A Path to a Fusion DEMO as a Next Step After ITER

A.M. Garofalo,

V.S. Chan, R.D. Stambaugh, T.S. Taylor

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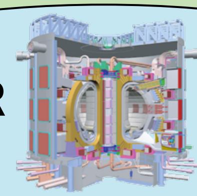
GENERAL ATOMICS

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

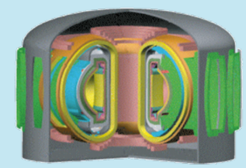
ITER



High energy gain burning plasma physics
Reactor scale superconducting technology

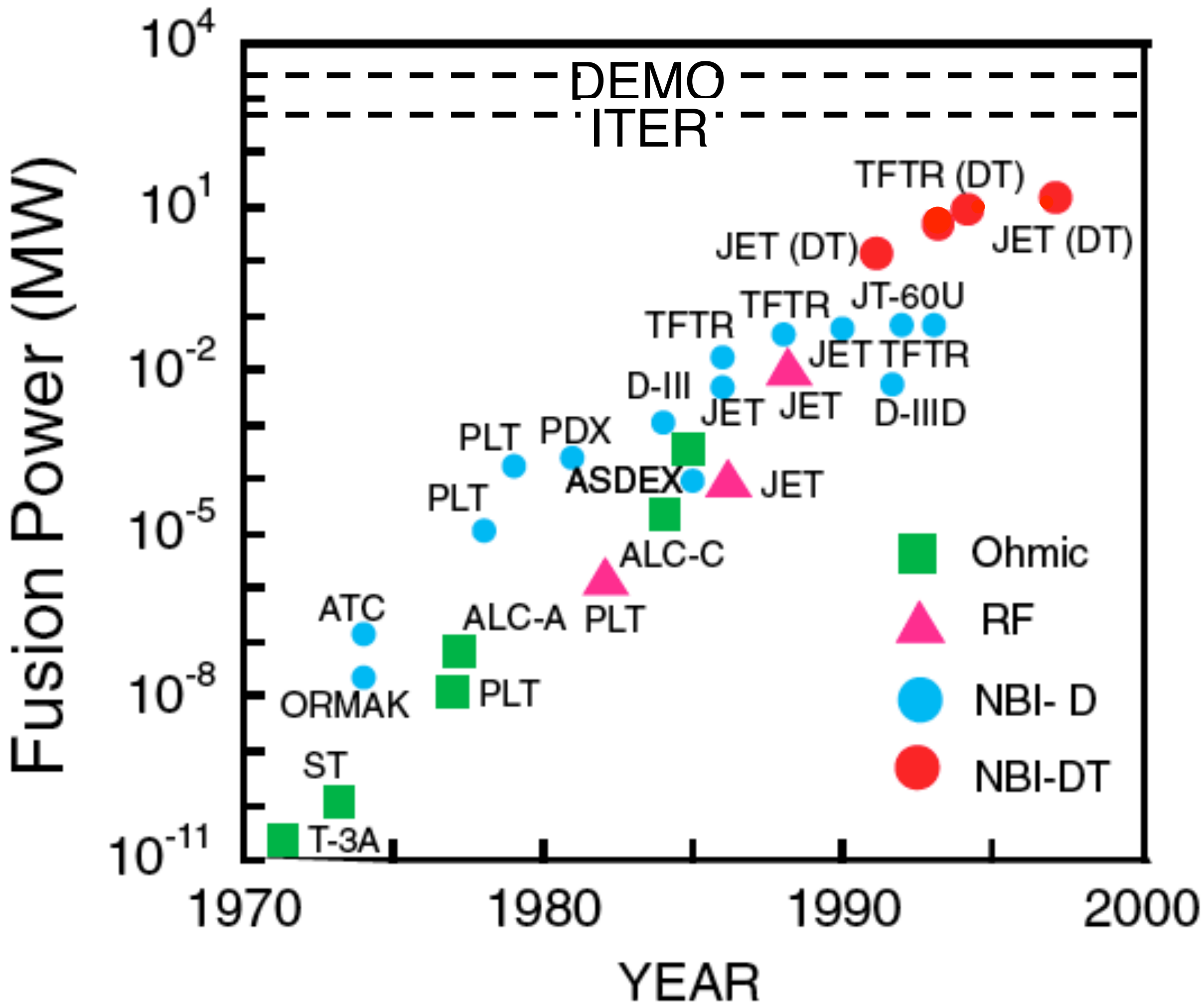
?

