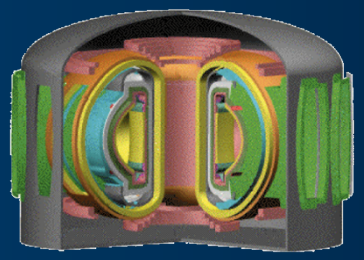
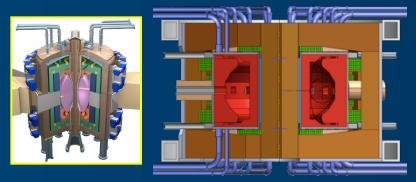
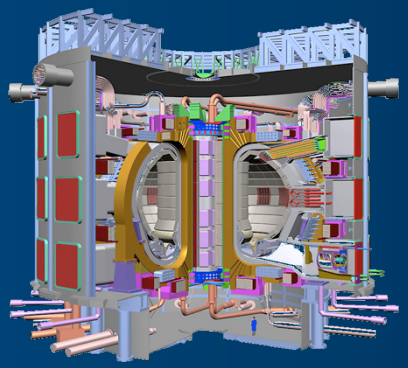
Strategy of a Fast Track Path to Fusion Energy

by
T.S. Taylor,



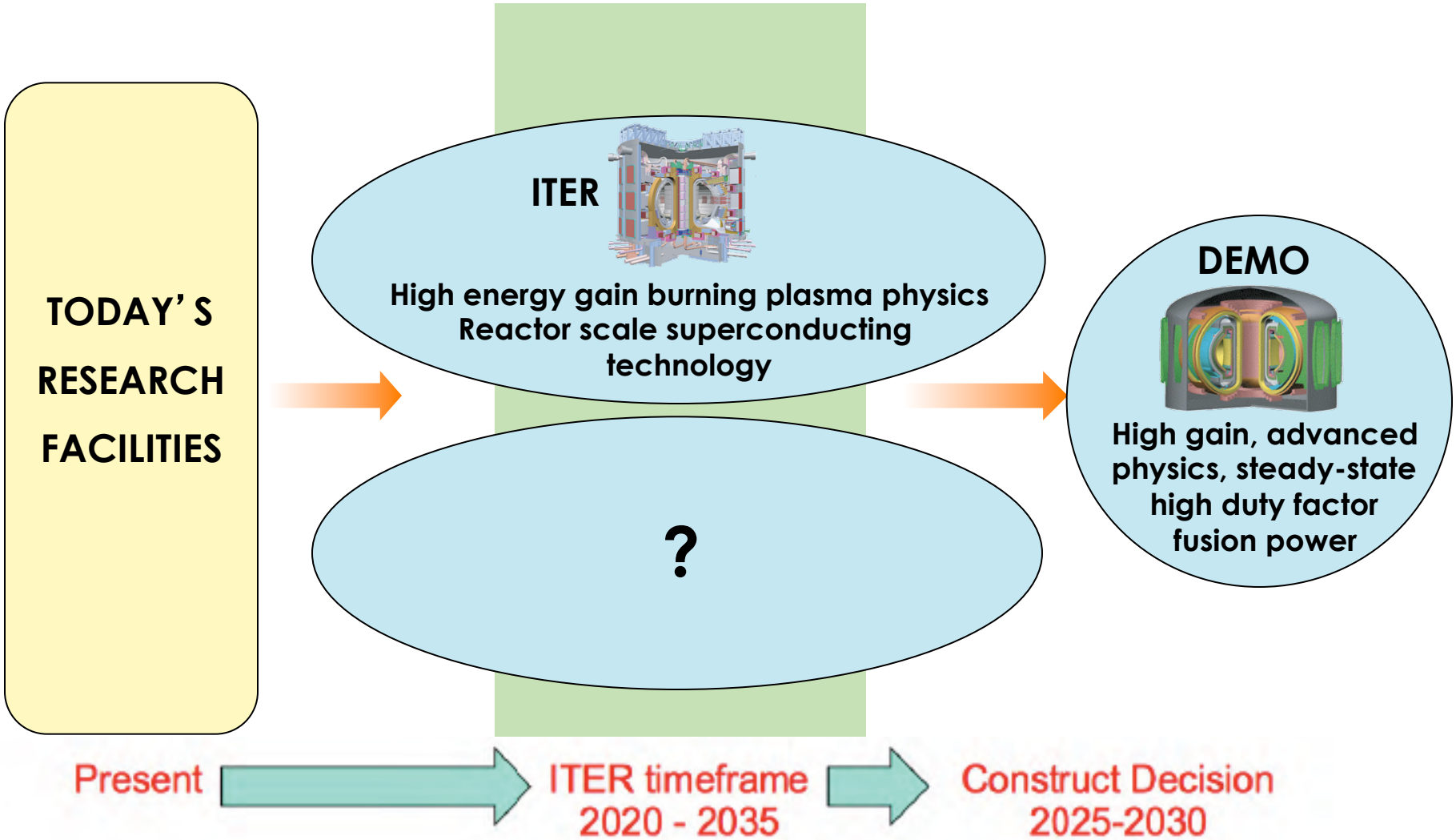
Presented at
Second Workshop on MFE Development Strategy
Hefei, China





May 30, 2012

In Addition to What We Learn in ITER, What Else Do We Need to Learn to Build an Electricity Producing DEMO?



