Overview of Fusion Research at General Atomics

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Fusion Power Associates Annual Meeting and Symposium

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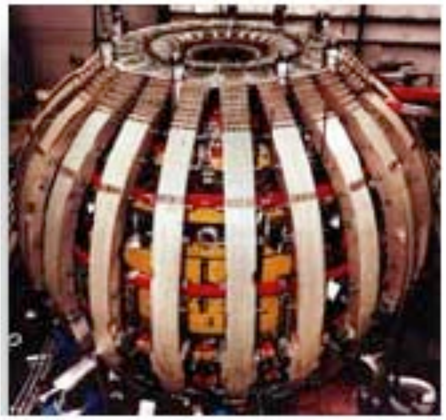
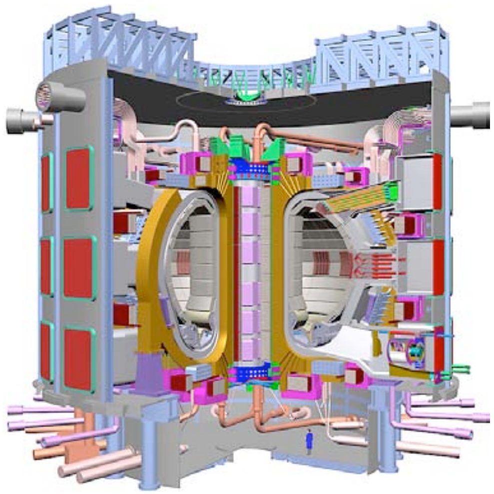
Magnetic Fusion, Inertial Fusion, and Fission Interact in the General Atomics Energy Group.

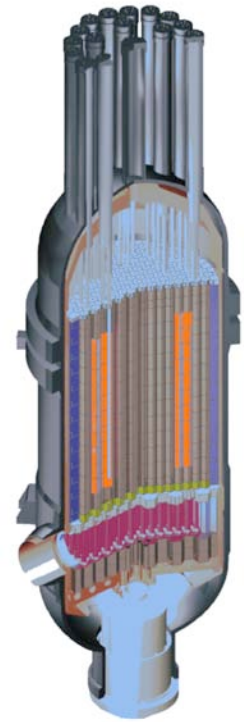
DIII-D



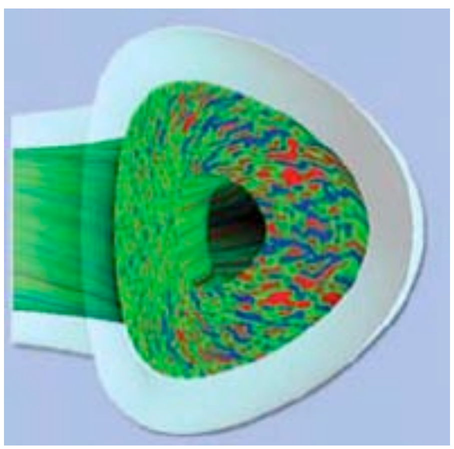
ITER



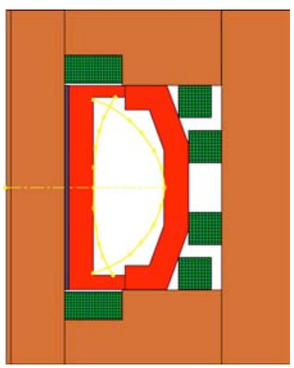
Fission



Theory



FDF



ICF

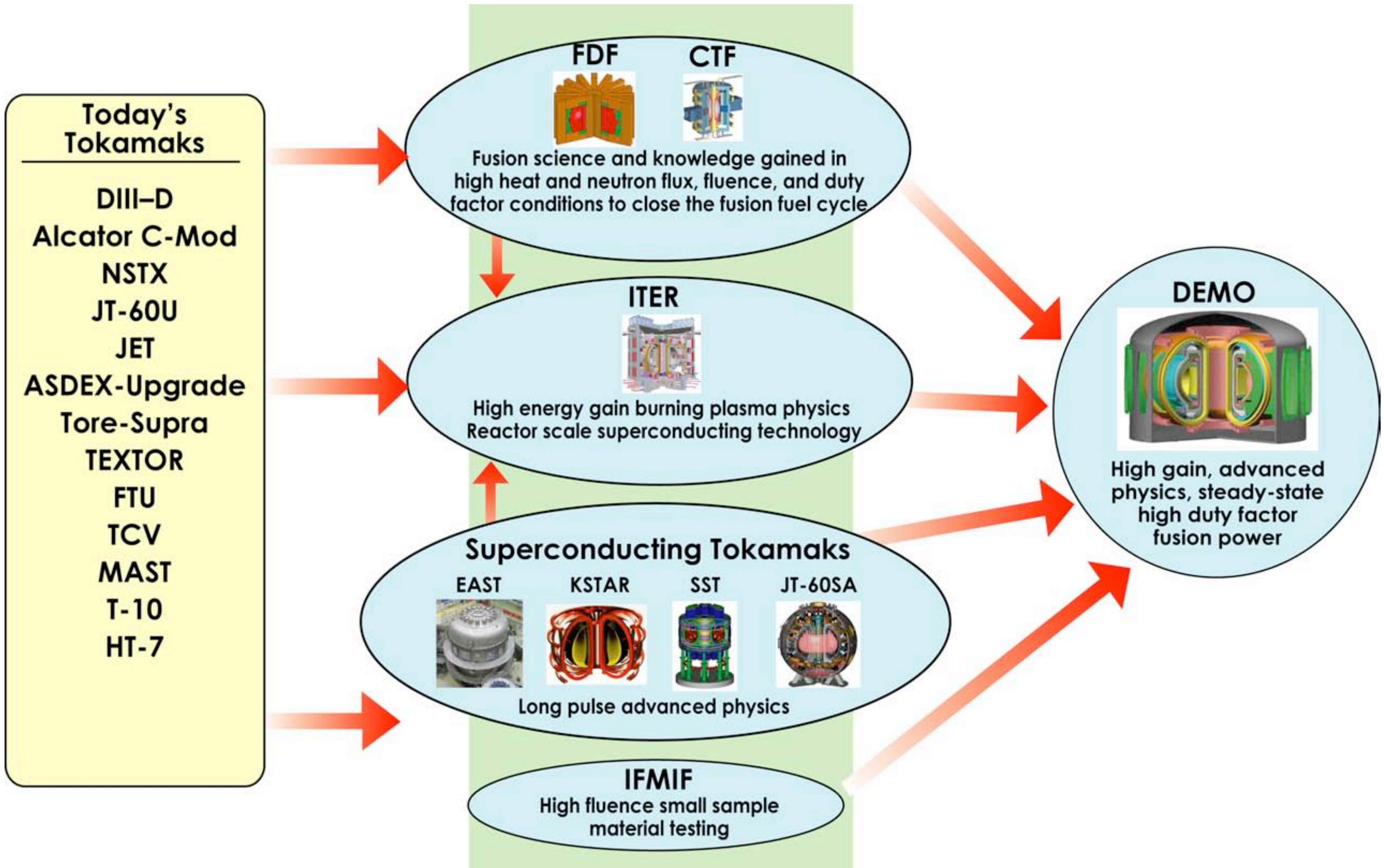
The Fusion Development Facility Mission: Develop Fusion's Energy Applications

- **Develop the technology to make**
  - **Tritium**
  - **Electricity**
  - **Hydrogen**

- **By using conservative Advanced Tokamak physics to run steady-state and produce 100-250 MW fusion power**
  - Modest energy gain (Q<5)
  - Continuous operation for 30% of a year in 2 weeks periods
  - Test materials with high neutron fluence (3-8 MW-yr/m^2)
  - Further develop all elements of Advanced Tokamak physics, qualifying them for an advanced performance DEMO

