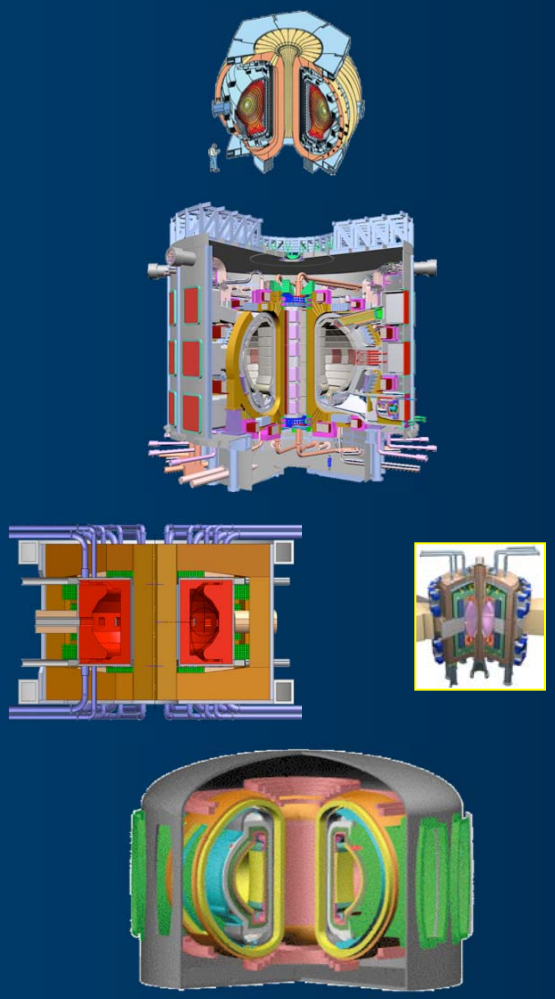
Mission Elements of the FNSP and FNSF

by
R.D. Stambaugh



Presented at
FNST Workshop

August 3, 2010

GENERAL ATOMICS

In Addition to What Will Be Learned in ITER, What Else Do We Need to Learn to Build a Net Electric Producing DEMO?

- **Fusion Nuclear Science:**
  - How to produce significant fusion power in true steady-state
  - How fusion can make its own fuel
  - How high grade process heat can be made from fusion reactions
  - How to make electricity from the process heat
  - How fusion chambers and blankets can survive high plasma and neutron fluences
  - How to measure plasma properties in the face of a high neutron fluence

The FESAC Planning Panel Identified the Gaps That Must Be Filled Between ITER and a DEMO

How Initiatives Could Address Gaps

Legend

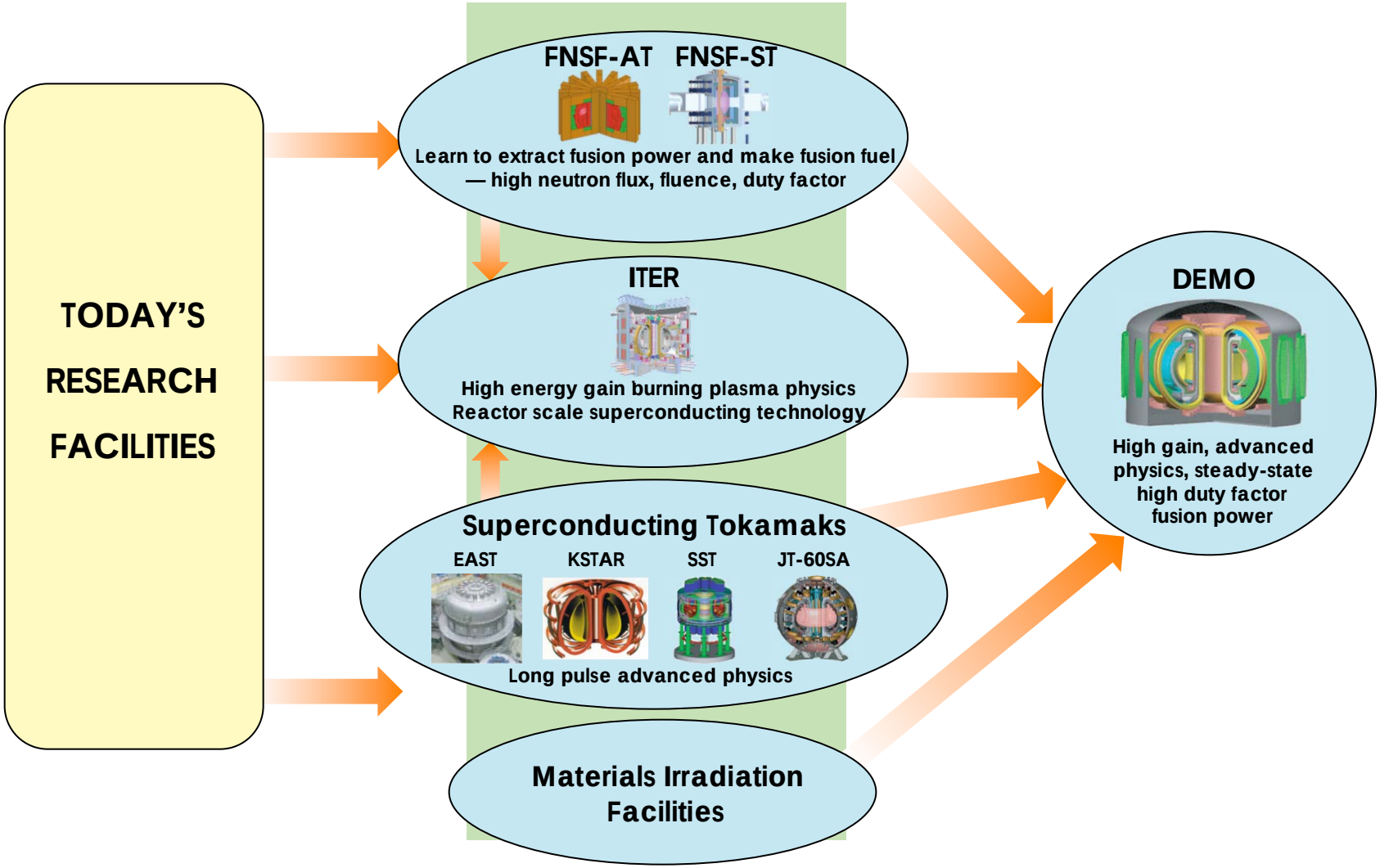
Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	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
FDF	2	3	3	3	3		3		3	3	3	3	3	3	3

*** A Fusion Nuclear Science Program and Facility Fills Nearly All the Gaps**

GENERAL ATOMICS

A Fusion Nuclear Science Facility Provides the U.S. With a World Leading Research Facility Running in Parallel With ITER



