Fusion Development Facility (FDF) Mission

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GENERAL ATOMICS

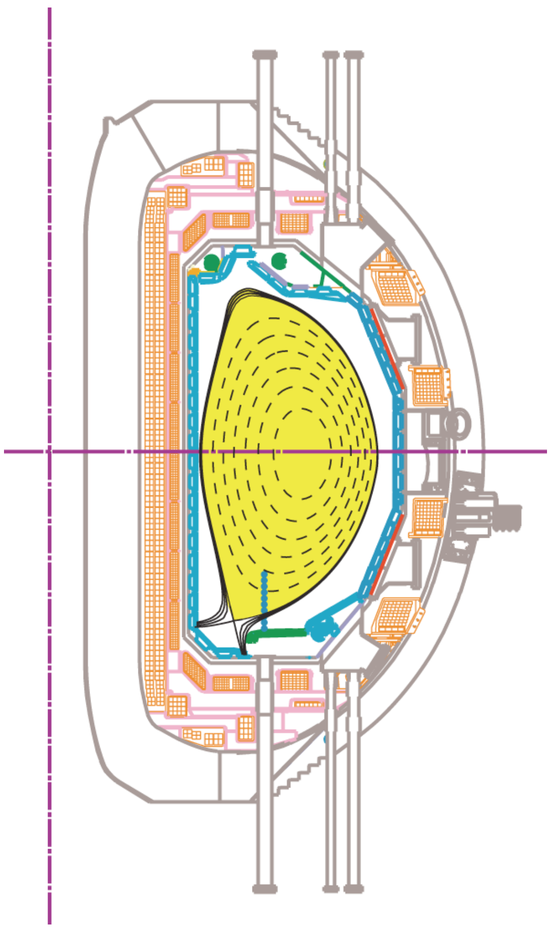
Abstract

A Fusion Development Facility (FDF) is proposed to fill the gaps between ITER and current experiments and a fusion demonstration power plant (DEMO). FDF should carry forward Advanced Tokamak physics and enable development of fusion's energy applications. Near term advanced tokamak physics will be used to achieve steady-state with burn, producing 100-250 MW fusion power with modest energy gain (Q<5) in a modest sized device (between DIII-D and JET). FDF will further develop all elements of AT physics for an advanced performance DEMO. With neutron flux at the outboard midplane of 1-2 MW/m^2, continuous operation for periods up to two weeks, and a goal of a duty factor of 0.3 on a year, FDF can produce fluences of 3-6 MW-yr/m^2 in ten years of operation. The development of blankets suitable for tritium, electricity, and hydrogen production will be done in port modules. The most promising candidates will be deployed as full blankets in FDF. FDF will have a goal of demonstrating closure of the fusion fuel cycle, producing its own tritium. FDF, ITER, IFMIF, and other AT devices will provide the basis for a fusion DEMO power plant of the ARIES-AT type.

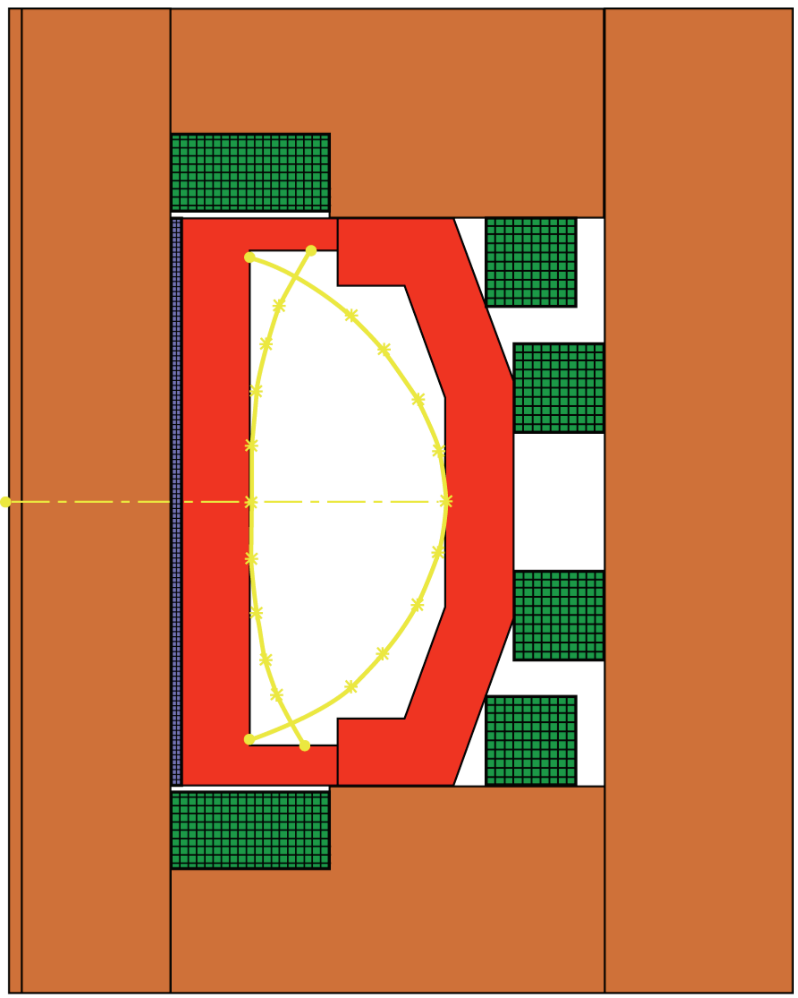
*Supported by GA IR&D funding.

