Physics Analysis for Equilibrium, Stability, and Divertors

ARIES Power Plant Studies

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ARIES Configurations

• ARIES-RS (1995-1996); reversed shear

• ARIES-ST (1996-1998); spherical torus

• ARIES-AT (1999-2000); extended reversed shear
## ARIES-RS, ST, AT Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARIES-RS</th>
<th>ARIES-ST</th>
<th>ARIES-AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ip(MA)</td>
<td>11.3</td>
<td>28.4</td>
<td>12.8</td>
</tr>
<tr>
<td>B(r)(T)</td>
<td>7.98</td>
<td>2.08</td>
<td>5.86</td>
</tr>
<tr>
<td>R(m)</td>
<td>5.52</td>
<td>3.20</td>
<td>5.20</td>
</tr>
<tr>
<td>a(m)</td>
<td>1.38</td>
<td>2.00</td>
<td>1.30</td>
</tr>
<tr>
<td>(\kappa^*)</td>
<td>1.70</td>
<td>3.40</td>
<td>2.15</td>
</tr>
<tr>
<td>(\delta^*)</td>
<td>0.50</td>
<td>0.67</td>
<td>0.78</td>
</tr>
<tr>
<td>(\kappa(Xpt))</td>
<td>1.90</td>
<td>3.40</td>
<td>2.20</td>
</tr>
<tr>
<td>(\delta(Xpt))</td>
<td>0.70</td>
<td>0.67</td>
<td>0.90</td>
</tr>
<tr>
<td>(\beta_p)</td>
<td>2.29</td>
<td>1.79</td>
<td>1.98</td>
</tr>
<tr>
<td>(\beta(%))</td>
<td>4.98</td>
<td>50.4</td>
<td>9.15</td>
</tr>
<tr>
<td>(\beta^*(%))</td>
<td>6.18</td>
<td>55.0</td>
<td>11.0</td>
</tr>
<tr>
<td>(\beta_s(%)) (max)</td>
<td>4.84 (5.35)</td>
<td>7.40 (8.20)</td>
<td>5.40 (6.00)</td>
</tr>
<tr>
<td>(q_{axis})</td>
<td>2.80</td>
<td>4.35</td>
<td>3.50</td>
</tr>
<tr>
<td>(q_{min})</td>
<td>2.45</td>
<td>4.35</td>
<td>2.40</td>
</tr>
<tr>
<td>(q_{edge,*})</td>
<td>3.52</td>
<td>11.5</td>
<td>3.70</td>
</tr>
<tr>
<td>I_{bs}(MA)</td>
<td>10.0</td>
<td>25.6</td>
<td>11.4</td>
</tr>
<tr>
<td>I_{self}/Ip</td>
<td>0.91</td>
<td>0.99</td>
<td>0.91</td>
</tr>
<tr>
<td>I_{CD}(MA)</td>
<td>1.15</td>
<td>0.00</td>
<td>1.25</td>
</tr>
<tr>
<td>q_{cyl}</td>
<td>2.37</td>
<td>3.00</td>
<td>1.85</td>
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<tr>
<td>(\bar{l}(3))</td>
<td>0.42</td>
<td>0.13</td>
<td>0.29</td>
</tr>
<tr>
<td>n(0)/&lt;n&gt;</td>
<td>1.36</td>
<td>1.24</td>
<td>1.34</td>
</tr>
<tr>
<td>T(0)/&lt;T&gt;</td>
<td>1.98</td>
<td>1.24</td>
<td>1.72</td>
</tr>
<tr>
<td>p(0)/&lt;p&gt;</td>
<td>2.20</td>
<td>1.41</td>
<td>1.93</td>
</tr>
<tr>
<td>(b/a)_{kink})</td>
<td>0.25</td>
<td>0.15</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* value corresponds to fixed-boundary equilibrium
Detailed Physics Analysis is Used for ARIES Designs

• High accuracy equilibrium
• Ideal MHD stability
• Vertical stability and control
• Free-boundary equilibria and PF coil design
• Divertor physics/Plasma radiation
• New physics analysis and issues
High Accuracy Equilibria are Essential to Assess Stability

- *JSOLVER* fixed boundary flux-coordinate code has continued to **evolve during the ARIES studies**.
- *JSOLVER* uses pressure and parallel current density profiles as input.
- Several **new methods** for addressing bootstrap current, realistic CD sources, and loop voltage self-consistently have been incorporated.
ARIES-AT Equilibrium
ARIES-ST Equilibrium
ARIES-RS Equilibrium
Extensive Ideal MHD Stability Calculations are Performed

- Low-n external kink stability analysis is performed with *PEST2*.
- High-n ballooning stability analysis is performed with *BALMSC*.
- Recent studies have required high resolution calculations (2400 radial zones by 500 theta zones for ARIES-ST).
- The impact of plasma shape, aspect ratio, and current and pressure profiles on stability is examined.
ARIES-AT Stability Studies Showed that Elongations Above 2.2 Have Worsening Stability
ARIES-AT Stability Analysis Examines Optimization Over Several Parameters

ARIES-AT Ballooning Stability Dependence on Local Pressure Gradient

- $\beta_N \geq 7.25$ (6.85)
- $\beta_N = 6.50$
- $\beta_N = 6.00$
- $\beta_N = 4.20$
- $\beta_N = 4.75$
- $\beta_N = 5.40$

