# A Fusion Development Facility (FDF) on the Path to DEMO

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Fusion Power and Associates Annual Meeting and Symposium

At Oak Ridge, Tennessee

December 5, 2007

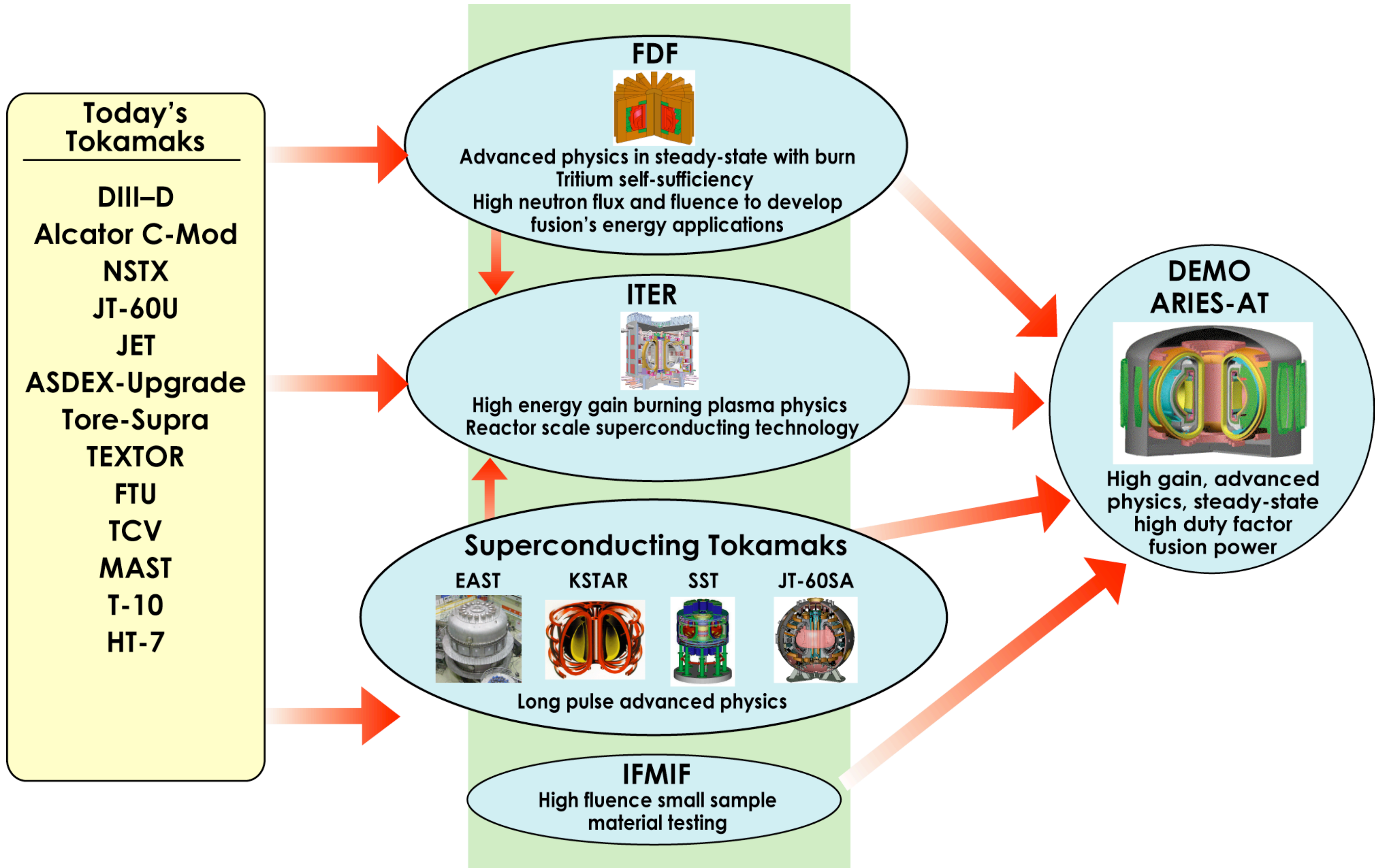
# FDF Mission: Carry Forward Advanced Tokamak Physics and Enable Development of Fusion's Energy Applications

- **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 1-2 MW/$m^2$ neutron fluxes
  - Develop fusion blankets that produce hydrogen

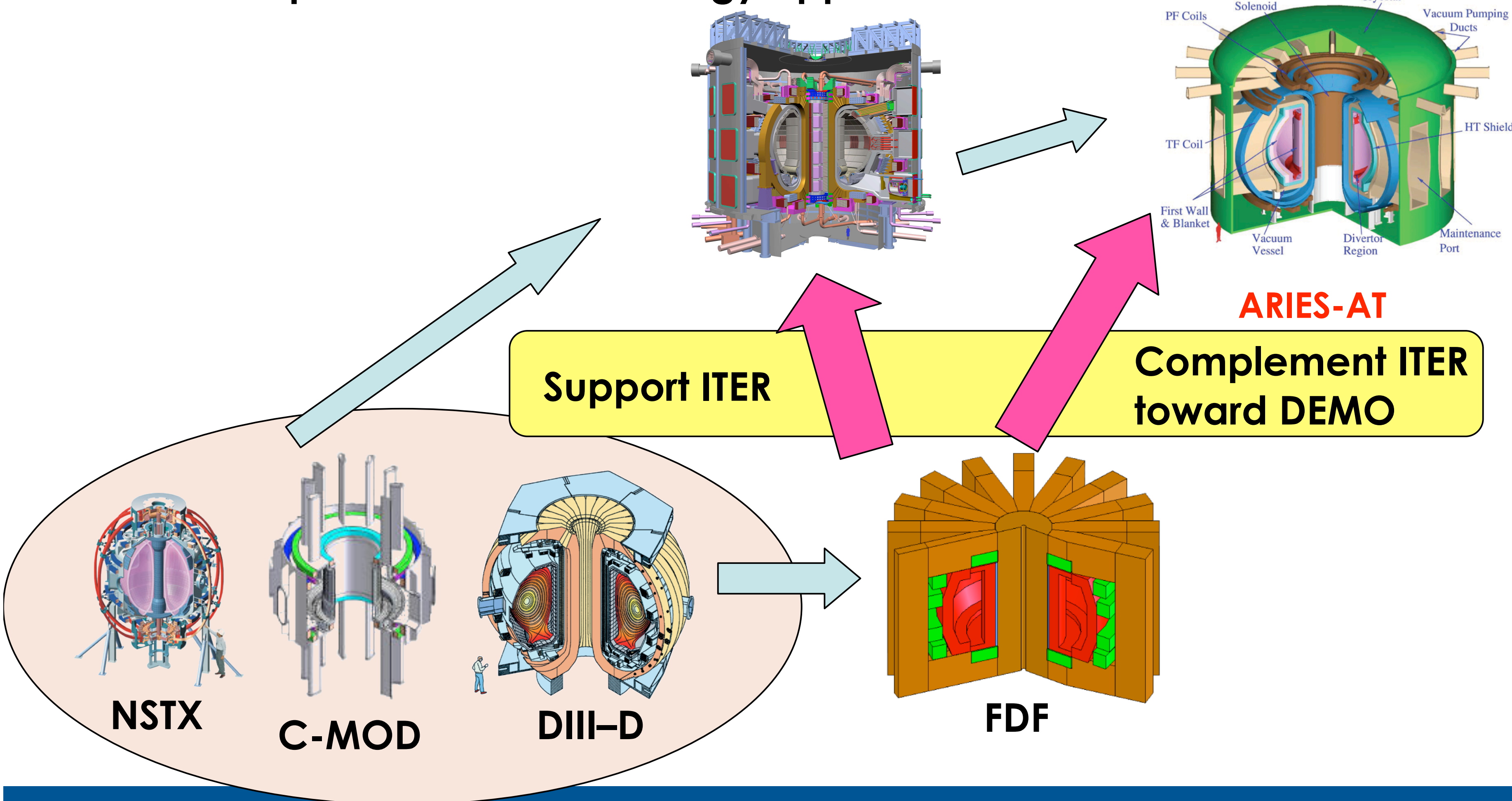
- **With ITER and IFMIF, provide the basis for a fusion DEMO Power Plant**

# Integration of Advanced Tokamak Physics, Burning Plasmas, and Fusion Nuclear Technology for DEMO Requires an FDF



# In the US Domestic Program, an FDF is Needed to Support ITER and Complement ITER Toward Demo

- **FDF will carry forward advanced tokamak physics and enable development of fusion's energy applications**



# ITER, FDF, and IFMIF Enable a DEMO

| Issue | Today's Exp'ts | ITER | FDF | IFMIF | ITER +IFMIF +FDF | DEMO |
|---|---|---|---|---|---|---|
| High Gain Q > 10 ($n\tau_E$) | | 3 | 2 | | 3 | R |
| Alpha Containment & Physics | | 3 | 2 | | 3 | R |
| Steady-State @ High Beta ($\beta_N$, $f_{bs}$) | 1 | 2 | 3 | | 3 | R |
| High Neutron Wall Loading ($\Gamma_n$ ~ 2 $MWm^{-2}$) | 1 | 2 | 3 | | 3 | R |
| Exhaust Power Handling ( ~10 $MWm^{-2}$) | 1 | 3 | 3 | | 3 | R |
| Integrated Plasma Performance in SS | 1 | 2 | 2 | | 3 | R |
| NB/RF Heating Systems Performance | 2 | 3 | 3 | | 3 | R |
| Tritium Handling and Safety | 1 | 3 | 3 | | 3 | R |
| Tritium Self-Sufficiency (TBR > 1) | | 1 | 3 | | 3 | R |
| PFC and Divertor Mat'ls Lifetime | 1 | 2 | 3 | | 3 | R |
| Materials Characterisation (>100 dpa) | | | 2 | 3 | 3 | R |
| FW/Blanket Mat'ls and Components Lifetime | | 1 | 3 | 1 | 3 | R |
| High Temperature Blankets (electricity, $H_2$) | | 2 | 3 | | 3 | R |
| Reactor Scale Superconducting Technology | 1 | 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 desirable |
| R | Solution is essential |