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

DIII-D

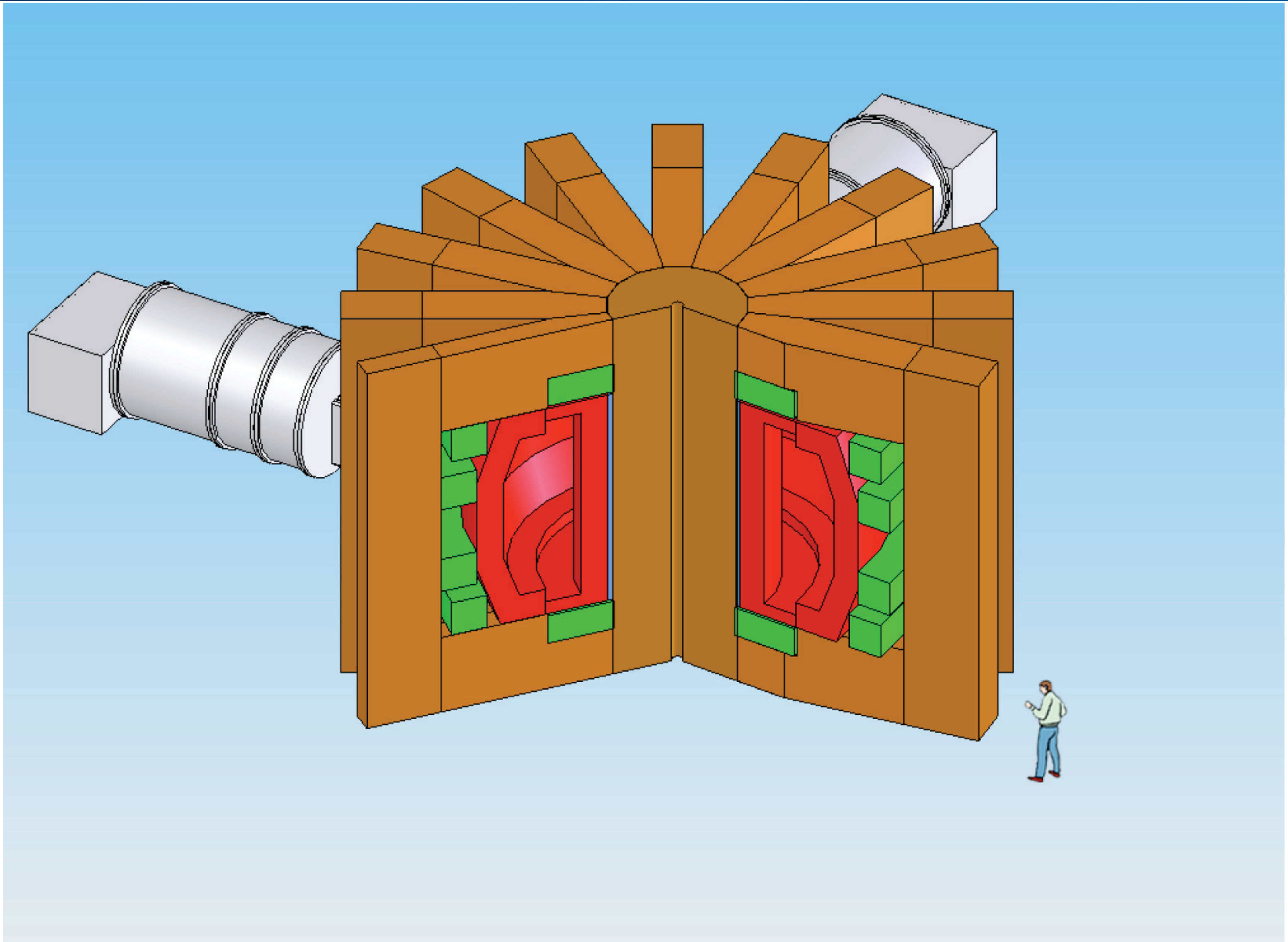


FDF



- 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

3-D Cutaway View with DIII-D Sized Neutral Beams



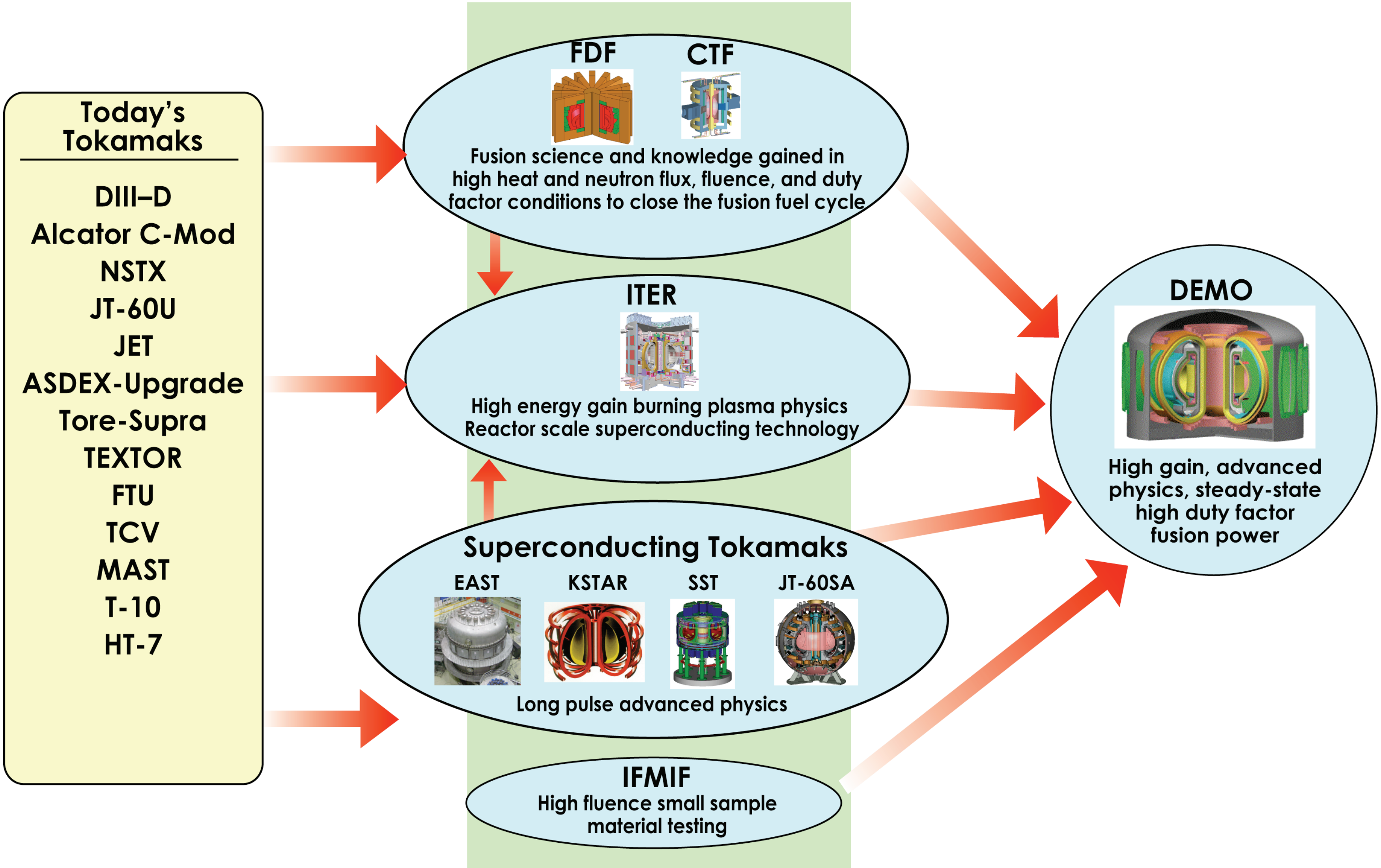
FDF Mission: Carry Forward Advanced Tokamak Physics and Enable Development of Fusion's Energy Applications

- **Demonstrate advanced physics operation of a tokamak in steady-state with Burn**
  - Utilize conservative expressions of all elements of Advanced Tokamak physics to produce 100-250 MW fusion power with modest energy gain (Q<5) in a modest sized device
  - Utilize full non-inductive, high bootstrap operation to achieve continuous operation for > 2 weeks
  - Further develop all elements of Advanced Tokamak physics, qualifying them for an advanced performance DEMO

- **Develop fusion's nuclear technology**
  - Test materials with high neutron fluence (3-6 MW-yr/m^2) with duty factor 0.3 on a year
  - Demonstrate tritium self-sufficiency
  - Develop fusion blankets that make both tritium and electricity at 1-3 MW/m^2 neutron fluxes
  - Develop fusion blankets that produce hydrogen

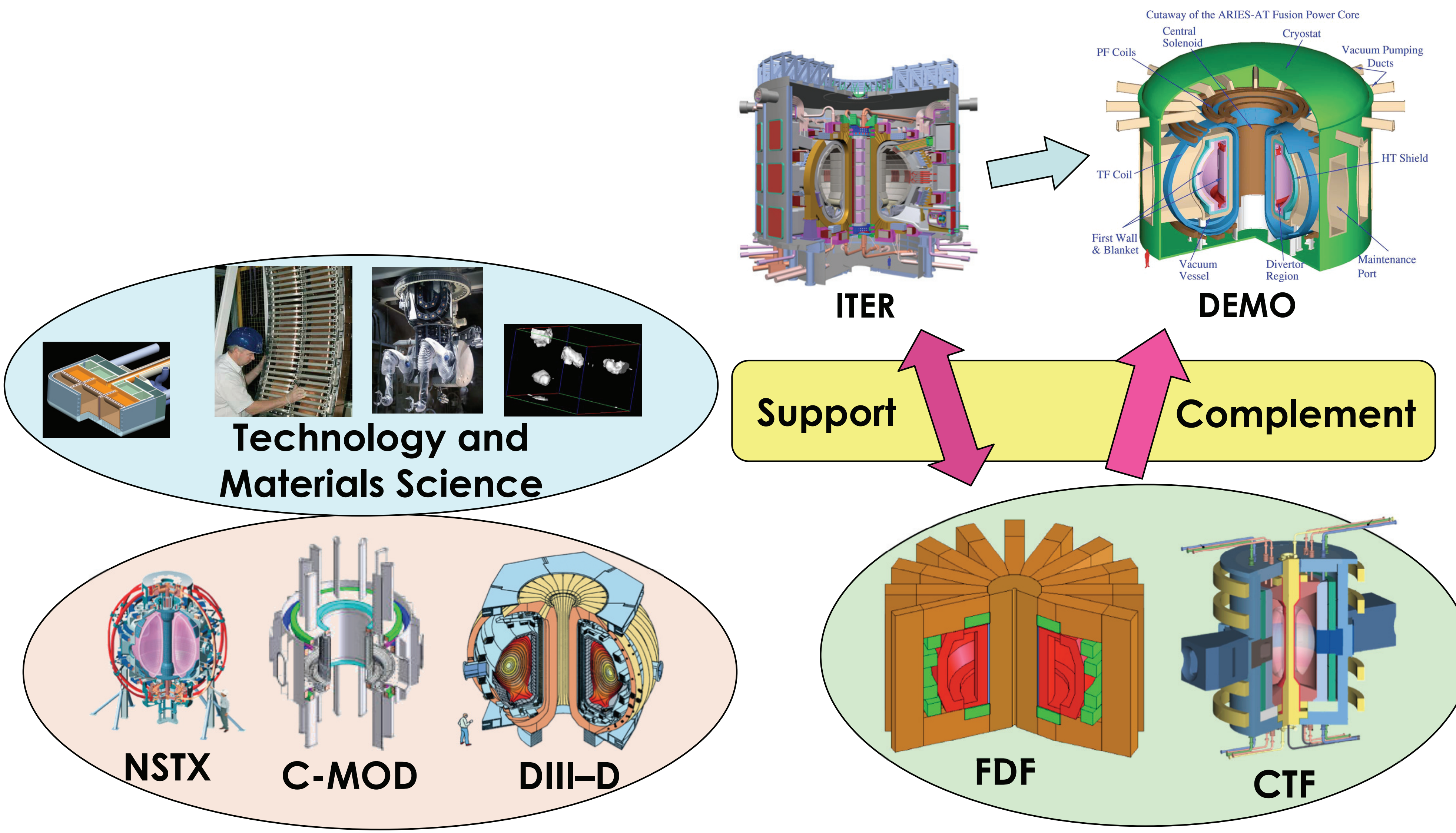
- **With ITER and IFMIF, provide the basis for a fusion DEMO Power Plant**

