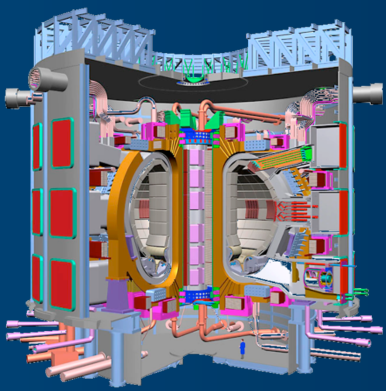
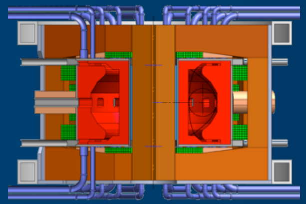
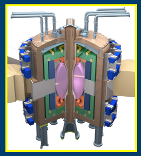
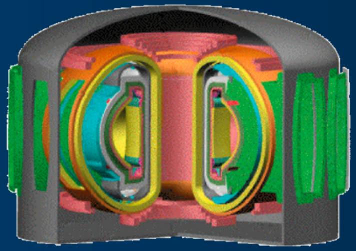
A Path to a Fusion DEMO after ITER

by
**T.S. Taylor, V. Chan,
A.M. Garofalo**









Presented at
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Beijing, China**

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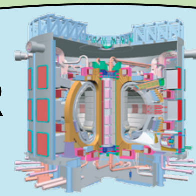
In Addition to What We Learn in ITER, What Else Do We Need to Learn to Build an Electricity Producing DEMO?

TODAY' S

RESEARCH

FACILITIES

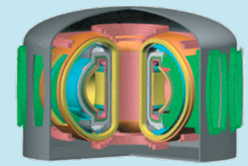
ITER



High energy gain burning plasma physics
Reactor scale superconducting technology

?