Steps in Fusion Development Are Known

Fast track development requires parallel steps and management of risk

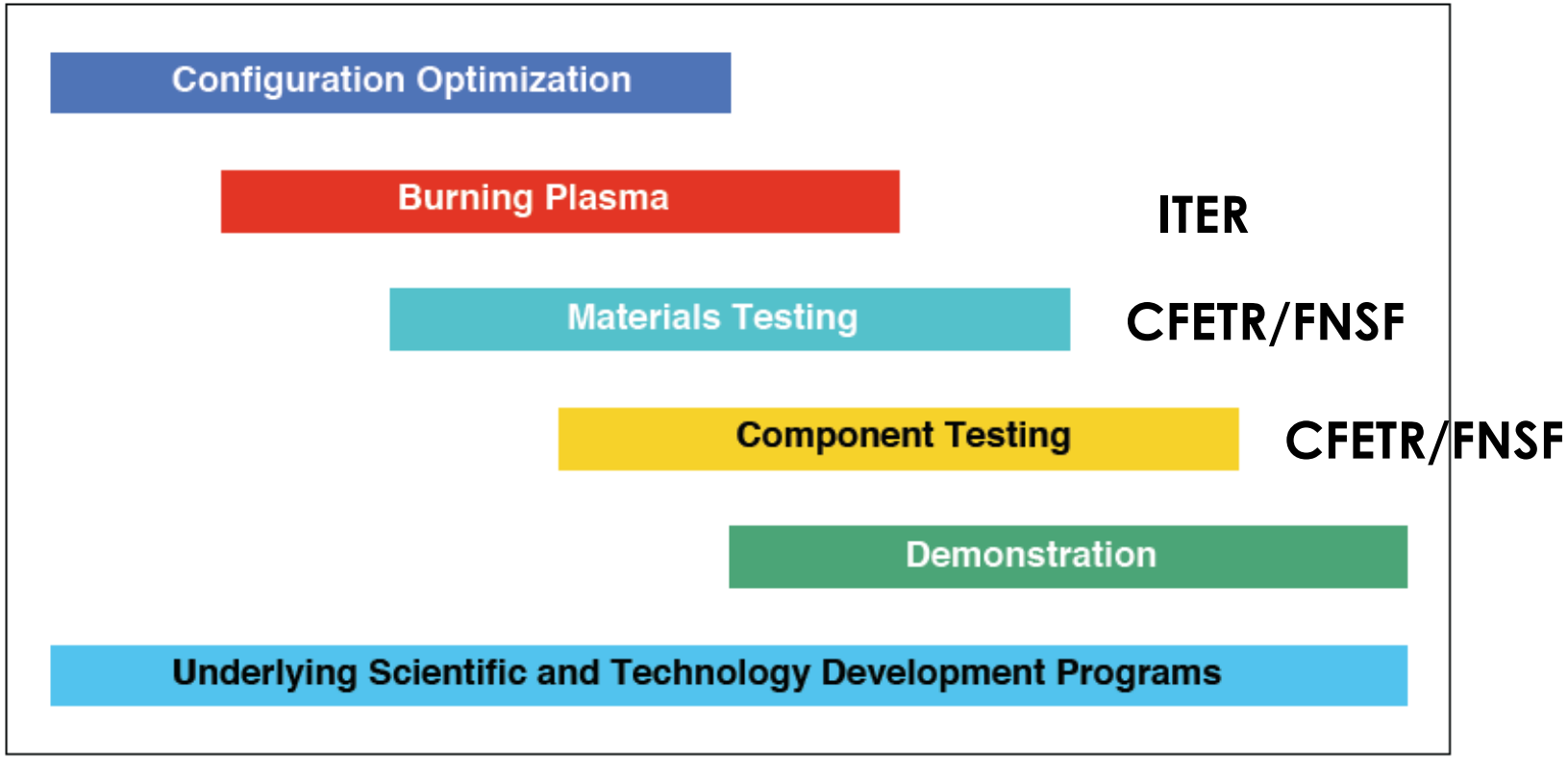
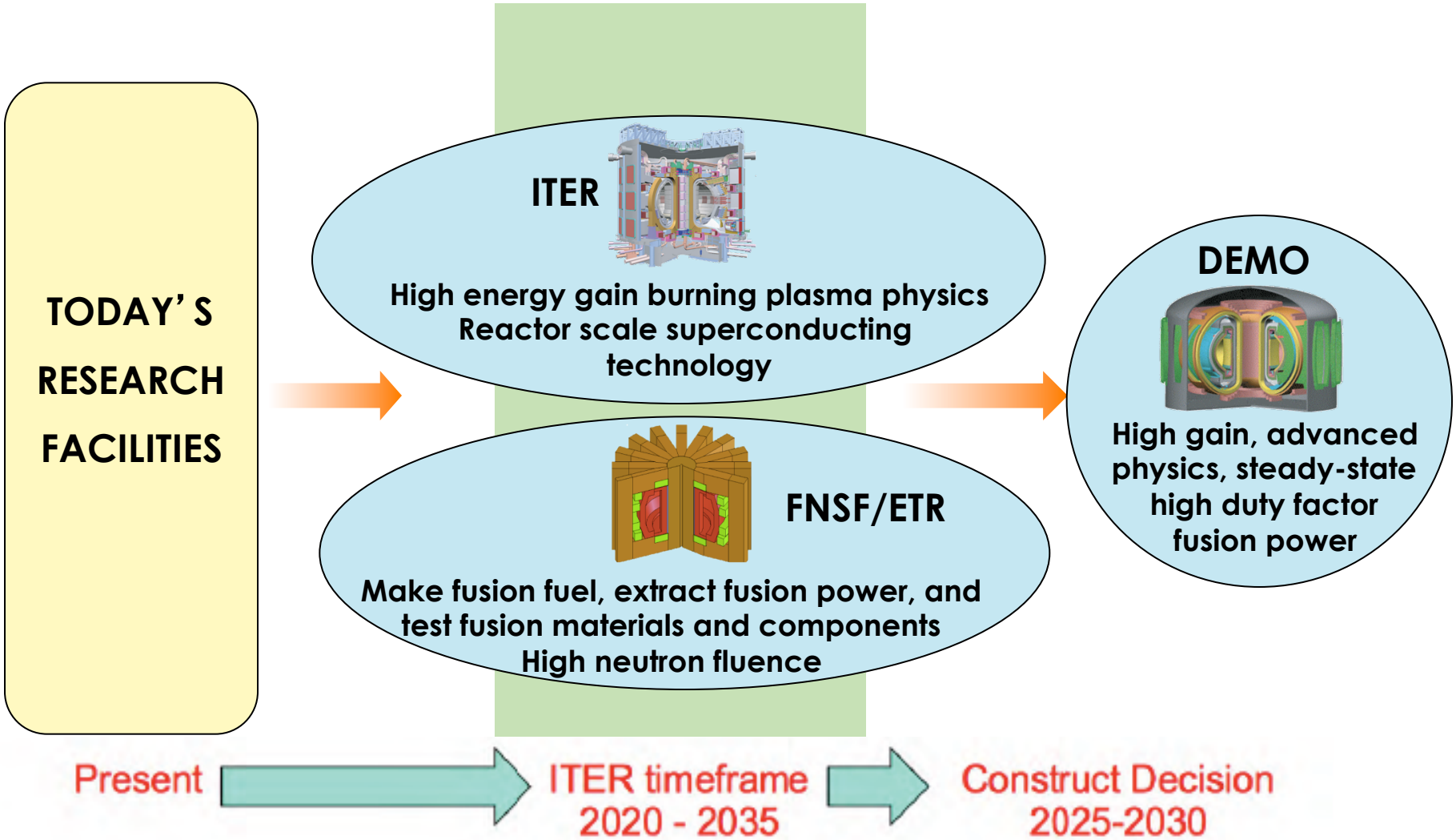


Figure XS3. Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma, fusion chamber and power technologies form the foundation for research on the major facilities.