ARIES-AT Ideal MHD Kink Wall Stabilization

- $\kappa = 2.15$
- $\delta = 0.78$
- $\beta_N = 6.0$
- ARIES-AT reference
- $\beta_N = 6.9$
ARIES-ST Stability Studies Show Strong Interplay of Aspect Ratio and Shape (final $\kappa=3.4$, $\delta=0.65$)
The Importance of **Self-Consistent Bootstrap Current** was Recognized by ARIES

- Including the **consistent bootstrap current for a given pressure profile** is critical for accurate stability predictions.
- **Accurate bootstrap models** are necessary to properly determine CD requirements and stability.
- **Finite edge density** that is required for the divertor affects the bootstrap current, CD requirement, and stability.
- Studies have shown that the minimum $P_{CD}$ doesn’t occur at the highest $\beta$ values.
Comparison of Collisional and Collisionless Bootstrap Models Show Significant Differences
Vertical Stability and Control is a Critical Physics/Engineering Interface

- N=0 axisymmetric stability determines the maximum plasma elongation allowed (examined by Corsica).
- Conducting structures in the blanket (tungsten) provide stability margin and a growth time long enough for feedback control.
- TSC nonlinear dynamic simulations were used to calculate feedback control requirements.
- Approximately 90% of feedback power is reactive.
ARIES-AT Vertical Stability showed that $\kappa=2.2$ is consistent with allowed stabilizer location.

Vertical Stability Scan for ARIES-AT:
- Tungsten, 3.5 cm thick, $\rho = 8 \times 10^8$ ohm-m
- $\delta_x = 0.9$
- $\beta_p = 0.25$
- $\iota_i = 0.8$

Stability factor, $f_s = 1 + \frac{q_0}{\tau n}$

Shell location normalized by minor radius (measured from plasma boundary)
ARIES-AT Vertical Stability and Feedback Control Show The Tradeoff of Power and Accessible Plasmas
Free-Boundary Equilibria and PF Coil Design

- Free-boundary equilibria are used for fixed boundary definition and PF coil optimization (TSC).
- New methods for solving equilibria using parallel current for high $\beta$ plasmas were developed.
- Use of 99% free-boundary flux surface in fixed boundary analysis led to increased $\beta$ and strict consistency between analyses.
- Free-boundary flux geometry is used for divertor analysis.
ARIES-ST Free-Boundary Calculations Showed that Shaping is Limited by Realistic PF Coils
ARIES-AT PF Solution Shows all Coil Currents Below 10 MA

+ note that inboard solenoid is fixed and is modeled as 7 coils
Divertor Physics/Plasma Radiation Couples Plasma Core and Edge

- ARIES-RS included first simultaneous optimization of MHD stability, CD, and divertor, showing that high core radiation fraction was not compatible with high bootstrap/low $P_{CD}$.
- Two-point divertor modelling showed that radiating SOL/divertor solutions are possible with reasonable impurity and plasma edge density.
- Finite edge density is included in MHD and CD calculations.
- *UEDGE* analysis is being done on ARIES-AT.
ARIES Continues to Expand Its Physics Analysis and Utilize New Theoretical Developments

- Resistive wall modes, stabilization of kink mode by wall/rotation or feedback control from analysis with MARS (ARIES-AT)
- Neoclassical tearing modes (ARIES-AT)
- T,n profile constraints/transport predictions with GLF23 (ARIES-AT)
- Pellet fueling (ARIES-RS)
- 0-D startup calculations with non-inductive startup (ARIES-ST)
- Ripple losses for high q configurations require very low ripple (ARIES-RS, ST, AT)
RWM Stability and NTM Stability Provide More Stringent Requirements Than Ideal MHD

Low local pressure or RFCD is required to stabilize NTM’s

Plasma rotation is one method to provide a stable window for RWM’s, and may be necessary with feedback control

\[ \frac{l_r}{l_p} = 0.05 \]

\[ \frac{l_r}{l_p} = 0 \]

\[ \beta_0 = 2.65 \]

\[ w/w_{pol} \]

\[ m/n = 5/2 \]

\[ q_0 = 2.76, \ q_{\text{min}} = 2.09 \]

\[ \Delta r = -0.06 ("\text{TEAR}"") \]

\[ \epsilon^{1/2} = 0.47 \]

\[ L_p/L_p = 5.0 \]

\[ w_{pol}/r = 0.02 \]

\[ \beta_0 = 2.65 \]
Fueling Analysis for ARIES-RS
Shows that Low Velocity Pellets Reach Inside ITB
ARIES Incorporates New Experimental Results

- Neutral particle control can allow the plasma density to exceed the Greenwald limit without confinement degradation (DIII-D, TEXTOR).
- Helium particle control is demonstrated with pumped divertors giving $\tau_p^*/\tau_E = 3−15$ (DIII-D, JT-60).
- Detachment of inboard strike point plasma allows high triangularity (DIII-D).
- LHCD is shown to stabilize neoclassical tearing modes (COMPASS, ECCD on ASDEX-U).
- Vertical and inboard pellet launch show better penetration (ASDEX-U, DIII-D).
High $\beta$, High $f_{bs}$ Configurations Have Been Developed as the Physics Basis for Fusion Power Plants

- High accuracy equilibria
- Large ideal MHD database over profiles, shape and aspect ratio
- RWM stable with wall/rotation or wall/feedback control
- NTM stable with L-mode edge and LHCD
- Bootstrap current consistency using advanced bootstrap models
- External current drive
- Vertically stable and controllable with modest power (reactive)
- Modest core radiation with radiative SOL/divertor
- Accessible fueling
- No ripple losses
- 0-D consistent startup
- Rough kinetic profile consistency with RS /ITB experiments, examining GLF23 model consistency
- Several assumptions based on experimental/theoretical results