GENERAL ATOMICS

The FNSF Must Be Complementary to ITER

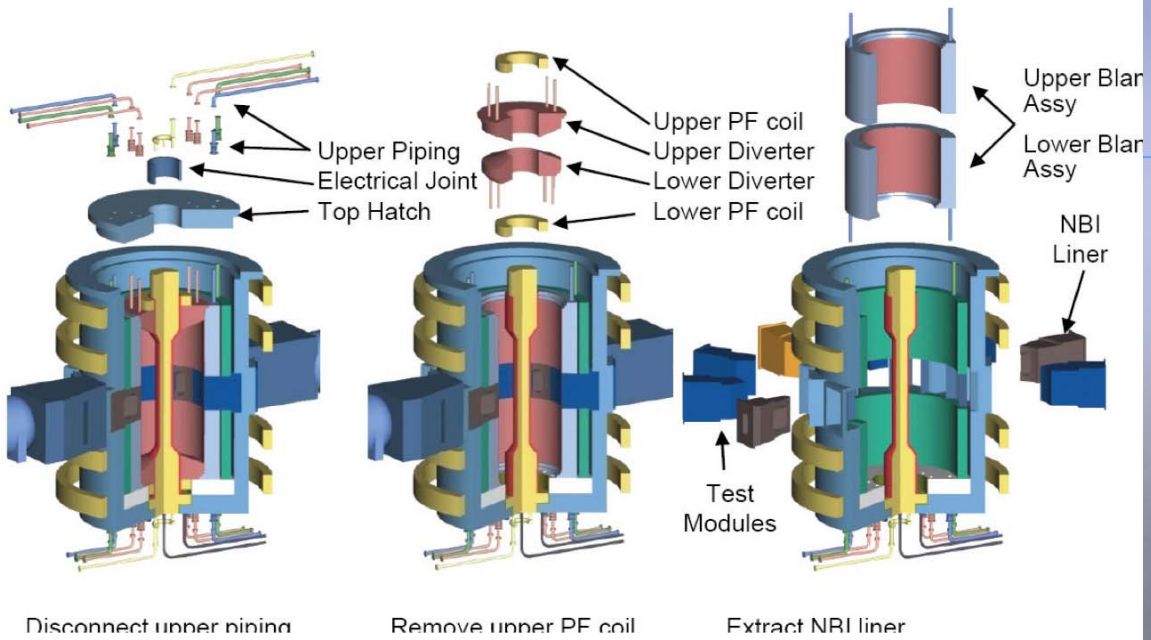
Issue	Today's Exp'ts	ITER	FDF	IFMIF	ITER +IFMIF +FDF	DEMO
High Gain Q > 10		3	2		3	R
Alpha Containment & Physics	1	3	2		3	R
Confinement at Large Size	1	3	1		3	R
Pulsed Heat Loads	1	3	1		3	R
Reactor Scale Superconducting Technology	1	3			3	R
Exhaust Power Handling (~10 MWm^{-2})	1	3	3		3	R
Tritium Handling and Safety	1	3	3		3	R
Integrated Plasma Performance in SS	1	2	2		3	R
Steady-State @ High Beta (β_N, f_{bs})	1	2	3		3	R
High Neutron Wall Loading (Γ_n ~ 2 MWm^{-2})	1	2	3		3	R
Tritium Self-Sufficiency (TBR > 1)		1	3		3	R
PFC and Divertor Materials Lifetime	1	2	3		3	R
FW/Blanket Materials/Components Lifetime		1	3	1	3	R
Materials Characterisation (>100 dpa)		1	2	3	3	R
High Temperature Blankets (electricity, H_2)		2	3		3	R

Key:

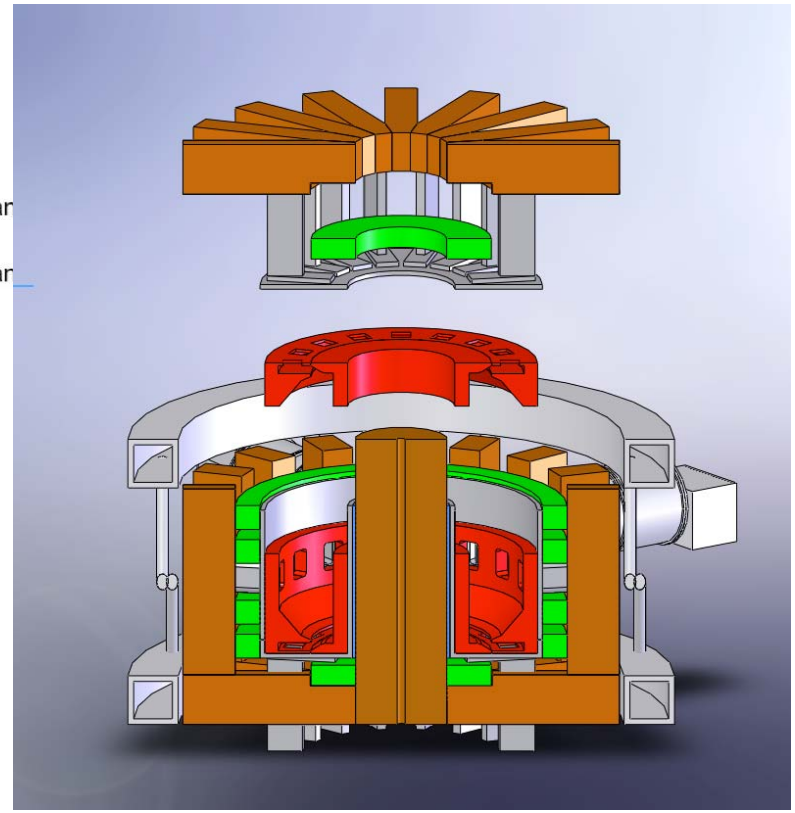
1	Will help to resolve the issue
2	Will contribute significantly to resolution of the issue
3	Should resolve the issue
R	Solution is essential

Today's Expt's = DIII-D, C-Mod, NSTX, JT-60U, JET, ASDEX-U, Tore Supra, JT-60 SA, KSTAR, EAST, SST-1

A Fusion Nuclear Science Facility Must Be a Research Device, Maintainable, Flexible, Re-configurable



ORNL FNSF-ST



GA FNSF-AT (FDF)