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



GENERAL ATOMICS

A Steady-State Burning Plasma Fusion Nuclear Science Facility Will Support and Complement ITER Toward DEMO



ITER, FDF, and IFMIF Solve the Gap Issues for DEMO

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

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

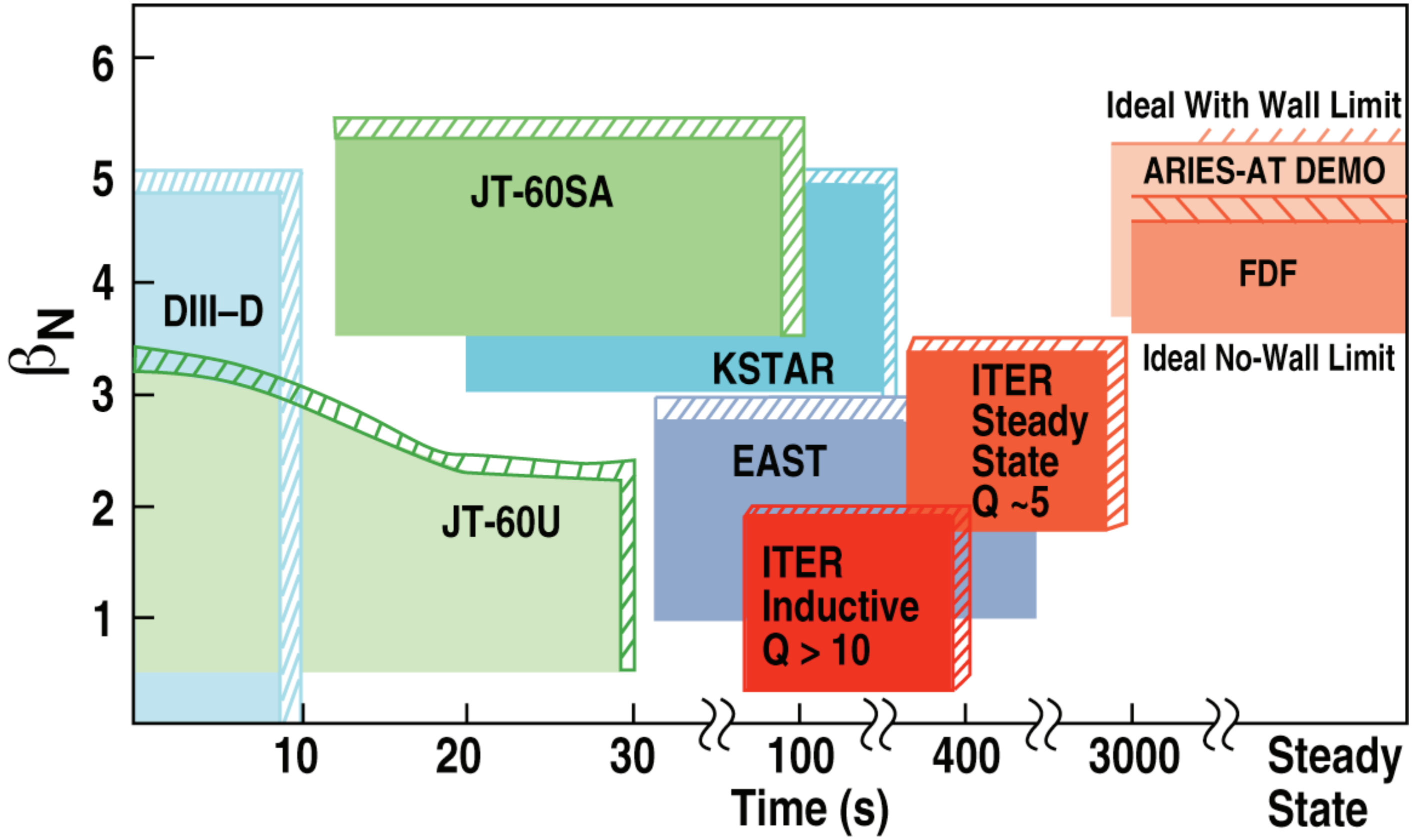
How Initiatives Could Address Gaps

Legend

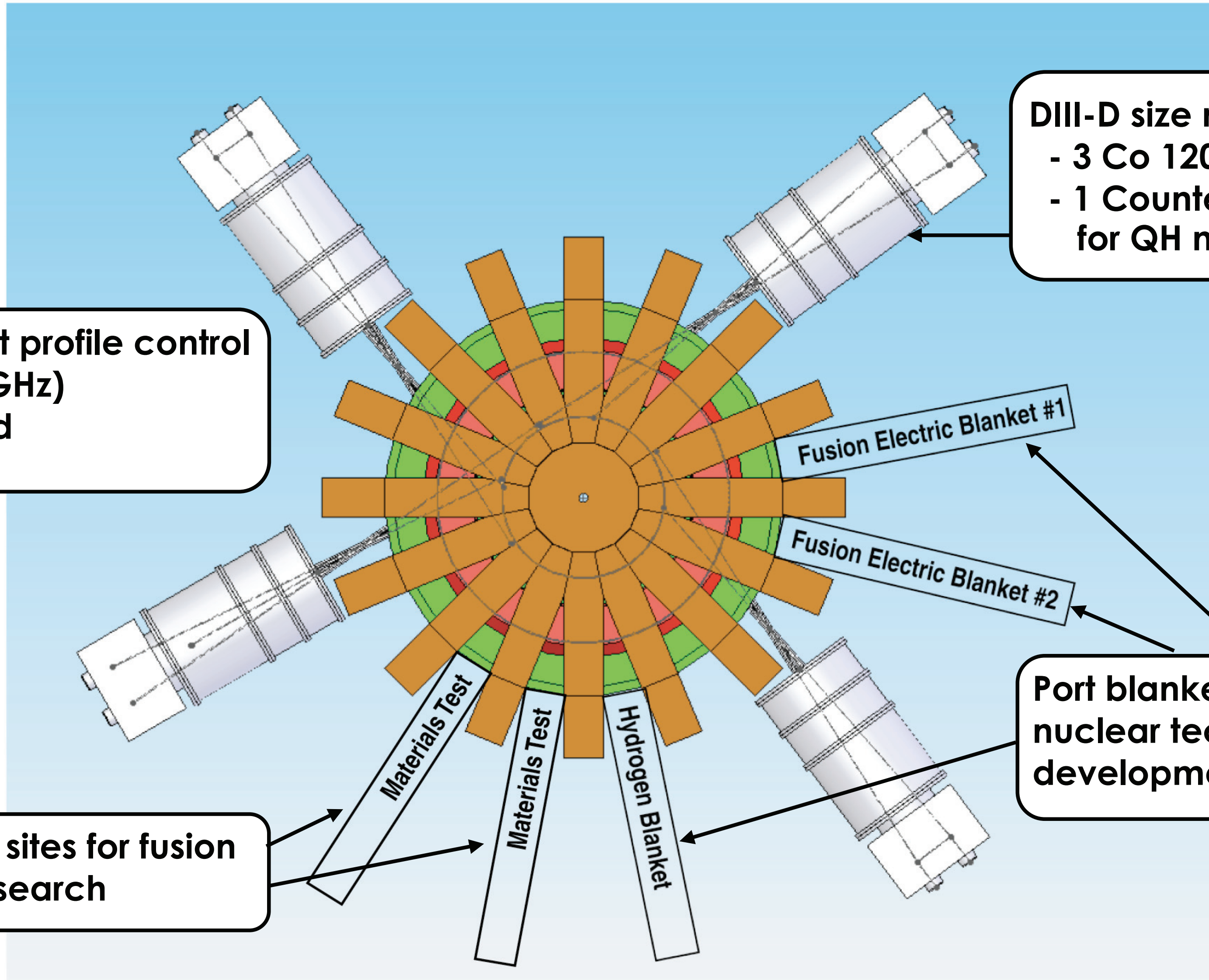
Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	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

