RESEARCH THRUSTS MADE POSSIBLE BY A FUSION DEVELOPMENT FACILITY

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1.0 MISSION AND SCOPE SUMMARY

To make possible a fusion demonstration power plant (DEMO) of the ARIES-AT type as the next step after ITER, a Fusion Development Facility (FDF) is needed. FDF should enable:

Development of fusion's energy applications and the operating modes needed in DEMO.

We must learn how to close the fusion fuel cycle and make electricity and hydrogen from the fusion process. Before a DEMO project can be committed, ***net tritium production must be demonstrated and assured***. It is not practical to first make this demonstration in the initial phase of DEMO operation, owing to the high tritium consumption rates. Assurance of tritium self-sufficiency must be made first in a more modest device. FDF will have a goal of producing its own tritium and building a supply to start up DEMO. The approach taken will be to engineer a first full blanket with the simplest technology that just produces net tritium. All other design requirements are secondary. Then in parallel, more advanced blankets will be tested in port blanket modules and successful ones will then be engineered into second generation full blankets. FDF will be designed to facilitate changeout of the full first wall/blanket structures and will do so at least twice in the life of the project.

In port blanket modules, ***the development of blankets suitable for both tritium production and electricity production will be made***. FDF will provide the necessary facility to test perhaps ten different blanket concepts or variants in 2–3 ports over a ten year time period. FDF will be the necessary facility to learn how to make blankets that support high temperature and high thermodynamic efficiency for power conversion for electric power production. Another port site should be devoted to ***the development of blankets that can support hydrogen production,*** which can require even more demanding temperatures of extracted coolant, over 900°C. Although FDF will not attempt electric power production from its full blankets, actual demonstrations of both electricity production (300 kW) and of hydrogen production (one metric ton per week) should be made on the most successful port blankets.

With neutron fluence at the outer midplane of 1–2 MW/m^2 and a goal of a duty factor on a year of 0.3, FDF can ***produce fluences of 3–6 MW-yr/m^2*** in ten years of operation onto complete blanket structures and/or material sample volumes of about 1 m^3. FDF can enable irradiation qualification of materials in port material sample exposure stations. This level of fluence should enable qualification of at least the first few years of DEMO operation.

FDF should ***demonstrate advanced physics operation of a tokamak in steady-state with burn***. FDF will be designed using already proven and conservative implementations 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. Modest size (we envision a device between DIII-D and JET in size) is needed to minimize the cost consistent with the mission. Even so, the cost will be substantial and the ambition of the mission must match the cost. Modest size means modest Q; in tokamaks size and Q are strongly coupled. FDF with Q<5 does not compete with ITER for the high energy gain burning plasma mission. Conservative AT physics will enable ***full non-inductive, high bootstrap operation to demonstrate continuous operation of a tokamak for periods up to two weeks***, a necessary step before DEMO and essential to a blanket development mission.

Building on secure baseline operating modes, FDF must be capable of ***further developing all elements of AT physics, qualifying them for an advanced performance DEMO***. The many advances made in the last decade must be captured in a next step device in order to make progress toward the even more advanced operating modes called for by ARIES-AT. The FDF, operating in a compact D-T regime prototypical of high power density fusion reactors, will provide burning plasma physics understanding to complement the contributions from the new Asian superconducting tokamaks and ITER.

2.0 FILLING RESEARCH GAPS TO DEMO

FDF and the necessary supporting research program can fill in most of the 15 gaps identified by the recent FESAC Planning Panel between ITER, the new superconducting tokamaks, and IFMIF and the DEMO (Figure 2). Here we very briefly discuss the main issues FDF can address for each of the ReNeW Panels in the first four themes. We plan to write a short white paper jointly with the FNSF and FNST communities expanding the key points below for each Panel.

2.1 HARNESSING FUSION POWER

<u>Fuel Cycle</u>: Closing the fusion fuel cycle is a major goal of FDF. Net tritium production must be demonstrated before a DEMO can be committed. FDF will develop blankets in port modules at 1–2 MW/m^2 neutron fluxes and will deploy blankets on the 130 m^2 area of its first wall to enable a definitive demonstration of net tritium production. Operating durations of up to 2 weeks will enable demonstration of actual continuous closed loop tritium extraction for fusion systems. FDF will demonstrate for DEMO the whole fuel cycle including extraction, accountability, and safety in a steady-state DT device.