DEMO



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

Tokamaks Have Made Excellent Progress in Fusion Power



- **JET: 16 MW, 0.68 GJ fusion energy**
- **TFTR: 10.7 MW, 1.55 GJ fusion energy**
- **Worldwide research efforts since 2000 have focused on building ITER, to carry actual fusion power output up to reactor scale**
  - **Q=10 in 2030**

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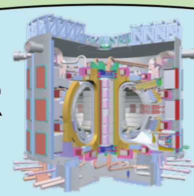
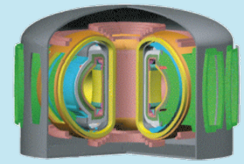


High energy gain burning plasma physics
Reactor scale superconducting technology

- Addresses remaining gaps to DEMO
- Can be done now
  - Get us ready for DEMO construction triggered by Q=10 in ITER (~2030)

DEMO



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

US MFE Community –
Remaining Gaps to DEMO Have Been Identified

2007 FESAC Planning Panel

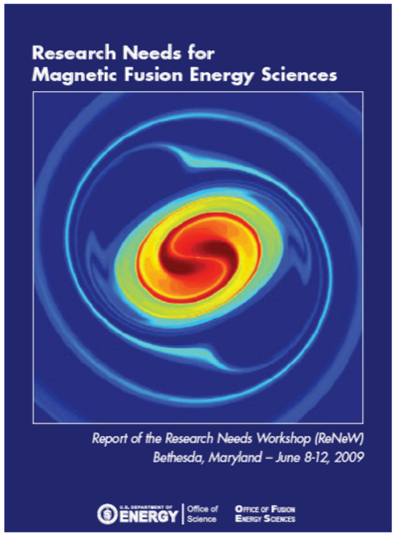
How Initiatives Could Address Gaps

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

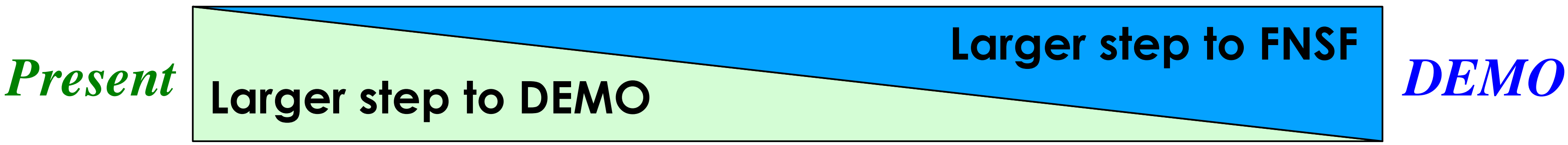


US MFE Leadership –

- **Towards a Fusion Nuclear Science Facility**
  - **Burning Plasma Dynamics and Control**
  - **Materials in a Fusion Environment and Harnessing Fusion Power**

Appropriate Size of Next Step Forward?