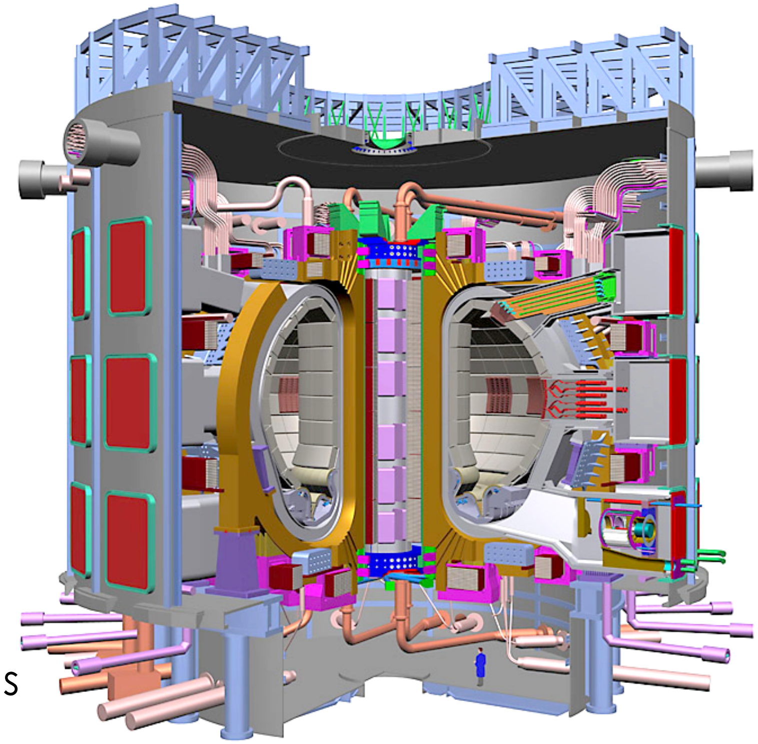
DEMO



High gain, advanced physics, steady-state high duty factor fusion power

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



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

2007 FESAC Planning Panel

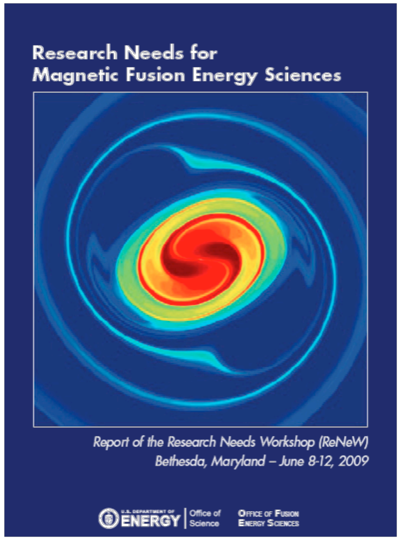
How Initiatives Could Address Gaps

Legend

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

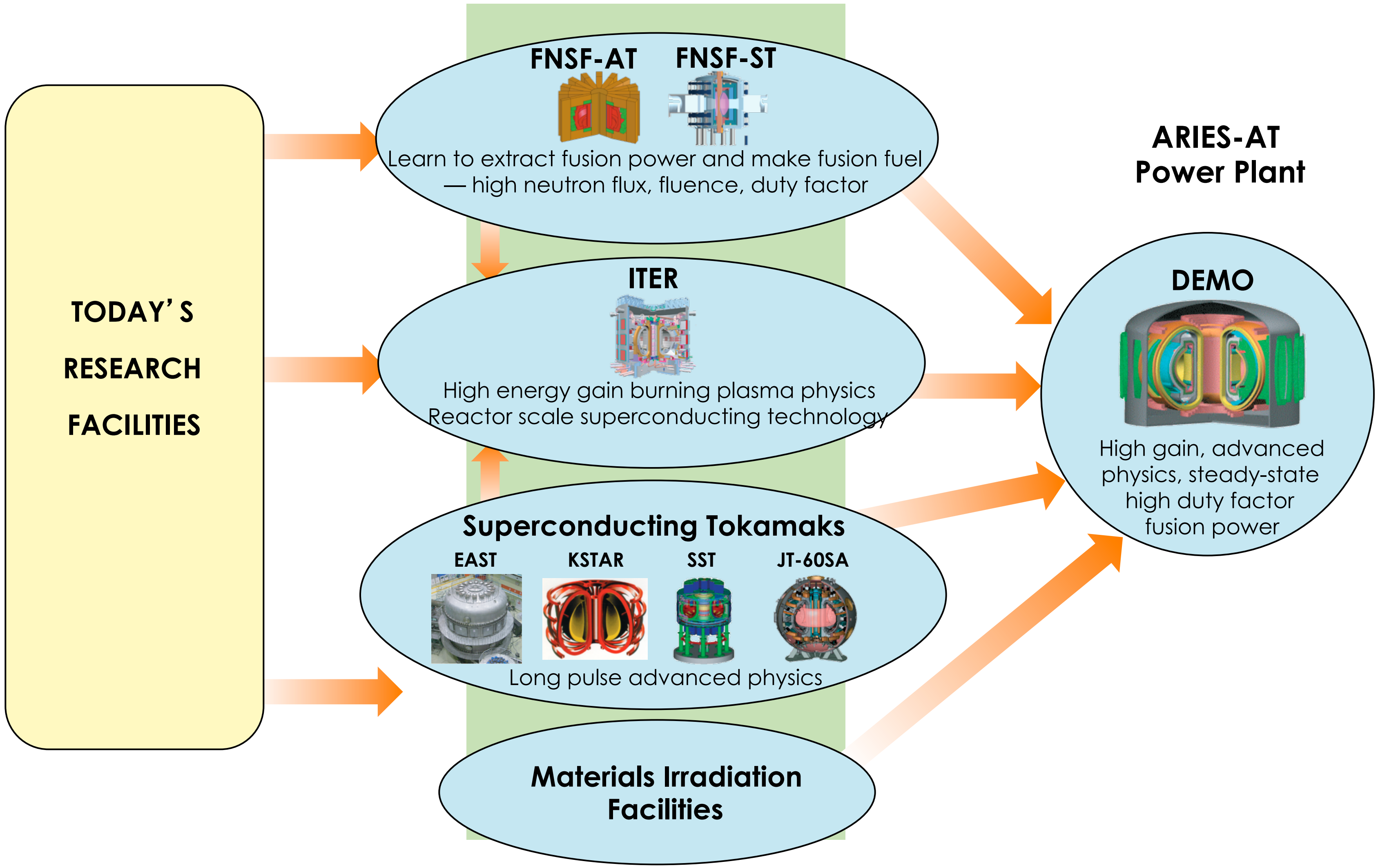


US MFE Leadership –

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

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

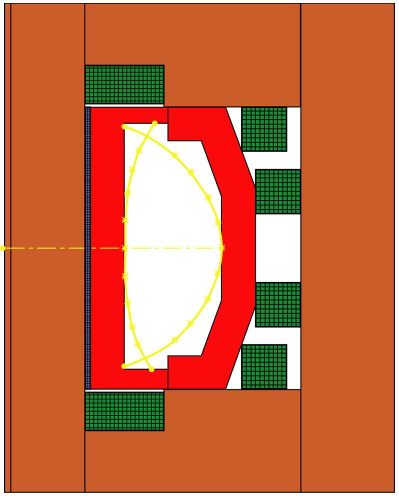
Research on FNSF, ITER, Superconducting Tokamaks, and Materials Irradiation Facilities Enables DEMO



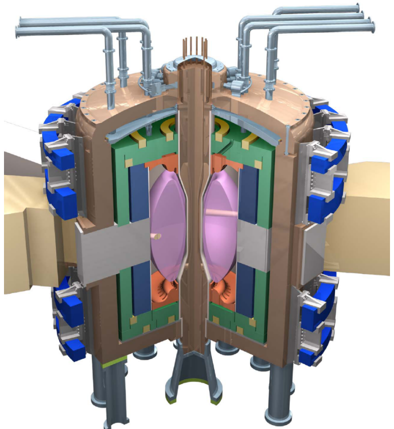
A Fusion Nuclear Science Facility (FNSF)
A Place to Learn How to Make and Use Fusion Energy

