# 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

| | ARIES-RS | ARIES-ST | ARIES-AT |
|---|---|---|---|
| | | | |
| Ip(MA) | 11.3 | 28.4 | 12.8 |
| $B_T$(T) | 7.98 | 2.08 | 5.86 |
| R(m) | 5.52 | 3.20 | 5.20 |
| a(m) | 1.38 | 2.00 | 1.30 |
| κ* | 1.70 | 3.40 | 2.15 |
| δ* | 0.50 | 0.67 | 0.78 |
| κ(Xpt) | 1.90 | 3.40 | 2.20 |
| δ(Xpt) | 0.70 | 0.67 | 0.90 |
| $\beta_P$ | 2.29 | 1.79 | 1.98 |
| β(%) | 4.98 | 50.4 | 9.15 |
| β*(%) | 6.18 | 55.0 | 11.0 |
| $\beta_N$(%) (max) | 4.84 (5.35) | 7.40 (8.20) | 5.40 (6.00) |
| $q_{axis}$ | 2.80 | 4.35 | 3.50 |
| $q_{min}$ | 2.45 | 4.35 | 2.40 |
| $q_{edge}$ * | 3.52 | 11.5 | 3.70 |
| $I_{bs}$(MA) | 10.0 | 25.6 | 11.4 |
| $I_{self}$/Ip | 0.91 | 0.99 | 0.91 |
| $I_{CD}$(MA) | 1.15 | 0.00 | 1.25 |
| $q_{cyl}$ | 2.37 | 3.00 | 1.85 |
| li(3) | 0.42 | 0.13 | 0.29 |
| n(0)/<n> | 1.36 | 1.24 | 1.34 |
| T(0)/<T> | 1.98 | 1.24 | 1.72 |
| p(0)/<p> | 2.20 | 1.41 | 1.93 |
| $(b/a)_{kink}$ | 0.25 | 0.15 | 0.33 |
| * value corresponds to fixed-boundary equilibrium | | | |

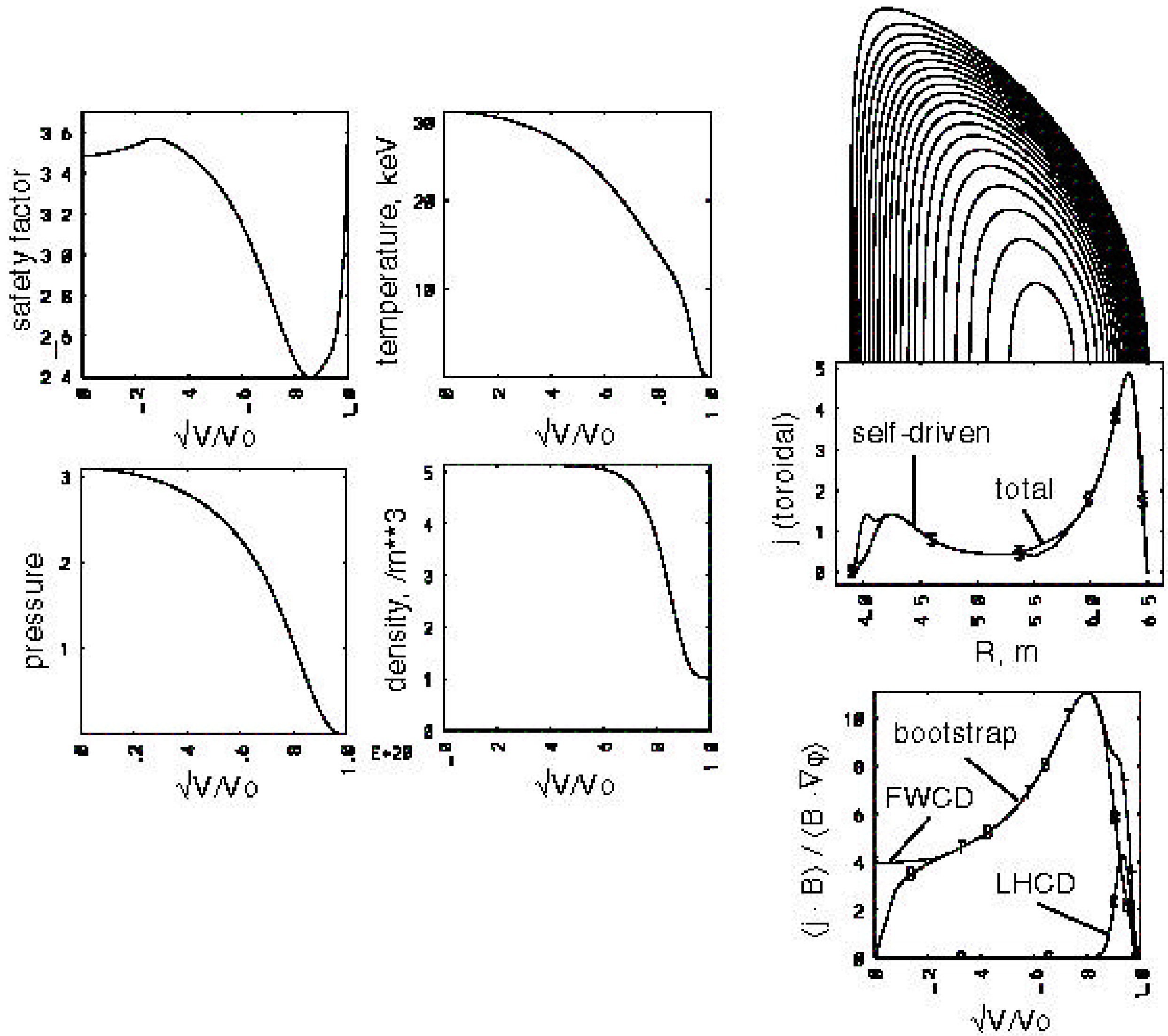
# Detailed Physics Analysis is Used for ARIES Designs