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

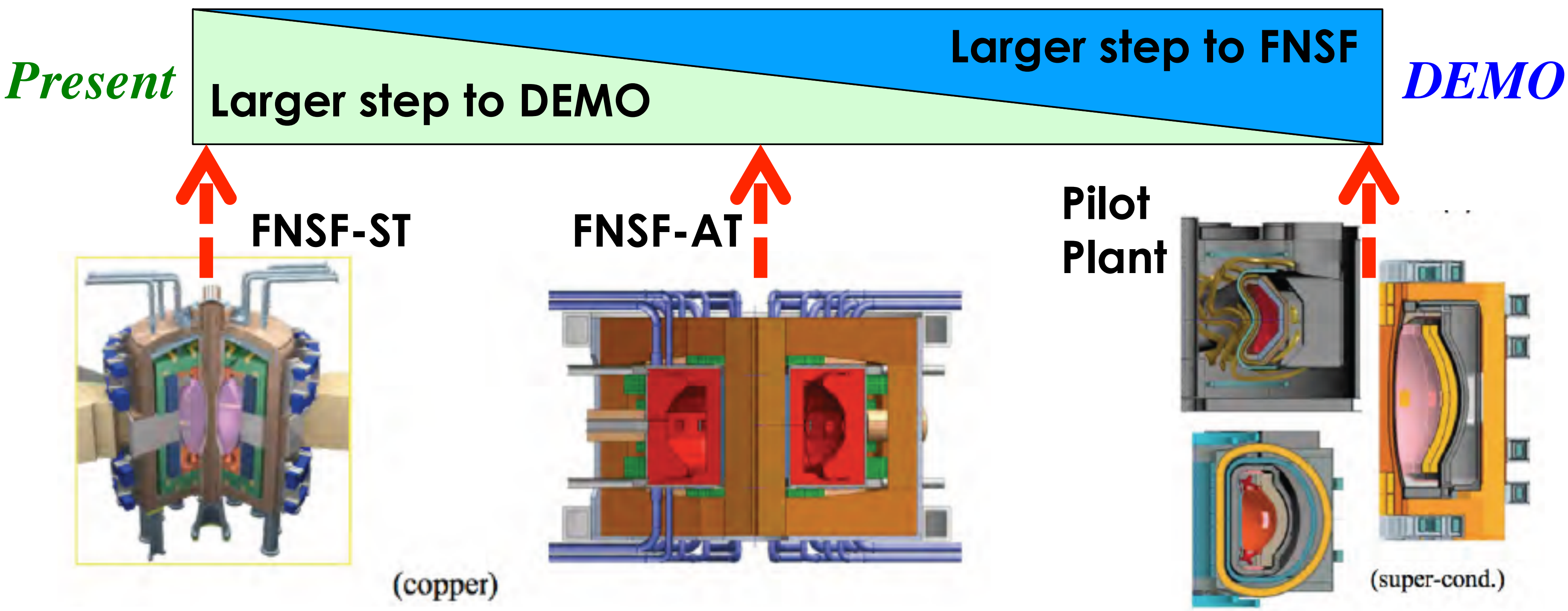


Options for the Fusion Nuclear Science Facility

- **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

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)**

Nuclear Science Mission Can Be Accomplished by FNSF-AT Baseline Mode with Operating Margin

- **Baseline FNSF-AT: 4x neutron flux of ITER and annual duty factor of 30%**
  - **10x neutron fluence of ITER**
  - **Materials/components qualification for first few years of DEMO**

			Baseline	Lower BetaN, fbs, H98	Lower BT, fbs	Advanced
A	aspect ratio		3.5	3.5	3.5	3.5
k	plasma elongation		2.31	2.31	2.31	2.31
Pf	fusion power	MW	290.07	159.07	144.65	476.44
Pinternal	power to run plant	MW	499.75	526.57	348.22	500.35
Qplasma	Pfusion/Paux		6.88	2.93	3.52	12.37
Pn/Awall	Neutron Power at Blanket	MW/m2	2.00	1.10	1.00	3.28
BetaN	normalized beta	mT/MA	3.69	2.65	3.69	4.50
fbs	bootstrap fraction		0.75	0.54	0.56	0.85
Ip	plasma current	MA	6.60	6.56	6.39	7.09
Bo	field on axis	T	5.44	5.44	3.90	5.44
Paux	Total Auxiliary Power	MW	42.16	54.22	41.11	38.53
Peak Heat Flux	Peak Heat Flux to Outer Divertor	MW/m2	6.70	6.83	5.19	7.26

Nominal parameters for some of the operating modes evaluated from a 0-D system optimizer model [Chan, Stambaugh, et al, FS&T (2010)]

AT Physics Enables Nuclear Mission at Modest Size

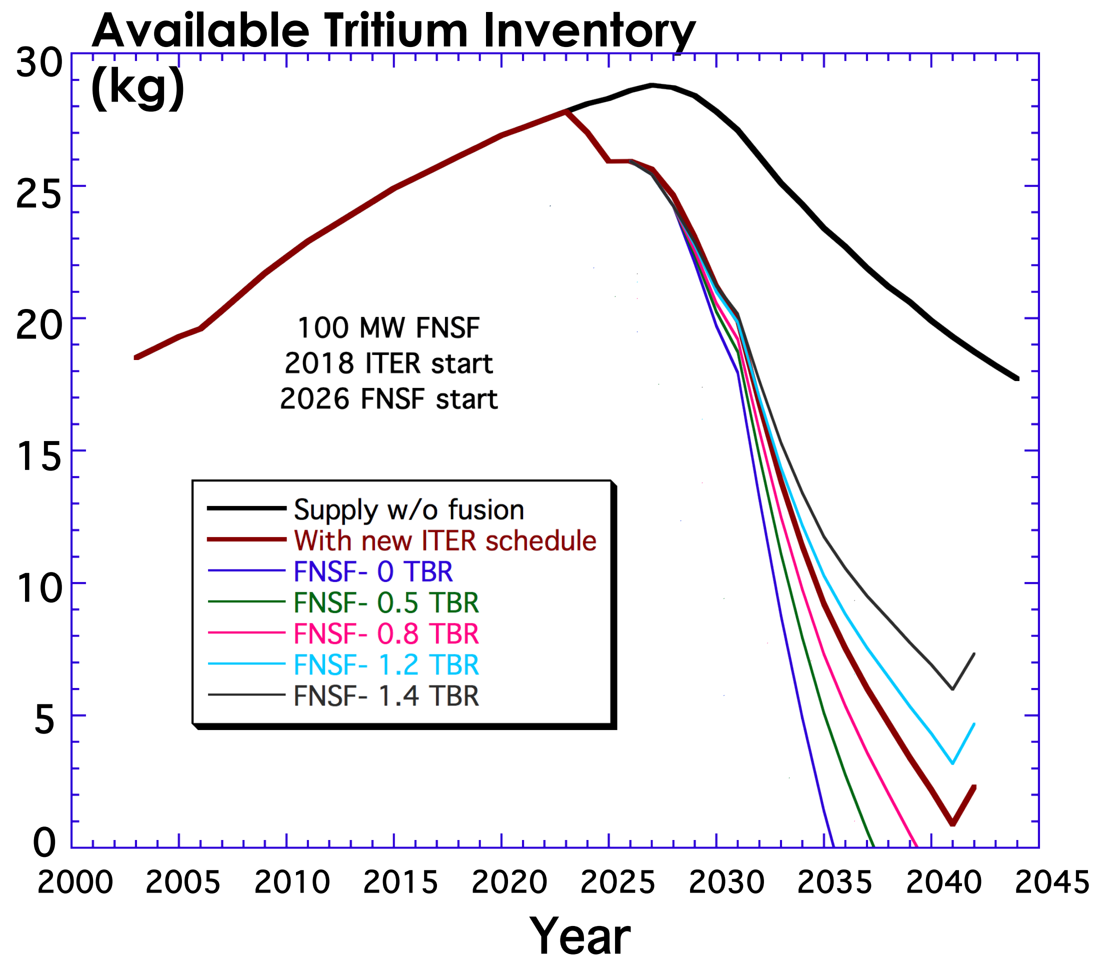
Demonstrate AT operation in steady-state with burn ⟷ Develop fusion's nuclear technology