* some capability but no activity planned

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

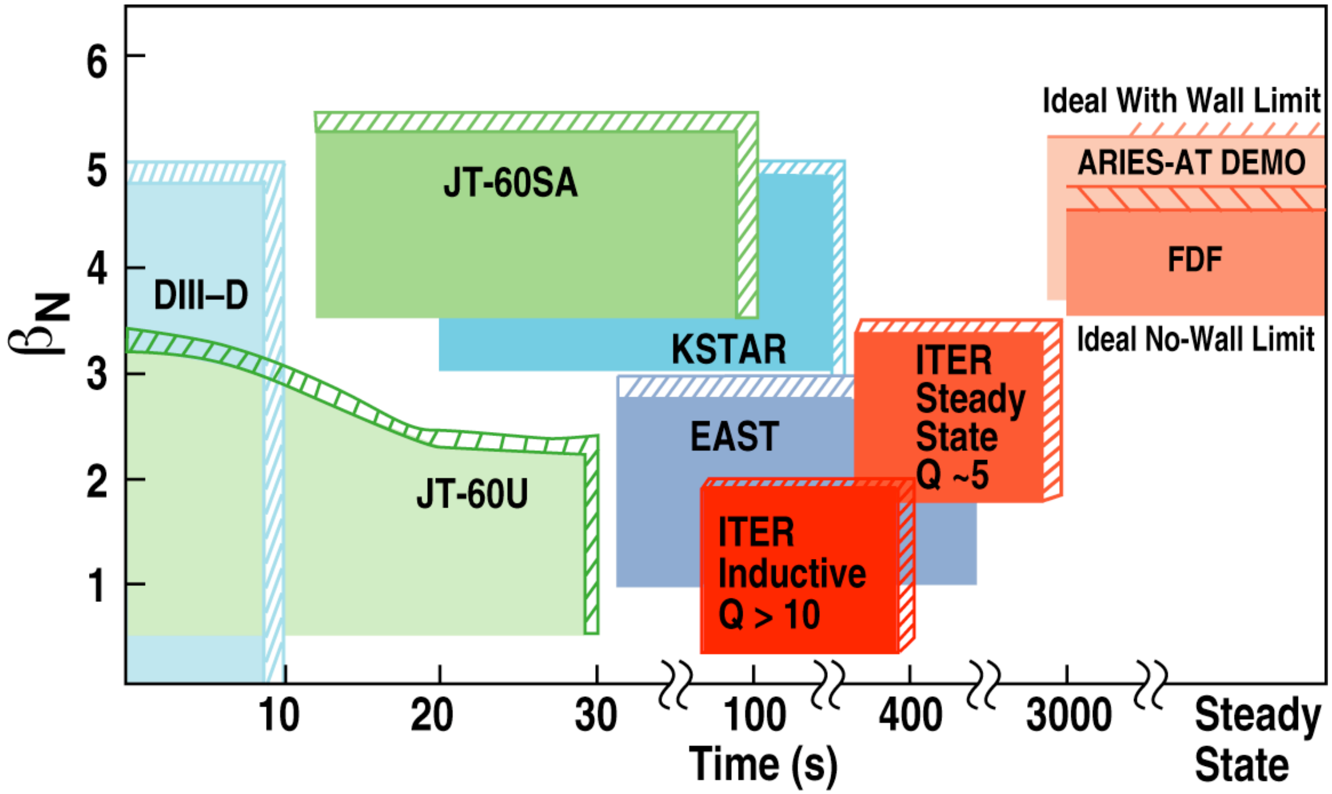
Legend

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

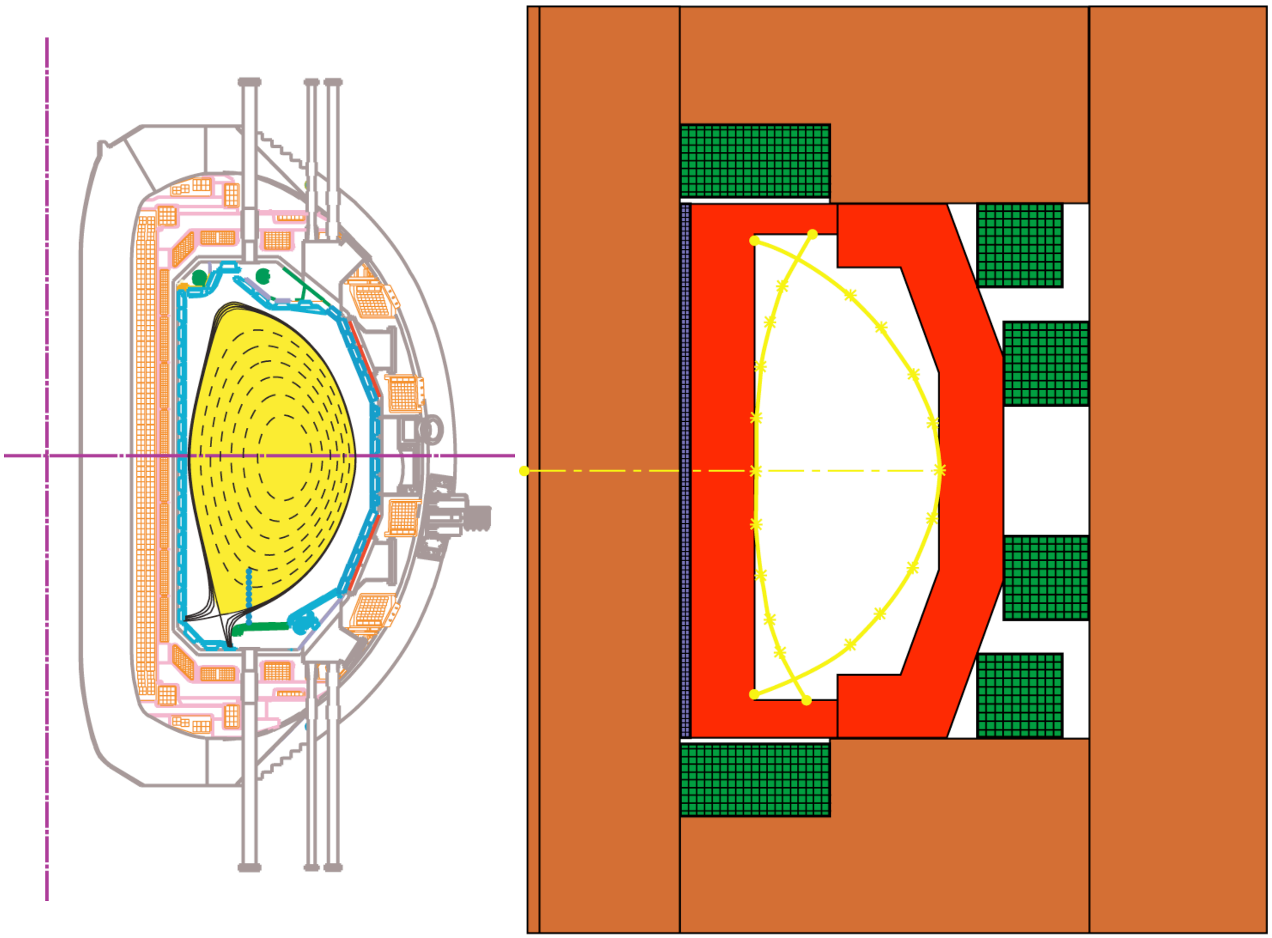
| | G-1 Plasma Predictive capability | G-2 Integrated plasma demonstration | G-3 Nuclear-capable Diagnostics | G-4 Control near limits with minimal power | G-5 Avoidance of Large-scale Off-normal events in tokamaks | G-6 Developments for concepts free of off-normal plasma events | G-7 Reactor capable 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 |