* A defining characteristic of device approaches

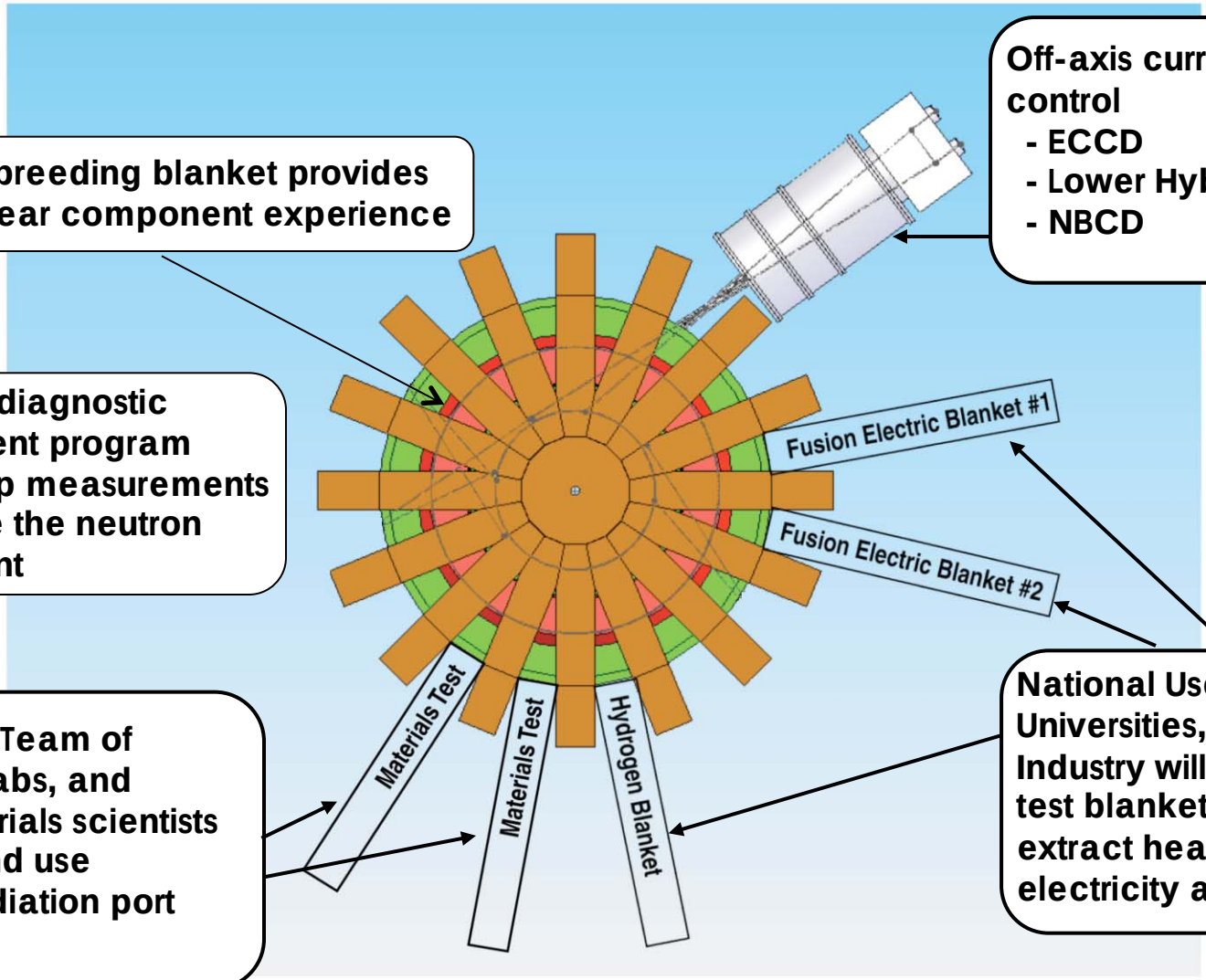
GENERAL ATOMICS

FNSF Will Support Large National User Teams (Goal 1000 users)

Full tritium breeding blanket provides fusion nuclear component experience

Off-axis current profile control
- ECCD
- Lower Hybrid
- NBCD

A national diagnostic development program will develop measurements that survive the neutron environment



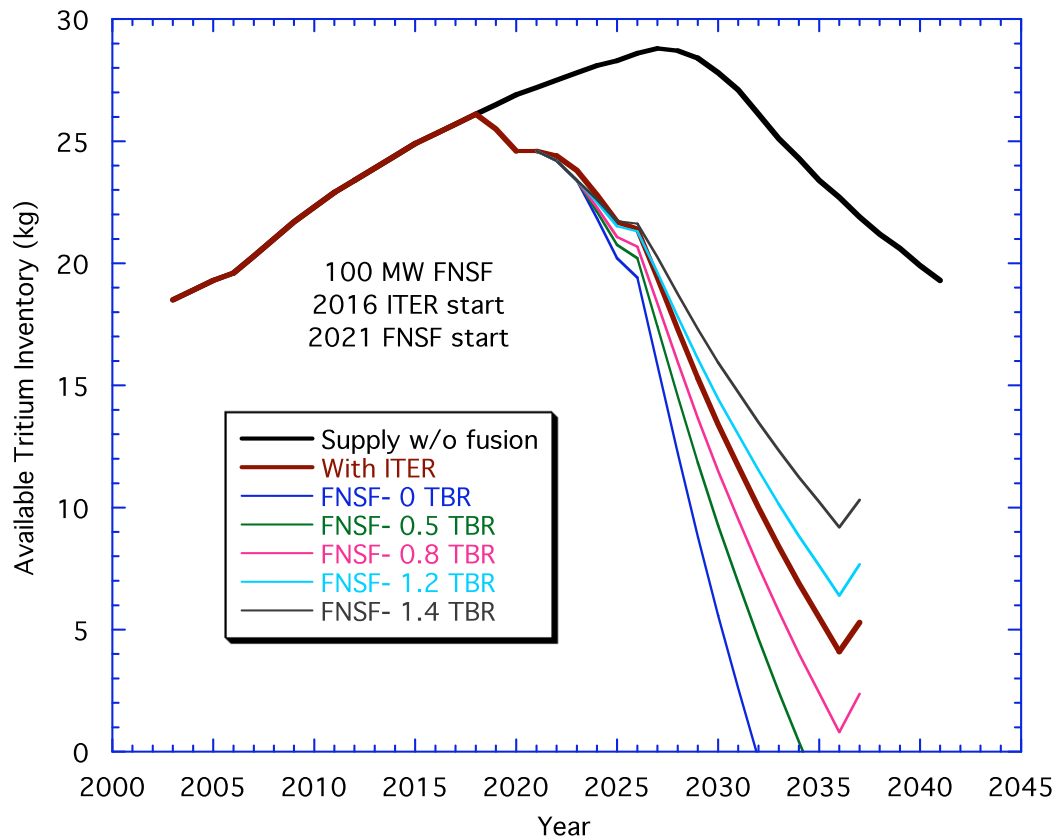
National User Team of Universities, Labs, and Industry materials scientists will control and use materials irradiation port sites

National User Teams of Universities, Labs, and Industry will field and study test blanket modules to extract heat to make electricity and hydrogen

To Show Fusion Fuel Self-Sufficiency, FNSF-AT Will Demonstrate Efficient Net Tritium Production

Tritium inventory available for DEMO at end of ITER and FDF operation depends strongly on TBR in FDF.

A 1000 MWe DEMO will burn 12 kg tritium per month.



(From M. Sawan, Wisconsin and M. Abdou, UCLA, August 2009)