- 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

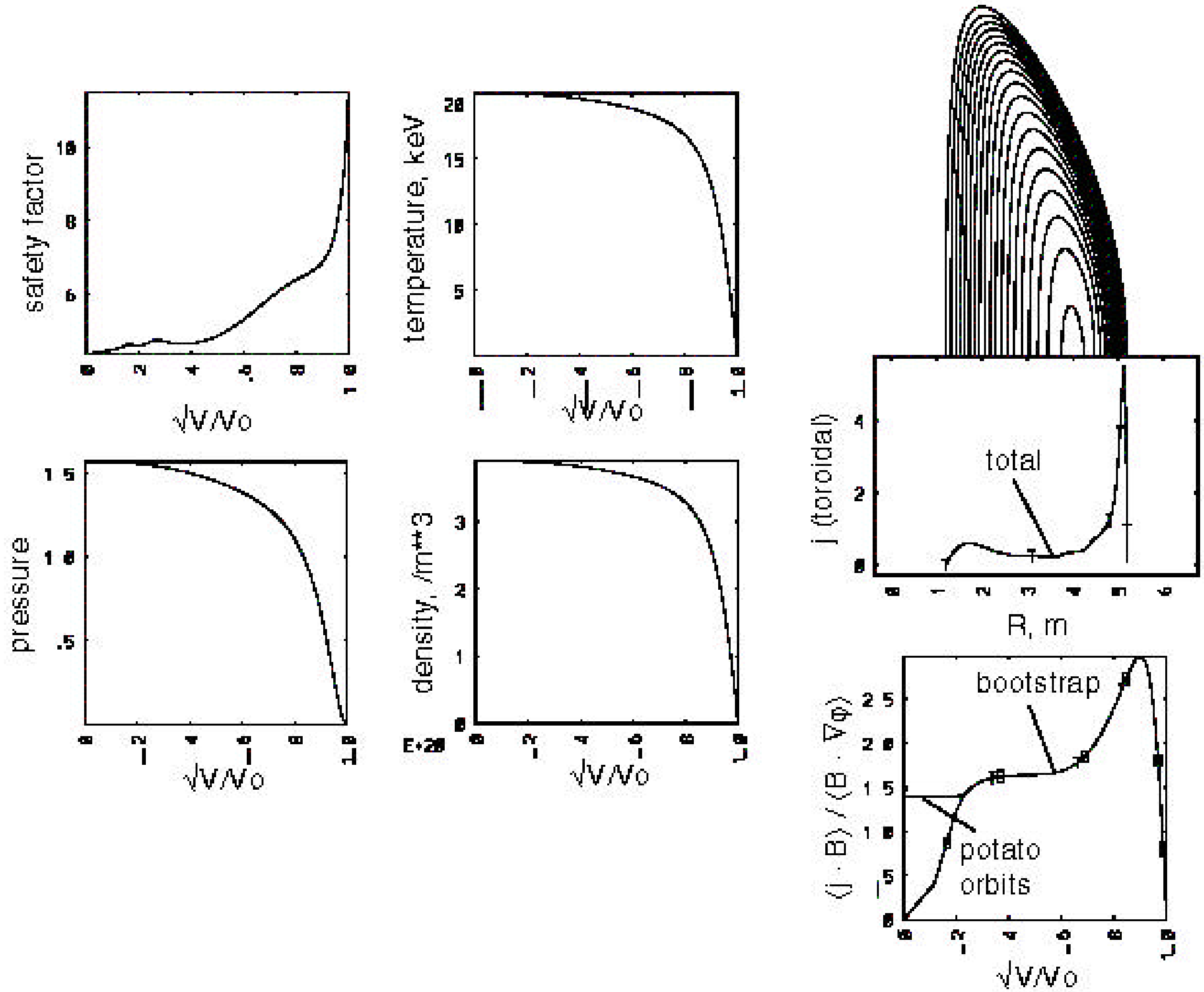
# High Accuracy Equilibria are Essential to Assess Stability

- *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.