FESAC Planning Panel Final Report October 23, 2007

# FDF Will Enable A Leap to the Advanced Tokamak Reactor Regime



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

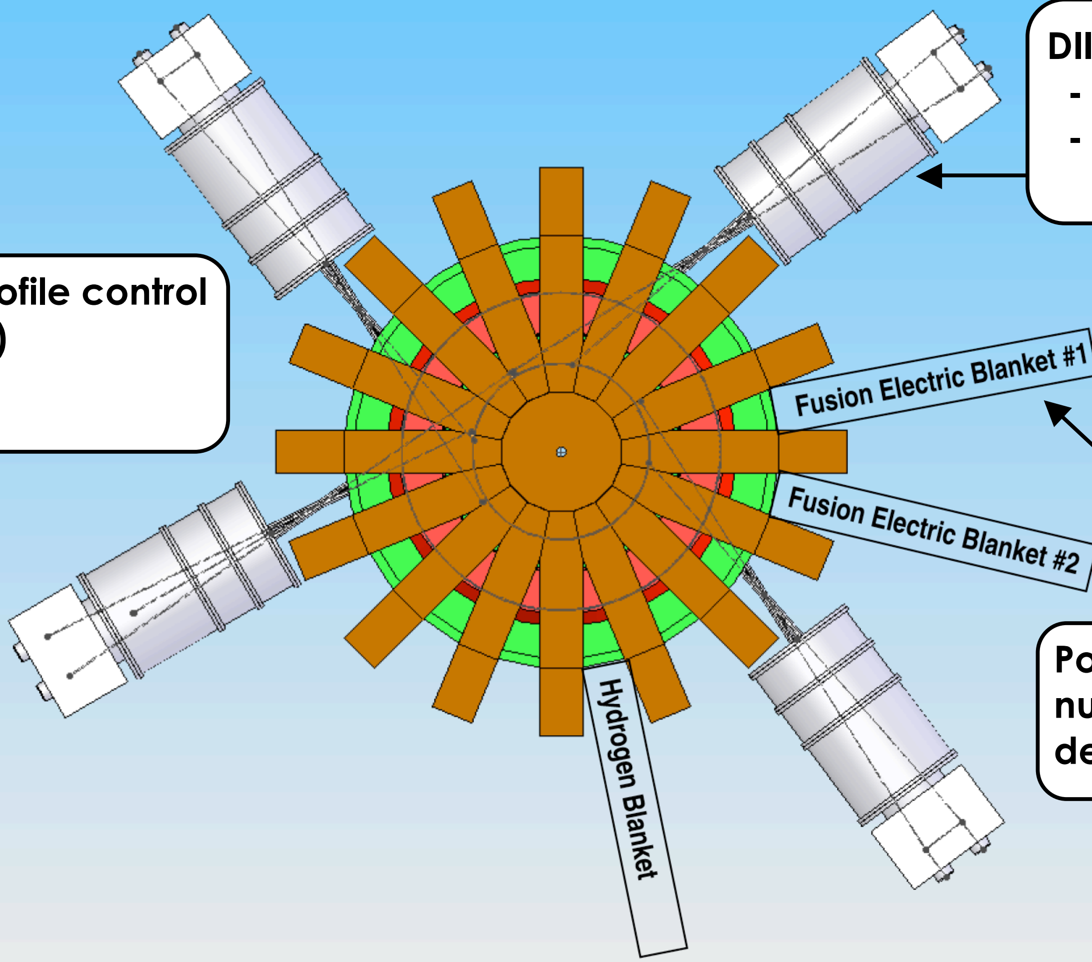


- Plate constructed copper TF Coil which enables..
- TF Coil joint for complete dissasembly and maintenance
- OH Coil wound on the TF Coil to maximize Volt-seconds
- High elongation, high triangularity double null plasma shape for high gain, steady-state
- Red blanket produces net Tritium

# FDF Supports a Variety of Operating Modes To Develop Advanced Tokamak Physics for 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 | 3.3 |
| 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 | 6.0 |
| 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 | 16.0 |

# FDF Auxiliary Systems Similar to DIII-D and Alcator Cmod



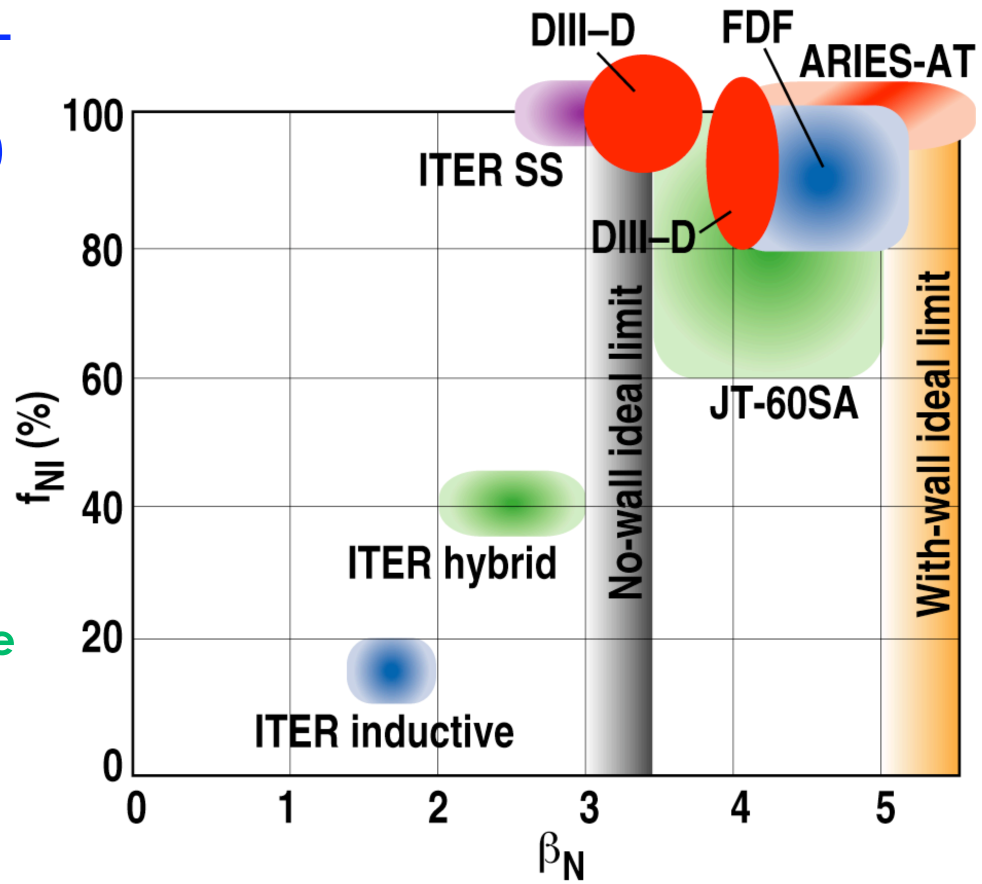

DIII-D size neutral beams
- 3 Co 120 keV, rotation
- 1 Counter, 80 keV for QH mode edge

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

Port blanket sites for fusion nuclear technology development

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

- Required stability values ($\beta_N$ = 4 at DIII-D aspect ratio) can be available in steady-state in 2-3 years
- 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

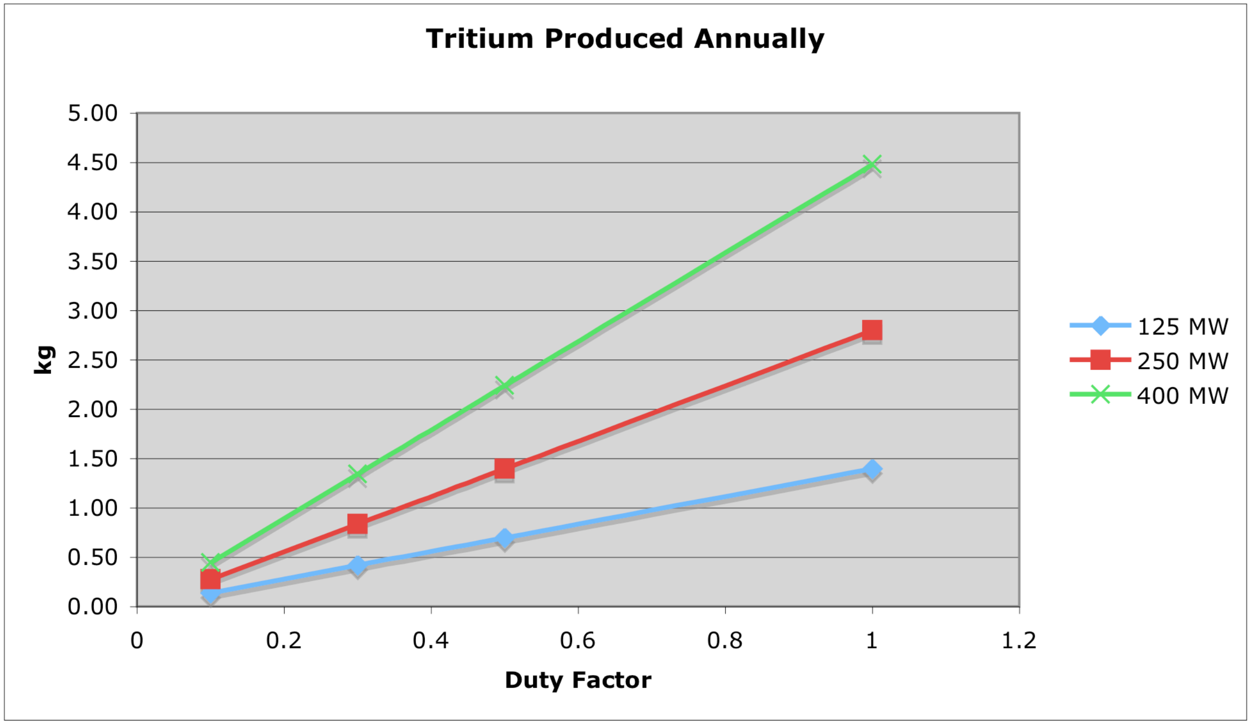
# Fusion Development Facility – A Phased Approach

- **Steady progress through sequenced objectives**

| Year | 1 – 5: START UP | | | 6 – 10: FIRST BLANKET TESTS | | 11 – 15: ADVANCED BLANKETS, ADVANCED PLASMAS | | 16 – 20: ADVANCED PLASMAS, HIGH FLUENCE | |
|---|---|---|---|---|---|---|---|---|---|
| | H | D | DT | DT | | DT | | DT | |
| Fusion Power (MW) | 0 | 0 | 125 | 125 | 250 | 250 | ≤400 | ≤400 | ≤400 |
| $P_N/A_{WALL}$ $MW/m^2$) | | | 1 | 1 | 2 | 2 | 3.2 | 3.2 | 3.2 |
| Pulse Length (Min) | 1 | | 10 | SS | SS | SS | SS | SS | SS |
| Duty Factor | 0.01 | | 0.04 | 0.1 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 |
| T Burned/Year (kG) | | | 0.28 | 0.7 | 2.8 | 4.2 | 5 | 5 | 5 |
| Net Produced/Year (kG) | | | 0 | 0 | 0.56 | 0.84 | 1.0 | 1.0 | 1.0 |
| Main Blanket | Shield (ss/$H_2O$) | | | T Producer | | First Fusion Blanket | | Second Fusion Blanket | |
| TBR | | | 0 | 0.8 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Test Blankets | | | | 1,2 | 3,4 | 5,6 | 7,8 | 9,10 | 11,12 |
| Accumulated Fluence ($MW\text{-}yr/m^2$) | | | 0.06 | | 1.2 | | 4.1 | | 8.9 |
| $P_{AUX}/P_{CD}$ (MW) | 70/50 | | 50/50 | 50/50 | 60/60 | 60/60 | 70/70 | 70/70 | 70/70 |