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

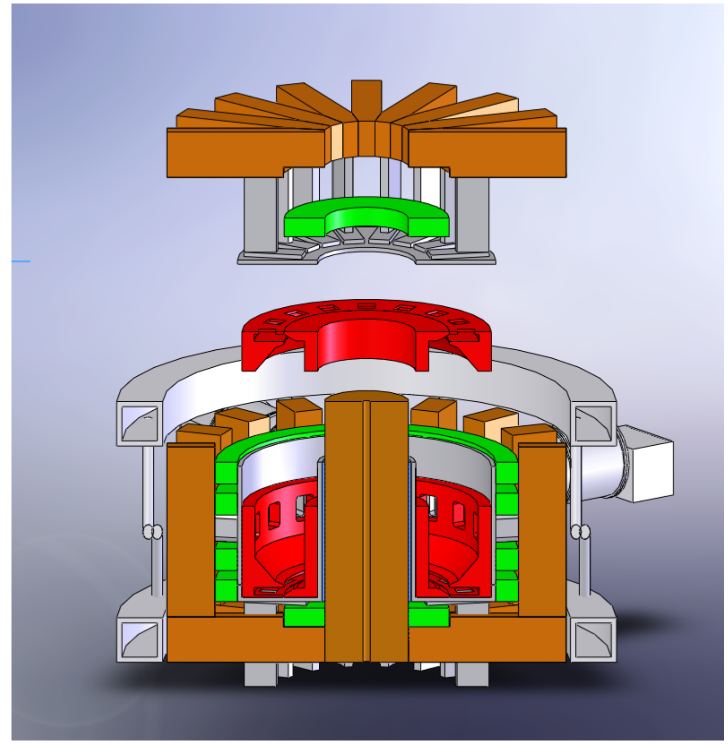
- **A 1000 MWe DEMO will burn 12 kg Tritium per month**
- **Tritium inventory available for DEMO at end of ITER and FNSF operation depends strongly on TBR in FNSF**



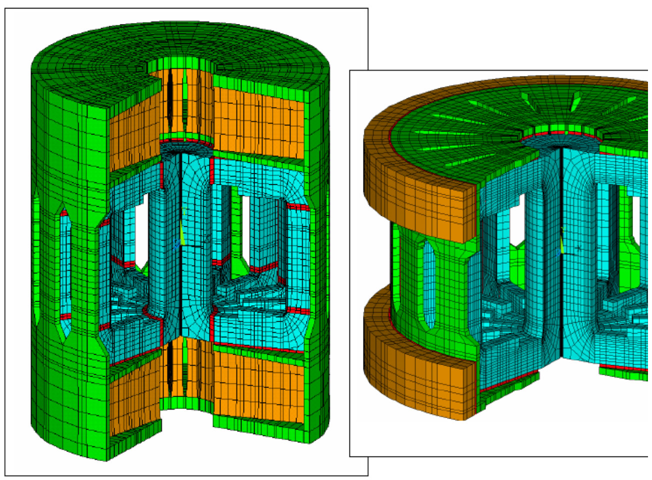
[M.E. Sawan, TOFE (2010)]

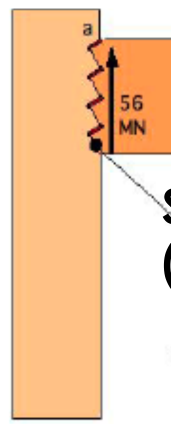
Demountable Copper Coils Enable Effective Nuclear Science Progress

- **A Fusion Nuclear Science Facility must be a research device, maintainable, accessible, re-configurable**
  - Change device components as understanding evolves
- **Jointed copper coil enables changeouts of wall, blanket, divertor**
  - Other devices will address superconducting coil issues