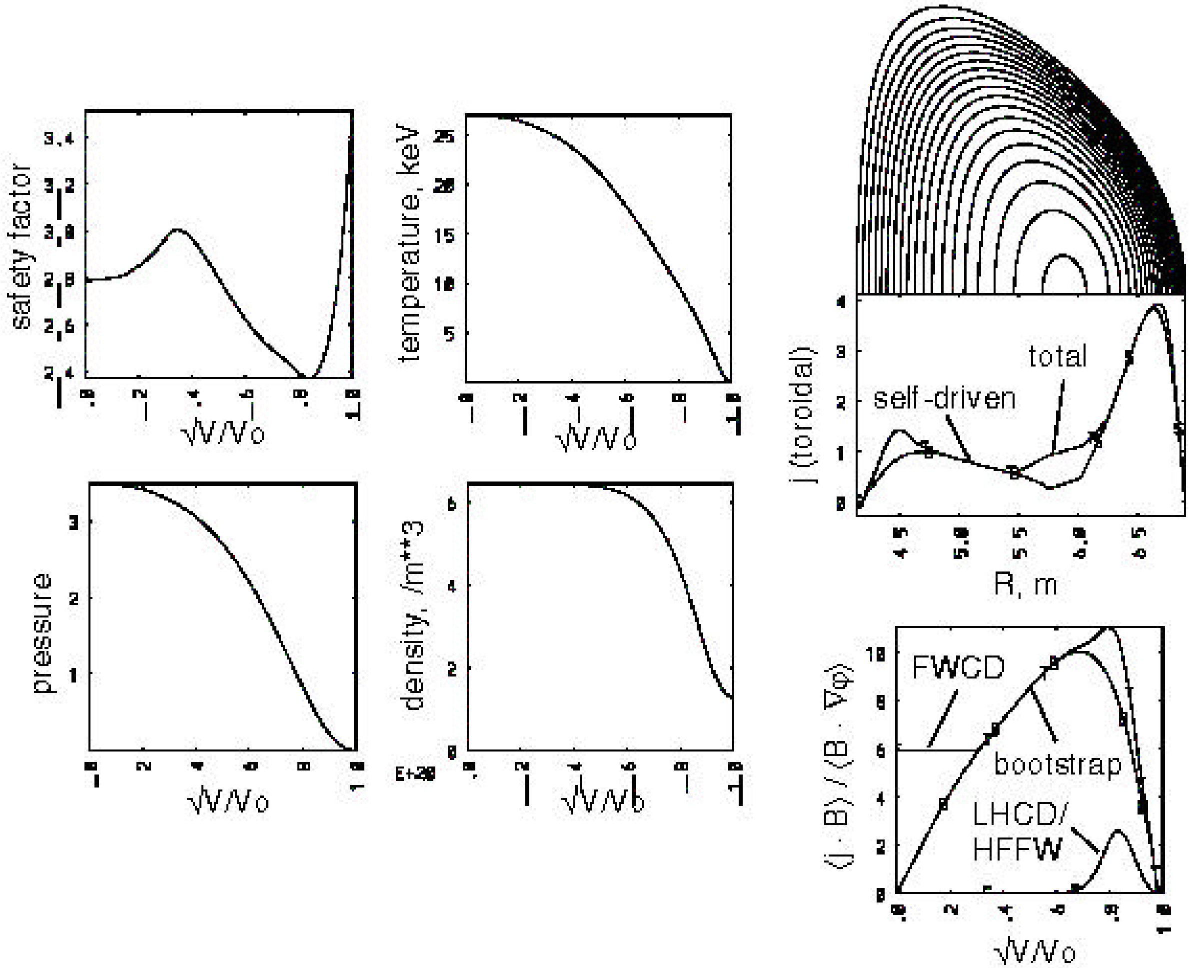
# ARIES-AT Equilibrium



# ARIES-ST Equilibrium



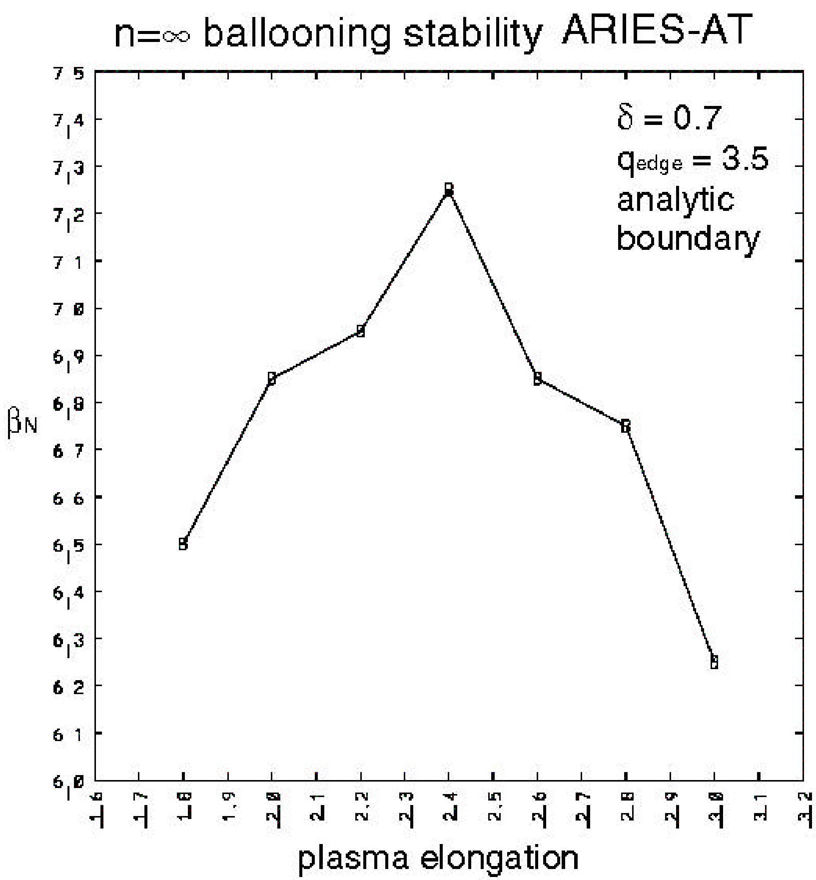
# ARIES-RS Equilibrium

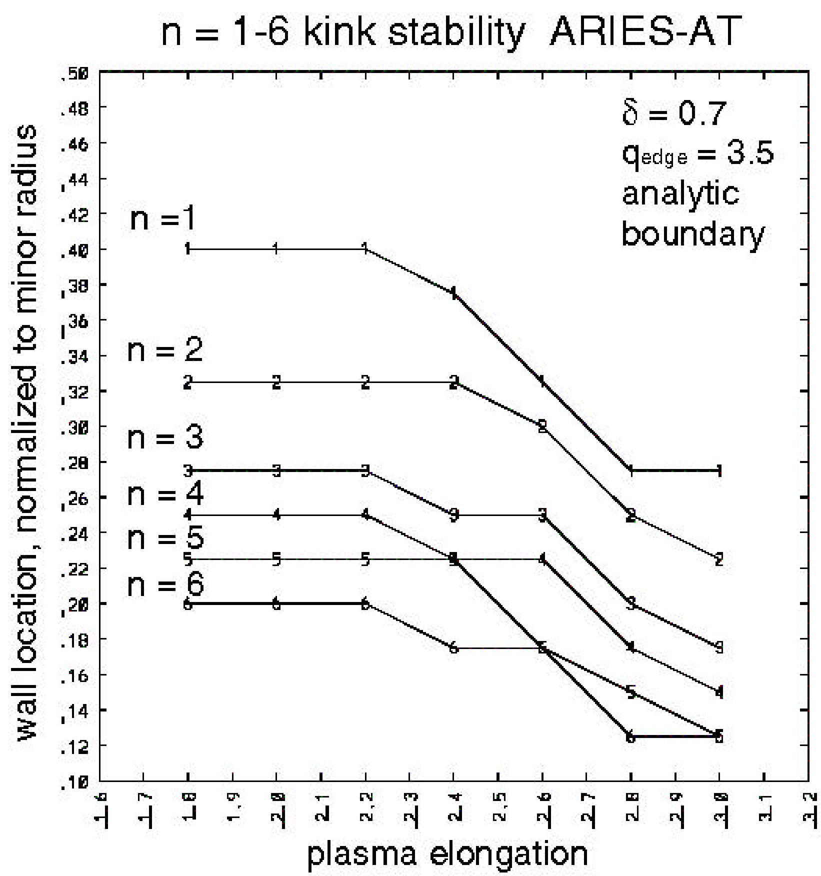


# Extensive Ideal MHD Stability Calculations are Performed

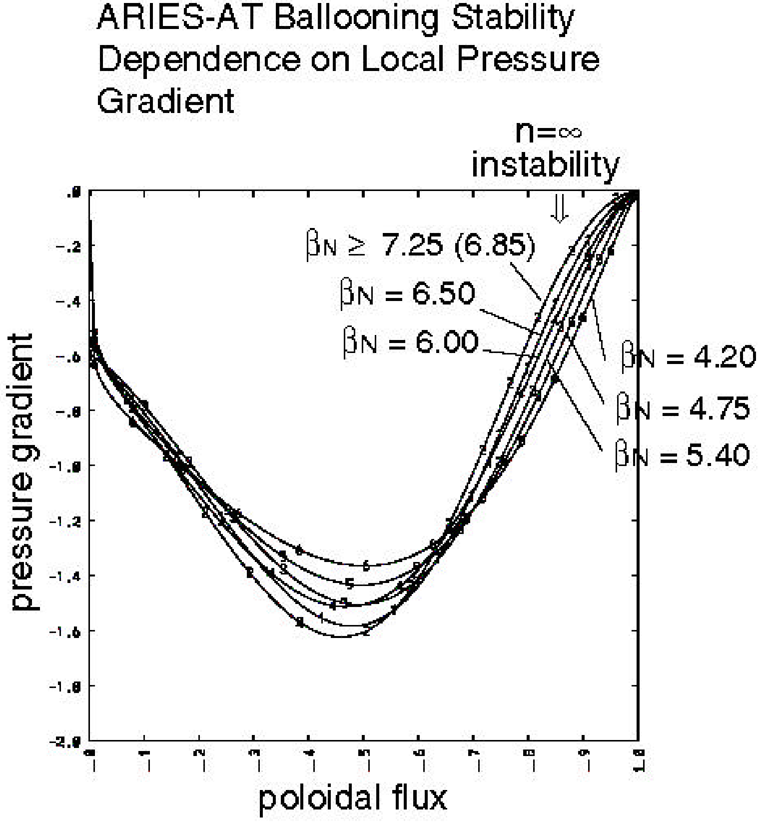
- Low-n external kink stability analysis is performed with *PEST2*.
- High-n ballooning stability analysis is performed with *BALMSC*.
- Recent studies have required high resolution calculations (2400 radial zones by 500 theta zones for ARIES-ST).
- The impact of plasma shape, aspect ratio, and current and pressure profiles on stability is examined.