FDF Will Enable A Leap to the Advanced Tokamak Reactor Regime



Port Sites Enable Nuclear and Materials Science. Auxiliary Systems Similar to DIII-D and Alcator Cmod



DIII-D size neutral beams
- 3 Co 120 keV, rotation
- 1 Counter, 80 keV for QH mode edge

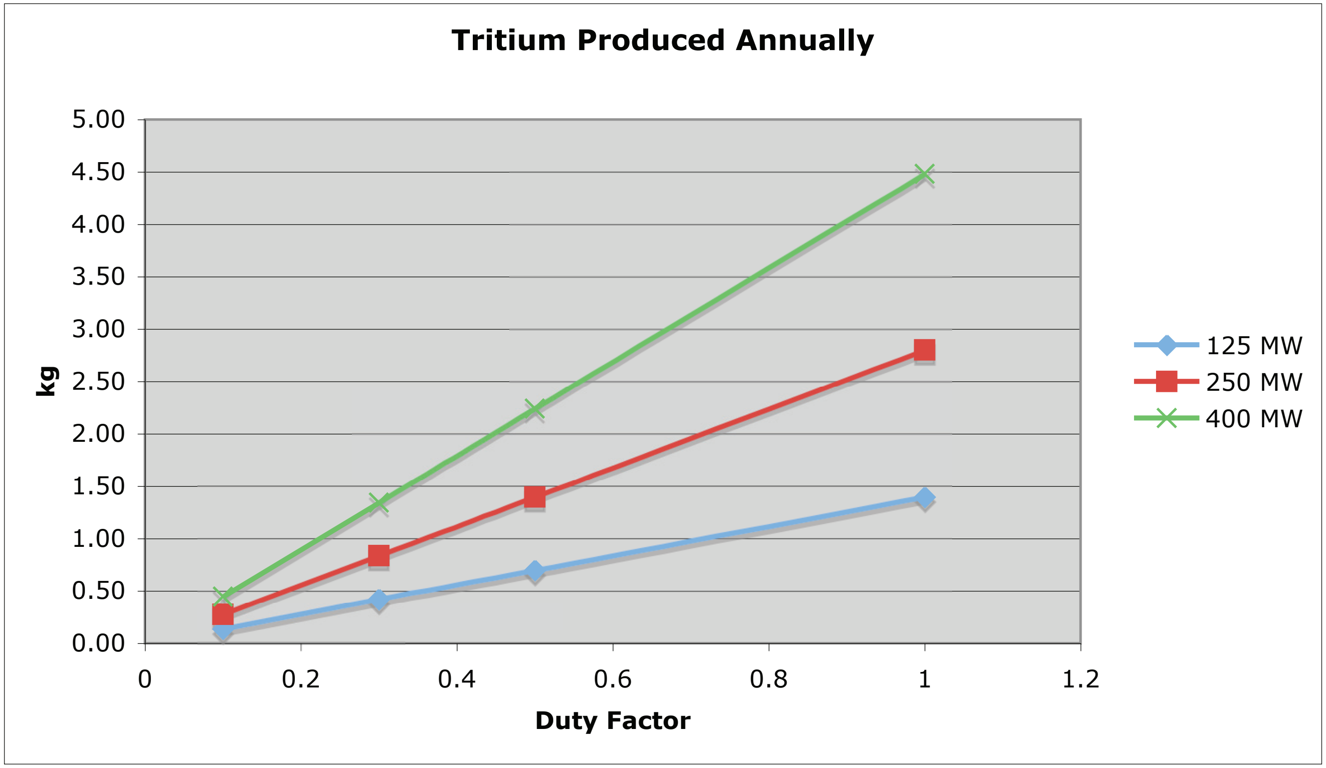
Off-axis current profile control
- ECCD (170 GHz)
- Lower Hybrid
- NBCD

