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INTEGRATION OF HIGH-PERFORMANCE, STEADY-STATE BURNING PLASMAS

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GENERAL ATOMICS

ARIES-AT DEMO REQUIREMENTS

Integration of high-performance and steady-state conditions in an ARIES-AT DEMO plasma requires the simultaneous realization of several physics and engineering requirements. Several of these requirements interact with good synergy, as characteristic of the Advanced Tokamak concept. Others, however, have seemingly incompatible features.

Magnetic Equilibrium & Stability

- To produce a sufficient fusion power density, and to utilize high bootstrap fraction regimes to achieve economic attractiveness, DEMO should aim to achieve steady-state with β_N up to 5 and f_{boot} ~90% [1]
- MHD stability limits can be increased by optimizing the equilibrium configuration (cross-sectional shape and radial profiles) and by combined use of conducting walls surrounding the plasma and feedback stabilization of modes
- AT DEMO requirements for high β_N stability include:
  - — Triangularity of 0.7–0.9
  - — Elongation of 2.2–2.4

Confinement

- In order to utilize small amounts of external heating to achieve economic attractiveness, DEMO will need to have good confinement, with H_{98Y2} ~1.4 [1]
- AT DEMO requirements for good confinement include:
  - — High pedestal pressure (see Fig. 1) [2]
    - ★ High pedestal broadens the pressure profiles, improves core confinement by reducing heat and particle transport which is driven primarily by gradient driven microinstabilities
      - ♦ Broader pressure profiles also results in higher global beta limits
    - ★ High pedestal allows fusion relevant temperatures in most of the volume
  - — ExB shear for turbulence suppression and improved confinement
  - — Negative central magnetic shear (NCS), thought to reduce turbulent growth rates
  - — Strong Shafranov shift (α stabilization of turbulence)

good synergy: High triangularity and elongation lead to a high pedestal

good synergy: Large edge bootstrap current also favorable for a high pedestal, since it can open second stability to high-n modes

good synergy: High beta leads to strong Shafranov shift

good synergy: Higher bootstrap fraction gives broader NCS

good synergy: NCS with qmin>2 increases global with-wall beta limit

bad synergy: High pedestal limits penetration and therefore use of LHCD

bad synergy: High pedestal limits neutral beam penetration, leading to low ExB shear in core

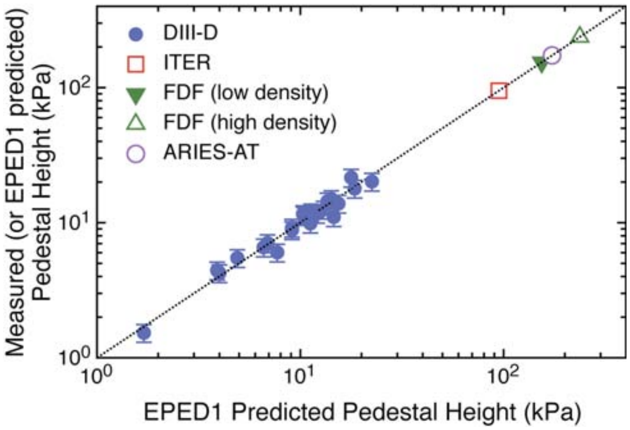

Fig. 1. Pedestal height predicted by the EPED1 model compared to observed pedestal height for series of DIII-D discharges encompassing a wide range of plasma current, magnetic field and triangularity (solid circles). Predicted pedestal height from EPED1 also shown for planned ITER baseline operation (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).