— Our Perspective —

- **FNSF will**
  - Show fusion can **make its own fuel**
  - Provide a materials **irradiation facility** to test/validate fusion materials
  - Produce **fusion power** in steady-state
  - Show fusion can produce high grade **process heat and electricity**
  - Enable research on **high performance, steady-state, burning** plasmas for Demo
  - Produce **Net Electricity ??**
- **By operating steady-state with**
  - Modest energy gain
  - Operate 30% of a year in 2 week periods
  - Significant neutron fluence (3–6 MW-yr/m^2, 30–60 dpa)



FNSF-AT (FDF)



FNSF-ST (ST-CTF)

Options for the Fusion Nuclear Science Facility

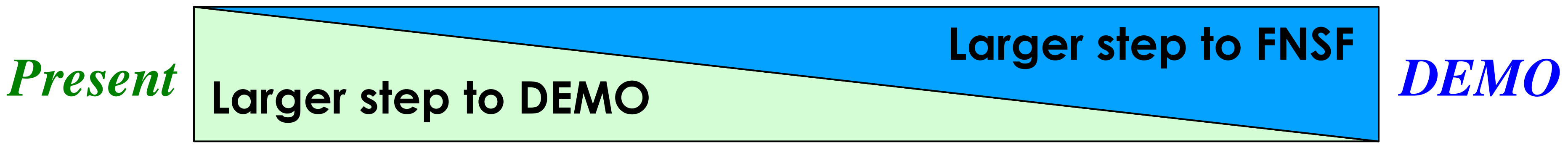
- **FNSF-ST** (larger step to DEMO)
  - Operate steady-state
  - High neutron fluence for component testing
  - Provide a materials irradiation facility to test/validate fusion materials
  - Demonstrate Tritium breeding
  - Show fusion can produce high grade process heat and electricity
- **FNSF-AT** *adds:*
  - Produce significant fusion power (100-300 MW)
  - Demonstrate Tritium self-sufficiency
  - Further develop AT physics towards Demo regimes
- **Pilot Plant** (larger step from present program) *adds:*
  - Generate net electricity
  - Reactor maintenance schemes

What is the Appropriate Size and Scope of Next Step Forward?

- **Addresses key identified gaps to DEMO**
- **Complements ITER**
  - Not necessary to duplicate main efforts on ITER
- **Can be done now** [start design]
  - Define project scope to allow rapid progress in fusion energy development
  - **Prepare for DEMO construction triggered by Q=10 in ITER (~2030)**

Appropriate Size of Next Step Forward?

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



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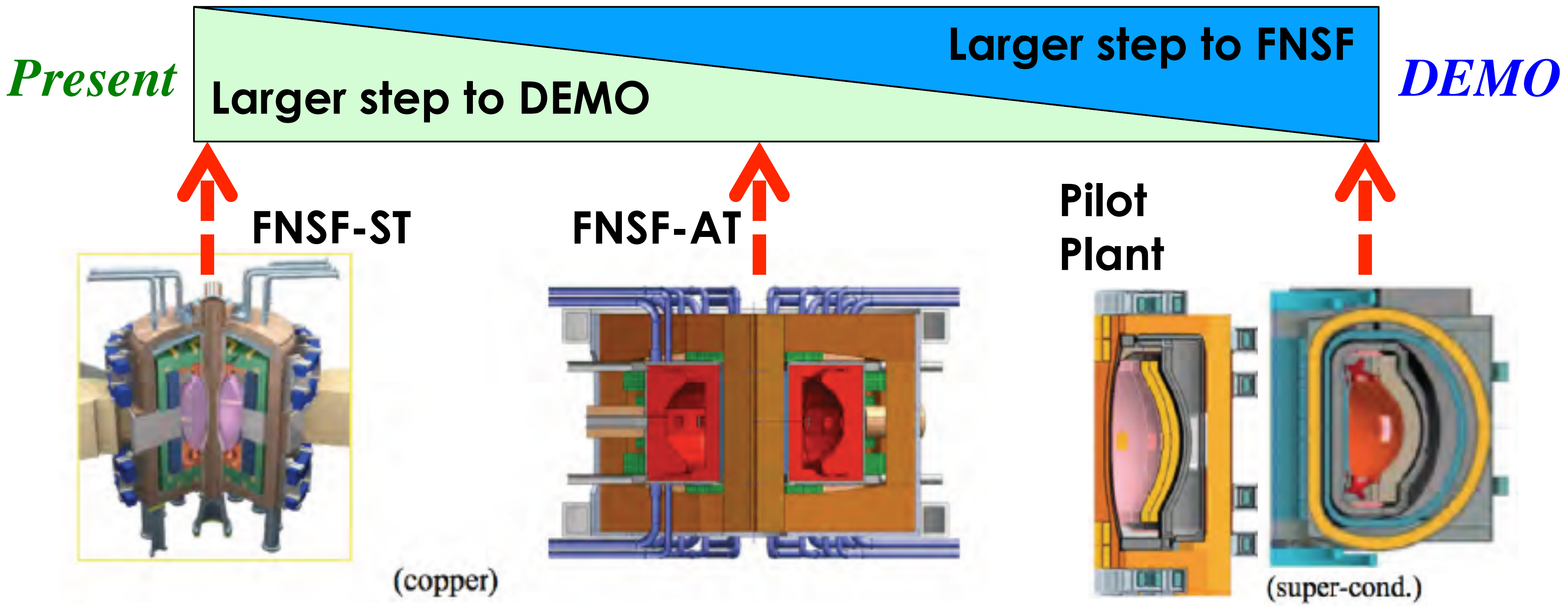