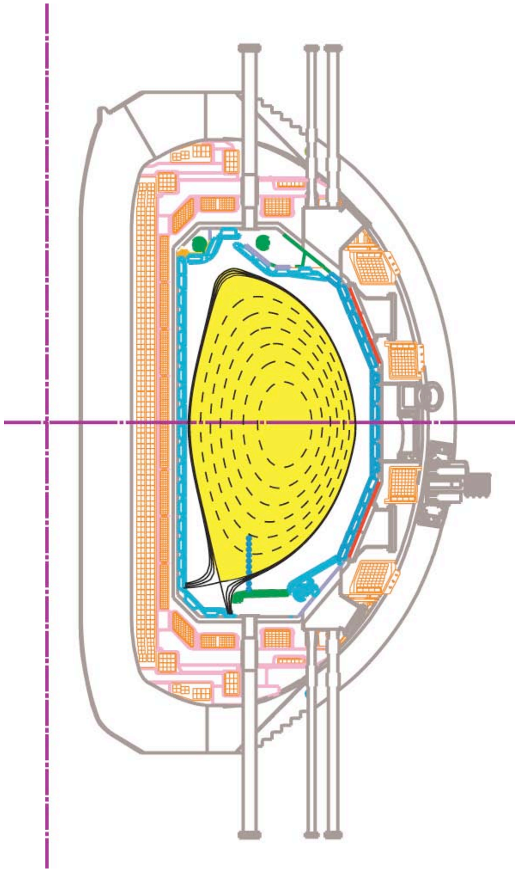
- **With ITER and IFMIF, provide the basis for a fusion DEMO Power Plant**

A Fusion Nuclear Science Facility, ITER, Superconducting Tokamaks, and a Materials Test Facility Enable Demo

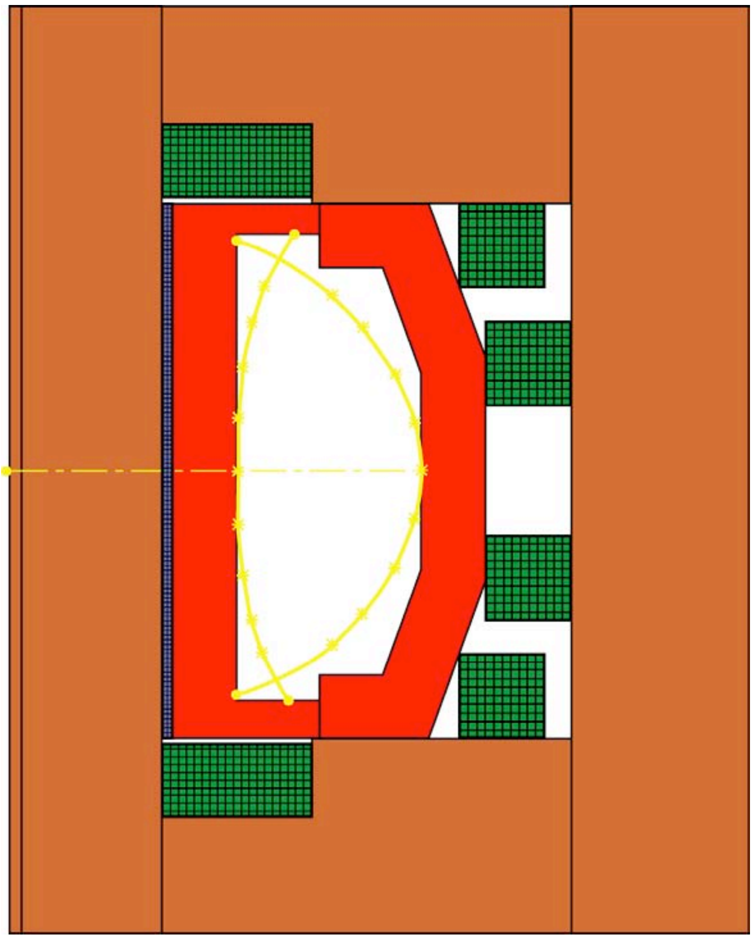


FDF is Viewed as a Direct Follow-on of DIII-D (50% larger) and Alcator Cmod, Using Their Construction Features

DIII-D



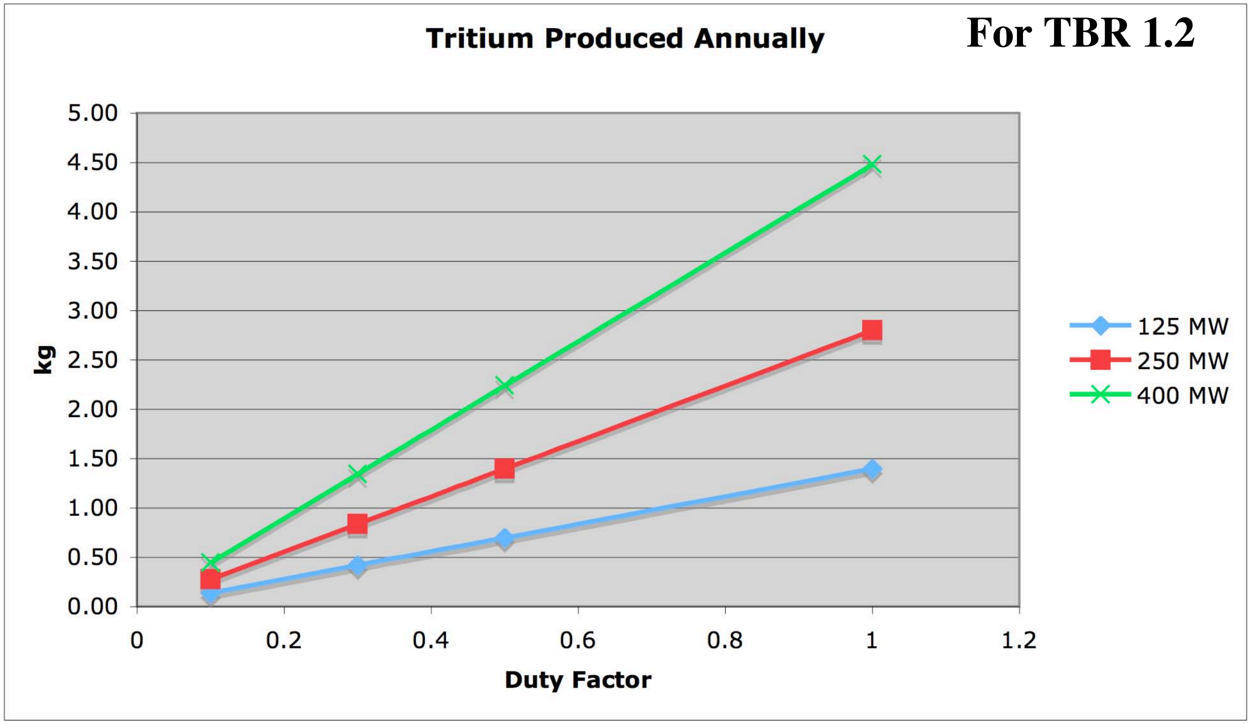
FDF

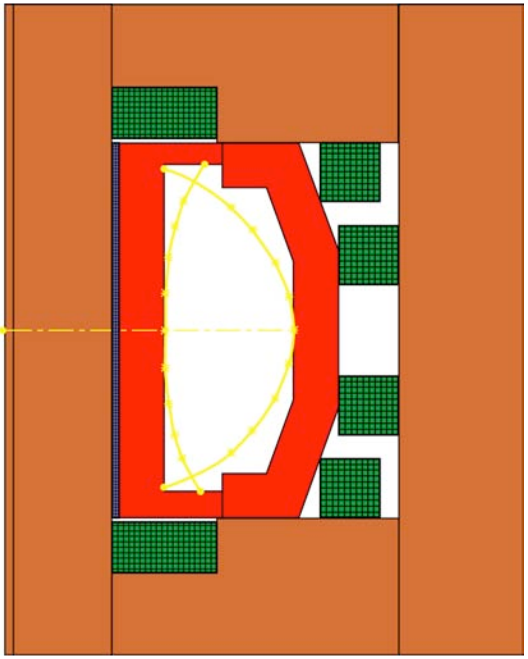


- Plate constructed copper TF Coil which enables..
- TF Coil joint for complete dissasembly and maintenance
- OH Coil wound on the TF Coil to maximize Volt-seconds
- High elongation, high triangularity double null plasma shape for high gain, steady-state
- Red blanket produces net Tritium