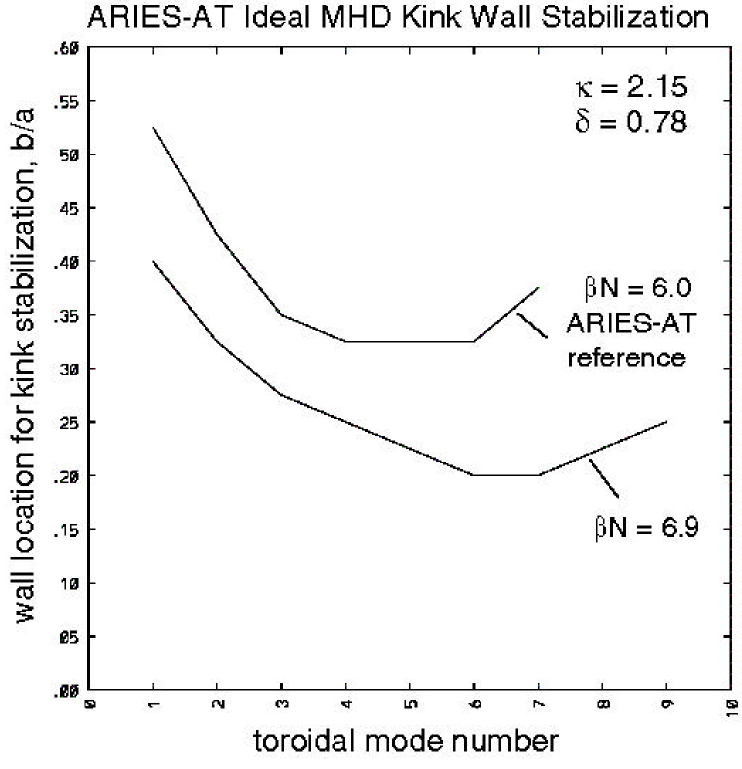
# ARIES-AT Stability Studies Showed that Elongations Above 2.2 Have Worsening Stability



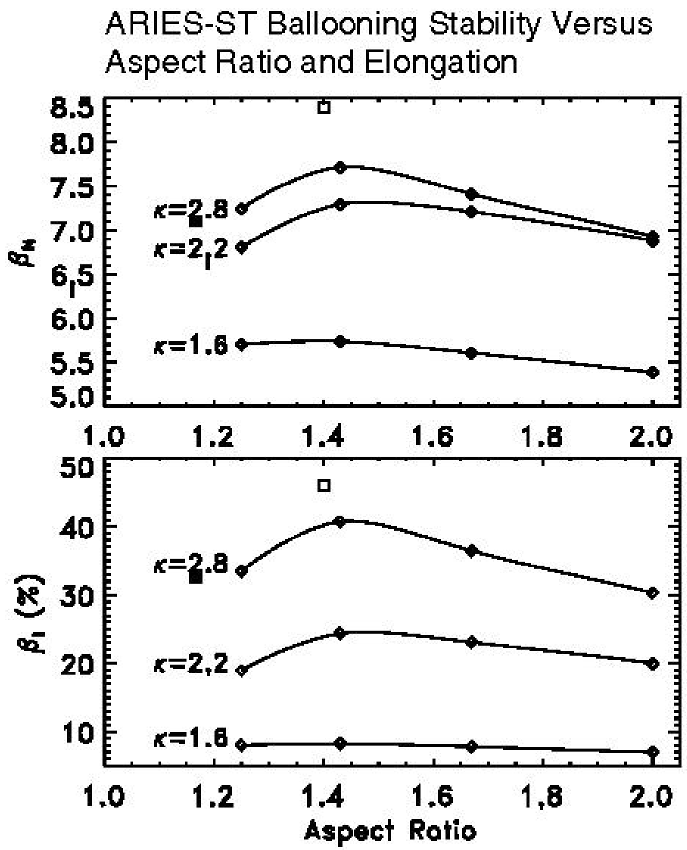



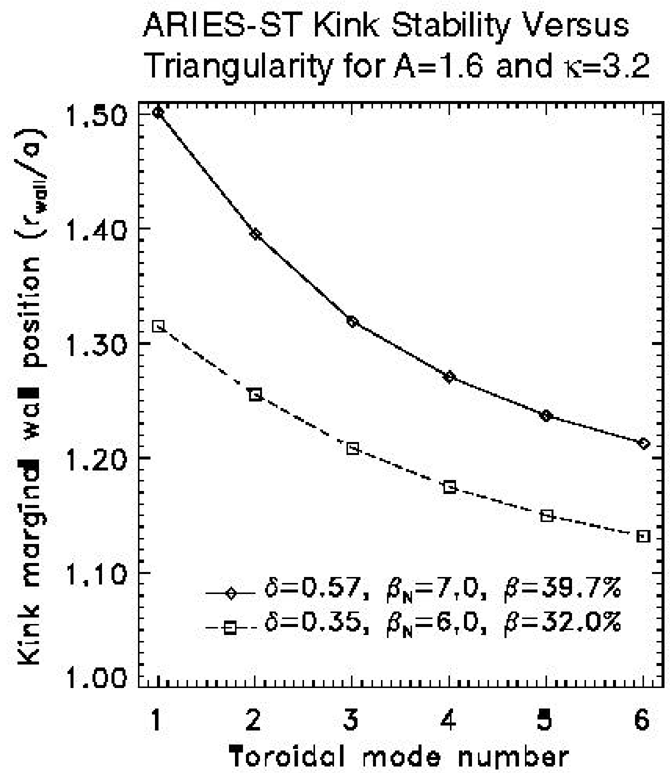
# ARIES-AT Stability Analysis Examines Optimization Over Several Parameters