Port blanket sites for fusion nuclear technology development

Port blanket sites for fusion materials research

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

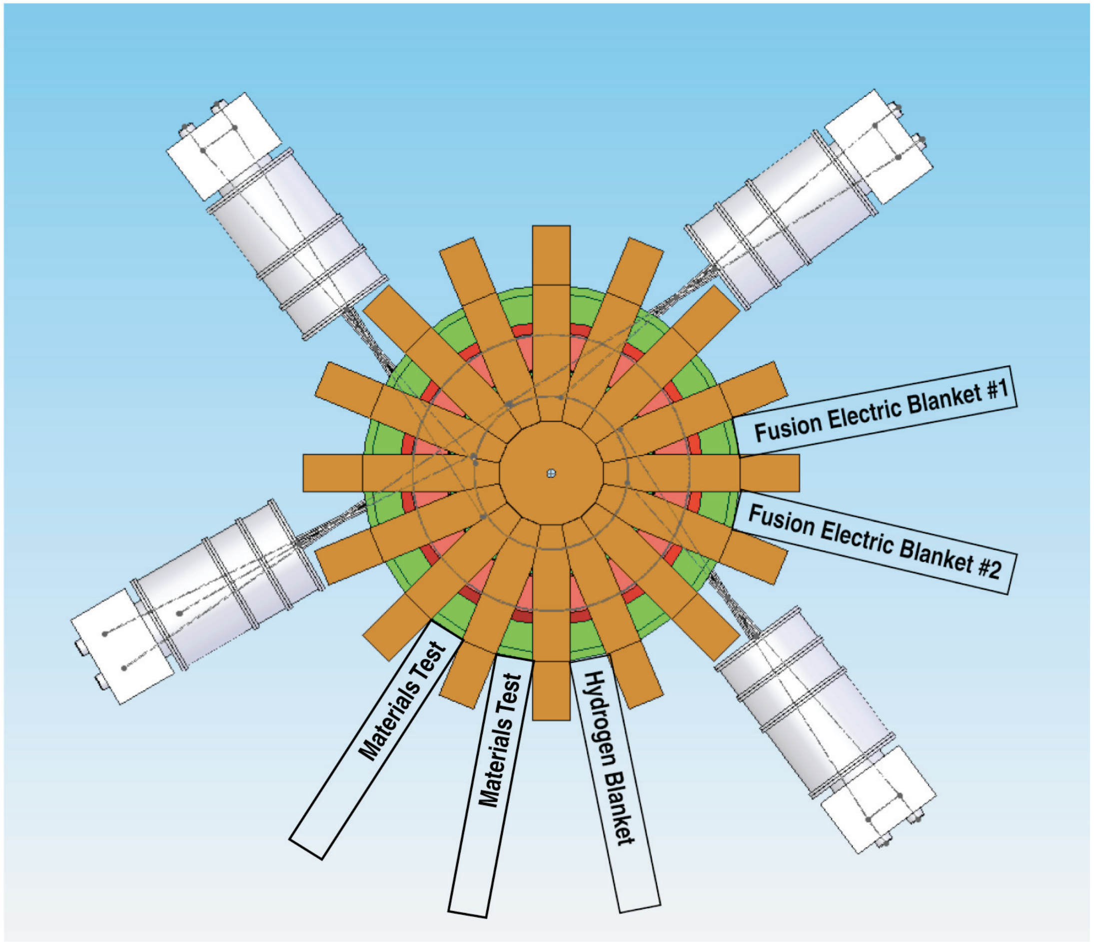


For TBR 1.2

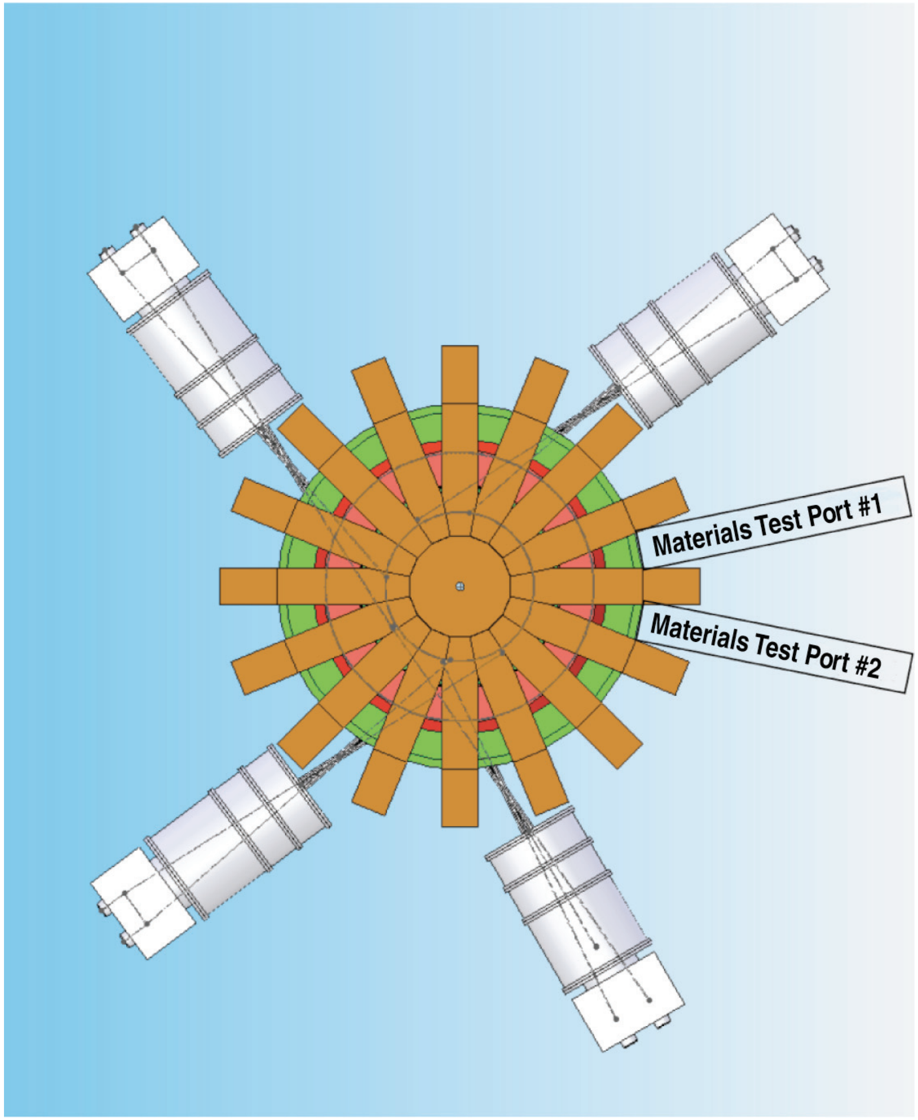
FDF will Motivate the Needed, Large, Supporting Fusion Nuclear Science Program

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…..



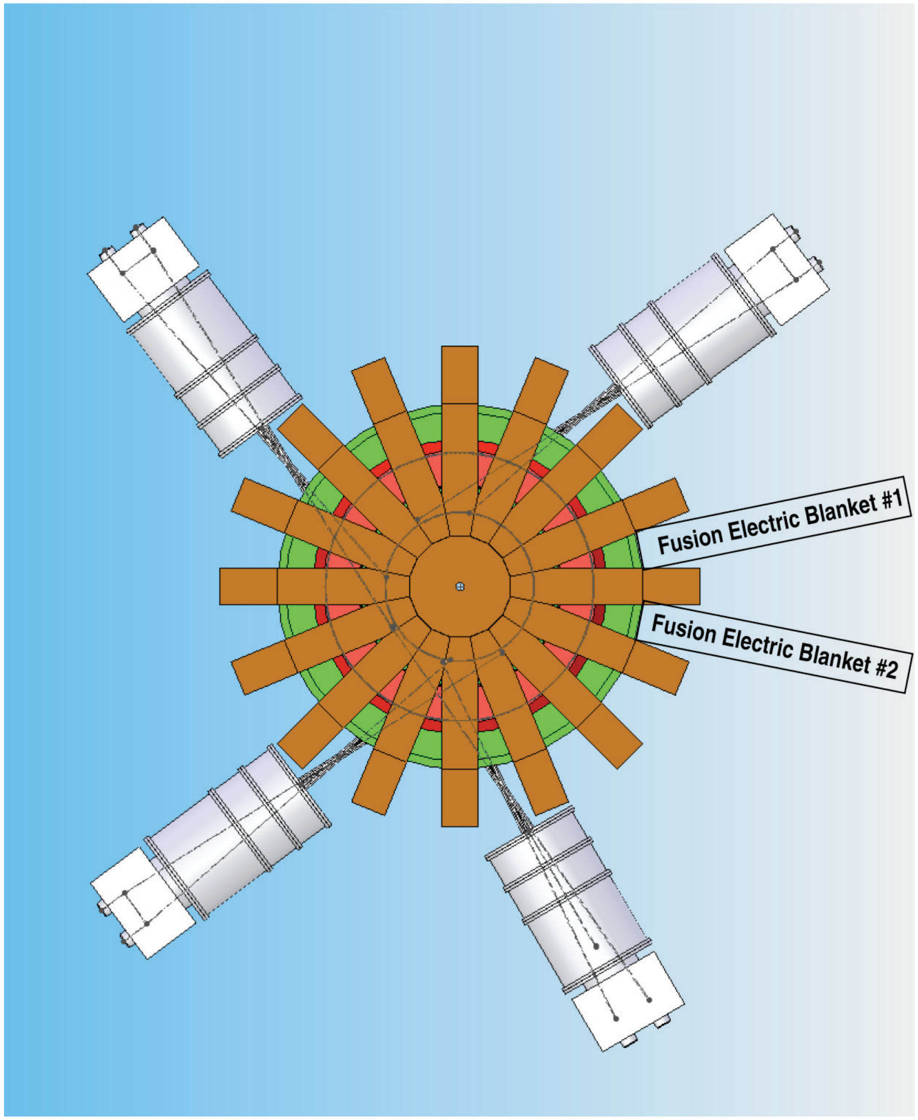
FDF Provides A Materials Irradiation and Research Facility



- **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)