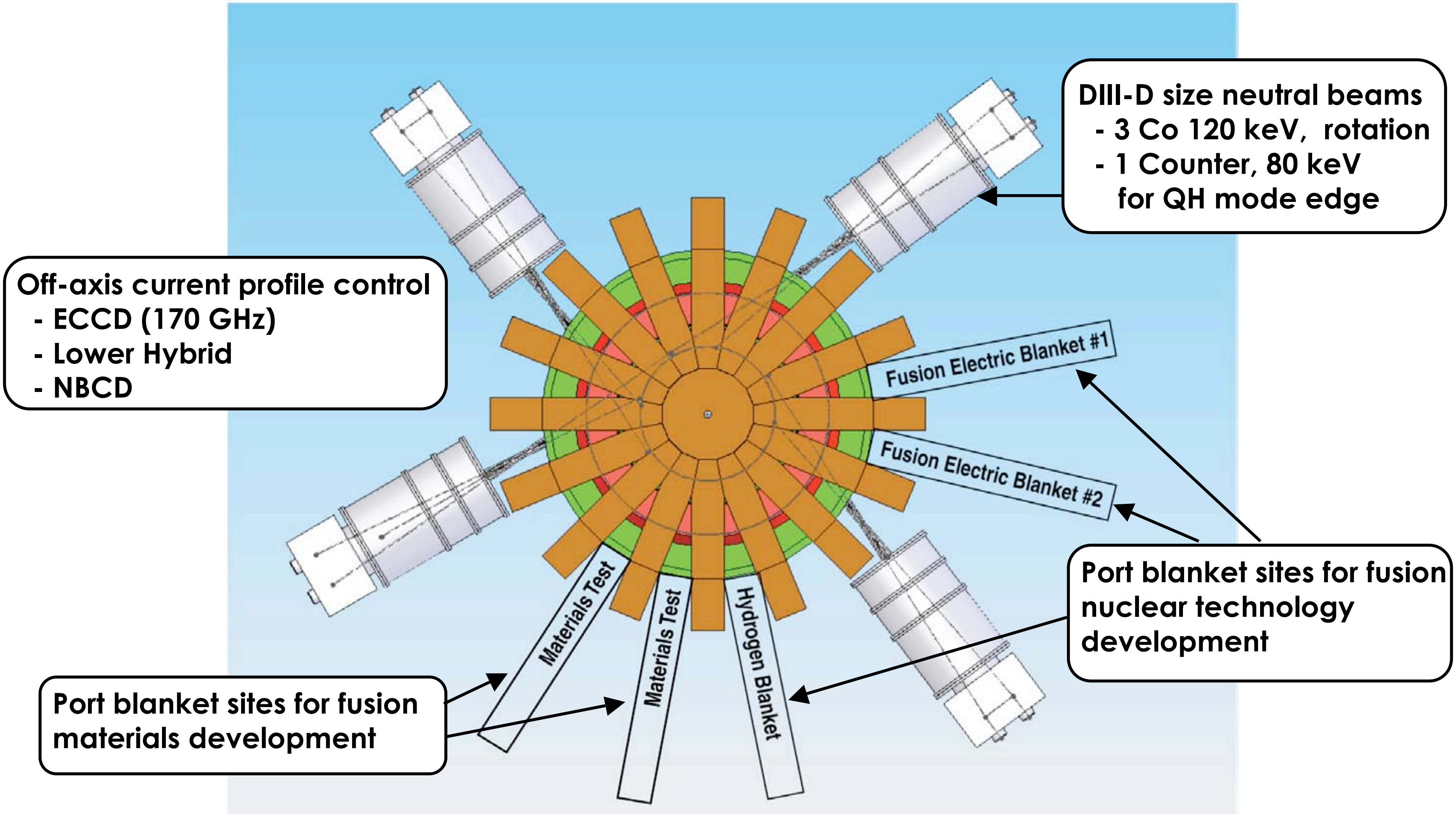
FDF Will Demonstrate Efficient Net Tritium Production

- FDF will produce 0.4–1.3 kg of Tritium per year at its nominal duty factor of 0.3
- This amount should be sufficient for FDF and can build the T supply needed for DEMO





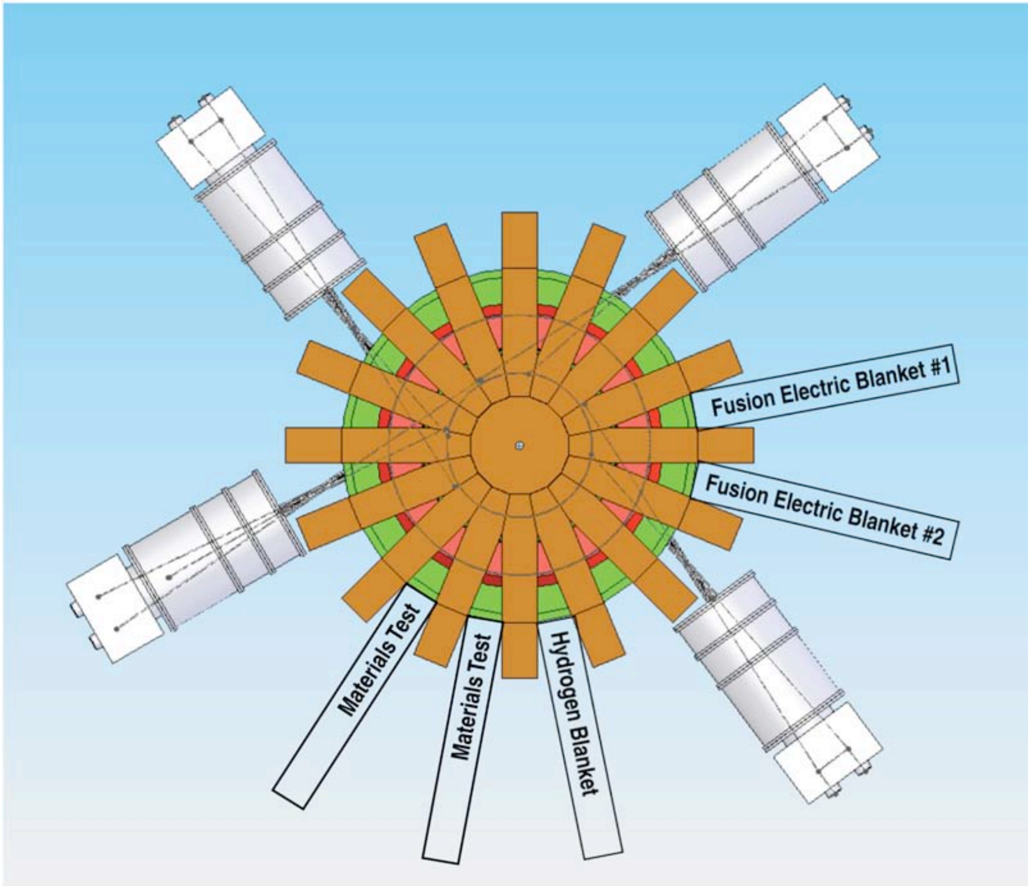
Port Sites Enable Nuclear and Materials Science.