# ARIES-ST Stability Studies Show Strong Interplay of Aspect Ratio and Shape (final κ=3.4, δ=0.65)

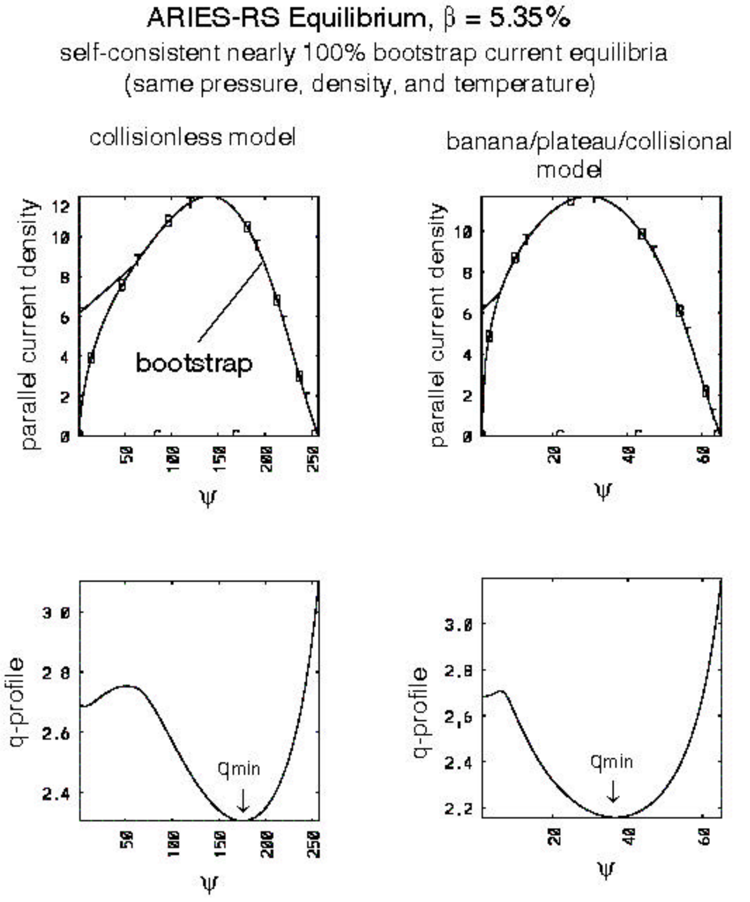


# The Importance of Self-Consistent Bootstrap Current was Recognized by ARIES

- 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.

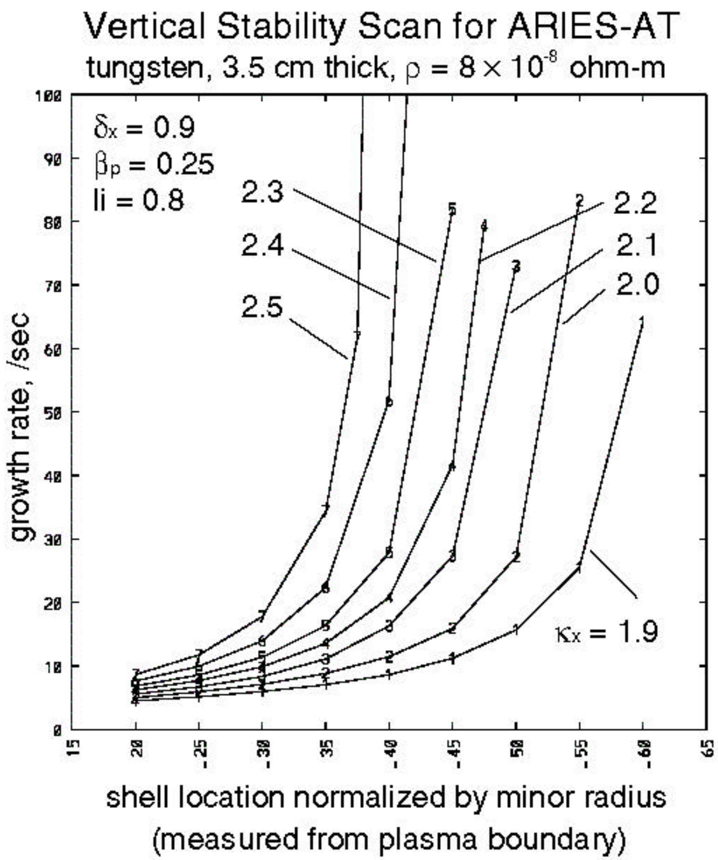
# Comparison of Collisional and Collisionless Bootstrap Models Show Significant Differences

