in present experiments, 10–15 MW of electron heating in the plasma is needed for 10 s (present systems 7.5 MW)

What Will it Take to Reach These Goals? (Cont.)

- Pulse length extension to 10 s (coils, NBI, FW)
  - With increased electron heating, the resistive time will approach 4s, therefore 2 τ_R = 8 s
  - Demonstration of control on the resistive time scale requires long pulses or much higher power