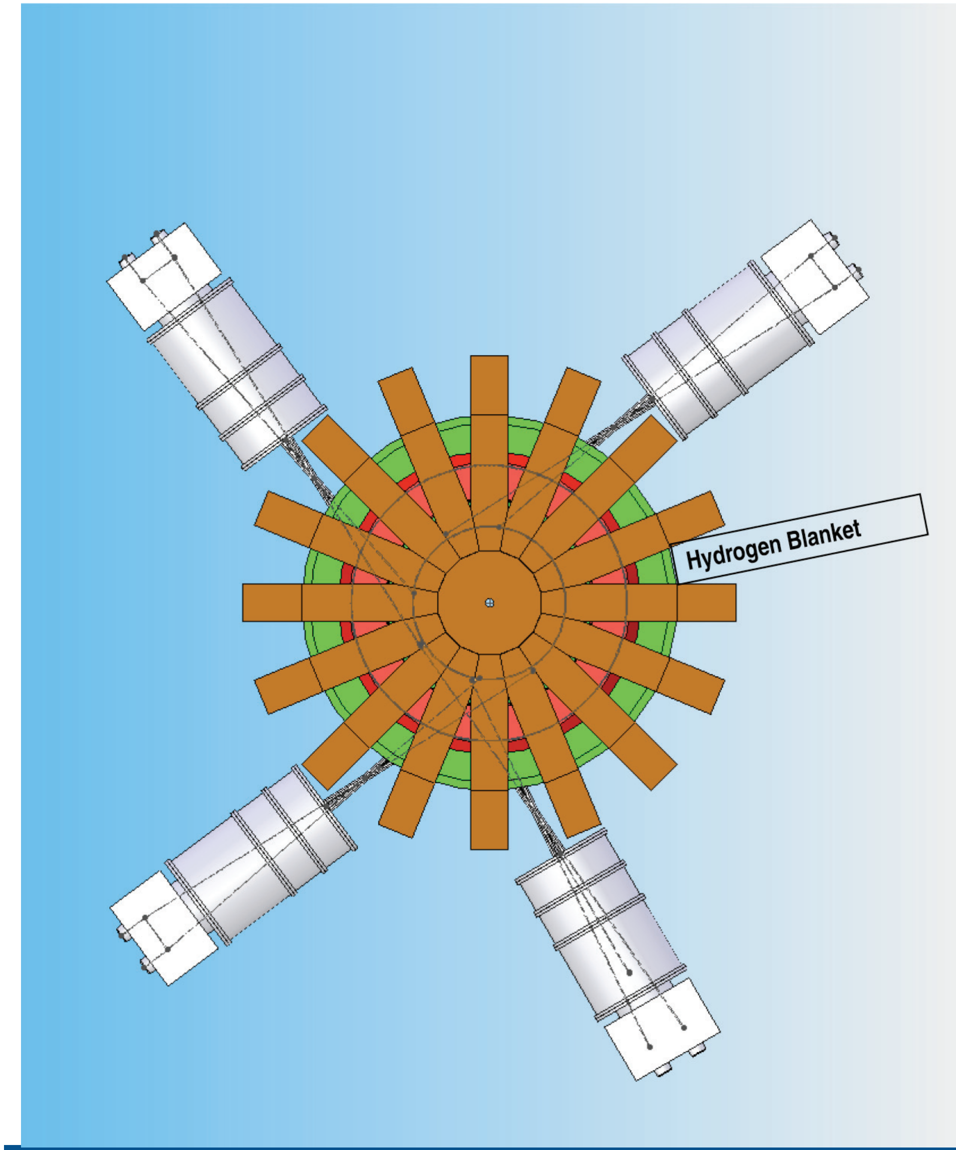
- **Fusion blanket development requires testing**
  - Solid breeders (3), Liquid breeders (2)
  - Various Coolants (2)
  - Advanced, Low Activation, Structural materials (2)

- **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

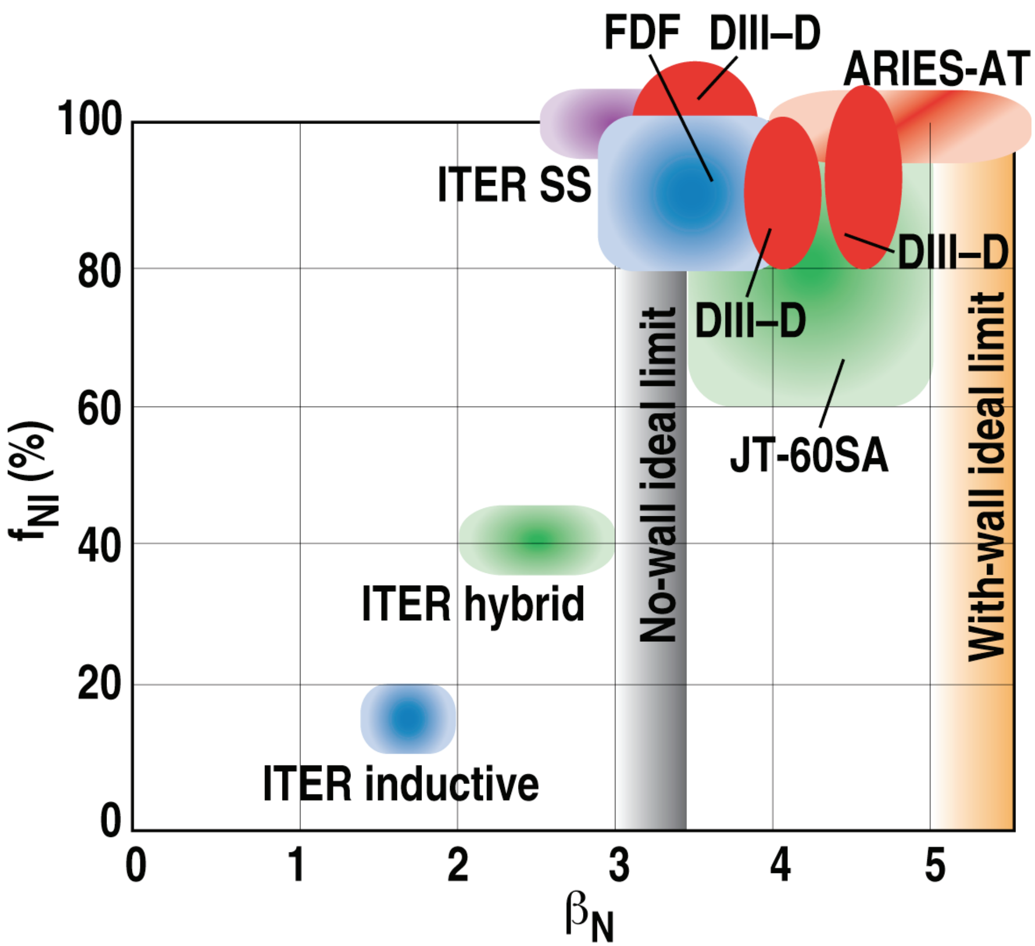


Sulfur-Iodine Cycle

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

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



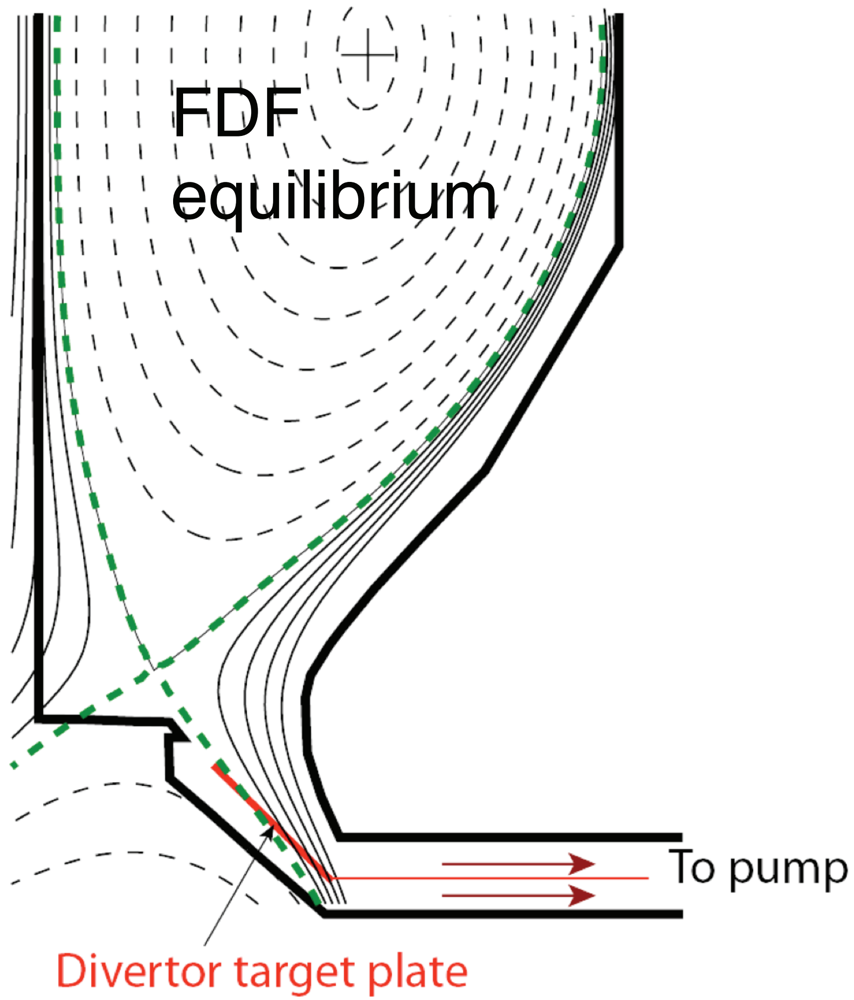
Green = already achieved, Blue = near term, Red = main challenge