A Fusion Nuclear Science Program (FNSP) is Needed to Prepare for an Electricity Producing DEMO following ITER



Principles for a Fusion Nuclear Science Facility or Experimental Test Reactor in Preparation for DEMO

- **Addresses key identified gaps to DEMO**
- **Complements ITER**
  - Not necessary to duplicate main efforts on ITER
- **Modest size and Q: complements ITER, contains cost**
- **Can be done now** [start design]; **impacts project scope**
- **Research device: accessible, maintainable, replaceable**
- **Modest tritium consumption ➔ limited total fusion power ➔ size**
- **Staged approach: early start, rely on existing materials, learn and improve as you go**
- **On the direct path to an attractive DEMO reactor**

→ **Prepare for DEMO construction triggered by Q=10 in ITER (~2030)**

Remaining Gaps to DEMO Have Been Identified — U.S. MFE Community

2007 FESAC Planning Panel

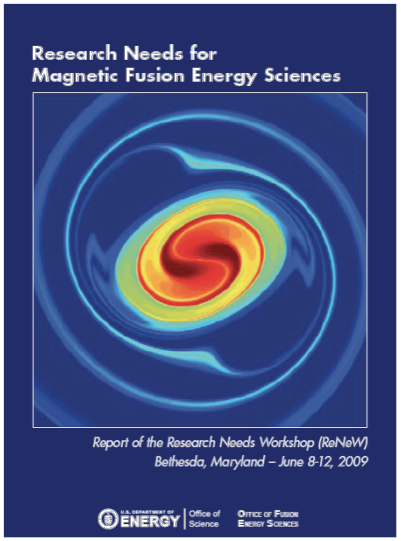
How Initiatives Could Address Gaps

Legend

Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

2009 Research Needs Workshop



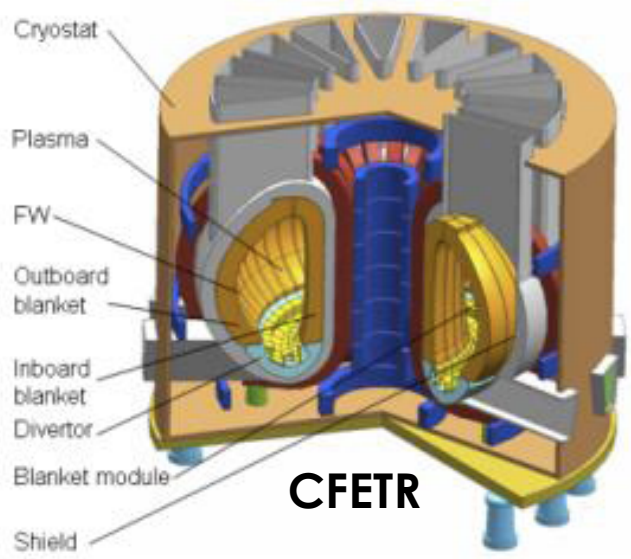
US MFE Leadership –

➡ **Towards a Fusion Nuclear Science Facility (FNSF)**

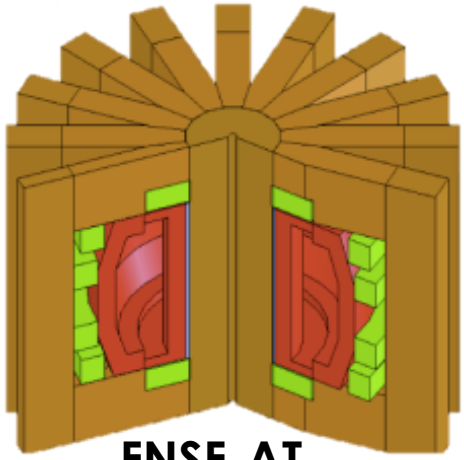
- **Burning Plasma Dynamics and Control** (reliable steady-state)
- **Materials in a Fusion Environment and Harnessing Fusion Power**

Mission Elements of a FNSF/CFETR to Allow Construction Decision on DEMO ~ 2030

- **Tritium Self Sufficiency**
  - Must demonstrate that fusion can make its own fuel
  - Breeding blanket testing
  - Tritium supply is limited
- **Test/validate fusion materials**
  - Test materials and components in fusion neutron environment
  - High heat flux components in nuclear environment
- **Produce fusion power in steady-state**
  - Produce high grade heat
  - Demonstrate fusion can make electricity
  - Demonstrate reliable high performance steady-state operation of fusion plasma
  - Produce significant neutron fluence (3–6 MW-yr/m^2, 30–60 dpa)