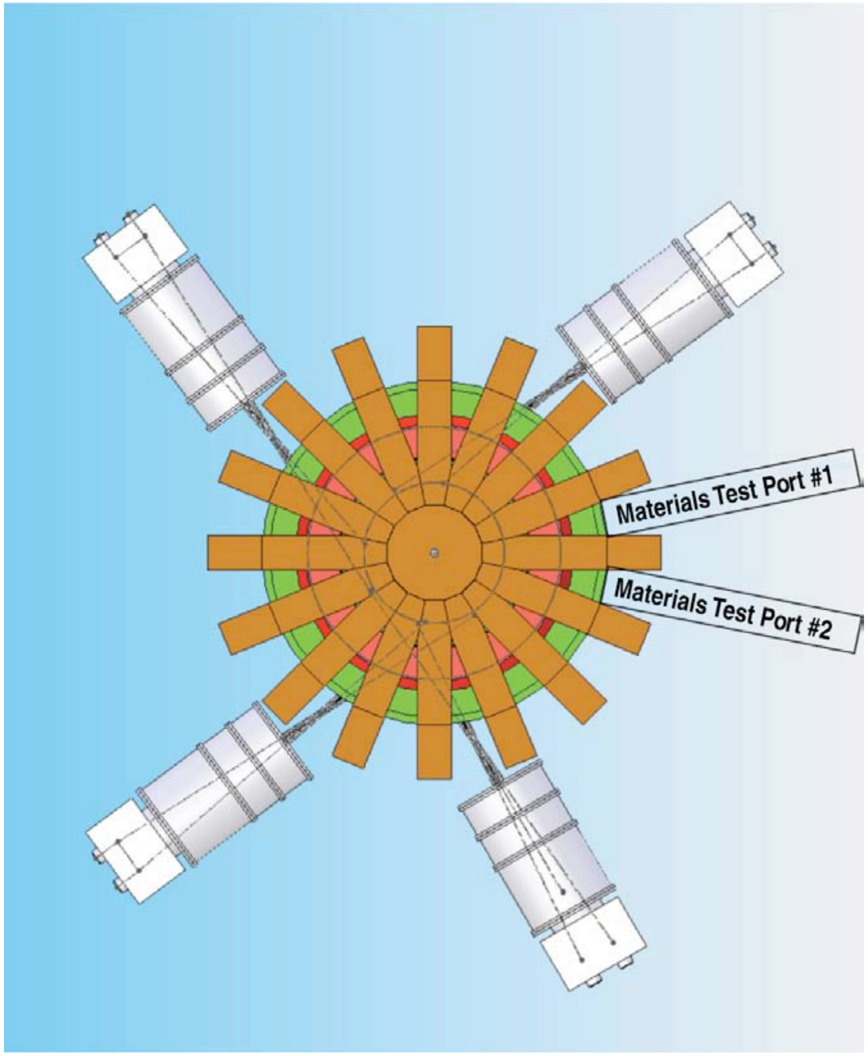
FDF will Motivate the Needed, Large, Supporting Fusion Nuclear Science Program

On Test Specimens and Components,

- **Materials compositions**
- **Activation and transmutation**
- **Materials properties (irradiated)**
- **Thermo-hydraulics**
- **Thermal expansion and stress**
- **Mechanical and EM stresses**
- **Tritium breeding and retention**
- **Solubility, diffusivity, permeation**
- **Liquid metals crossing magnetic fields**
- **Coolant properties**
- **Chemistry**
- **and more…..**



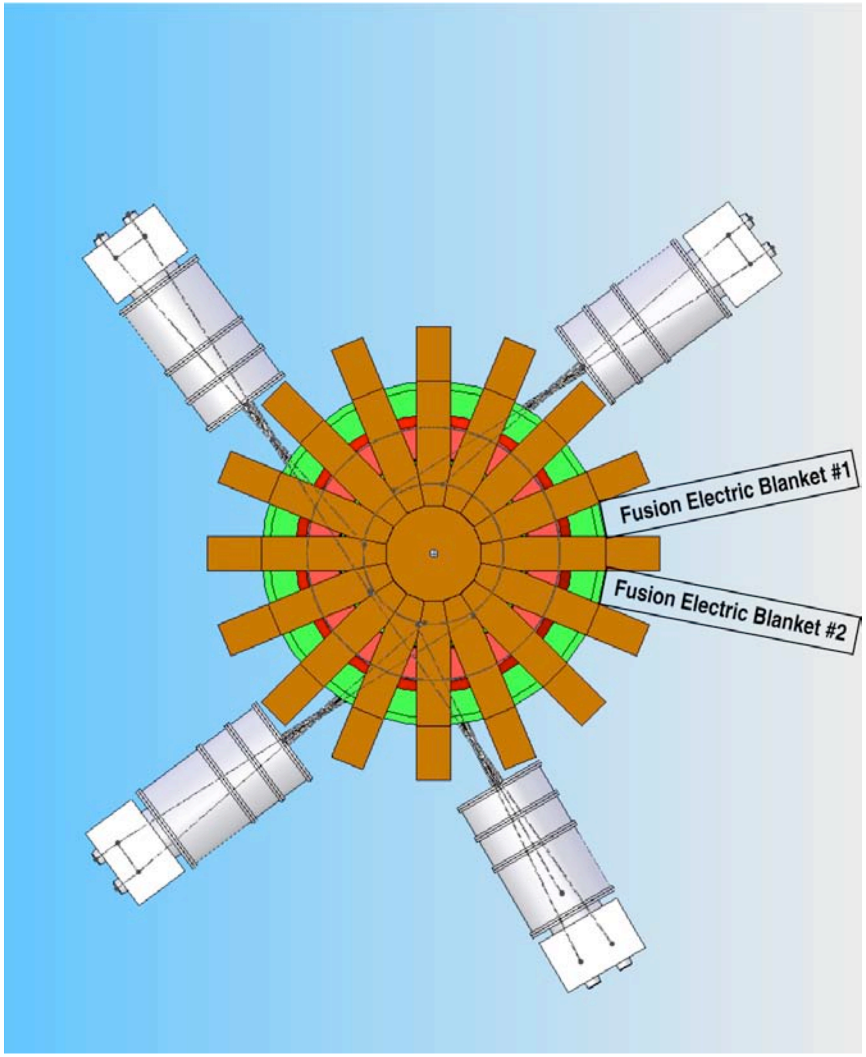
FDF is a materials irradiation and research facility



- **Provides up to 80 dpa of DT fusion neutron irradiation in controlled environment** **materials test ports** **for:**
  - First wall chamber materials
  - Structural materials
  - Breeders
  - Neutron multipliers
  - Tritium permeation barriers
  - Composites
  - Electrical and thermal insulators

- **Materials compatibility tests in an integrated tokamak environment**
  - Flow channel inserts for DCLL blanket option
  - Chamber components and diagnostics development

FDF Will Develop Blankets for Fusion Electric Power



- **Fusion electric blankets require**
  - High temperature (500-700 ^{0}C) heat extraction
  - Complex neutronics issues
  - Tritium breeding ratio > 1.0
  - Chemistry effects (hot, corrosive, neutrons)
  - Environmentally attractive materials
  - High reliability, (disruptions, off-normal events)

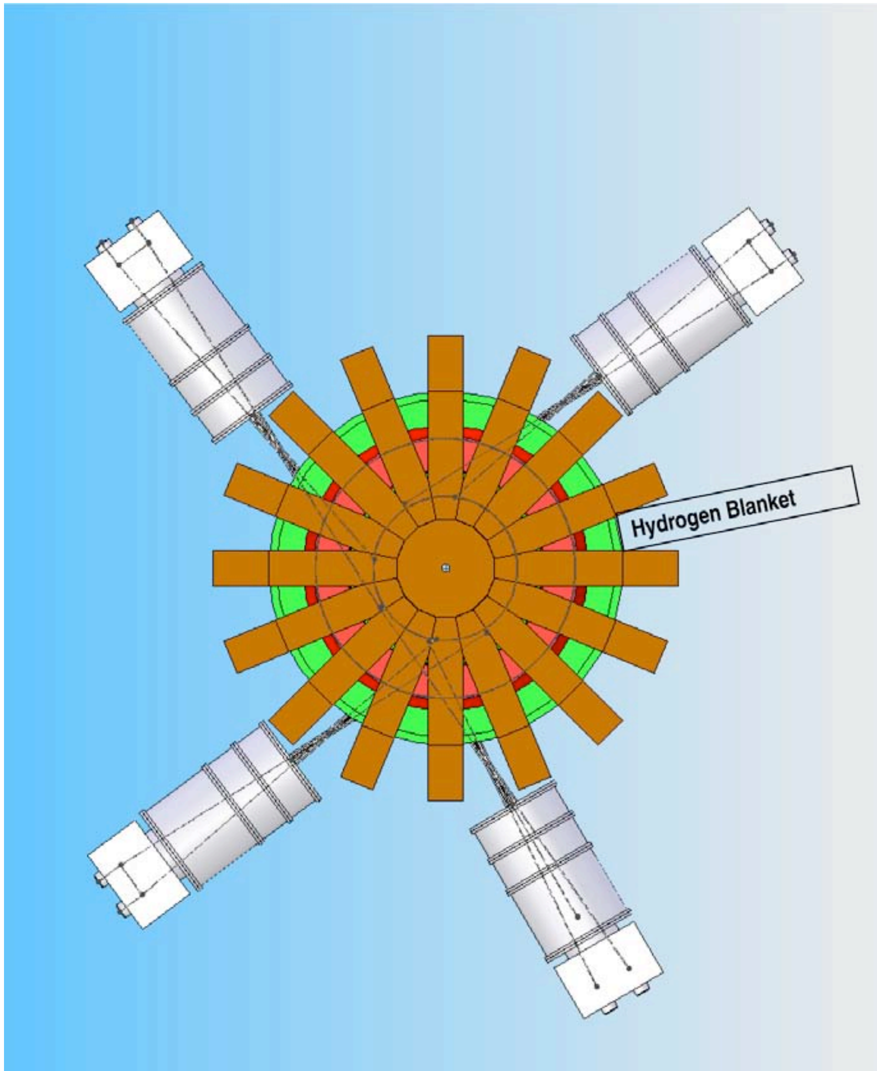
- **Fusion blanket development requires testing**
  - Solid breeders (3), Liquid breeders (2)
  - Various Coolants (2)
  - Advanced, Low Activation, Structural materials (2)