Emerging Double Null Divertor Concept in FDF

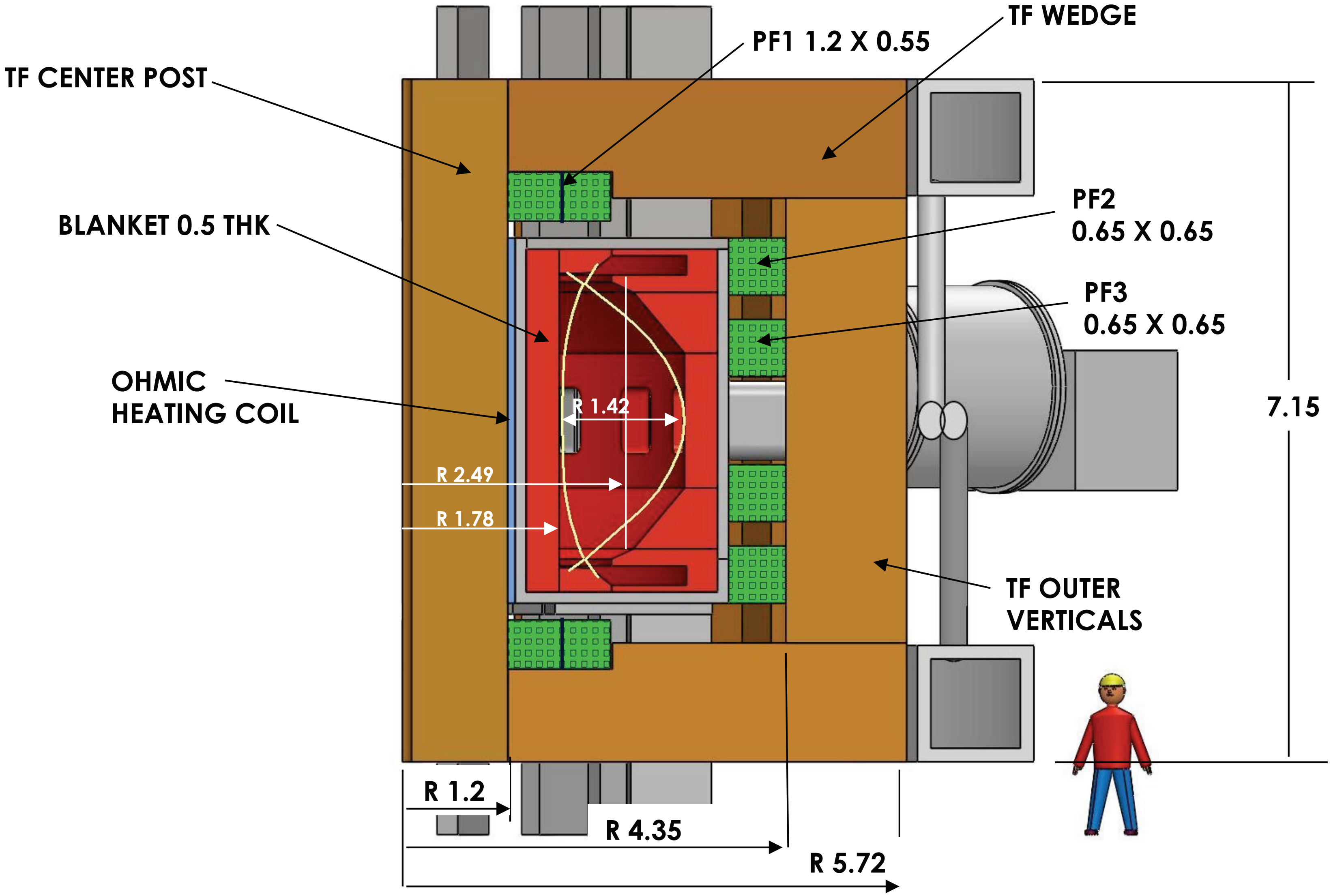
- **Structures impede the mobility of neutrals away from the divertor target area and ExB flows that couple the outer and inner divertors**

- **Up/down symmetric design, allowing pumping from outboard side**

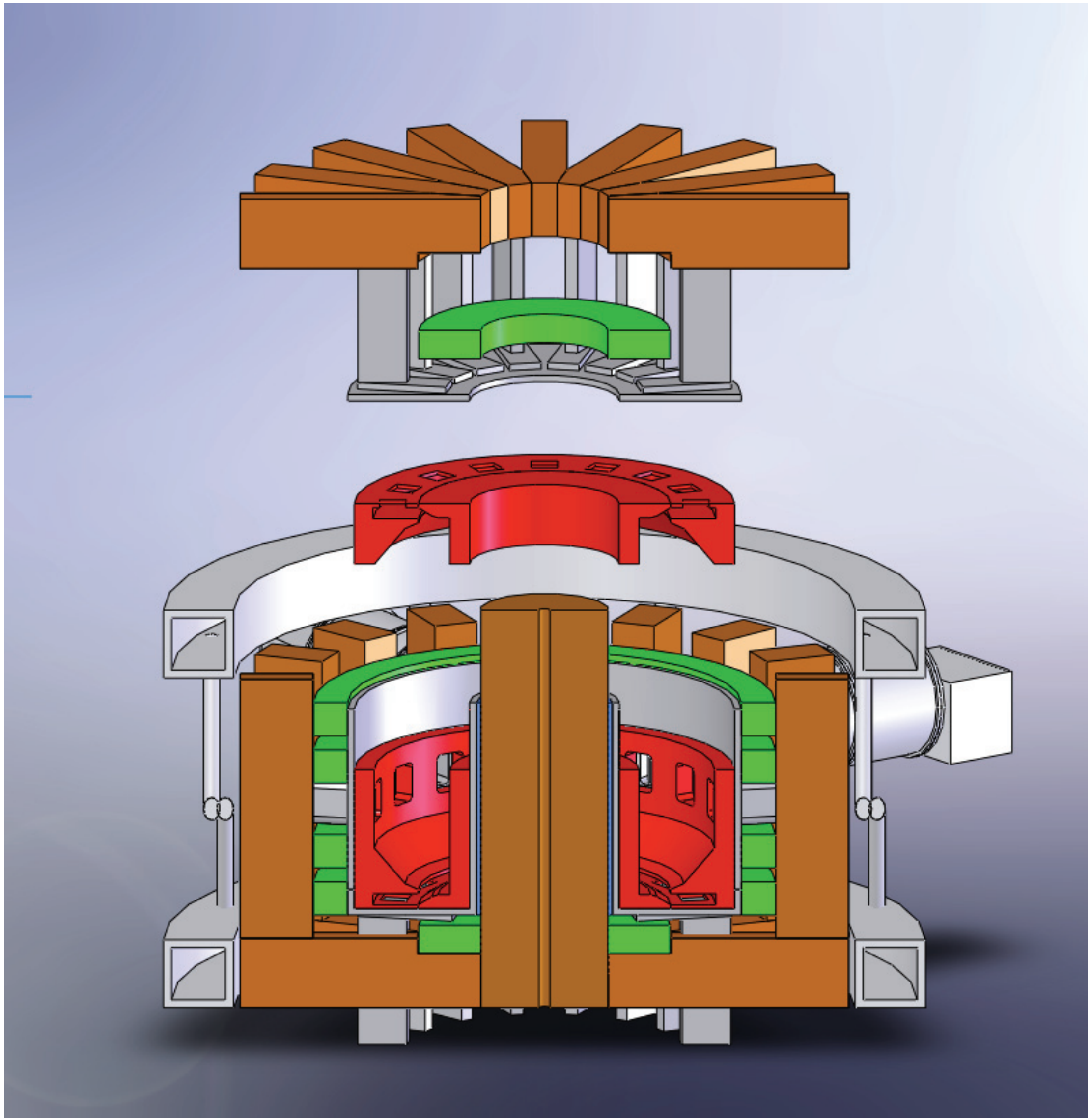
- **Tilted divertor plate and pumping access**