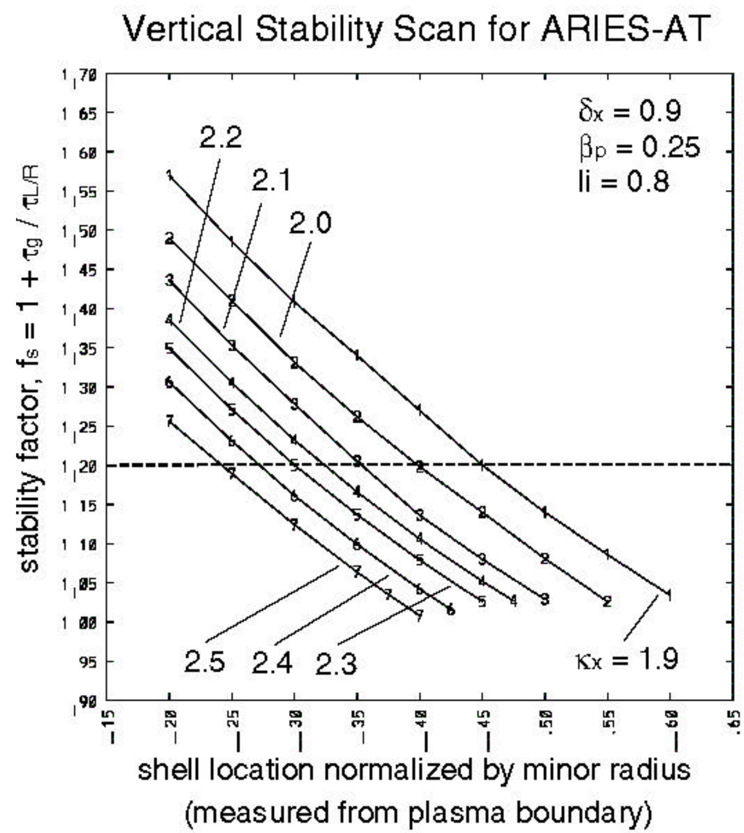


# Vertical Stability and Control is a Critical Physics/Engineering Interface

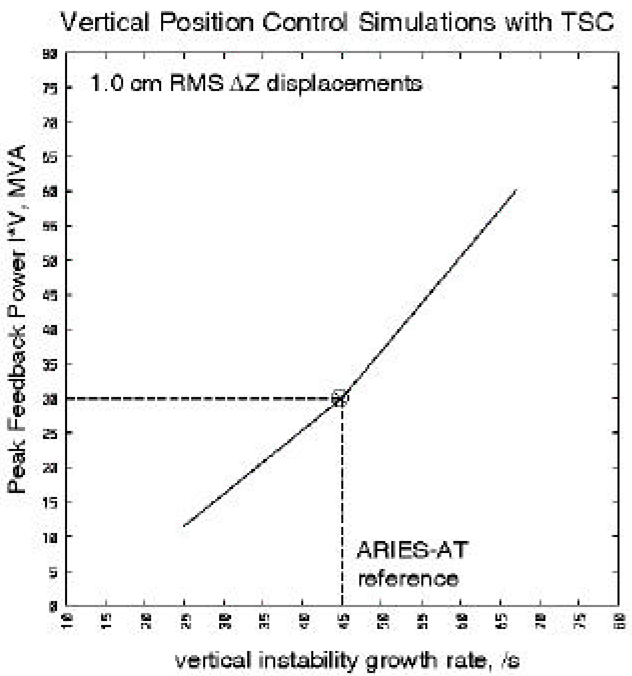
- N=0 axisymmetric stability determines the maximum plasma elongation allowed (examined by *Corsica*).
- Conducting structures in the blanket (tungsten) provide stability margin and a growth time long enough for feedback control.
- *TSC* nonlinear dynamic simulations were used to calculate feedback control requirements.
- Approximately 90% of feedback power is reactive.

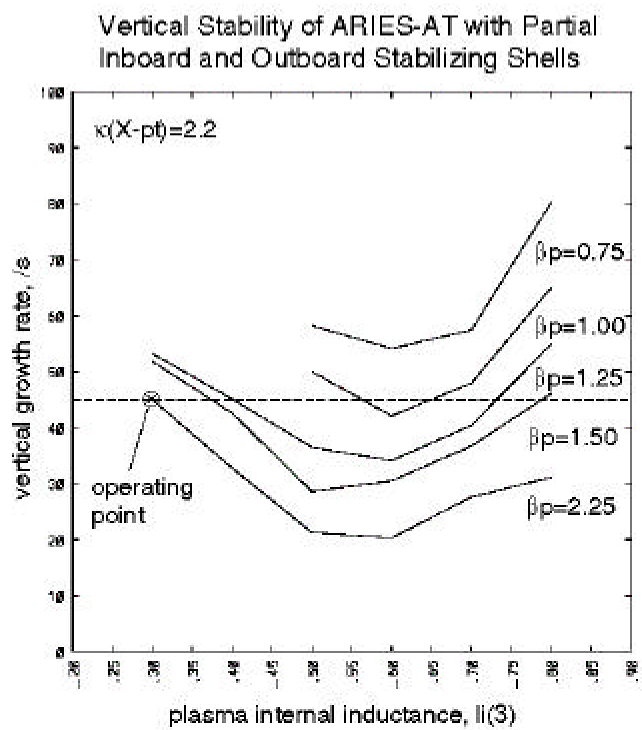
# ARIES-AT Vertical Stability Showed That κ=2.2 Is Consistent with Allowed Stabilizer Location



# ARIES-AT Vertical Stability and Feedback Control Show The Tradeoff of Power and Accessible Plasmas

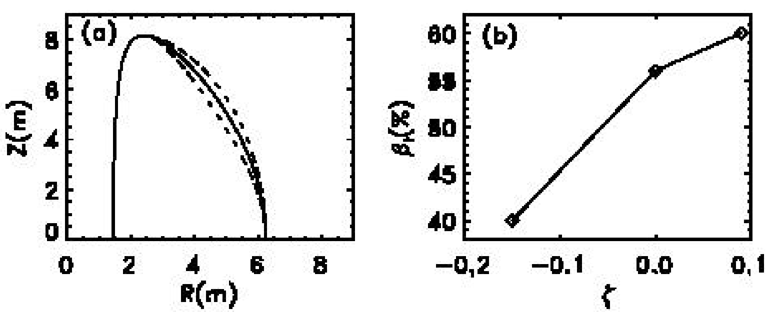


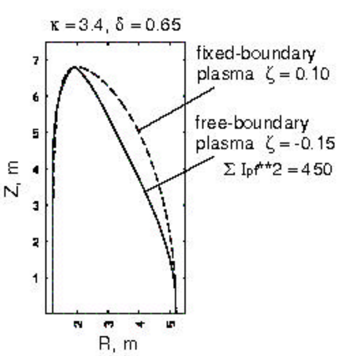



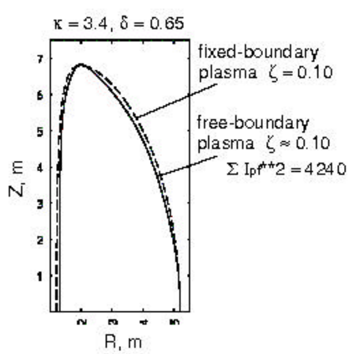
# Free-Boundary Equilibria and PF Coil Design