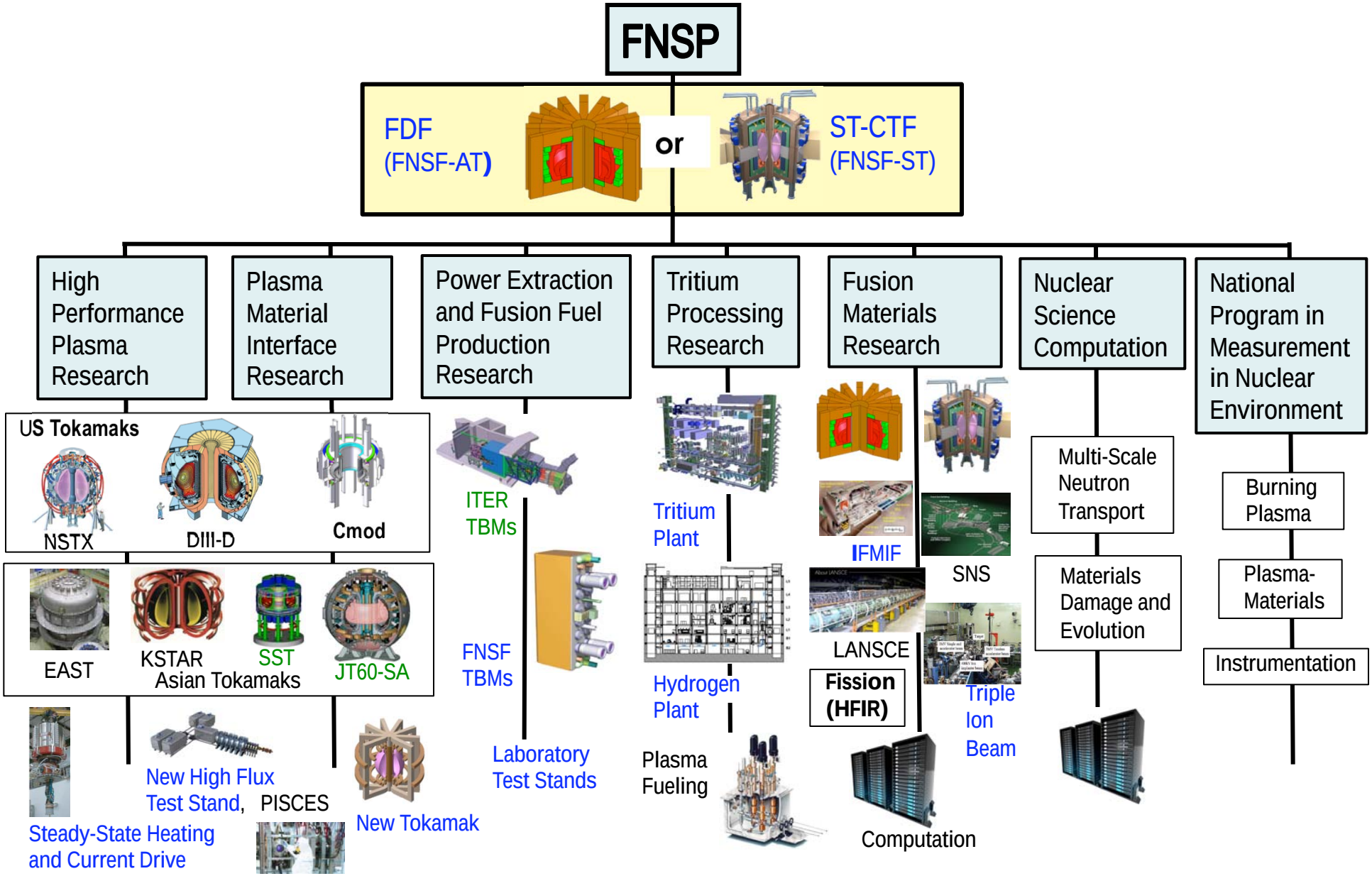
FDF must have Tritium Breeding Ratio > 1

GENERAL ATOMICS

The Critical Issues of Plasma Wall Interactions and Plasma Facing Components Will Be Squarely Addressed in FDF

- **Hot wall operation**, above 400^0C at least, will be an entirely new regime.
- **Erosion**
  - Biggest step FDF makes is in on time, 10^7 seconds per year, and hence neutron and particle fluence. (100 times ITER).
  - Divertor gross erosion estimates range from mm (W) to cms (C) per year.
  - Tons of material per year will erode and redeposit. Properties?
  - Solutions? Tungsten? Detached divertor? Others?
- **Tritium Retention**
  - Cannot be allowed to prevent TBR > 1
  - Even for carbon, codep estimates (very temperature dependent) < 0.5 kg retained in two weeks, then quickly removed by oxygen baking
- **Heat Flux Handling**
  - Axisymmetric maintenance scheme allows precision alignment of surfaces to hide edges and allow maximal use of flux expansion, progressing through the "x-divertor, snowflake divertor, super x-divertor."
  - High density helps promote radiation and containment of neutrals in the divertor, helping separate core and divertor plasmas (super-x?)
- **Other issues**
  - Fast plasma shutdowns,first wall heat fluxes in fault conditions, EM forces

An FNSF Can Be the Lead Element in a Broader Fusion Nuclear Science Program (FNSP)



The Research Program Envisions Three Main Blanket Phases and a TBM Program

	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	

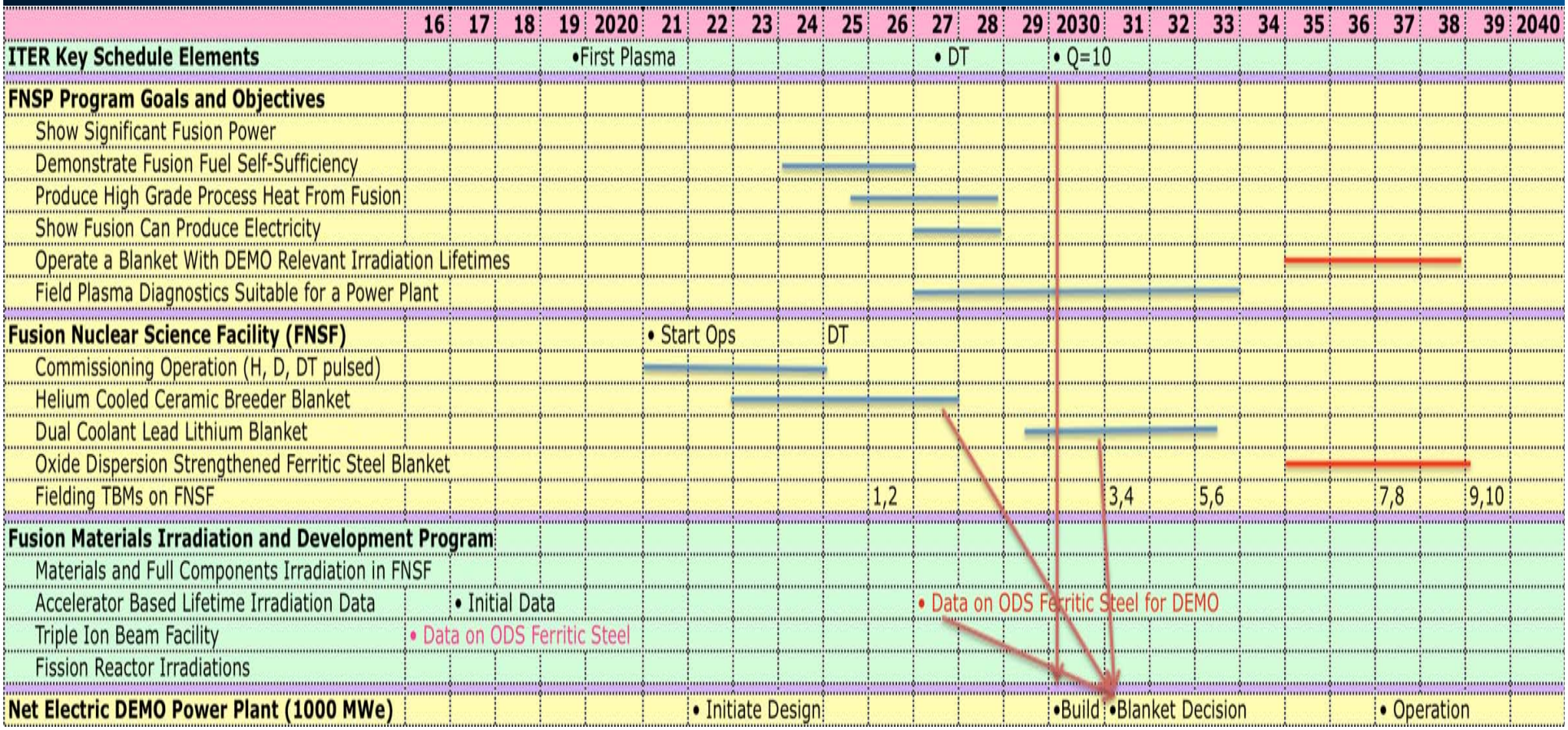
GENERAL ATOMICS

FNSF Must Be a DT Device, Making Fusion Power and a Continuous String of Progress Elements Toward Fusion Energy