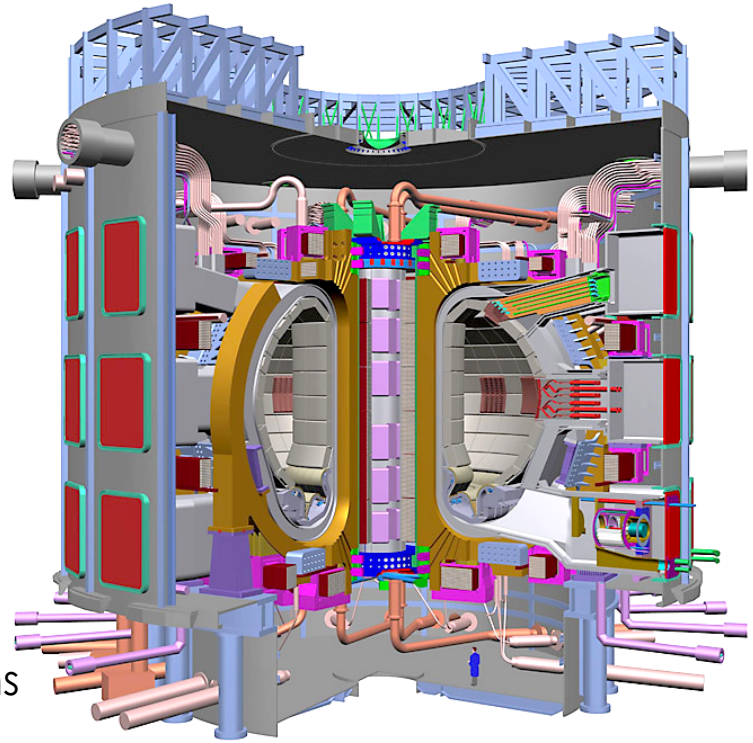
CFETR



FNSF-AT

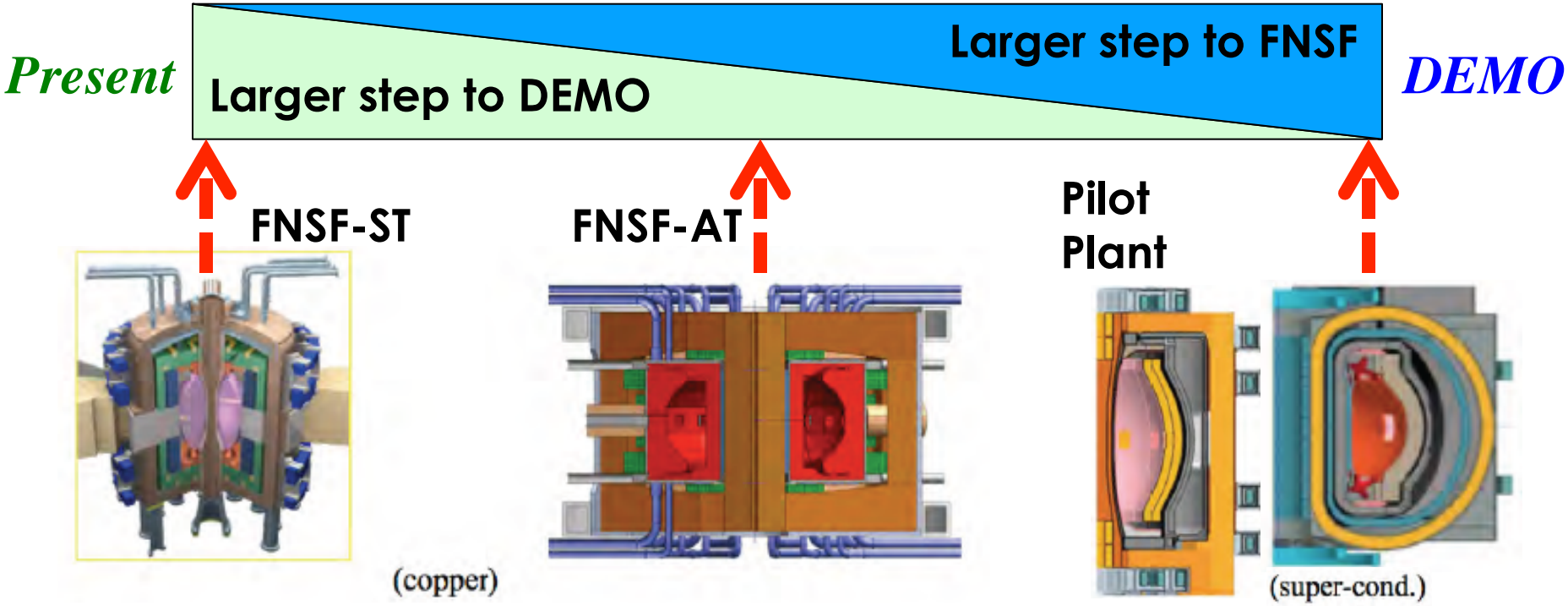
ITER Will Make Significant Progress Toward Fusion Energy

- **ITER is a joint project of the Europe, Japan, United States, Russia, China, South Korea, and India**
  - **Mission:** "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes"
- **ITER will evaluate high gain burning plasmas**
  - Q > 10, dominant self heating
  - Aim at non-inductive steady-state
- **ITER will develop power plant technologies**
  - Large superconducting magnets
  - Remote maintenance and handling
  - Test breeding blankets
  - Tritium fueling/processing systems
  - Diagnostics in harsh environment (neutrons)
  - High heat flux energy removal systems
  - Long pulse heating and current drive systems
  - Plasma quench detection/remediation systems
  - ELM control



Appropriate Size of Next Step Forward?

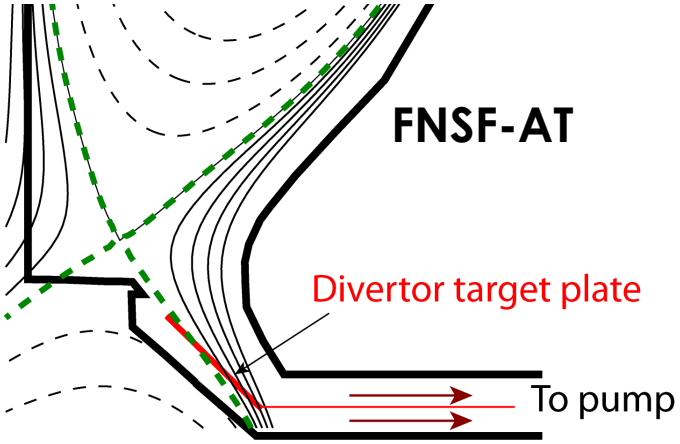
- FNSF choices lie on continuum between present program and DEMO [Ray Fonck, EPRI 2011]

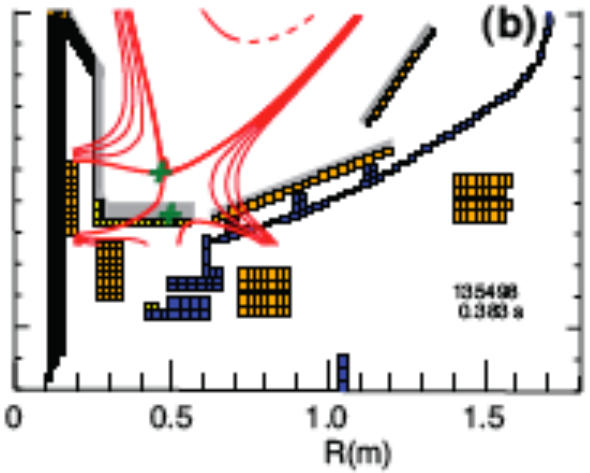


- FNSF-AT can be designed now and operate in parallel with ITER
- Readiness for DEMO construction triggered by Q=10 in ITER (~2030)