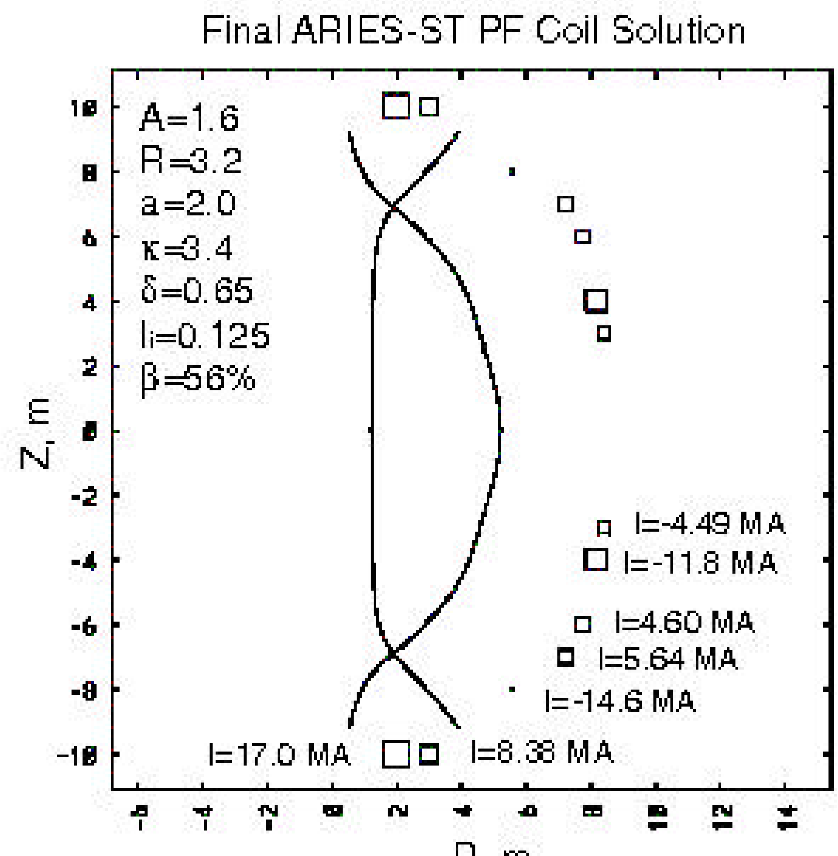
- Free-boundary equilibria are used for fixed boundary definition and PF coil optimization *(TSC)*.
- New methods for solving equilibria using parallel current for high β plasmas were developed.
- Use of 99% free-boundary flux surface in fixed boundary analysis led to increased β and strict consistency 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

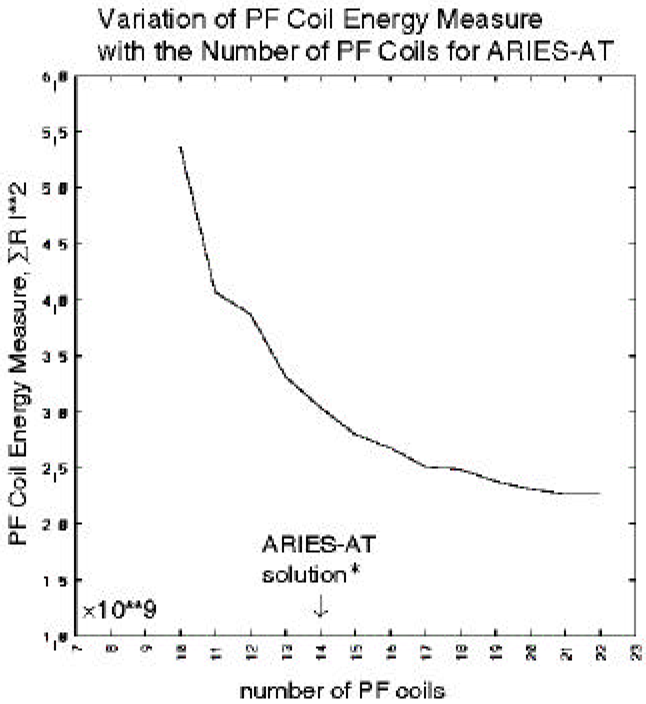


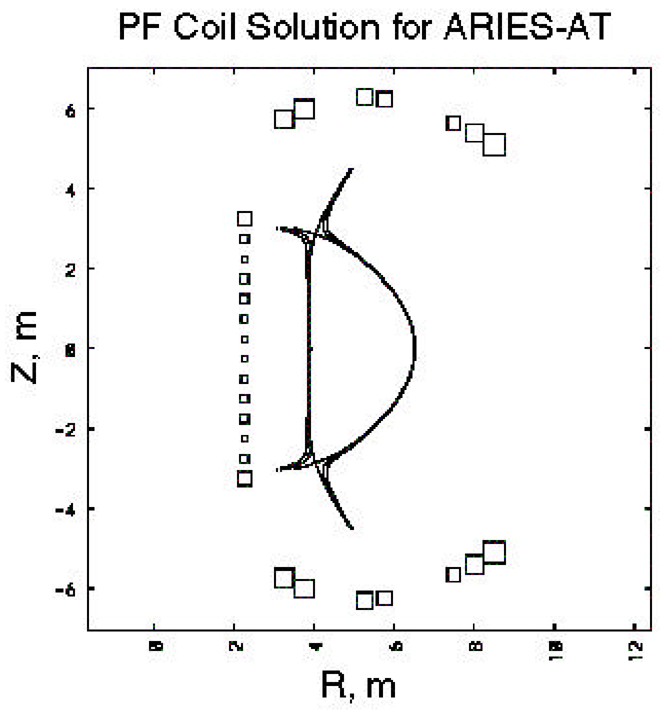



# ARIES-AT PF Solution Shows all Coil Currents Below 10 MA




* note that inboard solenoid is fixed and is modelled as 7 coils



# Divertor Physics/Plasma Radiation Couples Plasma Core and Edge

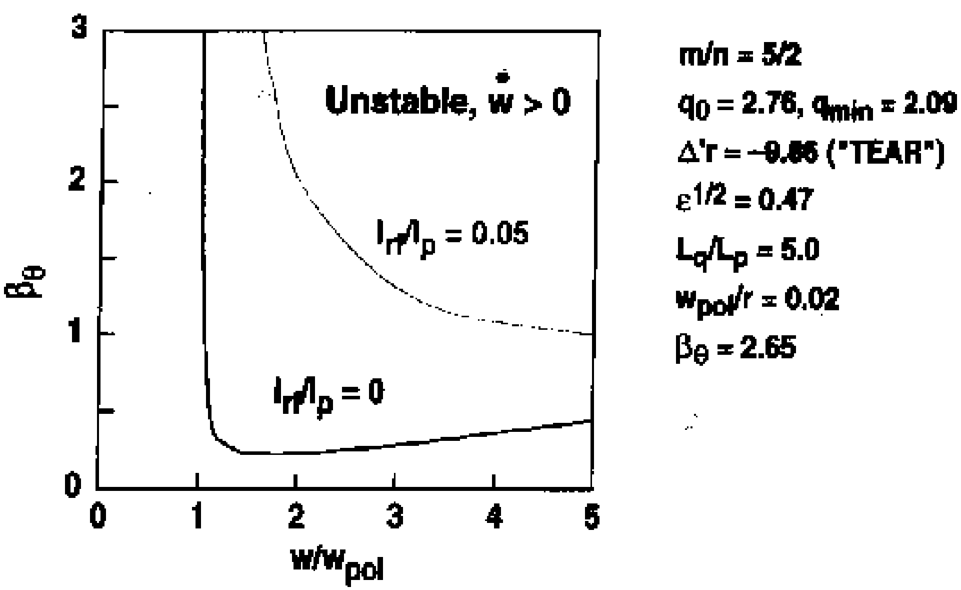
- ARIES-RS included first simultaneous optimization of MHD stability, CD, and divertor, showing that high core radiation fraction was not compatible with high bootstrap/low $P_{CD}$.
- Two-point divertor modelling showed that radiating SOL/divertor solutions are possible with reasonable impurity and 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