- **Produce significant fusion power in true steady-state (< 3 dpa)**
- **Show fusion can make its own fuel**
  - Initial result in < 3 dpa
  - Full blanket development program in 10-20 dpa
- **Extract high grade process heat from fusion reactions**
  - Initial result in < 3dpa, full results in 10-20 dpa
- **Show electricity produced from the process heat**
  - 300 kW from one of the first test blanket modules (< 3dpa)
- **Show fusion chambers can survive high plasma and neutron fluences**
  - results obtained for three blanket types (10-20 dpa to each)
- **Develop plasma measurements suitable for a DEMO (10-20 dpa)**
- **Obtain high fluence irradiation data on materials, assemblies, welds, etc. (30-60 dpa)**

No blanket stays in the machine more than 20 dpa

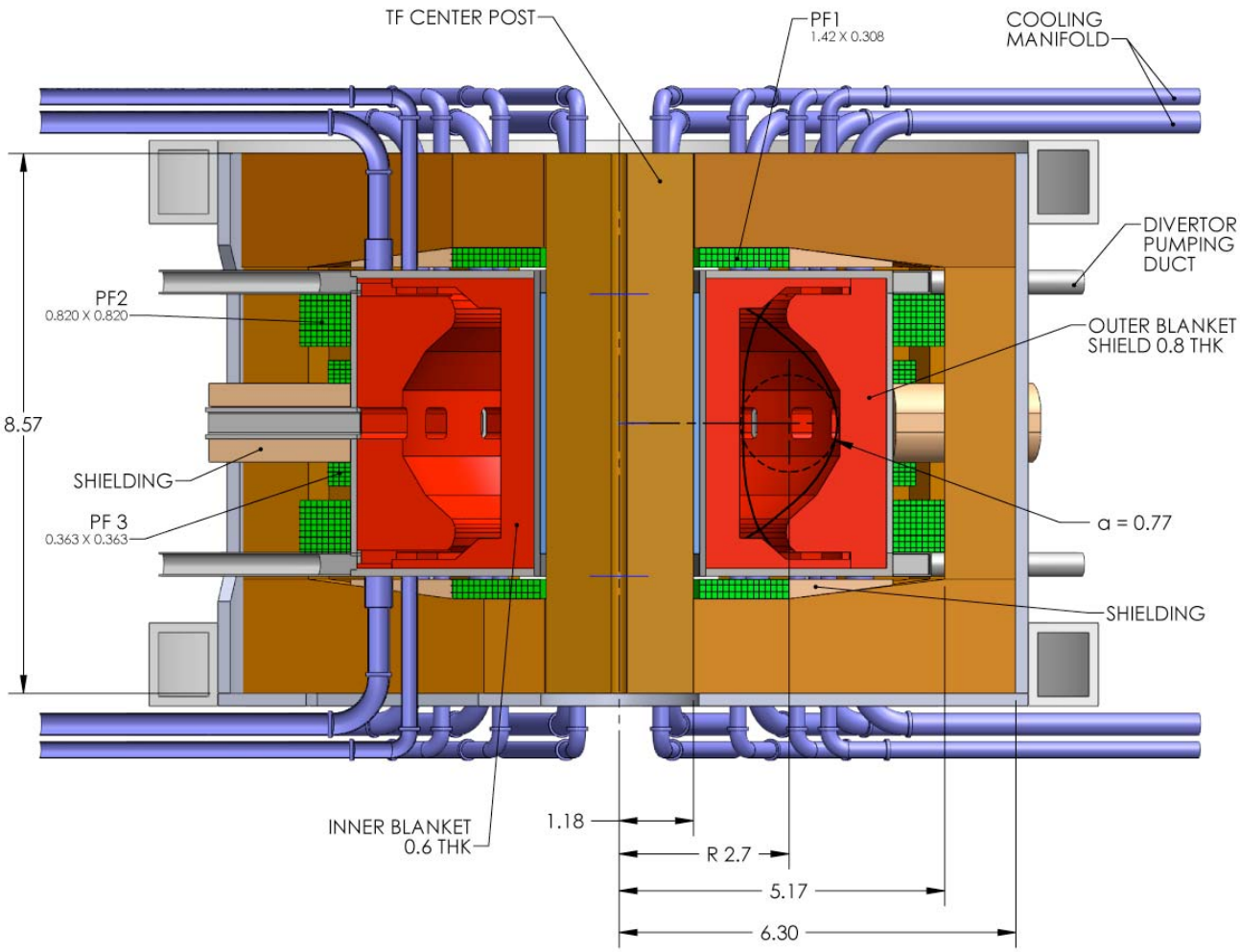
A Fast Track Plan to Get to a Net Electric DEMO



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.

GENERAL ATOMICS

Rebaselined FNSF-AT Incorporating Increased Blanket/ Shield, Realistic Divertor Geometry, Plasma Wall Gaps