Can Start FNSF-AT Design Now

- **Ready now:**
  - Standard coils
  - Standard NBI, EC
  - Standard divertor
  - Proven AT physics "Driven" steady state
  - Proven materials up to 20 dpa
- **Concept is open to new advances:**
  - Demountable superconducting coils
  - Snowflake, SX divertor
  - Negative NBI technology
  - Advanced materials

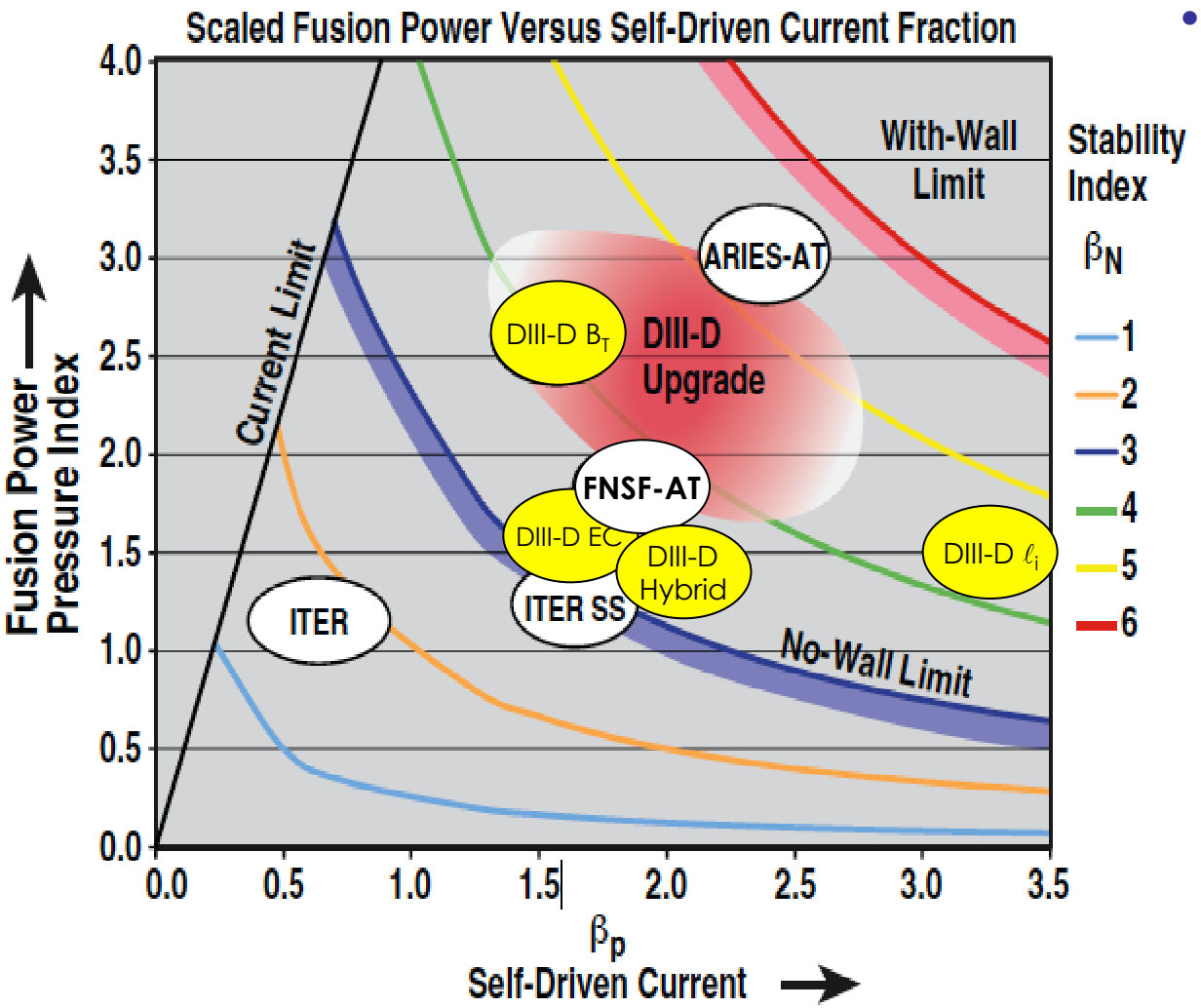




NSTX Snowflake Divertor experiment achieves large reduction of peak heat flux

Soukhanovskii, et al., IAEA 2010

FNSF -AT Can Be Designed Using Proven Tokamak Physics, Can Develop More Advanced Physics Towards DEMO



- **100% non-inductive modes developed on DIII-D bracket FNSF-AT baseline**
  - Negative central magnetic shear
  - High bootstrap fraction
  - Strong shaping beneficial
  - Driven steady-state is less demanding
    - Range of scenarios

Pulse length extension remains

- in next few years, EAST?