FDF Dimensions for Reference



The Baseline Maintenance Scheme is Toroidally Continuous Blanket Structures



Remove

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

Access to blanket structure obtained

- Blanket segments removed as toroidally continuous rings

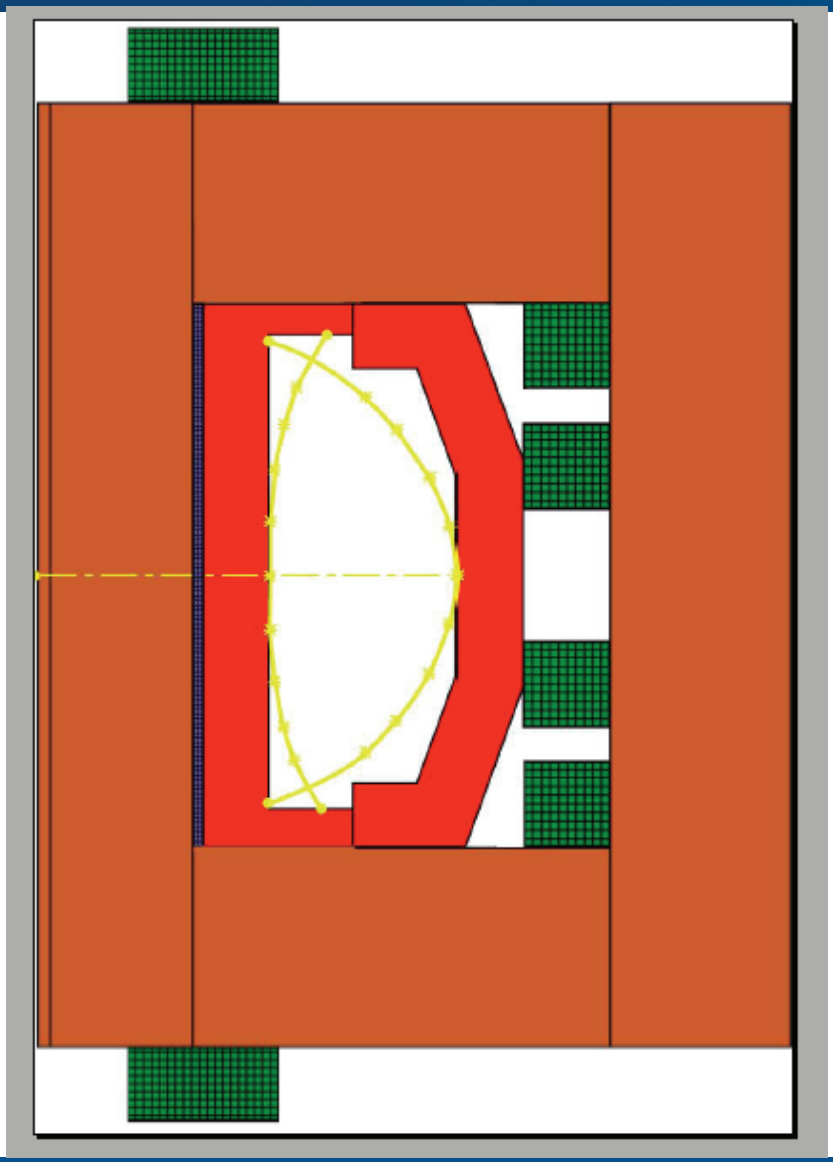
Benefits

- Blankets strong for EM loads
- Toroidal alignment assured

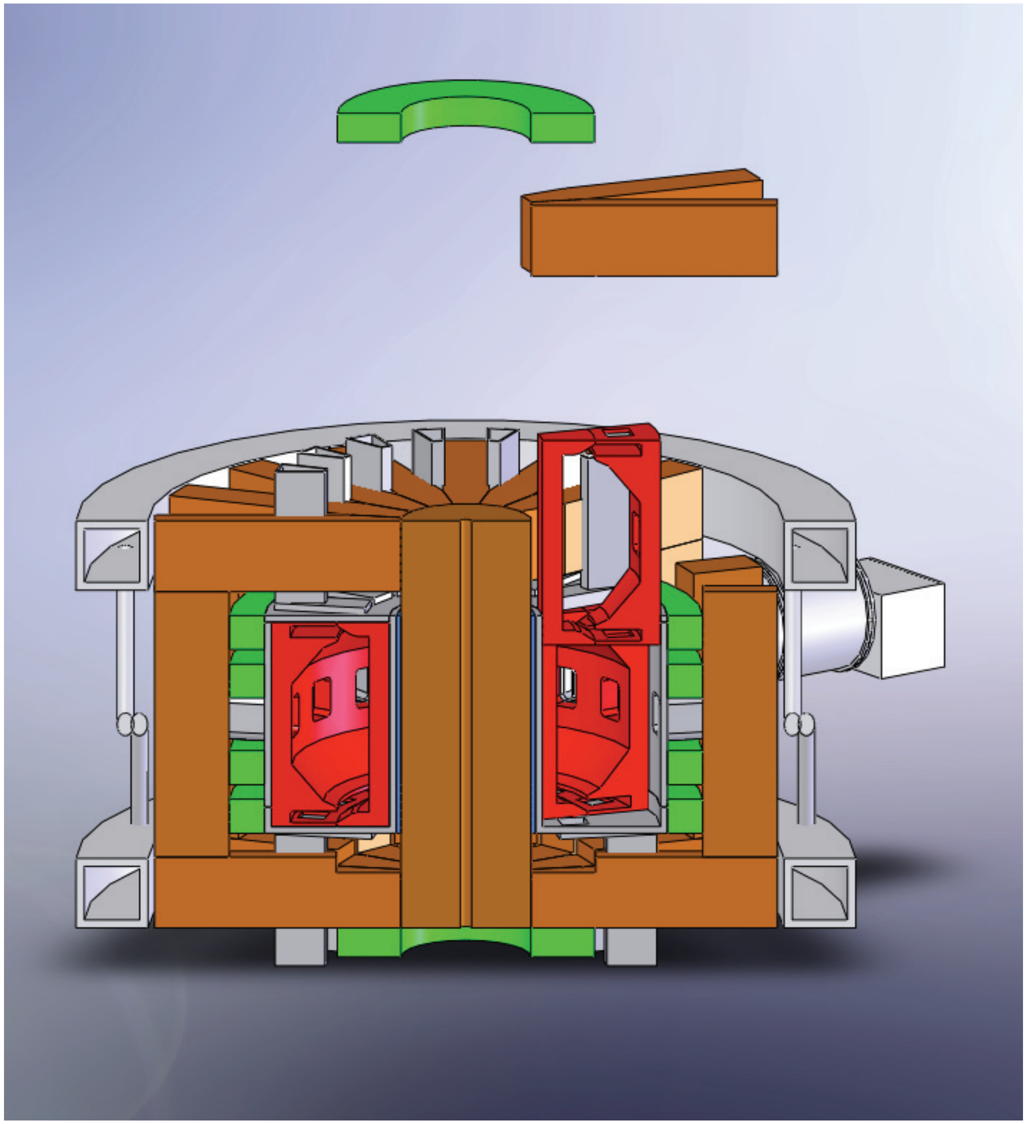
Difficulties

- 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

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

		Wall Load	1.0 MW/m2,	High Gain	Very	Very	ITER-SS	ARIES-AT
		2 MW/m2	Lower B, fbs	Inductive	Advanced	Advanced		
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

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

	Years 1–4: START UP			Years 5–9: FIRST MAIN BLANKET		Years 10–11	Years 12–16: SECOND MAIN BLANKET		Years 17–18	Years 19–23: 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 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

To Develop Fusion Energy, a Fusion Development Facility (FDF) is Needed

- ITER will provide high energy gain burning plasma physics and power plant scale technology
- IFMIF, an accelerator based neutron source, could provide high neutron fluence materials data on small samples
- An FDF is needed to carry forward Advanced Tokamak Physics and enable development of Fusion's energy applications.
- FDF should be the next major U.S. facility running in parallel with ITER