- **Desirable capabilities of a development facility**
  - 1–2 MW/m^2 14 MeV neutron flux
  - 10 m^2 test area, relevant gradients(heat, neutrons)
  - Continuous on time of 1-2 weeks
  - Integrated testing with fluence 6 MW-yr/m^2

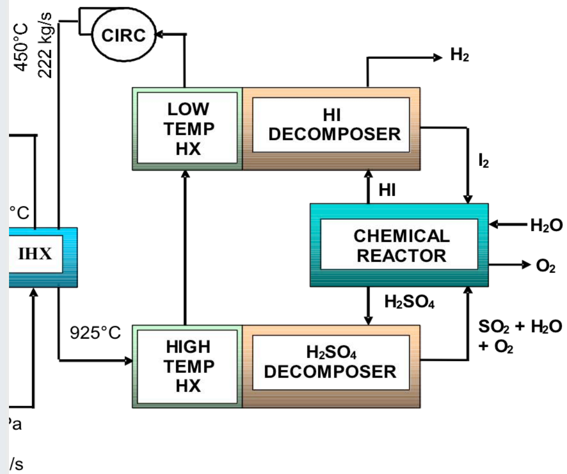
- **FDF can deliver all the above testing requirements**
  - Test two blankets every two years
  - In ten years, test 10 blanket approaches

Produce 300 kW electricity from one port blanket

FDF Will Develop Hydrogen Production from Fusion



Sulfur-Iodine Cycle



Requires 900-1000˚C Blankets
Perhaps one metric ton per week from one port plug

GENERAL ATOMICS

The U.S. Blanket Community Prefers a More Aggressive Phased Research Plan

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	D	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	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 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

GENERAL ATOMICS

FDF Makes Major Contributions to Almost All Gaps Identified by the FESAC Planning Panel