- **FNSF-AT can be designed now and operate in parallel with ITER**
- **Readiness for DEMO construction triggered by Q=10 in ITER (~2030)**

AT Physics Enables Nuclear Mission at Modest Size

Demonstrate AT operation in steady-state with burn ⟷ **Develop fusion's nuclear technology**

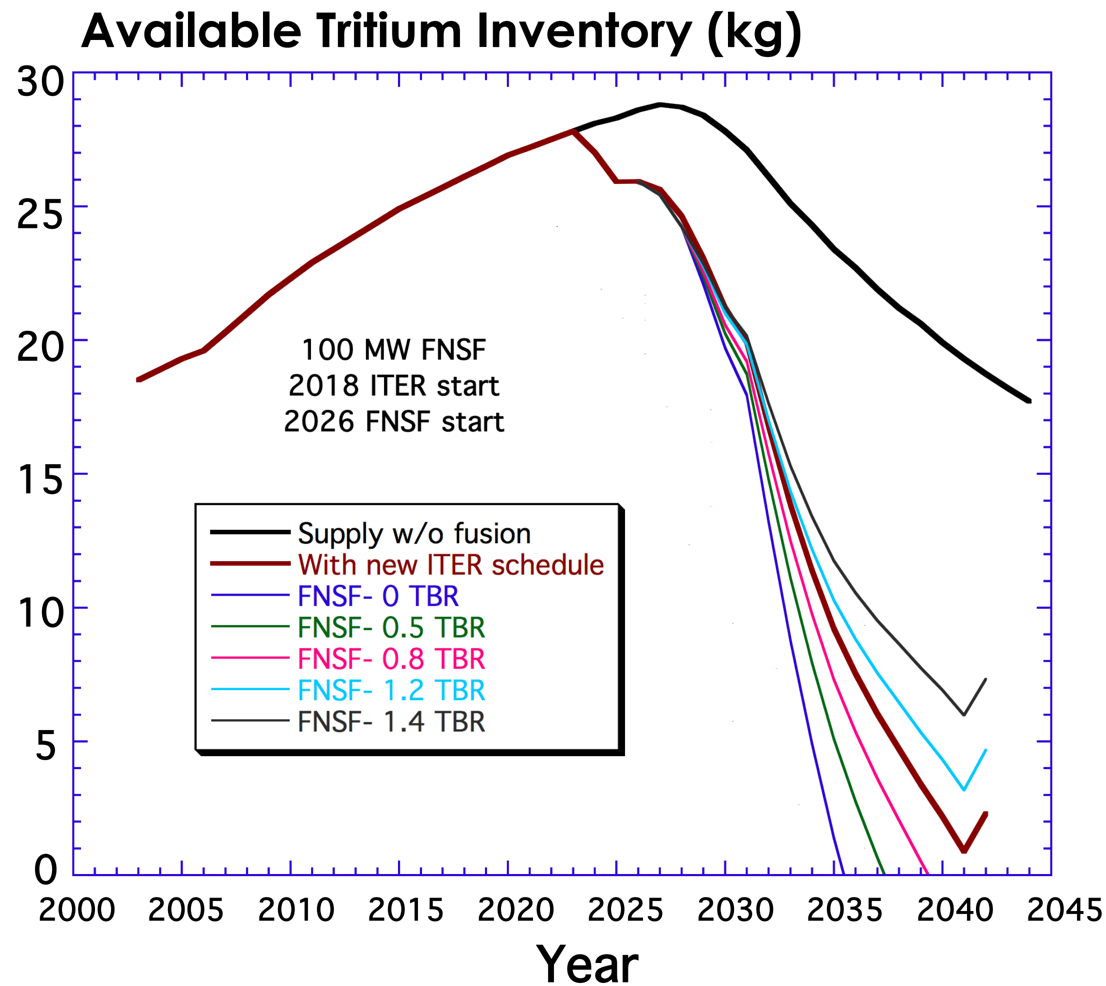
AT physics enables steady-state burning plasmas with

- **>10x ITER neutron fluence**
  - High fluence is required for FNSF's nuclear science development objective
- **In compact device**
  - Moderate size is required to demonstrate TBR>1 using only a moderate quantity of limited supply of tritium fuel