<u>Power Extraction:</u> High Neutron Wall Loading (Γ_n ~ 2 MW/m^2). FDF will be designed for Γ_n ~ 2 MW/m^2 into the midplane port blanket modules and will have a goal of duty factor 0.3 for a ten year integrated fluence of 3–6 MW-yr/m^2. These are the essential capabilities for fusion nuclear technology development. ITER's goals are 0.5 MW/m^2 midplane neutron flux and a lifetime fluence of 0.3 MW-yr/m^2. FDF will be about 1/10 and ITER about 1/100 of reactor fluence.
High Temperature Blankets (Electricity, Hydrogen Production). FDF will have reactor relevant neutron fluxes and fluences to develop blankets in port test modules. FDF should take one of the best performing electric and hydrogen producing blankets and actually make a small demonstration of electricity and hydrogen production.
FW/Blanket Materials and Components Lifetime. FDF will test whole, full size first wall/blanket structures with significant neutron fluxes and fluences, relevant first wall heat and plasma fluxes, and in a real system with disruptions and other challenges. FDF will be designed with the flexibility and maintainability to allow ten test blanket variations to be tested in ten years and 1–2 changeouts of the main full tritium producing blanket.

<u>Materials Science</u>: With fluences of 3–6 MW-yr/m^2 (dpa of about 30–60, perhaps more), FDF can make a significant contribution on relatively large, fully integrated and engineered components. FDF could take two ports and fill each with about a cubic meter of samples including welds and small assemblies and leave them there in controlled conditions for ten years to accumulate a fluence of 3–6 MW-yr/m^2. Samples can be removed periodically to accumulate data versus dose.

<u>Safety</u>: The challenges of tritium handling (kg quantities) and safety will be fully engaged in FDF, as in ITER.

<u>RAMI</u>: The FDF Program will be a test bed for learning how to engineer reliable first wall/blanket structures and gain first information on reliability growth. Because FDF is research machine with the intention to make planned changes in the entire blanket structure, it will be designed with a jointed copper TF coil so the entire machine can be taken apart readily, any component remotely serviced, and in particular the nuclear components accessible by simple crane lift. The machine must be reliable to achieve two week continuous operation and the availability to achieve a 30% duty factor on a year. It must be maintainable because it is a research environment and failures must be repairable and the blankets must be changeable. Inspection of the components is an integral part of the research; we need to find out what is happening to these components.

2.2 TAMING THE PLASMA MATERIAL INTERFACE

<u>Plasma-Wall Interactions</u>: Pulsed Heat Loads. Since the plasma stored energy in ITER will be about five times that of FDF, ITER has more challenges in such pulsed heat loads as disruptions and ELMs. Nevertheless, FDF must develop methods of operating ELM free and limiting unmitigated disruptions to about one per year.

<u>Plasma Facing Components</u>: PFC and Divertor Materials Lifetime. The main issue here is erosion of plasma facing surfaces. With ten times greater plasma fluence onto surfaces than ITER, FDF will make the major contribution.
Tritium Retention. Because of the major goal of demonstrating TBR>1, FDF must develop solutions to the Tritium retention issue. Operation with hot walls will enable research in the reactor relevant regime not previously investigated.
Exhaust Power Handling. Here the contributions of ITER and FDF are comparable since the peak heat fluxes expected onto divertor components range up to 10 MW/m^2. Even at 400 seconds, ITER must engineer steady-state heat removal. As with the plan for blanket changeouts in FDF, various plasma facing materials and attachment schemes can be investigated.

<u>Internal Components</u>: First wall materials and structures and near first wall components like rf launchers and diagnostics will be developed in a fusion relevant environment. FDF will be a test bed for learning how to engineer reliable first wall/blanket structures and provide first data on reliability.

2.3 CREATING PREDICTABLE, HIGH PERFORMANCE, STEADY-STATE PLASMAS

<u>Auxiliary Systems</u>: DEMO applicable Tritium plant systems, fueling systems, disruption mitigation systems, ELM suppression systems, RWM control systems, plasma control systems, Lower Hybrid systems, EC systems, and remote handling systems will be developed for FDF. Positive ion neutral beams may be used to create edge transport and rotation barriers for high confinement and RWM stabilization by rotation. Such techniques could be DEMO relevant.