How Initiatives Could Address Gaps

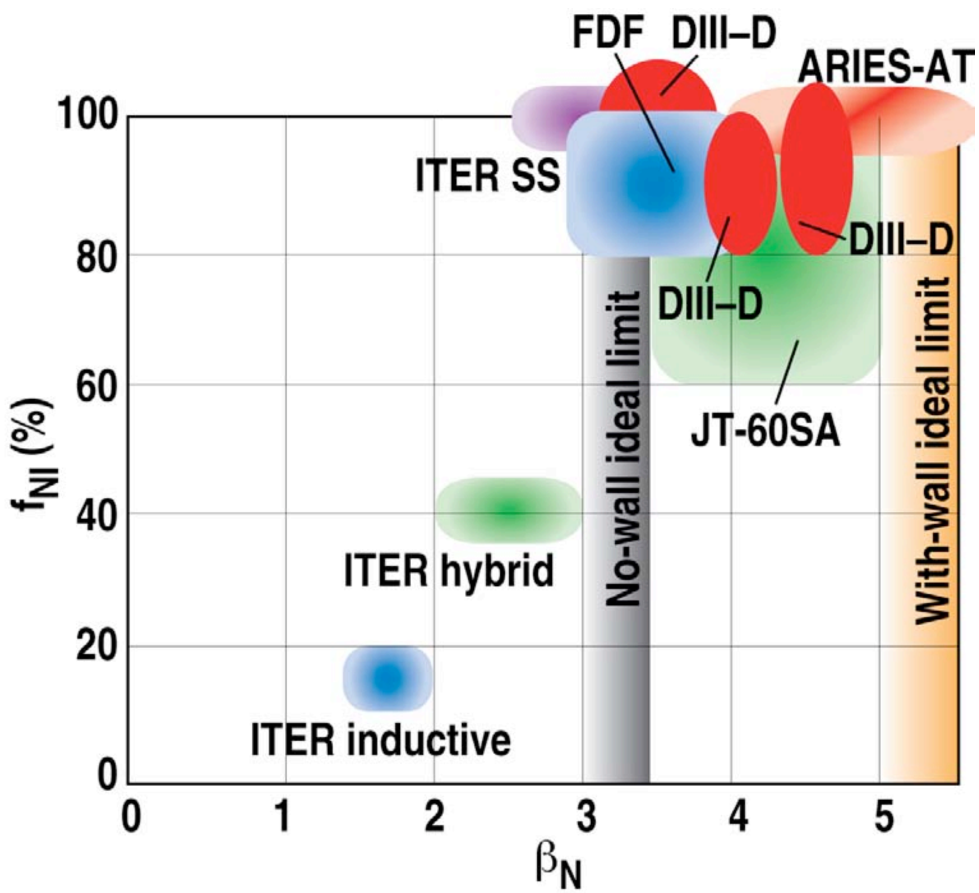
Legend

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

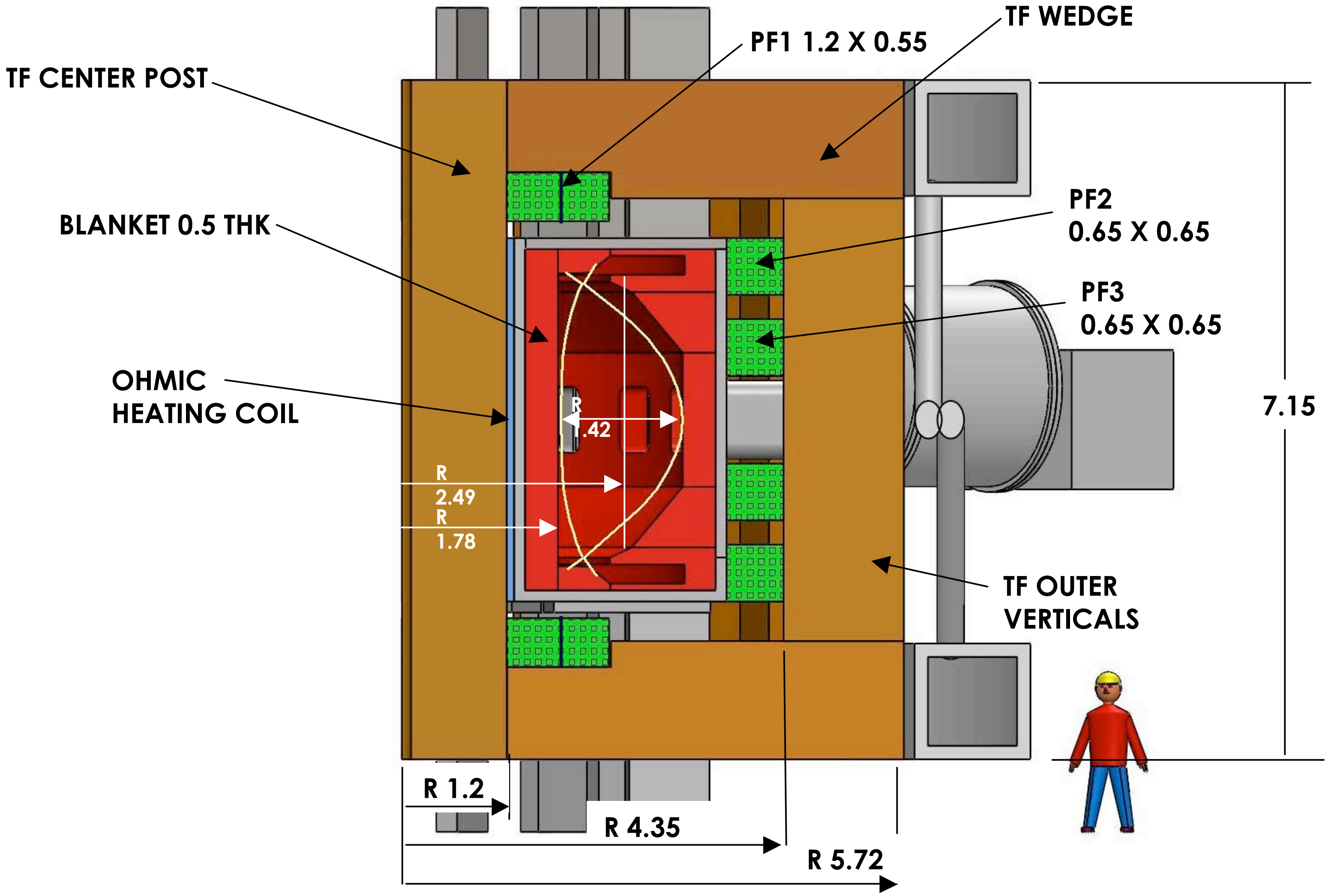
The Physics Basis for FDF Is or Can Be Available from Experiments and Simulation in 2–3 Years

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



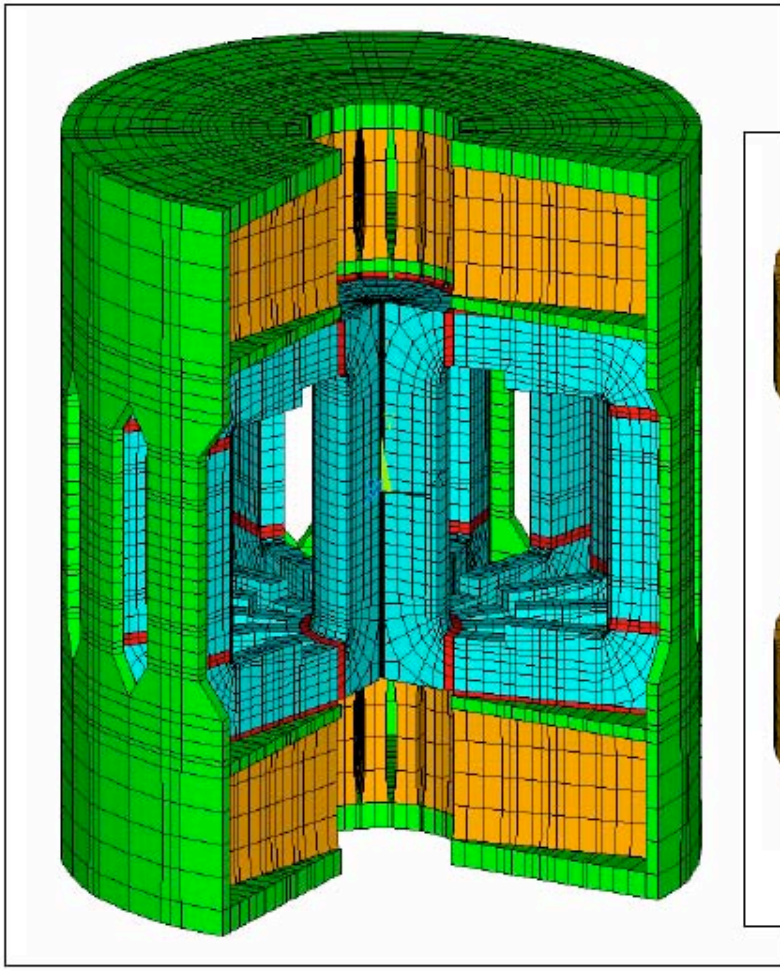
Green = already achieved, Blue = near term, Red = main challenge

FDF Dimensions for Reference

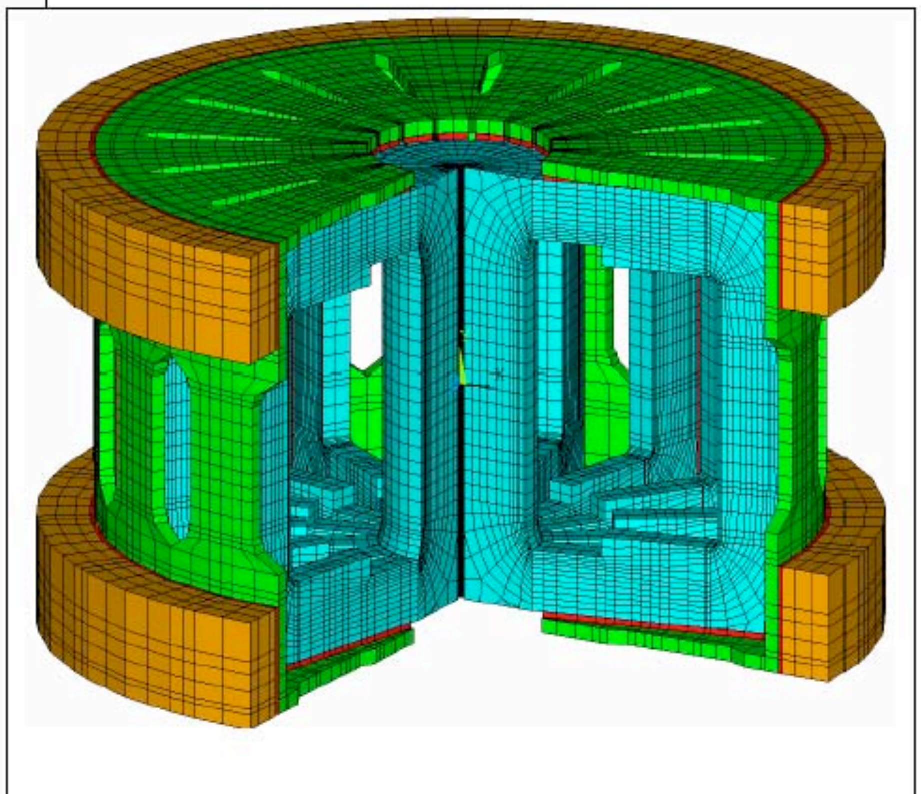


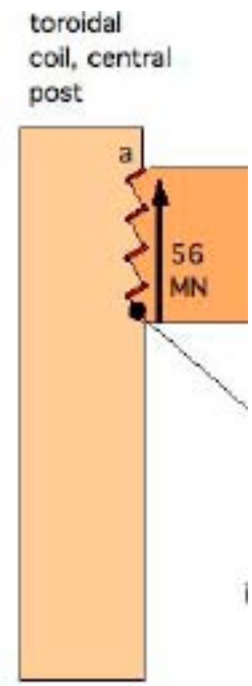
Two Options Being Considered for TF Coil Joint: C-mod Type Sliding and Sawtooth Joint (Rebut)