# 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

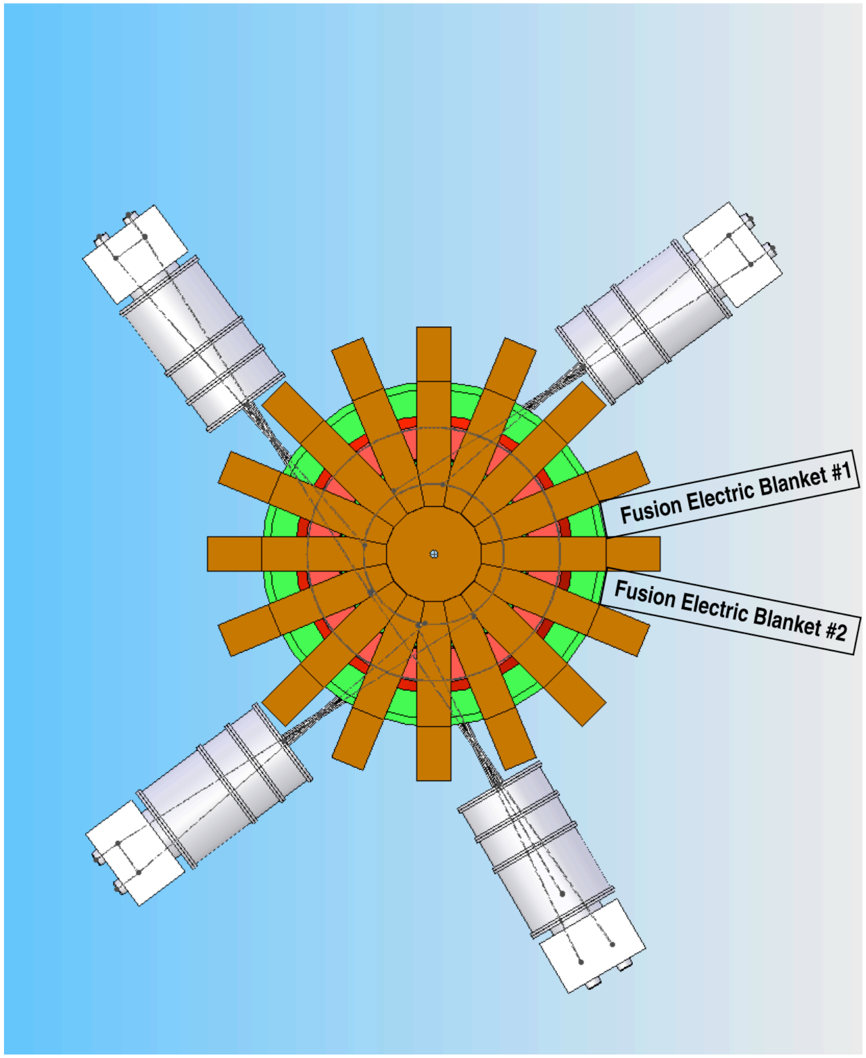



For TBR 1.2



GENERAL ATOMICS

# 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 fluence
  - 10 m$^2$ test area, relevant gradients(heat, neutrons)
  - Continuous on Time of 1-2 weeks
  - Integrated testing with fluence 6 MW-yr/m$^2$

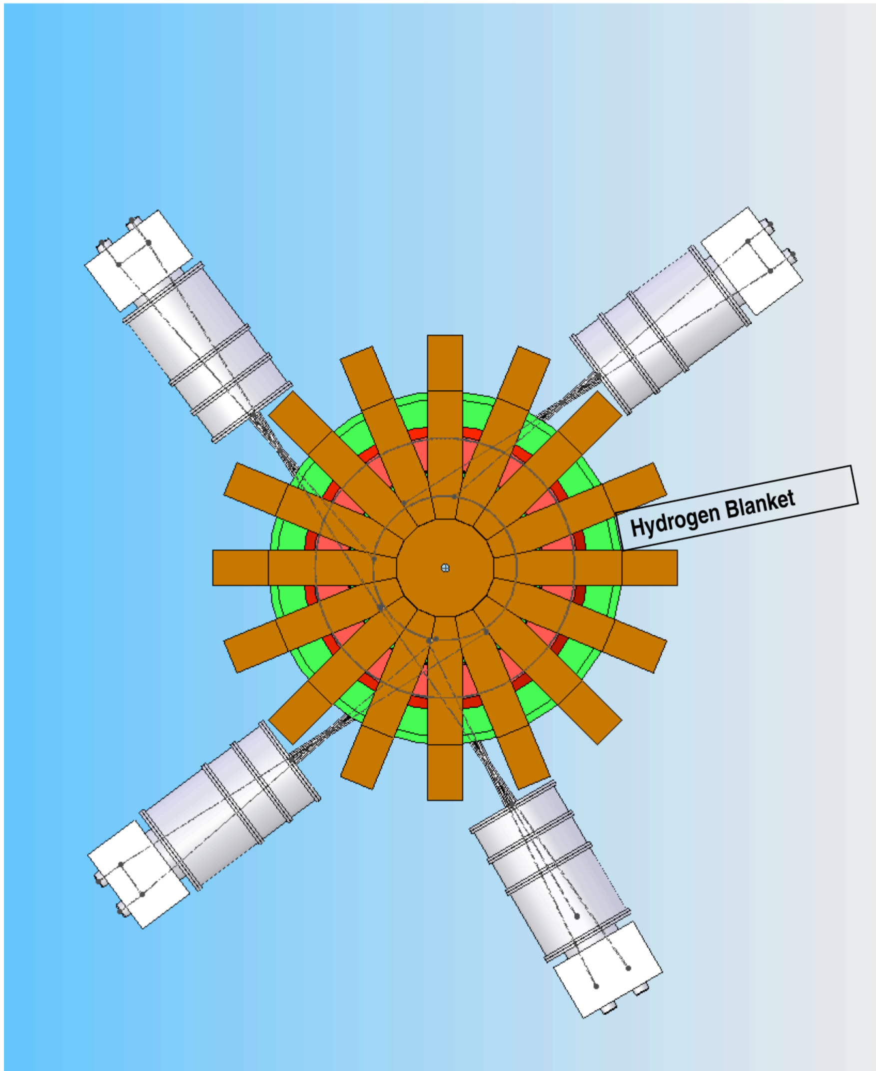
- **FDF can deliver all the above testing requirements**
  - Test two blankets every two years
  - In ten years, test 10 blanket approaches

**Produce 300 kW electricity from one port blanket**

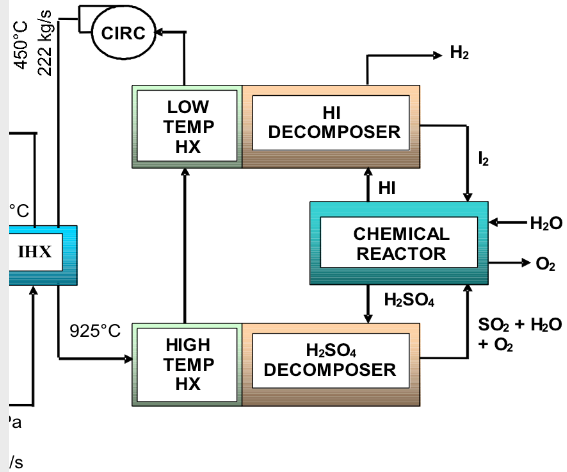
# Stages of FNT Testing in Fusion Facilities

| Fusion "Break-in" & Scientific Exploration | Engineering Feasibility & Performance Verification | Component Engineering Development & Reliability Growth | DEMO |
|---|---|---|---|
| **Stage I** | **Stage II** | **Stage III** | |
| **0.1 – 0.3 MW-y/m²** | **1 - 3 MW-y/m²** | **> 4 - 6 *MW-y/m²*** | |
| $\geq$ **0.5 MW/m², burn > 200 s** | **1-2 MW/m²,<br>steady state or long pulse<br>COT ~ 1-2 weeks** | **1-2 MW/m²,<br>steady state or long burn<br>COT ~ 1-2 weeks** | |
| **Sub-Modules/Modules** | **Modules** | **Modules/Sectors** | |
| • Initial exploration of **coupled phenomena** in a fusion environment<br>• Uncover unexpected synergistic effects, Calibrate non-fusion tests<br>• Impact of rapid property changes in early life<br>• Integrated environmental data for model improvement and simulation benchmarking<br>• Develop experimental techniques and test instrumentation<br>• Screen and narrow the many material combinations, design choices, and blanket design concepts | • Uncover unexpected synergistic effects coupled to radiation interactions in materials, interfaces, and configurations<br>• Verify performance beyond beginning of life and until changes in properties become small (changes are substantial up to ~ 1-2 MW · y/m²)<br>• Initial data on failure modes & effects<br>• Establish **engineering feasibility** of blankets (satisfy basic functions & performance, up to 10 to 20 % of lifetime)<br>• Select 2 or 3 concepts for further development | • Identify lifetime limiting failure modes and effects based on full environment coupled interactions<br>• Failure rate data: Develop a data base sufficient to predict mean-time-between-failure with confidence<br>• Iterative design / test / fail / analyze / improve programs aimed at **reliability growth** and safety<br>• Obtain data to predict mean-time-to-replace (MTTR) for both planned outage and random failure<br>• Develop a database to predict overall availability of FNT components in DEMO | |

# 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**

# Near Term Progress in All Elements of AT Physics Needed in US Program and Elsewhere for FDF Toward DEMO (1)

| Issue | Source of Progress |
|---|---|
| Stability of $\beta_N$ of 4 at the DIII-D aspect ratio in steady-state. | DIII-D has $\beta_N$ = 3.5 in true steady-state and 4 for a few seconds not fully non-inductive. Further advances are planned near term.<br>NSTX research is supportive. Cmod research with LHCD will be supportive. ASDEX Upgrade plans needed upgrades. (EAST, KSTAR later) |
| RWM stabilization by rotation (feedback) | Rotational stabilization has been shown on DIII-D and NSTX. Both machines are working on direct feedback stabilization and results should be near term. (ASDEX Upgrade may join later). |
| NTMS stabilized | ECCD is known to work. The preferred approach in FDF will be avoidance by qmin > 2. DIII-D and ASDEX Upgrade continue research. |
| ELMs eliminated by RMP | RMP works well enough that ITER is trying hard to implement it. But more physics understanding from DIII-D would be useful. MAST may join soon, ASDEX Upgrade later. |
| ELMS eliminated by QH-mode | DIII-D needs to show one counter beam can make QH-mode while more co-beams are injected. Preliminary results are not promising. Two years to finish the issue. JT-60U research also important. |
| Confinement quality required. | FDF needs only what has been demonstrated in DIII-D. GLF23 says that quality can be obtained in FDF. More work needs to be done to establish Petty's scaling which has correct dimensionless parameter dependences and implies significant margin. |