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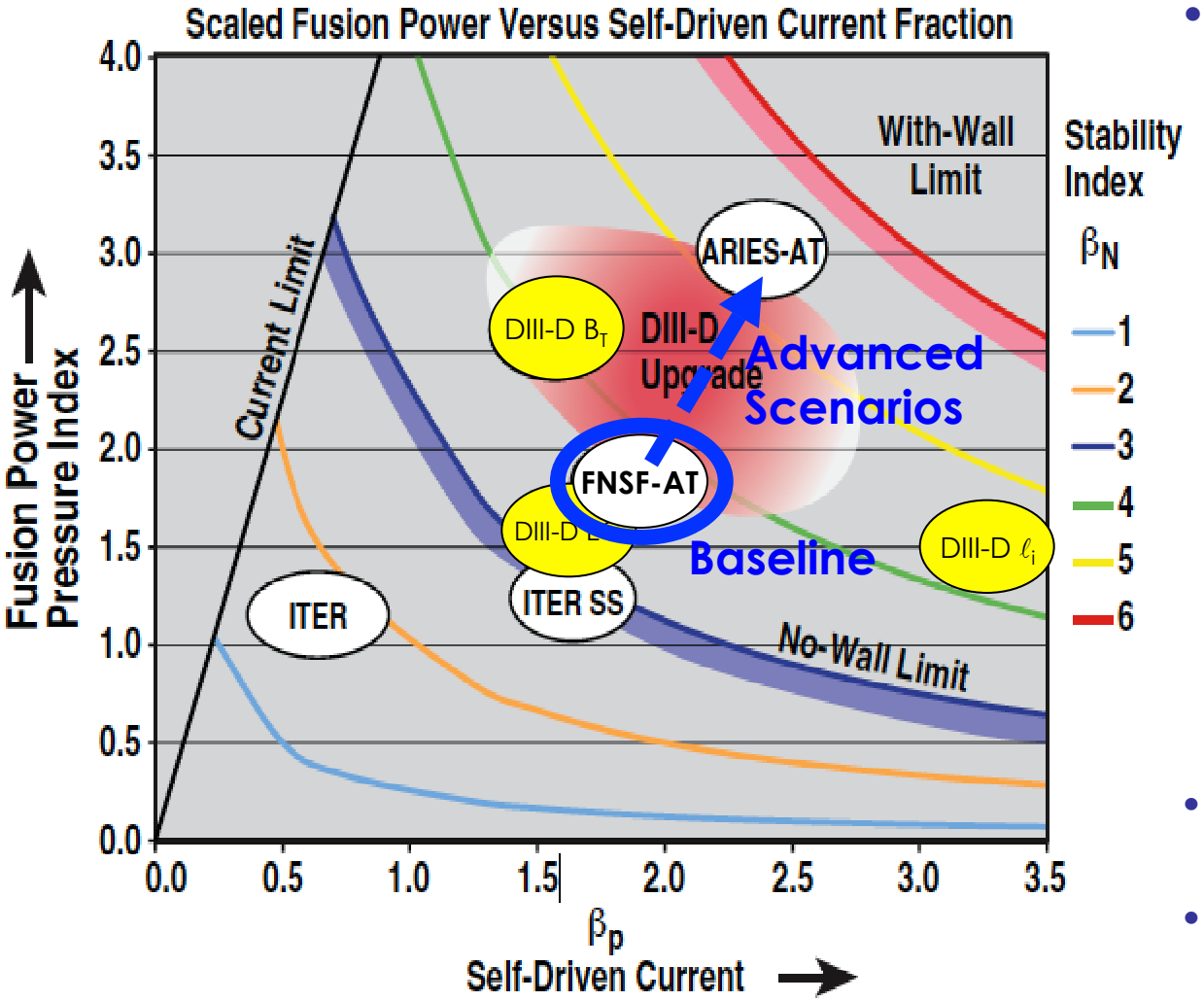

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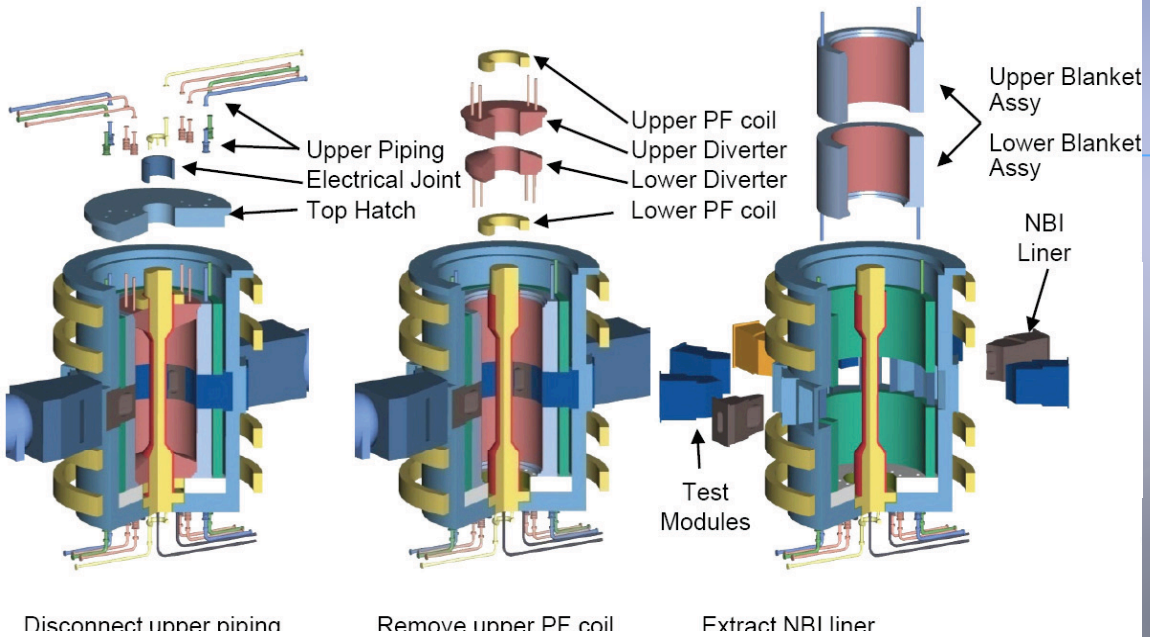
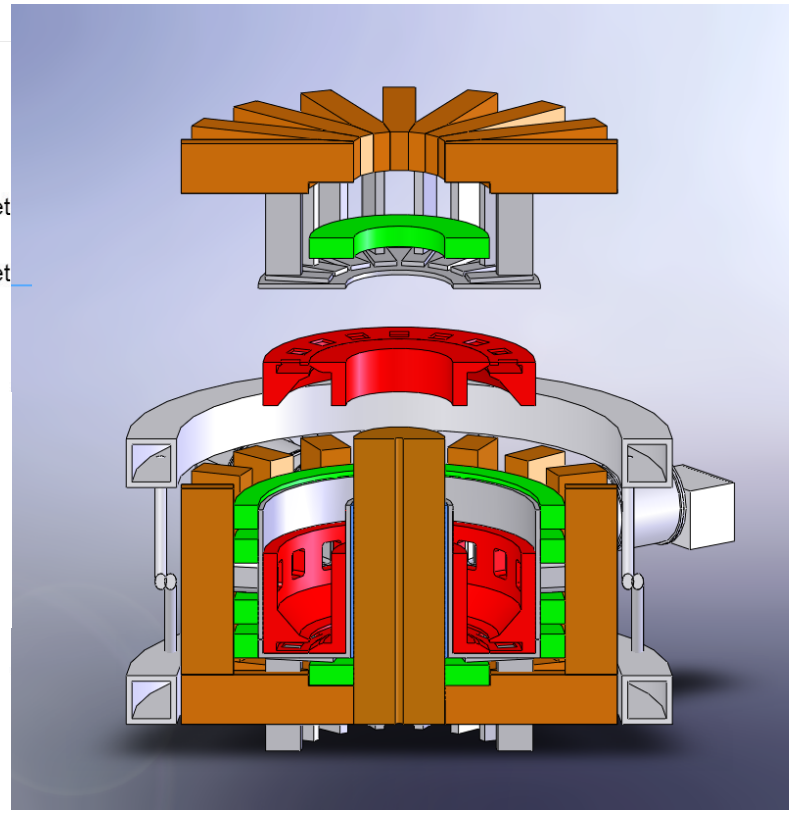
- Baseline FNSF-AT to meet nuclear science mission
- More advanced scenarios to close physics gaps to DEMO