<u>Control</u>: A plasma control system able to operate a tokamak close to but not exceeding the beta limit will enable the two weeks of continuous operation without disruptions. Such a system can be developed on existing facilities. Key issues in FDF will be providing the diagnostic measurements in a high neutron fluence environment and provision of adequate actuators.

<u>Integration</u>: Integrated Plasma Performance in Steady-State. The combination of both ITER and FDF efforts is needed to provide the necessary basis for DEMO. ITER will look at very long pulse issues at high energy gain and FDF will look at true steady-state but at modest energy gain and high bootstrap fraction.
Steady-State at High Beta (High β_N and Bootstrap Fraction). FDF makes the major contribution by fully embracing reactor level β_N operation through an optimally designed RWM stabilization coils and with substantial plasma rotation to enable high bootstrap fraction operation with significant fusion gain. Auxiliary H&CD systems will be optimized for plasma rotation and current drive. FDF aims to show operation for arbitrary time durations, days to two weeks. ITER's contributions depend on whether RWM coils are implemented, the ITER plasma rotates fast enough, there will be sufficient off-axis current drive for AT modes, ITER startup can support AT modes; and whether ITER can implement ELM suppression.

<u>Validated Predictive Modeling</u>: FDF will provide a platform for validation of codes in DEMO relevant plasma regimes.

<u>Measurement</u>: The development of diagnostics that can function in a DEMO level high neutron flux environmentis a key issue. High quality measurements are essential to the steady-state plasma control near the beta limit.

<u>Magnets</u>: FDF's copper magnets are not DEMO relevant, but the implementation of ELM and RWM coils will be relevant. **Reactor Scale Superconducting Technology** is another unique ITER contribution with its reactor size all superconducting coils. FDF is a copper coil machine to keep the size down and enable efficient maintenance.

<u>Off-Normal Events</u>: ELM free operation is essential. Disruptions will be avoided by operating below the beta limit with effective realtime control. Disruptions that do occur will be mitigated. The goal will be one unmitigated disruption per year.

2.4 BURNING PLASMA IN ITER

<u>Alpha Particle Physics</u>: Alpha Containment and Physics. ITER provides the essential burning plasma information. FDF makes a meaningful contribution with modest gain, fusion power, reactor level alpha beta, and alpha speed/Alfven speed.

<u>Creating a Self-heated Plasma</u>: High Gain (Q > 10). Exploration of this burning plasma physics regime is a mission unique to ITER. FDF makes a meaningful contribution with Q up to 5.

<u>Extending Confinement to Reactor Conditions</u>: FDF will have reactor level plasma parameters in a burning plasma. ITER will make the unique contribution of confinement data at low ρ*.

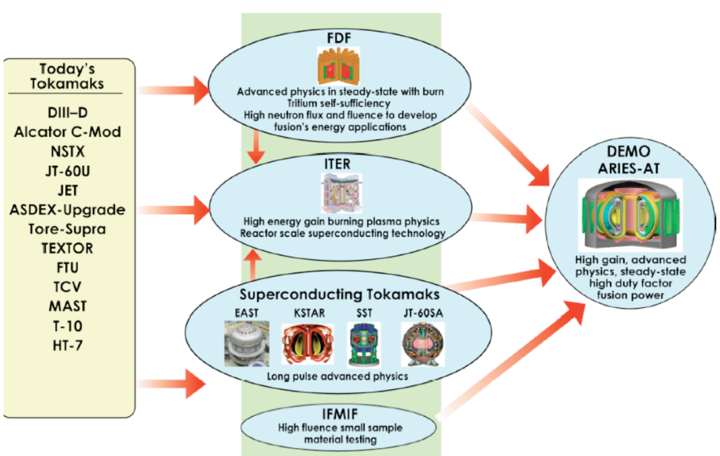

Fig. 1. FDF, ITER, IFMIF, and other AT devices, will ***provide the basis for a DEMO power plant of the ARIES-AT type.***

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

Fig. 3. Gaps chart from FESAC Planning Panel. Our addition of the last line shows FDF addresses nearly all the gaps.