# Near Term Progress in All Elements of AT Physics Needed in US Program and Elsewhere for FDF Toward DEMO (2)

| Issue | Source of Progress |
|---|---|
| Bootstrap fractions over 60% | Up to 100% has been achieved in several machines. Only issue is high $\beta_N$ (see above) to enable simultaneous high $\beta_T$ and $\beta_P$. |
| LH coupling to H-mode and penetration past a high pedestal temperature | Alcator Cmod and JET need to show that a coupler close enough to couple does not inhibit H-mode. JET results are promising. Penetration of LH waves past a high pedestal temperature must be addressed with computations and perhaps in experiments. |
| Pumped high triangularity DN shape | Now running in DIII-D. Cmod to join soon with pumping on one end. NSTX, MAST run DN. |
| Plasma control system | Extensions of DIII-D system will suffice. Real time stability calculations coming. Mainly a question of diagnostics implemented on FDF. |
| Power Exhaust | High radiation fraction research in DIII-D and Alcator Cmod. Heat flux spreading by RMP coils. DN studies. UEDGE calculations for divertor design. |
| Tritium retention in PFC's | Carbon research in DIII-D and JT-60U. B and Mo research in Alcator Cmod,. B and W research in ASDEX Upgrade. W and Be research in JET. PISCES and other laboratory studies. |

# FDF Can Provide the Needed Progress in All Elements of AT Physics to Enable a DEMO of the ARIES-AT Type (1)

| Issue | What Will Be Done in FDF |
|---|---|
| Stability of $\beta_N$ of 4 at the DIII-D aspect ratio in steady-state. | Machine hardware and configuration can support $\beta_N$ toward 5 for ARIES-AT. |
| RWM stabilization by rotation (feedback) | An optimal coil system for direct feedback will be designed into the blanket system. Low energy beams will be provided for enough rotation. |
| NTMS stabilized | Enough ECCD will be provided. Current profile control will show NTM avoidance by high qmin. |
| ELMs eliminated by RMP | Optimal RMP coil set will be engineered and implemented. |
| ELMS eliminated by QH-mode | Counter beam will be provided if the physics is proven in near term research. |
| Confinement quality required. | Beams are configured to make optimal edge transport barriers in the ions and rotation. Electrons expected to be limiting per GLF23. Good diagnostics needed. |

* Should Resolve the Issue

# FDF Can Provide the Needed Progress in All Elements of AT Physics to Enable a DEMO of the ARIES-AT Type (2)

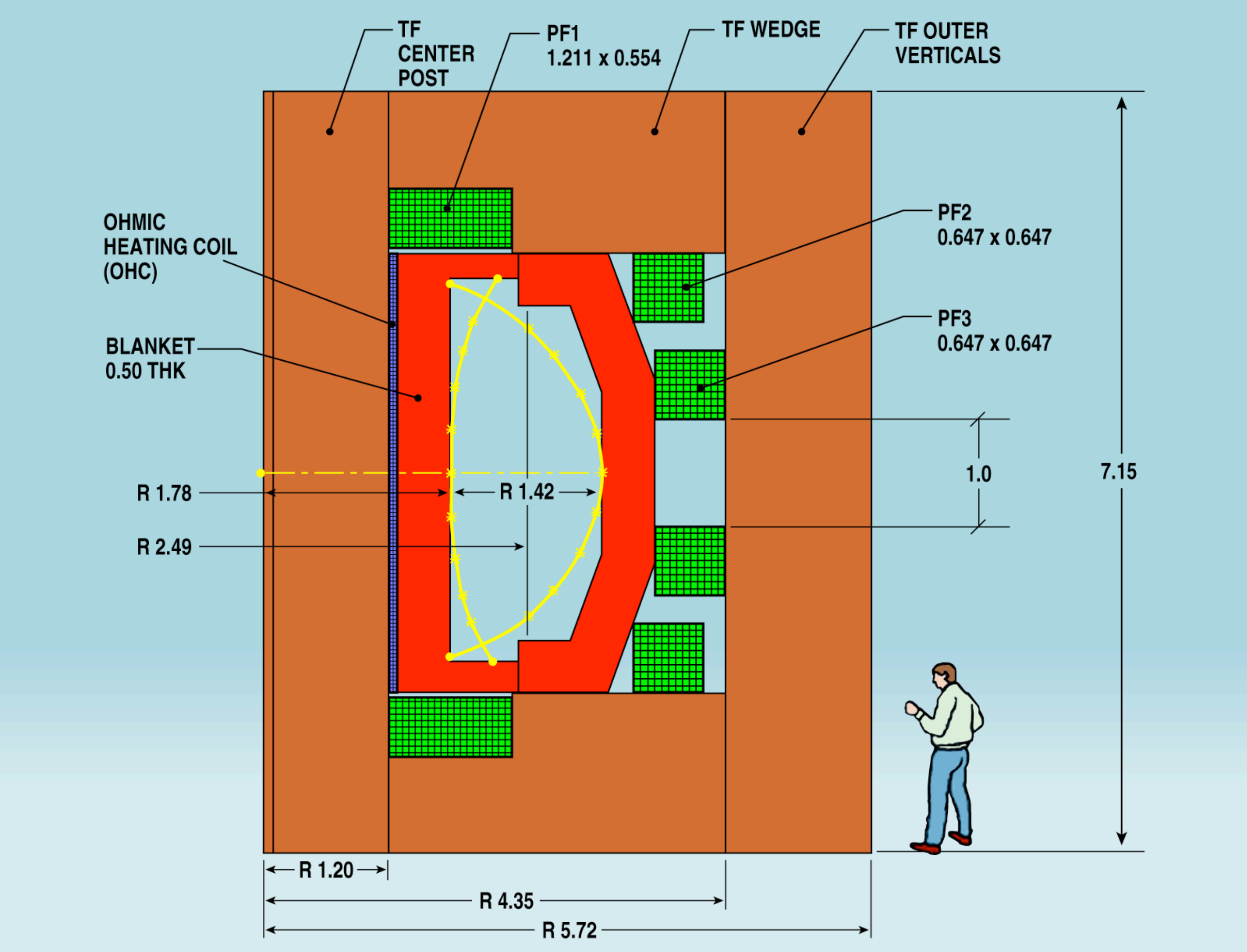
| Issue | What Will Be Done in FDF for DEMO |
|---|---|
| Bootstrap fractions over 60% | Will be capable of and seek very high bootstrap operation (>60%) |
| LH coupling to H-mode and penetration past a high pedestal temperature | Show off-axis J(r) control by LHCD with high pedestal temperature. |
| Pumped high triangularity DN shape | Run both DN and SN for ITER and DEMO. |
| Plasma control system | Show multi-day operation of a tokamak without interruption. |
| Power Exhaust | Show integrated physics/technical solutions for DEMO. |
| Tritium retention in PFC's | Change first wall materials 2-3 times to make a basis for DEMO.  Operate with high first wall temperature. Demonstrate net tritium production. |

* Should Resolve the Issue

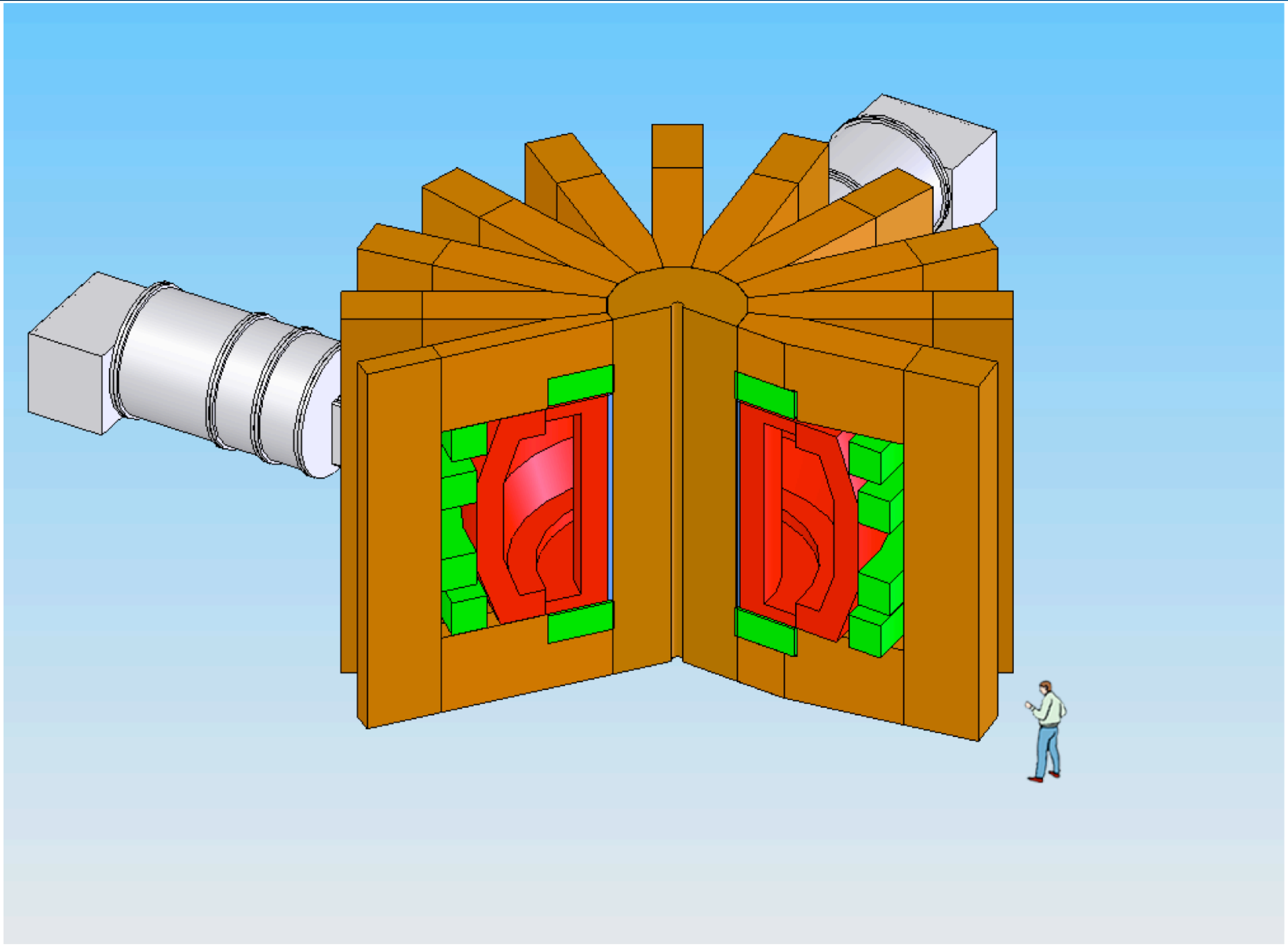
# To Develop Fusion Energy, a Fusion Development Facility (FDF) is Needed