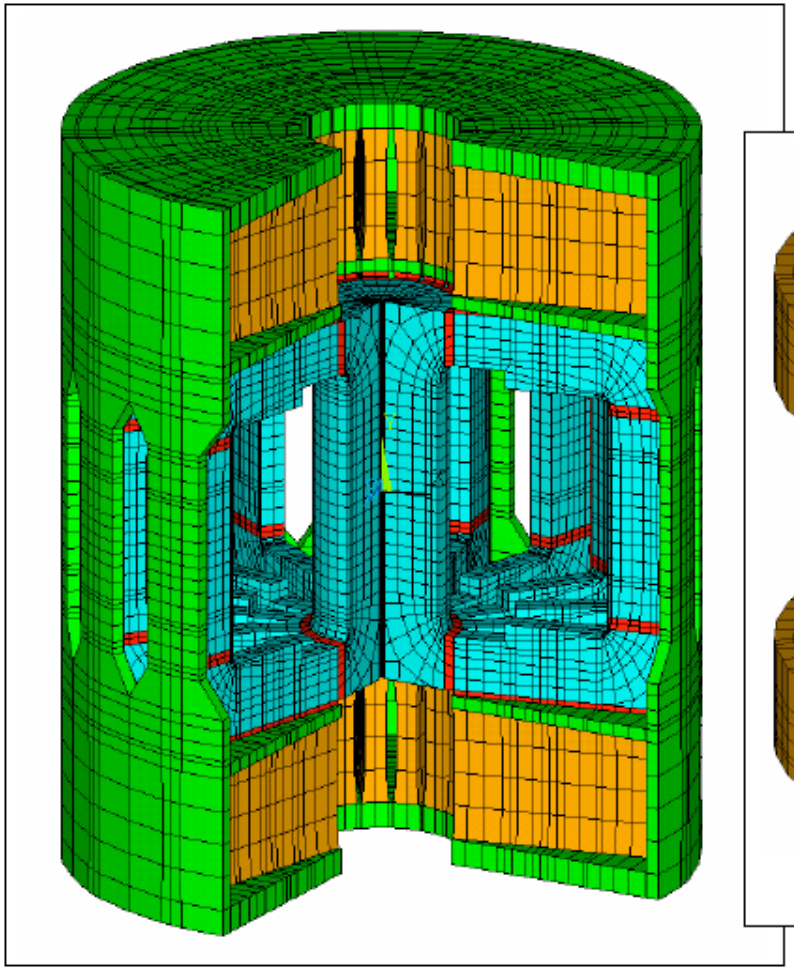
GENERAL ATOMICS

A Path Forward for Fusion in the United States

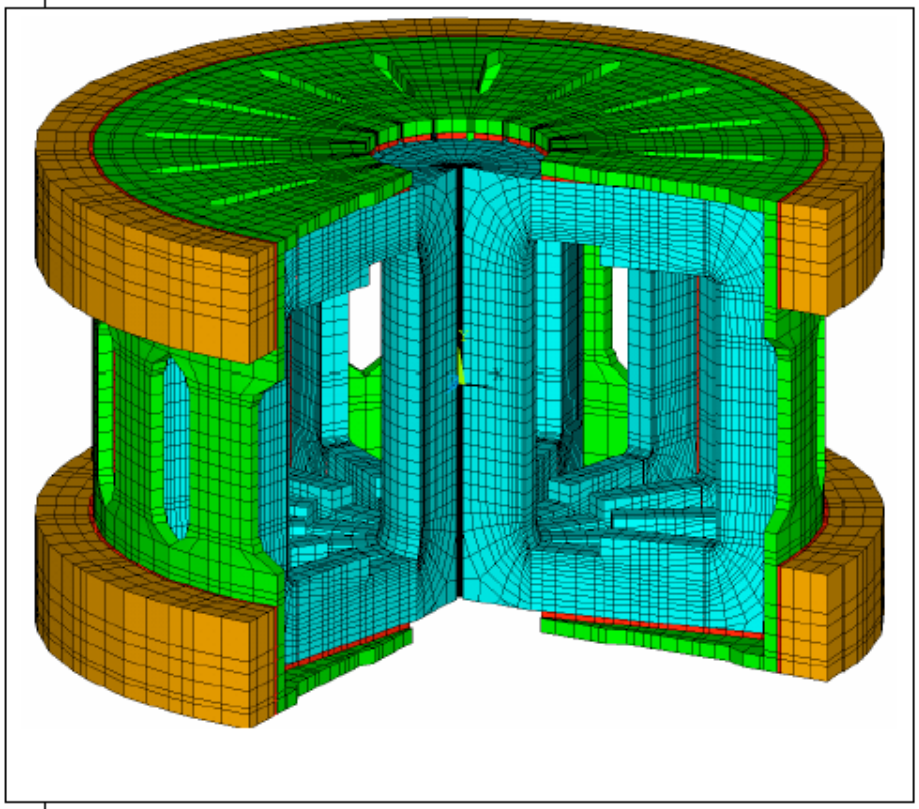
- To get to a net electric producing DEMO, a Fusion Nuclear Science Program is needed, in addition to the ongoing confinement research and the burning plasma research in ITER.
- MFE can build a high power steady-state neutron source that can enable Fusion Nuclear Science.
- The FNSP, ITER, and ongoing tokamak research will provide an adequate basis for a net electric MFE DEMO plant.

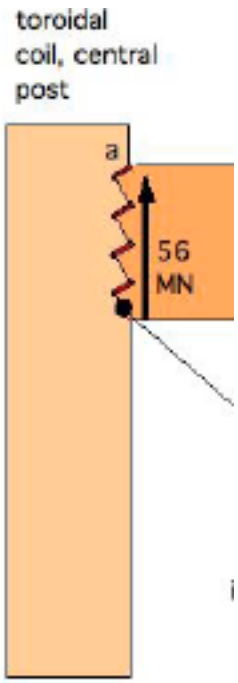
Two Options Being Considered for TF Coil Joint: C-mod Type Sliding and Sawtooth Joint (Rebut)

Model with Cover Weldment and Sliding



Model with Rebut Toothed Engagement of Horizontal and Vetrical TF Legs, Compression Ring Holds it Together





GENERAL ATOMICS

FNSF-AT Supports a Variety of Operating Modes, Some of Which Can Reach Toward an ARIES-AT Type DEMO

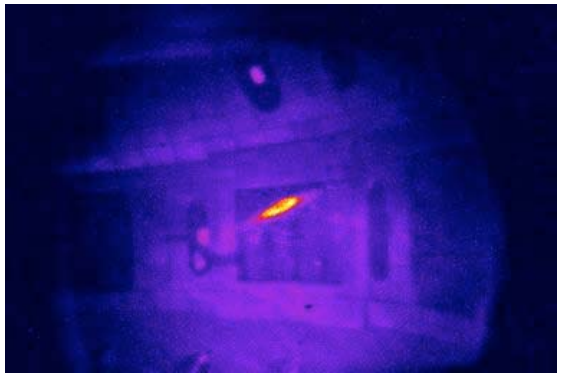
			Baseline	Lower B, fbs	Lower BetaN	Advanced	Very
			2 MW/m2	1.0 MW/m2	fbs, H98		Advanced
A	aspect ratio		3.5	3.5	3.5	3.5	3.5
a	plasma minor radius	m	0.77	0.77	0.77	0.77	0.77
Ro	plasma major radius	m	2.70	2.70	2.70	2.70	2.70
k	plasma elongation		2.31	2.31	2.31	2.31	2.31
Jc	centerpost current density	MA/m2	16.7	12.0	16.7	16.7	16.7
Pf	fusion power	MW	290	145	159	476	635
Pinternal	power to run plant	MW	500	348	527	501	492
Qplasma	Pfusion/Paux		6.9	3.5	2.9	12.4	19.8
Pn/Awall	Neutron Power at Blanket	MW/m2	2.0	1.0	1.1	3.3	4.4
BetaT	toroidal beta		0.058	0.078	0.041	0.076	0.088
BetaN	normalized beta	mT/MA	3.69	3.69	2.65	4.50	5.00
fbs	bootstrap fraction		0.75	0.56	0.54	0.85	0.90
Pcd	current drive power	MW	42	41	54	39	32
Ip	plasma current	MA	6.60	6.39	6.56	7.09	7.43
Bo	field on axis	T	5.44	3.90	5.44	5.44	5.44
TF Stress	Stress in TF Coil	MPa	276	142	276	276	276
q	safety factor		5.00	3.70	5.02	4.65	4.43
Ti(0)	Ion Temperature	keV	16.4	18.2	16.4	15.0	15.5
n(0)	Electron Density	E20/m3	3.14	1.96	2.22	4.32	5.11
nbar/nGR	Ratio to Greenwald Limit		0.60	0.38	0.42	0.76	0.86
Zeff			2.00	1.98	1.96	2.02	2.03
W	Stored Energy in Plasma	MJ	73	51	52	96	112
Paux	Total Auxiliary Power	MW	42	41	54	39	32
TauE	TauE	sec	0.73	0.73	0.61	0.72	0.70
HITER98Y2	H factor over ELMY H		1.60	1.60	1.36	1.60	1.60
PSOL/Adiv	Peak Divertor Heat Flux	MW/m2	6.7	5.2	6.8	7.3	7.6

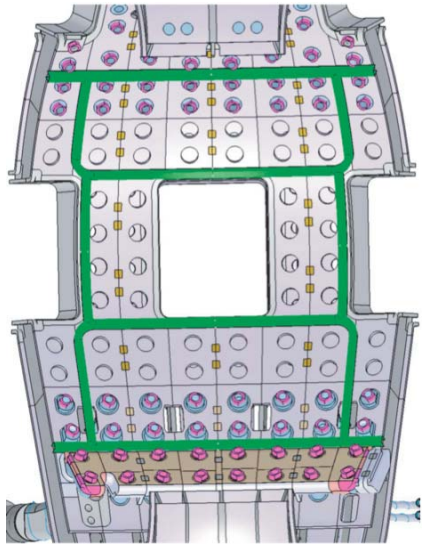
ORNL FNSF-ST Supports a Variety of Operating Modes, Extending to Highly Self-Organized Plasmas