Sliding Joint (C-mod)





Sawtooth Joint (Rebut)

Titus et al. SOFE (2009)

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

Year: 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 H	START UP D	START UP DT	FIRST MAIN BLANKET			SECOND MAIN BLANKET			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 ($MW\text{-}yr/m^2$)			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

	Start up (years 1–4)			First Main Blanket (years 5–9)		(years 10–11)	Second Main Blanket (years 12–16)		(years 17–18)	Third Main Blanket (years 19–23)	
	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
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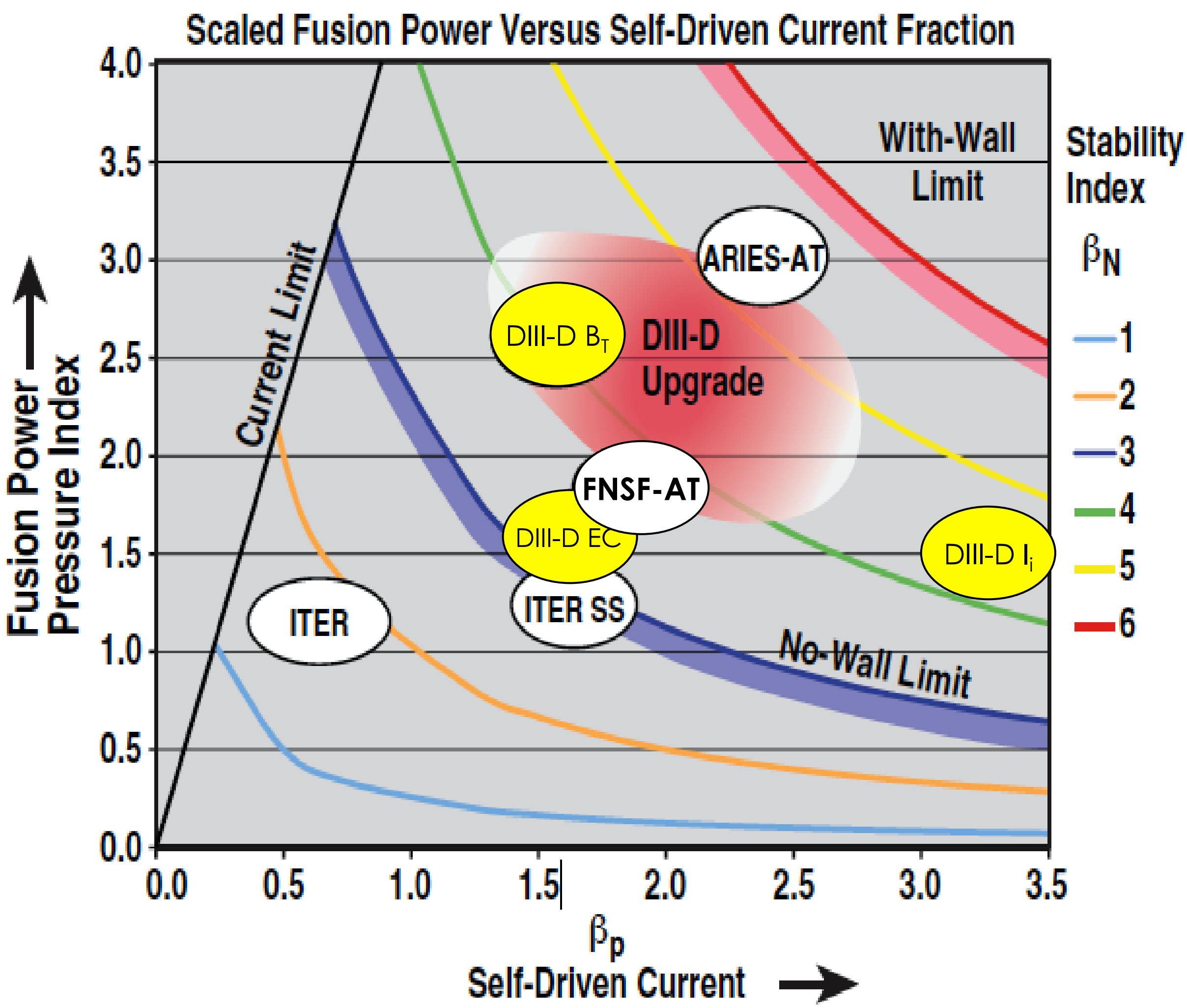
Diagnostics development and testing:

- *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

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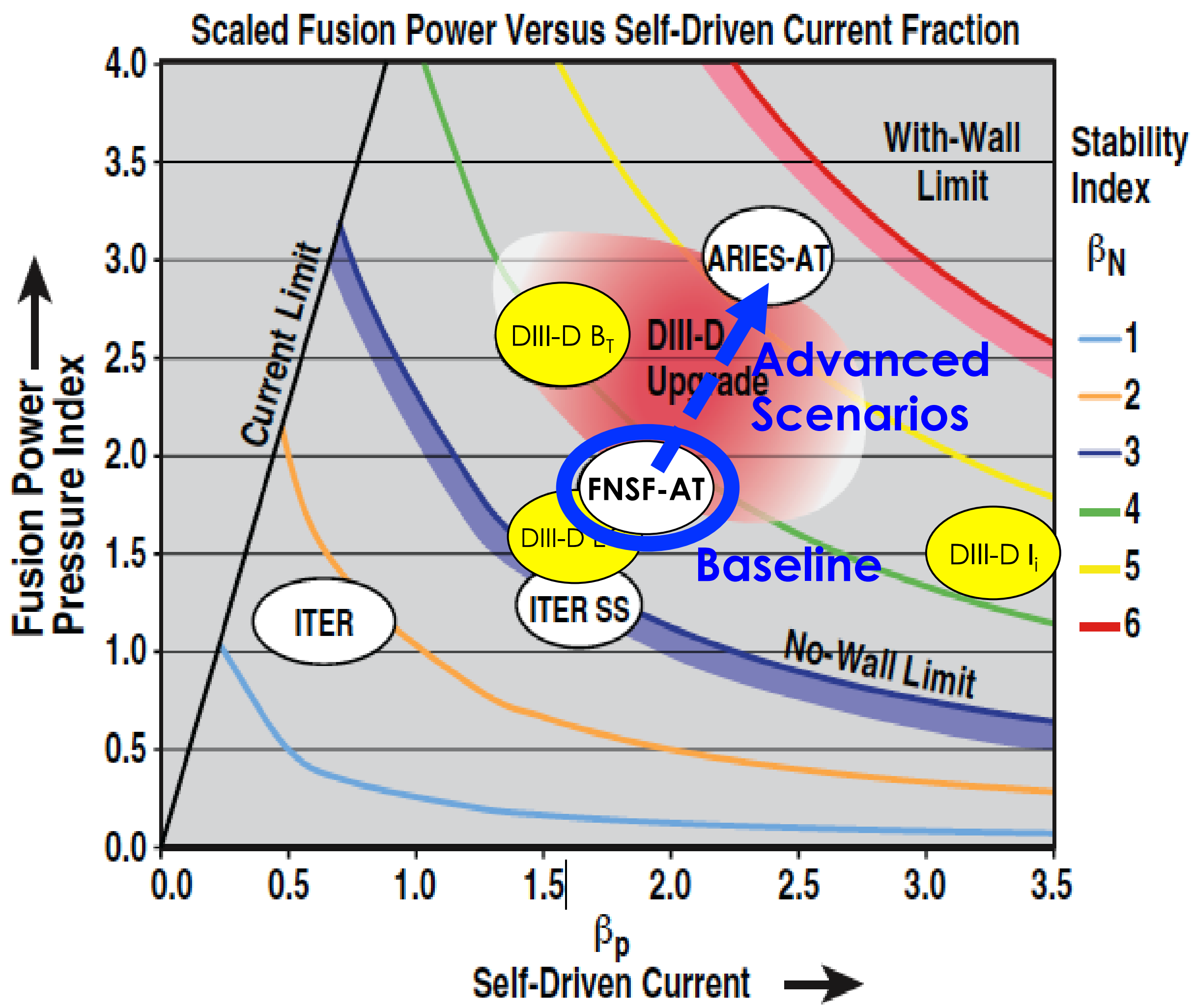

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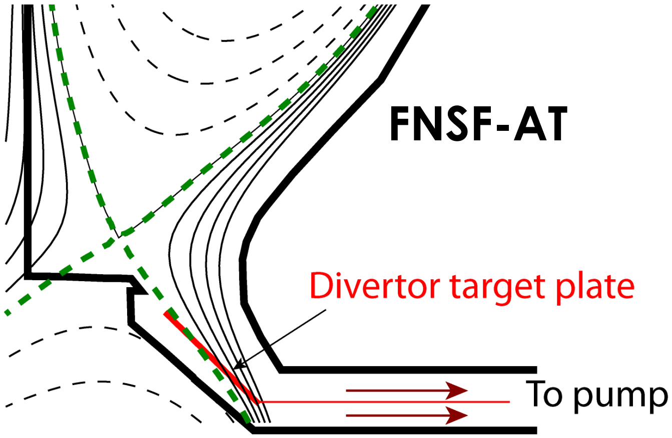
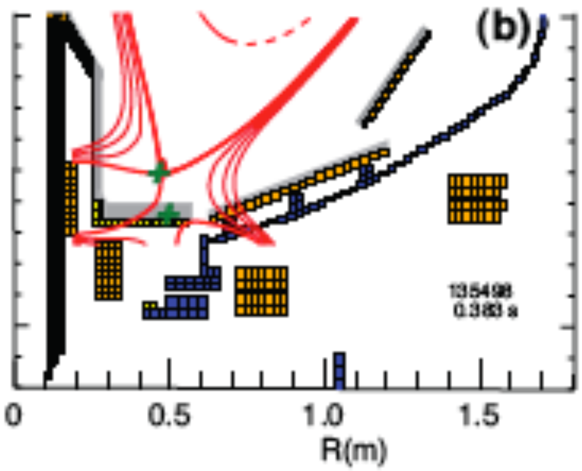
  Pulse length extension in next few years
- Baseline FNSF-AT to meet nuclear science mission
- More advanced scenarios to close physics gaps to DEMO