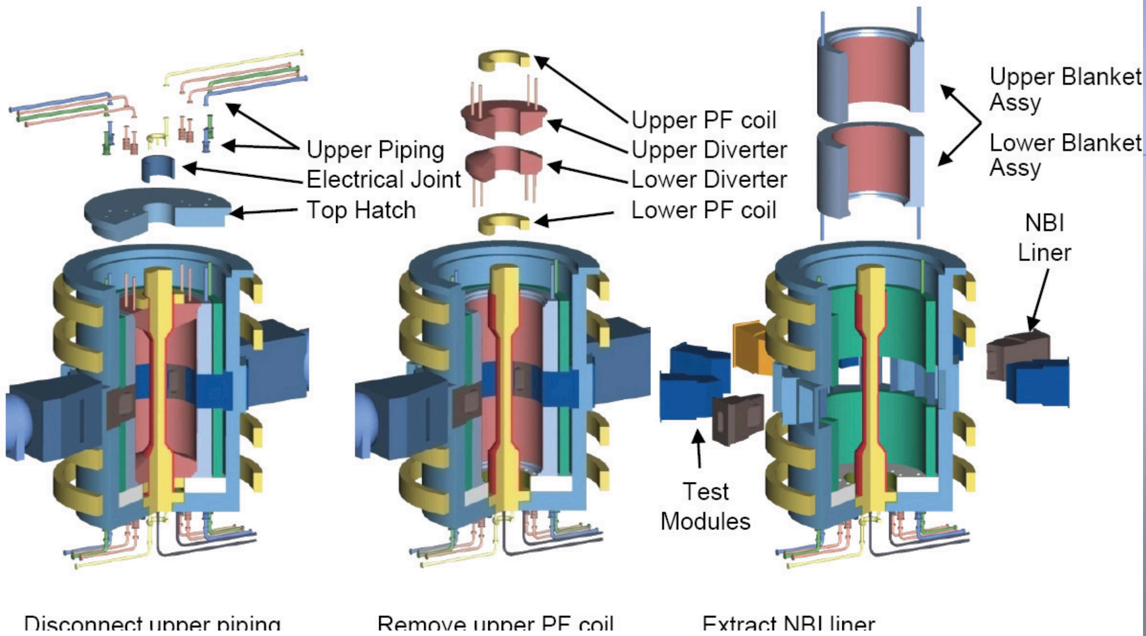
FNSF Must Have Tritium Breeding Ratio > 1 to Build a Supply to Start Up DEMO

- **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**

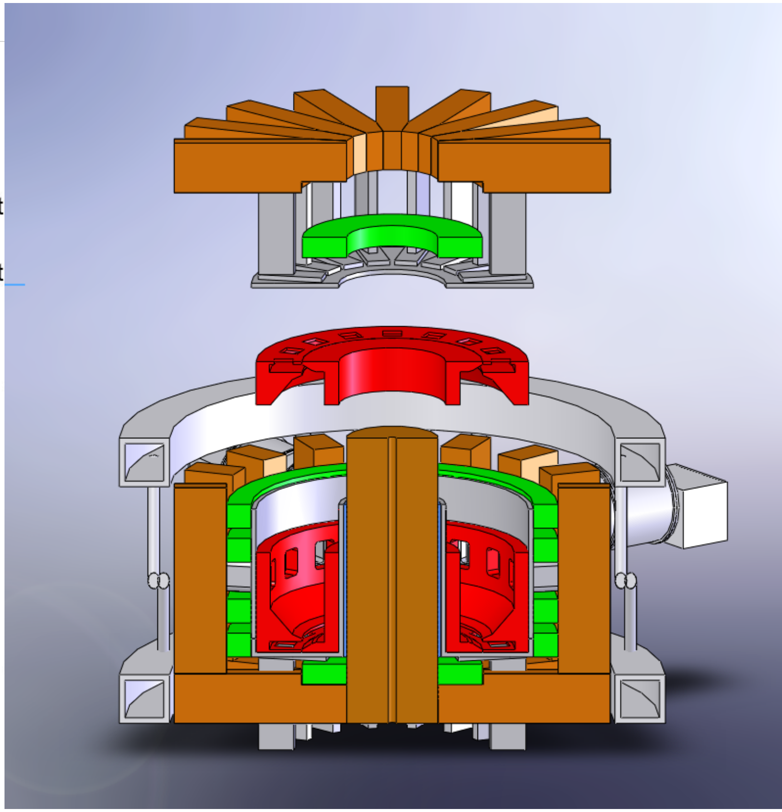
[M.E. Sawan, TOFE (2010)]



A Fusion Nuclear Science Facility Must Be a Research Device with Maintainable, Flexible, Replaceability



ORNL FNSF-ST



GA FNSF-AT (FDF)

A defining characteristic of device approaches

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

Year	1–4: START UP H	D	DT	5–9: FIRST MAIN BLANKET		10–11	12–16: SECOND MAIN BLANKET		17–18	19–23: THIRD MAIN BLANKET	
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