	SUMMARY		ST-CTF	ST-ORNL	ST-ORNL	ST-ORNL	ST-ORNL	ST-ORNL
			Optimum	2 MW/m2	FDF Physics	Advanced	Very Advanced	Lower BT
A	aspect ratio		1.7	1.7	1.7	1.7	1.7	1.7
a	plasma minor radius	m	0.61	0.78	0.78	0.78	0.78	0.78
Ro	plasma major radius	m	1.04	1.32	1.32	1.32	1.32	1.32
k	plasma elongation		2.98	2.98	2.98	2.98	2.98	2.98
Jc	centerpost current density	MA/m2	60	43	43	43	43	40
Pf	fusion power	MW	111	177	368	557	797	621
Pinternal	power to run plant	MW	355	475	442	450	452	414
Qplasma	Pfusion/Paux		2.64	2.86	7.74	12.11	19.61	14.77
Pn/Awall	Neutron Power at Blanket	MW/m2	2.0	2.0	4.2	6.3	9.0	7.0
BetaT	toroidal beta		0.26	0.17	0.26	0.32	0.38	0.38
BetaN	normalized beta	mT/MA	5.2	3.5	5.2	6.2	7.0	7.0
fbs	bootstrap fraction		0.75	0.50	0.75	0.85	0.90	0.90
Pcd	current drive power	MW	42.1	62.0	47.5	46.0	40.7	42.1
Ip	plasma current	MA	8.4	12.0	11.9	12.5	13.3	12.4
Bo	field on axis	T	2.8	3.1	3.1	3.1	3.1	2.9
TF Stress	Stress in TF Coil	MPA	276	276	276	276	276	242
q	safety factor		8.2	8.2	8.2	7.8	7.3	7.3
Ti(0)	Ion Temperature	keV	10.7	13.8	16.0	15.3	15.5	13.6
n(0)	Electron Density	E20/m3	5.4	3.60	4.64	6.13	7.24	7.20
nbar/nGR	Ratio to Greenwald Limit		0.51	0.38	0.49	0.62	0.69	0.73
Zeff			1.9	2.0	2.0	2.0	2.0	2.0
W	Stored Energy in Plasma	MJ	25	44	65	81	97	85
Paux	Total Auxiliary Power	MW	42	62	47	46	41	42
TauE	TauE	sec	0.4	0.45	0.53	0.52	0.49	0.51
HITER98Y2	H factor over ELMY H		1.6	1.25	1.59	1.60	1.58	1.59
PSOL/Adiv	Peak Divertor Heat Flux	MW/m2	6.8	8.4	8.7	9.3	10.5	8.4

FNSF-AT Will Be a Necessary Progress Step to DEMO in Dealing With Off-Normal Events

- **Goals**
  - Operate for 10^7 seconds per year, duty factor 0.3.
  - Run two weeks straight without disruption
  - Only one unmitigated disruption per year
- **Disruption Strategy**
  - Real-time stability calculations in the control loop.
  - Active instability avoidance and suppression - RWMs, NTMs
  - Control system good enough to initiate soft shutdowns and limit firing the disruption mitigation system more than 20 times per year.
  - Disruption mitigation system 99% reliable.
- **ELM Suppression**
  - Resonant magnetic perturbation coils
  - QH-mode





Targets for Disruption Handling

Device	ITER	FDF	DEMO
Pulse length (s)	400	$1x10^6$	$3x10^7$
Number of pulses per year	1000	10	1
Fast shutdowns per year	100	20	5
Time between fast shutdowns (s)	$4x10^3$	$5x10^5$	$6x10^6$
Unmitigated disruptions per year	5	1	0.3

Diagnostics: FNSF-AT Can Bridge the Gap Between ITER and DEMO

- **First Set: ITER-like**
  - Validate physics
  - Verify performance
  - Optimize plasma
- **Second Set: Reduced**
  - Reduced profile information
  - Test reliability and components
  - Requires detailed physics models
- **Third set: DEMO-like**
  - Test of optimized, minimal, reliable set for DEMO

	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				0.8			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 ODS Ferritic Steel				
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

ITER-like set (start)

Reduced set

DEMO-like set

- **Conditions (fluence, pulse length, control relevant to diagnostic development and testing)**

GENERAL ATOMICS

FNSF Must Be a DT Device, Making Fusion Power and a Continuous String of Progress Elements Toward Fusion Energy

- **Objectives Achievable with 1 dpa fluence:**
  - Produce significant **fusion power** (150-400 MW)
  - Show avoidance and mitigation of **off-normal events**

- **Objectives Achievable with 3 dpa fluence:**
  - Show high performance, **steady-state**, burning plasmas (two weeks pulse)
  - Opportunity to show **very high performance** needed in ARIES-AT DEMO
  - Test and develop **auxiliary systems** for steady-state
  - Develop **PFC surfaces** for high fusion power in steady-state
  - Demonstrate high grade **process heat** from fusion
  - Demonstrate fusion **fuel self-sufficiency**
  - Show **electricity** production from fusion (from a test blanket module)
  - Show **hydrogen** production from fusion (from a test blanket module)

FNSF Must Be a DT Device, Making Fusion Power and a Continuous String of Progress Elements Toward Fusion Energy

- **Objectives Achievable with 10-20 dpa fluence:**
  - Develop plasma **measurements** suitable for a power plant
  - Develop **PFC surfaces** that survive alteration of properties by neutrons
  - Develop blankets that produce tritium efficiently
  - Develop **high temperature** blankets for efficient electricity production
  - Study **materials** in complex neutron, plasma, electromagnetic, thermal environment

- **Objectives Achievable with 30-60 dpa fluence:**
  - Show significant fusion power can be produces with significant **duty factor**
  - Develop and perform **irradiation tests** on low activiation, high strength, high temperature materials, material combinations, welded assemblies, etc. for long lived fusion blankets
  - Test full assemblies in the **neutron environment** with transmutation, activation, helium and hydrogen production
  - Develop **reliability data** on fusion components for DEMO