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

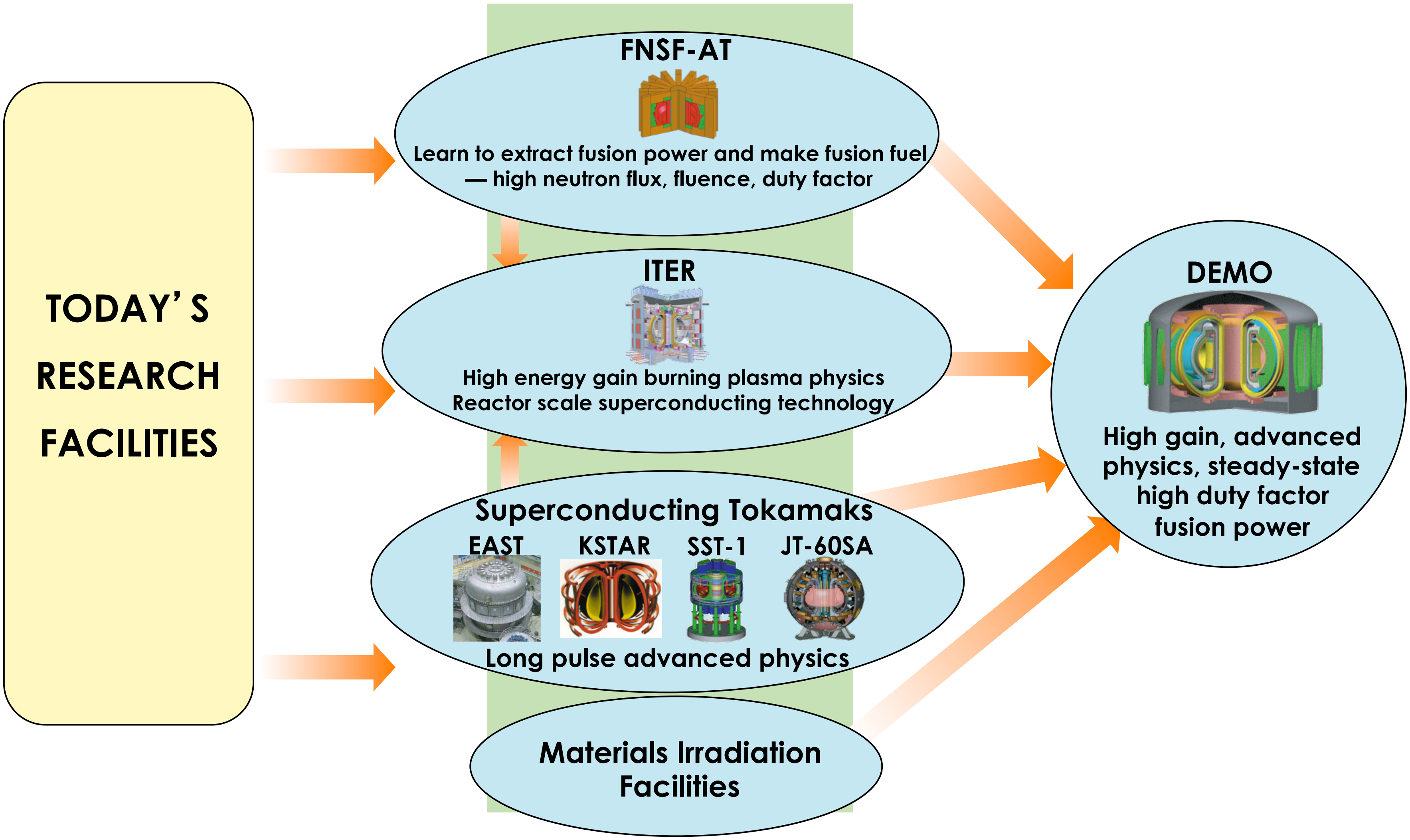




NSTX Snowflake Divertor experiment achieves large reduction of peak heat flux

Soukhanovskii, et al., IAEA 2010

Complementary Research on FNSF-AT, ITER, SC Tokamaks, and Materials Irradiation Facilities Enables DEMO