Year	1–4: START UP (H, D, DT)			5–9: FIRST MAIN BLANKET		10–11	12–16: SECOND MAIN BLANKET		17–18	19–23: THIRD MAIN BLANKET	
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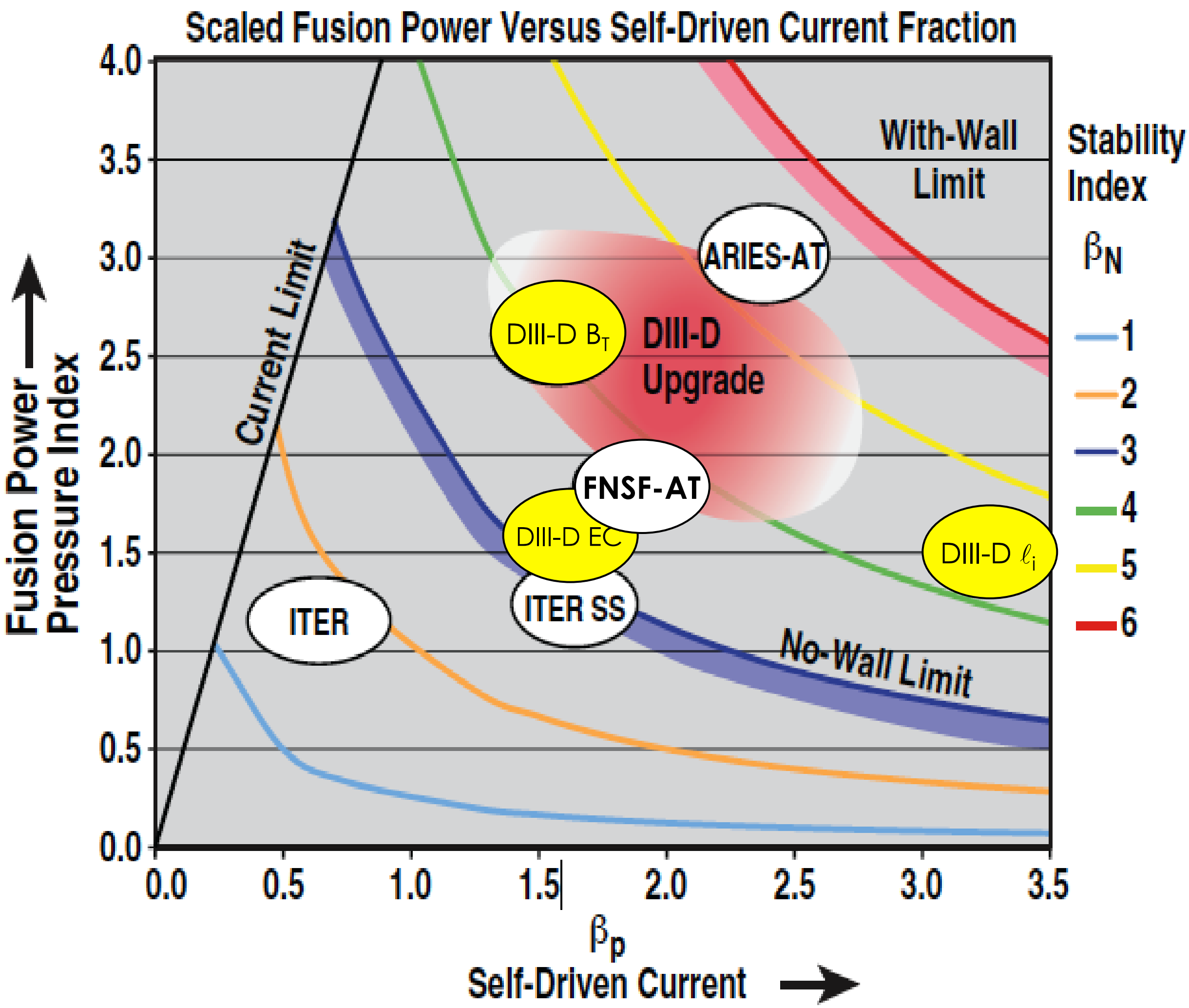
Diagnostics development and testing:

Years 5–9	Years 12–16	Years 19–23
ITER-like set (start)	*Reduced set*	*DEMO-like set*