- 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

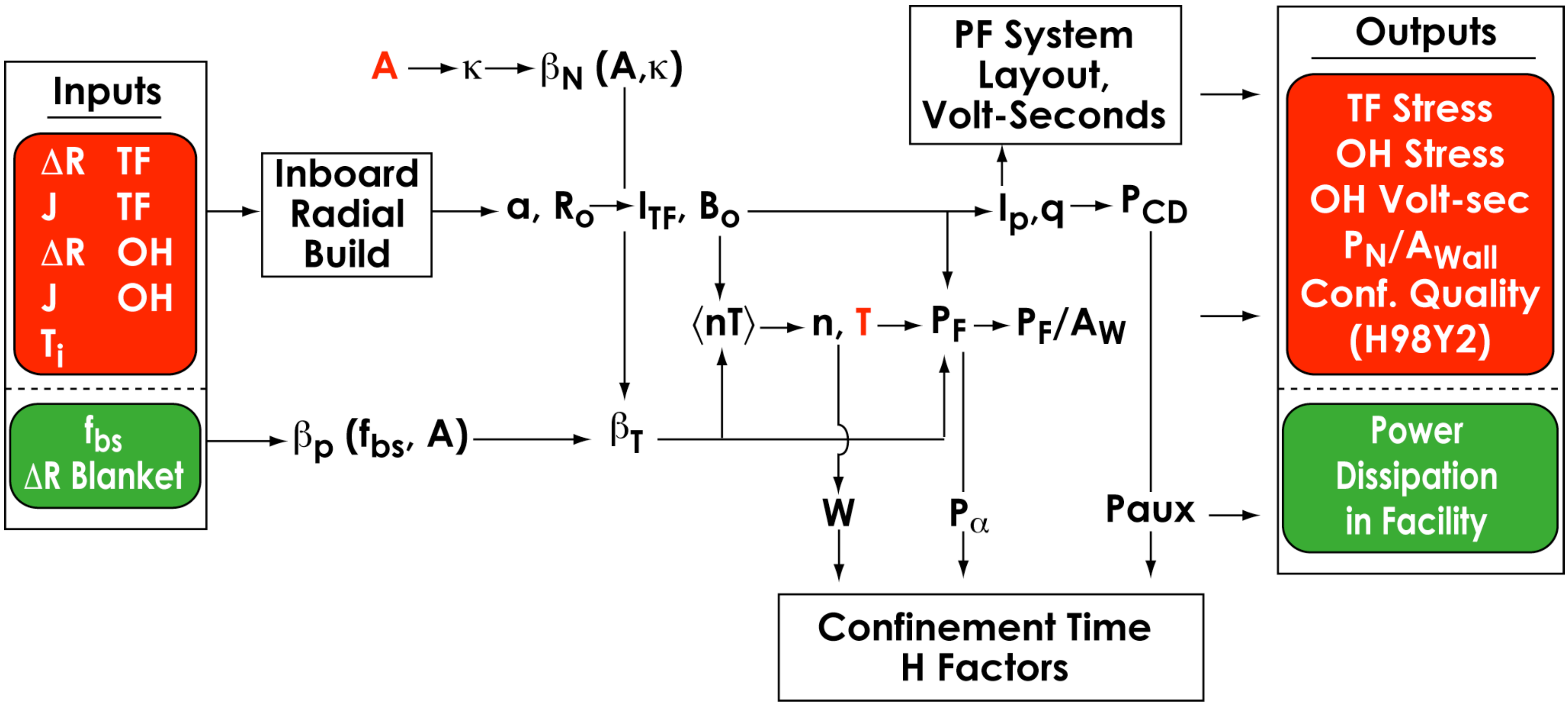
# FDF Dimensions for Reference



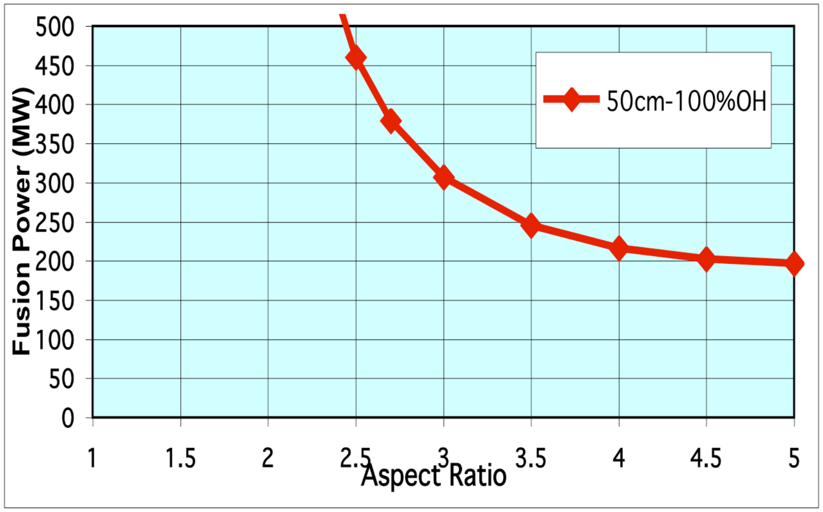
# 3-D Cutaway View with DIII-D Sized Neutral Beams

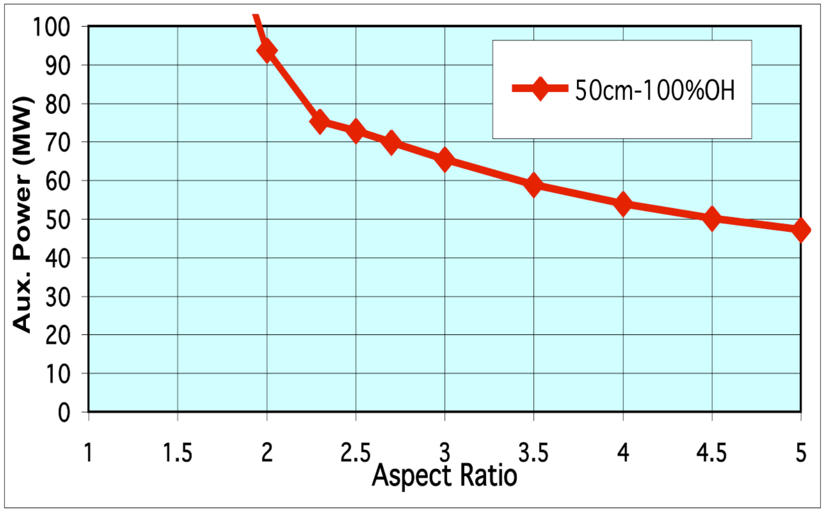


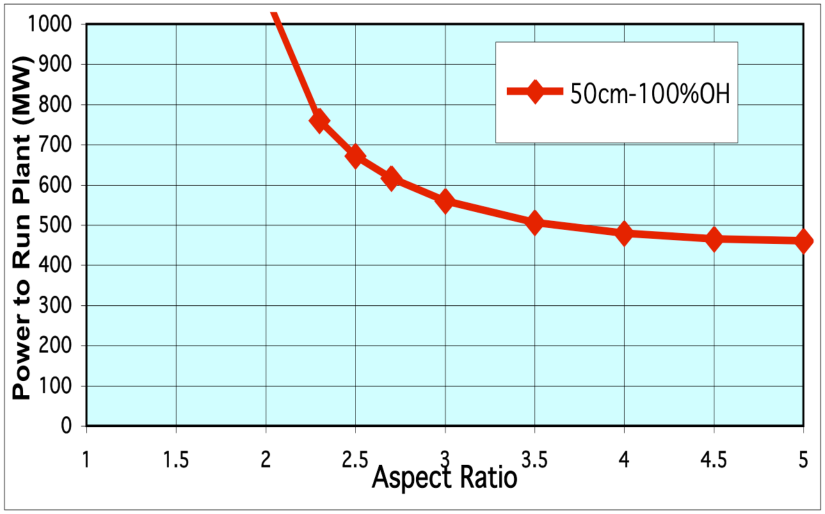
# The FDF Design Point Resulted from a Systematic Study Versus Aspect Ratio