The Physics Basis for FNSF-AT Can Be Available from Experiments and Simulation in the Next Few Years

- Required stability values achieved in 100% non-inductive plasmas (extend pulse length)
- RWM stabilization by rotation/kinetic effects
- NTM stabilization by ECCD
- ELM elimination by QH mode operation, RMPs
- Disruption avoidance and mitigation
- Confinement quality required already obtained in long pulse DIII-D plasmas
- Bootstrap fraction already achieved
- Far off-axis LHCD in high density H-mode
- Pumped, high triangularity plasma
- Plasma control system
- Power exhaust: more challenging than DIII-D and comparable to ITER
- PFC tritium retention – oxygen bake and hot wall

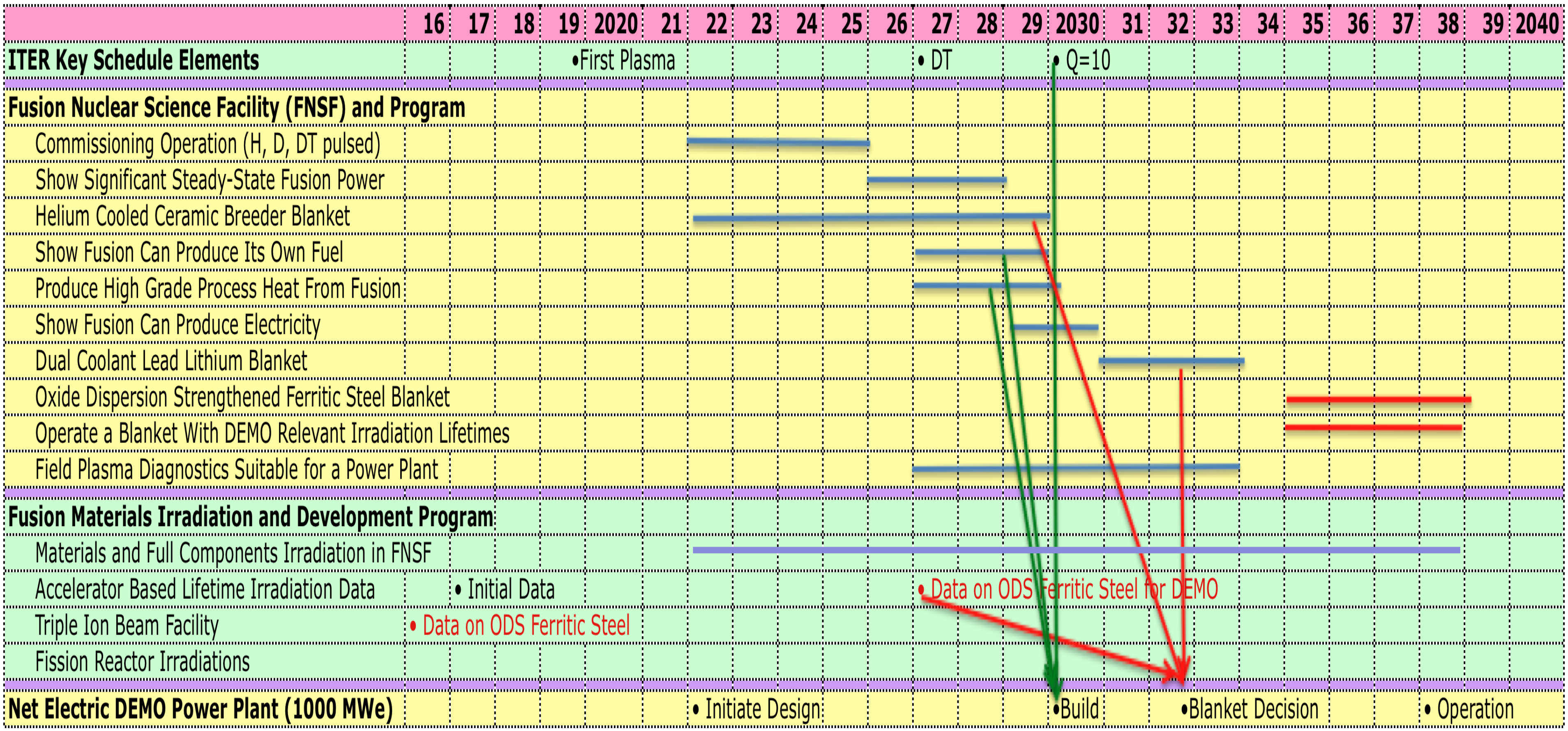
Green=done
Blue=near term

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**

A Fast Track Plan to Get to a Net Electric DEMO



DEMO design initiated by first plasma in ITER. DEMO construction triggered by Q=10 in ITER, first phase accomplishments in FNSF, and materials data on ODS Ferritic Steel. FNSF enables choice between two most promising blanket types for DEMO.