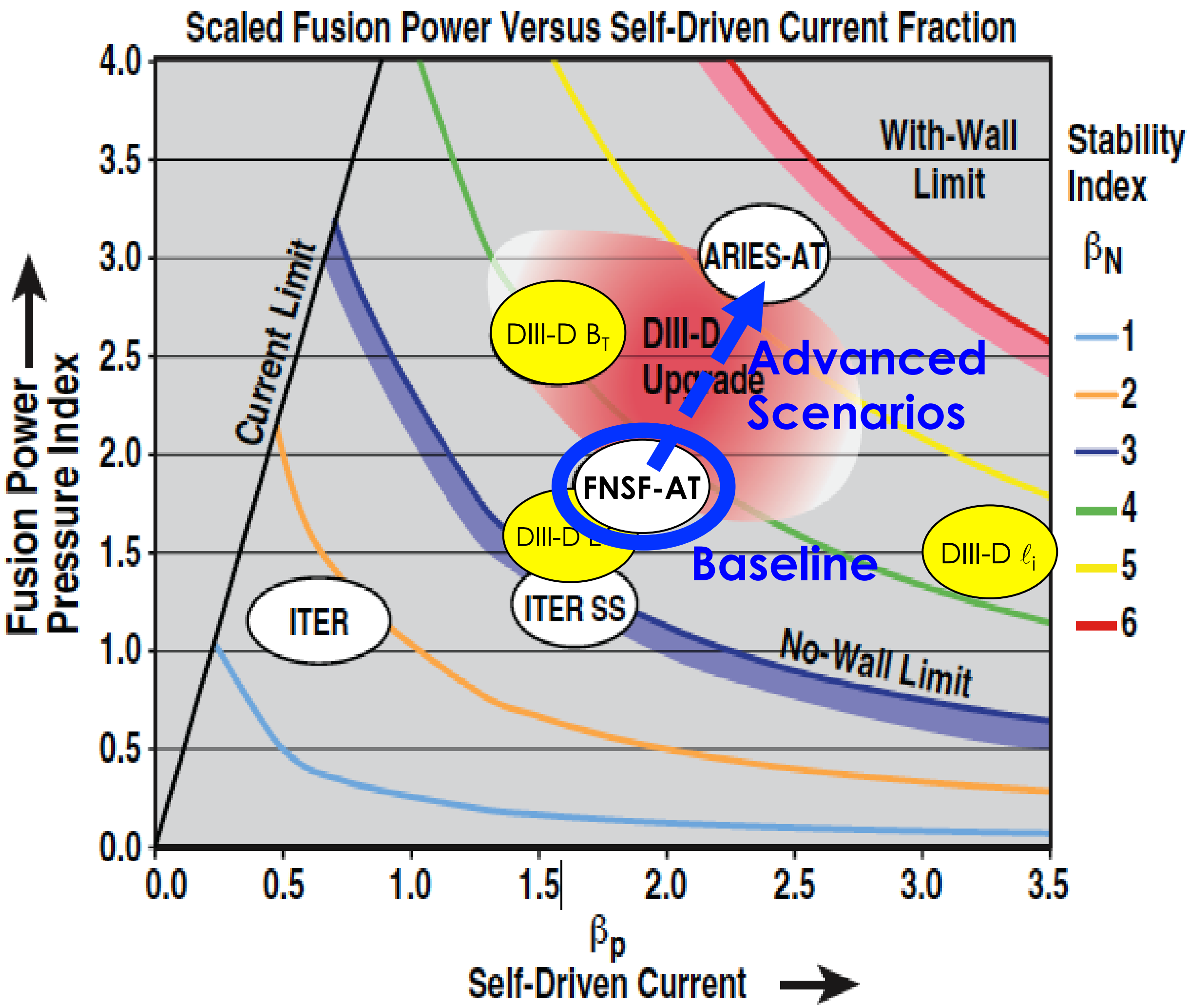
FNSF-AT Can Be Designed Using Proven AT Physics, Can Develop More Advanced Physics Towards DEMO



- **100% non-inductive modes developed on DIII-D bracket FNSF-AT baseline**
  - Negative central magnetic shear
  - High bootstrap fraction
  - Near-stationary profiles

Pulse length extension in next few years

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



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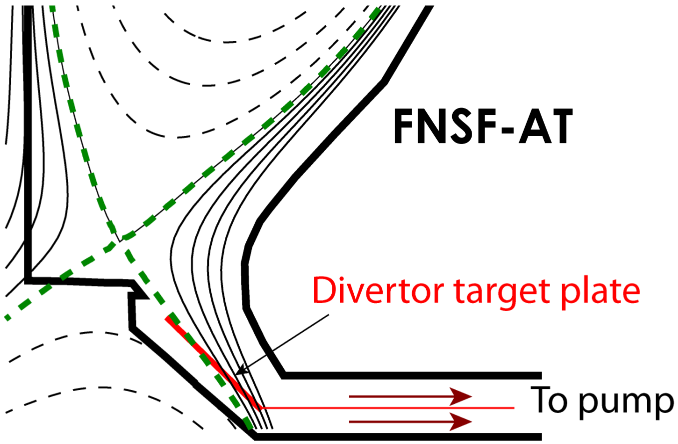
  - Negative central magnetic shear
  - High bootstrap fraction
  - Near-stationary profiles