A Fusion Nuclear Science Facility Must Be a Research Device with Maintainability, Flexibility, Replaceability



ORNL FNSF-ST



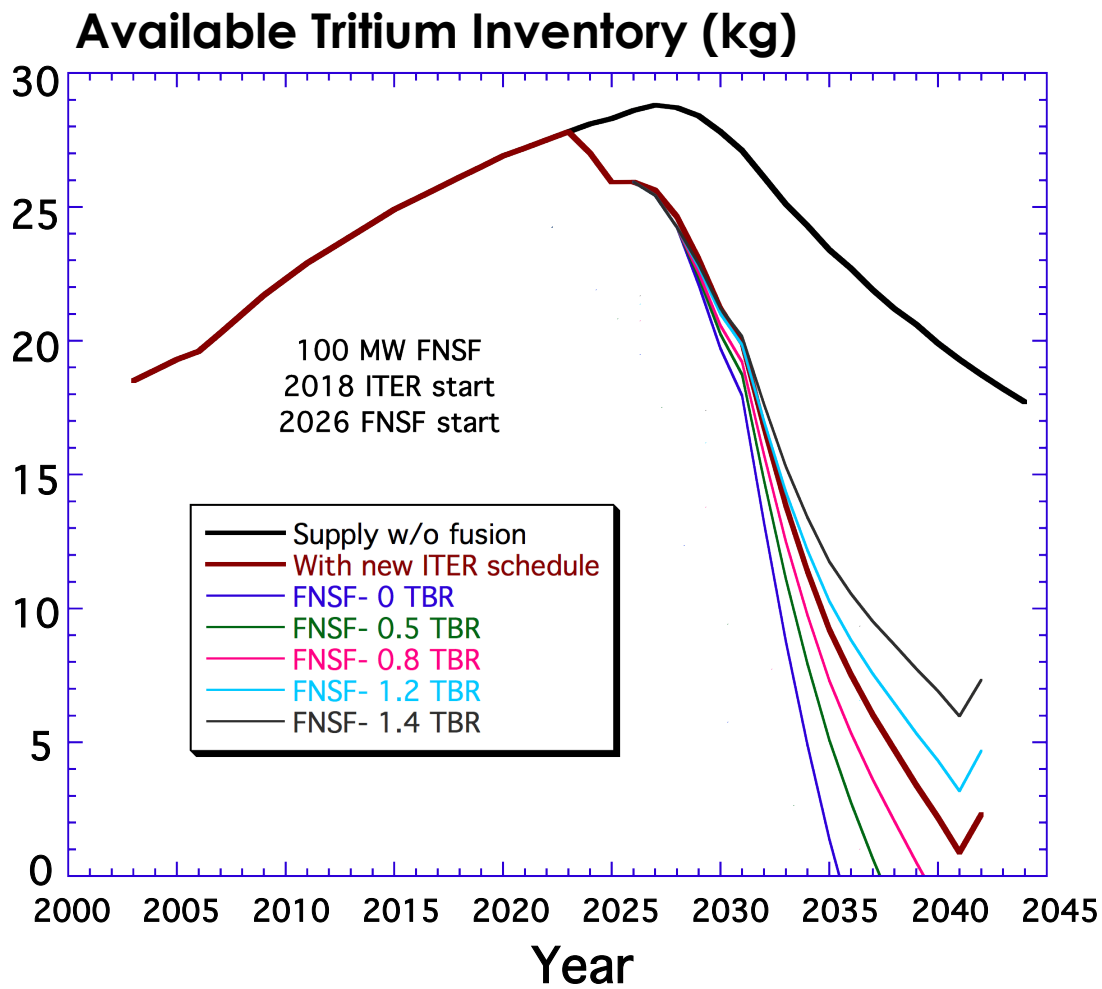
GA FNSF-AT (FDF)

A defining characteristic of device approaches

FNSF/CFETR Must Have Tritium Breeding Ratio > 1 to Build a Supply to Start Up DEMO

- A 1000 MWe DEMO will burn 12 kg Tritium per month
- Tritium inventory available for DEMO at end of ITER and FNSF operation depends strongly on TBR in FNSF
- Pilot Plant option has a larger tritium consumption and increased risk to tritium availability

[M.E. Sawan, TOFE (2010)]



A Staged Approach to Learn and Improve Nuclear Components, Diagnostics, Operating Scenario

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	← START UP →				FIRST MAIN BLANKET							SECOND MAIN BLANKET							THIRD MAIN BLANKET				
	H	D	DT																				
Fusion Power (MW)	0	0	125		125				250			250			250				250				400
P_N/A_{WALL} (MW/m^2)			1		1				2			2			2				2				3.2
Pulse Length (Min)	1		10		SS				SS			SS			SS				SS				SS
Duty Factor	0.01		0.04		0.1				0.2			0.2			0.3				0.3				0.3
T Burned/Year (kG)			0.28		0.7				2.8			2.8			4.2				4.2				5
Net Produced/Year (kG)					–0.14				0.56			0.56			0.84				0.84				1
Main Blanket	He Cooled Solid Breeder Ferritic Steel											Dual Coolant Pb-Li Ferritic Steel							Best of TBMs RAFS?				
TBR					0.8				1.2			1.2			1.2				1.2				1.2
Test Blankets						1,2							3,4		5,6					7,8		9,10	
Accumulated Fluence (MW-yr/m^2)			0.06						1.2						3.7								7.6

Radiation damage survival strategy:

Nuclear facing structures do not see more than 2 MW-yr/m2 (20 dpa) before removal

A Staged Approach to Learn and Improve Nuclear Components, Diagnostics, Operating Scenario

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
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Diagnostics development and testing:

ITER-like set (start)