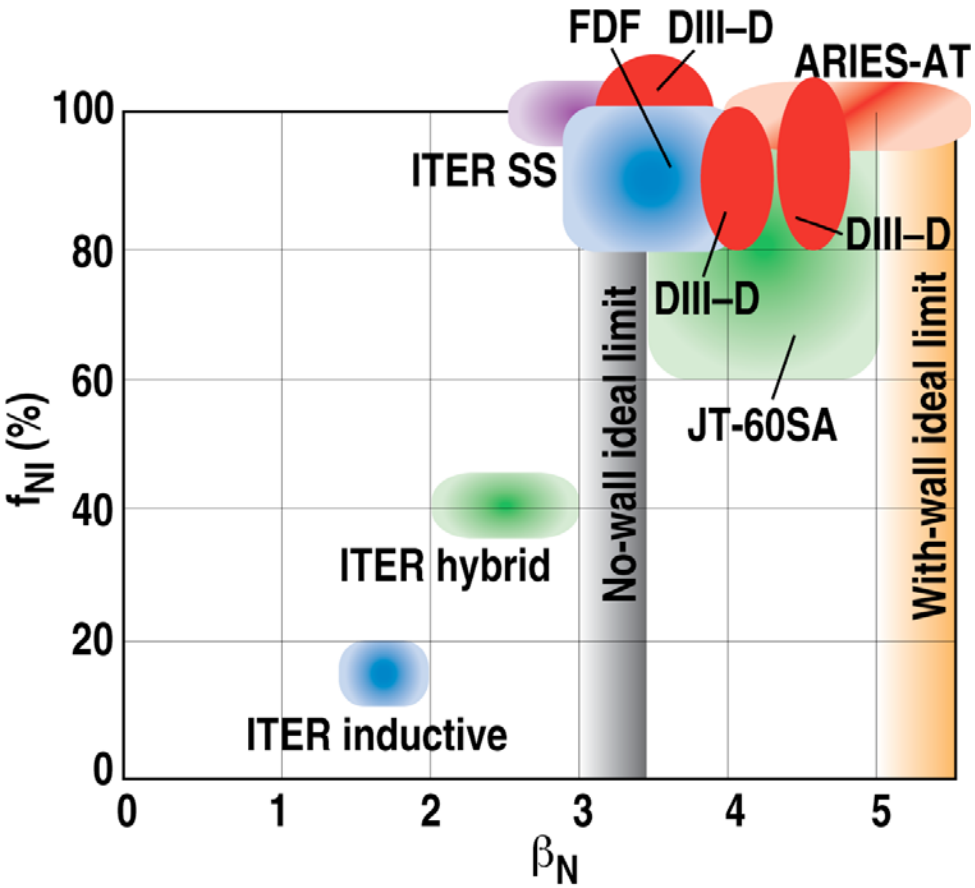
FDF Baseline Parameters More Conservative Than ARIES-AT, But FDF Can Reach for ARIES-AT Operating Modes

ITEM	FDF	ARIES-AT
Aspect Ratio	3.5	4.0
Elongation κ	2.31	2.21
Fraction of κ	0.95	0.95
Triangularity δ	0.7	0.78
Fraction of the Beta Limit *	67%	104%
β_N	3.69	5.4
$C_{bs} = f_{bs}/(\beta_p/A^{1/2})$	0.75	0.784
Peak Midplane Neutron Wall Loading (MW/m^2)	2.0	4.8
Neutron Wall Loading Peaking Factor	1.3	1.45
Zeff	2.10	1.99
Peak Divertor Heat Flux Without/With SOL and Divertor Radiation	8/3	14/5

* Y. R. LIN-LIU and R. D. STAMBAUGH, *Nucl. Fusion* **44**, 548 (2004).

DIII-D and Other Tokamaks Can Solidify the Physics Basis for the FNSF-AT in 2–5 Years

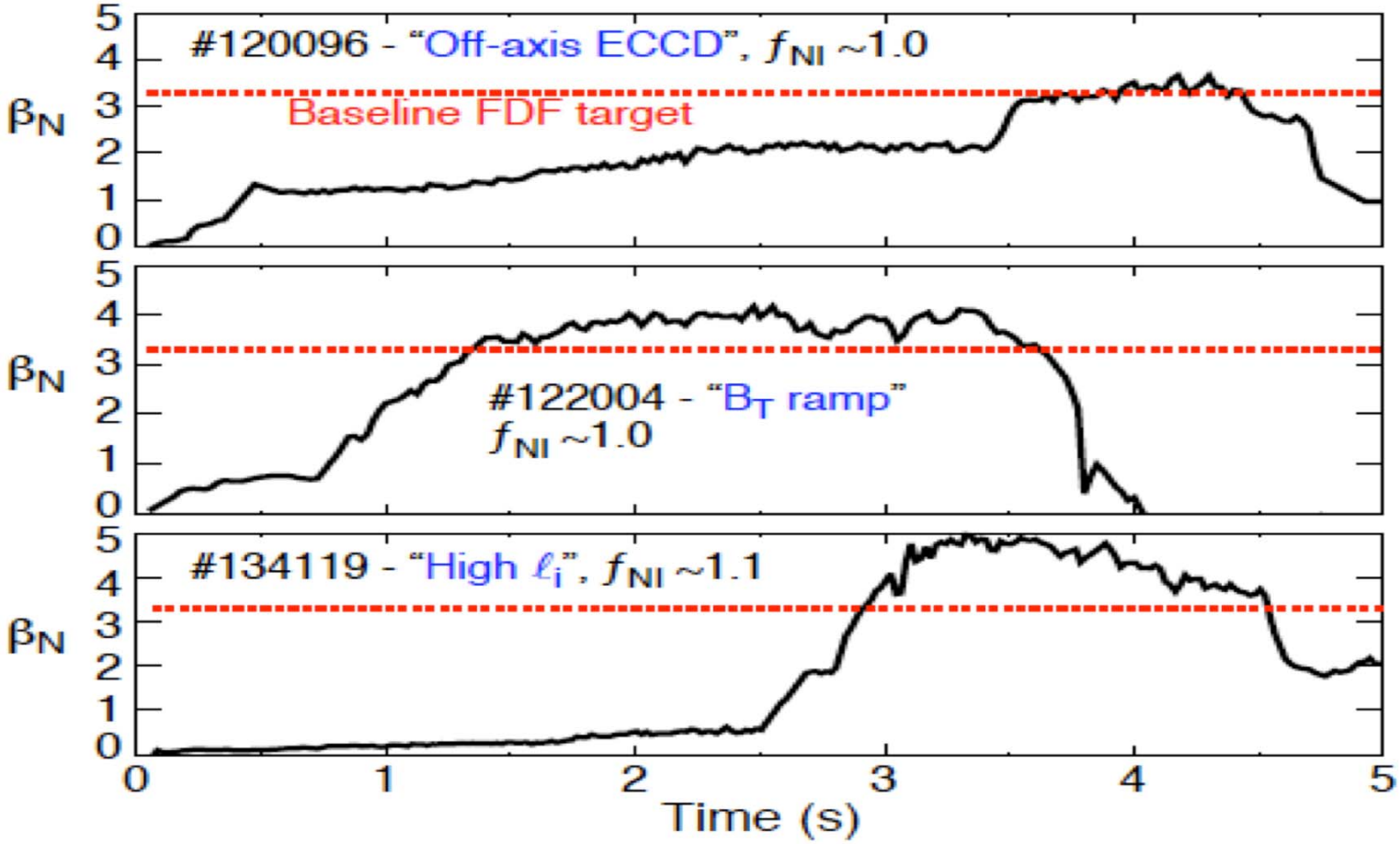
- Required stability values already achieved in 100% non-inductive plasmas in DIII-D (extend pulse length)
- RWM stabilization by rotation
- NTMs already stabilized
- ELMs gone - stochastic edge field
- ELMs gone - QH mode operation
- Confinement quality required already obtained in long pulse DIII-D plasmas
- Bootstrap fractions already achieved
- Far off-axis LHCD in H-mode (Alcator)
- Pumped, high triangularity plasma
- DIII-D plasma control system
- Power exhaust more challenging than DIII-D and comparable to ITER
- Main challenge is PFC tritium retention



Green = already achieved, Blue = near term, Red = main challenge

GENERAL ATOMICS

DIII-D Has Developed Three Operating Modes at 100% Non-inductive Current and BetaN Exceeding FDF Needs



GENERAL ATOMICS