Model with Cover Weldment and Sliding

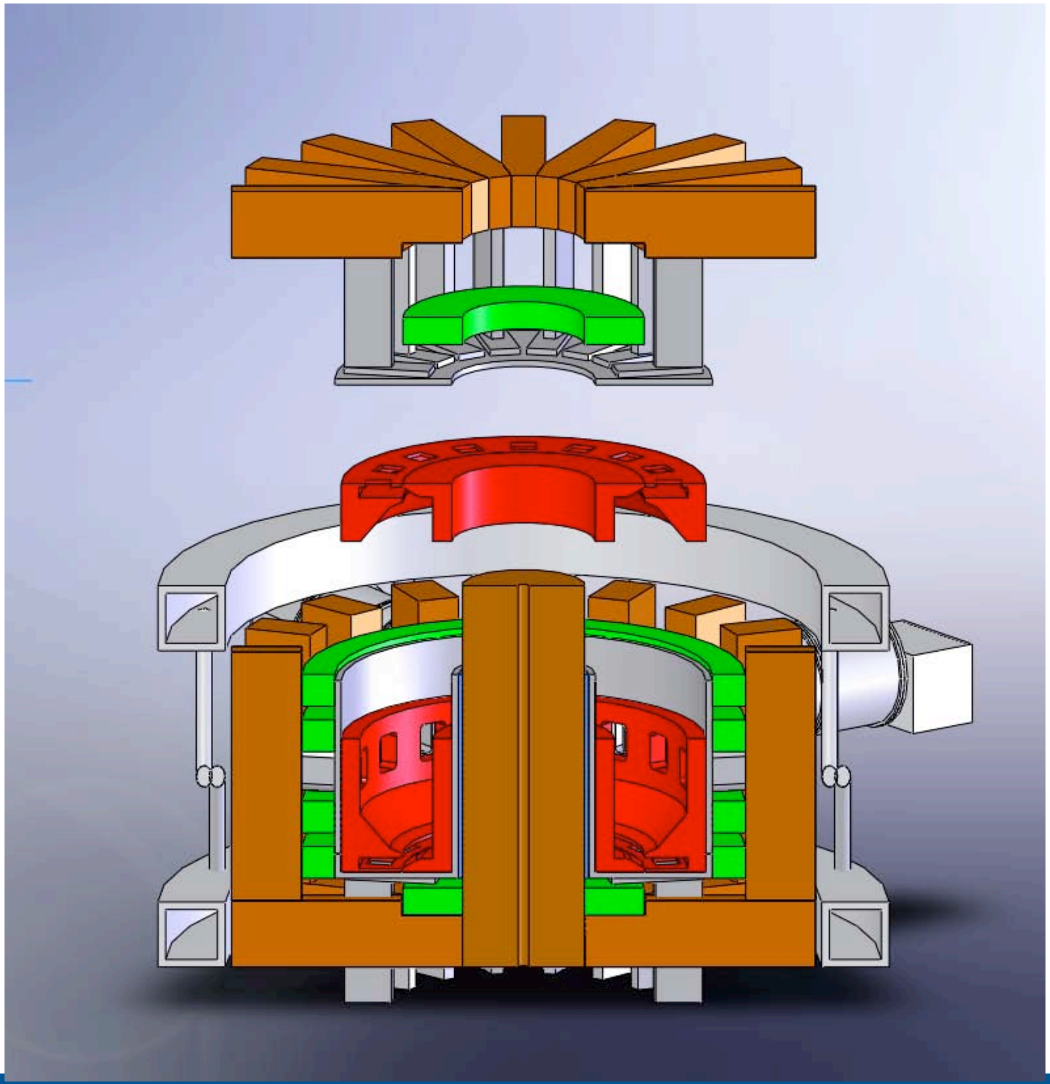


Model with Rebut Toothed Engagement of Horizontal and Vetrical TF Legs, Compression Ring Holds it Together





