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CREATING A SELF-HEATED PLASMA

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A manifestation of an economically attractive compact fusion power plant is ARIES-AT [1], which is designed based on more aggressive AT physics extrapolating from on-going research. Scientific understanding from existing fusion facilities is providing the basis for conceptual design of an AT DEMO. However, operating parameters of existing facilities are typically different from those of an AT DEMO, e.g. operating in a fast ion mode instead of an electron-ion equilibrated high density regime; pulse durations that are orders of magnitude shorter; current profiles quite different from the broad negative shear profile expected in ARIES-AT, with 90% bootstrap current that peaks near the plasma edge.

The new superconducting tokamaks in Asia will extend the AT operating space to much longer durations, and develop start-up and control methodologies that will be valuable for an AT DEMO. However, since they do not have a nuclear science mission imposing operation at high absolute plasma pressure, that particular aspect of scientific information will have to be obtained elsewhere.

ITER, being a superconducting tokamak with plans for a steady-state AT burning plasma campaign, comes closest to reactor conditions. ITER has a high gain mission with Q>10. It will create a plasma dominated by alpha heating unlike any of the experiments that come before ITER. This will present unique challenges for stability, transport and burn control. With its large size, ITER will take advantage of the small ρ^* to achieve adequate confinement for its mission. According to theory, a high edge pedestal temperature (> 4 keV) is also necessary. ITER will provide the essential information on alpha particle behavior. The presence of 1 MeV negative ion neutral beam will also present an opportunity to evaluate the consequences of beam- alpha particle interactions in a burning plasma.

Because of the size difference, ITER would not fully replicate the ARIES-AT conditions. ARIES-AT operates at 80% higher β_N and requires much stronger shaping. The six times larger neutron flux requirement for ARIES-AT also means a higher absolute pressure. ARIES-AT will have a higher edge pedestal (Fig. 1) and a broad negative shear profile that impact both stability and transport.

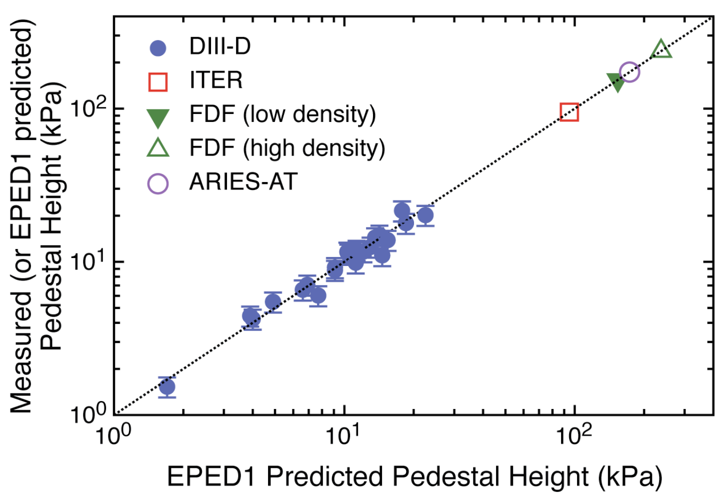

Figure 1: The pedestal height predicted by the EPED1 model is compared to observed pedestal height for a series of DIII-D discharges encompassing a wide range of plasma current, magnetic field and triangularity (solid circles). Good agreement between the model and observations is found, with a ratio of predicted to observed pedestal height of 1.02 ± 0.13. Predicted pedestal height from EPED1 is also shown for the planned ITER baseline operation (open square), ARIES-AT (open circle), and FDF at low ($n_{e,ped}$=2 10^{20} m^{-3}) and high ($n_{e,ped}$=3.6 10^{20} m^{-3}) density operation (open triangles).

The Fusion Development Facility (FDF) [2] will complement ITER by approaching the ARIES-AT physics performance with valuable opportunities to fully diagnose and control the unexplored regime. FDF will contribute significantly to resolution of the issues in high gain and alpha physics (containment and fast ion instabilities). It will help to resolve the issues in confinement at large size and pulse heat loads. The combination of ITER and FDF should resolve the issues in exhaust power handling and integrated plasma performance in steady-state. With strong shaping capability, FDF will significantly extend the performance of ITER in steady-state at high β_N.

TECHNICAL REQUIREMENTS

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. Both ITER and FDF will need high pedestal temperature to achieve the desired fusion gain. Edge rotation and strong shaping may be the key.

Alpha Physics. Here again, ITER provides the essential burning plasma information. But FDF makes a meaningful contribution with its modest gain, significant fusion power, reactor level alpha beta and ratio of alpha speed/Alfven speed.

Confinement at Large Size. Both ITER and FDF will operate at high density with electron-ion fully equilibrated. ITER will make the unique contribution of confinement data at low ρ^*. FDF, being more compact and with a larger edge bootstrap current, will have a broad negative central magnetic shear equilibrium. Modeling predicts neoclassical ion confinement and possible alpha stabilization of electron turbulence from high β_N.

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. ITER plans to use Resonant Magnetic Perturbation to mitigate ELMs. FDF plans to demonstrate Quiescent H-Mode ELM-free operation.

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. FDF's P/R values span from ITER to ARIES-AT, depending on how FDF is operated, but its nominal peak heat fluxes stay below 10 MW/m^2.

Integrated Plasma Performance in Steady-State. Here both ITER and FDF are rated as contributing significantly to resolution of the issue and the combination of both 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. FDF will use ECCD for noninductive current drive and positive NBI to provide edge rotation.

Steady-State at High Beta (High β_N and Bootstrap Fraction). Here the main contribution will come from FDF since it plans to fully embrace reactor level β_N operation through an optimally designed RWM stabilization coil system 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 to supplement high bootstrap fraction. FDF aims to show operation for arbitrary time durations, days to two weeks. While ITER will certainly make an important contribution here, how much it can contribute will depend on the result of the ongoing design review which will decide whether RWM coils will be implemented; whether the ITER plasma can be rotated fast enough; whether there will be sufficient off-axis current drive for AT modes; whether ITER startup can support AT modes; and whether ITER can implement ELM suppression.

RESEARCH OPPORTUNITIES TO ADDRESS DEMO ISSUES

- The machine hardware and configuration in FDF can support extending β_N up toward 5.
- Robust, disruption-free operation would require knowing the stability boundary and the stabilization techniques with high accuracy and reliability.
- ITER, FDF and ARIES-AT have strongly coupled electron and ion transport. Alpha stabilization of electron turbulence at higher β_N can further improve confinement.
- Integration of high bootstrap fraction (> 80%) peaked near the edge with non-inductive current drive, high β_N and good confinement will be a feasibility demonstration of ARIES-AT physics operation.
- FDF provides an environment to study alpha particle physics uncoupled with other energetic particle drive.
- Controlling the shape in both DN and SN and optimizing stability in a plasma dominated by alpha-heating will produce valuable information for DEMO design.
- Plasma control system will show multiple-day operation of a burning plasma tokamak without interruption.
- 3-D magnetic field and rotational stabilization of edge instabilities with high pedestal β will expand control techniques to reactor relevant regimes.
- Techniques for start-up of a burning plasma leading to a steady-state with high pressure and well-aligned bootstrap current for stability can be developed on FDF.
- Innovative divertor configurations compatible with steady-state particle exhaust and shaping control can be tested.

References

[1] Farrokh Najmabadi, the ARIES Team, Fusion Engin. Design 80 (2006) 3-23.

[2] R.D. Stambaugh, et al., "Research Thrusts Made Possible by a Fusion Development Facility," General Atomics White Paper WP 09-01, 2009.