# An Aspect Ratio 3.5 FDF Gives a Reasonable Fusion Power and Power to Run the Plant



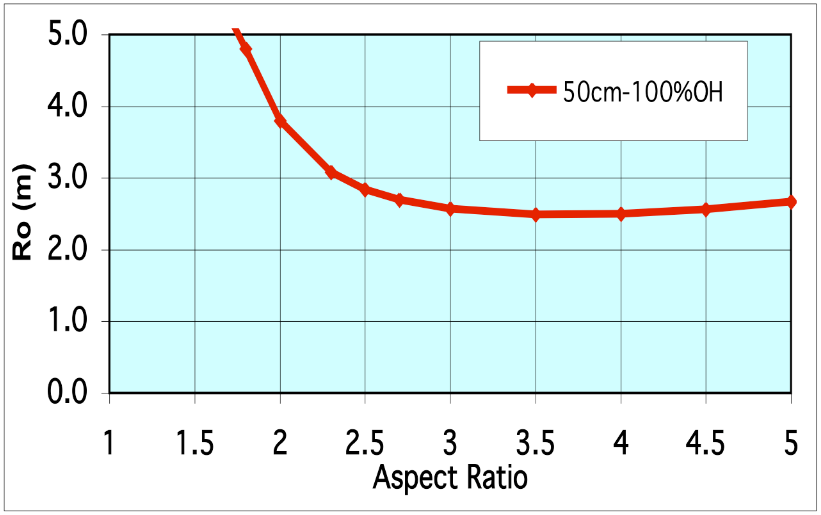



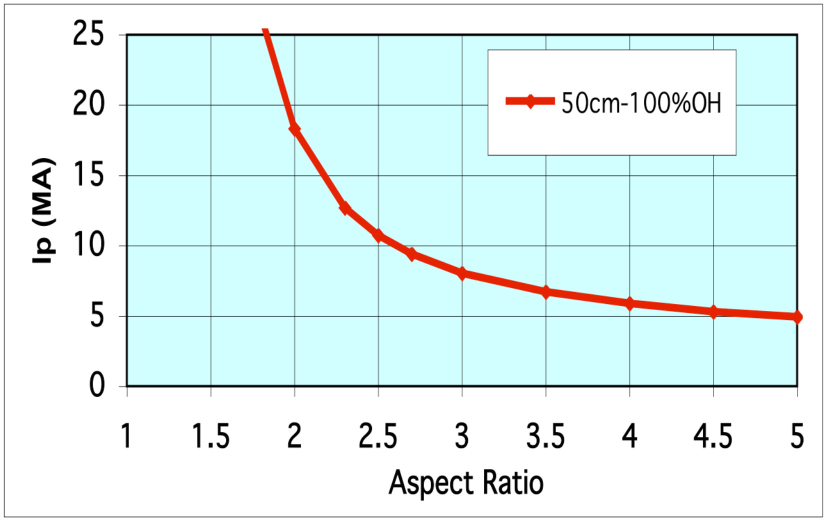



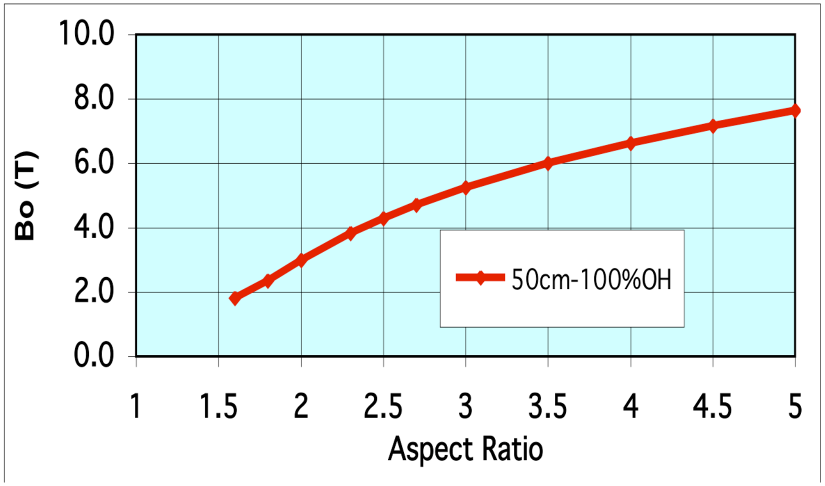



GENERAL ATOMICS

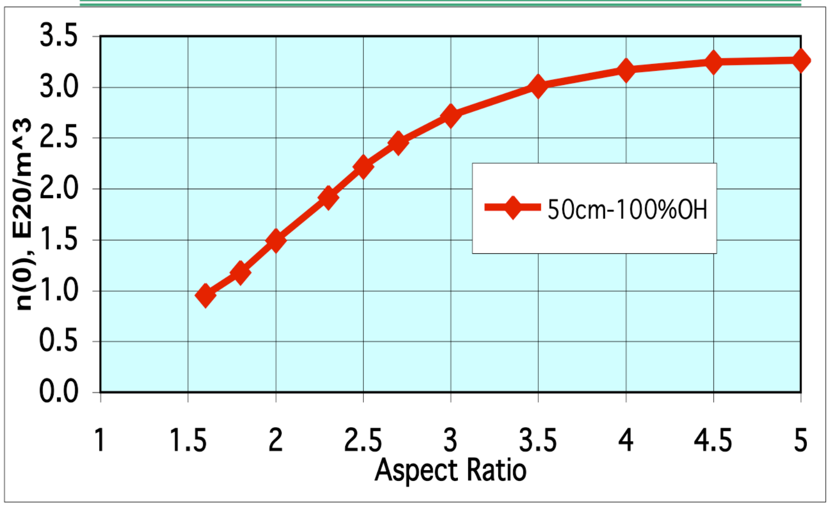
# A=3.5 Gives a Minimum Size and a Reasonable Plasma Current and Magnetic Field