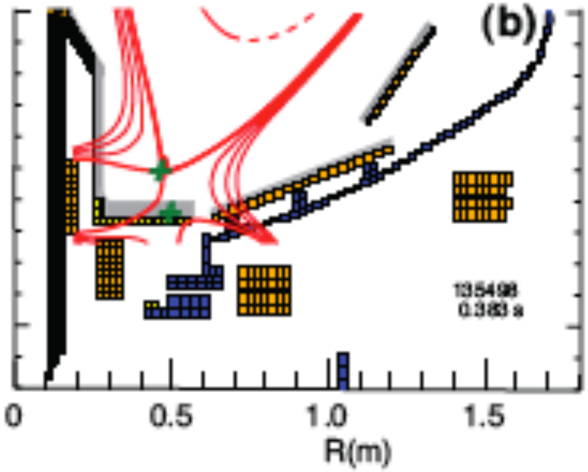
  Pulse length extension in next few years
- Baseline FNSF-AT to meet nuclear science mission
- More advanced scenarios to close physics gaps to DEMO

GENERAL ATOMICS
001-12/TST/rs

Can Start FNSF-AT Design Now

- **Shovel-ready:**
  - Standard coils
  - Standard NBI
  - Standard divertor
  - Proven AT physics
  - Proven materials
- 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

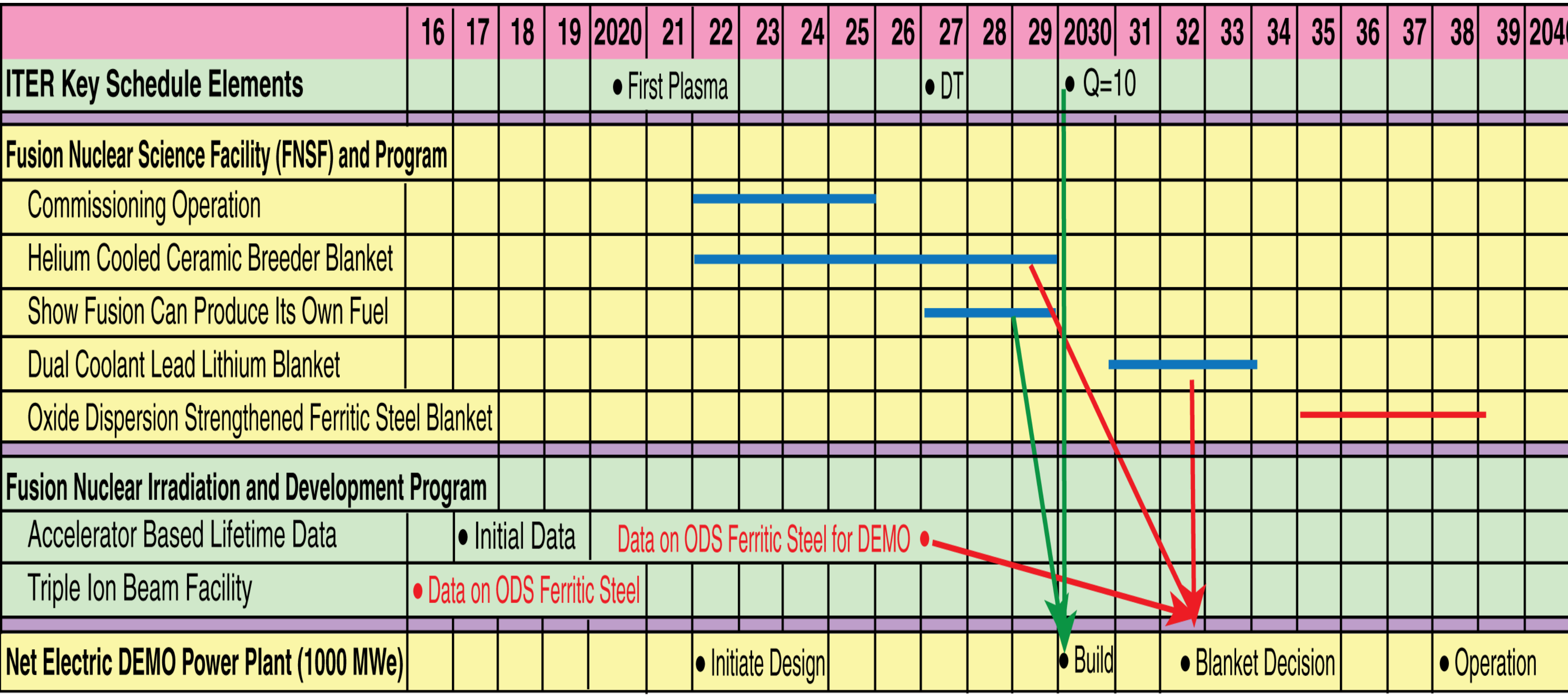
Soukhanovskii, et al., IAEA 2010

FNSF-AT Will Get Us Ready For DEMO Construction Triggered By Q=10 in ITER

Key features of the FNSF-AT approach:

- **FNSF-AT is on direct path towards attractive DEMO**
- **FNSF-AT plus ITER fill gaps to DEMO**
- **Ready to design FNSF-AT now**

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