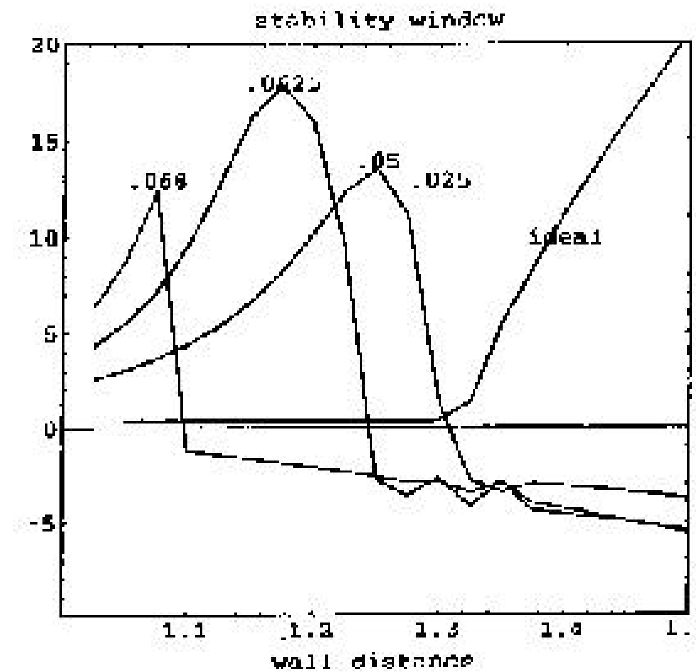
- Resistive wall modes, stabilization of kink mode by wall/rotation or feedback control from analysis with *MARS* (ARIES-AT)
- Neoclassical tearing modes (ARIES-AT)
- T,n profile constraints/transport predictions with GLF23 (ARIES-AT)
- Pellet fueling (ARIES-RS)
- 0-D startup calculations with non-inductive 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

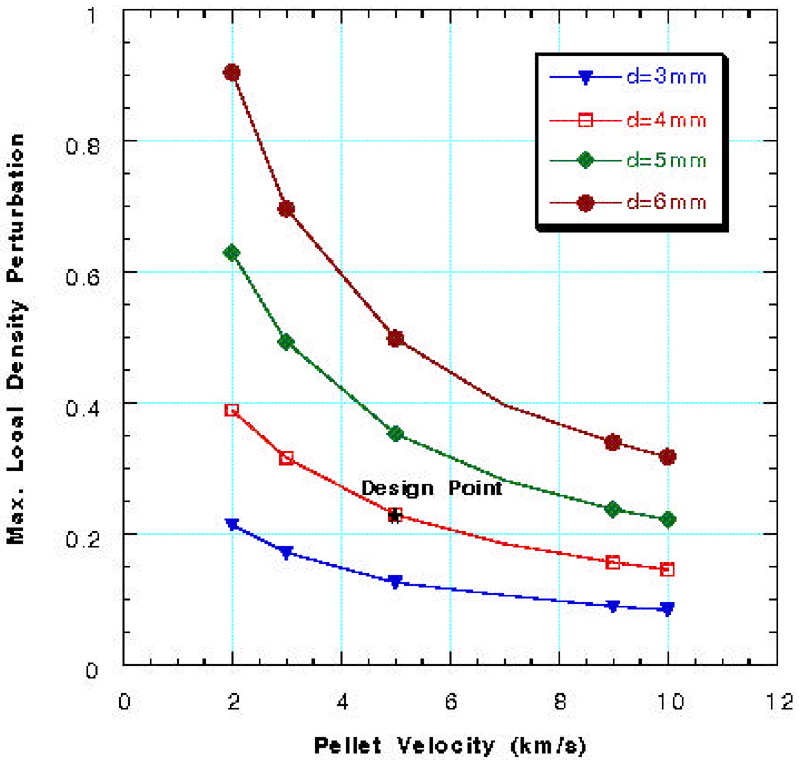
Low local pressure or RFCD is required to stabilize NTM's

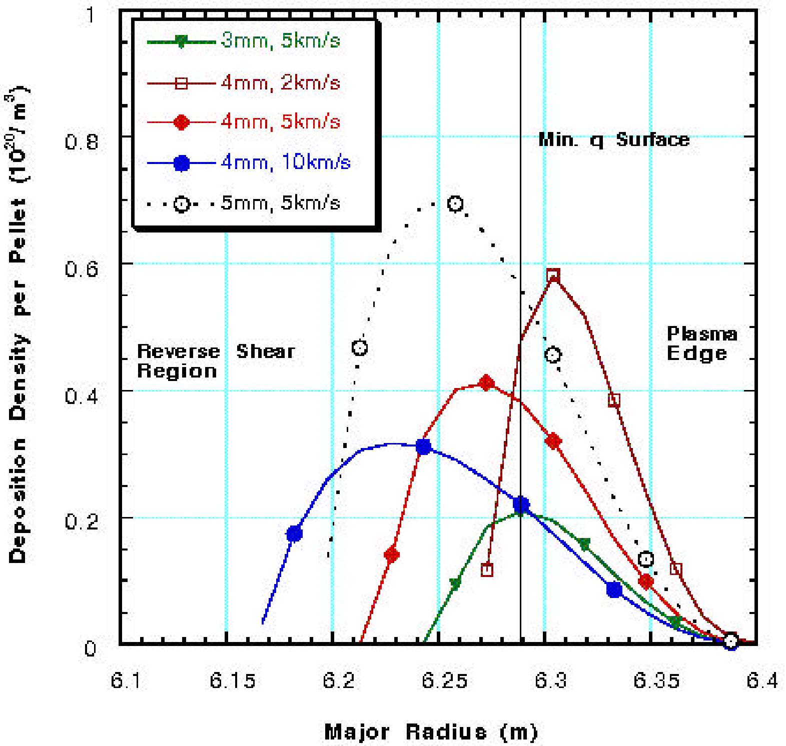



Plasma rotation is one method to provide a stable window for RWM's, and may be necessary with feedback control



# 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