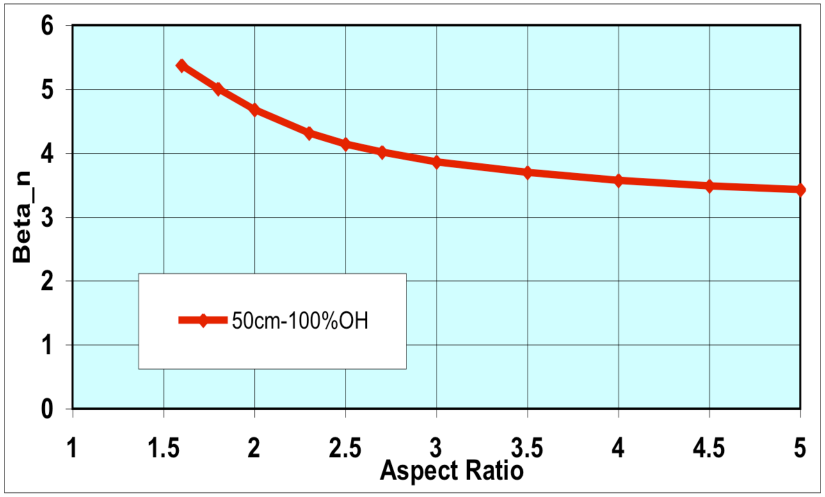


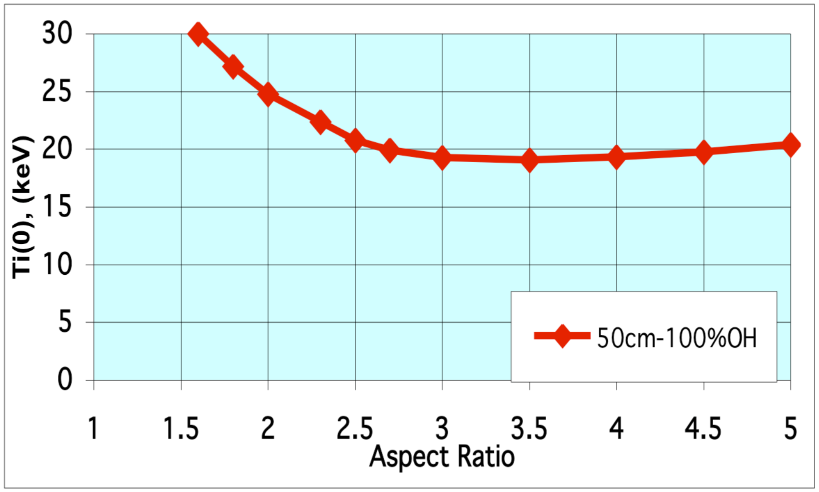



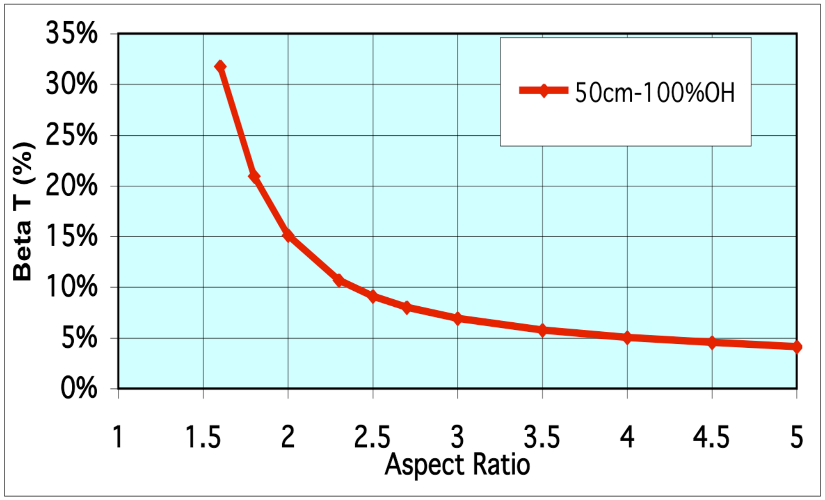



# Plasma Parameters Versus Aspect Ratio



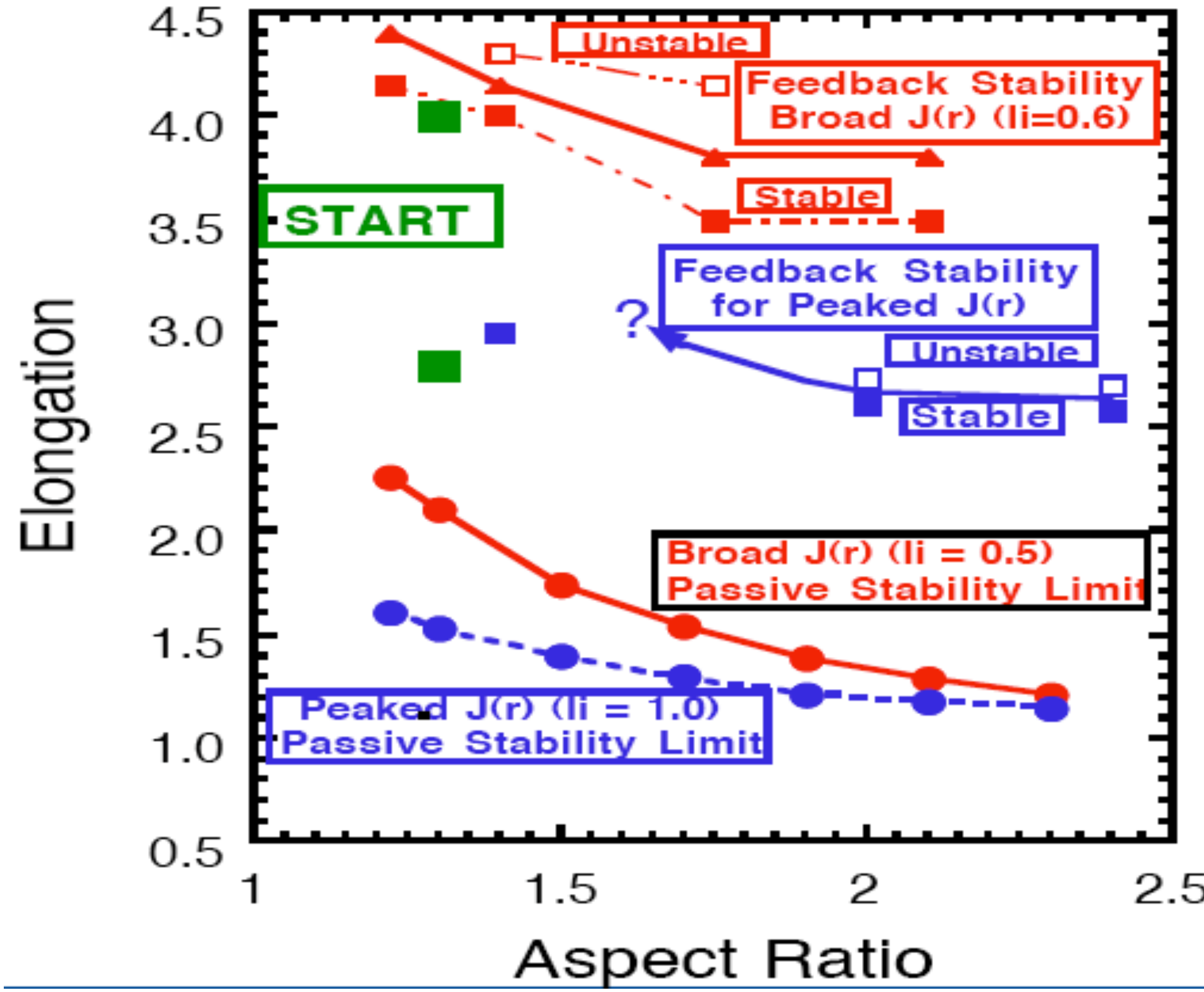



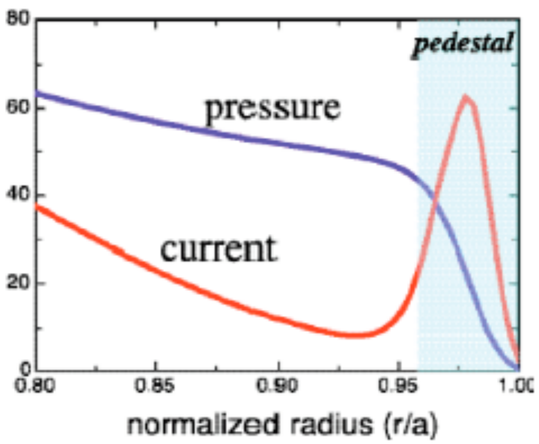



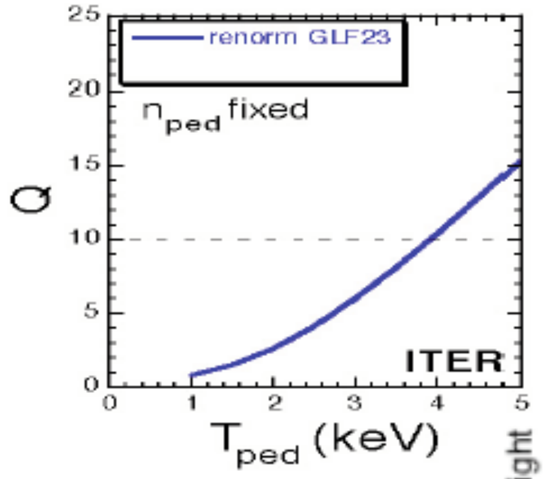
# FDF Should Be Vertically Stable at Kappa 2.3

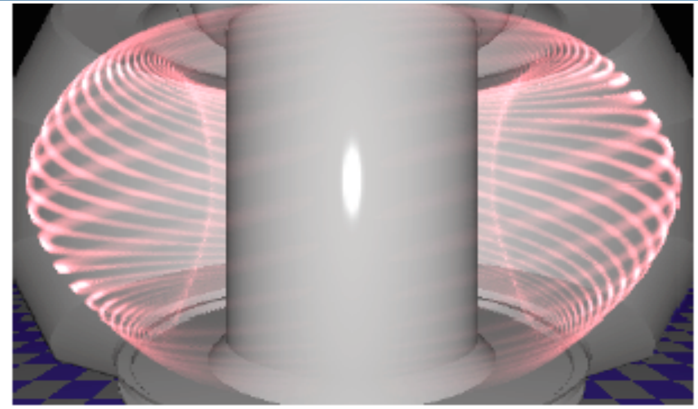
- Asymptotic ideal limit for peaked current profiles is kappa 2.6
- DIII-D confirmed this limit reaching kappa 2.5 at aspect ratio 2.7
- Asymptotic ideal limit for broad current profiles is kappa 3.7
- FDF has broad current profiles and a nearby conducting wall

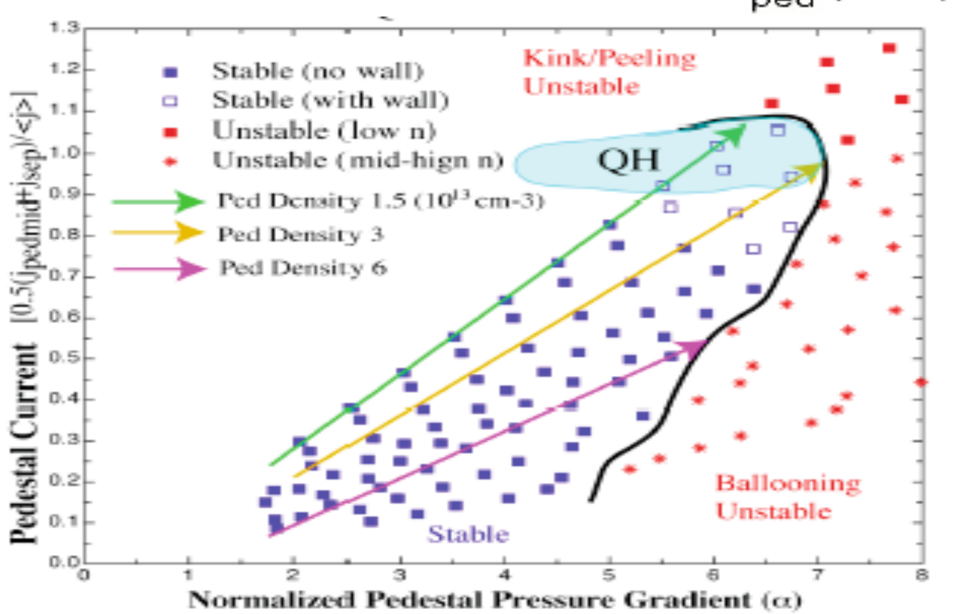


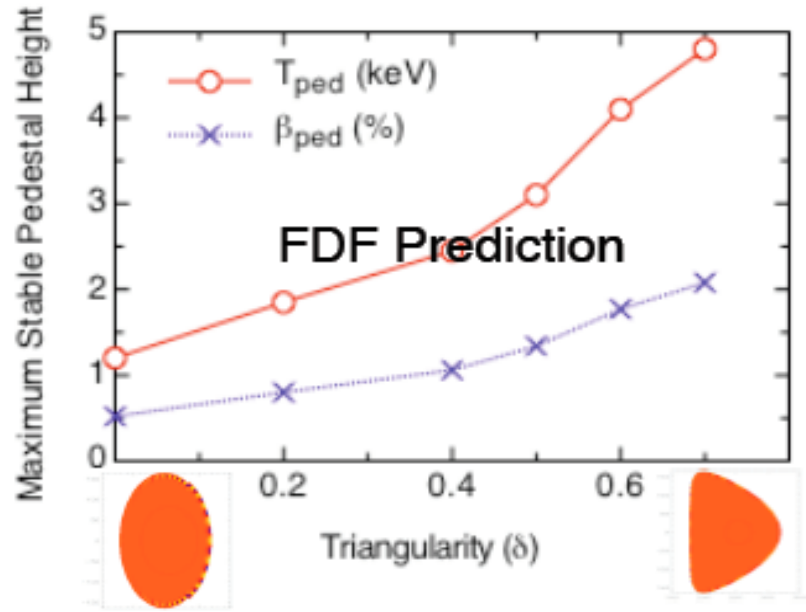
# FDF Is Designed for High Pedestal Pressure and ELM-Free Operation with Either RMP Or QH-mode








GENERAL ATOMICS