The Baseline Maintenance Scheme is Toroidally Continuous Blanket Structures



<u>Remove</u>

- **Upper sections of TF**
- **Divertor coil**
- **Top of vacuum vessel**

<u>Access to blanket structure obtained</u>

- **Blanket segments removed as toroidally continuous rings**

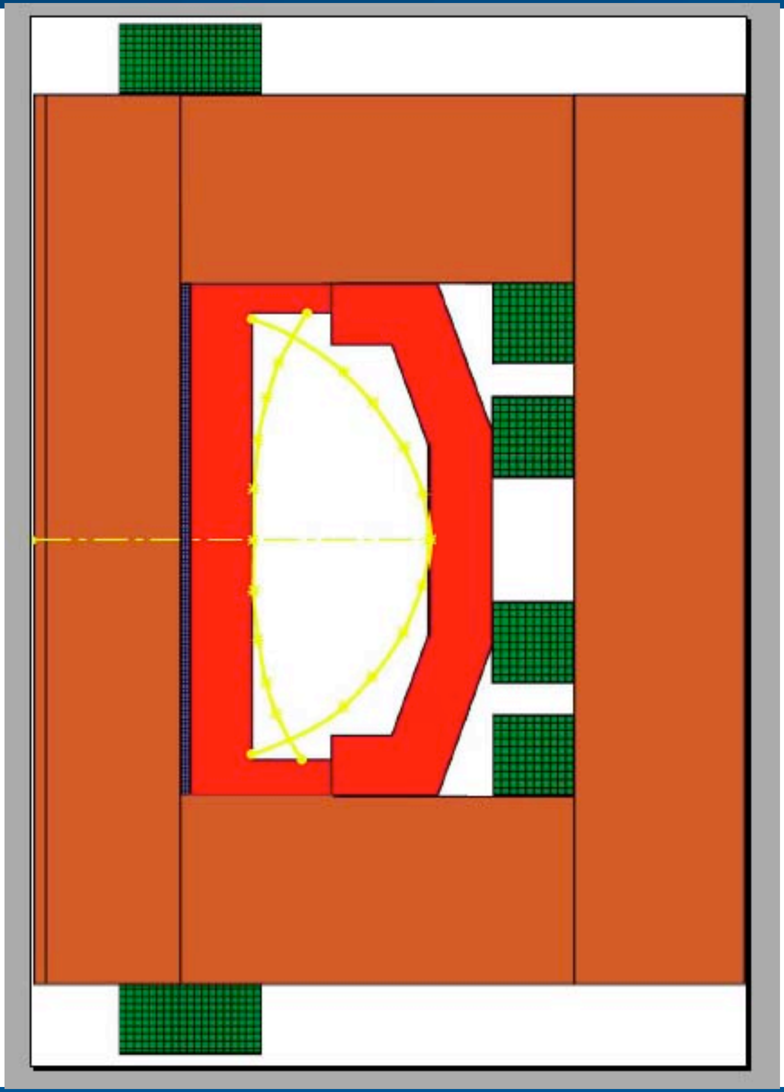
<u>Benefits</u>

- **Blankets strong for EM loads**
- **Toroidal alignment assured**

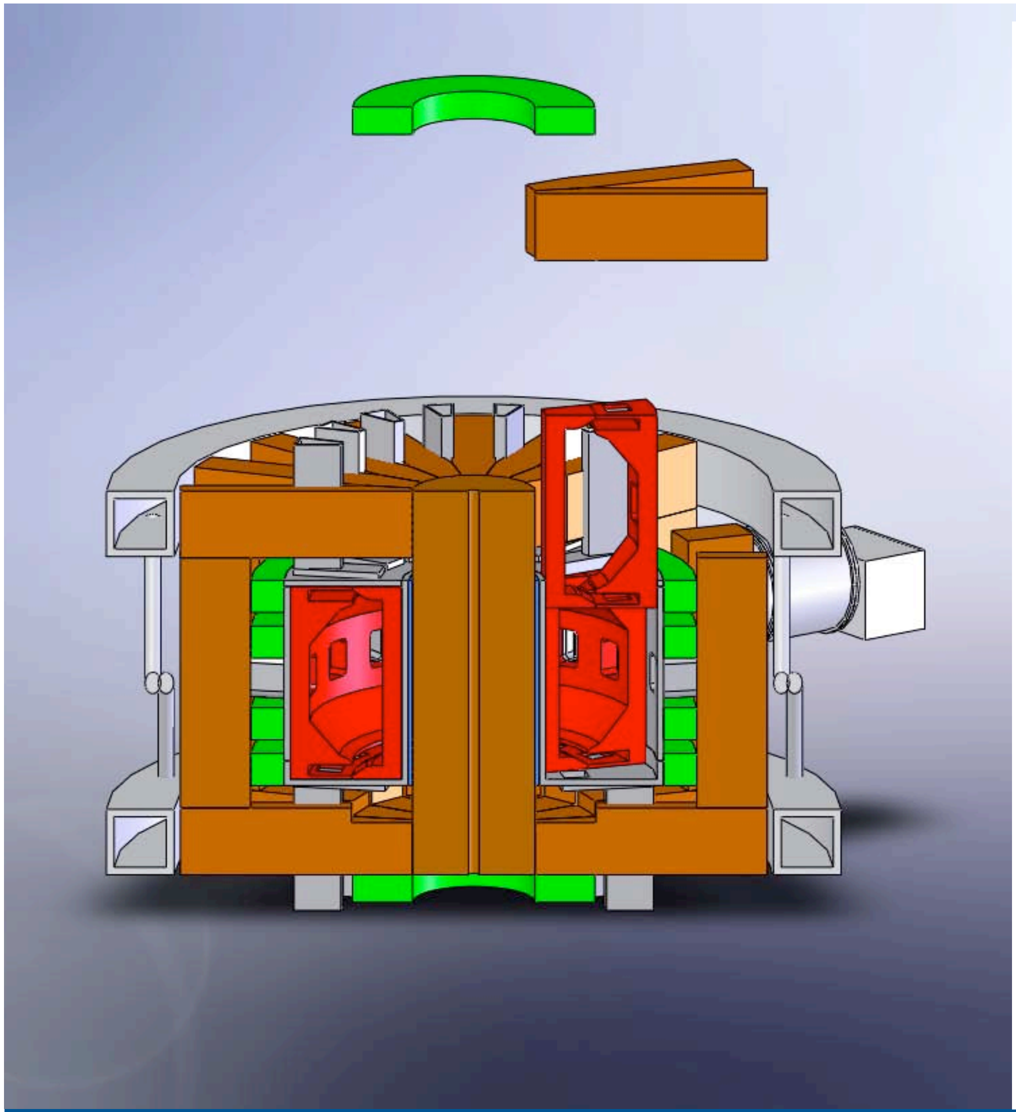
<u>Difficulties</u>

- **Provision of services (coolants) to blanket rings near the midplane through blankets above**

Option Being Considered to Put Divertor Coil Outside to Enable Vertical Lift Sector Maintenance Scheme.



Vertical Removal of Poloidal Blanket Wedge Sectors



Features:
- Divertor coil located outside TF

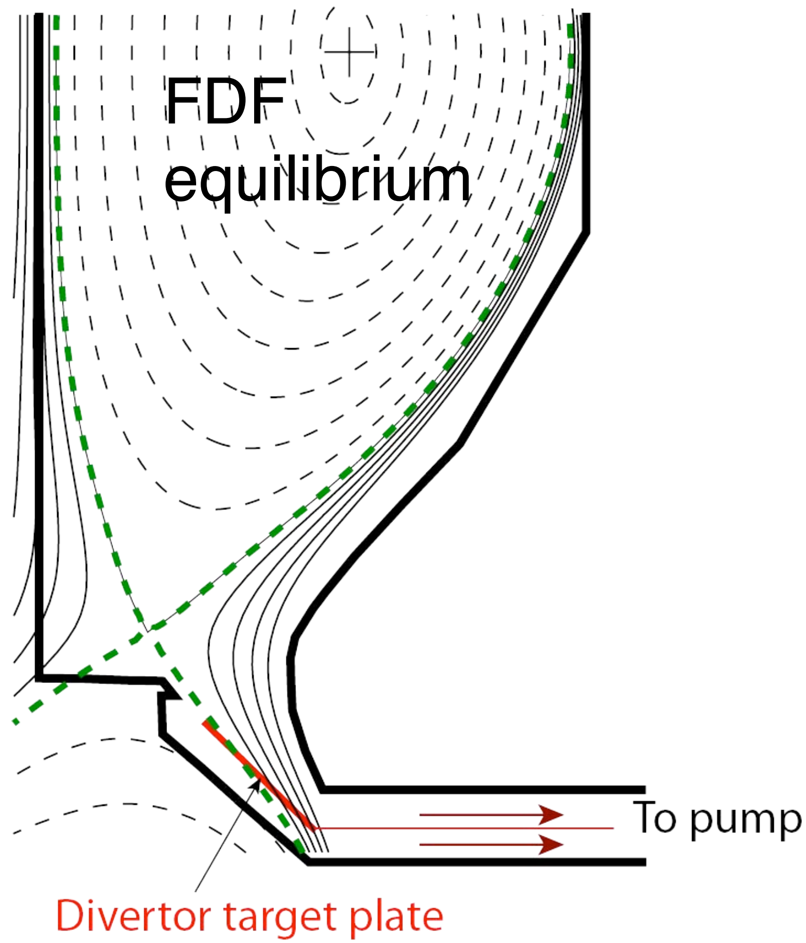
Process:
- Lift off Divertor coil
- TF upper section(s) removed
- Remove top vessel section
- Blanket sector removed vertically

Benefits
- Access for localized repair
- Blankets of different types could be installed
- Coolant services from top and bottom localized to each sector

Difficulty
- Alignment of modules critical

Emerging Double Null Divertor Concept in FDF

- **Structures impede the mobility of neutrals away from the divertor target area and ExB flows that couple the outer and inner divertors**
- **Up/down symmetric design, allowing pumping from outboard side**
- **Tilted divertor plate and pumping access**



FDF Supports a Variety of Operating Modes to Support Nuclear Science and Advanced Tokamak to DEMO

		Wall Load 2 MW/m2	1.0 MW/m2, Lower B, fbs	High Gain Inductive	Very Advanced	Very Advanced	ITER-SS	ARIES-AT
A		3.5	3.5	3.5	3.5	3.5	3.4	4
a	m	0.71	0.71	0.71	0.71	0.71	1.85	1.30
Ro	m	2.49	2.49	2.49	2.49	2.49	6.35	5.20
Elongation		2.31	2.31	2.31	2.31	2.31	1.85	2.20
Fusion Power	MW	246	123	231	301	401	356	1755
Plant Power	MW	507	362	395	482	536		
Pn/Awall	MW/m2	2.0	1.0	1.9	2.5	3.3	0.5	4.8
Qplasma		4.2	2.5	11.5	4.5	6.1	6.0	45.0
BetaT		5.8%	7.6%	9.2%	7.9%	7.4%	2.8%	9.2%
BetaN	mT/MA	3.7	3.7	3.3	4.5	4.5	3.0	5.4
fbs		60%	46%	30%	65%	70%	48%	91%
Pcd	MW	59	50	20	65	66		35
Paux	MW	59	50	20	67	66	59	36
Ip	MA	6.7	6.5	9.3	6.8	7.0	9.0	12.8
Bo	T	6.0	4.4	4.7	5.4	6.0	5.2	5.8
q		5.0	3.8	2.8	4.4	4.8	5.3	3.7
Ti(0)	keV	19	20	16	18	18	19	31
n(0)	E20/m3	3.0	2.0	3.5	3.5	4.1	0.7	2.9
nbar/nGR		0.57	0.40	0.47	0.66	0.74	0.82	0.96
Zeff		2.1	2.1	2.1	2.1	2.1	2.1	1.7
W	MJ	70	50	67	77	89	287	640
TauE	sec	0.6	0.7	1.0	0.6	0.6	3.1	2.0
HITER98Y2		1.60	1.60	1.36	1.59	1.60	1.57	1.40
PTotal/R	MW/m	43	30	27	51	59	21	74
Peak Heat Flux	MW/m2	5.9	4.4	2.7	6.7	7.3	10.0	9.3

A New DT Burning Plasma Facility Should Be Built in the US to provide a Fusion Nuclear Science "Laboratory."

- Develop fusion's energy applications.
- Close the fusion fuel cycle.
- Develop blankets for fusion electric power.
- Develop hydrogen production from fusion.
- Address nearly all gaps Identified by FESAC.
- Motivate the needed, large, supporting fusion nuclear science program
- Provide a materials irradiation and research facility

- FDF should be the next major U.S. facility running in parallel with ITER