Reduced set

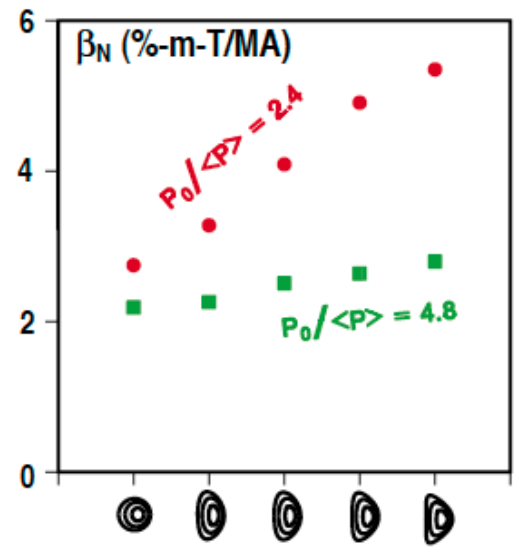
DEMO-like set

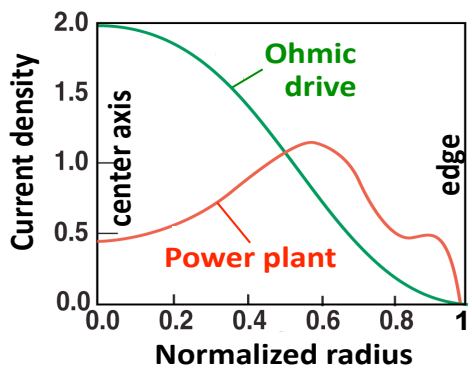
A FNSF/CFETR with Advanced Tokamak Capability is on the Direct Path to an Attractive Power Plant

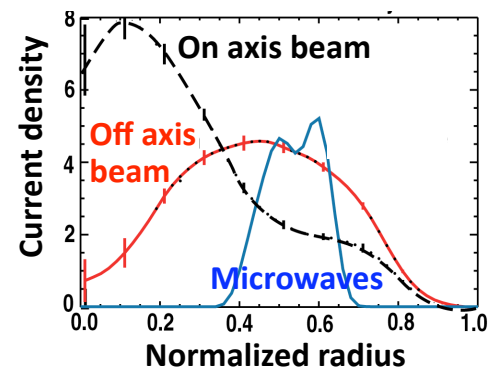
Key features of the FNSF-AT

(similar to general Tokamak)

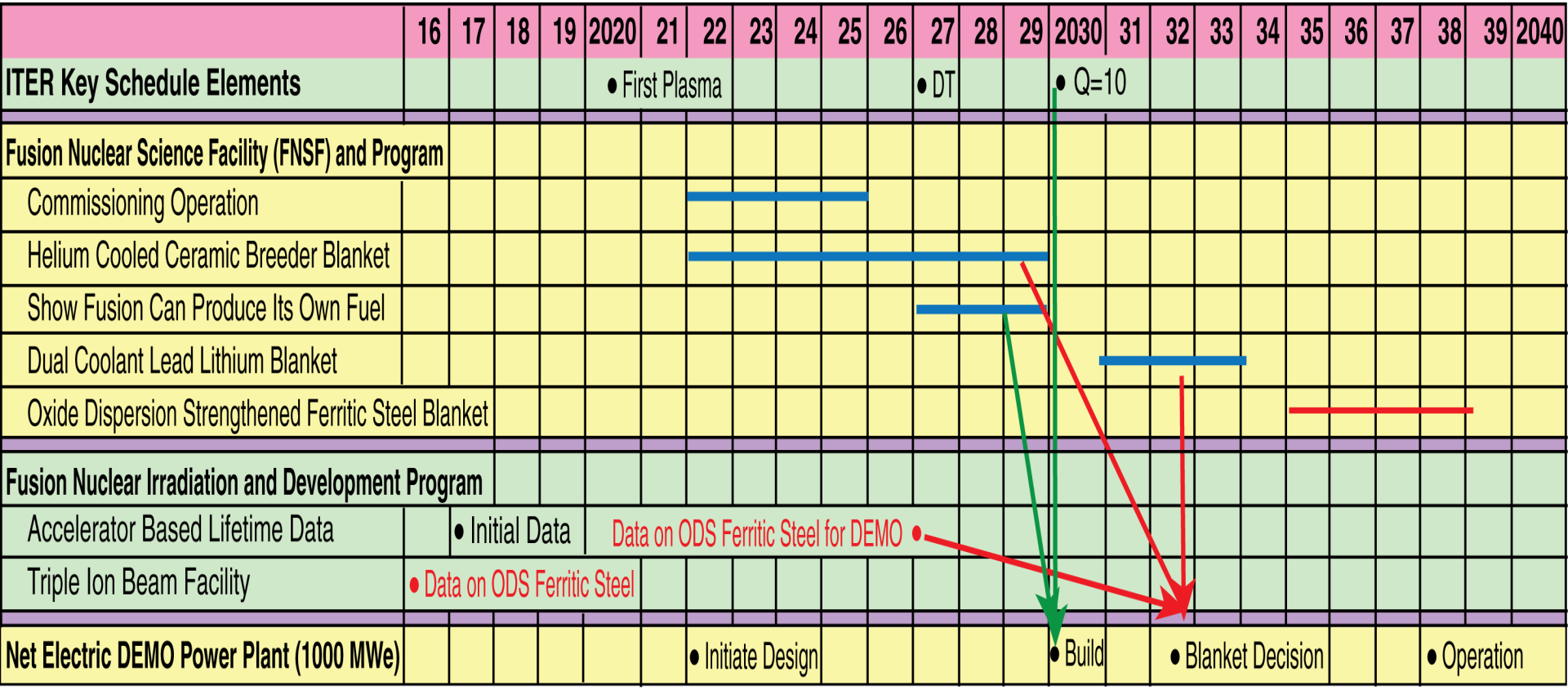
- **Steady-state operation**
  - High bootstrap fraction: Less demanding for low Q driven systems
  - Efficient current drive
- **Plasma Shaping**
  - High pressure; compact
  - High bootstrap, $f_{BS} \sim q\beta_N$
  - High confinement
  - Neutral point for disruptions
- **Profile Control**
  - Current profile consistent
  - Pressure profile: broad
  - Improved confinement







FNSF-AT is a Key Element of a Fast Track Plan to Net Electric DEMO



ITER, FIRST Plasma ➡ DEMO Design
Q=10 in ITER, FNSF Breeds Own Fuel ➡ Demo Construction
FNSF Data on Breeding Blankets ➡ Demo Blanket Decision