Heating

- AT DEMO requirements for efficient central heating include:
  - — NBI: beam energy must exceed 1 MeV for sufficient penetration, therefore negative ion sources must be used. This technology is expensive and inflexible.
  - — ICRF: coupling of ICRF waves to high performance plasma cores has yet to be demonstrated at the required power density levels for realistic plasma-limiter gaps
  - — ECH:
    - ★ Gyrotrons being validated at 170 GHz are close to the needs of ARIES-AT
    - ★ Antenna is much simpler and more robust than today’s designs for ICRF antennas
    - ★ Heating location may be controlled by steering the waves, unlike ICRF for which absorption depends on resonance location and kinetic profiles

Current Drive

- Current drive is needed to provide the fraction of the plasma current not sustained by the bootstrap current, and to develop and support the target current profile
- AT DEMO requirements for current drive include:
  - — High efficiency
  - — Capability to place at easily controlled locations
    - ★ Negative ion based NBCD: can supply central current drive, but technology is poorly developed
    - ★ Positive ion based NBCD: can supply current drive near or outside $\rho = 0.8$
    - ★ FWCD: can supply central current drive but antenna coupling problem requires progress

- ★ Lower hybrid current drive (LHCD): has quite high current drive efficiency, but its location is determined by local plasma parameters and only weakly by launched $n_{||}$ spectrum.
  - ♦ For ARIES-AT parameters and kinetic profiles, modeling has shown that the LHCD lies near or outside $\rho = 0.9$
- ★ Electron Cyclotron Current Drive: most flexible current drive system
  - ♦ ECCD efficiency is modest especially at large minor radii

Rotation

- Toroidal rotation benefits tokamak plasmas by flow shear stabilization of turbulence and suppression of macroscopic plasma instabilities
- AT DEMO requirements for plasma rotation include [2]:
  - — Minimum plasma rotation ~0.5% of the Alfven frequency for stability at β_N up to the ideal-wall limit
  - — Large core rotation shear for turbulence suppression
  - — Large edge rotation shear to enable ELM free operation in QH-mode

good synergy: Intrinsic rotation at large minor radius increases with β_N

good synergy: Large edge rotation shear from positive ion based NB is favorable for QH-mode access

bad synergy: RMPs for ELM suppression will reduce co-I_p rotation

good synergy: RMPs can be used to establish rotation in counter-I_p direction

Alpha Particle Physics

- Self-heating in DEMO will be provided by the slowing down of 3.5 MeV alphas generated through D-T fusion reactions
- Fast ion driven instabilities such as Alfvén eigenmodes (AEs) can resonate with fast ions and be driven unstable, possibly causing enhanced transport of the energetic particles necessary for heating, reducing plasma performance and potentially damaging the first wall
  - — Fast ions can provide net drive or net damping to AE instabilities, depending on plasma parameters
- RWM stabilization at slow plasma rotation may depend strongly on the presence of a fast ion population
  - — Fast ion loss should be avoided or mitigated in DEMO

Divertor

- Localized divertor heating can be expected to be much greater for an ARIES-AT DEMO than for ITER or present day and planned tokamaks
- High neutron flux on divertor and wall could have significant consequences (plasma-wall interaction changes with neutron damage)
- AT DEMO requirements for the divertor include:
  - — Balanced double-null (DN) configuration for high triangularity
  - — Peak poloidally projected heat flux <10 MW/m^2

- ★ High tilting of target plate, axi-symmetric construction (divertor must present a perfectly toroidally flat surface to the divertor field lines)
- ★ Strongly radiative divertor regime (compatibility with high performance?)
- ★ Super X Divertor, or other novel configuration (physics not yet tested)

good synergy: DN choice over SN reduces peak heat flux by ~20%

good synergy: DN choice requires less heat protective armor at the inner divertor targets

bad synergy: DN choice requires second divertor structure, increases machine complexity

bad synergy: DN choice requires shaping/control coils to maintain divertor balance

GAPS TO ARIES-AT DEMO

The ITER device is designed as a lower single null configuration with moderate elongation and triangularity:

- ITER plasma triangularity ~0.3–0.5, elongation ~1.7–1.85.
  - — Baseline/hybrid ITER β_N=1.8/2.5
  - — Modestly advanced scenario β_N~3 and f_{boot}~50%, (with additional investments)

The study of high-beta AT modes and their long pulse operation will be carried out intensively on three new superconducting magnet tokamaks under development:

- EAST, KSTAR, and JT60-SA designed to explore $\beta_N > 4$ and f_{boot}~90%
  - — Pressure profile control quite different from that of a D-T plasma with strong alpha heating
  - — Pedestal pressure comparable to present day devices (« DEMO)

gap to DEMO: High performance core ($\beta_N > 4$ and f_{boot} ~90%) in the presence of fast ion populations truly dominated by fusion generated alphas

gap to DEMO: High performance core with shallowly penetrating NBI and LHCD (demanding new ideas for providing rotation and profile control)

gap to DEMO: High performance core with high density, low collisionality pedestal

gap to DEMO: High performance core coupled to high heat load, high neutron flux divertor target

ROLE OF FDF AS A RESEARCH THRUST FOR ADDRESSING GAPS TO ARIES-AT DEMO

- **FDF is designed as a new compact D-T experiment operating with $\beta_N > 3.5$, $T_{PED} > 5$ keV, $f_{\text{boot}} > 60\%$ and with strong shaping and control capabilities [2]**
- Double-null divertor plasmas with triangularity of 0.6–0.7 and elongation of 2.2–2.3
- Close-by conducting wall and PF coils, optimally designed non-axisymmetric coils
- With 30MW of ECCD and 20 MW of shallowly penetrating (r/a > 0.7) positive NBI (to drive edge rotation), self-consistent modeling using the ONETWO transport code has shown a Q ~ 4.4 and H_{98Y2} ~ 1.5
  - — Predicted NBI-driven toroidal rotation is ~$3\text{x}10^5$ rad/sec, i.e. larger than 10% of the Alfven frequency.
  - — This rotation profile is likely to exceed the minimum edge rotation shear necessary for ELM free operation in QH-mode

- At high β_N, α-stabilization is effective in the core resulting in neoclassical ion confinement without ExB shear
    - Electron transport is larger by two orders of magnitude suggesting an open and fruitful research area in electron confinement improvement
- Steady-state, high performance properties fully supported by 75 MW of ECCD power deposited near rho=0.6, plus a modest central ECCD
    - FDF plasmas, without NBI populations in the core will be unique for testing of AE and RWM stability with fast ion populations truly dominated by fusion generated alphas
- **Successful FDF operation should result in optimization of realistic scheme to achieve a high pedestal without ELMs which can be directly applied to an ARIES class reactor**
    - Pedestal height of FDF in physical units will be in the range of interest for ARIES-AT
    - RMP coils will allow exploration of RMP ELM control in the pedestal parameter regime relevant to a reactor (high pedestal, very strong magnetic shear, low collisionality, high Greenwald fraction, high q/q_*)
    - Strong shaping of FDF allows a high value of the QH mode maximum density, meaning that QH mode may be accessible at any achievable value of the density
    - Without NBI, nonresonant magnetic field torque from RMP coils could be used to drive plasma rotation towards the neoclassical offset rotation, predicted for the baseline FDF to be >1% of the Alfven frequency, in the counter-I_P direction
        - ★ Because of its very high shear close to the plasma edge, the neoclassical offset rotation may also be sufficient to provide access to QH-mode of operation
- **Baseline divertor design for FDF is a conventional tilted plate type with the intention to make maximal use of flux expansion**
    - FDF's divertor will be built in a factory setting as a single precision toroidal ring with precision placement of tiles on it, for fully axisymmetric heat flux handling
    - Advanced divertor concepts, such as the Super-X divertor (U. of Texas) and the Snow Flake divertor (Lawrence Livermore National Laboratory), can be viewed as forms of the flux expansion approach
    - Simple projections and modeling calculations indicate that for this baseline divertor the peak poloidally projected heat flux will stay below 10 MW/m^2
    - In strongly radiative detached regime, SOLPS analysis predicts a peak heat flux ≤2 MW/m^2

References

[1] Farrrokh Najmabadi, the ARIES Team, “ The ARIES-AT Advanced Tokamak, Advanced Technology Fusion Power Plant,” Fusion Engineering and Design 80 (2006) 3–23.

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